



The Response of the GLE Alert++ System during GLE74, GLE75, and GLE76

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Abstract

Three years after GLE73 (2021 Oct 28), three distinct GLEs took place before the end of 2024. The first event, GLE74, was registered on 2024 May 11, followed by GLE75 on 2024 Jun 8 and GLE76 on 2024 Nov 21. Each event exhibited unique characteristics in terms of intensity, temporal evolution, and spectral properties. Notably, GLE74 occurred during an irregular Forbush decrease with sharp amplitude reduction and rapid recovery. Specifically, a 15 % decrease was recorded, followed by an exceptionally fast 10 % recovery within 1.5 hours, as observed by the Oulu neutron monitor station. This event triggered the strongest geomagnetic storm in two decades (2024 May 10–11). GLE75 was a rather weak event which evolved in a quiet background as did GLE76. In this study, apart from the solar, interplanetary and geomagnetic conditions existing during these events, the response of the GLE Alert++ system, implemented by A.Ne. Mo.S. of the National and Kapodistrian University of Athens, to these Ground Level Enhancements is also being presented and analyzed, offering insights into their implications for space weather forecasting and radiation hazard.

1. Introduction

Space weather is characterized by various phenomena of cosmic rays, i.e. solar or galactic, one of the most important being the Ground Level Enhancements (GLEs) events of solar cosmic rays. Over the years many definitions have been attributed to these events (Souvatzoglou et al. 2009; Miroshnichenko et al. 2013; Hubert and Aubry 2021; Papaioannou et al. 2022; Papaioannou et al. 2023; Guo et al. 2023) but the most recent and maybe the most complete is provided by Poluianov et al. (2017). Therein it is stated that, when almost simultaneous and statistically significant enhancements of the count rates of at least two differently located neutron monitors are recorded and a corresponding enhancement in the proton flux

measured by a space-borne instrument(s) is registered, a GLE event has occurred. Importantly, one, at least, of the aforementioned neutron monitors stations must be located near sea level.

GLE events were first observed in the early 40's (Forbush, 1946), i.e. the GLE01 was recorded on February 28, 1942 (Mavromichalaki 2012) and since then nearly every year a new GLE event is recorded. In total, to this day, 76 GLEs have been recorded (Papaioannou et al. 2025), with the last three of them, i.e. GLE74, GLE75 and GLE76, being observed in the year 2024, a period that approaches or even includes the maximum of solar cycle 25. It is known that GLEs are dependent on the solar cycle (Souvatzoglou et al. 2014; Mavromichalaki et al. 2022) and are most likely to be recorded during a solar cycle's maximum and descending phase (Shea and Smart 1990; Kravtsova et al. 2021).

Nowadays, GLEs are an important part of the fundamental research concerning space weather and more precisely space weather phenomena forecasting due to their possible impact not only on technological applications (Baker, 1998) but also and most importantly on human health or even human life (Baker et al. 2004; Eastwood et al. 2017; Buzulukova and Tsurutani 2022).

Such phenomena can be responsible for interfering extensively with a variety of human activities (Wrenn et al. 2002; Wrenn 2009; Rao et al. 2009; Chapman et al. 2020) and inflicting direct damages such as single-event effects, single-event upset, polar cap absorption, etc. (Dyer et al. 2018; Larsen and Mishev 2023). In addition to navigations, telecommunications, high-potential power grids systems and other similar ground-based systems that can be influenced by GLE events, also the performances and reliability of spacecraft operation, i.e. satellite's electronics, can be affected.

Moreover, the disturbed space environment during a GLE event can also directly affect aviation flights as well as space missions. Regarding galactic cosmic rays, a number of limitations and directions imposed by airline companies, e.g. limited airtime in the polar regions and annual radiation exposure allowances, regulate the health risk. However, GLEs are events that cannot be predicted; consequently, the danger posed by them is less controllable. Thus, enhanced radiation doses during GLEs events can constitute a major threat for exposed air crews and passengers.

In this work the three GLE events, i.e. GLE74 on May 11, GLE75 on June 8 and GLE76, on November 21 that occurred during 2024 are being presented. Solar, interplanetary, geomagnetic and cosmic rays' conditions during these time periods are described using satellite data and neutron monitor data. Furthermore, the response of the GLE Alert++ system, implemented by A.Ne.Mo.S. of the National and Kapodistrian University of Athens, for each event is being thoroughly discussed.

2. The GLE74 on May 11, 2024

GLE74 was recorded on May 11, 2024 during a highly active period in terms of solar activity (Mavromichalaki et al. 2024). A detailed analysis of the disturbed background (solar, geomagnetic and cosmic rays activity) and the full response of the GLE Alert++ system (pre-alert status, alert status and post-alert status) to GLE74 is presented in Gerontidou et al. (2026). However, in the following a brief description of the events that took place during the time period under consideration is included.

2.1 Space-borne observations

It is interesting to note that 89 significant X-ray flares (48 of M-class and 10 of X-class) were recorded in AR13664 during a time period of almost a fortnight (2024 May 02–15). Many of these flares were accompanied by very fast halo CMEs. The increased solar activity started reflecting in proton flux levels on May 9.

2.2 Ground-based recordings

The GLE74 evolved during the deep phase of a strong Forbush decrease and as a result was registered by the neutron monitor network. The Forbush decrease was characterized by a sharp reduction of 15 % and a rapid recovery, i.e. the Oulu neutron monitor station recorded a 10 % recovery within 1.5 hours. As a result, a G5 geomagnetic storm (i.e. the strongest in the two last decades) was registered on May 10 – 11, 2024, causing auroras at unprecedented latitudes worldwide. Table 1 shows the NM stations (7) that recorded the GLE74 more clearly according to OULU GLE Database (<https://gle oulu.fi/#/>, last accessed 2026 Jan 21). In Table 1, as for Tables 2 and 3 that correspond to GLE75 and GLE76 respectively and are included in the following, the increases were calculated for 1-minute data from NMs.

Tab. 1: Characteristics even NM stations, which recorded the largest relative count rate increase during GLE74 according to OULU GLE database (<https://gle oulu.fi/#/>).

Station	Latitude (°)	Longitude (°)	Altitude (m)	Rigidity (GV)	Date / Time (DD/MM HH:MM)	Increase (%)	Date (DD/MM/YYYY)	Time (UT)
DOMB	75.1	-123.38	3233	<0.01	10/05 23:00 – 11/05 01:00	9.23	11/05/2024	04:20
DOMC	75.1	-123.38	3233	<0.01	10/05 23:00 – 11/05 01:00	7.51	11/05/2024	03:35
DRBS	50.1	4.6	225	3.18	10/05 23:30 – 11/05 01:30	4.12	11/05/2024	02:55
NAIN	56.6	-61.7	0	0.3	10/05 23:30 – 11/05 01:30	5.67	11/05/2024	03:45
SNAE	-71.67	-2.85	856	0.73	10/05 23:30 – 11/05 01:30	5.45	11/05/2024	03:10
SOPB	-90	0	2820	0.1	10/05 23:30 – 11/05 01:30	9.96	11/05/2024	02:45
SOPD	-90	0	2820	0.1	10/05 23:30 – 11/05 01:30	8.67	11/05/2024	03:00

2.3 GLE Alert++ system

Over the last years, A.Ne.Mo.S. of the National and Kapodistrian University of Athens has developed and operates a real-time GLE Alert system, named GLE Alert++ system (Crosby et al. 2024). This tool generates an alert during the initial phase of a GLE and is provided, as a federated product on the ESA SWE Portal (<https://swe.ssa.esa.int/anemos-federated>, last accessed 2026 Jan 21) of the ESA Space Safety Program Space Weather Service Network under the Space Radiation Expert Service Center (R-ESC).

In the case of the GLE74, the GLE Alert++ system successfully issued an alert on 2024 May 11 at 02:05 UT. This alert was issued based on the neutron monitor stations of Oulu, Finland (OULU, R= 0.81, 15m a.s.l.), South Pole, Antarctica (SOPD, R=0.1GV, 2820m a.s.l.), Lomnický štít, Slovakia (LMKS, R=3.84GV, 2634m a.s.l.) as shown in [Figure 1](#). One minute after the initial alert, a new polar station, South Pole Bares, Antarctica (SOPB, R = 0.1GV, 2820m a.s.l.), also entered into Alert mode.

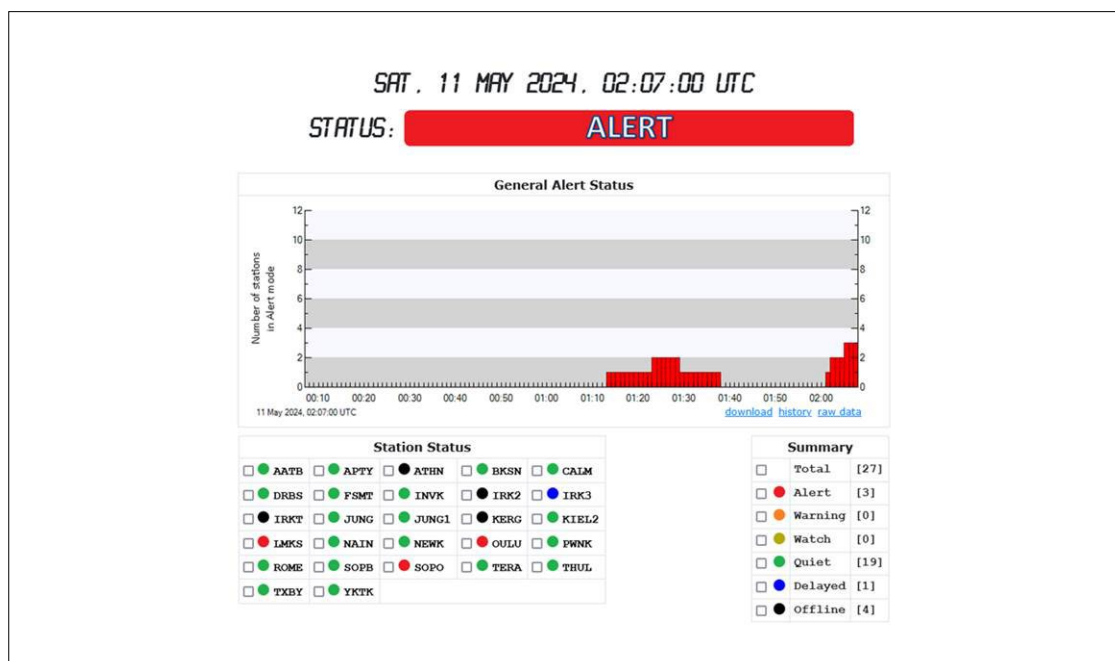


Fig. 1: General Alert status on 2024 May 11 at 02:07 UT as recorded by the ANeMoS GLE Alert++ system (<https://swe.ssa.esa.int/anemos-federated>).

3. The GLE75 on June 8, 2024

It should be mentioned that GLE75 that was recorded on 2024 Jun 8 meets the criteria for the GLE definition, since, in addition to SOPO, SOPB, DOMB, Antarctica (R <0.01, 3233m a.s.l.) and DOMC, Antarctica (R <0.01, 3233m a.s.l.), a weak but statistically significant response (~2 %*hr) was also registered in the neutron monitor station Peawanuck, Canada (PWNK, R=0.3GV, 53m a.s.l.) dataset.

3.1 Space-borne observations

On June 7, 2024 at 09:13 UT peak time, AR3709 erupted producing two M-class solar flares, the biggest of class M4.0 (Figure 2a) and a radio blackout of category R1. For the time period June 4 - 6, LASCO imagery showed no obviously Earth directed CMEs, but a coronal hole (CH1224) at northern hemisphere rotated across the central meridian. Moreover, another coronal hole (CH1225) at southern hemisphere had become Earth facing on June 10. Furthermore, GOES Proton Flux for particles with energies above 10 MeV exceed the SWPC 10 MeV warning threshold on June 8 at 02:50 UT (Figure 2b). A solar radiation storm of level S2 was also observed.

On June 7 at 19:40 UT, the solar wind speed, measured by ACE satellite, reached the maximum value 503 km/s, while from STEREO A was detected at 400 km/s. On June 7 at 14:00 UT, the vertical component of IMF Bz reached the max value -14nT. The geomagnetic activity was quiet to moderate (geomagnetic storm G2). The Kp index was at unsettled levels with Kp=3 (Figure 2c).

3.2 Ground-based recordings

The GLE75 was a weak event that was mainly registered by high latitude stations, i.e. DOMC and DOMB (see Table 2). However, according to OULU GLE Database (<https://gle oulu.fi/#/>, last accessed 2026 Jan 21)

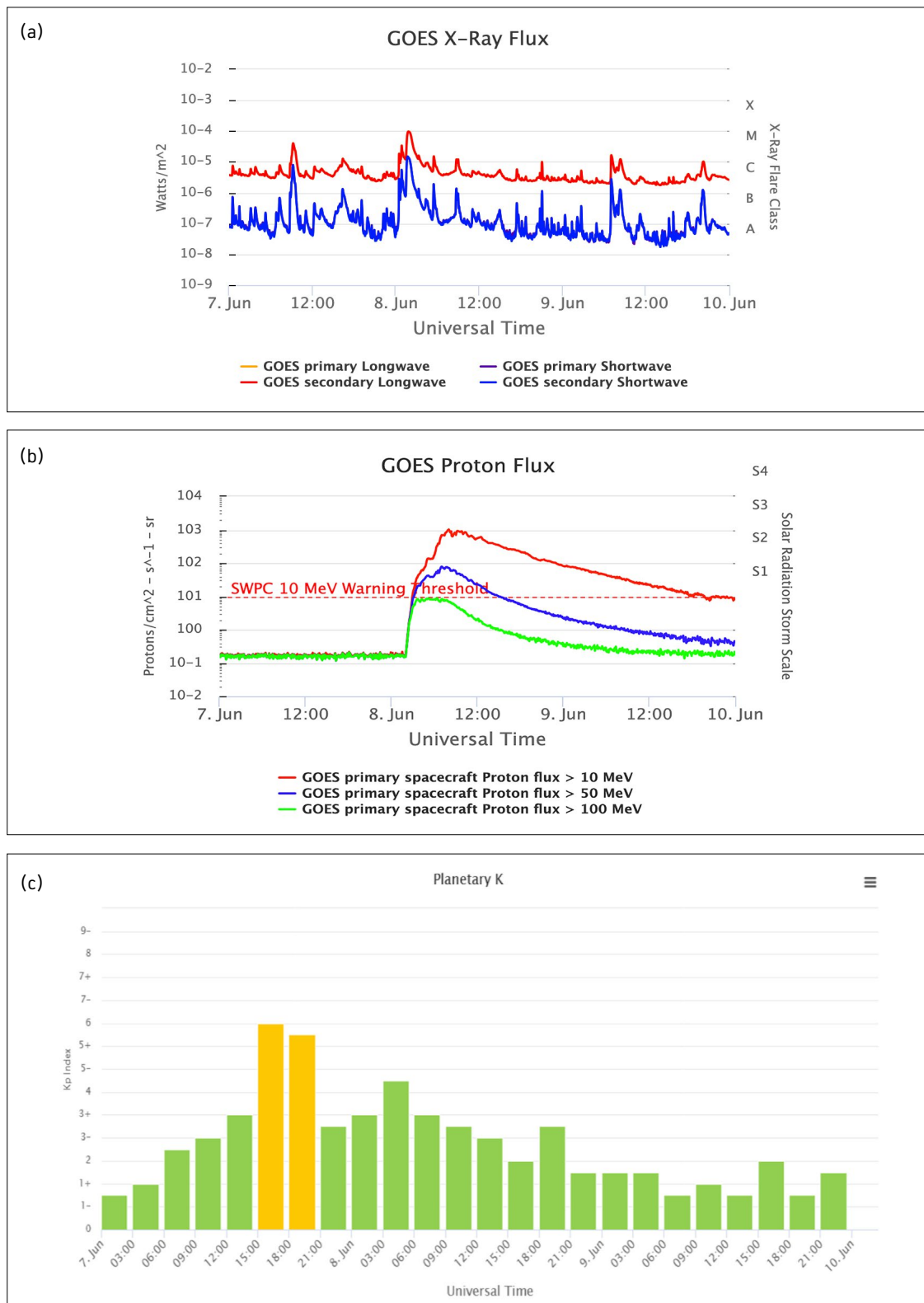


Fig. 2: GOES-16 X-ray flux in 0.5–4.0 Å and 1.0–8.0 Å (a), GOES proton flux >10 MeV and > 100MeV (b) and geomagnetic index Kp values (c) for the time period 2024 Jun 07–10 as derived from <https://lasp.colorado.edu/space-weather-portal/goes-proton-flux/>.

the 7 stations that best recorded this event also included low latitude stations such as Mawson, Antarctica/Australia (MWSB, $R=0.22$, 30m a.s.l.), OULU, and PWNK. The cosmic ray variations for the aforementioned stations are presented in [Figure 3](#).

Tab. 2: Characteristics of the seven best NM stations that recorded GLE75 according to OULU GLE database. (<https://gle.oulu.fi/#/>)

Station	Latitude (o)	Longitude (o)	Altitude (m)	Rigidity (GV)	Date / Time (DD/MM HH:MM)	Increase-max (%)	Date (DD/MM/YYYY)	Time (UT)
DOMB	75.1	-123.38	3233	<0.01	08/06 00:00 – 08/06 02:00	8.65	08/06/2024	04:35
DOMC	75.1	-123.38	3233	<0.01	08/06 00:00 – 08/06 02:00	5.76	08/06/2024	02:30
MWSB	-67.60	62.88	30	0.22	08/06 00:00 – 08/06 02:00	3.43	08/06/2024	03:25
OULU	65.05	25.47	15	0.8	08/06 00:00 – 08/06 02:00	2.89	08/06/2024	02:55
PWNK	54.98	-85.44	53	0.00	08/06 00:00 – 08/06 02:00	2.7	08/06/2024	02:45
SNAE	-71.67	-2.85	856	0.68	08/06 00:00 – 08/06 02:00	2.64	08/06/2024	03:00
SOPB	-90	0	2820	0.1	08/06 00:00 – 08/06 02:00	2.66	08/06/2024	03:15

3.3 GLE Alert++ system

The GLE Alert++ system did not issue an alert for GLE75, since the only station that entered in Alert mode was SOPO ([Figure 4](#)). The system could not be in General Alert status, as there were no three stations in Alert mode simultaneously, possibly due to the small amplitude of the event. Because GLE75 was such a weak event the only way to issue an alert would be by using neutron monitor stations DOMB, DOMC and MWSB. However, these stations are not used in the application since they are not real-time stations.

4. The GLE76 on 2024 Nov 21

A new GLE of the cosmic ray intensity on 2024 Nov 21, identified as GLE76, was recorded by the real-time neutron monitor stations and was caused by a proton event.

4.1 Space-borne observations

On November 20 at 19:48 UT peak time the AR3889 erupted and produced a M1.2-class solar flare ([Figure 5a](#)). The available LASCO imagery showed no obvious Earth directed CMEs on November 18-20. On November 21 at 19:20 UT GOES Proton Flux for particles with energies above 10 MeV exceeded the SWPC 10 MeV warning threshold (S2 solar radiation storm) as shown in [Figure 5b](#). Additionally, the geomagnetic field was quiet to unsettled on 2024 Nov 20–21 ([Figure 5c](#)).

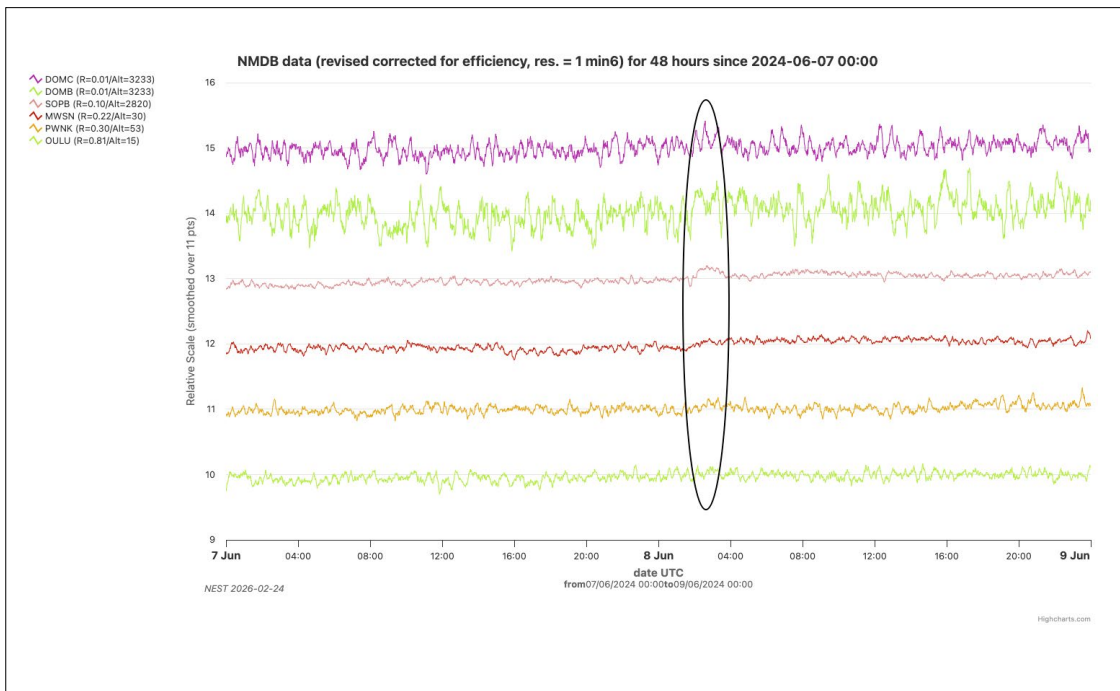


Fig. 3: GLE75 as recorded by the DOMC, DOMB, SOPB, MWSB, PWNK and OULU neutron monitor stations (NMDB; <https://www.nmdb.eu/nest/>), GLE75 is marked in the circle.

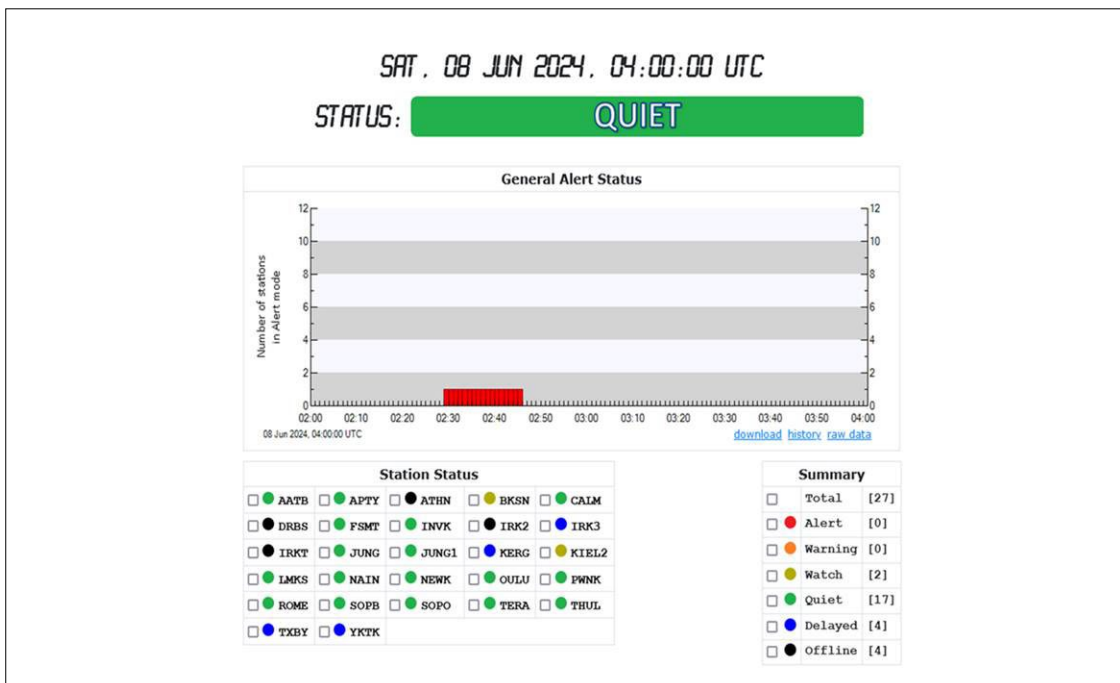


Fig. 4: The SOPO station entered in Alert mode.

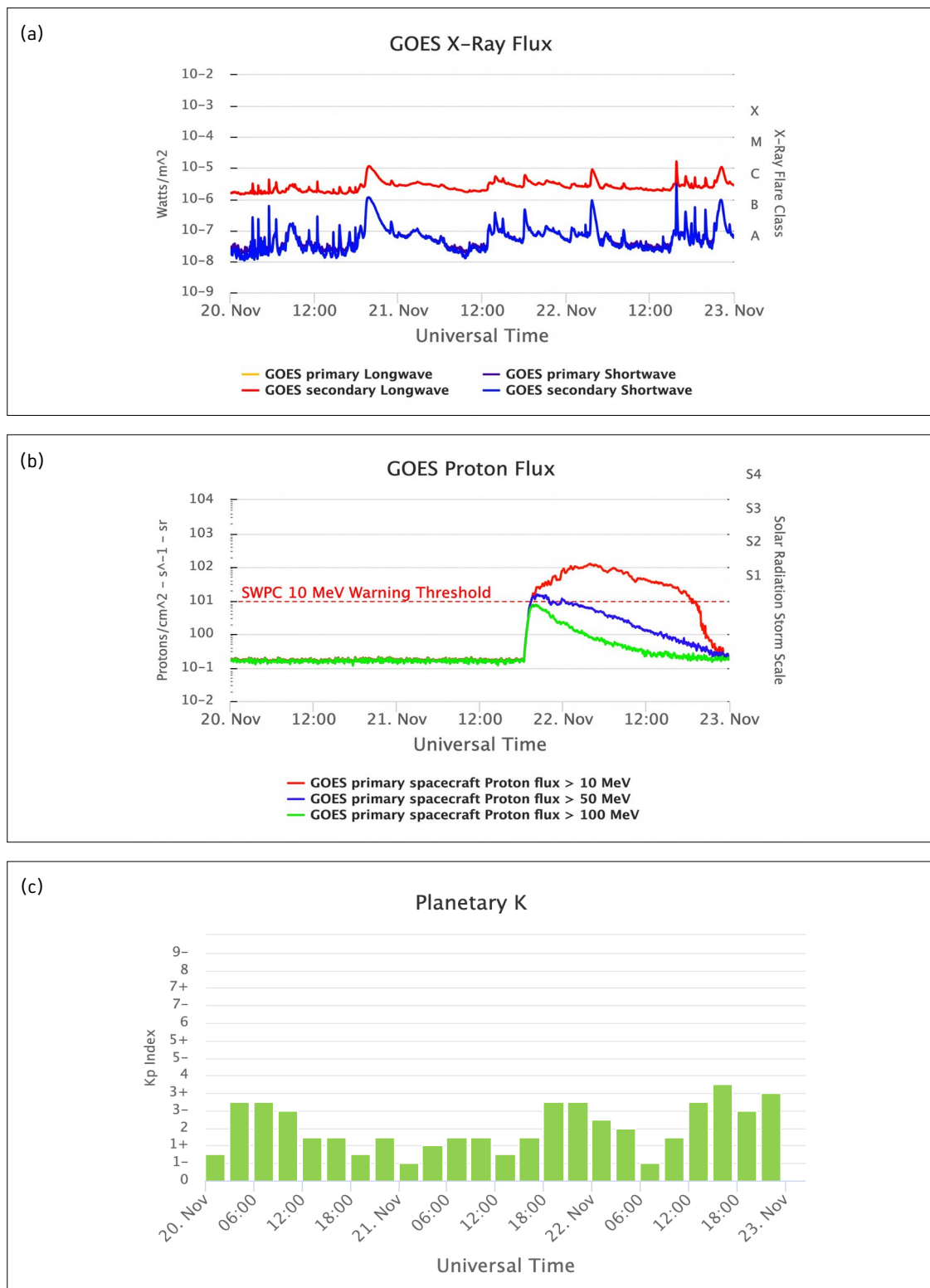


Fig. 5: GOES-16 X-ray flux in 0.5–4.0 Å and 1.0–8.0 Å (a), GOES proton flux >10 MeV and > 100MeV (b) and geomagnetic index Kp values (c) for the time period 2024 Nov 20–23 as derived from <https://lasp.colorado.edu/space-weather-portal/goes-proton-flux/>.

4.2 Ground-based recordings

Figure 6 shows the cosmic ray intensity variations from November 20 to November 23 for the neutron monitor stations Terre Adelie, Antarctica (TERA, $R = 0\text{GV}$, 32 a.s.l.), DOMC, DOMB, SOPO and SOPB. As can be seen a GLE was recorded on November 21 (TERA: max 4.25 % at 19:00 UT, DOMC: max 6.98 % at 19:05 UT, DOMB: max 8.64 % at 20:05 UT, SOPO: max 3.17 % at 18:50 UT) and (SOPB: max 3.68 % at 19:00 UT) (<https://gle.oulu.fi/#/>, last accessed 2026 Jan 21). More information about these stations is presented in Table 3.

Tab. 3: Characteristics of the five best NM stations that recorded GLE76 according to OULU GLE database (<https://gle.oulu.fi/#/>).

Station	Latitude (o)	Longitude (o)	Altitude (m)	Rigidity (GV)	Date / Time (DD/MM HH:MM)	Increase-max (%)	Date (DD/MM/YYYY)	Time (UT)
DOMB	75.1	-123.38	3233	<0.01	21/11 16:00 - 21/11 18:00	8.64	21/11/2024	20:05
DOMC	75.1	-123.38	3233	<0.01	21/11 16:00 - 21/11 18:00	6.98	21/11/2024	19:05
TERA	-66.65	140.00	32	0.02	21/11 16:00 - 21/11 18:00	4.25	21/11/2024	19:00
SOPB	-90	0	2820	0.1	21/11 16:00 - 21/11 18:00	3.68	21/11/2024	19:00
CALM	40.64	-3.16	708	6.95	21/11 16:00 - 21/11 18:00	3.85	21/11/2024	16:10

4.3 GLE Alert++ system

In the GLE Alert++ system at first, two polar stations, SOPO and SOPB, were in Alert mode (18:43–18:54 UT) and the system's status was Warning (Figure 7). For the next 2 minutes (18:55–18:56 UT) only SOPB was in Alert mode and the system's status was Watch. At 18:57 UT two stations, Kerguelen, Antarctica (KERG, $R = 1.14\text{GV}$, 33m a.s.l.) and SOPB, were in Alert mode and the system's status was again Warning. From there on only the station KERG was in Alert mode and the system's status was Watch (Figure 8). At 19:00 UT the station KERG was in Alert mode and Kiel, Germany (KIEL2, $R = 2.36\text{GV}$, 54m a.s.l.) in Watch mode (Figure 9). Consequently, the GLE Alert++ system could not be in General Alert status, as there were no three stations in Alert mode simultaneously (for only 3 minutes the alert was missed). However, it should be noted that such short time differences may be due to deficient synchronization of stations.

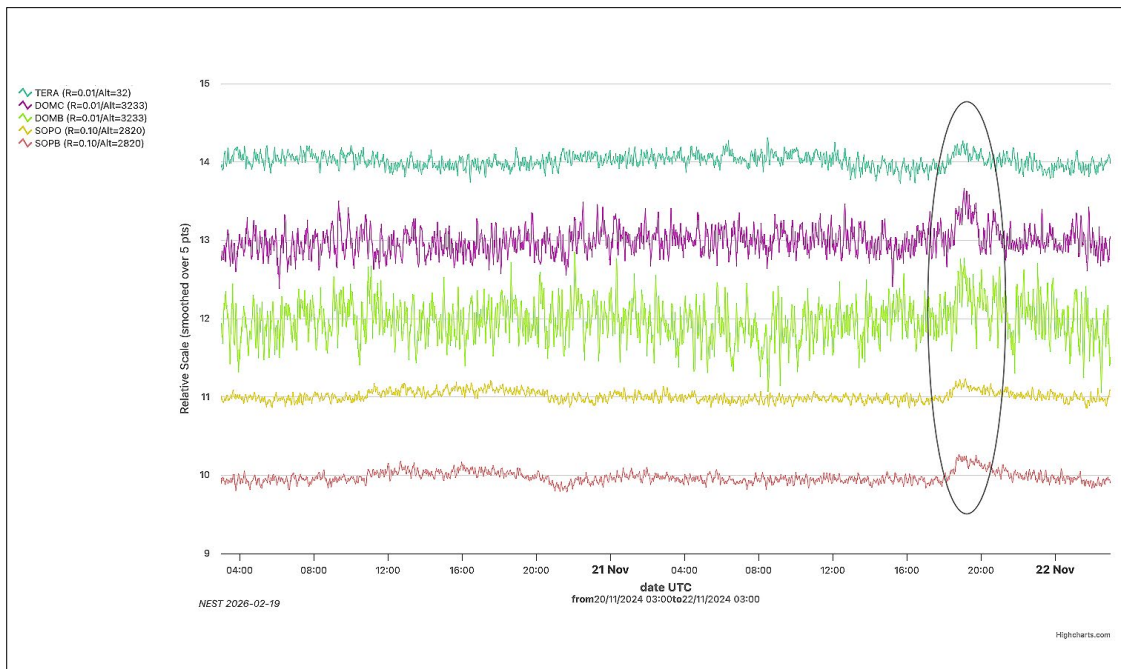


Fig. 6: Cosmic ray intensity variations for the time period from Nov 20–23 for the neutron monitor stations TERA, DOMC, DOMB, SOPO and SOPB (<https://www.nmdb.eu>). GLE76 is marked in the circle.

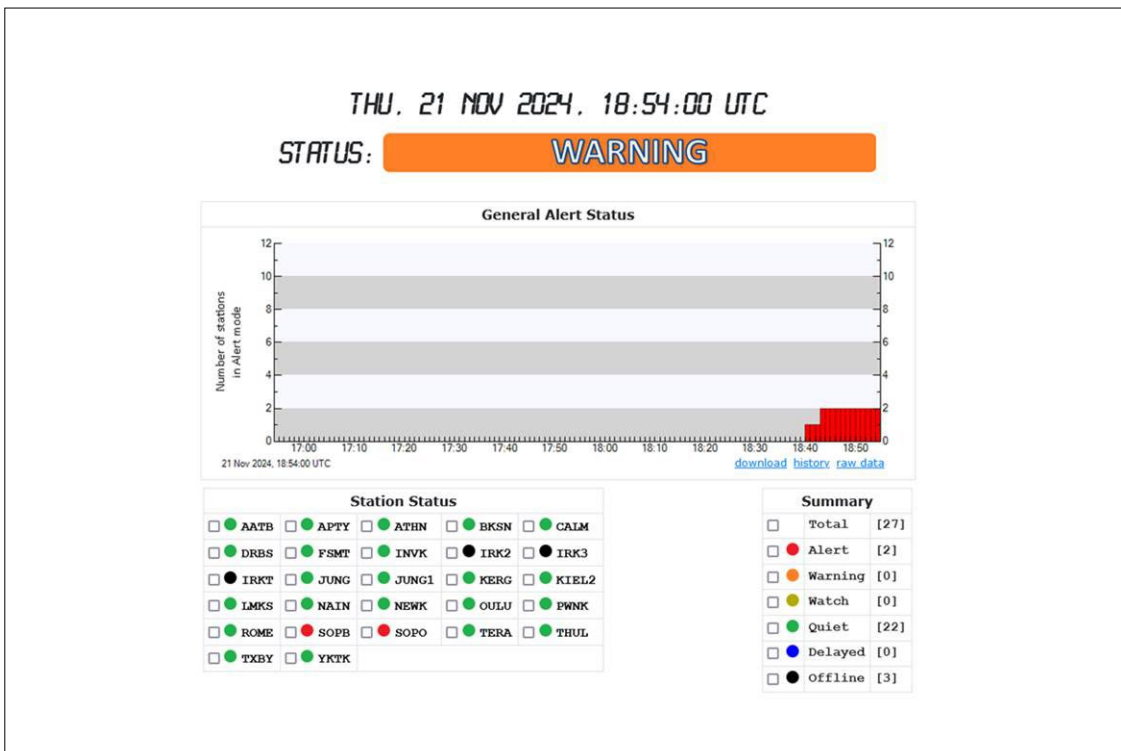


Fig. 7: The two stations in Alert mode (SOPB and SOPO) are marked.

2024-11-21 19:04:02	2024-11-21 18:43:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:44:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:45:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:46:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:47:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:48:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:49:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:50:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:51:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:52:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:53:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:54:00	2	SOPB SOPO	WARNING
2024-11-21 19:04:02	2024-11-21 18:55:00	1	SOPB	WATCH
2024-11-21 19:04:02	2024-11-21 18:56:00	1	SOPB	WATCH
2024-11-21 19:04:02	2024-11-21 18:57:00	2	KERG SOPB	WARNING
2024-11-21 19:04:02	2024-11-21 18:58:00	1	KERG	WATCH
2024-11-21 19:04:02	2024-11-21 18:59:00	1	KERG	WATCH
2024-11-21 19:04:02	2024-11-21 19:00:00	1	KERG	WATCH

Fig. 8: Raw data of the GLE Alert++ system for the time period from 18:43 UT until 19:00 UT on 2024 Nov 21. The columns represent the Server's timestamp, the Stations' timestamp, the number of stations, the Stations' abbreviation and the GLE status

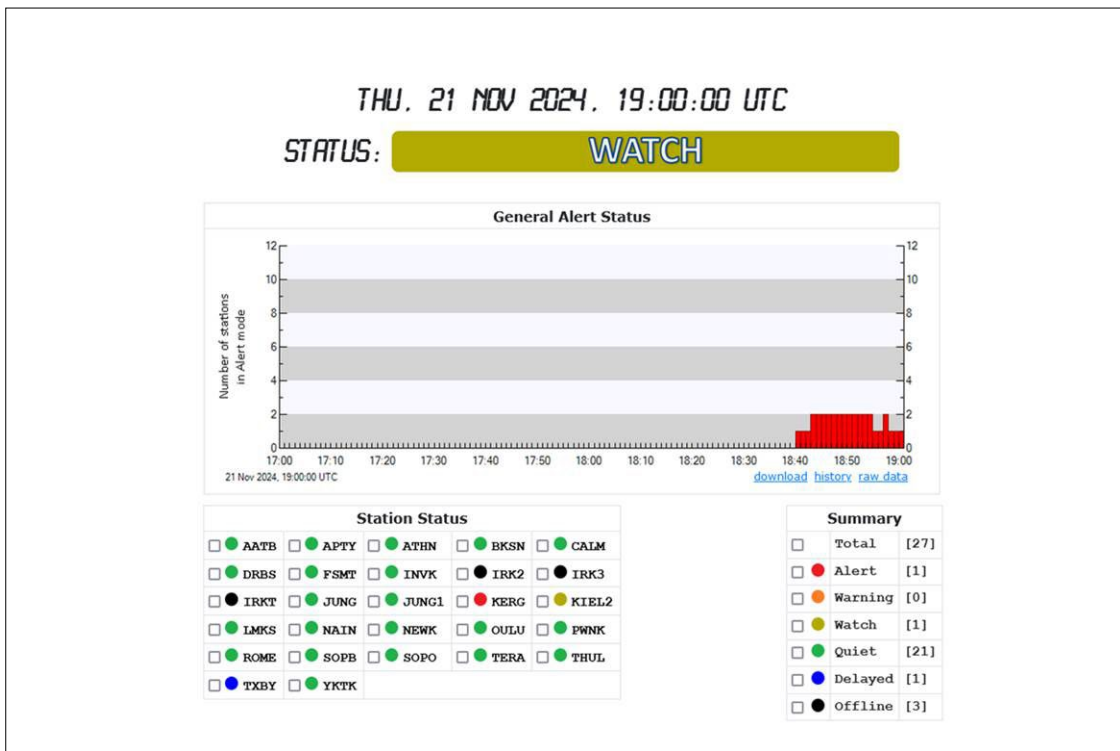


Fig. 9: The stations KERG and SOPB were in Alert mode only for 1 minute.

5. Conclusions

In this study, the three Ground Level Enhancements (GLEs) of 2024 — namely GLE74, GLE75, and GLE76 — were thoroughly analyzed using data from the Neutron Monitor Database (NMDB). Furthermore, the response of the GLE Alert++ system, operated by the A.Ne.Mo.S. Group at the National and Kapodistrian University of Athens and provided as federated product at SWE Portal of the ESA Space Safety Program Space Weather Service Network under the Space Radiation Expert Service Center (<https://swe.ssa.esa.int/anemos-federated>, last accessed 2026 Jan 21), was evaluated for each of these events.

The main findings are as follows:

- The GLE Alert++ system responded to all detected events.
- For **GLE74**, a General Alert was successfully issued at 02:05 UTC on 2024 May 11.
- For **GLE75**, which was a weak event primarily observed by high-altitude polar stations DOMB and DOMC, the system entered Alert mode only for the polar station SOPO. As a result, no General Alert was triggered. This behavior was consistent with expectations, as the primary contributing stations (DOMB and DOMC) are not integrated into the real-time monitoring database of the GLE Alert++ system.
- For **GLE76**, the system entered *Watch* and *Warning* status, but a General Alert was not issued. This missed detection may be attributed to delayed data delivery to the NMDB, which feeds the alert system.

To enhance the reliability and completeness of the GLE Alert++ system and mitigate such limitations, the integration of satellite-based observations is proposed as a necessary future development.

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