

Strategies for the Assessment of Tidal Current Energy Resources through Numerical Models

Dissertation

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Acknowledgements

I still remember the day I've arrived at Hamburg Airport. It was my first international flight, and again, my first time abroad. I was full of curiosity, excitement, and a healthy amount of fear. I didn't know where Kiel was, I didn't know who lived there, and I had no idea what was waiting for me. I just dived in... Since then, Kiel became my home; I am surrounded by lovely people, and my childhood dream of becoming a scientist is coming true. For all of this, I have many people to thank.

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Abstract

The tidal current energy is highly predictable, and it can provide a stable output to the grid. Especially in the coastal regions, it might enhance the diversity of the energy mix, contribute to the decarbonization of electricity production, increase energy security by exploiting indigenous resources, and fuel economic growth. Due to their advanced technological readiness levels, tidal energy conversion systems are likely to become commercially attractive within a decade, with the potential for a significant market share in future energy systems. Indonesia, with a significant potential of tidal current energy, is one of the many countries aiming to increase the contribution of the tidal currents in their national energy mix. Hence, the country intensifies the research and development efforts to reach this goal.

The presented study stresses fundamental research issues regarding the characterization of tidal current energy resources with a focus on Indonesia, leading to a concluding overview of the country's potentials on tidal current energy. Developed approaches and tools such as high-resolution, three-dimensional numerical models validated by state-of-the-art measurements, are presented. Analyses of the tidal current energy potentials of several promising straits between the Indian Ocean and inner Indonesian Seas are performed. A resource assessment methodology is developed to define energy hotspots within the target domains and to estimate technically extractable powers from each of them. The influence of density-induced flow on tidal stream power generation for the Sunda Strait, located between Java and Sumatra islands, is investigated. Physical impacts of tidal current energy extraction on hydro-environment and performance of tidal turbine arrays are presented in detail for the Strait of Larantuka, which divides East Flores and Adunara islands in eastern Indonesia. Changes in the local flow field due to the operation of turbines as well as the turbine performances for various dissipation levels and array configurations are evaluated.

The results underline the potentials of the Indonesian straits of Bali, Larantuka, Boling, Alas, Lombok, Sunda, and Badung for the production of renewable electricity from tidal currents. While the currents with highest power densities are observed in the straits of Bali and Larantuka, Alas Strait was found to have the biggest potential for tidal current energy extraction due to the larger size of its energy hotspot. The technically extractable power potential of all the investigated straits is estimated to exceed a total of 5,000MW. It is found that in the Sunda Strait, the density gradients caused by the water exchange between the Java Sea and the Indian Ocean can seasonally amplify tidal current speeds by up to 100% at the free sea surface. During both northwest and southeast monsoonal seasons, electricity production in Sunda Strait rated for the baroclinic mode resulted in more than

twice the electricity production estimated for the barotropic mode. Concerning the impacts of tidal energy extraction, an overall change is observed in the flow fields, which have been simulated due to different dissipation levels and array configurations. Up to 30 – 40% decrease in current speeds is observed downstream the turbine arrays. On the contrary, within the adjacent nearshore shallow waters, up to 80% increase in current speeds was observed mainly due to the blockage effect. Turbines seemed to reach their rated capacities for short periods and to operate with a maximum of 60% efficiency compared to their rated power.

The findings emphasize the importance of high-resolution modelling tools for a comprehensive assessment of tidal current energy resources, for optimizing the layout of multi-turbine arrays and for the assessment of potential physical impacts due to tidal current energy extraction.

Zusammenfassung

Die Gewinnung von Energie aus Meeresströmungen ist gut prognostizierbar und kann dem Stromnetz zuverlässig zugeführt werden. Insbesondere in Küstenregionen kann die Nutzung von Gezeitenströmungsenergie den Energiemix verbreitern, zur Reduzierung des Ausstoßes von Kohlendioxid in der Energiegewinnung beitragen, durch Nutzung lokaler Ressourcen die Sicherung der Energieversorgung verbessern und Wirtschaftswachstum anregen. Aufgrund der hohen technologischen Reife von Umwandlungssystemen für Meeresströmungsenergie wird dieses Verfahren spätestens im Laufe der nächsten Dekade wirtschaftlich interessant sein, mit dem Potenzial, zukünftig große Anteile am Markt für Energiesysteme zu gewinnen. Indonesien ist, mit seinen bedeutenden Möglichkeiten im Bereich der Meeresströmungsenergie, eines von zahlreichen Ländern, die versuchen, den Anteil aus Gezeitenströmung am Energiemix zu erhöhen. Entsprechend intensiviert das Land seine Bemühungen im Bereich Forschung und Entwicklung, um dieses Ziel zu erreichen.

Die vorliegende Arbeit legt ihren Fokus auf grundlegende Forschungsfragen bezüglich der Charakteristika von Meeresströmung als Energieressource mit dem Schwerpunkt auf Indonesien, um am Ende einen Überblick über das Potenzial des Landes im Bereich Meeresströmungsenergie zu geben. Dargestellt werden die für diese Arbeit entwickelten Ansätze und Instrumente, wie z.B. hochauflösende dreidimensionale numerische Modelle, deren Validität durch Messungen mit Instrumenten auf dem neuesten Stand der Technik bestätigt wurde. Durchgeführt werden Analysen der Potenziale von Gezeitenströmungsenergie mehrerer vielversprechender Meeresstraßen zwischen Indischem Ozean und der Java-, Bali- bzw. Floressee. Entwickelt wird weiterhin eine Methodologie zur Bewertung von Energieressourcen, mit dem Ziel, innerhalb der Zielgebiete Energiehotspots zu identifizieren und jeweils abzuschätzen, wie viel Energieleistung technisch extrahierbar ist. Untersucht wird außerdem die Auswirkung von wasserdichtebedingter Strömung auf die Energiegewinnung aus Gezeitenströmung für die Sunda Meerenge, welche sich zwischen den Inseln Java und Sumatra befindet. Mögliche physikalische Folgen der Energiegewinnung aus Gezeitenströmung auf die Meeresumwelt sowie eine Abschätzung der Leistungsfähigkeit eines Meeresströmungsturbinenfeldes werden im Detail für die Larantuka Meerenge dargelegt, welche in Ostindonesien die östliche Floresinsel von der Adunaraininsel trennt. Es werden sowohl mögliche Veränderungen im lokalen Strömungsfeld aufgrund des Turbinenbetriebs als auch unterschiedliche Turbinenleistungen in verschiedenen Verlustlevels und Aufstellungsszenarios evaluiert.

Die Ergebnisse verdeutlichen das Potenzial der indonesischen Meeresstraßen von Bali, Larantuka, Boling, Alas, Lombok, Sunda und Badung für die Stromproduktion aus Meeresströmungen. Während Strömungen mit den höchsten Leistungsdichten in den Meerengen von Bali und Larantuka zu beobachten sind, zeichnet sich die Alasmeerenge wegen der größeren Dimensionierung ihres Energiehotspots durch das größte Potenzial für die Gewinnung von Gezeitenströmungsenergie aus. Das mögliche technisch extrahierbare Energiepotenzial aller untersuchten indonesischen Meerengen insgesamt wird auf mehr als 5000 MW geschätzt. Es zeigt sich, dass das Wasserdichtegefälle zwischen Javasee und Indischem Ozean die Meeresströmungsgeschwindigkeiten in der Sunda Meerenge an der Oberfläche saisonabhängig um bis zu 100% erhöhen kann. Sowohl während der Nordwest- als auch während der Südostmonsunzeit ergibt sich für die Einschätzung der Energiegewinnung in der Sunda Meerenge mehr als der doppelte Wert, wenn sie nach Baroklinität anstatt nach Barotropie vorgenommen wird. Hinsichtlich der Auswirkungen der Energiegewinnung aus Meeresströmung kann man insgesamt eine Veränderung der Strömungsfelder der Turbinen beobachten, welche in dieser Arbeit mit verschiedenen Verlustlevels und Aufstellungsanordnungen simuliert werden. Beobachtbar ist eine Verringerung der Strömungsgeschwindigkeiten um bis zu 30-40% stromabwärts des Turbinenfeldes. Im angrenzenden küstennahen Flachwasser hingegen kann man, hauptsächlich aufgrund der Stauwirkung, einen Anstieg der Strömungsgeschwindigkeiten um bis zu 80% feststellen. Die Turbinen erreichen das prognostizierte Leistungsvermögen aber nur für kurze Zeiträume und arbeiten mit einem Effizienzmaximum von 60% im Vergleich zur vorausgesagten Leistungsfähigkeit.

Die Untersuchungsergebnisse unterstreichen die Bedeutung hochauflösender Modellierungsinstrumente, sowohl für die umfassende Bewertung von Energieressourcen aus Gezeitenströmung und für die Optimierung der räumlichen Verteilung von Mehrturbinenfeldern als auch für die Einschätzung möglicher physikalischer Auswirkungen der Energiegewinnung aus Meeresströmungen.

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List of Acronyms and Symbols

BPPT	Badan Pengkajian dan Penerapan Teknologi (Bahasa Indonesia)
CFD	Computational fluid dynamics
DSS	Decision support system
EMEC	European Marine Energy Centre
EPRI	Electric Power Research Institute
GFS	Global Forecast System
HAMSOM	Hamburg Shelf Ocean Model
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
ITF	Indonesian Throughflow
JRC	Joint Research Centre
MADT	Momentum Actuator Disc Theory
NOAA	National Oceanic and Atmospheric Administration
NWM	Northwest Monsoon
ORE	Ocean renewable energy
RD	Rotor diameter
RMSD	Root-mean-square deviation
RMSE	Root-mean-square error
SEM	Southeast Monsoon
SPICE	Science for the Protection of Indonesian Coastal Ecosystems
TISEC	Tidal in-stream energy conversion
TRL	Technology readiness level
WEF	World Economic Forum
$A_{turbine}$	Turbine rotor swept area (m ²)
C_p	Power coefficient
C_t	Thrust coefficient
$E_{turbine}$	Tidal turbine operating efficiency
P	Hydro-kinetic power density (kW/m ²)
$P_{average}$	Time-averaged operating capacity of the tidal turbine
$P_{electric}$	Electric power (kW)

P_{rated}	Rated operating capacity of the tidal turbine
U	Current velocity (m/s)
U_{hub}	Current velocity magnitude at the turbine hub height (m/s)
$\eta_{turbine}$	Tidal turbine rotor efficiency
$\eta_{take-off}$	Tidal turbine power take-off efficiency
$\eta_{drivetrain}$	Tidal turbine drivetrain efficiency
$\eta_{generator}$	Tidal turbine generator efficiency
η_{con}	Tidal turbine grid connection efficiency
ρ	Density of seawater (kg/m ³)

Chapter 1

General Introduction

General Scope

The global energy sector is facing severe challenges. Geopolitical and military conflicts involving oil-rich countries, exhaustion of the oil reserves, final storage, and disposal of nuclear wastes and security of the energy supply are amongst growing concerns (Asif & Muneer, 2007). Moreover, emission of the greenhouse gas carbon dioxide (CO₂), due to burning fossil fuels, is identified as a major cause of climate change and sea-level rise. Hence, pressure increases for the development and fast implementation of technologies for renewable energy production.

Indonesia, located in Southeast Asia, has great potential for electricity production from renewable resources. However, the portion of the renewable energy contribution to the country's primary energy mix is currently very low, and utilizing renewable resources might be of great help to meet constantly increasing energy demand of the growing Indonesian population. Thus, to advance the adoption of renewable resources, the development of renewable energy in Indonesia is regulated by a Presidential Decree stating that the contribution of renewable energy should be increased to 17% of the total national primary energy mix by 2025, and efforts shall be intensified to reach this goal (Blunden et al., 2013). Utilizing ocean renewable energy resources of the country might very well be a crucial step to reach this goal. The ocean covers as much as 70% of Indonesia and represents a vast amount of energy in the form of wind, wave, ocean current/thermal, and tidal energy. Due to the targets set by the Indonesian government, tidal current energy, alongside wind energy, is likely to have the biggest installed capacity on the electrical grid of the country within the next decade (Purba et al., 2015).

The exchange of water and heat between the Pacific Ocean and the Indian Ocean occurs through Indonesian Throughflow (ITF), and the Indonesian archipelago has large quantities of tidal power input from both oceans. Hence, strong tidal currents following complex patterns are flowing through the country's straits. Especially the straits between the Indian Ocean and inner Indonesian seas (see Figure 1-1) are promising with intense barotropic energy fluxes. Estimating the energy budget of these straits requires a reliable information base as well as tools for high-resolution analysis and advanced techniques for resource characterization (Ray et al., 2005).

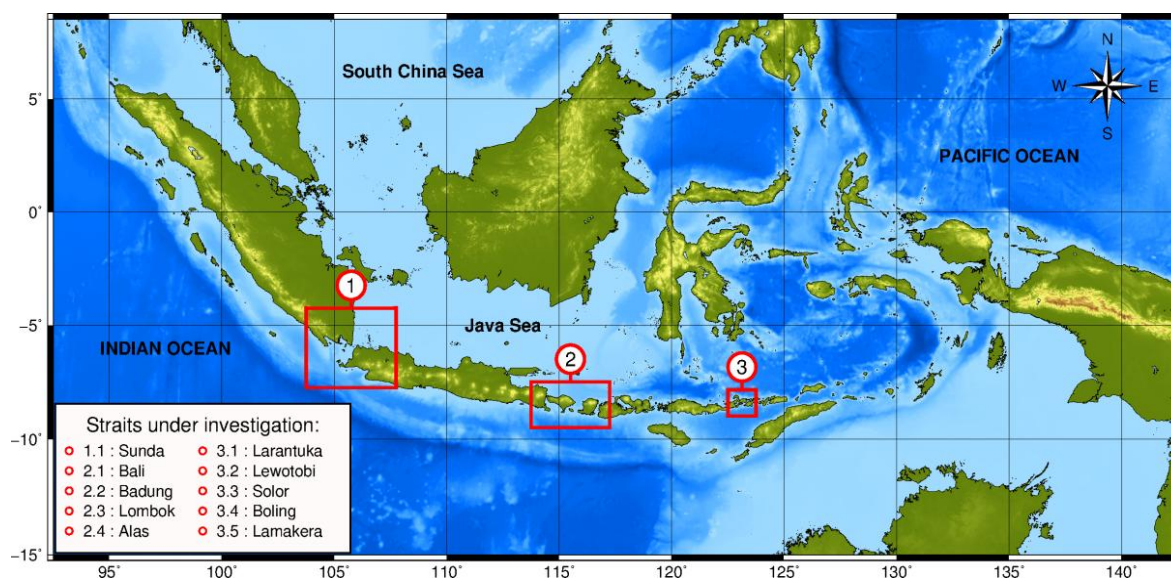


Figure 1 - 1: Locations of the straits with intense barotropic energy fluxes in Indonesia.

This study aims at the characterization of tidal current resources in Sunda, Bali, Badung, Lombok, Alas, Lantuka, Lewotobi, Solor, Boling, and Lamakera straits in Indonesia (see Figure 1-2), and the advancement of available resource assessment strategies for better identification of marine areas which are suitable to deploy tidal energy converters, or so-called “energy hotspots”. Technically extractable power from the energy hotspots, the influence of regional atmospheric and oceanographic dynamics on tidal stream power generation as well as the potential impacts of the tidal energy extraction on hydro-environment shall be analyzed within this study’s framework.

Tidal Current Energy: An Overview

Ocean renewable energy (ORE) is a promising alternative for replacing the energy produced from fossil fuels and nuclear resources. It enhances the diversity of the energy mix, reduces the risk of energy shortages, and may secure long-term sustainable energy supply. It uses local resources, and hence, might fuel the economic growth of coastal regions/states by providing affordable and renewable electricity as well as new employment opportunities (Magagna & Uihlein, 2015; Magagna et al., 2016; Uihlein & Magagna, 2016). Thus it can contribute to the decarbonization of electricity production and help to mitigate environmental, societal, and economic hazards related to climate change. So far, the development of ORE technologies to harness offshore winds, waves, tidal currents, ocean thermal resources, and salinity gradients are on different stages. Following the recently established offshore wind energy technologies, wave energy, and tidal current energy conversion systems are likely to contribute the most in short to medium term (2025-2030) mainly due to their advanced technology readiness levels (Mankins, 1995; Sannino & Cavicchioli, 2013; Magagna & Uihlein, 2015).

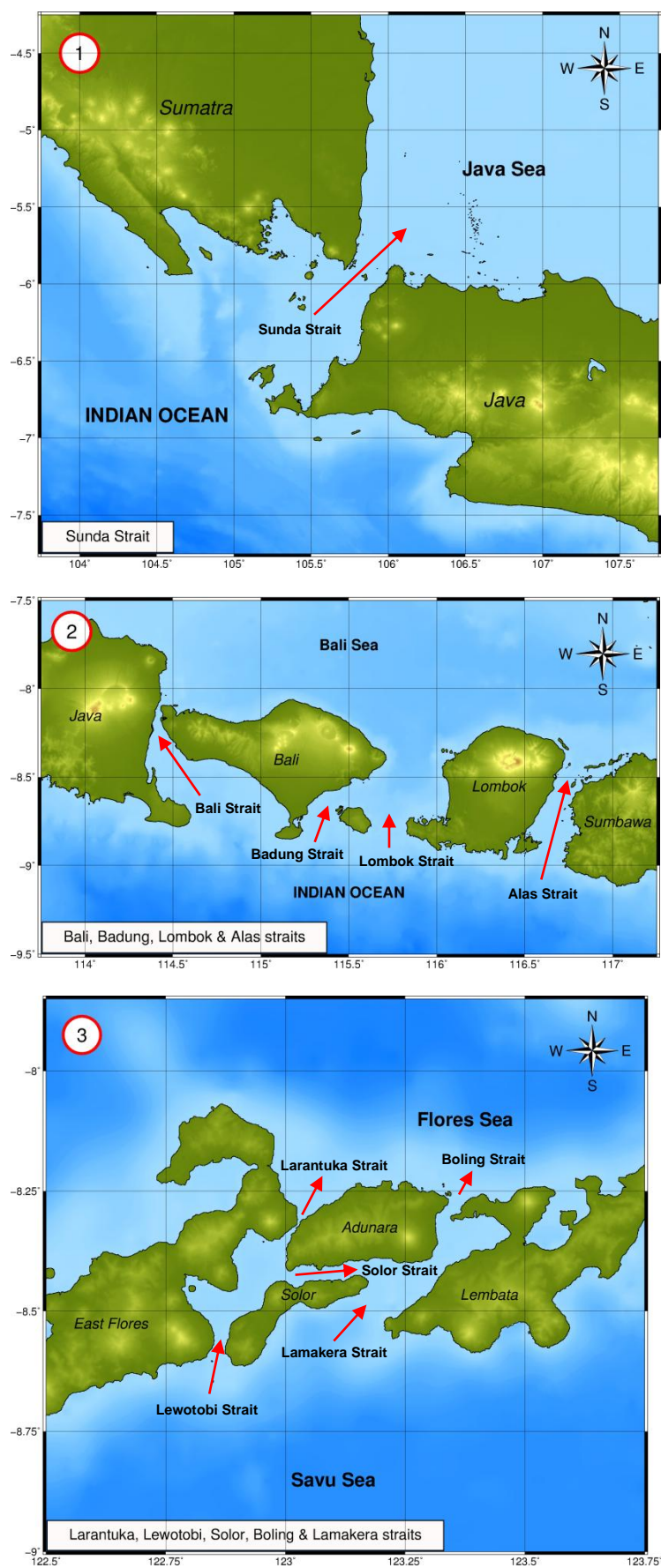


Figure 1 - 2: Straits selected for the characterization of tidal current energy resources in Indonesia. See Figure 1-1 for the locations of the straits.

Figure 1-3 shows the portions of research and development efforts focusing on tidal current and wave energy technologies. R&D efforts on wave energy converters emphasize point absorber, attenuator, and oscillating wave surge technologies (Magagna & Uihlein, 2015). Tidal current turbine designs similar to the horizontal-axis wind turbines currently account for 76% of the R&D efforts on tidal energy converters worldwide. They have reached the technology readiness level 8 (TRL 8) out of a total of 9 levels, and have made significant progress towards commercialization (Kempener & Neumann, 2014; Magagna & Uihlein, 2015; Magagna et al., 2016).

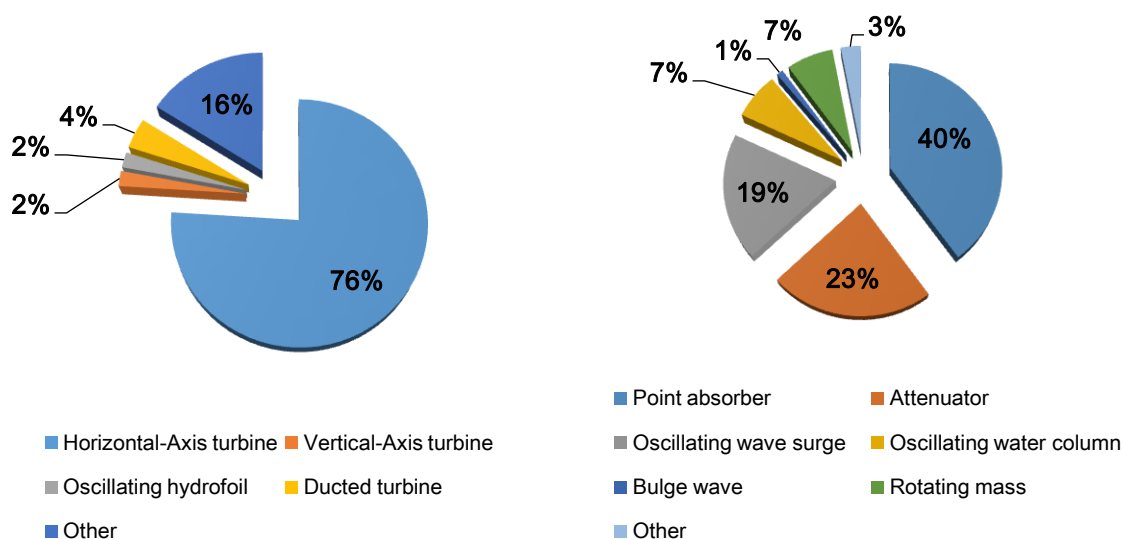


Figure 1 - 3: Portions of R&D efforts for the development of tidal (left hand) and wave (right hand) energy conversion technologies.

Regarding the commercialization efforts, Scotland (UK), already operating in 17 leased sites for tidal farms, aims to meet a significant portion of the country's power need by tidal current energy. Canada, United States, and France have tidal farm projects in the planning or development stages. UK, France, Denmark, and Italy are among the countries with an active interest in developing wave energy technologies (Neill et al., 2017). In 2017, tidal current energy production achieved a net capacity contribution of 17MW, mainly due to the energy produced by tidal turbine arrays deployed in Northern Scotland. Thus, the tidal current energy sector is still in a critical phase of development. A larger number of demonstration farms are needed for tidal current turbines to be proven feasible and reliable in the actual operational environment (Magagna et al., 2016; REN21, 2018).

Tidal current turbines typically feature blades like wind turbines and operate due to the principals of aerodynamic lift (Hau & von Renouard, 2013). However, they operate underwater, and hence, there is a need to tackle different and much harsher physical conditions than wind turbines. Although tidal currents are much slower than the wind, greater density of the water compared to the density of the air makes tidal turbines comparable with the wind turbines in terms of power production (Bahaj & Myers, 2003). State-of-the-art tidal turbines have power production capacities rated as high as 2MW (Roberts et al., 2016). Turbines can be moored on the seabed using several techniques such as gravity base, pile-mounting, and flexible mooring (O'Rourke et al., 2009).

Conventionally, turbines start operating with current speeds of about 1m/s (cut-in speed), and they reach their maximum capacity with current speeds as high as approximately 2-3m/s (rated speed). Although unlike wind turbines, tidal turbines do not generally need to operate in extreme flow speeds that can potentially damage those (Blunden & Bahaj, 2006); some devices are designed to stop operating when flow velocities exceed about 4.5-5m/s.

Several technology developers such as Andritz Hydro-Hammerfest, SIMEC Atlantis Energy, Openhydro, Orbital Marine Power, and Sabella have optimized their tidal turbine technologies for deployment (Magagna et al., 2016). Figure 1-4, as an example, demonstrates the components of a commercially available tidal turbine designed by Sabella SAS (Zhou, 2017). Figure 1-4-A shows the sketch of the device with its mooring (gravity base). In Figure 1-4-B and 1-4-C, we can see the turbine hub and the turbine components (drive-train and generator). Due to the mechanical efficiency of the turbine rotor in harnessing the hydro-kinetic power, and the efficiencies of the drive-train and the generator components, turbines have different capabilities in converting hydro-kinetic power to renewable electricity. Generally, the overall efficiency of the turbine (power coefficient, C_p) equals ca. 40% (Roberts et al., 2016).

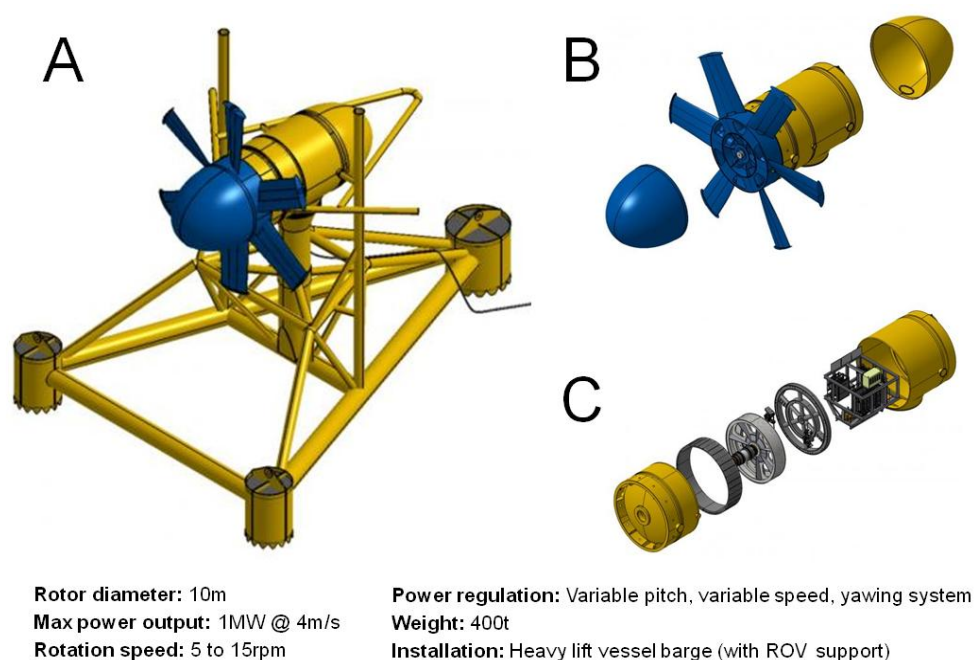


Figure 1 - 4: Sketch of the Sabella D10 tidal turbine and its components (Zhou, 2017).

Although tidal turbines help to decarbonize electricity production, they might cause several impacts on their operational environment. First of all, tidal turbines usually change flow patterns in adjacent areas. They decrease current speeds both upstream and downstream the devices and might increase the current speeds on the sides. These phenomena can have serious implications in the sediment dynamics and water quality within and around the turbine arrays (Neill et al., 2009; Ahmadian et al., 2012). Also, other impacts on the marine environment, such as alteration of benthic habitats, noise pollution, generation of magnetic fields, and the striking of marine animals with rotor

blades are possible (Gill, 2005). Thus, deployment of tidal turbines requires comprehensive environmental impact studies, and research effort should be intensified to consider the impacts mentioned above during resource characterization processes.

Assessment of Tidal Current Energy Resources Using Numerical Models

Numerical models can calculate non-steady flow and transport phenomena over a computational domain by solving the equations of motion, continuity, and transport, and they can simulate flows, sediment transports, waves, water quality, and morphological development. The computational domain of the model is connected to the “outside world” through open sea boundaries. The conditions at the open sea boundaries or so-called “boundary conditions” of the model can be represented by scalars or equations on the water level, current velocity, wave, seawater density, sediment concentration, etc. The model can also account for the wind stress and the heat exchange at the free surface.

Generally, two-dimensional and three-dimensional hydrodynamic models are preferred for the modelling studies concerning the coastal areas. Two-dimensional hydrodynamic models (2DH) use horizontal computational grids and vertically integrated values for the fluid flow at the nodal point. In three-dimensional models (3D), the hydrodynamic equations are covering three dimensions, schematizing the domain over a 3D-grid. Nowadays, those modeling solutions have grown up to powerful tools in research and development and are used for simulation and prediction of hydrodynamics (Blumberg & Mellor, 1980; Hsu et al., 1999; Palacio et al., 2005; Öztürk et al., 2012), sediment dynamics (Douillet et al., 2001; Mayerle et al., 2015) and morphodynamics (Roelvink, 1995; Hibma et al., 2003; Mayerle & Zielke, 2005) and are increasingly applied for characterization of ocean/tidal current energy resources. Starting with the 21st century, studies using different modelling approaches and modelling systems for the assessment of tidal current energy resources became available in the literature (Bryden et al., 2007; Sutherland et al., 2007; O’Rourke et al., 2010; Blunden et al., 2013; Plew & Stevens, 2013; Serhadlioglu et al., 2013; Work et al., 2013; Marta-Almeida et al., 2017). Examples for the application of the models are introduced below.

Sutherland et al. (2007) determined the interaction between the flow conditions on the Johnstone Strait (Canada) and connecting channels. O’Rourke et al. (2010) applied a 2DH numerical model for a tidal current energy resource assessment of the marine areas around Ireland. Serhadlioglu et al. (2013) simulated tidal currents within the Anglesey Skerries (UK) in their natural state and concerning the deployment of tidal arrays. Work et al. (2013) developed a 3D numerical model of the Beaufort River (South Carolina, USA). The study reveals the tidal current power contained in the channel cross-section with and without tidal current energy extraction. Blunden et al. (2013) utilized the developed a 3D numerical model of the Alas Strait in Indonesia. Considering a scenario with a maximum depth of 80m for turbine deployment, the practically exploitable annual energy yield from the strait has been estimated as 640GWh by the researchers in this study.

The examples listed above provide valuable insight regarding the assessment of tidal current energy resources. Sutherland et al. (2007) show the significance of the interaction between interlinked channels and their influences on each other's energy potential. The majority of the studies emphasize the importance of using computational grids with sufficient resolutions to preserve important coastline and bathymetric features within the target domains. The model presented by O'Rourke et al. (2010) contains sub-models with grid resolutions ca. 45m, capturing the flow patterns in detail around the energetic sections. Serhadlioglu et al. (2013) demonstrate the relationship between the array locations, the connectivity of arrays, and the available power. Work et al. (2013) concludes that 3D hydrodynamic models are the most suitable tools to resolve nonlinear power dissipation in a flow field caused by tidal turbines. Finally, Blunden et al. (2013) provides a better understanding of the influence of physical constraints, such as depth limitations, over the extractable power potentials. However, the studies listed above, much like the majority of the studies available in the literature so far, neglect the influence of the water density gradients and the wind in resource assessment. Also, while modelling the tidal energy extraction via turbines, the models pre-dominantly fail to resolve the impact of isolated devices, mainly as a consequence of the coarse grid resolutions. Both of these issues are addressed within the framework of this dissertation.

In this study, a series of 3D flow models based on Delft3D modelling suite (Delft Hydraulics, 2006) has been developed to simulate hydrodynamics in the Indonesian straits selected by the Agency for the Assessment and Application of Technology (BPPT) in Indonesia for the characterization of tidal energy resources (see Figure 1-1 and Figure 1-2). The FLOW module of Delft3D numerically solves a set of differential equations (Navier-Stokes equations) based on finite differences and under shallow water assumption. It is capable of resolving velocity fields taking salinity and temperature gradients as well as meteorological input into account. The discretization of the equations is done through orthogonal and well-structured curvilinear grids (Roelvink, 1995; Van Rijn & Walstra, 2003; Lesser et al., 2004). The ocean heat flux module of Delft3D-FLOW, which typically applies to large water bodies such as the target domains of this study, is activated to account for the temperature gradients alongside the salinity gradients (Lane, 1989). Due to its significant advantages in resolving stratified flows, k- ϵ model, which is a second-order turbulence closure scheme, is selected to include the effects of the turbulent kinetic energy and turbulent kinetic energy dissipation (Burchard and Baumert, 1995; Postma et al., 1999). In Delft3D-FLOW, the recommended value for the horizontal eddy viscosity depends on the computational grid size. For grid sizes of tens of meters or less, the values for the horizontal eddy viscosity are typically in the range of 1 to 10m²/s. For grid sizes of hundreds of meters or more, the coefficients typically range from 10 to 100m²/s (Delft Hydraulics, 2006). In this study, a sensitivity analysis was carried out during the model development stage, and the models for each domain were run with horizontal eddy viscosity values of 1m²/s, 10m²/s, and 100m²/s. The results showed that the hydro-kinetic energy flux, which is the main focus of this study, didn't show a significant change corresponding to different horizontal eddy viscosity values. Therefore, the default value (1m²/s) was kept for all the models.

Due to the difficulties of gathering data from the remote domains, depth soundings were only available for the Strait of Larantuka, and they were used to create the model bathymetry. Bathymetries of the remaining models were based on the SRTM15_PLUS land and sea topography global dataset (Olson et al., 2014; Tozer et al., 2019). The horizontal resolution of the SRTM15_PLUS grid is 15-arcseconds, which is roughly 0.27km at the equator, and it is based on bathymetric predictions of the latest global gravity model from CryoSat-2 and Jason-1 along with depth soundings. To determine water level elevations at the open sea boundaries of the models, tidal forcing was extracted from TPXO Indian Ocean Atlas (1/12° regional model) and prescribed as time series (Egbert & Erofeeva, 2002). Data to determine the values of the salinity and the temperature at the open sea boundaries are supplied from the Hamburg Shelf Ocean Model (HAMSOM) developed at the Institute of Oceanography at the University of Hamburg (Mayer et al., 2010). HAMSOM is a 3D free surface baroclinic hydrodynamic model with a horizontal resolution of ca. 9km. Meteorological data with a 28km horizontal resolution were obtained from the Global Forecast System (GFS) of NOAA's National Climatic Data Center (Environmental Modeling Center, 2003). Cloudiness, air temperature, atmospheric pressure, relative air humidity, and wind data obtained from the GFS database were used to consider meteorological forcing in the models.

To simulate the effects of hydro-kinetic energy extraction by tidal turbines, so far mainly three methods have been implemented in numerical models namely bottom friction (Neil et al., 2012), momentum sink (Defne et al., 2011; Yang et al., 2013; Chen et al., 2014) and blade element actuator disk (Bai et al., 2013). The bottom friction method is primarily suitable for 2DH hydrodynamic models. The blade element actuator disk method requires grid resolutions in the order of centimeters, and it is applicable for the domains smaller than 10m². Therefore, the momentum sink method was found most suitable for this study. In momentum sink method, a momentum sink term is introduced into the momentum equations in the horizontal direction to represent the external forces in the flow field. Momentum sinks, in the form of porous plates, were implemented in the 3D hydrodynamic model developed for the Strait of Larantuka to represent the turbines. The porous plates have been located at the grid cell faces, covering several vertical layers (Delft Hydraulics, 2006; EMEC, 2009). Thus, the pre-existing kinetic power within the flow cross-section is dissipated to account for the tidal energy extraction by the turbines. In this study, the hydrodynamic impacts of the tidal turbine operations, as well as the turbine performances, have been analyzed due to different dissipation levels and array capacities.

The assessment of the models' ability to predict tidal water levels was done through the comparison of simulated water level elevations with available measurements. Radar gauge data from the Sea Level Station Monitoring Facility (UNESCO/IOC, 2019) was utilized for validation of the Sunda Strait circulation model. The numerical model covering Larantuka, Lewotobi, Solor, Boling, and Lamakera straits has been validated through the measurements of a tide gauge deployed within the framework of the SPICE project (Ferse et al., 2012). There was no water level data available concerning the models developed for Bali, Alas, and Lombok Straits during the investigations. There

was also no data available concerning the current speeds in any of the target domains. Therefore, simulated tidal current speeds were compared with the findings of the studies conducted in the same domains to find out if the results were in the correct range (Erwandi et al., 2011; Blunden et al. 2013; Li et al., 2017; Syamsudin et al., 2017). Due to the lack of field measurements regarding the hydrodynamic impacts of the operational tidal turbines, simulated hydrodynamic impacts of the devices were controlled through the findings of the available numerical and physical numerical modelling studies in the literature (Chen et al., 2014; Chen et al., 2017).

Study Area: Indonesian Archipelago

The Indonesian archipelago stretches across 6°N-11°S and 94°-141°E (see Figure 1-1). It consists of more than 17,000 islands (Indonesian Hydro-Oceanographic Office, 2003), and with a total of 1.9 million km² land area and a total of 93.000 km² sea area, it encompasses the equatorial throughflow zone between the Indian and Pacific Oceans. The largest five islands are Java, Sumatra Kalimantan, Sulawesi (Greater Sunda Islands), and New Guinea (Indonesian part is Irian Jaya). The total population is approximately 268 million (World Bank, 2019). The densest populated island is Java, with around 140 million inhabitants. According to the World Bank, electric power consumption in the country was around 800kwh per capita by 2014, which approximates a total of 25,000MW electric power demand on average. Also, by 2014, oil, gas and coal sources constituted 66% of the total electricity production in the country while renewables, excluding hydroelectric, constituted less than 5% (World Bank, 2019).

Indonesia has many shelf seas with less than 200m depth and deep areas with more than 3,000m depth. Tidal phenomena in the Indonesian Seas are highly complex featuring multiple amphidromic points, strong tidal currents, residual circulations, internal waves, and solitons. The charts based on ten years of satellite altimeter measurements show that the semi-diurnal M2 component from the Indian Ocean and diurnal K1 component from the Pacific Ocean dominate the tides in Indonesian seas (Ray et al., 2005; Robertson & Field, 2005). Furthermore, the difference of the sea surface level between the Pacific and the Indian Oceans causes the currents to flow from the Pacific to the Indian Ocean through Indonesian waters, which is usually called the Indonesian Throughflow (ITF). Although the ITF, which encapsulates the exchange of water and heat from the Pacific Ocean into the Indian Ocean, is very difficult to investigate due to its high spatial and temporal variability, it has a significant impact over the flow conditions of the Indonesian waters (Gordon, 2005; Potemra, 2005; Sprintall & Liu, 2005).

Furthermore, the specific geographical position of Indonesia influences the characteristics of climate and ocean dynamics. The inter-tropical convergence zone (ITCZ) shifts from the northern hemisphere in July to the southern hemisphere in January, crossing the equatorial line. Therefore, the difference of air pressure between the continents of Asia and Australia that shifts every six months causes the monsoonal winds over Indonesia and drives the sea surface current patterns. The latter influences the sea surface temperature as well as the sea surface salinity (Pohlmann, 1987).

The characteristics and the regional atmospheric/oceanographic dynamics mentioned above makes the assessment of tidal current energy resources in the Indonesian straits a very complex procedure. The very large number of small islands, complex features of the seabed topography, strong and seasonally varying wind systems, and the flow of Pacific water into the Indian Ocean via Indonesian seas are all key elements to be taken into account during investigations. Modelling strategies and the approach for the assessment of the tidal current energy resources within the target domains must be determined accordingly.

Objectives

Although it is well known that the straits between the Indian Ocean and inner Indonesian seas, with intense barotropic energy fluxes, are promising for the renewable electricity production, the energy budget of these straits are largely unknown. Tools for the analysis of the hydrodynamic conditions in these domains with sufficient spatiotemporal resolution are missing, and advances are required in the existing resource characterization methods. A practical approach accounting for physical constraints is therefore needed to identify suitable marine areas for the deployment of the tidal turbines and to calculate the potential energy yields. Not much is known about the influence of the regional atmospheric and oceanographic dynamics over tidal current energy generation. An improved understanding concerning the potential hydrodynamic impacts of the tidal current energy generation within the target domains is missing, and highly necessary.

This study aims at filling the research gaps mentioned above and helping us to understand the capabilities and importance of comprehensive coastal numerical models for the assessment of tidal current energy resources. Especially today, where technologically mature tidal current turbines are becoming commercially available, identifying suitable marine areas for their deployment and resolving flow fields with better precision is of utmost importance. Hence, researchers, engineers, and policymakers can be provided with a proper knowledge base and sufficient tools for the development and optimization of tidal farms as well as efficient use of the resources of marine renewable energy.

The main goals of this study and activities identified to reach these goals are listed below:

1. Development and application of the numerical models for the characterization of the tidal current energy resources
 - 3D numerical models with sufficient spatiotemporal resolutions will be developed to simulate the flow patterns covering Sunda, Bali, Badung, Lombok, Alas, Larantuka, Lewotobi, Solor, Boling, and Lamakera straits. Much attention will be given to preserve important coastline and bathymetric features of the target domains in the models and to account for atmospheric and oceanographic dynamics alongside tidal forcing, which is the main focus of the study.

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- The annual trends and seasonal changes in the target domains, as well as the cycles of all the main forcing components, will be captured through the simulations covering one year. Based on the simulation results, spatiotemporal changes of the hydro-kinetic power densities will be determined for each domain.
2. Development and application of a methodology for the assessment of tidal current energy resources
 - A site selection methodology accounting for the hydrokinetic power densities alongside site and turbine-dependent physical constraints will be developed and used to identify the suitable marine areas for the deployment of turbines.
 - The range of applicable tidal turbine rotor diameters and the amount of electric power that can be extracted with tidal turbines from the target domains will be determined.
 3. Evaluating the influence of regional atmospheric and oceanographic dynamics on tidal currents and tidal power generation
 - The hydrodynamic model developed for the Sunda Strait will be utilized to simulate tidal currents in barotropic and baroclinic modes. To understand the annual trends and seasonal changes, and to represent the cycles of the main forcing components, monthly time frames from the northwest and southeast monsoonal seasons and an annual time frame will be considered in simulations.
 - Through the comparison of the simulation results, spatial and temporal influences of the density-induced flow over the tidal currents and tidal current energy generation will be determined.
 4. Evaluating the hydrodynamic impacts and the performances of multi-turbine arrays considering different dissipation levels and array capacities
 - The computational grid of the Lantoka Strait hydrodynamic model will be refined to have sufficient grid resolution in horizontal (ca. 15-20m) for the representation of the isolated turbines.
 - A momentum sink term will be introduced into the momentum equations in the horizontal direction to represent the external forces in the flow field caused by tidal turbines. “Porous plate” feature of the Delft3D-FLOW will be utilized for this purpose.
 - Potential hydrodynamic impacts of a single-row multi-turbine array will be evaluated for different dissipation levels. Changes in the flow field surrounding the array and wake recoveries downstream tidal turbines will be analyzed.
 - Potential hydrodynamic impacts of multi-row multi-turbine arrays will be evaluated for different array capacities. Changes in the surrounding flow fields, as well as wake characteristics and interactions within and around the arrays, will be investigated.
 - Performances of multi-row multi-turbine arrays with different capacities and turbine efficiencies will be analyzed.

To reach these goals, the thesis is structured into six chapters. The content of the following chapters is as follows:

In Chapter 2, entitled “Tidal Current Energy Resources of Indonesia,” Orhan et al. (2016) provide an overview of Indonesia’s tidal current energy resources. It describes the set-up of high-resolution models to simulate the flow patterns within the straits in question, and the strategies/approaches developed for the assessment of their tidal current energy potentials. Within the framework of this paper, energy hotspots in target domains are identified, and technically extractable power through tidal current turbines in each domain is calculated.

In Chapter 3, entitled “Influence of Regional Ocean Dynamics on Tidal Stream Power Generation,” Orhan et al. (2019) evaluate the influence of the regional ocean dynamics on tidal current power generation. For this purpose, the high-resolution, three-dimensional flow model of the Sunda Strait developed within the framework of Orhan et al. (2016) is used. Through the comparison of simulation results in barotropic and baroclinic modes, the influence of density-induced flow on tidal currents and tidal current power generation during the northwest and southeast monsoonal seasons of the region is presented.

In Chapter 4, entitled “Tidal Power Generation: Influence on Flow Conditions and Performance of Turbine Arrays,” initially Orhan and Mayerle (2017) evaluate the potential hydrodynamic impacts of a multi-turbine array consisting of a single row of turbines. Following, Orhan and Mayerle (2019) analyze the wake characteristics within the multi-row, multi-turbine arrays, and array performances due to different configurations. For the investigations, the high-resolution, three-dimensional flow model of the Strait of Lantoka developed within the framework of Orhan et al. (2016) is used. The hydrodynamic impacts of the turbines were represented with momentum sinks. Through the simulation results, spatial and temporal changes in current speeds around the arrays, and wake recoveries downstream of the turbines are resolved for different energy dissipation levels. Changes in the flow field and the wake properties within and around the arrays due to different array configurations have been determined. The array performances are evaluated for each layout and compared.

In Chapter 5, entitled “General Conclusions,” concluding remarks of the study have been provided. In the final chapter, an outlook to the current research is provided.

Chapter 2

Tidal Current Energy Resources of Indonesia

Investigation of the energy potential from tidal stream currents in Indonesia

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Investigation of the energy potential from tidal stream currents in Indonesia

Kadir Orhan¹, Roberto Mayerle¹, Rangaswami Narayanan¹ and Wahyu Widodo Pandoe²

In this paper, an advanced methodology developed for the assessment of tidal stream resources is applied to several straits between the Indian Ocean and the inner Indonesian seas. Due to the high current velocities up to 3-4 m/s, the straits are particularly promising for the efficient generation of electric power. Tidal stream power potentials are evaluated based on calibrated and validated high-resolution, three-dimensional numerical models. It was found that the straits under investigation have tremendous potential for the development of renewable energy production. Suitable locations for the installation of the turbines are identified in all the straits, and sites have been ranked based on the level of power density. Maximum power densities are observed in the Bali Strait, exceeding around 10kw/m². Horizontal axis tidal turbines with a cut-in velocity of 1m/s are considered in the estimations. The highest total extractable power resulted equal to about 1,260MW in the Strait of Alas. Preliminary assessments showed that the power production at the straits under investigation is likely to exceed previous predictions reaching around 5,000MW.

Keywords: renewable energy; tidal stream currents; numerical model; Indonesia

Introduction

The global energy supply is facing severe challenges in terms of long-term sustainability, fossil fuel reserve exhaustion, global warming, and other energy-related environmental concerns, geopolitical and military conflicts surrounding oil-rich countries, and secures supply of energy. Renewable energy sources such as solar, wind, wave, and tidal energy are capable of meeting the present, and future energy demands with ease without inflicting any considerable damage to the global ecosystem (Asif & Muneer, 2007). Carbon dioxide emissions from electricity generation, especially from burning fossil fuels, are a major cause of anthropogenic climate change, and growing concern over the threat of climate change has led to an increased interest in research and development of renewable energy technologies.

The ocean provides a vast source of potential energy resources, and the conversion of tidal current power is recently growing up to a crucial sector of renewable ocean energy. Although in the recent years modelling approaches have become more sophisticated and have been performed for many regions in the world to identify prospective locations for tidal stream farms, lack of reliable data necessary for the assessments, particularly in more remote areas, causing major limitations for investigations. To improve the reliability of the information concerning the potential of tidal stream resources, it is essential to improve resource characterization and rationale for site selection.

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Indonesia has various potential sources for renewable energy production; nevertheless, the percentage of renewable energy contribution in the primary energy mix is currently very low. The development of renewable energy in Indonesia is regulated by a Presidential Decree, which states that the contribution of renewable energy should be increased to 17% of the total national primary energy mix by 2025, which includes the wave and tidal energy. The decree also states that efforts, including research, should be intensified to reach this goal (Blunden et al., 2013).

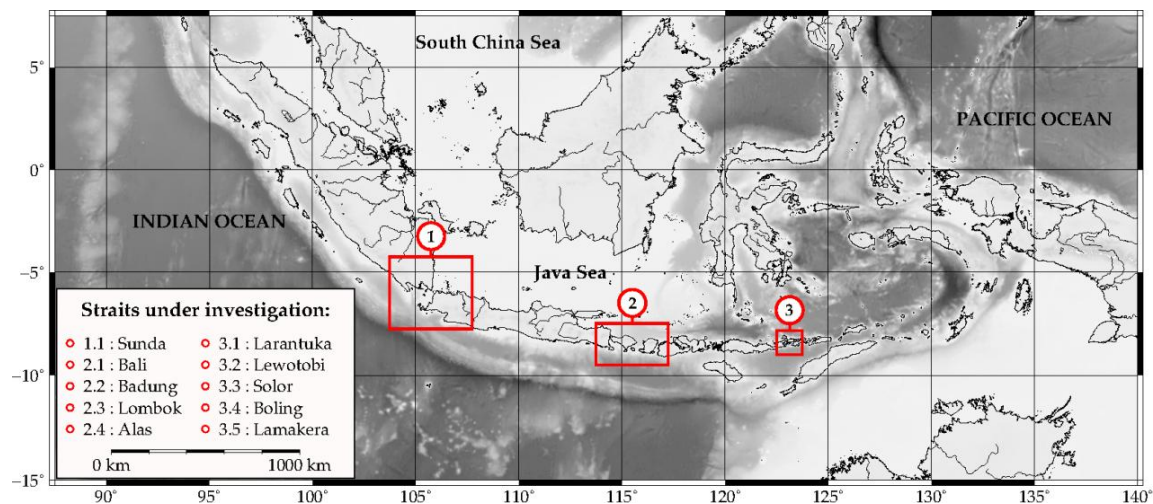


Figure 2 - 1: Straits in Indonesia being investigated.

To install the technology to capture ocean renewable energy, however, it may be necessary to mitigate conflict with existing ocean space users. To this end, involving stakeholders from various fields in the development process, and taking policy issues and existing zoning plans into account is of utmost importance. Otherwise, particularly in districts like Alas and Bali, where coastal areas are being used for a wide range of activities such as aquaculture, fishing, and tourism, it is inevitable to face major problems.

In this paper, the results of the tidal stream resource assessment performed for the straits between the Indian Ocean and inner Indonesian seas (Figure 2-1) are presented. The investigations have been carried out in the framework of the joint research project “Potentials of Ocean Renewable Energy in the Indonesian Seas - ORE-12,” funded by the German Ministry of Education and Research. The project aimed at the identification of marine environments in the Indonesian Archipelago, which are suitable for the efficient generation of electric power by tidal in-stream energy conversion (TISEC) devices and wave converters. As the overall goal of ORE-12, a “Decision Support System (DSS)” to process, to analyze and to evaluate the results of the numerical simulations of flow, and to estimate the tidal stream power potentials in order to identify best sites for the use of ocean renewable energy is established and currently being improved.

Methodology and application

A stepwise methodology comprising the modelling of tidal stream currents, selection of suitable sites for the converters, resource assessment, and estimation of the power potentials is followed (Orhan et al., 2015). The methodology is applied to the straits indicated in Figure 2-1: Sunda, Bali, Badung, Lombok, Alas, Lamakera, Boling, Solor, Lewotobi, and Lantuka. The straits are located between islands starting from Sumatra in the west till Lembata in the east. They link the Indian Ocean and the Savu Sea in the south to the Java Sea, Bali Sea, and Flores Sea in the north. The Strait of Lantuka is the shortest strait with a 3km length, and it is also the narrowest one with a 650m width at its bottleneck. Alas Strait, with a 75km length, is the longest strait, and Sunda Strait is the widest, with a 30km width at its narrowest section. Complicated coastal geometries, countless small islands, rugged bottom topography next to wide shelves of shallow water, and large quantities of tidal power input from the adjoining Indian and Pacific oceans, all combine to form complex systems within these domains (Ray et al., 2005). While predicted tidal ranges diversify between 1m and 3m, tidal currents typically have peak velocities during spring tides, exceeding 4m/s. Moreover, the exchange of water and heat from the Pacific Ocean to the Indian Ocean occurs through Indonesian Throughflow (ITF), which is the only natural connection between two tropical oceans on Earth. A minor portion of the ITF is being transported through the Lombok Strait as a subsurface jet (Mayer et al., 2012). Flow conditions on Sunda Strait are also affected by the regional excess of freshwater entering into Pacific waters through Sunda Shelf (Gordon, 2005).

Modelling of tidal currents

Tidal stream currents are computed with the Delft3D Modelling System, developed by Deltares, the Netherlands. 3D models with fixed layers in depth-wise direction were developed. Grids were constructed with a resolution up to 20m in horizontal and 3m in vertical. Computational grids used for simulations, and the nesting sequence comprising of two models set up for the Strait of Lantuka are illustrated in Figure 2-2. Bathymetric data for the Strait of Lantuka have been obtained from single beam echo sounding surveys, and for the rest, data have been obtained from SRTM15_PLUS, a data fusion of global seafloor topography from satellite altimetry and ship depth soundings. Much attention has been given to the meteorological forcing and conditions at the open sea boundaries to adequately capture the density gradients and flow fields along the straits. Tidal forcing is extracted from TPXO Indian Ocean Atlas (1/12° regional model). Eleven harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) were considered in this study. Data to determine the sea surface height, salinity and temperature at the open sea boundaries are supplied from HAMSOM, the Hamburg Shelf Ocean Model, which is a 3D free surface baroclinic hydrodynamic model developed in the Institute of Oceanography at the University of Hamburg. Data from the Global Forecast System of NOAA's National Climatic Data Center have been used as meteorological input. Thus, the effects of air cloudiness, air temperature, atmospheric pressure, relative air humidity, and wind (in E and N directions) have been considered in simulations.

Model verifications using tidal records show excellent agreement. The location of an operational measuring device is indicated in Figure 2-2, and Figure 2-3 shows comparisons of modelled values and the values measured by the indicated device, from 1 to 31 of July 2014. The agreement between modelled and measured values was tested with Pearson's product-moment correlation coefficient. The r -value was resulted equal to 0.98, which indicates a strong, positive linear relationship.

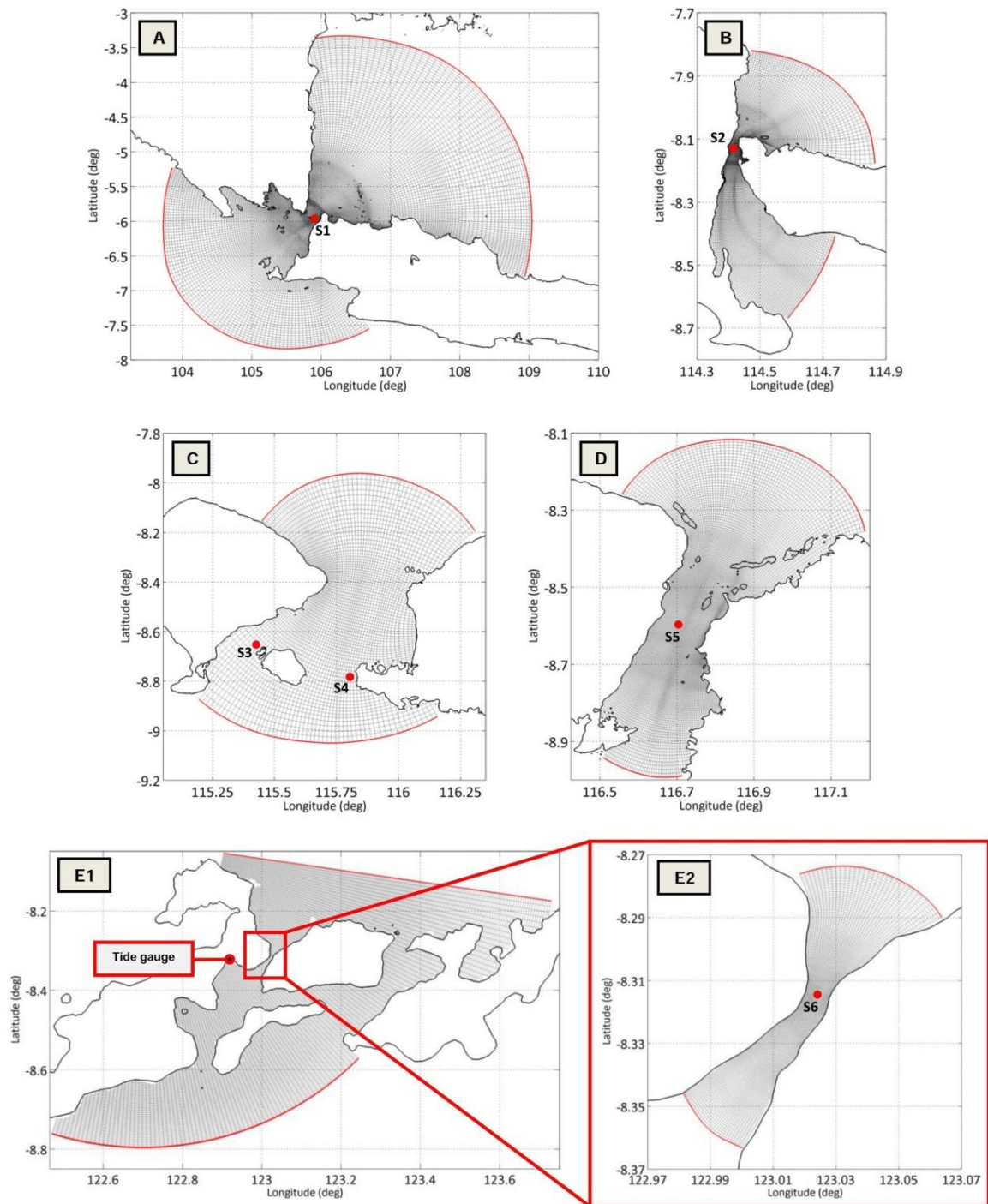


Figure 2 - 2: Computational grids of numerical models (A: Sunda Strait, B: Bali Strait, C: Badung & Lombok straits, D: Alas Strait, E1 [Overall Model]: Lamakera, Boling, Solor, Lewotobi and Larantuka straits, E2 [Detailed Model]: Strait of Larantuka).

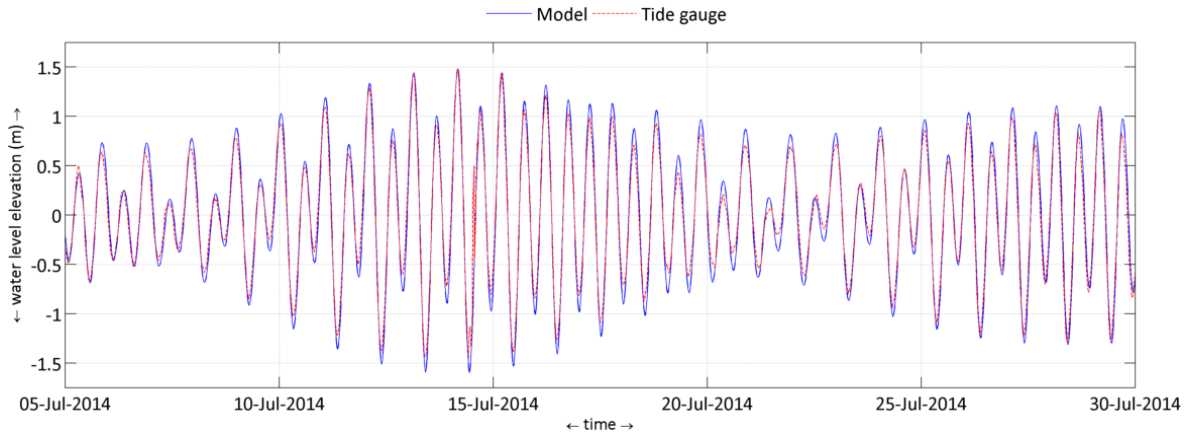


Figure 2 - 3: Comparison of measured and modelled tidal water levels ($r = 0.98$).

Suitability criteria and energy hotspots

Site selection for the installation of TISEC devices depends on available power, site characteristics, and possible environmental and socio-economic impacts of the projects (Defne et al., 2011). In this study, a multi-criteria assessment methodology that accounts for physical constraints is applied to determine suitable locations for tidal stream power conversion. Horizontal axis tidal turbines that can harness a strongly bi-directional flow are considered in the evaluations. The near free surface upper 5m is eliminated for recreational activities (small boats, swimmers, etc.) and to minimize turbulence and wave loading effects on the turbines, as well as damage from floating materials (EMEC, 2009). At the bottom, the turbines are located above the low-speed benthic boundary layer, which is usually 10% of the mean lower low water depth (EPRI, 2006). Considering these clearances, minimum depth is defined as 7.5m, which is adequate to install a turbine with a rotor diameter of 1.5m. Average kinetic power densities in the region have been estimated as follows:

$$P = \frac{1}{2} \cdot \rho \cdot U^3 \quad (2 - 1)$$

where P is tidal stream power per unit area of flow (kW/m^2), ρ is the density of seawater (kg/m^3), and U is the current velocity (m/s). Generally, TISEC devices require a minimum flow velocity (cut-in velocity) to start operating, which ranges from 0.5m/s to 1m/s depending on their design (EPRI, 2006). Considering also this limitation, regions with the average kinetic power density larger than 0.5 kW/m^2 (corresponding to a current velocity of 1m/s), surface area larger than 0.5 km^2 , and water depths larger than 7.5m are defined as energy hotspots, suitable locations for tidal stream power conversion.

Modelled tidal stream current velocities taken from observation stations S1, S2, S3, S4, S5, and S6 (Figure 2-2) are shown in Figure 2-4. Figure 2-5 shows the spatial variation of the average kinetic power densities at the energy hotspots within investigated domains.

Regarding the identification of suitable locations for tidal stream power conversion, future research efforts should be widened to accommodate conflicting use of marine environment such as fishing, shipping, offshore wind, habitat protection, and also technical limitations. Comprehensive

life cycle assessments of power converter arrays that would also include areas like fluctuation of power output, storage, or grid integration are still missing (Uihlein & Magagna, 2016). In this study, a methodology is currently being developed to take main environmental constraints and accessibility of the resources into account alongside physical constraints. Moreover, the intersectoral Zoning Plan for Marine, Coast, and Small islands proposed by the Directorate General of Coastal Zones and Small Islands shall be accounted for. The scheme envisages the reduction of conflicts with other activities and stakeholders and defines guidelines and activities, which are allowed, permitted with license, and/or prohibited in the region under consideration.

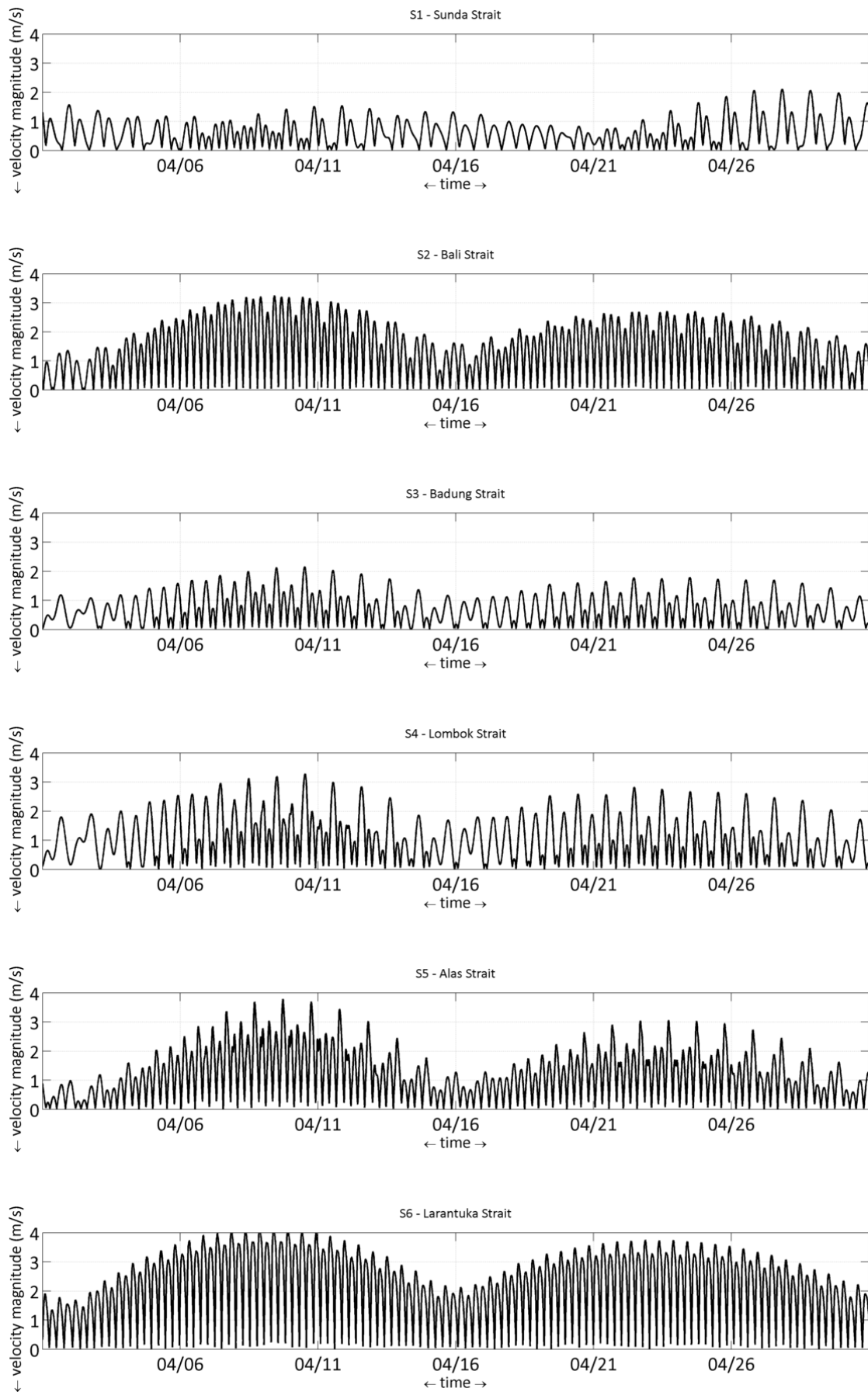


Figure 2 - 4: Modelled depth-averaged tidal stream current velocities (01.04.2012 – 30.04.2012).

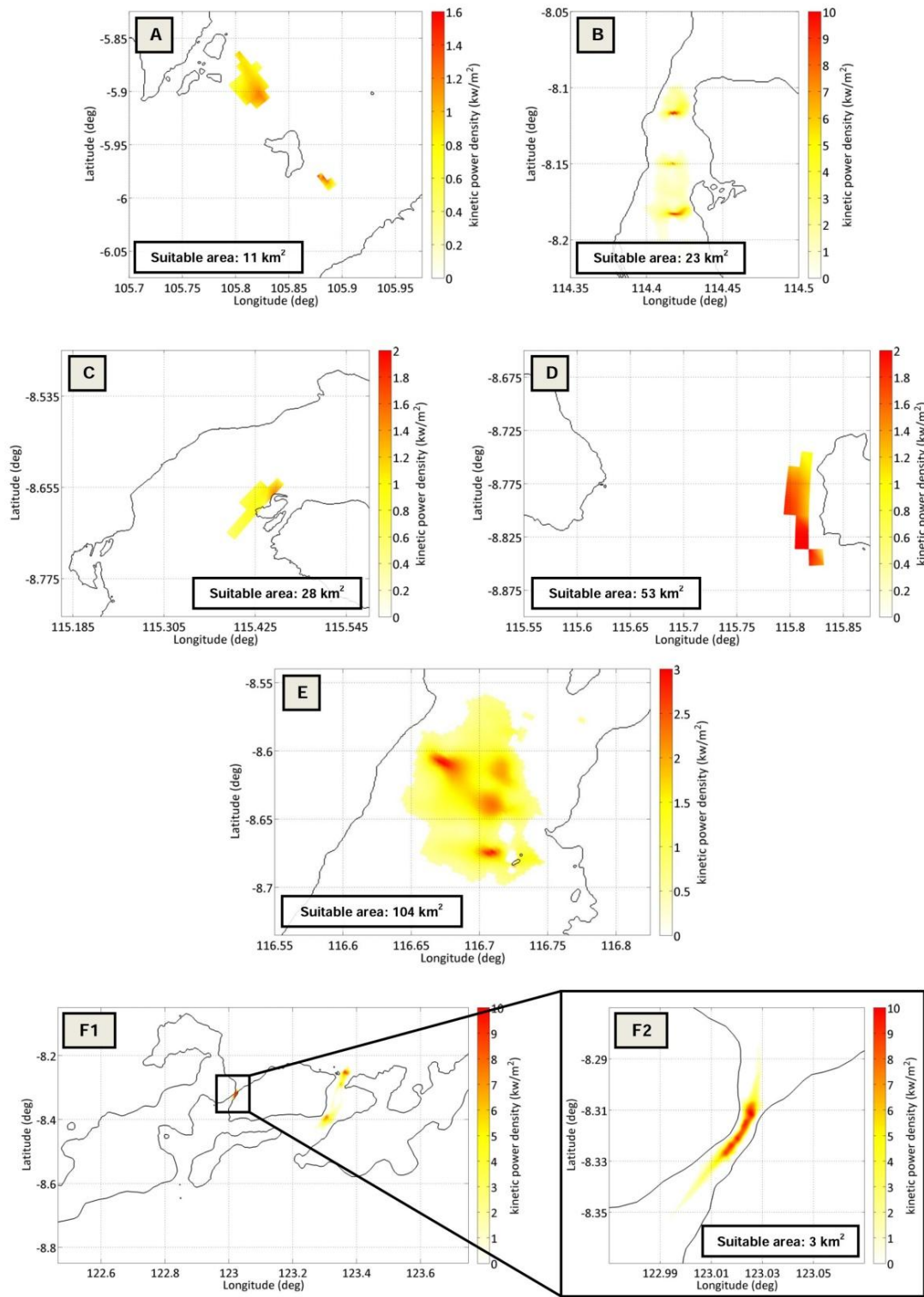


Figure 2 - 5: Spatial variation of the average kinetic power densities in the energy hotspots within investigated domains (A: Sunda, B: Bali, C: Badung, D: Lombok, E: Alas, F1: Lamakera, Boling, Solor, Lewotobi and Larantuka, F2: Larantuka - Detailed).

Resource assessment and tidal stream power potentials

To compute the exploitable power densities using tidal turbines, current velocities at the hub heights of the turbines have been used, and rated flow velocities of the turbines have been neglected. Considering a chain of water to wire efficiencies, the electric power that can be delivered to the local grid by each turbine was estimated using:

$$P_{electric} = A_{turbine} \cdot \frac{1}{2} \cdot \rho \cdot U_{hub}^3 \cdot \eta_{turbine} \cdot \eta_{ptake-off} \quad (2 - 2)$$

where $A_{turbine}$ is the turbine rotor swept area (m²), and U_{hub} is current velocity magnitude at the turbine hub height (m/s). $\eta_{turbine}$ (= 45%) is the efficiency with which the turbine extracts kinetic energy from the incoming flow, and $\eta_{ptake-off}$, power take-off efficiency, was given using equation (2-3).

$$\eta_{ptake-off} = \eta_{drivetrain} \cdot \eta_{generator} \cdot \eta_{pcon} \quad (2 - 3)$$

where $\eta_{drivetrain}$ (= 96%) is the efficiency with which the energy extracted from the flow is delivered to the generator, $\eta_{generator}$ (= 95%) is the efficiency with which the mechanical energy input to the generator is converted to electricity and η_{pcon} (= 98%) is the efficiency with which the electricity produced by the generator is conditioned to meet phase and voltage requirements of the local electrical grid interconnection point (EPRI, 2006). Analysis showed that the turbines with rotor diameters ranging between 1.5m to 20m are suitable for installation in identified energy hotspots. Examples of power curves used to compute the expected turbine output power are shown in Figure 2-6. Considering the criteria described in the previous section and estimated power curves for the tidal turbines, distributions of the applicable tidal turbine rotor diameters within the Strait of Larantuka is shown as an example in Figure 2-7-A, and Figure 2-7-B shows the spatial variation of the estimated electric power that can be delivered to local electrical grid by turbines. It can be seen that the resulting density of the extractable electric power corresponds more with current velocities than with rotor diameter. At the locations where the current velocities are higher, extractable electric power density can exceed about 1,200MW.

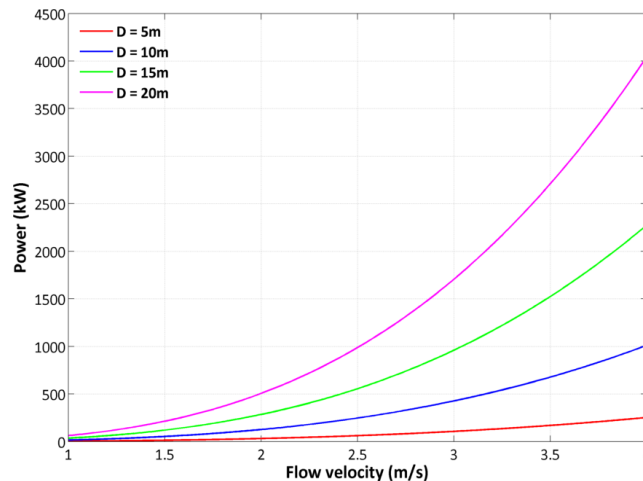


Figure 2 - 6: Power curves for tidal turbines with the rotor diameters (D) of 5, 10, 15, 20 meters.

Table 2-1 shows the results of the tidal stream resource assessment and ranking of the investigated domains based on the level of kinetic power densities. The total extractable powers were calculated based on a variation of the “per-generator” method (Blunden et al., 2013). The extracted energy is calculated from the flow fields in their natural states, considering the size and performance of the devices and packing density within the energy hotspots. The wake effects of turbines have been ignored, avoided by setting the spacing among generators to minimize the interferences.

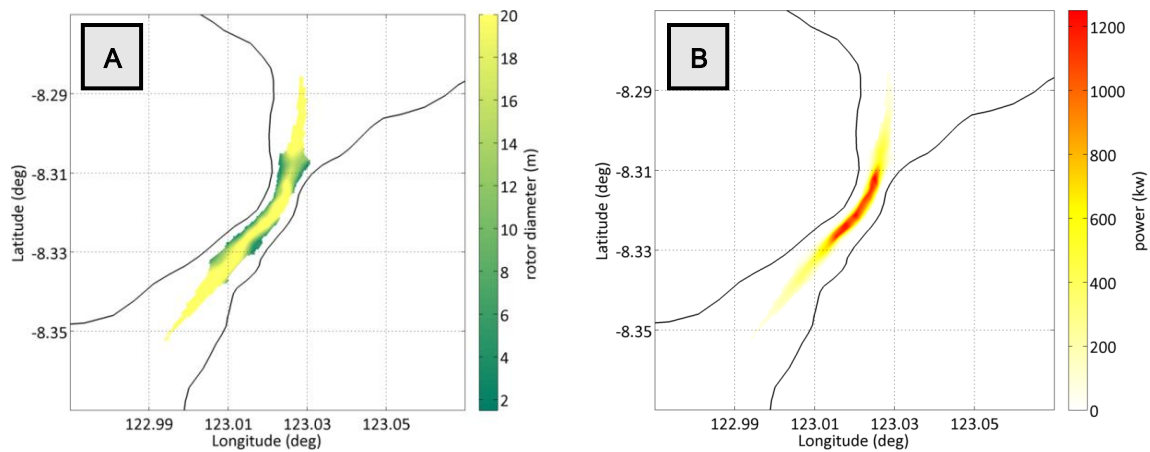


Figure 2 - 7: Spatial variation of the applicable tidal turbine rotor diameters (A) and average extractable electric power with the tidal turbines (B) at the Strait of Lantuka.

Table 2 - 1: Summary of the resource mapping of investigated domains.

				Cut-in velocity = 1.0 m/s		Cut-in velocity = 0.5 m/s	
	Strait	Max kinetic power density (kW/m ²)	Max extractable power by a turbine (kW)	Suitable area (km ²)	Total extractable power (MW)	Suitable area (km ²)	Total extractable power (MW)
1	Bali	14.75	1,459	23	462	104	1,045
2	Larantuka	10.20	1,250	3	199	6	299
3	Boling	3.49	430	36	593	106	736
4	Alas	3.07	396	104	1,261	403	2,258
5	Lombok	2.36	236	53	754	114	865
6	Sunda	1.56	165	11	107	145	335
7	Badung	1.52	161	28	238	162	551

Conclusions and outlook

Tidal stream resource assessments are done for the straits between the Indian Ocean and inner Indonesian seas. Energy hotspots are determined considering the available power and site characteristics. Applicable rotor diameters within the energy hotspots are defined, and diameters ranging between 1.5m and 20m resulted. Spacing among the units is set to minimize the interferences. Power potentials are estimated considering typical power curves. The results obtained

showed that the straits in question have tremendous potential for the production of ocean renewable energy. Current velocities are up to 3-4m/s, and the power density at some locations can exceed 10kW/m². Selected sites have been ranked based on the level of power density, and the highest power densities are observed in the Strait of Larantuka. For each site, total tidal stream energy resource is estimated, and spatial variation of the average exploitable electric power is determined. Although the Strait of Larantuka has highest power densities, it was seen that Alas Strait has the biggest potential for energy production, mainly as a consequence of its bigger energy hotspot size. According to the preliminary assessments, power production at the straits is likely to exceed previous predictions reaching around 4,800MW. Investigations accounting for other coastal uses, environmental, economic, and social impacts are currently underway.

Acknowledgments

This study is funded by the German Ministry of Education and Research under grant number 03F0646A. Bathymetric data provided by the Indonesian Agency “Badan Informasi Geospasial (BIG)” is highly appreciated. We are also grateful to the Indonesian “Agency for the Assessment and Application of Technology (BPPT)” for supporting the installation and maintenance of the measuring devices in Larantuka.

Chapter 3

Influence of Regional Ocean Dynamics on Tidal Stream Power Generation

About the influence of density-induced flow on tidal stream power generation in the Sunda Strait, Indonesia

Kadir Orhan, Roberto Mayerle and Bernhard Mayer

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About the influence of density-induced flow on tidal stream power generation in the Sunda Strait, Indonesia

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In this paper, the results of a numerical model study evaluating the influence of density-induced flow on tidal stream power generation in the Sunda Strait, Indonesia, are summarized. Tidal stream currents with speeds reaching about 2-3m/s and total extractable power of around 300MW turn the Sunda Strait into a promising location for renewable electricity production from the ocean. Furthermore, seasonally varying share of the density currents on the energy flux through the Sunda Strait emphasize the importance of a more comprehensive modelling approach for the selection and evaluation of the deployment sites of tidal turbines. A high-resolution, three-dimensional circulation model providing sufficient spatiotemporal coverage has been developed to simulate tidal currents in barotropic and baroclinic modes. Simulation outputs have been used to reveal the influence of density-induced flow on tidal stream power generation during both northwest and southeast monsoonal seasons. Up to 100% increase in current speeds has been simulated in the strait due to the density gradients, which leads to an enormous increase of the kinetic power. Additionally, energy hotspot shows significant changes due to the variations in density. The energetic section of the strait becomes significantly larger, with an overall increase of the kinetic power densities. The findings may help us to understand the importance of including the ocean water density to resolve flow fields with better precision, which can lead to more accurate assessment and more efficient use of the resources of marine renewable energy.

Keywords: renewable energy; tidal stream current; density-induced flow; numerical model; Indonesia

Introduction

Humankind is drifting deeper into global economic, environmental, geopolitical, and societal problems every day. Environmental risks such as failure of climate change mitigation and adaptation, extreme weather events, natural disasters, biodiversity loss, and ecosystem collapse are intensifying alongside societal risks like water and food crises together with economic risks like energy price shock (WEF, 2019). Storms, forest fires, droughts, coral bleaching, heat waves and floods, which we already experience due to the global warming, are likely to get significantly worse in the upcoming decades, and impacts are expected to be felt across ecosystems, human communities and economies (IPCC, 2018). To mitigate further damage requires a quick and strengthened global response, which involves greater policy design and decision-making regarding energy system transitions and universal access to renewable electricity. Meanwhile, ocean energy remains a largely untapped renewable energy source (REN21, 2018).

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Horizontal axis tidal turbines are closest to technological maturity among other ocean renewable energy (ORE) technologies (TRL 8), and they have reached a pre-commercial state. In 2017, tidal stream power production achieved a net capacity addition of 17MW, mainly from the tidal turbine arrays deployed in Scotland. However, the tidal sector is still in a critical phase of development, where demonstration farms are needed for systems to be proven in the actual operational environment (Magagna et al., 2016; REN21, 2018). Thus, a clear focus on prioritizing deployment is required.

Concerning the identification of suitable areas for tidal turbine deployment and optimization of tidal energy farms, it is of utmost importance to define flow patterns with precision as well as to understand hydrodynamics within the areas of interest before and after the deployment. In recent years, computational models to evaluate the energy potential of tidal currents have been developed for many regions of the world. However, often for the sake of simplicity and because only tidal currents were of interest, density gradients due to horizontal salinity or temperature variations were neglected in simulations. In reality, patterns of tidal currents and currents resulting from density differences add to complex flow structures. The “tide-only” approach might be highly misleading for domains such as Sunda Strait in Indonesia (Kamphuis, 2010; Uihlein & Magagna, 2016).

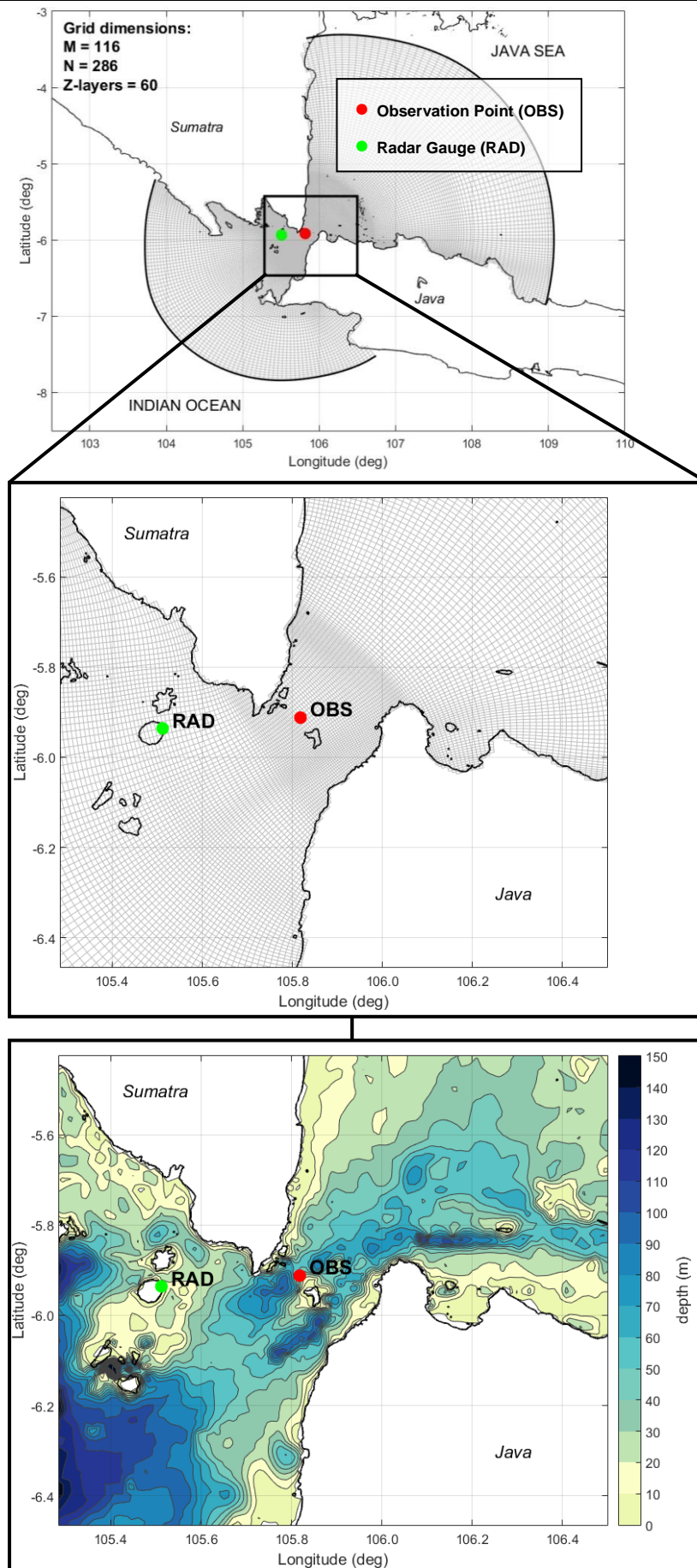


Figure 3 - 1: Computational grid and bathymetry of the Sunda Strait circulation model.

The Sunda Strait, located between the Sumatra and Java Islands, connects the Java Sea and Indian Ocean (Figure 3-1). The Strait has a width of 24km in its bottleneck. It exhibits a large slope with 18km width and 35m depth near the Java Sea along with 50km width and 500m depth near the Indian Ocean (Putri, 2005). The tidal range is mostly around 1m in the strait, and current velocities are exceeding 3m/s during peak periods. Meanwhile, flow conditions in the Sunda Strait are strongly affected by the regional excess of freshwater entering into Pacific waters through the Sunda Shelf as well as the monsoon and other sea-air-land interactions such as El Niño and Dipole Mode Event (Gordon, 2005; Putri, 2005; Mayer et al., 2012).

Previously, within the framework of the joint research project “Potentials of Ocean Renewable Energy in the Indonesian Seas (ORE-12)” funded by the German Ministry of Education and Research, tidal stream resources of several promising straits between the Indian Ocean and inner Indonesian seas, involving Sunda Strait, have been investigated (Orhan et al., 2016; Orhan & Mayerle, 2017). Orhan et al. (2016) provided an overview regarding the energy potential of tidal stream currents within the straits in question, utilizing state-of-the-art measurements and high-resolution, 3D flow models. The total extractable power from the Sunda Strait was calculated as 300MW based on a variation of the “per-generator” method (Blunden et al., 2013). The extracted energy was calculated from the flow fields in their natural states, considering the size and performance of the devices and packing density within the energy hotspot. The wake effects of turbines were ignored, avoided by setting the spacing among generators to minimize the interferences. Orhan and Mayerle (2017) studied the possible impacts of the tidal turbines on the flow conditions in the Strait of Larantuka, located in the eastern part of the Indonesian archipelago. Research regarding the hydrodynamic impacts and the performance of a commercial-scale tidal farm is currently underway.

This paper summarizes the results of a modelling experiment showing the influence of density-induced flow on the tidal stream power potential of the Sunda Strait. Considering the stratified nature of the strait’s flow structure and higher hydrokinetic power densities observed closer to its free surface, emphasis in this paper is put on surface currents. The effect of the density currents has been evaluated throughout the year, and a close look is given to the changes occurring during the northwest and southeast monsoon seasons of the region. Seasonal changes of the density gradients and their influence on current speeds and kinetic power densities (temporal & spatial) are demonstrated.

Methodology and application

Currents are computed with the Delft3D, an integrated numerical flow and transport modelling system developed by Deltares, the Netherlands (Delft Hydraulics, 2006). The 3D finite element model was adapted with a z-layer grid. Z-layers, fixed in the vertical direction, are preferred in the model for the accuracy of the vertical distribution of salinity and temperature (Cornelissen, 2004). Grids with various resolutions both in the horizontal and in the vertical have been tried to provide the

highest resolution with acceptable run time. The selected grid is constructed with a resolution up to 500m in horizontal (at the bottleneck), and 10m in vertical (near the free surface). Thus, hydrodynamic conditions are resolved in sufficient detail around the Sunda Strait, and also density gradients within the model domain can be captured, which show significant changes mainly in the upper 400m (Gordon, 2005; Mayer et al., 2012). To reduce the computational costs, the mesh size of the model is gradually increased towards the open sea boundaries in the horizontal plane, and towards the seabed in vertical. Computational grid and bathymetry of the model are illustrated in Figure 3-1. For the simulations, three different time frames were chosen. To understand the annual trends and seasonal changes, and to represent the cycles of the main forcing components (water level & density), the model was run throughout the year 2012 (Ozturk et al., 2017). Afterward, to have a more temporally detailed look at the regional hydrodynamics during dry and wet seasons, the model was run throughout the July 2012 and February 2012, respectively. For temporal discretization, a time step of 3s was described, corresponding to the maximum Courant-Friedrichs-Lewis criterion of 0.8 (Ozturk et al., 2017). The model has been forced by the tide only (barotropic mode with constant water density, 1029kg/m^3) and by tide combined with the density gradients to include the density-induced flow (baroclinic mode). Meteorological forcing was involved in both scenarios. Model grid (Figure 3-1, top) was extended into the Java Sea in the north and into the Indian Ocean in the south to capture the impacts from both systems. Model bathymetry has been obtained from SRTM15_PLUS, data fusion of global seafloor topography from satellite altimetry and ship depth soundings (Olson et al., 2014). Much attention has been given to the meteorological forcing and conditions at the open sea boundaries to adequately capture the density gradients and flow fields along the strait. Tidal forcing is extracted from TPXO Indian Ocean Atlas ($1/12^\circ$ regional model) and prescribed as time series (Egbert & Erofeeva, 2002). Eleven harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) are considered in this study. Data to determine the salinity and the temperature at the open sea boundaries are supplied from HAMSOM, the Hamburg Shelf Ocean Model, which is a 3D free surface baroclinic hydrodynamic model developed in the Institute of Oceanography at the University of Hamburg (Mayer et al., 2010). Data from the Global Forecast System of NOAA's National Climatic Data Center have been used as meteorological input (Environmental Modeling Center, 2003). Thus, effects of air cloudiness, air temperature, atmospheric pressure, relative air humidity and wind (in E and N directions) have been considered in simulations. To specify the exchange of heat through the free surface, ocean heat flux module of Delft3D is activated, which typically applies to large water bodies (Lane, 1989). Due to its significant advantages in resolving stratified flows, k- ϵ model, which is a second-order turbulence closure scheme, is selected to include the effects of the turbulent kinetic energy and turbulent kinetic energy dissipation (Burchard and Baumert, 1995; Postma et al., 1999).

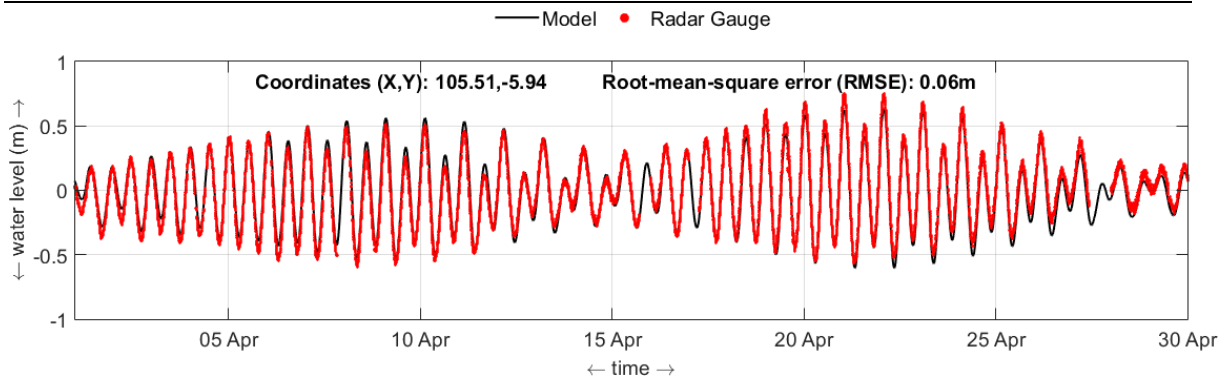


Figure 3 - 2: Comparison of modelled and measured tidal water levels at the radar gauge location.

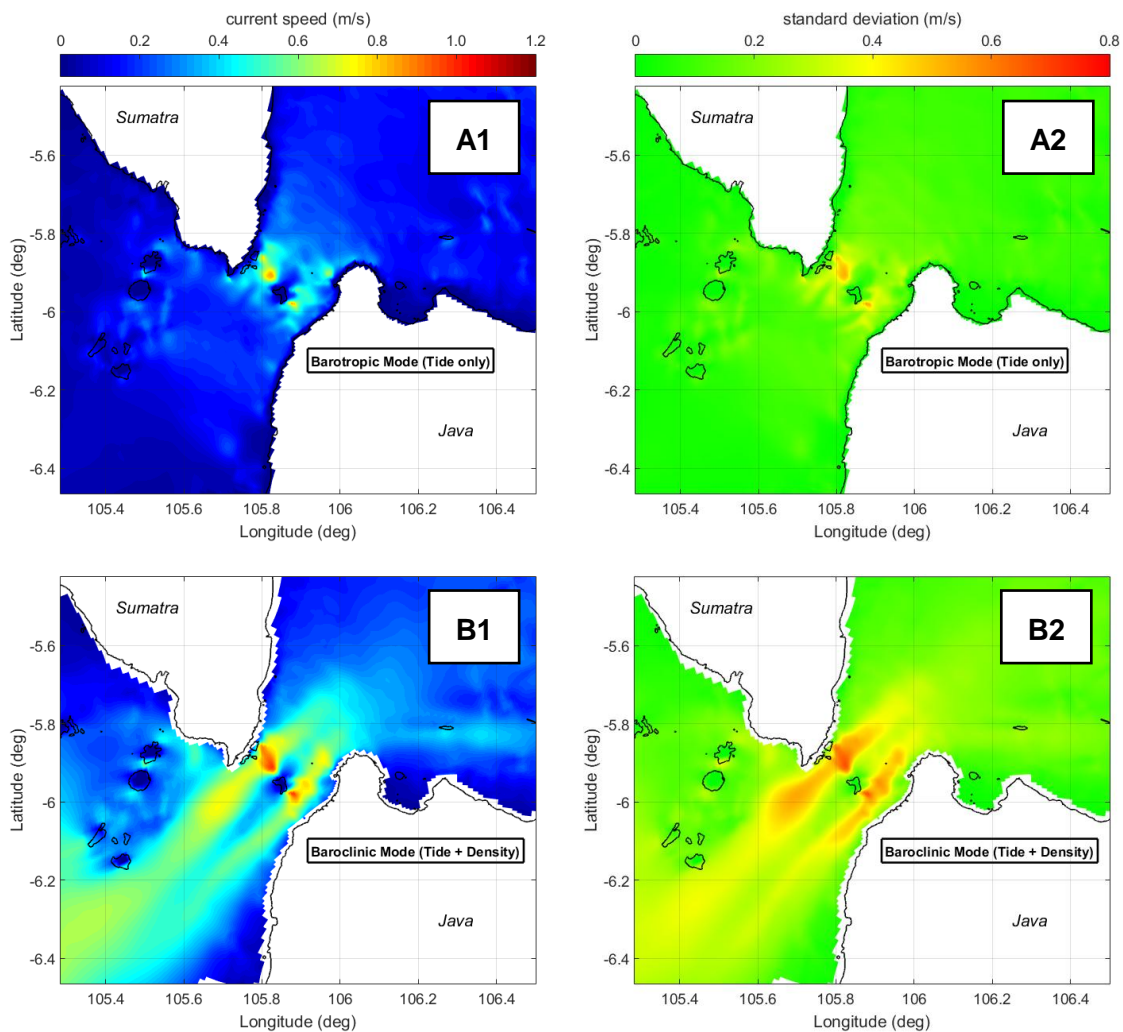


Figure 3 - 3: Simulated annual mean current speeds and their standard deviations for barotropic (A1, A2) and baroclinic (B1, B2) model runs.

Model verification using tidal records shows a strong positive linear correlation between the modelled and the measured values (Figure 3-2). The location of the operational radar gauge is indicated in Figure 3-1 (the point RAD with green color), and Figure 3-2 shows the comparison of the modelled values and the values measured by the indicated device, from 1st to 30th of the April 2019. The agreement between modelled and measured values was tested with the RMSE method. The RMSE value was resulted in equal to 0.06m, which indicates a good agreement.

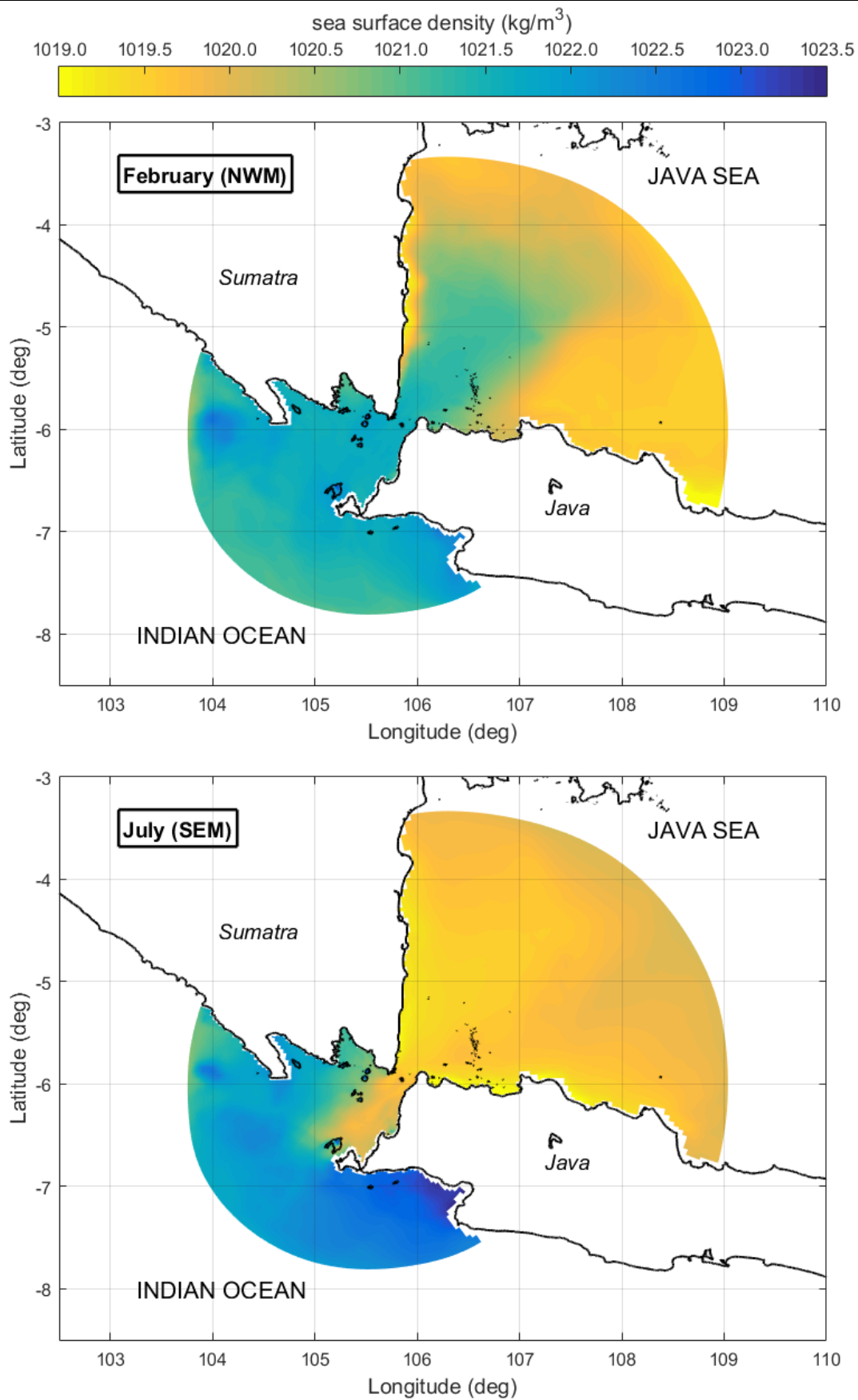


Figure 3 - 4: Spatial variation of the monthly mean sea surface density during February 2012/NWM (top) and July 2012/SEM (bottom).

Results

Seasonal changes in flow conditions

Mainly dominated by the M2 lunar semidiurnal constituent governed by the Indian Ocean and K1 lunar diurnal constituent governed by the Pacific Ocean, phase or amplitude of the tidal water level elevations don't change much in the region throughout the year (Ray et al., 2005). Figure 3-3, top and bottom panels (A1-A2, B1-B2), illustrate the spatial distribution of the annual mean tidal current speeds at the free surface and their standard deviations, based on the simulation results in barotropic and baroclinic modes. As it can be easily noticed, although tidal water level elevations do not show much seasonal variation, under the influence of the density-induced flow, important changes occur in the characteristics of the tidal currents. It can be seen that the baroclinic tidal currents are much stronger compared to the barotropic tidal currents. In baroclinic mode, the energetic section of the strait becomes significantly larger with higher standard deviations.

The Java Sea is highly influenced by the semi-annual reversing monsoon system in the region (Pohlmann, 1987). Generally, from June to September, the wind is directed towards Asia (Southeast Monsoon, SEM), and from December to March, the wind is directed towards Australia (Northwest Monsoon, NWM) (Putri, 2005). Among other things, these monsoonal winds have a great impact on the water exchange of the Java Sea with the South China Sea and the Indian Ocean, which mainly occurs through Karimata and Sunda Straits, respectively. Figure 3-4 illustrates the spatial distribution of the sea surface density (density of the model's surface layer of 10m) within the study area during the NWM (February 2012) and the SEM (July 2012) seasons. The overall transport through the Sunda Strait (Sunda Strait throughflow) is predominantly directed to the Indian Ocean (Potemra et al., 2016) but the direction varies with the seasons. Therefore, an influence of the high-density Indian Ocean waters can be observed over the waters of the Java Sea during the NWM (Figure 3-4, top). On the contrary, during the SEM, waters of the Java Sea move towards the Indian Ocean (Figure 3-4, bottom). This phenomenon is likely to be one of the main underlying causes of the seasonal variations of the baroclinic tidal currents in the Sunda Strait. Figure 3-5 presents the simulated surface current velocities at the point OBS (with red color, see Figure 3-1) with the tide and tide+density type of forcing for 2012 (Figure 3-5, top) as well as for the NWM (Figure 3-5, middle) and the SEM (Figure 3-5, bottom) seasons. From the top panel, it is obvious that the magnitude of the tidal currents shows no significant seasonal change in both cases. However, including density-driven currents alters the hydrodynamics and does it due to the season.

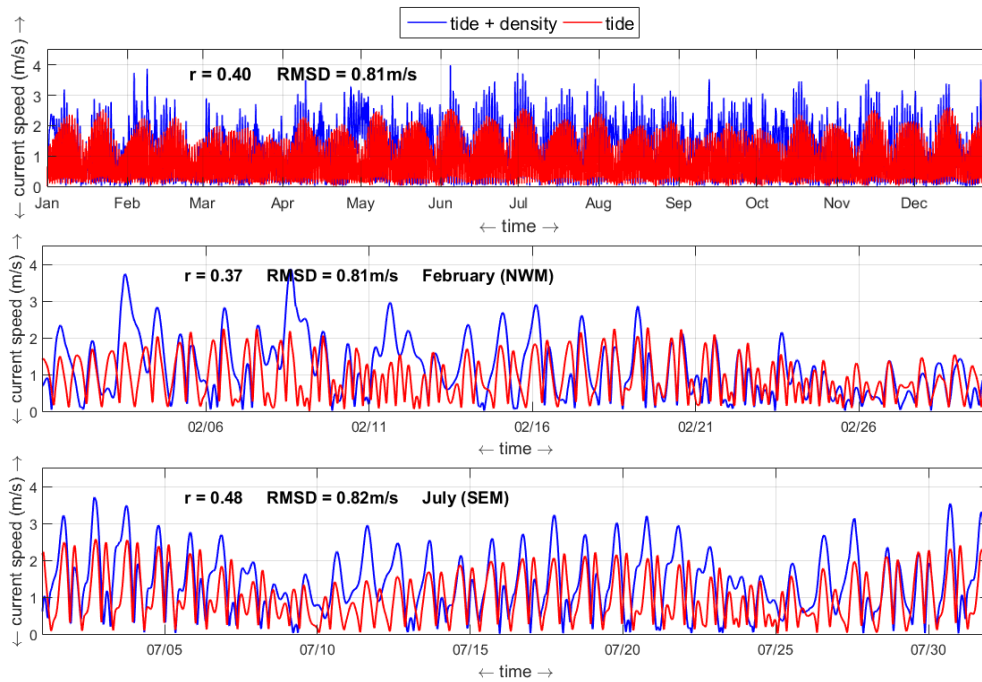


Figure 3 - 5: Time series of surface current speeds simulated by the model at the point OBS (see Figure 3-1). 2012 (top); February 2012/NWM (middle); July 2012/SEM (bottom).

To demonstrate the change between the currents simulated for tide+density and tide alone scenarios more understandably, root-mean-square deviation (RMSD) and Pearson's r methods have been used. While the RMSD does not show a significant change throughout the year between the baroclinic and barotropic tidal currents (ca. 80cm/s), we can see that the amplitude of the currents is altered less by the density gradients during the SEM ($r = 0.48$) than during the NWM ($r = 0.37$). During both seasons, we can observe an increase of the velocity magnitudes at the point of observation up to 100% during tidal peaks.

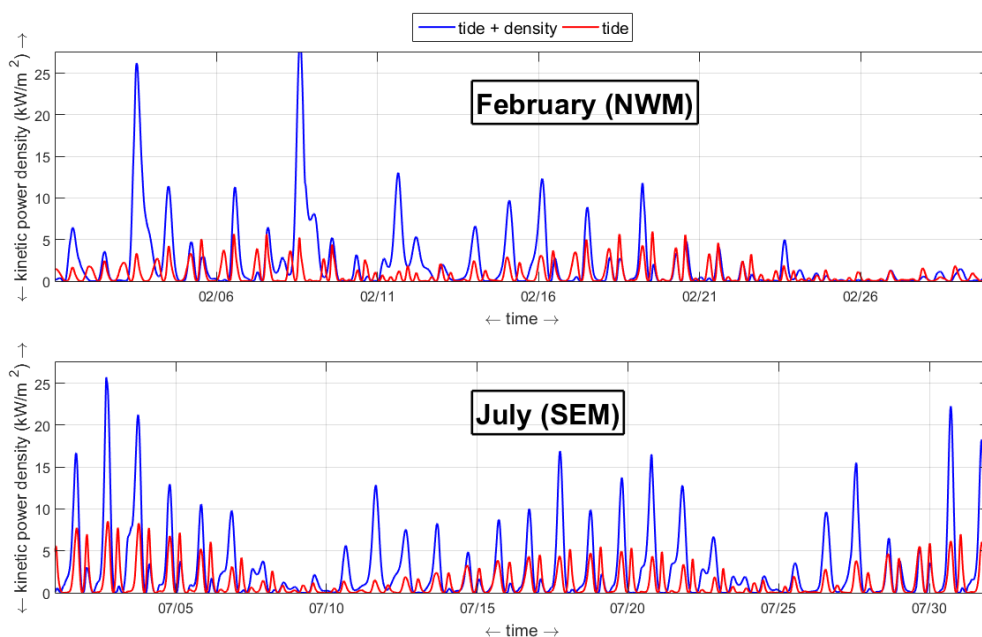


Figure 3 - 6: Time series of surface kinetic power densities estimated at the point OBS (see Figure 3-1) during February 2012/NWM (top) and July 2012/SEM (bottom).

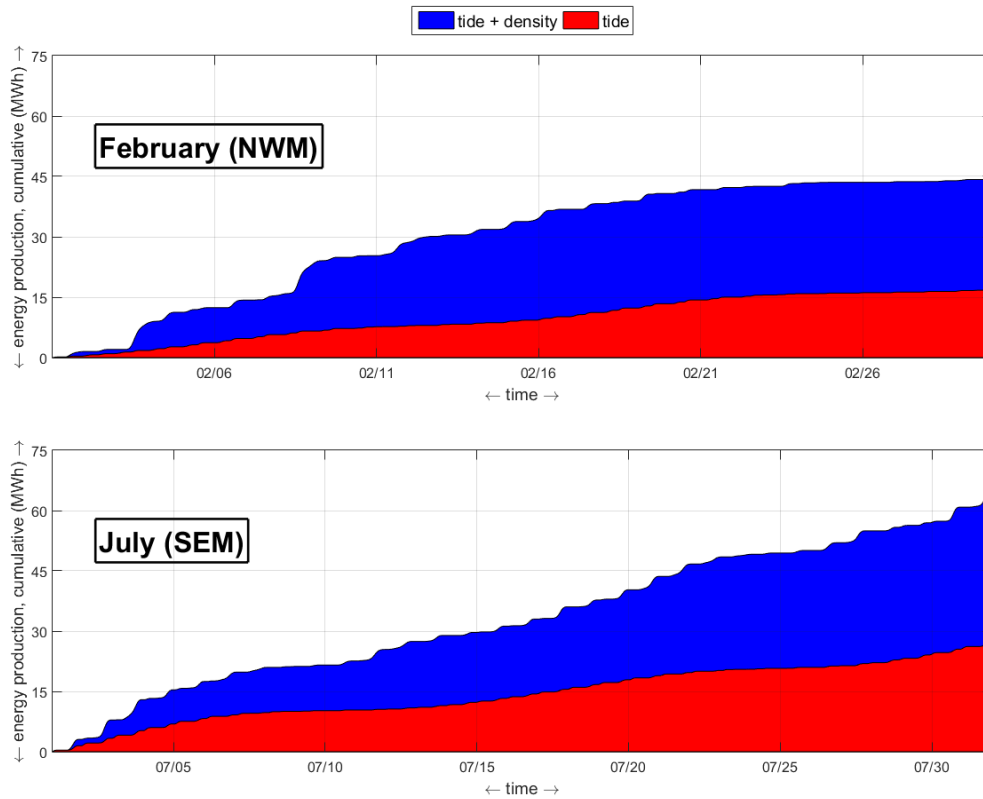


Figure 3 - 7: Time series of cumulative energy production estimated at the point OBS (see Figure 3-1) during February 2012/NWM (top) and July 2012/SEM (bottom). A horizontal axis tidal turbine with a 10m rotor diameter has been considered in calculations.

Impacts on tidal stream power generation

As Figure 3-5 illustrates, density currents in the Sunda Strait can amplify tidal current speeds by up to 100% at the free surface (i.e., from 2m/s to 4m/s). The hydrokinetic power increases with the cube of the current speed. It is given by $P = \frac{1}{2} \times \rho \times U^3$, with ρ = water density [kg/m^3], U = current speed [m/s]. Thus, a 100% increase in the current speed might lead to a much larger increase in power density. Figure 3-6 shows the time series of the current power densities simulated by the model at the free surface during NWM and SEM. During NWM, when tidal currents have a power density in the order of 5kW/m^2 during a peak spring tide, current power density increases to the order of 25kW/m^2 under the influence of the density-driven currents. Similarly, during SEM, it can be observed that the density currents can amplify the power densities of the tidal currents by up to 150% at the peaks of tidal cycles. To demonstrate the cumulative impact of the density-induced flow in both seasons, accumulation of the electricity produced by a generic, horizontal axis tidal turbine with a 10m rotor diameter (fitting into the surface layer of the model), located at the point OBS (see Figure 3-1), is illustrated in Figure 3-7. The method introduced in the Orhan et al. (2016) and Orhan and Mayerle (2017) has been used for the calculation of the energy output. It can be seen that during both seasons, electricity production in the baroclinic mode is more than twice of electricity production in the barotropic mode.

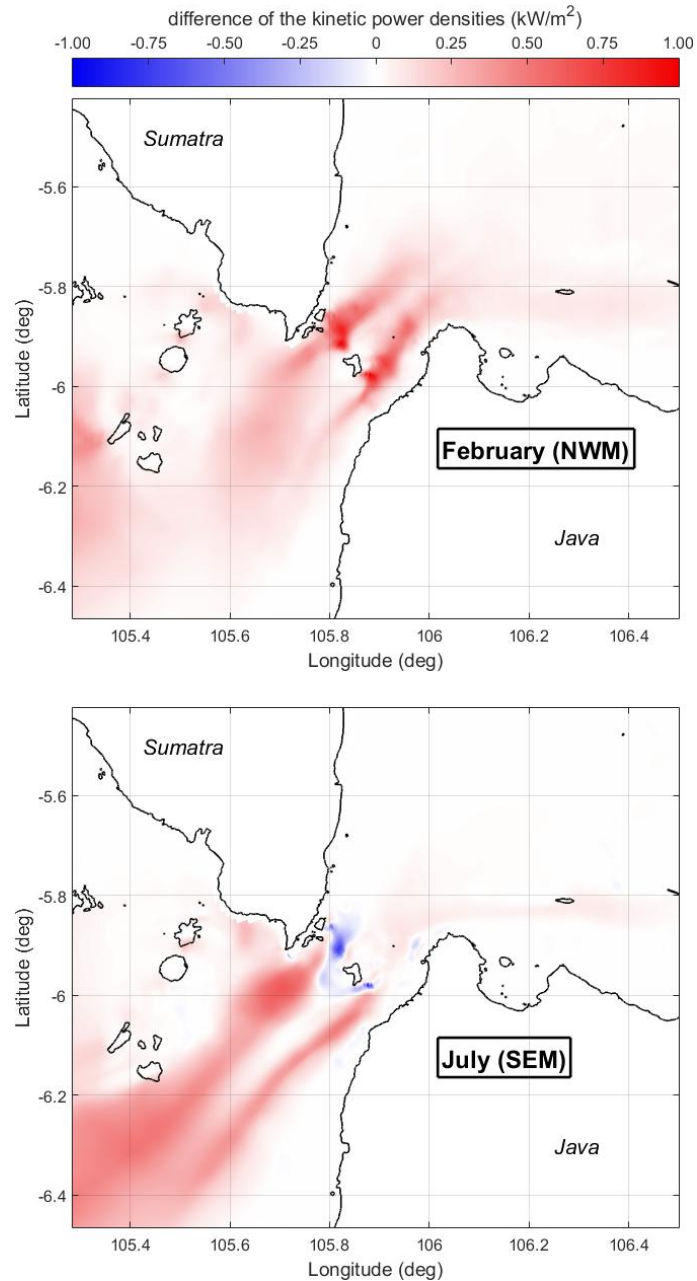


Figure 3 - 8: Differences between the simulated monthly means of the surface kinetic power densities of the tide and the tide + density cases during the NWM (top) and the SEM (bottom) seasons.

Generally, tidal stream devices require a minimum current velocity (cut-in velocity) to start operating, which ranges from 0.5m/s to 1m/s depending on their design. Thus, regions with an average kinetic power density larger than 0.5kW/m^2 (corresponding to a current velocity of 1m/s), with adequate surface area for tidal farm deployment (ca. 0.5km^2) and with adequate depth to install tidal turbines are defined as energy hotspots, suitable locations for tidal stream power conversion (EPRI, 2006; EMEC, 2009; Orhan et al., 2016; Orhan & Mayerle, 2017). Figure 3-8 shows the spatial distributions of the differences between monthly averages of the current power densities within the domain of interest, estimated for tide and tide + density scenarios. During NWM, an overall increase can be observed in the monthly means of the power densities. Especially at the bottleneck of the strait,

where the cross-section of the strait is divided in half by the Sangiang Island, increases of up to 1kW/m^2 can be observed. On the other hand, during SEM, we have a different outcome. Although we have an increase of the monthly means of the current power densities of up to 0.5kW/m^2 towards the south entrance of the Sunda Strait, around the Sangiang Island, a decrease of the similar magnitude can be observed. When it is considered that the limit of suitability for the deployment of tidal turbines is a kinetic power density of 0.5kW/m^2 , the importance of the alterations in flow conditions caused by the density-driven currents can be understood in a better way. Average kinetic power densities spatially changing in the order of $0.5\text{kW/m}^2 - 1\text{kW/m}^2$ means great differences in the geometries of determined energy hotspots. Therefore, it can be said that ignoring the influence of density gradients might be highly misleading for the assessment of the power potential of tidal currents. We can easily underestimate or overestimate the magnitude of the currents, the size of the energy hotspot, and, eventually, the technically extractable power from the area of interest.

Conclusions and outlook

In recent years, potentials of the tidal stream power generation have been evaluated for many regions of the world via numerical models. Due to numerous reasons such as an emphasis put mainly on tidal currents, density gradients due to salinity or temperature variations were neglected in evaluations. However, the “tide-only” approach might be highly misleading for domains like the Sunda Strait in Indonesia, where patterns of the tides, the tidal currents, and the density currents add to complex flow structures. Sunda Strait, with tidal current velocities reaching about 2-3m/s and with a total extractable power around 300MW, has a great potential for electricity production from tidal stream currents. Furthermore, impacts of the seasonally varying density currents make Sunda Strait a great example for showing the importance of a holistic modelling approach for the selection and evaluation of the deployment sites of tidal turbines.

A high-resolution, three-dimensional circulation model providing sufficient spatiotemporal coverage has been developed to evaluate the hydrodynamics of the Sunda Strait. The model has been used to simulate spatial and temporal variations of the sea surface density in the region as well as its influence on the tidal currents. It was seen that the density currents resulting from the water exchange between the Java Sea and the Indian Ocean could amplify tidal current speeds by up to 100% at the free sea surface. Thus, the tidal power densities, which increase with the cube of the tidal current speeds, show a significant and seasonally varying change in the Sunda Strait. The results showed that during both NWM and SEM seasons, electricity production calculated in the baroclinic mode is likely to be more than twice of electricity production in the barotropic mode. During NWM, at the bottleneck of the strait, where the cross-section of the strait is divided in half by the Sangiang Island, increases of up to 1kW/m^2 have been observed in the monthly means of the hydrokinetic power densities due to the density currents. Whereas during SEM, increases in the monthly means of the hydrokinetic power densities of up to 0.5kW/m^2 have been observed towards the south entrance of the Sunda Strait, alongside a decrease of the similar magnitude around the

Sangiang Island. Considering the limit of suitability for the deployment of tidal turbines and renewable electricity production from the tidal currents (a kinetic power density of $0.5\text{kW}/\text{m}^2$), the alterations in flow conditions have been found extremely important.

The findings may help us to understand the importance of using more comprehensive numerical models for future resource assessments. Especially today, in the application stage of tidal current energy where demonstration farms are needed for systems to be proven in the actual operational environment, resolving flow fields with better precision is of utmost importance for the optimization of tidal farm configurations and efficient use of the resources of marine renewable energy. Modelling approaches must be refined to this end, as well as measurement techniques. Especially in megacities with more physical and socio-economic constraints, it is important to have the right approach for site selection as well as energy forecasting and harmonization of the ORE resources. To this end, a project is currently underway.

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Chapter 4

Tidal Power Generation: Influence on Flow Conditions and Performance of Turbine Arrays

Assessment of the tidal stream power potential and impacts of tidal current turbines in the Strait of Larantuka, Indonesia

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Assessment of the tidal stream power potential and impacts of tidal current turbines in the Strait of Larantuka, Indonesia

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In this paper, results of a tidal stream resource assessment performed for the Strait of Larantuka, Indonesia, are presented. The methodology followed comprises of the estimates of power yield and evaluation of the effects of power extraction via high-resolution, three-dimensional flow models. Power densities exceeding 10kW/m² are observed in the main channel. Current velocities and wake characteristics of the turbines have been resolved reasonably well with low computational cost, considering different levels of energy dissipation. Although the results are promising, investigations using in-situ measurements alongside more advanced modelling techniques are still needed, and currently underway.

Keywords: numerical model; tidal-stream current; tidal turbine wake; Indonesia

Introduction

The ocean provides a vast source of potential energy resources. Although there is still much to be examined regarding the ocean dynamics and challenges facing developers, the global ocean energy sector is continuously growing. The various types of ocean energy technologies, such as tidal, wave, ocean thermal energy, and salinity gradient energy conversion, have reached different stages of technical and commercial development. According to the report of JRC, tidal and wave conversion systems are likely to contribute the most in the short to medium term (2025-2030) mainly due to their technological readiness levels, and tidal stream devices represent the biggest untapped potential for tidal energy, with the potential for a significant market share in future energy systems (Magagna & Uihlein, 2015).

Tidal stream energy conversion is highly predictable and can provide a stable output to the grid. It can contribute to the decarbonization of energy supply, increasing energy security by exploiting indigenous resources, and fuelling economic growth in the coastal regions (Magagna & Uihlein, 2015). Scotland (UK), already with 17 leased sites for tidal farms, is aiming to meet a significant portion of the country's power need by tidal stream energy (Neill et al., 2017). Canada and United States (North America), and France (Europe), have tidal farm projects in planning or development stages. In Southeast Asia, Indonesia is intensifying efforts both in research and application, to exploit the immense tidal stream energy resource of the country. The development of renewable energy in the Indonesian archipelago is regulated by a Presidential Decree, which states that the contribution of renewable energy should be increased to 17% of the total national primary energy mix by 2025, which includes the wave and tidal energy (Blunden et al., 2013).

In order to install the technology to capture tidal stream energy, however, it may be necessary to mitigate conflict with existing ocean space users. Studying the disturbances on the marine

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environments associated with the installation of tidal farms, and to assess the possible impacts on the hydrodynamics is of utmost importance. Otherwise, particularly in districts like Alas and Bali, where coastal areas are being used for a wide range of activities such as aquaculture, fishing, and tourism, it is inevitable to face major problems.

Tidal stream resources of several straits between the Indian Ocean and inner Indonesian seas have been investigated, and results showed that tidal stream power potential of Indonesia is likely to exceed previous predictions reaching around 5,000MW (see Figure 4-1 and Table 4-1) (Orhan et al., 2016). In this paper, results of the tidal stream resource assessment performed for the Strait of Larantuka (Site 3 on Figure 4-1) are presented in detail. Impacts of the tidal stream energy conversion on flow conditions are also investigated, alongside wake characteristics of tidal current turbines and wake recovery in the downstream of devices.

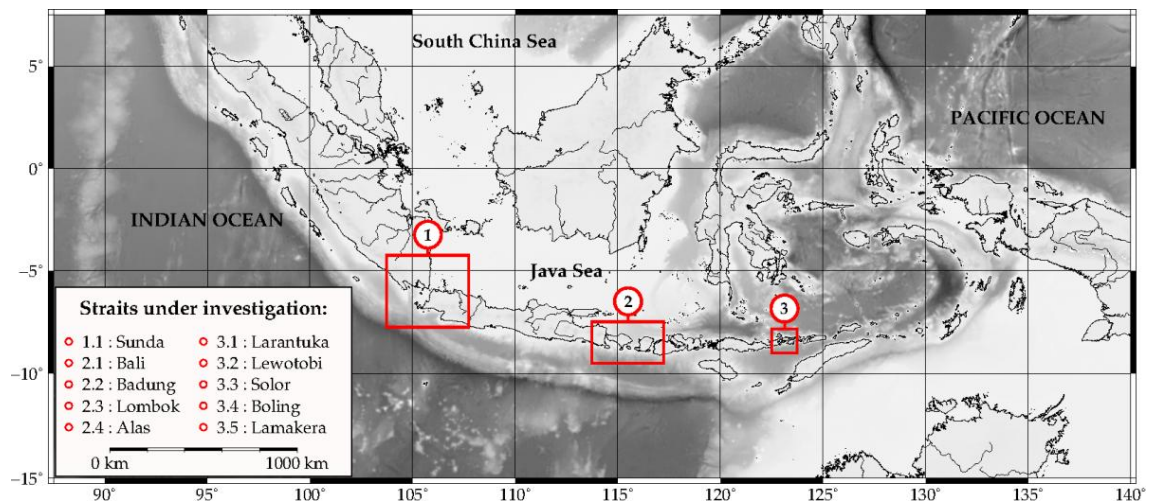


Figure 4 - 1: Straits in Indonesia being investigated.

Table 4 - 1: Summary of the resource mapping of investigated domains.

				Cut-in velocity = 1.0 m/s		Cut-in velocity = 0.5 m/s	
	Strait	Max kinetic power density (kW/m ²)	Max extractable power by a turbine (kW)	Suitable area (km ²)	Total extractable power (MW)	Suitable area (km ²)	Total extractable power (MW)
1	Bali	14.75	1,459	23	462	104	1,045
2	Larantuka	10.20	1,250	3	199	6	299
3	Boling	3.49	430	36	593	106	736
4	Alas	3.07	396	104	1,261	403	2,258
5	Lombok	2.36	236	53	754	114	865
6	Sunda	1.56	165	11	107	145	335
7	Badung	1.52	161	28	238	162	551

Methodology and application

A methodology comprising of the estimates of power yield and evaluation of the effects of power extraction on flow conditions is described and applied to the Strait of Larantuka (Orhan et al., 2016; Orhan et al., 2015). The strait divides East Flores from Adunara Island (see Figure 4-2). It has a 3km length and a 650m width at its bottleneck. The Strait of Larantuka links Flores Sea in the north to Flores Strait in the south. The predicted tidal amplitude in the Flores Sea is slightly larger than 1m, and it is reaching around 1.5m in the Flores Strait. Tidal stream currents typically have peak spring velocities, exceeding 3-4m/s.

Modelling of tidal currents

Tidal stream currents are computed with the Delft3D Modelling System, developed by Deltares, the Netherlands. 3D models with fixed layers in depth-wise direction were developed. Grids were constructed with a resolution up to 20m in horizontal, and 3m in vertical near free surface, providing sufficient spatial resolution for the analysis. Computational grids and the nesting sequence comprising of two models set up for the Strait of Larantuka are illustrated in Figure 4-2. Open boundaries of the coarse overall model (Figure 4-2, top) were extended into the Flores Sea in the north, and Indian Ocean in the south to capture the impact from both systems, and a detailed model (Figure 4-2, middle) was later nested into the overall model to simulate the flow conditions in the Strait of Larantuka with greater detail. Bathymetric data have been obtained from single beam echo sounding surveys and SRTM15_PLUS, a data fusion of global seafloor topography from satellite altimetry and ship depth soundings. Much attention has been given to the meteorological forcing and conditions at the open sea boundaries to adequately capture the density gradients and flow fields along the strait. Tidal forcing is extracted from TPXO Indian Ocean Atlas (1/12° regional model). Eleven harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) were considered in this study. Data to determine the sea surface height, salinity and temperature at the open sea boundaries are supplied from HAMSOM, the Hamburg Shelf Ocean Model, which is a 3D free surface baroclinic hydrodynamic model developed in the Institute of Oceanography at the University of Hamburg. Data from the Global Forecast System of NOAA's National Climatic Data Center have been used as meteorological input. Thus, the effects of air cloudiness, air temperature, atmospheric pressure, relative air humidity, and wind (in E and N directions) have been considered in simulations.

Model verification using tidal records shows excellent agreement. The location of an operational measuring device is indicated in Figure 4-2, and Figure 4-3 shows a comparison of modelled and measured tidal water levels from 1st to 31st of July 2014. The agreement between modelled and measured values was tested with Pearson's product-moment correlation coefficient. The r -value (correlation coefficient) was resulted equal to 0.98, which indicates a strong, positive linear relationship. Although the models with tidal elevation validation can provide a good understanding of the flow conditions in the area of interest, in-situ measurements to validate the predicted current

velocities and to improve model performance are still needed and shall be accounted for in the investigations.

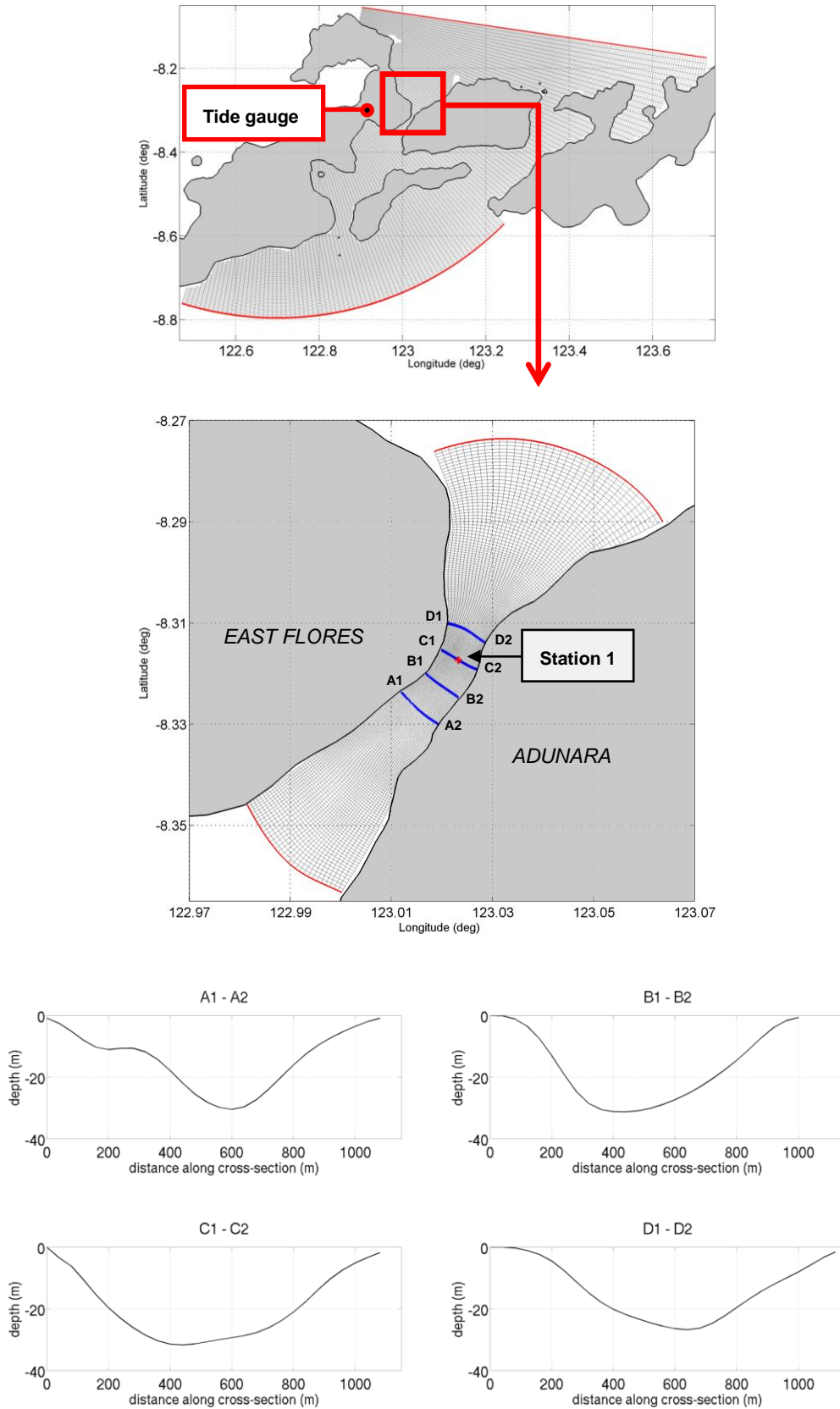


Figure 4 - 2: Nesting sequence, computational grids (top), and cross-sectional variation along the Strait of Larantuka (bottom).

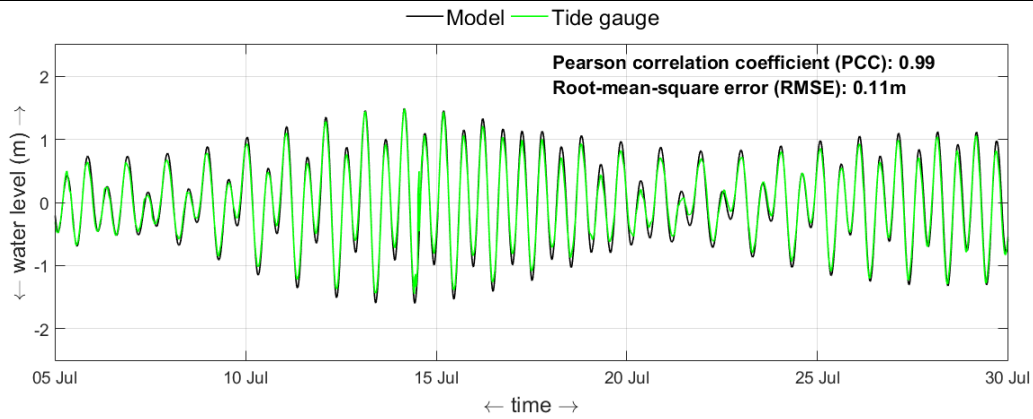


Figure 4 - 3: Comparison of modelled and measured tidal water levels at the tide gauge location.

Site selection and resource assessment

Site selection for the installation of tidal stream devices depends on available power, site characteristics, and possible environmental and socio-economic impacts of the projects (Defne et al., 2011). In this study, a multi-criteria assessment methodology that accounts for physical constraints is applied to determine suitable locations for tidal stream power conversion. Horizontal axis tidal turbines that can harness a strongly bi-directional flow are considered in the evaluations. The near free surface upper 5m is eliminated for recreational activities (small boats, swimmers, etc.) and to minimize turbulence and wave loading effects on the turbines, as well as damage from floating materials (EMEC, 2009). At the bottom, the turbines are located above the low-speed benthic boundary layer, which is usually 10% of the mean lower low water depth (EPRI, 2006). Considering these clearances, minimum depth is defined as 7.5m, which is adequate to install a smaller scale turbine with a rotor diameter of 1.5m. Average kinetic power densities in the region have been estimated as follows:

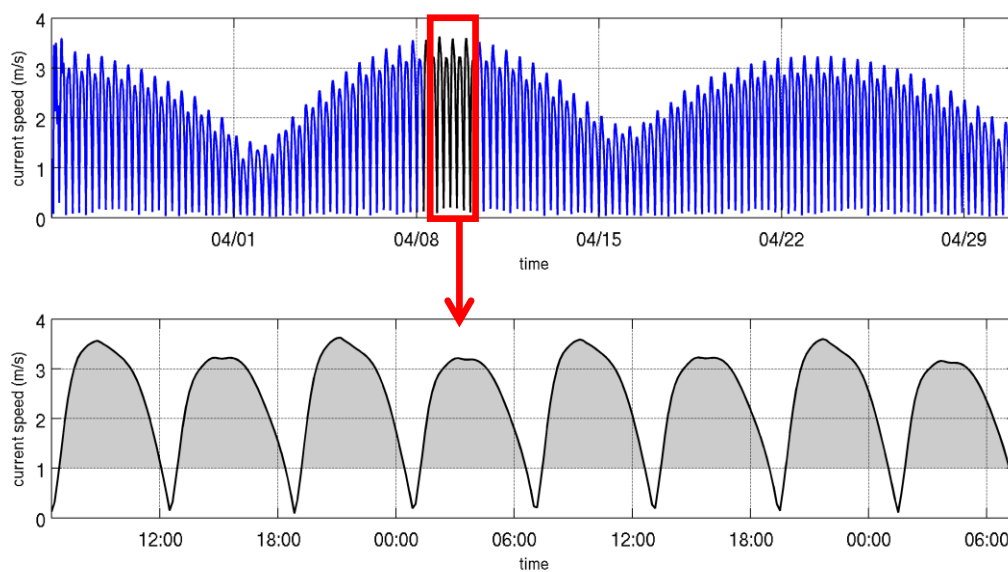


Figure 4 - 4: Modelled depth-averaged current velocity magnitudes at the station 1 (top, see Figure 4-2). The grey area indicates the velocity magnitudes greater than the cut-in speed of the turbines (bottom).

$$P = \frac{1}{2} \cdot \rho \cdot U^3 \quad (4 - 1)$$

where P is tidal stream power per unit area of flow (kW/m^2), ρ is the density of seawater (kg/m^3), and U is the current velocity (m/s). Generally, tidal stream devices require a minimum flow velocity (cut-in velocity) to start operating, which ranges from $0.5\text{m}/\text{s}$ to $1\text{m}/\text{s}$ depending on their design (EPRI, 2006). Considering also this limitation, regions with the average kinetic power density larger than $0.5\text{kW}/\text{m}^2$ (corresponding to a current velocity of $1\text{m}/\text{s}$), surface area larger than 0.5km^2 and water depths larger than 7.5m are defined as energy hotspots, suitable locations for tidal stream power conversion.

Modelled tidal stream current velocities, taken from the station 1 (see Figure 4-1) and with the indication of velocities higher than a cut-in velocity of $1\text{m}/\text{s}$, are shown in Figure 4-4. Figure 4-5 shows the spatial variation of the average kinetic power densities at the energy hotspot within the Strait of Lantuka, which has a size of 3km^2 .

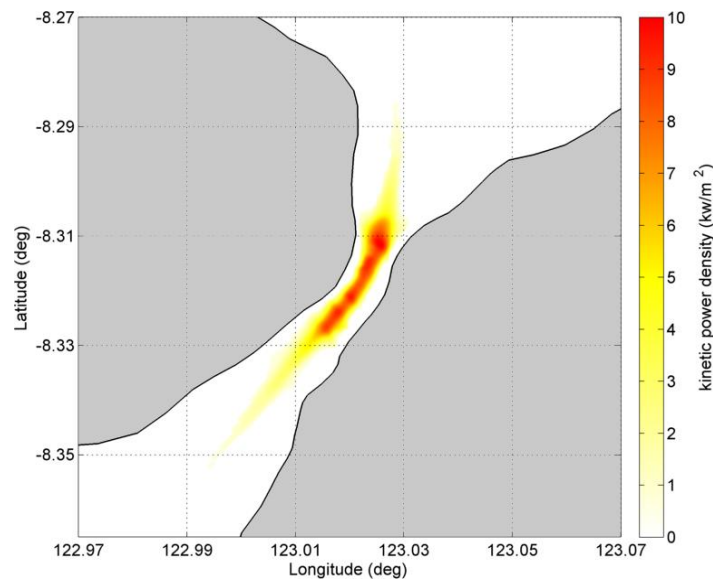


Figure 4 - 5: Spatial variation of the average kinetic power density within the energy hotspot.

Regarding the identification of suitable locations for tidal stream energy conversion, future research efforts should be widened to accommodate conflicting use of marine environments such as fishing, shipping, offshore wind, habitat protection, and also technical limitations. Comprehensive life cycle assessments of power converter arrays that would also include areas like fluctuation of power output, storage, or grid integration are still missing (Uihlein & Magagna, 2016). In this study, a methodology is currently being developed to take main environmental constraints and accessibility of the resources into account alongside physical constraints.

To compute the exploitable power by tidal turbines, current velocities at the hub heights of the turbines have been used. Rated current velocities of the turbines have been neglected to take the full range of predicted current velocities into account. Hub heights of the devices were defined, assuming rotors placed right above the low-speed benthic boundary layer. Considering typical values for

component efficiencies, the electric power that can be delivered to the local grid by each turbine was estimated using:

$$P_{electric} = A_{turbine} \cdot \frac{1}{2} \cdot \rho \cdot U_{hub}^3 \cdot \eta_{turbine} \cdot \eta_{ptake-off} \quad (4 - 2)$$

where $A_{turbine}$ is the turbine rotor swept area (m²), and U_{hub} is the current velocity magnitude at the turbine hub height (m/s). $\eta_{turbine}$ (= 45%) is the efficiency with which the turbine extracts kinetic energy from the incoming flow, and $\eta_{ptake-off}$, power take-off efficiency, was given using equation (4-3).

$$\eta_{ptake-off} = \eta_{drivetrain} \cdot \eta_{generator} \cdot \eta_{pcon} \quad (4 - 3)$$

where $\eta_{drivetrain}$ (= 96%) is the efficiency with which the energy extracted from the flow is delivered to the generator, $\eta_{generator}$ (= 95%) is the efficiency with which the mechanical energy input to the generator is converted to electricity, and η_{pcon} (= 98%) is the efficiency with which the electricity produced by the generator is conditioned to meet phase and voltage requirements of the local electrical grid interconnection point (EPRI, 2006). Analysis showed that the turbines with rotor diameters ranging between 1.5m to 20m are suitable for installation in the identified energy hotspot. Considering the criteria described in the previous section and estimated power curves for the tidal turbines (see Equation 4-2 and Equation 4-3), distribution of the applicable tidal turbine rotor diameters and spatial variation of the estimated electric power that can be delivered to local electrical grid by the turbines are shown in Figure 4-6. It can be seen that the resulting density of the extractable electric power corresponds more with current velocities than with rotor diameters. At the locations where the current velocities are higher, extractable electric power density can exceed about 1.2MW.

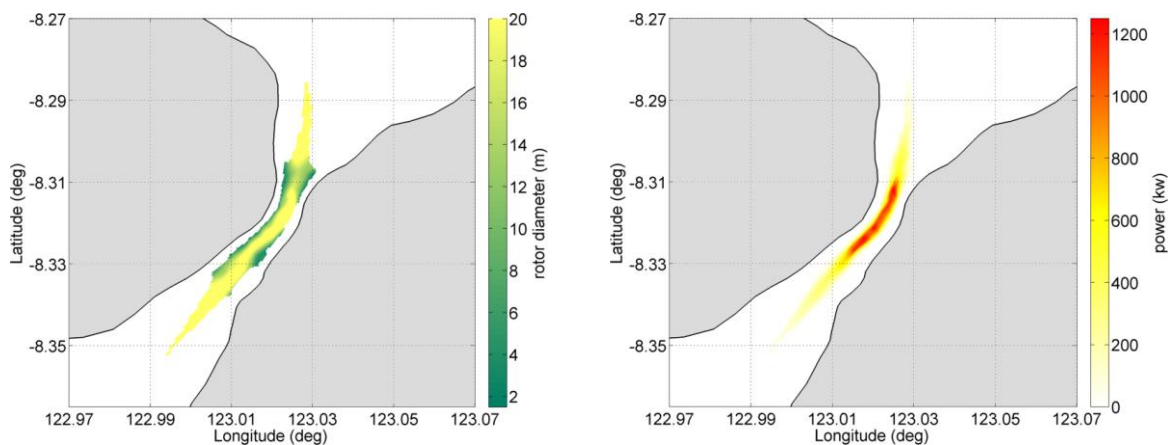


Figure 4 - 6: Spatial variation of the applicable tidal turbine rotor diameters (left), and average extractable electric power with the tidal turbines (right).

Impact on flow conditions

Resolution of the detailed model has been increased to assess the impacts of the tidal stream energy conversion on flow conditions and to resolve tidal turbine wakes in greater detail. An array consisting of 7 tidal turbines with rotor diameters of ca. 20m has been located in mid-channel (in the

core of the current) with an inter-device spacing around 50m (ca. 2.5 times the rotor diameter. see EMEC, 2009), where water depth is around 30m (see Figure 4-7). Turbines have been modelled as momentum sinks, resulting in dissipation of the pre-existing kinetic power from 20% to 60% within a flow cross-section. K- ϵ model, which is a second-order turbulence closure model, is selected to involve the effects of the turbulent kinetic energy and turbulent kinetic energy dissipation.

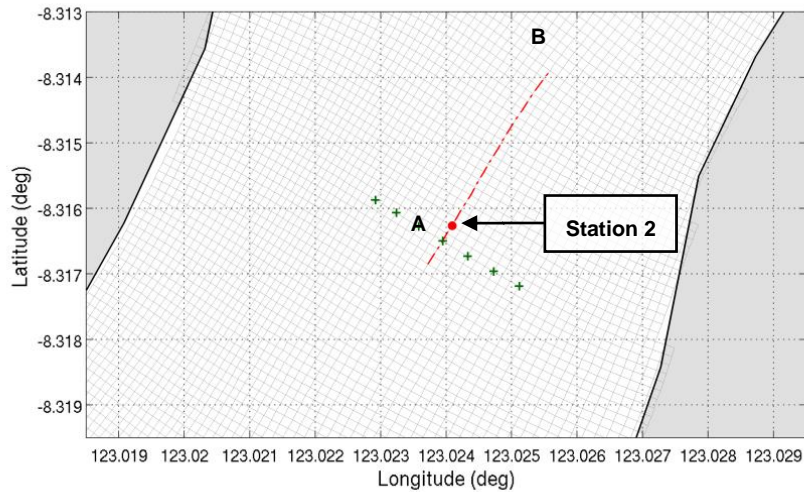


Figure 4 - 7: Illustration of the refined computational grid and locations of the turbines, station 2, and transect A-B.

Preliminary results show the effectiveness of the method to capture the effects of power extraction, and wake characteristics reasonably well with low computational cost. The results, obtained from the station 2, located ca. 20m in the downstream direction of the array (see Figure 4-7), reveal effects of dissipation on current velocities in adjacent areas, which are relatively small even at the 60% dissipation level (see Figure 4-8). Spatial variation of the difference of current speeds, considering 40% and 60% dissipation of the pre-existing kinetic power and the reference state, are shown in Figure 4-10. Although no significant impact was observed on water level elevations, as a result of velocity profile adjusting to the increased momentum transfer (blockage effect), while current velocities tend to decrease in both upstream and downstream directions of the turbines, they increase when they get closer to the sides of the channel (see Figure 4-10). At this point, it is highly recommended considering measures aimed at protecting the coast against erosion and degradation alongside the installation of tidal turbines.

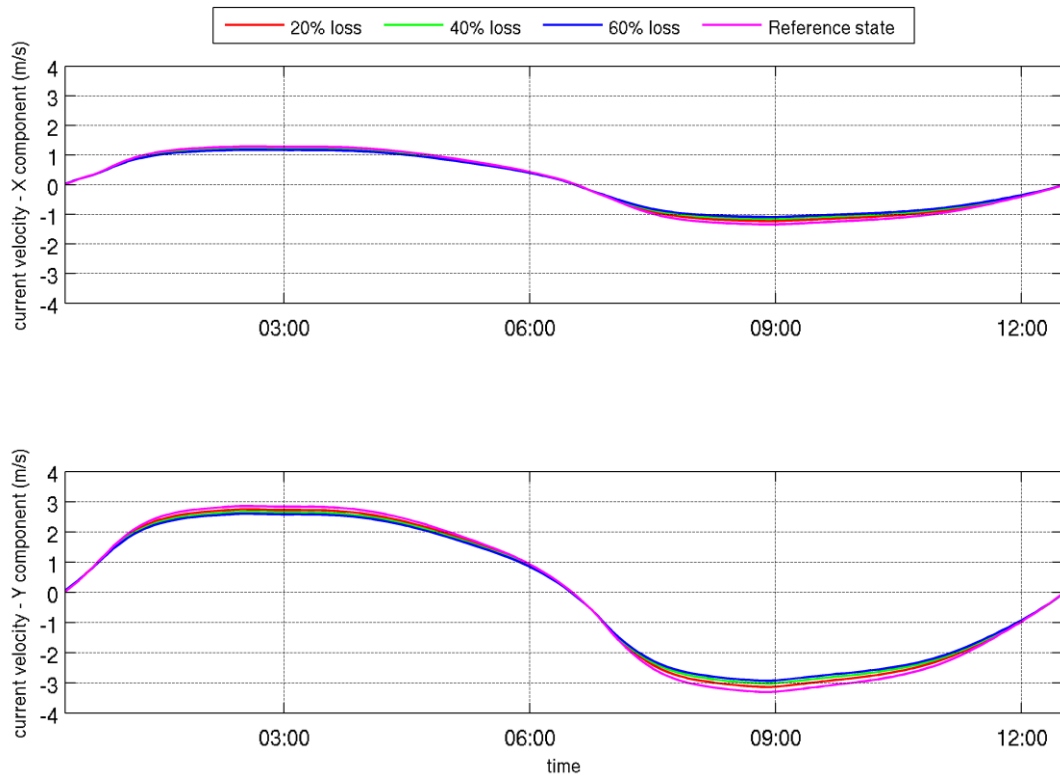


Figure 4 - 8: Predicted current velocities for a flood and an ebb tide at the station 2 (see Figure 4-7), considering 20%, 40%, and 60% dissipation of the pre-existing kinetic power and the reference state.

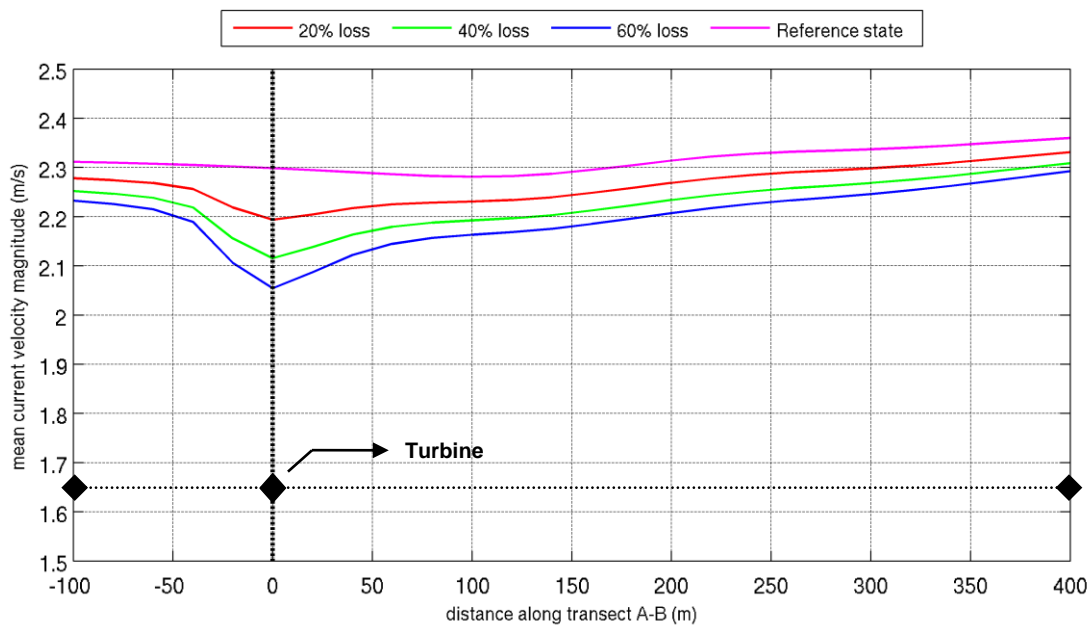


Figure 4 - 9: Predicted mean current velocity magnitudes for a flood tide period along the transect A-B (see Figure 4-7), considering 20%, 40%, and 60% dissipation of the pre-existing kinetic power and the reference state.

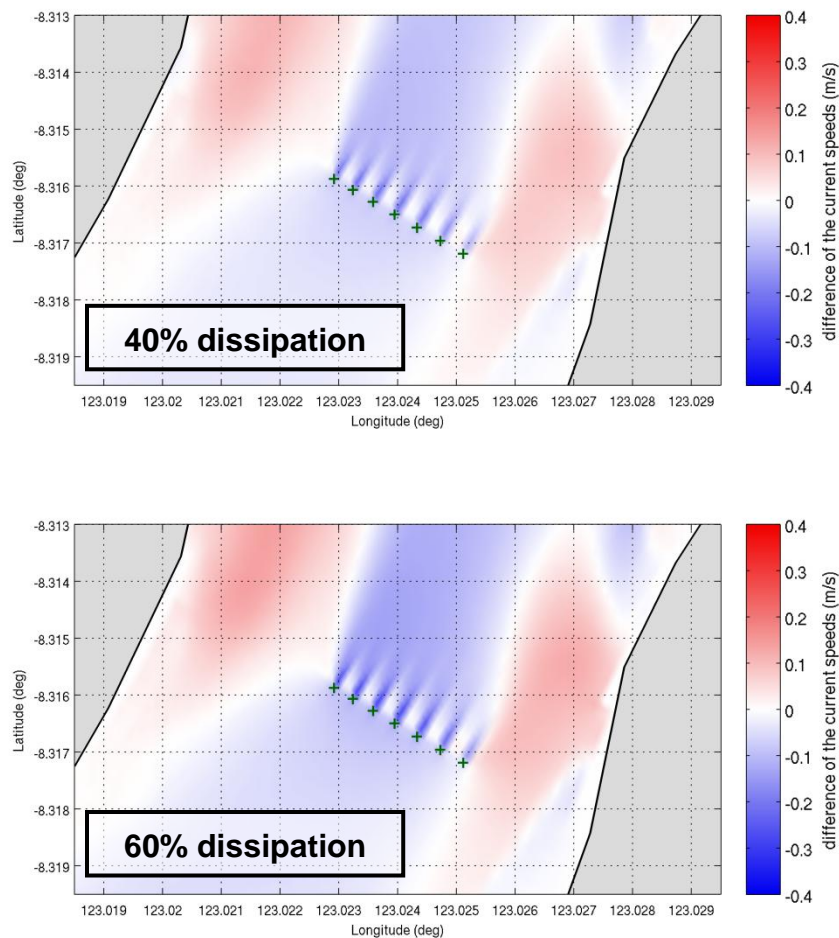


Figure 4 - 10: Spatial variation of the difference of mean current speeds for a flood tide period, considering 40% and 60% dissipation of the pre-existing kinetic power and the reference state.

According to the guideline of the EMEC for the assessment of tidal energy resource, the downstream spacing between devices should be about ten times the rotor diameter (EMEC, 2009). Figure 4-9 shows the predicted mean current velocity magnitudes along the transect A-B (see Figure 4-7). It can be seen that in all three dissipation levels, turbine wakes recover reasonably well within the first 200m, which corresponds to recommended downstream spacing given the rotor diameters taken into account in the models (ca. 20m). Although the results indicate a validation for the recommendation of the EMEC for device spacing, studies are required for different layouts of tidal farms to understand the nature of the wake recoveries and interactions. Different rotor diameters and device geometries should be taken into account for further analyses (Vennell, 2011; Fallon et al., 2014).

Conclusions and outlook

Tidal stream resource assessments carried on for the straits between the Indian Ocean, and inner Indonesian seas showed the tremendous potential of the region for tidal stream energy conversion, which is likely to exceed previous predictions reaching around 5,000MW (Orhan et al., 2016). In this study, analyses performed for the Strait of Larantuka in Indonesia are presented in

detail. The results obtained showed that the strait in question has a great potential for the production of ocean renewable energy with current velocities up to 3-4m/s and average kinetic power densities around 10kW/m². Applicable rotor diameters within the channel are ranging between 1.5m and 20m, and extractable power with a single tidal turbine exceeds 1.2MW in certain locations. Technically exploitable power from the Strait of Larantuka is around 200MW, which can go up to 300MW with technological advancement of the devices, generally by exploiting energy from the areas with lower power densities (Table 4-1) (Orhan et al., 2016).

Impacts of the tidal stream energy conversion on flow conditions have been resolved by a higher resolution flow model to observe the changes in the hydrodynamics with sufficient detail. An additional momentum sink term is introduced to the model, resulting in dissipation of the pre-existing kinetic power from 20% to 60% within a flow cross-section, and k-ε model is selected to involve the effects of the turbulence. Preliminary results show the effectiveness of the method to capture the effects of power extraction and wake characteristics reasonably well with low computational cost. Due to the blockage effect of the devices, decreasing current velocity magnitudes were observed in the upstream and downstream directions of the array, while stronger velocities were observed closer to the coastline. Analysis regarding the risk of coastal erosion and degradation around the tidal farms should be undertaken to assess the necessity of the coastal protection measures.

Although the results are promising, further analyses involving different designs and geometries of the tidal current turbines and different tidal farm layouts are still needed. To this end, an approach utilizing flexible mesh models alongside CFD simulations is currently being developed to understand the true nature of wake recoveries and interactions within tidal farms. In-situ measurements from operational arrays are essential to validate the model results, and they shall be used in the following investigations.

Acknowledgements

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Potential hydrodynamic impacts and
performance of commercial-scale
multi-turbine arrays in the Strait of Larantuka,
Indonesia

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Potential hydrodynamic impacts and performance of commercial-scale multi-turbine arrays in the Strait of Larantuka, Indonesia

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In this paper, the results of an assessment regarding the potential hydrodynamic impacts and the performances of commercial-scale, multi-turbine, multi-row arrays in the Strait of Larantuka, Indonesia, are presented. Tidal stream currents with speeds up to about 3-4m/s turn the Strait of Larantuka into a promising site for renewable electricity production from the ocean. A high-resolution, three-dimensional hydrodynamic model with sufficient spatiotemporal coverage has been developed to simulate tidal currents in the strait. The energy of the tidal currents is assumed to be extracted by horizontal-axis tidal turbines, which can harness strong bi-directional flow, positioned on sequential rows and alternating downstream arrangements. The momentum sink approach was adopted to represent the influence of energy extraction by the tidal turbines. Four different layouts consisting of different numbers of rows/turbines were investigated. The impacts of the layouts on the flow field, the wake characteristics, and the performances of the turbines were analyzed. The efficiencies of the turbines deployed due to the proposed layouts were calculated. Decreases in current speeds with respect to natural conditions of up to about 0.6m/s alongside increases in currents speeds in the order of 80% near-shore were observed. Maximum operating efficiency rates of turbines of about 50 – 60% resulted in the arrays consisting of smaller numbers of rows/turbines.

Keywords: renewable energy; tidal stream current; numerical model; Indonesia

Introduction

Intergovernmental Panel on Climate Change (IPCC) recently reported on the current and potential impacts of anthropogenic global warming. The report states that human activities have caused a warming of 1.0°C above the pre-industrial levels since 1950 with a rate of increase of 0.2°C per decade, and global warming is likely to reach 1.5°C between 2030 and 2052. Storms, forest fires, droughts, coral bleaching, heat waves and floods, which have already been experienced due to the global warming, are likely to get significantly worse in the upcoming decades, and impacts are expected to be felt across ecosystems, human communities and economies (IPCC, 2018). The mitigation of further damage requires an effective and appropriate response focused on accelerating the reduction of global greenhouse gas emissions. Thus, over the last few decades, ocean renewable energy (ORE) has become a promising alternative and supplement to fossil fuels and nuclear power. ORE might enhance the diversity of the energy mix, contribute to the decarbonization of electricity production, increase energy security by exploiting local resources, and fuel economic growth in the coastal regions. To this end, the conversion of tidal current power is recently growing up to a crucial sector of the ORE (Magagna & Uihlein, 2015; Magagna et al., 2016).

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The Strait of Larantuka, located in the eastern part of the Indonesian archipelago, divides East Flores from Adunara Island (see Figure 4-11). The strait links the Flores Sea in the north to the Flores Strait in the south. While the predicted tidal amplitude in the Flores Sea is slightly larger than 1m, it reaches around 1.5m in the Flores Strait. The Strait of Larantuka has ca. 3km in length. Around the bottleneck of the strait, which is the area of interest for this study (see Figure 4-11 and Figure 4-13), the channel width is ca. 650m, and the water depth along the mid-channel is around 30-35m.

Previously, tidal stream resources of several promising straits between the Indian Ocean and inner Indonesian seas, including the Strait of Larantuka, have been investigated (Orhan et al., 2017; Orhan & Mayerle, 2017). Orhan et al. (2017) provided an overview regarding the energy potential of tidal stream currents within the straits in question, utilizing state-of-the-art measurements and high-resolution, three-dimensional (3D) flow models. The results of this study showed that the highly energetic tidal stream currents of the strait of Larantuka has tremendous potential for renewable electricity production. Current speeds in the strait exceed 3m/s during peak periods while the kinetic power densities reach ca. 10kW/m². The energy hotspot of the strait encompassing an area around 3km² provides enough space for ORE development. In a follow-up study, Orhan and Mayerle (2017) studied the possible impacts of the tidal turbines on flow conditions in the Strait of Larantuka. To this end, researchers refined the computational grid of the hydrodynamic model used by Orhan et al. (2017) and adopted a practical method to study the far-field impacts of the devices for different dissipation levels. Thus, the turbine wakes, wake recoveries, and velocity deficits in the adjacent areas due to the tidal current energy extraction were resolved in more detail.

In this study, potential hydrodynamic impacts, and the performances of commercial-scale, multi-turbine, multi-row arrays in the Strait of Larantuka is investigated. As previously done by Orhan and Mayerle (2017), high resolution, three-dimensional hydrodynamic models representing the tidal energy extraction by introducing a momentum sink term into the momentum equations in the horizontal direction have been used for the investigations. Arrays with various capacities are studied to evaluate the changes in the flow field, wake characteristics, and performances of arrays and turbines. Finally, efficiencies of tidal turbines are evaluated for the proposed layouts through a simplistic approach.

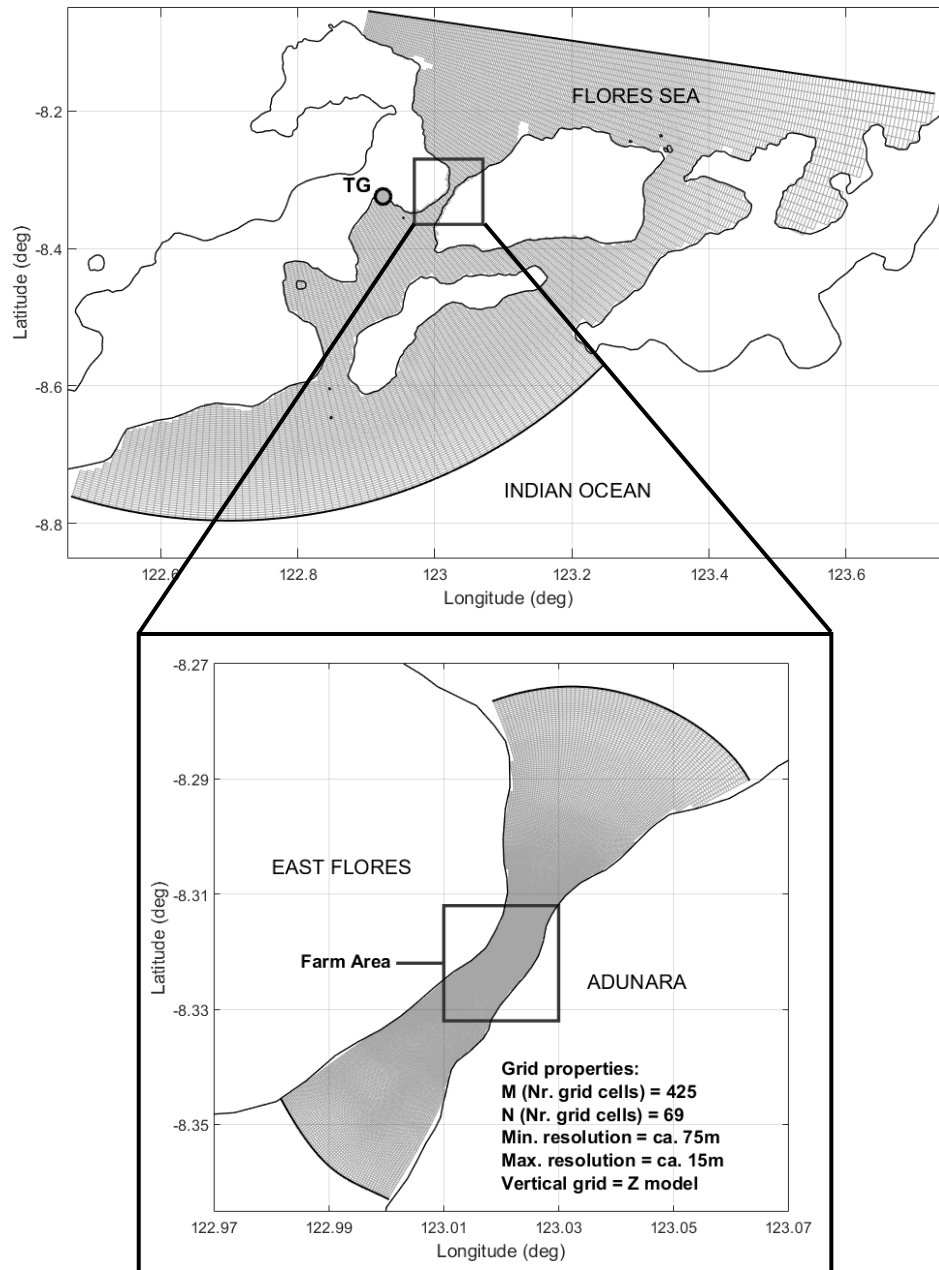


Figure 4 - 11: Nesting sequence of the computational grids for the Strait of Larantuka.

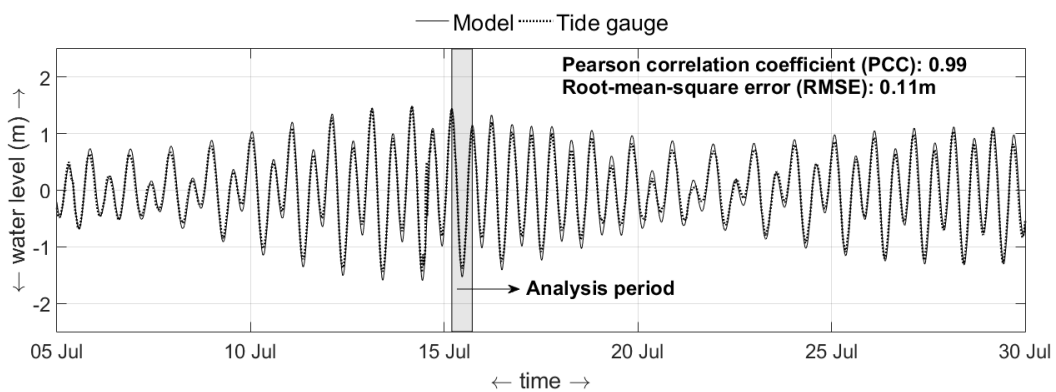


Figure 4 - 12: Comparison of modelled and measured tidal water levels at the tide gauge location "TG" (see Figure 4-11) during July 2014. Grey bar indicates the analysis period considered in the study.

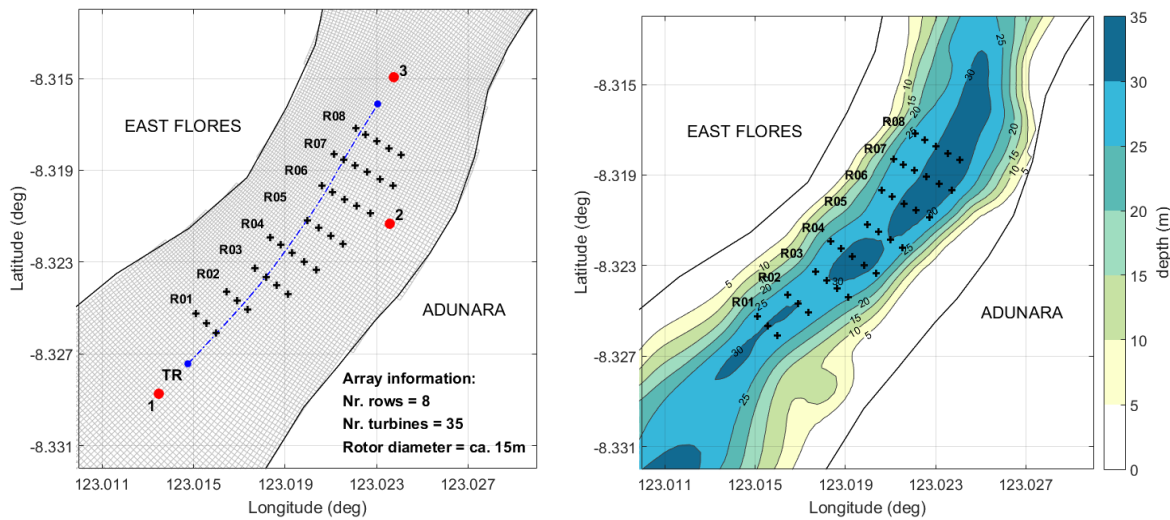


Figure 4 - 13: Computational grid, observational points 1, 2, and 3 (red marker) and transect TR (blue line, left), bathymetry (right), and turbine arrangement due to the proposed layout 4 (left and right).

Methodology and Application

Tidal stream currents are computed with the Delft3D Modelling System, developed by Deltares, the Netherlands (Lesser et al., 2004; Delft Hydraulics, 2006). Bathymetric data for the hydrodynamic models have been obtained from single beam echo sounding surveys and SRTM15_PLUS land and sea topography global dataset (Olson et al., 2014; Tozer et al., 2019). An overall model to simulate flow conditions in several interlinked straits, including the Strait of Larantuka, was developed with horizontal grid spacing around 300m (Figure 4-11, top). Open boundaries of the overall model were extended into the Flores Sea in the north, and the Indian Ocean in the south to capture the input from both systems. To simulate the flow conditions in the Strait of Larantuka with greater resolution, a detailed model of the strait was nested into the overall model (Figure 4-11, bottom). Computational grid of the detailed model was constructed with a resolution up to ca. 16m in horizontal and 2-3m in vertical within the area of interest (i.e., farm area), providing sufficient spatial resolution for the analysis of hydrodynamic impacts from isolated tidal turbines. Z-layers fixed in the vertical direction were preferred in models for the accuracy of the vertical distribution of salinity and temperature (Cornelissen, 2004).

Much attention has been given to the meteorological forcing and conditions at the open sea boundaries to adequately capture the density gradients and flow fields along the strait. Tidal forcing is extracted from TPXO Indian Ocean Atlas ($1/12^\circ$ regional model) and prescribed as time series (Egbert & Erofeeva, 2002). Eleven harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, and MN4) were taken into account. Data to determine the salinity and the temperature at the open sea boundaries are supplied from Hamburg Shelf Ocean Model (HAMSOM), which is a 3D free surface baroclinic hydrodynamic model (Mayer et al., 2010). Data from the Global Forecast System of NOAA's National Climatic Data Center have been used as meteorological input (Environmental Modeling Center, 2003). Thus, the effects of air cloudiness, air temperature, atmospheric pressure,

relative air humidity, and wind (in E and N directions) have been considered in simulations. To account for the exchange of heat through the free surface, ocean heat flux module of Delft3D is activated, which typically applies to large water bodies (Lane, 1989). K- ϵ model is selected to include more adequately the effects of the turbulent kinetic energy and turbulent kinetic energy dissipation in simulations (Burchard & Baumert, 1995; Postma et al., 1998).

Time steps of 3s and 1s were set for the overall model and the detailed model, respectively. The chosen time steps correspond to a maximum Courant-Friedrichs-Lewis criterion of around 0.5 for both models. Earlier studies concerning the Strait of Larantuka (Orhan et al., 2017; Orhan & Mayerle, 2017) present the tidal current energy potential of the strait through the simulations covering a monthly period. This study mainly aims at analyzing the changes occurring in the flow field with increasing turbine array capacities as well as wake characteristics and performances of tidal turbines. Therefore, a peak spring tidal cycle comprising of an ebb and a flood tide was considered as a time frame for simulations. This period, with particularly high current speeds, was chosen to analyze the flow field, turbine wake characteristics, and turbine array performances while the current speeds are sufficient for devices to operate and provide electric output.

The ability of the overall model to simulate water level elevations has been verified through tide gauge measurements. Figure 4-11, top panel, indicates the location of the measuring device. Figure 4-12 displays the comparison of simulated and measured tidal water levels for July 2014. The agreement between modelled and measured values was checked with Pearson's product-moment correlation coefficient (r) and root-mean-square deviation (RMSD). RMSD and r values resulted respectively equal to 0.11m and 0.99, indicating a strong, positive linear relationship.

The energy of the tidal currents in the strait is assumed to be extracted by horizontal-axis tidal turbines, positioned on sequential rows, and in alternating downstream arrangements where the flow was in general bound only by the seabed and the free surface. The design turbine has been described based on the properties of actual, commercially available tidal turbines (Magagna et al., 2016; Roberts et al., 2016). The device, which can harness a strongly bi-directional flow, was assumed to have a rotor diameter (RD) of ca. 16m corresponding to a swept area of ca. 201m². Minimum operational depth of the device was considered as 25m. Rated, cut-in and cut-out current speeds of the device were defined as 3.0m/s, 1.0m/s and 4.5m/s respectively, and its rated power is ca. 1MW. Considering the efficiencies of the various components, namely turbine rotor, drive train, generator, and grid connection, the turbine power coefficient has been assumed as 0.41 (Orhan et al., 2017; Orhan & Mayerle, 2017; Roberts et al., 2016). Downstream and lateral spacing between the devices were set to about 10RD and 3RD, respectively (Orhan & Mayerle, 2017; EMEC, 2019; Chen et al., 2017). Figure 4-13 shows the arrangement of the turbines over the computational grid and bathymetric conditions within the proposed farm area (see Figure 4-11).

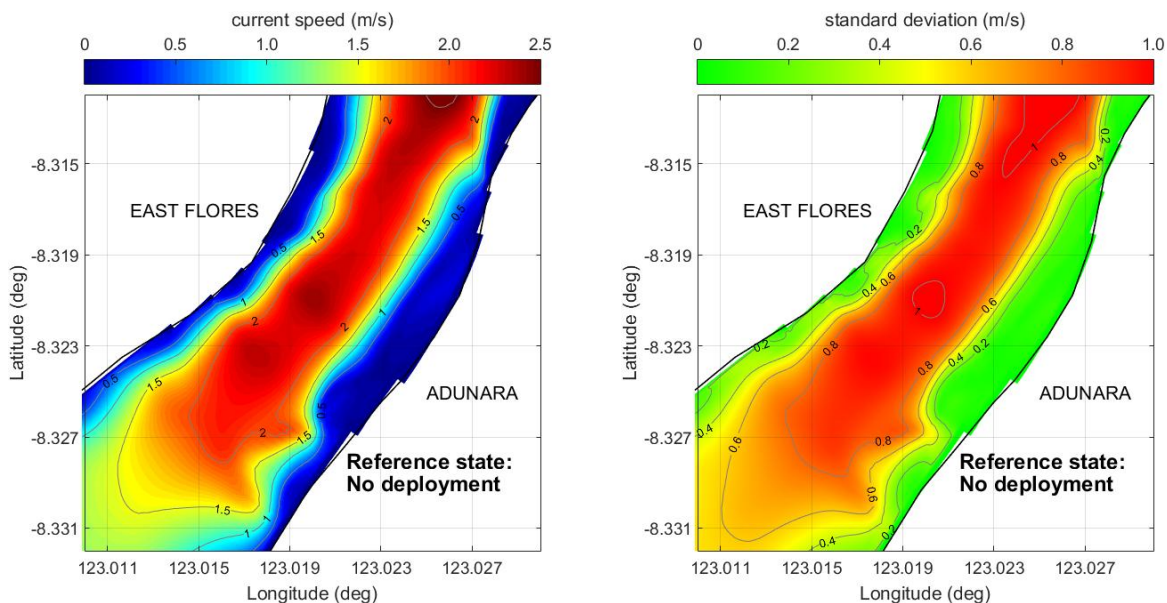


Figure 4 - 14: Simulated depth and time-averaged current speeds (left) and standard deviations (right) during the flood tide (15.07.2014 13:30 - 15.07.2014 19:50) in the natural (reference) state of the currents.

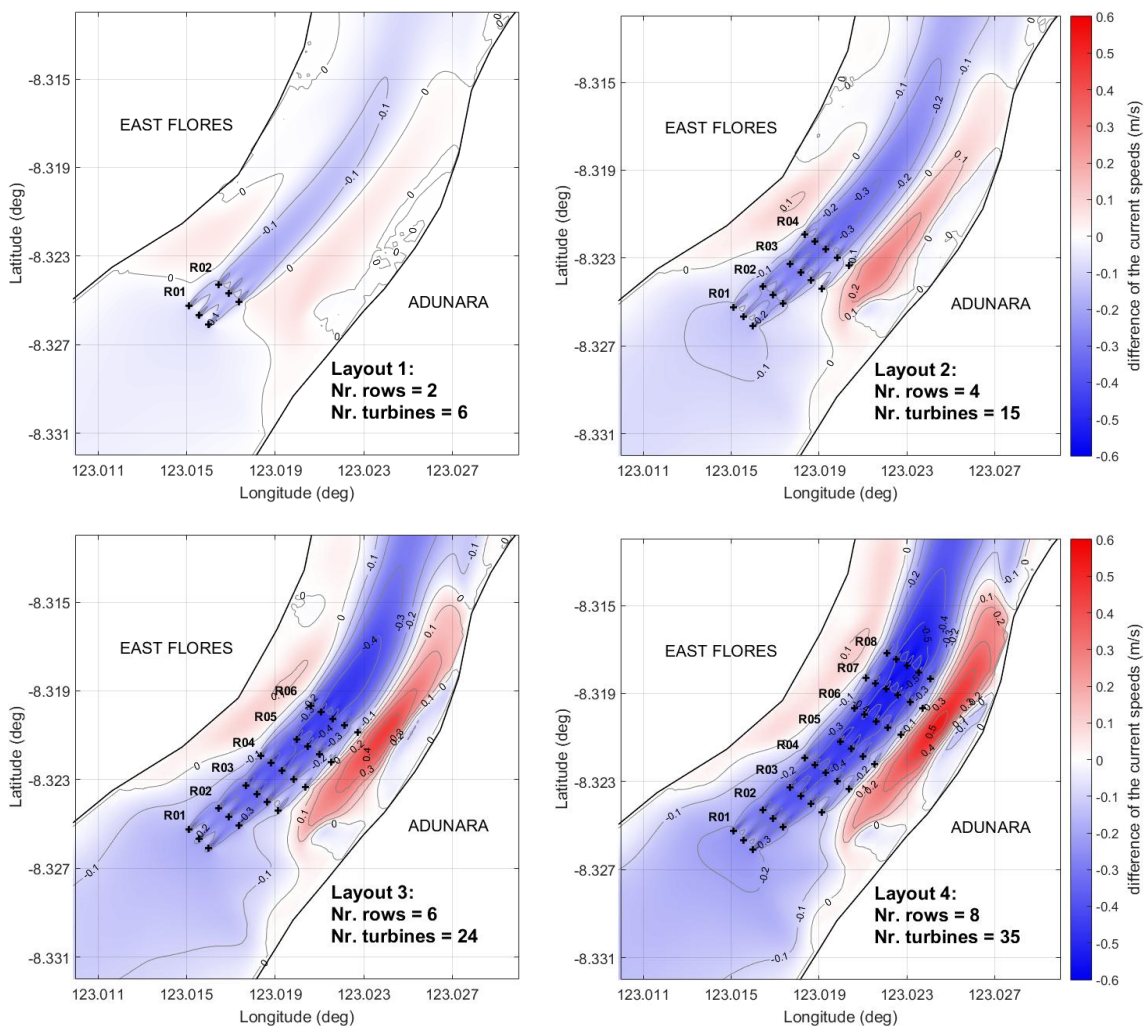


Figure 4 - 15: Difference of the depth and time-averaged current speeds between the reference state (see Figure 4-14) and the tidal energy extraction scenarios (15.07.2014 13:30 - 15.07.2014 19:50).

The drag force, induced by the physical structure of turbine blades and supporting poles, is not taken into account in this study. Momentum is assumed to be exchanged only across the rotors and partially dissipated due to the power generation (Chen et al., 2014). Porous plates set as momentum sinks and covering the faces of single grid cells on several vertical layers have been implemented in the model to represent the tidal current energy extraction (Delft Hydraulics, 2006; Chen et al., 2014; Defne et al., 2011; Yang & Wang, 2015). Considering the power coefficient of the design turbine ($C_p = 0.41$), the thrust coefficient of the porous plates was chosen as 0.8 ($C_t = 0.8$) and assumed to be constant for the simplicity (Chen et al., 2014; Plew & Stevens, 2013). Thereby, changes in the flow field within and around the arrays, and the wake properties have been determined concerning different array layouts. Turbine arrays deployed with four different layouts were considered. To capture the changes occurring in the flow field in response to increasing array capacities, with each layout, two additional rows of tidal turbines were introduced into the existing arrays. Thus, the proposed layouts consist of 2, 4, 6, and 8 rows of tidal turbines, comprising respectively of a total of 6, 15, 24, and 35 devices (see Figure 4-15). The performances of the arrays and individual rows/turbines are evaluated for each layout separately, and comparisons among the results of the various layouts are provided.

Results

Flow field

Figure 4-14 shows simulated depth and time-averaged current speeds for a flood tide during a spring tidal cycle on July 15, 2014. During the flood tide, the currents in the Strait of Larantuka flow predominantly in the northeast direction, towards the Flores Sea (see Figure 4-11). It can be seen that while the depth and time-averaged current speeds exceed 2m/s at the main channel in places with water depths above 25m, they are rather weak closer to the banks ($< 0.5\text{m/s}$). The largest standard deviations of the currents, reaching values of about 1m/s, are also observed at the energetic main channel. Thus, in this study, tidal turbine arrays with various capacities have been located at the highly energetic reach of the strait, as shown in Figure 4-15.

Figure 4-15 demonstrates the influence of tidal current energy extraction on the flow field due to the various turbine arrays. Properties of the tidal turbines considered in the investigations are explained in section 2. In vertical, the upper 5m near the free surface was eliminated for recreational activities such as small boats and swimmers, to minimize turbulence and wave loading effects on the turbines, and to avoid damage from floating materials. At the bottom, the turbines were placed above the low-speed benthic boundary layer, which is approximately 10% of the mean lower low water depth and equals to ca. 3m within the farm area (Orhan et al., 2017; Orhan & Mayerle, 2017; EMEC, 2019; EPRI, 2006). It can be seen that, compared to the reference state, the deficit of the current speeds can reach 0.5 - 0.6m/s on average due to the chosen layout. In layout 1 (Figure 4-15, top - left), the change in the flow field is minor (0.1 - 0.2m/s deficit). On the other hand, increased numbers of rows and turbines deployed due to the proposed layout 4 (Figure 4-15, bottom - right) resulted in a

deficit of about 0.5 - 0.6m/s. This corresponds to decreases in current speeds of about 25 - 30% on average. Furthermore, as previously pointed out by Ahmadian & Falconer (2012), besides the decrease in the current speeds both upstream and downstream the turbine arrays, stronger current velocities can be observed on the sides, closer to the banks (Ahmadian & Falconer, 2012). Especially due to the meandering geometry of the strait and the proximity of turbines to the shoreline and near-shore shallow waters, bigger impacts resulted closer to Adunara Island. It can be seen that the stronger blockage effects due to the larger number of turbines in layouts 2, 3, and 4 led to increases in the current speeds of up to about 0.5 - 0.6 m/s on the shoreline. This means that the deployment of tidal turbines with dense layouts in the vicinity of the Adunara Island's shoreline can increase the current speeds in the area by approximately 70 - 80%, with respect to the current speeds in the reference state.

Figure 4-16 depicts the temporal changes in the natural state of the flow field during a half-daily tidal cycle consisting of an ebb tide and a flood tide, caused by the turbines deployed due to the proposed layout 4. The time series of current speeds at the observation points 1, 2, and 3 (see Figure 4-13), reveal the effects of tidal energy extraction on current speeds in adjacent areas (Figure 4-16, top). Observation points 1 and 3 are located respectively 20RD upstream and 20RD downstream of the multi-row array. Although they are on the opposite directions of the turbine arrays, observations from both points demonstrate decreases in currents speeds as compared to the reference state during flood and ebb tides alike. This means that the momentum dissipation caused by the tidal turbine arrays have similar influences on the flow field both downstream and upstream. On the other hand, time series of the current speeds obtained from the observation point 2 (see Figure 4-13), close to the Adunara Island, indicate an increase in the current speeds of ca. 0.6m/s during the flood tide and ca. 0.3m/s during the ebb tide. As the sediment transport is proportional to the cube of the current speeds, a change in this scale can have a huge impact on the coastline through erosion and degradation (Neill et al., 2009). In such situations, measures aimed at protecting the shoreline or alternative sites/layouts for the tidal arrays are highly recommended (Orhan & Mayerle, 2017; Neill & Couch, 2011; Neill et al., 2012). Figure 4-16, bottom shows the time-averaged current speeds computed along the "TR" transect (see Figure 4-13) on three different vertical layers: above, center, and below the turbines. It is visible that there's an overall decrease in current speeds along with the center layer, which is aligned with the rotor centers. Compared to the reference state, the decrease in current speeds along the transect can go as high as 1.1 - 1.2m/s. The average velocity deficit caused by the turbines is about 0.5 - 0.6m/s, corresponding to approximately 25 - 30% of the current speeds upstream of the devices. Increasing current speeds seemed to occur between the laterally aligned turbines both above and below the turbine rotors, indicating stronger current speeds below the free surface and above the benthic layer.

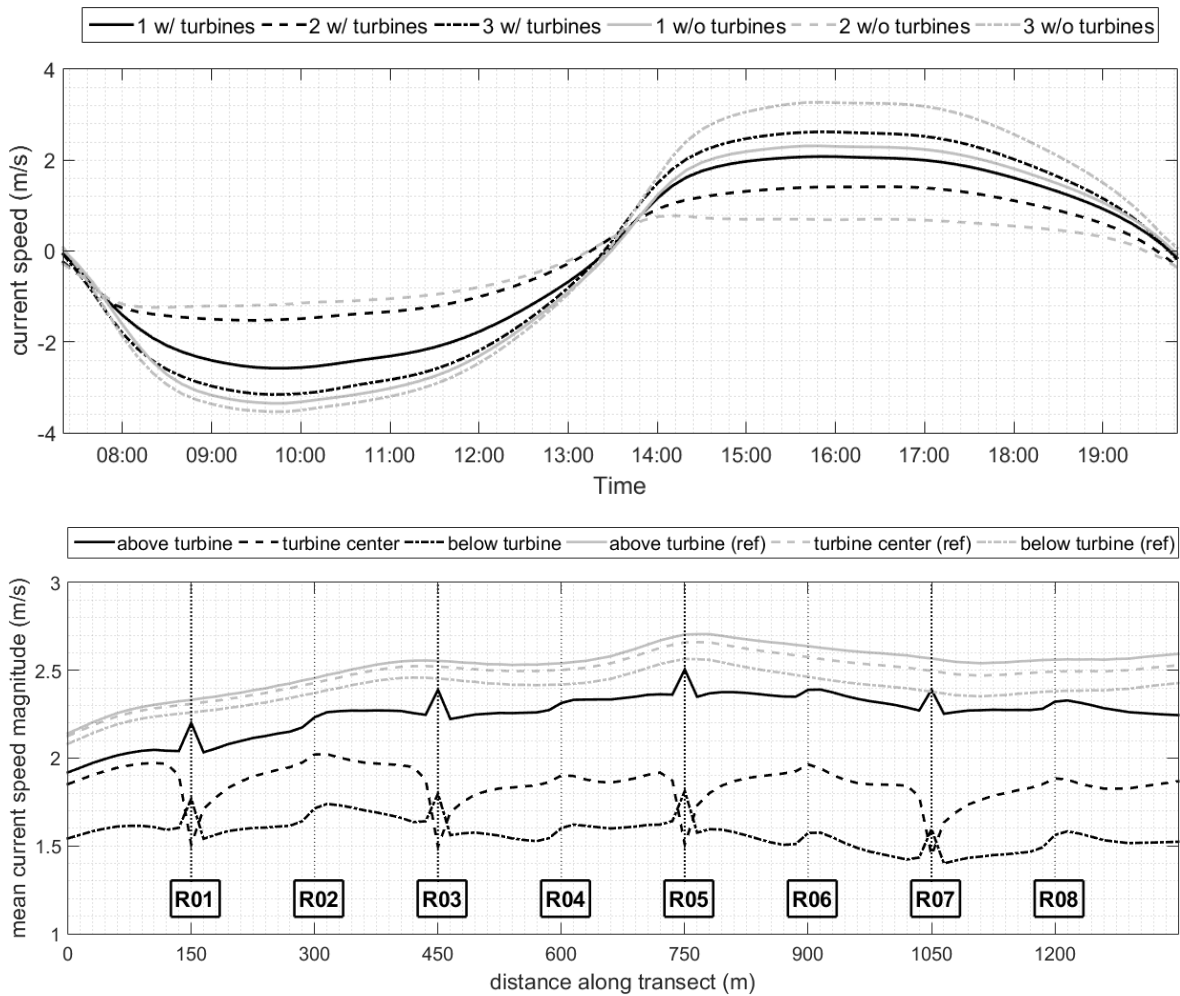


Figure 4 - 16: Time-series of depth-averaged currents speeds from the observation points 1, 2, and 3 (see Figure 4-13) simulated for the ebb and the flood tides, respectively (top); time-averaged currents speeds from above, center, and below the turbines over the transect TR (see Figure 4-13) calculated for the flood tide (bottom). Plots show the currents speed simulated considering the turbines deployed due to the proposed layout 4 (see Figure 4-15).

Farm performance

The method introduced in Orhan et al. (2016) and Orhan and Mayerle (2017) was utilized for calculation of the extractable electric power of each device. Findings were used to estimate the total power production for each row of turbines (R01 - R08) in all the proposed layouts (1 - 4). Current speeds at the hub heights were taken to compute the extractable power of the devices. Rated, cut-in and cut-out current speeds, as well as the power coefficient of the turbines, were accounted for.

Figure 4-17 presents the results in detail. As expected, higher levels of energy dissipation occurred in the proposed layout 4 (Figure 4-17, top). Especially closer to the shoreline of Adunara Island, energy dissipation is higher due to the increased blockage effect along the side banks. On the other hand, the turbine wakes seemed to recover significantly within the 10RD downstream spacing between the devices, even for the denser layouts 3 and 4. Figure 4-17, middle, shows the time series of the total power produced by the tidal arrays. It is found that the arrays with layouts 2, 3, and 4 are

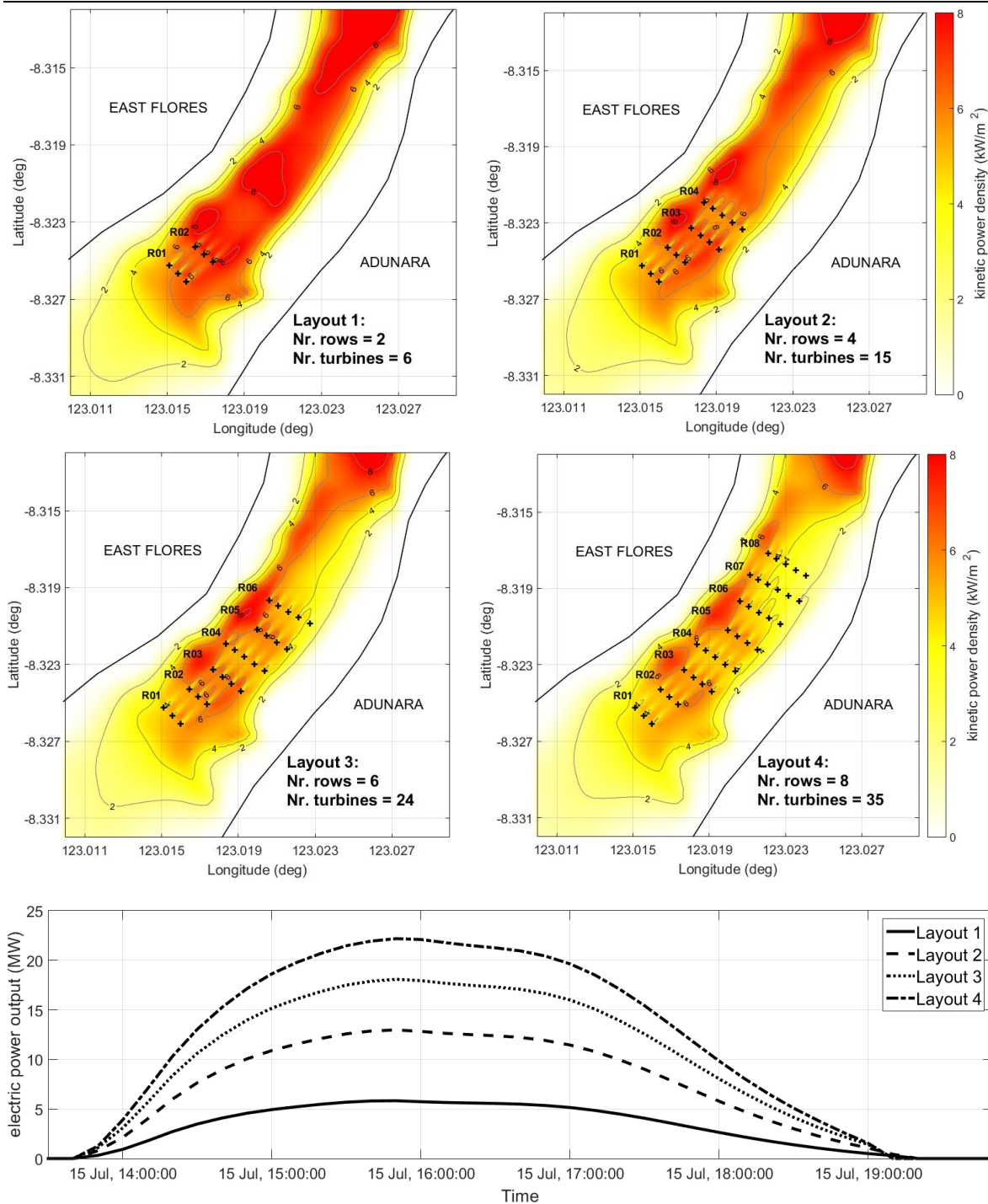
unable to reach their rated power productions of 15MW, 24MW, and 35MW, respectively. Only the array with layout 1 can produce electric power at its rated capacity (6MW) for around an hour.

Figure 4-17, bottom, shows the average electric power produced by each row of all the proposed layouts. It can be noticed that the deployment of additional rows leads to reductions of about 5 - 10% in the performance of the turbines upstream. The results are aligned with the findings of Serhadlioglu et al. (2013). They pointed out that in case of high blockage ratios, placing arrays in series can reduce arrays efficiencies. Hence to minimize hydro-environmental impacts and maximize energy yield, site-dependent factors such as bathymetry, number of turbines, and spatial extents of the designated farm area must be taken into account while choosing the array spacing (Fallon et al., 2014).

The efficiencies of the turbines deployed due to the proposed layouts ($E_{turbine}$) were calculated by comparing the time-averaged operating capacities of the turbines ($P_{average}$) to the rated turbine capacities (P_{rated}), which was assumed 1MW for the devices considered in this study, as follows:

$$E_{turbine} = \frac{P_{average}}{P_{rated}} \quad (4 - 4)$$

Figure 4-18 depicts the estimated efficiencies of the turbines concerning each proposed layout (1-4). Colors indicate the efficiency rate of each turbine. It can be seen that layouts 1 and 2 deliver the highest operating efficiency rate of the design turbine. Values up to about 50 - 60% are reached. It is also visible that the lowest efficiency rates occur with layout 4. Notice that turbines located behind the array operate with efficiencies around 20 - 30%.



Layout	R01 (MW)	R02 (MW)	R03 (MW)	R04 (MW)	R05 (MW)	R06 (MW)	R07 (MW)	R08 (MW)	TOTAL (MW)
1 (R01-02)	1.48	1.60	-	-	-	-	-	-	3.08
2 (R01-04)	1.34	1.43	1.94	2.10	-	-	-	-	6.81
3 (R01-06)	1.23	1.31	1.78	1.91	1.55	1.71	-	-	9.49
4 (R01-08)	1.14	1.21	1.64	1.77	1.44	1.56	1.64	1.25	11.64

Figure 4 - 17: Spatial variation of the average kinetic power densities at the center flow layer during the flood tide, considering different array capacities (top); time series of the total power productions of the arrays during the flood tide (middle); time-averaged electric power that can be delivered to the local grid (in MW) by tidal turbine rows (R01-08) during the flood tide considering different array capacities (bottom).

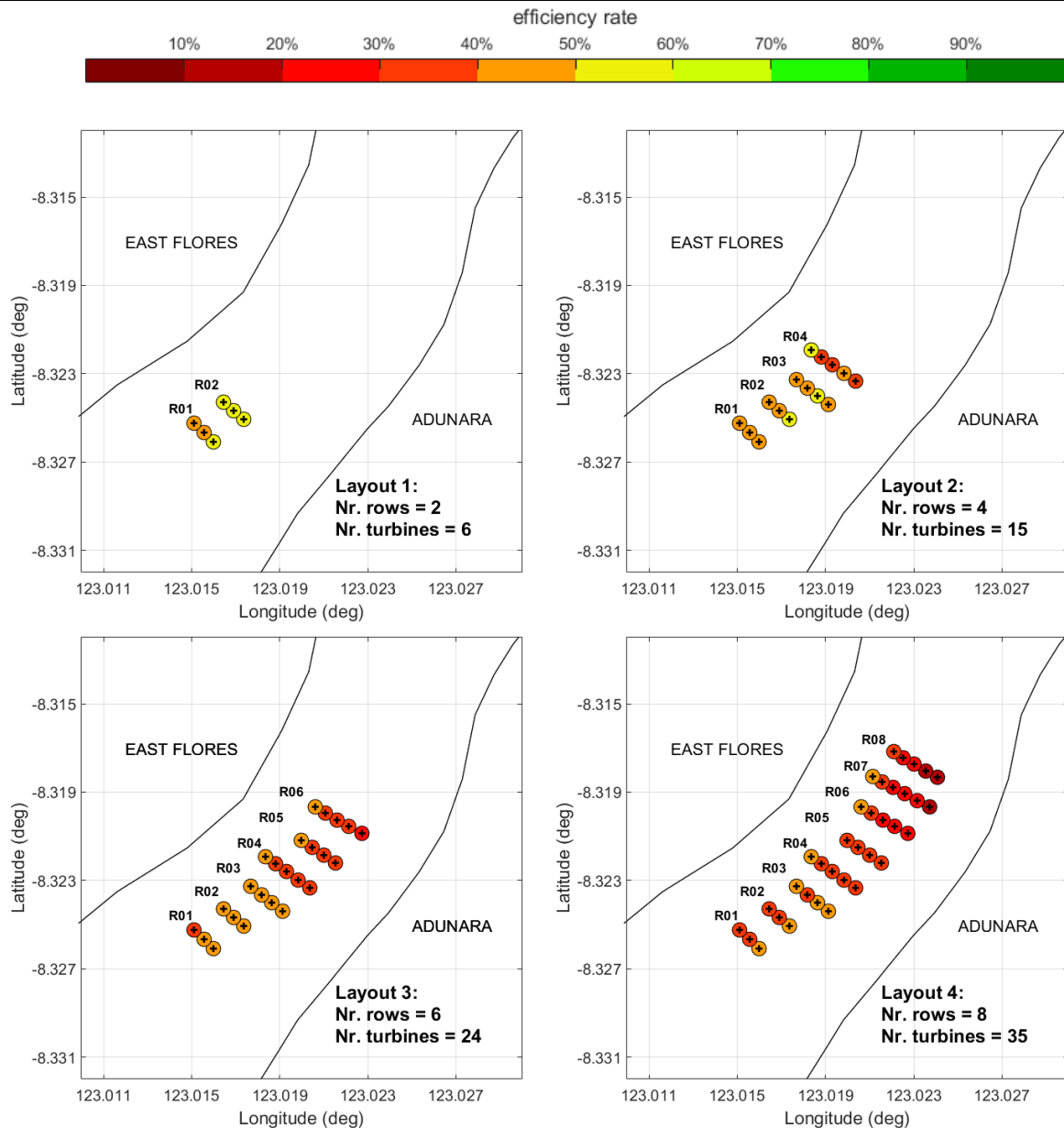


Figure 4 - 18: Turbine efficiencies in proposed layouts (15.07.2014 13:30 - 15.07.2014 19:50). The colored markers indicate the efficiency rates of the devices.

Discussion

The Strait of Larantuka, located in eastern Indonesia between East Flores and Adunara Island, has a great potential for renewable electricity production from the tidal currents. In this study, the flow field of the strait was simulated in its natural state, and considering tidal energy extraction scenarios due to four proposed multi-turbine, multi-row arrays. Design turbine, which was assumed capable of harnessing a strong bi-directional flow, was defined based on the properties of state-of-the-art, commercially available tidal turbines. The momentum sink approach was used to account for the influence of tidal energy extraction by the turbines on the flow conditions. For each proposed array, changes in the flow field, wake characteristics, and performances of arrays and turbines were analyzed. Main findings are as follows:

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- The highly energetic tidal stream currents of the Strait of Larantuka have tremendous potential for renewable electricity production, which might bring huge improvements to the energy portfolio of the region. In their natural states, current speeds exceed 3m/s in the main channel while the hydro-kinetic power densities reach 10kW/m² (Orhan et al., 2017; Orhan & Mayerle, 2017).
 - The decrease in current speeds caused by the tidal energy extraction differs from 0.1m/s to 0.6m/s within and around the tidal arrays due to the chosen layout. A drastic increase in currents speeds (80%) was observed along the side banks of Adunara Island, because of the proximity of the devices to the near-shore shallow waters of the island. Such alterations can have a significant influence over the sediment dynamics within the farm area and in adjacent marine environments. Measures aimed at protecting the shoreline against erosion and degradation or, when necessary, seeking alternative sites/layouts for the tidal arrays is highly recommended (Ahmadian & Falconer, 2012; Neill et al., 2009; Neill & Couch, 2011; Neill et al., 2012).
 - Decreases in currents speeds overtime resulted in both downstream and upstream of the arrays during flood and ebb tides alike. The energy dissipation and the blockage effect of the devices caused an overall change in the flow field and not just downstream of the devices.
 - Due to the arrangement of the devices in proposed layouts, turbine wakes showed different characteristics as compared to those occurring behind isolated turbines. Current speeds seemed to increase between the laterally aligned turbines as well as above and below the turbine rotors. As indicated in an earlier study (Chen et al., 2014), increased velocities around the turbine swept area enhance the wake mixing process and therefore speeds up the wake recovery downstream the tidal turbines.
 - The arrays with layouts 2, 3, and 4 were unable to reach their rated power productions. Only the turbine array with layout 1 was able to produce electric power at its rated capacity for a significant time. Each time new rows were added downstream of the existing array, there is a 5 - 10% reduction in the performances of the rows located upstream. Results confirm the disadvantage of placing turbine rows in series (Serhadlioglu et al., 2013). Thus, especially while deploying large scale arrays, it is highly recommended to take site-dependent factors such as bathymetry, number of turbines, and spatial extents of the designated farm area into account while deciding array layouts (Fallon et al., 2014). It might also be useful to revisit and update the recommendations concerning the spacing between tidal turbines (EMEC, 2009).
 - The maximum operating efficiency rates of the turbines in the order of 50 – 60% resulted in the layouts 1 and 2. The lowest efficiency rates occur with the tidal energy extraction scenario due to layout 4. Turbines located behind the array operate with the efficiencies around 20 - 30%.
 - Despite the sparsity of measurements, the detailed hydrodynamic model was able to simulate the flow conditions in the Strait of Larantuka reasonably well. Although the results concerning the tidal current speeds in their natural state and deficits in tidal current speeds caused by the

turbines are aligned with the findings of earlier studies (Chen et al., 2017; Chen et al., 2014; Erwandi et al., 2011), enhancing the performance of the model through more comprehensive field surveys might prove useful for future investigations.

The findings may help us to understand the effects of tidal energy extraction on the hydro-environment, and provide a practical approach to oversee array performances and device efficiencies throughout the development of commercial arrays. Modelling approaches and methods developed within this study shall be refined and adopted to resolve the interactions between the tidal turbines and stratified ocean currents, where the tides are negligible.

Acknowledgments

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Chapter 5

General Conclusions

In this chapter, the main conclusions from the investigations are summarized. The concluding remarks are organized in accordance with the objectives set in the section entitled “General Introduction”.

Regarding the development and application of the numerical models for the characterization of the tidal current energy resources, the following conclusions have been drawn:

- An advanced modelling approach has been successfully developed and applied to analyze the tidal current energy budget in Sunda, Bali, Badung, Lombok, Alas, Larantuka, Lewotobi, Solor, Boling, and Lamakera straits in Indonesia. Tidal currents in the target domains have been simulated through a series of 3D hydrodynamic models with well-structured curvilinear computational grids. Results of the simulations were used to determine spatiotemporal variations of the available hydrokinetic power in the straits under investigation.
- Considering the complexity of the flow patterns in target domains, advancements were made in the establishment of boundary conditions of the models. To capture the impacts of the phenomena such as the wind-induced circulation and resulting density gradients in the Sunda Strait or the interaction between the Indonesian Throughflow and the tidal currents in the Lombok Strait, the tide-only approach was proven inadequate. Therefore, unlike the majority of modelling studies available regarding the characterization of tidal current energy resources, the models developed in this study accounted for regional atmospheric and oceanic dynamics alongside tidal forcing. The annual trends and seasonal changes in the target domains, as well as the cycles of all the main forcing components, were captured through the simulations covering one year.
- While deciding for the horizontal resolution of the computational grids, the main concern was preserving important coastline and bathymetric features. Required level of detail, the scale of the target domain, and necessary computational time to run the models were also considered. At the bottlenecks of the straits, where the strongest tidal currents occur, grids were constructed with the highest resolutions. Horizontal grid spacing was gradually increased (with a growth rate smaller than 10%) towards the open sea boundaries to reduce the computational costs. As a result, whereas the Sunda Strait model, covering a large domain, has a resolution around ca.

500m at the most energetic section of the strait and larger than 5km close to the open sea boundaries, hydrodynamic model of the Strait of Larantuka, covering a much smaller area and aiming to resolve the wakes of isolated tidal turbines, has a resolution around 15-20m at the bottleneck of the strait and 75m at the open boundaries.

- To reach the required level of detail for capturing the far-field impacts of isolated tidal turbines, model development for the Strait of Larantuka took place in three stages. Initially, an overall model with approximately 300m resolution was developed to capture the flow conditions and interactions between Larantuka, Lewotobi, Solor, Boling, and Lamakera straits. Then, a detailed model with ca. 40m resolution was nested in the overall model to simulate the flow conditions in the Strait of Larantuka in greater detail, which was particularly promising with high hydro-kinetic power densities. In later stages of the study, to match the dimensions of tidal turbines with rotor diameters around 15-20m and to simulate their isolated impacts, the detailed model was refined further. To individually represent and simulate far-field impacts of the turbines with smaller rotors, further refinement/alteration of the model grid might still be required in the future.
- To account for the salinity and temperature gradients more accurately and to model stratification without unwanted mixing between layers of different density, Z-layers fixed in the vertical direction were preferred in the models. Required level of detail, water depth in the area of interest, and necessary computational time to run the models were taken into account to decide the vertical resolution of the computational grids. Seawater density within the target domains seemed to show significant changes throughout the depth, mainly in the upper 400m near the free surface. Thus, the layers were placed more frequently within the first 400m. Especially, the layers closer to the free surface, where the energetic tidal currents predominantly occur, vertical grid resolution of the models is in the order of meters. To be able to capture the impacts of the tidal turbines, vertical grid resolution of the hydrodynamic model of the Strait of Larantuka goes up to ca. 3m. Vertical spacing between the model layers is gradually increased (with a growth rate smaller than 25%) towards the seabed to reduce the computational costs.
- Scarcity of the field measurements caused the main challenges during the model development stage. Depth soundings providing information on bathymetry were not available for any of the targeted domains except for the Strait of Larantuka. The two models covering Sunda Strait and Larantuka, Lewotobi, Solor, Boling, and Lamakera straits, have been validated by comparing simulated and measured water levels. Unfortunately, there were no water level or current velocity measurements available concerning the models developed for Bali, Alas, and Lombok Straits during the investigations. Although the simulated tidal currents were compared to the findings of other studies conducted in the same domains to verify if the results are in the correct range, first-hand verification was not possible. Moreover, measurements regarding the density gradients in the Java, Bali, and Flores seas and the Indian Ocean could be highly useful, especially for the set-up and validation of the models.

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- Highly energetic tidal currents with current speeds up to 3-4m/s were simulated in Sunda, Bali, Badung, Lombok, Alas, Larantuka, and Boling straits. Especially in the Bali and the Larantuka straits, calculated average hydro-kinetic power densities exceed 10kW/m^2 . Straits were ranked based on the level of hydro-kinetic power density, and the highest power densities were observed in Bali, Larantuka, and Boling straits, respectively.

As for the development and application of a methodology for the assessment of tidal current energy resources in the straits investigated, the main conclusions from the investigations are as follows:

- The horizontal-axis tidal turbines were taken into account throughout the investigations due to their advanced technological status. To overcome the scarcity of information concerning the characteristics of target domains, a practical site selection method has been adopted to identify the suitable domains for the deployment of turbines. The method accounts for the available hydrokinetic power, typical site-related physical constraints, and turbine properties.
- Possible conflicts of interest with the recreational activities (small boats, swimmers, etc.), turbulence and wave loading effects on the turbines, damage from floating materials near the free surface, and low-speed benthic boundary layers were avoided while selecting suitable locations for turbine deployment. For this purpose, 5m near the free sea surface and 10% of the mean lower low water depth near the seabed was eliminated. Turbines were assumed to be capable of harnessing a strongly bi-directional flow and have a cut-in velocity of 1m/s. The minimum required area for array development was chosen as 0.5km^2 . Considering these limitations, regions which have adequate water depths to deploy the turbines, average hydro-kinetic power densities larger than 0.5kW/m^2 (corresponding to a current velocity of 1m/s) and a surface area larger than 0.5km^2 were identified as “energy hotspots”.
- For each strait, suitable area for the deployment of the tidal turbines, the applicable range of the turbine rotor diameters, and technically extractable tidal current power was determined. The results showed that turbine rotors with diameters ranging between 1.5m and 20m, which encapsulates the full range of the rotor dimensions of commercially-available tidal turbines, are applicable in the investigated straits. The tidal currents in Alas Strait have the biggest potential for energy production (ca. 1,200MW) despite having relatively lower hydrokinetic power densities (ca. 3kW/m^2). The higher energy production potential of the strait is mainly as a consequence of the large suitable area it provides for the deployment of tidal turbines (ca. 104km^2).
- Tidal power generation at the investigated straits has enough potential to exceed around 5,000MW, which corresponds to approximately 20% of Indonesia’s electric power demand. Hence, tidal current energy might be a significant contribution to Indonesia’s primary energy mix. Tidal currents flowing through the straits close to the population-dense areas such as Sunda, Bali, Alas, and Lombok straits as well as the straits in more remote and isolated areas such as the

Straits of Larantuka and Boling might bring significant improvements to the country's energy portfolio.

Regarding the evaluation of the influence of regional atmospheric and oceanographic dynamics on tidal currents and tidal power generation along the straits, the main conclusions are as follows:

- The Java Sea is highly influenced by the semi-annual reversing monsoon system in the region. This, in turn, has a great impact on the water exchange of the Java Sea and the Indian Ocean, linked by the Sunda Strait. Consequently, wind-induced circulation occurring between these systems and resulting density gradients has a great influence over the tidal currents of the Sunda Strait. The level of the influence from these regional atmospheric and oceanographic dynamics over the tidal currents and tidal power generation in the Sunda Strait was assessed by comparing the results of barotropic and baroclinic model runs. Considering the greater influence of the density gradients over the tidal currents and higher hydrokinetic power densities closer to the free surface, within the framework of this study, the emphasis was put on the currents occurring within 10m from the free surface.
- Density-induced flow can amplify the magnitude of tidal currents, on average, by about 60-70% throughout the depth in the Sunda Strait. Closer to the free surface, the increase in current speeds can be as high as 100%. Thus, the hydro-kinetic power densities, which increase with the cube of the tidal current speeds, show significantly higher values.
- Decreases in tidal current speeds might also occur due to density-induced flow. While current speeds in the Sunda Strait predominantly increase during NWM (northwest monsoon), a decrease of a similar magnitude can be observed during the SEM (southeast monsoon).
- In the Sunda Strait, irrespective of the monsoonal season, the electricity that can be generated by a tidal turbine calculated in the baroclinic mode is likely to be more than twice the amount calculated in the barotropic mode.
- The findings show the relevance of density-induced flow to tidal current power generation. Hence, adopting a comprehensive modelling approach for the characterization of the tidal current energy resources is of great importance. In the domains such as the Sunda Strait where density-induced flow has a strong influence over the tidal currents and the Lombok Strait where the tidal currents are modulated by the Indonesian Throughflow, having the right modelling approach which accounts for the right driving forces is essential to capture the flow conditions with precision. Under such conditions, the consideration of the "tide-only" approach can be highly misleading. In domains where long term changes in sea-level, hydrological conditions, salinity, and temperature of the seawater and atmospheric systems might have significant effects on the flow patterns, sensitivity studies are highly recommended to see the degree of impact while developing modelling strategies.

Regarding the evaluation of the hydrodynamic impacts and the performances of multi-turbine arrays considering different dissipation levels and array capacities, the main conclusions are listed below:

- Potential far-field impacts of multi-turbine arrays, characteristics of tidal turbine wakes, wake interactions in multi-turbine arrays, and performances of the arrays with different capacities have been analyzed through the results of high resolution, 3D model simulations in the Strait of Larantuka.
- The resolution of the computational grid was set to ca. 15-20m in horizontal to match the rotor diameters of the tidal turbines which were accounted for, and to be able to simulate the effects of the energy extraction by isolated devices. In vertical, the computational grid was constructed with a resolution up to 2-3m. To represent the tidal turbines, momentum sinks in the form of porous plates have been located at the single grid cell faces, covering several vertical layers.
- An overall change occurred in the flow field due to tidal energy extraction. Decreasing current velocity magnitudes were observed both upstream and downstream of the arrays, while stronger velocities were observed on the sides, closer to the coastline. Thus, results emphasize the importance of measures aimed at protecting the coastal areas nearby such arrays against erosion and degradation coastline.
- The turbine wakes in the presence of the additional turbines downstream demonstrated different characteristics than the turbine wakes developing behind isolated turbines. Behind isolated turbines, turbine wakes seemed to recover significantly within a distance of around 10RD (ten times the rotor diameter). With the additional turbines downstream, wakes showed quicker recoveries, and increasing current speeds were observed between the laterally aligned turbines. Increases in current velocities were also observed above and below the turbine rotors.
- Each time new rows were added downstream, the efficiency of the rows upstream decreased. The maximum average efficiency rates that the devices operate with, which are around 50 - 60%, were observed for the farm layout consisting of the smallest number of turbine rows.
- Although in comparison with the results of the experimental studies, the hydrodynamic model of the Strait of Larantuka performed reasonably well in capturing the far-field impacts of the multi-turbine arrays as well as wake interactions and recoveries, the current methodology has several shortcomings mainly due to the limitations of Delft3D-FLOW and the lack of data about the operational tidal turbines. The coarser resolution of the model compared to a CFD (computational fluid dynamics) model might have resulted in the underestimation of the near-field impacts of the tidal turbines. Whereas in the model used for the investigations, a tidal turbine with a 15m rotor diameter was represented by a single grid cell and an approximate geometry at best, in a CFD model it might be represented by tens of thousands of elements. Due to the scarcity of the information on operational tidal turbines, calibrating the model to simulate both the far-field and near-field impacts of the turbines was not possible. Such problems might

have caused the model to operate with less than optimal performances. Moreover, to simulate far-field impacts of the turbines with smaller rotors requires computational grids with higher resolutions (to match the rotor diameter) and simulating the impacts of the devices with different designs (tidal kite, vertical axis turbine, etc.) might require different modelling approaches.

Chapter 6

Outlook

The first and foremost, better monitoring of the coastal areas is essential to improve the performances of hydrodynamic models covering these areas (Uihlein & Magagna, 2016). Throughout the investigations, measurements concerning the bathymetry, water levels, current speeds, and density gradients were found to be scarce but also essential for the development of the hydrodynamic models with sufficient precision. Enhancing the performances of the models developed within this study through more comprehensive field surveys, and compiling them in a decision support system might prove useful for the researchers, policy-makers, and engineers working towards the ORE development in Indonesia.

To represent the hydrodynamic impacts of the tidal turbines, porous plates were used in this study. Although results provide valuable insight on the impacts of turbines as well as multi-turbine arrays, there's still room for improvement. Recently, a new tool (Actuator Disc) based on the Momentum Actuator Disc Theory (MADT) was developed in Delft3D-FLOW, overcoming the limitations of porous plates and showing excellent results against laboratory data (Ramos et al., 2019). The Strait of Larantuka and other domains targeted in this study might be revisited utilizing the Actuator Disc tool in the models. Thus, issues which were not addressed in this study, such as the impacts of the tidal turbines on sediment dynamics, coastal morphology, and water quality (Roberts et al., 2016), might be involved in the investigations. When made available, observations concerning the operational tidal turbines and multi-turbine arrays might be helpful to improve the tools and the methods used in the investigations.

For the resource characterization, the emphasis was on available hydrokinetic power and certain physical constraints related to the turbines and the target domains. Issues regarding the flow asymmetry and turbine misalignment (Piano et al., 2017) as well as power variability of the tidal current energy (Lewis et al., 2019) were not addressed. Resource characterization method developed and applied in this study might be improved considering these aspects of the tidal current energy generation as well as issues related to grid connection (Uihlein & Magagna, 2016). Hence strategies for providing stable electric output from the target domains to the local grid might be developed. In the long term, investigations might be extended to develop an approach harmonizing tidal currents with offshore wind and wave resources (Purba et al., 2015). A methodology to evaluate the overall

potential of ORE in target domains, and to overcome the variability of power output from the combination of ORE resources might be developed.

Furthermore, it is necessary to connect resource characterization with local environmental, societal, and economic limitations (Copping et al., 2014; Uihlein & Magagna, 2016). Throughout the investigations, maps addressing vulnerable habitats, and zoning plans indicating areas prioritizing tourism, shipping, and fishing activities around the target domains were largely missing. When made available and taken into account, such information might improve the quality of the ORE resource characterization in target domains and also provide better guidance for the development of tidal farms.

As it was addressed earlier in this study, the investigations concerning hydrokinetic energy focus mainly on strong tidal currents (see Chapter 3). Modulation of the tidal stream resource by ocean currents or ocean currents, in general, is only nowadays becoming of interest (Alcérreca-Huerta et al., 2019; Brown et al., 2019). Although ocean currents in low-tide areas might be slower-moving compared to the strong tidal currents, they are nearly continuous and unidirectional. Research concerning the energy potentials of such systems is scarce and highly necessary. There is a need to improve the understanding of related mechanisms and modelling approaches. In such domains, seawater density or long term sea-level change might play a major role in the flow conditions. Hence, studies capturing spatiotemporal variations of the salinity and water temperature gradients or the long term changes in sea-level via thorough field campaigns are needed to improve the understanding of the mechanisms and develop hydrodynamic models with higher precision.

Moreover, not much is known regarding the turbine wake characteristics in stratified flow conditions. The interaction between the turbines and the different layers of stratified flows must be examined. In the studies concerning the hydrodynamic impacts and the performances of tidal turbines, alongside MW rated devices considered in this dissertation, small-size turbines should also be taken into account. The development of small-size turbines was identified as one of the key transitions in the tidal energy market, and therefore they need to be involved in the characterization efforts of the tidal stream resources worldwide (Magagna et al., 2016).

The challenges of ORE development in population-dense areas such as in megacities should be determined, and solutions must be provided to help the policymakers. Possible conflicts with the users of the marine areas in such regions must be investigated, and strategies for the improvement of the policies regarding marine environments must be developed. Feasibility of electricity production from the ocean currents must be analyzed.

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Appendix A

Specific contributions to the manuscripts

The contributions of the authors to the manuscripts are indicated as follow:

Orhan, K., Mayerle, R., Narayanan, R. and Pandoe, W.W. (2017). Investigation of the energy potential from tidal stream currents in Indonesia. *Coastal Engineering Proceedings*, 1.35:10.

Specific contributions: K. Orhan prepared the concept of the paper, developed the hydrodynamic models, analyzed and interpreted the output, and wrote the original manuscript. R. Narayanan and R. Mayerle made contributions to the manuscript and the writing. R. Mayerle and W. Pandoe are the project holders.

Orhan, K., Mayerle, R. and Mayer, B. (2019). About the Influence of Density-Induced Flow on Tidal Stream Power Generation in the Sunda Strait, Indonesia. 38th IAHR World Congress.

Specific contributions: K. Orhan prepared the concept of the paper, developed the hydrodynamic models, analyzed and interpreted the output, and wrote the manuscript. R. Mayerle and B. Mayer made contributions to the manuscript and the writing.

Orhan, K. and Mayerle, R. (2017). Assessment of the tidal stream power potential and impacts of tidal current turbines in the Strait of Larantuka, Indonesia. *Energy Procedia*, 125:230-239.

Specific contributions: K. Orhan prepared the concept of the paper, developed the hydrodynamic models, analyzed and interpreted the output, and wrote the original manuscript. R. Mayerle made contributions to the manuscript and the writing.

Orhan, K. and Mayerle, R. (2019). Potential hydrodynamic impacts and performance of commercial-scale multi-turbine arrays in the Strait of Larantuka, Indonesia.

Specific contributions: K. Orhan prepared the concept of the paper, developed the hydrodynamic models, analyzed and interpreted the output, and wrote the original manuscript. R. Mayerle made contributions to the manuscript and the writing.

Appendix B

Declaration

Kadir Orhan

Eckernförder Str. 421

24104 Kiel

Declaration for my dissertation entitled:

“Strategies for the Assessment of Tidal Current Energy Resources through Numerical Models”

Dear Sir/Madam,

I hereby declare that apart from the supervisor’s guidance, the content and design of the thesis is all my own work. The thesis has been submitted neither partially nor wholly as part of a doctoral degree to another examining body, and no academic degree has ever been withdrawn. It has neither been published nor submitted for publication. I also assure that the thesis has been prepared subject to the Rules of Good Scientific Practice of the German Research Foundation.

Place, date

Kiel, 6th of January 2020

Signature