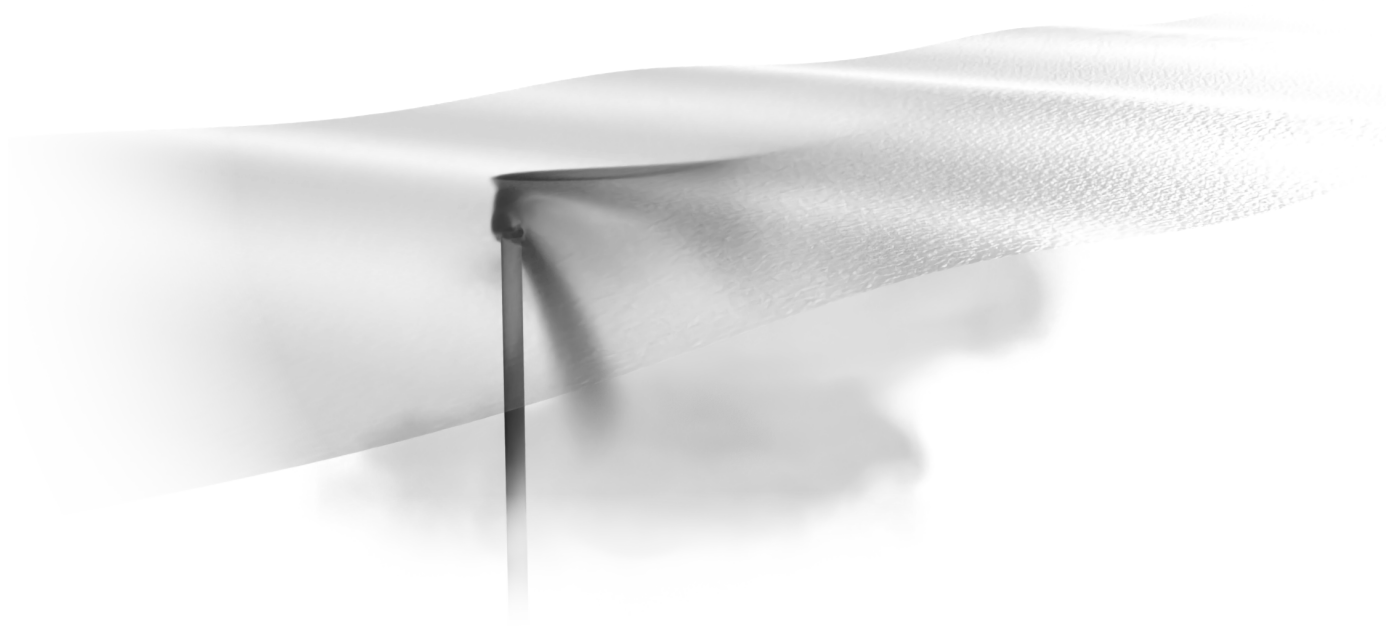


Numerical Flow Modeling of Artificial Upwelling



Dissertation

zur Erlangung des akademischen Grades
Doktor der Ingenieurwissenschaften
(Dr.-Ing.)

der Technischen Fakultät
der Christian-Albrechts-Universität zu Kiel

vorgelegt von
Jost Kemper
Kiel, 2025

Erster Gutachter: Prof. Dr. Thomas Slawig

Zweiter Gutachter: Prof. Dr. Stephan Juricke

Tag der mündlichen Prüfung: 13. Februar 2026

Recommended citation:

Kemper, J., 2026. Numerical flow modeling of artificial upwelling [Doctoral dissertation, Kiel University]. MACAU. URN: [urn:nbn:de:gbv:8:3-2026-00845-7](https://nbn-resolving.org/urn:nbn:de:gbv:8:3-2026-00845-7).

This thesis is licensed under a Creative Commons Attribution 4.0 International license. Please note that individual components of the publication are subject to other licensing or copyright conditions.



Zusammenfassung

Emissionspfade, die, wie im Pariser Klimaabkommen von 2015 international festgelegt, zu einer globalen Erwärmung von deutlich unter 2°C führen, sehen neben einer schnellen und drastischen Reduktion von Treibhausgas-Emissionen auch den Einsatz von aktiven Methoden zur Kohlenstoffentnahme aus der Atmosphäre vor. Künstlicher Auftrieb von nährstoffreichem Tiefenwasser in den Oberflächenozean wird als Einzelmaßnahme oder in Kombination mit zusätzlichen Maßnahmen wie Makroalgenzucht als eine solche CDR (Carbon Dioxide Removal) Methode untersucht. Diese Arbeit zielt darauf ab, durch Beiträge zu einer simulationsbasierten Abschätzung der techno-ökonomischen Machbarkeit und Effektivität unterschiedlicher technischer Ansätze für künstlichen Auftrieb eine übergeordnete Bewertung im Kontext der Kohlenstoffentnahme zu unterstützen.

Im frühen technischen Entwicklungsstadium, in dem sich künstlicher Auftrieb gegenwärtig befindet, kann zuverlässige, realitätsgetreue numerische Modellierung einen zeit- und kosteneffizienten Beitrag zur Technologieentwicklung leisten. Ausgehend von der Notwendigkeit einer Erweiterung und Vereinheitlichung des Wissensstandes zu unterschiedlichen technischen Ansätzen für künstlichen Auftrieb, wird in dieser Arbeit eine Toolbox für numerische Modellierung im Rahmen der techno-ökonomischen Machbarkeits- und Effektivitätsabschätzung von künstlichem Auftrieb entwickelt. Die numerischen Methoden basieren auf der quelloffenen OpenFOAM[®] Umgebung und zielen auf eine generelle Anwendbarkeit für die Modellierung von nicht-hydrostatischer ozeanischer Strömung ab. Die neuen Methoden erweitern die OpenFOAM[®] Umgebung um Möglichkeiten zur Modellierung der Reynolds-gemittelten Navier-Stokes-Gleichungen (RANS) für ozeanische Strömungen mit dynamischem Transport von Temperatur, Salinität und passiven skalaren Größen. Die Toolbox bietet zudem erweiterte Methoden zur Turbulenzmodellierung in Strömungen mit Auftriebseinfluss sowie zur Modellierung der freien Wasseroberfläche und zur adaptiven Netzverfeinerung. In den Beiträgen zu dieser Thesis werden ausführliche Verifizierungs- und Validierungsstudien zu unterschiedlichen Anwendungen der neuen Methoden durchgeführt. Innerhalb dieser Studien wird eine hohe Wiedergabegenauigkeit für unterschiedliche Strömungen mit Auftriebsinfluss festgestellt, und es bestätigt sich, dass der neue Ansatz zur Modellierung der freien Wasseroberfläche eine genaue und numerisch effiziente Alternative zu verbreiteten Standardansätzen darstellt.

Nach der Bestätigung ihrer allgemeinen Vorhersagegenauigkeit werden die neuen Methoden im Bereich der techno-ökonomischen Machbarkeits- und Effektivitätsabschätzung für künstlichen Auftrieb eingesetzt. Es werden drei unterschiedliche technische Konzepte für künstlichen Auftrieb untersucht, welche mechanisch, durch Seegang sowie durch Konvektion angetrieben werden. Für mechanisch angetriebenen künstlichen Auftrieb werden detaillierte Untersuchungen zur Dynamik der Tiefenwasserfahne am Oberflächenauslass sowie zu geometrischen Varianten durchgeführt. Die Auswirkungen von Querströmungen und Seegang auf die Tiefenwasserfahne werden anhand von seegangsgetriebenen Systemen evaluiert. Zudem werden umfassende Untersuchungen des Potenzials von konvektionsgetriebenen Systemen für künstlichen Auftrieb im Kontext der Kohlenstoffentnahme durchgeführt. Mithilfe eines neu entwickelten numerischen Leistungsprognoseverfahrens, sowie des RANS-Lösers, werden erstmals zuverlässige Leistungsprognosen erzielt, welche die Grundlage für eine globale Bewertung des Leistungspotenzials dieser Geräte und dessen Variabilität sowie für Optimierungsstudien bilden. Basierend auf diesen Ergebnissen wird konvektionsgetriebener künstlicher Auftrieb als eigenständige CDR-Maßnahme in einem Erdsystemmodell parameterisiert. Eine Synthese der Ergebnisse wird zudem im Rahmen einer Fallstudie zu konvektionsgetriebenem künstlichem Auftrieb in Kombination mit Makroalgenzucht präsentiert.

Die Effizienz großer mechanisch betriebener Auftriebssysteme wird in den Studien durch eine ausgeprägte Tendenz zum Wiederabsinken des kalten Tiefenwassers in Tiefen außerhalb der ozeanischen Deckschicht reduziert. Die Studien zu seegangsgetriebenen Systemen zeigen hingegen, dass Querströmung und Wellen einen erheblichen Beitrag zur Durchmischung des geförderten Tiefenwassers in der ozeanischen Deckschicht leisten können. Da sich das Tiefenwasser bei konvektionsgetriebenen Systemen während des Auftriebsprozesses erwärmt, kann hier ein Absinken nach dem Verlassen des Geräts vermieden werden. Durch diesen

Effekt hat konvektionsgetriebener künstlicher Auftrieb ein spezifisches Portfolio kumulativer Umweltauswirkungen, welche teilweise im Widerspruch zu bisherigen allgemeinen Annahmen für künstlichen Auftrieb stehen.

Die Ergebnisse dieser Arbeit zeigen, dass Entwicklung auf der technischen Ebene erhebliche Auswirkungen auf die Umweltauswirkungen sowie auf die übergeordnete Bewertung von Kohlenstoffentnahmeverfahren haben kann. Der Wert numerischer Modellierung solcher Effekte wird dadurch bestätigt.

Summary

Pathways towards limiting global warming to well below 2°C , as internationally determined in the 2015 Paris Agreement, typically include active Carbon Dioxide Removal (CDR) from the atmosphere in addition to fast and drastic reduction of greenhouse gas emissions. Artificial upwelling of nutrient-rich deep ocean water to the surface ocean is studied as a standalone marine CDR option or in combination with other measures, such as macroalgae farming. This thesis aims to inform the overarching assessment of artificial upwelling in the context of CDR by contributing to a simulation-based evaluation of the techno-economic feasibility and effectiveness of different technical approaches.

In the present early technical development stage of artificial upwelling, high-fidelity numerical modeling provides a valuable tool for a time- and cost-efficient advancement of this new technology. Motivated by the need to extend and unify the knowledge about different technical options for artificial upwelling, a numerical modeling toolbox for studies on the techno-economic feasibility and effectiveness of artificial upwelling is developed in this thesis. The numerical methods are based on the open-source framework OpenFOAM[®] and aim to be generally applicable to studies of buoyant oceanic flow. The new methods extend the OpenFOAM[®] framework with capabilities for modeling the Reynolds-averaged Navier-Stokes equations for buoyant oceanic flow with dynamic temperature, salinity, and passive scalar transport. Advanced methods are implemented for turbulence modeling in buoyant and stratified flows, as well as for free-surface and wave modeling, and adaptive mesh refinement. Throughout the thesis work, the new methods are rigorously verified and validated for numerous applications. They are found to predict different types of buoyancy-affected flows with high accuracy. The new mixed Lagrangian-Eulerian free-surface modeling approach is found to provide an accurate and efficient alternative to standard free-surface modeling approaches.

Having evaluated their predictive capabilities, the new methods are applied in the realm of techno-economic feasibility and effectiveness assessment for artificial upwelling. Three proposed artificial upwelling concepts are studied: propeller-driven, wave-driven, and buoyancy-driven upwelling. Detailed studies on the plume dynamics are performed for propeller-driven upwelling, along with geometric variant studies. The effects of cross-flow and free-surface waves on the plumes of wave-driven devices are assessed. Comprehensive assessments of the potential of buoyancy-based devices for artificial upwelling-based CDR measures are carried out. Using a newly developed reduced-order performance prediction method and the Reynolds-averaged Navier-Stokes solver, reliable performance predictions for these devices are obtained, based on which a global assessment of their potential and its variability is performed, along with optimization studies. Based on these results, buoyancy-based artificial upwelling is parameterized as a standalone CDR measure in an Earth system model to study its climate effects. The results are also synthesized into a case study for a combined application of buoyancy-based artificial upwelling and macroalgae farming.

While large propeller-driven upwelling devices are found to suffer from the tendency of the cold upwelled water to sink back out of the surface region, the results obtained for wave-driven devices indicate that waves and cross-flow effects can help in keeping the upwelled water suspended. Buoyancy-driven upwelling devices heat the deep ocean water during the upwelling process, thereby avoiding the sinking of the plume at the outlet. As a consequence, buoyancy-driven upwelling has a different cumulative environmental impact profile, which partly contradicts previous assessments of artificial upwelling as a marine CDR measure.

The results of this thesis demonstrate how research and development on the technical level affects the environmental impact and overarching assessment of CDR measures. The value of numerical modeling of these effects is thus confirmed.

Acknowledgments

First and foremost, I would like to express my sincerest gratitude to my supervisor, Thomas Slawig, who has not only taken on the supervision of this thesis but also invited me to join his working group at Kiel University after the end of my project at University of Applied Sciences Kiel. Without his support, this thesis could neither have been started nor completed. Equally, I want to extend my gratitude to my day-to-day supervisors and mentors at University of Applied Sciences Kiel. To Kai Graf, who has lit the spark for CFD modeling in me and believed in me through every step of my career, and to Jörn Kröger, from whom I learned a lot about professional use of CFD and project management. Both have tirelessly supported this work with their technical expertise and experience, and through the acquisition and management of research funding. My special gratitude is extended to Stephan Juricke, my secondary supervisor for this thesis, who introduced me to the world of ocean modeling. I would also like to express my gratitude to Ulf Riebesell, the mastermind behind the numerical modeling efforts for artificial upwelling, who is not only the true initiator of this work but also supported me throughout this thesis by letting me become a member of his working group at GEOMAR and by letting me benefit from his immense scientific experience. A special thanks to Jan Mense, my colleague, co-author, and co-developer, who has been through thick and thin with me. I can not imagine a better comrade. And to *my* master's students, Jon Steinlein and Carlo Brudöhl, who did a tremendous job. Thanks to my office partners, Martje Buhr, Christoph von Viråg, Tobias Pawlowitz, Michael Krenzel, and Sven Lütt, for their moral and practical support, as well as the numerous technical (and less technical) discussions. Thanks also to my colleagues in the GEOMAR biological oceanography department, who have been incredibly welcoming, and to all my comrades-in-arms from the *CDRmare* research mission. A special thanks to the ALE-IT working group, Tomislav Maric, Moritz Schwarzmeier, and Željko Tuković, who have been incredibly supportive, and to Mar Fernández-Méndez and Victor Smetacek, who have sparked the Stommel-pipe upwelling research. Thanks to Tordis Rolf, Silvana Gagliardi, and others who have provided the administrative support that enables this work. Finally, I would like to thank my wonderful wife Eva, who has been with me on this journey, and my entire family and friends for their endless support.

Institutional

The author thankfully acknowledges financial support from the German Federal Ministry of Education and Research (BMBF) within the *Test-ArtUp* project (Grant No. 03F0897B), which contributes to the *CDRmare* research mission led by the German Marine Research Alliance (DAM). Additional support through an Advanced Grant of the European Research Council (ERC) in the framework of the Ocean Artificial Upwelling project (*Ocean artUp*, Grant No. 695094) is acknowledged. The publication of parts of this thesis has been supported by *Land Schleswig-Holstein* within the funding program *Open Access Publikationsfonds*.

Contents

1	Introduction	1
1.1	Carbon Dioxide Removal	1
1.2	Artificial Upwelling	2
1.3	Flow modeling in the context of AU	4
1.4	Thesis motivation	5
1.5	Thesis objectives and contributions	5
1.5.1	Objectives	6
1.5.2	Contributions	6
1.5.3	List of publications	8
1.6	Thesis Structure	9
2	Derivation of the numerical methodology	11
2.1	Fundamental equations	11
2.1.1	Conservation of mass and momentum	11
2.1.2	Scalar transport	12
2.1.3	Conservation of energy	12
2.1.4	The Boussinesq assumption	12
2.2	Pressure decomposition	13
2.3	RANS turbulence modeling	14
2.3.1	Reynolds averaging	14
2.3.2	Eddy viscosity turbulence modeling	15
2.4	The finite volume method	16
2.5	The PIMPLE algorithm	19
2.6	The OpenFOAM [®] framework	21
2.6.1	Usage	22
2.7	<i>ocean4Foam</i> : A new toolbox for oceanic flow in OpenFOAM [®]	25
2.7.1	Usage	26
3	Modeling buoyant oceanic flow in the context of AU	31
3.1	The AU modeling problem	31
3.2	Previous work	31
3.3	Contributions to model development for buoyant oceanic flow	32
3.4	Additional advances in RANS turbulence modeling approaches for buoyant plumes	32
3.4.1	Buoyancy adaptations for eddy viscosity turbulence models	33
3.4.2	RANS modeling of turbulent scalar fluxes	36
3.5	Application to AU	39
4	Modeling of free-surface and cross-flow effects	41
4.1	Previous work on ALE-IT modeling of free-surface waves	42
4.2	Advancement of the ALE-IT method for OpenFOAM [®]	42
4.3	Verification, validation, and performance assessment	43
4.4	Adaptive mesh refinement	43
4.5	Application to AU	44

5	Techno-economic feasibility and effectiveness studies for AU	49
5.1	Performance prediction for Stommel’s perpetual salt fountain and its potential in the context of AU-based CDR	49
5.2	Assessment of proposed technical options for artificial upwelling	52
5.2.1	Wave-driven upwelling	52
5.2.2	Propeller-driven upwelling	53
5.2.3	Buoyancy-driven upwelling	54
6	Conclusions and outlook	55
6.1	Model development	55
6.2	Flow modeling for AU	56
	Bibliography	67
	Appendix	69
[JPA]	Numerical Flow Modeling of Artificial Ocean Upwelling	71
[JPB]	Performance prediction for Stommel’s perpetual salt fountain in the context of artificial ocean upwelling	85
[JPC]	On the potential of Stommel’s perpetual salt fountain for artificial upwelling	99
[JPD]	Exploring Site-Specific Carbon Dioxide Removal Options With Storage or Sequestration in the Marine Environment – The 10 Mt CO ₂ yr ⁻¹ Removal Challenge for Germany	111
[CPA]	Towards Reliable Performance Predictions for Stommel’s Perpetual Salt Fountain	145
[PPA]	ALE interface tracking for wave propagation and effects on submerged buoyant plumes: A modified OpenFOAM [®] approach including adaptive mesh refinement	165
[PPB]	Artificial upwelling via Stommel-Pipe as a marine CDR option? A present to future performance assessment in an Earth system model	189
	Supporting information	211

Nomenclature

<i>General</i>		<i>Accents</i>	
D	diffusivity of salinity $[\text{m}^2/\text{s}]$	ϕ_0	constant reference quantity
e	specific internal energy $[\text{m}^2/\text{s}^2]$	ϕ_t	quantity modeling turbulence effects
$\mathbf{f}_u$	momentum source term $[\text{m}/\text{s}]$	$\bar{\phi}$	Reynolds-averaged quantity
$\mathbf{g}$	gravity vector $[\text{m}/\text{s}^2]$	ϕ'	fluctuation from Reynolds-avg. $\phi = \bar{\phi} + \phi'$
$\mathbf{I}$	identity matrix $[-]$	$\hat{\phi}$	arithmetic mean of quantity
K	specific kinetic energy $[\text{m}^2/\text{s}^2]$	ϕ^T	transpose of tensor ϕ
k	turbulent kinetic energy $[\text{m}^2/\text{s}^2]$	<i>Abbreviations</i>	
$\mathbf{n}_i$	unit normal vector of face i $[-]$	AFM	Algebraic Flux Model
P	pressure $[\text{N}/\text{m}^2]$	ALE	Arbitrary Lagrangian-Eulerian
p	kinematic pressure $[\text{m}^2/\text{s}^2]$	AU	Artificial Upwelling
$\mathbf{q}$	heat flux $[\text{W}/\text{m}^2]$	CDR	Carbon Dioxide Removal
$\mathbf{r}$	position vector w. r. t. surface level $[\text{m}]$	CFD	Computational Fluid Dynamics
$\mathbf{S}$	strain rate tensor $[\text{1}/\text{s}]$	DNS	Direct Numerical Simulation
S	scalar source term	GGDH	Generalized Gradient Diffusion Hypothesis
S_A	absolute salinity $[\text{g}/\text{kg}]$	IT	Interface Tracking
$\mathbf{S}_i$	face area vector of face i $[\text{m}^2]$	LES	Large Eddy Simulation
T	temperature $[\text{K}]$	LIF	Laser-Induced Fluorescence
t	time $[\text{s}]$	OAE	Ocean Alkalinity Enhancement
$\mathbf{u}$	velocity vector $[\text{m}/\text{s}]$	PIV	Particle Image Velocimetry
V	volume $[\text{m}^3]$	RANS	Reynolds-Averaged Navier-Stokes
β	expansion coefficient	SGDH	Simple Gradient Diffusion Hypothesis
Γ	diffusivity of scalar quantity $[\text{m}^2/\text{s}]$	SUP	Stommel Upwelling Pipe
ϵ	dissipation rate of k $[\text{m}^2/\text{s}^3]$	VOF	Volume Of Fluid
Θ	conservative temperature $[\text{K}]$		
λ	thermal diffusivity $[\text{m}^2/\text{s}]$		
μ	dynamic viscosity $[\text{kg}/\text{m s}]$		
ν	kinematic viscosity $[\text{m}^2/\text{s}]$		
ρ	density $[\text{kg}/\text{m}^3]$		
σ_t	turbulent Prandtl number $[-]$		
$\boldsymbol{\tau}$	viscous stress tensor $[\text{kg s}^2/\text{m}]$		
$\boldsymbol{\tau}^*$	kinematic viscous stress tensor $[\text{m}^2/\text{s}^2]$		
Φ_i	volume flux through face i $[\text{m}^3/\text{s}]$		
ϕ	(arbitrary) scalar quantity		
∇	differentiation operator (nabla)		

Chapter 1

Introduction

Burning of fossil fuels, large-scale land use, and land use change, as well as other unsustainable human activities, have contributed to a substantial increase in greenhouse gas emissions into Earth’s atmosphere since the 19th century (IPCC, 2023). With unequal regional and individual contributions, humankind has thereby caused a mean increase in Earth’s surface temperatures, presently estimated to about 1.5 °C (Forster et al., 2025). Although anthropogenic greenhouse gas emissions are presently ongoing and intensifying, in the 2015 Paris Agreement, global leaders have committed to limiting the temperature increase to well below 2 °C in an effort to avoid severe adverse effects. It is well understood that a stabilization of global temperatures via the greenhouse effect can only be reached if anthropogenic greenhouse gas emissions are either ceased entirely or remaining emissions are balanced with so-called negative emissions (IPCC, 2018). Projected pathways to achieving a stable global surface temperature level include such negative emissions in the form of Carbon Dioxide Removal (CDR) to offset residual or hard-to-abate anthropogenic greenhouse gas emissions (IPCC, 2018).

1.1 Carbon Dioxide Removal

The term CDR refers to deliberate actions that extract the greenhouse gas CO₂ from the atmosphere and permanently store it (especially the carbon) in some form. A wide variety of CDR measures have been proposed and are currently subject to active research and development (Babiker et al., 2022). While there is currently no evidence to suggest that a replacement of consequent avoidance and reduction of emissions with CDR would be feasible or desirable, current predictions indicate that large-scale CDR will still be required in the near term to complement other mitigation efforts (IPCC, 2021). On a systematic level, CDR approaches must introduce transfer of carbon from Earth’s atmospheric reservoir to its terrestrial or oceanic reservoirs or into the technosphere (durable products). The marine reservoir is by far the largest carbon reservoir on Earth (Oschlies et al., 2025), such that a transfer of all anthropogenic atmospheric CO₂ into the ocean would only lead to a small increase in its relative concentration. However, while the relative reservoir size serves to illustrate the potential of marine CDR, it does not represent a justification of such interventions, as a simple relocation of the anthropogenic CO₂ pollution from the atmosphere to the ocean would likely be considered unlawful dumping under the law of the sea (International Tribunal for the Law of the Sea, 2024). Yet, if negative consequences for the ocean can be avoided, its size and limited occupation by other human uses constitute a substantial and realistic potential for large-scale CDR applications.

Marine CDR approaches can be subdivided into two categories: Geochemical approaches, which alter the ocean’s chemical properties, and biotic approaches, which target ocean or coastal biology to enhance carbon uptake from the atmosphere. Some geochemical marine CDR approaches mimic or enhance naturally occurring processes that lead to ocean carbon uptake. Ocean Alkalinity Enhancement (OAE) mimics the process of natural rock weathering in enhancing the ocean’s chemical capacity to take up CO₂ through increased alkalinity.

Such alkalinity changes can be achieved by deposition or dissolution of alkaline material (e. g., as ground rock powder) or by electrochemical methods. As another geochemical approach, direct ocean capture aims to alter merely the inorganic carbon concentration of ocean water, thus ideally avoiding interference with natural cycles. Biotic marine CDR approaches typically aim to increase the uptake of CO_2 through photosynthesis, in combination with preventing the return flux to the atmosphere after degradation of the carbon-containing biomass. A natural analog for such a process in the open ocean is known as the biological carbon pump. Biological primary production in the surface ocean reduces the inorganic carbon content in the surface waters, thus invoking an uptake of atmospheric CO_2 through equilibration across the ocean surface. Although most of the organic carbon is recycled in the upper ocean, a portion is exported into the deep ocean through sinking particles and other transport mechanisms. Even when remineralized, this exported carbon remains out of contact with the atmosphere for decades to centuries (DeVries et al., 2012). An augmentation of this natural carbon transport pathway has been encompassed as a basis for multiple biotic marine CDR options, such as iron fertilization and Artificial Upwelling (AU).

1.2 Artificial Upwelling

For the remainder of this work, we will concentrate on AU of nutrient-rich deep ocean water to the surface ocean. This process has been proposed as a standalone biotic CDR measure (Lovelock and Rapley, 2007; Oschlies et al., 2010) or in combination with other marine CDR measures such as macroalgae farming and sinking (Wu et al., 2023; Koweek, 2022). AU approaches generally aim to emulate natural ocean upwelling, a feature of ocean circulation that naturally leads to transport of deep ocean water to the surface, along continental coasts. In large parts of the global oceans, especially in open ocean regions, the surface waters, where light for photosynthesis is available, are oligotrophic, i. e., primary production is limited due to the scarcity of nutrients in these regions. In turn, deep ocean water (below a depth of about 200 m) is typically rich in inorganic nutrients that are prevented from entering the surface waters by the stable density stratification, which limits vertical mixing. Natural upwelling regions, where the nutrients from the deep water enter the surface ocean, are thus associated with very productive ecosystems (Chavez and Messié, 2009). The high productivity, however, does not generally render these regions sinks for atmospheric CO_2 (Chavez and Messié, 2009). When AU is considered as a standalone CDR approach, suitable deployment locations and deep ocean water source depths must thus be chosen to selectively enhance CO_2 sequestration via the ocean’s biological carbon pump.

As a CDR method, AU was first proposed by Lovelock and Rapley (2007). Several authors have parameterized the method in Earth system models to study its climate effects. While the studies of Dutreuil et al. (2009) and Yool et al. (2009) find limited or no effectiveness of the approach as a CDR measure, Oschlies et al. (2010) and Keller et al. (2014) find significant atmospheric CO_2 reduction but report undesirable side effects. Also, simpler models give a limited overall effectiveness (Koweek, 2022), even when AU is combined with macroalgae farming. Other studies find significant CDR potential for the combination of AU with macroalgae cultivation and subsequent active sinking of the produced biomass (Wu et al., 2023). A recent body of work has concentrated on the separation of the underlying processes and their individual contributions to the CDR potential of AU (Jürchott et al., 2023, 2024). Jürchott et al. (2023) find that both biological and solubility effects influence the CDR potential of AU, with the cumulative effect being strongly dependent on the modeled CO_2 emission scenario. A later extension of their work, with respect to the modeled iron cycle, shows that AU would likely have to be combined with ocean iron fertilization to be effective as a CDR method (Jürchott et al., 2024). So far, AU modeling results do not capture the effects of variable nutrient stoichiometry and variable sinking behavior of organic matter. Such effects might significantly influence the CDR potential of AU, as shown in physical mesocosm experiments (Goldenberg et al., 2022; Baumann et al., 2023; Ortiz et al., 2024).

A number of potential limitations and side effects of AU have been reported in the lit-

erature. While deep ocean water typically has higher concentrations of inorganic nutrients compared to the surface water, its concentration of dissolved inorganic carbon is also typically elevated. In the absence of biological responses, AU would thus lead to elevated carbon concentrations in the surface ocean and thus to outgassing of CO_2 under present atmospheric CO_2 concentrations (Dutreuil et al., 2009). However, under high future emission scenarios, this direct solubility effect may be reversed (Jürchott et al., 2023). Another reported abiotic side effect of AU is its direct impact on ocean physics. If cold water from the interior ocean is mechanically upwelled to the surface on a large scale, this leads to a reduction in stratification stability and increased upper ocean mixing (Dutreuil et al., 2009). While this could momentarily increase oceanic heat uptake (Jürchott et al., 2025), the absorbed heat would be released again after termination of the AU operation, causing rapid global warming (Oschlies et al., 2010). This ocean physics response to AU could additionally have consequences for atmospheric evaporation and precipitation patterns, as well as the global radiative budget (Kwiatkowski et al., 2015). The biotic CDR effect of AU via the biological carbon pump is generally the intended main effect of the intervention. Even though the resulting climate effect is not generally larger than the previously reported side effects (Jürchott et al., 2025), its individual contribution is generally positive (Jürchott et al., 2023). The CDR effect is limited, however, due to a large fraction of the biomass being remineralized in relatively shallow depth, such that the contained carbon is not permanently stored in the ocean (Yool et al., 2009). As oxygen is required in the remineralization of the additional biomass, deoxygenation at depth can occur as a subsequent side effect of AU (Keller et al., 2014). Availability of iron for primary production in the surface ocean poses an additional limitation to the effectiveness of AU, as sufficient amounts to support the intended biological response are not generally supplied with the upwelled deep ocean water (Jürchott et al., 2024). While, in sum, the reported side effects and limitations may render the overall impact of large-scale AU deployments undesirable in numerous studies, it is worth noting that not all AU-based marine CDR measures are subject to all of the reported side effects to the same extent. It will be shown throughout this thesis that some of the reported side effects are, in fact, not inherently linked to AU and can be avoided.

The motivation of the present thesis is based on the need to assess AU as a marine CDR measure. Several other potential uses of AU outside of the CDR context have been proposed in the literature. Due to its high nutrient concentrations, upwelled deep ocean water can be used to locally enhance fish production (Kirke, 2003) and mariculture yields (Roels et al., 1977). An abundance of work on AU has been carried out in this context. The surface ocean cooling effect of mechanically forced AU has been proposed as a means for active meteorological interventions, such as hurricane prevention (Kithil, 2006) and drought reversal (Ricke et al., 2021). Finally, upwelling of deep ocean water for ocean thermal energy conversion has been proposed as a renewable energy harvesting method (Takahashi, 2000).

An integrated assessment of AU-based marine CDR measures can be made along dimensions of *feasibility* and *desirability* of the proposal (Batz et al., 2025). While the literature cited above largely assesses the desirability and effectiveness of AU-based marine CDR, few works have considered aspects of techno-economic feasibility. Most technical studies on AU have been initially performed for applications other than CDR.

Proposed technical options for AU can be grouped into four main categories, based on the process driving the upwelling flow:

- Wave-driven upwelling devices use the energy of ocean surface waves to drive the upwelling process.
- Propeller-driven upwelling devices employ mechanical pumping using transformed energy to drive the flow. This is typically proposed in combination with renewable wind power as an energy source (Viúdez et al., 2016).
- Buoyancy-driven upwelling devices, or Stommel Upwelling Pipes (SUP), establish a self-sustaining buoyant flow inside an upwelling pipe, based on a principle proposed by Stommel et al. (1956).
- Air-lift devices invoke an upward flow through rising bubbles by injecting air.

A schematic of the proposed technical options is shown in Figure 1.1. In the CDR context,

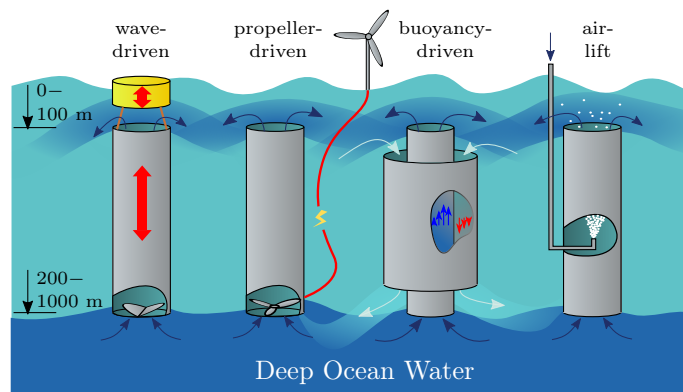


Figure 1.1: Basic technical concepts for AU systems.

AU applications on very large scales are generally considered. As a technologically simple option with no need for external energy supply or energy conversion, wave-driven upwelling is the most widely proposed technical option in the CDR context (Lovelock and Rapley, 2007). Its key drawback is that the upwelled deep ocean water retains its low source temperature throughout the upwelling process and thus tends to sink back out of the surface region after release from the system (Kirke, 2003). Throughout this thesis, this will be referred to as the *re-sinking* problem. Scaled experiments (Fan et al., 2016; Zhou et al., 2019) and prototype tests of wave-driven upwelling devices have been reported (Liu, 1999; White et al., 2010; GEOMAR, 2022; Kimball et al., 2025). The full-scale test reported by White et al. (2010) led to a structural failure of the upwelling device after a few hours in the marine environment. A similar result was obtained in a prototype test conducted in connection with this thesis (GEOMAR, 2022). The structural design of such systems thus seems to be a challenge, at present.

A full-sized prototype of a propeller-driven upwelling device has been operated in Sagami Bay, Japan, for over five years (Ouchi, 2009). Like wave-driven AU devices, propeller-driven systems also suffer from re-sinking of the cold upwelled water. For large-scale applications in the context of CDR, propeller-driven applications are not typically considered, likely due to the added complexity of a low-carbon energy supply. The same analysis applies to air-lift upwelling devices. While a number of successful applications have been previously reported (Lin et al., 2019; Pan et al., 2019; McClimans et al., 2010), a large-scale open ocean application in the context of CDR is deemed unlikely at present due to the energy and maintenance requirements of such an installation. Buoyancy-driven upwelling through Stommel Upwelling Pipes (SUP) does not require an external energy supply, generally rendering it a suitable option for large-scale AU applications in the context of CDR. This concept has been studied through model calculations (Groves, 1958; Johnson and Decicco, 1983) and experiments (Maruyama et al., 2004), which yielded small upwelling rates. Due to the high level of uncertainty associated with the potential and implications of this concept, buoyancy-driven upwelling has not previously been assessed in the context of CDR.

As can be seen from this overview of technical options for AU, all options are presently at a prototype stage, with varying levels of sophistication and proof of concept. For applications in the context of CDR, a low technology readiness level must presently be assigned for AU technology (Yao et al., 2025). To be able to assess the techno-economic feasibility of AU as a CDR measure, more information is required across all technical options.

1.3 Flow modeling in the context of AU

Numerical modeling enables fast and detailed analyses of technical systems at an early stage of development. While ultimately only field tests can deliver a proof of concept for AU technologies, at the present early development stage, it can be expected that significant

knowledge gains can be achieved through numerical modeling of flow dynamics in and around AU systems. In the CDR context, modeling efforts have so far been limited to climate effects on the global scale. However, in other contexts, such as AU-enhanced mariculture, a wide range of technical modeling efforts has been reported across all technical options. A number of simple analytical and numerical methods have been developed to predict the performance of wave-driven upwelling devices (Isaacs et al., 1976; Liu and Jin, 1995; Kirke, 2003; Kithil, 2006; Fan et al., 2016). Liang and Peng (2005) propose a method to calculate upwelling flow rates from Air-lift upwelling. Similar calculations are performed by Meng et al. (2013) using a Computational Fluid Dynamics (CFD) model. Simple analytical and numerical performance prediction methods have also been presented for buoyancy-driven AU using SUP devices (Groves, 1958; Hinman, 1966; Johnson and Decicco, 1983). Beyond mere performance prediction, numerical flow modeling can provide valuable insights into the local flow dynamics around AU systems, thus enabling the assessment of local environmental impacts, nutrient concentrations, and efficiency aspects, such as the re-sinking behavior of the upwelled deep ocean water. Simple numerical models for plume dynamics and mixing of upwelled deep ocean water have been proposed by several authors (Liu et al., 2003; Fan et al., 2015). These calculations are similar to those carried out for buoyant jets and plumes in other contexts (Jirka, 2004). CFD models have also been applied for plume dynamics and mixing of upwelled deep ocean water (Williamson et al., 2009; Kogawa et al., 2013; Fan et al., 2015). Williamson et al. (2009) and Kogawa et al. (2013) study weakly buoyant plumes from a buoyancy-driven upwelling device in cross-flow, using commercial CFD methods. Fan et al. (2015) use a CFD method to validate a simpler model for predicting buoyant plumes in a cross-flow. These studies will be discussed in more detail in later sections of this thesis.

While this review of previous modeling efforts shows that specific questions have been addressed by partly very sophisticated modeling approaches, partly allowing for some degree of generalization in the context of techno-economic feasibility assessment, it has to be concluded that, like the technological development, also the level to which numerical flow modeling has been applied is very heterogeneous across the different technical AU approaches. While CFD methods have been applied for modeling plume dynamics in some cases, the performance assessment of AU technologies still widely relies on simple analytical or numerical models with varying degrees of complexity, assumption, and generality. Only few works contain model validation or uncertainty quantification efforts (Zhang et al., 2004; Meng et al., 2013; Fan et al., 2015, 2016; Zhou et al., 2019). As none of the previously mentioned studies have been carried out in the context of large-scale AU-based CDR measures, implications of local-scale performance for large-scale deployments and vice versa remain largely unstudied to date.

1.4 Thesis motivation

To provide the information needed to assess the techno-economic feasibility and effectiveness of AU-based CDR measures, the degree to which the different technical options for AU are studied must be unified to an extent that allows for intercomparison. Assessments of the different options must provide reliable and comparable information that includes aspects of suitability for large-scale applications and thus informs assessments of climate impacts on the relevant scales.

The present thesis is motivated by the need to unify and extend the level of knowledge about different technical options for AU and their local effects by numerical flow modeling with the aim of supporting assessments of the techno-economic feasibility and effectiveness of AU-based marine CDR measures.

1.5 Thesis objectives and contributions

In the following, the formal objectives of this thesis are defined, and the contributions made by this thesis are listed before providing an overview of publications containing the original work and contributions.

1.5.1 Objectives

This thesis has been carried out under two main objectives. In line with the motivation to *unify* the level of knowledge about different technical options for AU, the first aim of this thesis is to provide new and adapted numerical methods for studies of flow problems in the context of AU. To allow for a unification in the assessment of different AU technologies, the developed methods must fulfill the following requirements:

- Methods must be applicable to a wide range of AU technologies.
- Methods must be modular, expandable, and customizable.
- Methods must be openly available as free software.

In line with the motivation to *extend* the present knowledge about AU technologies, the second aim of this thesis is to apply the developed numerical methods to studies of the techno-economic feasibility of different types of AU devices. To mark an extension of the current level of knowledge, the applications are carried out using high-fidelity CFD methods and accompanied by rigorous verification and validation efforts. It is further attempted to provide useful results for assessing the effectiveness of AU-based CDR measures, in terms of their cumulative climate impact, and to incorporate learnings from such assessments where possible.

From these objectives, a dual focus on model development and application in the context of AU arises. The model developments made throughout the course of this thesis aim to make novel and significant contributions to the field of engineering-scale numerical modeling of oceanic flows in general, and are partly introduced as such in the respective publications. In this thesis, the motivation and value of these developments in the context of AU are highlighted to make the contributions along both thematic lines appreciable as an integral effort to advance the understanding of AU-based marine CDR measures.

A limitation to these objectives adopted throughout this thesis is that no studies of air-lift upwelling are performed, and the developed methods are not presently applicable to the dispersed bubbly flows encountered in such studies. A CFD method for air-lift AU has been previously presented by Meng et al. (2013).

1.5.2 Contributions

In summary, the three main contributions, reflecting Chapters 3 through 5 of this thesis, are:

1. **Modeling buoyant oceanic flow in the context of AU:** This thesis presents advances in Reynolds-Averaged Navier-Stokes (RANS) modeling of buoyant oceanic flow. A new RANS solver is described along with advanced turbulence modeling approaches. The method is applied to studies of several technical questions regarding the implementation of AU devices. Additionally, the accuracy of the new method in modeling buoyant plumes in a stratified ambient is demonstrated through validation against experimental data.
2. **Modeling of free-surface and cross-flow effects:** This thesis presents advances in modeling AU devices in a realistic ocean environment, including cross-flow and wave action. A modified, mixed Lagrangian-Eulerian interface tracking model for free surface waves with simultaneous adaptive mesh refinement is described and implemented. The new approach is rigorously verified and validated, and its numerical efficiency is compared to a standard free surface modeling approach.
3. **Techno-economic feasibility and effectiveness studies for AU:** This thesis presents advances in assessing the techno-economic feasibility and effectiveness of propeller-driven, wave-driven, and buoyancy-driven artificial upwelling approaches. Special emphasis is placed on the buoyancy-driven Stommel-pipe concept, where considerable advances in process understanding, performance prediction accuracy, and assessment of the potential of the approach in the context of marine CDR are made.

Mirroring the dual objective of this thesis, contributions are made to two fields in particular: the development and evaluation of numerical methods for modeling buoyant oceanic flow, and the techno-economic feasibility and effectiveness assessment of AU-based CDR options. In the following, key individual contributions to these two fields are listed.

Development and evaluation of numerical methods for modeling buoyant oceanic flow:

- Development
 - Implementation of a new solver for buoyant oceanic flow in OpenFOAM®
 - Implementation and evaluation of multiple buoyancy source terms for eddy viscosity turbulence models
 - Implementation and evaluation of multiple modeling approaches for turbulent scalar fluxes in RANS models
 - Modification and advancement of a mixed Lagrangian-Eulerian interface tracking method for OpenFOAM® and adaptation to free surface wave modeling
 - Modification and advancement of a load-balanced adaptive mesh refinement method for OpenFOAM® and adaptation to simultaneous mesh motion
 - Adaptation of the wave generation and absorption toolbox *waves2foam* (Jacobsen et al., 2011) to the mixed Lagrangian-Eulerian interface tracking method
 - Development of a reduced-order model for performance prediction for Stommel-pipe AU devices
 - Open-source publication of all developments
- Verification and validation
 - Validation of the new solver against experiments for buoyant plumes in a stratified ambient
 - Validation against experiments for mixed convection in vertical cylindrical and annular pipes
 - Evaluation of buoyancy source terms and advanced scalar flux modeling approaches for RANS models
 - Verification and validation of the mixed Lagrangian-Eulerian interface tracking method for free surface waves against theory and experiments, as well as inter-comparison with standard approaches
 - Model intercomparison between the new RANS solver and the reduced-order model for Stommel-pipe AU devices

Techno-economic feasibility assessment for AU:

- Description of plume dynamics and mixing near a propeller-driven upwelling device
- Shape optimization for a propeller-driven upwelling device
- Description of the effects of waves and currents on upwelling plume dynamics for a wave-driven upwelling device
- Description of fundamental mechanisms responsible for the performance of Stommel-pipe AU devices and their scaling laws
- Assessment of the potential of Stommel-pipe devices to drive large-scale AU in the context of marine CDR, as well as its spatial and temporal variability
- Contribution to the assessment of the cumulative climate impact of buoyancy-driven upwelling by Stommel-pipe devices in an Earth system model
- Contribution to a case study on buoyancy-driven upwelling in combination with macroalgae farming

1.5.3 List of publications

Throughout the thesis work, the following works have been published or contributed to:

Journal publications

- [JPA] **Kemper, J.**, Riebesell, U., Graf, K., 2022. Numerical flow modeling of artificial ocean upwelling. *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.804875.
- [JPB] **Kemper, J.**, Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025c. Performance prediction for Stommel’s perpetual salt fountain in the context of artificial ocean upwelling. *Applied Ocean Research* 160, 104624. doi:10.1016/j.apor.2025.104624.
- [JPC] **Kemper, J.**, Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025b. On the potential of Stommel’s perpetual salt fountain for artificial upwelling. *Environmental Research Letters* 20, 074047. doi:10.1088/1748-9326/ade0d3.
- [JPD] Yao, W., Morganti, T.M., Wu, J., Borchers, M., Anschütz, A., Bednarz, L., Bhau-mik, A., Böttcher, M., Burkhard, K., Cabus, T., Chua, A.S., Diercks, I., Esposito, M., Fink, M., Fouqueray, M., Gasanzade, F., Geilert, S., Hauck, J., Havermann, F., Hellige, I., Hoog, S., Jürchott, M., Kalapurakkal, H.T., **Kemper, J.**, Kremin, I., Lange, I., Lencina-Avila, J.M., Liadova, M., Liu, F., Mathesius, S., Mehendale, N., Nagwekar, T., Philippi, M., Luz, G.L.N., Ramasamy, M., Stahl, F., Tank, L., Vorrath, M., Westmark, L., Wey, H., Wollnik, R., Wölfelschneider, M., Bach, W., Bischof, K., Boersma, M., Daewel, U., Fernández-Méndez, M., Geuer, J.K., Keller, D.P., Kopf, A., Merk, C., Moosdorf, N., Oppelt, N., Oschlies, A., Pongratz, J., Proelss, A., Rehder, G.J., Rüpke, L., Szarka, N., Thraen, D., Wallmann, K., Mengis, N., 2025. Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment – the 10 Mt CO₂ yr⁻¹ removal challenge for Germany. *Earth’s Future* 13. doi:10.1029/2024ef004902.

Conference publications

- [CPA] **Kemper, J.**, Mense, J., Graf, K., Riebesell, U., Kröger, J., 2023. Towards reliable performance predictions for Stommel’s perpetual salt fountain, in: *Proceedings of the 10th Conference on Computational Methods in Marine Engineering*, Madrid, Spain. doi:10.23967/marine.2023.018.

Preprints

- [PPA] **Kemper, J.**, Slawig, T., 2025a. ALE interface tracking for wave propagation and effects on submerged buoyant plumes: A modified OpenFOAM® approach including adaptive mesh refinement. [Preprint] Manuscript in preparation.
- [PPB] Jürchott, M., **Kemper, J.**, 2025. Artificial upwelling via Stommel-pipe as a marine CDR option? A present to future performance assessment in an Earth system model. [Preprint] Manuscript in preparation.

Software publications

- [SPA] **Kemper, J.**, 2024. ocean4Foam [computer software]. doi:10.3289/sw_9_2024.
- [SPB] **Kemper, J.**, Mense, J., 2024. SP1D [computer software]. doi:10.3289/sw_8_2024.

The above print publications are included in the appendix of this thesis. Throughout this thesis, the publications will be referenced using the labels introduced above (i.e., [JPA], [JPB]...).

1.6 Thesis Structure

The remainder of this thesis is structured as follows: First, in Chapter 2, an introduction to the numerical modeling methodology developed throughout this thesis is given, starting from the fundamental equations and including their simplification, turbulence closure, and discretization, before finishing with the implementation in the OpenFOAM[®] environment. In Chapters 3 through 5, the individual contributions of this thesis are discussed and partly extended. These chapters are structured along the three main contributions of this thesis (see Section 1.5.2). In each chapter, a brief overview of previous work in the field is given before discussing the advances throughout the original work of this thesis, presenting additional results where available, and outlining the motivation and value of the contributions in the context of AU-based CDR. Conclusions and an outlook are provided in Chapter 6. The individual print publications are included in the appendix in the order shown in Section 1.5.3.

Chapter 2

Derivation of the numerical methodology

In this chapter, key elements of the methodology for the numerical flow modeling throughout this thesis are derived, and an introduction to finite volume modeling of buoyant oceanic flow is given. The aim of this chapter is to introduce the relevant fundamental equations along with approximations and closure models applied throughout this thesis, as well as the discretization and solution of the equations. As the scope of this chapter ranges from aspects of ocean modeling and fluid dynamics to computer science, the descriptions of the individual topics are by no means exhaustive and aim to provide an overview of the complete methodology rather than a full treatise of its theoretical foundation.

2.1 Fundamental equations

In the following, the fundamental equations for fluid flow are introduced in a general form, before discussing their formulation and approximation in the context of buoyant oceanic flow. To maintain generality, the equations are presented without the boundary conditions necessary for their solution. The boundary conditions vary based on the problem the model is applied to and are thus generally discussed with the specific applications.

2.1.1 Conservation of mass and momentum

Viscous fluid flow can be modeled using the Navier-Stokes equations, which govern the conservation of momentum. A general tensor representation of the Navier-Stokes equations for a Newtonian fluid in an Eulerian frame of reference reads

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \nabla \cdot \boldsymbol{\tau} - \nabla P + \rho \mathbf{f}_u , \quad (2.1)$$

where ρ is the fluid density, $\mathbf{u}$ is the velocity vector, t is time, and P is pressure. In a Cartesian three-dimensional coordinate system, the differential operator ∇ is defined as

$$\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) . \quad (2.2)$$

Further, in Equation (2.1), $\boldsymbol{\tau}$ is the viscous stress tensor

$$\boldsymbol{\tau} = 2\mu \mathbf{S} - \frac{2}{3}\mu (\nabla \cdot \mathbf{u}) \mathbf{I} , \quad (2.3)$$

where μ is the dynamic viscosity, $\mathbf{I}$ is the identity matrix, and $\mathbf{S}$ is the strain rate tensor

$$\mathbf{S} = \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) . \quad (2.4)$$

The final term in Equation (2.1) combines all body forces acting on the fluid. In the present work, especially the buoyancy force $\rho\mathbf{g}$ is of interest. Also, momentum sources or the Coriolis force can be represented by $\rho\mathbf{f}_u$.

The mass conservation equation for a general fluid reads

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 . \quad (2.5)$$

2.1.2 Scalar transport

For many flow problems, the transport of scalar quantities in the flow is of interest. These can be passive quantities, whose transport has no effect on the dynamics of the flow, or active quantities that affect the flow by modifying the fluid's density or other physical properties. The transport of a general scalar quantity ϕ in the flow can be described by the equation

$$\frac{\partial \rho \phi}{\partial t} + \nabla \cdot (\rho \phi \mathbf{u}) = \nabla \cdot (\Gamma \nabla \phi) + S_\phi , \quad (2.6)$$

where Γ is the quantity's molecular diffusivity, and S_ϕ describes any additional transport mechanism as well as source and sink terms.

2.1.3 Conservation of energy

Considering only thermal and mechanical energy, the first law of thermodynamics can be expressed by the equation

$$\frac{\partial}{\partial t} (\rho e + \rho K) + \nabla \cdot (\rho \mathbf{u} (e + K)) = -\nabla \cdot \mathbf{q} + \rho S_e + \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u}) - \nabla \cdot (P \mathbf{u}) + \rho \mathbf{g} \cdot \mathbf{u} . \quad (2.7)$$

Here, e is specific internal energy, $K = 1/2|\mathbf{u}|^2$ is specific kinetic energy, $\mathbf{q}$ is the heat flux vector, and S_e is the specific heat source term. Often, not all forms of energy are equally relevant to a flow problem, such that some terms of Equation (2.7) can be neglected. In both geophysical and technical fluid dynamics, energy conservation is often represented by a simple transport equation for heat, which takes the form of Equation (2.6). Throughout this thesis, the conservative temperature, denoted Θ , is used as a temperature variable. As described by McDougall (2003), a simple transport equation for Θ (See section 2.1.4) models the first law of thermodynamics in oceanic flows to a high degree of accuracy.

2.1.4 The Boussinesq assumption

So far, the fundamental equations have been introduced in their general form. Under certain conditions, simplifications to the equations can be made. If the density ρ is considered constant, it can be removed from the equations completely, in which case the continuity equation (Equation (2.5)) reduces to a zero-divergence condition for the velocity field. The resulting equations are known as the incompressible (or hydrostatic) Navier-Stokes equations. For buoyant flows with small density variations, a similar assumption, known as the Boussinesq (or Oberbeck-Boussinesq) assumption, can be made. Thereby, density is assumed constant throughout the fundamental equations except for the buoyancy term in the momentum equation. The equations thus take their incompressible form, which is significantly easier to solve numerically. In technical fluid dynamics, the Boussinesq assumption is typically combined with the assumption of a linear equation of state of the form $\rho/\rho_0 = 1 - \beta(T - T_0)$, where ρ_0 is a constant reference density, β is the thermal expansion coefficient, and T and T_0 are temperature and reference temperature, respectively. Other fluid properties, like viscosity, are considered constant. For oceanic flow, generalized forms of the Boussinesq assumption are used. Here, an important goal is to filter out acoustic modes from the system, which can occur in the full compressible equations and destabilize the solution process.

In technical fluid mechanics, the use of the Boussinesq approximation is usually not recommended for water when temperature differences above 2°C occur across the fluid domain (Ferziger et al., 2020). A rigorous analysis presented by Gray and Giorgini (1976) supports

this general range of applicability. The temperature differences typically encountered in oceanic flow significantly exceed this limit. This extended range of application can be justified under the assumption of low Mach number flow. Also, unlike technical models, oceanic Boussinesq models typically use a non-linear equation of state, which further extends the range of applicability. A theoretical foundation for an energy-conserving Boussinesq set in the oceanic context was provided by Young (2010). A thorough discussion of the consequences of the Boussinesq assumption in an oceanic-flow context is given in Auclair et al. (2018). In this context, the main condition for the applicability of the Boussinesq assumption is that density differences are small compared to a reference density ($\Delta\rho/\rho_0 \ll 1$). In the applications studied in this thesis, density differences are typically below 0.3 %, which justifies the use of the Boussinesq assumption. Note that this range of applicability can also be justified based on the work of Gray and Giorgini (1976) if it is assumed that the pressure work term in the energy equation (i.e., the fourth term on the right-hand side of Equation (2.7)) is negligible, which is generally the case in the low Mach number flows studied here. The method developed throughout this thesis is thus based on a Boussinesq-type set of fundamental equations which closely resembles the oceanic Boussinesq set of Young (2010). It reads

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) = \frac{1}{\rho_0} (\nabla \cdot \boldsymbol{\tau} - \nabla P + \rho \mathbf{g}) + \mathbf{f}_u \quad (2.8a)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2.8b)$$

$$\frac{\partial \Theta}{\partial t} + \nabla \cdot (\mathbf{u}\Theta) = \nabla \cdot (\lambda \nabla \Theta) + S_\Theta \quad (2.8c)$$

$$\frac{\partial S_A}{\partial t} + \nabla \cdot (\mathbf{u}S_A) = \nabla \cdot (D \nabla S_A) + S_{S_A} \quad (2.8d)$$

$$\rho = f(S_A, \Theta, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r}) , \quad (2.8e)$$

where S_A is absolute salinity and λ and D are the molecular diffusivities of temperature and salinity, respectively. Note that, as suggested by Young (2010), the density is calculated from $P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r}$ as an approximated pressure. Here, P_0 is the pressure at the sea surface, ρ_0 is a constant reference density, and $\mathbf{r}$ is the position vector with respect to a reference position at the free-surface level.

2.2 Pressure decomposition

One of the aims of the developments in this work is the study of buoyant or non-hydrostatic flows. Non-hydrostatic effects arise from an imbalance between the buoyancy term and the pressure gradient in the momentum equation (Equation (2.8a)). In stagnant, stably stratified conditions, these two terms are balanced. For the applications considered in this work, merely small deviations from such stable conditions are expected. To improve the numerical conditioning of the pressure-buoyancy balance, it is thus advisable to remove (at least partially) hydrostatic parts from both sides of the balance. More importantly, such an adaptation decreases the absolute value of the pressure variable and thus improves the conditioning of the numerical calculation of the pressure gradient. Since the exact hydrostatic pressure is usually unknown, different pressure decomposition approaches exist. A standard approach followed in OpenFOAM[®] is to introduce the modified pressure $P_{rgh} = P - \rho \mathbf{g} \cdot \mathbf{r}$. The pressure-buoyancy balance from Equation (2.8a) becomes

$$\begin{aligned} \rho \mathbf{g} - \nabla P &= \rho \mathbf{g} - \nabla (P_{rgh} + \rho \mathbf{g} \cdot \mathbf{r}) \\ &= \rho \mathbf{g} - \nabla P_{rgh} - \nabla (\rho \mathbf{g} \cdot \mathbf{r}) \\ &= \rho \mathbf{g} - \nabla P_{rgh} - \rho \mathbf{g} \cdot \nabla \mathbf{r} - \mathbf{g} \cdot \mathbf{r} \nabla \rho \\ &= \rho \mathbf{g} - \nabla P_{rgh} - \rho \mathbf{g} - \mathbf{g} \cdot \mathbf{r} \nabla \rho \\ &= -\nabla P_{rgh} - \mathbf{g} \cdot \mathbf{r} \nabla \rho . \end{aligned} \quad (2.9)$$

This transformation follows from the application of the chain rule for differentiation and the assumption of a constant $\mathbf{g}$ (OpenCFD Ltd., 2021). It has the advantage that, since

both sides of the pressure-buoyancy balance now include gradients, consistent finite volume discretization schemes can be employed on both sides to guarantee a physically correct balance. A side-effect of this standard approach is that it introduces a horizontal balance proportional to the horizontal density gradient times the vertical coordinate, where previously the pressure-buoyancy balance was purely vertical. For problems with large vertical dimensions, this can lead to ill conditioning of the pressure-buoyancy balance even if horizontal density gradients are small. In the present work, after initially adopting the P_{rgh} approach, a different approach is employed by using a pressure variable $P_{gh} = P - \rho_0 \mathbf{g} \cdot \mathbf{r}$, where ρ_0 is the constant Boussinesq reference density. Here, the pressure-buoyancy balance becomes

$$\begin{aligned} \rho \mathbf{g} - \nabla P &= \rho \mathbf{g} - \nabla (P_{gh} + \rho_0 \mathbf{g} \cdot \mathbf{r}) \\ &= (\rho - \rho_0) \mathbf{g} - \nabla P_{gh} . \end{aligned} \quad (2.10)$$

While this approach lacks the well-balancedness of the standard formulation (The pressure gradient is discretized differently from the buoyancy source term), it retains the pressure-buoyancy balance as a purely vertical balance. This approach was found to be more numerically stable for problems with large vertical dimensions.

In the following, the kinematic pressure $p_{gh} = P_{gh}/\rho_0$ will be used in the context of the Boussinesq-type equations. With this, Equation (2.8a) becomes

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u} \mathbf{u}) = \nabla \cdot \boldsymbol{\tau}^* - \nabla p_{gh} + \left(\frac{\rho}{\rho_0} - 1 \right) \mathbf{g} + \mathbf{f}_u , \quad (2.11)$$

where $\boldsymbol{\tau}^*$ is the kinematic viscous stress tensor (i.e., calculated as in Equation (2.3) but using the kinematic molecular viscosity).

2.3 RANS turbulence modeling

Die der Hauptbewegung überlagerte Schwankungsbewegung ist in ihren Einzelheiten so hoffnungslos kompliziert, dass ihre theoretische Berechnung aussichtslos erscheint. Die von ihr verursachte Mischbewegung ist jedoch für den Ablauf der Strömung und für den Kräftehaushalt von sehr großer Bedeutung. Sie bringt Wirkungen hervor, als ob die Viskosität hundertfach, zehntausendfach oder noch stärker erhöht wäre.

—Schlichting and Gersten, 1997, p. 533

Practical flows on both technical and geophysical scales are predominantly turbulent (Ferziger et al., 2020). Such flows exhibit seemingly chaotic, non-stationary, three-dimensional motion across a wide range of length and time scales, which present a challenge for their numerical prediction. Turbulence modeling approaches range from Direct Numerical Simulation (DNS) to simple averaged methods. In this thesis, we will concentrate solely on Reynolds-averaged Navier-Stokes (RANS) turbulence modeling. While the methods developed in this work can be readily used with other turbulence modeling approaches, the scale of the problems typically studied in the context of AU requires that turbulence be modeled as efficiently as possible to reduce computational cost. The following descriptions will thus be limited to RANS turbulence modeling. First, the process of Reynolds averaging itself will be discussed before describing turbulence closure models for the Reynolds-averaged equations.

2.3.1 Reynolds averaging

When only the gross effects of turbulence are of interest, the variation of a measured quantity ϕ can be split into mean and fluctuating components.

$$\phi = \bar{\phi} + \phi' . \quad (2.12)$$

For instationary flows, the Reynolds averaging concept is derived from the idea of ensemble averaging, where $\bar{\phi}$ is considered the average of a large ensemble of measurements

$$\bar{\phi}(\mathbf{x}, t) = \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{n=1}^N \phi(\mathbf{x}, t) . \quad (2.13)$$

The ensemble average of ϕ' is equal to zero. Thus, when the ensemble average is applied to the fundamental equations, the fluctuating contributions from linear terms vanish, leaving the corresponding term for the averaged variable, e. g.,

$$\begin{aligned} \frac{\partial \bar{\phi}}{\partial t} &= \frac{\partial}{\partial t} (\bar{\phi} + \phi') \\ &= \frac{\partial}{\partial t} (\bar{\phi} + \overset{0}{\cancel{\phi'}}) \\ &= \frac{\partial \bar{\phi}}{\partial t} . \end{aligned} \quad (2.14)$$

For non-linear terms, the fluctuation does not vanish

$$\begin{aligned} \overline{\nabla \cdot (\mathbf{u}\phi)} &= \nabla \cdot (\overline{(\bar{\mathbf{u}} + \mathbf{u}')(\bar{\phi} + \phi')}) \\ &= \nabla \cdot (\bar{\mathbf{u}}\bar{\phi} + \overline{\mathbf{u}'\phi'} + \overset{0}{\cancel{\bar{\mathbf{u}}\phi'}} + \overset{0}{\cancel{\bar{\phi}'\mathbf{u}'}}) . \end{aligned} \quad (2.15)$$

The covariances $\overline{\mathbf{u}'\phi'}$ are henceforth referred to as turbulent scalar fluxes or, in the case of velocity, as the (kinematic) Reynolds stresses $\overline{(\mathbf{u}'\mathbf{u}')}$. These terms introduce a closure problem to the set of equations, as they cannot be modeled exactly in terms of the averaged quantities. Approximate turbulence models thus have to be applied to close the RANS equations.

2.3.2 Eddy viscosity turbulence modeling

As indicated in the epigraph of this section by Schlichting and Gersten (1997), the gross effect of turbulence on the mean flow is similar to that of a significantly enhanced viscosity. A simple model for the Reynolds stresses can thus be derived in analogy to the viscous stresses in a Newtonian fluid

$$-\overline{\mathbf{u}'\mathbf{u}'} = 2\nu_t \bar{\mathbf{S}} - \frac{2}{3}\nu_t (\nabla \cdot \bar{\mathbf{u}}) \mathbf{I} - \frac{2}{3}\mathbf{I}k = \bar{\boldsymbol{\tau}}_t^* - \frac{2}{3}\mathbf{I}k , \quad (2.16)$$

where $k = 1/2 \text{tr}(\overline{\mathbf{u}'\mathbf{u}'})$ is the turbulent kinetic energy and ν_t is the unknown eddy viscosity, which has to be defined through further modeling efforts. Equation (2.16) is known as the linear eddy viscosity hypothesis. Non-linear eddy viscosity models use the eddy viscosity concept in a generalized expression

$$-\overline{\mathbf{u}'\mathbf{u}'} = 2\nu_t \mathbf{f} , \quad (2.17)$$

where $\mathbf{f}$ is typically a function of the mean strain rate and vorticity (e. g., Speziale, 1987).

Most turbulence models describe ν_t based on the turbulent kinetic energy k and a length-scale defining variable such as ϵ , the dissipation rate of k . The two variables can be modeled by two additional transport equations. Such turbulence models are known as two-equation models. They are widely applied in technical and geophysical modeling (Menter et al., 2003; Rodi, 1987). At this point, the theory and equations of eddy viscosity turbulence models will not be further discussed. The full transport equations for the k - ϵ turbulence model are given in Chapter 3. Additionally, the equations of the widely applied k - ω SST turbulence model (Menter, 1994) are given in Contribution [JPA] of this thesis.

For the turbulent scalar fluxes $\overline{\mathbf{u}'\phi'}$, the Simple Gradient Diffusion Hypothesis (SGDH) is typically applied in RANS models.

$$-\overline{\mathbf{u}'\phi'} = \frac{\nu_t}{\sigma_t} \nabla \bar{\phi} , \quad (2.18)$$

where σ_t is the turbulent Prandtl number, which is usually modeled as a constant value close to 0.9. The SGDh approximates the turbulence as fully isotropic and the resulting scalar flux to be aligned with the mean gradient $\nabla\bar{\phi}$. The Generalized Gradient Diffusion Hypothesis (GGDH) of Daly and Harlow (1970) represents a more general formulation. It correlates the scalar fluxes to the Reynolds stresses

$$-\overline{\mathbf{u}'\phi'} = C_1 \frac{k}{\epsilon} \overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla\bar{\phi} , \quad (2.19)$$

where C_1 is a constant model parameter. Even more generality is achieved by Algebraic Flux Models (AFM), which can be directly derived from the transport equations for $\overline{\mathbf{u}'\phi'}$ by applying closure approximations and assuming a local equilibrium. E.g., Kenjereš et al. (2005) propose

$$-\overline{\mathbf{u}'\phi'} = C_0\tau \left(C_1 \overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla\bar{\phi} + C_2 \nabla\bar{\mathbf{u}} \cdot \bar{\phi}'\mathbf{u}' + C_3 \beta \bar{\phi}'^2 \mathbf{g} \right) - C_4 \left(\frac{1}{k} \overline{\mathbf{u}'\mathbf{u}'} - \frac{2}{3} \mathbf{I} \right) \cdot \bar{\phi}'\mathbf{u}' . \quad (2.20)$$

where $\tau \sim k/\epsilon$, β is the expansion coefficient of the fluid with respect to ϕ (only relevant for active scalars), and C_0 through C_4 are coefficients. The scalar variance $\bar{\phi}'^2$ has to be modeled by an additional transport equation.

It is interesting to note that the GGDH (Equation (2.19)) can be recovered from the model of Kenjereš et al. (2005) by neglecting all terms except the leading term, while the SGDh (Equation (2.18)) can be recovered from the GGDH by neglecting contributions due to the anisotropic turbulent stresses (i. e., by setting $\bar{\tau}_t^* = 0$). Other scalar flux modeling approaches apply the SGDh in conjunction with a modeled, non-constant turbulent Prandtl number (Combest et al., 2011). This will be discussed further in Section 3 along with aspects related to RANS turbulence modeling in buoyant and stratified flows.

2.4 The finite volume method

To be numerically solvable, the fundamental equations introduced in Section 2.1 have to be discretized, i. e., the equations must be transferred from their differential form to an algebraic form by making suitable approximations. In the following, the Finite Volume Method (FVM) will be introduced as a discretization method. The methodology and naming conventions are adapted from Ferziger et al. (2020), Jasak (1996), and Moukalled et al. (2016).

The aim of the described finite volume method is to solve the fundamental equations in a spatial domain defined by a finite number of polyhedral control volumes, which are interconnected by a finite number of flat faces. Variables are stored at the geometric centers of each cell. The time domain is discretized by a finite number of time steps of length Δt .

In the following, the discretization of the incompressible transport equation for a generic solution variable ϕ is described. The transport equation reads

$$\frac{\partial\phi}{\partial t} + \nabla \cdot (\phi\mathbf{u}) = \nabla \cdot (\Gamma \nabla\phi) + S_\phi . \quad (2.21)$$

The equation must be satisfied for each finite control volume (cell) ΔV and each time step Δt

$$\int_{\Delta t} \left[\int_{\Delta V} \left(\frac{\partial\phi}{\partial t} + \nabla \cdot (\phi\mathbf{u}) \right) dV \right] dt = \int_{\Delta t} \left[\int_{\Delta V} (\nabla \cdot (\Gamma \nabla\phi) + S_\phi) dV \right] dt . \quad (2.22)$$

The final discretized equation will take the form of a linear system

$$A\phi = B , \quad (2.23)$$

where A is the coefficient matrix, and the right-hand side B includes explicit contributions that do not directly depend on the unknown solution variable.

Source terms The volume integration of a constant source term $S_\phi = G$ across the cell volume ΔV yields

$$\int_{\Delta V} G \, dV = G \int_{\Delta V} dV = G \Delta V . \quad (2.24)$$

This term can be added directly to the right-hand side of the algebraic equation (Equation (2.23)). The volume integration of a linear source term $S_\phi = G\phi$ for the solution variable ϕ across the cell volume can be approximated using the midpoint rule

$$\int_{\Delta V} G\phi \, dV = G \int_{\Delta V} \phi \, dV = G \widehat{\phi_{\Delta V}} \Delta V \approx G \phi_P \Delta V , \quad (2.25)$$

where the hat indicates the arithmetic mean and the subscript P denotes the value at the geometric center of the cell. The approximation in Equation (2.25) is second-order accurate. It is exact for a linear variation of ϕ across the cell volume. The term enters the algebraic system as an implicit contribution by adding $G \Delta V$ to the diagonal of the coefficient matrix. Higher-order source terms (e.g., $S_\phi = G\phi^2$) are typically linearized by using known values of ϕ from a previous iteration or time step for all factors down to a linear contribution of ϕ . Such terms can then be treated as shown in Equation (2.25).

Divergence operator Using Gauss' divergence theorem, the volume integral of the divergence of a vector field $\mathbf{f}$, as encountered in the convective ($\mathbf{f} = \mathbf{u}\phi$) and diffusive ($\mathbf{f} = \Gamma \nabla \phi$) terms of the transport equation for the generic solution variable ϕ , can be expressed as a surface integral. The surface integral for a cell can be equivalently calculated by summing up the contributions from each of the n plane faces individually

$$\int_{\Delta V} \nabla \cdot \mathbf{f} \, dV = \int_S \mathbf{f} \cdot \mathbf{n} \, dS = \sum_{i=1}^n \int_{S_i} \mathbf{f} \cdot \mathbf{n}_i \, dS_i . \quad (2.26)$$

Here, $\mathbf{n}_i$ is the outward-pointing normal vector of the face i . The approximation of the surface integral across a cell face i requires two steps. For this, we will consider the example of a one-dimensional mesh, consisting of two cells, shown in Figure 2.1. As a first step

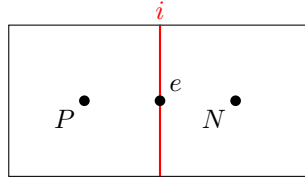


Figure 2.1: Schematic of one-dimensional mesh, consisting of two cells.

towards approximating the surface integral across face i , an approximation of the integral must be found. Typically, the midpoint rule is applied, which approximates the integral by the value of $\mathbf{f}$ at the geometric face center e multiplied by the face area. This yields

$$\int_{S_i} \mathbf{f} \cdot \mathbf{n}_i \, dS_i = \mathbf{n}_i \cdot \int_{S_i} \mathbf{f} \, dS_i \approx \mathbf{n}_i \cdot \mathbf{f}_e \Delta S_i = \mathbf{f}_e \cdot \mathbf{S}_i , \quad (2.27)$$

where $\mathbf{S}_i = \Delta S_i \mathbf{n}_i$ is the face area vector. Similar to Equation (2.25), Equation (2.27) represents a second-order approximation of the surface integral. As a second step towards approximating the surface integral, the value of $\mathbf{f}_e$ must be interpolated in terms of the values at the cell centers P and N . Here, the treatment varies between the convective and diffusive terms.

Convective term For the convective term, the vector field $\mathbf{f}$ becomes $\mathbf{u}\phi$. The discretized form of Equation (2.26) can thus be interpreted as the cumulative transport of ϕ across the faces of the cell based on the signed volume flux $\Phi_i = \mathbf{u}_e \cdot \mathbf{S}_i$. The calculation of Φ_i will

be discussed in Section 2.5. Here, we assume that this quantity is known, but note that Φ_i must satisfy the continuity equation to avoid any artificial loss or creation of ϕ inside the cell. Multiple interpolation schemes exist to perform the interpolation for ϕ_e . Well-known examples are the linear scheme, which uses linear interpolation between the cell-centered values ϕ_P and ϕ_N , and the upwind scheme, which approximates the value at the face center using the cell value upstream of the face (i.e., against the direction of $\mathbf{u}$).

Diffusive term For the diffusive term $\mathbf{f}$ becomes $\Gamma \nabla \phi$. Here, Γ_e is typically interpolated from Γ_P and Γ_N using linear interpolation. The face-normal component of the gradient $\nabla \phi \cdot \mathbf{n}$ at location e can simply be approximated by

$$(\nabla \phi)_e \cdot \mathbf{n}_i \approx \frac{\phi_N - \phi_P}{|\mathbf{d}|}, \quad (2.28)$$

where $\mathbf{d}$ is the vector connecting the cell centers. On general meshes, where $\mathbf{d}$ is not parallel to $\mathbf{n}_i$, this approximation has to be corrected by a suitable non-orthogonality correction approach.

As Equation (2.28) shows, the interpolation procedures for the convective and diffusive terms introduce a linear dependence on the values of ϕ at the centers of all neighboring cells to the algebraic equation for any given cell, thus populating the off-diagonal elements of the coefficient matrix A in Equation (2.23). The matrix A is thus populated along the diagonal as well as for all off-diagonal elements corresponding to physically connected cells¹.

Temporal discretization Finite volume methods typically employ a finite differences approach for time discretization. Common time discretization schemes can be constructed by rearranging Equation (2.22) to take the form of an initial value problem

$$\begin{aligned} \int_{\Delta t} \int_{\Delta V} \frac{\partial \phi}{\partial t} dV dt &= \int_{\Delta t} \left[\int_{\Delta V} (-\nabla \cdot (\phi \mathbf{u}) + \nabla \cdot (\Gamma \nabla \phi) + S_\phi) dV \right] dt \\ &= \int_{\Delta t} \int_{\Delta V} f(t, \phi(t)) dV dt \\ &= \int_{\Delta t} F(t, \phi(t)) dt. \end{aligned} \quad (2.29)$$

Here, the function f includes all terms of the transport equation except for the transient term, and F is the corresponding spatially discretized operator, which can be derived using the previously introduced spatial discretization schemes. The spatial integration of the left-hand side of Equation (2.29) can be performed as in Equation (2.25). For a fixed mesh, we obtain

$$\int_{\Delta t} \int_{\Delta V} \frac{\partial \phi}{\partial t} dV dt \approx \Delta V \int_{\Delta t} \frac{\partial \phi_P}{\partial t} dt. \quad (2.30)$$

The time integration across the time step Δt can be expressed as an integration from the time level t_n to the next time level $t_{n+1} = t_n + \Delta t$. Henceforth, we will use the common short notation $\phi_P(t_n) = \phi_P^n$. It follows

$$\int_{t_n}^{t_{n+1}} \frac{\partial \phi_P}{\partial t} dt = \phi_P^{n+1} - \phi_P^n. \quad (2.31)$$

Combining Equations (2.29) and (2.31) yields

$$\phi_P(t_{n+1}) = \phi_P^n + \frac{1}{\Delta V} \int_{t_n}^{t_{n+1}} F(t, \phi(t)) dt. \quad (2.32)$$

This equation is exact in time. However, the function F can only be evaluated at discrete time levels. Common time discretization schemes provide approximations of the integral in

¹ Approximations that would introduce a larger computational stencil are typically avoided in finite volume methods.

Equation (2.32) using different time levels². The well-known implicit Euler scheme uses

$$\int_{t_n}^{t_{n+1}} F(t, \phi(t)) dt \approx F(t_{n+1}, \phi_P^{n+1}) \Delta t . \quad (2.33)$$

This is a first-order approximation. The backward scheme (Ferziger et al., 2020), which is widely used throughout this thesis, provides a second-order approximation using

$$\int_{t_n}^{t_{n+1}} F(t, \phi(t)) dt \approx \frac{1}{3} \phi_P^n \Delta V + \frac{1}{3} \phi_P^{n-1} \Delta V + F(t_{n+1}, \phi_P^{n+1}) \Delta t . \quad (2.34)$$

Both of these schemes are fully implicit, as F is only evaluated on the new time level. Another second-order approximation is given by the Crank-Nicolson scheme

$$\int_{t_n}^{t_{n+1}} F(t, \phi(t)) dt \approx \frac{1}{2} [F(t_n, \phi_P^n) + F(t_{n+1}, \phi_P^{n+1})] \Delta t . \quad (2.35)$$

Here, F is evaluated on the new and old time level. The contributions of $F(t_n, \phi_P^n)$ are based on known values of the solution variable ϕ on the previous time level. The spatial discretization of the corresponding terms thus does not contribute to the coefficient matrix A of the algebraic system (see Equation (2.23)) as previously described, but adds an explicit contribution to the right-hand side B instead.

The above description outlines the discretization procedure for all terms in the generic transport equation, such that the algebraic system can be built from the individual contributions. Efficient computational algorithms can be employed to solve the resulting system for the unknown ϕ .

2.5 The PIMPLE algorithm

In the previous sections, the fundamental equations and their discretization have been discussed. In this section, an algorithm for solving the discretized equations as a coupled problem will be discussed. The problem is solved in a segregated, sequential manner. Thus, a separate linearized system (see Section 2.4) is solved for each solution variable at each time step. The PIMPLE algorithm is widely used for transient flow problems in OpenFOAM[®]. The algorithm was developed as a configurable combination of the well-known SIMPLE (Patankar and Spalding, 1972) and PISO (Issa, 1986) algorithms. It represents a pressure-based solution process for the Navier-Stokes equations. The general solution process will be described here briefly, following the reasoning and naming conventions of Jasak (1996), Moukalled et al. (2016), and the OpenFOAM[®] user guide (OpenCFD Ltd., 2023). For a more detailed description, the reader is referred to these sources.

One of the key difficulties when solving the Boussinesq set of fundamental equations (Equation (2.8)) is that an obvious way of calculating pressure does not exist. Additionally, the set contains the continuity equation, which the velocity field $\mathbf{u}$ has to satisfy simultaneously with the momentum equation. Pressure-based methods thus formulate a pressure equation based on the continuity equation and a semi-discretized form of the momentum equation. Following the discretization procedures outlined in Section 2.4, a semi-discretized form of the momentum equation can be written as

$$M\mathbf{u} = \mathbf{B} - \nabla p . \quad (2.36)$$

Here, the coefficient matrix is named M to be consistent with OpenFOAM[®] naming conventions. The pressure gradient is separated from the source terms and remains non-discretized, for now. Note that, even though $\mathbf{u}$ is a vectorial quantity, OpenFOAM[®] constructs a single scalar coefficient matrix from the momentum equation. A vector field $\mathbf{H}$ is now defined, such that

$$M\mathbf{u} - \mathbf{B} = A\mathbf{u} - \mathbf{H} , \quad (2.37)$$

² Here, a constant time step size Δt is implied. The presented schemes can be easily extended for variable time step sizes.

where A is a matrix containing only the diagonal coefficients. Consequently, $\mathbf{H}$ contains the off-diagonal contributions along with some previous solution for $\mathbf{u}$ (typically from the solution of the discretized momentum equation), as well as the explicit contributions from $\mathbf{B}$. With this definition, Equation (2.36) can be rewritten as

$$A\mathbf{u} - \mathbf{H} = -\nabla p . \quad (2.38)$$

Since A is diagonal, a velocity can be approximated as

$$\mathbf{u} = A^{-1}\mathbf{H} - A^{-1}\nabla p . \quad (2.39)$$

Equation (2.39) is known as the velocity correction equation. Substituting Equation (2.39) into the continuity equation (Equation (2.8b)) yields a Poisson equation for pressure

$$\nabla \cdot (A^{-1}\nabla p) = \nabla \cdot (A^{-1}\mathbf{H}) . \quad (2.40)$$

This equation can be discretized as described in Section 2.4 and solved for p . Given a solution for p from Equation (2.40), the velocity field can be corrected based on Equation (2.39). Additionally, Equation (2.39) can be interpolated to the cell faces and dotted with the face area vector $\mathbf{S}_f$ to yield an equation for the volume flux Φ , which is required in the discretization of the convective terms of the transport equations (see Section 2.4)

$$\Phi = (A^{-1}\mathbf{H})_f \cdot \mathbf{S}_f - (A^{-1})_f \mathbf{S}_f \cdot (\nabla p)_f . \quad (2.41)$$

If consistent discretization and interpolation schemes are applied, it can be ensured that Φ is a conservative volume flux if p satisfies the discretized pressure equation. The procedure outlined above thus provides an equation for pressure and ensures conservation of the face volume fluxes.

A simultaneous satisfaction of the momentum and continuity equations is not yet ensured. An iterative process must thus be employed. Figure 2.2 depicts the PIMPLE solution process. The end of the PISO loop is defined based on a fixed number of iterations. The end of the PIMPLE loop can either be defined based on a fixed number of iterations or based on the residuals of the linear equation solvers. Optional switches exist to include the mesh motion and the turbulence model into the PIMPLE loop, such that multiple iterations over these steps are possible within each time step.

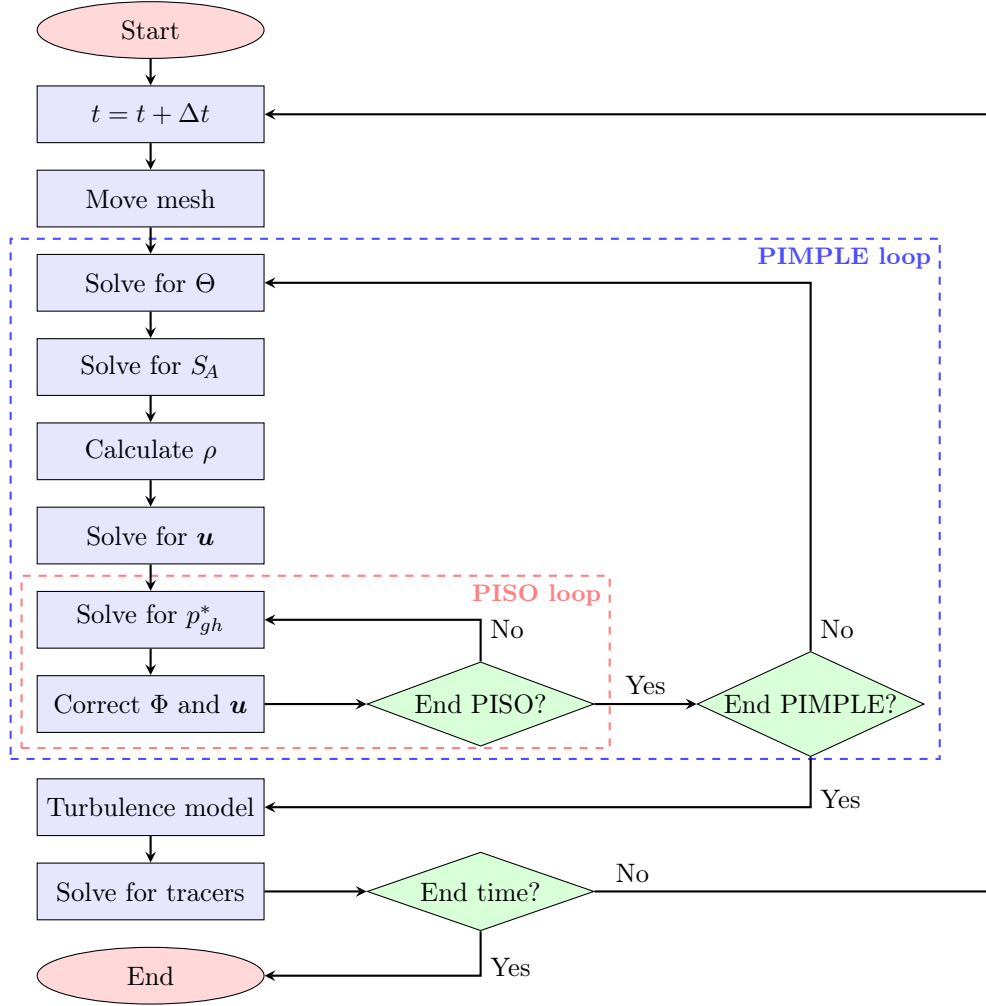


Figure 2.2: Schematic of the PIMPLE algorithm.

2.6 The OpenFOAM[®] framework

The name *OpenFOAM* stands for Open Field Operation And Manipulation. *OpenFOAM* was developed as a C++ library for computational continuum mechanics (Weller et al., 1998). Using object-oriented programming techniques, it provides data types and operations that closely resemble mathematical field operations. As a result, *OpenFOAM* provides a high-level syntax for tensor operations, which enables the convenient development of methods for computational continuum mechanics. Its rich object-oriented structure and consequent use of the *virtual constructor* idiom also enable a high level of modularity at run-time, allowing the user to easily change numerical schemes, physical models, and solution algorithms without having to recompile the source code. Today, the OpenFOAM[®] framework comprises a large number of physical modeling libraries, applications, and methods, building upon its core capabilities and focusing mainly on the solution of finite volume CFD problems. The OpenFOAM[®] source code is publicly available and licensed under a GPL license, allowing for continued development efforts throughout its user community and a wide variety of derived methods. Figure 2.3 gives an overview of the structure of OpenFOAM[®].

For this thesis, OpenFOAM[®] was chosen as a basis for method development due to its ease of use, its modular structure, and the wide variety of available libraries and methods. As an example, Listing 2.1 shows the implementation of the salinity transport equation (Equation (2.8d)) in OpenFOAM[®] source code. This listing demonstrates the convenient high-level syntax and the ease of use. Here, the `fvm` (short for finite volume matrix)

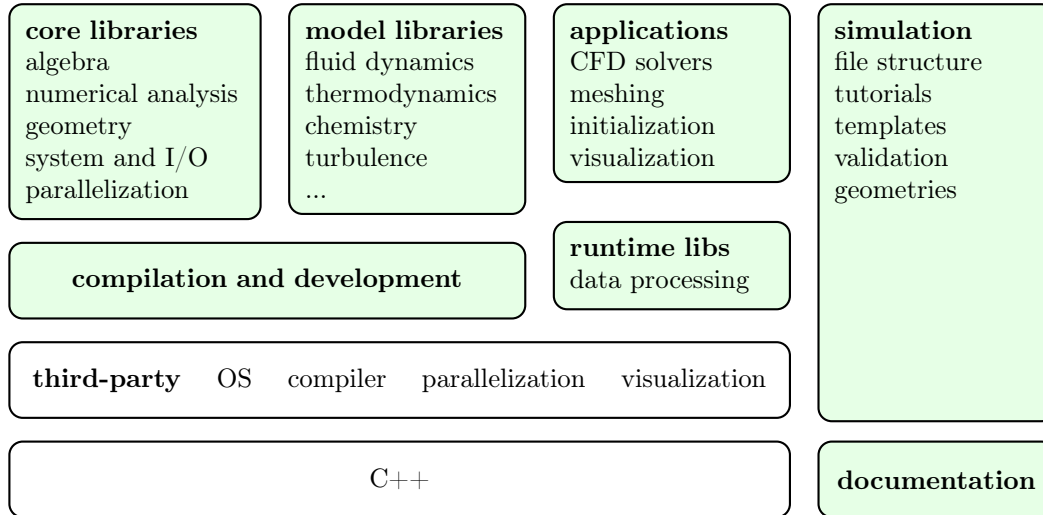


Figure 2.3: Schematic of the OpenFOAM[®] code structure. Adapted from Greenshields (2018).

```

1 // Construct the salinity equation
2 fvScalarMatrix salinityEqn
3 (
4     fvm::ddt(salinity) // Time derivative
5     + fvm::div(phi, salinity) // Convective term
6     + salinityFluxModel->divPhiU() // Turbulent flux
7     - fvm::laplacian(D_salinity, salinity) // Diffusive term
8     ==
9     fvOptions(salinity) // Additional source terms defined at runtime
10 );
11 salinityEqn.relax(); // Optional implicit relaxation
12 fvOptions.constrain(salinityEqn); // Constraints defined at runtime
13
14 // Solve the equation
15 salinityEqn.solve();
16
17 fvOptions.correct(salinity); // Corrections defined at runtime

```

Listing 2.1: OpenFOAM[®] code example. Implementation of the salinity transport equation.

class performs the finite volume discretization, using the discretization schemes specified at runtime, and constructs the linear system. The `fvScalarMatrix` class stores and solves the algebraic system. Polymorphism is employed, such that the same syntax can be used for the scalar salinity equation and the vectorial momentum equation. The mathematical operators are overloaded to perform the necessary operations on the coefficient matrix while checking for consistency of the physical units.

A modular structure and the possibility for customization are enabled in OpenFOAM[®] through the possibility of including additional libraries at runtime. Use of this is made throughout this thesis to provide additional capabilities (e.g., new boundary conditions, mesh motion solvers, turbulence models) to the method in a modular fashion.

2.6.1 Usage

In the following, a brief introduction to the setup of a CFD simulation in OpenFOAM[®] is given. Any CFD simulation setup consists of typical elements: A description of the spatial discretization (mesh), a definition of boundary conditions, descriptions of physical properties, an initial condition for the solution, as well as settings for the applied mathematical model and its discretization and solution (or time integration). In OpenFOAM[®], a standardized directory structure is employed to control these elements through a number of input

files. Figure 2.4 shows the typical directory structure with explanations of the directories and input files. Additional input files are required to control special functionalities, such as

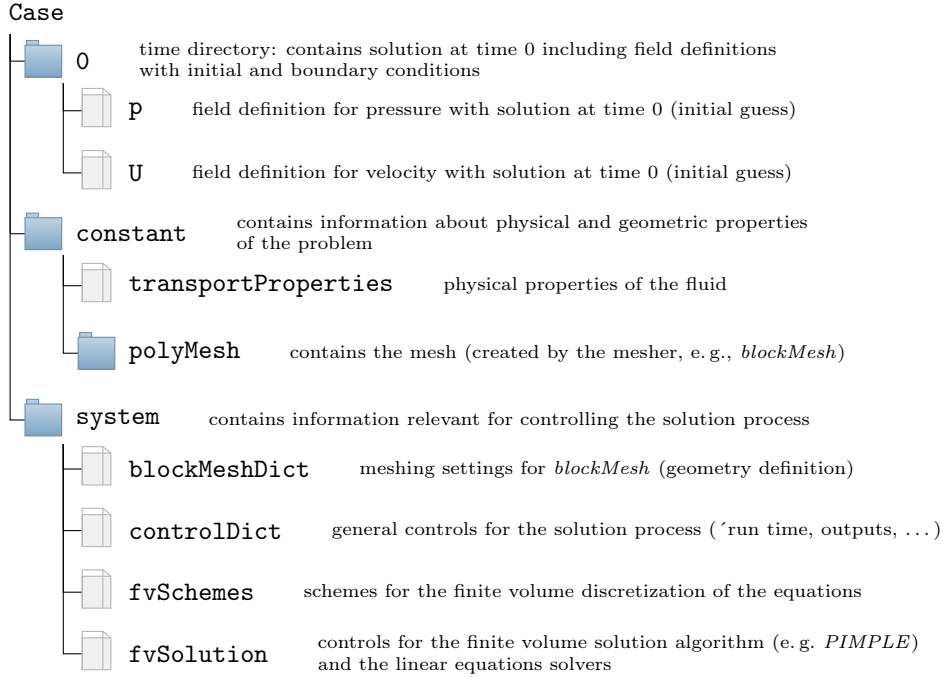


Figure 2.4: Standard case structure for an OpenFOAM® case.

dynamic mesh motion, turbulence modeling, or run-time post-processing. Listing 2.2 shows the standardized syntax of the OpenFOAM® input files on the example of the `controlDict` file. Listing 2.3 shows the definition of the velocity field, including initial and boundary conditions, in the file `0/U`. The case is prepared and run by sequentially calling OpenFOAM® (or custom) applications for mesh generation (e.g., *blockMesh*), optional initialization (e.g., *setFields*), solution through the employed solver application (e.g., *icoFoam*), and optional post-processing (e.g., *postProcess*). The solution is written into new time directories, which have the same structure as the initially provided time directory (`0` in Figure 2.4) and, in fact, can be used as initial guess for a restart of the solution process. The results are typically visualized using the visualization platform *ParaView*.

```

1  /*----- C++ -----*/
2  | ===== |
3  | \ \ / F i e l d | OpenFOAM: The Open Source CFD Toolbox |
4  | \ \ / O p e r a t i o n | Version: v2412 |
5  | \ \ / A n d | Website: www.openfoam.com |
6  | \ \ / M a n i p u l a t i o n | |
7  /*-----*/
8  FoamFile
9  {
10     version      2.0;
11     format        ascii;
12     class         dictionary;
13     object        controlDict;
14 }
15 // *****
16 application      icoFoam;          // Solver application --> basic math. model
17 startFrom        startTime;        // Run time controls
18 startTime        0;
19 stopAt           endTime;
20 endTime          0.5;
21 deltaT           0.005;            // Time step size
22 writeControl      timeStep;        // Output controls
23 writeInterval     20;
24 purgeWrite        0;
25 writeFormat       ascii;
26 writePrecision    6;
27 writeCompression off;
28 timeFormat        general;
29 timePrecision     6;
30 runtimeModifiable true;
31 libs              ();              // Optional libraries to include
32 // *****

```

Listing 2.2: Example of OpenFOAM® input file controlDict.

```

1  /*----- C++ -----*/
2  | ===== |
3  | \ \ / F i e l d | OpenFOAM: The Open Source CFD Toolbox |
4  | \ \ / O p e r a t i o n | Version: v2412 |
5  | \ \ / A n d | Website: www.openfoam.com |
6  | \ \ / M a n i p u l a t i o n | |
7  /*-----*/
8  FoamFile
9  {
10     version      2.0;
11     format        ascii;
12     class         volVectorField;
13     object        U;
14 }
15 // *****
16 dimensions       [0 1 -1 0 0 0 0]; // Units: power of bases [kg m s K mol A cd]
17 internalField     uniform (0 0 0);  // Initial guess for velocity field
18 boundaryField
19 {
20     // Boundary condition definition for boundary named "inlet"
21     inlet
22     {
23         type       fixedValue;          // Dirichlet-type boundary
24         value       uniform (1 0 0);
25     }
26 }
27 // [...]
28 }
29 // *****

```

Listing 2.3: Example of OpenFOAM® input file o/u.

2.7 *ocean4Foam*: A new toolbox for oceanic flow in OpenFOAM[®]

In this thesis, the OpenFOAM[®] framework is used to develop a new toolbox of libraries and applications focused on the simulation of oceanic flow problems in OpenFOAM[®]. While OpenFOAM[®] is widely used in marine and coastal engineering (Huang et al., 2022), such applications generally assume isothermal and isohaline conditions, such that the water density is constant. Only few works study variable-density flows in a marine and coastal engineering context. Alfaifi et al. (2019) study buoyant jets in water driven by either temperature or salinity. Rouhnia et al. (2016) and Zhang et al. (2024) use a custom OpenFOAM[®] solver *gravityCurrentFoam*, which includes a transport equation for salinity, to study salinity-induced buoyancy. Other authors use the standard OpenFOAM[®] solver, *twoLiquidMixingFoam*, to study gravity currents (Lam et al., 2018) and wastewater outfalls (Kheirkhah Gildeh et al., 2021), based on a two-fluid approach. Alvir et al. (2022) extend this approach with a one-way coupling to the regional ocean modeling system ROMS (Shchepetkin and McWilliams, 2005). An OpenFOAM[®] framework for large-scale geophysical and environmental applications has been presented by Girfoglio et al. (2024), yet this is not useful for the local scales encompassed in this thesis.

While the previously cited publications apply OpenFOAM[®] for specific problems related to oceanic flow, they are not generally applicable to flow problems with both temperature- and salinity-induced density changes, as encountered in general oceanic flow. To the author's knowledge, the only report of a general OpenFOAM[®] solver for oceanic flow is found online under the name *marineFoam* (Scanlon, 2018). This solver implements a Boussinesq approach with a bilinear equation of state, including both temperature and salinity. *marineFoam* is not publicly available or open-source.

To fulfill the thesis objective of developing methods that are applicable to AU studies in the widest possible sense (see Section 1.5.1), the OpenFOAM[®] methods developed throughout this thesis aim to provide a toolbox for oceanic flow in general. The new toolbox, named *ocean4Foam*, is thus applicable to a wide range of problems beyond AU technology. After applying Reynolds averaging, as described in Section 2.3, and pressure decomposition, as described in Section 2.2, the final form of the oceanic Boussinesq set implemented in *ocean4Foam* reads

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\mathbf{u}}) = \nabla \cdot (\bar{\boldsymbol{\tau}}^* - \overline{\mathbf{u}' \mathbf{u}'}') - \nabla \bar{p}_{gh} + \mathbf{g} \left(\frac{\rho}{\rho_0} - 1 \right) + \mathbf{f}_u \quad (2.42a)$$

$$\nabla \cdot \bar{\mathbf{u}} = 0 \quad (2.42b)$$

$$\frac{\partial \bar{\Theta}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\Theta}) = \nabla \cdot (\lambda \nabla \bar{\Theta} - \overline{\Theta' \mathbf{u}'}') + S_\Theta \quad (2.42c)$$

$$\frac{\partial \bar{S}_A}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{S}_A) = \nabla \cdot (D \nabla \bar{S}_A - \overline{S'_A \mathbf{u}'}') + S_{S_A} \quad (2.42d)$$

$$\rho = f(\bar{S}_A, \bar{\Theta}, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r}) . \quad (2.42e)$$

The seawater properties are modeled using the polynomial of McDougall et al. (2003), which is part of the *TEOS-10* standard (IOC et al., 2010), for ρ . The transport properties ν and λ can be calculated based on the polynomials of Sharqawy et al. (2010) and Jamieson and Tudhope (1970), respectively, if variable properties are used. In addition to the Boussinesq set, the *ocean4Foam* solvers include a passive tracer transport equation. The tracer can be interpreted as a nutrient or deep ocean water concentration in the context of AU. The transport equation reads

$$\frac{\partial \bar{\phi}}{\partial t} + \nabla \cdot (\bar{\phi} \bar{\mathbf{u}}) = \nabla \cdot (\Gamma \nabla \bar{\phi} - \overline{\phi' \mathbf{u}'}') + S_\phi . \quad (2.43)$$

Overall, the *ocean4Foam* toolbox contains the following libraries and methods:

- Solvers
 - *oceanPimpleFoam* solver for transient oceanic flow
 - *oceanSimpleFoam* steady-state solver for oceanic flow
- Methods for physical properties of seawater
- Basic *ocean4Foam* library
 - Boundary conditions (e. g., hydrostatic *open* boundary)
 - Models for turbulent scalar fluxes
 - Post-processing functions
- Turbulence modeling library
 - Derived turbulence models
 - New buoyancy source terms for turbulence models
- ALE-IT library
 - Modified and extended ALE-IT method
 - New ALE-IT adaptive mesh refinement methods
- Wave modeling library
 - New adapter for *waves2foam* toolbox (Jacobsen et al., 2011)
 - Derived wave generation and absorption methods

ocean4Foam is developed as a toolbox extending OpenFOAM®’s standard capabilities. It can thus not be used independently of OpenFOAM®. During the development, care was taken to maintain the modularity of the method and avoid duplication with other methods already available for OpenFOAM®. This will reduce maintenance efforts and enhance the usefulness of the developments to others. The *ocean4Foam* source code is distributed via the software publication [SPA] and a public git repository (<https://git.geomar.de/open-source/ocean4foam.git>).

2.7.1 Usage

ocean4Foam provides the solver applications *oceanPimpleFoam* and *oceanSimpleFoam*. These applications require a number of additional input files, compared to the basic structure shown in Figure 2.4. The following fields need to be defined:

<code>mixingRatio</code>	transported passive scalar
<code>p_rgh</code>	modified kinematic pressure
<code>ph_rgh</code>	modified kinematic hydrostatic pressure (only calculated at initialization)
<code>p</code>	kinematic pressure (only for post-processing)
<code>salinity</code>	absolute salinity
<code>T</code>	conservative temperature
<code>U</code>	velocity

Additionally, fields for the turbulent diffusivity of `T`, `salinity`, and `mixingRatio` must be defined. The names for these fields can be defined with the controls for the turbulent scalar flux model. Depending on the choice of turbulence model, additional fields need to be defined as in standard OpenFOAM® cases. Run-time selection of the turbulent scalar flux model is controlled via the file `constant/scalarFluxProperties`. Listing 2.4 gives an example of this file. As for all non-hydrostatic OpenFOAM® solvers, the (constant) gravitational acceleration and a reference height can be defined through the files `constant/g` and `constant/hRef`. A

number of *ocean4Foam*-specific settings can be made in the `constant/transportProperties` file. Listing 2.5 gives an example of this file for an *ocean4Foam* case. Additionally, the *ocean4Foam* solvers can be controlled via the `system/fvSolution` file. Listing 2.6 shows the relevant part of this file. The above description and examples demonstrate the specific settings necessary to set up an OpenFOAM® case for running the *ocean4Foam* solvers. To include further functionality of *ocean4Foam*, such as modified boundary conditions or turbulence models, the respective libraries have to be included in the `system/controlDict` file. This is achieved by adding the line `libs (ocean4Foam 04FTurbulence 04FWaves 04FInterfaceTracking);` (see Listing 2.2), to add the basic capabilities, turbulence modeling, the *waves2foam* adapter, and the ALE interface tracking capabilities, respectively. Further information about the installation and usage of *ocean4Foam* is provided with the source code in the form of readme files, tutorials, and descriptions in the source files. Additional usage examples are provided with the data publications accompanying the journal publications [JPB] and [PPA].

```

1  /*-----*- C++ -*-----*/
2  | ===== |
3  | \ \ / F i e l d | OpenFOAM: The Open Source CFD Toolbox |
4  | \ \ / O peration | Version: v2412 |
5  | \ \ / A n d | Website: www.openfoam.com |
6  | \ \ / M anipulation |
7  /*-----*- C++ -*-----*/
8  FoamFile
9  {
10     version      2.0;
11     format        ascii;
12     class         dictionary;
13     location      constant;
14     object        scalarFluxProperties;
15 }
16 // *****
17 T
18 {
19     scalarFluxModel SGDh; // SGDh scalar flux model for T
20     DtName alphas; // Name of the turbulent diffusivity field
21     writeDt yes; // Write switch for turbulent diffusivity
22     sigma_t 0.85; // Turbulent Prandtl number
23 }
24
25 mixingRatio
26 {
27     scalarFluxModel GGDH; // GGDH scalar flux model for mixingRatio
28     writePhiU yes; // Write switch for turbulent flux
29     C1 0.15; // Model coefficient
30     // For SGDh submodel:
31     DtName Dt; // Name of turbulent diffusivity field (dummy)
32     sigma_t 0.9; // Turbulent Prandtl number (dummy)
33 }
34
35 salinity
36 {
37     scalarFluxModel Kenjeres; // Kenjeres (2005) model for salinity
38     writePhiU yes; // Write switch for turbulent flux
39     sigmaTvariance 0.75; // Turbulent Prandtl number for ...
40     // ... salinity variance field 'salinity2'
41     Rvariance 0.5; // Turbulence scale ratio for 'salinity2' eqn
42     Dvariance Dvariance [0 2 -1 0 0 0 0] 1e-9; // Diffusivity of 'salinity2'
43     beta -7.37033e-4; // Haline contraction coefficient
44     C0 0.15; // Model coefficients
45     C1 0.6;
46     C2 0.6;
47     C3 0.6;
48     C4 1.5;
49     // For SGDh submodel:
50     DtName Dt; // Name of turbulent diffusivity field (dummy)
51     sigma_t 0.9; // Turbulent Prandtl number (dummy)
52 }
53 // *****

```

Listing 2.4: Example of *ocean4Foam* input file `constant/scalarFluxProperties`.

```

1  /*----- C++ -----*/
2  | ===== |
3  | \ \ / F i e l d | OpenFOAM: The Open Source CFD Toolbox |
4  | \ \ / O p e r a t i o n | Version: v2412 |
5  | \ \ / A n d | Website: www.openfoam.com |
6  | \ \ / M a n i p u l a t i o n | |
7  /*-----*/
8  FoamFile
9  {
10     version      2.0;
11     format        ascii;
12     class         dictionary;
13     location      constant;
14     object        transportProperties;
15 }
16 // *****
17 transportModel CorrectableNewtonian; // transportModel for variable viscosity
18
19 D_salinity 1e-9; // Molecular diffusivity of salinity
20 D_mixingRatio 1e-9; // Molecular diffusivity of mixingRatio
21
22 rho_0 rho_0 [1 -3 0 0 0 0] 1025; // Boussinesq reference density
23 // *****

```

Listing 2.5: Example of *ocean4Foam* input file `constant/transportProperties`.

```

1  /*----- C++ -----*/
2  | ===== |
3  | \ \ / F i e l d | OpenFOAM: The Open Source CFD Toolbox |
4  | \ \ / O p e r a t i o n | Version: v2412 |
5  | \ \ / A n d | Website: www.openfoam.com |
6  | \ \ / M a n i p u l a t i o n | |
7  /*-----*/
8  FoamFile
9  {
10     version      2.0;
11     format        ascii;
12     class         dictionary;
13     location      system;
14     object        fvSolution;
15 }
16 // *****
17 PIMPLE
18 {
19     momentumPredictor yes; // Switch for momentum eqn predictor step
20     turbOnFinalIterOnly yes; // Include turb. model in PIMPLE loop?
21     nOuterCorrectors 6; // Number of PIMPLE loops
22     nCorrectors 2; // Number of PISO loops
23     nNonOrthogonalCorrectors 1; // Number of non-orthogonality corrector loops
24
25     // *** ocean4Foam-specific settings ***
26     constantSalinity no; // Switch off dynamic salinity
27     constantT no; // Switch off dynamic Temperature
28     hydrostaticInitialisation numerical; // Hydrostat. initialization type...
29     // ...analytical(file)/numerical/none
30     nHydrostaticCorrectors 20; // Number of hydrostatic loops
31     phrghSolutionFrequency -1; // Frequency for solving hydrostat...
32     // ...pressure during run (-1 off)
33 }
34 // [ ...]

```

Listing 2.6: Example of *ocean4Foam* input file `system/fvSolution`.

Chapter 3

Modeling buoyant oceanic flow in the context of AU

This chapter discusses advances in modeling buoyant oceanic flow in the context of AU throughout the work of this thesis. Following a brief review of the AU modeling problem, as well as previous work in the field, contributions to model development from the publications [JPA] and [JPB] will be discussed, along with additional, previously unpublished results. Finally, a discussion of advances in the understanding of buoyant plumes from AU, through the application of the new models, will be presented.

3.1 The AU modeling problem

As stated in Section 1.4, AU is in an early stage of technology development, where numerical modeling can be a valuable and effective tool for quickly assessing technical concepts and gaining process understanding. To be effective in contributing to an overall assessment of AU as a marine CDR measure, a numerical model must be able to provide, or contribute to, answers to a number of key questions:

- Can deep ocean water be upwelled to the surface ocean on large scales?
- How effectively (at what cost) can deep ocean water be upwelled?
- What are the large-scale effects on temperature, salinity, and nutrient concentrations?

To assess whether and at what cost deep ocean water can be transported to the surface ocean against its tendency to stay in hydrostatic equilibrium, a model has to resolve the hydrostatic balance. To assess the effectiveness of the overall process, a numerical model for AU must also predict whether the upwelled water permanently remains in the surface ocean beyond the initial upwelling process or sinks back down, as indicated by Kirke (2003). To answer the above key questions, the nature of the AU modeling problem thus requires the use of a non-hydrostatic numerical model, which must be able to resolve the upwelling process as well as mixing of the upwelled water into the surface ocean.

3.2 Previous work

Non-hydrostatic ocean models typically operate on geophysical scales, resolving processes like coastal upwelling, gravity currents on coastal shelves, and internal wave propagation (Marshall et al., 1997; Fringer et al., 2006; Kanarska et al., 2007; Lai et al., 2010). Due to the use of structured grids and/or coordinate transformations, these models are typically unable to explicitly resolve engineering structures such as AU pipes. Non-hydrostatic technical CFD models, on the other hand, are well-suited to modeling flow on the scale of AU devices and have been previously used to model buoyant jets and plumes (Kheirkhah Gildeh et al.,

2021; Bordbar et al., 2024; Fan et al., 2015). Typically, such models are referred to as non-isothermal or compressible CFD models. However, for oceanic applications of such methods, with both temperature and salinity influencing the flow, only a limited body of work exists (Williamson et al., 2009; Scanlon, 2018). A brief review of previous applications of OpenFOAM® for oceanic flow problems is given in Section 2.7. The contributions reported in this chapter enable RANS-based modeling of non-hydrostatic flow with dynamic temperature, salinity, and passive scalar transport.

3.3 Contributions to model development for buoyant oceanic flow

Throughout the course of this thesis, the *ocean4Foam* toolbox [SPA] for finite volume CFD modeling of buoyant oceanic flow has been developed. A description of the numerical methodology and a derivation of the mathematical model are presented in Chapter 2 of this thesis. A first version of the *ocean4Foam* method was published in Contribution [JPA]. This first version still carried the variable density in all terms of the fundamental equations and solved a compressible form of the continuity equation. Later, the method was simplified through the consistent application of the oceanic Boussinesq hypothesis (Young, 2010) (see Section 2.1.4). Due to its incompressible form, the oceanic Boussinesq set is easier to solve numerically and eliminates sound waves from the solution, which can introduce numerical instability. The final version of the *ocean4Foam* method, with Boussinesq-type fundamental equations, as presented in Section 2.7, was originally published in Contribution [JPB]. Due to its efficient Boussinesq approach and the pressure-based non-hydrostatic solution process, the new method is applicable to a wider range of oceanic flows on the scale of millimeters (e.g., internal flows in AU pipes [JPB]) to kilometers (e.g., far-field mixing of AU plumes [JPA]). The *ocean4Foam* method is thereby well-suited to fulfill the thesis objectives formulated in Section 1.5.1.

Contribution [JPA] identifies a number of limitations of the proposed method at the time of publication and proposes corresponding future work. The following areas of future work are named in the publication:

1. Evaluation of turbulence modeling approaches
2. Implementation of open boundary conditions for free in- and outflow
3. Evaluation of turbulent scalar flux modeling approaches
4. Inclusion of natural mixing processes (e.g., through currents and waves) in the model

While points 2 and 4 will be addressed in Chapter 4, later work on points 1 and 3 has not yet been published and is therefore presented in the following. Advances in the understanding of AU through the previously described developments are discussed at the end of this chapter.

3.4 Additional advances in RANS turbulence modeling approaches for buoyant plumes

RANS modeling of turbulence and turbulent fluxes has been introduced in Section 2.3, and the linear eddy-viscosity hypothesis has been introduced, which models the Reynolds stresses using

$$-\overline{\mathbf{u}'\mathbf{u}'} = \nu_t (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \nu_t (\nabla \cdot \bar{\mathbf{u}}) \mathbf{I} - \frac{2}{3} \mathbf{I} k . \quad (3.1)$$

A key drawback of linear eddy-viscosity turbulence models is that they neglect any anisotropy of the turbulence beyond the anisotropy of the mean strain rate tensor. In stratified and buoyant flows, gravity effects can cause considerable anisotropy, which is not captured by the linear eddy viscosity hypothesis. (E.g., a stable density stratification suppresses vertical turbulence while horizontal turbulence remains largely unaffected.) In ocean modeling,

where the anisotropy of turbulence is typically extreme, different approaches are often used to model horizontal and vertical turbulence. In technical simulations of buoyant and stratified flows, a single model is generally applied for turbulence in all geometrical directions. In this case, turbulence anisotropy can only be fully captured by models that either resolve the turbulent motions entirely (DNS) or partially (LES), or by approaches that model the components of the Reynolds stress tensor individually, such as Reynolds stress models or algebraic stress models. Also, non-linear eddy viscosity models (see Section 2.3) at least theoretically offer a means of accounting for additional anisotropic effects on turbulence beyond the linear eddy viscosity assumption.

The effect of inadequate modeling of buoyancy effects on turbulence is well understood (Launder, 2005; Hanjalić, 2002). In the context of AU, Kogawa et al. (2013) have reported considerable differences between the trajectories and spreading rates of an AU plume when modeled with LES and a linear eddy viscosity turbulence model. While the work of Kogawa et al. (2013) highlights the importance of adequate turbulence modeling for buoyant oceanic flow in the context of AU, they also point out that the computational cost of LES models can be prohibitive when AU is studied on larger scales. In the present work, advanced RANS eddy viscosity modeling approaches are thus explored. As RANS models do not have to resolve the turbulent length and time scales numerically, they have considerably lower discretization requirements and thus incur lower computational costs.

3.4.1 Buoyancy adaptations for eddy viscosity turbulence models

Buoyancy adaptations for RANS eddy viscosity models have been widely studied. A comprehensive review of literature and key concepts of the different proposed adaptations has been presented by Van Maele and Merci (2006). In this thesis, the adaptations of Van Maele and Merci (2006) have been implemented and tested for modeling buoyant jets in a stratified ambient.

In the following, the buoyancy adaptations will be described and tested on the example of the k - ϵ turbulence model (Launder and Spalding, 1974). This simple model is chosen for the present study over more modern models, such as the k - ω SST model (Menter, 1994), to highlight the relative effect of the buoyancy adaptations. All adaptations presented in the following are equivalently applicable to other turbulence models. The k - ϵ model calculates the kinematic eddy viscosity ν_t as

$$\nu_t = C_\mu \frac{k^2}{\epsilon} . \quad (3.2)$$

Here, C_μ is a model constant, which is typically set to 0.09. As can be seen from Equation (3.2), the k - ϵ model defines ν_t based on the turbulent kinetic energy k and its dissipation rate ϵ , as the scale-defining variable. The transport equations for these quantities read

$$\frac{\partial k}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}k) - \nabla \cdot \left(\left(\nu + \frac{\nu_t}{\sigma_k} \right) \nabla k \right) = G_k - \epsilon \quad (3.3a)$$

$$\frac{\partial \epsilon}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\epsilon) - \nabla \cdot \left(\left(\nu + \frac{\nu_t}{\sigma_\epsilon} \right) \nabla \epsilon \right) = C_1 \frac{\epsilon}{k} G_k - C_2 \frac{\epsilon^2}{k} . \quad (3.3b)$$

Here, G_k is the shear production term

$$G_k = \nabla \bar{\mathbf{u}} : \bar{\boldsymbol{\tau}}_t^* , \quad (3.4)$$

where $:$ represents the double dot product and $\bar{\boldsymbol{\tau}}_t^*$ is the turbulent kinematic viscous stress tensor¹ (see Equation (2.16)). The model constants C_1 , C_2 , σ_k , and σ_ϵ take values of 1.44, 1.92, 1.0, and 1.3, respectively.

The buoyancy modifications of Van Maele and Merci (2006) are implemented based on an additional production term due to the turbulent buoyancy flux

$$G_b = \frac{1}{\rho_0} \mathbf{g} \cdot \overline{\mathbf{u}'\rho'} . \quad (3.5)$$

¹ Equation (3.4) typically contains the full Reynolds stress tensor. However, the additional term $-2/3 \mathbf{I}k$ can be omitted for incompressible flow, since $\nabla \bar{\mathbf{u}} : (-2/3 \mathbf{I}k) = -2/3 k \nabla \bar{\mathbf{u}} : \mathbf{I} = -2/3 k \nabla \cdot \bar{\mathbf{u}} = 0$.

This term can be derived from the closure equations for the Reynolds stresses. It is directly added to the right-hand side of Equation (3.3a), while for Equation (3.3b) the additional term reads $C_1 \epsilon / k C_3 \max(G_b, 0)$. The constant C_3 takes a value of 0.2 by default. As suggested by Van Maele and Merci (2006), the production term is only applied to the ϵ equation if the stratification is unstable (i.e., if $G_b > 0$).

Two models for turbulent buoyancy flux $\overline{\mathbf{u}'\rho'}$ in Equation (3.5) were implemented, based on the Simple Gradient Diffusion Hypothesis (SGDH) and the Generalized Gradient Diffusion Hypothesis (GGDH) (see Equations (2.18) and (2.19)). The SGDH formulation reads

$$G_b = -\frac{\nu_t}{\rho_0 \sigma_t} \nabla \rho \cdot \mathbf{g} . \quad (3.6)$$

A first implementation of this source term was already presented in Contribution [JPA]. The GGDH formulation reads

$$G_b = -\frac{3}{2} \frac{\nu_t}{\rho_0 \sigma_t k} (\overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla \rho) \cdot \mathbf{g} , \quad (3.7)$$

where the Reynolds stresses are calculated using the eddy viscosity hypothesis (see Equation (2.16) on p. 15). The factor σ_t takes a value of 0.85 by default. Since Equation (3.7) tends to become numerically unstable in the laminar limit (i.e., when both ν_t and k tend to zero), a stabilization was developed, which forces the term to zero in laminar regions by multiplying it with $\min(\nu_t/\nu, 1)$, where ν is the molecular viscosity.

A modular implementation of the additional source terms was achieved using OpenFOAM[®]'s `fvOptions` functionality (see Listing 2.1), such that the buoyancy modifications can be applied to different RANS turbulence models in OpenFOAM[®].

In the following, the effect of the turbulence modification will be tested, and the modified model will be validated against experimental data. Modern measurement methods, such as high-resolution Particle Image Velocimetry (PIV) and Laser-Induced Fluorescence (LIF), enable detailed, non-intrusive measurements of velocity and temperature fields, as well as turbulence characteristics, in experimental studies of buoyant flow. Such high-quality experimental datasets allow for a separate calculation of the turbulent fluxes of temperature and momentum and thus enable validation and tuning of numerical methods to a degree that has previously not been accessible (see e.g., Xu and Chen (2012)). Unfortunately, the number of available experimental datasets on buoyant plumes in a stratified ambient is still limited. The studies of Xu and Chen (2012) and Mirajkar and Balasubramanian (2016) only consider the initial region of a buoyant jet and plume. Gharavi et al. (2020) study weakly buoyant jets interacting with cross-flow and the free water surface. Chen et al. (2021) provide high-quality results from a heated jet, discharged into an ambient fluid stratified by salinity and ethanol. While these results would be generally of interest for the present validation studies, the interaction of the salinity-ethanol stratification with the thermal jet adds an additional complexity to this dataset, making the results difficult to reproduce numerically. It was thus chosen to resort to older studies of salinity-based jets in a salinity-stratified ambient from Fan (1967), which rely on photographs of dyed jets as the main result. Case 1 from Fan et al. (2015) was chosen, which is a 45° downwards inclined jet into a stagnant tank with a linear salinity stratification. Table 3.1 provides the details about this case setup. Here, D_0 , U_0 , and ρ_0 are the initial diameter, velocity, and density of the jet, while ρ_∞ and $\partial\rho/\partial z$ are the ambient density at the nozzle depth (0.11 m) and the ambient density gradient, respectively. Use of the symmetry of the problem is made, such that only a half jet is studied. The resulting computational domain has a width of 0.535 m, a length of 2.26 m, and a depth of 0.61 m. Adaptive mesh refinement² is used to adjust the spatial discretization to the spreading jet, starting from a coarse initial mesh, which is only refined in the vicinity of the nozzle. The calculation is run until a simulated time of 120 s is reached. Figure 3.1 shows the modeled jet trajectory and boundaries (represented by the 1% dilution contour) along with the experimental jet boundaries from Fan (1967). Additionally, the velocity magnitude (normalized by the initial jet velocity U_0) and the turbulence intensity along the jet centerline are shown. Results are shown for a standard case without buoyancy production term in

² Adaptive mesh refinement is discussed in Chapter 4.

Table 3.1: Validation case details

Jet Parameters			Ambient	
D_0	U_0	ρ_0	ρ_∞	$\partial\rho/\partial z$
[m]	[m/s]	[kg/m ³]	[kg/m ³]	[kg/m ⁴]
6.86×10^{-3}	0.214	1008.7	1000.4	-25.01

the turbulence model as well as with the SGD (Equation (3.6)) and GGDH (Equation (3.7)) buoyancy production term. As shown in Figure 3.1, the standard OpenFOAM[®] implemen-

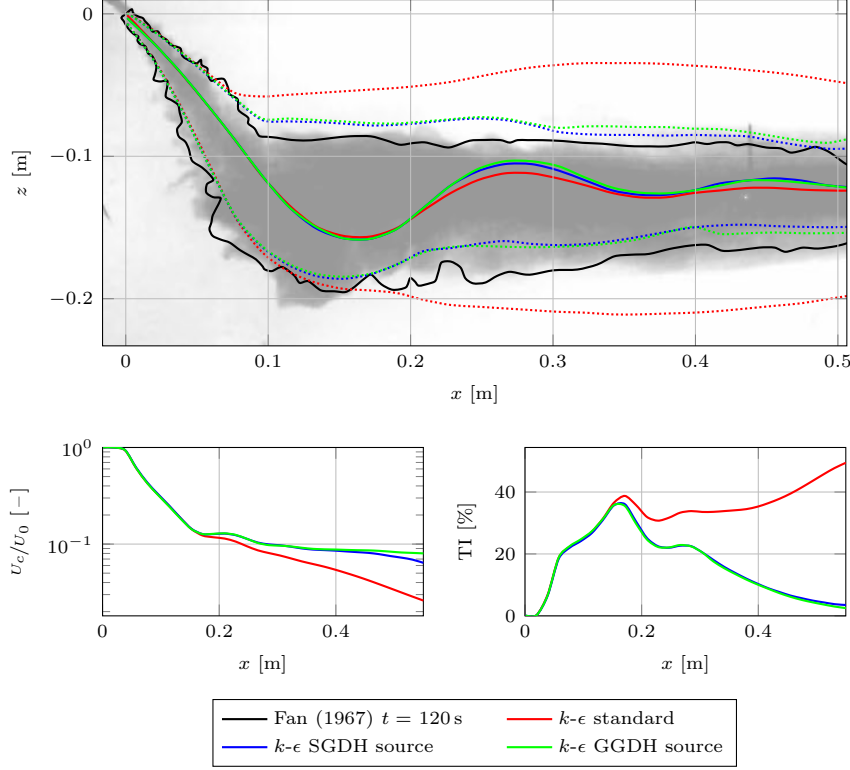


Figure 3.1: Results for buoyant jet in stratified ambient. Experimental jet boundaries from Fan (1967), as well as modeled jet trajectories and boundaries (1 % dilution contour) for different buoyancy sources in the k - ϵ turbulence model. Lower plots show jet centerline velocity, normalized by initial jet velocity (left), and centerline turbulence intensity (right) from the modeling results.

tation, which omits the buoyancy production term, leads to excessive spreading of the jet, especially in the stratified far field. Both the SGDH and GGDH buoyancy source terms yield a more realistic reproduction of the jet boundaries. From the lower plots in Figure 3.1, it can be seen that the buoyancy terms lead to a significant reduction of the turbulence levels in the far field, while the initial jet region remains largely unaffected. As a consequence, the centerline velocities are higher when the buoyancy terms are applied. Only minor differences are found between the results obtained with the SGDH and GGDH buoyancy source terms. Generally, the GGDH term leads to slightly lower turbulence levels in the stratified far field. While the reduction in turbulence levels due to the buoyancy source terms leads to less turbulent diffusion and thus a more realistic spreading of the jet, it also yields slightly higher terminal jet heights. As the terminal jet height is generally overestimated by the modeling results, the trajectory predicted by the standard approach appears more realistic in the present case. More detailed studies are needed to establish whether the apparent inability to simultaneously predict both correct trajectories and vertical spreading of the jet is owed to the computational setup or, in fact, a direct consequence of using the linear

eddy viscosity hypothesis, which reproduces shear-based but not buoyancy-based turbulence anisotropy. In general, the considerable improvement in the prediction of the spreading of the jet justifies the use of both versions of the buoyancy source term. Due to its better numerical stability, the SGDH source term (Equation (3.6)) is used in the following.

3.4.2 RANS modeling of turbulent scalar fluxes

Different models for the turbulent scalar fluxes have been introduced in Section 2.3. It has also been discussed that the Algebraic Flux Model (AFM) of Kenjereš et al. (2005) can be simplified to yield the GGDH, while the GGDH can be simplified to the SGDH by assuming perfect isotropy. While it may be argued that the first simplification for the GGDH is consistent with the use of the linear eddy viscosity hypothesis, the assumption yielding the SGDH clearly represents an additional simplification to the linear eddy viscosity hypothesis. A combination of linear eddy viscosity turbulence models with advanced modeling approaches for the turbulent scalar fluxes is thus a natural first step towards increasing the fidelity of turbulence modeling for non-hydrostatic applications. Such advanced approaches generally include modeling of the scalar fluxes with GGDH (Daly and Harlow, 1970) or AFM (Kenjereš et al., 2005; Younis et al., 2018) approaches, as well as SGDH approaches with non-constant turbulent Prandtl numbers (Kays and Crawford, 1993; Reynolds, 1975).

The capability to exchange scalar flux models at runtime has been implemented as a new functionality in *ocean4Foam* to replace the hard-coded SGDH approximation typically used throughout OpenFOAM[®]. In the following, different scalar flux models that have been implemented using the new *ocean4Foam* scalar flux modeling capability will be described and applied.

The SGDH and GGDH are briefly reintroduced here. They model the turbulent scalar flux as

$$-\overline{\mathbf{u}'\phi'} = \frac{\nu_t}{\sigma_t} \nabla \bar{\phi} \quad (3.8)$$

and

$$-\overline{\mathbf{u}'\phi'} = C_1 \frac{k}{\epsilon} \overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla \bar{\phi}, \quad (3.9)$$

respectively, where σ_t is the turbulent Prandtl number and C_1 is a constant. For the AFM approach of Kenjereš et al. (2005), the full equation reads

$$-\overline{\mathbf{u}'\phi'} = C_0 \tau \left(C_1 \overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla \bar{\phi} + C_2 \nabla \bar{\mathbf{u}} \cdot \bar{\phi}'\mathbf{u}' + C_3 \beta \bar{\phi}'^2 \mathbf{g} \right) - C_4 \left(\frac{1}{k} \overline{\mathbf{u}'\mathbf{u}'} - \frac{2}{3} \mathbf{I} \right) \cdot \bar{\phi}'\mathbf{u}'. \quad (3.10)$$

Here, $\tau = \max(k/\epsilon, 6\sqrt{\nu/\epsilon})$ is a characteristic time scale and β is the expansion coefficient of the fluid with respect to the transported quantity ϕ . This term is only relevant for active scalars (i. e., for temperature and salinity)³. Different values for the coefficients C_0 through C_4 , which have been proposed in the literature, are given in Table 3.2. The variance $\bar{\phi}'^2$ is

Table 3.2: Coefficients for the Kenjereš et al. (2005) scalar flux model

Reference	C_0	C_1	C_2	C_3	C_4
Kenjereš et al. (2005)	0.15	0.6	0.6	0.6	1.5
Shams et al. (2014)	0.2	0.25	0.6	2.5	0.0
Chai et al. (2020)	0.15	0.5	0.1	0.6	0.0
Kenjereš and Hanjalić (2000)	0.2	1.0	0.6	0.6	0.0

modeled by the additional transport equation

$$\frac{\partial \bar{\phi}'^2}{\partial t} + \nabla \cdot (\bar{\phi}'^2 \bar{\mathbf{u}}) - \nabla \cdot \left(\left(D_{\phi 2} + \frac{\nu_t}{\sigma_{\phi 2}} \right) \nabla \bar{\phi}'^2 \right) = -2 \overline{\mathbf{u}'\phi'} \cdot \nabla \bar{\phi} - \frac{\epsilon}{Rk} \bar{\phi}'^2, \quad (3.11)$$

³ In the present implementation of *ocean4Foam* and throughout this work, the turbulent scalar flux models are derived for each scalar individually, i. e., without considering any interaction. This simplification is often made in ocean modeling to avoid having to model turbulent covariances, such as $\Theta' S'_A$ (Burchard and Bolding, 2001).

where the diffusion coefficient $D_{\phi 2}$ and the turbulent Prandtl number $\sigma_{\phi 2}$ are 1×10^{-9} and 0.75, respectively. The momentum-to-scalar turbulent time scale ratio R is set to 0.5 by default.

Younis et al. (2018) propose a different algebraic flux model. Their model, while not being directly derived from the second moment closure equations, aims to capture the same physical phenomena with a formulation that is explicit in $-\overline{\mathbf{u}'\phi'}$. This model reads

$$-\overline{\mathbf{u}'\phi'} = C_1 \frac{k^2}{\epsilon} \nabla \bar{\phi} + C_2 \frac{k}{\epsilon} \overline{\mathbf{u}'\mathbf{u}'} \cdot \nabla \bar{\phi} + C_3 \frac{k^2}{\epsilon^2} (\overline{\mathbf{u}'\mathbf{u}'} \cdot (\nabla \bar{\mathbf{u}} + (\nabla \bar{\mathbf{u}})^T)) \cdot \nabla \bar{\phi} + C_4 \frac{k}{\epsilon} \beta g \bar{\phi'^2}. \quad (3.12)$$

Again, Equation (3.11) can be used as the scalar variance equation. The coefficients for this model are given in Table 3.3. The sign of C_4 is reversed with respect to the original publication of Younis et al. (2018), as it is imperative that buoyancy acts against the mean gradient transport in stable stratification. This is also consistent with the Kenjereš et al. (2005) model.

Table 3.3: Coefficients for the Younis et al. (2018) scalar flux model

Reference	C_1	C_2	C_3	C_4
Younis et al. (2018)	0.01	0.19	-0.06	0.07

While algebraic flux models represent a high-fidelity approach and thus offer a high degree of generality, their complexity increases the computational cost of the overall computation, especially when additional transport equations for scalar variances have to be solved. As a simple alternative approach, the SGDH can be used with a non-constant formulation for the turbulent Prandtl number σ_t . Such formulations for σ_t are typically made based on some knowledge about the specific flow problem, whereby their applicability is limited compared to algebraic flux models. A wide variety of turbulent Prandtl number models have thus been proposed in the literature for different applications (Reynolds, 1975; Combet et al., 2011). In Contribution [JPB] of this thesis, the Prandtl number model of Kays and Crawford (1993) and the Kenjereš et al. (2005) algebraic flux model (with the original coefficients) are validated against DNS data for heat transfer in a pipe flow. Both models are found to accurately reproduce the heat transfer in the pipe as well as the velocity and temperature profiles, while a standard SGDH approach with a constant turbulent Prandtl number was unable to correctly reproduce both the heat transfer and the DNS temperature profiles at the same time, even when the constant σ_t value was tuned to the problem. For the application to AU plumes in a stratified ambient, no sufficiently general σ_t model is known to the author. The non-constant Prandtl number approach is thus not pursued in this chapter.

In the following, the presented scalar flux models will be applied to the previously introduced validation case for a buoyant jet in a stratified ambient. All scalar flux models are tested in combination with the k - ϵ turbulence model, combined with the SGDH-based buoyancy adaptation (Equation (3.6)). The SGDH case uses a turbulent Prandtl number of $\sigma_t = 0.9$, while $C_1 = 0.15$ is used in the GGDH case⁴. The standard coefficients from the original publication are used for the Kenjereš et al. (2005) model. Figure 3.2 shows the modeled jet trajectory and boundaries (represented by the 1 % dilution contour) along with the experimental jet boundaries from Fan (1967) as well as the centerline velocity and turbulence level for the numerical simulations (lower plots). The effect of the different scalar flux models on the jet trajectory and spread can be seen from Figure 3.2. The difference between the SGDH and GGDH cases is small, with no significant effect on the spread of the jet and only a minor difference in the trajectory. The algebraic flux models show more pronounced differences from the standard SGDH case. The Younis et al. (2018) model predicts a slightly lower terminal height of the trajectory, which is likely driven by increased turbulence during the rising phase of the jet ($x \approx 0.2$ m). The Kenjereš et al. (2005) model predicts a more curved trajectory and a wider jet, despite generally lower turbulence levels at the jet centerline. Generally, the Younis et al. (2018) model appears to agree best with

⁴ In the isotropic limit ($\overline{\mathbf{u}'\mathbf{u}'} = 2/3 k \mathbf{I}$), the GGDH with $C_1 = 0.15$ reduces to the SGDH with $\sigma_t = 0.9$, such that the chosen coefficients are consistent throughout this study.

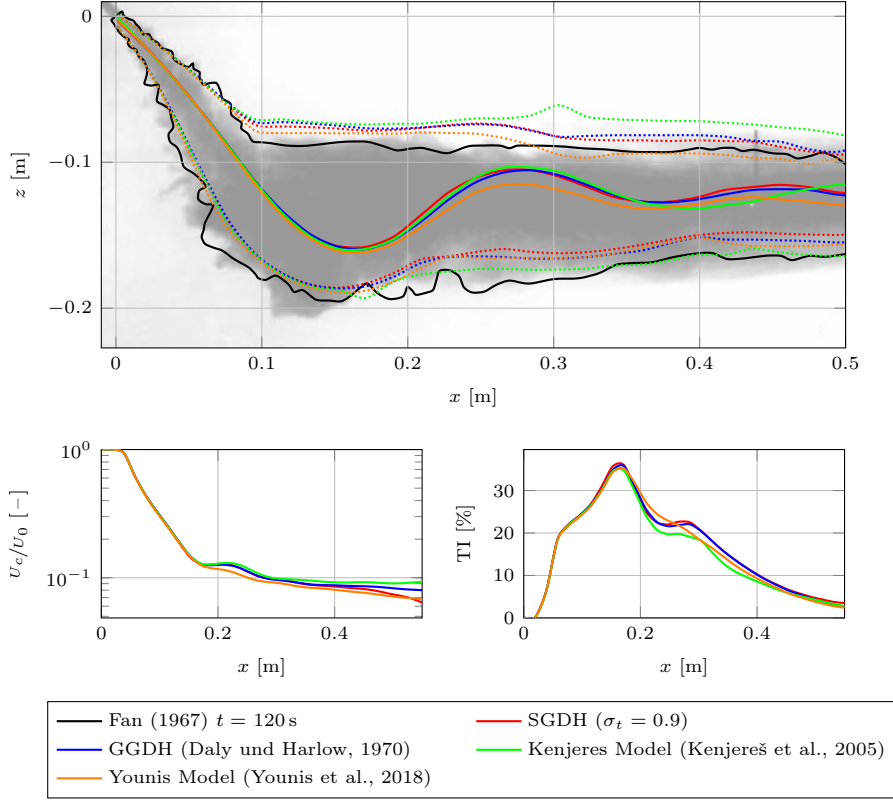


Figure 3.2: Like Figure 3.1 but for different scalar flux models.

the experimental shape of the jet. It remains to be discussed whether the better performance of the Younis et al. (2018) model in the present study is due to the inclusion of buoyancy effects in its formulation. This seems unlikely, as a comparison of the coefficients between the Younis et al. (2018) and Kenjereš et al. (2005) models shows that the buoyancy term receives a lower weight in the Younis et al. (2018) model. The Kenjereš et al. (2005) model should thus show a stronger buoyancy effect. Instead, it can be shown that, when employed in combination with a linear eddy viscosity turbulence model (i.e., when $\overline{\mathbf{u}'\mathbf{u}'}$ is calculated using Equation (3.1)), the Younis et al. (2018) model reduces to the SGDH with $\sigma_t = C_\mu (C_1 + 2/3 C_2)^{-1} \approx 0.66$ in the limit of perfect isotropy and no buoyancy influence. The superior performance of the Younis et al. (2018) model is thus likely explained by increased gradient-based salinity transport rather than buoyancy effects. It is known from the literature that lower turbulent Prandtl numbers are beneficial for the prediction of jets (see e.g., Tominaga and Stathopoulos (2007)).

The jet trajectory is governed by the balance of buoyancy (i.e., salinity in the present case) and momentum diffusion. It is thus not surprising that the trajectory is affected by the choice and calibration of the scalar flux model as well as the turbulence model itself. While the present results show that a significant improvement in the prediction of turbulence in buoyant and stratified flows can be achieved by using buoyancy-adapted turbulence models, and some further improvement is possible through the use of higher-accuracy scalar flux models, further room for improvement still remains. Further studies and more detailed validation data are required to be able to separately assess and calibrate models for turbulent momentum and scalar fluxes. Modern measurement techniques enable a separation of these effects from experiments. Also, high-fidelity simulations, such as DNS and LES, can be employed to obtain the required data. Thus, while the present study serves to highlight general differences in the results obtained with the various modeling approaches, future work is required to allow for a complete assessment in the context of buoyant and stratified oceanic flows.

3.5 Application to AU

This section provides a discussion of applications of *ocean4Foam*'s buoyant oceanic flow modeling capabilities in the realm of techno-economic feasibility and effectiveness assessment for AU throughout this thesis. Mainly, advances from the thesis contribution [JPA] are discussed.

In Contribution [JPA], a large propeller-driven upwelling device is studied. The device concept broadly follows the idea of Viúdez et al. (2016), who first proposed a large propeller-driven AU device powered by a floating wind turbine. The device was conceptualized as an AU prototype for field tests in the Guinea Dome region in the tropical North Atlantic, where nutrient-rich deep ocean water naturally rises to depths above 100 m and is thus easily accessible for AU. The device dimensions are chosen based on a number of prior calculations, assuming an energy input of 500 kW. The pipe has a diameter of 10 m and a bottom depth of 75 m. Based on propeller theory, it was estimated that a flow rate of $155 \text{ m}^3/\text{s}$ can be achieved by the device. Several studies are carried out in Contribution [JPA] to assess the dynamics of the nutrient-rich plume generated by the device and optimize its potential for elevating nutrient concentrations in the mixed surface layer. Previous CFD modeling studies of buoyant plumes in the context of AU have been carried out by several authors (Fan et al., 2015; Williamson et al., 2009; Kogawa et al., 2013). While these publications invariably study AU plumes in cross-flow, studies of a pure AU plume have not previously been documented⁵. As will be discussed in Chapter 4, the consideration of cross-flow is generally realistic for AU devices. Nevertheless, some basic principles of AU plume dynamics can better be studied on pure plumes. In Contribution [JPA], the extent to which the effectiveness of the studied AU device is impaired by re-sinking of the cold upwelled water out of the mixed surface region is thus quantified in the absence of additional environmental effects. The publication describes the general flow dynamics, which include a fountain-like buoyant flow with features of Raleigh-Taylor instability close to the device and a return to a purely stratified flow in the far field. The horizontal spreading of a concentrated layer of deep ocean water at the bottom of the mixed surface layer is identified as the main fertilizing effect of the studied device on the mixed surface layer. Further research is needed to assess how the nutrients are mixed into the surface ocean from this layer. Previous studies on AU for mariculture projects explicitly aim to maintain the upwelled water in a confined plume with high nutrient concentrations, rather than dispersing it throughout the mixed surface layer (Fan et al., 2015). As a confined plume also exhibits a stronger re-sinking tendency, the goals of confining the plume and preventing re-sinking are contradictory, and an optimal balance must be found (Fan et al., 2015). In the context of CDR, where a large-scale fertilization is encompassed, mixing of the plume should generally be maximized.

In addition to assessments of the re-sinking and fertilization effects of the proposed AU device, Contribution [JPA] describes two geometric variant studies, featuring different shapes and depths of the pipe outlet. While all studied variants lead to similar general plume dynamics, interesting new conclusions for the device design are drawn. The studies indicate that, while turbulent mixing is generally important to reduce the re-sinking tendency of the upwelled water, the shear-based turbulence production at the device outlet is possibly less important than the buoyancy-based production during the re-sinking process itself. The study also finds that device designs that support a large spreading radius of the upwelled water along the free surface before the re-sinking occurs are generally beneficial. This finding supports a theoretical analysis of Viúdez et al. (2016), who propose that the upwelled water should be dispersed to a certain radius at the free surface to avoid re-sinking below the mixed layer depth.

Overall, Contribution [JPA] contributes to the assessment of the technical feasibility and effectiveness of AU devices by studying the buoyant plume dynamics from a large propeller-driven AU device without cross-flow. While the device achieves a significant fertilization effect on the mixed layer in all studies, it is generally found that not all of the upwelled

⁵ Technically, Soloviev (2016) shows results of a simplified CFD model for a pure AU plume from a specific device. As these results are presented without any documentation and have little generality, they are not discussed here.

nutrients are retained in the mixed surface layer, thus likely limiting the effectiveness of the device in the absence of additional environmental effects. Further studies are required to generalize these results with respect to propeller-driven upwelling.

Chapter 4

Modeling of free-surface and cross-flow effects

Ocean models typically treat short-period free-surface waves in a phase-averaged manner, thus accounting for statistical properties of the wave field rather than individual wave motions. In marine and coastal engineering, on the other hand, phase-resolved models are widely used to study wave dynamics and wave-structure interactions in great detail, often only modeling time frames of a few wave periods. High-fidelity modeling of some real-world processes, such as scour around offshore structures or wave influences on buoyant plumes, requires both phase-resolved dynamics and long modeled time frames. A common feature of such processes is that the process of primary interest is not the wave motion itself, but another process that evolves on a longer timescale under the direct influence of the wave dynamics. When high-fidelity free-surface modeling approaches are used for such cases, the computational effort required can be prohibitive. There is thus a need for simplified free-surface modeling approaches. In Contribution [PPA], such a simplified approach is presented and combined with the *ocean4Foam* method, presented in Section 2.7. An Arbitrary Lagrangian-Eulerian (ALE) Interface Tracking (IT) approach is chosen, which significantly reduces the computational demand for free-surface wave simulation, when compared to the standard Volume Of Fluid (VOF) interface capturing approach implemented in OpenFOAM®. ALE-IT methods model the free surface by dynamically moving the boundary of the fluid domain, which represents the free surface, while the computational mesh is fixed in space at the sea-floor or around engineering objects (e.g., AU pipes). Throughout the fluid domain, the mesh is stretched to accommodate the free-surface motion while maintaining acceptable mesh quality. With VOF methods, on the other hand, the free surface is obtained by modeling a two-phase flow, resolving both the water and air phases on a fixed mesh. Figure 4.1 schematically depicts the two approaches. The key advantage of the ALE-IT approach, that the air flow and the sharp interface do not need to be resolved, can clearly be seen from this simple schematic, as well as its key disadvantage, that free-surface motion is limited by the ability of the computational mesh to deform. In Contribution [PPA], the new approach is verified and validated against theory and experiments for free-surface waves. The capabilities of the approach are then demonstrated through an advanced application to wave effects on an AU plume under the combined influence of waves and cross-flow.

In the following, the individual contributions made by this work will be outlined briefly and discussed in relation to the prior state of knowledge and development, before discussing lessons learned for the techno-economic feasibility and effectiveness of AU.

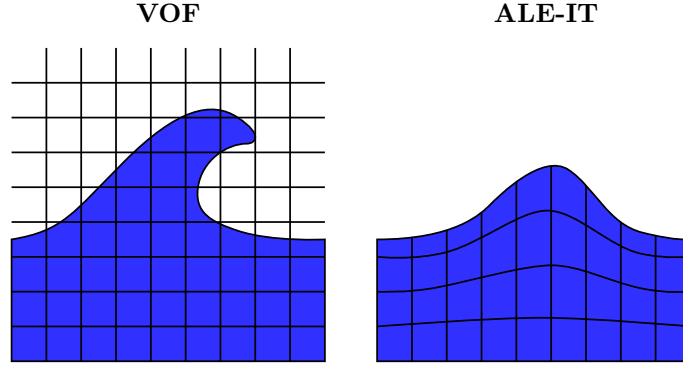


Figure 4.1: Schematic depiction of the Volume Of Fluid (VOF) approach and the Arbitrary Lagrangian-Eulerian (ALE) Interface Tracking (IT) approach for free-surface modeling.

4.1 Previous work on ALE-IT modeling of free-surface waves

As such, the ALE-IT method does not represent a new approach for free-surface modeling in CFD simulations. A comprehensive summary of early works in the field has been presented by Floryan and Rasmussen (1989). An early application to wave propagation was presented by Huerta and Liu (1988). Also recently, ALE-IT methods have been developed and applied for wave modeling (Ferrand and Harris, 2021; Wang and Özgökmen, 2018), as the discretization requirements and computational costs of VOF models can still be prohibitive for large three-dimensional applications. Wang and Özgökmen (2018) apply an ALE-IT method to phase-resolved simulations of Langmuir circulation, taking advantage of the possibility to apply wind stress boundary conditions on the free-surface boundary. Ferrand and Harris (2021) develop an ALE-IT methodology for the CFD framework *Code_Saturne* and apply it to wave propagation problems. For OpenFOAM[®], an ALE-IT methodology has been developed by Tuković and Jasak (2012). However, this method has primarily been applied to surface-tension-dominated flows, such as gas bubbles and liquid droplets. The author is only aware of a single application of this method to wave propagation, considering only a simple two-dimensional case (Bai et al., 2020).

4.2 Advancement of the ALE-IT method for OpenFOAM[®]

The ALE-IT method described in Contribution [PPA] is based on the standard OpenFOAM[®] ALE-IT method, first published by Tuković and Jasak (2012). The source code was initially published as part of the *foam-extend* project and introduced to OpenFOAM[®] with release v1912. As the method was developed for surface-tension-dominated flow problems, it had to be adapted in several regards to be applicable to free-surface wave modeling. Problems with parallel inconsistency led to numerical artifacts at the processor boundaries, which had to be eliminated. Additionally, the least squares fitting algorithm, which transfers face-centered control point motion at the free surface to the mesh points, had to be corrected, and scaling was introduced to accommodate small free-surface motions relative to the scale of the computational domain. The implemented time discretization scheme was adapted, as described in Contribution [PPA], to improve consistency and accuracy for large time step sizes. Finally, the efficiency of the method was improved by introducing new, displacement-based (as opposed to velocity-based) mesh motion solvers and reducing the motion interval for the distortion of the internal mesh to once per time step. On subsequent (PIMPLE) iterations of the solution algorithm (see Figure 2.2), only the free-surface points

are moved¹. As the new motion solver calculates the mesh motion based on the displacement with respect to a fixed reference position, drifting of the mesh due to error accumulation in the cyclic motion over long time periods is avoided.

To be able to apply the ALE-IT method as an optional module within the *ocean4Foam* framework, mesh motion capabilities first had to be implemented for the *ocean4Foam* solvers. Since OpenFOAM® presently only provides insufficient wave-generation and absorption capabilities, an adapter for the widely used *waves2foam* toolbox (Jacobsen et al., 2011) was developed, which allows for a modular use of this toolbox with any OpenFOAM® solver through the `fvOptions` class. In sum, the described adaptations enable three-dimensional engineering applications of the ALE-IT method in free-surface wave modeling.

4.3 Verification, validation, and performance assessment

CFD methods that replicate physical wave tanks in their ability to study free-surface waves and their interaction with structures are often referred to as numerical wave tanks. Such methods must be able to accurately reproduce specific sea states, model realistic wave propagation, and avoid unphysical wave reflection from the boundaries of the computational domain. Contribution [PPA] assesses the capabilities of the *ocean4Foam* method to act as a numerical wave tank when combined with the modified ALE-IT extension and the *waves2foam* toolbox. The assessment criteria for numerical wave tanks set up by Windt et al. (2019) are followed. A full discretization convergence study is carried out for a simple two-dimensional case with a monochromatic sea state. Based on this study, standard temporal and spatial discretizations are defined for the new ALE-IT method as well as a standard VOF solver. This procedure allows for a comparison of the relative discretization requirements and computational performance of the two methods. It is found that the ALE-IT method has less restrictive discretization requirements, which lead to a lower computational demand for a comparable accuracy in reproducing the wave field. For a two-dimensional test case, the ALE-IT setup is found to require about 80 % less computation time than the comparable VOF setup. This result validates the goal of this work to provide an effective modular free-surface modeling technique for engineering problems with simple free-surface shapes, such as wave effects on submerged structures and plumes.

4.4 Adaptive mesh refinement

Studies of jets and plumes in stagnant environments or steady cross-flows deal with a temporally expanding region of interest. For such problems, adaptive spatial discretizations are particularly useful, as they allow for a sufficiently fine discretization of the region of interest at all times, while the background mesh can remain coarse. Static meshes, on the other hand, must be refined in all areas that may become regions of interest during the calculation time. Static meshes are thus associated with a significantly higher computational cost and require prior knowledge about the flow field. With the introduction of mesh motion capabilities in the context of the ALE-IT method, OpenFOAM®’s standard adaptive mesh refinement capabilities are also available in the *ocean4Foam* framework. However, to apply adaptive mesh refinement to the cases presented in Contribution [PPA], a significantly modified methodology had to be introduced. Standard OpenFOAM® does not provide dynamic processor load balancing capabilities in combination with adaptive mesh refinement. Since any isotropic refinement step in a three-dimensional hexagonal mesh leads to an 8-fold increase in the cell count, a significant imbalance of processor cell counts can occur if the decomposition of the mesh is not adapted in parallel computations. Also, the standard OpenFOAM® adaptive mesh refinement library offers little flexibility with respect to the refinement indication function (i. e., the function indicating which cells need to be refined or unrefined). The adaptive mesh refinement developments in this thesis are thus based on

¹ Note that the option to include the mesh motion into the PIMPLE loop must be used when employing ALE-IT to allow for an iterative solution process to satisfy both the RANS equations and the free-surface boundary conditions.

the *blastAMR* library (Heylmun et al., 2023), which offers a more general implementation of load-balanced adaptive mesh refinement for OpenFOAM®. The *blastAMR* library was updated as part of this work to allow for its use with current versions of OpenFOAM®. (Version v2412 is used in [PPA].)

While OpenFOAM® generally allows for the combination of mesh topology changes (i.e., refinement and unrefinement) and motion, a combined use of ALE-IT capabilities and adaptive mesh refinement is not possible by default. While implementing this capability, an incorrect function of combined topology changes and mesh motion was discovered when used in conjunction with second-order time discretization schemes. The problem could be attributed to the use of the cell volumes on the old time level (i.e., from the previous time step) in second-order time discretization schemes for moving meshes. When the mesh is simultaneously refined and distorted, the volumes of refined cells cannot be correctly reconstructed on the old time level. The problem was finally alleviated by implementing a refinement procedure that includes moving the mesh back to its position on the old time level, refining as appropriate, storing the mesh volume, and restoring the new mesh position. This way, the volume of the new (refined or unrefined) cells on the old time level can be calculated accurately to avoid any continuity errors. Additional modifications to the ALE-IT methodology, the mesh motion solver, and OpenFOAM®’s *finiteArea* methodology (which is used for field operations in the free-surface plane by the ALE-IT method) had to be introduced to enable simultaneous operation with adaptive mesh refinement. In sum, the implementations and adaptations enable the combined use of adaptive mesh refinement and ALE-IT free-surface modeling in the *ocean4Foam* framework.

The new capabilities are presently subject to two limitations: First, refinement of the cells directly adjacent to the free surface is not possible, as topology changes of the free-surface boundary faces are not presently supported by OpenFOAM®’s *finiteArea* methodology. Second, the adaptive load-balancing capabilities provided by the *blastAMR* library cannot be used in combination with the ALE-IT method. In Contribution [PPA], adaptive load balancing is thus only used for applications without waves, while the wave cases had to be stopped regularly to balance the processor load. While these limitations should be addressed in the future to increase the generality of the method, they did not severely affect the applications considered throughout this thesis.

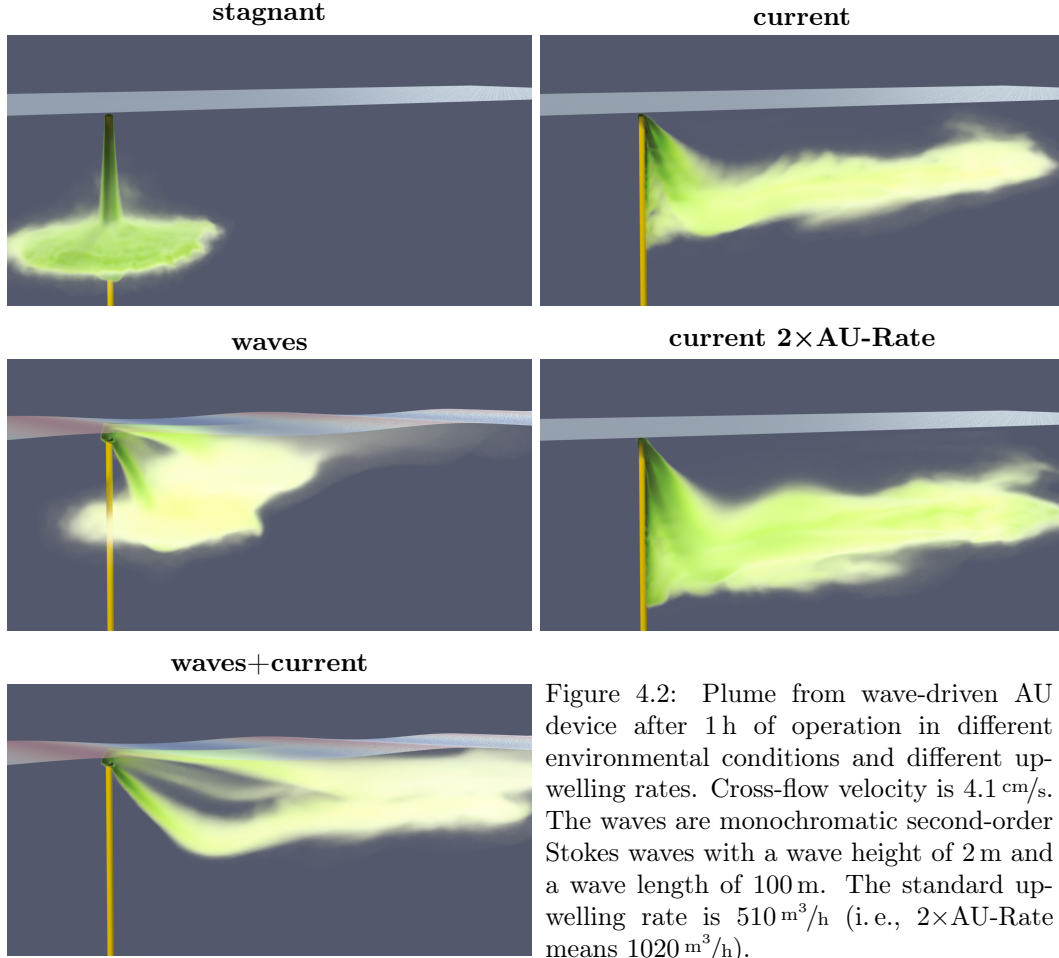
4.5 Application to AU

In Contribution [PPA], a study of a wave-driven upwelling pipe subject to cross-flow and waves is presented. The deep water plumes from both moored and free-floating AU devices are typically influenced by cross-flow. While moored AU devices are subject to the full force of the surrounding ocean currents, free-floating devices move with the currents, in principle. However, since the surrounding currents typically change significantly in direction and strength over the pipe depth of 200 m to 1000 m, the surface outlet of the pipes will realistically also experience cross-flow in the case of free-floating deployments. The prediction of cross-flow effects on upwelling plumes is thus of great relevance for the assessment of AU technology. Only the uppermost surface region is influenced by direct effects of wave motion. AU devices with deeper surface outlets can thus possibly avoid direct wave effects. However, since the orbital wave motion contributes significantly to mixing in the surface region, surface waves can play a role in keeping upwelled nutrients suspended in the mixed surface layer and thus aid the upwelling process.

The AU device studied in Contribution [PPA] has a pipe diameter of 1.9 m. The top of the pipe is located at a depth of 5 m, while the bottom depth is 200 m. These dimensions were chosen to represent a wave-pump prototype deployment reported by GEOMAR (2022). The upwelling rate of the device is assumed to be $510 \text{ m}^3/\text{h}$. This was roughly confirmed by the results from the GEOMAR field test² and is in line with previous assumptions

² While a final report on the test conducted by GEOMAR has not yet been issued, a review of the available data suggests that the upwelling rate during the field trial, which was conducted south of the Canary Islands, was about $600 \text{ m}^3/\text{h}$ in waves with a significant height of 1.6 m and a dominant period of 10 s.

of Oschlies et al. (2010) and Jürchott et al. (2023). In the *ocean4Foam* calculations, the upwelling pipe is fixed in space and upwells cold deep ocean water at a constant rate. In Contribution [PPA], two cases are studied, examining the effects of cross-flow and combined cross-flow and waves. In this section, the study from Contribution [PPA] will be extended with previously unpublished results for a purely wave-affected AU plume, a case with twice the assumed upwelling rate, and a case with a stagnant environment (no cross-flow or waves). As in the original study, a cross-flow velocity of 4.1 cm/s and a monochromatic sea state with a wave height of 2 m and a wave length of 100 m are considered. Figure 4.2 visually shows the different upwelling plumes after a time of 1 h. As can be seen, the environmental conditions



have a significant influence on the spreading and re-sinking behavior of the AU plumes. Both cross-flow and waves act to reduce the terminal depth of the plume, while stronger upwelling ($2 \times \text{AU-Rate}$) increases the re-sinking tendency. Under wave influence, the plume tends to separate into a part that directly remains in the free-surface region and a part with a more typical buoyant plume behavior.

A key question in assessing the plume in the context of AU is, to what extent the upwelled water sinks below a given depth. In Contribution [PPA], a vertical histogram analysis is thus carried out to evaluate the concentration of upwelled water throughout the modeled water column. Figure 4.3 shows the result of this study for all modeled cases. The histogram analysis generally confirms the visual impression from Figure 4.2. Only under wave mixing, significant amounts of upwelled water are retained in the immediate surface region (above 20 m). In a stagnant environment, the plume is strongly confined, with over 50 % of the upwelled water at depths between 40 and 45 m. The modeled cross-flow of 4.1 cm/s leads to significantly more vertical spread of the plume and a smaller terminal depth, with 50 % of the upwelled water retained above 30 m. With higher upwelling rates ($2 \times \text{AU-Rate}$), the

plume sinks deeper in the same cross-flow, indicating a lower relative efficiency in bringing deep ocean nutrients to the surface. Based on the temperature and salinity profile used in the calculations, the mixed layer depth is 24 to 33 m³. For the considered case, it can thus be concluded that under the effect of waves, most of the upwelled water is retained in the mixed surface layer, where it is subject to further natural mixing, and the contained nutrients are fully available for primary production. The considered cross-flow effect alone leads to part of the upwelled water (up to 75 %) being retained in the mixed surface layer, while without any environmental effects, the upwelled water almost entirely settles below the mixed layer depth. A duplication of the upwelling rate results in significantly less upwelled water retained in the mixed layer, both in relative and absolute terms.

Following (Huq, 1997), a length scale for the final sinking depth of a buoyant plume in cross-flow can be defined as

$$l_b = \frac{B}{U_\infty^3}, \quad (4.1)$$

based on the cross-flow velocity U_∞ and the buoyancy flux $B = Qg\frac{\rho-\rho_0}{\rho}$, where Q is the volume flux of the plume, g is gravity, and ρ and ρ_0 are the density of the background flow and plume, respectively (Huq, 1997). As can be seen from Equation (4.1), the final sinking depth of an AU plume in a cross-flow scales with the upwelling rate and the density offset of the upwelled water. This suggests that an upper limit for flow rates from AU devices exists if the final sinking depth of the AU plume has to remain inside the mixed surface layer for a given cross-flow scenario.

In general, the present results are in line with the assessment for AU devices in pure cross-flow reported by Fan et al. (2015). Fan et al. study cases with a sharp density interface representing the bottom of the mixed surface layer, aiming to create an AU plume with minimal dilution (to support mariculture within the plume) that does not penetrate the density interface in a cross-flow. To the best of the author's knowledge, no numerical investigations of wave effects on vertical negatively buoyant plumes (such as AU plumes) have previously been reported. A limited body of work exists on wave effects on positively buoyant plumes (Bordbar et al., 2024) as well as negatively buoyant inclined jets, which are studied in the context of sewage outfall modeling (Ferrari et al., 2018). Ferrari et al. (2018) also cite references on horizontal jets and non-buoyant jets. While these references invariably report increased dilution due to the influence of waves, Ferrari et al. find that waves may act to reduce the dilution of negatively buoyant inclined jets. The present results show a considerable increase in dilution as a result of wave action. A key difference between the present study and the studies of Ferrari et al. (2018), lies in the location of the outlet, which is placed in the direct vicinity of the free surface, here, whereas in the experiments of Ferrari et al. (2018) the outlet is located near the bottom. This interpretation suggests that AU devices with deeper surface outlets may be subject to the negative wave dilution effects reported by Ferrari et al. (2018). Other interpretations, based on the fact that AU plumes are vertical (not inclined) and have a much lower initial momentum than the jets studied by Ferrari et al., are possible. Wave effects and combined wave and cross-flow effects on the mixing of AU plumes have been studied experimentally by Liu et al. (2003), finding increased dilution of the AU plume through both waves and cross-flow, as observed in the present study. However, while Liu et al. (2003) conclude that the individual effects of waves and currents on plume dilution do not accumulate to a combined effect, some accumulative effect in terms of the settling depth of the upwelled water is clearly visible from the present results.

As this discussion indicates, further studies are required to fully understand environmental effects on AU plumes and negatively buoyant plumes in general. Nevertheless, the present results allow for some general conclusions for the techno-economic assessment of AU devices, beyond demonstrating the capabilities of the new numerical method. These general aspects will be further discussed in Chapter 5.

³ Calculated using a 0.03 kg/m³ criterion with a reference depth of 10 m and a 0.2 °C criterion with the same reference depth, respectively.

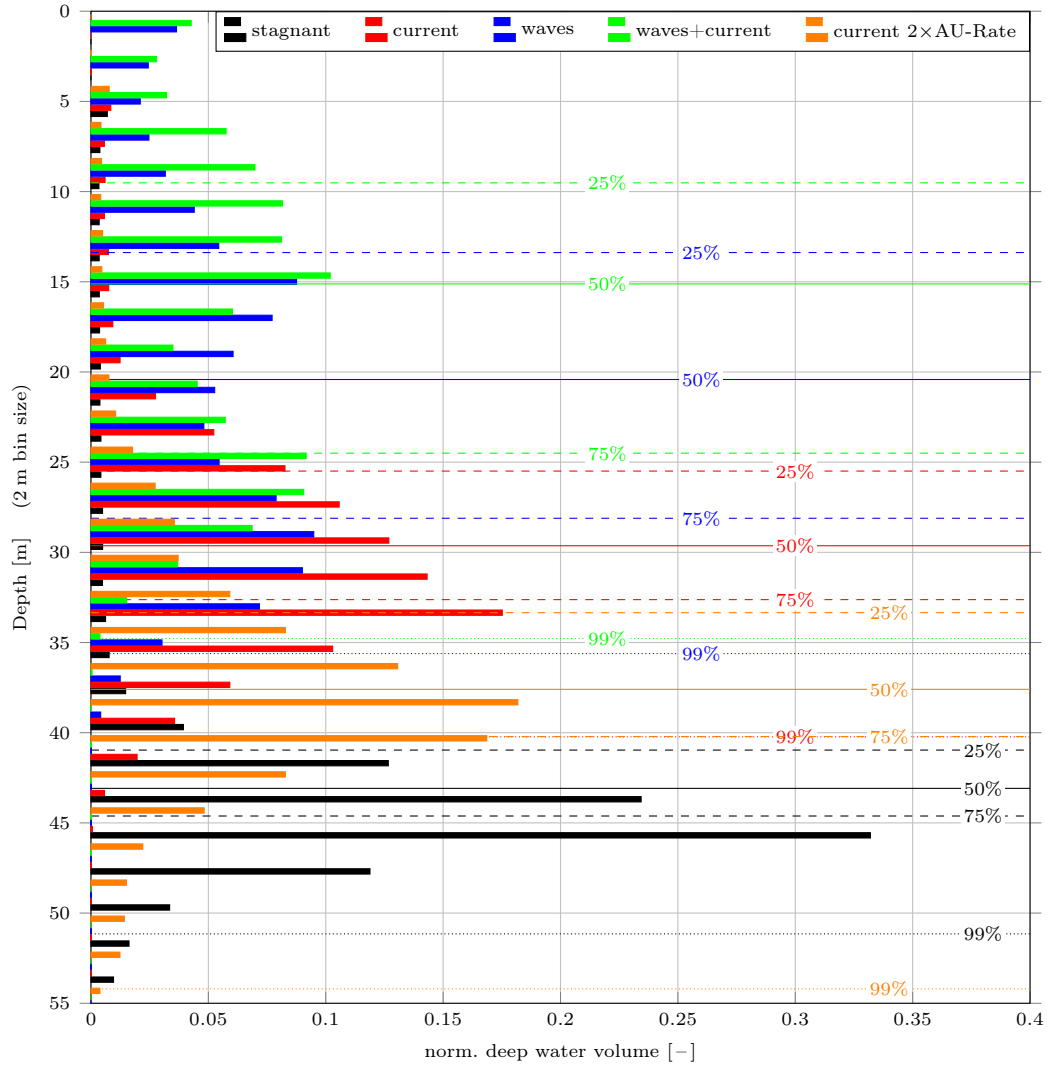


Figure 4.3: Histogram analysis of upwelled deep water concentration over the water column after 1 h of operation. Cases with stagnant environment (black), pure current influence (red), pure wave influence (blue), current and waves (green), and current with increased upwelling rate (orange). Concentration is analyzed in 2 m depth bins and normalized by the total amount of upwelled deep water. Lines give quantiles of upwelled deep water retained above a given depth.

Chapter 5

Techno-economic feasibility and effectiveness studies for AU

This chapter is split into two parts. Section 5.1 provides a complete demonstration of how the methods developed throughout this thesis can be used to evaluate technical options for AU and inform an overarching assessment process, on the example of buoyancy-driven AU through Stommel Upwelling Pipe (SUP) systems. This part summarizes original work from the publications [JPB], [JPC], [JPD], [CPA], and [PPB]. The second part of this chapter, Section 5.2, provides a synthesis of the current state of knowledge about all technical options studied in this thesis by discussing results from both previous work and advances throughout all contributions of this thesis.

The term *techno-economic feasibility* is widely used in integrated assessments (e. g., Baatz et al., 2025) of CDR measures. The term combines two assessment dimensions that are closely related to the technical development of CDR options. In this thesis, questions of *techno-environmental* feasibility assess whether an AU implementation concept is physically and technically possible. Questions of *economic* feasibility assess whether a technically feasible AU concept is a viable (and desirable) option in terms of its cost-benefit structure. The dimension of economic feasibility is generally not explored in absolute terms in this thesis. Nevertheless, aspects related to the benefits and costs of different technical AU options are discussed, which go beyond a mere technical feasibility assessment. Contributions to absolute cost estimates for AU devices have been made in the framework of a case study published in Contribution [JPD]. However, such estimates are subject to large uncertainties due to the low technological readiness of AU. Questions related to the assessment dimension of *effectiveness* in this thesis assess how well a technical AU concept supports the overall CDR process.

5.1 Performance prediction for Stommel’s perpetual salt fountain and its potential in the context of AU-based CDR

In large parts of the global oceans, both temperature and salinity are higher at the surface than in the deep ocean. Driven by evaporation, the high surface salinity acts to destabilize the ocean’s density stratification, thus increasing its potential energy budget. As a consequence of the second law of thermodynamics, the ocean will generally tend to decrease its potential energy through natural processes. This can be observed in the salt-fingering process, a double-diffusive convection process through which high-salinity surface water is transported downwards while exchanging heat. A similar process was proposed by Stommel et al. (1956) to drive AU. If a vertical pipe were inserted into the ocean and filled with deep ocean water once, the water in the pipe would be able to exchange heat but not salt with its surroundings. The (initially cold) deep ocean water in the pipe would thus heat up

and eventually become buoyant with respect to its surroundings due to its low salinity, thus initiating a convective upward flow in the pipe. The flow would drag new deep ocean water into the pipe and thus sustain the process. The convection in the pipe would run without any energy input for as long as it acts to stabilize the ocean stratification, i.e., as long as the salinity of the surface water is still higher than that of the deep ocean water. This AU concept was initially proposed by Stommel et al. (1956). Johnson and Decicco (1983) extend the technical concept by introducing a more efficient counterflow design, where one or multiple upwelling pipes are placed in an outer shell in which downwelling is established based on the same principle. This concept can be scaled up by adding more upwelling pipes, thus increasing the flow rate. The different device types are depicted in Figure 5.1. Model predictions of the potential of SUP systems have been published by Groves (1958),

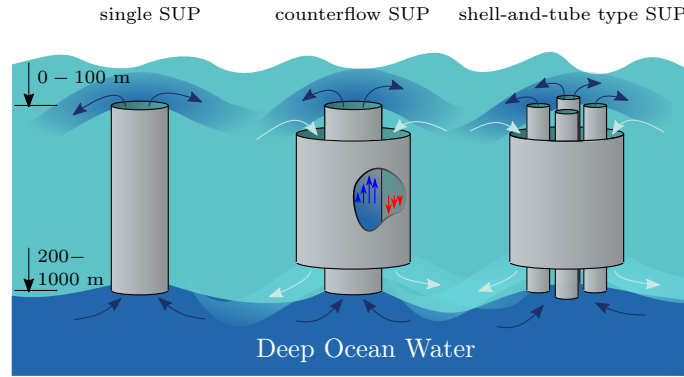


Figure 5.1: Basic types of SUP systems. Adapted from Kemper et al. (2025). CC BY 4.0.

Hinman (1966), and Johnson and Decicco (1983), and first field tests have been reported by Maruyama et al. (2004). However, as explained in Contribution [JPB], these previous efforts did not yield sufficient reliability of SUP performance predictions to enable a rigorous assessment of their potential as an enabling technology for large-scale AU in the context of CDR. In line with the dual focus of this thesis on numerical model development and application in the context of AU, two main contributions have been published in an effort to close the existing knowledge gaps with respect to SUP systems as a potential enabling technology for AU.

The first publication constitutes Contribution [JPB] of this thesis. An early version of this work was presented at the 2023 International Conference on Computational Methods in Marine Engineering (MARINE) and is published in Contribution [CPA]. To overcome the previously high uncertainty in performance predictions for SUP systems, rigorous verification, validation, and model intercomparison efforts were carried out. For efficient studies of several types of SUP systems, a one-dimensional reduced-order method was developed and implemented. The method is published in the software publication [SPB] and is described in detail in Contribution [JPB]. As in the respective publications, the method will be referred to as the *SP1D* (short for Stommel-pipe one-dimensional) method in the following. Basic concepts of the method were adopted from Groves (1958) and Johnson and Decicco (1983) and implemented as a flexible Python package, which allows different types of SUP systems to be studied under arbitrary temperature and salinity conditions. The method can be used via a graphical user interface or in batch mode. To assess the predictive capabilities of the new reduced-order method, comprehensive model validation efforts were carried out using both the new *SP1D* method and the *ocean4Foam* method. As the *ocean4Foam* method is largely based on first principles (i.e., conservation of mass, momentum, and energy), a predictive validation for SUP systems can be performed, i.e., the method can be expected to predict the performance of SUP systems correctly, provided it is able to capture the individual relevant pipe flow phenomena correctly. In turn, the *SP1D* method is based to a higher degree on empirical assumptions and must thus be validated in an application-specific manner, i.e., against data for actual SUP systems. At present, suitable

data for such a validation are not available. The only experimental datasets were provided by a set of experiments with very low upwelling velocities (Maruyama et al., 2004; Tsubaki et al., 2007) (2.45 mm/s and 7.5 mm/s , respectively). As can be seen from the results of Contribution [JPC], such a point of operation is unsuitable for a general validation of the *SP1D* method. Since the available experimental data are additionally influenced by strong disturbances due to waves and a considerable inclination of the pipes by cross-current, a validation of the *SP1D* method against the data of Maruyama et al. (2004) and Tsubaki et al. (2007) was not pursued. Instead, a comprehensive model intercomparison between the *SP1D* method and the *ocean4Foam* method was carried out following a rigorous verification and predictive validation of the *ocean4Foam* method against theory and DNS data for the relevant pipe-flow phenomena. In Contribution [JPB], a model intercomparison for different SUP types across various ocean conditions, geometries, and pipe flow regimes is presented. Additionally, with the assumption of no heat transfer through the outer wall of counterflow and shell-and-tube type SUP systems, a central simplifying assumption of the *SP1D* model is critically reviewed based on a comparison with *ocean4Foam* results. A similar comparison study between *SP1D* and *ocean4Foam* is also presented in the conference publication [CPA] to evaluate the upscaling model for shell-and-tube type SUP systems implemented in the *SP1D* method. In sum, the performed verification, validation, and model intercomparison efforts enable performance predictions for SUP systems with a previously unattained level of confidence and sophistication. Additionally, Contribution [JPB] for the first time points out the importance of mixed-convection flow and related transition and relaminarization phenomena for SUP systems, thus advancing the understanding of the involved flow physics.

Having validated the *SP1D* method in Contribution [JPB], Contribution [JPC] focuses on the application of the method to assess the potential of SUP systems as an enabling technology for AU in the context of CDR. Advances published in this publication include the first published global assessment of suitable ocean conditions for SUP systems, the first study on seasonal and small-scale spatial variability of SUP performance using instantaneous (non-averaged) ocean data, and a comprehensive study on upscaling and optimization of shell-and-tube type SUP systems to achieve practically relevant flow rates for AU. Generally, the results presented in Contribution [JPC] underline the potential of SUP systems as a technical concept for AU. The global assessment primarily indicates potential for high upwelling flow rates near the subtropical ocean gyres, with the highest potential in and around the South Atlantic Gyre. It is further found that, to achieve upwelling flow rates comparable to other technical concepts (e.g., wave-driven upwelling devices), shell-and-tube type systems are required. The fact that SUP systems heat the deep ocean water during upwelling is identified as one of the key advantages of this AU concept. The statistical results from the performance variability study suggest that the upwelled water from SUP systems has a lower tendency to sink back down, compared to other AU approaches. When designed accordingly, SUP systems can upwell deep ocean water buoyant with respect to the surroundings at the surface outlet. Besides the reduced re-sinking tendency, the heating of the upwelled water implies that large-scale AU deployments based on SUP systems would not significantly cool the surface ocean, and in turn, would not lead to enhanced heating of the interior ocean. Increased ocean heat uptake has previously been reported as a major side effect of AU when wave-driven upwelling devices were deemed the most likely technical concept (Oschlies et al., 2010; Jürchott et al., 2025).

The results published throughout the work of this thesis thus suggest that the cumulative climate impact of AU has to be reevaluated, including SUP systems as a possible enabling technology. Such a reevaluation is pursued in Contribution [PPB]. Here, a parameterization for SUP systems in an Earth system model of intermediate complexity is developed in the form of a polynomial fit through global SUP performance data obtained with the *SP1D* method. Simple indicators, such as temperature and salinity at the sea surface as well as their differences between the surface and the pipe’s source depth, are used as parameters in this meta-model. The SUP performance is dynamically calculated during runtime of the Earth system model to capture climate feedbacks and saturation effects on SUP-based AU. The simple model implementation assumes a perfect heat exchange inside the SUP pipes,

such that no heat is upwelled or downwelled. Simulations are run for three shell-and-tube type pipe designs (with 303 m, 643 m, and 1103 m source depth) under two future CO₂ emission scenarios (RCP 2.6 and RCP 8.5). A maximum potential approach is investigated by assuming a dense deployment of SUP systems (1 pipe/km² and 10 pipes/km²) wherever they produce upwelling. The runs extend from year 2025 to 2100. Significant upwelling (up to 0.45 m³/s) is obtained, especially with the longer pipe designs, which are additionally found to be less affected by seasonal performance variations. As SUP systems upwell low-salinity water to the surface ocean, large-scale deployments impair their own efficiency over time. In the simulations, a moderate decline in the SUP performance is observed, which can be attributed to this saturation effect. A termination effect on the climate system due to interior ocean heating, as reported for wave-driven AU, is not observed. As the simulations are based on the simplistic assumption of perfect heat exchange inside the SUP devices, this result has to be confirmed with more sophisticated calculations. However, from a potential-energy perspective, it seems plausible that wave-driven AU systems, which increase the ocean’s potential energy budget, lead to increased upper ocean mixing, while SUP systems, which reduce the ocean’s potential energy budget, should have an opposed effect. In fact, the results show a global increase in ocean stratification stability due to the SUP operation, which leads to reduced ocean heat and carbon uptake and a decline in the overturning circulation. In terms of the cumulative climate impact of AU, it is found that, while the provision of nutrients from the deep ocean increases primary production in the surface ocean, the net effect on atmospheric CO₂ levels is positive (i.e., increasing atmospheric CO₂) due to outgassing of upwelled carbon from the interior ocean. Also, ocean deoxygenation is identified as a likely side effect. While the results of Contribution [PPB] thus suggest that SUP-based AU likely has low potential as a standalone CDR measure, it remains a significant result that many potential side effects that have previously been considered inherently linked to AU can, in fact, be reversed based on the choice of AU technology. This knowledge will be useful in developing future specialized AU-based CDR measures, such as deployments in high-potential regions or combinations of AU with additional CDR measures. A combination of AU with macroalgae farming and sinking has shown significant CDR potential in a study by Wu et al. (2023) and in a case study presented in Contribution [JPD] of this thesis.

As the present work on SUP-based upwelling shows, targeted AU technology not only optimizes the techno-economic performance of AU deployments but also affects the overall effectiveness and desirability of such measures. The applications thus successfully demonstrate the approach of this thesis in informing the overall assessment of AU-based CDR measures through research and model development on the technical level.

5.2 Assessment of proposed technical options for artificial upwelling

In line with the thesis motivation to unify and extend the knowledge about different technical AU options, this section synthesizes current knowledge about the techno-economic feasibility and effectiveness of different concepts and advances through the contributions of this thesis.

Three technical concepts are studied in this thesis: wave-driven upwelling, propeller-driven upwelling, and SUP-based upwelling. Air-lift upwelling, where an upwelling flow is initiated by an injection of air at the source depth, is not studied. As in the project work of this thesis, here the focus will be on large-scale open-ocean implementations of AU as a marine CDR measure.

5.2.1 Wave-driven upwelling

Large-scale AU for the purpose of carbon removal was initially proposed by Lovelock and Rapley (2007). Following their proposal, many early works on AU-based CDR have, implicitly or explicitly, considered wave-energy-driven upwelling devices (Dutreuil et al., 2009; Oeschies et al., 2010). Such devices had already been proposed earlier for AU in different contexts (Isaacs et al., 1976; Liu, 1999; Kirke, 2003; Kithil, 2006). Typically, wave-driven

upwelling devices consist of a rigid or flexible pipe, a float, which is excited into motion by the wave action, and a no-return valve, which restricts the flow in one direction.

A wide range of device sizes has been proposed. An equally wide range of flow rate predictions exists based on mathematical models of various levels of complexity (Liu and Jin, 1995; Kirke, 2003; Kithil, 2006; Fan et al., 2016) as well as model experiments (Fan et al., 2016; Zhou et al., 2019). Proposed flow rates range from $5 \text{ m}^3/\text{h}$ (Fan et al., 2016) to $1.8 \times 10^4 \text{ m}^3/\text{h}$ (Kirke, 2003). A comprehensive review of previous work is presented by Koweek (2022). Koweek identifies a gap between predicted flow rates and values achieved in field trials. Based on his review, Koweek proposes a flow rate of $180 \text{ m}^3/\text{h}$ and a bottom depth of 500 m as near-term technology limits. This is in agreement with the results of Fan et al. (2016), who propose a range of 5 to $360 \text{ m}^3/\text{h}$ based on a mathematical model, which they validated against model experiments. Throughout this thesis, no efforts have been made to improve the flow-rate predictions for wave-driven AU systems.

Compared to other technical AU concepts, the technology readiness for wave-driven AU devices is relatively high. Even though many prototype tests have ended in structural failure of the devices (White et al., 2010; GEOMAR, 2022), the literature generally supports the technical feasibility of large-scale wave-driven AU for carbon removal. Regarding the economic feasibility of the concept, the literature and study of previous projects suggest that wave-driven upwelling devices can be designed simply and produced and deployed at a relatively low economic cost compared to other AU concepts. This assessment is primarily driven by the fact that wave-driven AU devices have previously been constructed using flexible pipe material, which greatly simplifies the deployment process. Nevertheless, the high periodic structural loads on these systems will likely necessitate regular maintenance, which would incur considerable operational costs.

Throughout the wave-driven upwelling process, the deep ocean water does not undergo significant heating and is thus discharged at the surface with a low temperature close to that at the pipe source depth. This constitutes the re-sinking problem, which has been previously discussed in Chapter 4. Earlier proposals to resolve this problem included transferring the upwelled water to a nearby shallow region or natural confinement (Kirke, 2003), which is obviously impracticable in the context of large-scale AU in the open ocean. The dynamics of deep water plumes from AU devices have previously been studied by Fan et al. (2015), Williamson et al. (2009), Kogawa et al. (2013), and Liu et al. (2003). In the context of this thesis, calculations of plumes from wave-driven upwelling devices under the effect of waves and cross-flow have been studied. It was found that these natural effects can contribute significantly to keeping the upwelled water suspended within the mixed surface layer, where it is expected to be available for primary production. The re-sinking problem generally leads to reduced effectiveness of wave-driven AU in supporting primary production in the surface ocean. However, the results of this thesis suggest that its effect might not be as pronounced as previously suggested (Kirke, 2003) in a real ocean environment. Wave-driven AU thus remains a potential enabling technology for large-scale AU. Due to the effect on ocean heat uptake (Oschlies et al., 2010; Jürchott et al., 2025) and other direct physical effects (Kwiatkowski et al., 2015), it appears likely, however, that the AU process does not lead to a desirable overall climate impact profile when wave-driven AU devices are used.

5.2.2 Propeller-driven upwelling

A propeller-driven upwelling device has been continuously operated for multiple years in Japanese waters to enhance local primary production (Ouchi, 2009). The device was first deployed in the year 2000 and upwelled up to $1.2 \text{ m}^3/\text{s}$ of deep ocean water from a depth of about 200 m. To reduce re-sinking and dilution of the plume, the water was mechanically mixed with surface water and released at the bottom of the mixed surface layer. The substantial device was driven by a 115 kW diesel generator. Propeller-driven upwelling is also performed to improve the water quality in commercial fish farms. However, the current technology is not suitable for the large source depths required for nutrient upwelling in the context of CDR. Viúdez et al. (2016) were the first to propose a large propeller-driven upwelling device, powered by a dedicated renewable energy source (e.g., a floating wind

turbine).

In principle, the results obtained for wave-driven upwelling can be directly transferred to propeller-driven upwelling, as both concepts provide a forced-convection flow of deep ocean water to the surface ocean without significant heating during the upwelling process. However, in the context of this thesis, propeller-driven upwelling devices have been assumed to be considerably larger in scale compared to wave-driven devices. This assumption was made based on concepts proposed in literature (Viúdez et al., 2016) and on the practical consideration that propeller-driven devices require more maintenance due to their higher technical complexity, which would likely favor the deployment of a small number of large devices. From a fluid dynamics perspective, large devices are less desirable, as the large upwelling plumes produced by these devices profit less from the favorable interaction with the natural mixed layer processes. As shown in Chapter 4 of this thesis, the efficiency in permanently providing nutrients to the ocean’s mixed surface layer can be significantly impaired by re-sinking of the upwelled water without the effect of natural mixed layer processes. While re-sinking can be limited through the geometric design of the device (as studied in Contribution [JPA]) or through mechanical mixing with surface water (as pursued by Ouchi (2009)), a limited effectiveness in terms of enhancing primary production must still be expected even when the upwelled deep ocean water settles at the bottom of the mixed layer (Pan et al., 2015).

Due to its high technical complexity and maintenance requirements, along with a potentially impaired effectiveness in permanently providing nutrients to the mixed surface layer suggested by the results of this thesis, propeller-driven upwelling is likely not technoeconomically competitive with other AU options for large-scale AU deployments in the open ocean. It might, however, be competitive for coastal AU applications, where maintenance and energy supply are less problematic and smaller devices can be realized.

5.2.3 Buoyancy-driven upwelling

Initially described by Stommel et al. (1956), buoyancy-driven upwelling has previously obtained little interest as a technical concept in the context of large-scale AU for carbon removal. Single SUP pipes, even when more efficient counterflow designs are used (see Figure 4.2), only achieve minor upwelling flow rates and will thus likely not be used in practical implementations. Upscaled shell-and-tube type SUP systems were initially proposed by Johnson and Decicco (1983). The modeling results presented throughout the work of this thesis (especially Contribution [JPC]) confirm that these systems can achieve flow rates comparable to wave-driven upwelling devices and thus have a comparable technical potential for driving AU. The economic potential of SUP systems can be evaluated based on their technical complexity when compared to other AU options. In principle, SUP systems could be viewed as the technologically simplest AU option, based on the fact that, except for the pipe (and some installation to initially prime the flow), they require no functional elements. Unlike wave-driven upwelling pipes, the pipes of SUP systems do not have to transmit any functional loads and just have to withstand the environmental forces. However, since considerable upwelling flow rates can only be achieved with shell-and-tube type SUP systems, the geometrical complexity of such devices has to be considered. Due to this geometrical complexity, it seems less likely that upscaled SUP systems could be constructed from flexible material, as typically proposed for wave-driven AU pipes. Upscaled SUP systems would thus likely have a much higher cost for construction and deployment, while the maintenance cost could be lower when compared to wave-driven AU. The relative economic feasibility of Stommel-pipe upwelling thus likely depends on future developments of low-cost implementation approaches for shell-and-tube type SUP systems. The effectiveness of SUP systems in supporting AU as an overall CDR concept is seen as superior to that of other technical approaches, based on the results of this thesis (especially Contribution [PPB]). This assessment is primarily driven by the fact that the water upwelled by SUP systems is heated, resulting in less re-sinking tendency and the avoidance of global temperature side effects.

Chapter 6

Conclusions and outlook

Following the dual objective of this thesis in model development and application in the field of AU, the conclusions and outlook from the present thesis are divided into two parts. The first part presents conclusions from the development work conducted throughout this thesis, while the second part draws conclusions from the modeling efforts carried out in the context of this thesis with the objective of unifying and extending the knowledge about AU-based marine CDR measures.

6.1 Model development

Throughout this thesis, *ocean4Foam*, a new toolbox for modeling oceanic flow in OpenFOAM[®], has been developed. The *ocean4Foam* toolbox provides solvers and methods for modeling buoyant and stratified flows of seawater with dynamic temperature, salinity, and passive scalar transport. Advanced turbulence modeling options are available to improve the predictive capabilities of RANS turbulence models for buoyant and stratified flow applications. Optional, computationally efficient free-surface modeling capabilities are provided through a modified ALE interface tracking approach. Phase-resolved free-surface wave generation and absorption are enabled through an adapter for the widely used *waves2foam* toolbox of Jacobsen et al. (2011). Adaptive mesh refinement capabilities with dynamic processor load balancing are provided through an updated and extended fork of the *blastAMR* library (Heylmun et al., 2023). A new method has been developed to allow for combined free-surface modeling with adaptive mesh refinement.

Throughout the original work of this thesis, the capabilities of the *ocean4Foam* toolbox have been subject to various verification and validation efforts. The basic non-hydrostatic flow and turbulence modeling capabilities have been validated against experimental data for a buoyant jet in a stratified ambient in Chapter 3 of this thesis. The free-surface wave modeling capabilities have been rigorously verified and validated against both theory and experimental data as part of the work reported in Contribution [PPA], and the performance of the ALE interface tracking approach has been compared to other free-surface modeling approaches, finding a substantial advantage in the computational efficiency. Rigorous verification and validation efforts against theory and DNS data for mixed-convection flow in vertical pipes and annular sections have been reported in Contribution [JPB].

All development efforts have been conducted with the aim of maximizing the future usefulness of the methods by making them modular, expandable, and customizable. The *ocean4Foam* toolbox, including the ALE interface tracking library and the *waves2foam* adapter, is published via the software publication [SPA] and maintained via a public git repository (see Section 2.7). The adaptive mesh refinement capabilities are maintained via a public fork of the *blastAMR* git repository.

While the *ocean4Foam* toolbox has been successfully applied for various studies throughout the course of this thesis, it is still subject to a number of limitations that hamper its general applicability as an engineering-scale ocean modeling system and should be addressed as part of future work. The applicability of the ALE interface tracking library is limited with

respect to wave interaction with surface-piercing structures and shores. Only vertical structures and shores can be handled at present. Also, no model is implemented to parameterize wave breaking and stabilize the mesh deformation in the case of breaking waves. The applicability of the ALE interface tracking approach to wave interaction with realistic coastal zones is thus limited. Additional limitations exist regarding the implemented boundary conditions. The present implementation of a hydrostatic open boundary allows for free inflow and outflow through the boundary, based on the local hydrostatic conditions with respect to an initially defined reference pressure profile. Transient changes in the density profile at the boundary are accepted through a mixed Dirichlet-Neumann formulation for the pressure boundary condition. However, this formulation likely reflects internal gravity waves in the stratified fluid. A non-reflective boundary, or a relaxation zone approach, should be implemented in the future to avoid internal wave reflection. Free-surface boundary conditions for wind shear and heat flux, as well as source terms for radiative forcing, have not yet been implemented. Finally, the turbulence modeling capabilities should be further extended with additional methods for geophysical flows.

While the applications of the *ocean4Foam* toolbox presented throughout this work demonstrate its suitability for a wide range of studies in the context of AU, only few studies in a more general context of oceanic flow modeling have been shown. Additional tests and validation studies should thus be conducted. Especially, the method should be validated for stratified flow on larger spatial and temporal scales, and it should be ensured that variations in mixed-layer depth can be reproduced, as well as geophysical boundary-layer flow characteristics.

Due to its generality and modularity, the *ocean4Foam* toolbox can be applied across a wide range of oceanic flow modeling problems. While the focus on AU applications throughout this thesis has led to the development and validation of relevant features in this context, the author hopes that future applications will lead to a further extension and diversification of the toolbox, such that eventually full functionalities for a versatile engineering-scale ocean modeling system become available.

6.2 Flow modeling for AU

It has been the motivation of this thesis to unify and extend the knowledge about different technical options for AU and their effects, with the aim of supporting assessments of the techno-economic feasibility and effectiveness of AU-based CDR measures. Several studies in this thesis have investigated the dynamics of deep water plumes from AU. Detailed studies on the plume of a large propeller-driven upwelling device have been presented. The studies reveal that the efficiency of the device is impaired by the tendency of the upwelled water to sink back below the mixed surface layer. While further studies have shown that wave and current influences act to reduce the re-sinking of the upwelled water, propeller-driven upwelling devices are likely to benefit less from these influences due to their large prospective scale and upwelling flow rates. Geometric variant studies have shown that the shape of the device outlet has a limited effect on the device's effectiveness in transporting deep ocean water to the mixed surface layer, despite notable effects on turbulent mixing near the outlet. Studies on plumes of smaller wave-driven upwelling devices showed a strong influence of the environmental wave and current conditions. While generally, the effectiveness of wave-driven upwelling devices must thus be seen as strongly case-dependent. The results indicate that a significant amount of the upwelled deep ocean water is retained in the mixed surface layer under realistic conditions, provided that upwelling rates are small.

In addition to the studies on AU plume dynamics, numerous studies on buoyancy-driven upwelling, based on Stommel Upwelling Pipes (SUP), have been conducted throughout this thesis. As little work had previously been carried out on this AU concept in the context of CDR, a wider approach towards techno-economic feasibility assessment was taken, in line with the goal of a unification of the knowledge about different AU options. A one-dimensional reduced-order model (*SP1D*) was developed to enable efficient evaluations of large sets of pipe geometry variations and environmental conditions. Based on this approach, reliable

and general information on the potential of SUP systems for AU was provided. It was found that, given suitable ocean conditions, upscaled SUP systems can provide upwelling flow rates comparable to those of wave-driven AU devices. A key advantage of these systems is that the upwelled water is heated during the upwelling process. Re-sinking and unwanted cooling of the surface ocean can thus be largely avoided. A parameterization of SUP-based AU in an Earth system model was developed to study the cumulative climate effects of this AU concept in a maximum-potential scenario. It was found that, while some unwanted side effects of other AU concepts could be avoided, the intervention did not lead to a global oceanic CO₂ uptake from the atmosphere when deployed as a standalone CDR measure and led to new, unique side effects on the climate system. While previously, AU has often been considered to be directly connected to upper ocean cooling and mixing (Dutreuil et al., 2009; Oschlies et al., 2010; Jürchott et al., 2025), the results published in the context of SUP upwelling show that differences regarding the technical implementation have direct consequences for the global potential and impacts of AU-based marine CDR measures. The present work can thus be seen as an example of a reliable simulation-based parameterization of such technical differences across modeling scales, which informs overarching assessments of the techno-economic feasibility and effectiveness in the context of CDR.

The above conclusions summarize how the knowledge about different technical options for AU has been extended and unified through the development and application of numerical models throughout this thesis. As technologies progress from a concept stage towards prototypes and specific deployments, high-fidelity numerical modeling will become an increasingly valuable tool for reducing the need for complex field tests and providing much-needed predictions for their potential impacts and outcomes. The applications in this thesis have focused on the assessment of general technical concepts for AU devices. While more general results can still be obtained by extending the presented studies in the context of AU, future applications will likely encompass more specific technical questions arising from real-world applications and field trials.

This thesis has shown that to assess technical climate interventions in a wider context, scales between technical and geophysical modeling must be bridged by suitable modeling and parameterization efforts. In a time when geophysical and global impacts of human technology can no longer be overlooked, responsible and timely development of marine CDR measures requires synchronized research and development across disciplines and scales. The author thus hopes that the present work strikes a balance between specific and targeted advancement of CDR technology and its overarching interdisciplinary assessment as a means of addressing human-induced climate change.

Bibliography

- Alfaifi, H., Mohammadian, A., Gildeh, H.K., Gharavi, A., 2019. Experimental and numerical study of the characteristics of thermal and nonthermal offset buoyant jets discharged into stagnant water. *Desalination and Water Treatment* 141, 171–186. doi:10.5004/dwt.2019.23477.
- Alvir, M., Grbčić, L., Sikirica, A., Kranjčević, L., 2022. OpenFOAM-ROMS nested model for coastal flow and outfall assessment. *Ocean Engineering* 264, 112535. doi:10.1016/j.oceaneng.2022.112535.
- Auclair, F., Bordois, L., Dossmann, Y., Duhaut, T., Paci, A., Ulses, C., Nguyen, C., 2018. A non-hydrostatic non-Boussinesq algorithm for free-surface ocean modelling. *Ocean Modelling* 132, 12–29. doi:10.1016/j.ocemod.2018.07.011.
- Baatz, C., Tank, L., Bednarz, L.K., Böttcher, M., Morganti, T.M., Voget-Kleschin, L., Cabus, T., Doorn, E.v., Dorndorf, T., Havermann, F., Holzhüter, W., Keller, D., Kreuzburg, M., Matz-Lück, N., Mengis, N., Merk, C., Moustakis, Y., Pongratz, J., Wehnert, H., Yao, W., Rehder, G., 2025. A holistic assessment framework for marine carbon dioxide removal options. *Environmental Research Letters* 20, 054047. doi:10.1088/1748-9326/adc93f.
- Babiker, M., Berndes, G., Blok, K., Cohen, B., Cowie, A., Geden, O., Ginzburg, V., Leip, A., Smith, P., Sugiyama, M., Yamba, F., 2022. Cross-sectoral perspectives. In: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Shukla, P.R., Skea, J., Slade, R., Al Khouradajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157926.005.
- Bai, X.D., Zhang, W., Zheng, J.H., Wang, Y., 2020. On the mass source internal wave making method for ALE based numerical wave tank. *Journal of Marine Science and Technology* 25, 1093–1102. doi:10.1007/s00773-020-00702-z.
- Baumann, M., Goldenberg, S.U., Taucher, J., Fernández-Méndez, M., Ortiz, J., Haussmann, J., Riebesell, U., 2023. Counteracting effects of nutrient composition (Si:N) on export flux under artificial upwelling. *Frontiers in Marine Science* 10. doi:10.3389/fmars.2023.1181351.
- Bordbar, A., Dai, Y.M., Michele, S., Zawalna-Geer, O., Chen, Z., Faroughi, S.A., Lee, Y.C., 2024. Thermal-induced buoyant water jet discharge under shallow coastal water conditions. *International Journal of Thermofluids* 24, 100857. doi:10.1016/j.ijft.2024.100857.
- Burchard, H., Bolding, K., 2001. Comparative analysis of four second-moment turbulence closure models for the oceanic mixed layer. *Journal of Physical Oceanography* 31, 1943–1968. doi:10.1175/1520-0485(2001)031<1943:caofsm>2.0.co;2.

- Chai, X., Liu, X., Xiong, J., Cheng, X., 2020. Numerical investigation of turbulent heat transfer properties at low Prandtl number. *Frontiers in Energy Research* 8. doi:10.3389/fenrg.2020.00112.
- Chavez, F.P., Messié, M., 2009. A comparison of eastern boundary upwelling ecosystems. *Progress in Oceanography* 53, 80–96. doi:10.1016/j.pocean.2009.07.032.
- Chen, Y., He, Z., Lou, Y., Zhang, H., Zhu, R., Okon, S.U., 2021. Experimental study of horizontal heated buoyant jets in a linearly stratified ambience. *Physics of Fluids* 33, 047116. doi:10.1063/5.0045906.
- Combest, D.P., Ramachandran, P.A., Dudukovic, M.P., 2011. On the gradient diffusion hypothesis and passive scalar transport in turbulent flows. *Industrial & Engineering Chemistry Research* 50, 8817–8823. doi:10.1021/ie200055s.
- Daly, B.J., Harlow, F.H., 1970. Transport equations in turbulence. *Physics of Fluids* 13, 2634. doi:10.1063/1.1692845.
- DeVries, T., Primeau, F., Deutsch, C., 2012. The sequestration efficiency of the biological pump. *Geophysical Research Letters* 39. doi:10.1029/2012gl051963.
- Dutreuil, S., Bopp, L., Tagliabue, A., 2009. Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability. *Biogeosciences* 6, 901–912. doi:10.5194/bg-6-901-2009.
- Fan, L.N., 1967. Turbulent buoyant jets into stratified or flowing ambient fluids. Tech. Rep. KH-R-15.
- Fan, W., Pan, Y., Liu, C.C., Wiltshire, J.C., Chen-Tung, A.C., Chen, Y., 2015. Hydrodynamic design of deep ocean water discharge for the creation of a nutrient-rich plume in the South China Sea. *Ocean Engineering* 108, 356–368. doi:10.1016/j.oceaneng.2015.08.006.
- Fan, W., Pan, Y., Zhang, D., Xu, C., Qiang, Y., Chen, Y., 2016. Experimental study on the performance of a wave pump for artificial upwelling. *Ocean Engineering* 113, 191–200. doi:10.1016/j.oceaneng.2015.12.056.
- Ferrand, M., Harris, J.C., 2021. Finite volume arbitrary Lagrangian-Eulerian schemes using dual meshes for ocean wave applications. *Computers & Fluids* 219, 104860. doi:10.1016/j.compfluid.2021.104860.
- Ferrari, S., Badas, M.G., Querzoli, G., 2018. On the effect of regular waves on inclined negatively buoyant jets. *Water* 10, 726. doi:10.3390/w10060726.
- Ferziger, J.H., Perić, M., Street, R.L., 2020. *Computational Methods for Fluid Dynamics*. Springer International Publishing, Cham. doi:10.1007/978-3-319-99693-6.
- Floryan, J.M., Rasmussen, H., 1989. Numerical methods for viscous flows with moving boundaries. *Applied Mechanics Reviews* 42, 323–341. doi:10.1115/1.3152416.
- Forster, P.M., Smith, C., Walsh, T., Lamb, W.F., Lamboll, R., Cassou, C., Hauser, M., Hausfather, Z., Lee, J.Y., Palmer, M.D., von Schuckmann, K., Slangen, A.B.A., Szopa, S., Trewin, B., Yun, J., Gillett, N.P., Jenkins, S., Matthews, H.D., Raghavan, K., Ribes, A., Rogelj, J., Rosen, D., Zhang, X., Allen, M., Aleluia Reis, L., Andrew, R.M., Betts, R.A., Borger, A., Broersma, J.A., Burgess, S.N., Cheng, L., Friedlingstein, P., Domingues, C.M., Gambarini, M., Gasser, T., Gütschow, J., Ishii, M., Kadow, C., Kennedy, J., Killick, R.E., Krummel, P.B., Liné, A., Monselesan, D.P., Morice, C., Mühle, J., Naik, V., Peters, G.P., Pirani, A., Pongratz, J., Minx, J.C., Rigby, M., Rohde, R., Savita, A., Seneviratne, S.I., Thorne, P., Wells, C., Western, L.M., van der Werf, G.R., Wijffels, S.E., Masson-Delmotte, V., Zhai, P., 2025. Indicators of global climate change 2024: Annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data* 17, 2641–2680. doi:10.5194/essd-17-2641-2025.

- Fringer, O., Gerritsen, M., Street, R., 2006. An unstructured-grid, finite-volume, nonhydrostatic, parallel coastal ocean simulator. *Ocean Modelling* 14, 139–173. doi:10.1016/j.ocemod.2006.03.006.
- GEOMAR Helmholtz Centre for Ocean Research Kiel, 2022. Greening the ocean to combat climate change: Wave-driven upwelling pump deployed south of the Canary Islands. *GEOMAR News*. URL: <https://www.geomar.de/en/news/article/greening-the-ocean-to-combat-climate-change>. accessed: Sept. 23, 2025.
- Gharavi, A., Mohammadian, A., Nistor, I., Peña, E., Anta, J., 2020. Experimental study of surface buoyant jets in crossflow. *Environmental Fluid Mechanics* doi:10.1007/s10652-020-09737-7.
- Girfoglio, M., Quaini, A., Rozza, G., 2024. A linear filter regularization for POD-based reduced-order models of the quasi-geostrophic equations. *Comptes Rendus. Mécanique* 351, 457–477. doi:10.5802/crmeca.183.
- Goldenberg, S.U., Taucher, J., Fernández-Méndez, M., Ludwig, A., Arístegui, J., Baumann, M., Ortiz, J., Stühr, A., Riebesell, U., 2022. Nutrient composition (Si:N) as driver of plankton communities during artificial upwelling. *Frontiers in Marine Science* 9. doi:10.3389/fmars.2022.1015188.
- Gray, D.D., Giorgini, A., 1976. The validity of the Boussinesq approximation for liquids and gases. *International Journal of Heat and Mass Transfer* 19, 545–551. doi:10.1016/0017-9310(76)90168-x.
- Greenshields, C., 2018. What is sustainable OpenFOAM development? [conference presentation], in: *OpenFOAM Open Day 2018*. URL: <https://youtu.be/QQf0HIGwqa0?feature=shared>. accessed: Jul. 31, 2025.
- Groves, G.W., 1958. Flow estimate for the perpetual salt fountain. *Deep Sea Research (1953)* 5, 209–214. doi:10.1016/0146-6313(58)90013-3.
- Hanjalić, K., 2002. One-point closure models for buoyancy-driven turbulent flows. *Annual Review of Fluid Mechanics* 34, 321–347. doi:10.1146/annurev.fluid.34.082801.161035.
- Heylmun, J., Fadel, M.E., Macpherson, G., Hoehler, J., Openfoam-Com, Luanmingyi, 2023. STFS-TUDa/blastAMR: Load-balanced AMR library release [computer software]. doi:10.5281/ZENODO.8427734.
- Hinman, K.G., 1966. Flow velocity calculations for a "perpetual salt fountain". URL: <http://hdl.handle.net/10945/9520>.
- Huang, L., Li, Y., Benites-Munoz, D., Windt, C.W., Feichtner, A., Tavakoli, S., Davidson, J., Paredes, R., Quintana, T., Ransley, E., Colombo, M., Li, M., Cardiff, P., Tabor, G., 2022. A review on the modelling of wave-structure interactions based on OpenFOAM. *OpenFOAM® Journal* 2, 116–142. doi:10.51560/ofj.v2.65.
- Huerta, A., Liu, W.K., 1988. Viscous flow with large free surface motion. *Computer Methods in Applied Mechanics and Engineering* 69, 277–324. doi:10.1016/0045-7825(88)90044-8.
- Huq, P., 1997. Observations of jets in density stratified crossflows. *Atmospheric Environment* 31, 2011–2022. doi:10.1016/s1352-2310(97)00281-1.
- International Tribunal for the Law of the Sea, 2024. Advisory Opinion: Request for an Advisory Opinion submitted by the Commission of Small Island States on Climate Change and International Law (Case No. 31). Technical Report. International Tribunal for the Law of the Sea. URL: https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_orig.pdf. accessed: Sept. 23, 2025.

- IOC, SCOR, IAPSO, 2010. The international thermodynamic equation of seawater - 2010: Calculation and use of thermodynamic properties. Intergovernmental Oceanographic Commission, Manuals and Guides 56.
- IPCC, 2018. Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., Zhai, P., Pörtner H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., and Waterfield, T. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157896.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B., (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/9781009157896.
- IPCC, 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Lee, H. and Romero, J. (eds.)]. IPCC, Geneva, Switzerland. doi:10.59327/ipcc/ar6-9789291691647.
- Isaacs, J.D., Castel, D., Wick, G.L., 1976. Utilization of the energy in ocean waves. *Ocean Engineering* 3, 175–187. doi:10.1016/0029-8018(76)90022-6.
- Issa, R., 1986. Solution of the implicitly discretised fluid flow equations by operator-splitting. *Journal of Computational Physics* 62, 40–65. doi:10.1016/0021-9991(86)90099-9.
- Jacobsen, N.G., Fuhrman, D.R., Fredsøe, J., 2011. A wave generation toolbox for the open-source CFD library: OpenFoam®. *International Journal for Numerical Methods in Fluids* 70, 1073–1088. doi:10.1002/flid.2726.
- Jamieson, D., Tudhope, J., 1970. Physical properties of sea water solutions: Thermal conductivity. *Desalination* 8, 393–401. doi:10.1016/S0011-9164(00)80240-4.
- Jasak, H., 1996. Error Analysis and Estimation for the Finite Volume Method With Applications to Fluid Flows. Ph.D. thesis. Imperial College London.
- Jirka, G.H., 2004. Integral model for turbulent buoyant jets in unbounded stratified flows. part I: Single round jet. *Environmental Fluid Mechanics* 4, 1–56. doi:10.1023/a:1025583110842.
- Johnson, D.H., Decicco, J., 1983. Artificial upwelling driven by salinity differences in the ocean. Technical Report. Solar Energy Research Inst., Golden, CO (USA).
- Jürchott, M., Koeve, W., Oschlies, A., 2024. The response of the ocean carbon cycle to artificial upwelling, ocean iron fertilization and the combination of both. *Environmental Research Letters* 19, 114088. doi:10.1088/1748-9326/ad858d.
- Jürchott, M., Oschlies, A., Koeve, W., 2023. Artificial upwelling—a refined narrative. *Geophysical Research Letters* 50. doi:10.1029/2022gl1101870.
- Jürchott, M., Oschlies, A., Mengis, N., Frenger, I., Koeve, W., 2025. Direct cooling effect of artificial upwelling dominates over its marine carbon dioxide removal potential. *Environmental Research Letters* doi:10.1088/1748-9326/ae0054.

- Kanarska, Y., Shchepetkin, A., McWilliams, J., 2007. Algorithm for non-hydrostatic dynamics in the regional oceanic modeling system. *Ocean Modelling* 18, 143–174. doi:10.1016/j.ocemod.2007.04.001.
- Kays, W.M., Crawford, M.E., 1993. Convective heat and mass transfer. McGraw-Hill series in mechanical engineering. third edition. ed., McGraw-Hill, New York.
- Keller, D.P., Feng, E.Y., Oschlies, A., 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications* 5. doi:10.1038/ncomms4304.
- Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025. Performance prediction for stommel’s perpetual salt fountain in the context of artificial ocean upwelling. [Preprint] Accepted for publication by Applied Ocean Research doi:10.5281/zenodo.14779759.
- Kenjereš, S., Gunarjo, S., Hanjalić, K., 2005. Contribution to elliptic relaxation modelling of turbulent natural and mixed convection. *International Journal of Heat and Fluid Flow* 26, 569–586. doi:10.1016/j.ijheatfluidflow.2005.03.007.
- Kenjereš, S., Hanjalić, K., 2000. Convective rolls and heat transfer in finite-length Rayleigh-Bénard convection: A two-dimensional numerical study. *Physical Review E* 62, 7987–7998. doi:10.1103/physreve.62.7987.
- Kheirkhah Gildeh, H., Mohammadian, A., Nistor, I., 2021. Inclined dense effluent discharge modelling in shallow waters. *Environmental Fluid Mechanics* 21, 955–987. doi:10.1007/s10652-021-09805-6.
- Kimball, C., Swift, M.R., Wosnik, M., 2025. Wave-powered water pump for upwelling in aquaculture: Numerical model and ocean test. *Renewable Energy* 239, 122040. doi:10.1016/j.renene.2024.122040.
- Kirke, B., 2003. Enhancing fish stocks with wave-powered artificial upwelling. *Ocean & Coastal Management* 46, 901–915. doi:10.1016/s0964-5691(03)00067-x.
- Kithil, P.W., 2006. A device to control sea surface temperature and effects on hurricane intensity, in: *Proceedings of the 27th Conference on Hurricanes and Tropical Meteorology*, Monterey, california, USA.
- Kogawa, T., Maruyama, S., Behnia, M., Chisaki, M., Okajima, J., Komiya, A., 2013. Large eddy simulation of the diffusion process of nutrient-rich up-welled seawater. *Frontiers in Heat and Mass Transfer* 4. doi:10.5098/hmt.v4.2.3002.
- Kowek, D.A., 2022. Expected limits on the potential for carbon dioxide removal from artificial upwelling. *Frontiers in Marine Science* 9. doi:10.3389/fmars.2022.841894.
- Kwiatkowski, L., Ricke, K.L., Caldeira, K., 2015. Atmospheric consequences of disruption of the ocean thermocline. *Environmental Research Letters* 10, 034016. doi:10.1088/1748-9326/10/3/034016.
- Lai, Z., Chen, C., Cowles, G.W., Beardsley, R.C., 2010. A nonhydrostatic version of FV-COM: 1. validation experiments. *Journal of Geophysical Research* 115. doi:10.1029/2009jc005525.
- Lam, W., Chan, L., Hasini, H., Ooi, A., 2018. An analysis of two-dimensional stratified gravity current flow using OpenFOAM. *International Journal of Engineering & Technology* 7, 589–595. doi:10.14419/ijet.v7i4.35.22919.
- Launder, B., Spalding, D., 1974. The numerical computation of turbulent flows. *Computer Methods in Applied Mechanics and Engineering* 3, 269–289. doi:10.1016/0045-7825(74)90029-2.

- Launder, B.E., 2005. RANS modelling of turbulent flows affected by buoyancy or stratification, in: Hewitt, G., Vassilicos, C. (Eds.), *Prediction of Turbulent Flows*, Cambridge University Press. pp. 50–127. doi:10.1017/cbo9780511543227.003.
- Liang, N.K., Peng, H.K., 2005. A study of air-lift artificial upwelling. *Ocean Engineering* 32, 731–745. doi:10.1016/j.oceaneng.2004.10.011.
- Lin, T., Fan, W., Xiao, C., Yao, Z., Zhang, Z., Zhao, R., Pan, Y., Chen, Y., 2019. Energy management and operational planning of an ecological engineering for carbon sequestration in coastal mariculture environments in china. *Sustainability* 11, 3162. doi:10.3390/su11113162.
- Liu, C., Sou, I., Lin, H., 2003. Artificial upwelling and near-field mixing of deep-ocean water effluent. *Journal of Marine Environmental Engineering* 7, 1–14.
- Liu, C.C., Jin, Q., 1995. Artificial upwelling in regular and random waves. *Ocean Engineering* 22, 337–350. doi:10.1016/0029-8018(94)00019-4.
- Liu, C.C.K., 1999. Research on artificial upwelling and mixing at the university of Hawaii at Manoa. IOA Newsletter URL: <https://argonauts.club/research-on-artificial-upwelling.html>.
- Lovelock, J.E., Rapley, C.G., 2007. Ocean pipes could help the earth to cure itself. *Nature* 449, 403–403. doi:10.1038/449403a.
- Marshall, J., Adcroft, A., Hill, C., Perelman, L., Heisey, C., 1997. A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. *Journal of Geophysical Research: Oceans* 102, 5753–5766. doi:10.1029/96jc02775.
- Maruyama, S., Tsubaki, K., Taira, K., Sakai, S., 2004. Artificial upwelling of deep seawater using the perpetual salt fountain for cultivation of ocean desert. *Journal of Oceanography* 60, 563–568. doi:10.1023/b:joce.0000038349.56399.09.
- McClimans, T., Handå, A., Fredheim, A., Lien, E., Reitan, K., 2010. Controlled artificial upwelling in a fjord to stimulate non-toxic algae. *Aquacultural Engineering* 42, 140–147. doi:10.1016/j.aquaeng.2010.02.002.
- McDougall, T.J., 2003. Potential enthalpy: A conservative oceanic variable for evaluating heat content and heat fluxes. *Journal of Physical Oceanography* 33, 945–963. doi:10.1175/1520-0485(2003)033<0945:peacov>2.0.co;2.
- McDougall, T.J., Jackett, D.R., Wright, D.G., Feistel, R., 2003. Accurate and computationally efficient algorithms for potential temperature and density of seawater. *Journal of Atmospheric and Oceanic Technology* 20, 730–741. doi:10.1175/1520-0426(2003)20<730:aaceaf>2.0.co;2.
- Meng, Q., Wang, C., Chen, Y., Chen, J., 2013. A simplified CFD model for air-lift artificial upwelling. *Ocean Engineering* 72, 267–276. doi:10.1016/j.oceaneng.2013.07.006.
- Menter, F., Kuntz, M., Langtry, R.B., 2003. Ten years of industrial experience with the SST turbulence model. *Heat and Mass Transfer* 4.
- Menter, F.R., 1994. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA Journal* 32, 1598–1605. doi:10.2514/3.12149.
- Mirajkar, H., Balasubramanian, S., 2016. Dynamics of a buoyant plume in a linearly stratified environment using simultaneous PIV-PLIF measurements, in: *Proceedings of the VIIIth Int. Symposium on Stratified Flows*, San Diego, USA.
- Moukalled, F., Mangani, L., Darwish, M., 2016. *The Finite Volume Method in Computational Fluid Dynamics*. Springer International Publishing. doi:10.1007/978-3-319-16874-6.

- OpenCFD Ltd., 2021. OpenFOAM: User Guide v2112, Hydrostatic pressure effects, [Online]. URL: <https://www.openfoam.com/documentation/guides/latest/doc/guide-applications-solvers-variable-transform-p-rgh.html>. accessed: Aug. 8, 2025.
- OpenCFD Ltd., 2023. OpenFOAM: User Guide v2312, Pressure-velocity algorithms, [Online]. URL: <https://doc.openfoam.com/2312/tools/processing/solvers/pressure-velocity/#eqn-solver-pressure>. accessed: Jul. 31, 2025.
- Ortiz, J., Aristegui, J., Goldenberg, S.U., Fernández-Méndez, M., Taucher, J., Archer, S.D., Baumann, M., Riebesell, U., 2024. Phytoplankton physiology and functional traits under artificial upwelling with varying Si:N. *Frontiers in Marine Science* 10. doi:10.3389/fmars.2023.1319875.
- Oschlies, A., Bach, L.T., Fennel, K., Gattuso, J.P., Mengis, N., 2025. Perspectives and challenges of marine carbon dioxide removal. *Frontiers in Climate* 6. doi:10.3389/fclim.2024.1506181.
- Oschlies, A., Pahlow, M., Yool, A., Matear, R.J., 2010. Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters* 37. doi:10.1029/2009gl041961.
- Ouchi, K., 2009. Results from real sea experiment of ocean nutrient enhancer takumi, in: *Proceedings of the ASME 2009 28th International Conference on Ocean, Offshore and Arctic Engineering*. Volume 4: Ocean Engineering; Ocean Renewable Energy; Ocean Space Utilization, Parts A and B, Honolulu, Hawaii, USA. pp. 1473–1480. doi:10.1115/omae2009-79866.
- Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., Jiang, Z., Di, Y., Tong, M., Chen, Y., 2015. Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences* 59, 236–248. doi:10.1007/s11430-015-5195-2.
- Pan, Y., Li, Y., Fan, W., Zhang, D., Qiang, Y., Jiang, Z.P., Chen, Y., 2019. A sea trial of air-lift concept artificial upwelling in the East China Sea. *Journal of Atmospheric and Oceanic Technology* 36, 2191–2204. doi:10.1175/jtech-d-18-0238.1.
- Patankar, S., Spalding, D., 1972. A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows. *International Journal of Heat and Mass Transfer* 15, 1787–1806. doi:10.1016/0017-9310(72)90054-3.
- Reynolds, A., 1975. The prediction of turbulent Prandtl and Schmidt numbers. *International Journal of Heat and Mass Transfer* 18, 1055–1069. doi:10.1016/0017-9310(75)90223-9.
- Ricke, K., Ivanova, D., McKie, T., Rugenstein, M., 2021. Reversing sahelian droughts. *Geophysical Research Letters* 48. doi:10.1029/2021gl093129.
- Rodi, W., 1987. Examples of calculation methods for flow and mixing in stratified fluids. *Journal of Geophysical Research: Oceans* 92, 5305–5328. doi:10.1029/jc092ic05p05305.
- Roels, O.A., Laurence, S., Farmer, M.W., Hemelryck, L.V., 1977. Organic production potential of artificial upwelling marine culture, in: *Microbial Energy Conversion*. Elsevier, pp. 69–81. doi:10.1016/b978-0-08-021791-8.50015-9.
- Rouhnia, M., Strom, K., Liu, X., 2016. Experiments and modeling of density instabilities driven by interface shear and their influence on removal of sediment from buoyant plumes, in: *Proceedings of the International Conference on Fluvial Hydraulics, RIVER FLOW 2016*, St. Louis, USA. pp. 495–502. doi:10.1201/9781315644479-79.
- Scanlon, T., 2018. marinefoam: A computational tool for modelling chemical discharge from marine fish farms, [online]. URL: https://www.mts-cfd.com/_files/ugd/f6b0cc_618c11396fd24a32b5eb205e31b991a9.pdf. accessed: Aug. 25, 2025.

- Schlichting, H., Gersten, K., 1997. Grundzüge der turbulenten strömungen, in: Grenzschicht-Theorie, Springer, Berlin, Heidelberg. pp. 533–555. doi:10.1007/978-3-662-07554-8_16.
- Shams, A., Roelofs, F., Baglietto, E., Lardeau, S., Kenjeres, S., 2014. Assessment and calibration of analgebraic turbulent heat flux model for low-Prandtl fluids. International Journal of Heat and Mass Transfer 79, 589–601. doi:https://doi.org/10.1016/j.ijheatmasstransfer.2014.08.018.
- Sharqawy, M.H., Lienhard V, J.H., Zubair, S.M., 2010. Thermophysical properties of seawater: A review of existing correlations and data. Desalination and Water Treatment 16, 354–380. doi:10.5004/dwt.2010.1079.
- Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modelling 9, 347–404. doi:10.1016/j.ocemod.2004.08.002.
- Soloviev, A.V., 2016. Ocean upwelling system utilizing energy of surface waves, in: Proceedings of the 2016 Techno-Ocean Conference, Kobe, Japan. pp. 221–224. doi:10.1109/techno-ocean.2016.7890650.
- Speziale, C.G., 1987. On nonlinear k-l and k- ϵ models of turbulence. Journal of Fluid Mechanics 178, 459–475. doi:10.1017/s0022112087001319.
- Stommel, H., Arons, A.B., Blanchard, D., 1956. An oceanographical curiosity: the perpetual salt fountain. Deep Sea Research (1953) 3, 152–153. doi:10.1016/0146-6313(56)90095-8.
- Takahashi, M.M., 2000. DOW: Deep Ocean Water As Our Next Natural Resource. translated from japanese by k. kitazawa and p. snowden ed., Terra Scientific Publishing Company, Tokyo.
- Tominaga, Y., Stathopoulos, T., 2007. Turbulent Schmidt numbers for CFD analysis with various types of flowfield. Atmospheric Environment 41, 8091–8099. doi:10.1016/j.atmosenv.2007.06.054.
- Tsubaki, K., Maruyama, S., Komiya, A., Mitsugashira, H., 2007. Continuous measurement of an artificial upwelling of deep sea water induced by the perpetual salt fountain. Deep Sea Research Part I: Oceanographic Research Papers 54, 75–84. doi:10.1016/j.dsr.2006.10.002.
- Tuković, Ž., Jasak, H., 2012. A moving mesh finite volume interface tracking method for surface tension dominated interfacial fluid flow. Computers & Fluids 55, 70–84. doi:10.1016/j.compfluid.2011.11.003.
- Van Maele, K., Merci, B., 2006. Application of two buoyancy-modified – turbulence models to different types of buoyant plumes. Fire Safety Journal 41, 122–138. doi:10.1016/j.firesaf.2005.11.003.
- Viúdez, Á., Balsells, M.F.P., Rodríguez-Marroyo, R., 2016. Artificial upwelling using offshore wind energy for mariculture applications. Scientia Marina 80, 235–248. doi:10.3989/scimar.04297.06b.
- Wang, P., Özgökmen, T.M., 2018. Langmuir circulation with explicit surface waves from moving-mesh modeling. Geophysical Research Letters 45, 216–226. doi:10.1002/2017g1076009.
- Weller, H.G., Tabor, G., Jasak, H., Fureby, C., 1998. A tensorial approach to computational continuum mechanics using object-oriented techniques. Computers in Physics 12, 620–631. doi:10.1063/1.168744.

- White, A., Björkman, K., Grabowski, E., Letelier, R., Poulos, S., Watkins, B., Karl, D., 2010. An open ocean trial of controlled upwelling using wave pump technology. *Journal of Atmospheric and Oceanic Technology* 27, 385–396. doi:10.1175/2009jtecho679.1.
- Williamson, N., Komiya, A., Maruyama, S., Behnia, M., Armfield, S.W., 2009. Nutrient transport from an artificial upwelling of deep sea water. *Journal of Oceanography* 65, 349–359. doi:10.1007/s10872-009-0032-x.
- Windt, C., Davidson, J., Schmitt, P., Ringwood, J.V., 2019. On the assessment of numerical wave makers in CFD simulations. *Journal of Marine Science and Engineering* 7, 47. doi:10.3390/jmse7020047.
- Wu, J., Keller, D.P., Oeschles, A., 2023. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: An earth system modeling study. *Earth System Dynamics* 14, 185–221. doi:10.5194/esd-14-185-2023.
- Xu, D., Chen, J., 2012. Experimental study of stratified jet by simultaneous measurements of velocity and density fields. *Experiments in Fluids* 53, 145–162. doi:10.1007/s00348-012-1275-7.
- Yao, W., Morganti, T.M., Wu, J., Borchers, M., Anschütz, A., Bednarz, L., Bhaumik, A., Böttcher, M., Burkhard, K., Cabus, T., Chua, A.S., Diercks, I., Esposito, M., Fink, M., Fouqueray, M., Gasanzade, F., Geilert, S., Hauck, J., Havermann, F., Hellige, I., Hoog, S., Jürchott, M., Kalapurakkal, H.T., Kemper, J., Kremin, I., Lange, I., Lencina-Avila, J.M., Liadova, M., Liu, F., Mathesius, S., Mehendale, N., Nagwekar, T., Philippi, M., Luz, G.L.N., Ramasamy, M., Stahl, F., Tank, L., Vorrath, M., Westmark, L., Wey, H., Wollnik, R., Wölfelschneider, M., Bach, W., Bischof, K., Boersma, M., Daewel, U., Fernández-Méndez, M., Geuer, J.K., Keller, D.P., Kopf, A., Merk, C., Moosdorf, N., Oppelt, N., Oeschles, A., Pongratz, J., Proelss, A., Rehder, G.J., Rüpke, L., Szarka, N., Thraen, D., Wallmann, K., Mengis, N., 2025. Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment – the 10 mt co2 yr-1 removal challenge for germany. *Earth's Future* 13. doi:10.1029/2024ef004902.
- Yool, A., Shepherd, J.G., Bryden, H.L., Oeschles, A., 2009. Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide. *Journal of Geophysical Research: Oceans* 114. doi:10.1029/2008jc004792.
- Young, W.R., 2010. Dynamic enthalpy, conservative temperature, and the seawater Boussinesq approximation. *Journal of Physical Oceanography* 40, 394–400. doi:10.1175/2009jpo4294.1.
- Younis, B.A., Jooß, Y., Spring, S., Weigand, B., 2018. Accounting for the effects of buoyancy on the turbulent scalar fluxes. *Environmental Fluid Mechanics* 19, 495–512. doi:10.1007/s10652-018-9635-3.
- Zhang, J., Hong, K., Yuan, Y., Lin, Y.T., Han, D., 2024. The role of quantified parameters on river plume structure: Numerical simulation. *Journal of Marine Science and Engineering* 12, 321. doi:10.3390/jmse12020321.
- Zhang, X., Maruyama, S., Sakai, S., Tsubaki, K., Behnia, M., 2004. Flow prediction in upwelling deep seawater—the perpetual salt fountain. *Deep Sea Research Part I: Oceanographic Research Papers* 51, 1145–1157. doi:10.1016/j.dsr.2004.03.010.
- Zhou, S., Fan, W., Yao, Z., Qiang, Y., Pan, Y., Chen, Y., 2019. Experimental study on the performance of a wave pump for artificial upwelling in irregular waves. *Ocean Engineering* 189, 106353. doi:10.1016/j.oceaneng.2019.106353.

Appendix

Contribution [JPA]

Numerical Flow Modeling of Artificial Ocean Upwelling

Citation:

Kemper, J., Riebesell, U., Graf, K., 2022. Numerical flow modeling of artificial ocean upwelling. *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.804875.

Author contributions:

Conceptualization	J. Kemper
Methodology	J. Kemper
Software	J. Kemper
Validation	U. Riebesell, K. Graf
Investigation	J. Kemper
Resources	U. Riebesell, K. Graf
Writing - Original Draft	J. Kemper
Writing - Review & Editing	U. Riebesell, K. Graf
Visualization	J. Kemper
Supervision	U. Riebesell, K. Graf
Project administration	U. Riebesell, K. Graf
Funding acquisition	U. Riebesell, K. Graf

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.





Numerical Flow Modeling of Artificial Ocean Upwelling

Jost Kemper^{1*}, Ulf Riebesell² and Kai Graf¹

¹ Naval Architecture and Maritime Technology, Faculty of Mechanical Engineering, University of Applied Sciences, Kiel, Germany, ² Marine Biogeochemistry, Biological Oceanography, GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

OPEN ACCESS

Edited by:

Eugen Victor Cristian Rusu,
Dunarea de Jos University, Romania

Reviewed by:

Haocai Huang,
Zhejiang University, China
Weiwen Zhao,
Shanghai Jiao Tong University, China

*Correspondence:

Jost Kemper
jost.kemper@fh-kiel.de

Specialty section:

This article was submitted to
Ocean Solutions,
a section of the journal
Frontiers in Marine Science

Received: 29 October 2021

Accepted: 29 November 2021

Published: 03 January 2022

Citation:

Kemper J, Riebesell U and Graf K
(2022) Numerical Flow Modeling of
Artificial Ocean Upwelling.
Front. Mar. Sci. 8:804875.
doi: 10.3389/fmars.2021.804875

Artificial Upwelling (AU) of nutrient-rich Deep Ocean Water (DOW) to the ocean's sunlit surface layer has recently been put forward as a means of increasing marine CO₂ sequestration and fish production. AU and its possible benefits have been studied in the context of climate change mitigation as well as food security for a growing human population. However, extensive research still needs to be done into the feasibility, effectiveness and potential risks, and side effects associated with AU to be able to better predict its potential. Fluid dynamic modeling of the AU process and the corresponding inorganic nutrient transport can provide necessary information for a better quantification of the environmental impacts of specific AU devices and represents a valuable tool for their optimization. Yet, appropriate capture of all flow phenomena relevant to the AU process remains a challenging task that only few models are able to accomplish. In this paper, simulation results obtained with a newly developed numerical solution method are presented. The method is based on the open-source modeling environment *OpenFOAM*. It solves the unsteady Reynolds-Averaged Navier-Stokes (RANS) equations with additional transport equations for energy, salinity, and inorganic nutrients. The method aims to be widely applicable to oceanic flow problems including temperature- and salinity-induced density stratification and passive scalar transport. The studies presented in this paper concentrate on the direct effects of the AU process on nutrient spread and concentration in the ocean's mixed surface layer. Expected flow phenomena are found to be captured well by the new method. While it is a known problem that cold DOW that is upwelled to the surface tends to sink down again due to its high density, the simulations presented in this paper show that the upwelled DOW settles at the lower boundary of the oceans mixed surface layer, thus keeping a considerable portion of the upwelled nutrients available for primary production. Comparative studies of several design variants, with the aim of maximizing the amount of nutrients that is retained inside the mixed surface layer, are also presented and analyzed.

Keywords: artificial upwelling, computational fluid dynamics (CFD), RANS, *OpenFOAM*, oceanic flow, scalar transport, buoyancy-affected flow, stratified flow

1. INTRODUCTION

In view of a continuing growth in human population, compliance with planetary boundaries is increasingly becoming the central challenge of our time. Past human resource consumption has led to a state, where marine fish stocks are largely overexploited (FAO, 2018) and mere reduction of greenhouse gas emissions is no longer sufficient to meet international climate goals (Lawrence et al., 2018). In the search for ways to mitigate these consequences of resource overconsumption, Artificial Upwelling (AU) of nutrient-rich Deep Ocean Water (DOW) to the ocean's sunlit surface layer has recently been proposed (Kirke, 2003; Lovelock and Rapley, 2007).

By bringing DOW to the ocean's surface, AU aims to replicate processes that occur in natural upwelling systems. Here, the supply of inorganic nutrients stimulates a high primary production, thereby providing the basis for highly efficient food chains, which make natural upwelling systems some of the world's richest fishing grounds (Roels et al., 1977). So far, it has not been shown whether AU can effectively replicate important features of natural upwelling systems. Nevertheless, AU is seen as a possible way of increasing fishery yields in less productive oceanic regions. As such, AU could promote food security for a growing human population (Kirke, 2003) and reduce pressure on natural fish stocks. Further, it has been pointed out that an increased primary production induced by AU could act as a driver for the biologic carbon pump, a process that naturally extracts CO₂ from the atmosphere (Lovelock and Rapley, 2007). This has led to a discussion on whether AU can contribute to future climate change mitigation efforts (Lovelock and Rapley, 2007; Oschlies et al., 2010; Williamson et al., 2012; Bauman et al., 2014; Pan et al., 2015; GESAMP, 2019). Despite its potential, a wide range of ecological responses and biogeochemical consequences of AU remain largely unstudied to date. Responsible use of AU on a large scale demands thorough understanding and accurate quantification of all environmental and ecological impacts associated with this process.

Numerical modeling of the involved fluid dynamic processes plays an important role in this context. Numerical models provide information for the technical design and optimization of AU systems. Additionally, the detailed information on the associated spread and concentration levels of nutrient-rich DOW can be used as a basis for biological model calculations and thus contribute to the quantification of environmental and ecological impacts of specific AU devices. Numerical methods based on the Reynolds-Averaged Navier-Stokes (RANS) equations are capable of accurately predicting both small-scale flow phenomena inside the AU device and large-scale far-field phenomena. They thus represent a valuable tool for assessing the AU processes with high accuracy.

A number of hydrodynamic studies on AU are reported in literature. Several publications deal with artificial upwelling by utilizing the energy of ocean waves. A first overview of the topic was given by Kirke (2003). Beyond pointing out the potential of the use of DOW for increasing fish stocks, Kirke also mentions the problem that the cold DOW, when artificially upwelled, generally tends to sink back down due to its high density and thus

does not remain available for primary production. Liu and Jin (1995) apply a simple mathematical model to calculate upwelling volumes of a wave-driven device. They find that a flow rate of 0.95 [m³/s] could be obtained with their device in a typical sea state off the Hawaiian islands. Similar calculations are presented by Soloviev (2016), who additionally applied a numerical model that is not specified in detail. Both of these studies do not model nutrient transport.

The *air lift* method proposed by Liang and Peng (2005) has also been studied. Here, artificial upwelling is achieved by pumping air into the ocean at a certain depth. Thereby a flow of air bubbles is created which transports DOW to the surface. A RANS-based numerical model for this type of upwelling was presented by Meng et al. (2013). Here, it is found that the applied, simplified model was able to accurately predict the dispersed flow and achieve a satisfactory agreement with experimental data. Some authors have reported results of sea trials with air lift AU systems (Fan et al., 2013; Pan et al., 2019).

Other publications deal with a device referred to as *perpetual salt fountain*, which was initially proposed by Stommel et al. (1956). Here, the opposing effect which a decrease in temperature and salinity with depth (i.e., a typical open ocean depth profile) has on water density are used to drive a self-sustaining upwelling process in a long ocean pipe. Once the pipe is filled with DOW, temperature differences between the pipe- and surrounding water diminish over time while salinity differences remain and account for a positive buoyancy of the DOW in the pipe. Results of sea trials with this device are reported in Maruyama et al. (2004) and Tsubaki et al. (2007). Maruyama et al. (2004) also apply a RANS-based numerical model to predict the flow inside their device. However, they do not apply any turbulence model but use turbulent diffusion data from their experiment in the calculations. Williamson et al. (2009) extend this work to studies of near-field mixing in crossflow at the device outlet, using a commercial RANS code. Williamson et al. find that the flow can be characterized into a region with high turbulent diffusion local to the pipe outlet and a second region further downstream with very little diffusion. They further point out the problem of turbulence anisotropy in buoyancy-affected flows, which also plays a role in the present paper. Finally, Williamson et al. find that, given the small observed diffusion, the outlet depth of their device is too large for the pumped DOW to be mixed into the ocean's surface layer.

Fan et al. (2015) propose a simple mathematical model for the optimization of forced upwelling in a pipe. To maintain high nutrient concentrations for mariculture inside a confined DOW plume, Fan et al. aim to minimize dilution of the plume. They find that the plume trajectory and the DOW concentration inside the plume are highly dependent on several technical parameters, like flow rate, pipe diameter, and outlet depth as well as environmental influences, like current speed and stratification strength. A validation of their mathematical model against steady-state RANS CFD data is also provided in Fan et al. (2015) along with some validation of the CFD model.

The present paper reports of AU simulations with a new RANS solution method. The development of the new method is based on Computational Fluid Dynamics (CFD) methods

available within the open-source framework *OpenFOAM*, namely the *buoyantPimpleFoam* solver and the thermophysical and turbulence modeling libraries. A transport equation for salinity is added to the *buoyantPimpleFoam* solver, the thermophysical modeling library is extended to correctly reproduce the physical properties of seawater, and a simple modification is introduced into the *k- ω SST* turbulence model to better capture turbulence effects for buoyancy-affected flows. Thus, a numerical method for small-scale oceanic flow is created which, due to its open-source basis, allows for flexible adjustment and extension to specific modeling problems, like AU. For the simulations presented in this paper the method is further extended with a transport equation for nutrient concentration, which enables a direct quantification of the nutrient transport introduced by the AU device.

The remainder of this paper is structured as follows. First, the applied method and the underlying equations will be described. Then, the results of some studies carried out with the new method will be presented and discussed. Finally, conclusions from the presented work will be drawn before finishing with recommendations for necessary future extensions.

2. NUMERICAL METHOD

The method presented in this paper solves the RANS modeling problem for buoyancy-affected oceanic flow. The mathematical model and its numerical solution will be outlined briefly in this section.

At present, the method incorporates a single-phase (i.e., water) only and does not model influences of deformation of the water surface. This approach was chosen because early studies indicated that the influences of the water surface on the general flow were very small, while accurate modeling of free surface motion would have been associated with high computational cost. Also, this approach enabled a more direct control over the heat transfer processes at the surface than a multiphase simulation using the volume of fluid method.

2.1. Momentum and Mass Equations

A flow of a Newtonian fluid in an Eulerian reference frame is considered. To account for density fluctuations, Favre averaging is used instead of the more common Reynolds averaging. In the following, Favre-averaged quantities are marked by an overtilde, while Reynolds averaging is indicated by an overscore. The conservation equations for momentum and mass, in their conservative form, can thus be written as

$$\frac{\partial (\tilde{\rho} \tilde{\mathbf{u}})}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{\mathbf{u}} \tilde{\mathbf{u}}) = \nabla \cdot \left(2\mu_e \tilde{\mathbf{S}} - \frac{2}{3} \mu_e (\nabla \cdot \tilde{\mathbf{u}}) \mathbf{I} \right) - \frac{2}{3} \nabla (\tilde{\rho} k) - \nabla \bar{p} + \bar{\rho} \mathbf{g} \quad (1)$$

and

$$\frac{\partial \bar{\rho}}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{\mathbf{u}}) = 0. \quad (2)$$

In Equations (1) and (2), $\tilde{\mathbf{u}}$ is the Favre-averaged velocity, $\bar{p}$ is Reynolds-averaged pressure and $\bar{\rho}$, μ_e and $\mathbf{g}$ are

Reynolds-averaged density, effective dynamic viscosity and the gravitational acceleration vector, respectively. The tensor $\mathbf{I}$ represents the unit matrix, and $\tilde{\mathbf{S}}$ is the mean strain rate tensor, which is defined as

$$\tilde{\mathbf{S}} = \frac{1}{2} (\nabla \tilde{\mathbf{u}} + (\nabla \tilde{\mathbf{u}})^T). \quad (3)$$

Boussinesq's linear eddy viscosity theory is applied in Equation (1) to model the effect of turbulence. The effective dynamic viscosity consist of the molecular and eddy viscosities as follows

$$\mu_e = \mu + \mu_t. \quad (4)$$

The eddy viscosity μ_t and the turbulent kinetic energy k have to be modeled by turbulence closure models as discussed in section 2.4. For convenience, a modified pressure $\bar{p}^* = \bar{p} + \frac{2}{3} \bar{\rho} k$ is introduced. Also, in Equation (1) the main hydrostatic impact is subtracted from $\bar{p}^*$ yielding

$$\bar{p}_{rgh}^* = \bar{p}^* - \bar{\rho} \mathbf{g} \cdot \mathbf{r}, \quad (5)$$

where $\mathbf{r}$ is the position vector with respect to a reference position. The pressure and buoyancy terms in Equation (1) can then be restructured as follows

$$-\nabla \bar{p}^* + \bar{\rho} \mathbf{g} = -\nabla \bar{p}_{rgh}^* - (\mathbf{g} \cdot \mathbf{r}) \nabla \bar{\rho}. \quad (6)$$

With these changes, the implemented momentum equation reads

$$\frac{\partial (\tilde{\rho} \tilde{\mathbf{u}})}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{\mathbf{u}} \tilde{\mathbf{u}}) = \nabla \cdot \left(2\mu_e \tilde{\mathbf{S}} - \frac{2}{3} \mu_e (\nabla \cdot \tilde{\mathbf{u}}) \mathbf{I} \right) - \nabla \bar{p}_{rgh}^* - (\mathbf{g} \cdot \mathbf{r}) \nabla \bar{\rho}. \quad (7)$$

2.2. Energy Equation

A conservation equation for energy needs to be solved to account for buoyancy effects. Here, potential enthalpy, i.e., the enthalpy that a parcel of water would have if adiabatically and without salt exchange raised to the sea surface, is used as energy variable. As pointed out by McDougall (2003), a simple conservation equation for potential enthalpy is, to a high degree of accuracy, equivalent to the first law of thermodynamics in the ocean. The conservation equation for potential enthalpy per unit mass h reads

$$\frac{\partial (\tilde{\rho} \tilde{h})}{\partial t} + \nabla \cdot (\tilde{\rho} \tilde{\mathbf{u}} \tilde{h}) = \nabla \cdot (\alpha_e \nabla \tilde{h}). \quad (8)$$

Here, α_e is the effective thermal diffusivity

$$\alpha_e = \frac{\mu_t}{Pr_t} + \frac{\mu}{Pr} = \frac{\mu_t}{Pr_t} + \frac{\kappa}{c_p}. \quad (9)$$

As for the momentum equation, the turbulent fluctuations are modeled as additional diffusion by applying the gradient diffusion hypothesis. In Equation (9) κ is thermal conductivity, c_p is specific heat capacity and Pr and Pr_t are Prandtl number and turbulent Prandtl number, respectively. Throughout this study a value of 1 was used for Pr_t . For c_p a constant value of 3991.867 957 119 63 [J/kgK] was used, as suggested by IOC et al. (2010). κ is calculated from the thermophysical model (see section 2.4).

2.3. Scalar Transport Equation

Scalar transport equations have to be solved for salinity and nutrient concentration. By again applying the gradient diffusion hypothesis, the conservation equation for these quantities reads

$$\frac{\partial (\bar{\rho} \tilde{\phi})}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{u} \tilde{\phi}) = \nabla \cdot (\bar{\rho} D_e \nabla \tilde{\phi}), \quad (10)$$

where $\tilde{\phi}$ is salinity or nutrient concentration. The effective diffusion coefficient D_e is defined as

$$D_e = \frac{\mu_t}{\bar{\rho} S n_t} + D, \quad (11)$$

where D is the molecular diffusivity in [m^2/s] and $S n_t$ is the turbulent Schmidt number. For $S n_t$, a value of 1 was used throughout this study. D was set to 1×10^{-9} [m^2/s] for both, salinity and nutrients. This represents a typical value for mass diffusion in water (see e.g., Zhang et al., 2004; Thorpe, 2007).

2.4. Thermophysical Model for Seawater

The flow behavior of any fluid is tightly coupled to its physical properties, which in turn depend on the state of the fluid and its composition. In the *OpenFOAM* framework this relation is replicated by a thermophysical model. In its standard version, the thermophysical model calculates fluid properties based on pressure and temperature. This functionality was extended here, to include the influence of salinity. For the present study, the modeled fluid properties are:

- Viscosity μ
- Thermal conductivity κ
- Density ρ .

To model ρ based on temperature, salinity, and pressure, the 75-term polynomial of McDougall et al. (2003) was used. This is part of the widely used *TEOS-10* (IOC et al., 2010) standard. By including pressure dependence in the calculation, the full compressibility is captured in the system of equations. Since the time steps for the applications considered here are small (about 1×10^{-1} [s]), acoustic modes do not need to be filtered from the system, as often done in ocean models (Griffies and Adcroft, 2008). For μ and κ , the pressure-independent polynomials of Sharqawy et al. (2010) and Nayar et al. (2016) were implemented.

2.5. Turbulence Model for Buoyancy-Affected Flow

In Equations (7), (8), and (10) the turbulent fluxes are expressed in terms of the turbulent viscosity μ_t , by means of the eddy viscosity and gradient diffusion hypotheses. Eddy viscosity turbulence models are concerned with determining μ_t . This is usually achieved by solving one or more transport equations for different turbulence variables. Numerous approaches have been presented in the past, of which the standard $k-\epsilon$ model (Launder and Spalding, 1974) and the $k-\omega$ SST model (Menter, 1994) are the ones most widely used for industrial applications. For the present study, the $k-\omega$ SST model was chosen with a simple modification. This model is known to provide a more realistic approximation of the turbulence level in stagnation

regions. Within this study, it also proved preferable for cases where a jet of DOW meets the water surface. The $k-\omega$ SST model and its application for buoyancy-affected flow will be presented here briefly.

The $k-\omega$ SST model describes μ_t as a function of turbulent kinetic energy k and its specific dissipation rate ω . The transport equations for these two quantities, as implemented in *OpenFOAM*, read

$$\begin{aligned} \frac{\partial \bar{\rho} k}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{u} k) - \nabla \cdot ((\mu + \sigma_k \mu_t) \nabla k) \\ = P_k - \bar{\rho} \beta^* k \omega \end{aligned} \quad (12)$$

and

$$\begin{aligned} \frac{\partial \bar{\rho} \omega}{\partial t} + \nabla \cdot (\bar{\rho} \tilde{u} \omega) - \nabla \cdot ((\mu + \sigma_\omega \mu_t) \nabla \omega) \\ = \bar{\rho} \gamma \frac{P_k}{\mu_t} - \bar{\rho} \beta \omega^2 + 2(1 - F_1) \bar{\rho} \frac{\sigma_\omega}{\omega} (\nabla k \cdot \nabla \omega). \end{aligned} \quad (13)$$

Here, P_k is the shear production term, β^* is a model constant, and σ_k , σ_ω , β and γ are blended between values reproducing $k-\omega$ (Wilcox, 1988) (subscript 1) and $k-\epsilon$ (Launder and Spalding, 1974) (subscript 2) model behavior, using the wall distance dependent blending factor F_1 . The turbulent dynamic viscosity is calculated by

$$\mu_t = \frac{\bar{\rho} a_1 k}{\max(a_1 \omega, \sqrt{S_2} F_2)}, \quad (14)$$

where a_1 is a model constant, $\sqrt{S_2}$ is the vorticity magnitude and F_2 is an additional blending function based on the wall distance.

Within the present study a considerable overprediction of vertical diffusion was observed for the standard *OpenFOAM* implementation of the $k-\omega$ SST model. This problem can be accounted to the inadequate representation of buoyancy effects on turbulence and is often treated by adding additional terms to Equations (12) and (13) (Van Maele and Merci, 2006). A simple approach was recently presented by Devolder et al. (2017) following the work of Van Maele and Merci (2006). This approach was adopted for the present work. The formulation of the buoyancy term, which is added to Equation (12), reads

$$- \frac{\mu_t}{\bar{\rho} S n_t} \mathbf{g} \cdot (\nabla \bar{\rho}). \quad (15)$$

Here, the turbulent Schmidt number $S n_t$ is set to 0.85, to be in line with Van Maele and Merci (2006) and Devolder et al. (2017).

As stated by Van Maele and Merci (2006), the simple approach implemented here cannot be expected to provide a fully realistic capture of turbulence effects in buoyancy-affected flow. Namely, an overprediction of vertical turbulent diffusion in stably stratified flow must still be expected as shown by several authors (Stankov et al., 2001; Worthy et al., 2001; Van Maele and Merci, 2006). However, the implemented approach was seen to provide a much-needed improvement over the standard *OpenFOAM* implementation of the $k-\omega$ SST model. Since the implementation of a more sophisticated buoyancy treatment method was outside the scope of this study, the shortcomings of the present approach were accepted.

2.6. Solution Method

The set of equations described above has to be solved by a numerical solution method. To do so, the partial differential equations have to be approximated by algebraic equations at a finite number of locations in space and time. The flow domain (i.e., the fluid volume for which the equations are to be solved) is discretized by a large number of small volumes (cells) and the equations are solved for each of these volumes. Using Gauss's theorem, the divergence in the conservation equations can be calculated by considering the flux across the boundaries of each volume. This discretization method is known as the finite volume method. By further applying suitable discretization methods for the remaining differentials and integrals, a system of algebraic equations, containing the contributions from all cells, is created for each of the governing equations. These algebraic systems of equations are still both coupled and non-linear. For example, the momentum (Equation 7) contains the unknown eddy viscosity, pressure, and density. By taking these values from a previous solution (e.g., a previous iteration or a previous time step) and treating non-linearities in a similar manner, the coupled system of non-linear equations can be solved by iteratively solving linear systems of equations until the difference between the current and previous solution becomes small, and with it the error of the previously explained approximation.

Here, *OpenFOAMs* PIMPLE algorithm is employed for the iterative solution process. The PIMPLE algorithm represents a combination of the well-known SIMPLE (Patankar and Spalding, 1972) and PISO (Issa, 1986) algorithms. A pressure equation is formulated based on the continuity equation (Equation 2)¹. Including the necessary additional equations for salinity and nutrients, the implemented PIMPLE algorithm can be summarized by the following steps:

- | | | |
|--|---|----------------|
| 1. Solve momentum equation | } | PIMPLE
loop |
| 2. Solve salinity equation | | |
| 3. Solve potential enthalpy equation | | |
| 4. Calculate density based on new salinity and temperature | | |
| 5. Solve pressure equation | } | PISO
loop |
| 6. Correct velocity and density based on new pressure | | |
| 7. Solve turbulence equations | | |
| 8. Solve nutrient transport equation | | |
| 9. Advance to next time step. | | |

The steps of the PIMPLE loop (1–6) are repeated for a set number of times, or until a converged solution for the time step is reached. Also, one or two additional PISO loops (Steps 5 and 6) are usually included.

The following schemes are used for the discretization of the equation system. Linear interpolation is used to obtain cell face values from the cell centered data. Likewise, all gradients occurring in the equations are calculated by linear interpolation. For the divergence terms, the *limitedLinear* scheme is applied, which generally uses linear interpolation but limits toward

¹The derivation of the pressure equation is not discussed here for brevity. For more information please refer to standard literature (e.g., Ferziger et al., 2020).

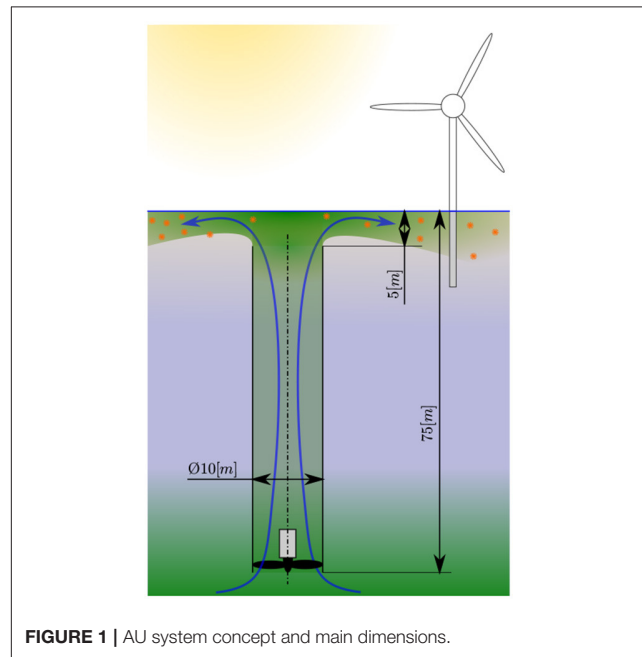


FIGURE 1 | AU system concept and main dimensions.

upwind interpolation in regions with strong gradient changes. For the temporal derivative, the second-order *backward* scheme is used for all equations except for the nutrient and salinity transport equations, where the implicit *Euler* scheme is used to ensure boundedness.

3. RESULTS

3.1. AU Application

The simulations presented in this paper concentrate on forced upwelling in a pipe, powered by a large propeller at the pipe inlet. Prior to the present project, the main dimensions of a prototype system had been optimized in a dedicated study. It was found that a large-diameter pipe in combination with a single propeller ensures a maximum energy efficiency of the system. A diameter of 10 [m] was recommended as a compromise between efficiency and technical feasibility. The prototype simulated in this paper is designed for field studies in the center of the Guinea Dome region, close to 10°N, 22°W. In this region, with a water depth of 4,000–5,000 [m], nutrient-rich DOW naturally rises to depths above 100 [m]. A depth of 75 [m] is thus sufficient for the DOW inlet of this specific device. The device is intended to be deployed free-floating and powered by a renewable energy source, providing 500 [kW] of electric power. The estimated volume flow rate is 155 [m³/s]. Since the pipe will be made from an elastic material, a positive pressure inside the pipe is desirable to prevent it from collapsing. Thus, the propeller is installed at the device inlet. A schematic of the device is shown in **Figure 1** along with its main dimensions. With larger inlet depths the same type of device can be deployed in other ocean regions, however, in this paper, the results concentrate solely on the Guinea Dome region.

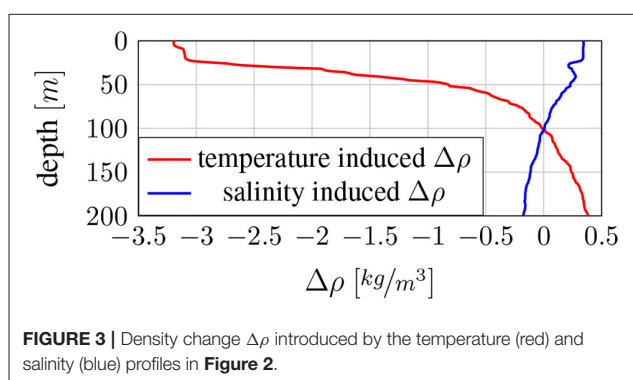
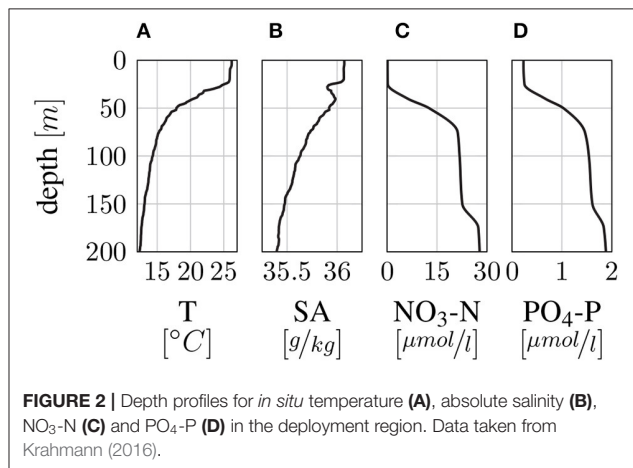


Figure 2 shows depth profiles of *in situ* temperature, absolute salinity, PO₄-P and NO₃-N for the deployment region. The data was taken from Krahmann (2016). As can be seen in Figure 2, high nutrient concentrations are already found at depths smaller than 100 [m] in the example region. The water column in this region is stably stratified due to large temperature and salinity-induced changes in water density. The mixed layer depth (MLD) is 21.8 [m]². Figure 3 depicts the counteracting effects of salinity and temperature on density in the modeled region. Here, profiles of the absolute density change $\Delta\rho$ introduced by temperature and salinity are shown for depths up to 200 [m]. $\Delta\rho$ is calculated with respect to a standard potential density of 1026.49 [kg/m³]. It can be seen from Figure 3 that, especially in the surface region, temperature has a much stronger influence on density than salinity.

Expected Flow Phenomena

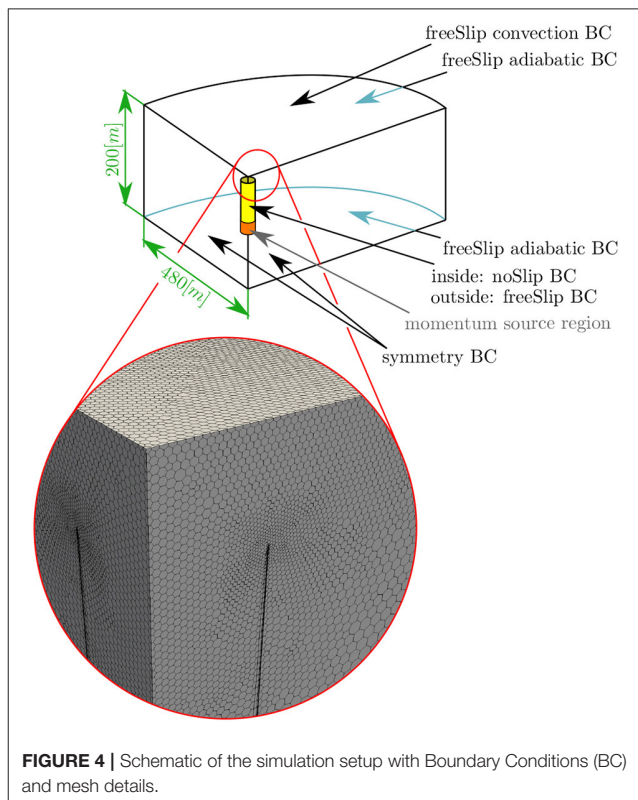
The vertical density gradient has important impacts on the general flow field created by the AU device. Stratified flow exhibits the tendency to return to a stable stratification once disturbed. This will generally dampen out vertical velocities that are not driven by buoyancy forces. Thus, when artificially

pumped to the surface, the cold DOW, after having dissipated its upwards directed momentum, starts sinking downwards again due to its high density. Williamson *et al.* therefore characterize the flow as a weak fountain (Williamson *et al.*, 2009). During the process, the density difference between the pumped DOW and the surrounding surface water is decreased by mixing as well as water surface heat transfer. Thus, the DOW does not sink to its original depth but creates a layer in the upper region of the water column, which spreads horizontally as more water is pumped up by the AU system. Consequently, the flow close to the AU system can be characterized as buoyant flow (i.e., the main flow direction is aligned with the direction of gravity) with forced convection, while in the far field the flow fulfills the characteristics of stratified flow (i.e., the main flow direction is normal to the direction of gravity).

Simulation Setup

The geometry of the AU system is idealized to a cylindrical shape for the simulations. All structural elements or construction details are thereby neglected, which is appropriate considering the early development stage of the system. A cylindrical shape was also chosen for the flow domain (i.e., the water volume which is modeled in the simulations). Use was made of the symmetry effects in the sense that only a quarter of the cylindrical flow domain was modeled. This allows for a significant reduction of the overall count of computational cells without compromising the three-dimensional resolution of the flow. The necessary radius of the cylindrical flow domain was actively studied. Since the influence of the AU system spreads over time, the size of the flow domain critically influences how long the simulation can run before an unwanted interaction of the flow with the outer boundary can occur. Eventually, a radius of 480 [m] was chosen, which kept the computational burden acceptable and enabled simulated times of 10,000 [s] with no visible outer-boundary effects. Equally, a depth of 200 [m] was chosen for the flow domain. A heat transfer boundary condition is used at the top boundary of the flow domain to model sensible heat flux through the water surface. The air temperature is assumed to be the same as the initial water temperature at the water surface. A sensible heat transfer coefficient of 13.5 [W/m²K] was derived from work of Komori *et al.* (2011). The propeller, which is driving the AU device, is modeled as a momentum source inside the lower part of the pipe. Here, the desired flow velocity of 1.969 [m/s] is uniformly prescribed. It has to be noted that this approach does not realistically model the complex flow field behind a propeller. However, since full modeling of the propeller and its influences was not feasible within this study, it was decided that this approach was most general and sufficiently accurate to not have an influence on the general behavior of the AU system. All simulations were started from an initial state of zero velocity with temperature and salinity profiles as depicted in Figure 2. To represent the nutrient concentration, a Nutrient Index (NI) was defined. Its initial value is calculated based on the NO₃-N profile (see Figure 2) divided by its value at the device inlet depth (i.e., 75 [m]). The initial NI value (i.e., before the start of the AU operation) is thus close to zero at the water surface and

²The MLD was established using a 0.03 [kg/m³] potential density criterion with a reference depth of 10 [m].



reaches one at 75 [m] depth³. The simulation setup is depicted in **Figure 4** along with the applied boundary conditions and the computational mesh.

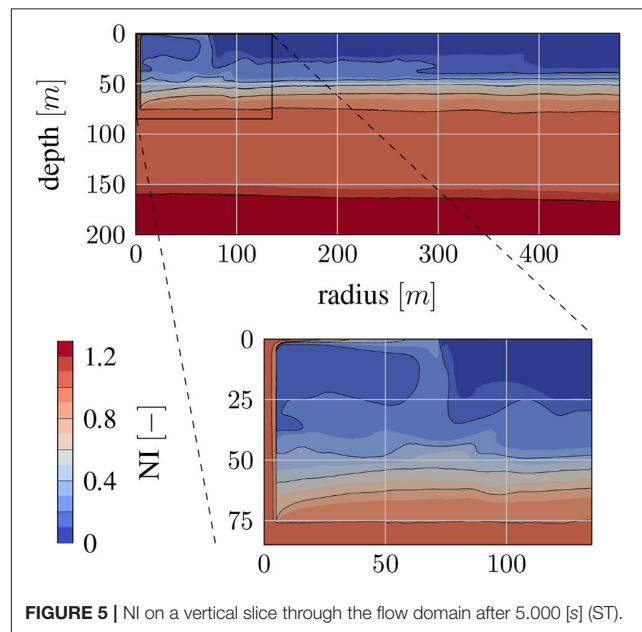
Discretization

The flow domain was discretized using an unstructured, polyhedral mesh. The mesh was gradually refined toward the water surface region as well as the pipe inlet and outlet. The boundary layer region inside the pipe was refined with prism layers to maintain a dimensionless wall distance (y^+) between 30 and 100. An average grid edge size⁴ of about 1.5 [m] and a time step size of 0.125 [s] were used for all studies presented in this paper. The described geometry is thus discretized by 9.3 million cells. This discretization was chosen based on experience and sensitivity studies carried out for similar problems. On a dedicated cluster⁵ about 100 [s] of Computation Time (CT) were needed per second of Simulated Time (ST).

³Since the nutrient concentration is still increasing with depth below the device inlet, NI values greater than one are common at depths greater than 75 [m], indicating that the nutrient concentration here is higher than the initial concentration at the device inlet.

⁴The basic grid edge size is calculated as $\sqrt[3]{\frac{\text{TotalVolume}}{\text{CellCount}}}$.

⁵Two dual CPU nodes were used for most of the studies presented. The nodes were based on AMD EPYC 7302, 16 Core Processors. FDR InfiniBand was used for distributed computations.



3.2. Basic Study

The aim of this first study is to establish whether the described numerical method is able to plausibly capture and quantify the expected flow effects corresponding to the AU process and the mixing of DOW and surface waters. This is studied here, using the previously described case setup. **Figure 5** shows typical, graphical results for NI on a vertical slice through the flow domain after 5,000 [s] of simulated time (i.e., 1.39 [hrs]).

The expected fountain-like flow close to the pipe outlet can be observed in **Figure 5**. The jet of DOW spreads on the free surface to a patch of about 130 [m] diameter before the cold DOW starts to sink due to its high density. Once the DOW has sunk to its depth of neutral buoyancy, the flow becomes almost purely horizontal and a layer with increased NI values is created, which can also be observed in **Figure 5**. Since the fountain-like flow feature close to the device is comparably small, changes in the NI-depth profiles need to be analyzed to be able to quantify the large-scale effect of the AU device. For this analysis a region of study between a 150 and 330 [m] radius around the AU system is defined, thus excluding the fountain-like flow feature local to the device as well as the outer part of the domain, where the nutrient-rich layer does not fully develop within the simulated time span. **Figure 6** shows average NI depth profiles for this region of study. Depth profiles for multiple points in time, after the start of the AU process, are depicted. The previously described layer creation process can be observed in **Figure 6**. The strongest changes in the depth profile due to the AU operation take place within a confined depth range of 10–40 [m]. In this region, the nutrient concentration is increased due to the influence of the nutrient-rich layer, which is initially created at a depth of about 30 [m] and expands in height over time. Between 40 and 70 [m] depth the initial nutricline is lowered slightly due to the extraction of the DOW below. After 7500 [s] the depth profile becomes temporally

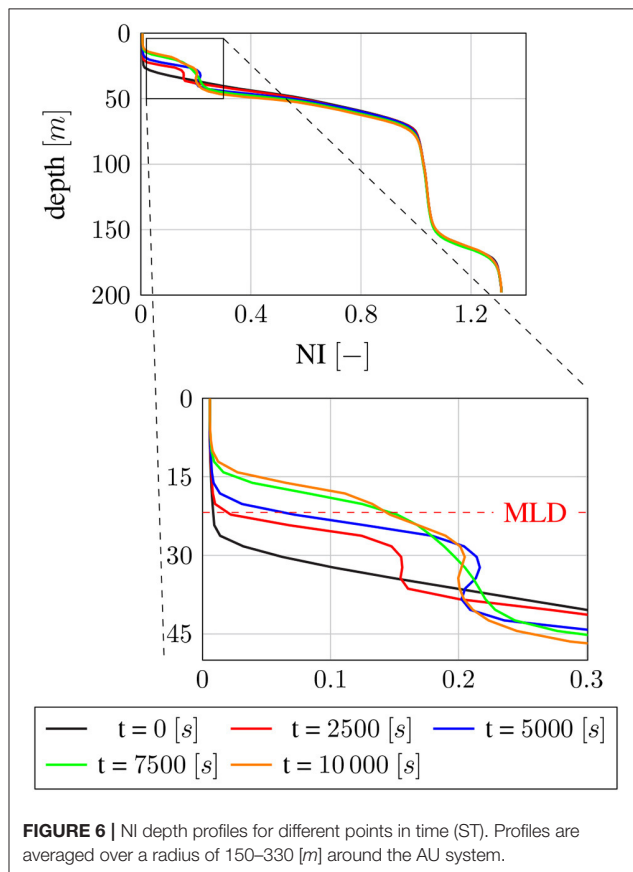


FIGURE 6 | NI depth profiles for different points in time (ST). Profiles are averaged over a radius of 150–330 [m] around the AU system.

stable, indicating that by this point the nutrient-rich layer is fully developed throughout the region of study.

It is not within the scope of this study to establish to which extent the upwelled nutrients in the nutrient-rich layer can be utilized for primary production. The change of the average NI value inside the mixed layer of the studied region is thus taken as measure for the upwelling efficiency of the AU device. From the depth profiles shown in **Figure 6** it can be calculated that the average NI inside the mixed surface layer is raised from an initial value of 0.0064 to 0.0402 after 10 000 [s]. This corresponds to $\text{NO}_3\text{-N}$ values of 0.14 and 0.85 [$\mu\text{mol/l}$], respectively.

3.3. Variant Studies

Having shown the general ability of the described model to capture and quantify the flow effects relevant to the AU process, comparative studies between device variations are possible. In a first study, three design variants were chosen, which were expected to exhibit different flow characteristics at the outlet of the AU system. The investigated variants are depicted in **Figure 7**. The first variant, referred to as *Cylinder*, represents the basic cylindrical geometry as described in the previous sections. Here the flow at the outlet of the AU system is characterized by its impingement on the surface. The second variant, referred to as *Funnel*, features a funnel-shaped outlet with a maximum diameter of 30 [m]. Also, a body (gray shaded area in **Figure 7**)

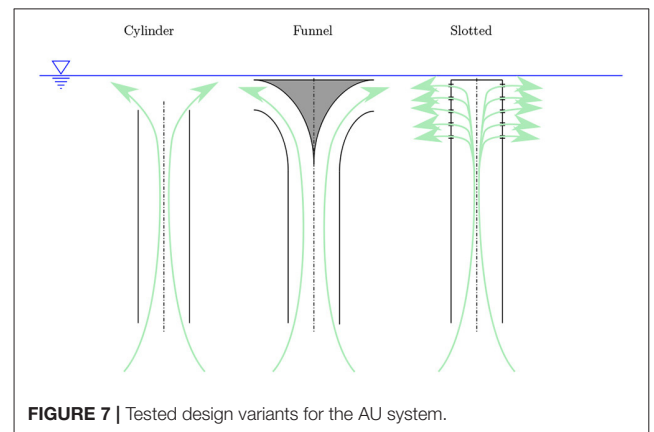


FIGURE 7 | Tested design variants for the AU system.

is installed inside the *Funnel* to make sure the flow follows the funnel surface (i.e., avoid flow separation). The flow for this variant is characterized by the horizontal decay of the momentum introduced by the AU system. The third variant, referred to as *Slotted*, represents a pipe that is closed at the top, such that the outflow occurs through multiple horizontal slots on the upper part of the pipe. Five slots are arranged over the top 10 [m] of the pipe. A width of 0.125 [m] was chosen for the slots such that the total area of all slots equals $1/4$ of the pipes cross-sectional area. The outflow for this variant is characterized by five planar jets. For all three variants a flow velocity of 1.969 [m/s] inside the pipe was specified.

Figure 8 shows the results of the variant study after 10 000 [s] (ST). Averaged NI depth profiles are shown in **Figure 8A**. Again only the region between a radius of 150 and 330 [m] around the AU system is analyzed. As can be seen from this figure, a similar nutrient-rich layer is created by all device variants. It can further be seen from **Figure 8A** that, between 20 and 40 [m] depth, the *Funnel* variant reaches higher NI values than the other variants, while inside the mixed surface layer (i.e., above the MLD) the *Cylinder* variant reaches slightly higher values. For the *Slotted* variant, the nutrient-rich layer seems to be slightly narrower, which leads to smaller NI values inside the mixed surface layer.

Again, the increase of the Average NI inside the mixed layer of the studied region is taken as measure for upwelling efficiency. **Figure 8C** shows the average mixed layer NI in the analyzed region for all device variants. Here, the superiority of the *Cylinder* variant becomes clearly visible.

To understand the origin of the different performances of the device variants, the amount of turbulent mixing created by these variants must be considered. **Figure 8B** shows the Average mixed layer eddy viscosity ratio ν_t/ν over the radial distance from the device center. This figure shows that turbulence is created near the device outlet and decays with larger distances to the device. The strongest turbulent mixing is found at some distance from the device outlet, where the DOW starts to sink down due to its high density. It becomes evident from **Figure 8B** that, while the *Slotted* variant reaches the highest eddy viscosity ratios, the *Cylinder* variant creates overall more turbulence, by maintaining higher values at greater radii. The *Funnel* variant

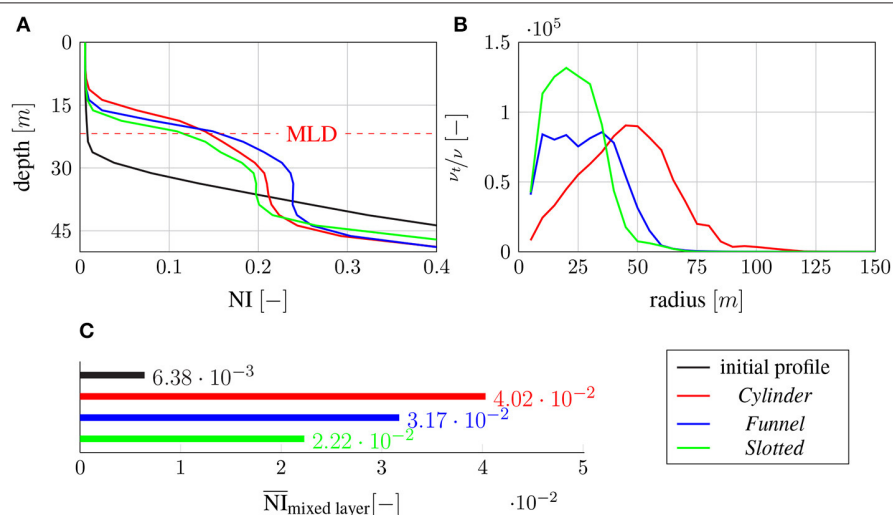


FIGURE 8 | Results of first variant study after 10 000 [s] (ST): **(A)** NI depth profiles averaged over a radius of 150–330 [m] around the AU system. The upper 50 [m] of the water column are shown. **(B)** Radial profiles of eddy viscosity ratio ν_t/ν averaged over the mixed layer. The inner 150 [m] of the domain are shown. **(C)** Average mixed layer NI values based on depth profiles in **(A)**.

produces generally lower eddy viscosity ratios, when compared to the *Cylinder* and *Slotted* variants, but maintains its maximum values over a relatively large range of radii.

For the *Cylinder* variant, the widest spread of DOW along the surface is achieved before the sinking occurs. This is reflected in **Figure 8B** in high eddy viscosity ratios further away from the AU system. For the *Slotted* variant, the horizontal momentum decays close to the device due to the high turbulence levels. Here, the sinking of the DOW occurs over a smaller region, close to the device. Finally, the *Funnel* variant produces a more confined jet of DOW with an intermediate spread along the water surface. Here, the peak in the eddy viscosity ratio at the maximum spreading radius along the free surface is less pronounced.

In a second variant study, different depths of the device outlet were tested for the *Cylinder* shape, and the influences on the DOW layer formation and nutrient enrichment in the mixed surface layer were studied. In addition to the standard version, with an outlet depth of 5 [m], two versions with outlet depths of 2.5 and 7.5 [m] were studied. Again, depth profiles and mixed surface layer average values after 10 000 [s] (ST) are analyzed to establish the influence of the device outlet depth on the nutrient-rich layer.

In **Figure 9**, the differences between the studied versions, in terms of nutrient enrichment, are much smaller than the ones observed in the previous variant study. As can be seen from **Figure 9A**, slightly higher NI values in the mixed surface layer are reached by the 2.5 [m] outlet depth variant. This is reflected in higher average values in **Figure 9C**, respectively. **Figure 9B** again shows the radial profile of the average mixed layer eddy viscosity ratio ν_t/ν . Here, much larger differences than for the NI depth profiles (**Figure 9A**) are observed. When compared to the other variants, the 2.5 [m] outlet depth variant reaches a slightly greater spreading radius of the DOW along the water surface

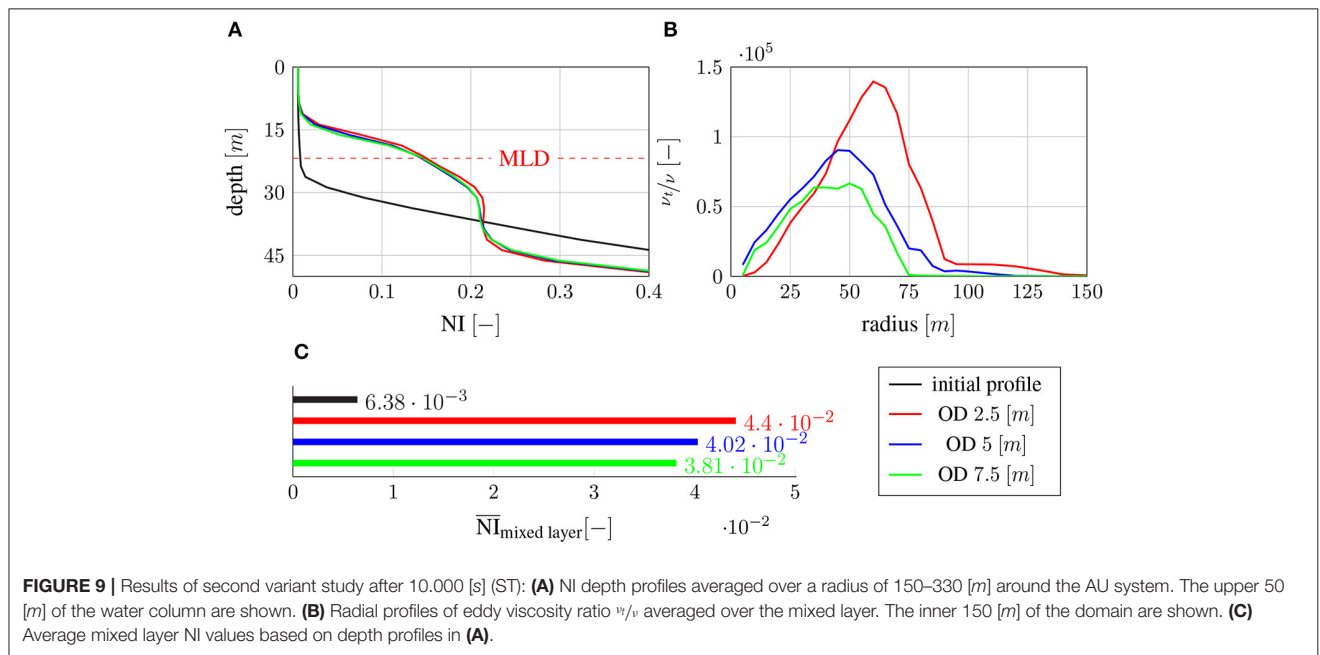
and much larger eddy viscosity ratios during the sinking phase of the upwelled DOW. The 7.5 [m] outlet depth variant shows the lowest eddy viscosity ratios.

4. DISCUSSION

The results presented in this paper show that RANS-based flow simulations with the newly developed numerical method provide valuable insight into the AU process. The numerical method has been successfully applied to studies of an AU device, including general flow phenomena and the relative performance of several design variants.

4.1. Basic Study

The expected flow behavior can clearly be observed in the results of the first study. In the device near field, the flow that Williamson et al. (2009) describe as a weak fountain is reproduced. At larger distances from the device, the flow becomes purely horizontal and a distinct layer containing the upwelled DOW is created. This was expected based on the stable stratification of the water column and has been described by Fan et al. (2015), who conducted flow simulations for a similar device in crossflow. The fact that, in all cases presented here, the nutrient-rich layer extended into the mixed surface layer can be seen as an unexpected result of this study. While Kirke (2003) states that DOW, when pumped to the surface, tends to sink below the mixed layer and thus becomes unavailable for primary production, the results of this study suggest that the horizontal spreading of the nutrient-rich layer still leads to a considerable increase in the mixed layer nutrient concentration despite the initial re-sinking of the DOW. In fact, the horizontal spreading of the nutrient-rich layer appears to be the main process by which the mixed layer is fertilized through the proposed AU system.



Since the horizontal spreading process is associated with very little vertical mixing, it can be assumed that the nutrient-rich layer can spread over large horizontal distances.

Within the region where the nutrient rich layer fully developed during the simulated time (i.e., between a radius of 150 and 330 [m] around the AU system) the average mixed layer $\text{NO}_3\text{-N}$ concentration was increased by a factor of 6.3, from an initial value of 0.14 to 0.85 [$\mu\text{mol/l}$]. These values are in the same order of magnitude as those observed in natural eastern boundary upwelling regions (Chavez and Messié, 2009). The results thus seem encouraging enough to motivate further research on the concept of forced upwelling.

4.2. Variant Studies

The presented variant studies show the effect of different device outlet configurations on the local and global flow characteristics and the intended mixed layer nutrient enrichment. Generally, the importance of turbulent mixing for nutrient enrichment in the mixed surface layer is highlighted by the results. All variants show the same general flow features which have already been described for the basic study. It was expected that strong turbulence introduced by the device as high up in the water column as possible would enhance mixing between the upwelled DOW and surface waters, and thus lead to a higher efficiency of the AU system. However, the strongest turbulent mixing was generally observed at some distance to the device, during the sinking phase, which follows the initial upwelling and spreading of the DOW along the water surface. This suggests that shear-based turbulence production at the device outlet is less important than expected. The results of both variant studies show that a greater spread of the DOW jet along the surface leads to more effective mixing during the sinking phase. High turbulence levels near the device outlet, on the other hand, decrease the spread

of the DOW jet, and thus the device efficiency, as observed for the *Slotted* variant. While the importance of turbulent mixing is confirmed by these results, they reveal that the design should be optimized for convective spreading of the nutrients along the water surface rather than for shear-based turbulent mixing local to the device outlet.

Throughout the studies presented here, the standard *Cylinder* variant with an outlet depth of 2.5 [m] achieved the strongest mixed layer nutrient enrichment with about 7 times the initial nutrient concentration.

It is noteworthy that the idea to maximize the dilution of the upwelled DOW contrasts with the approach of Fan et al. (2015), who aim to minimize dilution and thus maximize the nutrient concentration in the DOW plume. This is explained by the fact that Fan et al. aim to increase nutrient concentrations only local to a mariculture project within the DOW plume, whereas here the intention is to fertilize the mixed surface layer over a large area.

4.3. Limitations

While the results presented in this paper show the applicability of the newly developed method for AU simulations as well as its ability to provide insight into function principles and the effectiveness of AU devices, the significance of the results, in absolute terms, is still limited by simplifications made during both model development and experiment design.

It has to be noted that the eddy viscosity ratios observed in Figures 8B, 9B are significantly higher than the values typically obtained in engineering simulations. The high values mainly result from the coexistence of shear- and buoyancy-based turbulence production in the sinking region. While strong turbulence is a typical feature of the Rayleigh-Taylor instability

observed in this region, it yet has to be established whether the magnitude of the effect is realistically captured by the turbulence model.

Based on the second variant study, it may be assumed that a variant with an even smaller outlet depth than the ones studied here might perform even more desirable. It has to be noted, however, that the water surface is fixed in the simulations presented here. Thus, any water surface deformation due to the operation of the AU system is neglected. This simplification is expected to have an increasing influence as the outlet depth of the device decreases. It may thus impair the validity of simulations with very shallow outlet depths.

It also has to be noted that, since the same flow rate was taken for all variant studies, these studies do not consider the implications of the different variants on the necessary propeller shaft power to obtain the specified flow rate, which would be the limiting factor for upwelling volume in a realistic setting. This was chosen with the intention to first obtain an understanding of the implications of local design changes on the flow, before optimizing the AU system as a whole.

The results presented in this paper rely on a single set of depth profile data for a very specific ocean region. Since the efficiency in bringing nutrients to the ocean's mixed layer might depend strongly on the stratification in the deployment region, the presented results can not be generalized.

Further, in this paper the amount of permanent nutrient enrichment in the mixed surface layer was estimated by calculating the mean NI value above the initial MLD inside a region where the nutrient-rich layer was fully established within the simulated time (i.e., between a radius of 150 [m] to 330 [m] from the device center). It has to be noted that this method of estimating the amount of permanent mixed surface layer nutrient enrichment is based on simplification. It is assumed that all nutrients which permanently settle above the initial MLD can be further spread throughout the mixed surface layer by natural processes and thus remain available for primary production, while all nutrients which settle below the MLD are lost. While this assumption enables a simple comparison of device variants, it does not adequately reflect the physical processes in the ocean's surface region. In particular, this calculation method does not take into account any changes to the MLD due to AU. These changes cannot be evaluated without considering natural forcing effects which balance the perturbation in the water column caused by the AU device over time.

Finally, the total spatial extend and timescales of the device influence are not captured by the simulations presented here due to the limited availability of computational resources.

4.4. Conclusions

Flow simulations of AU have been carried out with a newly developed numerical method. The method is based on numerous modifications to the open-source framework *OpenFOAM*, which have been described in this paper. The capabilities of the new model have been demonstrated in several studies. The newly developed numerical method was able to reproduce expected flow phenomena and allow a first quantification of the local

nutrient enrichment potential in the affected region, as well as comparative studies for device optimization. The spreading of the nutrient-rich layer, which is created by the device, was identified as the main large-scale nutrient enrichment effect. The results suggest that device variants should be optimized for a large convective spread of the DOW jet along the water surface to achieve more permanent mixed layer nutrient enrichment. With a growing interest in ocean-based solutions to the emerging challenges of our time, the role of efficient modeling of these solutions is becoming increasingly important. The presented results should provide the reasoning for continued modeling efforts to improve the understanding of AU.

4.5. Future Work

To be able to obtain more general results from the proposed numerical method, some improvements have to be made:

1. The implemented buoyancy modification for the $k-\omega$ SST turbulence marks a simplified turbulence modeling approach for the AU flow problem. A separate study should be carried out on the applicability of different turbulence modeling approaches to stratified, oceanic flow. Different formulations of the buoyancy terms for the $k-\omega$ SST turbulence model and other approaches should be taken into account.
2. The simulations presented in this paper were stopped after 10 000 [s] (ST) to avoid boundary effects due to the spatial limitation of the flow domain. A boundary condition that allows free in- and outflow through the boundary would enable longer simulated times with spatially confined flow domains and should therefore be implemented.
3. Throughout this study, a value of 1 was invariably used for the turbulent Prandtl and Schmidt numbers. The use of the gradient diffusion hypothesis with global constant Pr_t and Sc_t values is generally criticized by Combest et al. (2011). Different constant values and other alternatives should be evaluated and compared against data.
4. The numerical model should further be extended with realistic modeling approaches for natural mixing in the mixed surface layer to be able to model the effect of these processes on mixed surface layer nutrient enrichment.

Finally, after careful verification and validation of the improved numerical method, studies on greater spatial and temporal scales should be undertaken to fully determine the influence of the proposed AU device on its environment. In particular, the horizontal extent of the nutrient-rich layer and its spreading rate should be studied, along with the question what fraction of the nutrients in the nutrient-rich layer can eventually be utilized for primary production.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JK developed and implemented the numerical method, performed the calculations, and analyzed the results under the scientific and technical supervision of UR and KG. JK wrote the manuscript with input from all authors.

FUNDING

This study was funded by an Advanced Grant of the European Research Council (ERC) in the framework of

the Ocean Artificial Upwelling project (Ocean artUp, No. 695094). Additional support was obtained by the Test-ArtUp project, which is funded by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung, BMBF) as part of the CDRmare research mission of the German Marine Research Alliance (Deutsche Allianz Meeresforschung, DAM) under Grant Agreement No. 03F0897B. The publication was financially supported by Land Schleswig-Holstein within the funding programme Open Access Publikationsfonds.

REFERENCES

- Bauman, S., Costa, M., Fong, M., House, B., Perez, E., Tan, M., et al. (2014). Augmenting the biological pump: the shortcomings of geoengineered upwelling. *Oceanography* 27, 17–23. doi: 10.5670/oceanog.2014.79
- Chavez, F. P., and Messié, M. (2009). A comparison of eastern boundary upwelling ecosystems. *Prog. Oceanogr.* 83, 80–96. doi: 10.1016/j.pocean.2009.07.032
- Combest, D. P., Ramachandran, P. A., and Dudukovic, M. P. (2011). On the gradient diffusion hypothesis and passive scalar transport in turbulent flows. *Ind. Eng. Chem. Res.* 50, 8817–8823. doi: 10.1021/ie200055s
- Devolder, B., Rauwoens, P., and Troch, P. (2017). Application of a buoyancy-modified $k-\omega$ SST turbulence model to simulate wave run-up around a monopile subjected to regular waves using OpenFOAM®. *Coastal Eng.* 125, 81–94. doi: 10.1016/j.coastaleng.2017.04.004
- Fan, W., Chen, J., Pan, Y., Huang, H., Chen, C.-T. A., and Chen, Y. (2013). Experimental study on the performance of an air-lift pump for artificial upwelling. *Ocean Eng.* 59, 47–57. doi: 10.1016/j.oceaneng.2012.11.014
- Fan, W., Pan, Y., Liu, C. C., Wiltshire, J. C., Chen-Tung, A. C., and Chen, Y. (2015). Hydrodynamic design of deep ocean water discharge for the creation of a nutrient-rich plume in the south china sea. *Ocean Eng.* 108, 356–368. doi: 10.1016/j.oceaneng.2015.08.006
- FAO (2018). *The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals*. Rome. Licence: CC BY-NC-SA 3.0 IGO.
- Ferziger, J. H., Perić, M., and Street, R. L. (2020). *Computational Methods for Fluid Dynamics*. Cham: Springer International Publishing.
- GESAMP (2019). “High level review of a wide range of proposed marine geoengineering techniques,” in *Rep. Stud. GESAMP No. 98, (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UN Environment/UNDP/ISA Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection)*, eds P. W. Boyd and C. M. G. Vivian (London: International Maritime Organization), 144p.
- Griffies, S. M., and Adcroft, A. J. (2008). Formulating the equations of ocean models. *Ocean Model. Eddy Regime* 177, 281–317. doi: 10.1029/177GM18
- IOC, SCOR, and IAPSO (2010). *The International Thermodynamic Equation of Seawater-2010: Calculation and Use of Thermodynamic Properties*. Paris: Intergovernmental Oceanographic Commission, Manuals and Guides.
- Issa, R. (1986). Solution of the implicitly discretised fluid flow equations by operator-splitting. *J. Comput. Phys.* 62, 40–65. doi: 10.1016/0021-9991(86)90099-9
- Kirke, B. (2003). Enhancing fish stocks with wave-powered artificial upwelling. *Ocean Coastal Manag.* 46, 901–915. doi: 10.1016/S0964-5691(03)00067-X
- Komori, S., Kurose, R., Takagaki, N., Ohtsubo, S., Iwano, K., Handa, K., et al. (2011). *Gas Transfer at Water Surfaces, Chapter Sensible and Latent Heat Transfer Across the Air-Water Interface in Wind-Driven Turbulence*. Kyoto: Kyoto University Press.
- Krahmann, G. (2016). Property changes of deep and bottom waters in the western tropical atlantic. *Deep Sea Res. I Oceanogr. Res. Pap.* 124, 103–125. doi: 10.1016/j.dsr.2017.04.007
- Launder, B., and Spalding, D. (1974). The numerical computation of turbulent flows. *Comput. Methods Appl. Mech. Eng.* 3, 269–289. doi: 10.1016/0045-7825(74)90029-2
- Lawrence, M. G., Schäfer, S., Muri, H., Scott, V., Oeschles, A., Vaughan, N. E., et al. (2018). Evaluating climate geoengineering proposals in the context of the paris agreement temperature goals. *Nat. Commun.* 9:3734. doi: 10.1038/s41467-018-05938-3
- Liang, N.-K., and Peng, H.-K. (2005). A study of air-lift artificial upwelling. *Ocean Eng.* 32, 731–745. doi: 10.1016/j.oceaneng.2004.10.011
- Liu, C. C., and Jin, Q. (1995). Artificial upwelling in regular and random waves. *Ocean Eng.* 22, 337–350. doi: 10.1016/0029-8018(94)00019-4
- Lovelock, J. E., and Rapley, C. G. (2007). Ocean pipes could help the earth to cure itself. *Nature* 449, 403–403. doi: 10.1038/449403a
- Maruyama, S., Tsubaki, K., Taira, K., and Sakai, S. (2004). Artificial upwelling of deep seawater using the perpetual salt fountain for cultivation of ocean desert. *J. Oceanogr.* 60, 563–568. doi: 10.1023/B:JOCE.0000038349.56399.09
- McDougall, T. J. (2003). Potential enthalpy: a conservative oceanic variable for evaluating heat content and heat fluxes. *J. Phys. Oceanogr.* 33, 945–963. doi: 10.1175/1520-0485(2003)033<0945:PEACOVandgt;2.0.CO;2
- McDougall, T. J., Jackett, D. R., Wright, D. G., and Feistel, R. (2003). Accurate and computationally efficient algorithms for potential temperature and density of seawater. *J. Atmos. Oceanic Technol.* 20, 730–741. doi: 10.1175/1520-0426(2003)20<0730:AAECFandgt;2.0.CO;2
- Meng, Q., Wang, C., Chen, Y., and Chen, J. (2013). A simplified CFD model for air-lift artificial upwelling. *Ocean Eng.* 72, 267–276. doi: 10.1016/j.oceaneng.2013.07.006
- Menter, F. R. (1994). Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J.* 32, 1598–1605. doi: 10.2514/3.12149
- Nayar, K. G., Sharqawy, M. H., Banchik, L. D., and Lienhard, V., J. H. (2016). Thermophysical properties of seawater: a review and new correlations that include pressure dependence. *Desalination* 387, 1–24. doi: 10.1016/j.desal.2016.02.024
- Oeschles, A., Pahlow, M., Yool, A., and Matear, R. J. (2010). Climate engineering by artificial ocean upwelling: channelling the sorcerer's apprentice. *Geophys. Res. Lett.* 37:L04701. doi: 10.1029/2009GL041961
- Pan, Y., Fan, W., Huang, T.-H., Wang, S.-L., and Chen, C.-T. A. (2015). Evaluation of the sinks and sources of atmospheric CO₂ by artificial upwelling. *Sci. Total Environ.* 511, 692–702. doi: 10.1016/j.scitotenv.2014.11.060
- Pan, Y., Li, Y., Fan, W., Zhang, D., Qiang, Y., Jiang, Z.-P., et al. (2019). A sea trial of air-lift concept artificial upwelling in the east china sea. *J. Atmos. Oceanic Technol.* 36, 2191–2204. doi: 10.1175/JTECH-D-18-0238.1
- Patankar, S., and Spalding, D. (1972). A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows. *Int. J. Heat Mass. Transf.* 15, 1787–1806. doi: 10.1016/0017-9310(72)90054-3
- Roels, O. A., Laurence, S., Farmer, M. W., and Hemelryck, L. V. (1977). “Organic production potential of artificial upwelling marine culture,” in *Microbial Energy Conversion* (Pergamon: Elsevier), 69–81.
- Sharqawy, M. H., Lienhard, V., J. H., and Zubair, S. M. (2010). Thermophysical properties of seawater: a review of existing correlations and data. *Desalination Water Treat.* 16, 354–380. doi: 10.5004/dwt.2010.1079
- Soloviev, A. V. (2016). “Ocean upwelling system utilizing energy of surface waves,” in *Proceedings of the 2016 Techno-Ocean Conference* (Kobe: IEEE), 221–224.
- Stankov, P., Denev, J., Barták, M. M., Drkal, F., Lain, M. M., Schwarzer, J., et al. (2001). “Experimental and numerical investigation of temperature distribution in room with displacement ventilation,” in *Proceedings of the 7th World Congress Clima 2000* (Naples).
- Stommel, H., Arons, A. B., and Blanchard, D. (1956). An oceanographical curiosity: the perpetual salt fountain.

- Deep Sea Res.* 3, 152–153. doi: 10.1016/0146-6313(56)90095-8
- Thorpe, S. A. (2007). *An Introduction to Ocean Turbulence*. Cambridge: Cambridge University Press.
- Tsubaki, K., Maruyama, S., Komiya, A., and Mitsugashira, H. (2007). Continuous measurement of an artificial upwelling of deep sea water induced by the perpetual salt fountain. *Deep Sea Res. I Oceanogr. Res. Pap.* 54, 75–84. doi: 10.1016/j.dsr.2006.10.002
- Van Maele, K., and Merci, B. (2006). Application of two buoyancy-modified –turbulence models to different types of buoyant plumes. *Fire Safety J.* 41, 122–138. doi: 10.1016/j.firesaf.2005.11.003
- Wilcox, D. C. (1988). Reassessment of the scale-determining equation for advanced turbulence models. *AIAA J.* 26, 1299–1310. doi: 10.2514/3.10041
- Williamson, N., Komiya, A., Maruyama, S., Behnia, M., and Armfield, S. W. (2009). Nutrient transport from an artificial upwelling of deep sea water. *J. Oceanogr.* 65, 349–359. doi: 10.1007/s10872-009-0032-x
- Williamson, P., Wallace, D. W., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., et al. (2012). Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance. *Process Safety Environ. Protect.* 90, 475–488. doi: 10.1016/j.psep.2012.10.007
- Worthy, J., Sanderson, V., and Rubini, P. (2001). A comparison of modified $k-\epsilon$ turbulence models for and buoyant plumes. *Numer. Heat Transfer B* 39, 151–165. doi: 10.1080/10407790150503486
- Zhang, X., Maruyama, S., Sakai, S., Tsubaki, K., and Behnia, M. (2004). Flow prediction in upwelling deep seawater—the perpetual salt fountain. *Deep Sea Res. I Oceanogr. Res. Pap.* 51, 1145–1157. doi: 10.1016/j.dsr.2004.03.010
- Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
- Publisher's Note:** All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.
- Copyright © 2022 Kemper, Riebesell and Graf. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Contribution [JPB]

Performance prediction for Stommel's perpetual salt fountain in the context of artificial ocean upwelling

Citation:

Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025c. Performance prediction for Stommel's perpetual salt fountain in the context of artificial ocean upwelling. Applied Ocean Research 160, 104624. doi:10.1016/j.apor.2025.104624.

Author contributions:

Conceptualization	J. Kemper , J. Mense
Methodology	J. Kemper , J. Mense
Software	J. Kemper , J. Mense
Validation	J. Kröger, T. Slawig, K. Graf
Investigation	J. Kemper , J. Mense
Resources	J. Kröger, T. Slawig, K. Graf
Data Curation	J. Kemper
Writing - Original Draft	J. Kemper
Writing - Review & Editing	J. Mense, J. Kröger, T. Slawig, K. Graf, U. Riebesell
Visualization	J. Kemper , J. Mense
Supervision	J. Kröger, T. Slawig, K. Graf, U. Riebesell
Project administration	J. Kröger, K. Graf, U. Riebesell
Funding acquisition	J. Kröger, K. Graf, U. Riebesell

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.





Research paper

Performance prediction for Stommel's perpetual salt fountain in the context of artificial ocean upwelling

Jost Kemper^{a,b}, Jan Mense^c, Jörn Kröger^b, Thomas Slawig^{a,d}, Kai Graf^b, Ulf Riebesell^c^a Department of Computer Science, Kiel University, Christian-Albrechts-Platz 4, 24118, Kiel, Germany^b Institute for Naval Architecture and Maritime Engineering, Kiel University of Applied Sciences, Grenzstraße 3, 24149, Kiel, Germany^c Biological Oceanography, GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstraße 1-3, 24148, Kiel, Germany^d Kiel Marine Science (KMS) – Centre for Interdisciplinary Marine Science, Christian-Albrechts-Platz 4, 24118, Kiel, Germany

ARTICLE INFO

Dataset link: [10.5281/zenodo.14394656](https://doi.org/10.5281/zenodo.14394656)

Keywords:

Carbon Dioxide Removal (CDR)

Artificial upwelling

Perpetual salt fountain

Stommel upwelling pipe

Computational fluid dynamics (CFD)

Mixed convection

ABSTRACT

Due to the typical temperature and salinity structure in wide parts of the global oceans, a self-sustaining, convective up or downflow within a vertical pipe can be established. This concept was introduced by Stommel et al. (1956) as the *perpetual salt fountain*. Recently, Stommel Upwelling Pipe (SUP) systems are gaining new interest as possible enabling technology for large-scale implementations of artificial upwelling of nutrient-rich deep ocean water to the ocean surface. This process is currently actively researched as part of several marine Carbon Dioxide Removal (CDR) approaches. Despite multiple studies conducted over the past decades, no method has yet been proposed to reliably predict performance and thus enable quantification of the potential of Stommel Upwelling Pipe (SUP) systems for artificial upwelling. In the present work, two performance prediction methods for SUP systems are introduced, one method based on the Reynolds-Averaged Navier–Stokes (RANS) equations and a one-dimensional method based on pipe flow equations. This twofold approach overcomes the limitations of previous studies and enables reliable performance estimation for a wide range of SUP setups. Both numerical methods are described in the present work, and their predictive capabilities are proven through rigorous verification, validation, and model intercomparison. The respective model assumptions are critically reviewed. Our results reveal key aspects of SUP performance and provide the basis for a reliable evaluation of the potential of SUP systems for artificial upwelling.

1. Introduction

In many ocean regions, the surface waters have both higher temperatures and a higher salinity than the deep ocean water. With regard to density, the temperature effect, which stabilizes the stratification of the water column, outweighs the destabilizing salinity effect. When viewing these ocean regions as a thermodynamic system, it is apparent that the system could be moved to a lower energy state if the salinity could be transferred to the deep ocean, or equally, the relatively fresh deep ocean water could be transferred to the surface, independent of its temperature. Such a transfer should thus run as a spontaneous process, i.e., without any energy input to the system. If a vertical pipe is deployed in such an ocean region and filled with deep ocean water once, the cold water in the pipe will eventually be heated by the surrounding water while retaining its low salinity. The water column inside the pipe will thus become buoyant with respect to the surrounding water, and a convective upward flow in the pipe will be initiated. Once a steady state of this process is reached, the flow

will continue without any external energy input (except ambient heat). Stommel et al. (1956) were the first to describe this effect, naming it the *perpetual salt fountain*. The effect is conceptually linked to double-diffusive convection, a well-known feature in oceanic flow, with the difference that here, the diffusion of salt is not only smaller than the heat diffusion but entirely suppressed due to the presence of the pipe wall. It is worth noting that in the same ocean regions, Stommel's effect can also be used to drive downwelling instead of upwelling if the pipe is initially filled with surface water instead of deep ocean water. Since its publication, several device concepts have been proposed on the basis of this principle. In the present work, we will summarize these device concepts under the term Stommel Upwelling Pipe (SUP).

Engineered transport of deep ocean water to the surface ocean is known as artificial upwelling. This process has been studied in numerous contexts, including enhancement of fish stocks (Kirke, 2003), open-ocean mariculture (Wu et al., 2023), and interventions for hurricane (Kithil, 2006) and drought mitigation (Ricke et al., 2021). Most

* Corresponding author at: Department of Computer Science, Kiel University, Christian-Albrechts-Platz 4, 24118, Kiel, Germany.

E-mail addresses: jost.kemper@email.uni-kiel.de, jost-kemper@gmx.de (J. Kemper).<https://doi.org/10.1016/j.apor.2025.104624>

Received 13 December 2024; Received in revised form 5 May 2025; Accepted 16 May 2025

Available online 9 June 2025

0141-1187/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Nomenclature	
General	
P	Pressure [N/m ²]
Q	Volume flow rate [m ³ /s]
S_A	Absolute salinity [g/kg]
Θ	Conservative temperature [°C]
ρ	Density [kg/m ³]
Bo	Buoyancy parameter = $\frac{Gr^*}{Re^{3.425} Pr^{0.8}}$ [-]
Gr	Grashof number = $\frac{g\beta(\Theta - \Theta_w)D_h^3}{\nu^2}$ [-]
Gr^*	Heat flux-based Grashof number = $\frac{g\beta q D_h^4}{\kappa \nu^2}$ [-]
N_D	Diameter-based Nusselt number = $\frac{hD}{\kappa}$ [-]
Pr	Prandtl number = $\frac{\nu}{\lambda}$ [-]
Re	Reynolds number = $\frac{wD}{\nu}$ [-]
Ri	Richardson number = $\frac{Gr}{Re^2}$ [-]
ocean4Foam method	
D	Diffusivity of Salinity [m ² /s]
g	Gravity vector [m/s ²]
I	Unit matrix [-]
k	Turbulent kinetic energy [m ² /s ²]
p_{gh}^*	Modified kinematic pressure = $\frac{1}{\rho_0} \bar{P} - g \cdot r + \frac{2}{3} k$ [m ² /s ²]
r	Position vector w.r.t. water surface [m]
S	Strain rate tensor = $\frac{1}{2} (\nabla \bar{u} + (\nabla \bar{u})^T)$ [1/s]
t	Time [s]
u	Velocity vector [m/s]
y^+	Dimensionless wall distance [-]
λ	Thermal diffusivity [m ² /s]
ν	Kinematic viscosity [m ² /s]
τ^*	Deviatoric part of kinematic Reynolds stress tensor [m ² /s ²]
σ_t	Turbulent Prandtl number [-]
Subscripts	
ϕ_0	Constant reference quantity
ϕ_e	Effective quantity = $\phi + \phi_t$
ϕ_t	Quantity modeling turbulence effects
Superscripts	
$\bar{\phi}$	Reynolds-averaged quantity
ϕ^T	Transpose of tensor ϕ
SP1D method	
A_c	Pipe cross-sectional area [m ²]
c_f	Darcy pipe friction factor [-]
C_h	Heat-transferring circumference [m]
c_p	Specific heat capacity [J/kg K]
D	Pipe diameter [m]
D_h	Hydraulic pipe diameter [m]
g	Gravity [m/s ²]
h	Convection heat transfer coefficient [W/m ² s]
L	Pipe length [m]
n	Number of inner pipes of satSUP systems
q	Heat flux [W/m ²]
s	Pipe wall thickness [m]
U	Overall heat transfer coefficient across pipe wall [W/m ² K]
w	Pipe velocity [m/s]
z	Vertical pipe coordinate (positive down) [m]
β	Volume expansion coefficient [1/K]
κ	Thermal conductivity [W/m K]
Subscripts and averaging	
$\hat{\phi}$	Averaged quantity over the pipe length
ϕ_e	Quantity w.r.t. external diameter of inner pipe
ϕ_i	Quantity w.r.t. inner pipe
ϕ_{top}	Quantity at upper pipe end
ϕ_{bottom}	Quantity at lower pipe end
ϕ_o	Quantity w.r.t. the shell of cSUP or satSUP systems
ϕ_{ocean}	Quantity w.r.t. the surrounding ocean
ϕ_{wall}	Quantity of pipe wall material
Abbreviations	
CDR	Carbon Dioxide Removal
RANS	Reynolds-Averaged Navier–Stokes
SGDH	Simple Gradient Diffusion Hypothesis
SUP	Stommel Upwelling Pipe
sSUP	single SUP
cSUP	counterflow SUP
satSUP	shell-and-tube type SUP

proposals target deep ocean water for its high inorganic nutrient concentrations, which are utilized to enable biological primary production in the surface ocean. Recently, artificial upwelling has received new scientific interest due to its potential to enhance oceanic CO₂ uptake and thus act as a marine Carbon Dioxide Removal (CDR) measure. Artificial upwelling can either represent a standalone CDR measure (Lovelock and Rapley, 2007; Dutreuil et al., 2009; Yool et al., 2009; Oschlies et al., 2010; Keller et al., 2014; Jürchott et al., 2023) or be used to support CDR in the context of open-ocean macroalgae farming (Koweek, 2022; Wu et al., 2023). While the salt fountain effect was initially introduced as a curiosity rather than a practical engineering concept for artificial upwelling (Stommel et al., 1956), SUP systems have several advantageous properties for driving large-scale deployments of artificial upwelling. Based on the fact that no external energy supply is required to drive SUP systems and their construction can be comparably simple (no moving parts), SUP systems could represent an enabling technology for large-scale upwelling-based CDR in the open ocean, provided they have the potential to upwell significant volumes of deep ocean water.

Several authors have tried to quantify and demonstrate the potential of SUP systems. A first effort to quantify possible flow rates has been undertaken by Groves (1958). Groves studied a simple ocean profile using an analytical method. He analyzed his results in the context of fish-farm fertilization but concluded that SUP-based fertilization with deep ocean water was not likely to be economically interesting due to the low flow rates. Hinman (1966) extended Groves's calculations, with the addition of vertical heat transfer and a numerical implementation. Even though Hinman found the effect of vertical heat transfer to be negligible, he found considerably larger upwelling flow rates than Groves by using different ocean depth profile data and pipe setups. Johnson and Decicco (1983) proposed a new type of SUP device, where downwelling, based on the salt fountain principle, is established in a number of tubes running through an outer shell, where upwelling is established. The aim of this counterflow arrangement was to obtain a more uniform temperature difference across the pipe wall throughout the device and thus enhance the heat transfer efficiency. Using a simplified analytical model, Johnson and Decicco showed that their concept could be up-scaled to achieve flow rates of 1.32 m³/s. A first successful prototype test of Stommel's concept was reported by Maruyama et al. (2004). Using a flexible 0.3 m diameter, 280 m long pipe, Maruyama et al. were able to achieve an upwelling flow rate of 1.7 × 10⁻⁴ m³/s. In a further field experiment, upwelling of 5.3 × 10⁻⁴ m³/s was achieved (Tsubaki et al., 2007). The results of Maruyama et al. (2004) were subsequently extended with numerical simulations, using a Reynolds-Averaged Navier–Stokes (RANS) equation model in laminar mode and with a fixed uniform eddy viscosity. As the laminar model simulations resulted in poor agreement with the observations, Maruyama et al. (2004) suggest that wave action on the surface buoy of their system might have caused turbulent flow in the pipe. Studies of Zhang et al. (2006) strengthen this explanation.

Based on the above literature review, three types of proposed SUP systems are defined in the present work. The three types are schematically shown in Fig. 1. In the following, they will be referred to as single SUP (sSUP), counterflow SUP (cSUP), and shell-and-tube type SUP (satSUP). While strictly the cSUP concept marks a special case of a satSUP system with a single inner pipe, it is treated as a separate concept throughout this work for its special geometric properties. It should be noted that in contrast to Johnson and Decicco (1983), who initially proposed this device type, in the present work, the inner pipe of cSUP and satSUP systems is the upwelling pipe, while downwelling is considered in the outer shell. This allows a more direct comparison between the system types.

Table 1 summarizes the previous studies on the performance of SUP systems. As can be seen here, sSUP and satSUP systems of varying sizes have previously been studied, mostly using simple one-dimensional pipe flow models and typically resulting in upwelling velocities between 0.1 m/s and 0.2 m/s. A substantial discrepancy between the SUP

Table 1
Results of previous studies on SUP systems.

Study	Pipe dimensions ($L \times D$) [m]	Concept	Method	Region	ΔS_A [‰/kg] ^b	Upwelling velocity [m/s]
Groves (1958)	600 × 0.2	sSUP	1D model	n.a.	0.5	0.175
Hinman (1966)	175 – 600 × 0.2 – 0.4	sSUP	1D model	generic	0.5 – 1.7	0.163 – 0.336
Johnson and Decicco (1983)	500 × 0.1/500 × 0.05 ^a	satSUP	1D model	Florida/Chile	1.0/0.5	0.116/0.037
Maruyama et al. (2004)	280 × 0.3	sSUP	Experiment	Mariana Trench	–0.3	2.45×10^{-3}
Tsubaki et al. (2007)	300 × 0.3	sSUP	Experiment	Mariana Islands	0.1	7.5×10^{-3}

^a Here, the inner pipe dimensions are given as a reference even though Johnson and Decicco propose the upwelling flow to be on the shell side.

^b Salinity difference between pipe top and bottom depth.

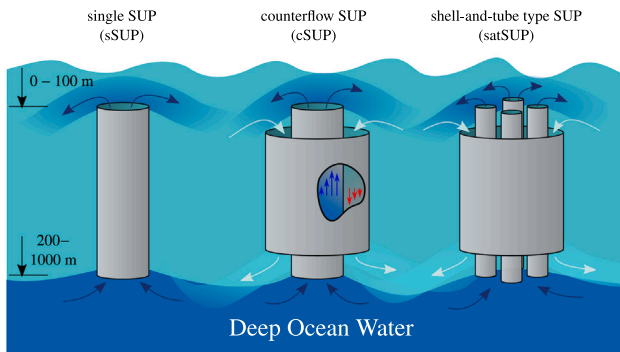


Fig. 1. Basic types of SUP systems.

performance from model predictions and experimental observations is evident in Table 1. This discrepancy, despite perhaps being mostly driven by the choice of deployment region for the field experiments, introduces a large uncertainty to the overall range of expected SUP performances and, thus, to the present understanding of the potential of these systems for artificial upwelling. At the same time, the low upwelling velocities and the large disturbances (due to waves) in the field experiments mean that the corresponding data cannot be used to validate new SUP performance prediction methods in a meaningful way. To overcome this situation and provide reliable SUP performance predictions in the absence of full-scale validation data, the present work focuses on a combination of model validation studies for individual well-studied flow phenomena essential to SUP performance, as well as model intercomparison efforts for different SUP types and ocean conditions. We introduce a new one-dimensional pipe flow model and a RANS model for SUP simulations. While the RANS model enables high-fidelity studies of arbitrary SUP geometries and also allows for validation with respect to specific flow phenomena, the one-dimensional model is directly based on pipe flow theory and enables extensive studies due to its low computational cost. The consistency of both models in predicting key aspects of SUP performance is demonstrated in this work, and some remaining model uncertainties are evaluated and quantified.

As the flow in SUP systems is partly driven by a global pressure gradient and partly by natural convection, it is inherently prone to mixed-convection effects. To the authors' knowledge, such effects have not been considered in previous SUP studies, despite their potentially significant impact on SUP performance predictions. Throughout this work, special emphasis is thus put on the correct reproduction of mixed-convection effects on SUP performance.

The remainder of this work is structured as follows: First, two numerical methods for predicting SUP performance are described in Section 2 and validated, where possible. Additionally, common SUP geometries and ocean profiles are defined for the subsequent studies. In Section 3, results from studies on several aspects of SUP performance are presented, discussed, and compared between both methods. Conclusions from the results are drawn in Section 4.

2. Numerical methods

In this section, two numerical methods for SUP systems are introduced, namely a RANS model, which will be referred to as the *ocean4Foam* (*o4F*) method (Kemper, 2024, version a5f80c2c), and a one-dimensional model, which will be referred to as the *SP1D* (short for *Stommel-Pipe one-dimensional*) method (Kemper and Mense, 2024, version db0309a3). Preceding implementations of both methods have been described by Kemper et al. (2023) as a work in progress. Here, the revised model equations of both methods are described in detail, and their discretization and solution are outlined. Verification and validation of the *ocean4Foam* method is carried out as indicated in Section 1. Finally, a benchmark case setup consisting of geometry information and ocean data is defined.

2.1. The *ocean4Foam* method

The RANS model used in this work is developed as part of the *ocean4Foam* toolbox. It implements the oceanic Boussinesq set of RANS equations (Young, 2010), using the Open-FOAM[®] environment. The oceanic Boussinesq approximation was described by Young (2010) as three steps:

1. The exact density ρ in the momentum equation is replaced by a constant reference density ρ_0 everywhere but in the buoyancy term.
2. The incompressible continuity equation $\nabla \cdot \mathbf{u} = 0$ is used.
3. An equation of state of the form $\rho = f(\bar{S}_A, \bar{\Theta}, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r})$ is used, where $\bar{\Theta}$ is the conservative temperature of McDougall (2003), $\bar{S}_A$ is absolute salinity, P_0 is the reference pressure at the water surface, ρ_0 is a constant reference density, $\mathbf{g}$ is the gravitational acceleration vector, and $\mathbf{r}$ is the position vector with respect to a reference position at the water surface.

The oceanic Boussinesq set of RANS equations, as implemented in the *ocean4Foam* method, reads:

$$\begin{aligned} \frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\mathbf{u}}) &= \nabla \cdot \bar{\boldsymbol{\tau}}_e^* - \nabla \bar{p}_{gh}^* + \mathbf{g} \left(\frac{\rho}{\rho_0} - 1 \right) \\ \nabla \cdot \bar{\mathbf{u}} &= 0 \\ \frac{\partial \bar{\Theta}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\Theta}) &= \nabla \cdot (\lambda \nabla \bar{\Theta} - \bar{\Theta} \bar{\mathbf{u}}) \\ \frac{\partial \bar{S}_A}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{S}_A) &= \nabla \cdot (D \nabla \bar{S}_A - \bar{S}_A \bar{\mathbf{u}}) \\ \rho &= f(\bar{S}_A, \bar{\Theta}, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r}) \end{aligned} \quad (1)$$

In Eq. (1), t is time and $\bar{\mathbf{u}}$ is the velocity vector. The tensor $\bar{\boldsymbol{\tau}}_e^*$ denotes the deviatoric part of the effective, kinematic Reynolds stress tensor

$$\bar{\boldsymbol{\tau}}_e^* = 2\nu_e \bar{\mathbf{S}} - \frac{2}{3}\nu_e (\nabla \cdot \bar{\mathbf{u}}) \mathbf{I}, \quad (2)$$

where ν_e is the effective viscosity, which includes laminar diffusion and the modeling of turbulence effects ($\nu_e = \nu + \nu_t$), and $\bar{\mathbf{S}}$ is the mean strain rate tensor (see nomenclature for details). The modified kinematic pressure $\bar{p}_{gh}^*$ in Eq. (1) is calculated from the static pressure as $\bar{p}_{gh}^* = \frac{1}{\rho_0} \bar{P} - \mathbf{g} \cdot \mathbf{r} + \frac{2}{3}k$, with k being the turbulent kinetic energy.

The molecular diffusivities of temperature and salinity are denoted λ and D in Eq. (1), while the terms $\overline{\theta u}$ and $\overline{S_A u}$ represent the respective turbulent fluxes. Typically, these fluxes are modeled using the Simple Gradient Diffusion Hypothesis (SGDH), whereby the right-hand side of the θ equation becomes

$$\nabla \cdot \left(\lambda \nabla \overline{\theta} - \overline{\theta u} \right) = \nabla \cdot \left(\lambda_e \nabla \overline{\theta} \right) = \nabla \cdot \left(\left(\lambda + \frac{\nu_t}{\sigma_t} \right) \nabla \overline{\theta} \right), \quad (3)$$

with σ_t being the turbulent Prandtl number. (The S_A equation is treated in the same way.) Alternative scalar flux models are available within *ocean4Foam* as well as models for non-constant turbulent Prandtl numbers. These aspects will be discussed in Section 2.4 along with the choice of the turbulence model.

The seawater properties are modeled using the method of McDougall et al. (2003) for ρ (following the *TEOS-10* standard (IOC et al., 2010)) and the polynomials of Sharqawy et al. (2010) and Jamieson and Tudhope (1970) for ν and λ , respectively.

The fundamental equations (Eq. (1)) are discretized using the finite volume method and implemented as a solver using the Open-FOAM® environment. Open-FOAM®'s *PIMPLE* algorithm (a transient version of the well-known *SIMPLE* algorithm) is employed to solve the coupled equation set in a pressure-based manner. The following numerical schemes are used: Gradients are discretized using the Gauss method with linear interpolation. For the convective terms in the momentum and scalar transport equations, linear upwind and limited linear schemes are employed, respectively. A pseudo-transient approach is used for temporal discretization, which was observed to be numerically more stable and converge to the final solution much faster than a steady-state simulation process. Due to the use of the pseudo-transient approach, only converged steady-state solutions are given in this work, and no data on the initial transient development of the flow inside a SUP system is generated.

2.2. The SPID method

The one-dimensional method described in this section is based on considerations of hydrostatic balance as well as pipe flow formulations for pressure loss and heat transfer. The method is one-dimensional in the sense that variations of the field variables are only resolved along the axial z coordinate (positive down). Consequently, the state variables conservative temperature (θ), absolute salinity (S_A), and pressure (P) at each vertical position represent bulk values, and the fluid properties are evaluated with respect to these values. The primary aim of the method is to predict the unknown upwelling velocity w along with the variation of the state variables for any given SUP geometry and background ocean profile.

The basic equations of the *SPID* method are equal for sSUP, cSUP, and satSUP systems. The equations are thus introduced in a generalized form. Differences between the formulations for different SUP types are pointed out where necessary and a full description is given in Appendix.

The first equation represents a pressure balance between the hydrostatic pressure head and the dynamic pressure loss for a fully developed steady-state flow

$$c_f \frac{\hat{\rho}}{2} \frac{w^2}{D_h} L = g \int_{z_{top}}^{z_{top}+L} (\rho_{ocean}(z) - \rho(z)) dz. \quad (4)$$

Here, w is the upwelling velocity, c_f is the corresponding Darcy pipe friction factor, D_h is the hydraulic pipe diameter (see Appendix for details), and g is the gravitational acceleration. Further, ρ and ρ_{ocean} are the density of the water inside the pipe and the background ocean, respectively, while $\hat{\rho}$ is the average density over the pipe length. The density of seawater is calculated from the equation of state

$$\rho = f(S_A, \theta, P). \quad (5)$$

The background ocean values θ_{ocean} and $S_{A,ocean}$ are known functions of z . Since the salinity is not changed inside the SUP system, S_A uniformly takes the value of the flow entering the pipe. Knowledge of

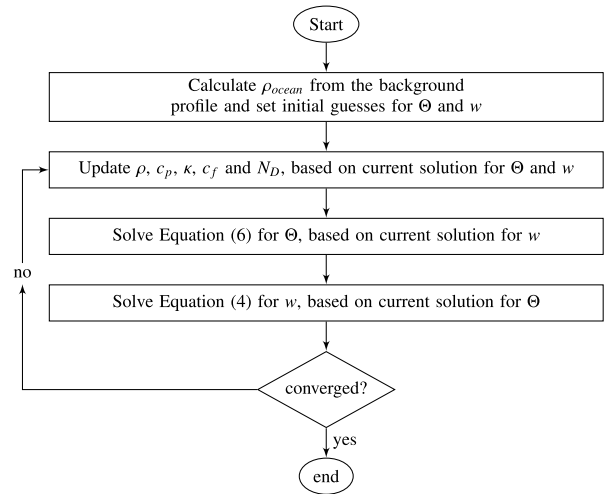


Fig. 2. Flow diagram of the *SPID* solution algorithm.

the temperature profile $\theta(z)$ inside the pipe would thus enable us to rearrange Eq. (4) and calculate the unknown upwelling velocity w at this point. (The hydrostatic pressure is used for P in Eq. (5).)

The temperature profile can be obtained by solving the following ordinary differential equation over the interval (z_{top}, z_{bottom}) , using the known inlet temperature as boundary condition

$$-A_c w \hat{\rho} c_p(z) \theta'(z) + C_h U(z) (\theta_{ot}(z) - \theta(z)) = 0. \quad (6)$$

Physically, this equation represents a balance between convective heat transfer in the axial direction and radial conductive heat transfer through the pipe wall. Here, A_c is the cross-sectional area of the pipe, C_h is the heat-transferring circumference, c_p is the heat capacity and θ_{ot} refers to the temperature of the fluid on the other side of the pipe wall. Hence, θ_{ot} is the background ocean temperature in the case of a sSUP system, the shell-side value when the equation is solved for the inner pipe of a cSUP or satSUP system, and the inner-pipe value when Eq. (6) is solved for the shell-side flow. The coefficient U in Eq. (6) represents an overall heat transfer coefficient, which incorporates the thermal resistance of the pipe wall as well as the influence of the convection on either side of the wall. The three components of U depend on the respective thermal conductivities κ and Nusselt numbers N_D (see Appendix for details).

With correlations for the pipe friction factor, the Nusselt number, and the fluid properties,¹ the system of Eqs. (4) and (6) is closed for a given pipe geometry and ocean profile (θ_{ocean} and $S_{A,ocean}$). For sSUP systems, only the coupling between Eqs. (4) and (6) has to be solved. This coupling is handled using the iterative process depicted in Fig. 2. For cSUP and satSUP systems, the two balances (Eqs. (4) and (6)) have to be solved for both the inner pipe² and the shell. As the two sides are coupled via the temperature difference in Eq. (6), a system of four coupled equations is obtained. Again, the process depicted in Fig. 2 is followed to solve this system of equations. The two instances of Eq. (6) (for the inner pipe and shell) are solved as a coupled boundary value problem in each iteration, using a collocation algorithm.

Several general points about the previously described set of equations for SUP systems should be noted: Eq. (6) describes a mere balance of vertical heat convection and horizontal heat conduction. Other energy forms, as well as vertical heat conduction, are not considered here.³ Additionally, as for cSUP and satSUP systems, Eq. (6) only

¹ In this work, the *TEOS-10* (IOC et al., 2010) standard is used for ρ and c_p , while κ is calculated using the method of Jamieson and Tudhope (1970).

² One representative inner pipe is solved in the case of satSUP systems.

balances the heat transfer between inner-pipe and shell-side flow, any possible heat transfer between the shell-side flow and background ocean (i.e., through the outer pipe wall) is not taken into account. The negligence of the outer pipe heat transfer for cSUP and satSUP systems largely simplifies the definition of the equations and enables the generic formulation for different SUP types. From an engineering point of view, the negligence of the outer pipe heat transfer can be justified by the fact that the outer pipe wall will usually have to provide structural stability to the SUP system and will thus likely have a considerably higher wall thickness than the inner pipe(s). To quantify the effect of this simplification, outer pipe heat transfer is studied for a cSUP system in Section 3.3, using the *ocean4Foam* method.

2.3. Empirical coefficients for the SPID method

The empirical coefficients, namely the Nusselt number N_D and the Darcy friction factor c_f , largely affect the solutions of the SPID method. Little has previously been published on the correct formulation of the corresponding correlations for SUP systems. The determination of these factors is significantly complicated by the fact that the flow can feature several different flow regimes.

The flow in SUP systems is driven by the interaction of a global pressure gradient and local heating through the pipe wall. These two effects are conceptually linked to forced and natural convection, respectively. A classification of the flow regime can be made based on the Richardson number ($Ri = Gr/Re^2$). Flows with $Ri < 0.1$ are typically viewed as forced convection, while flows with $Ri > 10$ correspond to natural convection. Richardson numbers between these values are associated with mixed convection. For flow in vertical passages and pipes, mixed-convection effects are known to scale with the dimensionless buoyancy parameter Bo (Jackson and Hall, 1979), which is defined as

$$Bo = \frac{Gr^*}{Re^{3.425} Pr^{0.8}} \quad (7)$$

Here, Gr^* is the heat flux-based Grashof number, Re is the Reynolds number, and Pr is the Prandtl number. Fig. 3 shows typical flow profiles in a vertical pipe for forced convection as well as different degrees of buoyancy influence. While natural and forced convection exhibit defined mean flow, shear, and turbulence production patterns, mixed convection is characterized by a complex nonlinear interaction of these patterns with corresponding changes in laminar-turbulent transition behavior, heat transfer, and wall friction (Jackson et al., 1989). In the laminar buoyancy-aided⁴ case of mixed convection, heat transfer in vertical passages and pipes is generally enhanced (i.e., Nusselt numbers are observed to be higher than the forced-convection values). However, in the turbulent buoyancy-aided case, the heat transfer shows a nonlinear behavior which is schematically depicted in Fig. 4 based on the model of Jackson et al. (1989). Here, the Nusselt number is normalized by its forced-convection value such that values below unity reflect heat transfer impairment, while higher values represent heat transfer enhancement due to buoyancy effects. As can be seen here, the heat transfer is significantly impaired when the buoyancy influence is small, and enhanced as buoyancy effects become dominant. This nonlinear behavior of turbulent mixed-convection heat transfer is of great importance for the performance of SUP systems, as will be shown throughout this work.

In the following, an engineering approach is described to obtain c_f and N_D across the entire range of relevant flow regimes. Since

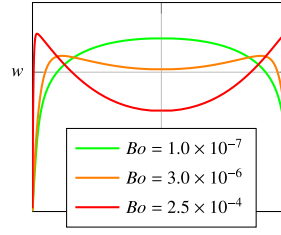


Fig. 3. Turbulent pipe velocity profiles for different degrees of buoyancy influence.

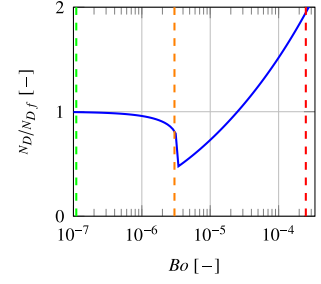


Fig. 4. Buoyancy-aided mixed-convection effects on the heat transfer efficiency in turbulent pipe flow.

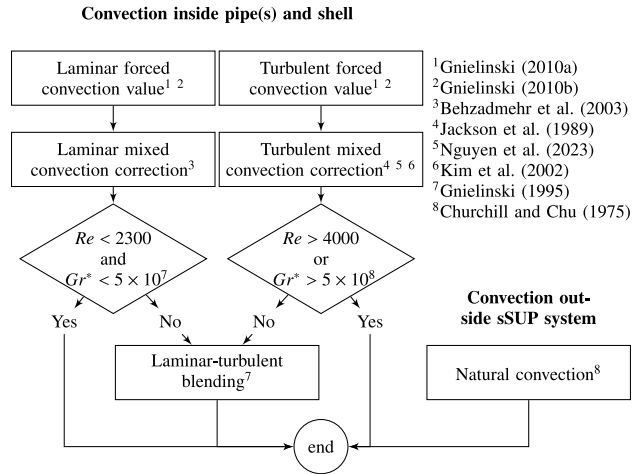


Fig. 5. Flow diagram of Nusselt number calculation for the SPID method.

empirical correlations are usually only formulated for one combination of turbulence and convection regime, blending between different formulations or their use outside the intended range of applicability can hardly be avoided.

2.3.1. Friction factor

The correlation of Morrison (2013) is invariably used for c_f . It reads

$$c_f = 4 \left(\frac{0.0076 \left(\frac{3170}{Re} \right)^{0.165}}{1 + \left(\frac{3170}{Re} \right)^7} + \frac{16}{Re} \right) \quad (8)$$

This correlation is valid for forced-convection pipe flow across the entire Reynolds number range up to 1×10^6 . A consistent formulation for mixed and natural convection was not pursued in the course of this work, due to the lack of established correlations for these flow regimes.

2.3.2. Nusselt number

The procedure used to calculate the Nusselt number N_D is depicted in Fig. 5. The Nusselt number is determined by first calculating the laminar and turbulent forced-convection values and then applying the respective mixed-convection corrections. The laminar and turbulent values are then blended in the case of transitional flow.

Forced convection. The forced convection value for both the laminar and turbulent regimes is calculated following Gnielinski (2010a,b) for cylindrical pipes (sSUP and inner pipe of cSUP) and annular pipes (shell of cSUP), respectively.

³ Vertical heat conduction in SUP systems has been studied by Hinman (1966), who found a negligible effect on the overall flow rate.

⁴ Mixed convection can either be buoyancy-aided (e.g., upward flow through a heated pipe or downward flow through a cooled pipe) or buoyancy-opposed (e.g., downward flow through a heated pipe). In this work, only the buoyancy-aided case is considered, since buoyancy-opposed mixed convection is not relevant for SUP systems.

Table 2
Coefficients for Eq. (9) following Nguyen et al. (2023).

	$c \text{ } Bo \leq 0.26$	$c \text{ } Bo > 0.26$
a	0.56	1.78
b	0.35	0.50
n	0.56	2.03

Mixed convection correction. In the laminar case, the mixed-convection correction is calculated following Behzadmehr et al. (2003). While this correlation was initially proposed for a small Re range, it remains consistent with commonly used formulations for laminar forced convection and is thus used for the entire laminar range here. For the turbulent case, Jackson et al. (1989) present a semi-empirical model to describe the nonlinear behavior of mixed-convection heat transfer. The resulting correction for the forced convection Nusselt number N_{Df} reads

$$N_D/N_{Df} = \left| 1 - c \frac{Bo}{(a N_D/N_{Df} - b)^2} \right|^n, \quad (9)$$

where Bo is the buoyancy parameter (Eq. (7)). The factor c is 8×10^4 for cylindrical pipes and 1.25×10^5 for annular pipes⁵ (Jackson et al., 1989; Kim et al., 2002). While Jackson et al. (1989) initially proposed a , b , and n to be 1, 0, and 0.46, respectively, Nguyen et al. (2023) recently proposed a deviation from this simple formulation. Based on extensive DNS studies, Nguyen et al. (2023) suggest the coefficients given in Table 2 for Eq. (9). This formulation is used throughout the present work.

Laminar-turbulent blending. The laminar forced and mixed-convection formulations are applied when $Re < 2300$ and $Gr^* < 5 \times 10^7$. The turbulent formulations are applied when $Re > 4000$ or when $Gr^* > 5 \times 10^8$. In the transition regions, linear blending is applied as suggested by Gnielinski (1995). As the turbulent formulation is applied across the entire Re range if $Gr^* > 5 \times 10^8$, the Re value used in the calculations is limited to a minimum of 4000 in these situations to account for the fact that the Nusselt number becomes independent of Re under low-flow conditions (Rouai, 1987).

satSUP systems. For lack of specialized correlations, the formulations for annular pipes are also applied to the shell side flow of satSUP systems. Kemper et al. (2023) have tested this procedure against RANS calculations of satSUP systems and generally found good agreement of the results.

sSUP systems. As the convection outside the pipe wall of sSUP systems (i.e., in the background ocean) marks an external natural-convection flow, the corresponding Nusselt number is treated separately. Here, the well-known correlation of Churchill and Chu (1975) is applied. Note that the assumption of pure natural convection in the background ocean is representative of a theoretical situation with no current. Since cross-flow generally increases the heat transfer from a vertical cylinder, this is a conservative assumption for sSUP performance.

2.4. Verification and validation

In the absence of full-scale validation data for SUP systems, validation of SUP performance prediction methods has to be carried out for well-studied flow phenomena that are relevant to SUP performance. Such validation efforts can only be carried out for the ocean4Foam method. In this section, the ocean4Foam method is validated for forced and mixed-convection flow of seawater in cylindrical and annular pipes.

⁵ For annular pipes N_D/N_{Df} is limited to values greater than 0.75, which is in line with the experimental results of Kim et al. (2002). For details see Section 2.4.

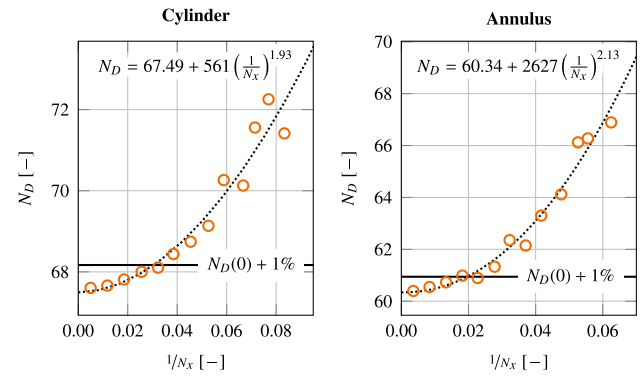


Fig. 6. Grid independence study. Nusselt number over the reciprocal of the radial cell count N_x . ocean4Foam results are given along with a regression analysis and the 1% error threshold.

A case setup with a simple, two-dimensional pipe mesh is used. The diameter is 0.15 m for the cylindrical pipe, while for the annular pipe, the inner and outer diameters are 0.15 m and 0.26 m, respectively. The height of the simulated section is 0.15 m. To obtain a fully developed flow field in the section, cyclic boundary conditions are used at the inlet and outlet for velocity and turbulent quantities. For temperature, a modified cyclic boundary condition is used, such that a constant mean value of 15 °C is maintained at the inlet. The salinity is constant and uniform at 35.5 g/kg in the modeled section. A uniform pressure gradient is applied and automatically adjusted to maintain a set mean velocity in the pipe, thus controlling the Reynolds number. A uniform heat flux is applied at the pipe wall. For the annular pipe, only the inner wall is heated, while the outer wall is adiabatic. This setup allows for the buoyancy parameter Bo (Eq. (7)) to be systematically varied, which is done here by keeping Re at a constant value of 8000 and varying the wall heat flux.

First, a grid independence verification is carried out by systematically varying the number of cells across the radial dimension (N_x). Throughout this study, a constant cell size is maintained at the pipe wall(s) ($y^+ = 0.25$) for all N_x values. This is achieved by applying different gradual refinements in the radial direction. The study is performed for forced convection ($Bo = 1 \times 10^{-7}$). The results are shown in Fig. 6 along with a regression analysis and the 1% error threshold with respect to the extrapolated exact solution (at $1/N_x = 0$). As can be seen from the regression analysis, the rate of convergence closely reflects the theoretical value for a second-order method (i.e., an exponent of 2). For all further studies, a value of 50 cells across the radial dimension ($1/N_x = 0.02$) is chosen for the cylindrical pipe, while 70 cells ($1/N_x = 0.014$) are used for the annular pipe. This choice ensures discretization errors below 1%, as shown in Fig. 6.

Having verified the numerical setup, the validation study can now be carried out using different turbulence and scalar flux modeling approaches implemented in ocean4Foam. As shown by Keshmiri et al. (2012), the choice of turbulence model can have a significant effect on the reproduction of heat transfer for mixed-convection flows. Of several turbulence models examined in their studies, Keshmiri et al. (2012) found the v^2 - f model (Durbin, 1991) to achieve the best overall agreement with LES and DNS results as well as experimental data. With the k - ϵ - ϕ_i - f turbulence model of Laurence et al. (2005), Open-FOAM® implements a version of the v^2 - f model which aims to be code-friendly and more numerically stable than the original formulation. The k - ϵ - ϕ_i - f model is thus tested here along with the well-known k - ω SST turbulence model (Menter, 1994). The turbulent thermal fluxes have been modeled using the SGDh (Eq. (3)) with a constant turbulent Prandtl number σ_t in most previous RANS studies on mixed convection (Keshmiri et al., 2012; Kim et al., 2008). Models for non-constant σ_t values (Reynolds,

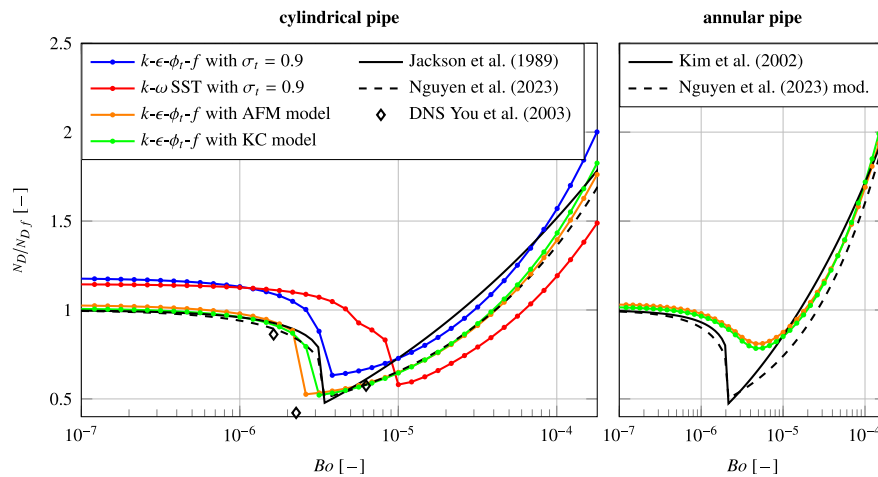


Fig. 7. Normalized Nusselt number over buoyancy parameter for cylindrical and annular pipe case. Results from the *ocean4Foam* model using different turbulence and turbulent thermal flux modeling approaches, along with appropriate empirical correlations as well as DNS data of You et al. (2003). For the cylindrical pipe, the correlations of Jackson et al. (1989) and Nguyen et al. (2023) are plotted, while for the annular pipe, the correlation of Kim et al. (2002) and a correspondingly modified version of the Nguyen et al. (2023) correlation are shown.

1975) and other scalar flux modeling options (Daly and Harlow, 1970; Kenjereš et al., 2005; Younis et al., 2005) have been widely discussed in the literature for different applications. Recently, Irrenfried and Steiner (2017) have found σ_t values from DNS calculations of heated pipe flow to increasingly deviate from a constant value as molecular Prandtl numbers exceed unity. These results suggest that for our work, which uses seawater ($Pr \approx 8.2$) as the working fluid, non-standard models for the turbulent thermal flux may have to be used. The SGDH with $\sigma_t = 0.9$ was thus tested against the variable σ_t model of Kays and Crawford (1993) (hereafter referred to as KC) and the algebraic flux model of Kenjereš et al. (2005) (hereafter referred to as AFM). The KC model gives the turbulent Prandtl number as

$$\sigma_t^{-1} = \frac{1}{2\sigma_{t\infty}} + C \frac{v_t}{v} \sqrt{\frac{1}{\sigma_{t\infty}}} - \left(C \frac{v_t}{v}\right)^2 \left[1 - \exp\left(-\frac{1}{C \frac{v_t}{v} \sqrt{\sigma_{t\infty}}}\right)\right], \quad (10)$$

where $\sigma_{t\infty} = 0.85$ and $C = 0.21$. We found that for seawater, the predicted σ_t values are in acceptable agreement with the DNS results of Irrenfried and Steiner (2017). For the sake of brevity, the AFM model of Kenjereš et al. (2005) will not be explained here in detail. In contrast to the previously described options, this model is directly derived from the second-moment closure equations for the turbulent thermal flux $\overline{\theta u}$ and thus entirely avoids the use of the SGDH.

Fig. 7 shows the Nusselt number predicted by the different model configurations over a Bo variation from 1×10^{-7} (forced convection) to 2×10^{-4} . The results for the cylindrical pipe are compared against the correlations of Jackson et al. (1989) and Nguyen et al. (2023) as well as three DNS data points of You et al. (2003). For the annular pipe, the correlation of Kim et al. (2002) is given along with a modified version of the Nguyen et al. (2023) correlation, which was adapted to the annular geometry following Kim et al. (2002). All results are normalized by the theoretical forced-convection value, which was calculated using Gnielinski's correlations (Gnielinski, 2010a,b).

It can be seen that the constant σ_t results have a significant offset to the theory and data. The $k-\omega$ SST model is generally found to predict the heat transfer impairment due to the onset of mixed convection at higher Bo values than the $k-\epsilon-\phi_t-f$ model. This is consistent with the poor performance of the $k-\omega$ SST model found by Keshmiri et al. (2012). Both the KC and AFM models perform much better than the constant σ_t model. Both models predict the correct forced-convection Nusselt number (within 3% error). For the annular pipe, the heat transfer impairment is predicted by *ocean4Foam* to be less pronounced and with a less sudden onset. This is in line with the experimental data of Kim

et al. (2002) but not represented by their theory, which Kim et al. (2002) adopted from the cylindrical pipe. To better adjust the theory to the data, the correlation for the annular pipe is limited to a minimum value of 0.75 in the implementation of the SP1D method.

To further demonstrate the validity for the forced convection case ($Bo = 1 \times 10^{-7}$), w^+ and θ^+ profiles across the pipe radius are shown in Fig. 8. The results are compared against DNS data of Irrenfried and Steiner (2017) and the theoretical solutions for the viscous sublayer and logarithmic region.⁶ Only the results for the cylindrical pipe are shown. Fig. 8 additionally shows results from a calculation with a constant tuned value of $\sigma_t = 1.35$, which produces the correct Nusselt number. It is evident from Fig. 8 that both the KC and AFM models, in combination with the $k-\epsilon-\phi_t-f$ turbulence model, ensure correct scaling of the velocity and temperature across the pipe diameter. The same is not found to be the case for the tuned constant turbulent Prandtl number. These results confirm the adequacy of the non-standard thermal flux models for the present case. For all further calculations in this work, the KC model is used. While arguably providing less generality, the KC model provides a numerically more stable and cost-effective alternative to the AFM approach.

2.5. Benchmark geometry

Benchmark SUP geometries are used for all further studies in this work. The geometries are developed based on considerations of technical feasibility, comparability, and good general upwelling performance. They do not represent optimized setups in any sense. Fig. 9 shows both setups and their main dimensions. Both setups have a bottom depth of 400 m, a top depth of 5 m, and a (inner) pipe diameter of 0.15 m. For the cSUP setup, the outer pipe diameter is obtained from the inner-to-outer-pipe cross-sectional flow area ratio, which is set to 0.5. The thickness and thermal conductivity of the (inner) pipe wall were chosen such that the thermal resistivity equates to $s/\kappa_{wall} = 2 \times 10^{-3} \text{ K m}^2/\text{W}$. This corresponds to a HDPE pipe with $s = 1 \text{ mm}$ or a steel pipe with $s = 90 \text{ mm}$. In the cSUP case, a 20 m separation is introduced between the ends of the inner pipe and shell to avoid any interference between the upwelling and downwelling flows. The free ends of the inner pipe are

⁶ Following Irrenfried and Steiner (2017), the coefficients $\kappa = 0.34$, $B = 0.45$, and $\sigma_t = 0.9$ are used for the logarithmic law of the wall. The function of Jayatilake (1969) is used for P .

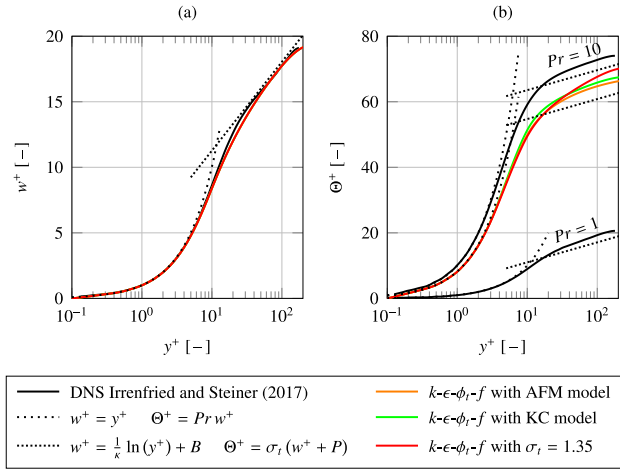


Fig. 8. Radial profiles of axial velocity (a) and temperature (b) in wall units. Results from the *ocean4Foam* model using different turbulent thermal flux modeling approaches, along with DNS data of Irrenfried and Steiner (2017) and theory. The Θ^+ results of Irrenfried and Steiner (2017) are given for molecular Prandtl numbers of 1 and 10. The Prandtl number in the present case is 8.2.

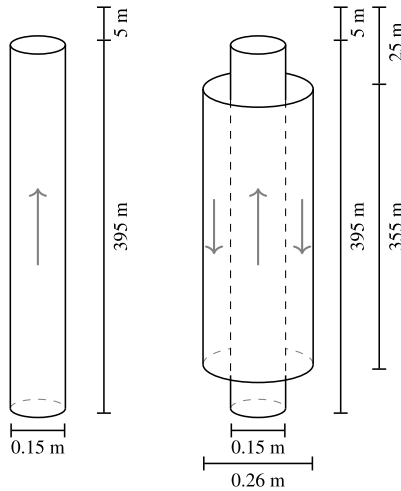


Fig. 9. Benchmark geometry for sSUP (left) and cSUP (right) system.

assumed adiabatic (i.e., no heat is transferred between the inner pipe and the background ocean in these areas).

The *ocean4Foam* calculations are set up using two-dimensional axisymmetrical pipe meshes (i.e., only the axial and radial directions are resolved). Only the fluid domain inside the pipe is resolved by the *ocean4Foam* calculations, whereas the background ocean is considered through boundary conditions. This choice is consistent for the cSUP case with adiabatic outer walls, where the flow outside the pipe has no influence on the convection inside the pipe. For the sSUP case, the effect of the outside flow on the wall heat transfer has to be parameterized. For idealized ocean conditions (i.e., no currents or waves), this can be conveniently achieved by a convective boundary condition on the pipe wall, which specifies the local wall temperature Θ_w as

$$\Theta_w = f \Theta_{ocean} + (1 - f) \Theta_C, \quad (11)$$

where Θ_C is the temperature at the centroid of the grid cell next to the wall and

$$f = \frac{1}{1 + \frac{\kappa}{h\delta}}. \quad (12)$$

Here, δ is the distance from the wall to the nearest cell centroid and the heat transfer coefficient h is calculated from the Nusselt number using the correlation of Churchill and Chu (1975).⁷ Arguably, the introduction of a Nusselt number correlation for the convection outside the pipe decreases the model fidelity compared to the option of resolving the outside flow in the calculation. Kemper et al. (2023) compared both options (i.e., with and without resolved outside flow) and found very little difference, indicating that the convective boundary condition for sSUP systems can be used with confidence.

In sum, the applied boundary conditions are as follows: All pipe inlets are specified as total pressure inlets, where the hydrostatic background pressure minus a dynamic contribution ($0.5 |\mathbf{u}|^2$) is prescribed, and the velocity is calculated from the flux (i.e., from the pressure equation). The transported scalar quantities Θ , S_A , and turbulence quantities are specified based on the background ocean profile. All pipe outlets are specified as pressure outlets, where the hydrostatic background pressure is prescribed, along with a Neumann boundary condition for velocity and transported scalar quantities. On all solid walls, no-slip conditions for velocity are specified together with the appropriate low-Re values for the turbulence quantities. In the cSUP cases, the outer pipe wall is adiabatic, and a thermal baffle boundary condition for Θ is applied to the inner pipe wall to take care of the heat transfer and thermal wall resistance. In the sSUP cases, the previously discussed convective boundary condition (Eq. (11)) for Θ is applied to the pipe wall.

For the *ocean4Foam* cases, the radial mesh resolution is chosen as indicated in Section 2.4, and 4500 cells are used across the pipe length.

2.6. Benchmark ocean profiles

The benchmark ocean profiles presented in this section are meant to provide an overview of different characteristics of possible SUP deployment regions. The potential of SUP systems is limited by the availability of suitable ocean (temperature and salinity) conditions. With calm weather conditions, low seasonality, and low biological productivity, the subtropical ocean gyres often serve as model regions for artificial upwelling. To derive the benchmark ocean profiles for this work, the four large subtropical gyres, North Atlantic Gyre (NAG), South Atlantic Gyre (SAG), North Pacific Gyre (NPG), and South Pacific Gyre (SPG) were thus considered. We define the extent of the subtropical gyres by the areas enclosed by the 1.2 g/kg contour of the salinity difference between surface and deep ocean water at 400 m depth (i.e., the source depth of the benchmark SUP geometries). With this definition, four regions with expectably good SUP performance but different depth profile characteristics are obtained. Based on annual mean data for the years 1955 to 2018 from the World Ocean Atlas 2018 (Boyer et al., 2018), mean depth profiles for all four regions were derived. The resulting profiles are shown in Fig. 10 along with the extent of the four regions.

The fact that some of the considered regions are very remote represents a hurdle for practical implementations of artificial upwelling. As the scope of the current work is limited to performance prediction, such feasibility considerations are not further taken into account here.

3. Results and discussion

In this section, both methods presented in Section 2 are used to predict the performance of SUP systems. The presented studies address key aspects of SUP performance and demonstrate the predictive capabilities of both methods through model intercomparison. Additionally, the simplifying model assumption of no heat transfer through the outer pipe of cSUP and satSUP systems is critically assessed.

⁷ In the implementation, the boundary condition additionally takes into account the thermal resistance of the pipe wall, which leads to a slightly expanded form of Eq. (12).

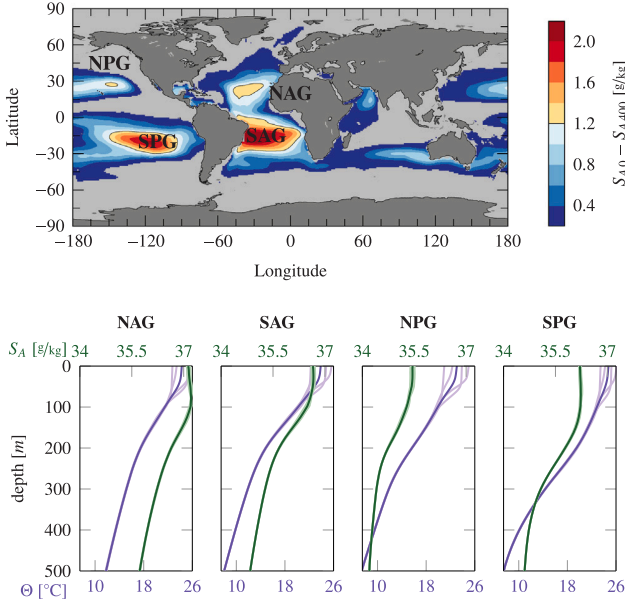


Fig. 10. Definition of subtropical gyres, based on S_A differences between surface and 400 m depth. Annual mean depth profiles for conservative temperature (violet) and absolute salinity (green) for NAG, SAG, NPG, and SPG, with seasonal variation (light colors).

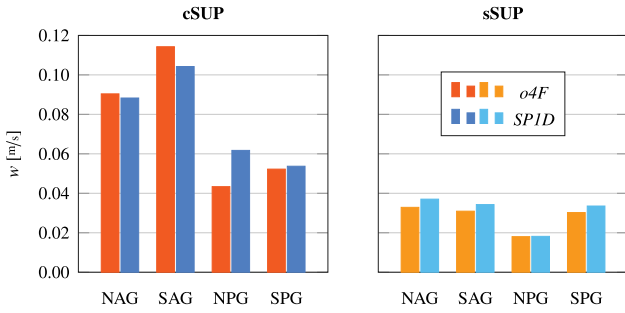


Fig. 11. Upwelling velocity (w) results from both methods for the sSUP and cSUP benchmark geometry and all four benchmark ocean profiles from Section 2.6.

3.1. Subtropical gyre study

In this study, results from the two numerical methods are compared for both benchmark geometries (cSUP and sSUP) introduced in Section 2.5 and all four benchmark profiles introduced in Section 2.6. Fig. 11 shows the upwelling velocity for the cSUP and sSUP system, as obtained by the *ocean4Foam* and the *SP1D* method. A first reference of SUP performance in the four subtropical gyre regions and the agreement between the two methods can be obtained from Fig. 11. In general, the upwelling velocities are within the range of previous predictions described in the literature review (Section 1). The upwelling velocities for the cSUP system are significantly higher than those for the sSUP system. The results show slightly different dynamics between the two SUP types. While for the cSUP system, the SAG region clearly shows the highest potential, the sSUP system performs similarly in all regions except for the NPG region. These differences are not surprising considering that the temperature profile inside the sSUP system is highly dependent on the background profile shape, while for the cSUP, the temperature profile is decoupled from the background ocean to a large extent.

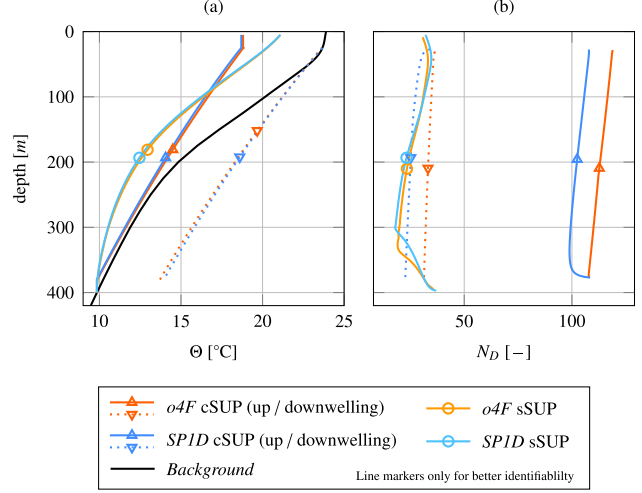


Fig. 12. Temperature (a) and Nusselt number (b) profiles inside the SUP system (colored) and the background ocean (black) for the SAG case. Results from both methods are shown for the benchmark sSUP and cSUP systems.

The relative differences between the results from both methods are within 12% for all cases except the cSUP-NPG case. Also, the qualitative agreement between the two methods is acceptable. Although the number of cases in this study is limited, the good agreement of the results can be seen as an indication that the effects of different profile characteristics and device types are reproduced consistently by both methods. The larger deviation in the cSUP-NPG case will be further studied in Section 3.2.

Fig. 12 shows the depth profile of the bulk temperature Θ as well as the Nusselt number N_D inside the cSUP and sSUP system. The results are only shown for the SAG ocean profile. A close agreement between the Θ and N_D profiles predicted by the *SP1D* and *ocean4Foam* method can be observed for both SUP types. The capability of the *SP1D* method to reproduce the Nusselt numbers variation inside the sSUP system is remarkable, considering the simplicity of the empirical N_D calculation (see Section 2.3). For the cSUP system, the *SP1D* method predicts slightly lower N_D values and a stronger thermal entrance effect than the *ocean4Foam* method. Despite these differences, the results shown in Fig. 12 indicate that the basic flow phenomena inside both SUP types are reproduced consistently by the numerical methods.

3.2. Pipe diameter study

The capability of both methods to realistically reproduce transitions in the flow regime is evaluated in this study. To study both transitions between forced and natural-convection-dominated flow, as well as laminar and turbulent flow, the (inner) pipe diameter is systematically varied from 0.05 m to 0.45 m while keeping the other geometric parameters as described in Section 2.5. Again, all four benchmark ocean profiles are used, and the study is carried out for both the sSUP and cSUP systems. The results of this study are presented in Fig. 13, which shows the flow velocity w (upwelling and downwelling), volume flow rate Q , and Nusselt number N_D over the varied diameter for all four benchmark regions. The distribution of the considered cases across the different flow regimes can be seen in Fig. 14, where the results from the *SP1D* method are plotted on a $Gr-Re$ chart.

Fig. 13 shows that w , Q , and N_D vary significantly with changing diameter. The upwelling and downwelling velocities generally show a maximum between (inner) pipe diameters of 0.05 m and 0.2 m with a sharp decline below the optimum value, which is associated with laminarization of the flow. Especially the shell-side flow of cSUP systems is subject to laminarization, as can be observed in Fig. 14. Above

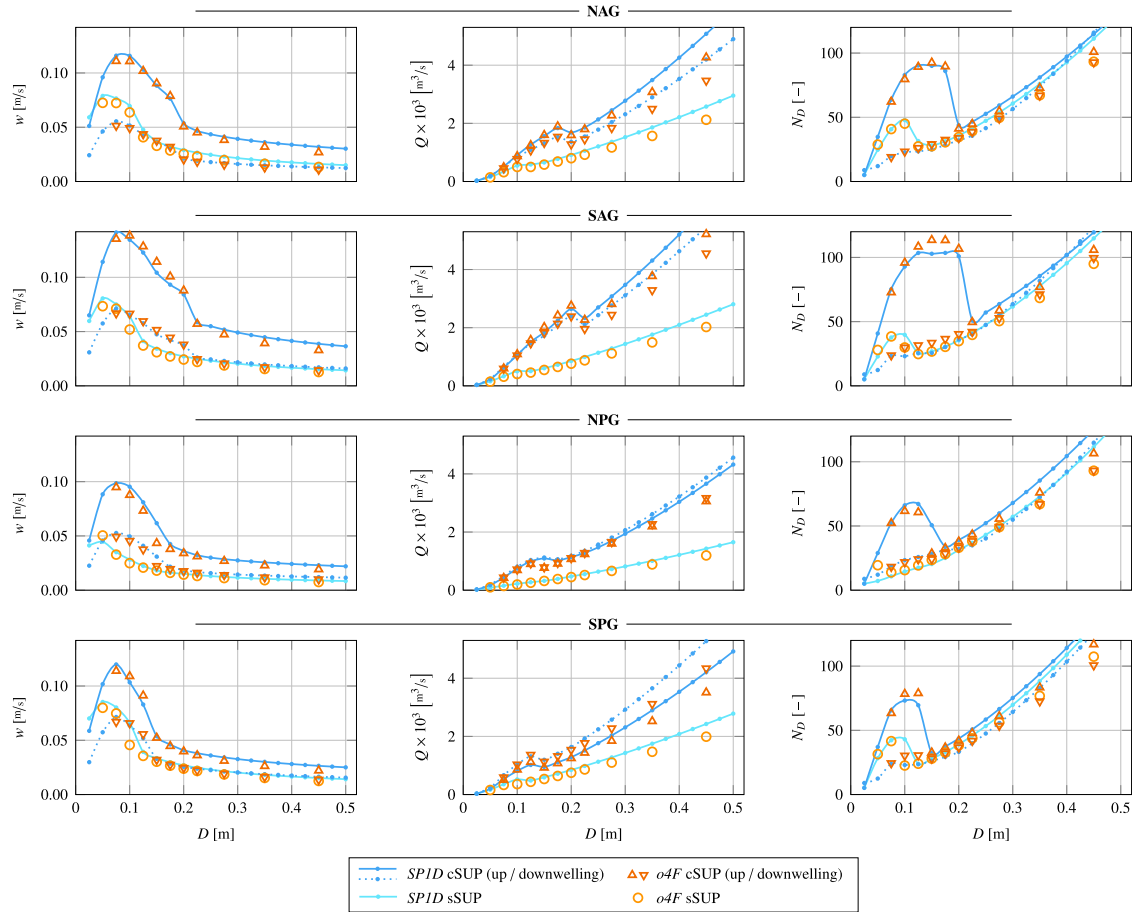


Fig. 13. Pipe diameter study results. Bulk velocity (w), volume upwelling rate Q , and average Nusselt number N_D over changing diameter. Results from both methods are shown for the sSUP and cSUP (upwelling and downwelling) benchmark geometry and all four benchmark depth profiles.

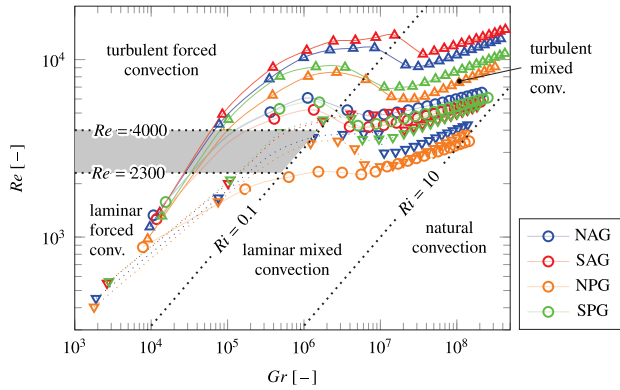


Fig. 14. Chart of flow regimes for the pipe diameter study results. Only the results of the SP1D method are shown for the sSUP and cSUP (upwelling and downwelling) benchmark geometry and all four benchmark depth profiles.

the optimum diameter, the flow velocity typically shows a gradual decline before dropping suddenly. The comparison with Fig. 14 shows that the sudden drop-off in velocity coincides with the onset of mixed convection. The velocity drop-off is thus likely the effect of the sudden onset of mixed-convection heat transfer impairment. At larger diameters, all studied cases show mixed-convection flow, tending to natural

convection with increasing (inner) pipe diameter. The flow velocities, as shown in Fig. 13, decrease gradually across this range.

The volume flow rate Q consistently increases with the pipe diameter throughout the studied range, with only small effects due to mixed-convection heat transfer impairment. For N_D , high values are observed in the turbulent forced-convection range with (inner) pipe diameters of about 0.1 m to 0.2 m, followed by a sharp decline at the onset of mixed convection and a slow recovery throughout the mixed-convection range. This is in line with the typical behavior described in Section 2.3.

A remarkable agreement between the SP1D and *ocean4Foam* results is observed in Fig. 13. All qualitative effects are reproduced consistently by both methods. Some quantitative differences between the *ocean4Foam* and SP1D solutions are observed at high (inner) pipe diameters. The SP1D method consistently seems to predict higher values for w , Q , and N_D in these cases. While this effect could not be entirely explained, it should be remembered that the Nusselt number calculation for the SP1D method is based on a corrected forced-convection value (see Section 2.3). It thus seems plausible that the method can exhibit inaccuracies if the flow tends towards natural convection. As expected from the validation studies presented in Section 2.4, the point of onset of mixed-convection heat transfer impairment is in good agreement between both methods, with only a small deviation being visible for the cSUP-NPG case at $D = 0.15$ m. It should be noted that this small difference in the onset of mixed-convection heat transfer impairment is responsible for the deviation in the upwelling velocity observed in Section 3.1 for the same case.

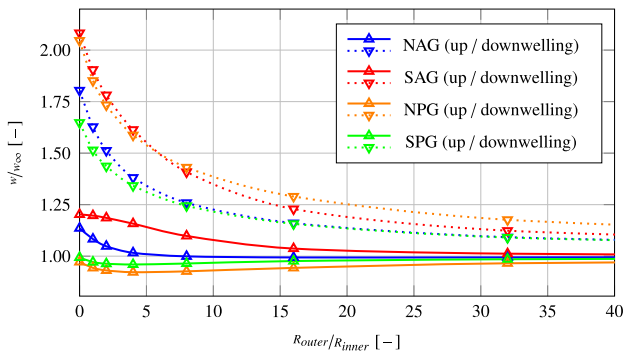


Fig. 15. Influence of outer pipe heat transfer: Bulk velocity (normalized by the value with no outer pipe heat transfer) over outer pipe thermal resistivity (normalized by the inner pipe value). Upwelling (solid lines) and downwelling velocities (dashed lines) for the benchmark cSUP system are given for all four benchmark depth profiles.

3.3. Outer pipe heat transfer

The assumption of no heat transfer with the background ocean through the outer pipe wall of cSUP systems (i.e., between the shell-side flow and the background ocean) has been discussed in Section 2.2. While this assumption plays an important role in formulating the equations of the *SP1D* method, it can easily be avoided using the *ocean4Foam* method. Here, the same convective boundary condition as used for the sSUP cases (see Section 2.5) can be applied to get a simplified model for the outer pipe heat transfer without having to resolve the background ocean. In this study, the thermal resistivity of the outer pipe wall is systematically varied from an idealized value of 0 (no resistivity) to 64 times the resistivity of the inner pipe ($R_{inner} = 2 \times 10^{-3} \text{ K m}^2/\text{W}$). Since the influence is expected to vary based on the background ocean temperature profile, the study was done for all four benchmark profiles. The geometry and the thermal resistivity of the inner pipe follow the benchmark cSUP setup from Section 2.5. The results of this study are shown in Fig. 15, which depicts the upwelling and downwelling velocities, normalized by the no-heat-transfer value from Section 3.1, over the outer-pipe thermal resistivity, normalized by the inner-pipe value. It can be seen that the downwelling velocities increase by a factor of up to 2.1 when heat transfer through the outer pipe is included. The effect on the upwelling velocities is much smaller. In the NAG and SAG cases, the upwelling velocities increase, while in the NPG and SPG cases, a slight reduction in upwelling due to outer pipe heat transfer is possible. This nonuniform effect on the upwelling velocity is caused by a combination of forced-convection and mixed-convection effects in the shell-side flow. While the increased Reynolds number leads to an increased forced-convection Nusselt number, this increase is balanced by a corresponding decrease in the buoyancy parameter Bo (Eq. (7)), which tends to decrease the Nusselt number (see Fig. 7). For the NAG and SAG cases, which generally operate at lower Bo values, the Re effect dominates and leads to an increased overall heat transfer efficiency, while for the NPG and SPG cases, the deteriorating Bo effect is slightly more pronounced. An optimized choice of the outer pipe diameter would likely lead to a significant performance improvement in these cases.

Due to the expected structural function of the outer pipe, a higher thermal resistivity of this pipe seems likely for practical applications. Additionally, the effect of outer pipe heat transfer can be expected to decrease for satSUP systems with more than one inner pipe (due to the lower relative surface area). For realistic applications, it thus seems likely that the negligence of outer pipe heat transfer does not lead to an error of more than 10% in terms of the upwelling velocity, which generally seems to justify this assumption. For setups where the outer pipe has a low thermal resistivity, and perhaps when an exact prediction of the downwelling velocity is of interest, the *SP1D* method should be applied with care.

4. Conclusions

In this work, we have introduced and applied two new performance prediction methods for various types of SUP systems. Both methods have been described in detail. While the RANS-based *ocean4Foam* method is subject to a much lower degree of empirical assumption and applicable to a wider range of geometries, the one-dimensional *SP1D* method runs considerably faster, typically in less than 1/1000 of the time required by the *ocean4Foam* method. The *SP1D* method thus allows for extensive studies while the *ocean4Foam* method enables the investigation of specialized questions (e.g., Section 3.3).

As suitable validation data for SUP systems is not presently available, the versatile *ocean4Foam* method was verified and validated for forced and mixed-convection pipe flow. Throughout this work, we have confirmed in several studies that a correct reproduction of mixed-convection flow phenomena is key for the performance prediction of SUP systems. By comparing the results from both methods for an extensive set of cases involving laminar and turbulent flow as well as forced convection and varying degrees of buoyancy influence, we were able to show that all qualitative phenomena are reproduced with remarkable consistency by the *ocean4Foam* and *SP1D* methods.

We applied the new methods to cSUP and sSUP systems with varying pipe diameters in several ocean conditions, generally finding a higher upwelling performance for cSUP systems. Our results reveal the key flow phenomena relevant to SUP systems while also providing an insight into the range of performance of both SUP types across four subtropical ocean gyres, which are viewed as likely deployment regions for SUP-based artificial upwelling.

We additionally assessed the model assumption of no outer pipe heat transfer using the *ocean4Foam* method. Depending on the deployment region, this assumption can lead to an over- or underprediction of the upwelling velocity. While the downwelling velocity can be considerably affected by outer pipe heat transfer, the effect on the upwelling velocity is unlikely to exceed 10% for realistic pipe geometries.

Being based on a thorough assessment of the involved flow phenomena as well as rigorous verification, validation, and model intercomparison efforts, the results presented in this work mark a new level of confidence in SUP performance prediction. While the presented values are generally encouraging, the results lack generality for a broader conclusion on the potential of the SUP concept. Whether SUP systems represent an enabling technology for large-scale artificial upwelling in the context of marine CDR has to be assessed based on a broader set of ocean and geometry data. Further effects like instantaneous (non-averaged) ocean data, seasonal performance variations, and upscaling of flow rates should be considered. The authors hope that the present work can provide new insights and methodologies to inform these assessments in the future.

CRediT authorship contribution statement

Jost Kemper: Writing – original draft, Visualization, Software, Methodology, Investigation, Data curation, Conceptualization. **Jan Mense:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Conceptualization. **Jörn Kröger:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Thomas Slawig:** Writing – review & editing, Validation, Supervision, Resources. **Kai Graf:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition. **Ulf Riebesell:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was funded by the German *Federal Ministry of Education and Research* (Bundesministerium für Bildung und Forschung, BMBF) in the framework of the *Test-ArtUp* project, which is part of the *CDR-mare* research mission led by the *German Marine Research Alliance* (Deutsche Allianz Meeresforschung, DAM), under Grant Agreement No. 03F0897B. Additional funding was received from the *German Federal Agency for Disruptive Innovations* (Bundesagentur für Sprunginnovationen, SPRIND GmbH) in the framework of the *C-CAUSE* project within the *Carbon-To-Value* challenge.

Appendix. Full equations for the SPID method

The equations of the SPID method were given in Section 2.2 in a generalized form, as

$$c_f \frac{\hat{\rho}}{2} \frac{w^2}{D_h} L = g \left| \int_{z_{top}}^{z_{top}+L} (\rho_{ocean}(z) - \rho(z)) dz \right|, \quad (A.1)$$

$$-A_c w \hat{\rho} c_p(z) \Theta'(z) + C_h U(z) (\Theta_{ot}(z) - \Theta(z)) = 0, \quad (A.2)$$

and

$$\rho = f(S_A, \Theta, P). \quad (A.3)$$

For specific types of SUP systems, the terms take the form given in Table A.3.

For the sSUP system, $D_e = D + 2s$ is the outside diameter of the pipe while N_D and N_{De} are the diameter-based Nusselt numbers (with respect to D and D_e) of the convection inside and outside the pipe wall.

Note that cSUP systems are treated as satSUP systems with a single inner pipe in Table A.3. The number of inner pipes is given by n . For cSUP and satSUP systems, D_i and $D_e = D + 2s$ are the inside and outside diameter of the inner pipe, while D_o is the inside diameter of the shell and D_{ho} represents the hydraulic diameter of the shell. The Nusselt numbers for the inner-pipe and shell-side flow are N_{Di} and N_{Dho} , respectively (i.e., with respect to the diameters D_i and D_{ho}).

Further, s and κ_{wall} are the thickness and thermal conductivity of the (inner) pipe wall, while κ_i , κ_o and κ_{ocean} are the thermal conductivities of the seawater in the inner pipe, shell, and background ocean, respectively.

Data availability

The data and methods that support the findings presented in this work are openly available at the following DOI: [10.5281/zenodo.14394656](https://doi.org/10.5281/zenodo.14394656).

Table A.3

Definition of the terms in the SPID model equations for single SUP (sSUP) systems as well as shell-and-tube type SUP systems (satSUP). Counterflow SUP (cSUP) systems are treated like satSUP systems with a single inner pipe ($n = 1$).

	sSUP	satSUP inner pipe	satSUP shell	Equation
D_h	D	D_i	$\frac{D_o^2 - nD_e^2}{D_o + nD_e}$	(A.1)
A_c	$\frac{\pi}{4} D^2$	$n \frac{\pi}{4} D_i^2$	$\frac{\pi}{4} (D_o^2 - nD_e^2)$	(A.2)
C_h	πD	$n\pi D_i$	$n\pi D_e$	(A.2)
Θ_{ot}	Θ_{ocean}	Θ_o	Θ_i	(A.2)
U	$\frac{1}{D \sum (D_n/h_m)}$	$\frac{1}{D_i \sum (D_n/h_m)}$	$\frac{1}{D_e \sum (D_n/h_m)}$	(A.2)
$\sum (D_n/h_m)$	$\frac{1}{N_D \kappa} + \frac{1}{2\kappa_{wall}} \ln\left(\frac{D_e}{D}\right) + \frac{1}{N_{De} \kappa_{ocean}}$	$\frac{1}{N_{Di} \kappa_i} + \frac{1}{2\kappa_{wall}} \ln\left(\frac{D_e}{D_i}\right) + \frac{1}{D_e N_{Dho} \kappa_o}$	$\frac{1}{N_{Di} \kappa_i} + \frac{1}{2\kappa_{wall}} \ln\left(\frac{D_e}{D_i}\right) + \frac{D_{ho}}{D_e N_{Dho} \kappa_o}$	

References

- Behzadmehr, A., Galanis, N., Laneville, A., 2003. Low Reynolds number mixed convection in vertical tubes with uniform wall heat flux. *Int. J. Heat Mass Transfer* 46 (25), 4823–4833. [https://doi.org/10.1016/S0017-9310\(03\)00323-5](https://doi.org/10.1016/S0017-9310(03)00323-5).
- Boyer, T.P., Baranova, O.K., Coleman, C., Garcia, H.E., Grodsky, A., Locarnini, R.A., Mishonov, A.V., Paver, C.R., Reagan, J.R., Seidov, D., Smolyar, I.V., Weathers, K.W., Zweng, M.M., 2018. *World ocean database 2018*. Mishonov A.V., Tech. Ed., NOAA Atlas NESDIS 87.
- Churchill, S.W., Chu, H.H.S., 1975. Correlating equations for laminar and turbulent free convection from a vertical plate. *Int. J. Heat Mass Transfer* 18 (11), 1323–1329. [https://doi.org/10.1016/0017-9310\(75\)90243-4](https://doi.org/10.1016/0017-9310(75)90243-4).
- Daly, B.J., Harlow, F.H., 1970. Transport equations in turbulence. *Phys. Fluids* 13 (11), 2634. <https://doi.org/10.1063/1.1692845>.
- Durbin, P.A., 1991. Near-wall turbulence closure modeling without “damping functions”. *Theor. Comput. Fluid Dyn.* 3 (1), 1–13. <https://doi.org/10.1007/bf00271513>.
- Dutreuil, S., Bopp, L., Tagliabue, A., 2009. Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability. *Biogeosciences* 6 (5), 901–912. <https://doi.org/10.5194/bg-6-901-2009>.
- Gnielinski, V., 1995. Ein neues berechnungsverfahren für die wärmeübertragung im übergangsbereich zwischen laminarer und turbulenter rohrströmung [a new method to calculate heat transfer in the transition region between laminar and turbulent tube flow]. *Forsch. Ingen.* 61 (9), 240–248. <https://doi.org/10.1007/bf02607964>.
- Gnielinski, V., 2010a. G1 heat transfer in pipe flow. In: *VDI Heat Atlas*. Springer Vieweg, Berlin, Heidelberg, pp. 691–700. https://doi.org/10.1007/978-3-540-77877-6_34.
- Gnielinski, V., 2010b. G2 heat transfer in concentric annular and parallel plate ducts. In: *VDI Heat Atlas*. Springer Vieweg, Berlin, Heidelberg, pp. 701–708. https://doi.org/10.1007/978-3-540-77877-6_35.
- Groves, G.W., 1958. Flow estimate for the perpetual salt fountain. *Deep. Sea Res.* (1953) 5 (2–4), 209–214. [https://doi.org/10.1016/0146-6313\(58\)90013-3](https://doi.org/10.1016/0146-6313(58)90013-3).
- Hinman, K.G., 1966. *Flow Velocity Calculations for a “Perpetual Salt Fountain”* (Master’s thesis). United States Naval Postgraduate School.
- IOC, SCOR, IAPSO, 2010. *The international thermodynamic equation of seawater - 2010: Calculation and use of thermodynamic properties*. Intergov. Ocean. Comm. Manuals Guid. 56.
- Irenfried, C., Steiner, H., 2017. DNS based analytical P-function model for RANS with heat transfer at high Prandtl numbers. *Int. J. Heat Fluid Flow* 66, 217–225. <https://doi.org/10.1016/j.ijheatfluidflow.2017.06.011>.
- Jackson, J., Cotton, M., Axcell, B., 1989. Studies of mixed convection in vertical tubes. *Int. J. Heat Fluid Flow* 10 (1), 2–15. [https://doi.org/10.1016/0142-727x\(89\)90049-0](https://doi.org/10.1016/0142-727x(89)90049-0).
- Jackson, J.D., Hall, W.B., 1979. Influences of buoyancy on heat transfer to fluids flowing in vertical tubes under turbulent conditions. In: Kakac, S., Spalding, D.B. (Eds.), *Turbulent Forced Convection in Channels and Bundles: Theory and Applications To Heat Exchangers and Nuclear Reactors*. vol. 2, Hemisphere, London, pp. 613–640.
- Jamieson, D., Tudhope, J., 1970. Physical properties of sea water solutions: Thermal conductivity. *Desalination* 8 (3), 393–401. [https://doi.org/10.1016/S0011-9164\(00\)80240-4](https://doi.org/10.1016/S0011-9164(00)80240-4).
- Jayatilake, C.L.V., 1969. The influence of Prandtl number and surface roughness on the resistance of the laminar sublayer to momentum and heat transfer. *Prog. Heat Mass Transf.* 1, 193, URL <https://cir.nii.ac.jp/crid/1573105975022941824>.
- Johnson, D.H., Decicco, J., 1983. *Artificial Upwelling Driven by Salinity Differences in the Ocean*. Technical Report, Solar Energy Research Inst., Golden, CO (USA).
- Jürchott, M., Oschlies, A., Koeve, W., 2023. Artificial upwelling—A refined narrative. *Geophys. Res. Lett.* 50, e2022GL101870. <https://doi.org/10.1029/2022GL101870>.
- Kays, W.M., Crawford, M.E., 1993. *Convective Heat and Mass Transfer*, third ed. In: *McGraw-Hill Series in Mechanical Engineering*, McGraw-Hill, New York.
- Keller, D.P., Feng, E.Y., Oschlies, A., 2014. Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nat. Commun.* 5 (1), <https://doi.org/10.1038/ncomms4304>.
- Kemper, J., 2024. ocean4Foam [computer software]. https://doi.org/10.3289/sw_9_2024.
- Kemper, J., Mense, J., 2024. SP1D [computer software]. https://doi.org/10.3289/sw_8_2024.
- Kemper, J., Mense, J., Graf, K., Riebesell, U., Kröger, J., 2023. Towards reliable performance predictions for stommel’s perpetual salt fountain. In: 10th Conference on Computational Methods in Marine Engineering. CIMNE, <https://doi.org/10.23967/marine.2023.018>.
- Kenjereš, S., Gunarjō, S., Hanjalic, K., 2005. Contribution to elliptic relaxation modelling of turbulent natural and mixed convection. *Int. J. Heat Fluid Flow* 26 (4), 569–586. <https://doi.org/10.1016/j.ijheatfluidflow.2005.03.007>.
- Keshmiri, A., Cotton, M.A., Addad, Y., Laurence, D., 2012. Turbulence models and large eddy simulations applied to ascending mixed convection flows. *Flow Turbul. Combust.* 89 (3), 407–434. <https://doi.org/10.1007/s10494-012-9401-4>.
- Kim, W., He, S., Jackson, J., 2008. Assessment by comparison with DNS data of turbulence models used in simulations of mixed convection. *Int. J. Heat Mass Transfer* 51 (5–6), 1293–1312. <https://doi.org/10.1016/j.ijheatmasstransfer.2007.12.002>.

- Kim, W., Talbot, C., Chung, B., Jackson, J., 2002. Variable property mixed convection heat transfer to air flowing through a vertical passage of annular cross section: Part 1. *Chem. Eng. Res. Des.* 80 (3), 239–245. <http://dx.doi.org/10.1205/026387602753581999>.
- Kirke, B., 2003. Enhancing fish stocks with wave-powered artificial upwelling. *Ocean & Coastal Management* 46 (9–10), 901–915. [http://dx.doi.org/10.1016/s0964-5691\(03\)00067-x](http://dx.doi.org/10.1016/s0964-5691(03)00067-x).
- Kithil, P.W., 2006. A device to control sea surface temperature and effects on hurricane intensity. In: *27th Conference on Hurricanes and Tropical Meteorology*.
- Koweek, D.A., 2022. Expected limits on the potential for carbon dioxide removal from artificial upwelling. *Front. Mar. Sci.* 9, <http://dx.doi.org/10.3389/fmars.2022.841894>.
- Laurence, D.R., Uribe, J.C., Utyuzhnikov, S.V., 2005. A robust formulation of the V2-f model. *Flow Turbul. Combust.* 73 (3–4), 169–185. <http://dx.doi.org/10.1007/s10494-005-1974-8>.
- Lovelock, J.E., Rapley, C.G., 2007. Ocean pipes could help the earth to cure itself. *Nature* 449 (7161), <http://dx.doi.org/10.1038/449403a>, 403–403.
- Maruyama, S., Tsubaki, K., Taira, K., Sakai, S., 2004. Artificial upwelling of deep seawater using the perpetual salt fountain for cultivation of ocean desert. *J. Ocean.* 60 (3), 563–568. <http://dx.doi.org/10.1023/b:joce.0000038349.56399.09>.
- McDougall, T.J., 2003. Potential enthalpy: A conservative oceanic variable for evaluating heat content and heat fluxes. *J. Phys. Oceanogr.* 33 (5), 945–963. [http://dx.doi.org/10.1175/1520-0485\(2003\)033<0945:peacov>2.0.co;2](http://dx.doi.org/10.1175/1520-0485(2003)033<0945:peacov>2.0.co;2).
- McDougall, T.J., Jackett, D.R., Wright, D.G., Feistel, R., 2003. Accurate and computationally efficient algorithms for potential temperature and density of seawater. *J. Atmos. Ocean. Technol.* 20 (5), 730–741. [http://dx.doi.org/10.1175/1520-0426\(2003\)20<730:aaceaf>2.0.co;2](http://dx.doi.org/10.1175/1520-0426(2003)20<730:aaceaf>2.0.co;2).
- Menter, F.R., 1994. Two-equation eddy-viscosity turbulence models for engineering applications. *AIAA J.* 32 (8), 1598–1605. <http://dx.doi.org/10.2514/3.12149>.
- Morrison, F.A., 2013. Data correlation for friction factor in smooth pipes. *Dep. Chem. Eng. Mich. Technol. Univ. Houghton, MI* 49931.
- Nguyen, T., Merzari, E., Tai, C.-K., Bolotnov, I.A., Jackson, B., 2023. Toward improved correlations for mixed convection in the downcomer of molten salt reactors. *Nucl. Technol.* 210 (7), 1119–1142. <http://dx.doi.org/10.1080/00295450.2023.2223036>.
- Oschlies, A., Pahlow, M., Yool, A., Matear, R.J., 2010. Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophys. Res. Lett.* 37, L04701. <http://dx.doi.org/10.1029/2009gl041961>.
- Reynolds, A., 1975. The prediction of turbulent Prandtl and Schmidt numbers. *Int. J. Heat Mass Transfer* 18 (9), 1055–1069. [http://dx.doi.org/10.1016/0017-9310\(75\)90223-9](http://dx.doi.org/10.1016/0017-9310(75)90223-9).
- Ricke, K., Ivanova, D., McKie, T., Rugenstein, M., 2021. Reversing sahelian droughts. *Geophys. Res. Lett.* 48 (14), <http://dx.doi.org/10.1029/2021gl093129>.
- Rouai, N.M., 1987. Influences of Buoyancy and Imposed Flow Transients on Turbulent Convective Heat Transfer in a Tube (Ph.D. thesis). University of Manchester.
- Sharqawy, M.H., Lienhard V, J.H., Zubair, S.M., 2010. Thermophysical properties of seawater: A review of existing correlations and data. *Desalination Water Treat.* 16 (1–3), 354–380. <http://dx.doi.org/10.5004/dwt.2010.1079>.
- Stommel, H., Arons, A.B., Blanchard, D., 1956. An oceanographical curiosity: The perpetual salt fountain. *Deep. Sea Res.* (1953) 3 (2), 152–153. [http://dx.doi.org/10.1016/0146-6313\(56\)90095-8](http://dx.doi.org/10.1016/0146-6313(56)90095-8).
- Tsubaki, K., Maruyama, S., Komiya, A., Mitsugashira, H., 2007. Continuous measurement of an artificial upwelling of deep sea water induced by the perpetual salt fountain. *Deep. Sea Res. Part I: Ocean. Res. Pap.* 54 (1), 75–84. <http://dx.doi.org/10.1016/j.dsr.2006.10.002>.
- Wu, J., Keller, D.P., Oschlies, A., 2023. Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: An earth system modeling study. *Earth Syst. Dyn.* 14 (1), 185–221. <http://dx.doi.org/10.5194/esd-14-185-2023>.
- Yool, A., Shepherd, J.G., Bryden, H.L., Oschlies, A., 2009. Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide. *J. Geophys. Res.: Ocean.* 114, C08009. <http://dx.doi.org/10.1029/2008jc004792>.
- You, J., Yoo, J.Y., Choi, H., 2003. Direct numerical simulation of heated vertical air flows in fully developed turbulent mixed convection. *Int. J. Heat Mass Transfer* 46 (9), 1613–1627. [http://dx.doi.org/10.1016/s0017-9310\(02\)00442-8](http://dx.doi.org/10.1016/s0017-9310(02)00442-8).
- Young, W.R., 2010. Dynamic enthalpy, conservative temperature, and the seawater Boussinesq approximation. *J. Phys. Oceanogr.* 40 (2), 394–400. <http://dx.doi.org/10.1175/2009jpo4294.1>.
- Younis, B.A., Speziale, C.G., Clark, T.T., 2005. A rational model for the turbulent scalar fluxes. *Proc. R. Soc. A: Math. Phys. Eng. Sci.* 461 (2054), 575–594. <http://dx.doi.org/10.1098/rspa.2004.1380>.
- Zhang, X., Maruyama, S., Tsubaki, K., Sakai, S., Behnia, M., 2006. Mechanism for enhanced diffusivity in the deep-sea perpetual salt fountain. *J. Ocean.* 62 (2), 133–142. <http://dx.doi.org/10.1007/s10872-006-0039-5>.

Contribution [JPC]

On the potential of Stommel's perpetual salt fountain for artificial upwelling

Citation:

Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025b. On the potential of Stommel's perpetual salt fountain for artificial upwelling. *Environmental Research Letters* 20, 074047. doi:10.1088/1748-9326/ade0d3.

Author contributions:

Conceptualization	J. Kemper , J. Mense
Methodology	J. Kemper , J. Mense
Software	J. Kemper , J. Mense
Validation	J. Kröger, T. Slawig, K. Graf
Investigation	J. Kemper , J. Mense
Resources	J. Kröger, T. Slawig, K. Graf
Data Curation	J. Kemper
Writing - Original Draft	J. Kemper
Writing - Review & Editing	J. Mense, J. Kröger, T. Slawig, K. Graf, U. Riebesell
Visualization	J. Kemper , J. Mense
Supervision	J. Kröger, T. Slawig, K. Graf, U. Riebesell
Project administration	J. Kröger, K. Graf, U. Riebesell
Funding acquisition	J. Kröger, K. Graf, U. Riebesell

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.



ENVIRONMENTAL RESEARCH
LETTERS

LETTER

On the potential of Stommel's perpetual salt fountain for artificial upwelling

OPEN ACCESS

RECEIVED
31 January 2025REVISED
2 May 2025ACCEPTED FOR PUBLICATION
4 June 2025PUBLISHED
16 June 2025Original Content from
this work may be used
under the terms of the
[Creative Commons
Attribution 4.0 licence](#).Any further distribution
of this work must
maintain attribution to
the author(s) and the title
of the work, journal
citation and DOI.Jost Kemper^{1,2,*} , Jan Mense³ , Jörn Kröger², Thomas Slawig^{1,4} , Kai Graf² and Ulf Riebesell³ ¹ Department of Computer Science, Kiel University, Christian-Albrechts-Platz 4, 24118 Kiel, Germany² Institute for Naval Architecture and Maritime Engineering, Kiel University of Applied Sciences, Grenzstraße 3, 24149 Kiel, Germany³ Biological Oceanography, GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstraße 1-3, 24148 Kiel, Germany⁴ Kiel Marine Science (KMS)—Centre for Interdisciplinary Marine Science, Christian-Albrechts-Platz 4, 24118 Kiel, Germany

* Author to whom any correspondence should be addressed.

E-mail: jost.kemper@email.uni-kiel.de**Keywords:** carbon dioxide removal (CDR), artificial upwelling, perpetual salt fountain, Stommel upwelling pipe, feasibility assessment, numerical modeling**Abstract**

Artificial upwelling (AU) of nutrient-rich deep ocean water to the surface ocean has been proposed to increase ecosystem productivity and enhance CO₂ uptake. AU is thus considered a marine carbon dioxide removal option among other potential uses. Due to the typical temperature and salinity depth profiles in wide parts of the oceans, a self-sustaining up or downflow within a vertical pipe can be established. This concept was introduced by Stommel *et al* (1956 *Deep Sea Res.* 3 152–3) as the *perpetual salt fountain*. Using a one-dimensional numerical performance prediction method for Stommel upwelling pipe (SUP) systems, previously developed and verified by Kemper *et al* (2025 *Appl. Ocean Res.* 160 104624), several studies on the potential of the SUP concept for AU are reported in the present work. A global assessment of the AU potential of SUP systems is presented, and the spatial and temporal variability of their performance is discussed. Additionally, an overview of upscaling and optimization design considerations for SUP systems is given based on a parametric study. Our results show that considerable parts of the global oceans are suitable for SUP-based AU of nutrients. The highest potential is found in the subtropical ocean gyres. We further find a significant seasonal pattern in the upwelling velocity. Upscaling of SUP systems to achieve practically significant flow rates for AU is found possible.

Nomenclature**Symbols**

P	hydrostatic pressure (N m ⁻²)
Q	volume flow rate (m ³ s ⁻¹)
S_A	absolute salinity (g kg ⁻¹)
Θ	conservative temperature (°C)
ρ	density (kg m ⁻³)
N_D	diameter-based Nusselt number = $\frac{hD}{\kappa}$
	(—)
A_c	pipe cross-sectional area (m ²)
c_f	Darcy pipe friction factor (—)
C_h	heat-transferring circumference (m)
c_p	specific heat capacity (J (Kg K) ⁻¹)
D	pipe diameter (m)
D_h	hydraulic pipe diameter (m)
g	gravity (ms ⁻²)
L	pipe length (m)
n	number of inner pipes of shell-and-tube type SUP systems

s	pipe wall thickness (m)
U	overall heat transfer coefficient across pipe wall (W (m ² K) ⁻¹)
w	pipe velocity (ms ⁻¹)
z	vertical pipe coordinate (positive down) (m)
κ	thermal conductivity (W (m K) ⁻¹)

Subscripts and averaging

$\hat{\phi}$	averaged quantity over the pipe length
ϕ_i	quantity w.r.t. inner pipe
ϕ_{top}	quantity at upper pipe end
ϕ_{bottom}	quantity at lower pipe end
ϕ_o	quantity w.r.t. shell side of counterflow or shell-and-tube type systems
ϕ_{ocean}	quantity w.r.t. the surrounding ocean
ϕ_{wall}	quantity of pipe wall material

Abbreviations

AU	Artificial upwelling
CDR	Carbon dioxide removal
SUP	Stommel upwelling pipe

1. Introduction

In accordance with the Paris Agreement's goal to balance anthropogenic sources and sinks of greenhouse gases in the atmosphere and stabilize the global temperature level, many countries have committed to reducing their CO₂ emissions to at least net zero (Black *et al* 2021). It is widely agreed within science and politics that pathways to achieve these targets include active CDR from the atmosphere (IPCC 2021). Within the portfolio of possible CDR measures, several options encompass the use of marine regions.

AU of nutrient-rich deep ocean water to the ocean's sunlit surface layer is being considered as a marine CDR option, either alone (Lovelock and Rapley 2007, GESAMP 2019) or in combination with other CDR measures such as open-ocean macroalgae mariculture and sinking (Kowek 2022, Wu *et al* 2023). By fertilizing ocean regions with currently low biological productivity, AU concepts typically aim to enhance oceanic CO₂ uptake via a natural process known as the biological carbon pump.

Several authors have studied the climate effects of AU, partially finding reduced effectiveness due to the typically high inorganic carbon (Yool *et al* 2009, Jürchott *et al* 2023) and low iron content (Jürchott *et al* 2024) of the upwelled water as well as substantial side effects on ocean physics (Oschlies *et al* 2010). Most studies in the context of CDR have focused on wave-driven upwelling devices (Lovelock and Rapley 2007). Other technical concepts include mechanical pumping using offshore wind energy (Viúdez *et al* 2016) or air injection (Liang and Peng 2005) to drive the flow. The present work will focus on an alternative technical concept proposed by Stommel *et al* (1956). Stommel's AU concept aims to generate a self-sustaining upwelling flow by using fundamental principles of thermohaline convection. In many ocean regions, surface waters have both higher temperatures and higher salinity than the deep ocean water. With regard to density, the effect of temperature predominates and stabilizes the stratification of the water column. The smaller salinity effect counteracts the temperature effect, thus reducing the stratification stability. If a vertical pipe is introduced and filled with deep ocean water once, the cold water in the pipe will eventually be heated by the surrounding water while retaining its low salinity. The water column inside the pipe will thus become buoyant with respect to the surrounding water, and an

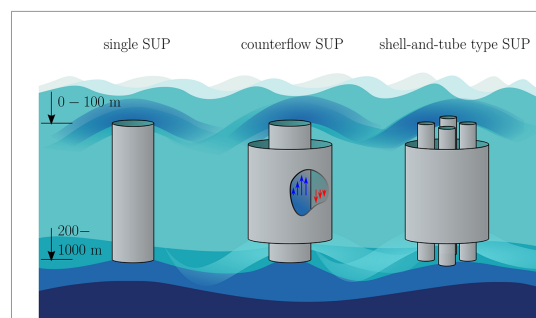


Figure 1. Basic types of SUP systems. Adapted from Kemper *et al* (2025). CC BY 4.0.

upward flow in the pipe will be initiated. Once a steady state of this process is reached, the flow will continue without any mechanical forcing. Stommel *et al* (1956) called this effect *perpetual salt fountain*. It is worth noting that Stommel's effect can also be used to drive downwelling instead of upwelling if the pipe is initially filled with surface water instead of deep ocean water. Since its publication, several device concepts have been proposed based on this principle (Stommel *et al* 1956, Johnson and Decicco 1983). In the present work, all these device concepts are summarized under the term SUP. Three SUP types are considered: A simple upwelling pipe, a counterflow pipe, where upwelling based on the salt fountain effect is established in the inner pipe and downwelling in the outer pipe, and an upscaled counterflow pipe with a shell-and-tube setup. The three types are referred to as single SUP, counterflow SUP, and shell-and-tube type SUP. A schematic overview is given in figure 1.

SUP systems combine several advantageous properties for AU: they do not require an external energy supply. They are technologically simple in the sense that they do not require any moving parts in their construction. Upon exiting the system at the surface, the deep ocean water is already heated up to some extent and thus exhibits a lower tendency to sink back down, as seen with other AU concepts (Kirke 2003).

A short review of previous efforts to quantify the performance of SUP systems was performed as part of recent work by Kemper *et al* (2025). As previous studies on SUP performance yielded a wide range of results with little confidence, two new numerical methods were introduced, the Reynolds-averaged Navier–Stokes equation solver *ocean4Foam* (Kemper 2024) and the one-dimensional pipe-flow model *SP1D* (short for *Stommel-Pipe one-dimensional*) (Kemper and Mense 2024). The predictive capabilities of both methods were proven through rigorous verification, validation, and model intercomparison (see Kemper

et al 2025 for details). Building on these efforts, the computationally efficient *SPID* model is used in the present work to quantify the global potential of SUP systems for AU, as well as its variability, and the potential for upscaling of SUP systems.

2. Numerical method

In this work, a numerical performance prediction method for SUP systems is used (Kemper and Mense 2024, version 8c679e96). Performance is typically evaluated in terms of the upwelling velocity w , which determines the volumetric flow rate and thus the potential nutrient transport for AU. The numerical method was described in detail by Kemper et al (2025), here only a summary of the main equations and their solution is given, followed by the definition of the studied pipe geometry.

2.1. The *SPID* method

This method solves the two basic equilibria introduced by Groves (1958). It is able to predict the performance for different SUP types. The basic equations are presented here in a generalized form. Differences between the formulations for different SUP types are pointed out where necessary.

The first equilibrium is formulated as a pressure balance between the hydrostatic pressure head and the dynamic pressure loss. For a fully developed steady-state flow, this equation reads

$$c_f \frac{\hat{\rho}}{2} \frac{w^2}{D_h} L = g \left| \int_{z_{top}}^{z_{top}+L} (\rho_{ocean}(z) - \rho(z)) dz \right|. \quad (1)$$

Here, w is the unknown bulk velocity, c_f is the Darcy pipe friction factor, D_h is the hydraulic pipe diameter, g is the gravitational acceleration, and z is the depth (positive downwards). Further, ρ and ρ_{ocean} are the bulk density of the water inside the pipe and the background ocean, respectively, and $\hat{\rho}$ is the average density over the pipe length. The density of seawater is calculated from the equation of state

$$\rho = f(S_A, \Theta, P), \quad (2)$$

where Θ , S_A , and P are conservative temperature, absolute salinity, and hydrostatic pressure, respectively. The background ocean values Θ_{ocean} and $S_{A,ocean}$ are known functions of z . Also, the salinity inside the pipe is known, as it uniformly takes the inlet value. Given the (yet unknown) temperature profile $\Theta(z)$, the velocity w can be calculated from equations (1) and (2).

To obtain the temperature profile, the second equilibrium is formulated as a balance between convective heat transfer in the axial direction and radial

conductive heat transfer through the pipe wall. This yields the following ordinary differential equation, which can be solved for the temperature profile over the interval (z_{top}, z_{bottom}) , using the known inlet temperature as boundary condition

$$-A_c w \hat{\rho} c_p(z) \Theta'(z) + C_h U(z) (\Theta_{ot}(z) - \Theta(z)) = 0. \quad (3)$$

Here, A_c is the cross-sectional area of the pipe, C_h is the heat-transferring circumference and Θ_{ot} refers to the temperature on the other side of the pipe wall (i.e. the background ocean temperature in the single SUP case, the shell-side value when the equation is solved for the inner pipe of a counterflow or shell-and-tube type system, and vice versa⁵). Further, c_p is the heat capacity of the seawater and U represents an overall heat transfer coefficient, which incorporates the thermal resistance of the pipe wall as well as the influence of the convection on either side of the wall. Consequently, U depends on the respective thermal conductivities κ and Nusselt numbers N_D .

For counterflow and shell-and-tube type systems, the unknowns w and Θ have to be calculated for the inner pipe as well as the shell⁶. Equations (1) and (3) thus yield a coupled system of four equations. With correlations for the pipe friction factor, the Nusselt number, and the fluid properties, the system is closed for any given pipe geometry and ocean profile (i.e. Θ_{ocean} and $S_{A,ocean}$). An iterative process is employed to solve the system of equations.

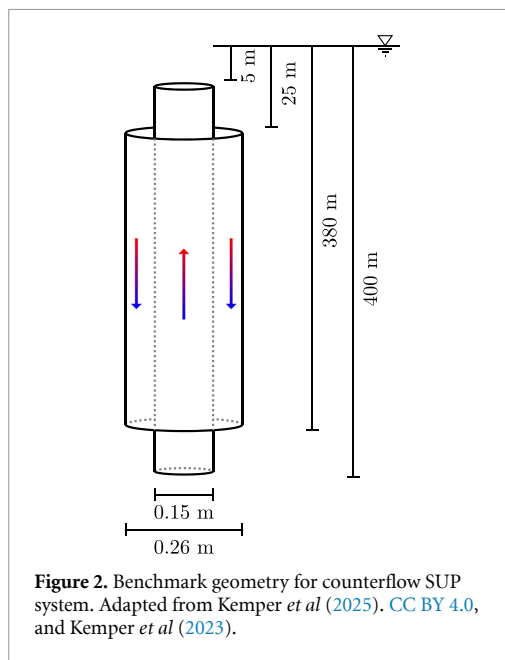
The above equation set contains two empirical coefficients, c_f and U . The *SPID* method calculates these coefficients by applying a combination of standard engineering correlations for pipe flows of various flow regimes (laminar and turbulent forced and mixed-convection flow). The full methodology was described and validated by Kemper et al (2025).

2.2. The pipe geometry

The present work mainly deals with counterflow SUP systems. A benchmark geometry is thus defined for this type of system. Upscaling of the geometry to shell-and-tube type systems is discussed in section 3.3, while single SUP systems are discussed in the appendix. The benchmark counterflow SUP setup is depicted in figure 2 along with the relevant dimensions. The outer pipe diameter is set based on an inner-to-outer-pipe cross-sectional flow area ratio (A_i/A_o) of 0.5. The thermal resistivity ($R = \frac{s}{\kappa_{wall}}$) of

⁵ Note, that for counterflow and shell-and-tube type systems any possible heat transfer between the shell side-flow and the background ocean (i.e. through the outer pipe wall) is neglected. This assumption was evaluated in Kemper et al (2025).

⁶ One representative inner pipe is considered in the case of shell-and-tube type systems.



the inner pipe wall is $2 \times 10^{-3} \text{ K m}^2 \text{ W}^{-1}$, which is representative of a HDPE pipe with a wall thickness of 1 mm. To avoid any direct interaction of the upwelling and downwelling flows, the ends of the inner pipe and shell are separated by a depth difference of 20 m. The dimensions of the system were chosen based on feasibility considerations. They do not represent ideal values from a performance perspective, as will be seen in section 3.3.

3. Results

In the following, the method described in section 2 will be applied to study the potential of counterflow and shell-and-tube type SUP systems for AU. Results for a single SUP system are given in the appendix. The data presented in this section are available as part of the supplementary material to this work (Kemper *et al* 2024).

3.1. Global upwelling potential

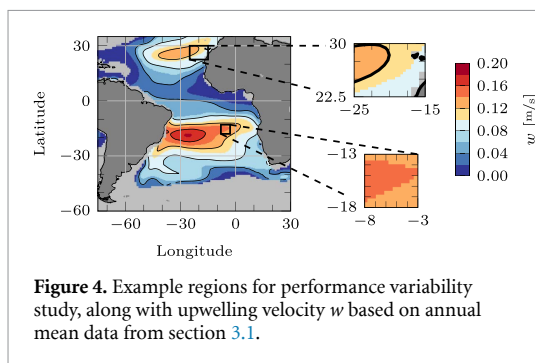
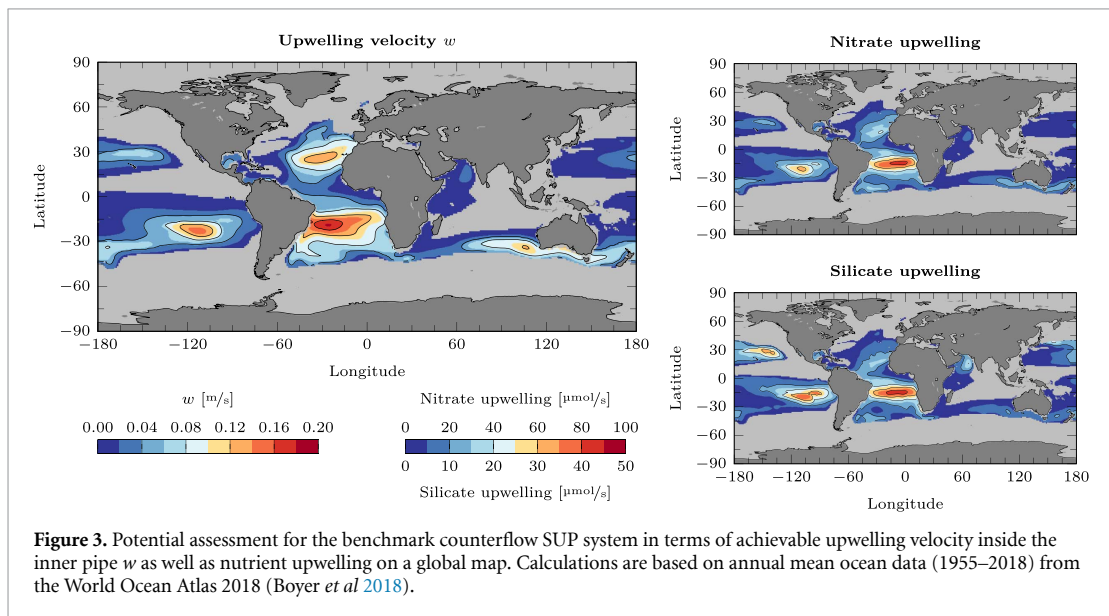
The potential for SUP-based upwelling is evaluated by studying a global set of discrete annual mean data (over the years 1955–2018) from the World Ocean Atlas 2018 (Boyer *et al* 2018). Figure 3 shows the results in terms of achievable upwelling velocities inside the pipe⁷ on a global map. Also, the nitrate and silicate fluxes are shown.

⁷ Figure 3 indicates the potential for upwelling velocities inside a single benchmark counterflow SUP system in various locations. The results should not be mistaken as area-averaged values for a hypothetical global-scale deployment.

Figure 3 indicates considerable potential for AU in and around the subtropical ocean gyres, with large areas of the South Atlantic providing ideal conditions for SUP systems. Additionally, considerable upwelling velocities can be achieved in the South Indian Ocean and along the Australian south coast. When considering the AU potential in terms of nutrient upwelling, the available area is strongly decreased and slightly shifted with respect to the upwelling velocity pattern. Only the South Atlantic around latitude 10° S provides ideal conditions for SUP-based nitrate upwelling, with some potential also available in the South Pacific. SUP-based silicate upwelling follows a similar global pattern, with some exceptions. High silicon-to-nitrogen (Si:N) ratios of the upwelled deep ocean water are considered favorable for AU-based CDR (Goldenberg *et al* 2022). In the Atlantic, the Si:N ratio of the upwelled water for the benchmark geometry is typically around 0.5. Values above unity can be achieved in the Pacific at the expense of lower nitrate upwelling. The bottom depth of the benchmark geometry of 400 m limits the nutrient upwelling potential to some extent. Longer SUP systems would provide more potential in wider ocean regions and likely also higher upwelling velocities (see section 3.3). Finally, it should be noted that the upwelling of nutrients does not directly translate to CDR potential, as the upwelled water may also contain excess dissolved carbon (Yool *et al* 2009, Jürchott *et al* 2023) and iron limitation may constrain the biological productivity (Jürchott *et al* 2024).

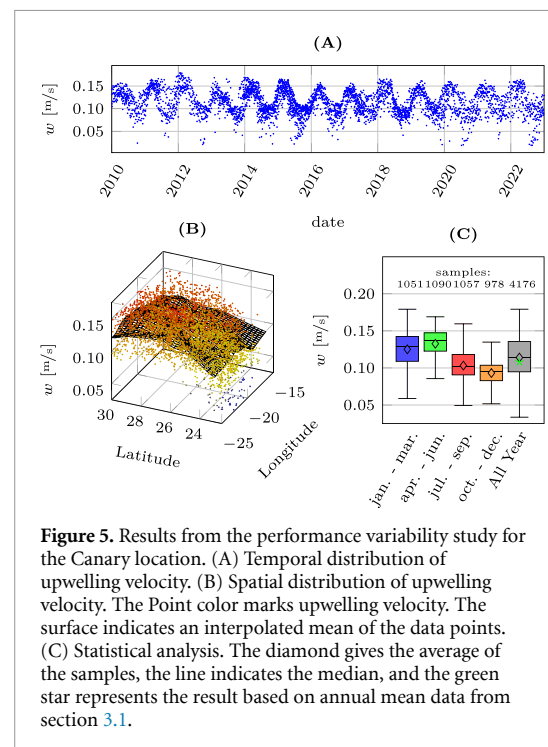
3.2. Variability of the upwelling performance

In the previous study, the potential of SUP systems for AU has been evaluated based on annual mean ocean data. These results are extended here with studies on instantaneous depth profiles, based on ARGO data (Wong *et al* 2020), which are more representative of the ocean conditions encountered by the SUP system on a typical day. Two example regions, north of the island of St. Helena (13° S to 18° S and 3° W to 8° W) and south of the Canary Islands (22.5° N to 30° N and 15° W to 25° W), are studied. The St. Helena location was chosen as a maximum-potential case, as this region showed the highest nutrient upwelling in the global study of section 3.1, while the Canary location was chosen as a typical prototype testing location with good accessibility and infrastructure. The extent of both study regions is shown in figure 4 along with the upwelling performance based on annual mean profile data from section 3.1. All ARGO datasets from the years 2010 to 2023 were used to calculate the performance of the benchmark counterflow SUP system (section 2.2). In total, 1353 cases were studied for the St. Helena location and 4176 cases for the Canary location. Figures 5 and 6 show the results of this study



for the Canary and St. Helena locations, respectively. Here, the temporal (A) and spatial (B) variation of the upwelling velocity is shown along with a statistical analysis (C). For a better appreciation of the mean spatial variability, an interpolated surface through the individual data points is added to the spatial variability plots. The results shown in figures 5 and 6 provide a good insight into the SUP performance in the respective regions. Both regions show a certain degree of spatial variability (figures 5 and 6(B)), the mean variation is in good agreement with the annual mean predictions from figure 4. Additionally, a large temporal variability with distinct seasonal patterns is found (figures 5 and 6(A)). High upwelling velocities are observed around local springtime in both locations.

In the Canary location, upwelling velocities are generally lower than in the St. Helena location. Over the entire year, the values are almost invariably above 0.05 m s^{-1} , while upwelling velocities above 0.13 m s^{-1} are achieved in about 25% of the cases.



Over the first half of the year, about 50% of the values are above 0.13 m s^{-1} .

In the St. Helena location, the upwelling velocities are consistently above 0.08 m s^{-1} and show slightly less variability than in the Canary location. Here, the upwelling velocities are higher in the second half of the year (around austral spring). The all-year probability of achieving velocities above 0.15 m s^{-1} is about

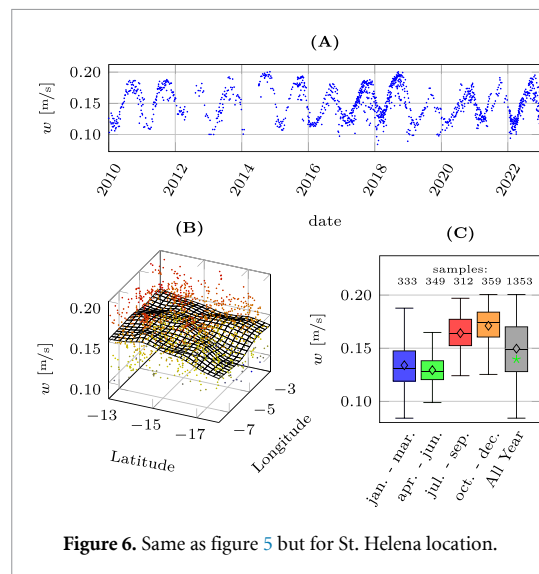


Figure 6. Same as figure 5 but for St. Helena location.

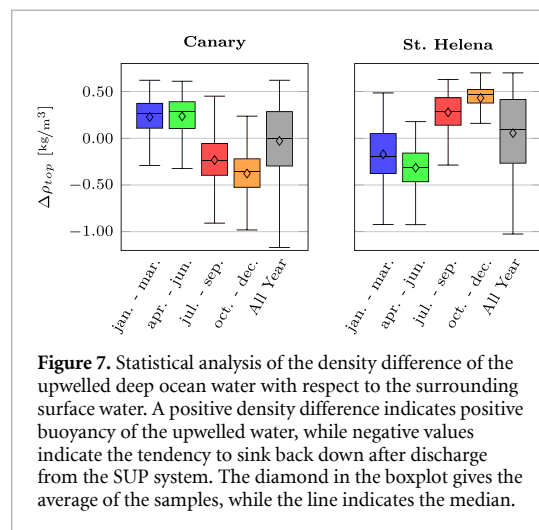


Figure 7. Statistical analysis of the density difference of the upwelled deep ocean water with respect to the surrounding surface water. A positive density difference indicates positive buoyancy of the upwelled water, while negative values indicate the tendency to sink back down after discharge from the SUP system. The diamond in the boxplot gives the average of the samples, while the line indicates the median.

50%. The present study confirms the South Atlantic as an ideal location for SUP-based upwelling, with both high mean performance and low variability.

The upwelling velocity based on the global study presented in section 3.1 is indicated by the green star in figures 5(C) and 6(C). For both locations, the value is in reasonable agreement with the average performance from the present study, considering the different types of data.

In section 1, the reduced tendency of the upwelled deep ocean water to sink back down has been mentioned as a potential advantage of SUP systems over other AU concepts. This is due to the fact that in an SUP system, the deep ocean water is significantly heated through the upwelling process and thus has a lower density when discharged at the surface. Figure 7 shows a statistical analysis of the absolute density difference between upwelled deep ocean water and

Table 1. Studied parameter ranges for shell-and-tube type SUP parameter study. D_o is the shell diameter, A_i/A_o is the cross-sectional flow-area ratio between inner pipes and shell, R is the thermal resistivity of the pipe wall, z_{bottom} is the bottom depth of the system and n is the number of inner pipes.

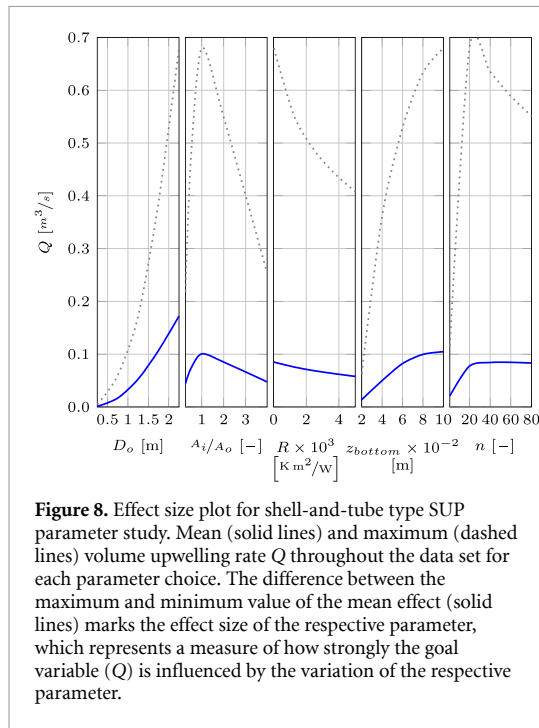
Parameter	Studied range
D_o	0.25–2.25 m
A_i/A_o	0.25–4
R	2×10^{-5} – 5×10^{-3} K m ² W ⁻¹
z_{bottom}	200–1000 m
n	1–80

surrounding water at the pipe outlet depth for both study locations. Here, a positive value indicates positive buoyancy of the upwelled water, while negative values indicate negative buoyancy (i.e. the tendency to sink back down). Figure 7 shows that typical density differences are in the range of -0.5 kg m⁻³ to 0.5 kg m⁻³. This is considerably less than the initial density difference between deep ocean and surface water, which is 3.3 kg m⁻³ on average across both regions. Only 50% of the cases achieve positive buoyancy of the upwelled water in the Canary location, while the value is slightly higher in the St. Helena location. As expected, the results are highly variable and especially show a strong seasonal variability. These results demonstrate that the problem of negative buoyancy of the upwelled water (Kirke 2003) is not generally avoided by SUP systems. However, by extending the pipe horizontally inside the warm surface region, further heating of the upwelled water can be achieved. While such extensions have not been studied in this work, it seems likely that they would be used in a real deployment to avoid negative buoyancy of the upwelled water under all conditions.

3.3. Upscaling and optimization

Shell-and-tube type SUP systems offer the potential to scale up flow rates from SUP-based upwelling to practically relevant magnitudes for AU. The two main scaling considerations for these systems are the shell diameter D_o and the number of inner pipes n . Yet, multiple other geometrical parameters need to be optimized simultaneously to achieve optimal scaling.

The following optimization study was done for a shell-and-tube type system with one (counterflow SUP) to 80 inner pipes. All parameter variations are given in table 1. The geometry is in line with the benchmark design defined in section 2.2, except for the varied or directly affected (D_i and κ_{wall}) parameters. A full factorial experimental design with 3125 cases (5 variations per parameter) was chosen. A typical South Atlantic ocean profile was used. Figure 8 shows the mean effect size of all parameter variations on the volume upwelling rate Q . Not surprisingly, the volume upwelling rate Q increases with



the shell diameter D_o , which governs the total system size and has the strongest effect of all studied parameters. Upwelling rates above $0.5 \text{ m}^3 \text{ s}^{-1}$ are only achieved with large shell diameters, above 1.9 m. The cross-sectional flow-area ratio A_i/A_o has a much smaller effect size, with an optimum at A_i/A_o for both the mean and the maximum effect (solid and dashed line in figure 8). The thermal resistivity R has a monotonic negative effect on the volume upwelling rate and a comparably small effect size. However, upwelling rates above $0.5 \text{ m}^3 \text{ s}^{-1}$ are almost exclusively found with R below $2 \times 10^{-3} \text{ K m}^2 \text{ W}^{-1}$ (i.e. a 1 mm HDPE pipe). The system's bottom depth z_{bottom} has a large, positive effect (i.e. the performance is better for longer pipes), making z_{bottom} an important parameter. Finally, the effect of the number of inner pipes n on the volume upwelling rate Q is slightly smaller than that of z_{bottom} . The effect seems to be stronger at lower values (below 20 inner pipes). Typically, an optimum n can be found within the studied range.

Figure 9 shows the correlation of the mean effects of the shell diameter D_o and the number of inner pipes n on the volume upwelling rate Q . This representation shows the interaction of the two upscaling options. The results are given for $z_{\text{bottom}} = 400 \text{ m}$ and $z_{\text{bottom}} = 800 \text{ m}$. The cross-sectional flow-area ratio A_i/A_o is limited to the optimum value of 1 while the given results are averaged over all variations of R . Generally, the effects observed in figure 8 are confirmed in figure 9. While n and D_o seem equally

effective for upscaling the volume upwelling rate for small bottom depths (figure 9(A)), D_o becomes the dominant upscaling option for large bottom depths (figure 9(B)).

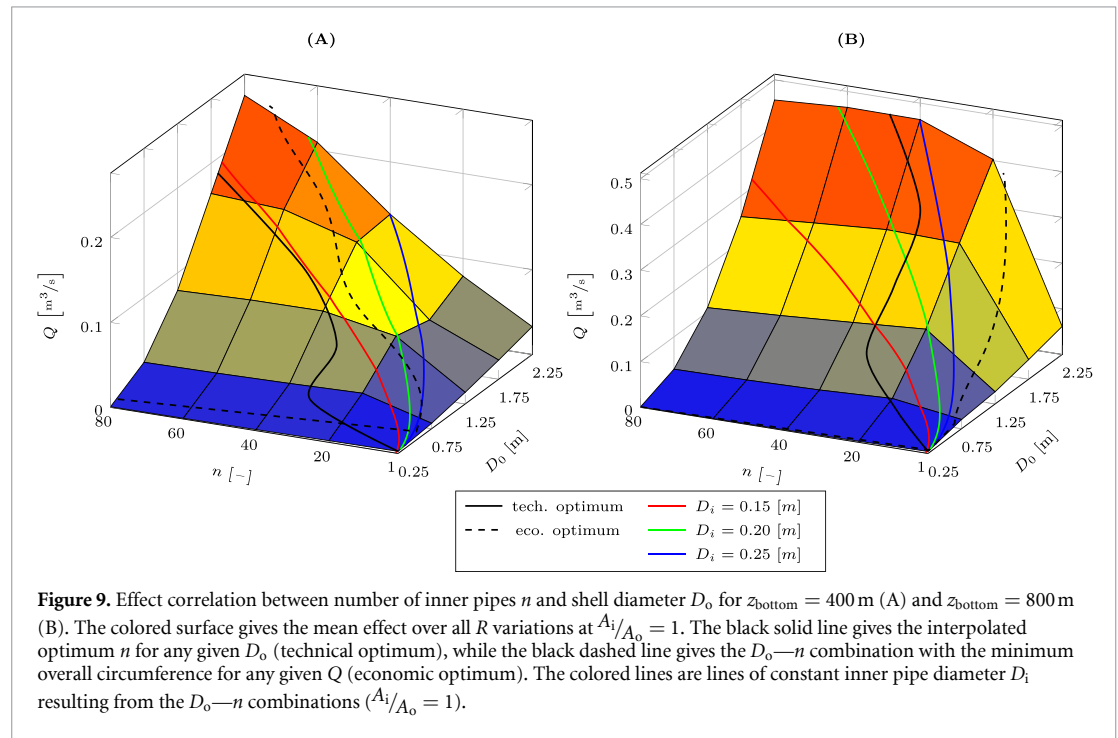
An optimum number of inner pipes can typically be found for any given shell diameter. This can be viewed as a technical optimum, which maximizes the upwelling flow rate for given overall dimensions. This optimum $D_o - n$ combination is indicated by the black solid line in figure 9. Systems with one inner pipe (counterflow SUP systems) seem ideal for the smallest shell diameters, while with increasing shell diameters, larger n values are preferable.

For a practical system optimization, the goal is typically to achieve a given target flow rate at minimum economic cost. Here, the overall circumference of all outer and inner pipes $\pi(D_o + nD_i)$ is taken as a proxy for economic cost. The black dashed line in figure 9 marks the setup with the minimum cost for any given upwelling flow rate Q . This is viewed as the economic optimum $D_o - n$ combination in the following. Generally, larger D_o and lower n values than for the technical optimum are found to be economically favorable.

Since the inner pipe diameter D_i is a derived parameter in this study, its mean effect is not separately evaluated in figure 8. Iso-lines for D_i are given by the colored lines in figure 9. As can be seen, both optima (technical and economic) occur around a limited set of inner pipe diameters. These results suggest that upscaling of shell-and-tube type SUP systems with a constant D_i and A_i/A_o , as done in our previous work (Kemper et al 2023), represents a valid assumption of optimal scaling. Under these conditions, an approximately linear scaling of Q with the number of inner pipes is found (e.g. a shell-and-tube type system with $n = 20$ achieves about 20 times the flow rate of a corresponding counterflow SUP with equal D_i and A_i/A_o). The fact that this guideline provides a simplistic and perhaps incomplete model of optimal scaling can easily be seen from the present results. However, the linear scaling model at constant D_i and A_i/A_o can provide a valuable first assumption of achievable flow rates in the context of techno-economic feasibility assessment.

4. Discussion

To provide some context to the results presented in section 3, a comparison with upwelling rates assumed in previous studies on AU is appropriate. Previous studies on AU as a marine CDR option have been predominantly based on wave-driven AU pipes. Mostly, upwelling volumes of $0.12 \text{ m}^3 \text{ s}^{-1}$ to $0.23 \text{ m}^3 \text{ s}^{-1}$, and pipe depths of 200 m to 1000 m have been assumed (Yool et al 2009, Oschlies et al 2010, Keller et al 2014,



Jürchott *et al* 2023). Koweek (2022) provides a comprehensive overview of previous assumptions, calculations, and results of field trials of AU devices. Finding that the upwelling rates and system depths achieved in field trials were generally lower than the values assumed (or predicted) in modeling studies, Koweek (2022) defines a rate of $0.05 \text{ m}^3 \text{ s}^{-1}$ and a pipe depth of 500 m as a feasibility limit for the near future.

In the present work, upwelling velocities above 0.08 m s^{-1} are predicted over significant parts of the global oceans (about 8%) with a system depth of 400 m. Considering that the benchmark counterflow SUP system only transports $1.4 \times 10^{-3} \text{ m}^3 \text{ s}^{-1}$ at this upwelling velocity, a corresponding shell-and-tube type system with about 40 inner pipes would be necessary to achieve the upwelling rate of $0.05 \text{ m}^3 \text{ s}^{-1}$ envisioned by Koweek (2022). Although the results of section 3.3 suggest that perhaps a more optimized shell-and-tube type design could achieve the same flow rate with a less complicated geometry, this discussion indicates that, outside of the ideal ocean regions, SUP systems are likely not economically competitive with wave-driven AU devices in terms of the achieved upwelling flow rate. However, several additional findings from the present work affect the techno-economic competitiveness of SUP systems and should thus be discussed. As seen in section 3.3, the effectiveness of SUP systems generally increases with increasing bottom depth (length) of the system. Considering that longer pipes allow for deep ocean water with higher nutrient concentrations to be reached, this scaling behavior of SUP systems marks a distinct advantage over wave-driven

AU systems, which tend to become less effective with increasing bottom depth (Kirke 2003). Additionally, as seen in section 3.2, SUP systems can upwell deep ocean water heated and buoyant with respect to their surroundings. This fact is viewed primarily as an aid in keeping the upwelled nutrients in the euphotic zone, where they can be utilized for primary production. When considering a global-scale application of AU (as previously done in modeling studies (Yool *et al* 2009, Oschlies *et al* 2010, Keller *et al* 2014, Jürchott *et al* 2023)), the same effect is additionally expected to reduce several reported side effects of AU, such as heating of the interior ocean (Oschlies *et al* 2010) and reduction of the upper ocean stratification stability (Dutreuil *et al* 2009)⁸. Consequently, the relative techno-economic potential of SUP systems will likely depend on the question of whether effective low-cost, low-tech implementation approaches can be developed, on the importance of positive buoyancy of the upwelled water, and on the specific deployment region and source depth considered.

5. Conclusions

The AU potential of SUP systems has been evaluated in this work based on numerical studies, using the one-dimensional SPID method.

The global AU potential for a benchmark counterflow SUP system was studied based on annual

⁸ As SUP systems are driven by the ocean's potential energy, their operation will generally act to reduce this energy budget and thus stabilize rather than destabilize the ocean's density stratification.

mean ocean data. While large areas of the global oceans provide significant potential for SUP performance, nutrient availability in the deep ocean water can limit the AU potential to some extent, depending on the system's bottom depth. The South Atlantic provides the most favorable conditions for SUP-based AU. Additionally, the temporal and small-scale spatial variability of the upwelling performance was studied for two example regions, yielding valuable insight into the statistical aspects of SUP performance and revealing a considerable seasonal variation.

Finally, an overview of the upscaling and optimization potential of shell-and-tube type SUP systems was obtained by performing a full design parameter study.

Stommel *et al* (1956) considered any practical potential of their discovery improbable. After first predictions of achievable flow rates, Groves (1958) came to a similar conclusion. Today, global climate change and the resulting need for large-scale CDR lead to a renewed interest in the concept and motivate a reevaluation of its viability. While the present work has shown the considerable potential of SUP systems to drive large-scale upwelling of nutrients in the open ocean, it appears that the practical significance of this potential should ultimately be determined based on further considerations regarding the desirability and effectiveness of the overall CDR measure. The authors hope that, beyond answering relevant technical questions, their work can provide a solid, quantitative basis for these considerations.

Data availability statement

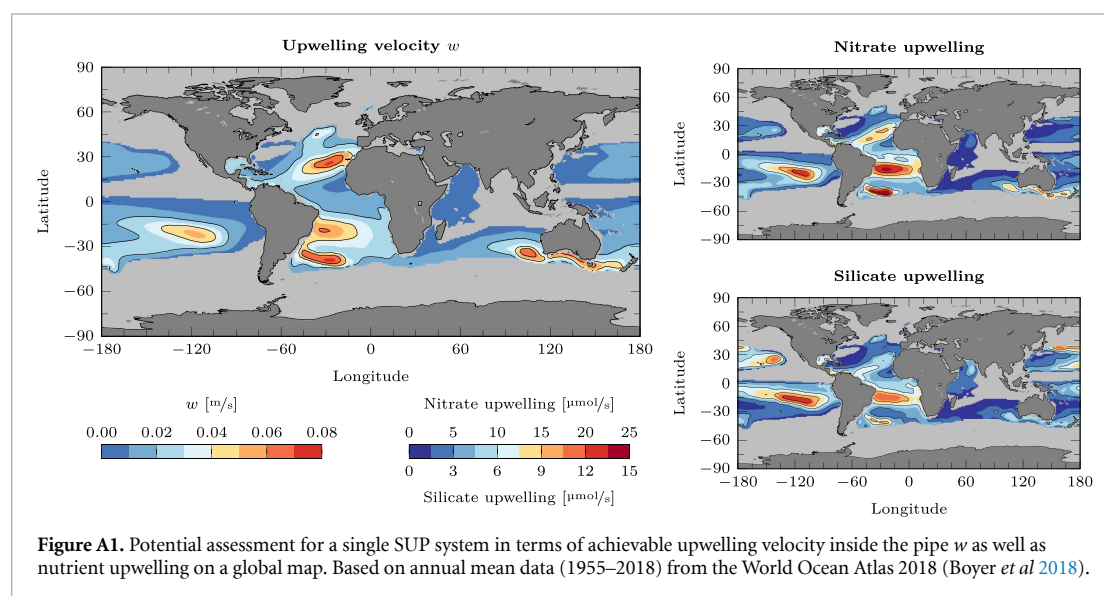
The data that support the findings of this study are openly available at the following URL/DOI: <http://dx.doi.org/10.5281/zenodo.13996043>.

Acknowledgments

J Ke acknowledges funding from the German *Federal Ministry of Education and Research* (BMBF) within the *Test-ArtUp* project (Grant No. 03F0897B). This is a contribution to the *CDRmare* research mission led by the *German Marine Research Alliance* (DAM). J M acknowledges funding from the German *Federal Agency for Disruptive Innovations* (SPRIND GmbH) in the framework of the *C-CAUSE* project within the *Carbon-To-Value* challenge. For the publication of this work, we have received public financial support from *Land Schleswig-Holstein* within the funding program *Open Access Publikationsfonds*.

Appendix. Global potential assessment for a single SUP system

While in section 3.1 only the results for a counterflow SUP system were given, figure A1 shows the result of the global potential assessment for a single SUP system with equivalent dimensions and a pipe diameter of 0.15 m. The study was carried out in analogy to the counterflow SUP study presented in section 3.1.



ORCID iDs

Jost Kemper <https://orcid.org/0009-0005-0381-9630>

Jan Mense <https://orcid.org/0009-0005-8349-3553>

Thomas Slawig <https://orcid.org/0000-0002-1266-3181>

Ulf Riebesell <https://orcid.org/0000-0002-9442-452X>

References

- Black R, Cullen K, Fay B, Hale T, Lang J, Mahmood S and Smith S M 2021 *Taking Stock: A Global Assessment of net Zero Targets* (Energy & Climate Intelligence Unit and Oxford Net Zero)
- Boyer T P *et al* 2018 *World Ocean Database 2018* vol 87, ed A V Mishonov (NOA A Atlas NESDIS)
- Dutreuil S, Bopp L and Tagliabue A 2009 Impact of enhanced vertical mixing on marine biogeochemistry: lessons for geo-engineering and natural variability *Biogeosciences* **6** 901–12
- GESAMP 2019 *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques* (GESAMP Reports and Studies vol 98) ed P W Boyd and C M G Vivian (GESAMP)
- Goldenberg S U, Taucher J, Fernández-Méndez M, Ludwig A, Arístegui J, Baumann M, Ortiz J, Stühr A and Riebesell U 2022 Nutrient composition (Si:N) as driver of Plankton communities during artificial upwelling *Front. Mar. Sci.* **9** 1015188
- Groves G W 1958 Flow estimate for the perpetual salt fountain *Deep Sea Res.* **5** 209–14
- IPCC 2021 *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed V Masson-Delmotte *et al* (Cambridge University Press) p 2391
- Johnson D H and Decicco J 1983 Artificial upwelling driven by salinity differences in the ocean *Technical Report* (Solar Energy Research Inst.)
- Jürchott M, Koeve W and Oeschles A 2024 The response of the ocean carbon cycle to artificial upwelling, ocean iron fertilization and the combination of both *Environ. Res. Lett.* **19** 114088
- Jürchott M, Oeschles A and Koeve W 2023 Artificial upwelling—a refined narrative *Geophys. Res. Lett.* **50** e2022GL101870
- Keller D P, Feng E Y and Oeschles A 2014 Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario *Nat. Commun.* **5** 3304
- Kemper J, Mense J, Kröger J, Slawig T, Graf K and Riebesell U 2024 Supplemental data to Kemper *et al* (2025) on the potential of Stommel's perpetual salt fountain for artificial upwelling *Zenodo* (<https://doi.org/10.5281/zenodo.13996043>)
- Kemper J 2024 ocean4Foam [computer software] (https://doi.org/10.3289/sw_9_2024)
- Kemper J and Mense J 2024 SP1D [computer software] (https://doi.org/10.3289/sw_8_2024)
- Kemper J, Mense J, Graf K, Riebesell U and Kröger J 2023 Towards reliable performance predictions for Stommel's perpetual salt fountain *10th Conf. on Computational Methods in Marine Engineering' CIMNE* (<https://doi.org/10.23967/marine.2023.018>)
- Kemper J, Mense J, Kröger J, Slawig T, Graf K and Riebesell U 2025 Performance prediction for Stommel's perpetual salt fountain in the context of artificial ocean upwelling *Appl. Ocean Res.* **160** 104624
- Kirke B 2003 Enhancing fish stocks with wave-powered artificial upwelling *Ocean Coastal Manage.* **46** 901–15
- Kowek D A 2022 Expected limits on the potential for carbon dioxide removal from artificial upwelling *Front. Mar. Sci.* **9** 841894
- Liang N K and Peng H K 2005 A study of air-lift artificial upwelling *Ocean Eng.* **32** 731–45
- Lovelock J E and Rapley C G 2007 Ocean pipes could help the earth to cure itself *Nature* **449** 403–403
- Oeschles A, Pahlow M, Yool A and Matear R J 2010 Climate engineering by artificial ocean upwelling: channelling the Sorcerer's apprentice *Geophys. Res. Lett.* **37** L04701
- Stommel H, Arons A B and Blanchard D 1956 An oceanographical curiosity: the perpetual salt fountain *Deep Sea Res.* **3** 152–3
- Viúdez A, Balsells M F P and Rodríguez-Marroyo R 2016 Artificial upwelling using offshore wind energy for mariculture applications *Sci. Mar.* **80** 235–48
- Wong A P S *et al* 2020 Argo data 1999–2019: two million temperature-salinity profiles and subsurface velocity observations from a global array of profiling floats *Front. Mar. Sci.* **7** 700
- Wu J, Keller D P and Oeschles A 2023 Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study *Earth Syst. Dyn.* **14** 185–221
- Yool A, Shepherd J G, Bryden H L and Oeschles A 2009 Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide *J. Geophys. Res.: Oceans* **114** C08009

Contribution [JPD]

Exploring Site-Specific Carbon Dioxide Removal Options With Storage or Sequestration in the Marine Environment – The 10 Mt CO₂ yr⁻¹ Removal Challenge for Germany

Citation:

Yao, W., Morganti, T.M., Wu, J., Borchers, M., Anschütz, A., Bednarz, L., Bhaumik, A., Böttcher, M., Burkhard, K., Cabus, T., Chua, A.S., Diercks, I., Esposito, M., Fink, M., Fouqueray, M., Gasanzade, F., Geilert, S., Hauck, J., Havermann, F., Hellige, I., Hoog, S., Jürchott, M., Kalapurakkal, H.T., **Kemper, J.**, Kremin, I., Lange, I., Lencina-Avila, J.M., Liadova, M., Liu, F., Mathesius, S., Mehendale, N., Nagwekar, T., Philippi, M., Luz, G.L.N., Ramasamy, M., Stahl, F., Tank, L., Vorrath, M., Westmark, L., Wey, H., Wollnik, R., Wölfelschneider, M., Bach, W., Bischof, K., Boersma, M., Daewel, U., Fernández-Méndez, M., Geuer, J.K., Keller, D.P., Kopf, A., Merk, C., Moosdorf, N., Oppelt, N., Oschlies, A., Pongratz, J., Proelss, A., Rehder, G.J., Rüpke, L., Szarka, N., Thraen, D., Wallmann, K., Mengis, N., 2025. Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment – the 10 Mt CO₂ yr⁻¹ removal challenge for Germany. *Earth's Future* 13. doi:10.1029/2024ef004902.

Note:

My direct contributions to this work are reported in Sections 3.2.3 and 3.2.4.

Author contributions:

Conceptualization	W. Yao, T. M. Morganti, N. Mengis
Methodology	W. Yao, T. M. Morganti, N. Mengis
Validation	W. Yao, T. M. Morganti
Investigation	W. Yao, T. M. Morganti, J. Wu, A. Anschütz, A. Bhaumik, T. Cabus, I. Diercks, M. Esposito, M. Fink, M. Fouqueray, F. Gasanzade, F. Havermann, I. Hellige, S. Hoog, M. Jürchott, H. T. Kalapurakkal, J. Kemper , I. Kremin, I. Lange, J. M. Lencina-Avila, M. Liadova, F. Liu, S. Mathesius, N. Mehendale, T. Nagwekar, M. Philippi, G. L. N. Luz, M. Ramasamy, F. Stahl, L. Tank, L. Westmark, H.-W. Wey, R. Wollnik, M. Wölfelschneider, N. Mengis
Data Curation	W. Yao, T. M. Morganti, N. Mengis
Writing - Original Draft	W. Yao, T. M. Morganti, J. Wu, A. Anschütz, A. Bhaumik, I. Diercks, M. Fink, M. Fouqueray, I. Hellige, M. Jürchott, H. T. Kalapurakkal, J. Kemper , I. Kremin, I. Lange, J. M. Lencina-Avila, M. Liadova, F. Liu, S. Mathesius, T. Nagwekar, M. Philippi, M. Ramasamy, F. Stahl, L. Tank, L. Westmark, H.-W. Wey, R. Wollnik, N. Mengis
Writing - Review & Editing	W. Yao, T. M. Morganti, M. Borchers, L.-K. Bednarz, M. Böttcher, K. Burkhard, T. Cabus, A. S. Chua, S. Geilert, J. Hauck, F. Havermann, M.-E. Vorrath, W. Bach, K. Bischof, M. Boersma, U. Daewel, M. Fernández-Méndez, J. K. Geuer, D. P. Keller, A. Kopf, C. Merk, N. Moosdorf, N. Oppelt, A. Oschlies, J. Pongratz, A. Proelss, G. J. Rehder, L. Rüpke, N. Szarka, D. Thraen, K. Wallmann, N. Mengis
Visualization	W. Yao, T. M. Morganti, N. Mengis
Supervision	D. P. Keller, A. Oschlies, G. J. Rehder, N. Mengis
Project administration	W. Yao
Funding acquisition	W. Yao, T. M. Morganti, A. S. Chua, J. Hauck, F. Havermann, K. Bischof, M. Boersma, U. Daewel, M. Fernández-Méndez, D. P. Keller, A. Kopf, N. Moosdorf, N. Oppelt, A. Oschlies, J. Pongratz, A. Proelss, G. J. Rehder, L. Rüpke, N. Szarka, D. Thraen, K. Wallmann, N. Mengis

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.



Earth's Future

RESEARCH ARTICLE

10.1029/2024EF004902

W. Yao and T. M. Morganti contributed equally to this work and share the first authorship.

Key Points:

- The site-specific context of carbon dioxide removal options is crucial for serious considerations regarding their possible implementation
- Marine carbon dioxide removal options in Germany have the potential to help counterbalance projected future residual emissions
- Further site-specific studies are needed to assess the socio-economic, legal, political and ethical aspects of such implementations

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

W. Yao, T. M. Morganti and N. Mengis,
wyao@geomar.de;
teresa.morganti@io-warnemuende.de;
nmengis@geomar.de

Citation:

Yao, W., Morganti, T. M., Wu, J., Borchers, M., Anschütz, A., Bednarz, L.-K., et al. (2025). Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment – the 10 Mt CO₂ yr⁻¹ removal challenge for Germany. *Earth's Future*, 13, e2024EF004902. <https://doi.org/10.1029/2024EF004902>

Received 21 MAY 2024

Accepted 12 FEB 2025

Author Contributions:

Conceptualization: W. Yao,

T. M. Morganti, N. Mengis

Data curation: W. Yao, T. M. Morganti, N. Mengis

Funding acquisition: W. Yao,

T. M. Morganti, A. S. Chua, J. Hauck, F. Havermann, K. Bischof, M. Boersma, U. Daewel, M. Fernández-Méndez, D. P. Keller, A. Kopf, N. Moosdorf,

© 2025. The Author(s).

This is an open access article under the terms of the [Creative Commons](#)

[Attribution License](#), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Exploring Site-Specific Carbon Dioxide Removal Options With Storage or Sequestration in the Marine Environment – The 10 Mt CO₂ yr⁻¹ Removal Challenge for Germany

W. Yao¹, T. M. Morganti², J. Wu³, M. Borchers⁴, A. Anschütz², L.-K. Bednarz⁵, K. A. Bhaumik³, M. Böttcher^{6,7}, K. Burkhard⁸, T. Cabus⁹, A. S. Chua¹⁰, I. Diercks¹, M. Esposito¹, M. Fink¹¹, M. Fouquerey¹², F. Gasanzade⁹, S. Geilert^{1,13}, J. Hauck³, F. Havermann¹⁴, I. Hellige^{15,16}, S. Hoog¹⁷, M. Jürchott¹, H. T. Kalapurakkal¹, J. Kemper¹⁸, I. Kremin¹, I. Lange¹⁶, J. M. Lencina-Avila², M. Liadova¹, F. Liu¹⁹, S. Mathesius²⁰, N. Mehendale¹, T. Nagwekar³, M. Philippi³, G. L. N. Luz¹¹, M. Ramasamy¹², F. Stahl¹⁶, L. Tank⁹, M.-E. Vorrath¹¹, L. Westmark¹¹, H.-W. Wey¹, R. Wollnik²¹, M. Wölfelschneider¹², W. Bach¹⁶, K. Bischof¹⁶, M. Boersma^{3,16}, U. Daewel¹⁹, M. Fernández-Méndez³, J. K. Geuer¹⁵, D. P. Keller¹, A. Kopf¹⁶, C. Merk⁵, N. Moosdorf^{9,12}, N. Oppelt⁹, A. Oschlies¹, J. Pongratz^{14,22}, A. Proelss¹¹, G. J. Rehder², L. Rüpke¹, N. Szarka²¹, D. Thraen⁴, K. Wallmann¹, and N. Mengis¹

¹GEOMAR, Helmholtz Centre for Ocean Research, Kiel, Germany, ²Leibniz Institute for Baltic Sea Research (IOW), Rostock, Germany, ³Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, ⁴Department of Bioenergy, Helmholtz Centre for Environmental Research, Leipzig, Germany, ⁵Kiel Institute for the World Economy, Kiel, Germany, ⁶SWP-German Institute for International and Security Affairs, Berlin, Germany, ⁷Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, The Netherlands, ⁸Leibniz University Hannover, Hannover, Germany, ⁹Kiel University, Kiel, Germany, ¹⁰Dalhousie University, Halifax, NS, Canada, ¹¹University of Hamburg, Hamburg, Germany, ¹²Leibniz Centre for Tropical Marine Research (ZMT), Bremen, Germany, ¹³Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands, ¹⁴Ludwig-Maximilians-Universität München, Munich, Germany, ¹⁵Max Planck Institute for Marine Microbiology, Bremen, Germany, ¹⁶University of Bremen, Bremen, Germany, ¹⁷Fichtner GmbH & Co. KG, Hamburg, Germany, ¹⁸University of Applied Sciences Kiel, Kiel, Germany, ¹⁹Helmholtz Centre Hereon, Hamburg, Germany, ²⁰Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany, ²¹German Biomass Research Centre, Leipzig, Germany, ²²Max Planck Institute for Meteorology, Hamburg, Germany

Abstract Marine carbon dioxide removal (mCDR) and geological carbon storage in the marine environment (mCS) promise to help mitigate global climate change alongside drastic emission reductions. However, the implementable potential of mCDR and mCS depends, apart from technology readiness, also on site-specific conditions. In this work, we explore different options for mCDR and mCS, using the German context as a case study. We challenge each option to remove 10 Mt CO₂ yr⁻¹, accounting for 8%–22% of projected hard-to-abate and residual emissions of Germany in 2045. We focus on the environmental, resource, and infrastructure requirements of individual mCDR and mCS options at specific sites, within the German jurisdiction when possible. This serves as an entry point to discuss main uncertainty factors and research needs beyond technology readiness, and, where possible, cost estimates, expected environmental effects, and monitoring approaches. In total, we describe 10 mCDR and mCS options; four aim at enhancing the chemical carbon uptake of the ocean through alkalinity enhancement, four aim at enhancing blue carbon ecosystems' sink capacity, and two employ geological off-shore storage. Our results indicate that five out of 10 options would potentially be implementable within German jurisdiction, and three of them could potentially meet the challenge. Our exercise serves as an example on how the creation of more tangible and site-specific CDR options can provide a basis for the assessment of socio-economic, ethical, political, and legal aspects for such implementations. The approach presented here can easily be applied to other regional or national CDR capacity considerations.

Plain Language Summary There is a growing consensus within the scientific community that carbon dioxide removal (CDR) and carbon storage will play crucial roles in global climate change mitigation efforts. Marine-based CDR (mCDR) or carbon storage (mCS) for climate mitigation have gathered significant attention due to their substantial global potential. While numerous studies have assessed global CDR capacities and associated side effects or co-benefits of individual methods, it is important to recognize that global potential does not necessarily translate into local effectiveness. The implementable potential of mCDR and mCS depends

N. Oppelt, A. Oschlies, J. Pongratz, A. Proelss, G. J. Rehder, L. Rüpke, N. Szarka, D. Thraen, K. Wallmann, N. Mengis

Investigation: W. Yao, T. M. Morganti, J. Wu, A. Anschütz, K. A. Bhaumik, T. Cabus, I. Diercks, M. Esposito, M. Fink, M. Fouqueray, F. Gasanzade, F. Havermann, I. Hellige, S. Hoog, M. Jürchott, H. T. Kalapurakkal, J. Kemper, I. Kremin, I. Lange, J. M. Lencina-Avila, M. Liadova, F. Liu, S. Mathesius, N. Mehendale, T. Nagwekar, M. Philippi, G. L. N. Luz, M. Ramasamy, F. Stahl, L. Tank, L. Westmark, H.-W. Wey, R. Wollnik, M. Wölfelschneider, N. Mengis

Methodology: W. Yao, T. M. Morganti, N. Mengis

Project administration: W. Yao

Supervision: D. P. Keller, A. Oschlies, G. J. Rehder, N. Mengis

Validation: W. Yao, T. M. Morganti

Visualization: W. Yao, T. M. Morganti, N. Mengis

Writing – original draft: W. Yao, T. M. Morganti, J. Wu, A. Anschütz, K. A. Bhaumik, I. Diercks, M. Fink, M. Fouqueray, I. Hellige, M. Jürchott, H. T. Kalapurakkal, J. Kemper, I. Kremin, I. Lange, J. M. Lencina-Avila, M. Liadova, F. Liu, S. Mathesius, T. Nagwekar, M. Philippi, M. Ramasamy, F. Stahl, L. Tank, L. Westmark, H.-W. Wey, R. Wollnik, N. Mengis

Writing – review & editing: W. Yao, T. M. Morganti, M. Borchers, L.-K. Bednarz, M. Böttcher, K. Burkhard, T. Cabus, A. S. Chua, S. Geilert, J. Hauck, F. Havermann, M.-E. Vorrath, W. Bach, K. Bischof, M. Boersma, U. Daewel, M. Fernández-Méndez, J. K. Geuer, D. P. Keller, A. Kopf, C. Merk, N. Moosdorf, N. Oppelt, A. Oschlies, J. Pongratz, A. Proelss, G. J. Rehder, L. Rüpke, N. Szarka, D. Thraen, K. Wallmann, N. Mengis

not only on technological readiness, but also on site-specific conditions. Our study explores the capacity of marine-based methods considering local resource availability, geophysical conditions, infrastructure, and land/sea-area availability to be developed by Germany. We identified 10 proposed options, with half of them being implementable exclusively within German jurisdictions and 3 capable of achieving the 10 Mt CO₂ annual removal target, significantly contributing to Germany's net-zero goal. This underscores the critical importance of considering site-specific contexts in any discussion of mCDR/mCS implementation. Additionally, our study highlights the potential of mCDR/mCS for Germany and calls for further site-specific studies to assess these options beyond natural science or techno-environmental considerations.

1. Introduction

The Paris Agreement (UNFCCC, 2016) requires achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. Such a net-zero goal first and foremost requires substantial reductions and avoidances in greenhouse gas (GHG) emissions. In addition to drastically reducing current emissions, the implementation of carbon dioxide removal (CDR) approaches will play a role in achieving net-zero by counterbalancing residual emissions (i.e., where emission reduction is technologically and/or financially too challenging; Buylova et al., 2021; Fridahl et al., 2020; Mengis et al., 2022; Oschlies et al., 2017). The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2023) shows that all 1.5°C scenarios applied CDR to reach their goal. However, the CDR options implemented in the scenarios depend, among others, on assumptions that could reasonably be made about cost-effectiveness and storage availability of CO₂ (IPCC, 2022). Until now, most considered CDR methods are land-based, relying primarily on afforestation as well as bioenergy in combination with carbon capture and storage (BECCS). Most of the CDR options mentioned in national long-term low-emission development strategies worldwide rely on the expansion or management of existing natural ecosystem sink capacities (Thoni et al., 2020). Accordingly, a considerable amount of research has been devoted to these CDR options, which has resulted in first considerations of limiting factors or bottlenecks. For instance, large-scale, land-based CDR options relying on photosynthetic carbon capture require substantial land area, compete with other land uses such as food, fiber, and energy production, settlement and infrastructure development, and ecosystem services (Boysen et al., 2017; Fujimori et al., 2022; Williamson, 2016). While it is expected that large-scale implementation of any CDR option faces limitations, risks, and biophysical, technical, political and social challenges (Creutzig et al., 2015; Fuss et al., 2018), assessments of marine CDR (mCDR) and marine carbon storage (mCS) approaches within a portfolio of CDR options to reach net-zero emissions are lacking. This omission of marine approaches is a shortcoming, given the high carbon storage inventory of the marine environment and the large fraction of anthropogenic CO₂ that will finally be stored by the ocean.

Germany has set its goal to become GHG neutral by 2045. Optimistic roadmaps to reach this goal provide estimates of residual emissions ranging from 40 to 60 megatons (Mt) carbon dioxide equivalent (CO_{2eq}) annually (Federal Climate Change Act, 2019; Mengis et al., 2022), which corresponds to 5%–10% of Germany's current GHG emissions. These will need to be counterbalanced by the implementation of CDR methods. Less optimistic annual residual GHG emission estimates are even higher, ranging from 45 to 130 Mt CO_{2eq} (Luderer et al., 2021; Merfort et al., 2023). Initial studies of CDR potential within Germany point to a theoretical CDR potential that could reach this scale by employing terrestrial CDR options (Borchers et al., 2022; Merfort et al., 2023). However, the CDR potential on land might be reduced, if current optimistic assumptions about land, fresh water, and energy requirements, as well as the development of storage capacities, are not met – possibly because their implementations would exceed environmental guardrails (Heck et al., 2018).

Here, we aim to complement such efforts by considering the potential of CDR options with storage or sequestration in the marine environment for Germany. To do so, we envision potential implementations of different mCDR categories: (a) the enhancement of the ocean's chemical carbon uptake through alkalinity addition, (b) the enhancement of the “blue carbon” sink capacity (such as in salt marshes, seaweed, or mangrove ecosystems), and (c) offshore geological CO₂ storage coupled with different carbon capture components. We challenge each mCDR option to reach a 10 Mt CO₂ yr^{−1} removal capacity, as this is a significant fraction of the residual emissions projected for Germany and allows us to assess side effects and challenges, which are likely to be notable on that scale. In addition, by leveling the playing field for all options, we can compare common attributes

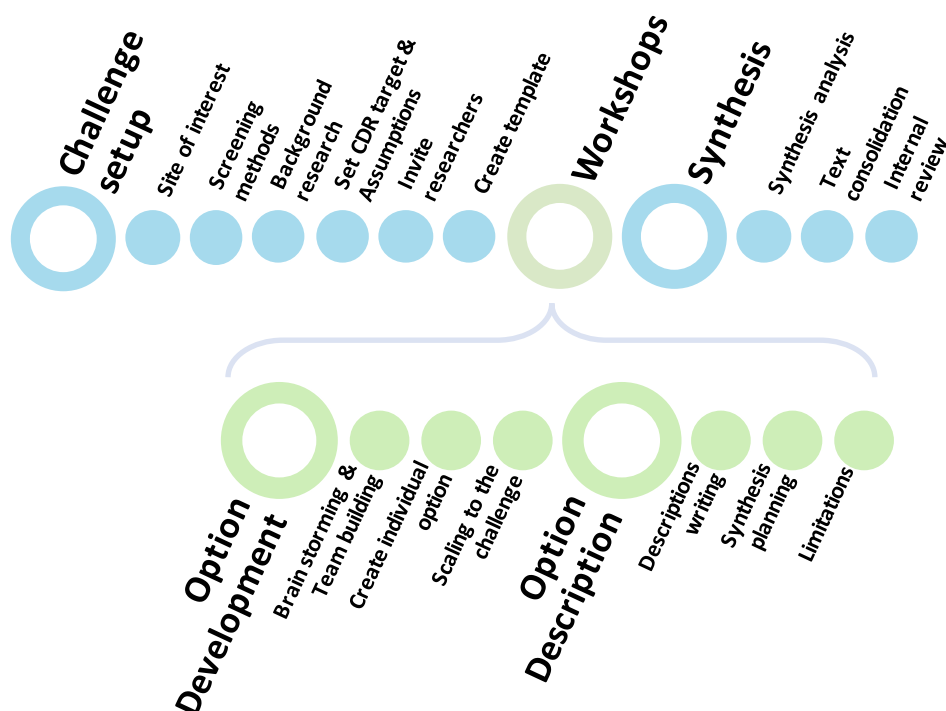


Figure 1. Roadmap for exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment pursued in this work.

of the aforementioned mCDR options at the same scale of operation. Our exercise does not aim to provide a comprehensive assessment of mCDR options or a dedicated life-cycle assessment, but rather to present a collection of options that can serve as a basis for further discussion, by making the scale of CDR implementation—relevant to national climate targets—more tangible. By doing so we aim to provide a basis for context-specific discussion and promote further studies that adopt a similar approach in other contexts worldwide.

To this end, we provide first insights into mCDR options on a larger scale, their technological feasibility, infrastructure and resource demands, on the example scale under the site-specific constraints. We first describe how we selected the mCDR and mCS options (Section 2). We then provide a short description of each option, including technological readiness, resource requirements, uncertainties and, if available, cost estimates (Section 3). This is followed by a comparison of the options, expected possible environmental effects, and a discussion of the limitations of our approach (Section 4). For the case study, we conclude that mCDR options are a valuable addition to the net-zero tool box, and that further research is needed to help some of the technology to reach maturity and to reduce the uncertainty in efficiency and environmental effects. Ultimately, the approach we present here may serve as a template for exploring mCDR and mCS feasibility in further contexts worldwide.

2. Materials and Methods

This study aimed to develop site-specific CDR options through three phases: challenge setup, workshops, and synthesis (Figure 1). In the challenge setup, we identified the region of interest (Germany), compiled an initial list of CDR and carbon capture and storage (CCS) methodologies leveraging the knowledge in our research networks (CDRmare and CDRterra), and invited workshop participants. Background research included regional emissions, land/sea area, low-emission energy, material availability, and infrastructure capacity—factors influencing potential deployment (details are given in Section 2.2). These inputs informed our CDR scaling target and assumptions, defining criteria for significant contributions to reaching net-zero in our region of interest. We also designed a unified CDR options template (Table 1) to be employed during the workshop.

The second phase involved two workshops: the first focused on the creation and scaling of the options, generating over 13 options. The latter were screened resulting in merging similar options or excluding options due to

Table 1

Description of the Categories and Parameters Used in the Fact Sheet for the Generation of mCDR Options With the Aim to Reach 10 Mt CO₂ Yr⁻¹ Removal; for Details See Supporting Information (SI)

Category	Parameter	Description
Option description	Maturity level	Extent to which an option is available for implementation, following the Technology Readiness Level (TRL) scale (European Commission, 2014) (see Supporting Information S1 Table S1)
	Infrastructure	Necessary infrastructure along the chain of implementation
	Biophysical conditions	Necessary environmental conditions for the functioning of the option
	Location	Description of the possible locations and explanation for specific choice made, including the location for resource extraction, material processing, logistic centers, and carbon reservoir
Demand/Input	Area/land	Necessary amount of area on land or ocean
	Material/resources	Necessary amount and type of matter (e.g., rock, soil, etc.)
	Energy demand	Energy demand along the chain of implementation
	Water demand	Necessary amount and type of water
Output	CO ₂ removal potential	If the option cannot reach 10 Mt CO ₂ yr ⁻¹ removal, estimate the maximum yearly CO ₂ removal rate
	By-products	Additional products with or without market value generated
	Energy output	Energy provision in the form of usable electricity/heat
Environmental impacts	Soils/sediment	Effect of the option causing changes in the state of soils/sediments (e.g., through substance release)
	Water	Effect of the option causing changes in the state of groundwater, runoff water and seawater (e.g., through substance release)
	Air	Effect of the option on the atmosphere (e.g., through release of non-CO ₂ GHGs)
	Noise	Effect of the mCDR option on the ambient noise level
	Ecosystem	Effect of the mCDR option on biota
Cost parameters	CO ₂ removal costs	Marginal removal cost (assuming a fully established system)
	Investment intensity	Investment cost to build at least one unit
	Maintenance cost	Cost for maintenance, including human resources
	MRV costs	Effort and costs for carbon accounting and evaluation of removal
Systemic parameters	max. CO ₂ removal potential	Maximum removal capacity scaling as permitted by constraints (e.g., area, energy, resource limitations)
	Permanence	Carbon reservoir for storage/sequestration (geological, marine biomass, marine soils/sediments), and the expected length of storage
	MRV capability	The concept MRV is about “Monitoring, Reporting, and Verification.” Here, we use this term to describe the ability to measure/estimate carbon fluxes/stock changes and to monitor the environmental impacts, and to verify the amount of removed CO ₂

insufficient data. As a result, we generated a list of 10 CDR options, five of which could be implemented in the jurisdiction of the region of interest. The second workshop emphasized detailed option descriptions, discussed approach limitations (session 4.4), and planned the synthesis phase, including metrics for comparison and result formatting.

In the synthesis phase, we conducted comparative analyses (session 4.1–4.3) and an internal review within the research networks.

2.1. CDR Options Development

Following the methodological approach presented by Borchers et al. (2022) with experts from the CDRmare (cdrmare.de) research program, we developed a collection of possible mCDR options for implementation in Germany (Figure 2A1). These mCDR options were generated based on three CDR methods researched in the program: ocean alkalinity enhancement (OAE), blue carbon enhancement (blueCDR), and off-shore geological

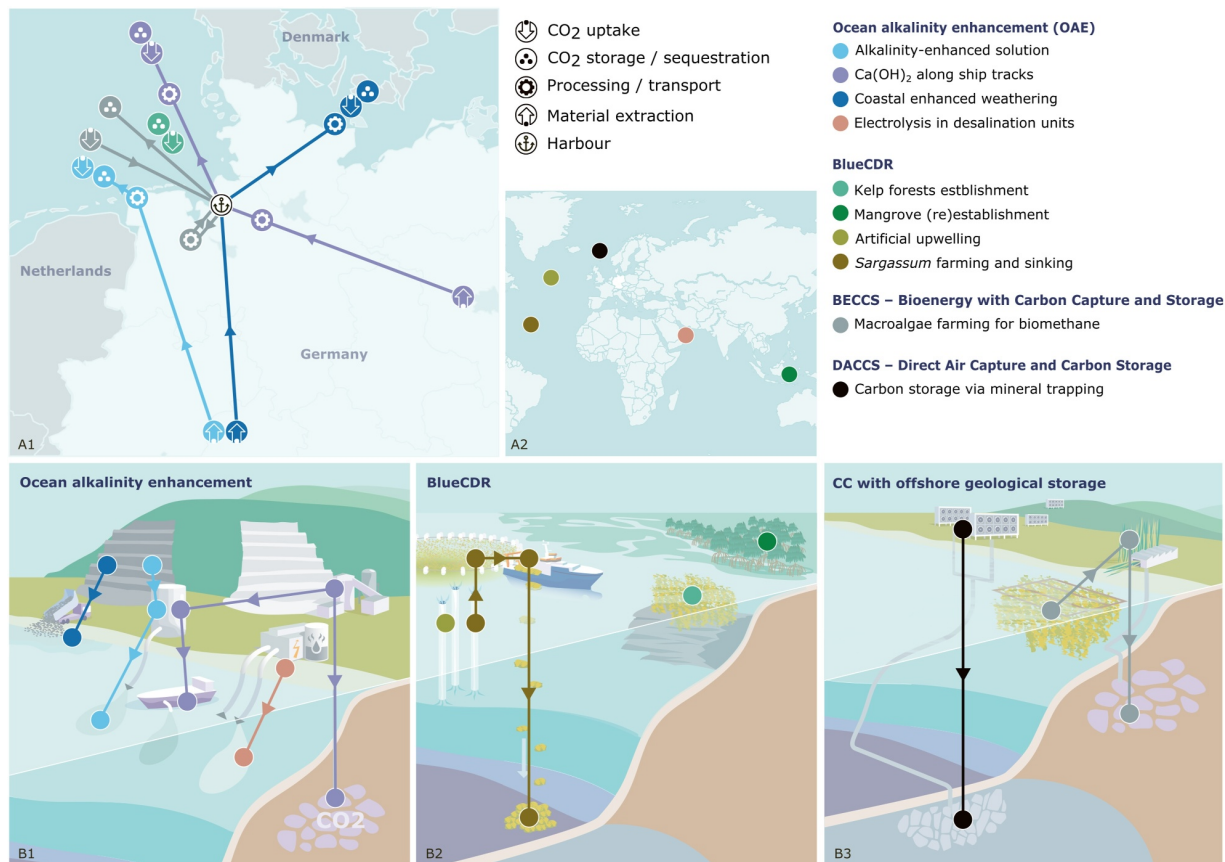


Figure 2. Schematic overview of the 10 mCDR options (clustered in three categories).

1. Map of Germany indicating the locations chosen for the implementation linked to the region where resources would be available;
2. World map for chosen implementation locations for international options (3.1.4, 3.2.2–3.2.4, 3.3.2).
3. (B1–3) Schematic drawings of the mCDR options showing sources for CO₂ capture linked to CO₂ storage for the different mCDR categories: ocean alkalinity enhancement (OAE, B1), ecosystem-based carbon dioxide removal in the marine environment (blueCDR, B2), and options with marine geological carbon storage (mCS, B3). The colored dots in B1–3 denote processes in the whole chain of operation, for example, material extraction, material processing, and implementation, while the arrows denote the movement of material down the chain. Note, for option coastal enhanced weathering, the deployment area is both in the North Sea and the Baltic Sea.

carbon storage (mCS) captured from the atmosphere, for example, through bioenergy plants or direct air capture, in collaboration with the research mission CDRterra (cdrterra.de).

The aim was to identify site-specific mCDR options, if possible, within the German jurisdiction, yet, due to option-specific geophysical constraints, some mCDR options are partially (e.g., basalt CO₂ trapping) or entirely (e.g., mangrove planting) located outside of it. Such options would require international cooperation as outlined in Article six of the Paris Agreement (UNFCCC, 2015).

This study describes necessary conditions for each option's implementation, including environmental conditions, infrastructure, technology and resource availability, as well as possible environmental effects. The options were created using a tabular fact sheet, adapted from Borchers et al. (2022), with a unified set of categories and parameters (see Table 1).

At this point, the implementation of OAE, blueCDR and mCS options were envisioned disregarding economic (beyond cost), legal, societal, or political constraints (similar to Borchers et al., 2022), and assuming—where no other information was available—linear scalability to 10 Mt CO₂ removal potentials. The locations in Germany for resource extraction, material processing, and establishment of logistics centers were chosen based solely on

resource and infrastructure availability, which were only used to provide a basis for estimates such as transportation requirements, energy demands, and operational costs. This approach allowed us to fully explore techno-environmental feasibility and operational locations, necessary infrastructure, and resources under idealized, hypothetical conditions. Although we outline and discuss limitations arising from these assumptions in the overarching discussion, we recommend a detailed assessment of these disregarded factors as the subject of a follow-up study.

2.2. Data Collection, Calculations and Quality Check

Data on mCDR options were assembled by researchers from the German BMBF funded research programs CDRmare and CDRterra, gathered during two workshops (Drübbelholz, November 2022; Kiel, June 2023; Figure 1). This expert-driven process brought together participants from various academic disciplines involved in CDR-related research addressing technological, environmental, social, legal, and economic aspects. The participants developed mCDR options based on peer-reviewed literature, reports, resources from their current projects and German-specific information provided by state agencies like the Federal Environment Agency (UBA) and Federal Institute for Geosciences and Natural Resources (BGR). Additionally, literature databases specifically focused on CDR such as the carbon dioxide removal portal (<https://carbondioxide-removal.eu/en/news/>) were used. Nevertheless, the list of options based on the three main mCDR methods is not meant to be exhaustive.

The data was compiled in a fact sheet for each mCDR option (see Supporting Information S1). Each option targets an annual removal of 10 Mt CO₂, with all demand, input, and output estimates calculated at this scale. The removal estimates and corresponding demands are derived from existing scientific literature, including laboratory observations, modeling works, method-based synthesis reports, and detailed life cycle analyses. If an option did not reach this scale due to, for example, resource restrictions, a maximum removal estimate (in units of Mt of CO₂ yr⁻¹) was provided and all other estimates related to the demand/input and output categories were calculated accordingly; however, if the option reached 10 Mt CO₂ yr⁻¹ removal, we asked for an estimate of the maximum annual CO₂ removal rate that could be achieved. The cost and technical feasibility were estimated by using the sources described above and supported by our technology consulting partner (fichtner.de). The technology readiness level (TRL) (Supporting Information S1 Table S1), assigned to each method is the lowest level depicted in the whole chain of technologies necessary for the respective mCDR implementation. The permanence, including the form of carbon sequestration, and expected length of storage was also detailed for each option, considering that permanent carbon storage after at least 1,000 years of storage (Brunner et al., 2024). Together with the fact sheets, schematic drawings of the options was developed (see Figures S1–S4 in Supporting Information S1) together with a summary figure (Figure 2). Finally, the experts were asked to provide possible bottlenecks with regard to, for example, resource constraints, and to identify unknowns and research gaps.

3. Collection of Marine Carbon Dioxide Removal (mCDR) Options

The mCDR collection includes 10 options (displayed in 3 classes in Figure 2) for carbon storage and sequestration in the marine environment. In the following, we will briefly describe the functioning of the option, the estimated technology readiness, the resources that would be required to scale this option up to 10 Mt CO₂ yr⁻¹ removal rate, the expected costs for such operations, and key uncertainties (for more details, please see Supporting Information S1). Discussions of the expected environmental effects, and challenges with regard to monitoring, reporting and verification for the options will be in Section 4.

3.1. Ocean Alkalinity Enhancement – mCDR Options Increasing Physical-Chemical Carbon Uptake Through the Addition of Alkalinity

Solutes of weathered silicate and carbonate rocks naturally add alkalinity to the ocean, which increases its CO₂ storage as dissolved inorganic carbon (DIC) (Archer, 2005; Bach et al., 2019). The alkalinity-enhanced seawater at the ocean surface reacts with the CO₂ at the air-sea interface and forms bicarbonate ions, which can be kept in solution for time scales of 100,000 years (Falkowski et al., 2000; Ilyina et al., 2013; Köhler, 2020; Köhler et al., 2013; Renforth & Henderson, 2017). The weathering of alkaline minerals is a negative feedback of the Earth's system regulating atmospheric CO₂ (Archer, 2005; Berner et al., 1983). Ocean Alkalinity Enhancement (OAE) refers to anthropogenic activities with the aim of mimicking the natural process of weathering by adding

alkalinity to the ocean to increase its CO₂ uptake (Hartmann et al., 2023; Köhler et al., 2013; Rau et al., 2013) while stabilizing the pH (Hauck et al., 2016; Hinrichs et al., 2023), which has a positive effect on pH-sensitive ecosystems (Albright et al., 2016; Weatherley, 1988).

In the following we describe four OAE options (Figure 2B1): option 3.1.1 explores the possibility of enhancing the alkalinity of the German EEZ (North Sea) through electrolysis of seawater in the presence of silicate minerals, option 3.1.2, explores the possibility of ocean liming in the German EEZ (North Sea), option 3.1.3 explores dissolving basalt powder along the German coastline. Finally, option 3.1.4 explores upgrading existing desalination plants to produce alkalinity. Because this option would only be possible on a small scale in Germany, namely on Heligoland (Germany), we decided to explore this concept in an area outside Germany, where freshwater production from desalination plants reaches a scale of 0.6 km³ yr⁻¹, about the rate related to a CO₂ removal of 10 Mt yr⁻¹, to see its full potential and impacts.

3.1.1. Electrolytic Production and Addition of Alkalinity-Enhanced Solution From Silicate Rock on the German North Sea Coast

Mined and ground silicate rock from quarries in central-Germany could be transported by carrier/berge to an electrolysis facility on the coast in Northern Germany. The North Sea wind farms would be able to provide off-peak renewable energy that could be used for the electrolysis of the seawater with anodes encased by rock powder (details see Rau et al., 2013). The reaction produces hydrogen, oxygen, silicate and magnesium/other-metal salt (solid), and alkaline enhanced (sodium hydroxide, NaOH) seawater (see Supporting Information S1, Eq. 3.1.1a; Rau et al., 2013). The alkalinity-enhanced seawater could then be released to the North Sea. Since the water with enhanced alkalinity needs to be in contact with the atmosphere for efficient CO₂ uptake (Jones et al., 2014), the oceanographic conditions of the German North Sea characterized by shallow depth and high mixing rates (Sündermann & Pohlmann, 2011) would be very amenable to this approach. However, the actual efficiency of CO₂ uptake per unit of alkalinity added in the North Sea would need to be further investigated.

While the technology for electrolysis with brine is already commercially used to produce hydrogen, oxygen, chlorine, hydroxide, and acid for various industries (Lakshmanan & Murugesan, 2014), electrolysis with seawater is currently under development (e.g., Ebb Carbon, 2024; Rau et al., 2018), hence we estimate the TRL of this option to be 3 (according to Table S1 in Supporting Information S1).

To scale this mCDR option to 10 Mt CO₂ yr⁻¹, one would need to dedicate around 30 Mt basalt yr⁻¹ (equivalent to 94% of the current German basalt mining capacity) and around 19 TWh electricity per year (8% of the German renewable electricity production capacity in 2021; House et al., 2007; Rau et al., 2013; for calculations see Supporting Information S1 3.1.1). The mining of the rock would use 0.2 Mm³ of fresh water per year (0.004% of the total groundwater abstraction in 2019; Gerbens-Leenes et al., 2018; Wayman et al., 2021) and a minimum of 460 Mm³ of seawater for electrolysis (Dormann, 2023; 0.001% of the North Sea volume; for calculations see Supporting Information S1 3.1.1). At the same time, the byproducts, namely hydrogen, chlorine, and oxygen, could be utilized and reduce the energy demand and the cost of the option (Rau et al., 2013).

There is no commercial pilot study available for such an option, hence the cost of such an endeavor is highly uncertain. However, in an optimum case scenario, we estimated a cost of 770–1,100 million € yr⁻¹ for a 10 Mt CO₂ yr⁻¹ removal rate including mining, transportation, energy, and investment costs without monitoring (for calculations see Supporting Information S1 3.1.1).

One of the remaining challenges regarding electrolysis with seawater is that the constraints on the discharging rate of the alkalinity-enhanced water are unknown. Recent studies recommend values of between 250 and 600 μmol L⁻¹ to avoid triggering the precipitation of aragonite in coastal regions (Hartmann et al., 2023; Moras et al., 2022). With an assumed 0.86 years of water turnover rate in the North Sea (Sündermann & Pohlmann, 2011), this option would require about 55% of the German EEZ in the North Sea for alkalinity dispersal under a conservative estimation (for calculation see Supporting Information S1 3.1.1) and additional in situ modeling studies may help to reduce the uncertainty. Also, the role of particles as a trigger for precipitation is not clarified yet (Hartmann et al., 2023; Wurgalt et al., 2021). Another challenge is the erosion of the anode and the formation of precipitates on the electrode surface, which reduces the process efficiency (James & Harb, 2021). Although in the presence of silicate minerals, the occurrence of chlorine and hydrogen chloride would be suppressed, the question of how to safely dispose or use possible byproducts (e.g., up to 7 Mt of chlorine without applying minerals, similar to 3.1.4)

also remains a challenge. Co-emissions from the energy-intensive mining (Moosdorf et al., 2014) could be reduced if the national energy mix is further decarbonized and transportation requirements are reduced if quarries are located close to rivers. Furthermore, a suitable framework for monitoring, reporting and verification (MRV) of alkalinity enhancement is yet to be developed.

3.1.2. Production and Spread of Slaked Lime Along Ship Tracks in the North Sea

In this option, limestone would be mined in quarries in Germany, which are widely spread over the countries adjacent to the North Sea and Baltic Sea. The production of slaked lime ($\text{Ca}(\text{OH})_2$) would then be conducted in the lime quarries on-site. The slaked lime would be transported to a harbor (in northern Germany), where it would be fully mixed with freshwater to produce lime milk. The lime milk is subsequently loaded onto bulk carrier ships and spread into the North Sea along shipping routes. The method could be applied in the German EEZ, and can be extended to the entire North Sea over existing vessel routes.

The production of lime is a mature industrial process with a TRL 9 (Foteinis et al., 2022). The dispersion of alkalinity via ship tracks is less developed. It has been estimated so far mainly based on theoretical discussions with the TRL of 3–4 (Caserini et al., 2022; McLaren, 2012). So currently, we estimate the TRL of this option to be 3.

To reach the $10 \text{ Mt CO}_2 \text{ yr}^{-1}$ removal target, this option would require a minimum of 17.9 Mt limestone (equivalent to 32% of the current German annual limestone production), 15.27 TWh of electricity (~6% of German renewable electricity/energy production in 2021), as well as 6.78 Mt of freshwater for the slaked lime production per year. The required land for the mining operation is estimated to be $1,858 \text{ m}^2$ while the sea area needed for the alkalinity spreading is $15,500 \text{ km}^2$. Under the assumption that mCDR could have a higher priority for the use of these resources, all the requirements could be fulfilled. During the energy-intensive lime production process (with a kiln type that consumes fossil fuels), CO_2 emissions would arise from the calcination process and consumption of fossil fuels (Dowling et al., 2015), which would need to be captured and stored in geological sites (see Section 3.3). Applying less carbon intensive technology (kiln type), and transitioning to renewable energy (Foteinis et al., 2022) would be highly beneficial for this option's efficiency. Low-grade heat is generated during CaO hydration. Currently, its recovery is not practical with the existing lime kilns, but it might be possible with new lime plants (EuLA, 2014).

The total cost for $10 \text{ Mt CO}_2 \text{ yr}^{-1}$ removal is estimated at 800–1,450 million € with CCS applied for the lime production (calculation see Supporting Information S1 3.1.2).

One of the remaining challenges is the decarbonization of the slaked lime production. Even though some processes aiming at zero emission have been proposed (Caserini et al., 2019; Renforth & Henderson, 2017), they still need further evaluation. Another challenge is the assessment of the localized impact produced by slaked lime at the discharge point, due to a temporary increase of pH and alkalinity, of which the environmental side effect is not yet well evaluated and requires additional dedicated experimental studies (Locke et al., 2009; Pedersen & Hansen, 2003). Furthermore, there are presently almost no MRV standards for this practice and a suitable framework thus needs to be built.

3.1.3. Coastal Enhanced Weathering (CEW) Along the German Coast

Similar to option 3.1.1, mined and ground alkaline volcanic rock (e.g., basalt) from quarries in central-Germany (Amann et al., 2022) would be transported by carrier/barge to the coast of northern Germany. For this option, the ground rock powder (less than $10 \mu\text{m}$ grain size) would then be deposited on the coastline in a high-energy environment (we take a 100-m-wide band, with an average depth less than 10 m along the beach; see Supporting Information S1 3.1.3). The high energy coastal environment could then weather down the grains of alkaline rocks and thus further reduce the energy requirement and cost of the process (Eisaman et al., 2023; Flipkens et al., 2023; Meysman & Montserrat, 2017). The theory would be that the on-site ground rock will dissolve in the coastal seawater, which enhances the alkalinity and the CO_2 uptake of seawater (Flipkens et al., 2023).

The technological feasibility for conducting CEW is high, since this technique has been applied commercially (TRL 8; “Vesta,” 2022). However, the experiment aimed at demonstrating the efficiency of this method has yet to yield accessible results, so as of our study, the concept remains partially unproven. Hence by the time of our study, not all of the concepts are proven, and we assess that CEW has a TRL of 5.

Germany has coastlines extending over 3,700 km, with approximately 3,300 km shallow and suitable for the coastal enhanced weathering approach (Sterr, 2008), which in an optimal condition can sustain the dissolution of 3 Mt of fine basalt powder annually (for calculation see Supporting Information S1 3.1.3). This amount of basalt is roughly 10% of the current German basalt production (BGR, 2021). The total energy consumption for this option is around 614 GWh annually (0.3% of the German renewable electricity production capacity in 2021), which includes mining and grinding, without transportation. The overall CO₂ removal potential is 1.1 Mt of CO₂ yr⁻¹ (for calculation see Supporting Information S1 3.3.3), with the possibility of expansion into the continental shelf (e.g., Fuhr et al., 2024; Hylén et al., 2023).

The cost of 1.1 Mt CO₂ yr⁻¹ removal is around 160 million € (excluding MRV cost, for calculation see Supporting Information S1 3.1.3).

Currently, there are no large-scale implementations of CEW that have achieved the 10 Mt CO₂ yr⁻¹ removal target. The verification of the effectiveness as well as the environmental side effects are currently topics of research. The effectiveness would be influenced by the reactivity of minerals (e.g., basalt) under in situ conditions (Ramasamy et al., 2024), the relocation or redistribution of the rock grains (e.g., by wave and tides; Flipkens et al., 2023; Meysman & Montserrat, 2017), or the possibility of spontaneous precipitation of CaCO₃ in the basalt minerals pore waters in lower mixing regimes. Concerning verification, remaining challenges are the scale of deployment with the area coverage and the detection of downstream effects due to the continuous dissolution in seawater. The corresponding research questions include: (a) What are the basalt dissolution kinetics in German coastal habitats under different biological, chemical, and physical variables, and what are the corresponding carbon sequestration timescales? (b) What effects do the release and dispersion of dissolution products have on North Sea/Baltic Sea coastal ecosystems?

3.1.4. Direct Electrosynthesis of Sodium Hydroxide in Desalination Units in Upwelling Regions

In many arid regions or on islands, desalination plants are the primary source of freshwater. During the desalination process, seawater is separated into freshwater and brine. The retained salt in the brine can be split into sodium hydroxide (NaOH) and hydrochloric acid (HCl) through electrolysis. Retaining the acidic HCl on land and reintroducing the brine along with the alkaline NaOH to the ocean enhances ocean alkalinity. In upwelling areas this approach of OAE would reduce CO₂ emissions into the atmosphere by CO₂-rich upwelled water (Ali et al., 2021; Rau et al., 2013), creating net CDR in the region. While this option could potentially be implemented in a desalination plant on Heligoland, where it would not reach a 10 Mt CO₂ removal scale, we decided to explore its potential in upwelling regions (Sea of Oman) where desalination plants produce more than half a gigaton of fresh water annually (DEWA, 2022). This option's implementation could be connected to Germany through capacity building and carbon trading (please refer to Section 4 for further discussion).

As this approach is currently in the lab-experiment phase with a prototype ("Ebb Carbon," 2024) in development, we assess this option with a TRL of 3.

Utilizing all NaCl from seawater to produce NaOH, achieving 10 Mt CO₂ yr⁻¹ removal would require a minimum of 0.47 km³ of seawater at ~35 g kg⁻¹ salinity to be processed by a desalination plant yearly (calculation in Supporting Information S1 3.1.4). For example, in 2020, a single large desalination plant in the United Arab Emirates (UAE) produced 0.62 km³ of freshwater (DEWA, 2022), equating to a processing of 0.6–1.2 km³ of seawater per year (assuming a recovery rate between 50% and 90%). Upgrading such existing desalination plants to remove 10 Mt CO₂ would, however, require 42.7 TWh of additional energy per year (Supporting Information S1 3.1.4). This equals ca. eight times the total renewable electricity production in the UAE in 2020 (IEA, 2023). Therefore, the optimistic capacity of this option at this site would be about 1.3 Mt CO₂ yr⁻¹, limited by the currently available renewable energy. Yet, the demand for freshwater production is expected to increase particularly in arid regions (Baggio et al., 2021), which would likely increase the availability of plants for this option. At an efficiency of 70% of the method, the extraction of 10 Mt CO₂ is expected to produce around 0.6 km³ of freshwater.

Making this CDR option energy- and cost-efficient as well as safe faces several challenges. The 8.3 Mt of the by-product HCl for 10 Mt CO₂ would need safe disposal and storage. In 2022, the global HCl market was estimated to be 15 Mt with an expected growth of 4.2% by 2032 (ChemAnalyst, 2023). If it was possible to have this CDR option produces H₂ and Cl₂ as byproducts instead of HCl (House et al., 2007; Rau et al., 2018), the by-product Cl₂

gas could be further marketed for various industries (e.g., sewage and wastewater treatment and water cooling systems). The current estimated cost of the electrolysis process (main energy demanding factor) ranges from approximately 900 million € (“Ebb Carbon,” 2024; Rau et al., 2018) to 3,850 million € (Rau et al., 2013; Renforth & Henderson, 2017) for a 10 Mt CO₂ removal rate.

It is currently uncertain how OAE in general and this method particularly could affect the environment (see 4.1.3), how MRV could be established (see 4.1.4) and how to safely store the byproduct of HCl if it cannot be sold. It showcases how large-scale CDR can alter the market of substantial markets for by-products, that is, HCl, or Cl₂.

3.2. Blue Carbon Enhancement – mCDR Options Increasing Carbon Capture and Sequestration by Marine Ecosystems

Marine ecosystems are habitats of efficient primary producers, such as phytoplankton and seagrass. Primary producers can assimilate CO₂ from the atmosphere through photosynthesis and store it in their biomass, underlying sediments, and/or ultimately release the carbon in the form of detritus and/or dissolved recalcitrant carbon sinking to the deep ocean. Kelp forests are estimated to sequester globally about 643 Mt CO₂ yr⁻¹ (224–983 Mt CO₂ yr⁻¹), making them a viable marine CDR option (Krause-Jensen & Duarte, 2016). Though the direct CDR capacity might be limited, these options have co-benefits with no/few disadvantages compared to other CDR measures (Gattuso et al., 2018). The permanence of carbon storage in coastal ecosystems is estimated to range from decades to millennia (Duarte et al., 2013; Fourqurean et al., 2012). Organic carbon sunk into the open ocean is estimated to be out of contact with the atmosphere for years to millennia depending on location, storage depth and general ocean circulation and stratification (Siegel et al., 2021). Permanent carbon storage is considered after at least 1,000 years of storage (Brunner et al., 2024). Expanding or managing of such marine ecosystems for enhanced carbon uptake in coastal areas and the open ocean are considered contributions to blue carbon dioxide removal (blueCDR) activities (Mengis et al., 2023).

In the following we describe four blueCDR options (Figure 2B2): option 3.2.1 focuses on the introduction and expansion of kelp forests in Heligoland, as the only site in the German Bight characterized by rocky substrate as prerequisite to kelp forest establishment. This was the only blueCDR option that we were able to explore with the expertise present and at scale within the German jurisdiction. The (re)establishment of seagrass meadows and salt (tidal) marshes as mCDR options might hold blueCDR potential, especially for non-tropical coastal regions like Germany (Borchers et al., 2022; Macreadie et al., 2021; Stevenson et al., 2023). Nevertheless, since blueCDR options are of large interest and likely a low-regret method (Gattuso et al., 2021), and the potential development of carbon trading schemes under Article six of the Paris Agreement could allow for the exploration of CDR outside one's own territory, we decided to explore some of the options outside of Germany to comprehend the scale and efforts associated. For discussions concerning the implications of such activities, please see Section 4. Option 3.2.2 similar to option 3.2.1 explores the possibility of (re)planting and expanding of coastal ecosystems, in this case mangroves at the coast of Indonesia. For the last two options, we move to recently suggested open ocean blueCDR options (Gouvêa et al., 2020; Wu et al., 2023). Option 3.2.3 explores the use of artificial upwelling (AU) systems to fertilize phytoplankton, enhance productivity and subsequent carbon sequestration through enhanced export. Option 3.2.4 employs the same AU systems to fertilize *Sargassum* farms in the South Atlantic gyre, where the biomass is subsequently harvested and sunk.

When the chosen reference baseline represents a time when the marine ecosystem was established and not degraded, the suggested (re)establishment approach is considered restoration. This restores degraded ecosystems to their baseline state, which avoids GHG emissions, but is not CDR (Mengis et al., 2023). However, if the reference baseline is the present—meaning the (re)established ecosystem is an “addition” carbon sink to the baseline—it qualifies as CDR.

3.2.1. Introduction of Kelp Forests in the Coastal Waters of Heligoland

The expansion of existing and introduction of new kelp forests poses an option to sequester CO₂ from the atmosphere. Currently, the only kelp site in the German Bight is Heligoland, which could be used as a testing site. For any planting measure, young kelp sporophytes need to be produced for seeding. Therefore, local kelp sporophytes (*Laminaria hyperborea*) would be collected when they are fertile and their spores would be released. The spores would be used to produce “green gravel”, little stones seeded with young kelp (Fredriksen et al., 2020). After an initial growth period in the lab, the green gravel would be ready to be brought out to the planting site,

where they could be directly dropped from a boat. Several environmental parameters, such as suitable rocky substrate, light availability, water temperature, and nutrients, are required for the growth of kelp (Dean & Jacobsen, 1984; Tittley, 1991). While suitable temperature conditions prevail within most parts of the German Bight (Bolton & Lüning, 1982), a necessary rocky substrate for the kelp to attach to is found only around Heligoland. For further expansion, a rocky substrate would be needed to be established at sites with suitable depth ranges.

The green gravel approach is an established method and already in use in other regions (Alsuwaiyan et al., 2022; Fredriksen et al., 2020), therefore, we rate the TRL between 8 and 9. To achieve the target of 10 Mt of CO_2 yr^{-1} removal with this option, an area of about 8,000 km^2 , equivalent to about one-tenth of the German Bight's total area, of kelp forest would be needed (for calculation see Supporting Information S1 3.2.1). The potential area for the introduction or expansion of kelp in Heligoland is around 13 km^2 (calculation see Supporting Information S1 3.2.1). Most of the coastal area of the German Bight has a muddy substrate, hence the potential within the German Bight is not as big as in other coastal areas. In contrast, most of the shores along the European Atlantic coast have a rocky substrate and would therefore be better suited for kelp planting.

To establish 8,000 km^2 of kelp forest, about 3,000,000 t of green gravel would be needed. With an estimated price of 6.28 € per m^2 of newly established or restored kelp forest, the costs to afforest 8,000 km^2 would accumulate to a total of about 50 billion € (Fredriksen et al., 2020), with an unknown cost for additional substrate on top. This would be a one-time investment, with subsequent annual costs focused on monitoring carbon uptake and addressing potential replanting needs to maintain sequestration in case of disturbances. The material and energy needs are limited to the time of collection of fertile kelp, the cultivation phase, and the deployment of the green gravel.

Currently, one of the major questions is the long-term fate of the carbon captured in the kelp, once the plant detaches. For a long-term storage of CO_2 , it would need to drift to the open ocean and sink deep enough to be sequestered in the sediment (Filbee-Dexter, 2020; Krause-Jensen & Duarte, 2016). However, if the kelp gets washed ashore, it would decompose and the CO_2 would be released back into the atmosphere. The washed-up kelp could potentially be used as a co-product like fertilizer or for the production of bioenergy, but only durable sequestration or storage of the carbon would qualify as CDR (Smith et al., 2023). To further scale up this option within the German Bight, the challenge will be the establishment of a rocky substrate in large coastal areas. However, this option could be applied on many rocky shores in other locations.

3.2.2. Mangrove (Re)establishment in Indonesia

Mangrove forests store a considerable amount of carbon in their biomass and sediments (Alongi, 2014), sequestering ca. 15–73 Gt CO_2 yr^{-1} globally (Donato et al., 2011). They grow in tropical to subtropical areas, making them currently unsuitable for the German coast. It is estimated that 20%–35% of the world's mangrove forests have been lost over the last 50 years, mostly due to anthropogenic activities and extreme climate events (Polidoro et al., 2010). In this option, the potential of mangrove (re)establishment in Indonesia is explored. Indonesia is chosen as a case study since it currently hosts over 20% of the area of the world's mangrove population (Giri et al., 2011). Over the last 30 years, Indonesia has lost about 8,000 km^2 of mangroves, and estimates of the initial area of mangrove forests in Indonesia range between 42,000 km^2 and 77,000 km^2 about 35 years ago (Ilman et al., 2016), while the current area is about 31,900 km^2 (Alongi et al., 2016). Therefore, Indonesia has great potential for mangrove (re)establishment and consequently, carbon dioxide capture and storage.

Planting mangroves is a process that is well studied and established, we estimate the TRL to be 9. Before replanting, certain abiotic parameters such as physico-chemical characteristics (salinity, pH), hydrodynamics (waves energy, inundation time) and topography (slope) would have to be checked to select species for planting in suitable zones and improve survivability of the seedlings. Propagules or seeds can be gathered and planted directly, or nurseries can be set up. While nurseries would require a larger time and cost investment, they increase seedling survivability (Hsiung et al., 2024). If necessary, hydrologic conditions might need to be restored to address stressors that have previously caused their declining numbers, by for example, setting up breakwaters, or digging channels. In this case, more time and resources would be needed.

While replanting mangroves describes a simple enough approach, scaling the operation to achieve the 10 Mt CO_2 uptake remains a challenge, since it would require the availability of an area of ~9,400 km^2 (see Supporting

Information S1 3.2.2). However, Sasmito et al. (2023) showed that only about 1,900 km² are currently suitable for mangrove (re)establishment, which would lead to an uptake of 2 Mt CO₂. Planting mangroves on an area of 9,400 km² would require an investment of 3.4 billion € (Cameron et al., 2019), which includes 1 billion seeds, planting facilities and infrastructure, and maintenance per km² for a 10 Mt CO₂ yr⁻¹ removal scale.

Remaining uncertainties concerning this approach include the exploration of sufficient areas if there would be an intent to scale up this approach, including the corresponding investment costs. Monitoring, reporting and verification of the carbon sequestration, which is currently mainly driven by the efforts of volunteers, would have to be scaled up and operationalized, for which organizational structures would need to be established.

3.2.3. Artificial Upwelling to Enhance Plankton Production in the North Atlantic

Artificial upwelling (AU) is based on the idea to introduce pipes in open ocean oligotrophic waters to pump up nutrient-rich deeper water to the surface ocean and thereby enhance primary production and export production with the aim to generate an additional CO₂ flux from the atmosphere into the surface ocean.

If this idea (for which we currently estimate a TRL of 2) would be further developed, one possible application of the option could be the North Atlantic Ocean, where long wave-energy powered pipes of 1,000 m length would be installed (see Supporting Information S1 3.2.3 for more info). The necessary infrastructure for this option would include facilities to produce durable pipes made out of steel, plastic or other new materials, ships to install and maintain the pipes in the North Atlantic and a large network of remote sensing technologies (e.g., satellite images and ARGO floats) for MRV purposes (e.g., Mengis et al., 2023). The pipe-covered area needed in the North Atlantic to hypothetically reach 10 Mt CO₂ yr⁻¹ removal via 1,000 m long pipes may be calculated from down-scaled global modeling experiments and would reach a size of 682,000–1,706,000 km² (2–5 times the size of Germany; Jürchott et al., 2023).

This would translate into 40,000 individual pipes and an investment of around 2.2 billion € (based on the assessment that one individual 500 m pipe would cost approximately \$ 60,000 and would be able to remove 250 t of CO₂ yr⁻¹ without maintenance costs, see Supporting Information S1 3.2.3 for more information). Although shorter pipes are expected to cost less money compared to longer pipes, longer pipes in model experiments have been found to be more effective in removing CO₂ from the atmosphere (Oschlies, Pahlow, et al., 2010; Yool et al., 2009). The calculated pipe-covered area as well as the costs to reach 10 Mt CO₂ yr⁻¹ removal in the North Atlantic are highly uncertain (also given the low TRL), but some expected side effects and the duration time (see discussion below) of the additionally added CO₂ can already be assessed based on modeling studies. The option is expected to require a total energy demand of 1.4 TWh yr⁻¹ including the pipes production and ship operation (see Supporting Information S1 3.2.3 for more details).

One concern to this AU option, is the fact that the approach would also transport heat and salinity and thereby change the ocean stratification and, eventually, the ocean circulation with potentially substantial impacts on climate (Kwiatkowski et al., 2015). As long as AU is continuously applied, the duration time of additionally stored CO₂ in the ocean is expected to range from decades to millennia (Siegel et al., 2021). It is, however, worth noting that AU, once deployed, would need to be deployed continuously to further increase and keep the additionally added CO₂ stored in the ocean (Keller et al., 2014; Oschlies, Pahlow, et al., 2010). If AU is abruptly discontinued, the surface ocean would immediately respond with CO₂ outgassing, while at the same time additionally stored heat in the ocean interior would radiate back to the atmosphere and within years to decades atmospheric temperatures would rise even above the reference simulation (Oschlies, Pahlow, et al., 2010). Another considerable uncertainty within the development of this option is the durability and stability of the pipes once deployed. As of today, no existing pipe can operate at a depth of 500 m. Another challenge is the assessment of the localized impact that the increase of primary productivity induced by the upwelled water may have in the local food chain. So far, the impact has been studied only at the base of the food web (Ortiz et al., 2022; Tames-Espinosa et al., 2020) and additional experimental studies are required.

3.2.4. Sargassum Farming and Sinking in the South Atlantic Gyres

For this CDR option, holoplagic Sargassum (*Sargassum fluitans* and *S. natans*) would be grown offshore in free-floating aquafarms placed in the South Atlantic subtropical gyre. Nutrients for growth would be provided through artificial upwelling of nutrient-rich deep water from 400 m depth, using upwelling pipes based on the Stommel

principle for a perpetual salt fountain (Stommel et al., 1956). This type of artificial upwelling would not require external energy, as the nutrient-rich deep cold water would warm as it comes up and parallelly downwelling warm water from the surface. Environmental conditions (temperature, light, salinity) in this region are favorable for growth of pelagic Sargassum (Gouvêa et al., 2020) and make the implementation of the Stommel upwelling pipe system possible (Kemper et al., 2023).

We estimate the TRL of this option as 2, with the main bottleneck being the cost of the development of the prototype pipes (see Section 3.2.3).

To sequester 10 Mt of $\text{CO}_2 \text{ yr}^{-1}$, 57.5 Mt of Sargassum biomass would need to be sunk to the deep sea every year and the total energy demand is 1.7 TWh yr^{-1} (for calculation see Supporting Information S1 3.2.4). Sargassum increases its biomass by fragmentation at a rate of 5%–10% per day, which means to grow and harvest 0.16 Mt of biomass on a daily basis, a Sargassum standing stock of 4.63 Mt biomass would need to be maintained. To sustain growth, 8,578 m^3 of deep ocean water from 400 m depth would need to be upwelled per second ($\sim$ half of the water discharge of the Mississippi river). This farm would take up an area of 1,324 km^2 . The harvested biomass would be mechanically shredded to extract the nutrients that could be fed back to the aquafarms, reducing the above-mentioned amount of deep water needed for fertilization (“Sarga Agriscience,” 2021). The shredded biomass will then be pressed into bales and released back to the ocean, where it would sink down, since gas vesicles of the Sargassum would be destroyed in the shredding process, which causes the biomass to lose its natural buoyancy (Baker et al., 2018; Johnson & Richardson, 1977). The logistical effort could be reduced by automated on-platform workflows for farming, harvesting and sinking at the same place.

Due to the low TRL, cost estimations for this option are highly uncertain. Costs of investment and maintenance of infrastructure, including workforce and transportation, would amount to around 1,060 € per tonne of CO_2 removed. If scaled-up linearly, this would come up to 10.6 billion € for the 10 Mt $\text{CO}_2 \text{ yr}^{-1}$ removal.

Many uncertainties arise with this option, mainly due to the need to establish the infrastructure, as well as the monitoring. Consequences of impacts on ocean physics and circulation via changes in stratification, as well as from the Sargassum farms and the sunken biomass (e.g., on oxygen levels) are not well understood and need to be addressed in future studies.

3.3. Off-Shore Geological Carbon Storage (mCS) – mCDR Options With Technological Carbon Capture and Subsequent Storage in Geological Formations

Carbon storage in geological formations represents a necessary contribution if technological carbon capture approaches want to achieve carbon removal, like bioenergy carbon capture (BECC) and direct air carbon capture (DACC). In the following, we consider maritime or offshore storage of CO_2 (mCS) in combination with BECC or DACC. Note that geological storage of carbon emissions from fossil or mineral processes (here referred to as fossilCCS following Smith et al., 2023) is distinct from these mCDR approaches, since in this case the CO_2 emissions are avoided, rather than atmospheric carbon being removed; fossilCCS does not constitute a CDR method (Smith et al., 2023).

The concept of geological CO_2 storage is based on controlled injection of dissolved or liquefied CO_2 into porous rocks in the subsurface, so in a geological reservoir. Depending upon the properties/type of the target host rock, the CO_2 can be trapped by several mechanisms, which comprise trapping by an impermeable cap rock or sediment cover (structural trapping), capillary forces in pores (residual trapping), dissolution in water (solubility trapping), and mineral carbonation reactions (mineral trapping).

Two options for geological storage are of particular interest and explored here in more detail (Figure 2B3): option 3.3.1 looks into the possibility of marine biomass for bioenergy generation combined with structural trapping of CO_2 in sandstone formations/saline aquifers that exist in the German North Sea. Deep saline aquifers have a high CO_2 storage capacity due to their regionally large extent, but are still mostly unexplored (Bachu, 2015). Estimates for CO_2 storage in the German EEZ suggest total storage capacities of 4–24 Gt CO_2 (Knopf & May 2017). Time scales of geological CO_2 storage in sandstone formations, while dependent on the regional conditions, can mostly be considered long-term, if not permanent, with a projected minimum of 98% of the stored CO_2 remaining in the reservoir for 10,000 years (Alcalde et al., 2018). Another option (3.3.2), albeit outside of Germany, explores the possibility of DACC combined with mineral trapping of CO_2 through injection of CO_2 into porous basaltic rocks. The basalts form the upper part of the oceanic crust, which is why the majority of them are located offshore in the

deep sea and outside the German EEZ. Mineral trapping in the upper ocean crust is an interesting option for CO₂ storage, as basaltic rocks in general have the ability to react more rapidly with CO₂ to produce carbonates than sedimentary sandstones. The accelerated mineral trapping mechanism in basaltic reservoirs compared to conventional sandstone formations facilitates long-term storage by immobilizing the CO₂ (Kelemen et al., 2019). Due to the chemical composition of basalts, which is rich in calcium, magnesium, and iron, the injected CO₂ can react with these elements to form carbonate minerals in the pore space of the rock. Furthermore, impermeable sediments that cover most of the oceanic crust are assumed to impede CO₂-leakage from the reservoir and, thus, contribute to safe storage conditions. According to the calculations of Snæbjörnsdóttir and Gislason (2016), fractured and porous basaltic flanks of mid-ocean ridges bear a storage capacity of >10⁵ Gt CO₂, exceeding the expected CDR needs manifold. This option would take CO₂ captured in Germany and store it in Norwegian waters, which would require refined agreements concerning CO₂-trade between Germany and Norway, as discussed in Section 4.

3.3.1. Biomass From Macroalgae Farming for Biomethane Production Combined With Carbon Storage in Saline Aquifers in the North Sea

For a marine feedstock for bioenergy combined with carbon capture and storage, macroalgae could be cultivated and harvested. Plantlets would be set into nearshore floating macroalgae farms (Buck & Buchholz, 2004), which would then be transported offshore and moored within the German EEZ (Buck et al., 2018). The macroalgae would be harvested once a year, and transported to biogas processing and upgrading plants, ideally located in northwestern Germany. The bioenergy plants would need to be retrofitted with carbon capture units, from which the CO₂ is then collected and transported to saline aquifers in the North Sea (with a capacity between 4 and 24 Gt CO₂; Knopf & May 2017).

At present, given the highly commercialized coastal seaweed cultivation in Asia, and its absence in North Europe, we estimate the TRL of this option to be 6 (see Supporting Information S1 for estimation).

For this option, to reach 10 Mt CO₂ yr⁻¹ removal, assuming an average annual productivity of 20 kg fresh mass per square meter (FMm⁻²; Buck & Buchholz, 2004; Chen et al., 2015; Chung et al., 2013; Fernand et al., 2017; Kim et al., 2017; Roesijadi et al., 2010), one would need a total area of 2,358 km² (approximately 8.3% of the total area of the German EEZ) for macroalgae cultivation to produce a total of 115 million tonnes macroalgae FM per year (see Supporting Information S1 3.3.1 for calculations). A benefit is the production of biomethane as an energy carrier: although energy is required for harvesting, bioenergy plant operation, and CCS, the model plant produces 4.8 million m³ biomethane, as well as additional heat for external use.

Not considering potential revenues from selling the products, the CO₂ removal cost is estimated at 83 € per tonne of CO₂, which would amount to 830 million € for the 10 Mt CO₂ yr⁻¹ removal scale. If this option was scaled up to this order of magnitude, the construction of new, large-scale (megawatt scale) power plants close to the shore would be reasonable, instead of relying on a big number of decentralized, small-scale plants. While this would impact investment costs, it would reduce the efforts of biomass and CO₂ transportation.

One challenge associated with open ocean macroalgae cultivation is the durability and maintenance of the floating farms, which are susceptible to damage under severe weather conditions in the North Sea (Buck & Buchholz, 2004). One uncertainty of this mCDR option concerns the productivity of macroalgae in the German EEZ, as the estimation given here is highly idealized. Macroalgae growth depends on water temperature, nutrient availability, light and ambient ocean currents. These conditions exhibit significant seasonal variations and are also affected by climate change (Buck & Buchholz, 2004; Grabemann & Weisse, 2008). Previous studies have illustrated that cultivated macroalgae in the North Sea showcase resilience to the high energy environment, even amid severe storm conditions. This implies a potential for macroalgal cultivation within such challenging maritime settings (Bartsch et al., 2008; Buck & Buchholz, 2005; Fortes & Lüning, 1980). Finally, the use of more than 10% of the German EEZ area for the macroalgae production is surely challenging, given the strong competition for area usage within the EEZ. Another challenge for the CDR option is the anaerobic digestion process in biogas plants for macroalgae feedstocks due to unwanted impurities, for example, polyphenols, sulfur, sodium chloride, and heavy metals (Murphy et al., 2015). However, several pre-treatment methods have been suggested in the literature to enhance biomethane yields (Chen et al., 2015; Chung et al., 2013; Suutari et al., 2015).

3.3.2. Off-Shore Carbon Storage via Mineral Trapping in North East Atlantic Basalts Combined With Direct Air Carbon Capture

For this CDR option, we explore the possibility of CO₂ being captured in Germany by DACC facilities fed with energy generated by offshore wind parks in the North Sea. The captured CO₂ could be transported via cargo ships to an offshore injection site. In the North East Atlantic a basalt volume of approximately 90,000 km³ has been identified, of which 30,000 km³ are in Norway at subsurface depths between 1,500–1503,000m (Planke et al., 2021). For this CDR option, we assume this platform to be located at the Vøring plateau at the North Western Norwegian margin, since the basalts of this region are well studied (Planke et al., 2022) and may have a storage potential of several Gigatons of CO₂ (under investigation; Planke et al., 2021; Rosenqvist et al., 2023). Capturing CO₂ from the atmosphere by using DACC facilities is at the demonstration stage at TRL 6 (IEA, 2022). The concept of offshore CO₂ mineralization still needs to be prototyped and applied in the future. Therefore, the TRL for offshore CO₂ storage in basalts is estimated to be 3–4.

If this option was to be scaled to capture and remove 10 Mt CO₂ yr⁻¹, the DACC would need 18 TWh of energy generated by renewable energy sources (Borchers et al., 2022; Heß et al., 2020), that is ~85% of the energy currently transferred to shore by the North Sea wind parks (Tennet, 2023). The area and the amount of material required to build DACC facilities to capture this quantity of CO₂ are highly uncertain and subject to debate (Chatterjee & Huang, 2020; Realmonte et al., 2019, 2020). For CO₂ transport, the captured CO₂ has to be liquefied (~1.51 TWh/10 Mt CO₂, see Text S3.3.2 in Supporting Information S1) and stored in intermediate tanks. Assuming a distance of 1,800 km, three injection wells, and discharge rates between 1,375 and 2,750 m³ hr⁻¹, transporting 10 Mt CO₂ yr⁻¹ requires ~40 to 140 trips with at least three large, four medium, or eight small cargo ships, respectively. On site, floating production and offloading units (FPSO) with risers for each well are needed for continuous CO₂ injection. Regarding the injection of CO₂, two different approaches exist: either CO₂ can be injected as a “pure” phase or it can be mixed with seawater (see Supporting Information S1 3.3.2). In case of “pure” CO₂ injection, the CO₂ can be heated and compressed by seawater or waste heat recovery on board (to 10°C, 60 bar). Then, compression for injection to, for example, 300 bar, requires 0.094 TWh/10 Mt CO₂ (see Supporting Information S1 3.3.2).

Among others, the costs of capturing CO₂ depend on the DACC technology and the energy costs, which makes the calculation of future capture costs challenging and highly uncertain (IEA, 2022). The same applies for the storage technologies, due to low TRLs future cost estimates are not feasible.

In Iceland, ongoing small-scale projects combine DACC (capturing on the kt CO₂ yr⁻¹ scale) and basalt CO₂ storage onshore (“Mammoth,” 2022; “Orca,” 2021). While in this option DACC is used for the feed of CO₂, it is also possible to use bioenergy (similar to 3.3.1). Since storing CO₂ via mineral trapping in offshore basalt formations is still below the prototype stage, many research questions remain: Is the injection of supercritical CO₂ or CO₂ dissolved in water the more suitable option for the Norwegian Sea? Is there an active aquifer in the basaltic layers with flow fostering CO₂ distribution? How does clathrate formation affect the injection scenario? How fast do the carbonates precipitate, how does the reaction affect the pore space geometry and hydraulic properties of the host rock? In which sub-bottom depth is the CO₂ injection safest and most efficient? Getting a profound knowledge of these fundamental questions facilitates finding the best location to drill and estimate the amount of drill holes required to trap a certain amount of CO₂, which in turn affects the costs to realize this mCDR option.

4. Discussion

The collection of mCDR and mCS options in this study covers different approaches for carbon removal technologies with sequestration or storage in the marine environment. We explore four options for ocean alkalinity enhancement (OAE), four options for enhancing the uptake of blue carbon ecosystems (blueCDR), two of which use artificial upwelling systems (AU), and two options involving geological offshore storage (mCS).

Within the generated mCDR option collection, six out of 10 options could potentially reach the scale of 10 Mt CO₂ yr⁻¹ removal, of these six, four would have the CO₂ captured within German borders, and three options are located entirely within German jurisdiction (see Figure 2). The blueCDR options based on introducing kelp on Heligoland (3.2.1), and mangrove replanting in Indonesia (3.2.2), as well as the OAE options through electrolysis in desalination plants (3.1.2) and coastal enhanced weathering (3.1.3) did not reach 10 Mt CO₂ yr⁻¹ removal under the assumptions made here.

From a global viewpoint, the assessment of marine-based CDRs by Gattuso et al. (2021) saw alkalinity enhancement as the front runner when it comes to CDR potentials, but our site-specific assessment highlights that different implementations of the same method can result in differences in the regional capacity. Taking the options for OAE as an example, adding an alkalinity-enhanced solution in the North Sea (3.1.1) and liming along ship tracks (3.1.2) could potentially reach the scale of $10 \text{ Mt CO}_2 \text{ yr}^{-1}$ removal, while neither coastal enhanced weathering (3.1.3) on the same site nor electrosynthesis in desalination units (3.1.4) on a more suitable site could do it. Similarly, while Gattuso et al. (2021) consider blueCDRs to have very low direct CDR potential globally, our assessment shows that while it is possibly true for kelp forest establishment (3.2.1), other blueCDR options, like mangrove (re)establishment (3.2.2) can reach the megaton scale, and both artificial upwelling (3.2.3) and sargassum farming and sinking (3.2.4) can potentially rise to the challenge.

The techno-environmental comparison of these approaches is challenging, since the options are distinct in both their capture mechanisms – ranging from ecosystem sink capacity enhancement, to enhanced chemical weathering, to technological direct air or point source carbon capture – and their storage processes – ranging from marine biomass, to dissolved inorganic carbon in the water column, marine sediments or varying geological formations. As a result, the mCDR options require different types and amounts of resource inputs, rely on different technologies and infrastructure, and have different co-benefits and side effects. By scaling the CDR options to the same annual removal rate ($10 \text{ Mt CO}_2 \text{ yr}^{-1}$), we attempt to allow for some comparability with respect to factors like area or energy demand, environmental effects and MRV challenges and possibilities, which we will explore in the following.

4.1. Comparison of Marine CDR Options – TRL, Energy and Area Demand, and Bottlenecks

The technology readiness level (TRL) assigned to the mCDR options gives an estimate of the current availability of the technological components of the options, and therefore the development time before possible implementation. The generated collection encompasses mCDR options at all TRLs, with low TRL for both AU options (3.2.3, 3.2.4), and reasonably high TRL for the two blueCDR options managing ecosystems (3.2.1, 3.2.2). While high TRL options are in a rather mature state, having most technological components proven and tested in past and ongoing pilot projects (e.g., IEA, 2022; Raw et al., 2023), low TRL options are still in the concepts' development phase and only some theoretical estimations exist in the literature. For those low TRL options, many of the parameters in this study hence are first-order estimates and therefore rely on reasonable assumptions when scaled up to a $10 \text{ Mt CO}_2 \text{ yr}^{-1}$, which is a clear limitation to our study, and should be considered when interpreting our findings.

Low TRLs certainly can be considered bottlenecks for most of the mCDR options (e.g., 3.1.1, 3.1.2, 3.1.4, 3.2.3, 3.2.4, 3.3.2), except for the ecosystem-based options 3.2.1 and 3.2.2 with TRLs of 8–9 (Figure 3, Table 2). Other bottlenecks are more method-specific (Table 2). For the high energy demand OAE options (3.1.1, 3.1.2, 3.1.4) as well as for the DACCS option (3.3.2), the main limiting factor would be the supply of renewable energy to decarbonize the process chain, whereas the BECCS option (3.3.1) shows a net energy provision in the form of biomethane and heat. For rock-based OAE options, the considerable demand for material would also pose a challenge.

In contrast, the blueCDR options would have low energy demands, since the energy demand in nurseries or upwelling pipes is relatively small, but would require considerable marine space for their implementation. This limitation prevented both ecosystem-based options (3.2.1, 3.2.2) to reach the $10 \text{ Mt CO}_2 \text{ yr}^{-1}$ removal scale. If marine biomass for BECCS or Sargassum farming are to be employed to relieve pressures on land, the engineering for suitable open ocean farms for seaweed in the North Sea remains a challenge. The area and energy demand of harvesting and transporting 115 Mt of macroalgae biomass could potentially present another bottleneck in an at-scale implementation due to possible conflicts with other sea areas usage (e.g., wind parks). In addition, technological innovation in the open ocean engineering, deployment and maintenance of the farm structures and upwelling pumps would be necessary before these options can be implemented. Similarly, spreading alkaline solutions in the ocean requires access to large areas (3.1.1, 3.1.2, 3.1.4).

In contrast, area demand of the DACCS option is less than 100 km^2 (3.3.2), with the highest demand arising from the DAC plants. While the area demand is often assumed to be less problematic for mCDR options compared to land-based CDR options, challenges with respect to accessibility of large ocean areas (3.1.1, 3.1.2, 3.1.4, 3.2.3)

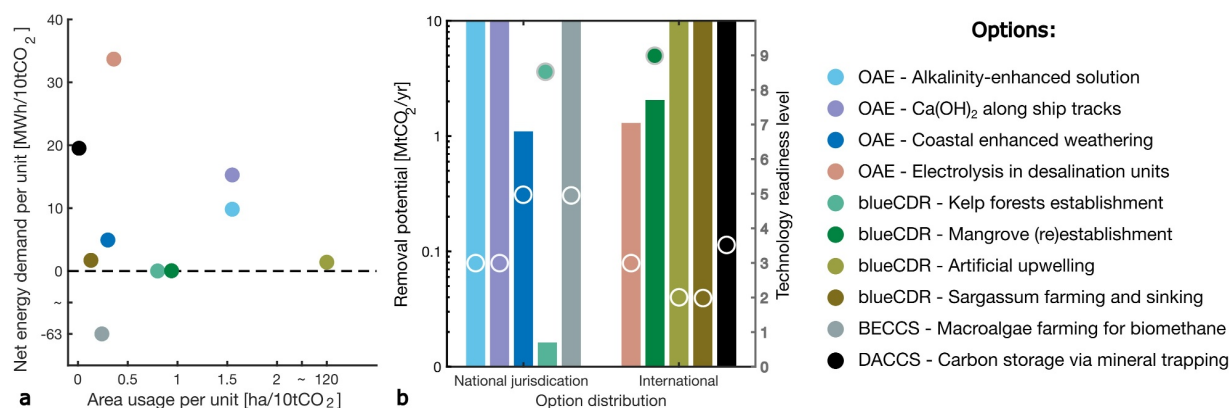


Figure 3. Summary and comparison of mCDR options at a scale of 10 tonnes of CO_2 removal. This figure shows net energy demand against area usage (a); and technology readiness level (white circles) against whether or not the option would be implementable in German jurisdiction and could reach a scale of $10 \text{ MtCO}_2 \text{ yr}^{-1}$ (b). The area usage displayed here includes estimated land and sea surface area. Net energy demand is given as demand minus supply, which can lead to negative values (produced energy). We chose to compare our options here on the basis of 10 tonnes rather than 10 megatonnes, to allow for a comparison at a scale that all the options could reach, and that would be significant to compensate for one person's annual emissions in Germany (8.7 t yr^{-1} for 2021).

and potential conflicts with other uses (e.g., marine protected areas, offshore wind, etc.) in more coastal areas (3.1.3, 3.2.1, 3.2.2, 3.3.1) remain (Table 2).

For the BECCS and DACCS options (3.3.1, 3.3.2), the lack of existing infrastructure (carbon capture facilities, transport infrastructure and offshore platforms) for the geological carbon storage as well as the high energy demand for the carbon capturing process limit their potential (Table 2).

4.2. Comparison of Marine CDR Options – Environmental Effects

The mCDR options aim to alter biological, chemical or geological processes with the goal to increase carbon uptake, yet alongside this desired effect likely come a variety of unintended environmental effects of varying predictability. The extent of the possible environmental effects at a specific scale at a specific site is difficult to quantify without dedicated studies (e.g., model studies with site-specific boundary conditions) and will have to be subject to further investigation. We indicated the research gaps and uncertainty related to possible environmental effects (Table 2) and we compiled here possible expected environmental effects gathered from the literature.

The possible impacts of OAE on the wider marine ecosystem on short to long time scales require more research (Albright et al., 2016; Bach et al., 2019; Cripps et al., 2013; Ferderer et al., 2022; Gately et al., 2023; NAS, 2021). The introduction of alkaline substances into seawater could allow for additional CO_2 uptake while stabilizing the pH, although this does not reverse previous acidification (Hinrichs et al., 2023; Hutchins et al., 2023). The addition of alkalinity is reported to have a positive effect on ecosystems that are sensitive to ocean acidification (Albright et al., 2016; Weatherley, 1988), however, it is also shown that less dissolved CO_2 may reduce growth rates of calcifying organisms (Langer et al., 2006). At the point of alkalinity injection, OAE might cause localized temporary pH and alkalinity spikes, which might be ecotoxic and detrimental for the affected ecosystems (Locke et al., 2009). On a longer timescale, such an intervention could impact the physiology of marine organisms and the ecosystem structure (Roberts et al., 2010). If OAE options introduced minerals or their solution into the ecosystem (3.1.1, 3.1.3), this would likely have a fertilization effect (Hauck et al., 2016; Köhler et al., 2013). OAE therefore could increase the primary productivity on site, but decrease oxygen level and increase acidification in the water column downstream (Oschlies, Koeve, et al., 2010). Depending on the geochemical composition of the used rock, heavy metals could also get into the water through mineral dissolution or electrolysis and desalination processes (Arribère et al., 2003; Lattemann & Höpner, 2008), which needs to be regulated. In the case of upgrading existing desalination plants, the discharge from plants (3.1.4) might be contaminated with filter-cleaning products (anti-scalants and antifoulants) which would impose potential danger to the local environment (e.g., Ahmed & Anwar, 2012; Al-Anzi et al., 2021; Jones et al., 2019). Furthermore, indirect effects from OAE options due to mining activities (3.1.1, 3.1.2, 3.1.3) would likely negatively impact soil, air, and water quality on land, and introduce noise pollution to the environment on and off site (Sengupta, 2021). Also, there are

Table 2
Overview of Bottlenecks and Research Gap/Uncertainty Identified During the Development of the Ten mCDR Options

Category	OAE				blueCDR		mCS			
	3.1.1 Alkalinity-enhanced solution	3.1.2 Ca(OH) ₂ along ship tracks	3.1.3 Coastal enhanced weathering	3.1.4 Electrolysis in desalination units	3.2.1 Kelp forest establishment	3.2.2 Mangrove (re) establishment	3.2.3 Artificial upwelling	3.2.4 Sargassum farming and sinking	3.3.1 Macroalgae farming for biomethane	3.3.2 Carbon storage via mineral trapping
Bottleneck factor for reaching 10 Mt CO ₂ per year removal capacity										
Infrastructure/Technology/TRL	TRL = 3. Electrolysis technology for commercial usage.*	TRL = 3. Installation of tanks, pumping and piping systems on ships.*	TRL = 5. Transport, grinding and distribution of minerals at coastline.*	TRL = 3. Electrolysis technology for commercial usage.*	Possible conflict with other sea area usage* Area availability for creation of suitable substrate*	Possible conflict with other land or sea area usage*	TRL = 2. Pipe efficiency under development.*	TRL = 2. Upwelling infrastructure under development.*	TRL = 5. Farming infrastructure in the open ocean.*	TRL = 3-4. Infrastructure to capture, transport and inject CO ₂ has to be built.*
Land/sea area demand	Limited area for implementation and its possible conflict with other uses (e.g., marine protected areas)* For 3.1.4 there is possible conflict with space on land (safe storage of waste product HCl)								High area demand and possible conflict with other uses (e.g., marine protected areas)*	Potential high area demand on land for DACC facilities
Material demand		Mining and production capacity could restrict further scaling up*			Large scale supply of propagules and seedlings for implementation					Material needed to build and run DACC facilities to achieve large scale capture
Clean Energy Demand	Decarbonation of the slaked lime production reduces the CDR efficiency Emission during mining, transportation, and deployment reduces the CDR efficiency			Availability of renewable energy*				Off-shore renewable energy (e.g., floating solar) still under development		High energy demand for DACC
Research gap/uncertainty										
Environmental effect (±)	Unclear effects of higher alkalinity and temporal increase of water parameters (e.g., pH, nutrient level, trace metal, and salinity) on marine life				Increases diversity in established areas. Offering shelter for fish, invertebrates, birds, mammals. Establishment of an alternative ecosystem. Coastal erosion protection			Unknown		Unknown
CDR effectiveness	Alkalinity injection rate and dissolution kinetics need further research (linked to area demand) to prevent secondary precipitation. Long term fate of sequestered carbon is uncertain For 3.1.3 option implementation of CCS for the lime production. Method efficiency without a low carbon energy source						Method efficiency needs more research	Fate of sunken biomass in the deep sea is unknown	Method efficiency needs more research	Method efficiency without a low carbon energy source
MRV		Not established yet				High effort due to the vast area	Not established yet			No pilot projects exist, which makes storage cost estimates uncertain
Cost	No pilot plant available			Cost of electrolysis technology at commercial level			Upwelling pipe cost uncertain			
Durability	Long-term stability of added alkalinity	Keeping the weathering material within the reactive (wave) zone		Long-term stability of added alkalinity	Long-term fate of the sequestered carbon is uncertain	Long-term stability of stored carbon depends on the system's stability (subject to climatic changes and human activities)		Depends on the pre-treatment of the biomass before sinking and the remineralization rate at the deep sea		Long-term evolution of pore space and permeability
Other	Safe disposal of waste			Safe storage of waste product HCl	Uncertainty in the area estimation	Uncertainty in area estimates (strong local variations)	Lack of permits to operate in international waters		Macroalgae productivity in the region	DACC capacity dependency

Note. “*” marks the current factor(s) restricting further upscaling of the option.

concerns about health risks associated with finely crushed (1–10 μm) material containing fibrous serpentine minerals like asbestos, as well as potential problems with wind-borne transport of fine ground olivine (Hangx & Spiers, 2009).

Environmental effects from blueCDR options could include changes in species compositions, light availability for organisms living on the seafloor or ambient nutrient levels. Furthermore, if biomass is mobilized, its decomposition would cause a decrease of oxygen levels in the adjacent deeper water or on the seabed. However, the introduction of kelp or mangrove forests would provide several co-benefits such as coastal protection, provision of services like food, timber or medicine, provision of habitat for (commercially important) fish species, water purification (Castro et al., 2022; Kayalvizhi & Kathiresan, 2019; Theuerkauff et al., 2020), as well as cultural services, including tourism, religion, and contributing to general well-being (Bandaranayake, 1998; Cuba et al., 2022; Eger et al., 2023).

The environmental effect of AU options is highly uncertain and has so far mostly been assessed within modeling studies. Ocean fertilization from AU options, introducing nutrient-rich deep water to the surface, may increase primary production and shift plankton community structure (Baumann et al., 2021; Ortiz et al., 2022). An increase of primary production results in an increase of carbon export and remineralization that could reduce oxygen concentration in deeper waters and increase GHG release (e.g., methane and nitrous oxide; Williamson et al., 2012). Additionally, the artificial upwelling of water may vertically transport microbes, likely impacting the microbiological environment. Changes in temperature, salinity, stratification, and circulation induced by AUs require meticulous study due to their irreversible nature (Oschlies, Pahlow, et al., 2010).

Environmental effects from large-scale macroalgae or sargassum farms are still understudied, but likely include increased or changed biodiversity both at the surface and in the deep sea (Baker et al., 2018; Casazza & Ross, 2008), increased albedo (Bach et al., 2021), reduced light at the surface and possibly co-emission of halocarbons (Keng et al., 2013; Mithoo-Singh et al., 2017). While growing, Sargassum excretes large amounts of dissolved organic matter (DOM) (Powers et al., 2019). Some of the excreted compounds are likely to persist in the ocean as recalcitrant DOM, which would contribute to CDR due to its persistence against microbial degradation (Buck-Wiese et al., 2023). It has also been shown that existing off-shore Sargassum ecosystems can also contribute to increasing biodiversity and providing a habitat for several species such as turtles, dolphins, and several fish species (Martin et al., 2021). A careful evaluation of open ocean macroalgae farms considering impacts and potential co-benefits on marine ecology, biogeochemistry and fishery is required (Chung et al., 2013; Fernand et al., 2017; Gao et al., 2021; Wu et al., 2023). This includes accounting for offsets from the remineralization of particulate organic carbon (POC) export, the generation of halocarbons, calcification by encrusting marine life, and changes in surface albedo (Bach et al., 2021; Chen et al., 2020; Jia et al., 2022; Krause-Jensen & Duarte, 2016; Pedersen et al., 2021; Wada et al., 2015; Wang et al., 2023). Potential oxygen depletion through biomass remineralization and potential methane and hydrogen sulfide production in the deep sea have been proposed (Levin et al., 2023), but are a subject for further studies.

The expected environmental impacts of offshore geological carbon storage are mainly noise (e.g., Marappan et al., 2022) and CO_2 leakage events. Noise is generated by drilling and pumping or may be produced if active seismic methods are used to explore and monitor the storage site. Passive seismic methods have the potential to reduce noise stressors (Goertz-Allmann et al., 2014). Leakage, in the case of dissolved CO_2 injection, is prevented by the higher density of CO_2 -charged seawater compared to normal seawater. A higher leakage risk arises if CO_2 is injected as pure phase. Results of a controlled CO_2 release experiment near the Sleipner CO_2 storage site showed that, in case of leakage, CO_2 gas bubbles are dissolved within 2 m above the seafloor and the excess dissolved CO_2 is further dispersed by tidal currents (Vielstädte et al., 2019). Their model indicates that pH changes exceeding seasonal changes are only found within a distance of approx. 80 m from the well. Still, particularly for prolonged leakage and higher CO_2 release rates, increased CO_2 concentrations and low pH bottom waters could have noxious effects on benthic organisms in the vicinity of a leaky well (Vielstädte et al., 2019). The risk of CO_2 leakage is reduced if fast crystallization processes are triggered by the injection.

It is noteworthy that in contrast to land-based CDR options, the environmental impacts of mCDR options are even less constrained by the deployment site due to the continuous ocean medium (Mengis et al., 2023). The blueCDR (including AU) and OAE options, in particular, might not only affect the region of the operation, but could also cause changes downstream as the water masses move (e.g., Berger et al., 2023; Wu et al., 2023), causing challenges for the long-term monitoring and verification of carbon storage (Mengis et al., 2023).

4.3. Comparison of Marine CDR Options – Evaluation and Monitoring of mCDR

The ultimate goal of CDR is to remove CO₂ from the atmosphere. Hence it is important to know how much of the carbon sequestered and stored would translate to reduction of the atmospheric carbon dioxide pool (Bach et al., 2023). The options in this study differ in permanence: while OAE and mCS options can last over 10,000 years, blueCDRs exhibit greater variability, ranging from centuries to millennia (see Tables S1–S12 in Supporting Information S1). Comprehensive evaluation and monitoring would be needed to accurately assess the effectiveness and side effects of the mCDR options. Presently, no standard monitoring protocol for mCDR options is in place.

However, for OAE a best practice guide on responsible research including MRV has been published (Ho et al., 2023; Oschlies et al., 2023). MRV for OAE options would need to consider in situ pre-conditions. At the release site, mooring stations equipped with autonomous systems to monitor the carbonate system and biological components could provide initial alkalinity signals. Existing observational networks like the Ship-of-Opportunity, FerryBox-integrated, membrane-based sensor measurements in the surface North Sea, with the measuring instruments equipped on repeating commercial vessel, could provide a cost-effective way to observe the surface ocean at a relatively large temporal resolution and spatial coverage (Macovei, Petersen, et al., 2021). However, in the 10 Mt CO₂ removal scale, if the added alkalinity would spread in the North Sea evenly, it would be difficult to verify the effect on total alkalinity, since the expected change (4.3 μmol/L) is much smaller than the natural seasonal variation of alkalinity on site (Hoppema, 1990), smaller than the alkalinity sensor accuracy (Sonnichsen et al., 2023) and on par with the current laboratory alkalinity measuring techniques (Bockmon & Dickson, 2015). This means that one would depend on models alongside the observational effort near the discharging site (Ho et al., 2023). Accompanying the evaluation of the mCDR effect, environmental monitoring (e.g., water quality monitoring and fishery management) needs to be in place, due to the various potential side effects of OAE (see Section 4.1.2).

Challenges and ways forward concerning the evaluation and monitoring of blueCDR approaches have recently been outlined (Mengis et al., 2023). To evaluate, for example, the CDR potential of Sargassum aquafarming coupled with AU, the flow of CO₂ from the atmosphere to the Sargassum biomass needs to be demonstrated using surface ocean pCO₂ sensors and flux calculations based on gas-exchange parameterizations, as well as the permanence and stability of the biomass in the deep sea. After establishing key concepts, surface, submerged biomass stocks, biodiversity, bycatch and environmental parameters (nutrients, trace elements, pCO₂, O₂, DOM fractions) need to be monitored regularly to spot possible impacts and environmental changes. Environmental parameters can be collected to implement the data in a predictive model. Any MRV for AU would be highly challenging, since the additionally stored CO₂ in the interior ocean will move with the currents and get diluted (Mengis et al., 2023).

Finally, in terms of monitoring geological storage sites of mCDR options, many of the developments in petroleum reservoir monitoring could be adapted. The now widespread use of time-lapse seismic reservoir monitoring (Lumley, 2001), as demonstrated at the Sleipner project (Arts et al., 2004), time-lapse (4D) seismic monitoring, gravity field monitoring, surface gas monitoring, and distributed fiber-optic sensing are just some possibilities. Furthermore, the monitoring of storage sites can profit from existing regional geophysical monitoring, local deployment of landers that are equipped with sensors, for example, DIC sensors, or isotope measurements of cores from monitoring wells to confirm the carbonization reaction.

4.4. Limitation of This Approach – Considering Economics, Ethics, Acceptance, and Legality of mCDR Collection

Our focus lies on questions of effectiveness, scalability, and technological feasibility combined with some information on costs and environmental effects. Yet, there are other important questions that arise about these mCDR options and new technologies and practices. Even though an in-depth assessment is beyond the scope of this study, we want to briefly highlight four aspects we deem to be particularly pertinent for the potential deployment of mCDR or mCS: the economics, ethical arguments for or against deployment, societal acceptability, and legality.

The cost estimates for early-stage deployment or piloting, we can provide here vary widely between the different mCDR options. Since many concepts are not yet implemented at scale, and/or have a rather low TRL, there are

considerable uncertainties associated with these cost estimates. The ranges of the estimates for operative costs are substantial across different studies (NAS, 2021). Furthermore, when evaluating economic aspects of mCDR methods, it is necessary to go beyond operative cost assessments based on current prices and also account for price effects after a large-scale roll-out. For example, an increased demand for certain input materials will increase the price of these materials, thus affect the removal costs and the relative price for the mCDR option compared to other emissions reduction and CDR options and thus, the overall costs for reaching national climate targets (Klepper & Rickels, 2012). Other factors such as learning-by-doing, the permanence of CO₂-storage, and the cost of negative side effects and the value of co-benefits should also be considered (Rickels, 2023). An integrated economic analysis of mCDR deployment scenarios is urgently needed, but beyond the scope of this work.

Ethical convictions, namely on the impermissibility of letting people suffer the full consequences of unabated climate change, are a major part of what motivates interest in CDR. Implementation scenarios of CDR options can be evaluated from an ethical perspective, for example, looking at their impact on people and the natural world as well as their governance (Heyward, 2019). This paper affirms the value of these considerations (Lenzi et al., 2018) but restricts itself to assessing the techno-environmental feasibility and effectiveness of certain CDR options. This is a paper about what could potentially be done – it paves the way for later questions about what should be done (Tank et al., 2025; Zimm et al., 2024). In this context, one important issue that needs to be briefly discussed here, is the question of the moral (im)permissibility of the inclusion of CDR options outside of Germany or its territorial waters. One could argue that CDR options tasked with counterbalancing German emissions should be deployed on German territory, and not ‘outsourced’ to other countries. We want to highlight that the ethical implications of the extraterritorial use of CDR will heavily depend on the specific characteristics of the projects in question. Disregarding side effects on local people or the local environment abroad because they would happen ‘somewhere else’, would clearly be morally problematic. However, if the options in question receive the informed consent of the local inhabitants, and especially those potentially affected (Preston, 2013), we deem it an open question whether extraterritorial CDR, potentially in areas where its effectiveness is much higher than in Germany, could be morally permissible. While an exhaustive discussion of this issue is beyond the scope of the paper, we do see the need to discuss this further and hope to provide input for these debates.

Any CDR implementation happens within societal context, which involves opinions of the general public and of local communities affected by the measure (Chen et al., 2015; Segreto et al., 2020). Concerns that remain unaddressed and voices that remain unheard can negatively influence the socio-political feasibility of implementation (Wüstenhagen et al., 2007). Considering local knowledge and contexts such as governance structures, past experiences, and enabling participation through benefit-sharing on the ground can increase the chances for long-term success (Merk et al., 2022). Ideally, this would require time and financial investment prior to starting the project to organize participatory engagement workshops and information sessions to enable affected communities to provide input on project siting and planning processes (Satterfield et al., 2023). Societal engagement in the project planning process needs to be built on trust, which can be gained by adhering to norms of procedural justice like transparency and fair participation (Heyward, 2019). This starts with the transparent communication about moral, social, economic and environmental risks and benefits and the possibility to participate in decision-making processes. While our analysis strives to make basic risks and benefits transparent, the development of tools for co-producing knowledge (Norström et al., 2020; Satterfield et al., 2023) and for supporting informed decisions (Nanz & Fritsche, 2012) are beyond the scope of this paper.

Turning to questions of legality, mCDR deployment raises a dilemma. While mCDR poses immediate risks, renouncing to deploy it may leave climate change unabated and create risks in the future. Delayed emission reductions reinforce our dependency on mCDR to reach the 2100 target of 1.5°C of global warming and will exacerbate the sense of urgency in choosing the lesser evil. This ethical dilemma is naturally reflected in the applicable laws. On the one hand, ‘traditional’ environmental law discourages any activity that may have adverse effects on the environment. On the other hand, climate change law, which sets ambitious temperature goals, arguably supports the enhancement of sinks and reservoirs. The precautionary principle for instance can be interpreted to either prohibit mCDR as a precaution for safeguarding the integrity of marine ecosystems, an understanding that seems to be envisaged by the Convention on Biodiversity. At the same time, it can also be understood as encouraging, or even requiring, the implementation of mCDR options in light of the consequences of unabated climate change as established by Article three of the UNFCCC (Tedsen & Homann, 2013). Contemporary international law therefore needs to reposition itself in order to adapt to this new, more complex reality in which the status quo may no longer be the safest choice. In that regard, the 2009 amendment of the

London Protocol to allow for the geological sequestration of CO₂ and the 2013 amendment on marine geo-engineering demonstrate the ability of international law to evolve. At the German level, current legislation, written with strong environmental concerns in mind, act as showstoppers for the deployment, and even research, of mCDR (Ginzky et al., 2011; UBA, 2023). Developments on the matter of mCDR at the international and European levels could thus provide guidance for an innovative interpretation of the precautionary principle, in which research is enabled and risks are controlled through a regime of safeguards.

5. Conclusion and Outlook

Our study represents an example on how to create context-specific CDR options for a more tangible and concrete basis for further studies and discussions. We believe that this format warrants application in many more contexts worldwide to address the global challenge of net-zero at an actionable level of detail. The resulting study is the first attempt at developing site-specific CDR options with storage or sequestration in the marine environment for a German context. We challenged the mCDR options to reach a scale of 10 Mt CO₂ yr⁻¹ removal, which would represent a substantial contribution to Germany's net-zero goal by counterbalancing projected residual emissions. This approach allowed us to compare mCDR options on the same scale and in their actual context of implementation, thereby providing a more policy-relevant evaluation of the associated area, energy, and resource demands.

We find that six out of the 10 options considered in this study could potentially reach an annual removal rate of 10 Mt CO₂. Among them, three appear feasible within Germany: electrolytic production and addition of alkalinity-enhanced solution from silicate rock; production and spread of Ca(OH)₂ along ship tracks in the North Sea, and biomass from macroalgae farming for biomethane production combined with carbon storage in saline aquifers in the North Sea. This study does not consider the GHG emission life-cycle, which is not ideal when it comes to the comparison of CDR effectiveness. However, due to the varying TRLs, many of these options cannot get robust emissions factors for life-cycle exercises, without further research. This study does not exhaust all possible mCDR options in Germany nor assess their theoretical maximum potential for Germany, but with six options passing the 10 Mt CO₂ removal yr⁻¹ benchmark, we could envision that mCDR can provide a significant contribution to carbon removal, and should be considered in the option portfolio for German net-zero.

However, we also identified a multitude of bottlenecks concerning mCDR options for annual 10 Mt CO₂ removal, ranging from geophysical constraints to current material and clean energy availability to the current technology and infrastructure capacity (see Table 2). For example, with the exception of kelp forest management, the CDR potential of these options cannot currently be fully determined due to their low technological maturity, leading to high uncertainty in our estimates. Remaining research questions are method-specific: for OAE options, research concerning the understanding of the dissolution process of implemented materials is needed, which in turn will impact the spreading mechanisms, thereby impacting area, resource, and energy demands. For OAE and blueCDR options, one of the biggest remaining questions concerns the monitoring and verification of carbon fluxes. For the geological storage of carbon in the German EEZ, pilot studies are required to explore potential storage sites and determine achievable removal rates. For all of these options, thorough cost analyses along with GHG footprint life-cycle assessments are necessary to provide a realistic assessment of investment and market costs.

This study intends to provide a collection of mCDR options as the basis for more thorough assessments of mCDR options developed by Germany, both within and outside of German borders. Ideally, these future assessments will be supported by more comprehensive implementation scenarios that include evaluations of social, ethical, and political impacts. In addition, multiple CDR options should be jointly considered for potential synergies and trade-offs, especially regarding additivity and concomitant side effects, to better characterize possible future implementation scenarios.

Our exploration of mCDR options on a 10 Mt CO₂ yr⁻¹ removal scale has revealed a multitude of limitations, bottlenecks, and uncertainties. We believe more of such assessments are needed to bring the expectations about CDR option down-to-earth (Dean et al., 2021), because over-optimistic or untested assumptions about large-scale CDR implementation should not serve as a reason to delay emissions reduction by suggesting it is possible to “emit now and remove later” (Fuss et al., 2014; Williamson, 2016).

Data Availability Statement

This study did not involve the use of any datasets or computational models. The research is based on conceptual analysis and literature synthesis, with all sources explicitly cited in the main text of the article and the supplementary information.

Acknowledgments

The funding was provided within the framework of the Deutsche Allianz für Meeresforschung (DAM) mission CDRmare and CDRterra. This study was supported by the German Federal Ministry of Education and Research (BMBF) through the following projects: “ASMAYSYS” (Grant 03F0898), “CDRSynTra” (Grant 01LS2101), “AIMS³” (Grant 03F0964), “BioNET” (Grant 01LS2107A), “STEPSEC” (Grant 01LS2102D), “RETAKE” (Grant 03F0895), “GEOSTORE” (Grant 03F0893), “sea4soCieTy” (Grant 03F0896), and “Test-ArtUp” (Grant 03F0897). We also would like to acknowledge the National Key Research and Development Program of China (Grant 2020YFA0608304) and the Emmy Noether scheme by the German Research Foundation ‘FOOTPRINTS—From carbOn remOval To achieving the PaRIs agreemeNt’s goal: Temperature Stabilisation’ (ME 5746/1-1). We thank internal reviewers for valuable input in the manuscript, in particular Wolfgang Koeve. Open Access funding enabled and organized by Projekt DEAL.

References

- Ahmed, M., & Anwar, R. (2012). An assessment of the environmental impact of brine disposal in marine environment. *International Journal of Modern Engineering Research (IJMER)*, 2(4), 2756–2761.
- Al-Anzi, B. S., Al-Rashidi, A., Abraham, L., Fernandes, J., Al-Sheikh, A., & Alhazza, A. (2021). Brine management from desalination plants for salt production utilizing high current density electrodialysis-evaporator hybrid system: A case study in Kuwait. *Desalination*, 498, 114760. <https://doi.org/10.1016/j.desal.2020.114760>
- Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J. K., Mason, B. M., et al. (2016). Reversal of ocean acidification enhances net coral reef calcification. *Nature*, 531(7594), 362–365. <https://doi.org/10.1038/nature17155>
- Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C. E., et al. (2018). Estimating geological CO₂ storage security to deliver on climate mitigation. *Nature Communications*, 9(1), 2201. <https://doi.org/10.1038/s41467-018-04423-1>
- Ali, E. B., Skjelvan, I., Omar, A. M., Olsen, A., de Lange, T. E., Johannessen, T., & Elageed, S. (2021). Sea surface pCO₂ variability and air-sea CO₂ exchange in the coastal Sudanese Red Sea. *Regional Studies in Marine Science*, 44, 101796. <https://doi.org/10.1016/j.rsma.2021.101796>
- Alongi, D. M. (2014). Carbon cycling and storage in mangrove forests. *Annual Review of Marine Science*, 6(1), 195–219. <https://doi.org/10.1146/annurev-marine-010213-135020>
- Alongi, D. M., Murdiyarsa, D., Fourqurean, J. W., Kauffman, J. B., Hutahaean, A., Crooks, S., et al. (2016). Indonesia’s blue carbon: A globally significant and vulnerable sink for seagrass and mangrove carbon. *Wetlands Ecology and Management*, 24(1), 3–13. <https://doi.org/10.1007/s11273-015-9446-y>
- Alsawaiyan, N. A., Filbee-Dexter, K., Vranken, S., Burkholz, C., Cambridge, M., Coleman, M. A., & Wernberg, T. (2022). Green gravel as a vector of dispersal for kelp restoration. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.910417>
- Amann, T., Hartmann, J., Hellmann, R., Pedrosa, E. T., & Malik, A. (2022). Enhanced weathering potentials—The role of in situ CO₂ and grain size distribution. *Frontiers in Climate*, 4, 929268. <https://doi.org/10.3389/fclim.2022.929268>
- Archer, D. (2005). Fate of fossil fuel CO₂ in geologic time. *Journal of Geophysical Research*, 110(C9), C09S05. <https://doi.org/10.1029/2004JC002625>
- Arribère, M. A., Ribeiro Guevara, S., Sánchez, R. S., Gil, M. I., Román Ross, G., Daurade, L. E., et al. (2003). Heavy metals in the vicinity of a chlor-alkali factory in the upper negro river ecosystem, northern Patagonia, Argentina. *Science of the Total Environment*, 301(1–3), 187–203. [https://doi.org/10.1016/S0048-9697\(02\)00301-7](https://doi.org/10.1016/S0048-9697(02)00301-7)
- Arts, R., Eiken, O., Chadwick, A., Zweig, P., van der Meer, L., & Zinszner, B. (2004). Monitoring of CO₂ injected at Sleipner using time-lapse seismic data. *Energy*, 29(9), 1383–1392. <https://doi.org/10.1016/j.energy.2004.03.072>
- Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S., & Renforth, P. (2019). CO₂ removal with enhanced weathering and ocean alkalinity enhancement: Potential risks and Co-benefits for marine pelagic ecosystems. *Frontiers in Climate*, 1. <https://doi.org/10.3389/fclim.2019.00007>
- Bach, L. T., Ho, D. T., Boyd, P. W., & Tyka, M. D. (2023). Toward a consensus framework to evaluate air–sea CO₂ equilibration for marine CO₂ removal. *Limnology and Oceanography Letters*, 8(5), 685–691. <https://doi.org/10.1002/lol2.10330>
- Bach, L. T., Tamsitt, V., Gower, J., Hurd, C. L., Raven, J. A., & Boyd, P. W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications*, 12(1), 2556. <https://doi.org/10.1038/s41467-021-22837-2>
- Bachu, S. (2015). Review of CO₂ storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, 40, 188–202. <https://doi.org/10.1016/j.ijggc.2015.01.007>
- Baggio, G., Qadir, M., & Smakhtin, V. (2021). Freshwater availability status across countries for human and ecosystem needs. *Science of the Total Environment*, 792, 148230. <https://doi.org/10.1016/j.scitotenv.2021.148230>
- Baker, P., Minzlaff, U., Schoenle, A., Schwabe, E., Hohlfeld, M., Jeuck, A., et al. (2018). Potential contribution of surface-dwelling Sargassum algae to deep-sea ecosystems in the southern North Atlantic. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 148, 21–34. <https://doi.org/10.1016/j.dsr2.2017.10.002>
- Bandaranayake, W. M. (1998). Traditional and medicinal uses of mangroves. *Mangroves and Salt Marshes*, 2(3), 133–148. <https://doi.org/10.1023/A:1009988607044>
- Bartsch, I., Wiencke, C., Bischof, K., Buchholz, C. M., Buck, B. H., Eggert, A., et al. (2008). The genus *Laminaria* sensu lato: Recent insights and developments. *European Journal of Phycology*, 43(1), 1–86. <https://doi.org/10.1080/09670260701711376>
- Baumann, M., Taucher, J., Paul, A. J., Heinemann, M., Vanharanta, M., Bach, L. T., et al. (2021). Effect of intensity and mode of artificial upwelling on particle flux and carbon export. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.742142>
- Berger, M., Kwiatkowski, L., Ho, D. T., & Bopp, L. (2023). Ocean dynamics and biological feedbacks limit the potential of macroalgae carbon dioxide removal. *Environmental Research Letters*, 18(2), 024039. <https://doi.org/10.1088/1748-9326/abc06e>
- Berner, R. A., Lasaga, A. C., & Garrels, R. M. (1983). The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years. *American Journal of Science*, 283(7), 641–683. <https://doi.org/10.2475/ajs.283.7.641>
- BGR. (2021). *Deutschland rohstoffsituation*. Bundesanstalt für Geowissenschaften und Rohstoffe. Retrieved from https://www.bgr.bund.de/DE/Themen/Min_rohstoffe/Downloads/rohsit-2021.pdf?__blob=publicationFile&v=4
- Bockmon, E. E., & Dickson, A. G. (2015). An inter-laboratory comparison assessing the quality of seawater carbon dioxide measurements. *Marine Chemistry*, 171, 36–43. <https://doi.org/10.1016/j.marchem.2015.02.002>
- Bolton, J. J., & Lüning, K. (1982). Optimal growth and maximal survival temperatures of Atlantic *Laminaria* species (Phaeophyta) in culture. *Marine Biology*, 66(1), 89–94. <https://doi.org/10.1007/BF00397259>
- Borchers, M., Thrän, D., Chi, Y., Dahmen, N., Dittmeyer, R., Dolch, T., et al. (2022). Scoping carbon dioxide removal options for Germany—What is their potential contribution to Net-Zero CO₂? *Frontiers in Climate*, 4. <https://doi.org/10.3389/fclim.2022.810343>
- Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., & Schellnhuber, H. J. (2017). The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*, 5(5), 463–474. <https://doi.org/10.1002/2016ef000469>
- Brunner, C., Hausfather, Z., & Knutti, R. (2024). Durability of carbon dioxide removal is critical for Paris climate goals. *Communications Earth and Environment*, 5(1), 645. <https://doi.org/10.1038/s43247-024-01808-7>

- Buck, B. H., & Buchholz, C. M. (2004). The offshore-ring: A new system design for the open ocean aquaculture of macroalgae. *Journal of Applied Phycology*, 16(5), 355–368. <https://doi.org/10.1023/B:JAPH.0000047947.96231.ea>
- Buck, B. H., & Buchholz, C. M. (2005). Response of offshore cultivated Laminaria saccharina to hydrodynamic forcing in the North Sea. *Aquaculture*, 250(3), 674–691. <https://doi.org/10.1016/j.aquaculture.2005.04.062>
- Buck, B. H., Troell, M. F., Krause, G., Angel, D. L., Grote, B., & Chopin, T. (2018). State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). *Frontiers in Marine Science*, 5. <https://doi.org/10.3389/fmars.2018.00165>
- Buck-Wiese, H., Andskog, M. A., Nguyen, N. P., Bligh, M., Asmala, E., Vidal-Melgosa, S., et al. (2023). Fucoid brown algae inject fucoidan carbon into the ocean. *Proceedings of the National Academy of Sciences of the United States of America*, 120(1), e2210561119. <https://doi.org/10.1073/pnas.2210561119>
- Buylova, A., Fridahl, M., Nasiritousi, N., & Reischl, G. (2021). Cancel (out) emissions? The envisaged role of carbon dioxide removal technologies in long-term national climate strategies. *Frontiers in Climate*, 3. <https://doi.org/10.3389/fclim.2021.675499>
- Cameron, C., Hutley, L. B., Friess, D. A., & Brown, B. (2019). High greenhouse gas emissions mitigation benefits from mangrove rehabilitation in Sulawesi, Indonesia. *Ecosystem Services*, 40, 101035. <https://doi.org/10.1016/j.ecoser.2019.101035>
- Casazza, T. L., & Ross, S. W. (2008). Fishes associated with pelagic Sargassum and open water lacking Sargassum in the Gulf Stream off North Carolina. Retrieved from <https://aquadocs.org/handle/1834/25466>
- Caserini, S., Barreto, B., Lanfredi, C., Cappello, G., Ross Morrey, D., & Grosso, M. (2019). Affordable CO2 negative emission through hydrogen from biomass, ocean liming, and CO2 storage. *Mitigation and Adaptation Strategies for Global Change*, 24(7), 1231–1248. <https://doi.org/10.1007/s11027-018-9835-7>
- Caserini, S., Storni, N., & Grosso, M. (2022). The availability of limestone and other Raw materials for ocean alkalinity enhancement. *Global Biogeochemical Cycles*, 36(5), e2021GB007246. <https://doi.org/10.1029/2021GB007246>
- Castro, E., Pinedo, J., Marrugo, J., & León, I. (2022). Retention and vertical distribution of heavy metals in mangrove sediments of the protected area swamp of Mallorquin, Colombian Caribbean. *Regional Studies in Marine Science*, 49, 102072. <https://doi.org/10.1016/j.rsma.2021.102072>
- Chatterjee, S., & Huang, K.-W. (2020). Unrealistic energy and materials requirement for direct air capture in deep mitigation pathways. *Nature Communications*, 11(1), 3287. <https://doi.org/10.1038/s41467-020-17203-7>
- ChemAnalyst. (2023). Decode the future of hydrochloric acid. Retrieved from <https://www.chemanalyst.com/industry-report/hydrochloric-acid-market-707>
- Chen, H., Zhou, D., Luo, G., Zhang, S., & Chen, J. (2015). Macroalgae for biofuels production: Progress and perspectives. *Renewable and Sustainable Energy Reviews*, 47, 427–437. <https://doi.org/10.1016/j.rser.2015.03.086>
- Chen, S., Xu, K., Ji, D., Wang, W., Xu, Y., Chen, C., & Xie, C. (2020). Release of dissolved and particulate organic matter by marine macroalgae and its biogeochemical implications. *Algal Research*, 52, 102096. <https://doi.org/10.1016/j.algal.2020.102096>
- Chung, I. K., Oak, J. H., Lee, J. A., Shin, J. A., Kim, J. G., & Park, K.-S. (2013). Installing kelp forests/seaweed beds for mitigation and adaptation against global warming: Korean project overview. *ICES Journal of Marine Science*, 70(5), 1038–1044. <https://doi.org/10.1093/icesjms/fss206>
- Creutzig, F., Ravindranath, N. H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., et al. (2015). Bioenergy and climate change mitigation: An assessment. *GCB Bioenergy*, 7(5), 916–944. <https://doi.org/10.1111/gcbb.12205>
- Cripps, G., Widdicombe, S., Spicer, J. I., & Findlay, H. S. (2013). Biological impacts of enhanced alkalinity in Carcinus maenas. *Marine Pollution Bulletin*, 71(1–2), 190–198. <https://doi.org/10.1016/j.marpolbul.2013.03.015>
- Cuba, D., Guardia-Luzon, K., Cevallos, B., Ramos-Larico, S., Neira, E., Pons, A., & Avila-Peltroche, J. (2022). Ecosystem services provided by kelp forests of the Humboldt current system: A comprehensive review. *Coasts*, 2(4), 259–277. <https://doi.org/10.3390/coasts2040013>
- Dean, J., Kiendler-Scharr, A., Mengis, N., Rudich, Y., Schepanski, K., & Zimmermann, R. (2021). Above us only sky. *Communications Earth and Environment*, 2(1), 1–4. <https://doi.org/10.1038/s43247-021-00245-0>
- Dean, T. A., & Jacobsen, F. R. (1984). Growth of juvenile Macrocyctis pyrifera (Laminariales) in relation to environmental factors. *Marine Biology*, 83(3), 301–311. <https://doi.org/10.1007/BF00397463>
- DEWA. (2022). DEWA annual statistics. Dubai electricity and water authority. Retrieved from <https://www.dewa.gov.ae/en/about-us/strategy-excellence/annual-statistics>
- Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, 4(5), 293–297. <https://doi.org/10.1038/ngeo1123>
- Dormann, W. (2023). The surface salinity of the North Sea and Baltic Sea area. In D. Mossakowski & U. Imler (Eds.), *Terrestrial coastal ecosystems in Germany and climate change* (pp. 67–73). Springer International Publishing. https://doi.org/10.1007/978-3-031-12539-3_7
- Dowling, A., O'Dwyer, J., & Adley, C. C. (2015). Lime in the limelight. *Journal of Cleaner Production*, 92, 13–22. <https://doi.org/10.1016/j.jclepro.2014.12.047>
- Duarte, C. M., Losada, I. J., Hendriks, I. E., Mazarrasa, I., & Marbà, N. (2013). The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*, 3(11), 961–968. <https://doi.org/10.1038/nclimate1970>
- Ebb carbon. (2024). Retrieved February 20, 2024, from <https://www.ebbcarbon.com>
- Eger, A. M., Marzinelli, E. M., Beas-Luna, R., Blain, C. O., Blamey, L. K., Byrnes, J. E. K., et al. (2023). The value of ecosystem services in global marine kelp forests. *Nature Communications*, 14(1), 1894. <https://doi.org/10.1038/s41467-023-37385-0>
- Eisaman, M. D., Geilert, S., Renforth, P., Bastianini, L., Campbell, J., Dale, A. W., et al. (2023). Assessing the technical aspects of ocean-alkalinity-enhancement approaches. *State of the Planet*, 2-oae2023, 1–29. <https://doi.org/10.5194/sp-2-oae2023-3-2023>
- EuLA. (2014). A competitive and efficient lime industry. *The European Lime Association*. Retrieved from <https://www.eula.eu/wp-content/uploads/2019/02/A-Competitive-and-Efficient-Lime-Industry-Presentation.pdf>
- European Commission. (2014). Technology readiness levels (TRL). In *Horizon 2020—WORK PROGRAMME 2014-2015 general annexes, extract from Part 19—commission decision C*. European Commission Brussels. Retrieved from https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf
- Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., et al. (2000). The global carbon cycle: A test of our knowledge of earth as a system. *Science*, 290(5490), 291–296. <https://doi.org/10.1126/science.290.5490.291>
- Federal Climate Change Act. (2019). § Federal Law Gazette, I. Retrieved from <https://www.gesetze-im-internet.de/ksq/>
- Ferderer, A., Chase, Z., Kennedy, F., Schulz, K. G., & Bach, L. T. (2022). Assessing the influence of ocean alkalinity enhancement on a coastal phytoplankton community. *Biogeosciences*, 19(23), 5375–5399. <https://doi.org/10.5194/bg-19-5375-2022>
- Fernand, F., Israel, A., Skjermo, J., Wichard, T., Timmermans, K. R., & Golberg, A. (2017). Offshore macroalgae biomass for bioenergy production: Environmental aspects, technological achievements and challenges. *Renewable and Sustainable Energy Reviews*, 75, 35–45. <https://doi.org/10.1016/j.rser.2016.10.046>

- Filbee-Dexter, K. (2020). Ocean forests hold unique solutions to our current environmental crisis. *One Earth*, 2(5), 398–401. <https://doi.org/10.1016/j.oneear.2020.05.004>
- Flipkens, G., Fuhr, M., Fiers, G., Meysman, F. J. R., Town, R. M., & Blust, R. (2023). Enhanced olivine dissolution in seawater through continuous grain collisions. *Geochimica et Cosmochimica Acta*, 359, 84–99. <https://doi.org/10.1016/j.gca.2023.09.002>
- Fortes, M. D., & Lüning, K. (1980). Growth rates of North Sea macroalgae in relation to temperature, irradiance and photoperiod. *Helgoländer Meeresuntersuchungen*, 34(1), 15–29. <https://doi.org/10.1007/BF01983538>
- Foteinis, S., Andresen, J., Campo, F., Caserini, S., & Renforth, P. (2022). Life cycle assessment of ocean liming for carbon dioxide removal from the atmosphere. *Journal of Cleaner Production*, 370, 133309. <https://doi.org/10.1016/j.jclepro.2022.133309>
- Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., et al. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, 5(7), 505–509. <https://doi.org/10.1038/ngeo1477>
- Fredriksen, S., Filbee-Dexter, K., Norderhaug, K. M., Steen, H., Bodvin, T., Coleman, M. A., et al. (2020). Green gravel: A novel restoration tool to combat kelp forest decline. *Scientific Reports*, 10(1), 3983. <https://doi.org/10.1038/s41598-020-60553-x>
- Fridahl, M., Hansson, A., & Haikola, S. (2020). Towards indicators for a negative emissions climate stabilisation index: Problems and prospects. *Climate*, 8(6), 75. <https://doi.org/10.3390/cli8060075>
- Fuhr, M., Wallmann, K., Dale, A. W., Kalapurakkal, H. T., Schmidt, M., Sommer, S., et al. (2024). Alkaline mineral addition to anoxic to hypoxic Baltic Sea sediments as a potentially efficient CO₂-removal technique. *Frontiers in Climate*, 6, 1338556. <https://doi.org/10.3389/fclim.2024.1338556>
- Fujimori, S., Wu, W., Doelman, J., Frank, S., Hristov, J., Kyle, P., et al. (2022). Land-based climate change mitigation measures can affect agricultural markets and food security. *Nature Food*, 3(2), 110–121. <https://doi.org/10.1038/s43016-022-00464-4>
- Fuss, S., Canadell, J. G., Peters, G. P., Tavoni, M., Andrew, R. M., Ciais, P., et al. (2014). Betting on negative emissions. *Nature Climate Change*, 4(10), 850–853. <https://doi.org/10.1038/nclimate2392>
- Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., et al. (2018). Negative emissions – Part 2: Costs, potentials and side effects. *Environmental Research Letters*, 13(6), 063002. <https://doi.org/10.1088/1748-9326/aabf9f>
- Gao, G., Gao, L., Jiang, M., Jian, A., & He, L. (2021). The potential of seaweed cultivation to achieve carbon neutrality and mitigate deoxygenation and eutrophication. *Environmental Research Letters*, 17(1), 014018. <https://doi.org/10.1088/1748-9326/ac3fd9>
- Gately, J. A., Kim, S. M., Jin, B., Brzezinski, M. A., & Iglesias-Rodriguez, M. D. (2023). Coccolithophores and diatoms resilient to ocean alkalinity enhancement: A glimpse of hope? *Science Advances*, 9(24), eadg6066. <https://doi.org/10.1126/sciadv.adg6066>
- Gattuso, J.-P., Magnan, A. K., Bopp, L., Cheung, W. W. L., Duarte, C. M., Hinkel, J., et al. (2018). Ocean solutions to address climate change and its effects on marine ecosystems. *Frontiers in Marine Science*, 5, 337. <https://doi.org/10.3389/fmars.2018.00337>
- Gattuso, J.-P., Williamson, P., Duarte, C. M., & Magnan, A. K. (2021). The potential for ocean-based climate action: Negative emissions technologies and beyond. *Frontiers in Climate*, 2(January), 1–8. <https://doi.org/10.3389/fclim.2020.575716>
- Gerbens-Leenes, P. W., Hoekstra, A. Y., & Bosman, R. (2018). The blue and grey water footprint of construction materials: Steel, cement and glass. *Water Resources and Industry*, 19, 1–12. <https://doi.org/10.1016/j.wri.2017.11.002>
- Ginzky, H., Hermann, F., Kartschall, K., Leujak, W., Lipsius, K., Maeder, C., et al. (2011). Geo-engineering: Effective climate protection or megalomania? Retrieved from <https://www.osti.gov/etdeweb/biblio/21462852>
- Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., et al. (2011). Status and distribution of mangrove forests of the world using earth observation satellite data. *Global Ecology and Biogeography*, 20(1), 154–159. <https://doi.org/10.1111/j.1466-8238.2010.00584.x>
- Goertz-Allmann, B. P., Kühn, D., Oye, V., Bohloli, B., & Aker, E. (2014). Combining microseismic and geomechanical observations to interpret storage integrity at the in Salah CCS site. *Geophysical Journal International*, 198(1), 447–461. <https://doi.org/10.1093/gji/ggu010>
- Gouvêa, L. P., Assis, J., Gurgel, C. F. D., Serrão, E. A., Silveira, T. C. L., Santos, R., et al. (2020). Golden carbon of Sargassum forests revealed as an opportunity for climate change mitigation. *Science of the Total Environment*, 729, 138745. <https://doi.org/10.1016/j.scitotenv.2020.138745>
- Grabemann, I., & Weisse, R. (2008). Climate change impact on extreme wave conditions in the North Sea: An ensemble study. *Ocean Dynamics*, 58(3), 199–212. <https://doi.org/10.1007/s10236-008-0141-x>
- Hangx, S. J. T., & Spiers, C. J. (2009). Coastal spreading of olivine to control atmospheric CO₂ concentrations: A critical analysis of viability. *International Journal of Greenhouse Gas Control*, 3(6), 757–767. <https://doi.org/10.1016/j.ijggc.2009.07.001>
- Hartmann, J., Suitner, N., Lim, C., Schneider, J., Marin-Samper, L., Aristegui, J., et al. (2023). Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – Consequences for durability of CO₂ storage. *Biogeosciences*, 20(4), 781–802. <https://doi.org/10.5194/bg-20-781-2023>
- Hauck, J., Köhler, P., Wolf-Gladrow, D., & Völker, C. (2016). Iron fertilisation and century-scale effects of open ocean dissolution of olivine in a simulated CO₂ removal experiment. *Environmental Research Letters*, 11(2), 024007. <https://doi.org/10.1088/1748-9326/11/2/024007>
- Heck, V., Gerten, D., Lucht, W., & Popp, A. (2018). Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nature Climate Change*, 8(2), 151–155. <https://doi.org/10.1038/s41558-017-0064-y>
- Heyward, C. (2019). 21 – normative issues of geoengineering technologies. In T. M. Letcher (Ed.), *Managing global warming* (pp. 639–657). Academic Press. <https://doi.org/10.1016/B978-0-12-814104-5.00021-1>
- Heß, D., Klumpp, M., & Dittmeyer, R. (2020). Nutzung von CO₂ aus Luft als Rohstoff für synthetische Kraftstoffe und Chemikalien. Karlsruhe Institute of Technology (KIT). Retrieved from <https://vm.baden-wuerttemberg.de/fileadmin/redaktion/m-mvi/intern/Dateien/PDF/29-01-2021-DAC-Studie.pdf>
- Hinrichs, C., Köhler, P., Völker, C., & Hauck, J. (2023). Alkalinity biases in CMIP6 Earth system models and implications for simulated CO₂ drawdown via artificial alkalinity enhancement. *Biogeosciences*, 20(18), 3717–3735. <https://doi.org/10.5194/bg-20-3717-2023>
- Ho, D. T., Bopp, L., Palter, J. B., Long, M. C., Boyd, P. W., Neukermans, G., & Bach, L. T. (2023). Monitoring, reporting, and verification for ocean alkalinity enhancement. *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, 2-oae2023, 1–12. 2-oae2023, 12. <https://doi.org/10.5194/sp-2-oae2023-12-2023>
- Hoppema, J. M. J. (1990). The distribution and seasonal variation of alkalinity in the southern Bight of the North Sea and in the Western Wadden sea. *Netherlands Journal of Sea Research*, 26(1), 11–23. [https://doi.org/10.1016/0077-7579\(90\)90053-J](https://doi.org/10.1016/0077-7579(90)90053-J)
- House, K. Z., House, C. H., Schrag, D. P., & Aziz, M. J. (2007). Electrochemical acceleration of chemical weathering as an energetically feasible approach to mitigating anthropogenic climate change. *Environmental Science and Technology*, 41(24), 8464–8470. <https://doi.org/10.1021/es0701816>
- Hsiung, A. R., Ong, O. X. J., Teo, X. S., Friess, D. A., Todd, P. A., Swearer, S. E., & Morris, R. L. (2024). Determinants of mangrove seedling survival incorporated within hybrid living shorelines. *Ecological Engineering*, 202, 107235. <https://doi.org/10.1016/j.ecoleng.2024.107235>
- Hutchins, D. A., Fu, F.-X., Yang, S.-C., John, S. G., Romaniello, S. J., Andrews, M. G., & Walworth, N. G. (2023). Responses of globally important phytoplankton species to olivine dissolution products and implications for carbon dioxide removal via ocean alkalinity enhancement. *Biogeosciences*, 20(22), 4669–4682. <https://doi.org/10.5194/bg-20-4669-2023>

- Hylén, A., Kreuzburg, M., De Wolf, S., Burdorf, L., Fiers, G., Goossens, C., et al. (2023). Ocean alkalinity enhancement through enhanced silicate weathering in coastal areas: A long-term mesocosm study. <https://doi.org/10.5194/egusphere-egu23-14128>
- IEA. (2022). Direct air capture: A key technology for net zero. *OECD*. <https://doi.org/10.1787/bdd20707-en>
- IEA. (2023). United Arab Emirates – renewables. February 21, 2024, Retrieved from <https://www.iea.org/countries/united-arab-emirates>
- Ilman, M., Dargusch, P., & Dart, P., & Onrizal. (2016). A historical analysis of the drivers of loss and degradation of Indonesia's mangroves. *Land Use Policy*, 54, 448–459. <https://doi.org/10.1016/j.landusepol.2016.03.010>
- Ilyina, T., Wolf-Gladrow, D., Munhoven, G., & Heinze, C. (2013). Assessing the potential of calcium-based artificial ocean alkalization to mitigate rising atmospheric CO₂ and ocean acidification. *Geophysical Research Letters*, 40(22), 5909–5914. <https://doi.org/10.1002/2013GL057981>
- IPCC. (2022). *Global warming of 1.5°C. Global warming of 1.5°C*. Cambridge University Press. <https://doi.org/10.1017/9781009157940>
- IPCC. (2023). In *Climate change 2022 – mitigation of climate change: Working group III contribution to the sixth assessment report of the intergovernmental Panel on climate change* (1st ed.). Cambridge University Press. <https://doi.org/10.1017/9781009157926>
- James, M.-I., & Harb, M. (2021). Tuning the electronic structure of the earth-abundant electrocatalysts for oxygen evolution reaction (OER) to achieve efficient alkaline water splitting – a review. *Journal of Materials Chemistry A: Materials for Energy and Sustainability*, 56, 299–342. <https://doi.org/10.1016/j.jchem.2020.08.001>
- Jia, Y., Quack, B., Kinley, R. D., Pisso, I., & Tegtmeyer, S. (2022). Potential environmental impact of bromoform from Asparagopsis farming in Australia. *Atmospheric Chemistry and Physics*, 22(11), 7631–7646. <https://doi.org/10.5194/acp-22-7631-2022>
- Johnson, D. L., & Richardson, P. L. (1977). On the wind-induced sinking of Sargassum. *Journal of Experimental Marine Biology and Ecology*, 28(3), 255–267. [https://doi.org/10.1016/0022-0981\(77\)90095-8](https://doi.org/10.1016/0022-0981(77)90095-8)
- Jones, D. C., Ito, T., Takano, Y., & Hsu, W. (2014). Spatial and seasonal variability of the air-sea equilibration timescale of carbon dioxide. *Global Biogeochemical Cycles*, 28(11), 1163–1178. <https://doi.org/10.1002/2014GB004813>
- Jones, E., Qadir, M., Van Vliet, M. T. H., Smakhtin, V., & Kang, S. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment*, 657, 1343–1356. <https://doi.org/10.1016/j.scitotenv.2018.12.076>
- Jürchott, M., Oeschies, A., & Koeve, W. (2023). Artificial upwelling—A refined narrative. *Geophysical Research Letters*, 50(4). <https://doi.org/10.1029/2022gl101870>
- Kayalvizhi, K., & Kathiresan, K. (2019). Microbes from wastewater treated mangrove soil and their heavy metal accumulation and Zn solubilization. *Biocatalysis and Agricultural Biotechnology*, 22, 101379. <https://doi.org/10.1016/j.bcab.2019.101379>
- Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). An overview of the status and challenges of CO₂ storage in minerals and geological formations. *Frontiers in Climate*, 1. <https://doi.org/10.3389/fclim.2019.00009>
- Keller, D. P., Feng, E. Y., & Oeschies, A. (2014). Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario. *Nature Communications*, 5, 1–11. <https://doi.org/10.1038/ncomms4304>
- Kemper, J., Mense, J., Graf, K., Riebesell, U., & Kröger, J. (2023). Towards reliable performance predictions for stommel's perpetual salt fountain. In *Presented at the 10th conference on computational methods in marine engineering*. CIMNE. <https://doi.org/10.23967/marine.2023.018>
- Keng, F. S.-L., Phang, S.-M., Rahman, N. A., Leedham, E. C., Hughes, C., Robinson, A. D., et al. (2013). Volatile halocarbon emissions by three tropical brown seaweeds under different irradiances. *Journal of Applied Phycology*, 25(5), 1377–1386. <https://doi.org/10.1007/s10811-013-9990-x>
- Kim, J. K., Yarish, C., Hwang, E. K., Park, M., Kim, Y., Kim, J. K., et al. (2017). Seaweed aquaculture: Cultivation technologies, challenges and its ecosystem services. *Algae*, 32(1), 1–13. <https://doi.org/10.4490/algae.2017.32.3.3>
- Klepper, G., & Rickels, W. (2012). The real economics of climate engineering. *Economics Research International*, 2012, 1–20. <https://doi.org/10.1155/2012/316564>
- Knopf, S., & May, F. (2017). Comparing methods for the estimation of CO₂ storage capacity in saline aquifers in Germany: Regional aquifer based vs. Structural trap based assessments. *Energy Procedia*, 114, 4710–4721. <https://doi.org/10.1016/j.egypro.2017.03.1605>
- Köhler, P. (2020). Anthropogenic CO₂ of high emission scenario compensated after 3500 years of ocean alkalization with an annually constant dissolution of 5 Pg of olivine. *Frontiers in Climate*, 2, 575744. <https://doi.org/10.3389/fclim.2020.575744>
- Köhler, P., Abrams, J. F., Völker, C., Hauck, J., & Wolf-Gladrow, D. A. (2013). Geoengineering impact of open ocean dissolution of olivine on atmospheric CO₂, surface ocean pH and marine biology. *Environmental Research Letters*, 8(1), 014009. <https://doi.org/10.1088/1748-9326/8/1/014009>
- Krause-Jensen, D., & Duarte, C. M. (2016). *Substantial role of macroalgae in marine carbon sequestration*. Nature Publishing Group. <https://doi.org/10.1038/NCEO2790>
- Kwiatkowski, L., Ricke, K. L., & Caldeira, K. (2015). Atmospheric consequences of disruption of the ocean thermocline. *Environmental Research Letters*, 10(3), 034016. <https://doi.org/10.1088/1748-9326/10/3/034016>
- Lakshmanan, S., & Murugesan, T. (2014). The chlor-alkali process: Work in Progress. *Clean Technologies and Environmental Policy*, 16(2), 225–234. <https://doi.org/10.1007/s10098-013-0630-6>
- Langer, G., Biogeosciences, M. G., Oceanography, B., Wegener, A., Baumann, K.-H., Kläs, J., & Young, J. R. (2006). Species-specific responses of calcifying algae to changing seawater carbonate chemistry. *Geochemistry, Geophysics, Geosystems*, 7(9). <https://doi.org/10.1029/2005GC001227>
- Lattemann, S., & Höpner, T. (2008). Environmental impact and impact assessment of seawater desalination. *Desalination*, 220(1), 1–15. <https://doi.org/10.1016/j.desal.2007.03.009>
- Lenzi, D., Lamb, W. F., Hilaire, J., Kowarsch, M., & Minx, J. C. (2018). Don't deploy negative emissions technologies without ethical analysis. *Nature*, 561(7723), 303–305. <https://doi.org/10.1038/d41586-018-06695-5>
- Levin, L. A., Alfaro-Lucas, J. M., Colaço, A., Cordes, E. E., Craik, N., Danovaro, R., et al. (2023). Deep-sea impacts of climate interventions. *Science*, 379(6636), 978–981. <https://doi.org/10.1126/science.adf7521>
- Locke, A., Doe, K., Fairchild, W., Jackman, P., Reese, E., & Carman, M. (2009). Preliminary evaluation of effects of invasive tunicate management with acetic acid and calcium hydroxide on non-target marine organisms in Prince Edward Island, Canada. *Aquatic Invasions*, 4(1), 221–236. <https://doi.org/10.3391/ai.2009.4.1.23>
- Luderer, G., Günther, C., Sörgel, D., Kost, C., Benke, F., Auer, C., et al. (2021). Deutschland auf dem Weg zur Klimaneutralität 2045 Szenarien und Pfade im Modellvergleich.
- Lumley, D. E. (2001). Time-lapse seismic reservoir monitoring. *Geophysics*, 66(1), 50–53. <https://doi.org/10.1190/1.1444921>
- Macovei, V. A., Petersen, W., Brix, H., & Voynova, Y. G. (2021). Reduced ocean carbon sink in the south and central North Sea (2014–2018) revealed from FerryBox observations. *Geophysical Research Letters*, 48(11). <https://doi.org/10.1029/2021gl092645>

- Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., et al. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth and Environment*, 2(12), 826–839. <https://doi.org/10.1038/s43017-021-00224-1>
- Mammoth. (2022). Retrieved February 23, 2024, from <https://climeworks.com/news/climeworks-announces-groundbreaking-on-mammoth>
- Marappan, S., Stokke, R., Malinovsky, M. P., & Taylor, A. (2022). Assessment of impacts of the offshore oil and gas industry on the marine environment. *OSPAR Commission*. Retrieved from <https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/other-assessments/impacts-offshore-oil-and-gas-industry/>
- Martin, L. M., Taylor, M., Huston, G., Goodwin, D. S., Schell, J. M., & Siuda, A. N. S. (2021). Pelagic Sargassum morphotypes support different rafting motile epifauna communities. *Marine Biology*, 168(7), 115. <https://doi.org/10.1007/s00227-021-03910-2>
- McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, 90(6), 489–500. <https://doi.org/10.1016/j.psep.2012.10.005>
- Mengis, N., Kalhori, A., Simon, S., Harpprecht, C., Baetcke, L., Prats-Salvado, E., et al. (2022). Net-zero CO₂ Germany—A retrospect from the year 2050. *Earth's Future*, 10(2), 1–16. <https://doi.org/10.1029/2021EF002324>
- Mengis, N., Paul, A., & Fernández-Méndez, M. (2023). Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments. *PLOS Climate*, 2(8), e0000148. <https://doi.org/10.1371/journal.pclm.0000148>
- Merfort, A., Stevanović, M., & Streffer, J. (2023). *Energiewende auf Netto-Null: Passen Angebot und Nachfrage nach CO₂-Entnahme aus der Atmosphäre zusammen? Kopernikus-Projekt Ariadne*.
- Merk, C., Grunau, J., Riekhof, M.-C., & Rickels, W. (2022). The need for local governance of global commons: The example of blue carbon ecosystems. *Ecological Economics*, 201, 107581. <https://doi.org/10.1016/j.ecolecon.2022.107581>
- Meysman, F. J. R., & Montserrat, F. (2017). Negative CO₂ emissions via enhanced silicate weathering in coastal environments. *Biology Letters*, 13(4), 20160905. <https://doi.org/10.1098/rsbl.2016.0905>
- Mithoo-Singh, P. K., Keng, F. S.-L., Phang, S.-M., Leedham Elvidge, E. C., Sturges, W. T., Malin, G., & Abd Rahman, N. (2017). Halocarbon emissions by selected tropical seaweeds: Species-specific and compound-specific responses under changing pH. *PeerJ*, 5, e2918. <https://doi.org/10.7717/peerj.2918>
- Moosdorf, N., Renforth, P., & Hartmann, J. (2014). Carbon dioxide efficiency of terrestrial enhanced weathering. *Environmental Science and Technology*, 48(9), 4809–4816. <https://doi.org/10.1021/es4052022>
- Moras, C. A., Bach, L. T., Cyronak, T., Joannes-Boyau, R., & Schulz, K. G. (2022). Ocean alkalinity enhancement – Avoiding runaway CaCO₃ precipitation during quick and hydrated lime dissolution. *Biogeosciences*, 19(15), 3537–3557. <https://doi.org/10.5194/bg-19-3537-2022>
- Murphy, J. D., Drosig, B., Allen, E., Jerney, J., Xia, A., & Herrmann, C. (2015). A perspective on algal biogas. IEA Bioeconomy. Retrieved from <https://www.ieabioenergy.com/blog/publications/a-perspective-on-algal-biogas/>
- Nanz, P., & Fritsche, M. (2012). *Handbuch Bürgerbeteiligung: Verfahren und Akteure, Chancen und Grenzen*. Bundeszentrale für Politische Bildung. Retrieved from <https://play.google.com/store/books/details?id=CkSMwEACAAJ>
- NAS. (2021). *A research strategy for ocean-based carbon dioxide removal and sequestration*. National Academies Press (US). <https://doi.org/10.17226/26278>
- Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., et al. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, 3(3), 182–190. <https://doi.org/10.1038/s41893-019-0448-2>
- Orca. (2021). Retrieved February 23, 2024, from <https://climeworks.com/press-release/climeworks-launches-orca>
- Ortiz, J., Aristegui, J., Hernández-Hernández, N., Fernández-Méndez, M., & Riebesell, U. (2022). Oligotrophic phytoplankton community effectively adjusts to artificial upwelling regardless of intensity, but differently among upwelling modes. *Frontiers in Marine Science*, 9. <https://doi.org/10.3389/fmars.2022.880550>
- Oschlies, A., Held, H., Keller, D., Keller, K., Mengis, N., Quaas, M., et al. (2017). Indicators and metrics for the assessment of climate engineering. *Earth's Future*, 5(1), 49–58. <https://doi.org/10.1002/2016EF000449>
- Oschlies, A., Koeve, W., Rickels, W., & Rehdanz, K. (2010). Side effects and accounting aspects of hypothetical large-scale Southern Ocean iron fertilization. *Biogeosciences*, 7(12), 4014–4035. <https://doi.org/10.5194/bg-7-4017-2010>
- Oschlies, A., Pahlow, M., Yool, A., & Matear, R. J. (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters*, 37(4). <https://doi.org/10.1029/2009GL041961>
- Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., et al. (2023). *Guide to best practices in ocean alkalinity enhancement research* (0 ed.). Copernicus GmbH. <https://doi.org/10.5194/sp-2-oae2023>
- Pedersen, F. M., & Hansen, P. J. (2003). Effects of high pH on a natural marine planktonic community. *Marine Ecology Progress Series*, 260, 19–31. <https://doi.org/10.3354/meps260019>
- Pedersen, M. F., Filbee-Dexter, K., Frisk, N. L., Sárossy, Z., & Wernberg, T. (2021). Carbon sequestration potential increased by incomplete anaerobic decomposition of kelp detritus. *Marine Ecology Progress Series*, 660, 53–67. <https://doi.org/10.3354/meps13613>
- Planke, S., Bellwald, B., Millett, J., Planke, E. E. E., Zastrow, D., Carlevaris, P., et al. (2021). Permanent carbon sequestration potential in offshore basalt sequences on the NW European continental margins. In *Presented at the 82nd EAGE annual conference and exhibition*. European Association of Geoscientists and Engineers. <https://doi.org/10.3997/2214-4609.202011841>
- Planke, S., Berndt, C., & Alvarez Zarikian, C. A. (2022). Expedition 396 preliminary report: Mid-Norwegian margin magmatism and paleoclimate implications. *International Ocean Discovery Program*, 396. <https://doi.org/10.14379/iodyp.pr.396.2022>
- Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., et al. (2010). The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLoS One*, 5(4), e10095. <https://doi.org/10.1371/journal.pone.0010095>
- Powers, L. C., Hertkorn, N., McDonald, N., Schmitt-Kopplin, P., Del Vecchio, R., Blough, N. V., & Gonsior, M. (2019). Sargassum sp. Act as a large regional source of marine dissolved organic carbon and polyphenols. *Global Biogeochemical Cycles*, 33(11), 1423–1439. <https://doi.org/10.1029/2019gb006225>
- Preston, C. J. (2013). Ethics and geoengineering: Reviewing the moral issues raised by solar radiation management and carbon dioxide removal. *WIREs Climate Change*, 4(1), 23–37. <https://doi.org/10.1002/wcc.198>
- Ramasamy, M., Amann, T., & Moosdorf, N. (2024). Regional potential of coastal ocean alkalization with olivine within 100 years. *Environmental Research Letters*, 19(6), 064030. <https://doi.org/10.1088/1748-9326/ad4664>
- Rau, G. H., Carroll, S. A., Bourcier, W. L., Singleton, M. J., Smith, M. M., & Aines, R. D. (2013). Direct electrolytic dissolution of silicate minerals for air CO₂ mitigation and carbon-negative H₂ production. *Proceedings of the National Academy of Sciences*, 110(25), 10095–10100. <https://doi.org/10.1073/pnas.1222358110>
- Rau, G. H., Willauer, H. D., & Ren, Z. J. (2018). The global potential for converting renewable electricity to negative-CO₂-emissions hydrogen. *Nature Climate Change*, 8(7), 621–625. <https://doi.org/10.1038/s41558-018-0203-0>

- Raw, J. L., Van Niekerk, L., Chauke, O., Mbatha, H., Riddin, T., & Adams, J. B. (2023). Blue carbon sinks in South Africa and the need for restoration to enhance carbon sequestration. *Science of the Total Environment*, 859(Pt 1), 160142. <https://doi.org/10.1016/j.scitotenv.2022.160142>
- Realmonde, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, 10(1), 3277. <https://doi.org/10.1038/s41467-019-10842-5>
- Realmonde, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2020). Reply to "High energy and materials requirement for direct air capture calls for further analysis and R&D.". *Nature Communications*, 11(1), 3286. <https://doi.org/10.1038/s41467-020-17204-6>
- Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, 55(3), 636–674. <https://doi.org/10.1002/2016RG000533>
- Rickels, W. (2023). Kapitel 6.6: Wirtschaftliche Aspekte bei der atmosphärischen CO₂-Entnahme und dem Strahlungsmanagement. In *Warning signal climate: Does technology help against global warming?* (pp. 291–297). Retrieved from <https://www.ifw-kiel.de/de/publikationen/kapitel-66-wirtschaftliche-aspekte-bei-der-atmosphärischen-co2-entnahme-und-dem-strahlungsmanagement-31823/>
- Roberts, D. A., Johnston, E. L., & Knott, N. A. (2010). Impacts of desalination plant discharges on the marine environment: A critical review of published studies. *Water Research*, 44(18), 5117–5128. <https://doi.org/10.1016/j.watres.2010.04.036>
- Roesijadi, G., Jones, S. B., Snowden-Swan, L. J., & Zhu, Y. (2010). Macroalgae as a biomass feedstock: A preliminary analysis. <https://doi.org/10.2172/1006310>
- Rosenqvist, M. P., Meakins, M. W. J., Planke, S., Millett, J. M., Kjöll, H. J., Voigt, M. J., & Jamtveit, B. (2023). Reservoir properties and reactivity of the Faroe Islands basalt group: Investigating the potential for CO₂ storage in the North Atlantic Igneous Province. *International Journal of Greenhouse Gas Control*, 123, 103838. <https://doi.org/10.1016/j.ijggc.2023.103838>
- Sarga agriscience. (2021a). Retrieved November 2, 2023, from <https://sarga.ag/>
- Sasmito, S. D., Basyuni, M., Kridalaksana, A., Saragi-Sasmito, M. F., Lovelock, C. E., & Murdiyoso, D. (2023). Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. *Nature Ecology and Evolution*, 7(1), 62–70. <https://doi.org/10.1038/s41559-022-01926-5>
- Satterfield, T., Nawaz, S., & Boettcher, M. (2023). Social considerations and best practices to apply to engaging publics on ocean alkalinity enhancement. *Guide to Best Practices in Ocean Alkalinity Enhancement Research*, 11, 2–oae2023. <https://doi.org/10.5194/sp-2-oae2023-11-2023>
- Segreto, M., Principe, L., Desormeaux, A., Torre, M., Tomassetti, L., Tratzi, P., et al. (2020). Trends in social acceptance of renewable energy across Europe-A literature review. *International Journal of Environmental Research and Public Health*, 17(24), 9161. <https://doi.org/10.3390/ijerph17249161>
- Sengupta, M. (2021). *Environmental impacts of mining: Monitoring, restoration, and control*. Taylor and Francis Group. <https://doi.org/10.1201/9781003164012>
- Siegel, D. A., DeVries, T., Doney, S. C., & Bell, T. (2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. *Environmental Research Letters*, 16(10), 104003. <https://doi.org/10.1088/1748-9326/ac0be0>
- Smith, S. M., Geden, O., Nemet, G. F., Gidden, M. J., Lamb, W. F., Powis, C., et al. (2023). The state of carbon dioxide removal – 1st edition. The state of carbon dioxide removal. <https://doi.org/10.17605/OSF.IO/W3B4Z>
- Snebjörnsdóttir, S. Ó., & Gislason, S. R. (2016). CO₂ storage potential of basaltic rocks offshore Iceland. *Energy Procedia*, 86, 371–380. <https://doi.org/10.1016/j.egypro.2016.01.038>
- Sonnichsen, C., Atamanchuk, D., Hendricks, A., Morgan, S., Smith, J., Grundke, I., et al. (2023). An automated microfluidic analyzer for in situ monitoring of total alkalinity. *ACS Sensors*, 8(1), 344–352. <https://doi.org/10.1021/acssensors.2c02343>
- Sterr, H. (2008). Assessment of vulnerability and adaptation to sea-level rise for the coastal zone of Germany. *Journal of Coastal Research*, 242, 380–393. <https://doi.org/10.2112/07A-0011.1>
- Stevenson, A., Ó Corcora, T. C., Hukriede, W., Schubert, P. R., & Reusch, T. B. H. (2023). Substantial seagrass blue carbon pools in the southwestern Baltic Sea include relics of terrestrial peatlands. *Frontiers in Marine Science*, 10, 1266663. <https://doi.org/10.3389/fmars.2023.1266663>
- Stommel, H., Arons, A. B., & Blanchard, D. (1956). An oceanographical curiosity: The perpetual salt fountain. *Deep-Sea Research*, 3(2), 152–153. [https://doi.org/10.1016/0146-6313\(56\)90095-8](https://doi.org/10.1016/0146-6313(56)90095-8)
- Sündermann, J., & Pohlmann, T. (2011). A brief analysis of North Sea physics. *Oceanologia*, 53(3), 663–689. <https://doi.org/10.5697/oc.53.3.663>
- Suutari, M., Leskinen, E., Fagerstedt, K., Kuparinen, J., Kuuppo, P., & Blomster, J. (2015). Macroalgae in biofuel production. *Phycological Research*, 63(1), 1–18. <https://doi.org/10.1111/pre.12078>
- Tames-Espinosa, M., Martínez, I., Romero-Kutzner, V., Coca, J., Algueró-Muñoz, M., Horn, H. G., et al. (2020). Metabolic responses of sub-tropical microplankton after a simulated deep-water upwelling event suggest a possible dominance of mixotrophy under increasing CO₂ levels. *Frontiers in Marine Science*, 7, 307. <https://doi.org/10.3389/fmars.2020.00307>
- Tank, L., Voget-Kleschin, L., Garschagen, M., Boettcher, M., Mengis, N., Holland-Cunz, A., et al. (2025). Distinguish between feasibility and desirability when assessing climate response options. *Npj Climate Action*, 4(1). <https://doi.org/10.1038/s44168-025-00237-2>
- Tedsen, E., & Homann, G. (2013). Implementing the precautionary principle for climate engineering. *Carbon and Climate Law Review*, 7(2), 90–100. <https://doi.org/10.21552/cclr/2013/2/250>
- Tennet. (2023). Nordsee-„Windernte“ 2022 steigt um vier Prozent gegenüber dem Vorjahr auf gut 21 Terawattstunden. November 12, 2023, Retrieved from <https://www.tennet.eu/de/news/nordsee-windernte-2022-steigt-um-vier-prozent-gegenueber-dem-vorjahr-auf-gut-21>
- Theuerkauff, D., Rivera-Ingraham, G. A., Lambert, S., Mercky, Y., Lejeune, M., Lignot, J.-H., & Sucré, E. (2020). Wastewater bioremediation by mangrove ecosystems impacts crab ecophysiology: In-situ caging experiment. *Aquatic Toxicology*, 218, 105358. <https://doi.org/10.1016/j.aquatox.2019.105358>
- Thoni, T., Beck, S., Borchers, M., Förster, J., Görl, K., Hahn, A., et al. (2020). Deployment of negative emissions technologies at the national level: A need for holistic feasibility assessments. *Frontiers in Climate*, 2. <https://doi.org/10.3389/fclim.2020.590305>
- Tittley, I. (1991). Seaweeds: Their environment, biogeography and ecophysiology, by Klaus Lüning, Wiley Interscience, 1991. xiii + 527 pp. Price: £70.50. *Aquatic Conservation*, 1(2), 189. <https://doi.org/10.1002/aqc.3270010208>
- UBA. (2023). Geoengineering-governance [text]. March 5, 2024, Retrieved from <https://www.umweltbundesamt.de/en/topics/sustainability-strategies-international-environmental-law/international-environmental-law/geoengineering-governance>
- UNFCCC. (2015). Paris agreement, report of the conference of the parties to the united nations framework convention on climate change. (21st Sess). 30 Nov.–13 Dec., Retrieved from <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>
- UNFCCC. (2016). The Paris Agreement. Retrieved from <https://unfccc.int/documents/184656>
- Vesta. (2022). Retrieved February 23, 2024, from <https://www.vesta.earth/>

- Vielstädte, L., Linke, P., Schmidt, M., Sommer, S., Haeckel, M., Braack, M., & Wallmann, K. (2019). Footprint and detectability of a well leaking CO₂ in the Central North Sea: Implications from a field experiment and numerical modelling. *International Journal of Greenhouse Gas Control*, 84, 190–203. <https://doi.org/10.1016/j.ijggc.2019.03.012>
- Wada, S., Omori, Y., Kayamyo, Y., Tashiro, Y., & Hama, T. (2015). Photoreactivity of dissolved organic matter from macroalgae. *Regional Studies in Marine Science*, 2, 12–18. <https://doi.org/10.1016/j.rsma.2015.08.018>
- Wang, W.-L., Fernández-Méndez, M., Elmer, F., Gao, G., Zhao, Y., Han, Y., et al. (2023). Ocean afforestation is a potentially effective way to remove carbon dioxide. *Nature Communications*, 14(1), 4339. <https://doi.org/10.1038/s41467-023-39926-z>
- Wayman, M., Hassan, K. E., & Al-Kuwari, M. S. (2021). Water footprint analysis of construction aggregates in Qatar. In *Towards a sustainable water future* (pp. 201–210). ICE Publishing. <https://doi.org/10.1680/oicwe.65253.201>
- Weatherley, N. S. (1988). Liming to mitigate acidification in freshwater ecosystems: A review of the biological consequences. *Water, Air, and Soil Pollution*, 39(3–4), 421–437. <https://doi.org/10.1007/BF00279486>
- Williamson, P. (2016). Emissions reduction: Scrutinize CO₂ removal methods. *Nature*, 530(7589), 153–155. <https://doi.org/10.1038/530153a>
- Williamson, P., Wallace, D. W. R., Law, C. S., Boyd, P. W., Collos, Y., Croot, P., et al. (2012). Ocean fertilization for geoengineering: A review of effectiveness, environmental impacts and emerging governance. *Process Safety and Environmental Protection*, 90(6), 475–488. <https://doi.org/10.1016/j.psep.2012.10.007>
- Wu, J., Keller, D. P., & Oschlies, A. (2023). Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: An earth system modeling study. *Earth System Dynamics*, 14(1), 185–221. <https://doi.org/10.5194/esd-14-185-2023>
- Wurgaft, E., Wang, Z. A., Churchill, J. H., Dellapenna, T., Song, S., Du, J., et al. (2021). Particle triggered reactions as an important mechanism of alkalinity and inorganic carbon removal in river plumes. *Geophysical Research Letters*, 48(11), e2021GL093178. <https://doi.org/10.1029/2021GL093178>
- Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, 35(5), 2683–2691. <https://doi.org/10.1016/j.enpol.2006.12.001>
- Yool, A., Shepherd, J. G., Bryden, H. L., & Oschlies, A. (2009). Low efficiency of nutrient translocation for enhancing oceanic uptake of carbon dioxide. *Journal of Geophysical Research*, 114(C8), 2008JC004792. <https://doi.org/10.1029/2008JC004792>
- Zimm, C., Mintz-Woo, K., Brutschin, E., Hanger-Kopp, S., Hoffmann, R., Kikstra, J. S., et al. (2024). Justice considerations in climate research. *Nature Climate Change*, 14(1), 22–30. <https://doi.org/10.1038/s41558-023-01869-0>

References From the Supporting Information

- Anderson, L., & Dyrssen, D. (1994). Alkalinity and total carbonate in the Arabian sea. Carbonate depletion in the red Sea and Persian Gulf. *Marine Chemistry*, 47(3), 195–202. [https://doi.org/10.1016/0304-4203\(94\)90019-1](https://doi.org/10.1016/0304-4203(94)90019-1)
- Aspelund, A., & Jordal, K. (2007). Gas conditioning—The interface between CO₂ capture and transport. *International Journal of Greenhouse Gas Control*, 1(3), 343–354. [https://doi.org/10.1016/S1750-5836\(07\)00040-0](https://doi.org/10.1016/S1750-5836(07)00040-0)
- Barbot, Y., Al-Ghaili, H., & Benz, R. (2016). A review on the valorization of macroalgal wastes for biomethane production. *Marine Drugs*, 14(6), 120. <https://doi.org/10.3390/md14060120>
- Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrazio, R. M., Renforth, P., et al. (2020). Potential for large-scale CO₂ removal via enhanced rock weathering with croplands. *Nature*, 583(7815), 242–248. <https://doi.org/10.1038/s41586-020-2448-9>
- Blomberg, A. E. A., Waarum, I.-K., Totland, C., & Eek, E. (2021). Marine monitoring for offshore geological carbon storage—A review of strategies, technologies and trends. *Geosciences*, 11(9), 383. <https://doi.org/10.3390/geosciences11090383>
- BMDV. (2016). Waterways as transport routes. November 20, 2023, Retrieved from <https://bmdv.bund.de/SharedDocs/EN/Articles/WS/waterways-as-transport-routes.html>
- BMWK. (2023). Renewable energy sources in figures. February 13, 2024, Retrieved from <https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/renewable-energy-sources-in-figures-2022.html>
- Bruton, T., Lyons, H., Lerat, Y., Stanley, M., & Rasmussen, M. B. (2009). A review of the potential of marine algae as a source of biofuel in Ireland. *Sustainable Energy*. Retrieved from https://www.researchgate.net/publication/309185965_A_review_of_the_potential_of_Marine_Algae_as_a_Source_of_Biofuel_in_Ireland_Sustainable_Energy#fullTextFileContent
- BSH. (2009). Maritime spatial plan for the German EEZ in the North Sea. Retrieved March 5, 2024, Retrieved from <https://maritime-spatial-planning.ec.europa.eu/practices/maritime-spatial-plan-german-eez-north-sea>
- BSH. (2023). Flächenentwicklungsplan 2023 für die deutsche Nordsee und Ostsee. Retrieved from https://www.bsh.de/DE/THemen/Offshore/Meeresfachplanung/Flaechenentwicklungsplan/_Anlagen/Downloads/FEP_2023_1/Flaechenentwicklungsplan_2023.pdf?__blob=publicationFile&v=1
- Buck, B. H. & Langan, R. (Eds.). (2017). *Aquaculture perspective of multi-use sites in the open ocean*. Springer International Publishing. <https://doi.org/10.1007/978-3-319-51159-7>
- Carpenter, E. J. (1972). Nitrogen fixation by a blue-green epiphyte on pelagic sargassum. *Science*, 178(4066), 1207–1209. <https://doi.org/10.1126/science.178.4066.1207>
- Caserini, S., Pagano, D., Campo, F., Abbà, A., De Marco, S., Righi, D., et al. (2021). Potential of maritime transport for ocean liming and atmospheric CO₂ removal. *Frontiers in Climate*, 3. <https://doi.org/10.3389/fclim.2021.575900>
- CESNI. (2020). Evaluating the energy requirement of inland vessels using energy efficiency indices. Retrieved from https://www.cesni.eu/wp-content/uploads/2021/03/cesnpt_energyindex_en.pdf
- Chen, F., & Morosuk, T. (2021). Exergetic and economic evaluation of CO₂ liquefaction processes. *Energies*, 14(21), 7174. <https://doi.org/10.3390/en14217174>
- Chereau, E. (2019). Monitoring and evaluation of Sargassum collection operations summary report – sargassum information hub. Retrieved from <https://sargassumhub.org/monitoring-and-evaluation-of-sargassum-collection-operations-summary-report/>
- Chowdhury, A., Naz, A., Bhattacharyya, S., & Sanyal, P. (2018). Cost–benefit analysis of ‘Blue Carbon’ sequestration by plantation of few key mangrove species at Sundarban Biosphere Reserve, India. *Carbon Management*, 9(6), 575–586. <https://doi.org/10.1080/17583004.2018.1518105>
- Daniel-Gromke, J., Rensberg, N., Denysenko, V., Stinner, W., Schmalfuß, T., Scheffelowitz, M., et al. (2018). Current developments in production and utilization of biogas and biomethane in Germany. *Chemie Ingenieur Technik*, 90(1–2), 17–35. <https://doi.org/10.1002/cite.201700077>
- Dickson, A. G., & Et, A. (2007). Guide to best practices for ocean CO₂ measurement. <https://doi.org/10.25607/OBP-1342>

- Doney, S. C. (2010). The growing human footprint on coastal and open-ocean biogeochemistry. *Science*, 328(5985), 1512–1516. <https://doi.org/10.1126/science.1185198>
- du Bois, P. B., Dumas, F., Voiseux, C., Morillon, M., Oms, P.-E., & Solier, L. (2020). Dissolved radiotracers and numerical modeling in NorthNorth European continental shelf dispersion studies (1982–2016): Databases, methods and applications. *Water*, 12(6), 1667. <https://doi.org/10.3390/w12061667>
- Du, F., Warsinger, D. M., Urmi, T. I., Thiel, G. P., Kumar, A., & Lienhard, J. H. V. (2018). Sodium hydroxide production from seawater desalination brine: Process design and energy efficiency. *Environmental Science and Technology*, 52(10), 5949–5958. <https://doi.org/10.1021/acs.est.8b01195>
- Dutreuil, S., Bopp, L., & Tagliabue, A. (2009). Impact of enhanced vertical mixing on marine biogeochemistry: Lessons for geo-engineering and natural variability. *Biogeosciences*, 6(5), 901–912. <https://doi.org/10.5194/bg-6-901-2009>
- EBA. (2023). About biogas and biomethane. November 12, 2023, Retrieved from <https://www.europeanbiogas.eu/about-biogas-and-biomethane/>
- Eiken, O., Davis, T. L., Landrø, M., & Wilson, M. (2019). Twenty years of monitoring CO₂ injection at Sleipner. In *Geophysics and geo-sequestration* (pp. 209–234). Cambridge University Press. <https://doi.org/10.1017/9781316480724.014>
- Ejenstam, J. (2010). The lime industry, a potential business area for Kanthal. Retrieved from <http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A309947&dsid=-1900>
- Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO₂ direct air capture plants. *Journal of Cleaner Production*, 224, 957–980. <https://doi.org/10.1016/j.jclepro.2019.03.086>
- Flaathen, T. K., Gislason, S. R., Oelkers, E. H., & Sveinbjörnsdóttir, Á. E. (2009). Chemical evolution of the Mt. Hekla, Iceland, groundwaters: A natural analogue for CO₂ sequestration in basaltic rocks. *Applied Geochemistry*, 24(3), 463–474. <https://doi.org/10.1016/j.apgeochem.2008.12.031>
- Flipkens, G., Blust, R., & Town, R. M. (2021). Deriving nickel (Ni(II)) and chromium (Cr(III)) based environmentally safe olivine guidelines for coastal enhanced silicate weathering. *Environmental Science and Technology*, 55(18), 12362–12371. https://doi.org/10.1021/ACS.EST.1C02974/ASSET/IMAGES/LARGE/ESI1C02974_0003.JPEG
- FNR. (2019). Bioenergie in Deutschland: Zahlen und Fakten – Feste Brennstoffe, Biokraftstoffe and Biogas. *Fachagentur Nachhaltende Rohstoffe*.
- Fraunhofer. (2021). Levelized cost of electricity- renewable energy technologies. November 23, 2023, Retrieved from <https://www.ise.fraunhofer.de/en/publications/studies/cost-of-electricity.html>
- Furre, A.-K., Eiken, O., Alnes, H., Vevatne, J. N., & Kiær, A. F. (2017). 20 Years of monitoring CO₂-injection at sleipner. *Energy Procedia*, 114, 3916–3926. <https://doi.org/10.1016/j.egypro.2017.03.1523>
- Gao, G., Burgess, J. G., Wu, M., Wang, S., & Gao, K. (2020). Using macroalgae as biofuel: Current opportunities and challenges. *Botanica Marina*, 63(4), 355–370. <https://doi.org/10.1515/bot-2019-0065>
- Garcia, H. E., Locarnini, R. A., Boyer, T. P., Antonov, J. I., Baranova, O. K., Zweng, M. M., et al. (2013). World Ocean Atlas 2013. Vol. 4: Dissolved Inorganic Nutrients (phosphate, nitrate, silicate). S. Levitus, Ed.; A. Mishonov, Technical Ed., 4(September), 25. <https://doi.org/10.7289/V5J67DWD>
- GESAMP. (2019). High level review of a wide range of proposed marine geoengineering techniques. *GESAMP Reports and Studies*(98), 144.
- Ghaffour, N., Bundschuh, J., Mahmoudi, H., & Goosen, M. F. A. (2015). Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. *Desalination*, 356, 94–114. <https://doi.org/10.1016/j.desal.2014.10.024>
- Gordon, P. (2019). Dubai to power desalination with solar. Retrieved November 23, 2023, from <https://www.smart-energy.com/renewable-energy/dubai-to-power-desalination-with-solar/>
- García-Rodríguez, L., & Gómez-Camacho, C. (2001). Exergy analysis of the SOL-14 plant (Plataforma Solar de Almería, Spain). *Desalination*, 137(1), 251–258. [https://doi.org/10.1016/S0011-9164\(01\)00226-0](https://doi.org/10.1016/S0011-9164(01)00226-0)
- Gude, V. G. (2016). Desalination and sustainability--an appraisal and current perspective. *Water Research*, 89, 87–106. <https://doi.org/10.1016/j.watres.2015.11.012>
- Gunson, A. J. (2013). Quantifying, reducing and improving mine water use. <https://doi.org/10.14288/1.0071942>
- Harris, R. N., & Higgins, S. M. (2008). A permeability estimate in 56 Ma crust at ODP hole 642E, Vøring plateau Norwegian sea. *Earth and Planetary Science Letters*, 267(1–2), 378–385. <https://doi.org/10.1016/j.epsl.2007.11.055>
- Howard, K. L., & Menzies, R. J. (1969). Distribution and production of sargassum in the waters off the Carolina coast. *Botanica Marina*, 12(1–4). <https://doi.org/10.1515/botm.1969.12.1-4.244>
- Hughes, A. D., Kelly, M. S., Black, K. D., & Stanley, M. S. (2012). Biogas from macroalgae: Is it time to revisit the idea? *Biotechnology for Biofuels*, 5(1), 86. <https://doi.org/10.1186/1754-6834-5-86>
- ITA group. (2021). Milo's desalination. November 23, 2023, Retrieved from <https://itagroup.gr/en/milo-s-desalination/>
- Jakobsen, J., Roussanaly, S., & Anantharaman, R. (2017). A techno-economic case study of CO₂ capture, transport and storage chain from a cement plant in Norway. *Journal of Cleaner Production*, 144, 523–539. <https://doi.org/10.1016/j.jclepro.2016.12.120>
- Johnson, D. H., & Decicco, J. (1983). An artificial upwelling driven by salinity differences in the ocean. Retrieved from <https://www.nrel.gov/docs/legosti/old/2149.pdf>
- Kaltschmitt, M., Hartmann, H., & Hofbauer, H. (Eds.). (2016). *Energie aus Biomasse*. Springer. <https://doi.org/10.1007/978-3-662-47438-9>
- Kearns, D., Liu, H., & Consoli, C. (2021). *Technology readiness and cost of CCS*. Global CCS Institute. Retrieved from <https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf>
- Keith, D. W., Holmes, G., St. Angelo, D., & Heidel, K. (2018). A process for capturing CO₂ from the atmosphere. *Joule*, 2(8), 1573–1594. <https://doi.org/10.1016/j.joule.2018.05.006>
- Kellenberger, D., Althaus, H. J., Jungbluth, N., Künniger, T., Lehmann, M., & Thalmann, P. (2007). Life cycle inventories of building products. Final Report Ecoinvent Data v2. 0 No. 7. Retrieved from https://www.academia.edu/download/59905670/07_BuildingProducts20190701-59827-1etcl96.pdf
- Kerrison, P. D., Stanley, M. S., Edwards, M. D., Black, K. D., & Hughes, A. D. (2015). The cultivation of European kelp for bioenergy: Site and species selection. *Biomass and Bioenergy*, 80, 229–242. <https://doi.org/10.1016/j.biombioe.2015.04.035>
- Kroeker, K. J., Kordas, R. L., Crim, R., Hendriks, I. E., Ramajo, L., Singh, G. S., et al. (2013). Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. *Global Change Biology*, 19(6), 1884–1896. <https://doi.org/10.1111/gcb.12179>
- Kumar, A., Phillips, K. R., Cai, J., Schröder, U., & Lienhard, J. H. V. (2019). Integrated valorization of desalination brine through NaOH recovery: Opportunities and challenges. *Angewandte Chemie*, 131(20), 6570–6579. <https://doi.org/10.1002/ange.201810469>
- Kämpf, J., & Chapman, P. (2016). The functioning of coastal upwelling systems. In J. Kämpf & P. Chapman (Eds.), *Upwelling systems of the world* (pp. 31–65). Springer International Publishing. https://doi.org/10.1007/978-3-319-42524-5_2

- Lapointe, B. E., Brewton, R. A., Herren, L. W., Wang, M., Hu, C., McGillicuddy, D. J., et al. (2021). Nutrient content and stoichiometry of pelagic Sargassum reflects increasing nitrogen availability in the Atlantic Basin. *Nature Communications*, 12(1), 3060. <https://doi.org/10.1038/s41467-021-23135-7>
- Leedham, E. C., Hughes, C., Keng, F. S. L., Phang, S.-M., Malin, G., & Sturges, W. T. (2013). Emission of atmospherically significant halo-carbons by naturally occurring and farmed tropical macroalgae. *Biogeosciences*, 10(6), 3615–3633. <https://doi.org/10.5194/bg-10-3615-2013>
- Lin, R., Deng, C., Ding, L., Bose, A., & Murphy, J. D. (2019). Improving gaseous biofuel production from seaweed *Saccharina latissima*: The effect of hydrothermal pretreatment on energy efficiency. *Energy Conversion and Management*, 196, 1385–1394. <https://doi.org/10.1016/j.enconman.2019.06.044>
- Macovei, V. A., Voynova, Y. G., Becker, M., Triest, J., & Petersen, W. (2021a). Long-term intercomparison of two pCO₂ instruments based on ship-of-opportunity measurements in a dynamic shelf sea environment. *Limnology and Oceanography: Methods*, 19(1), 37–50. <https://doi.org/10.1002/lom3.10403>
- Malischek, R., & McCulloch, S. (2021). The world has vast capacity to store CO₂: Net zero means we'll need it – analysis. Retrieved March 5, 2024, from <https://www.iea.org/commentaries/the-world-has-vast-capacity-to-store-co2-net-zero-means-we-ll-need-it>
- Marinho, G. S., Holdt, S. L., Birkeland, M. J., & Angelidaki, I. (2015). Commercial cultivation and bioremediation potential of sugar kelp, *Saccharina latissima*, in Danish waters. *Journal of Applied Phycology*, 27(5), 1963–1973. <https://doi.org/10.1007/s10811-014-0519-8>
- Matter, J. M., Broecker, W. S., Stute, M., Gislason, S. R., Oelkers, E. H., Stefánsson, A., et al. (2009). Permanent carbon dioxide storage into basalt: The CarbFix pilot project, Iceland. *Energy Procedia*, 1(1), 3641–3646. <https://doi.org/10.1016/j.egypro.2009.02.160>
- McGrail, B. P., Spane, F. A., Amonette, J. E., Thompson, C. R., & Brown, C. F. (2014). Injection and monitoring at the Wallula basalt pilot project. *Energy Procedia*, 63, 2939–2948. <https://doi.org/10.1016/j.egypro.2014.11.316>
- Mirzabaev, A., Stringer, L. C., Benjaminsen, T. A., Gonzalez, P., Harris, R., Jafari, M., et al. (2022). Deserts, semiarid areas and desertification. In *Climate change 2022 – impacts, adaptation and vulnerability: Working group II contribution to the sixth assessment report of the intergovernmental Panel on climate change* (pp. 2195–2231). Cambridge University Press. Retrieved from <https://doi.org/10.1017/9781009325844.020>
- Missimer, T. M., & Maliva, R. G. (2018). Environmental issues in seawater reverse osmosis desalination: Intakes and outfalls. *Desalination*, 434, 198–215. <https://doi.org/10.1016/j.desal.2017.07.012>
- Montserrat, F., Renforth, P., Hartmann, J., Leermakers, M., Knops, P., & Meysman, F. J. R. (2017). Olivine dissolution in seawater: Implications for CO₂ sequestration through enhanced weathering in coastal environments. *Environmental Science and Technology*, 51(7), 3960–3972. <https://doi.org/10.1021/acs.est.6b05942>
- Nagare, H., Fujiwara, T., Inoue, T., Akao, S., Inoue, K., Maeda, M., et al. (2012). Nutrient recovery from biomass cultivated as catch crop for removing accumulated fertilizer in farm soil. *Water Science and Technology*, 66(5), 1110–1116. <https://doi.org/10.2166/wst.2012.291>
- Net Zero 2050 Team. (2021). Netto-Null-2050 web-Atlas. March 5, 2024, Retrieved from <https://atlas.netto-null.org/>
- Nilsson, H., Van Overloop, J., Mehdi, R. A., & Pålsson, J. (2018). *Transnational maritime spatial planning in the North Sea: The shipping context*. Interreg North Sea Programme. Retrieved from https://northsearegion.eu/media/4836/northsee_finalshippingreport.pdf
- NPD. (2019). Carbon storage. March 5, 2024, Retrieved from <https://www.sodir.no/en/facts/carbon-storage/>
- Øi, L. E., Eldrup, N., Adhikari, U., Bentsen, M. H., Badalge, J. L., & Yang, S. (2016). Simulation and cost comparison of CO₂ liquefaction. *Energy Procedia*, 86, 500–510. <https://doi.org/10.1016/j.egypro.2016.01.051>
- Paleologos, E. K., Al Nahyan, M. T., & Farouk, S. (2018). Risks and threats of desalination in the Arabian Gulf. *IOP Conference Series: Earth and Environmental Science*, 191(1), 012008. <https://doi.org/10.1088/1755-1315/191/1/012008>
- Palter, J., Cross, J., Long, M., Rafter, P., & Reimers, C. (2023). The science we need to assess marine carbon dioxide removal. *EOS*, 104. <https://doi.org/10.1029/2023EO230214>
- Paris, B., Vandroou, F., Balafoutis, A. T., Vaiopoulos, K., Kyriakarakos, G., Manolakos, D., & Papadakis, G. (2022). Energy use in greenhouses in the EU: A review recommending energy efficiency measures and renewable energy sources adoption. *Applied Sciences*, 12(10), 5150. <https://doi.org/10.3390/app12105150>
- Parkhurst, D. L., & Appelo, C. (1999). User's guide to PHREEQC (Version 2): A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. *Water-Resources Investigations Report*, 99(4259), 312.
- Polo, G. (2012). On maritime transport costs, evolution, and forecast. *Ciencia y Tecnología de Buques*, 5(10), 19–31. <https://doi.org/10.25043/19098642.57>
- Qasim, M., Badrelzaman, M., Darwish, N. N., Darwish, N. A., & Hilal, N. (2019). Reverse osmosis desalination: A state-of-the-art review. *Desalination*, 459, 59–104. <https://doi.org/10.1016/j.desal.2019.02.008>
- Roussanaly, S., & Anantharaman, R. (2017). Cost-optimal CO₂ capture ratio for membrane-based capture from different CO₂ sources. *Chemical Engineering Journal*, 327, 618–628. <https://doi.org/10.1016/j.cej.2017.06.082>
- Raven, J. A. (2017). The possible roles of algae in restricting the increase in atmospheric CO₂ and global temperature. *European Journal of Phycology*, 52(4), 506–522. <https://doi.org/10.1080/09670262.2017.1362593>
- Renforth, P., Jenkins, B. G., & Kruger, T. (2013). Engineering challenges of ocean liming. *Energy*, 60(2000), 442–452. <https://doi.org/10.1016/j.energy.2013.08.006>
- Reyes-Lúa, A., Røe, I. T., & Jordal, K. (2021). CO₂ ship transport: Benefits for early movers and aspects to consider. Retrieved from https://ccuszen.eu/sites/default/files/TG3_Briefing-CO2-ship-transport-Benefits-for-early-movers-and-aspects-to-consider.pdf
- Snæbjörnsdóttir, S. Ó., Sigfússon, B., Marieni, C., Goldberg, D., Gislason, S. R., & Oelkers, E. H. (2020). Carbon dioxide storage through mineral carbonation. *Nature Reviews Earth and Environment*, 1(2), 90–102. <https://doi.org/10.1038/s43017-019-0011-8>
- Schorcht, F., Kourti, I., Scalet, B. M., Roudier, S., & Sancho, L. D. (2013). *Best available techniques (BAT) reference document for the production of cement, lime and magnesium oxide* (p. 506). European Commission Joint Research Centre Institute for Prospective Technological Studies. Retrieved from <https://core.ac.uk/download/pdf/38626619.pdf>
- Schubert, P., Wein, J., & Bartsch, I. (2016). Laminaria bei Helgoland. Retrieved from https://www.schleswig-holstein.de/DE/fachinhalte/K/kuestengewasser/Downloads/vortrag16.pdf?__blob=publicationFile&v=1
- Smale, D. A., Pessarrodona, A., King, N., Burrows, M. T., Yunnice, A., Vance, T., & Moore, P. (2020). Environmental factors influencing primary productivity of the forest-forming kelp *Laminaria hyperborea* in the northeast Atlantic. *Scientific Reports*, 10(1), 12161. <https://doi.org/10.1038/s41598-020-69238-x>
- Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., et al. (2016). Biophysical and economic limits to negative CO₂ emissions. *Nature Climate Change*, 6(1), 42–50. <https://doi.org/10.1038/nclimate2870>
- Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., et al. (2011). Direct air capture of CO₂ with chemicals: A technology assessment for the APS Panel on public affairs. *American Physical Society*.

- Tarantola, F., & Gentile, E. (2021). Analysis of slaked lime spreading methodologies for ocean alkalinity enhancement. *Civil and Environmental Engineering, Politecnico di Milano*. Retrieved from <https://www.politesi.polimi.it/handle/10589/187644>
- Techsci Research. (2023). UAE desalination plant market share, trends and growth report 2028F. Retrieved from <https://www.techsciresearch.com/report/uae-desalination-plant-market/14913.html>
- Tegtmeier, S., Krüger, K., Quack, B., Atlas, E. L., Pisso, I., Stohl, A., & Yang, X. (2012). Emission and transport of bromocarbons: From the west Pacific ocean into the stratosphere. *Atmospheric Chemistry and Physics*, 12(22), 10633–10648. <https://doi.org/10.5194/acp-12-10633-2012>
- Tosun, A., & Konak, G. (2015). Development of a model estimating energy consumption values of primary and secondary crushers. *Arabian Journal of Geosciences*, 8(2), 1133–1144. <https://doi.org/10.1007/s12517-013-1260-3>
- UAE embassy. (2023). UAE energy diversification. Retrieved November 24, 2023, Retrieved from <https://www.uae-embassy.org/discover-uae/climate-and-energy/uae-energy-diversification>
- UAE Energy Report. (2015). *The UAE state of energy report* (p. 262). Ministry of Energy. Retrieved from <https://play.google.com/store/books/details?id=h5EwzgEACAAJ>
- US Department of Energy. (2013). Limestone and crushed rock. In *ITP mining: Energy and environmental profile of the U.S. Mining industry* (pp. 9.1–9.12).
- Van Zanten, B. T., Brander, L. M., Gutierrez Torres, D., Uyttendaele, G. Y. P., Herrera Garcia, L. D., Patrama, D., & Kaczan, D. J. (2021). The economics of large-scale mangrove conservation and restoration in Indonesia. Retrieved from <https://openknowledge.worldbank.org/bitstream/handle/10986/37605/156489-brief.pdf?sequence=4>
- Vangkilde-Pedersen, T., Anthonsen, K. L., Smith, N., Kirk, K., Neele, F., Van Der Meer, B., et al. (2009). Assessing European capacity for geological storage of carbon dioxide—the EU GeoCapacity project. *Energy Procedia*, 1(1), 2663–2670. <https://doi.org/10.1016/j.egypro.2009.02.034>
- Viebahn, P., Scholz, A., & Zelt, O. (2019). The potential role of direct air capture in the German energy research program—Results of a multi-dimensional analysis. *Energies*, 12(18), 3443. <https://doi.org/10.3390/en12183443>
- Wang, M., Hu, C., Cannizzaro, J., English, D., Han, X., Naar, D., et al. (2018). Remote sensing of sargassum biomass, nutrients, and pigments. *Geophysical Research Letters*, 45(22). <https://doi.org/10.1029/2018GL078858>
- Weinberger, F., Paalme, T., & Wikström, S. A. (2020). Seaweed resources of the Baltic Sea, Kattegat and German and Danish North Sea coasts. *Botanica Marina*, 63(1), 61–72. <https://doi.org/10.1515/bot-2019-0019>
- Weiss, R. F. (1974). Carbon dioxide in water and seawater: The solubility of a non-ideal gas. *Marine Chemistry*, 2(3), 203–215. [https://doi.org/10.1016/0304-4203\(74\)90015-2](https://doi.org/10.1016/0304-4203(74)90015-2)
- Wiese, F., Fridriksson, T., & Ármannsson, H. (2008). CO₂ fixation by calcite in high-temperature geothermal systems in Iceland. Report from the Iceland Geosurvey (ÍSOR). ÍSOR-2008/003, Reykjavik. Retrieved from <https://gogn.orkustofnun.is/Skyrslur/ISOR-2008/ISOR-2008-003.pdf>
- Wollnik, R., Borchers, M., Seibert, R., Abel, S., Herrmann, P., Elsasser, P., et al. (2023). Dynamics of bio-based carbon dioxide removal in Germany (preprint). *Review*. <https://doi.org/10.21203/rs.3.rs-3452150/v1>
- Xu, G., Liang, F., Yang, Y., Hu, Y., Zhang, K., & Liu, W. (2014). An improved CO₂ separation and purification system based on cryogenic separation and distillation theory. *Energies*, 7(5), 3484–3502. <https://doi.org/10.3390/en7053484>
- ZEP. (2019). The cost of subsurface storage of CO₂. Retrieved from <https://zeroemissionsplatform.eu/co2-storage-cost/>

Contribution [CPA]

Towards Reliable Performance Predictions for Stommel's Perpetual Salt Fountain

Citation:

Kemper, J., Mense, J., Graf, K., Riebesell, U., Kröger, J., 2023. Towards reliable performance predictions for Stommel's perpetual salt fountain, in: Proceedings of the 10th Conference on Computational Methods in Marine Engineering, Madrid, Spain. doi:10.23967/marine.2023.018.

Author contributions:

Conceptualization	J. Kemper , J. Mense
Methodology	J. Kemper , J. Mense
Software	J. Kemper , J. Mense
Validation	K. Graf, J. Kröger
Investigation	J. Kemper , J. Mense
Resources	J. Kröger, K. Graf
Writing - Original Draft	J. Kemper
Writing - Review & Editing	J. Mense, K. Graf, U. Riebesell, J. Kröger
Visualization	J. Kemper , J. Mense
Supervision	J. Kröger, K. Graf, U. Riebesell
Project administration	K. Graf, U. Riebesell, J. Kröger
Funding acquisition	K. Graf, U. Riebesell, J. Kröger

License:

This publication is licensed under a Creative Commons Attribution-NonCommercial 4.0 International license.



Towards Reliable Performance Predictions for Stommel's Perpetual Salt Fountain

Jost Kemper^{1*}, Jan Mense^{†1}, Kai Graf¹, Jörn Kröger¹ and Ulf Riebesell[†]

¹ Institute for Naval Architecture and Maritime Engineering, University of Applied Sciences Kiel, Grenzstraße 3, 24149 Kiel, Germany, web page: <http://www.fh-kiel.de>

[†] Biological Oceanography, GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24105 Kiel, Germany, web page: <http://www.geomar.de>

* Corresponding author: Jost Kemper, jost.kemper@fh-kiel.de

ABSTRACT

Artificial Upwelling (AU) of nutrient-rich Deep Ocean Water (DOW) to the ocean's sunlit surface layer is currently being investigated as a way of increasing the ecosystem productivity and enhancing the natural CO₂ uptake of the ocean. AU is thus considered a marine Carbon Dioxide Removal (CDR) option (GESAMP, 2019) in addition to its potential in the context of open ocean fish and macroalgae farming (Kirke, 2003; Wu *et al.*, 2023). A promising technical concept for AU was described by the oceanographer Stommel *et al.* (1956). Stommel proposed that the counteracting effects of typical open ocean temperature and salinity depth profiles on density can be utilized to drive a self-sustaining upwelling flow in a vertical ocean pipe. He termed this effect the "perpetual salt fountain". Despite several research efforts, none of the previous studies were able to reliably predict or demonstrate the potential of Stommel Upwelling Pipes (SUP)s. The growing interest in AU in light of current CDR research poses the need for reliable performance prediction methods and further development of Stommel's concept. To fill this gap, two models have been developed in the present work. A Reynolds-Averaged Navier-Stokes (RANS) model and a one-dimensional numerical model. While the RANS model enables detailed modeling of the heat transfer and flow phenomena, the one-dimensional numerical model allows for fast evaluation of simplified geometries for optimization and large-scale studies. This twofold approach allows for effective performance predictions while ensuring good reliability of the results. The present work shows the results of a number of studies, performed for different geometries and environmental conditions. The results of both models are compared and analyzed, and the respective potential is demonstrated. The presented results provide insight into some key aspects of the performance of SUPs and their potential for AU.

Keywords: Artificial Upwelling; Perpetual Salt Fountain; Open-Ocean Aquaculture; Macroalgae Farming; Carbon Dioxide Removal (CDR); Computational Fluid Dynamics (CFD); OpenFOAM, Heat Transfer; Buoyancy-Affected Flow

NOMENCLATURE

<i>General</i>		<i>1D model</i>	
P	pressure [N/m ²]	A_c	pipe cross sectional area [m ²]
Q	volumetric flow rate [L/s]	c_f	Darcy pipe friction factor [-]
S_A	absolute salinity [g/kg]	C_h	heat-transferring circumference [m]
Θ	conservative temperature [°C]	c_p	specific heat capacity [J/kg K]
ρ	density [kg/m ³]	D	pipe diameter [m]
<i>RANS model</i>		D_h	hydraulic pipe diameter [m]
D	diffusivity of Salinity [m ² /s]	g	gravity [m/s ²]
$\mathbf{g}$	gravity vector [m/s ²]	h	convection heat transfer coefficient [W/m ² s]
$\mathbf{I}$	unit matrix [-]	L	pipe length [m]
k	turbulent kinetic energy [m ² /s ²]	N_D	diameter-based Nusselt number $= \frac{hD}{\kappa}$ [-]
p_{rgh}^*	modified kinematic pressure $= \frac{1}{\rho_0} (\bar{P} - \rho \mathbf{g} \cdot \mathbf{r}) + \frac{2}{3} k$ [m ² /s ²]	s	pipe wall thickness [m]
$\mathbf{r}$	position vector w. r. t. water surface [m]	U	overall heat transfer coefficient across pipe wall [W/m ² K]
$\mathbf{S}$	strain rate tensor $= \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)$ [1/s]	w	pipe velocity [m/s]
t	time [s]	z	vertical pipe coordinate (positive down) [m]
$\mathbf{u}$	velocity vector [m/s]	κ	thermal conductivity [W/m K]
λ	thermal diffusivity [m ² /s]	$\Delta_r \Theta$	radial temperature difference [K]
ν	kinematic viscosity [m ² /s]	<i>Subscripts</i>	
$\boldsymbol{\tau}^*$	deviatoric part of kinematic Reynolds stress tensor [m ² /s ²]	ϕ_{av}	streamwise averaged quantity
<i>Subscripts</i>		ϕ_e	quantity in regards to the outer diameter of the inner pipe
ϕ_0	constant reference quantity	ϕ_i	quantity in inner pipe
ϕ_e	effective quantity $= \phi + \phi_t$	ϕ_{top}	quantity at upper pipe end
ϕ_t	quantity modeling turbulence effects	ϕ_o	quantity in outer pipe
<i>Superscripts</i>		ϕ_{ocean}	quantity in surrounding ocean
$\bar{\phi}$	Reynolds-averaged quantity	ϕ_{wall}	quantity of pipe wall material
ϕ^T	transpose of tensor ϕ		

1. INTRODUCTION

In the scientific community, a strong consensus exists on the fact that active removal of CO₂ from the atmosphere (CDR) is necessary to achieve net zero anthropogenic CO₂ emissions and limit global warming (IPCC, 2021). In current CDR proposals, the ocean plays an important role, with several marine CDR options currently being actively researched (GESAMP, 2019). Bringing nutrient-rich Deep Ocean Water (DOW) to the ocean's sunlit surface layer through a process called Artificial Upwelling (AU) can increase the productivity of ocean ecosystems, subsequently fostering CO₂ uptake. AU is thus considered as a standalone CDR option (Lovelock and Rapley, 2007; GESAMP, 2019) or in combination with other CDR measures, like open-ocean macroalgae mariculture and sinking (Wu *et al.*, 2023).

From a technical perspective, the task of providing nutrient-rich DOW for algal growth comes down to two main challenges, pumping the DOW to the surface and preventing it from sinking back down again, due to its high density. While several concepts for pumping the DOW to the surface have been proposed (Lovelock and Rapley, 2007; Liang and Peng, 2005; Stommel *et al.*, 1956), the challenge of keeping the DOW in the surface layer is still largely unresolved (Kirke, 2003; Kemper *et al.*, 2022; Fan *et al.*, 2015). A potential way of overcoming both challenges has been described by the oceanographer Stommel *et al.* (1956). In many ocean regions the surface waters have both, a higher temperature and a higher salinity than the DOW. With regard to density stratification, the effect of temperature predominates, so that the water column is stably stratified. The smaller salinity effect counteracts the temperature effect, thus reducing the stability of the water column. Stommel proposed to utilize these counteracting (stabilizing and destabilizing) effects for AU. If a vertical ocean pipe is filled with DOW (cold, low salinity) once, the water in the pipe will eventually be heated up by the surrounding ocean while the salinity difference persists, rendering the water in the pipe positively buoyant (i.e. lighter than the surrounding water). Stommel thus postulated that an upwelling flow in a vertical pipe, once triggered would sustain itself without additional energy input. Stommel called this phenomenon the *perpetual salt fountain*. In the present work, all AU concepts which are based on Stommel's principle will be subsumed under the term Stommel Upwelling Pipe (SUP). It should be noted at this point, that a self sustaining downwelling flow can be achieved in the same manner, if the pipe is initially filled with surface water (warm, high salinity) instead of DOW. For AU, which is usually proposed for implementation in remote ocean regions and potentially harsh environments, Stommel's concept has a number of desirable features. Apart from the initial triggering of the flow, it does not require any external energy supply. Its structure is technologically simple and the upwelled DOW is already heated up when leaving the system at the surface and thus has less tendency to sink back to depth.

A number of studies have been carried out in order to demonstrate and quantify the potential of Stommel's concept. In 1958, Groves published first flow rate calculations for SUP systems (Groves, 1958). Groves analyzed his results with respect to increased fish farming yields due to AU. He concluded that fertilization of fish farms by AU, using Stommel's concept, was not likely to be economically favorable over other fertilization options. Groves calculations were extended with respect to vertical heat conduction by Hinman (1966). Hinman found that vertical heat conduction had a negligible influence on the calculated flow rates. Yet, by investigating different ocean profiles and pipe geometries, he found significantly larger flow rates than Groves.

A new concept was introduced by Johnson and Decicco (1983). Based on the fact that Stommel's concept can be utilized for both, self sustaining up- and downwelling flow, Johnson and Decicco proposed a counterflow device where downwelling flow was realized in a large number of pipes running through an outer shell with upwelling flow.

As Johnson and Decicco point out, this device essentially mimics a shell-and-tube counterflow heat exchanger. From some optimization studies, using a simplified model, they concluded that the concept should be further studied in the context of mariculture farms. More recently, further research on SUP systems has been performed in the context of a Japanese mariculture project proposal (Maruyama *et al.*, 2004; Zhang *et al.*, 2004; Tsubaki *et al.*, 2007; Sato *et al.*, 2007; Maruyama *et al.*, 2011). Three field experiments with a single flexible 280 m pipe were carried out. The results were extended with calculations from a Reynolds-Averaged Navier-Stokes (RANS) model. The flow rates obtained in the field experiments, despite being of limited magnitude, strongly exceeded the model predictions. The disagreement of the model results with the experiments was attributed to the fact that turbulence was measured in the experiments while the model predicted laminar flow (Zhang *et al.*, 2004). Zhang *et al.* (2006) explained the measured turbulence based on the movement of the pipe due to surface waves.

The current lack of reliable performance predictions for SUPs can clearly be seen from this brief literature review. While only minor flow rates have been experimentally shown to date, mathematical and numerical models have not been validated in a way that would support their general predictive capabilities. Reliable modeling is needed to evaluate the potential of SUPs for AU. It thus represents a necessary milestone in the research and development around AU-based CDR approaches.

In the present work two new numerical methods are presented which are applicable to a wide range of SUP systems. The first method solves a set of pipe flow equations, based on a one-dimensional spatial discretization of the pipe. This method will be termed the one-dimensional method in the following. The second method solves the RANS equations, based on a two- or three-dimensional finite volume discretization. This method will further be referred to as the RANS method. While the one-dimensional method is capable of studying large experimental matrices within a short time, the RANS method offers full flexibility with respect to the device geometry. The latter also provides a more detailed insight into relevant flow features, like the velocity and temperature profiles across the pipe diameter, and generally implements a lower level of empirical assumptions. In the absence of full scale validation data,¹ the twofold approach at least allows for code-to-code validation between the results of the two models, thereby providing a first step towards reliable performance predictions for SUP systems.

The remainder of this paper will be structured as follows. The two methods will be described in detail in Section 2. In Section 3, first a description of relevant device geometries and deployment regions will be given. The results from both models will then be compared and discussed for a number of single SUP and counterflow SUP cases. Finally, results from a study on shell-and-tube type SUPs will be presented, before finishing with conclusions and recommended future work in Section 4.

2. NUMERICAL METHOD

2.1 RANS Method

The RANS method used in this work is similar to the method described in Kemper *et al.* (2022), however, instead of solving the full compressible set of RANS equations, the oceanic Boussinesq approximation is made here. The oceanic Boussinesq approximation, as described by Young (2010), consists of three steps:

1. The exact density ρ in the momentum equation is replaced by a constant reference density ρ_0 everywhere but in the buoyancy term.
2. The incompressible continuity equation $\nabla \cdot \mathbf{u} = 0$ is used.
3. An equation of state (EOS) of the form $\rho = f(\overline{S}_A, \overline{\Theta}, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r})$ is used, where $\overline{\Theta}$ is the conservative temperature of McDougall (2003), $\overline{S}_A$ is absolute salinity, P_0 is the reference pressure at the water surface, $\mathbf{g}$ is the gravitational acceleration vector and $\mathbf{r}$ is the position vector with respect to a reference position at the water surface, where P_0 is taken.

Note that in the equation of state the pressure is approximated as a linear hydrostatic pressure, based on the constant reference density. By using a full EOS (IOC *et al.*, 2010), the oceanic Boussinesq set has a wider range of applicability, when compared to the standard Boussinesq set of RANS equations.

¹The results of Maruyama *et al.* (2004) cannot be used for model validation, as these results are highly influenced by an effect they attribute to wave action on the pipe. Since the actual salt fountain effect is very small in the experiment it cannot be separated from the wave effect.

The oceanic Boussinesq set of RANS equations can be written as:

$$\begin{aligned}
 \frac{\partial (\bar{\mathbf{u}})}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\bar{\mathbf{u}}) &= \nabla \cdot \bar{\boldsymbol{\tau}}_e^* - \nabla \bar{p}_{rgh}^* + (\mathbf{g} \cdot \mathbf{r}) \nabla \frac{\rho}{\rho_0} \\
 \nabla \cdot \bar{\mathbf{u}} &= 0 \\
 \frac{\partial (\bar{\Theta})}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\bar{\Theta}) &= \nabla \cdot (\lambda_e \nabla \bar{\Theta}) \\
 \frac{\partial (\bar{S}_A)}{\partial t} + \nabla \cdot (\bar{\mathbf{u}}\bar{S}_A) &= \nabla \cdot (D_e \nabla \bar{S}_A) \\
 \rho &= f(\bar{S}_A, \bar{\Theta}, p_0 + \rho_0 \mathbf{g} \cdot \mathbf{r})
 \end{aligned} \tag{1}$$

In Equation (1) $\bar{\mathbf{u}}$ is the velocity vector, ρ and ρ_0 are density and reference density, respectively. Further, t is time, $\mathbf{g}$ is the gravitational acceleration vector and $\mathbf{r}$ is the position vector. The effective diffusivities of temperature and salinity are denoted as λ_e and D_e , respectively and include laminar diffusion and the modeling of turbulence effects. $\bar{\boldsymbol{\tau}}_e^*$ is the deviatoric part of the effective kinematic Reynolds stress tensor which is modeled based on the linear eddy viscosity hypothesis (Morrison, 2013, p. 850)

$$\bar{\boldsymbol{\tau}}_e^* = 2\nu_e \bar{\mathbf{S}} - \frac{2}{3}\nu_e (\nabla \cdot \bar{\mathbf{u}}) \mathbf{I}, \tag{2}$$

where ν_e is the effective viscosity and $\bar{\mathbf{S}}$ is the mean strain rate tensor.² $\bar{p}_{rgh}^*$ in Equation (1) is the modified kinematic pressure, which is calculated from the static pressure as $\bar{p}_{rgh}^* = \frac{1}{\rho_0} (\bar{P} - \rho \mathbf{g} \cdot \mathbf{r}) + \frac{2}{3}k$, with k being the turbulent kinetic energy.

The Finite Volume Method (FVM) is used to represent the equation set (1) by a set of algebraic equations for a finite number of locations in space and time. The *OpenFOAM* framework is used for the implementation. The equation set is solved in a pressure based manner, using *OpenFOAMs SIMPLE* and *PIMPLE* algorithms for steady state and transient flow, respectively. The following schemes are used for the discretization of the equations: Linear interpolation is used to obtain cell face values from the cell-centred data. Gradients are discretized using the Gauss method with linear interpolation. For the convective terms, the second-order accurate *Gamma* scheme of Jasak *et al.* (1999) and Linear Upwind schemes are applied. For the temporal derivative, the first-order implicit *Euler* scheme is used. This is appropriate, since the results presented here generally have a stable final state, which is of more interest than the exact temporal development towards this state.

Menters $k\text{-}\omega$ SST turbulence model is used for all simulations within this work (Menter, 1994). This choice was made based on the widespread use of this model for similar applications and its ability to run as a low-Reynolds turbulence model i.e. without the use of empirical wall functions. The details of this two-equation turbulence model will not be described here, for brevity. Detailed descriptions of the $k\text{-}\omega$ SST turbulence model can be found in (Menter, 1994) and (Menter *et al.*, 2003).

2.2 One-Dimensional Method

In this section, a one-dimensional model for the SUP is derived. The calculation method is described in a generalized form, highlighting the slight differences between the counterflow and single SUPs methods.

The self-sustaining flow in a SUP is driven by the differences in weight between the water-columns

²See nomenclature for details.

inside and outside of the respective pipe i.e. by an imbalance in the hydrostatic pressure at the pipes bottom end. For a fully developed steady-state flow, a balance between the viscous pressure loss of the pipe flow and the driving hydrostatic pressure imbalance can be formulated

$$c_{f\,av} \frac{\rho_{av}}{2} \frac{w_{av}^2}{D_h} L = g \left| \left(\int_{z_{top}}^{z=z_{top}+L} \rho_{ocean} dz - \int_{z_{top}}^{z=z_{top}+L} \rho dz \right) \right|. \quad (3)$$

Here, w_{av} is the flow velocity, $c_{f\,av}$ is the Darcy pipe friction factor, D_h is the hydraulic pipe diameter, L is the pipe length, g is the gravitational acceleration, z is the depth (positive downwards), and ρ and ρ_{ocean} denote the density of the water inside the pipe and the far-field, respectively. Please note that all flow quantities represent a radial averaged value over the respective region, e.g. the pipe, and just vary along the streamwise (z) direction. The subscript ϕ_{av} denotes, that the respective quantities are derived at the streamwise averaged density in the pipe. The water density can be calculated from the EOS

$$\rho = f(S_A, \Theta, P) . \quad (4)$$

where Θ , S_A and P are conservative temperature, absolute salinity and pressure, respectively. The hydrostatic pressure can be used for P , which leaves S_A and Θ as independent parameters. For the ocean outside the pipe, these parameters are known functions of the depth z . Inside the pipe, S_A uniformly takes the value of the water entering the pipe at the inlet, while Θ has to be modelled.

A simple model for the temperature inside the SUP can be developed based on the balance between convective heat transfer along the pipe (i.e. in the z -direction) and conductive heat transfer through the pipe wall. The resulting ordinary differential equation for Θ reads

$$-A_c w c_p \rho \frac{\partial \Theta}{\partial z} + C_h U \Delta_r \Theta = 0 . \quad (5)$$

Here, A_c is the cross sectional area of the pipe ($\frac{\pi}{4} D^2$ for a circular pipe), C_h is the heat-transferring circumference (πD for a circular pipe) and c_p is the heat capacity of the seawater, while $\Delta_r \Theta$ is the radial temperature difference. U is the overall heat transfer coefficient, which incorporates the thermal resistance of the pipe wall as well as the influence of the convection inside and outside the pipes. $U_n = f(D_n)$ with D_n being an arbitrary diameter can be calculated as

$$U_n = \frac{1}{D_n \sum (D_m/h_m)} . \quad (6)$$

$$D_m/h_m = \begin{cases} \frac{1}{N_{D_i} \kappa_i}, & \text{inner pipe} \\ \frac{1}{2\kappa_{wall}} \ln\left(\frac{D_e}{D_i}\right), & \text{pipe wall} \\ \frac{D_{ho}}{D_e N_{D_{ho}} \kappa_o}, & \text{outer pipe} \\ \frac{1}{N_{D_e} \kappa_{ocean}}, & \text{ocean} . \end{cases} \quad (7)$$

In Equation (7), D_i and $D_e = D_i + 2s$ are the inside and outside diameter of the inner pipe, while D_{ho} represents the hydraulic outer pipe diameter in a counterflow setup. The Nusselt numbers corresponding to the inner, inner external and hydraulic outer pipe diameter are denoted as N_{D_i} , N_{D_e} and $N_{D_{ho}}$. While s and κ_{wall} are the thickness and thermal conductivity of the pipe wall, κ_i , κ_o and κ_{ocean} are the thermal conductivities of the seawater within the inner pipe, outer pipe and the ocean, respectively. Please note that the heat transfer to the ocean was neglected for the counterflow setup. This may actually be a realistic assumption, considering that the outer shell will generally have to provide structural stability to the counterflow SUP system, such that the thickness of the inner pipes

can be minimized for lower thermal resistance. Although no extensive studies were performed in order to quantify the influence of outer pipe conductivity on the total upwelling and downwelling rates, the effect is estimated to be small.

In the proposed model, the Nusselt number N_D and the pipe friction coefficient c_f are the main empirical coefficients. Their correct determination has significant influence on the flow rates. A great number of correlations for N_D and c_f have been proposed in literature. While c_f was calculated using Morrisons formulation for smooth pipes over the entire Reynolds number range (Morrison, 2013, p. 533) with the Reynolds number correction proposed by Shah and Sekulić (2003, p. 487) for the outer pipe, the calculation of N_D required a more cautious handling. The natural convection N_D was calculated following the recommendations of Thess and Kaiser (2018b, p. 5, 6) while the forced convection N_D was calculated following the recommendations of Gnielinski (2018a) for the inner and (Gnielinski, 2018b) for the outer pipe. Natural and forced N_D were blended cubically following Thess and Kaiser (2018a, p. 7) and corrected for radially varying fluid properties following Shah and Sekulić (2003, p. 531). N_D for the ocean was calculated using the formulae of Churchill and Chu (Incropera *et al.*, 2013, p. 605) along with the correction of Popiel *et al.* (2007, p. 611) for vertical slender cylinders (fitted to the numerical results of Cebeci (1974)).

To find a solution for the proposed model for a given pipe geometry and a given ocean profile (i. e. Θ and S_A), the pipe is discretized in the axial direction and an iterative process is employed which solves Equations (5) and (3) within a given tolerance. For the counterflow setup $\Delta_r \Theta = f(\Theta_i(z), \Theta_o(z))$, so Equation (5) has to be solved in a coupled manner for the inner and outer pipe. This can be done using a collocation algorithm for boundary value problems. For a single pipe setup $\Delta_r \Theta = f(\Theta_i(z), \Theta_{ocean}(z))$ and Equation (5) can be efficiently solved for Θ , using the Runge-Kutta (Burg *et al.*, 2013, p. 55f) method. Equation (3) can be rearranged to obtain a solution for w (which can again feed into Equation (5)). Here, the following iterative solution process is used:

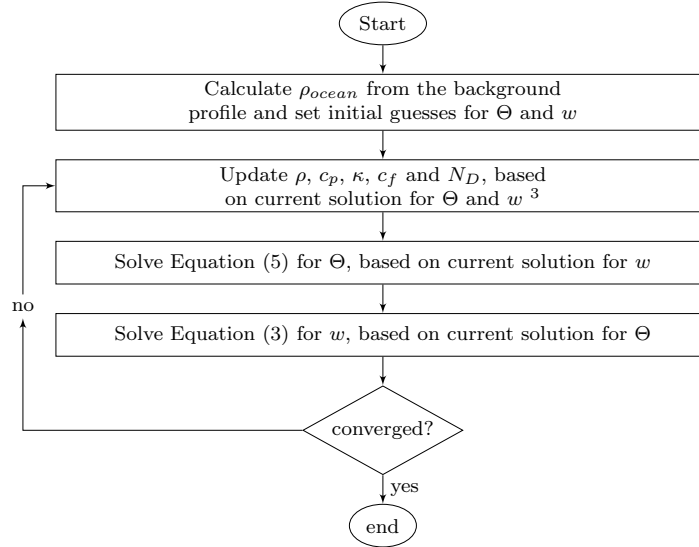


Figure 1: Flow diagram one-dimensional method

³In this work, the TEOS-10 equation of state for seawater IOC *et al.* (2010) is used for ρ and c_p , while κ was calculated using the method of Jamieson and Tudhope (1970).

A number of important details about this set of equations for SUP systems have to be pointed out: First, it has to be noted that the heat balance described in Equation (5) is a mere balance of vertical convection and horizontal conduction. A set of equations including vertical conduction has been described by Hinman (1966), who concluded that the effect on the flow rate was negligible. Further, potential and latent energy were not considered in Equation (5) as their effect on the flow is expected to be negligible.

Although the presented equations and methods can be used independently of the SUP setup, the calculation of N_D and c_f is strongly dependent on the geometry. Nevertheless, using $D_h = \frac{4A_c}{C}$ with C as wetted perimeter, the above methodology for determining N_D and c_f can also be used to calculate configurations with multiple inner pipes. This will be further discussed in Section 3.5.

3. RESULTS AND DISCUSSION

In this section, results from SUP studies carried out with both models are described and discussed. First, a benchmark geometry for a single and counterflow SUP is defined and the RANS calculation setup is described. Subsequently, after a brief discussion on relevant ocean conditions, studies on different deployment regions and different pipe diameters will be presented, each time comparing both single and counterflow SUPs and the results from both models described in Section 2. Finally, a study on shell-and-tube type SUPs will be presented, providing some insight into the scaling of these devices.

3.1 Pipe Geometry and Calculation Setup

Single and counterflow SUPs represent the two main types of SUPs studied in this work. For simplicity, a benchmark geometry for these SUP types is defined here which describes all main particulars relevant for the calculations. A corresponding shell-and-tube type SUP geometry will be derived in Section 3.5. The benchmark geometries are depicted in Figure 2.

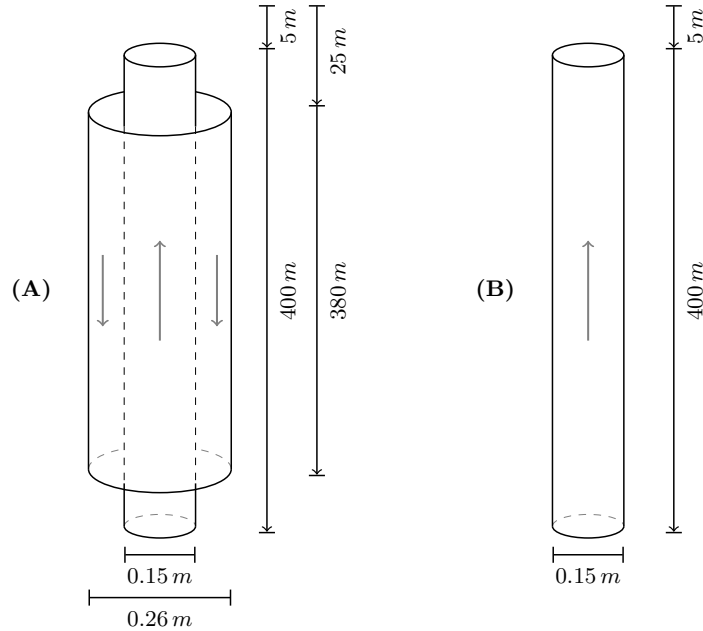


Figure 2: Stommel-pipe system concepts and main dimensions used in this study. (A) counterflow concept, (B) single pipe concept. All length dimensions are given with respect to the water surface.

As can be seen, both setups have a bottom depth of 400 m, a top depth of 5 m and a (inner) pipe diameter of 0.15 m. The outer pipe diameter of the counterflow SUP is chosen such that the inner-to-outer-pipe cross-sectional flow area ratio takes a value of 0.5. Thickness and thermal conductivity of the (inner) pipe wall were chosen such that a value of $2 \times 10^{-3} \text{ K m}^2/\text{W}$ for the thermal resistance $\frac{s}{\kappa_{\text{wall}}}$ is obtained. This is representative of a HDPE pipe with $s = 1 \text{ mm}$ or a steel pipe with $s = 90 \text{ mm}$. The outer pipe of the counterflow SUP is considered perfectly insulating as described in Section 2.2.

For the RANS model, several options are possible for the calculation setup. It generally seems advisable to exploit the axial symmetry of the system. The calculation thereby becomes two-dimensional, which greatly reduces the computational effort when compared to a full three-dimensional calculation. The surrounding ocean around the pipe can either be included in the model, as done by Zhang *et al.* (2004), or represented by boundary conditions. In the context of this work both options have been tested and it was found that the results generally agreed very well, as will be shown in Section 3.3. The results presented here thus generally use the idealized setup without a resolved background ocean. The following boundary conditions are specified. All inlets of the pipes are total pressure inlets (i.e. the pressure is specified as the hydrostatic pressure from the background ocean minus $0.5 |\mathbf{u}|^2$ while the velocity is calculated from the pressure equation). The transported scalar quantities (i.e. Θ , S_A and turbulence quantities) are specified based on the background ocean values. All outlets of the pipes are pressure outlets (i.e. the pressure is specified as the hydrostatic pressure from the background ocean and a Neumann boundary condition is applied for the velocity), where Neumann boundary conditions are applied for the transported scalar quantities. No-slip conditions are applied on all solid walls. For the counterflow SUP the outer pipe wall is adiabatic, while the inner pipe wall is implemented as a temperature baffle which accommodates for the appropriate heat transfer between the pipes. For the single SUP, the heat transfer with the background ocean is modeled, using a convective boundary condition at the pipe wall. This boundary condition sets Θ at the wall based on the background ocean value, taking into account the thermal resistance of the pipe wall and the assumed convection outside of the pipe. Here, the convection outside the pipe is calculated using the correlation of Churchill and Chu (1975).

Since both models described in Section 2 are solved numerically, it has to be ensured that the discretization is sufficiently fine. For the one-dimensional method the discretization is managed internally by the ordinary differential equation solver. For the RANS method discretization studies have been carried out to determine the appropriate mesh resolution. Based on these studies, a resolution of 25 cells across the pipe radius and 2500 cells across the pipe length was chosen, for which the discretization error in the upwelling velocity was estimated to be negligible.

3.2 Open ocean depth profiles

Salinity differences between the depths of a SUP's outlet and inlet can easily be identified as an important driver for the efficiency of SUP systems. Figure 3 shows the annual mean salinity difference between the sea surface and 400 m depth, based on WOA18 data (Boyer *et al.*, 2018) (mean over the years 1995 to 2018). Here, it can be seen that high salinity differences can almost exclusively be found in the subtropical ocean gyres. With relatively calm weather conditions, low seasonality, and low productivity, these regions are often seen as ideal regions for AU. If only areas with a salinity difference of 1.2 g/kg and above are considered, four confined regions are found, which correspond to the North Atlantic Gyre (NAG), the South Atlantic Gyre (SAG), as well as the North Pacific Gyre (NPG), and the South Pacific Gyre (SPG). Average annual depth profiles can now be derived as spatial average for each of these regions. Figure 4 shows these profiles along with seasonal (i.e. Spring, Summer, Autumn and Winter) mean profiles (over the years 1955 to 2018).

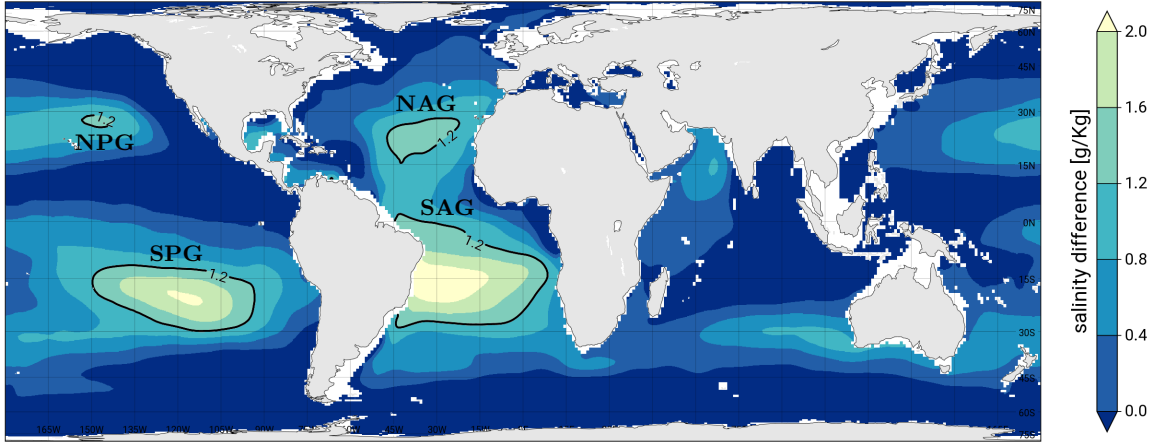


Figure 3: Annual mean S_A differences between surface and 400 m depth. Data taken from Boyer *et al.* (2018).

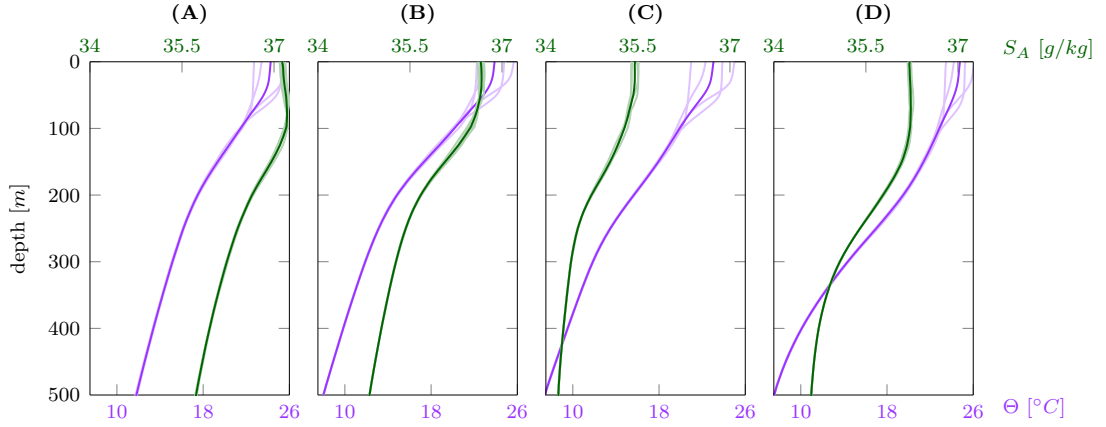


Figure 4: Annual mean depth profiles for conservative temperature (violet) and absolute salinity (green), for NAG (A), SAG (B), NPG (C), and SPG (D), with seasonal variation (light colors). Data taken from Boyer *et al.* (2018).

From Figure 4 it can be seen that, especially for the salinity profiles, the seasonal variability is very small. The temperature profiles show a slightly larger seasonal variability with greater surface temperatures in the local summer and autumn. The rest of the studies described in this work will be based on the mean profiles shown in Figure 4. It should be kept in mind that they do not represent the most ideal conditions for SUP-based AU, but rather the average conditions of all regions which might be of practical interest, based on the annual mean salinity differences from Figure 3.

3.3 Single pipe and counterflow pipe

In this section, results for a simple single SUP are compared to those of a counterflow SUP. The annual mean depth profiles from Section 3.2 are used along with the reference geometries and calculation setups from Section 3.1.

Figure 5 shows the results of this study. Here, the upwelling rates for both pipe setups under the different ocean conditions are depicted. Results from both models are shown. Additionally results from calculations of a single SUP including the surrounding ocean are given.

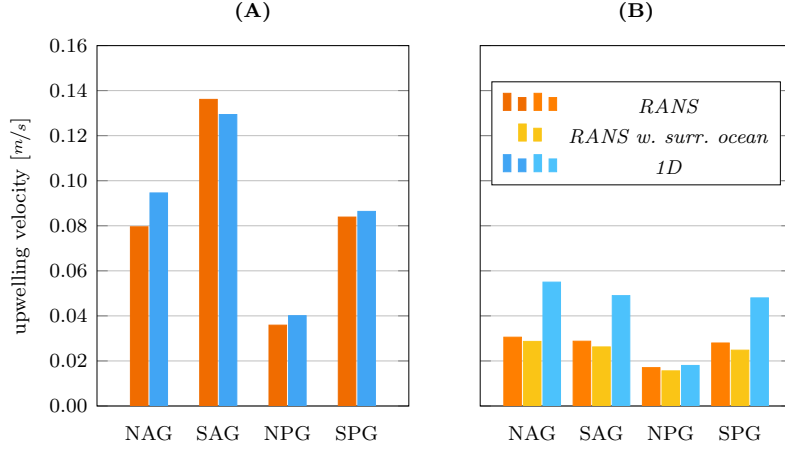


Figure 5: Upwelling velocities obtained by the counterflow- (A) and single pipe (B) setup, for the depth profiles described in Section 3.2, as predicted by the RANS (red, orange) and one-dimensional (blue, light blue) model.

From Figure 5 it can clearly be seen that the counterflow setup performs much better than the simple setup under all conditions. While it has to be taken into account that the relative performance of the two SUP concepts might change when both pipe geometries are thoroughly optimized, the magnitude of the differences observed in Figure 5 can be seen as an indication towards a clear superiority of the counterflow SUP design. Conceptually this is explained by the more efficient heat transfer of the counterflow setup. Figure 6 shows temperature profiles, from the RANS and one-dimensional calculations, for the SAG case. Here, it can be seen that, while for the counterflow SUP the temperature difference across the pipe wall ($\Delta_r \Theta$) is almost constant along the pipe, for the single SUP the temperature difference varies strongly in the axial direction. Efficient heat transfer is thus only possible over a smaller portion of the length of the single SUP.

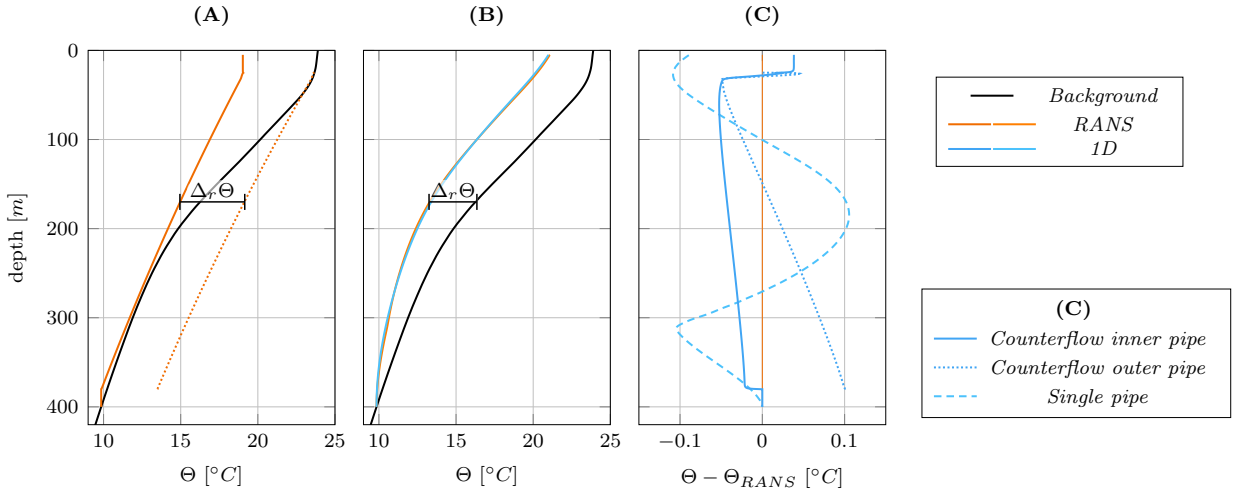


Figure 6: Temperature depth profiles in the Stommel-pipe system (colored) and the background ocean (black), from the RANS (orange) and one-dimensional (blue) calculations, for the SAG case. Results for a counterflow SUP (A) and a single SUP (B) are shown. A comparison of the temperature differences between the one-dimensional- and RANS results is shown in (C).

As can be seen in Figures 5 and 6, the differences between the results of both models are very small in the counterflow cases. Although the differences for the single pipe are non negligible for some cases, it will be shown later (Section 3.4) that the overall agreement is still reasonably good. In the absence of experimental data for validation, this is seen as an indication that both models can be used to predict SUP performance in different ocean regions with confidence. As clearly visible from Figure 6 (C), the difference in calculated temperature (between the one-dimensional and RANS results) shows steep changes for the counterflow case where the heat transferring region begins and ends. This is presumably caused by to the changing flow profile in the RANS calculations due to the unheated inlet and outlet region - an effect that is not accounted for in the one-dimensional calculations. It can be observed, that the heat transfer is slightly underestimated for this case, leading to a minor difference in absolute temperature. As shown in Figure 5, the difference in velocity for the single pipe case between the one-dimensional and the RANS solution is significant, thereby differences in predicted temperature are not surprising, although being mostly within 0.1°C .

3.4 Geometric Variation Study

The study presented in Section 3.3 has shown that the results from both models are in reasonable agreement. However, the computational effort needed to obtain these results varies by orders of magnitude between the two models, making the one-dimensional model far more suitable for large parametric studies. This capability will be demonstrated in this section by performing a simple study on the pipe diameter. Starting from the reference geometries for the single- and counterflow SUP from Section 3.1, the diameter of the (inner) pipe is systematically varied from 0.025 m to 0.5 m in 19 steps. For the counterflow SUP, the outer pipe diameter is determined from the constant cross sectional flow area ratio of inner and outer pipe, which has a value of 0.5. The SAG profile from Section 3.2 is used as a background ocean profile for this study. Figure 7 shows the variation of the upwelling flow velocity and flow rate over the changing diameter for both the single- and counterflow SUP. Additionally the density difference between the upwelled DOW leaving the pipe at the top and the surrounding water is shown. Here, a positive value indicates that the upwelled DOW has a lower density compared to the surrounding water when leaving the system, while a negative value indicates a higher density and thus a negative buoyancy of the upwelled DOW.

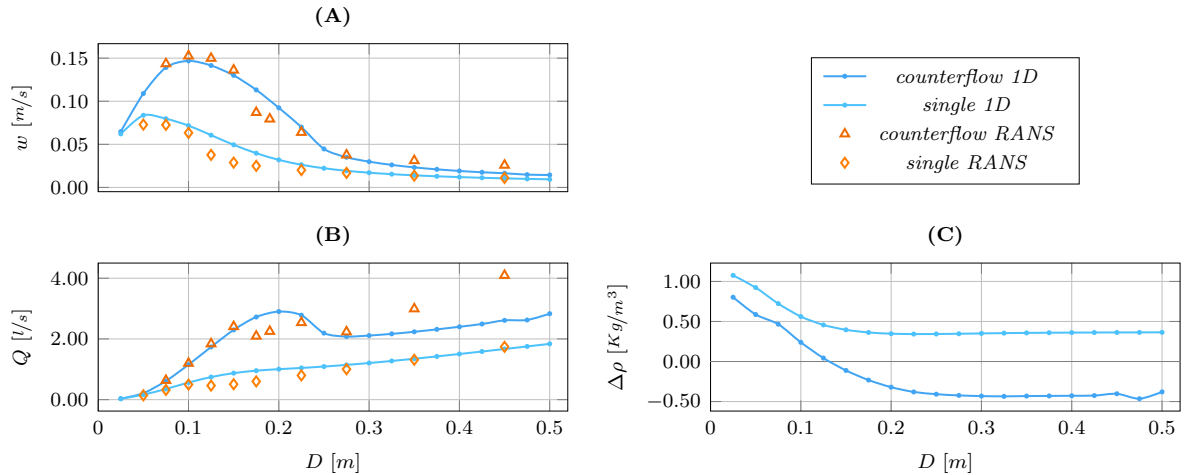


Figure 7: Pipe diameter study: Upwelling velocity (A), flow rate (B) and density difference at outlet (C) over (inner) pipe diameter of a counterflow SUP (orange) and a single SUP (blue).

It can be seen from Figure 7 (A) and (B) that the predicted flow rates of both methods show a good overall agreement, further underlining the capability of the one-dimensional method. Obvious deviations can be observed for diameters in the range of 0.10 m to 0.25 m, which might explain the differences for the single SUP observed in Figure 5 (B). Careful inspection of the RANS results indicated that those deviations could be explained by insufficient reproduction of mixed convection in the one-dimensional method. Deviations can also be observed for the counterflow setup at high diameters. Due to the small velocity differences in absolute terms, this effect was not further studied. It can be seen from Figure 7 (B) that the flow rate Q increases monotonically with the pipe diameter for the single pipe system, while the counterflow system shows an early peak at ≈ 0.2 m. The flow velocity w (Figure 7 (A)) increases with decreasing diameter until a certain diameter (0.1 m counterflow, 0.05 m single) below which w decreases rapidly with a further decrease in pipe diameter. This decrease of the velocity for small diameters can be attributed to laminarization of the flow, which drastically decreases the heat transfer efficiency. Generally, the flow rates for the counterflow SUP are higher than those of the single SUP, further supporting the superiority of the counterflow concept. Please note that the results of Figure 7 were obtained for a single ocean profile and will look differently for other boundary conditions.

While for general applications of AU it is usually sufficient that the upwelled DOW remains in the oceans mixed surface layer, further rise to the water surface marks an essential requirement for surface bound macroalgae farming. As can be seen from Figure 7 (C) the DOW is generally positively buoyant when leaving the system, in the single SUP case. For the counterflow SUP, the water is only positively buoyant if small diameter pipes are used. For many of the counterflow setups, the DOW will thus have the tendency to sink back down after leaving the pipe, even though it has been heated to some extent. This clearly depicts that the re-sinking problem of Kirke (2003) is not generally circumvented by using the salt fountain principle for AU. The buoyancy of the upwelled DOW leaving the system varies greatly, based on the pipe design and also the local ocean depth profiles (i. e. Θ and S_A). For instance, Maruyama *et al.* (2004) found the DOW upwelled by their single SUP to be negatively buoyant because the surface waters in their deployment region were of relatively low salinity. The higher re-sinking risk as consequence of a higher flow rate is a clear disadvantage of counterflow SUPs and stands against the advantages of these systems, which were previously described. In many cases, extending the upwelling pipe with a horizontal section at the top, will likely be sufficient to overcome this disadvantage at the cost of a moderately increased frictional flow resistance. Such an extension has not been studied to date, however, due to the high turbulence and the action of waves and currents in the surface ocean, it can be expected to have a high heat transfer efficiency. Finally, it should be noted that a high salinity difference between the DOW and the surface water is crucial for obtaining a positive buoyancy of the DOW. For the single SUP case presented in Figure 7 (C) positive buoyancy was obtained due to the salinity effect, despite the upwelled DOW being up to 3.3 °C colder than the surrounding surface water. If the DOW does not have a lower salinity than the surface water, as in the case of Maruyama *et al.* (2004), positive buoyancy of the upwelled DOW can obviously not be obtained with the salt fountain principle.

3.5 Shell-And-Tube Type SUP Systems

The possibility of arranging multiple inner pipes in a larger outer shell has already been pointed out by Johnson and Decicco (1983). Here, only counterflow SUPs with a single inner pipe have been studied so far. For these, the outer pipe takes the simple shape of a cylinder annulus. The complex geometries of shell-and-tube type SUPs can ideally be studied using the RANS model. For this purpose, two shell-and-tube setups with 7 and 19 inner pipes are studied, in addition to a counterflow setup with

a single inner pipe. The geometries follow the reference geometry defined in Section 3.1 with respect to inner pipe diameter, pipe lengths and material thickness. The shell diameter is determined from the constant cross sectional flow area ratio of 0.5. For the shell-and-tube setups, the inner pipes are arranged evenly on concentric circles whose diameters were optimized to provide an even spacing among the pipes and with respect to the outer shell.⁴ The symmetry of the setups was used, such that only a 60° section of each SUP system had to be resolved. The resulting computational meshes for the 1, 7 and 19 pipe case contained about 660, 3660 and 9400 cells in the horizontal plane and 1000 cells over the pipe length. Figure 8 shows cross sections of all three meshes, as well as velocity profiles at the medium depth, obtained from the RANS calculations.

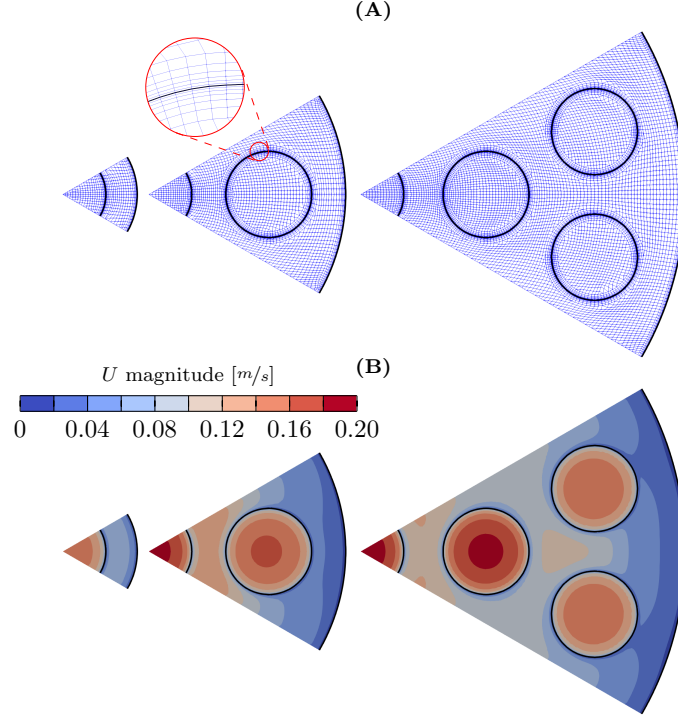


Figure 8: Shell-and-tube type SUP study: Cross sections of computational meshes with 1, 7 and 19 inner pipes (A) as well as predicted velocity magnitude over the cross sections (B).

From the velocity profiles shown in Figure 8 (B) it can be seen that upwelling velocity is generally highest in the innermost pipe and decreases in the outer rows. Equally, the downwelling velocity is highest in the center of the shell and decreases towards the sides. The decrease of the downwelling velocities leads to a less efficient heat transfer in the outer upwelling pipes and thus explains the lower upwelling velocities in these pipes. Generally, the installation of baffles, as typically seen in shell-and-tube heat exchangers, might help to even out the performance of the different inner pipes in a shell-and-tube type SUP, even though this would clearly impair the shell-side flow and might also be problematic from a technical point of view.

Figure 9 provides a more detailed picture of the scaling of the upwelling velocities with the number of inner pipes. Here, the average upwelling velocity over all pipes and the average downwelling velocity

⁴For the 7 inner pipe case, the pipes were arranged on a 0.419 m diameter circle. The shell diameter was 0.687 m. For the 19 inner pipe case, a 0.437 m and a 0.845 m diameter circle were used for pipe arrangement, while the shell diameter was 1.132 m.

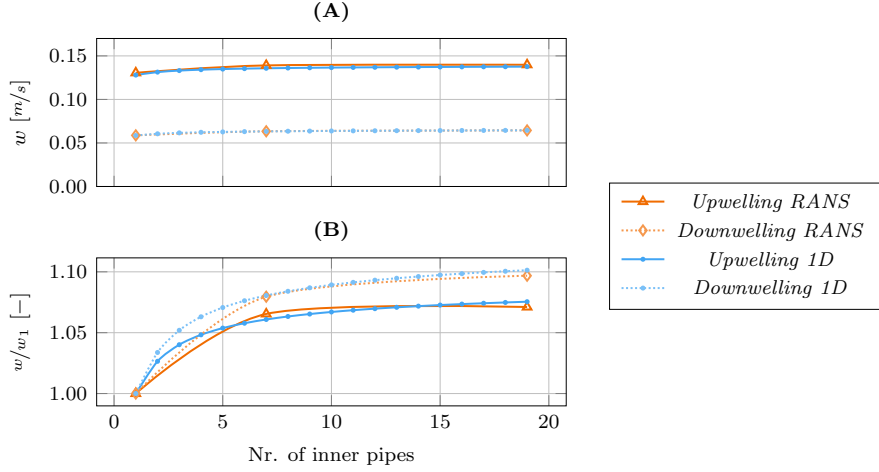


Figure 9: Shell-and-tube type SUP study: Variation of average up- (solid) and downwelling (dotted) velocities (RANS: orange, one-dimensional: blue) over the number of inner pipes in the system as absolute- (A) and normalized (B) values.

in the shell are plotted over the number of pipes in the shell-and-tube SUP. For comparison results from the one-dimensional method are shown. Here the scaling was done as described in Section 2.2. Figure 9 shows that the average up- and downwelling velocities are only weakly influenced by the overall SUP system size. A slight increase of both, up- and downwelling velocities is observed, which appears to tend towards a finite limit for large numbers of inner pipes. For the cases presented here, the maximum increase is about 10 % for downwelling and 7 % for upwelling. Again, the results of the one-dimensional method are in good agreement with the RANS results. The results suggest that the scaling of shell-and-tube type SUPs is very well reproduced by the one-dimensional method. While the inner pipe dimensions, as well as inner-to-outer-pipe cross-sectional flow area ratio, were kept constant throughout this study, the shell-side hydraulic diameter $D_{h,o}$ inevitably increases with an increasing number of inner pipes and varies by a factor of about 2 between the presented setups. For the one-dimensional calculations, the change in $D_{h,o}$ is in fact the only parameter change in this study. The shell-side hydraulic diameter thus seems to be an important quantity for understanding and optimizing the performance of shell-and-tube type SUPs. It should be noted that the scaling of the average up- and downwelling velocities observed in Figure 9 might depend significantly on other geometrical parameters of the SUP and cannot be seen as universal. For instance, it was noted during the RANS studies that the results depend to some extent on the arrangement of the inner pipes in the shell. The results of this study suggest that the hydraulic diameter scaling of the one-dimensional method resembles the idealized situation of evenly spaced inner pipes, which cannot always be achieved in reality. To what extent uneven pipe spacing influences the results remains to be studied.

4. CONCLUSIONS

Two numerical models for SUP systems have been proposed in this work. Both models have been described in detail. Results from both models have been compared for a range of variations in ocean depth profiles and SUP geometries. Finally, some studies of shell-and-tube type SUPs were presented, showing the upscaling potential for practical use cases.

In all calculations presented in this work, significant upwelling through the SUP principle was found. Counterflow SUPs generally perform superior to comparable single SUPs. However, the higher flow

rates of these systems result in a lower probability of the DOW leaving the system buoyant with respect to its surroundings at the surface. Additional measures may thus be necessary for counterflow SUPs to avoid re-sinking problem of conventional AU pumps. Shell-and-tube type systems were found to show a slight increase in upwelling velocity for increasing number of inner pipes. These systems thus offer high potential for scaling to desired volumetric flow rates for practical applications.

The results generally show very good agreement between both of the proposed models. In the absence of suitable experimental data for validation, the agreement of the presented models is seen as an indication towards a good reliability of both models in predicting the performance of different types of SUP systems with different geometries in various ocean regions.

In the strive to enhance the technology readiness level of AU-based CDR, reliable model predictions for the potential of various technical approaches are essential. Such general assessments require larger sets of technical parameters and ocean conditions to be studied. To quantify the CDR potential, consideration must be extended beyond the mere SUP system to include environmental influences as well as biogeochemical responses and feedback. The methods presented in this work provide a versatile and reliable basis for these efforts.

The following future work is recommended:

- Parametric studies on a wide range of technical parameters should be performed to provide a more general overview of the performance and potential of SUP systems for AU.
- A larger set of ocean conditions should be studied and potential regions for deployment and prototype testing should be identified.
- Practical use scenarios for SUP-based AU should be defined and studied, including corresponding environmental effects (e. g. currents and waves) as well as biogeochemical responses and feedback.
- Careful validation of both methods presented in this work against experimental data is needed to further prove their predictive capabilities.
- Since sufficient experimental data is not currently available, experiments of the salt fountain phenomenon have to be performed on both lab- and full-scale.

ACKNOWLEDGEMENTS

This study was funded by the German *Federal Ministry of Education and Research* (Bundesministerium für Bildung und Forschung, BMBF) in the framework of the the *Test-ArtUp* project, which is part of the *CDRmare* research mission lead by the *German Marine Research Alliance* (Deutsche Allianz Meeresforschung, DAM), under Grant Agreement No. 03F0897B. This study was further funded by the German *Federal Agency for Disruptive Innovations* (Bundesagentur für Sprunginnovationen, SPRIND GmbH) in the framework of the *C-CAUSE* project within the *Carbon-To-Value* challenge.

AUTHOR'S CONTRIBUTION

J. Ke. developed and implemented the numerical RANS method and performed the RANS calculations. J. Ke. and J. M. developed the one-dimensional method and analyzed the results under the scientific and technical supervision of U. R., J. Kr. and K. G.. J. Ke. and J. M. wrote the manuscript with input from all authors.

REFERENCES

- Boyer, T. P., Baranova, O. K., Coleman, C., Garcia, H. E., Grodsky, A., Locarnini, R. A., *et al.* (2018). *World Ocean Database 2018*. Tech. rep., National Centers for Environmental Information Ocean Climate Laboratory, Silver Spring, MD, USA
- Burg, K., Haf, H., Wille, F., and Meister, A. (2013). *Höhere Mathematik für Ingenieure: Band III: Gewöhnliche Differentialgleichungen, Distributionen, Integraltransformationen* (Wiesbaden: Springer Fachmedien Wiesbaden). doi:10.1007/978-3-8348-2334-2
- Cebeci, T. (1974). Laminar-Free-Convective-Heat Transfer from the Outer Surface of a Vertical Slender Circular Cylinder. In *Proceeding of International Heat Transfer Conference 5* (Tokyo, Japan: Begellhouse), 15–19. doi:10.1615/IHTC5.2830
- Churchill, S. W. and Chu, H. H. S. (1975). Correlating Equations for Laminar and Turbulent Free Convection from a Vertical Plate. *International Journal of Heat and Mass Transfer* 18, 1323–1329. doi:10.1016/0017-9310(75)90243-4
- Fan, W., Pan, Y., Liu, C. C., Wiltshire, J. C., Chen-Tung, A. C., and Chen, Y. (2015). Hydrodynamic Design of Deep Ocean Water Discharge for the Creation of a Nutrient-rich Plume in the South China Sea. *Ocean Engineering* 108, 356–368. doi:10.1016/j.oceaneng.2015.08.006
- GESAMP (2019). High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques. *GESAMP Reports and Studies* 98, 144
- Gnielinski, V. (2018a). Wärmeübertragung bei erzwungener Konvektion: Durchströmte Rohre. In *VDI-Wärmeatlas*, eds. P. Stephan, D. Mewes, S. Kabelac, M. Kind, K. Schaber, and T. Wetzel (Berlin, Heidelberg: Springer Berlin Heidelberg). 1–9. doi:10.1007/978-3-662-52991-1_42-1
- Gnielinski, V. (2018b). Wärmeübertragung bei erzwungener Konvektion: Konzentrischer Ringspalt und ebener Spalt. In *VDI-Wärmeatlas*, eds. P. Stephan, D. Mewes, S. Kabelac, M. Kind, K. Schaber, and T. Wetzel (Berlin, Heidelberg: Springer Berlin Heidelberg). 1–9. doi:10.1007/978-3-662-52991-1_43-1
- Groves, G. W. (1958). Flow Estimate for the Perpetual Salt Fountain. *Deep Sea Research (1953)* 5, 209–214. doi:10.1016/0146-6313(58)90013-3
- Hinman, K. G. (1966). *Flow Velocity Calculations for a "Perpetual Salt Fountain"*. Master's thesis, United States Naval Postgraduate School
- Incropera, F. P., DeWitt, D. P., Bergman, T. L., and Lavine, A. S. (eds.) (2013). *Principles of Heat and Mass Transfer* (Hoboken, NJ: Wiley), 7. ed., international student version edn.
- IOC, SCOR, and IAPSO (2010). The International Thermodynamic Equation of Seawater - 2010: Calculation and Use of Thermodynamic Properties. *Intergovernmental Oceanographic Commission, Manuals and Guides* 56, 196
- IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, vol. In Press (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press). doi:10.1017/9781009157896

- Jamieson, D. and Tudhope, J. (1970). Physical Properties of Sea Water Solutions: Thermal Conductivity. *Desalination* 8, 393–401. doi:10.1016/S0011-9164(00)80240-4
- Jasak, H., Weller, H., and Gosman, A. (1999). High Resolution NVD Differencing Scheme for Arbitrarily Unstructured Meshes. *International Journal for Numerical Methods in Fluids* 31, 431–449. doi:10.1002/(sici)1097-0363(19990930)31:2<431::aid-fld884>3.0.co;2-t
- Johnson, D. H. and Decicco, J. (1983). *Artificial Upwelling Driven by Salinity Differences in the Ocean*. Tech. rep., Solar Energy Research Inst., Golden, CO (USA)
- Kemper, J., Riebesell, U., and Graf, K. (2022). Numerical Flow Modeling of Artificial Ocean Upwelling. *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.804875
- Kirke, B. (2003). Enhancing Fish Stocks with Wave-powered Artificial Upwelling. *Ocean & Coastal Management* 46, 901–915. doi:10.1016/s0964-5691(03)00067-x
- Liang, N.-K. and Peng, H.-K. (2005). A Study of Air-lift Artificial Upwelling. *Ocean Engineering* 32, 731–745. doi:10.1016/j.oceaneng.2004.10.011
- Lovelock, J. E. and Rapley, C. G. (2007). Ocean Pipes Could Help the Earth to Cure Itself. *Nature* 449, 403–403. doi:10.1038/449403a
- Maruyama, S., Tsubaki, K., Taira, K., and Sakai, S. (2004). Artificial Upwelling of Deep Seawater Using the Perpetual Salt Fountain for Cultivation of Ocean Desert. *Journal of Oceanography* 60, 563–568. doi:10.1023/b:joce.0000038349.56399.09
- Maruyama, S., Yabuki, T., Sato, T., Tsubaki, K., Komiya, A., Watanabe, M., *et al.* (2011). Evidences of Increasing Primary Production in the Ocean by Stommel’s Perpetual Salt Fountain. *Deep Sea Research Part I: Oceanographic Research Papers* 58, 567–574. doi:10.1016/j.dsr.2011.02.012
- McDougall, T. J. (2003). Potential Enthalpy: A Conservative Oceanic Variable for Evaluating Heat Content and Heat Fluxes. *Journal of Physical Oceanography* 33, 945–963. doi:10.1175/1520-0485(2003)033<0945:peacov>2.0.co;2
- Menter, F. R. (1994). Two-equation Eddy-viscosity Turbulence Models for Engineering Applications. *AIAA Journal* 32, 1598–1605. doi:10.2514/3.12149
- Menter, F. R., Kuntz, M., and Langtry, R. (2003). Ten Years of Industrial Experience with the SST Turbulence Model. *Turbulence, heat and mass transfer* 4, 625–632
- Morrison, F. A. (2013). *An Introduction to Fluid Mechanics* (Cambridge University Press), 1 edn. doi:10.1017/CBO9781139047463
- Popiel, C., Wojtkowiak, J., and Bober, K. (2007). Laminar Free Convective Heat Transfer from Isothermal Vertical Slender Cylinder. *Experimental Thermal and Fluid Science* 32, 607–613. doi:10.1016/j.expthermflusci.2007.07.003
- Sato, T., Maruyama, S., Komiya, A., and Tsubaki, K. (2007). Numerical Simulation of Upwelling Flow in Pipe Generated by Perpetual Salt Fountain. In *Proceedings of the 16th Australasian Fluid Mechanics Conference, Crown Plaza, Gold Coast, Australia*. 394–397
- Shah, R. K. and Sekulić, D. P. (2003). *Fundamentals of Heat Exchanger Design* (Hoboken, NJ: John Wiley & Sons)

- Stommel, H., Arons, A. B., and Blanchard, D. (1956). An Oceanographical Curiosity: The Perpetual Salt Fountain. *Deep Sea Research (1953)* 3, 152–153. doi:10.1016/0146-6313(56)90095-8
- Thess, A. and Kaiser, R. (2018a). Wärmeübertragung bei freier Konvektion: Außenströmungen. In *Handbuch Vakuumtechnik*, ed. K. Jousten (Wiesbaden: Springer Fachmedien Wiesbaden). 1–10. doi:10.1007/978-3-662-52991-1.38-1. Series Title: Springer Reference Technik
- Thess, A. and Kaiser, R. (2018b). Wärmeübertragung bei freier Konvektion: Innenströmungen. In *Handbuch Vakuumtechnik*, ed. K. Jousten (Wiesbaden: Springer Fachmedien Wiesbaden). 1–11. doi:10.1007/978-3-662-52991-1.39-1. Series Title: Springer Reference Technik
- Tsubaki, K., Maruyama, S., Komiya, A., and Mitsugashira, H. (2007). Continuous Measurement of an Artificial Upwelling of Deep Sea Water Induced by the Perpetual Salt Fountain. *Deep Sea Research Part I: Oceanographic Research Papers* 54, 75–84. doi:10.1016/j.dsr.2006.10.002
- Wu, J., Keller, D. P., and Oeschles, A. (2023). Carbon Dioxide Removal Via Macroalgae Open-ocean Mariculture and Sinking: An Earth System Modeling Study. *Earth System Dynamics* 14, 185–221. doi:10.5194/esd-14-185-2023
- Young, W. R. (2010). Dynamic Enthalpy, Conservative Temperature, and the Seawater Boussinesq Approximation. *Journal of Physical Oceanography* 40, 394–400. doi:10.1175/2009jpo4294.1
- Zhang, X., Maruyama, S., Sakai, S., Tsubaki, K., and Behnia, M. (2004). Flow Prediction in Upwelling Deep Seawater—the Perpetual Salt Fountain. *Deep Sea Research Part I: Oceanographic Research Papers* 51, 1145–1157. doi:10.1016/j.dsr.2004.03.010
- Zhang, X., Maruyama, S., Tsubaki, K., Sakai, S., and Behnia, M. (2006). Mechanism for Enhanced Diffusivity in the Deep-Sea Perpetual Salt Fountain. *Journal of Oceanography* 62, 133–142. doi:10.1007/s10872-006-0039-5

Contribution [PPA]

ALE interface tracking for wave propagation and effects on submerged buoyant plumes: A modified OpenFOAM[®] approach including adaptive mesh refinement

Citation:

Kemper, J., Slawig, T., 2025a. ALE interface tracking for wave propagation and effects on submerged buoyant plumes: A modified OpenFOAM[®] approach including adaptive mesh refinement. [Preprint] Manuscript in preparation.

Author contributions:

Conceptualization	J. Kemper
Methodology	J. Kemper
Software	J. Kemper
Validation	T. Slawig
Investigation	J. Kemper
Resources	T. Slawig
Writing - Original Draft	J. Kemper
Writing - Review & Editing	T. Slawig
Visualization	J. Kemper
Supervision	T. Slawig

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.



ALE interface tracking for wave propagation and effects on submerged buoyant plumes: A modified OpenFOAM® approach including adaptive mesh refinement

Jost Kemper^{a,*}, Thomas Slawig^{a,b}

^aDepartment of Computer Science, Kiel University, Christian-Albrechts-Platz 4, 24118, Kiel, Germany

^bKiel Marine Science (KMS) – Centre for Interdisciplinary Marine Science, Christian-Albrechts-Platz 4, 24118, Kiel, Germany

Abstract

In marine and coastal engineering, Computational Fluid Dynamics (CFD) methods are widely used to study free-surface flows, including surface-wave propagation and wave structure interaction. Typically, interface capturing methods, such as the Volume Of Fluid (VOF) method, are applied to model the free water surface in these studies. In the present work, we present a modified Arbitrary Lagrangian-Eulerian (ALE) Interface Tracking (IT) method for free-surface CFD simulations in OpenFOAM®. We apply the adapted method to studies of free-surface waves. Following a rigorous verification and validation against theory and experiments, we present an advanced application to wave effects on a turbulent buoyant plume. For this study, the method is combined with an adaptive grid refinement approach. We find that the ALE-IT approach has low spatial and temporal discretization demands and thus offers significantly decreased computational costs compared to a standard VOF approach, for cases where its limitations with respect to the free-surface shape can be accepted.

Keywords: Interface tracking, ALE, Computational Fluid Dynamics (CFD), Free surface, numerical wave tank, Artificial Upwelling

1. Introduction

Accurate numerical modeling of free-surface water waves is of great importance for various fields of marine and coastal engineering. High-fidelity finite volume models usually rely on the Volume Of Fluid (VOF) method (Hirt and Nichols, 1981) to resolve the free water surface. By resolving the dynamics of both the water and air phases, VOF-based methods are able to capture arbitrary interface shapes. In the context of wave modeling, these capabilities play a role in modeling phenomena like wave breaking or certain types of wave-structure interaction (e. g., inundation, overtopping,

*Corresponding author.

Email address: jost.kemper@email.uni-kiel.de (Jost Kemper)

Nomenclature

General	ALE-IT
D diffusivity of salinity $[\text{m}^2/\text{s}]$	d free surface displacement direction $[-]$
$\mathbf{D}$ Cauchy stress tensor $[\text{N}/\text{m}^2]$	$\mathbf{n}$ unit normal vector $[-]$
$\mathbf{g}$ gravity vector $[\text{m}/\text{s}^2]$	$\mathbf{S}_f$ face area vector $[\text{m}^2]$
H wave height $[\text{m}]$	$\dot{V}$ instantaneous face flux $[\text{m}^3/\text{s}]$
h water depth $[\text{m}]$	$\mathbf{v}$ velocity of free surface $[\text{m}/\text{s}]$
$\mathbf{I}$ identity matrix $[-]$	Δt time step $[\text{s}]$
k turbulent kinetic energy $[\text{m}^2/\text{s}^2]$	δV swept volume $[\text{m}^3]$
P pressure $[\text{N}/\text{m}^2]$	δh displacement $[\text{m}]$
p_{gh} modified kinematic pressure $[\text{m}^2/\text{s}^2]$	κ surface curvature $[1/\text{m}]$
$\mathbf{r}$ position vector w. r. t. surface level $[\text{m}]$	σ surface tension $[\text{N}/\text{m}]$
S_A absolute salinity $[\text{g}/\text{kg}]$	∇_s tangential differentiation (nabla) operator = $\nabla - \mathbf{n} \frac{\partial}{\partial n}$
T wave period $[\text{s}]$	
t time $[\text{s}]$	
$\mathbf{u}$ velocity vector $[\text{m}/\text{s}]$	
α thermal diffusivity $[\text{m}^2/\text{s}]$	<i>Accents</i>
η free surface elevation $[\text{m}]$	ϕ^0 quantity from previous time step
Θ conservative temperature $[\text{K}]$	$\llbracket \phi \rrbracket$ jump of ϕ across interface = $\phi_a - \phi_w$
λ wavelength $[\text{m}]$	ϕ_a quantity on air side
μ dynamic viscosity $[\text{kg}/\text{m s}]$	ϕ_{fs} quantity evaluated at free surface
ν kinematic viscosity $[\text{m}^2/\text{s}]$	ϕ_m quantity w. r. t. mesh / free surface motion
ρ density $[\text{kg}/\text{m}^3]$	ϕ_{rel} quantity relative to mesh motion = $\phi - \phi_m$
σ_t turbulent Prandtl number $[-]$	ϕ_w quantity on water side
$\boldsymbol{\tau}$ kinematic viscous stress tensor $[\text{m}^2/\text{s}^2]$	
	<i>Abbreviations</i>
<i>Accents</i>	ALE Arbitrary Lagrangian-Eulerian
ϕ_0 constant reference quantity	CFD Computational Fluid Dynamics
ϕ_t quantity modeling turbulence effects	CPL Cells Per Wavelength
$\bar{\phi}$ Reynolds-averaged quantity	GABC Generating Absorbing Boundary Condition
ϕ' fluctuation from Reynolds-avg. $\phi = \bar{\phi} + \phi'$	IT Interface Tracking
ϕ^T transpose of tensor ϕ	RANS Reynolds-Averaged Navier-Stokes
	VOF Volume Of Fluid

and spray formation). In many other cases, e. g., for effects of non-breaking waves on mixing and dynamics around submerged structures, the free-surface elevation can be described as a single-valued function in the horizontal plane and the dynamics of the air phase are of no interest. In such cases, VOF's capabilities are not fully required, and it seems plausible that replacing it with a simpler method could benefit the computational efficiency.

Interface capturing methods like VOF inherently require a sufficiently fine spatial discretization to capture the interface deformation. Especially when small free-surface deformations have to be resolved, this can lead to high spatial discretization demands. When combined with transient free-surface motion (as in the case of wave propagation), the fine spatial discretization leads to an equally increased temporal discretization demand through CFL number limitations. For many engineering applications, the discretization demand of VOF is generally acceptable. However, when processes that evolve on timescales significantly longer than that of the free-surface motion are of

primary interest, VOF's CFL number limitations can result in a need to use proportionally small time steps. Examples for such processes include wave-induced sediment transport, scour, and wave effects on mixing and tracer transport (Baykal et al., 2017; Dutta et al., 2023; Alvir et al., 2022). An additional limitation of VOF methods for wave propagation is their tendency to produce spurious velocities and turbulence at the interface (Wroniszewski et al., 2014; Devolder et al., 2017). Especially when long simulated times and turbulence near the free surface are of interest, spurious velocities and spurious turbulence can significantly affect the solution. While in recent years, many advances have been made to improve the stability and efficiency of VOF methods (Fedkiw et al., 1999; Roenby et al., 2016), little work has been done on VOF alternatives in the marine and coastal engineering field (Schmitt et al., 2020).

Interface Tracking (IT) methods can serve as an alternative to interface capturing approaches like VOF. These methods employ an Arbitrary Lagrangian-Eulerian (ALE) approach where the computational mesh follows the deformation of the free surface. ALE-IT methods can be implemented as multi-phase methods (Schwarzmeier et al., 2025) or as single-phase methods where the free surface represents an outer boundary of the computational domain. As the computational mesh does not need to resolve gradients across the sharp interface, the discretization requirements are reduced for ALE-IT methods compared to VOF approaches. An additional advantage of the fact that the free surface can be represented by a boundary is that free-surface fluxes of heat and wind shear can be applied in a controlled manner, and unrealistic transport of quantities across the free surface (as sometimes observed in VOF simulations) can be avoided. However, additional computational demand and complexity are introduced through the mesh motion and the interface tracking process itself. Also, the application of ALE-IT methods is typically limited by the deformation of the free surface that can be performed by the mesh without extreme distortion of the cells. For applications in the marine and coastal engineering field, this usually means that ALE-IT methods cannot be used for free-surface interactions with complex geometries, wave breaking, inundation, overtopping, or spray formation.

IT methods have been used to model free-surface flows for a long time. A comprehensive review of early works was provided by Floryan and Rasmussen (1989). While applications in the field of wave propagation and marine hydrodynamics have been previously reported (Huerta and Liu, 1988; Muzaferija and Perić, 1999; Ferrand and Harris, 2021), recent works in this field mainly highlight the obvious limitations of the approach and focus on interface capturing methods like VOF (Huang et al., 2022; Vukcevic, 2016). For the open source framework OpenFOAM®, an ALE-IT methodology was first developed by Tuković and Jasak (2012). Despite this methodology being available within OpenFOAM® since version v1912, the authors are only aware of a single publication dealing with its application to wave propagation (Bai et al., 2020). Bai et al. successfully apply the method for a basic wave propagation problem in a two-dimensional, numerical wave tank, finding it to be more numerically efficient than a VOF simulation.

In the present work, we introduce a number of modifications to adapt the ALE-IT method of Tuković and Jasak (2012), which was initially introduced for surface-tension dominated flows (e. g., bubbles and droplets), to wave propagation problems. We describe the modified method and perform a rigorous verification and validation against

theory for simple two-dimensional wave propagation problems. The performance of the ALE-IT method is compared to an equivalent VOF setup. We further validate the method against experimental results for wave propagation over a bar, before presenting an advanced application to mixing of a buoyant vertical plume under wave effects.

2. Numerical method

The ALE-IT method of Tuković and Jasak (2012) can be applied to different solvers in OpenFOAM®. In the present work, we use the *oceanPimpleFoam* solver, which is part of the *ocean4Foam* toolbox (Kemper, 2024) for oceanic flow in OpenFOAM®. The solver and the ALE-IT methodology are described in this chapter. The modified ALE-IT methodology used in this work is available as part of *ocean4Foam* but can be used with various OpenFOAM® solvers.

2.1. RANS solver

The Reynolds-averaged Navier-Stokes (RANS) equation solver used in this work was developed for buoyant oceanic flows, including temperature, salinity, and passive scalar transport. Buoyancy is implemented using the oceanic Boussinesq approach (Young, 2010). A constant reference density ρ_0 is used in all terms of the Navier-Stokes equations with the exception of the buoyancy term in the momentum equation, and an incompressible continuity equation is solved. The density for the buoyancy term is calculated from a fully non-linear equation of state. Based on this, the following set of RANS equations is implemented in the *ocean4Foam* method

$$\frac{\partial \bar{\mathbf{u}}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\mathbf{u}}) = \nabla \cdot (\bar{\boldsymbol{\tau}} - \overline{\mathbf{u}' \mathbf{u}'}) - \nabla \bar{p}_{gh} + \mathbf{g} \left(\frac{\rho}{\rho_0} - 1 \right) \quad (1a)$$

$$\nabla \cdot \bar{\mathbf{u}} = 0 \quad (1b)$$

$$\frac{\partial \bar{\Theta}}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{\Theta}) = \nabla \cdot (\alpha \nabla \bar{\Theta} - \overline{\Theta' \mathbf{u}'}) \quad (1c)$$

$$\frac{\partial \bar{S}_A}{\partial t} + \nabla \cdot (\bar{\mathbf{u}} \bar{S}_A) = \nabla \cdot (D \nabla \bar{S}_A - \overline{S'_A \mathbf{u}'}) \quad (1d)$$

$$\rho = f(\bar{S}_A, \bar{\Theta}, P_0 + \rho_0 \mathbf{g} \cdot \mathbf{r}) , \quad (1e)$$

where Reynolds averaged quantities are denoted by the overbar and fluctuations are indicated by the prime. In Equation (1), t is time, $\bar{\mathbf{u}}$ is the mean velocity vector, $\bar{\Theta}$ is the conservative temperature (McDougall, 2003) and $\bar{S}_A$ is absolute salinity, while α and D denote the diffusivities of temperature and salinity, respectively. Further, P_0 is the reference pressure at the water surface, $\mathbf{g}$ is the gravitational acceleration vector, and $\mathbf{r}$ is the position vector with respect to a reference position at the water surface, while ρ and ρ_0 are the water density and a constant reference value. The tensor $\bar{\boldsymbol{\tau}}$ is the incompressible kinematic viscous stress tensor

$$\bar{\boldsymbol{\tau}} = \nu (\nabla \bar{\mathbf{u}} + (\nabla \bar{\mathbf{u}})^T) , \quad (2)$$

where ν is the kinematic viscosity. The kinematic pressure $\bar{p}_{gh}$ in Equation (1a) is calculated from the static pressure as $\bar{p}_{gh} = \frac{1}{\rho_0} \bar{P} - \mathbf{g} \cdot \mathbf{r}$. The terms $-\overline{\mathbf{u}' \mathbf{u}'}$, $-\overline{\Theta' \mathbf{u}'}$, and

105 $-\overline{S'_A \mathbf{u}'}$ represent the turbulent fluxes of momentum, temperature, and salinity, respec-
 106 tively. The turbulent momentum flux is generally modeled using the eddy viscosity
 107 assumption

$$108 \quad -\overline{\mathbf{u}' \mathbf{u}'} = \overline{\tau}_t - \frac{2}{3} \mathbf{I} k, \quad (3)$$

109 where $\mathbf{I}$ is the identity matrix and $\overline{\tau}_t$ is modeled as in Equation (2) but using the tur-
 110 bulent viscosity ν_t , which is calculated using a RANS turbulence model along with
 111 the turbulent kinetic energy k . The turbulent scalar flux is modeled using the simple
 112 gradient diffusion Hypothesis (here, only the treatment of the Θ equation is shown)

$$113 \quad -\overline{\Theta \mathbf{u}} = \frac{\nu_t}{\sigma_t} \nabla \overline{\Theta}, \quad (4)$$

114 with σ_t being the turbulent Prandtl number¹. For most of the cases presented in Sec-
 115 tion 3, laminar conditions are assumed (i. e., $\nu_t, k = 0$). In Section 3.3, the $k-\omega$ SST
 116 model of Menter (1994) is used.

117 The variable seawater properties are modeled following the *TEOS-10* standard
 118 (IOC et al., 2010) for ρ and using the polynomials of Sharqawy et al. (2010) and
 119 Jamieson and Tudhope (1970).

120 The transport equations are discretized using the finite volume method. Open-
 121 FOAM®'s *PIMPLE* algorithm (a transient version of the well-known *SIMPLE* algo-
 122 rithm) is employed to solve the coupled equation set with suitable boundary conditions
 123 in a pressure-based manner. The following numerical schemes are used: The tran-
 124 sient terms are discretized using an implicit three-level second-order scheme (Ferziger
 125 et al., 2020), known as the *backward* scheme. Gradients are discretized using the Gauss
 126 method with linear interpolation. For the convective term of the momentum equation,
 127 a mix of linear upwind and limited linear schemes is employed based on the local CFL
 128 number, while for the other transport equations, the *Gamma* scheme (Jasak et al., 1999)
 129 is used.

130 2.2. ALE-IT methodology

131 The aim of the description presented in this section is to provide the reader with a
 132 general understanding of the ALE-IT methodology. A full description of the method,
 133 including the discretization of the equations and further implementation details, has
 134 been presented by Tuković and Jasak (2012). Here, we will thus only provide an
 135 overview of the steps necessary to solve the RANS equations along with the free-
 136 surface boundary conditions.

137 The interface tracking procedure is a numerical process to ensure that the kinematic
 138 and dynamic free-surface boundary conditions are satisfied at each time step. The
 139 kinematic free-surface boundary condition states that there is no flow through the free
 140 surface. Thus, the normal component of the velocity field $\mathbf{u}$ at the free surface must be
 141 equal to the normal velocity of the interface $\mathbf{v}_{fs}$ itself

$$142 \quad ((\mathbf{u} - \mathbf{v}_{fs}) \cdot \mathbf{n})_{fs} = 0. \quad (5)$$

¹ A constant value of 0.85 is used for the turbulent Prandtl number σ_t throughout this work.

For a finite volume discretization, a zero-relative-flux condition results for a cell face located at the boundary of the computational domain that represents the free surface. The kinematic free-surface boundary condition thus demands that any instantaneous absolute flux through the cell face $\dot{V} = \mathbf{u} \cdot \mathbf{S}_f$ resulting from the solution of the RANS equations (Equation (1)) must be balanced by an equal and opposite flux resulting from the motion of the cell face through space $\dot{V}_m = \mathbf{v}_{fs} \cdot \mathbf{S}_f$. Here, $\mathbf{S}_f$ is the face area vector. It follows that

$$\dot{V} = \dot{V}_m . \quad (6)$$

The interface tracking procedure enforces this condition by adjusting the position of the free-surface mesh points. A valid new mesh position can be found by time integration of the flux $\dot{V}$ between the previous and current discrete time levels to obtain the total volume change through mesh motion (also known as swept volume) δV_m , from which the position of the cell face on the new time level can be calculated. The formulation for δV_m depends on the applied time differencing scheme: The implicit Euler scheme yields

$$\delta V_m = \dot{V} \Delta t . \quad (7a)$$

For the *backward* scheme (Ferziger et al., 2020), we obtain

$$\delta V_m = \frac{2}{3} \dot{V} \Delta t + \frac{1}{3} \delta V_m^0 , \quad (7b)$$

where δV_m^0 is the total (integrated) volume change through motion of the cell face during the previous time step. From Equation (7), the necessary movement of the cell face with respect to its position on the previous time level can be calculated as

$$\delta h_m = \frac{\delta V_m}{\mathbf{S}_f \cdot \mathbf{d}} , \quad (8)$$

where $\mathbf{d}$ is the motion direction, which can be a prescribed direction (throughout this work, the vertical direction is used) or the current normal direction of the cell face.

Equation (8) prescribes the required motion for each cell face on the boundary representing the free surface to satisfy Equation (6). As the position of the cell face is defined through its corner points, Equation (8) does not provide the necessary information. Following Muzaferija and Perić (1997), the position of each mesh point is thus calculated from the displacement of the surrounding cell faces using a least squares fit.

The dynamic free-surface boundary condition states that the forces acting on the fluid at the free surface are in equilibrium

$$\llbracket \mathbf{n} \cdot \mathbf{D} \rrbracket = \nabla_s \sigma - \sigma \kappa \mathbf{n} . \quad (9)$$

Here, $\llbracket \phi \rrbracket = \phi_a - \phi_w$ defines a jump of quantity ϕ between the water ϕ_w and air ϕ_a side of the interface. The tensor $\mathbf{D}$ is the Cauchy stress tensor $\mathbf{D} = \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - P \mathbf{I}$, while $\nabla_s = (\mathbf{I} - \mathbf{nn}) \cdot \nabla = \nabla - \mathbf{n} \frac{\partial}{\partial n}$ is the tangential nabla operator, σ is the surface tension, and κ is the free-surface curvature. The tangential gradients and divergences are discretized using the finite area method described by Tuković and Jasak (2012).

From a normal force balance of Equation (9), a jump condition for pressure can be obtained as

$$\llbracket P \rrbracket = -2\llbracket \mu \rrbracket (\nabla_s \cdot \mathbf{u}) + \sigma \kappa, \quad (10)$$

where μ is the dynamic viscosity. By assuming a static (kinematic) ambient pressure p_a on the air side and neglecting the small viscous contribution from the air side, the following boundary condition for the kinematic pressure on the free-surface boundary is derived

$$p_{gh} = p_a - \mathbf{g} \cdot \mathbf{r} + 2\nu_w (\nabla_s \cdot \mathbf{u}) - \frac{\sigma}{\rho_0} \kappa. \quad (11)$$

A tangential force balance of Equation (9) yields a jump condition for the surface normal velocity gradient

$$\llbracket \mathbf{n} \cdot \mu \nabla \mathbf{u} \rrbracket = -\llbracket \mu \rrbracket (\nabla_s \cdot \mathbf{u}) \mathbf{n} - \llbracket \mu \rrbracket \nabla_s \mathbf{u} \cdot \mathbf{n} + \nabla_s \sigma. \quad (12)$$

From this, a normal gradient boundary condition for velocity can be obtained as

$$\mathbf{n} \cdot \nabla \mathbf{u} = -(\nabla_s \cdot \mathbf{u}) \mathbf{n} - \nabla_s \mathbf{u} \cdot \mathbf{n} - \nabla_s \frac{\sigma}{\rho_0 \nu}. \quad (13)$$

Note that for wave propagation problems, viscous effects can often be neglected, which leads to simplified boundary conditions (Muzaferija and Perić, 1997). Throughout this work, a Neumann boundary condition is used for the velocity at the free surface instead of Equation (13).

An iterative procedure is employed to solve the governing equations while satisfying the free-surface boundary conditions. The mesh position motion is adjusted at the beginning of each outer iteration of the RANS equation solution process to satisfy the kinematic free-surface boundary condition, before the RANS equations are solved using the boundary conditions derived from Equation (9). Typically, about 5 outer iterations are employed per time step to ensure a converged solution. Note that the first free-surface motion iteration is done based on $\mathbf{u}$ and $\dot{V}$ from the previous time step. In any further iterations, only the leading terms on the right-hand side of Equation (7) are applied together with the relative flux $\dot{V}_{rel} = \dot{V} - \dot{V}_f$ instead of $\dot{V}$. This way, Equation (8) provides a correction to the current mesh position rather than a motion with respect to the position on the previous time level.

In sum, the following modifications are introduced to the ALE-IT method in this work with respect to the standard OpenFOAM® version, which is based on the work of Tuković and Jasak (2012).

- The time discretization of the kinematic free-surface boundary condition is modified to include the absolute flux on the first iteration and relative fluxes on subsequent iterations during each time step. Additionally, the old-time contribution is added for the *backward* time scheme (see Equation (7b)).
- A new mesh motion solver² is introduced to facilitate displacement-based defor-

²While the ALE-IT method prescribes the motion of the free-surface boundary, the motion of the internal mesh points is calculated from the boundary values (typically) by solving a Laplace equation. In OpenFOAM®, mesh motion solvers can be implemented based on the velocity of the mesh or its displacement with respect to a reference position.

216 mation of the mesh in the vertical coordinate direction only.

- 217 • A possibility to solve the internal mesh motion only on the first iteration of each
- 218 time step is introduced to reduce computational cost.
- 219 • The least-squares fitting process, which calculates the point position from the
- 220 face-centered values of δh_m is adapted for large-scale problems.
- 221 • The processor communication for parallel calculations is improved.

222 2.3. Wave generation and absorption

223 The *waves2foam* toolbox of (Jacobsen et al., 2011) is used for wave generation and
 224 absorption. Generating Absorbing Boundary Conditions (GABC)s (Borsboom and Ja-
 225 cobsen, 2021) are applied at the inlet and outlet boundaries. The GABC approach
 226 provides boundary conditions for velocity and pressure, to allow for wave generation
 227 while accepting reflected waves traveling out of the domain without undue reflection
 228 from the boundary. The boundary conditions are based on a combination of a modified
 229 non-reflective Sommerfeld condition for outgoing waves and a prescribed solution for
 230 incoming waves. For details, the reader is referred to the work of Borsboom and Ja-
 231 cobsen (2021). As the GABC approach alone did not achieve the necessary accuracy
 232 of wave generation and absorption, it is combined with a classical relaxation zone ap-
 233 proach in this work, which explicitly enforces a solution (wave theory at the inlet and
 234 a still water surface at the outlet) for the velocity with increasing weight towards the
 235 inlet and outlet boundaries. The theoretical solution is prescribed with the relaxation
 236 weight

$$w(x_r) = \frac{(1 + (e - 1)w_{max})^{x_r^p} - 1}{e - 1}. \quad (14)$$

237 Here, x_r is a relative coordinate, which varies linearly throughout the relaxation zone
 238 (i. e., from 0 inside the solution domain to 1 at the boundary) and p is a constant which
 239 is set to 3.5 by default. Due to the GABC, the theoretical solution does not need to
 240 be fully prescribed at the boundary. Thus, w takes a maximum value of $w(x_r = 1) =$
 241 w_{max} . Throughout this work, $w_{max} = 0.0538$ is used, whereby the variation of w is
 242 equivalent to that over the first half of a standard relaxation zone ($w_{max} = 1$). Through
 243 this combined relaxation zone GABC approach, the necessary length of the relaxation
 244 zones can be significantly reduced compared to a pure relaxation zone approach, while
 245 maintaining a high accuracy for wave generation and absorption (see Section 3.1). To
 246 be able to use the *waves2foam* toolbox with *ocean4Foam* and the ALE-IT approach,
 247 an adapter class was implemented, which provides *waves2foam* to any OpenFOAM®
 248 solver³.

³The *waves2foam* adapter is implemented in the form of a finite volume option (*fvOption*) for arbitrary OpenFOAM® solvers and part of the *ocean4Foam* toolbox.

2.4. Adaptive mesh refinement

Often, CFD problems contain regions of interest with high spatial resolution to capture specific physical phenomena. In the buoyant plume application presented in Section 3.3, the region of the plume must be highly resolved as it expands along a previously unknown trajectory, while a coarse mesh resolution is sufficient in the far field. In such cases, where the location of the regions of interest moves over time or is not known a priori, adaptive meshes offer an effective way to reduce computational cost. For meshes predominantly consisting of hexahedral cells, refinement can efficiently be achieved by splitting cells in all three Cartesian directions, such that each hexahedral cell is split into eight sub-cells. Refinement and subsequent unrefinement of the mesh can be controlled via any indicator function based on the instantaneous flow field. To combine adaptive mesh refinement with the ALE-IT approach, the method must accept simultaneous topology change (from adaptive mesh refinement) and motion (from ALE-IT) of the mesh. By default, OpenFOAM® implements a simple adaptive mesh refinement approach. A more general implementation is provided through the *blastAMR* library of Heylmun et al. (2023). This implementation additionally offers adaptive processor load-balancing capabilities. Adaptive load-balancing can be of great importance, given that, e. g., two subsequent cell splitting operations increase the cell count in a refined region by a factor of 64, potentially introducing a significant imbalance in the processor cell counts of parallel calculations. The *blastAMR* library was thus chosen as a basis for the present work, and an extension for moving meshes was implemented.

A key challenge when combining mesh motion and topology change is that second-order temporal discretization schemes for the RANS equations on moving meshes typically require the cell volume on different time levels. After a refinement/unrefinement step, the cell volume of the new, changed mesh on the old time level must thus be calculated. As any approximation of the old-time cell volumes introduces significant unboundedness to the solution of the RANS equations, the following adaptive mesh refinement algorithm was chosen:

1. Move the mesh to its position on the previous time level
2. Refine/unrefine the mesh as appropriate and calculate the cell volume
3. Move the mesh to its position on the current time level again

To the author's knowledge, this is the first implementation of a combined mesh motion and adaptive mesh refinement algorithm in OpenFOAM® that is consistent for second-order time discretization schemes. At present, the ALE-IT adaptive mesh refinement combination is still limited by OpenFOAM®'s finite area capabilities, which do not allow for a refinement of the free-surface boundary, such that this boundary has to be excluded from the refinement. Also, processor load-balancing is not presently functional for cases with finite area meshes (i. e., ALE-IT cases).

3. Results and discussion

In this section, we present several applications of the methodology described in Section 2. First, the ALE-IT method is verified and validated against theory and compared against a standard VOF solver using a two-dimensional numerical wave tank

case. A validation against experimental data is carried out for wave propagation over a submerged bar. Finally, an advanced application to three-dimensional mixing of a turbulent buoyant plume under wave effects with adaptive mesh refinement will be presented.

3.1. Verification and validation against theory

The aim of this study is to test the general ability of the ALE-IT approach to generate and propagate waves with realistic surface elevation and velocity characteristics and acceptable decay, as well as its ability to absorb the generated waves in a numerical wave tank setup without unrealistic reflection from the boundaries. For this, the convergence of the solution towards a discretization-independent solution is verified, and the accuracy of the solution is validated against theory. The results from the ALE-IT method are compared against results from a standard VOF method. As a VOF solver, the standard *interFoam* solver is used in the version of OpenFOAM® v2412. The details of this solver and the VOF method will not be discussed in this work. Applications of this method to wave propagation and other marine and coastal engineering applications are abundant in the literature.

Figure 1 shows the geometrical setup of the two-dimensional numerical wave tank used in this study, along with its dimensions, the applied boundary conditions, the size of the wave relaxation zones, the position of the wave probes, and a typical spatial discretization. For the VOF cases, the domain is extended 2.5 wave heights above the water level to resolve the air phase. A monochromatic sea state is used for this study. Details about the sea state are given in Table 1. The sea state can be described by second-order Stokes theory. All cases in this study were run for 65 wave periods,

T [s]	H [m]	h [m]	λ [m]
8.003	2	50	100

Table 1: Sea state details for verification and validation against theory, where T is wave period, H is wave height, h is water depth, and λ is wavelength

starting from a flat water surface.

For the spatial convergence study, the horizontal cell size is parametrically varied between 50 and 500 Cells Per Wavelength (CPL). The cell aspect ratio ($\frac{\text{vertical size}}{\text{horizontal size}}$) is 0.5 at the water surface and 2.5 at the bottom. For the VOF case, the cells near the surface are refined through horizontal splitting in two steps, such that a cell aspect ratio of 0.125 is achieved at the water surface (see Figure 1 for details). Base values for the temporal discretization of $\Delta t = \frac{5}{4} \frac{T}{CPL}$ and $\Delta t = \frac{5}{16} \frac{T}{CPL}$ are chosen for the ALE-IT and VOF cases, respectively. This yields constant maximum CFL numbers of about 0.2 throughout the study. Figure 2 shows the variation of the mean wave height H , measured at probe 2, and the wave decay⁴ between probes 1 and 5 over the mesh size variations, along with a regression analysis and the 1 % error threshold with respect to the extrapolated exact solution. Only the results of the last 39 simulated wave periods

⁴In this work, the wave decay is calculated as the decrease in mean wave height per distance the wave propagates ($\text{decay} = \frac{\Delta H}{\Delta x}$).

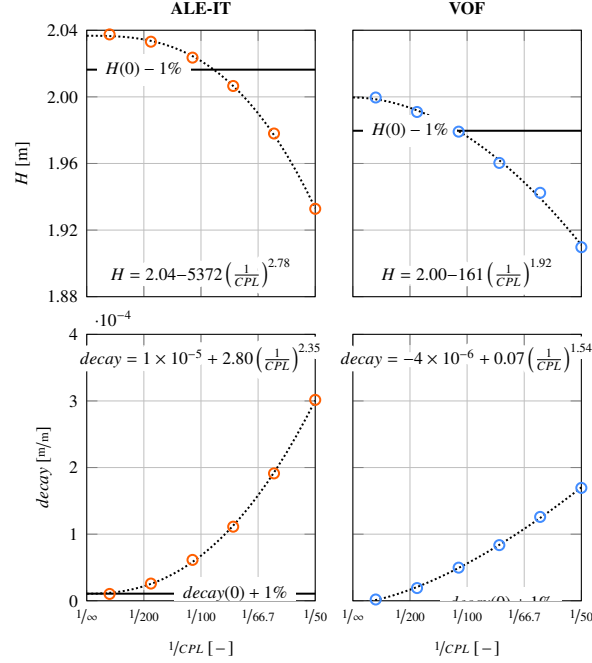


Figure 2: Results from spatial discretization study for ALE-IT (left) and VOF (right) approach. Mean wave height (upper row) and wave decay (lower row) over spatial discretization, along with regression analysis (dotted lines) and 1 % error threshold w. r. t. extrapolated solution at $CPL = \infty$

by the VOF method with $\Delta t = 0.01$ s. The results suggest that for cases where a small wave decay is not critical, larger time steps can be chosen for both methods without a significant error in the reproduction of the initial wave height.

From the combination of both convergence studies, the following recommendations are derived. For both methods, 200 cells per wavelength are recommended with a cell aspect ratio of 0.5 and 0.125 at the surface for the ALE-IT method and the VOF method, respectively. The time step is chosen to yield maximum CFL numbers of 0.1 and 0.2 for the ALE-IT method and the VOF method (for the pure wave propagation problem). At these discretizations, the ALE-IT and VOF methods produce a decay of 2.3×10^{-5} m/m and 1.2×10^{-5} m/m, respectively, which is considered acceptable for most engineering applications. On identical machines using 20 processors in parallel, the VOF method needed 54 s per second of simulated time, while the ratio was 10 for the ALE-IT method. The ALE-IT method thus calculates this two-dimensional reference case about 80 % faster than the VOF method. Despite best efforts, the present study cannot claim to fully exploit the acceleration potential of both methods. Nevertheless, the respective performance found in the present study provides a clear indication that the ALE-IT method can provide a significant gain in efficiency for numerical wave tanks compared to the VOF method, in cases where its obvious limitations can be

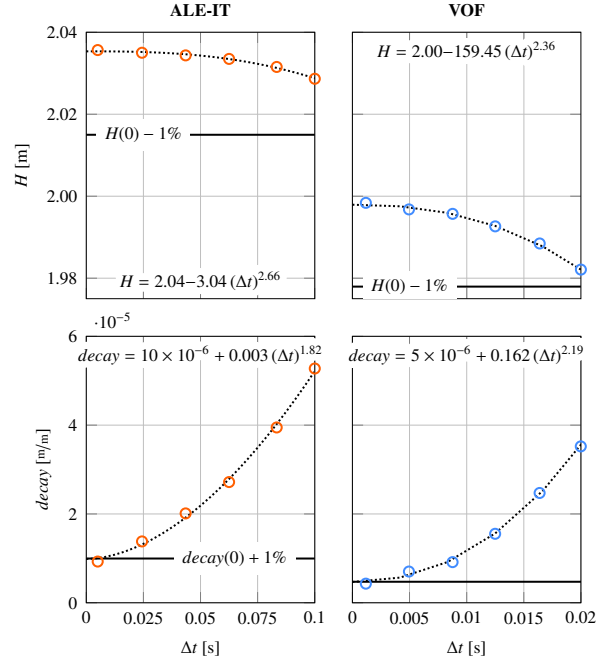


Figure 3: Like Figure 2, but for temporal discretization study

accepted.

Figures 4 and 5 show the full results for the reference setups. Here, the mean surface elevation signals at probe 2 (averaged over the last 39 wave periods) are shown along with mean profiles of the horizontal velocity at the wave crest and trough. It

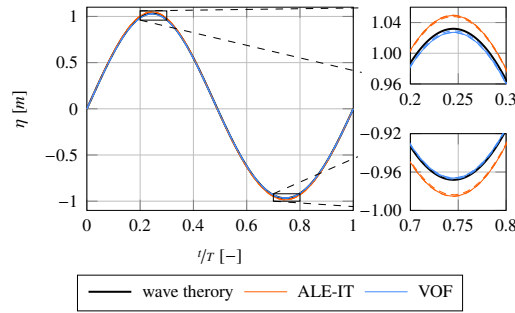


Figure 4: Mean surface elevation signal at probe 2 for reference discretizations

can be seen that, while the ALE-IT method produces a wave slightly higher than the intended sea state, it avoids possible numerical disturbances in the velocity field close

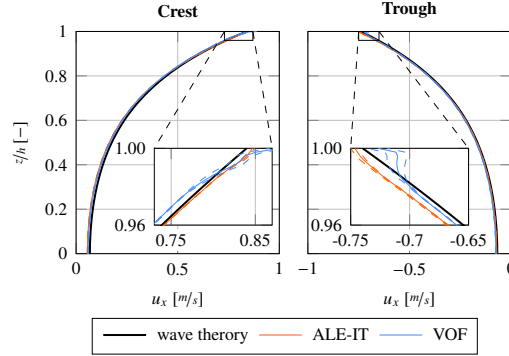


Figure 5: Mean wave crest (left) and trough (right) horizontal velocity profile at probe 2 over depth for reference discretizations

to the free surface.

Wave reflection from the outlet boundary is analyzed using a three-probe reflection analysis (Mansard and Funke, 1980). Probes 3, 4, and 5 are used for this analysis. The reflection coefficients⁵ are 1.8 % and 0.2 % for the ALE-IT and VOF case, respectively. For practical purposes, values below 5 % are considered acceptable for numerical wave tanks (Borsboom and Jacobsen, 2021).

3.2. Validation against experimental data for wave propagation over a bar

Numerical wave tanks are often used to study the interaction of waves with structures. Interface tracking methods especially lend themselves to studies of fully submerged structures. This capability will be validated here by reproducing an experimental study of wave propagation over a submerged bar by Beji and Battjes (1993). The geometric setup for the numerical validation study is shown in Figure 6. The probe locations are given in Table 2. The setup closely follows the experimental layout of Beji

Probe	1	2	3	4	5	6	7
[m]	5.7	10.5	12.5	13.5	14.5	15.7	17.3

Table 2: Probe locations for wave propagation over a bar (w.r.t. coordinates as shown in Figure 6)

and Battjes (1993). The water depth is 0.4 m in the deep region and 0.2 m above the shoal. The experimental domain is extended by a wave generation zone instead of the physical wave maker, and the physical beach is replaced by a (shorter) wave relaxation zone in the numerical calculations. The sea state properties are given in Table 3. Again, calculations with both the ALE-IT and VOF methods are carried out, and the results are compared. The cases are set up following the discretization recommendations of

⁵Following Windt et al. (2019), the wave reflection coefficient is defined by the ratio of the peak power spectral densities of the incident and reflected wave spectra in this work.

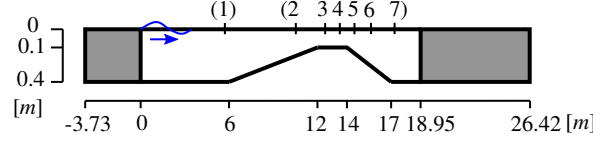


Figure 6: Geometrical setup for validation against experiments of wave propagation over a bar. Numbers in braces give wave probe locations (see Table 2).

T [s]	H [m]	h [m]	λ [m]
2.02	0.02	0.4	3.74

Table 3: Sea state details for wave propagation over a bar

Section 3.1, using 200 CPL and time steps of 5×10^{-3} s and 1.25×10^{-3} s for the ALE-IT and VOF method, respectively. Figure 7 shows the time series of the surface elevation at different probe locations compared to the experimental results. As can be seen from

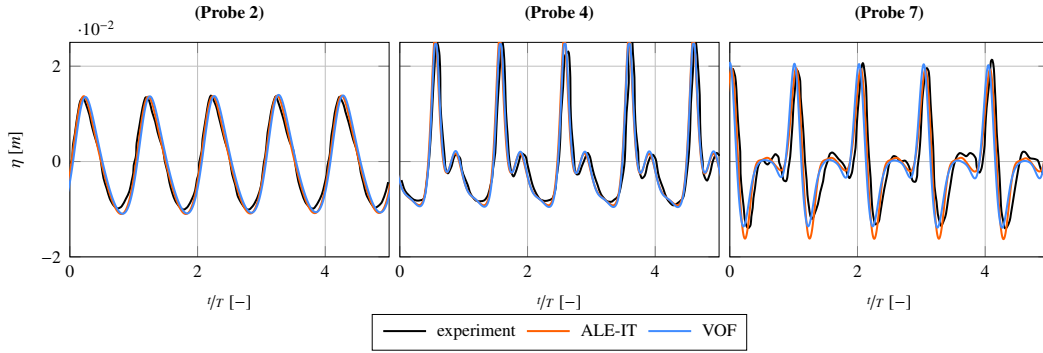


Figure 7: Time series of surface elevation for wave propagation over a bar, with experimental data of Beji and Battjes (1993).

Figure 7, both the VOF and ALE-IT methods produce results in good agreement with the experimental data. At probe 7, the numerical wave signals show slightly different dynamics from the experimental data. This might be caused by wave reflection from the beach in the experimental setup. These results show that the ALE-IT method is able to capture the interaction of waves with submerged structures both accurately and efficiently.

3.3. Example application to wave effects on a buoyant plume

So far, the ALE-IT method has been applied to two-dimensional cases with structured grids in this work. To demonstrate the applicability of the method to practical engineering problems, an advanced application with an unstructured three-dimensional grid will be presented in this section. The example case models a turbulent buoyant plume from an artificial upwelling device.

406 The term artificial upwelling describes the engineered transport of nutrient-rich
 407 deep ocean water to the surface. This process is currently being studied for its ability
 408 to contribute to marine carbon dioxide removal measures. For example, Lovelock and
 409 Rapley (2007) proposed that a pipe with a one-way valve at the bottom, moving with
 410 the wave motion, could provide a wave energy-driven method for upwelling of deep
 411 ocean water. As pointed out by Kirke (2003), the upwelled water in such a scenario
 412 would be negatively buoyant when discharged at the surface, due to its low tempera-
 413 ture, and could thus sink back out of the surface region. The present application studies
 414 this problem by modeling a discharge of cold deep ocean water from a vertical pipe.
 415 By comparing a case with and without free-surface waves, it will be studied how waves
 416 affect the mixing of the cold upwelled water. While the previous studies in this work
 417 have been done under isothermal and isohaline conditions (i. e., the temperature and
 418 salinity equations were not solved), the present study will be done with dynamic tem-
 419 perature and salinity. Also, the present study will employ a RANS turbulence model.
 420 The well-known $k-\omega$ SST turbulence model (Menter, 1994) is used. For more realistic
 421 plume dynamics, a simple buoyancy source term is applied to the turbulence model
 422 following Van Maele and Merci (2006). As shown by Larsen and Fuhrman (2018),
 423 the $k-\omega$ SST model is prone to producing exponentially growing turbulence levels in
 424 wave simulations and thus needs to be stabilized. As the limiter approach of Larsen
 425 and Fuhrman (2018) was found to be too intrusive on the plume dynamics, a vorticity-
 426 based turbulence production term is used in the present work. This modified version
 427 of the $k-\omega$ SST turbulence model is known as the $k-\omega$ SST-V model (Brown, 2011).
 428 Throughout this work, the modification has been found to provide the necessary stabi-
 429 lization of the turbulence levels without significant intrusion on the plume dynamics.
 430 Figure 8 shows the temperature and salinity depth profiles used in this study, along
 431 with the depth of the hypothetical wave pump device and the depth range resolved in
 432 the present study. The profiles represent typical autumn conditions close to the Canary
 Islands. Figure 9 shows the geometrical setup of the study domain. For simplicity,

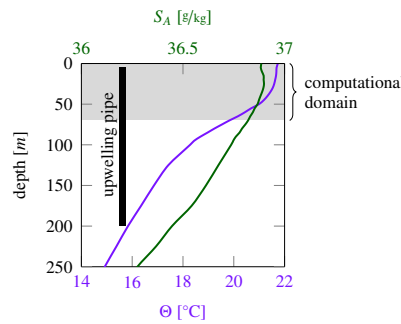


Figure 8: Temperature and salinity depth profiles with extent of upwelling pipe and computational domain

433 the pipe is fixed in space in this study, and steady inflow of deep ocean water with
 434 temperature and salinity conditions at the source depth (200 m) and a volume flow rate
 435

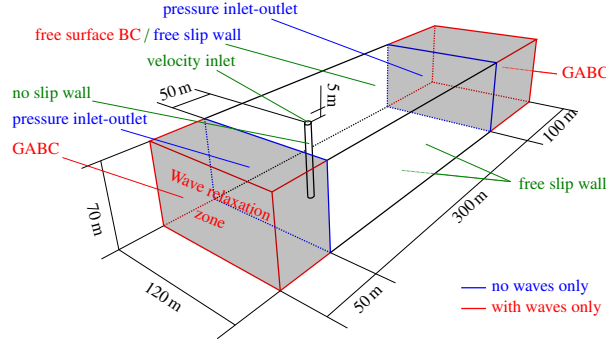


Figure 9: Geometrical setup and boundary conditions for buoyant plume case with (red) and without (blue) waves

of $510 \text{ m}^3/\text{h}$ is assumed⁶. The pipe diameter is 1.9 m. A small cross-flow velocity of 0.041 m/s is introduced (by means of a global pressure gradient) to account for the fact that the pipe, if not moored, would drift at the speed of the mean current across the pipe depth, which (assuming a non-constant current profile) would lead to a relative flow in the modeled surface region. The same sea state as in Section 3.1 is used (see Table 1), but with an increased water depth of 1000 m.

A hex-dominant meshing strategy is employed to discretize the computational domain. The base mesh follows the recommendations from Section 3.1 close to the pipe and is gradually coarsened in the far field. The mesh is permanently refined in four steps in the vicinity of the pipe, and prism layers are used on the pipe wall to ensure correct resolution of the boundary layer. The plume is resolved through adaptive mesh refinement, using up to three refinement steps based on the deep water concentration (as indicated by a passive tracer variable). This methodology ensures an optimal resolution of the plume without having to know its trajectory and refine the mesh a priori. Figure 10 shows a slice through the mesh at the beginning of the calculation and after 3600 s of simulated time. The initial cell count is 3 Mill. and 2.5 Mill. while the final cell count after 3600 simulated seconds is 6.3 Mill. and 6.7 Mill. for the case with and without waves, respectively. The cases ran for about 180 and 80 hours on 64 processor cores (Xeon Gold 6426Y) across two cluster nodes. Processor load balancing through the *blastAMR* library is applied in the case without waves, while the wave case had to be stopped and restarted a number of times to rebalance the processor load (see Section 2.4).

Figure 11 shows snapshots of the final solution after 3600 s. Here, the deep water concentration (indicated by the yellow color) is shown. It can be seen that the waves have a significant effect on the mixing of the discharged deep ocean water. The discharged deep ocean water is diluted faster and, as a result, shows less sinking tendency under wave influence. Figure 12 shows a histogram analysis of deep water concentra-

⁶The flow rate was chosen to be consistent with the assumptions of Oschlies et al. (2010) and Jürchott et al. (2023).

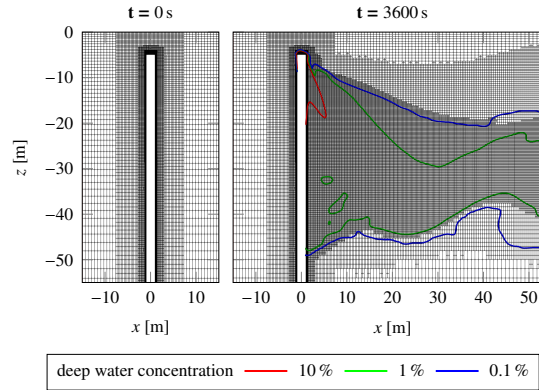


Figure 10: Computational mesh for buoyant plume case without waves at times 0 s and 3600 s along with upwelled deep water concentration contours

tion over depth at time 3600 s. The deep water concentration (as indicated by a passive tracer) is analyzed in 2 m depth bins across the entire computational domain. In Figure 12, the amount of deep water in each bin is given, normalized by the total amount released from the upwelling pipe. This representation allows for an analysis of the percentage of upwelled deep water located above a certain depth (lines in Figure 12). It can be seen that for the case with waves 50 % of the upwelled water is located above a depth of 15 m at this time, while for the case without waves the 50 % quantile is only reached at a depth of 30 m. Due to the wave effect, the upwelled water is distributed much more evenly throughout the ocean's mixed surface layer than without waves. The results thus show that waves significantly affect the mixing behavior of buoyant plumes in the surface ocean, leading to a faster dilution of the upwelled water and a strongly reduced tendency to sink back down as a result of its high density. While this result has to be generalized through additional studies with different sea states and upwelling rates,

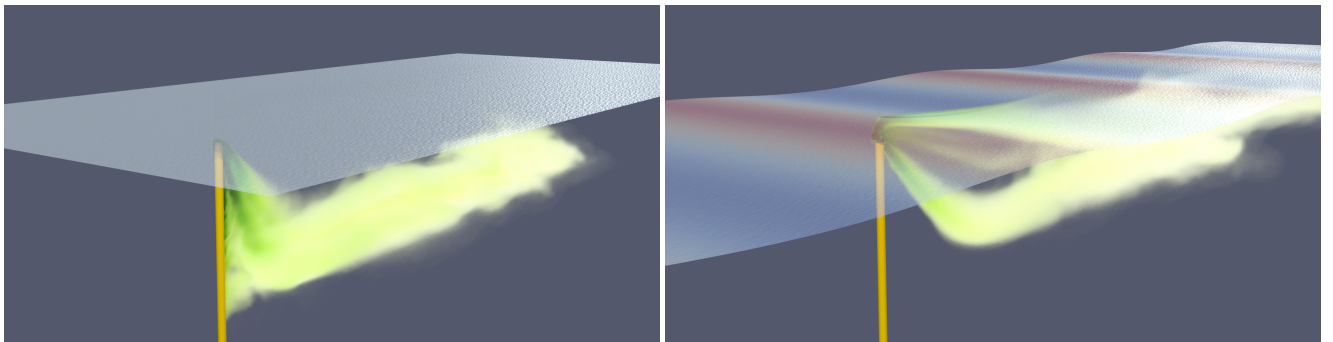


Figure 11: Buoyant deep ocean water plume in cross-flow. Snapshots of the solution with and without waves after 3600 s.

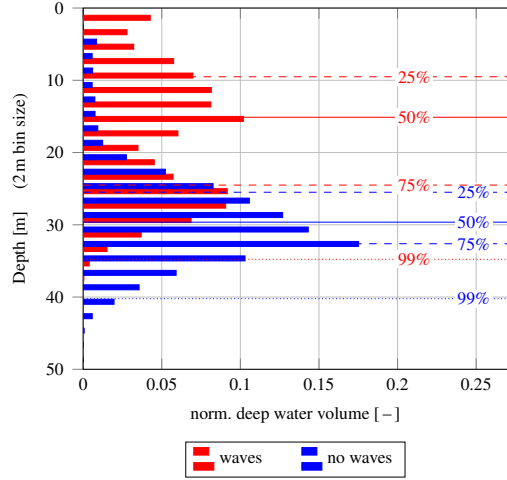


Figure 12: Histogram analysis of upwelled deep water concentration over depth at time 3600 s for case with (red) and without (blue) waves. Concentration is analyzed in 2 m depth bins and normalized by the total amount of upwelled deep water. Lines give quantiles of upwelled deep water retained above a given depth.

it marks an important indication for the feasibility of wave energy-driven artificial up-
welling and partly contradicts earlier assessments Kirke (2003); Kemper et al. (2022),
which indicated that the upwelled water would sink back out of the surface ocean if no
further action was taken. The present study thus demonstrates the applicability of the
ALE-IT method to practical engineering problems.

4. Conclusions

An OpenFOAM®-based arbitrary Lagrangian-Eulerian interface tracking approach
for free-surface wave propagation has been presented. The method is based on the
work of Tuković and Jasak (2012), with a modified time integration algorithm, new
mesh motion solvers, and several additional enhancements to enable efficient calcu-
lations of free-surface wave propagation. The method was further enhanced with an
adapter class for the wave generation and absorption toolbox *waves2foam* (Jacobsen
et al., 2011). Adaptive mesh refinement capabilities were implemented based on the
blastAMR library, which was extended to enable simultaneous mesh motion and refine-
ment.

A grid- and time-step convergence study has been performed to establish the dis-
cretization requirements for the method. It was found that, due to lower discretization
requirements, the ALE-IT method has significantly reduced computational cost com-
pared to an equivalent standard VOF approach for wave propagation. The accuracy of
the method was validated by a comparison against experimental data for wave propaga-
tion over a submerged bar. Finally, its applicability to advanced engineering problems
was demonstrated by performing a study on wave effects on the dynamics of a turbulent
buoyant plume from an artificial upwelling pump.

Due to their limitations regarding the free-surface shape, ALE-IT methods have a limited applicability to marine and coastal engineering problems. With recent advances in high-performance computing, more general methods like VOF have become the standard choice for free-surface flows. The present work shows that, in cases where its limitations can be accepted, ALE-IT can be an efficient and accurate alternative approach for free-surface flow problems. Its principal advantages are:

- Low spatial and temporal discretization demand
- Fewer numerical artifacts near the free surface
- Less spurious turbulence generation
- No unphysical transport across the interface
- Ability to apply boundary conditions (e. g., wind shear and heat flux) directly on the interface

The method should be extended in the future with capabilities to handle floating bodies and more general mesh motion in the free-surface plane. Existing limitations with respect to adaptive mesh refinement and processor load balancing should be resolved. Also, stabilization and parameterizations for breaking waves should be explored. Finally, the applicability of the method for marine and coastal engineering problems should be further evaluated with a wider range of studies.

Acknowledgments

This work was funded by the German *Federal Ministry of Education and Research* (Bundesministerium für Bildung und Forschung, BMBF) in the framework of the *Test-ArtUp* project, which is part of the *CDRmare* research mission led by the *German Marine Research Alliance* (Deutsche Allianz Meeresforschung, DAM), under Grant Agreement No. 03F0897B.

References

- Alvir, M., Grbčić, L., Sikirica, A., Kranjčević, L., 2022. Openfoam-roms nested model for coastal flow and outfall assessment. *Ocean Engineering* 264, 112535. doi:10.1016/j.oceaneng.2022.112535.
- Bai, X.D., Zhang, W., Zheng, J.H., Wang, Y., 2020. On the mass source internal wave making method for ALE based numerical wave tank. *Journal of Marine Science and Technology* 25, 1093–1102. doi:10.1007/s00773-020-00702-z.
- Baykal, C., Sumer, B., Fuhrman, D., Jacobsen, N., Fredsøe, J., 2017. Numerical simulation of scour and backfilling processes around a circular pile in waves. *Coastal Engineering* 122, 87–107. doi:10.1016/j.coastaleng.2017.01.004.
- Beji, S., Battjes, J., 1993. Experimental investigation of wave propagation over a bar. *Coastal Engineering* 19, 151–162. doi:10.1016/0378-3839(93)90022-z.

- 535 Borsboom, M., Jacobsen, N.G., 2021. A generating-absorbing boundary condition
536 for dispersive waves. *International Journal for Numerical Methods in Fluids* 93,
537 2443–2467. doi:10.1002/flid.4982.
- 538 Brown, J., 2011. Shock wave impingement on boundary layers at hypersonic speeds:
539 Computational analysis and uncertainty, in: 42nd AIAA Thermophysics Conference,
540 American Institute of Aeronautics and Astronautics. doi:10.2514/6.2011-3143.
- 541 Devolder, B., Rauwoens, P., Troch, P., 2017. Application of a buoyancy-modified
542 $k-\omega$ SST turbulence model to simulate wave run-up around a monopile subjected
543 to regular waves using OpenFOAM®. *Coastal Engineering* 125, 81–94. doi:10.
544 1016/j.coastaleng.2017.04.004.
- 545 Dutta, D., Afzal, M.S., Alhaddad, S., 2023. 3d cfd study of scour in combined
546 wave–current flows around rectangular piles with varying aspect ratios. *Water* 15,
547 1541. doi:10.3390/w15081541.
- 548 Fedkiw, R.P., Aslam, T., Merriman, B., Osher, S., 1999. A non-oscillatory eulerian
549 approach to interfaces in multimaterial flows (the ghost fluid method). *Journal of*
550 *Computational Physics* 152, 457–492. doi:10.1006/jcph.1999.6236.
- 551 Ferrand, M., Harris, J.C., 2021. Finite volume arbitrary lagrangian-eulerian schemes
552 using dual meshes for ocean wave applications. *Computers & Fluids* 219, 104860.
553 doi:10.1016/j.compfluid.2021.104860.
- 554 Ferziger, J.H., Perić, M., Street, R.L., 2020. *Computational Methods for Fluid Dynam-*
555 *ics*. Springer International Publishing, Cham. doi:10.1007/978-3-319-99693-6.
- 556 Floryan, J.M., Rasmussen, H., 1989. Numerical methods for viscous flows
557 with moving boundaries. *Applied Mechanics Reviews* 42, 323–341.
558 URL: [https://www.researchgate.net/publication/237951966_](https://www.researchgate.net/publication/237951966_Numerical_Methods_for_Viscous_Flows_With_Moving_Boundaries)
559 [Numerical_Methods_for_Viscous_Flows_With_Moving_Boundaries,](https://www.researchgate.net/publication/237951966_Numerical_Methods_for_Viscous_Flows_With_Moving_Boundaries)
560 doi:10.1115/1.3152416.
- 561 Heylmun, J., Fadeli, M.E., Macpherson, G., Hoehler, J., Openfoam-Com, Luanmingyi,
562 2023. Stfs-tuda/blastamr: Load-balanced amr library release [computer software].
563 doi:10.5281/ZENODO.8427734.
- 564 Hirt, C., Nichols, B., 1981. Volume of fluid (VOF) method for the dynamics of
565 free boundaries. *Journal of Computational Physics* 39, 201–225. doi:10.1016/
566 0021-9991(81)90145-5.
- 567 Huang, L., Li, Y., Benites-Munoz, D., Windt, C.W., Feichtner, A., Tavakoli, S., David-
568 son, J., Paredes, R., Quintana, T., Ransley, E., Colombo, M., Li, M., Cardiff, P.,
569 Tabor, G., 2022. A review on the modelling of wave-structure interactions based on
570 openfoam. *OpenFOAM® Journal* 2, 116–142. doi:10.51560/ofj.v2.65.
- 571 Huerta, A., Liu, W.K., 1988. Viscous flow with large free surface motion. *Com-*
572 *puter Methods in Applied Mechanics and Engineering* 69, 277–324. doi:10.1016/
573 0045-7825(88)90044-8.

- 574 IOC, SCOR, IAPSO, 2010. The international thermodynamic equation of seawater -
575 2010: Calculation and use of thermodynamic properties. Intergovernmental Oceano-
576 graphic Commission, Manuals and Guides 56.
- 577 Jacobsen, N.G., Fuhrman, D.R., Fredsøe, J., 2011. A wave generation toolbox for the
578 open-source cfd library: Openfoam®. *International Journal for Numerical Methods*
579 *in Fluids* 70, 1073–1088. doi:10.1002/flid.2726.
- 580 Jamieson, D., Tudhope, J., 1970. Physical properties of sea water solutions: Thermal
581 conductivity. *Desalination* 8, 393–401. doi:10.1016/S0011-9164(00)80240-4.
- 582 Jasak, H., Weller, H., Gosman, A., 1999. High resolution NVD differencing scheme
583 for arbitrarily unstructured meshes. *International Journal for Numerical Methods*
584 *in Fluids* 31, 431–449. doi:10.1002/(sici)1097-0363(19990930)31:2<431::
585 aid-flid884>3.0.co;2-t.
- 586 Jürchott, M., Oeschlies, A., Koeve, W., 2023. Artificial upwelling—a refined narrative.
587 *Geophysical Research Letters* 50. doi:10.1029/2022gl1101870.
- 588 Kemper, J., 2024. ocean4Foam [computer software]. doi:10.3289/sw_9_2024.
- 589 Kemper, J., Riebesell, U., Graf, K., 2022. Numerical flow modeling of artificial ocean
590 upwelling. *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.804875.
- 591 Kirke, B., 2003. Enhancing fish stocks with wave-powered artificial upwelling. *Ocean*
592 *& Coastal Management* 46, 901–915. doi:10.1016/s0964-5691(03)00067-x.
- 593 Larsen, B.E., Fuhrman, D.R., 2018. On the over-production of turbulence beneath sur-
594 face waves in reynolds-averaged navier–stokes models. *Journal of Fluid Mechanics*
595 853, 419–460. doi:10.1017/jfm.2018.577.
- 596 Lovelock, J.E., Rapley, C.G., 2007. Ocean pipes could help the earth to cure itself.
597 *Nature* 449, 403–403. doi:10.1038/449403a.
- 598 Mansard, E., Funke, E., 1980. The measurement of incident and reflected spectra
599 using a least squares method. *Coastal Engineering Proceedings* , 8doi:10.9753/
600 icce.v17.8.
- 601 McDougall, T.J., 2003. Potential enthalpy: A conservative oceanic variable for evalu-
602 ating heat content and heat fluxes. *Journal of Physical Oceanography* 33, 945–963.
603 doi:10.1175/1520-0485(2003)033<0945:peacov>2.0.co;2.
- 604 Menter, F.R., 1994. Two-equation eddy-viscosity turbulence models for engineering
605 applications. *AIAA Journal* 32, 1598–1605. doi:10.2514/3.12149.
- 606 Muzaferija, S., Perić, M., 1997. Computation of free-surface flows using the finite-
607 volume method and moving grids. *Numerical Heat Transfer, Part B: Fundamentals*
608 32, 369–384. doi:10.1080/10407799708915014.

- 609 Muzaferija, S., Perić, M., 1999. Nonlinear Water Waves Interaction. WIT Press.
 610 chapter Computation of free-surface flows using interface-tracking and interface-
 611 capturing methods. pp. 59–100.
- 612 Oeschlies, A., Pahlow, M., Yool, A., Matear, R.J., 2010. Climate engineering by arti-
 613 ficial ocean upwelling: Channelling the sorcerer’s apprentice. *Geophysical Research*
 614 *Letters* 37. doi:10.1029/2009gl041961.
- 615 Roenby, J., Bredmose, H., Jasak, H., 2016. A computational method for sharp interface
 616 advection. *Royal Society Open Science* 3, 160405. doi:10.1098/rsos.160405.
- 617 Schmitt, P., Windt, C., Davidson, J., Ringwood, J.V., Whittaker, T., 2020. Beyond
 618 VoF: alternative OpenFOAM solvers for numerical wave tanks. *Journal of Ocean*
 619 *Engineering and Marine Energy* 6, 277–292. doi:10.1007/s40722-020-00173-9.
- 620 Schwarzeimer, M., Raju, S., Tuković, Ž., Fricke, M., Bothe, D., Marić, T., 2025.
 621 twophaseintertrackfoam: An openfoam module for arbitrary lagrangian/eulerian in-
 622 terface tracking with surfactants and subgrid-scale modeling. *Computer Physics*
 623 *Communications* 308, 109460. doi:10.1016/j.cpc.2024.109460.
- 624 Sharqawy, M.H., Lienhard V, J.H., Zubair, S.M., 2010. Thermophysical properties
 625 of seawater: A review of existing correlations and data. *Desalination and Water*
 626 *Treatment* 16, 354–380. doi:10.5004/dwt.2010.1079.
- 627 Tuković, Ž., Jasak, H., 2012. A moving mesh finite volume interface tracking method
 628 for surface tension dominated interfacial fluid flow. *Computers & Fluids* 55, 70–84.
 629 doi:10.1016/j.compfluid.2011.11.003.
- 630 Van Maele, K., Merci, B., 2006. Application of two buoyancy-modified – turbulence
 631 models to different types of buoyant plumes. *Fire Safety Journal* 41, 122–138.
 632 doi:10.1016/j.firesaf.2005.11.003.
- 633 Vukcevic, V., 2016. Numerical Modelling of Coupled Potential and Viscous Flow for
 634 Marine Applications. Ph.D. thesis. University of Zagreb. doi:10.13140/RG.2.2.
 635 23080.57605.
- 636 Windt, C., Davidson, J., Schmitt, P., Ringwood, J.V., 2019. On the assessment of nu-
 637 merical wave makers in cfd simulations. *Journal of Marine Science and Engineering*
 638 7, 47. doi:10.3390/jmse7020047.
- 639 Wroniszewski, P.A., Verschaeve, J.C., Pedersen, G.K., 2014. Benchmarking of
 640 navier–stokes codes for free surface simulations by means of a solitary wave. *Coastal*
 641 *Engineering* 91, 1–17. doi:10.1016/j.coastaleng.2014.04.012.
- 642 Young, W.R., 2010. Dynamic enthalpy, conservative temperature, and the seawater
 643 boussinesq approximation. *Journal of Physical Oceanography* 40, 394–400. doi:10.
 644 1175/2009jpo4294.1.

Contribution [PPB]

Artificial upwelling via Stommel-Pipe as a marine CDR option? A present to future performance assessment in an Earth system model

Citation:

Jürchott, M., **Kemper, J.**, 2025. Artificial upwelling via Stommel-pipe as a marine CDR option? A present to future performance assessment in an Earth system model. [Preprint] Manuscript in preparation.

Author contributions:

Conceptualization	M. Jürchott, J. Kemper
Methodology	M. Jürchott, J. Kemper
Software	M. Jürchott, J. Kemper
Validation	J. Kemper
Investigation	M. Jürchott
Data Curation	M. Jürchott
Writing - Original Draft	M. Jürchott
Writing - Review & Editing	J. Kemper
Visualization	M. Jürchott

License:

This publication is licensed under a Creative Commons Attribution 4.0 International license.



Artificial upwelling via Stommel-Pipe as a marine CDR option?
A present to future performance assessment in an Earth system model.

Authors:

Jürchott, M.¹and Kemper, J.²

¹GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany

²Kiel University, Germany

Key Points:

- Stommel-Pipe design reaches upwelling intensities of up to 0.45 m³/s/pipe around subtropical gyres.
- Stommel-Pipe upwelling causes net ocean CO₂ outgassing into the atmosphere around South Pacific subtropical gyre.
- Stommel-Pipe upwelling shows low potential as a stand-alone marine CDR approach.

Keywords:

[1] carbon dioxide removal (CDR), [2] artificial upwelling, [3] stommel pipe, [4] marine carbon cycle, [5] ocean ecosystem productivity, [6] RCP CO₂-emission pathway, [7] UVic Earth system model

Corresponding Author: Malte Jürchott, mjuerchott@geomar.de

Abstract

Artificial upwelling has been proposed as a marine CDR approach to enhance the ocean's carbon sink, but found to disrupt the ocean thermocline through the upwelling of cold water, which leads to severe consequences for the Earth system, especially after pipe-termination. One potential approach to realize artificial upwelling are counterflow Stommel-Pipes. These pipes establish a self-sustaining upwelling and simultaneous downwelling flow through efficient heat exchange between both streams, which could avoid ocean thermocline disruption. In this study, we simulate a specific Stommel-Pipe design in an Earth system climate model between years 2025-2100 under low and high future CO₂-emission pathways to assess present to future pipe performance and impact on the Earth system. We find sustained peak upwelling intensities up to 0.45 m³/s/pipe around subtropical gyres. However, by redistributing interior DIC to the surface ocean, the Stommel-Pipe led to net CO₂ outgassing to the atmosphere especially around the South Pacific.

Plain Language Summary

Global mean surface air temperature has risen since preindustrial times due to the continuous release of anthropogenic greenhouse gas emissions (mainly CO₂) into the atmosphere. Marine carbon dioxide removal (mCDR) methods aim to enhance the CO₂ uptake of the ocean to offset anthropogenic CO₂-emissions in an attempt to limit future global mean surface air temperature increase. Artificial upwelling is a proposed mCDR technology that deploys vertical pipes in the ocean with the aim to upwell nutrient-rich interior water to the surface, fertilising plankton ecosystems and promoting additional CO₂ uptake by enhancing the ocean's biological carbon pump. In this study, we use an Earth system climate model of intermediate complexity to investigate the global upwelling potential, mCDR implications and potential side effects of the Stommel-Pipe upwelling concept, which establishes a self-sustaining upwelling and simultaneous downwelling flow through efficient heat exchange between both streams. We find sustained peak upwelling intensities up to 0.45 m³/s/pipe around subtropical gyres, but by redistributing interior ocean DIC to the surface ocean, the Stommel-Pipe led to net CO₂ outgassing to the atmosphere especially around the Southern Pacific subtropical gyre.

57 1 Introduction

58 [1] The CO₂ concentration in the Earth's atmosphere has continuously risen since preindustrial times due
59 to human activity, such as fossil fuel burning and land-use change, and causes an increase in global surface
60 air temperature (IPCC 2022). In addition to extensive CO₂ mitigation efforts, a variety of geochemical
61 and biotic marine carbon dioxide removal (CDR) approaches are currently under investigation, which aim
62 to enhance the global ocean's CO₂ uptake potential in an effort to compensate legacy and future hard-to-
63 abate CO₂-emissions (NASEM 2022, Oschlies et al., 2025). Artificial upwelling is one proposed biotic
64 marine CDR approach, which uses vertical pipes to be deployed in the open ocean to upwell nutrient-rich
65 ocean interior water in an effort to stimulate and enhance the biological carbon pump (Lovelock & Rapley,
66 2007). However, recent studies found that the potential of artificial upwelling to increase the ocean carbon
67 sink is quite limited, if not combined with ocean iron fertilization and / or open ocean macro-algae farming
68 (Wu et al., 2023, Jürchott et al., 2024). Like most biotic marine CDR methods artificial upwelling can also
69 enhance ocean deoxygenation and promote denitrification as a side effect (Oschlies et al., 2025).
70 Additionally, when done with, e.g., wave-driven pipes, artificial upwelling uniquely impairs Earth's
71 energy balance by enhancing ocean heat uptake via transporting cold water to the surface ocean (Jürchott
72 et al., 2025). The additional heat taken up by the ocean is stored in the ocean interior and can radiate back
73 to the atmosphere, which leads to an increase in surface air temperatures after pipe-termination at least
74 over the following decades in comparison to the reference (without artificial upwelling) experiment
75 (Oschlies et al., 2010). This specific side effect could be avoided through the use of a counterflow
76 Stommel-Pipe design, which simultaneously generates convective upwelling and downwelling, while
77 exchanging heat between both streams, leaving the ocean's thermocline largely unaffected (Stommel et
78 al., 1956, Figure 1d). As a consequence, the Stommel-Pipe concept offers a conceptual advantage over
79 e.g., wave-driven artificial upwelling, which has so far not been investigated in detail in the context of
80 marine CDR (Pan et al., 2016, Kemper et al., 2025). However, a Stommel-Pipe can only lead to upwelling
81 in ocean regions in which the surface ocean has a higher salinity concentration in comparison to the
82 salinity concentration at the pipe's source depth (Figure 1a-c). Additionally, the upwelling intensity of a
83 Stommel-Pipe is not constant, but depends on the specific pipe design, absolute surface salinity and
84 temperature, as well as their gradient between the surface ocean and the pipe's source depth, and the
85 overall length of the pipe. (Kemper et al., 2025).

86

[2] In this study we assess the present to future performance of a new Stommel-Pipe design in an Earth system climate model of intermediate complexity with a maximum technical potential approach under the future RCP 2.6 and 8.5 CO₂-emission pathways, quantify its impact on Earth's heat distribution, carbon cycle and ocean ecosystem and investigate the Earth system response after Stommel-Pipe termination.

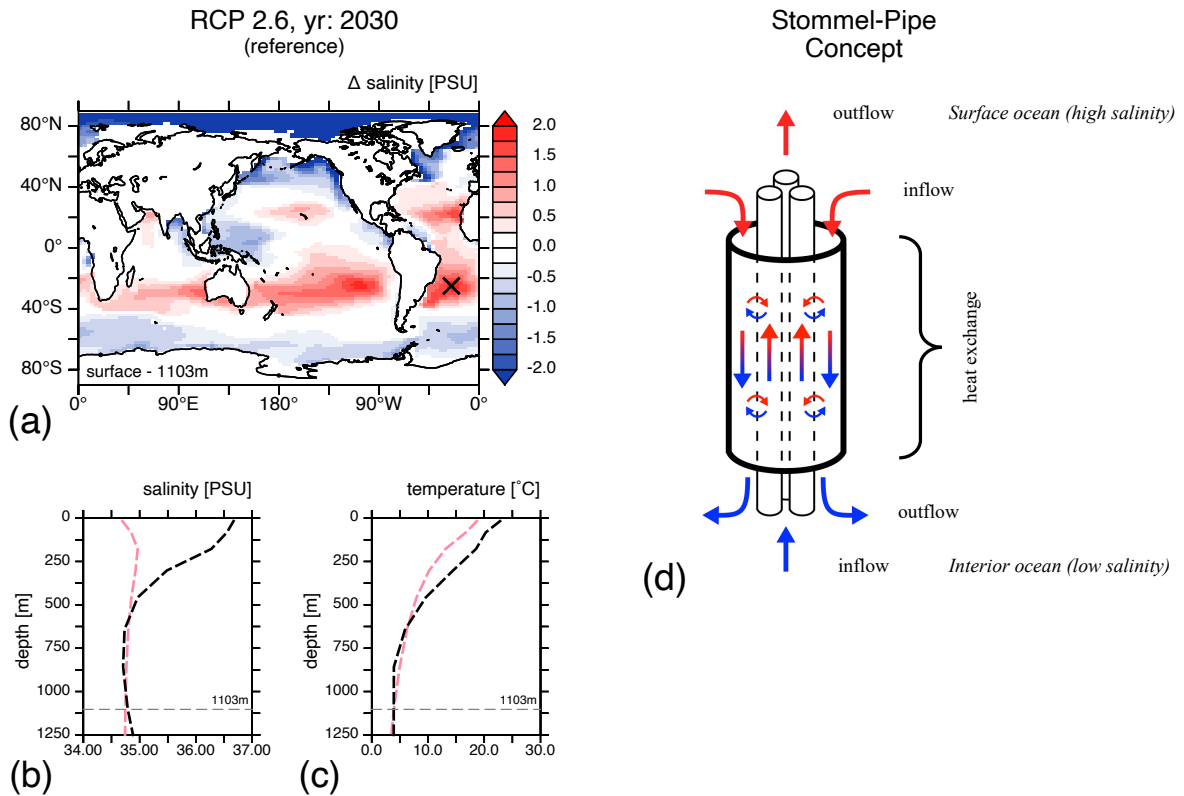


Figure 1: Overview of physical preconditions for a Stommel-Pipe to lead to upwelling. (a) Difference in salinity in PSU between surface ocean and 1103 meters depth for year 2030 along with global average depth profile (pink) and local profile in Southern Atlantic subtropical gyre (black, location marked in panel (a) with “X”) of (b) salinity in PSU and (c) potential temperature in °C for the reference (transient climate change experiment without any marine CDR being simulated) experiment performed under the future RCP 2.6 CO₂-emission pathway. (d) Schematic illustration of general counterflow Stommel-Pipe concept with color code representing water temperatures (red = warm, blue = cold), which leads to simultaneous upwelling and downwelling under temperature and salinity conditions found in e.g., Southern Atlantic subtropical gyre (Kemper et al., 2025). Note that the implicitly simulated Stommel-Pipe

design used in this paper assumes a technical design with 40 inner pipes with 25 cm in diameter each and one outer pipe with a diameter of 225 cm.

2 Methods

Model description

[3] In this study, we use the UVic 2.9 Earth System Climate Model of intermediate complexity (Keller et al., 2012, Yao et al., 2019), which consists of a three-dimensional ocean circulation model, including a sea-ice model, a land model and a simple one-layer atmospheric energy-moisture balance model (Weaver et al., 2001). All model components share a 3.6° longitude and 1.8° latitude resolution. The model ocean consists of 19 vertical levels with a 50 m thick layer at the surface and up to 500 m thick layers in the deep ocean and includes eddy-induced tracer advection, as well as physical parameterizations for diffusive mixing along and across isopycnals (Gent & McWilliams, 1990). Heat and carbon fluxes between all model components are interactively calculated. The land model includes terrestrial vegetation, which is sensitive to temperature and experiences a CO_2 -fertilization effect via atmospheric CO_2 concentrations, and soil organic matter respiration, which is sensitive to and accelerates by increased temperatures (Meissner et al., 2003). The model ocean contains a fully simulated carbon cycle, including CO_2 gas exchange (Orr et al., 1999) and prognostic tracers like alkalinity and DIC, as well as the nutrients phosphate, nitrate and iron. A marine NPZD-ecosystem model represents the biological carbon pump (Frenger et al., 2024), in which we assume a fixed C-N-P-Fe organic matter stoichiometry and no CO_2 -fertilization effect (Keller et al., 2012; Nickelsen et al., 2015; Yao et al., 2019). A simple CaCO_3 counter pump approximation is included as well, but the production and dissolution of CaCO_3 is not sensitive to CO_2 (Schmittner et al., 2008). A detailed description of the model is given in the Supporting Information S1.

Simulation of Stommel-Pipe

[4] We simulate a new shell-and-tube type Stommel-Pipe design as described in Kemper et al. (2025) in a maximum potential approach from a technical perspective (i.e., a maximum potential ocean area pipe-coverage) in the UVic Earth system climate model. The simulated pipe parameterization is based on modelling results for a design with 40 inner pipes with 25 cm in diameter each and one 225 cm in diameter outer pipe, which encloses the inner pipes. The dimensions were chosen based on an optimization study

presented in Kemper et al., 2025. As efficient heat exchange is assumed between the inner and outer pipe, salinity remains within the pipe as the dominant variable to determine water density (Figure 1). This leads to downwelling within the outer pipe, which is filled with heavier, high-salinity surface water, and upwelling within the inner pipes, which are filled with lighter, low-salinity ocean interior water. Overall, the upwelling intensity of a counterflow Stommel-Pipe design depends on absolute surface salinity and temperature, as well as their gradient between the surface ocean and the pipe's source depth, and the overall length of the pipe (Kemper et al., 2025). A different Stommel-Pipe design would lead to a different upwelling intensity per pipe under the same physical preconditions.

[5] We simulate 303, 643 and 1103 meter long pipes with different pipe per area ratios (Table S1) over the entire ocean as part of our maximum potential approach. All three chosen pipe lengths are consistent with depth levels on which ocean tracer calculations are performed within the used UVic model and cover different temperature and salinity gradients between surface ocean and pipe source depth (Figure 1b,c). The upwelling intensity per pipe is individually calculated in each ocean grid cell and time step during model run time and depends on the absolute salinity concentration and temperature at the surface ocean, as well as the relative gradients between the surface ocean and the pipe's source depth. Thus, upwelling intensity is expected to vary with pipe location, season and future CO₂-emission pathway, which also implies a dynamically changing Stommel-Pipe upwelling area during model experiments (see experimental design section). The pipe-length dependent equations to perform this calculation are derived from work of Kemper et al. (2025) and are shown in the Supporting Information (Equation S1 & Table S2). The upwelling and simultaneous downwelling between the surface ocean and the pipe's source depth redistributes all ocean tracers in the UVic model between both layers, including salinity, DIC, alkalinity and all nutrients, but excludes temperature. This implementation implies the assumption of a 100% efficient heat exchange between the inner and outer pipes of the Stommel-Pipe. Thus, the ocean thermocline is not directly impacted via the Stommel-Pipe's activity. The real-world heat exchange efficiency of a Stommel-Pipe would depend on pipe design and build material, length of the pipe and upwelling intensity, i.e., how much time would the upwelling and downwelling streams within the pipe have to exchange heat, and the temperature difference between surface ocean and pipe source depth. The heat exchange is a key advantage of the counterflow Stommel-Pipe design, as e.g., wave-driven artificial upwelling pipes are expected to redistribute heat in the ocean through the upwelling of cold water to the surface ocean and thus, cause major issues within the ocean's and atmosphere's heat content, especially

164 after pipe-termination (Oschlies et al., 2010). However, the Stommel-Pipe directly redistributes salinity
165 and thus, can lead over time to a reduced vertical salinity gradient, which impacts ocean physics and the
166 large-scale circulation in the model, as well as impairs the Stommel-Pipe's own upwelling potential, which
167 strongly depends on the vertical salinity gradient.

168

169 ***Experimental design***

170 [6] Following model spin-up under preindustrial pCO₂ conditions for 10,000 years, we simulate the
171 historical period from the year 1765 to 2006 with CO₂-emissions to the atmosphere, which are consistent
172 with historical fossil fuel and land-use CO₂-emissions, and continue until the year 2100 with either the
173 low RCP 2.6 or high RCP 8.5 CO₂-emission pathway as our reference experiments (Meinshausen et al.,
174 2011). Branching from the reference experiments in year 2025, artificial upwelling via the Stommel-Pipe
175 design is simulated continuously (from the year 2025) until 2100 ("AU-cont.") under both CO₂-emission
176 pathways with different pipe lengths and pipe per area ratios (Jürchott & Kemper 2025). Additionally, we
177 performed experiments in which we stop artificial upwelling in the year 2050 ("AU-stop"), but continue
178 the experiment until year 2100. An overview of all performed model experiments is shown in Table S1.
179 We choose both CO₂-emission pathways to assess i) the potential CO₂-emission pathway dependency for
180 future predicted Stommel-Pipe upwelling performance and ii) the Stommel-Pipe's impact on Earth's
181 carbon cycle. The simulated future CO₂-emission pathways has previously been shown to be one key
182 variable to determine the marine CDR potential of wave-driven artificial upwelling (Jürchott et al., 2023).
183 Artificial upwelling stop-experiments are performed to investigate potential termination issues, which
184 have previously been observed in wave-driven artificial upwelling simulations (Oschlies et al., 2010).

185

186

187 **3 Results and Discussion**

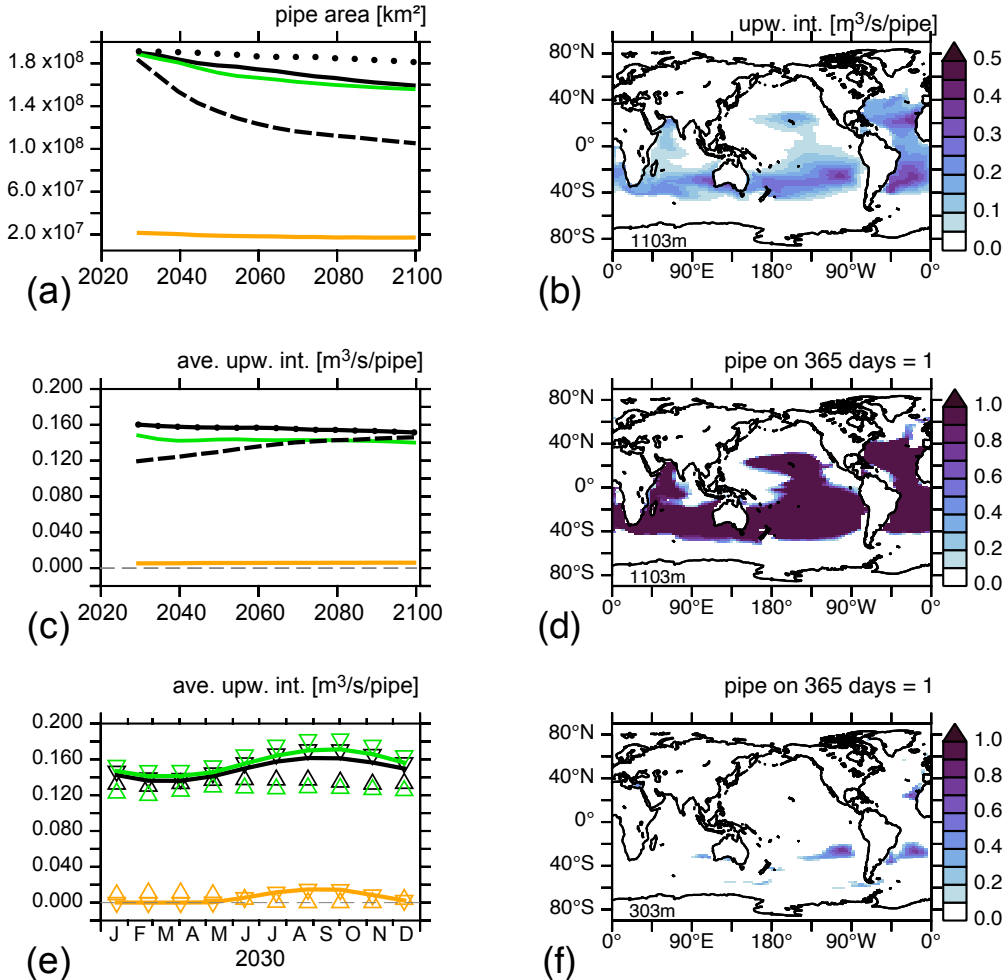
188 ***Stommel-Pipe upwelling potential***

189 [7] Stommel-Pipes with either 643 or 1103 meter length are able to generate significant upwelling over
190 up to $1.9 \cdot 10^8$ km² of the ocean's surface covering regions around the equator and subtropics with hotspots
191 around the subtropical Atlantic and Pacific gyres (Figure 2, S1 and S2). With annual mean upwelling
192 intensities of up to 0.45 m³/s/pipe (Figure 2b) the detected peak upwelling intensity of the Stommel-Pipe
193 in our model is nine times higher than what is currently assumed to be the technical feasibility limit of
194 ocean upwelling devices (0.05 m³/s/pipe, Kowcek 2022). The pipe-covered area for 643 and 1103 meter

pipe length experiments declines over time (Figure 2a). This reduction intensifies with an increase in the simulated pipes per km² ratio and causes a decline in the pipe covered area of 45% down to $1.05 \cdot 10^8$ km² for the 10 pipes per km² experiment until the end of the century under RCP 8.5. We trace the decrease in pipe-covered area back to a degradation of the vertical salinity gradient, which intensifies with stronger overall upwelling (Figure S4a,b). This causes pipes, especially in initially less efficient upwelling regions, to shut down over time, as the physical preconditions for the Stommel-Pipe to lead to upwelling are locally no longer present. However, the annual mean upwelling intensity within the remaining pipe-covered area remains quite stable, but the upwelling efficiency per pipe reduces with a greater pipe per km² ratio (-25% from 1 to 10 pipes per km², Figure 2c). Shorter 303 meter long pipes show overall very limited potential in terms of area and upwelling intensity, as the vertical salinity gradient is not particularly prominent and as a consequence of seasonality effects (Figure 2f, next paragraph).

RCP 8.5

(1 pipe/km², year: 2030)



Legend:

303m — 1 pipe / km² Δ northern Hemisphere
 643m -- 10 pipes / km² ∇ southern Hemisphere
 1103m ... 1 pipe / 10 km²

Figure 2: Overview of present to future Stommel-Pipe performance under future RCP 8.5 CO₂-emission pathway. Change in (a) global pipe-covered area in km² and (c) global mean upwelling intensity within the pipe-covered area in m³/s/pipe over time with (e) monthly resolution for year 2030. Color code represents simulated pipe lengths of 303 (orange), 643 (green) and 1103 meter (black), line style represents simulations of 1 pipe per 10 km² (dotted), 1 pipe per 1 km² (continuous) and 10 pipes per km² (dash) and upward / downward pointing triangles are contribution of pipes located in the Northern / Southern

Hemisphere. The (b) pipe-covered area is spatially resolved for simulations performed with 1 pipe per km² and for year 2030 and shown in shades of blue via the upwelling intensity in m³/s/pipe for 1103 meter long pipes and via the pipe's active upwelling days per year (1 = 365 days active, 0 = 0 days active) for (d) 1103 and (f) 303 meter pipe length. See Figure S2 for RCP 2.6 experiments.

[8] Seasonal changes in salinity and temperature impact the Stommel-Pipe's physical preconditions to lead to upwelling and thus, must be taken into account (Figure 2e and S2e). We find a consistent pattern of lower global mean upwelling intensities between February and March (up to 0.137 m³/s/pipe) and higher upwelling intensities between September and October (up to 0.164 m³/s/pipe). This pattern is dominated by the southern Hemisphere seasonal cycle, as the majority of upwelling generating pipes are located there (Figure 2e), and arises predominantly from seasonal surface ocean temperature changes, as the salinity gradient between the surface and the pipe's source depth is close to stable for 643 and 1103 meter long pipes (Figure S8 & S9). During local winter to spring, the temperature gradient over depth is weakest, which reduces stratification and promotes upwelling via the Stommel-Pipe, while a strong temperature gradient over depth in local summer to autumn reduces the pipe's upwelling potential. For 303 meter long pipes, seasonal changes in temperature and salinity are sufficient to cause global failure of the Stommel-Pipe to lead to upwelling between December and April. Despite simulating all experiments under RCP 2.6 and 8.5 and thus, causing differences in ocean circulation, stratification, ocean surface temperatures, sea-ice cover and evaporation, we find little to no future CO₂-emission pathway dependency for the upwelling intensities of the Stommel-Pipe over time (Figure 2 vs. S2).

Earth system response

[9] In our maximum potential approach, artificial upwelling via Stommel-Pipes does not lead to significant additional ocean carbon uptake but instead causes net ocean CO₂ outgassing (Table 1, Figure 3 and S3). We find stronger CO₂ outgassing under greater overall upwelling and the outgassing is CO₂-emission pathway dependent, with less outgassing under RCP 8.5 compared to experiments performed under RCP 2.6 (up to -168 Pg C under RCP 2.6) due to differences in the atmospheric CO₂ concentration (Figure S5a). The terrestrial carbon cycle partly compensates higher atmospheric CO₂-concentrations via a carbon-concentration feedback (Figure S3c,d). The CO₂ outgassing occurs predominantly over the pipe-covered area around the Southern Pacific (Figure 3g,h) due to the upwelling of DIC-rich ocean interior water to the surface ocean (Figure 3f and S5b) and is accompanied by the accumulation of phosphate and

nitrate at the surface ocean (Figure S6 and S7). The accumulation of phosphate and nitrate at the surface ocean is an indication of an iron-limited ecosystem. Note that we assume a fixed carbon to nutrient stoichiometry in the model's ocean ecosystem, which implies that additional ocean carbon uptake via the biological carbon pump can only occur via the utilization of upwelled preformed nutrients in addition to fully utilization of upwelled remineralized nutrients (Jürchott et al., 2023). Nonetheless, cumulative export production out of the 130 meter depth layer strongly increases by up to 302 Pg C due to the upwelling of ocean interior nutrients (Table 1) However, this increase does not lead to net ocean carbon uptake, but promotes ocean deoxygenation of up to -8 Pmol as a side effect, especially within the mesopelagic zone at around 300 meters depth (Figure 3i). Thus, the stimulated biological carbon pump via Stommel-Pipe upwelling did not compensate for the amount of simultaneously upwelled DIC and ultimately leads to net CO₂ outgassing into the atmosphere. As a consequence, artificial upwelling via the Stommel-Pipe causes a redistribution of carbon from the ocean interior with a relatively long residence time of up to centuries (DeVries & Primeau, 2011) directly to the surface ocean and atmosphere (Figure 3f).

[10] Artificial upwelling via the Stommel-Pipe enhances ocean stratification and slows down ocean circulation (Figure 3c and Table1). The increase in ocean stratification is the consequence of two processes. First, the Stommel-Pipe upwells low-saline water and simultaneously downwells high-saline water, without affecting the thermocline directly (Figure S4a,b), which increases potential density differences between surface ocean and interior ocean (Figure 3c). Second, the unintended CO₂ outgassing promotes higher global mean surface air temperature and, in consequence, higher sea surface temperatures, which reduces CO₂-solubility and further enhances CO₂ outgassing as a positive feedback loop. Additionally, the increased temperature difference between surface ocean and interior ocean promotes a stronger thermocline (Figure S4c,d) and further enhances ocean stratification. The consequence is a reduction in ocean circulation (AMOC decrease of up to -4.56 Sv) with further implications on ocean carbon and heat uptake and transport into the ocean interior (Table 1 and Figure S3e,f). Conclusively, artificial upwelling via the Stommel-Pipe shows low potential as a stand-alone marine CDR approach, as we find no significant additional ocean carbon uptake but net ocean CO₂ outgassing, especially around the Southern Pacific, and enhanced ocean stratification, which causes a significant slowdown in the overturning circulation.

Table 1: Earth system response to different Stommel-Pipe experiments shown for year 2100 with continuous upwelling done between year 2025-2100. Abbreviations: global mean surface air temperature (SAT), atmosphere (C^{atm}), ocean (C^{oce}) and terrestrial (C^{ter}) carbon inventory, cumulative net primary production (cum. NPP) and export production (cum. EP) out of the 130m depth layer, ocean oxygen (O_2) inventory, Atlantic Meridional Overturning Circulation (AMOC) and ocean heat uptake (OHU).

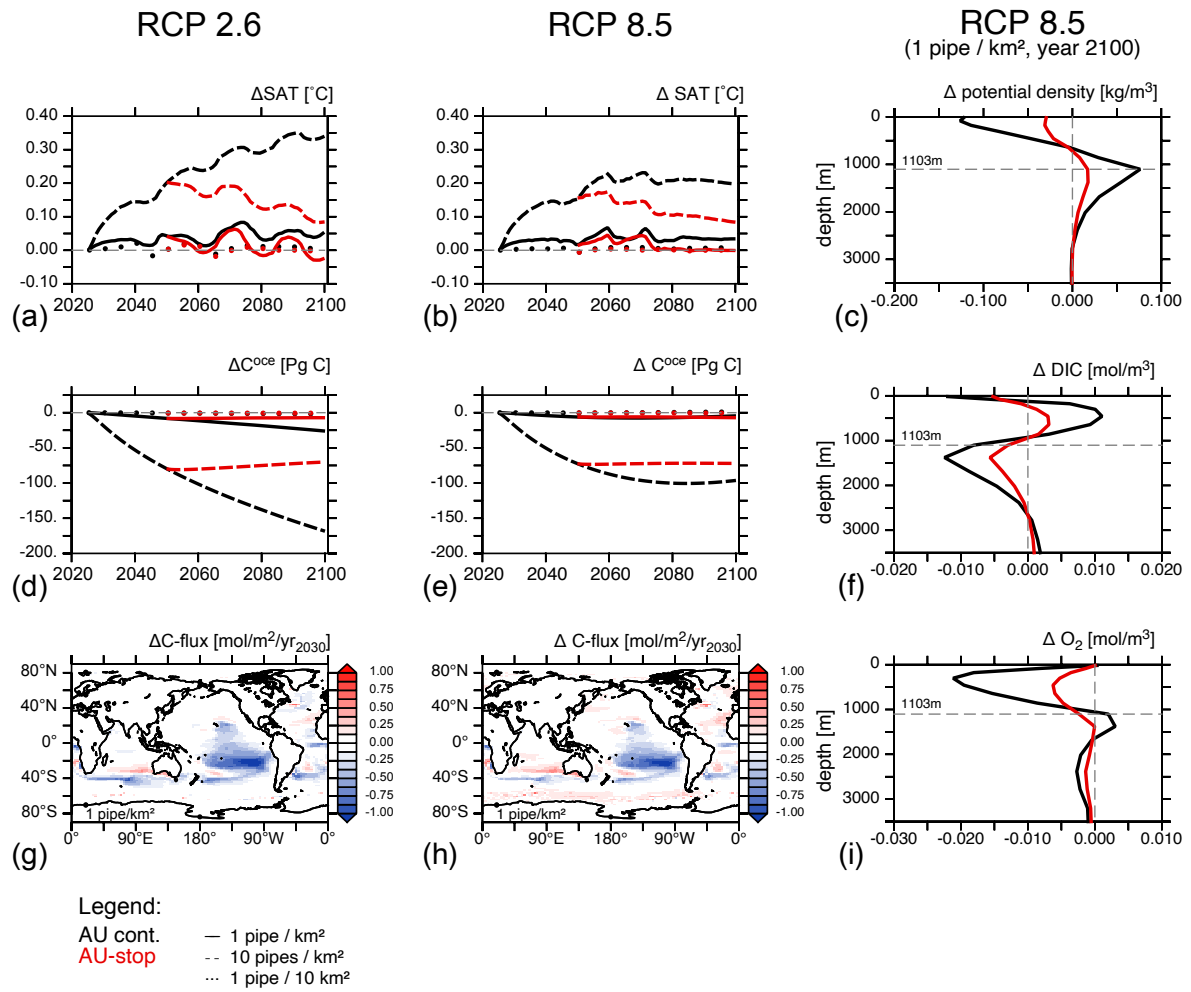
pipe configuration	SAT	C^{atm}	C^{oce}	C^{ter}	cum. NPP	cum. EP	O_2	AMOC	OHU
	[°C]	[Pg C]	[Pg C]	[Pg C]	[Pg C]	[Pg C]	[Pmol]	[Sv]	[W/m ²]
RCP 2.6 reference									
(n/a)	14.68	900	37551	2021	3594	468	223	14.55	0.92
AU – reference									
303m, 1 pipe / km ²	-0.04	-0.8	-0.2	0.9	0	0	0.0	-0.14	0.03
643m, 1 pipe / km ²	0.03	16.4	-20.9	4.5	1379	107	-4.4	-2.38	0.05
1103m, 1 pipe / km ²	0.05	19.3	-25.9	6.6	1644	127	-5.3	-2.45	0.06
1103m, 1 pipe / 10km ²	0.01	1.4	-1.8	0.4	213	20	-0.9	-0.51	-0.01
1103m, 10 pipes / km ²	0.34	122.1	-167.7	45.6	4350	288	-7.1	-4.56	0.39
RCP 8.5 reference									
(n/a)	17.06	2041	37791	2200	3598	459	221	12.47	3.45

301

				AU – reference						
302	303m, 1 pipe / km ²	0.00	-0.2	-0.1	0.3	1	0	0.0	-0.10	0.01
303	643m, 1 pipe / km ²	0.03	10.5	-6.5	-4.0	1490	112	-4.7	-1.95	-0.03
304	1103m, 1 pipe /1km ²	0.03	7.7	-4.6	-3.1	1745	131	-5.6	-1.71	-0.03
305										
306	1103m, 1 pipe / 10km ²	0.01	-0.2	1.1	-0.9	218	20	-1.0	-0.36	-0.01
307	1103m, 10 pipes / 1km ²	0.20	97.8	-96.6	-1.3	4737	302	-8.0	-3.04	0.03

308

309



311

312 **Figure 3:** Earth system response to 1103 meter long Stommel-Pipe perturbation (Stommel-Pipe –
 313 reference experiment). Temporal changes in global mean surface air temperature (a,b) in °C and ocean
 314 carbon inventory (d,e) in Pg C and spatial change in positive downward surface carbon-flux (g,h) in
 315 mol/m²/yr for year 2030 under RCP 2.6 (left column) and RCP 8.5 (middle column). Right column shows
 316 global average change over depth for year 2100 and 1 pipe / km² experiments under RCP 8.5 of (c)
 317 potential density in kg/m³, (f) DIC in mol/m³ and (i) oxygen in mol/m³. Color code represents continuous
 318 artificial upwelling between year 2025-2100 (black) and artificial upwelling being stopped after year 2050
 319 (red). Line style represents simulations of 1 pipe per 10 km² (dotted), 1 pipe per 1 km² (continuous) and
 320 10 pipes per km² (dash). Black and red lines do partly overlap. See Figure S3-S5 for additional
 321 information.

322

323

324 **Termination effect**

325 [11] After artificial upwelling via Stommel-Pipes is terminated in the year 2050, ocean CO₂ outgassing
326 stops and global mean surface air temperature, ocean temperatures and other impaired Earth system
327 variables slowly return towards reference experiment levels (Figure 3, S3, S4 and S6, red lines). However,
328 the ocean carbon inventory remains reduced until the end of the century under both CO₂-emission
329 pathways, especially for the 10 pipes per km² experiments. The redistribution of interior ocean DIC to the
330 surface ocean, the CO₂ outgassing into the atmosphere or the increase in ocean stratification do not resolve
331 50 years after pipe-termination. Therefore, in our model experiments, artificial upwelling via the
332 Stommel-Pipe has no immediate termination effects, as has been previously shown for wave-driven
333 artificial upwelling, where surface air temperatures spiked above reference experiment levels after pipe-
334 termination (Oschlies et al., 2010, see next section).

335

336 **Wave-driven vs. Stommel-Pipe upwelling**

337 [12] Artificial upwelling via wave-driven pipes and Stommel-Pipes conceptually differ in terms of their
338 potential ocean application area. While wave-driven pipes can be deployed in theory everywhere in the
339 ocean, Stommel-Pipes only function under previously discussed physical preconditions, which get altered
340 through the Stommel-Pipe's own upwelling activity (reduced salinity gradient over depth). Additionally,
341 the upwelling intensity of a Stommel-Pipe changes with length, location and season, whereas wave-driven
342 pipes would upwell a wave-dependent flow to the surface ocean. Second, Stommel-Pipe upwelling
343 enhances ocean stratification and reduces the overturning circulation, while wave-driven upwelling
344 reduces stratification, enhances the overturning circulation, and strongly enhances ocean heat uptake via
345 the upwelling of cold ocean interior water to the surface ocean (Oschlies et al., 2010, Jürchott et al., 2025).
346 Under large-scale simulation of wave-driven pipes the upwelling of cold water enhances surface ocean
347 CO₂ solubility and cools down the atmosphere, which causes a carbon-climate feedbacks and enhances
348 terrestrial carbon uptake (Jürchott et al., 2025). The thermocline disruption and terrestrial carbon-climate
349 feedback do not occur under Stommel-Pipe upwelling due to efficient heat exchange between the upward
350 and downward streams within the pipe. Furthermore, enhanced ocean heat uptake via wave-driven pipes
351 causes additional heat to be stored in the ocean interior, which resurfaces after pipe-termination, causing
352 global mean surface air temperature to rise beyond reference experiment levels without simulated artificial

upwelling (Oschlies et al., 2010). This undesirable termination effect also does not occur under simulated Stommel-Pipe upwelling. Artificial upwelling via wave-driven and via Stommel-Pipes are similar in terms of their stimulation of the ocean ecosystem. Both pipe types enhance net primary production, export production and promote deoxygenation, but fail to enhance ocean carbon uptake via the biological carbon pump as a consequence of iron-limitation especially in the Pacific Ocean (Jürchott et al., 2024).

5 Conclusions and Outlook

[13] From a technical perspective, artificial upwelling via the simulated counterflow Stommel-Pipe design (Kemper et al., 2025) can lead to significant upwelling, especially around the subtropical Atlantic and Pacific gyres, if done with either 643 or 1103 meter long pipes, and without the immediate risk of directly redistributing ocean heat throughout the water column via the pipe's upwelling and downwelling activity. However, the redistribution of salinity leads to an increase in ocean stratification and causes a slowdown in the overturning circulation. We note that the assumed and simulated 100% efficient heat exchange between the inner and outer pipes, as well as the calculated upwelling intensities, need to be verified with e.g., a prototype field trial, as these details are key assumptions of our study, which could impact the pipe's upwelling performance, marine CDR potential and the overall response of the Earth's carbon cycle and heat budget during pipe-deployment and after pipe-termination. From the perspective of the surface ocean ecosystem, artificial upwelling is very effective in upwelling nutrient-rich ocean interior water and promoting net primary production, possibly with the potential for improved fish production (Kirke 2003, Goldenberg et al., 2024), but is strongly limited by iron availability at the surface ocean in the Pacific ocean and leads through enhanced export production to enhanced ocean deoxygenation as a side effect. From a marine CDR perspective, artificial upwelling via the Stommel-Pipe would cause CO₂-emission pathway dependent net ocean CO₂ outgassing, especially around the Southern Pacific subtropical gyre, and accelerate future global mean surface air temperature increase via the redistribution of carbon from the ocean interior to the surface ocean and atmosphere. Conclusively, Stommel-Pipe upwelling should not be considered or pursued as a stand-alone marine CDR approach to be deployed in the Southern Pacific. However, artificial upwelling via the Stommel-Pipe could be further investigated around the Atlantic Ocean or as a supporting technology for other marine CDR approaches, such as ocean iron fertilization (Jürchott et al., 2024) or in combination with open ocean macro-algae farming (Wu et al., 2023), which strongly relies on additional nutrient supply to the surface ocean.

384 **Acknowledgment**

385 The author’s wish to acknowledge funding from German Federal Ministry of Education and Research,
386 (grant no. 03F0897A; project Test-ArtUp), which contributes to the CDRmare research mission and is
387 part of the DAM Mission “Marine carbon sinks in decarbonization pathways”. We acknowledge
388 discussions with colleagues from the Project Test-ArtUp and the Biogeochemical Modelling research unit
389 at GEOMAR. We thank Wolfgang Koeve (GEOMAR) for discussions and comments that helped to clarify
390 the manuscript, and acknowledge the use of the PyFerret program for analysis and graphics in this paper.
391
392

393 **Open Research**

394 Data is available at Jürchott & Kemper (2025).
395
396

397 **Conflict of interest statement**

398 All authors declare that there is no conflict of interest related to this manuscript.
399
400

401 **References**

402 DeVries, T., & Primeau, F. (2011). Dynamically and observationally constrained estimates of water-mass
403 distributions and ages in the global ocean. *Journal of Physical Oceanography*, 41(12), 2381-2401.
404 <https://doi.org/10.1175/JPO-D-10-05011.1>
405

406 Frenger, I., Landolfi, A., Kvale, K., Somes, C. J., Oeschlies, A., Yao, W., & Koeve, W. (2024).
407 Misconceptions of the marine biological carbon pump in a changing climate: Thinking outside the
408 “export” box. *Global Change Biology*, 30, e17124. <https://doi.org/10.1111/gcb.17124>
409

410 Gent, P. R., & McWilliams, J. C. (1990). Isopycnal mixing in ocean circulation models. *Journal of*
411 *Physical Oceanography*, 20(1), 150–155. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0485(1990)020<0150:IMIOCM>2.0.CO;2)
412 [0485\(1990\)020<0150:IMIOCM>2.0.CO;2](https://doi.org/10.1175/1520-0485(1990)020<0150:IMIOCM>2.0.CO;2)
413

- Goldenberg, S. U., Spisla, C., Sánchez, N., Taucher, J., Spilling, K., Sswat, M., ... & Riebesell, U. (2024). Diatom-mediated food web functioning under ocean artificial upwelling. *Scientific Reports*, 14(1), 3955. DOI:10.1038/s41598-024-54345-w
- IPCC. (2022). Summary for policymakers. In P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, et al. (Eds.), *Climate change 2022: Mitigation of climate change. Contribution of working group III to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press. <https://doi.org/10.1017/9781009157926.001>
- Jürchott, M., Oschlies, A., & Koeve, W. (2023). Artificial upwelling—A refined narrative. *Geophysical Research Letters*, 50(4), e2022GL101870. <https://doi.org/10.1029/2022GL101870>
- Jürchott, M., Koeve, W., & Oschlies, A. (2024). The response of the ocean carbon cycle to artificial upwelling, ocean iron fertilization and the combination of both. *Environmental Research Letters*, 19(11), 114088. DOI 10.1088/1748-9326/ad858d
- Jürchott, M., Oschlies, A., Mengis, N., Frenger, I., & Koeve, W. (2025). Direct cooling effect of artificial upwelling dominates over its marine carbon dioxide removal potential. *Environmental Research Letters*. DOI 10.1088/1748-9326/ac0054
- Jürchott, Malte, and Kemper, Jost (2025). Supplemental data to: Artificial upwelling via Stommel-Pipe as a marine CDR option? A present to future performance assessment in an Earth system model. [dataset]. GEOMAR Helmholtz Centre for Ocean Research Kiel [distributor]. <https://hdl.handle.net/20.500.12085/25c6e29a-192c-11f0-812d-005056a30ade>
- Keller, D. P., Oschlies, A., & Eby, M. (2012). A new marine ecosystem model for the University of Victoria Earth System Climate Model. *Geoscientific Model Development*, 5(5), 1195–1220. <https://doi.org/10.5194/gmd-5-1195-2012>

443 Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., & Riebesell, U. (2025). On the potential of
 444 Stommel's perpetual salt fountain for artificial upwelling. *Environmental Research Letters*.
 445 doi:10.1088/1748-9326/ade0d3
 446
 447 Kirke, B. (2003). Enhancing fish stocks with wave-powered artificial upwelling.
 448 *Ocean Coastal Manag.* 46, 901–915. doi: 10.1016/S0964-5691(03)00067-X
 449
 450 Kowek, D. A. (2022). Expected limits on the potential for carbon dioxide removal from artificial
 451 upwelling. *Frontiers in Marine Science*, 9, 841894. <https://doi.org/10.3389/fmars.2022.841894>
 452
 453 Lovelock, J. E., & Rapley, C. G. (2007). Ocean pipes could help the Earth to cure itself. *Nature*,
 454 449(7161), 403. <https://doi.org/10.1038/449403a>
 455
 456 Meinshausen, M., Smith, S. J., Calvin, K. V., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., et al.
 457 (2011). The RCP greenhouse gas concentrations and their extension from 1765 to 2300. *Climatic Change*,
 458 109(1–2), 213–241. <https://doi.org/10.1007/s10584-011-0156-z>
 459
 460 Meissner, K.J., Weaver, A.J., Matthews, H.D. *et al.* The role of land surface dynamics in glacial inception:
 461 a study with the UVic Earth System Model. *Climate Dynamics* 21, 515–537 (2003).
 462 <https://doi.org/10.1007/s00382-003-0352-2>
 463
 464 National Academies of Sciences, Engineering, and Medicine. 2022. *A Research Strategy for Ocean-based*
 465 *Carbon Dioxide Removal and Sequestration*. Washington, DC: The National Academies Press.
 466 <https://doi.org/10.17226/26278>.
 467
 468 Nickelsen, L., Keller, D. P., & Oeschies, A. (2015). A dynamic marine iron cycle module coupled to the
 469 University of Victoria Earth System Model: the Kiel Marine Biogeochemical Model 2 for UVic
 470 2.9. *Geoscientific Model Development*, 8(5), 1357-1381. <https://doi.org/10.5194/gmd-8-1357-2015>, 2015
 471
 472 Orr, J. C., Najjar, R., Sabine, C. L., & Joos, F. (1999). Abiotic-HOWTO, internal OCMIP report,
 473 LSCE/CEA Saclay, Gif-sur-Yvette, France (p. 25).

- Oschlies, A., Pahlow, M., Yool, A., & Matear, R. J. (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer's apprentice. *Geophysical Research Letters*, 37(4), L04701. <https://doi.org/10.1029/2009GL041961>
- Oschlies, A., Bach, L. T., Fennel, K., Gattuso, J. P., & Mengis, N. (2025). Perspectives and challenges of marine carbon dioxide removal. *Frontiers in Climate*, 6, 1506181. <https://doi.org/10.3389/fclim.2024.1506181>
- Pan, Y., Fan, W., Zhang, D., Chen, J., Huang, H., Liu, S., ... & Chen, Y. (2016). Research progress in artificial upwelling and its potential environmental effects. *Science China Earth Sciences*, 59(2), 236-248. doi: 10.1007/s11430-015-5195-2
- Schmittner, A., Oschlies, A., Matthews, H. D., & Galbraith, E. D. (2008). Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO₂ emission scenario until year 4000 AD. *Global biogeochemical cycles*, 22(1). <https://doi.org/10.1029/2007GB002953>
- Stommel, H., Arons, A. B., and Blanchard, D. (1956). An Oceanographical Curiosity: The Perpetual Salt Fountain. *Deep Sea Research* (1953) 3, 152–153. doi:10.1016/0146-6313(56)90095-8
- Weaver, A. J., Eby, M., Wiebe, E. C., Bitz, C. M., Duffy, P. B., Ewen, T. L., et al. (2001). The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates. *Atmosphere-Ocean*, 39(4), 361–428. <https://doi.org/10.1080/07055900.2001.9649686>
- Wu, J., Keller, D. P., & Oschlies, A. (2023). Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study. *Earth System Dynamics*, 14(1), 185-221. <https://doi.org/10.5194/esd-14-185-2023>

503 Yao, W., Kvale, K. F., Achterberg, E., Koeve, W., & Oschlies, A. (2019). Hierarchy of calibrated global
504 models reveals improved distributions and fluxes of biogeochemical tracers in models with explicit
505 representation of iron. *Environmental Research Letters*, 14(11), 114009. doi:10.1088/1748-9326/ab4c52
506

1	Supporting Information for
2	Artificial upwelling via Stommel-Pipe as a marine CDR option?
3	A present to future performance assessment in an Earth system model.
4	Jürchott, M. ¹ and Kemper, J. ²
5	¹ GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
6	² Kiel University, Germany
7	
8	Contents of this file
9	
10	Text S1
11	Equation S1
12	Table S1 to S2
13	Figures S1 to S9
14	
15	
16	Introduction
17	Here, we provide Supplementary Methods (Text S1), Equation (S1), Tables (S1 to S2)
18	and Figures (S1 to S9), which present details of our model experiments.
19	
20	
21	

Text S1.

Supplementary Methods

UVic model

The UVic 2.9 Earth System Climate Model of intermediate complexity (Weaver et al., 2001, Keller et al., 2012, Yao et al., 2019) consists of three components: a three-dimensional ocean circulation model, including a sea-ice model, a land model, and a simple one-layer atmospheric energy-moisture balance model. All model components share a 3.6° longitude and 1.8° latitude resolution.

In the atmospheric energy-moisture balance model, the heat and water fluxes to the ocean, sea-ice, and land model components are interactively calculated. We prescribe wind forcing via monthly mean winds from NCAR/NCEP climatological data. The CO₂ concentration in the atmosphere is influenced via introduced CO₂ emissions and the respective response of the terrestrial and ocean carbon sink / source behavior, which allows for carbon concentration and carbon climate Earth system feedbacks. Gas exchange of oxygen and CO₂ with the ocean model component is simulated as in Orr et al. (1999).

The ocean circulation model (MOM, Modular Ocean Model 2) includes physical parameterizations for diffusive mixing along and across isopycnals and eddy-induced tracer advection (Gent & McWilliams, 1990). The model ocean consists of 19 vertical levels with a 50 m thick layer at the surface and up to 500 m thick layers in the deep ocean and contains a fully simulated carbon cycle including prognostic tracers like alkalinity and dissolved inorganic carbon (DIC), as well as the nutrients phosphate, nitrate and iron (Nickelsen et al., 2015). The calibrated and prognostic iron cycle of the model includes a monthly and spatially resolved dust deposition surface mask, hydrothermal iron sources and the process of iron-scavenging, thus, affecting dissolved iron distribution through the water column (Figure S7h). A marine NPZD (Nutrients - Primary Producers - Zooplankton - Detritus) ecosystem model represents the biological

52 carbon pump (Keller et al., 2012). We assume a fixed nutrient organic matter
53 stoichiometry with C-N-P ratio following Redfield and a N-Fe ratio of 1 mol N per 10
54 $\mu\text{mol Fe}$ (Yao et al., 2019). The marine ecosystem experiences no CO_2 -fertilization effect
55 (Keller et al., 2012). A simple CaCO_3 counter pump approximation is included, but the
56 production and dissolution of CaCO_3 is not sensitive to CO_2 (Schmittner et al., 2008). In
57 order to avoid excessively long model spin-up times for our model experiments, we do
58 not simulate sediment processes. Any organic detritus or CaCO_3 reaching the bottom of
59 the model is dissolved in the deepest wet box instantaneously.

60

61 The land model is based on the Hadley Center model TRIFFID and contains vegetation
62 and an interactive carbon cycle with five soil depth levels (Meissner et al., 2003, Keller et
63 al., 2012). Terrestrial vegetation is sensitive to surface air temperature and experiences a
64 fertilization effect via atmospheric CO_2 concentrations. Soil organic matter respiration is
65 sensitive to and accelerates by an increase in surface air temperature (Meissner et al.,
66 2003).

67

68

69 Stommel-Pipe implementation

70 We simulate the shell-and-tube type Stommel-Pipe concept described in Kemper et al.
71 (2025) in a maximum potential approach from a technical perspective (i.e., everywhere in
72 the ocean, where upwelling is possible, Figure 2d,f) in the UVic Earth System Climate
73 Model. The simulated pipe design parameterization assumes 40 inner pipes with 25 cm in
74 diameter each and one 225 cm in diameter outer pipe. This system has a length of either
75 303, 643 or 1103 meters. All three chosen pipe lengths are consistent with depth levels on
76 which ocean tracer calculations are performed within the UVic model. The upwelling and
77 simultaneous downwelling between the surface ocean and the pipe's source depth
78 redistributes all ocean tracers in the UVic model between both layers, including salinity,
79 DIC, alkalinity, and all nutrients. Since we assume 100% efficient heat exchange between
80 the inner and outer pipe, we exclude the ocean's temperature tracer from the pipe's
81 pumping activity. The downwelling intensity is assumed to be equal to the upwelling

intensity. Thus, the Stommel-Pipe implementation does not violate mass conservation within the ocean model.

The upwelling intensity of the Stommel-Pipe is dynamically calculated at each ocean grid cell and during every model time step and depends on the prevalent absolute salinity concentration and temperature at the surface ocean, as well as the relative gradients between the surface ocean and the pipe's source depth. The pipe-length-dependent equations to perform these calculations are derived from Kemper et al. (2025) and are shown as Equation S1 and Table S2. These equations were fitted to data from global simulations using the numerical performance prediction method for Stommel-Pipes SP1D. The SP1D method solves two basic equilibria governing the flow in Stommel-Pipes on a one-dimensional grid using pipe flow theory. A full description of the SP1D method, along with extensive validation against Reynolds-Averaged Navier-Stokes based CFD calculations, is presented in Kemper et al. (2025) and references. As the run time required by the SP1D method to compute upwelling intensities for each UVic grid cell exceeds the runtime for one time step of the UVic model by several orders of magnitude, a direct coupling between both was not considered practical. We thus decided to fit an algebraic meta model to global upwelling data calculated with the SP1D method for a single time step. The resulting polynomial functions to calculate the upwelling intensity of the considered Stommel-Pipe system (see Equation S1 and Table S2) were directly implemented into the UVic model to control the pipe's upwelling intensity.

104 **Equation S1.** Calculation of Stommel-Pipe upwelling intensity in m³/s/pipe built into the
 105 UVic model after Kemper et al. (2025). Variables: “topPT” = surface potential
 106 temperature, “topPS” = surface practical salinity, “deltaPT” = difference in potential
 107 temperature between surface and pipe’s source depth, “deltaPS” = difference in practical
 108 salinity between surface and pipe’s source depth. Coefficients (C_(x)) are pipe-length
 109 dependent and are shown in Table S2.

110

$$\begin{aligned}
 111 \quad upwint = & C_{(1)} + (C_{(2)} * topPT) + (C_{(3)} * deltaPT) + (C_{(4)} * topSP) \\
 112 & + (C_{(5)} * deltaSP) + (C_{(6)} * topPT^2) + (C_{(7)} * topPT * deltaPT) \\
 113 & + (C_{(8)} * topPT * topSP) + (C_{(9)} * topPT * deltaSP) \\
 114 & + (C_{(10)} * deltaPT^2) + (C_{(11)} * deltaPT * topSP) \\
 115 & + (C_{(12)} * deltaPT * deltaSP) + (C_{(13)} * topSP^2) \\
 116 & + (C_{(14)} * topSP * deltaSP) + (C_{(15)} * deltaSP^2)
 \end{aligned}$$

117

118

119

Table S1: Overview of conducted experiments performed with the UVic 2.9 Earth System Climate Model of intermediate complexity with information about the experiment name, the future RCP CO₂-emission pathway, time period and simulated Stommel-Pipe length and amount deployed per area.

experiment name:	CO ₂ -emission pathway:	time period [years]:	pipe length [m]:	pipes per area:
REF_2.6	RCP 2.6	2025-2100	n/a	n/a
AU_303_1x_2.6	RCP 2.6	2025-2100	303	1 Pipe / 1 km ²
AU_643_1x_2.6	RCP 2.6	2025-2100	643	1 Pipe / 1 km ²
AU_1103_1x_2.6	RCP 2.6	2025-2100	1103	1 Pipe / 1 km ²
AU_1103_0.1x_2.6	RCP 2.6	2025-2100	1103	1 Pipe / 10 km ²
AU_1103_10x_2.6	RCP 2.6	2025-2100	1103	10 Pipes / 1 km ²
AU_stop_1103_1x_2.6	RCP 2.6	2050-2100	n/a	n/a
AU_stop_1103_0.1x_2.6	RCP 2.6	2050-2100	n/a	n/a
AU_stop_1103_10x_2.6	RCP 2.6	2050-2100	n/a	n/a
REF_8.5	RCP 8.5	2025-2100	n/a	n/a
AU_303_1x_8.5	RCP 8.5	2025-2100	303	1 Pipe / 1 km ²
AU_643_1x_8.5	RCP 8.5	2025-2100	643	1 Pipe / 1 km ²
AU_1103_1x_8.5	RCP 8.5	2025-2100	1103	1 Pipe / 1 km ²
AU_1103_0.1x_8.5	RCP 8.5	2025-2100	1103	1 Pipe / 10 km ²
AU_1103_10x_8.5	RCP 8.5	2025-2100	1103	10 Pipes / 1 km ²
AU_stop_1103_1x_8.5	RCP 8.5	2050-2100	n/a	n/a
AU_stop_1103_0.1x_8.5	RCP 8.5	2050-2100	n/a	n/a
AU_stop_1103_10x_8.5	RCP 8.5	2050-2100	n/a	n/a

Table S2: Overview of pipe-length dependent coefficients to be used in equation S1 to calculate Stommel-Pipe upwelling intensity in $\text{m}^3/\text{s}/\text{pipe}$ in the UVic model after Kemper et al. (2025).

coefficient:	pipe-length:		
	303 m	643 m	1103 m
$C_{(1)}$	4.5829	22.7668	30.3903
$C_{(2)}$	0.1119	0.5969	0.3285
$C_{(3)}$	-0.1217	-0.9968	-1.1713
$C_{(4)}$	-0.311	-1.3617	-1.7217
$C_{(5)}$	0.4625	1.8318	10.8028
$C_{(6)}$	0.0003	0.0007	-0.0025
$C_{(7)}$	-0.0007	-0.004	0.001
$C_{(8)}$	-0.0035	-0.0168	-0.0084
$C_{(9)}$	0.0012	0.0096	0.0444
$C_{(10)}$	0.0005	0.0039	0.0015
$C_{(11)}$	0.0036	0.0285	0.0332
$C_{(12)}$	-0.0083	-0.0447	-0.0853
$C_{(13)}$	0.0052	0.0203	0.0243
$C_{(14)}$	-0.0103	-0.0365	-0.3006
$C_{(15)}$	0.0162	0.0475	0.3224

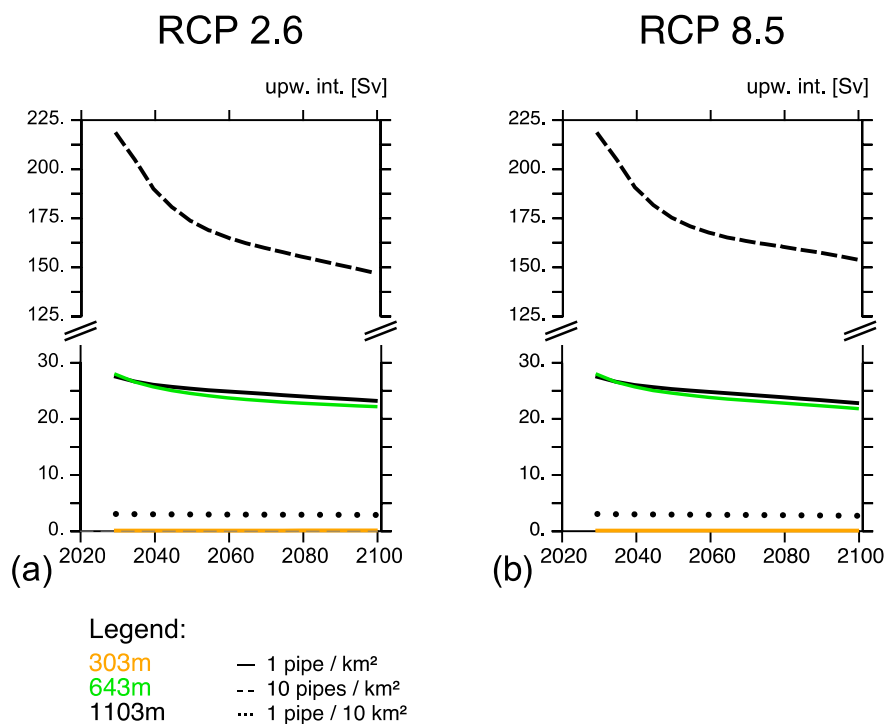
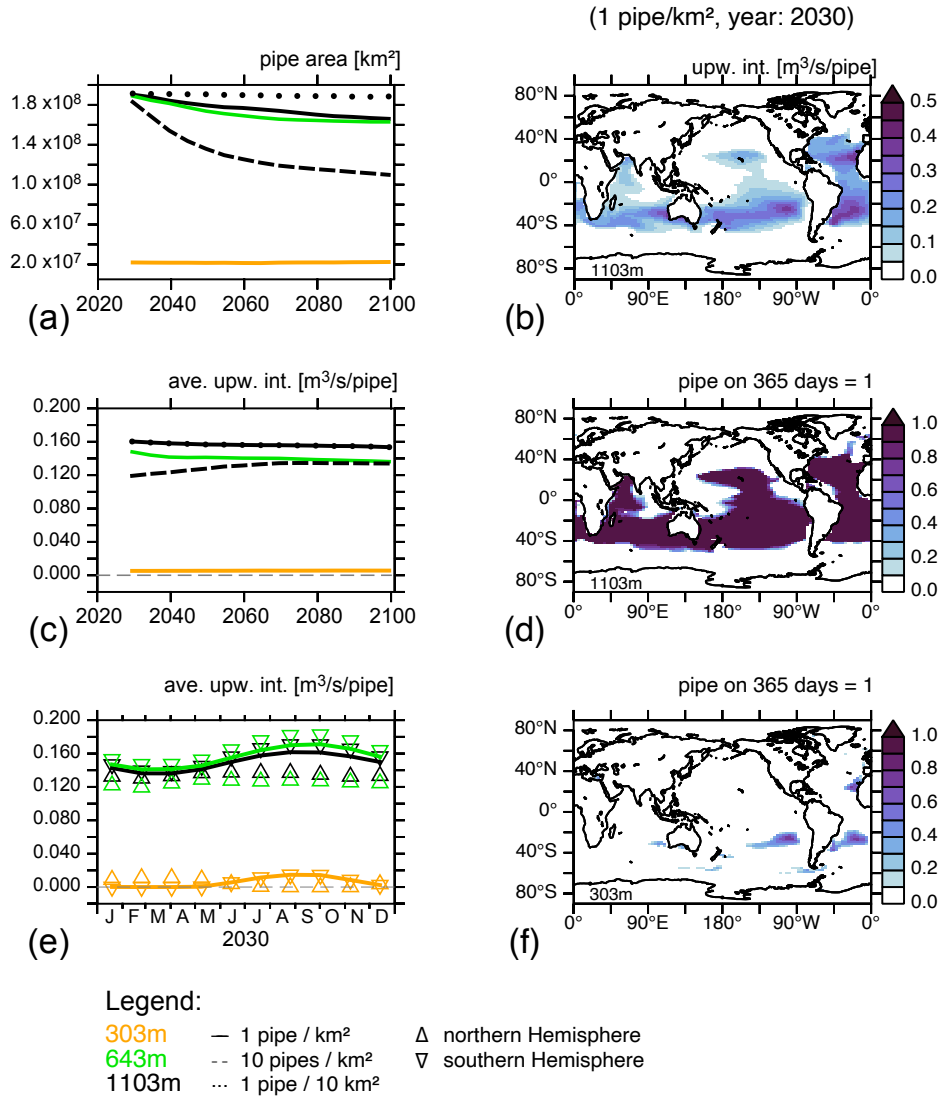


Figure S1. Present to future global Stommel-Pipe upwelling intensities in Sverdrup under RCP 2.6 (a) and RCP 8.5 (b). Color and line code same as in Figure 2.

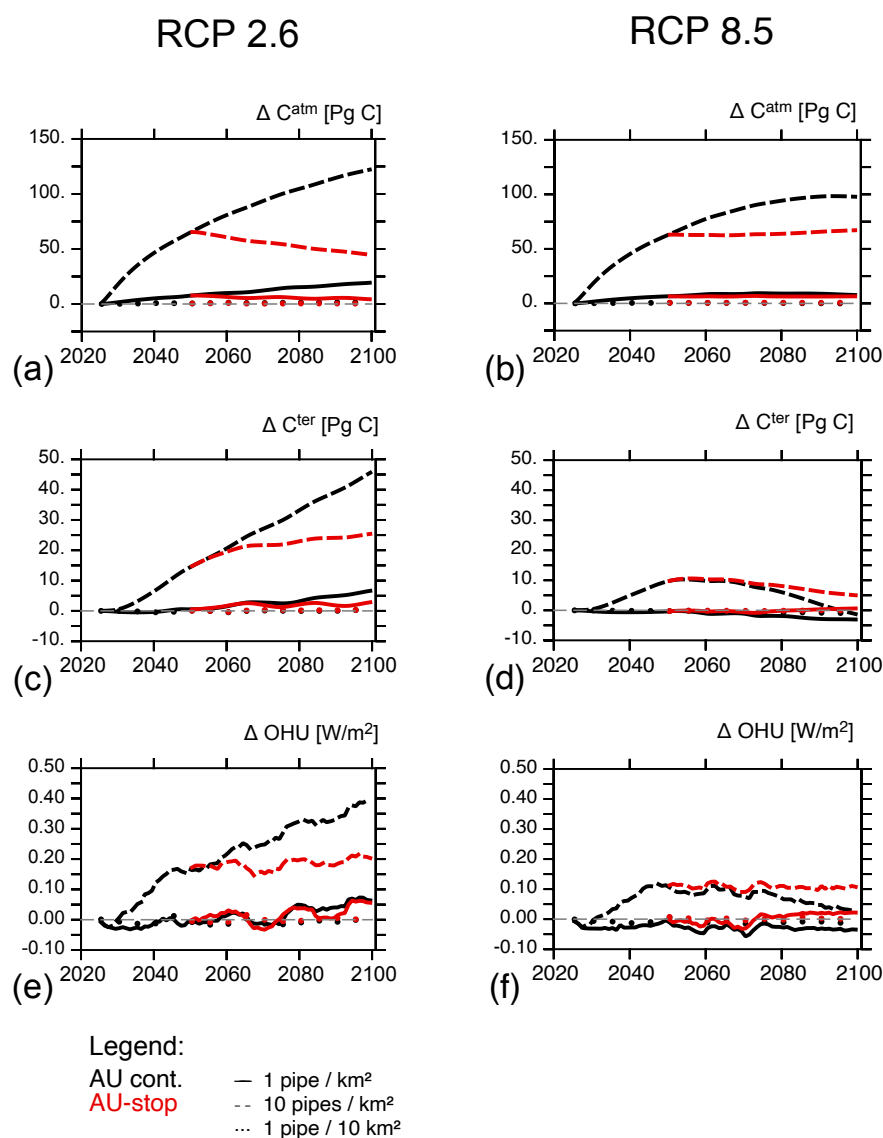
RCP 2.6



177

178 **Figure S2.** Overview of present to future Stommel-Pipe performance under future RCP
 179 2.6 CO₂-emission pathway . Change in (a) global pipe-covered area in km² and (c) global
 180 mean upwelling intensity within the pipe-covered area in m³/s/pipe over time with (e)
 181 monthly resolution for year 2030. The pipe-covered area is spatially resolved for
 182 simulations performed with 1 pipe per km² and for year 2030 and shown in shades of
 183 blue via the upwelling intensity in m³/s/pipe for 1103 meter long pipes (b) and via the
 184 pipe's active upwelling days per year (1 = 365 days active, 0 = 0 days active) for 1103 (d)
 185 and 303 (f) meter pipe length. Color code and line style same as in Figure 2.

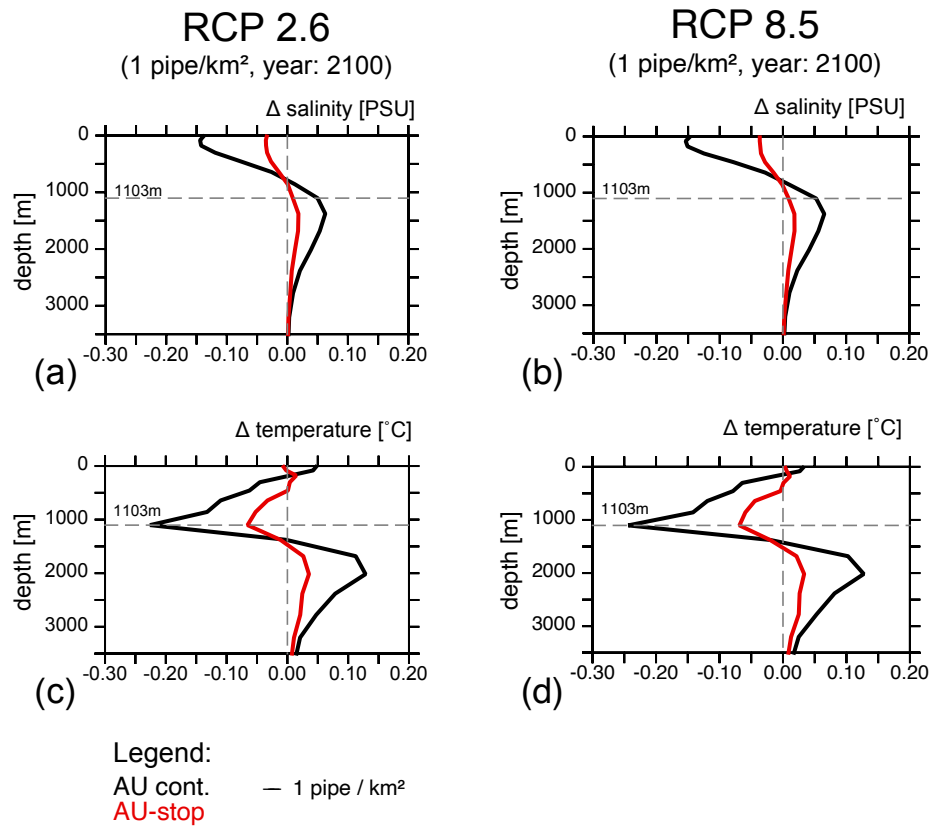
9



187

188 **Figure S3.** Earth system response to 1103 meter long Stommel-Pipe perturbation
 189 (Stommel-Pipe – reference experiment) under RCP 2.6 (left) and RCP 8.5 (right).
 190 Temporal changes in the atmosphere (a,b) and terrestrial (c,d) carbon inventory and
 191 ocean heat uptake (e,f, OHU). Color code and line style same as in Figure 3.

192



193

194 **Figure S4.** Change in global average depth profiles of salinity (a,b) and temperature (c,d)
 195 (Stommel-Pipe – reference experiment) under RCP 2.6 (left) and RCP 8.5 (right) with 1
 196 pipe per km² pipe-configuration. Color code and line style same as in Figure 3.

197

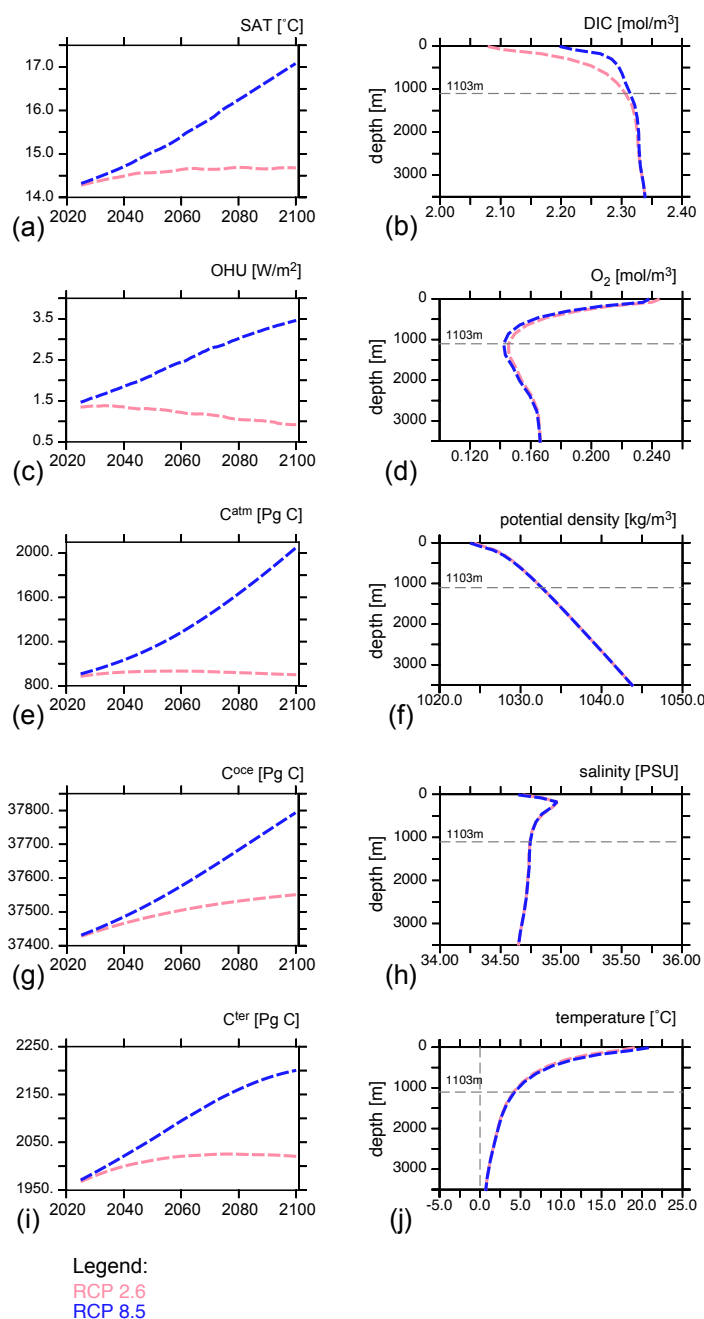
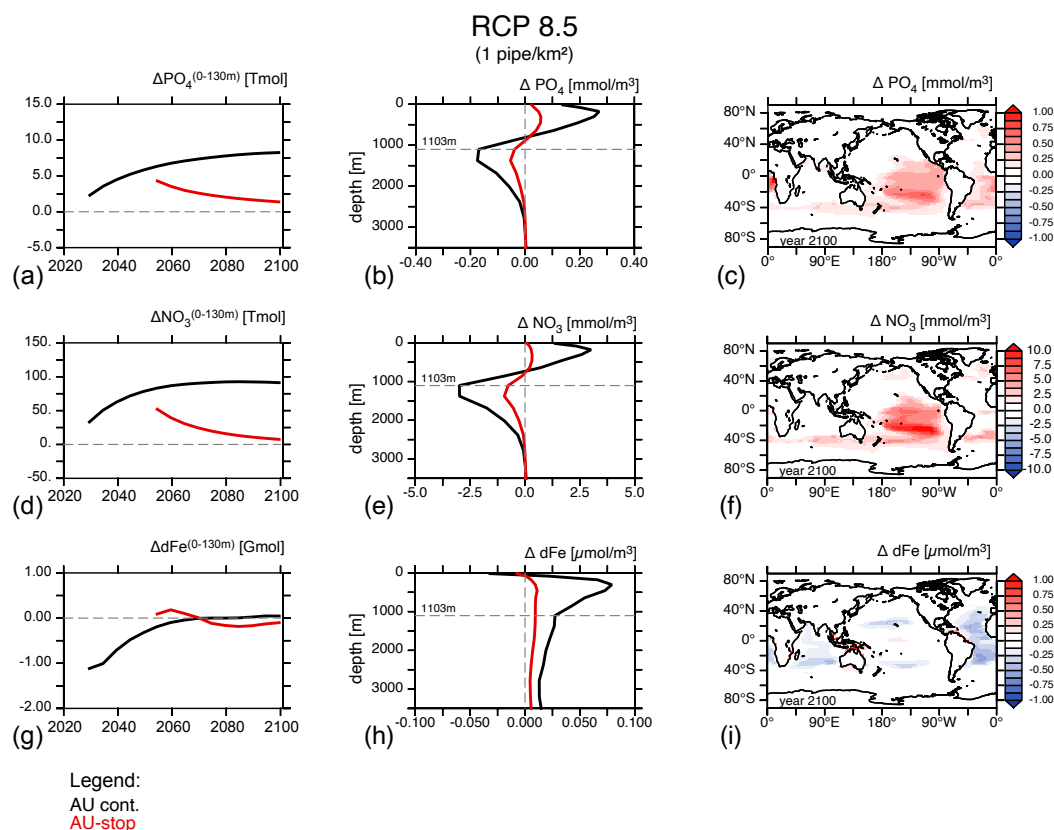


Figure S5. Overview of reference experiments for RCP 2.6 (pink) and RCP 8.5 (blue). Transient response in (a) global mean surface air temperature (SAT), (c) ocean heat uptake (OHU) and (e) atmosphere, (g) ocean and (i) terrestrial carbon inventory. Global average depth profiles for year 2100 of (b) DIC, (d) oxygen, (f) potential density, (h) salinity and (j) temperature.



205

206 **Figure S6.** Change in ocean phosphate (top row), nitrate (middle row) and dissolved iron
 207 (bottom row) nutrients (Stommel-Pipe – reference experiment) under RCP 8.5 with 1
 208 pipe per km² pipe-configuration. Change in ocean surface (0-130m) inventories (left
 209 column), global average depth profiles (middle column) and spatially resolved surface
 210 concentrations (right column) for year 2100. Color code and line style same as in Figure
 211 3.

212

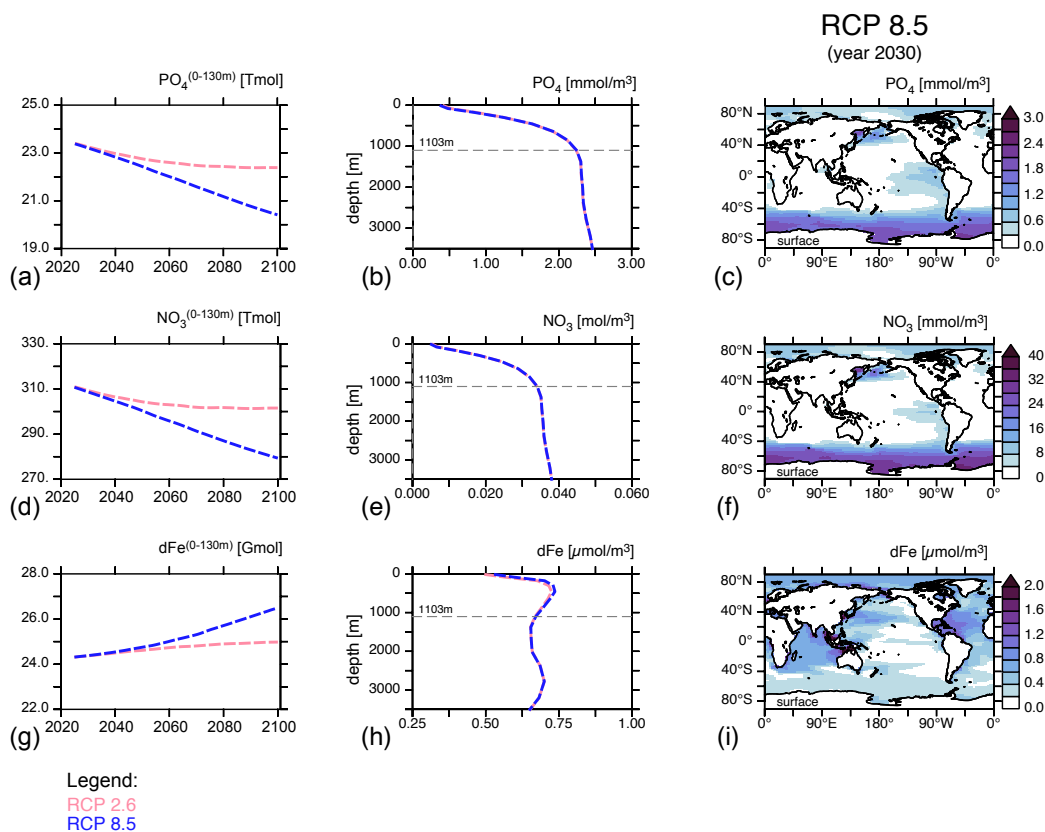
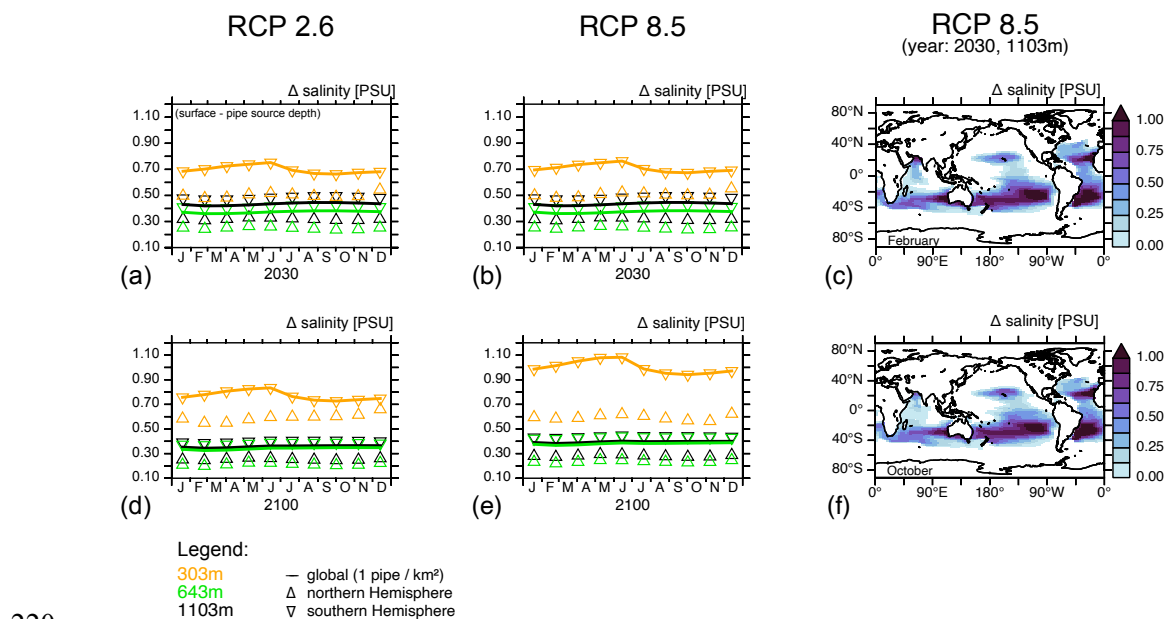


Figure S7. Overview of reference experiments for RCP 2.6 (pink) and RCP 8.5 (blue) for ocean phosphate (top row), nitrate (middle row) and dissolved iron (bottom row) nutrients. Change in ocean surface (0-130m) inventories (left column), global average depth profiles (middle column) and spatially resolved surface concentrations (right column) for year 2030.



220

221 **Figure S8.** Overview of seasonal changes in horizontally averaged salinity

222 concentrations in PSU over pipe-covered area between surface ocean and pipe length

223 (continuous lines) for 1 pipe per km² under RCP 2.6 (left column) and RCP 8.5 (middle

224 column) for year 2030 (a,b) and year 2100 (d,e). Color and line code same as in Figure 2.

225 Spatially resolved changes in salinity in PSU over pipe-covered area (shades of blue)

226 between surface ocean and 1103 meters depth under RCP 8.5 with 1 pipe per km² with

227 1103 meter long pipes for the months February (c) and October (f) of the year 2030.

228

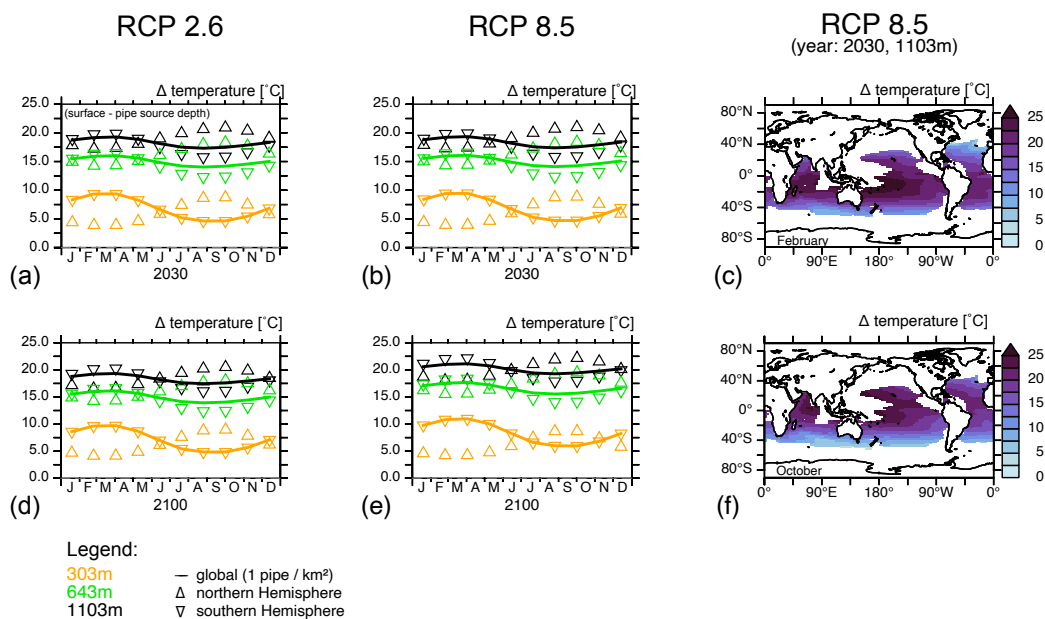


Figure S9. Overview of seasonal changes in horizontally averaged temperature in °C over pipe-covered area between surface ocean and pipe length (continuous lines) for 1 pipe per km² under RCP 2.6 (left column) and RCP 8.5 (middle column) for year 2030 (a,b) and year 2100 (d,e). Color and line code same as in Figure 2. Spatially resolved changes in temperature in °C over pipe-covered area (shades of blue) between surface ocean and 1103 meters depth under RCP 8.5 with 1 pipe per km² with 1103 meter long pipes for the months February (c) and October (f) of the year 2030.

Erklärung

Ich erkläre hiermit:

- a) dass die Abhandlung - abgesehen von der Beratung durch meine Betreuer - nach Inhalt und Form eine eigenständige und nur mit den angegebenen Hilfsmitteln von mir verfasste Arbeit ist.
- b) dass die Arbeit weder ganz noch zum Teil einer anderen Stelle im Rahmen eines Prüfungsverfahrens vorgelegen hat. Folgende Teile dieser Arbeit sind bereits an anderen Stellen veröffentlicht bzw. zur Veröffentlichung eingereicht:

[JPA] Kemper, J., Riebesell, U., Graf, K., 2022. Numerical flow modeling of artificial ocean upwelling. *Frontiers in Marine Science* 8. doi:10.3389/fmars.2021.804875.

(akzeptiert und veröffentlicht)

[JPB] Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025c. Performance prediction for Stommel's perpetual salt fountain in the context of artificial ocean upwelling. *Applied Ocean Research* 160, 104624. doi:10.1016/j.apor.2025.104624.

(akzeptiert und veröffentlicht)

[JPC] Kemper, J., Mense, J., Kröger, J., Slawig, T., Graf, K., Riebesell, U., 2025b. On the potential of Stommel's perpetual salt fountain for artificial upwelling. *Environmental Research Letters* 20, 074047. doi:10.1088/1748-9326/ade0d3.

(akzeptiert und veröffentlicht)

[JPD] Yao, W., Morganti, T.M., Wu, J., Borchers, M., Anschütz, A., Bednarz, L., Bhaumik, A., Böttcher, M., Burkhard, K., Cabus, T., Chua, A.S., Diercks, I., Esposito, M., Fink, M., Fouqueray, M., Gasanzade, F., Geilert, S., Hauck, J., Havermann, F., Hellige, I., Hoog, S., Jürchott, M., Kalapurakkal, H.T., Kemper, J., Kremin, I., Lange, I., Lencina-Avila, J.M., Liadova, M., Liu, F., Mathesius, S., Mehendale, N., Nagwekar, T., Philippi, M., Luz, G.L.N., Ramasamy, M., Stahl, F., Tank, L., Vorrath, M., Westmark, L., Wey, H., Wollnik, R., Wölfelschneider, M., Bach, W., Bischof, K., Boersma, M., Daewel, U., Fernández-Méndez, M., Geuer, J.K., Keller, D.P., Kopf, A., Merk, C., Moosdorf, N., Oppelt, N., Oschlies, A., Pongratz, J., Proelss, A., Rehder, G.J., Rüpke, L., Szarka, N., Thraen, D., Wallmann, K., Mengis, N., 2025. Exploring site-specific carbon dioxide removal options with storage or sequestration in the marine environment – the 10 Mt CO₂ yr⁻¹ removal challenge for Germany. *Earth's Future* 13. doi:10.1029/2024ef004902.

(akzeptiert und veröffentlicht)

[CPA] Kemper, J., Mense, J., Graf, K., Riebesell, U., Kröger, J., 2023. Towards reliable performance predictions for Stommel's perpetual salt fountain, in: *Proceedings of the 10th Conference on Computational Methods in Marine Engineering*, Madrid, Spain. doi:10.23967/marine.2023.018.

(akzeptiert und veröffentlicht)

- c) dass diese Arbeit unter Einhaltung der Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft entstanden ist.
- d) dass mir kein akademischer Grad entzogen wurde.