

# Sun-to-Mud observations of the May and October storms of 2024: impacts on Ireland's Space Weather

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**Abstract**—Near the peak of Solar Cycle 25 in 2024, Earth was impacted by two major solar eruptive events which triggered dramatic geomagnetic storm activity. In May 2024, multiple solar eruptive events generated the largest geomagnetic storm since the early 2000s; this was followed by a similar-sized geomagnetic storm in October 2024, driven by a single solar eruptive event. Both storms occurred in the “social media era”, when the widespread use of mobile imaging devices on “smartphones” encouraged the public to go outside and witness the storms, often capturing and sharing photographs; examples local to the island of Ireland are analysed in this study. While the socio-historic impact of the storms was significant, in this manuscript, the sources and effects of the two storms are compared and contrasted. A “Sun-to-Mud” analysis is presented, from the solar origins of the events down to regional electrodynamic effects over the island of Ireland. Results indicate that while the May storm was driven by a compound CME-CME event following a quiet period, the single CME driving the October storm arrived at a magnetosphere primed by previous activity. Both storms exhibit strong solar wind – magnetosphere-ionosphere coupling, and the precursor activity in October demonstrates that the time history of magnetosphere-ionosphere priming is an important factor that influences the ultimate effect of a transient solar-driven event. Locally over the island of Ireland, observations suggest auroral electrojets poleward of local magnetometers, and both events generate remarkable geomagnetically induced currents; these observations are presented along with local auroral photographs.

**Keywords:** Space Weather / May storm / October storm / Solar Cycle 25 / Solar wind magnetosphere ionosphere coupling / Gannon storm / Mother's Day Storm / Coronal mass ejection / Geomagnetic storm

## 1 Introduction

Near the peak of solar cycle 25, 2024 was an exciting year for aurora-chasers and space scientists alike. In this study, we compare the dramatic solar/geomagnetic storms of May and October 2024 in a Sun-to-Mud analysis, with focus on the locality of the island of Ireland. This comparative case study allows us to unpick the non-trivial nature of how different drivers can excite the Earth's magnetosphere.

Space weather effects, including those of dramatic solar storms, become more and more important as society becomes increasingly dependent on technology. Space weather can disrupt power grids (e.g., Bolduc, 2002), delay trains (e.g., Patterson et al., 2024), interrupt communications, and affect

Earth-orbiting satellites. The number of payloads launched into Earth's orbit has grown significantly since the last major storm (e.g., Parker & Linares, 2024), and past experience has shown that even moderate space weather events can result in catastrophic loss of satellites (e.g., Fang et al., 2022; Zhang et al., 2022; Hapgood et al., 2022; Baruah et al., 2024). However, Parker & Linares (2024) also highlight a potential benefit of space weather effects: increased thermospheric drag has the capability to naturally deorbit space debris, while functioning satellites are capable of performing orbit-raising manoeuvres (as many did during the May storm).

Local space weather effects vary based on local geology and the morphology of local systems such as electricity grids. The Magnetic Network of Ireland (MagIE<sup>1</sup>) has been used to

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<sup>1</sup> <https://www.magie.ie/>.

characterise space weather on the island of Ireland. Blake et al. (2016, 2018) modelled the effects of geomagnetically induced currents (GICs), while Campanyà et al. (2019); Malone-Leigh et al. (2023, 2024) investigated geoelectric fields, and Fogg et al. (2023b) modelled the occurrence of extreme space weather observations.

In the following subsections, we will highlight previous work on the May and October storms over recent months.

### 1.1 Observations in May 2024

During May 2024, several coronal mass ejections (CMEs) erupted from the Sun, impacting the Earth and generating the largest geomagnetic storm seen since 2003 (e.g., Yamazaki et al., 2024; Witze, 2024). This storm peaked on 10–11th May 2024. The USA’s National Oceanic and Atmospheric Administration’s (NOAA) Space Weather Prediction Center (SWPC) released its first G4 “severe” geomagnetic storm watch since 2005 (NOAA-SWPC, 2024b), which subsequently evolved into a G5 or “extreme” event (i.e., the maximum level NOAA-SWPC, 2024a).

Elvidge & Themens (2025) note that the May 2024 storm has been given many names. Firstly, the “Gannon Memorial Storm” (e.g., Yamazaki et al., 2024; Evans et al., 2024; Parker and Linares, 2024; Evans et al., 2024; Grandin et al., 2024; De Michelis & Consolini, 2025) after Dr J. L. Gannon, who passed away in the week prior. Also, the “Mother’s Day Storm” (e.g., Spogli et al., 2024; Mlynczak et al., 2024; Ang et al., 2025) as it coincided with some national Mother’s Day celebrations. Elvidge & Themens (2025) also refer to it as the “Han Anniversary Storm”, relating to the beginning of routine sunspot recordings in China, during the Han dynasty. Other authors have referred to it as a *superstorm* (e.g., Witze, 2024; Zhang et al., 2024; Fu et al., 2025; Jin et al., 2025; Olifer et al., 2025), *super geomagnetic storm* (e.g., Sun et al., 2024a; Guo et al., 2024; Wan et al., 2025; Xia et al., 2024; Xu et al., 2025) or even *great geomagnetic storm* (e.g., Sun et al., 2024b; Ambili et al., 2025), while the precise definition for these is debated across the community. In this manuscript, two geomagnetic storms that occurred in 2024 are compared and contrasted, and hence they are named based on the month they occurred in: the “May” storm and the “October” storm (described in the following section).

The May geomagnetic storm was triggered by the impact of multiple CMEs at the Earth’s magnetosphere (Ranjan et al., 2024; Kruparova et al., 2024; Hayakawa et al., 2025; Wan et al., 2025), accompanied by related decreases in galactic cosmic rays (known as Forbush decreases, Mavromichalaki et al., 2024). Fu et al. (2025) demonstrated this combination of events severely compressed the magnetosphere to a magnetopause stand-off distance between  $5.12 R_E$  and  $5.2 R_E$ , almost half the canonical position of  $10 R_E$  (e.g., Shue & Song, 2002), while Tulasi Ram et al. (2024) reports similarly severe magnetopause and bow shock contractions. Yamazaki et al. (2024) reports that the May 2024 storm was the third largest storm by Dst index since 1985, beaten only by storms in March 1989 and November 2003. Meanwhile, Elvidge (2025) and Elvidge & Themens (2025) estimate the May storm to be from a 1-in-10 to a 1-in-41 year event. These studies suggest that the May storm was rare in terms of the severe magnitude of impact on the Earth’s magnetosphere. In fact, Tulasi Ram et al. (2024) report that it was the unusual combination of strong solar wind

pressure and electric field that generated such a severe geomagnetic storm. Conversely, extrema in solar wind density may have reduced the dayside reconnection rate, slowing the effect of rapid sign changes in IMF  $B_Y$  (Ohtani et al., 2025).

A wealth of literature has been published on the ionosphere and thermosphere effects of the May storm, observed in various phenomena across the globe. The storm effected travelling ionospheric disturbances (Sun et al., 2024a), penetration electric fields (PEFs, Wan et al., 2025; Astafyeva et al., 2025; Rout et al., 2025), high energy proton fluxes (Xu et al., 2025), total electron content (TEC, Zhang et al., 2024; Spogli et al., 2024; Ang et al., 2025; Ambili et al., 2025; Huang et al., 2024), ionospheric currents (Xia et al., 2024; Rout et al., 2025), and ionospheric fountains (Vichare & Bagiya, 2024; Astafyeva et al., 2025; Carmo et al., 2024; Rout et al., 2025; Nayak et al., 2025). Ionospheric plasma density was depleted in multiple regions (Guo et al., 2024; Spogli et al., 2024), rapid recombination generating remarkable (in size and duration) polar ionospheric holes (a region of low electron density, Jin et al., 2025). In other regions, the storm enhanced ionospheric density (Aa et al., 2024; Singh et al., 2024) and shifted the height of the ionospheric density peak upwards (Themens et al., 2024). The storm also generated a sporadic-E layer (Themens et al., 2024), and affected the evolution of plasma blobs and equatorial plasma bubbles (Sun et al., 2024b; Carmo et al., 2024). Finally, strong correlations between the solar wind characteristics and ultra-low frequency wave activity were observed (Lazzús & Salfate, 2024). These authors have demonstrated the wide variety of storm effects across various latitudes and longitudes; the opportunity of this storm happening in an era with a wide variety and distribution of instrumentation allows for simultaneous results across different phenomena and regions.

In the thermosphere, an “all-time” high in thermosphere Nitric Oxide (NO) radiative cooling flux was observed (Ranjan et al., 2024), followed by rare post-storm thermospheric overcooling. Additionally, the May storm’s radiated power was the third largest observed by NASA’s TIMED satellite (launched 2001, Mlynczak et al., 2024). Changes to neutral wind direction and strengths were observed (Evans et al., 2024; Wang et al., 2025) along with morphological changes in the Equatorial Ionisation Anomaly over Africa and South America (Karan et al., 2024), along with an equatorial depletion in the O/N<sub>2</sub> ratio (Song et al., 2025). Finally, utilising a high-altitude balloon flight, Olifer et al. (2025) observed ultra-low frequency wave modulation of electron precipitation during the storm. Again, the May storm provided an interval to study the thermospheric storm effects across a wide range of locations.

The socio-historic nature of the storm is demonstrated by the public going outside en masse to view the aurorae at much lower latitudes than usual (Witze, 2024; Kataoka et al., 2025). Grandin et al. (2024) note that in the era of widespread mobile imaging and social media, around the world, people were alerted to go aurora-chasing, and indeed many saw and photographed the aurora (sometimes in areas where scientific instrumentation is sparse or absent). Grandin et al. (2024) invited such aurora-chasers to submit reports on what they saw and any technological outages. Their study highlighted that aurorae were seen between  $[30^\circ]$  and  $[60^\circ]$  (they studied both hemispheres), equatorward of model predictions. Spogli et al. (2024) also note the public interest in the storm, and mention the visibility of Stable Auroral Red (SAR) arcs at mid-latitudes.

The effects of the storm were reported across the world, with aurorae more equatorward than usual, observed in locations including: Namibia, Australia, Argentina, Gran Canaria, the UK, Japan, China, Jamaica, and Korea (e.g., Nanjo & Shiokawa, 2024; Kwak et al., 2024; Hayakawa et al., 2025; Kataoka et al., 2024, 2025; Menghan/China Daily<sup>2</sup>, Rannard/BBC<sup>3</sup>, NHK World Japan<sup>4</sup>).

Finally, effects on human-made technology were far-reaching. For example, O’Callaghan/Scientific American<sup>5</sup> reports that multiple farmers suffered issues with GPS during the May storm: One farmer’s tractor started driving in circles, while others experienced GPS outages. More quantitatively, Griffin et al. (2025) estimate that 1.7 billion USD was lost to the US corn industry due to the Global Navigation Satellite System (GNSS) outages caused by the May storm. A more well-known system to be affected, New Zealand’s grid operator Transpower released 12 “Grid Emergency Notices” between 11th and 13th May relating to the May storm (Transpower<sup>6</sup>). Additionally, Greshko (2024) reports that the Hubble Space Telescope descended 85 m per day from 11th to 13th May, twice its average daily rate. While Earth-orbiting spacecraft can be vulnerable to storm effects (e.g., Fang et al., 2022), the Arase satellite achieved continuous operation during the May storm, without adverse effects (Jun et al., 2025). An executive summary of the technological systems affected by the May storm is listed below:

- Radio communication (e.g., Witze, 2024; Elvidge, 2025).
- GPS communication (e.g., Witze, 2024; Elvidge, 2025; Younas et al., 2025).
- GNSS signals (e.g., Grandin et al., 2024).
- Electricity grids (e.g., Witze, 2024).
- Starlink-powered broadband/internet (e.g., Witze, 2024; Elvidge, 2025).
- Air travel (e.g., Elvidge, 2025).
- Drag on Earth-orbiting spacecraft (e.g., Parker & Linares, 2024; Greshko, 2024).
- Navigation for farm vehicles (GPS) (e.g., Griffin et al., 2025, O’Callaghan/Scientific American<sup>7</sup>, Moser/CBS News<sup>8</sup>).
- Electricity networks (e.g., Grandin et al., 2024, Transpower<sup>6</sup>, INews Reporters<sup>9</sup>).

<sup>2</sup> <https://www.chinadaily.com.cn/a/202405/15/WS664411d1a31082fc043c7279.html>, accessed on 22/04/2025.

<sup>3</sup> <https://www.bbc.com/news/articles/c163j8551ygo>, accessed on 16/04/2024.

<sup>4</sup> <https://www3.nhk.or.jp/nhkworld/en/news/backstories/3308/>, accessed on 22/04/2025.

<sup>5</sup> <https://www.scientificamerican.com/article/the-strongest-solar-storm-in-20-years-did-little-damage-but-worse-space/>, accessed on 16/04/2025.

<sup>6</sup> <https://www.transpower.co.nz/system-operator/notices-and-reporting/formal-notices>, accessed on 22/04/2025.

<sup>7</sup> <https://www.scientificamerican.com/article/the-strongest-solar-storm-in-20-years-did-little-damage-but-worse-space/>, accessed on 16/04/2025.

<sup>8</sup> <https://www.cbsnews.com/minnesota/news/solar-storms-cause-gps-outage-is-tractors-planting-season/>, accessed on 22/04/2025.

<sup>9</sup> <https://www.1news.co.nz/2024/05/12/solar-storm-transpower-extends-grid-emergency-declaration/>, accessed on 22/04/2025.

Detailed observations of these storm effects allow operators of these systems to bolster space weather preparedness for future events.

## 1.2 Observations in October 2024

At the time of writing, several studies have already been published about the October storm (although fewer than on the May storm so far). Like the May storm, the October storm still produced auroral sightings at lower latitudes than usual, including Ireland, New York, England, France and China (e.g., Xia et al., 2025, Burns/The Irish Times<sup>10</sup>). In the ionosphere, Pierrard et al. (2025) observed increases in ionisation in both the May and October storms and noted unusual effects on the secondary F2 density peak, suggesting rapid recombination. Paul et al. (2025) observed structural changes in the ionosphere, including dayside F-region uplifts in both hemispheres, storm-induced equatorial plasma bubbles, large-scale travelling ionospheric disturbances, and a poleward expansion of the equatorial ionisation anomaly. Additionally, Xia et al. (2025) observed interhemispheric effects in field-aligned currents during the May and October storms, relating to seasonal differences. Finally, from a technological standpoint, Oliveira et al. (2025) report that main phase of the October storm resulted in the orbital decay of a satellite from the Starlink constellation.

In this study, the two storms are compared and contrasted, and a “Sun-to-Mud” analysis is presented, tracking the solar sources right down to the ground impacts and specifically assessing regional effects on the island of Ireland. Analysis of this kind is important for regional space weather preparedness, but additionally, Ireland’s latitude position puts it near the auroral oval during the two storms. Therefore, leveraging Ireland’s network of ground instrumentation, the island is an ideal laboratory for sensing overhead electrodynamics.

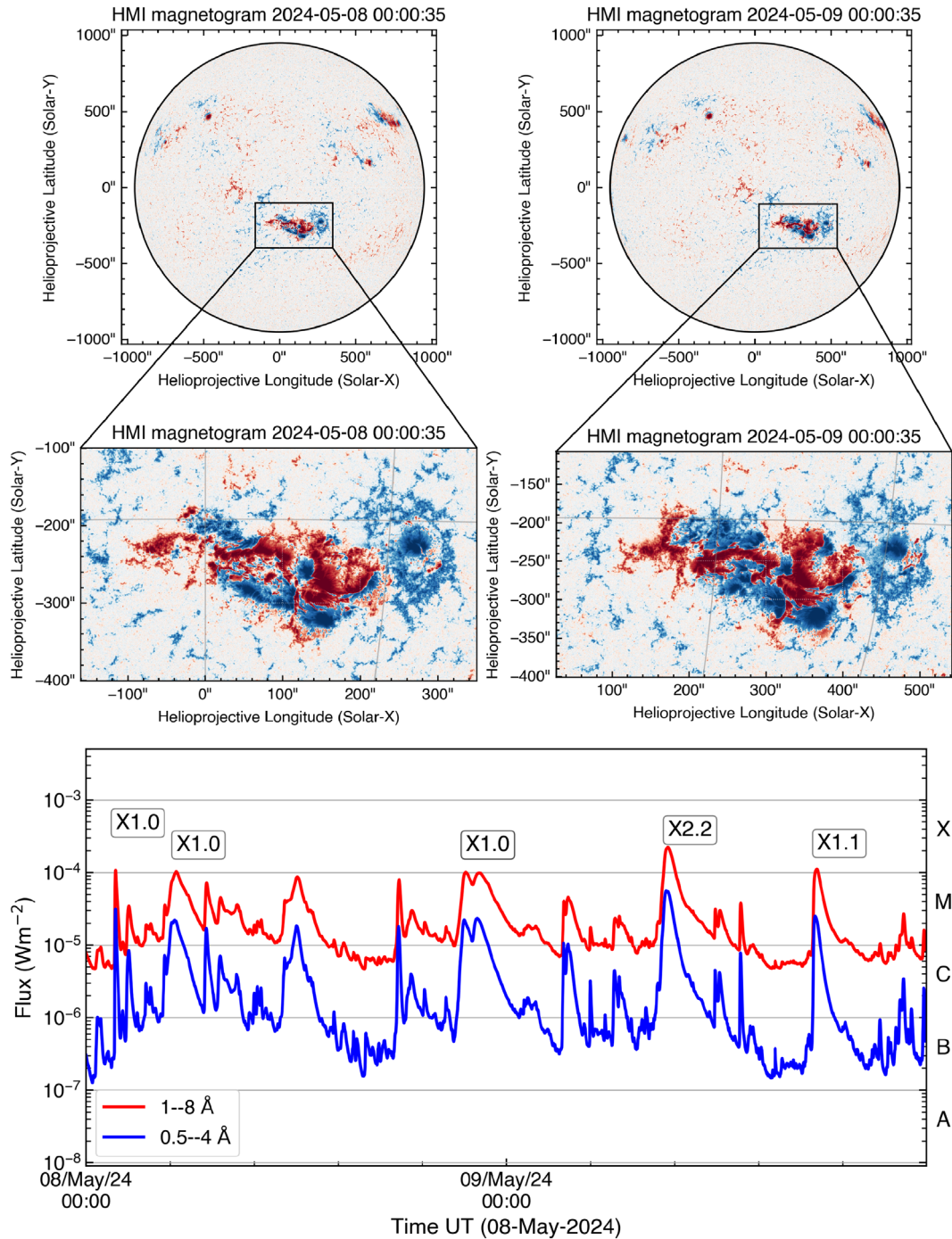
In Section 2, we discuss the solar sources of the two events, with an analysis of magnetograms, X-ray flux and coronagraphs. Subsequently, in Section 3, we examine observations of the solar eruptions from spacecraft at the Lagrange point (propagated to the Earth’s bow shock), followed by an analysis of the global geomagnetic response in Section 4. Locally in Ireland, ground magnetometer data are presented in Section 5.1, followed by modelling of the local geoelectric field and geomagnetically induced currents in Section 5.2. Finally, the social and historical impact of the storm is discussed with Irish auroral images in Section 5.3. This comprehensive “Sun-to-Mud” framework presents an in-depth, observational perspective on global to local space weather. Not only are the solar sources presented, but their effects are tracked through interplanetary space to a global space weather level and then more precisely locally in Ireland. These types of studies are important for local space weather preparedness: They indicate how phenomena observed in a global sense propagate down to local effects.

## 2 Solar sources

To understand the distinct geoeffectiveness of the May and October 2024 geomagnetic storms, we begin by characterising

<sup>10</sup> <https://www.irishtimes.com/ireland/2024/10/11/northern-lights-visible-across-ireland-on-thursday-night/>, accessed on 26/03/2025.





**Figure 1.** Top: SDO/HMI magnetogram of NOAA AR 13664 on 8 and 9 May 2024, with zoomed-in panels over the AR. Bottom: Time series of GOES X-ray flux (8–9 May 2024 inclusive) showing the sequence of flares from the same region. These flares were associated with multiple CMEs that drove the geomagnetic storm beginning on 10 May.

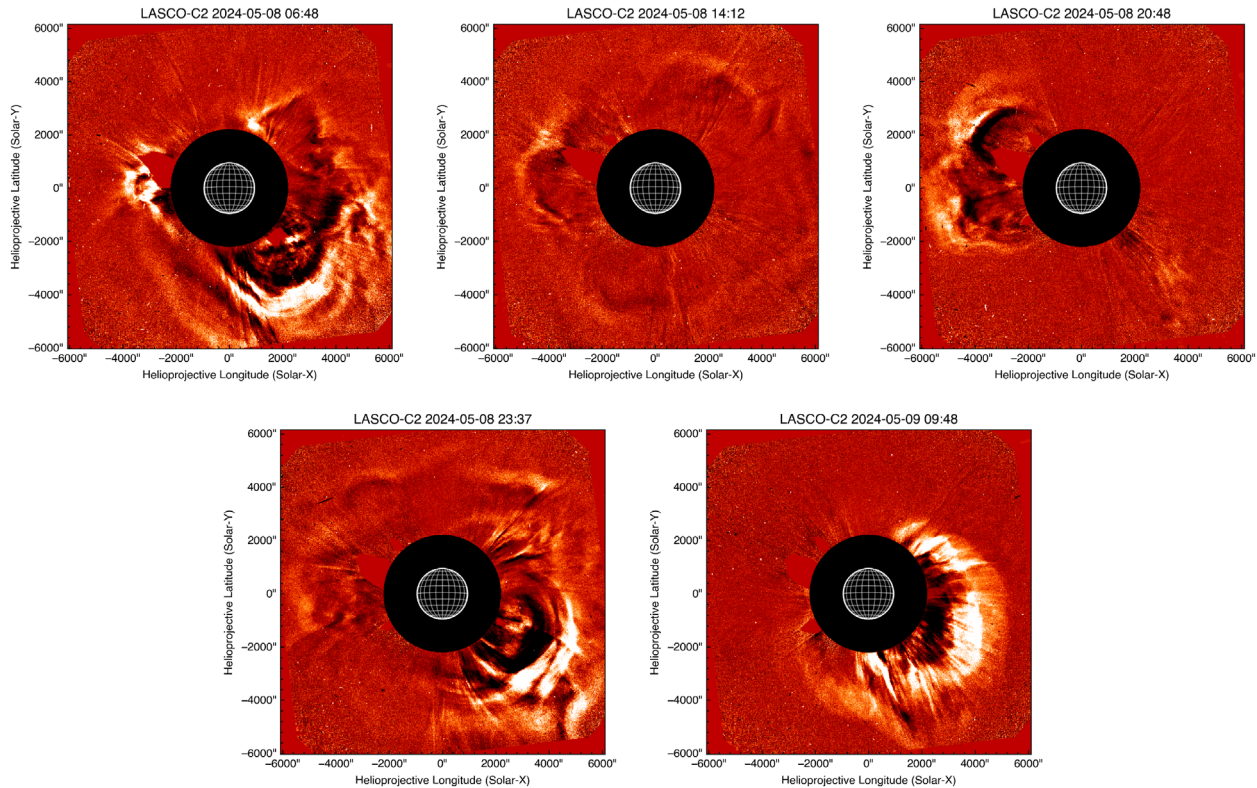
their solar source origins. To do this, we analyse the active regions involved, flaring activity, and associated CMEs that lead up to the storms observed at Earth.

## 2.1 Solar observations during the May 2024 storm

The May storm was associated with a sequence of solar eruptive events, consisting of solar flares and CMEs, originating

from NOAA active region (AR) 13664, located near the central solar disk at the time. Figure 1 (top row) shows a zoom in of the line-of-sight magnetograms from the Helioseismic and Magnetic Imager (HMI, Scherrer et al., 2012) on-board the Solar Dynamics Observatory (SDO, Pesnell et al., 2012). The AR exhibited a complex magnetic configuration and was classified as a  $\beta\gamma\delta$  Hale class (Hale et al., 1919) and Fkc McIntosh class (McIntosh, 1990), two classifications often associated with high





**Figure 2.** SOHO/LASCO C2 coronagraph observations showing five CMEs launched from the Sun between 8 and 9 May 2024, associated with activity in NOAA AR 13664. The rapid succession of eruptions, some within hours of each other, suggests the possibility of CME-CME interaction en route to Earth. These events collectively contributed to the geomagnetic storm that began on 10 May.

flaring potential (e.g., Toriumi & Wang, 2019). Between 8 and 9 May 2024, AR 13664 produced multiple M- and X-class solar flares. The bottom panel of Figure 1 shows the solar soft X-ray flux as measured by the X-ray Sensor (XRS) on board NOAA’s Geostationary Operational Environmental Satellites (GOES) spacecraft (e.g., Ludwig & Johnson, 1981).

These flares were associated with fast CMEs, some of which were launched within a relatively short time of one another. The temporal clustering of these events suggests a strong likelihood of CME-CME interaction during propagation through the solar system. Observations from the Large Angle and Spectroscopic Coronagraph (LASCO, Brueckner et al., 1995) on board Solar and Heliospheric Observatory (SOHO, Domingo et al., 1995) reveal a sequence of at least five CMEs erupting between 8 and 9 May 2024 (Fig. 2). The LASCO C2 coronagraph blocks the bright solar disk to observe the fainter corona from approximately 2 to 6 solar radii, enabling the detection of outward-propagating CMEs. Based on coronagraph observations and height-time fitting (height-time curves are presented next), CME arrivals at Earth were estimated to occur between 10 and 11 May, aligning with the onset of geomagnetic storm activity observed in terrestrial data, and discussed in later sections.

Finally, the possibility of CME-CME interaction is assessed. CME height-time propagation profiles in Figure 3 are presented for the five CMEs from Figure 2. CME height-time profiles are extracted from the SOHO LASCO CME Catalog<sup>11</sup>. While three

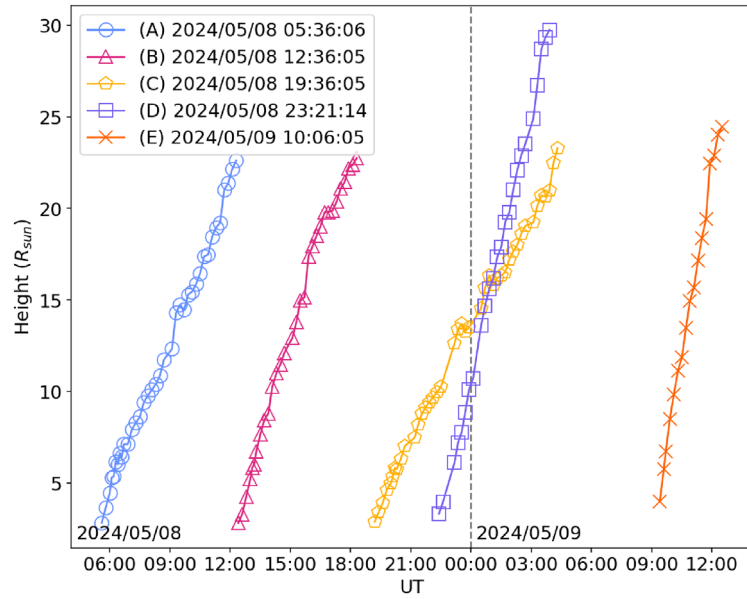
CMEs propagate through these distances without meeting (A, B, and E), the propagation paths for CMEs C and D overlap, suggesting CME-CME interaction. Adding weight to this conclusion, Khuntia et al. (2025) modelled and extrapolated CME propagation for the May storm, demonstrating many more crossover/interaction points and demonstrating arrival time at Earth in line with the start of related geomagnetic activity.

## 2.2 Solar observations during the October 2024 storm

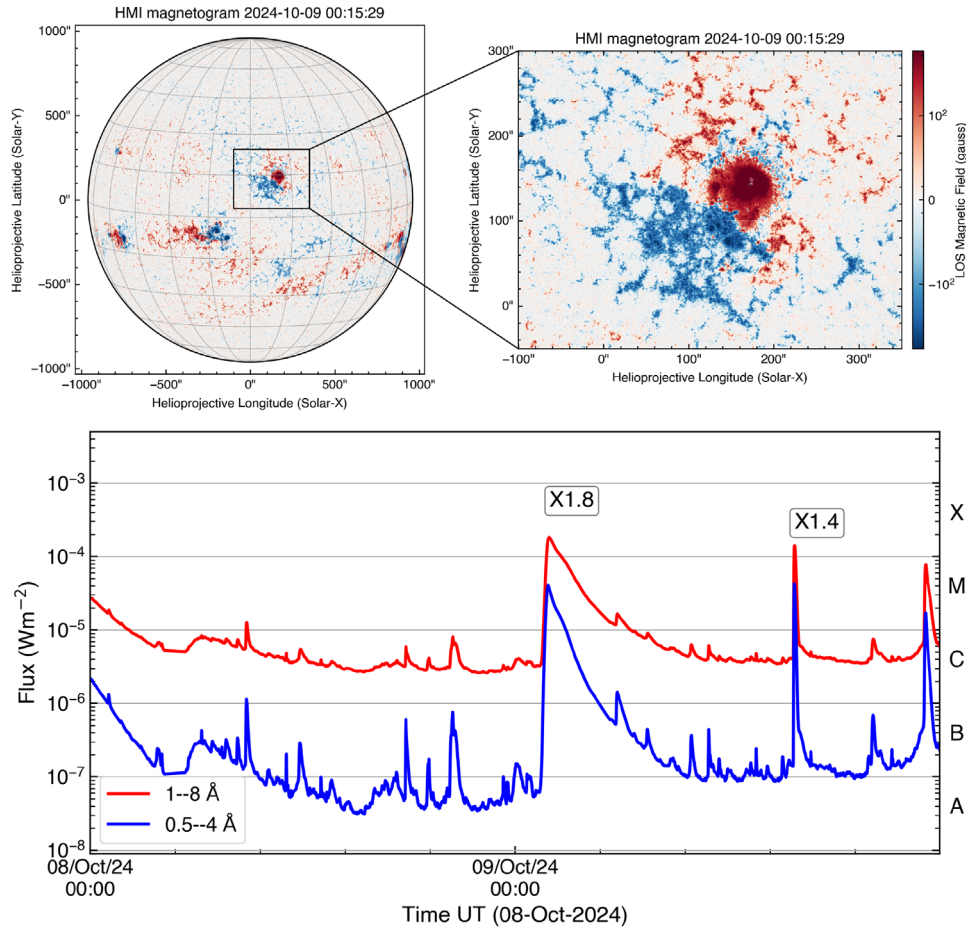
In contrast to the complex May event, the October storm was primarily driven by a single, isolated eruption. The flare associated with this storm originated from NOAA AR 13848, located near the disk centre at the time of eruption, as shown in the HMI magnetogram in the top panel of Figure 4. AR 13848 is also a  $\beta\gamma\delta$  Hale classification, but in contrast to the May AR, it has a simpler Dki McIntosh classification. This region produced an X1.8-class flare on 9 October 2024 (bottom panel of Fig. 4), which was the principal driver of the subsequent CME (see Fig. 5). A later X1-class flare occurred from another region, NOAA AR 13842, near the western limb; this is not associated with the CME that impacted Earth and generated the October storm. The GOES XRS lightcurve for the October event shows a sharp flare signature coinciding with the CME launch.

The LASCO C2 coronagraph data presented in Figure 5 capture the time evolution of the eruption over three panels. The CME had a relatively symmetric halo appearance, indicative of an Earth-directed CME. This CME propagated more

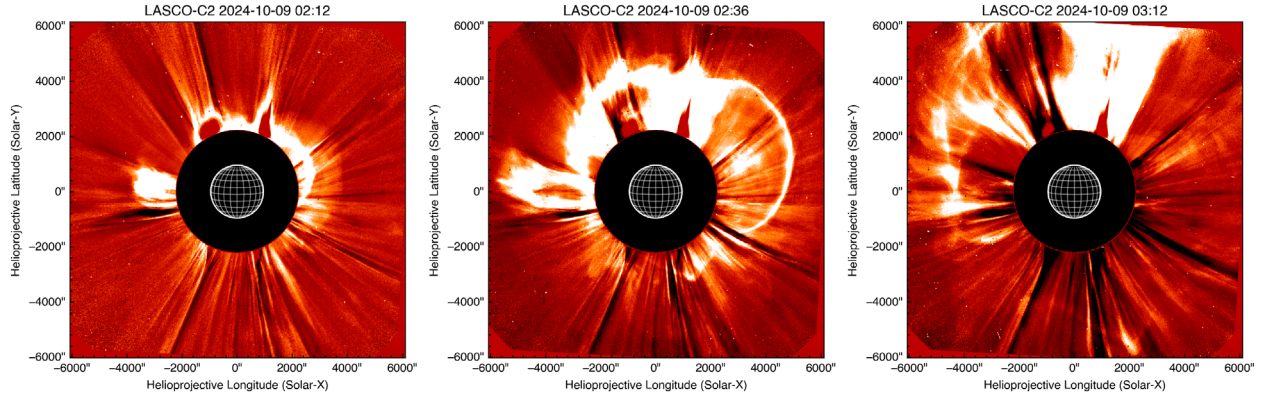
<sup>11</sup> [https://cdaw.gsfc.nasa.gov/CME\\_list/](https://cdaw.gsfc.nasa.gov/CME_list/), accessed on 16/07/2025.



**Figure 3.** CME height (in solar radii) as a function of time for the five CMEs presented in Figure 2. CMEs are named in the legend with a letter, and the time they were first observed: i.e., each coloured curve shows the propagation profile of an individual CME. A vertical, dashed grey line denotes the midnight boundary.



**Figure 4.** Top: SDO/HMI magnetogram of NOAA AR 13848 on 09 Oct 2024, with zoomed-in panel. Bottom: Time series of GOES X-ray flux of the X1.8 flare from AR 13848 that was associated with a fast CME. The X1.4 flare that occurred later came from AR 13842 near the western limb of the Sun.



**Figure 5.** SOHO/LASCO C2 coronagraph observations of the CME associated with the X1.8-class flare from NOAA AR 13848 on 9 October 2024. The three panels show the evolution of the same CME at different times following the eruption. This single, well-defined CME was the primary driver of the October geomagnetic storm observed at Earth on 11 October.

cleanly through interplanetary space than the May event, arriving at Earth on 11th October 2024. CME-CME interaction is not assessed in this case, as only one CME is observed in the coronagraphs in Figure 5. Therefore, the likelihood of CME-CME interaction is much lower, and hence the propagation is likely to be more straightforward.

### 3 Heliospheric observations

In this section, solar wind and interplanetary magnetic field (IMF) observations for both the May and October storms are presented. These data are retrieved from the OMNI database (King & Papitashvili, 2005; Papitashvili N, 2023). OMNI data come from spacecraft including Wind and ACE, and are propagated to the Earth's bow shock (Weimer et al., 2002, 2003; Weimer & King, 2008). IMF  $B_X$ ,  $B_Y$ , and  $B_Z$  are used to calculate the IMF total magnitude  $B_T = \sqrt{B_X^2 + B_Y^2 + B_Z^2}$  (all in Geocentric Solar Magnetospheric, GSM, coordinates). Similarly, the IMF clock angle is calculated from IMF  $B_Y$  and  $B_Z$ :  $\theta_{\text{clk}} = \tan^{-1} \left( \frac{B_Y}{B_Z} \right)$ . Finally, the Milan et al. (2012) dayside reconnection rate,  $\phi_D$ , is calculated as a “single value” descriptor of solar wind – magnetosphere coupling (e.g., Fogg et al., 2025).  $\phi_D$  is defined in equation (1) below (after equation (14) of Milan et al. (2012)):

$$\phi_D = \Lambda V_{\text{SW}}^{4/3} B_{YZ} \sin^{9/2} \left( \frac{1}{2} \theta_{\text{clk}} \right), \quad (1)$$

where  $V_{\text{SW}}$  is the solar wind flow speed in  $\text{m s}^{-1}$ ,  $B_{YZ} = \sqrt{B_Y^2 + B_Z^2}$  in T,  $\theta_{\text{clk}} = \tan^{-1} \left( \frac{B_Y}{B_Z} \right)$  and  $\Lambda = 3.3 \times 10^5 \text{ m}^{2/3} \text{ s}^{1/3}$  is a constant.  $\phi_D$  has units of voltage (although it is presented in kV hereafter).  $\phi_D$  (a measure of dayside reconnection rate) does not depend on solar wind density, and Milan et al. (2012) discuss in detail the reasoning for its dependencies (e.g., focus on solar wind velocity and clock angle with neglect of parameters such as solar wind density).

At first glance, Figures 6 and 7 show some broad similarities in the storms. Both storms show an IMF rotation characteristic of a CME in panels 6a and 7a, although during the May storm, IMF  $B_Z$  reaches a deeper negative value.

One key difference is some activity in the period preceding the solar wind and IMF signatures that trigger the October storm. It is important to note that the activity that primes the magnetosphere before the onset of an event has been shown to affect the magnitude of the resulting storm (e.g., Fogg et al., 2023a). A rotation in the IMF components is observed on the 7th and 8th October in panel 7a: A shift to positive for IMF  $B_Y$  and a shift to negative for IMF  $B_Z$ . This is accompanied by large spikes in solar wind density in panel 7-ci, which generate small-moderate increases in solar wind dynamic pressure (same panel). Only a small change is observed simultaneously in  $\phi_D$ , relating to the IMF and clock angle components.

Despite a more active period priming the magnetosphere before the October storm, the May storm is the strongest storm since 2003 (see Sect. 1): suggesting that the driving event for the May storm coupled with the magnetosphere effectively.

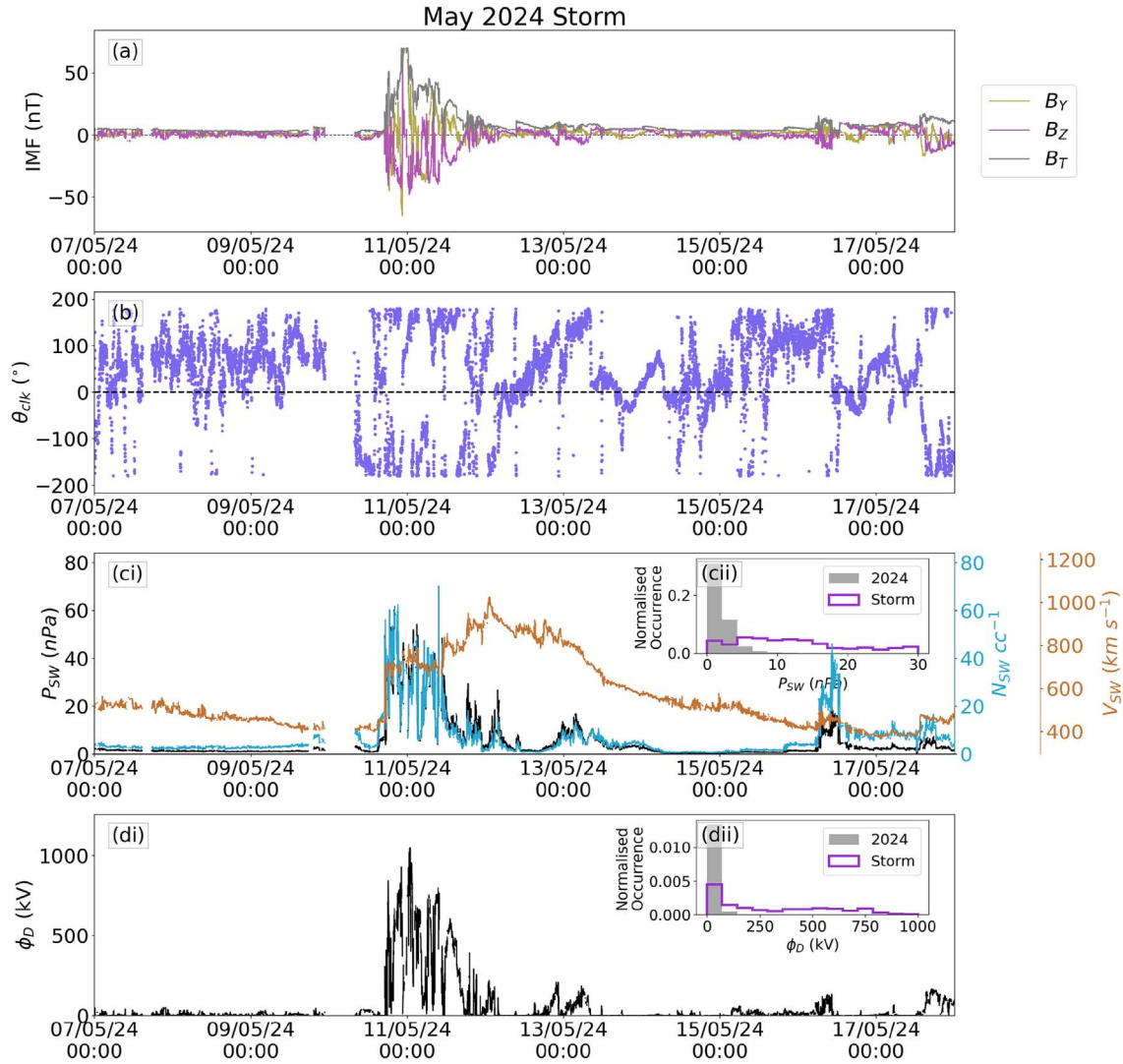
Examining panels 6-ci and 7-ci, the CMEs driving the May storm brought higher magnitude solar wind velocity ( $V_{\text{SW}}$ ), proton number density ( $N_{\text{SW}}$ ) and hence higher solar wind dynamic pressure ( $P_{\text{SW}}$ ). The inset Figures 6-cii and 7-cii show the  $P_{\text{SW}}$  distributions for the entirety of 2024 (grey bars) with 36 hours around the storm peak (purple step). For both events, the storm interval shows a much broader distribution, shifted to higher  $P_{\text{SW}}$  values than the rest of 2024. A similar analysis for  $\phi_D$  is presented in Figures 6-dii and 7-dii, showing broader distributions shifted to higher coupling values during storm time for both events.  $\phi_D$  is observed to spike during storm time for both events.

Interestingly, despite the comparative simplicity of the single CME event in October, it carries similar magnitude IMF characteristics. However, the solar wind characteristics in Figure 7-ci do not extend to the same extrema as in May (note the different y-scales). Both events exhibit a rapid increase in solar wind dynamic pressure, often termed a solar wind pressure pulse; pressure pulses have been shown to have dramatic effects on the internal electrodynamics of the magnetosphere (e.g., Coco et al., 2005, 2008, 2011).

### 4 Global geomagnetic response

Global measures of the Earth's geomagnetic response are presented in this section. SuperMAG auroral Electroject index





**Figure 6.** Time series of heliospheric conditions observed during the May storm, displaying observations from 0000 UT 7th–0000 UT 18th May 2024. (a) IMF  $B_T$  (grey),  $B_Z$  (magenta),  $B_Y$  (yellow) in GSM coordinates; (b) IMF clock angle; (c) solar wind  $P_{SW}$  (black),  $N_{SW}$  (blue) and  $V_{SW}$  (gold); (cii) histogram of all  $P_{SW}$  values from 2024 (grey) and only those from 12 UT 10th May–00 UT 12th May inclusive (purple, “storm”); (d) Milan et al. (2012)  $\phi_D$  coupling function; (dii) histogram of all  $\phi_D$  values from 2024 (grey) and only those from 12 UT 10th May – 00 UT 12th May inclusive (purple, “storm”).

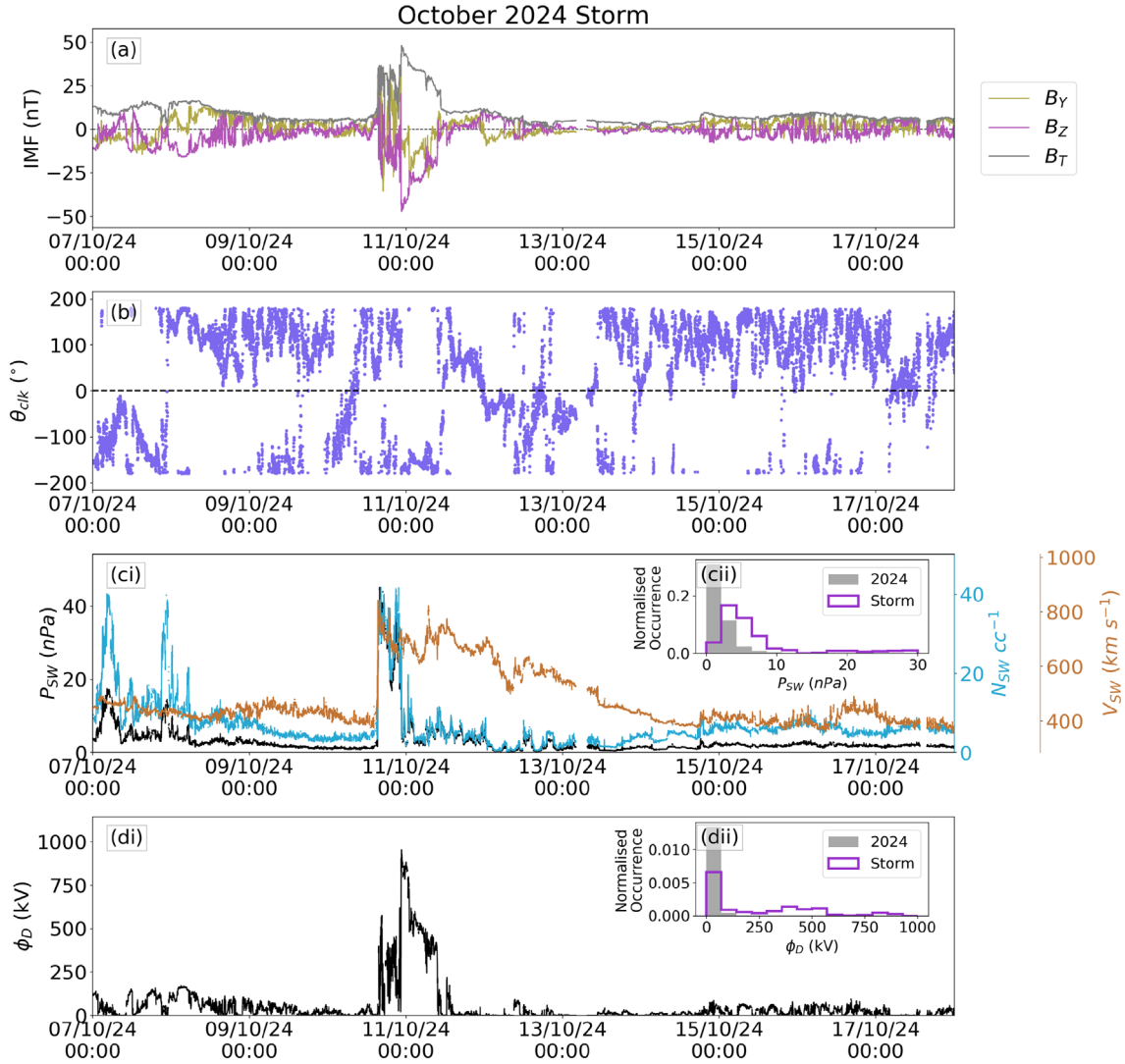
(SME), and its Upper (SMU) and Lower (SML) envelopes (Newell & Gjerloev, 2011) are retrieved at minute resolution. Analogous to the auroral indices AE, AU and AL (e.g., Bergin et al., 2020), these indices are determined from the horizontal component of magnetometers at auroral latitudes and indicate the level of activity in the auroral electrojets.

SuperMAG ring current index SMR (Newell & Gjerloev, 2012) is similarly calculated but using equatorial latitude observations. Minute resolution SMR is analogous to traditional ring current indices SYM-H (Iyemori, 1990) and Dst (e.g., Bergin et al., 2020), and shows characteristic storm signatures. Hourly resolution Dst is also presented here (retrieved from Papitashvili NE & King JH, 2020), along with an hour-ahead predictive Dst model (full details in Sect. 4.1).

Finally, the three-hour planetary K index Kp (Matzka et al., 2021) is presented, along with a new, 30-minute likeness Hp30 (Matzka et al., 2024; Yamazaki et al., 2024). Kp is determined

from the K index of 13 observatories, which themselves come from magnetometer observations of the horizontal component. Magnetometer observations are converted to K indices using a quasi-logarithmic scale look-up table, generating a number between 0 and 9. Hence, neither K nor Kp is a continuous variable; a given observation level is converted to a number from 0 to 9 (in steps of a third). Kp can suffer from saturation issues (e.g., Yamazaki et al., 2024), and so Hp30 is proposed as a new, higher-resolution alternative. Hp30 is determined by the level of disturbance at contributing geomagnetic observatories, and converted to integer values using a look-up table designed to scale similarly to Kp, but without an upper limit of 9.

Despite the differences in solar sources described in Section 2, the Earth’s response (i.e., geomagnetic storms) appears remarkably similar when comparing SMR/Dst in Figures 8b/8c and 9b/9c. Each storm begins with a sudden increase in SMR, indicating the propagation of pressure pulse



**Figure 7.** Time series of heliospheric conditions observed during the October storm, displaying observations from 0000 UT 7th – 0000 UT 18th October 2024. (a) IMF  $B_T$  (grey),  $B_Z$  (magenta),  $B_Y$  (yellow) in GSM coordinates; (b) IMF clock angle; (c) solar wind  $P_{SW}$  (black),  $N_{SW}$  (blue) and  $V_{SW}$  (gold); (cii) histogram of all  $P_{SW}$  values from 2024 (grey) and only those from 12 UT 10th October–00 UT 12th October inclusive (purple, “storm”) (di) Milan et al. (2012)  $\phi_D$  coupling function; (dii) histogram of all  $\phi_D$  values from 2024 (grey) and only those from 12 UT 10th October–00 UT 12th October inclusive (purple, “storm”).

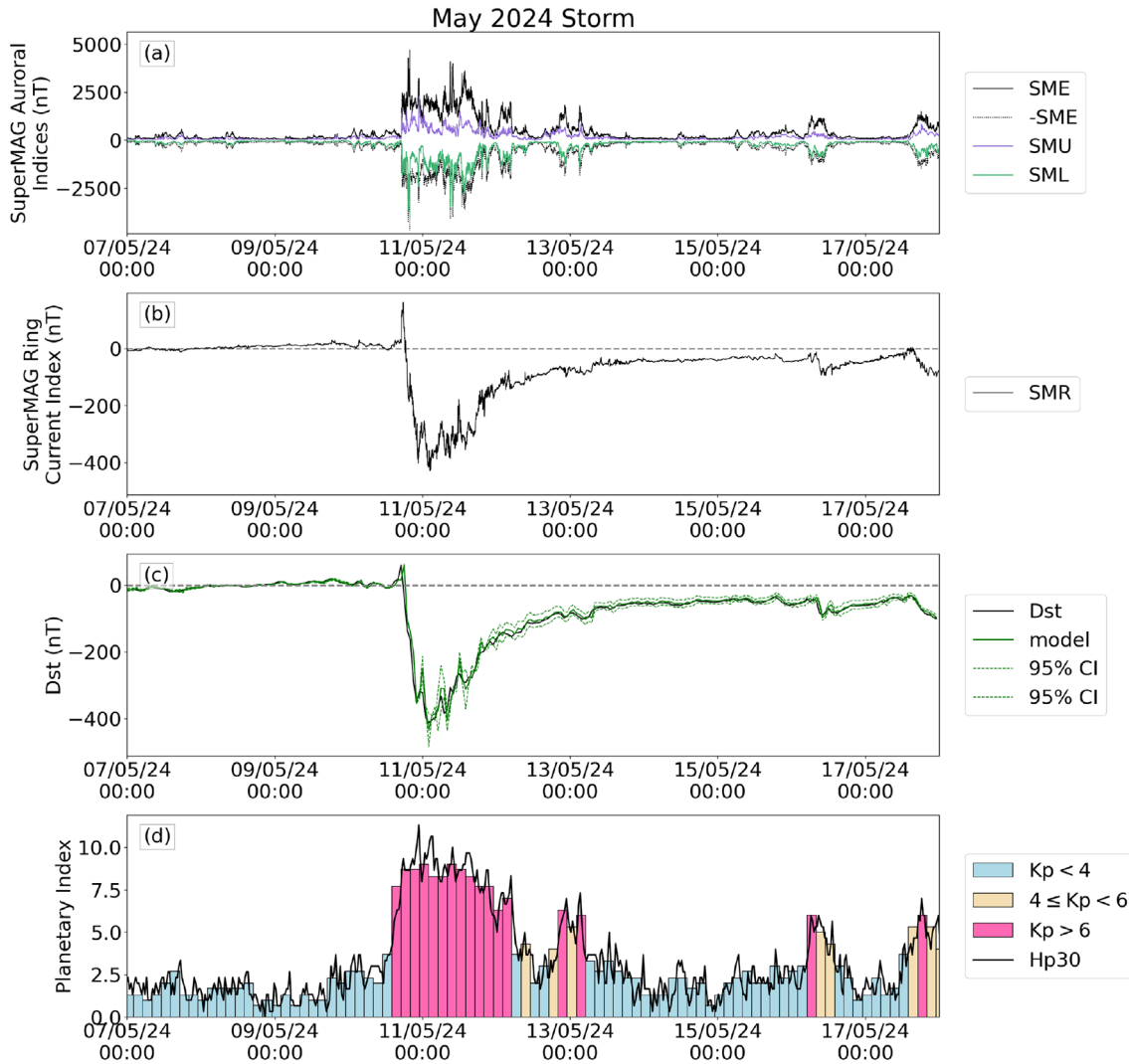
effects into the magnetosphere: a sudden commencement (SC, Araki, 1994). This is followed by a rapid decrease into storm time, making this SC a sudden *storm* commencement (SSC, Taylor et al., 1994). SSCs can have dramatic effects across the magnetosphere-ionosphere system (e.g., Hori et al., 2015; Fogg et al., 2023a, 2023c). The storms both have similar duration and reach similar negative peaks in SMR/Dst, although the May storm peaks slightly lower. While the May storm follows a quiet-time period with little activity in any of the indices in Figure 8, the October storm follows a small trough in SMR/Dst.

In the auroral zone (characterised by SME/U/L in Figs. 8a and 9a), again, the May storm is preceded by a quiet period, whereas the days leading up to the October storm contain multiple auroral signatures. The magnitude of these signatures is not insignificant: above 1,000 nT, suggesting strong auroral/substorm activity. Moving forward into the storm

periods for both events, the auroral indices indicate unusually strong activity in the auroral electrojets (both storms close to 5,000 nT SME!), suggesting enhanced energetic particle precipitation, and hence bright aurora.

Finally, Kp and Hp30 tell a similar story: the May storm reaches high intensities despite a quiet precursor period, whereas before the October storm, the magnetosphere/ionosphere system is primed by moderate-strong activity. This may suggest that while the May storm was driven by the complex interplay of multiple CMEs, the single CME driving the October storm impacted a magnetosphere that was primed by previous activity, which then can have impacts on storm magnitude (e.g., Fogg et al., 2023a).

An important point to emphasise here is that the time history of priming of the magnetosphere can play a significant role in the ultimate impact of any transient event. In this example



**Figure 8.** Time series of geomagnetic conditions observed during the May storm, displaying observations from 0000 UT 7th–0000 UT 18th May 2024. (a) SuperMAG Auroral Indices SME (black), SMU (purple) and SML (green); (b) SuperMAG Ring Current index SMR; (c) Dst (black), NARX-predicted Dst (green, solid) and 95% confidence interval (green, dashed); (d) planetary  $K$  index  $K_p$  (bars coloured according to magnitude, see legend) and  $H_p30$  (black line).

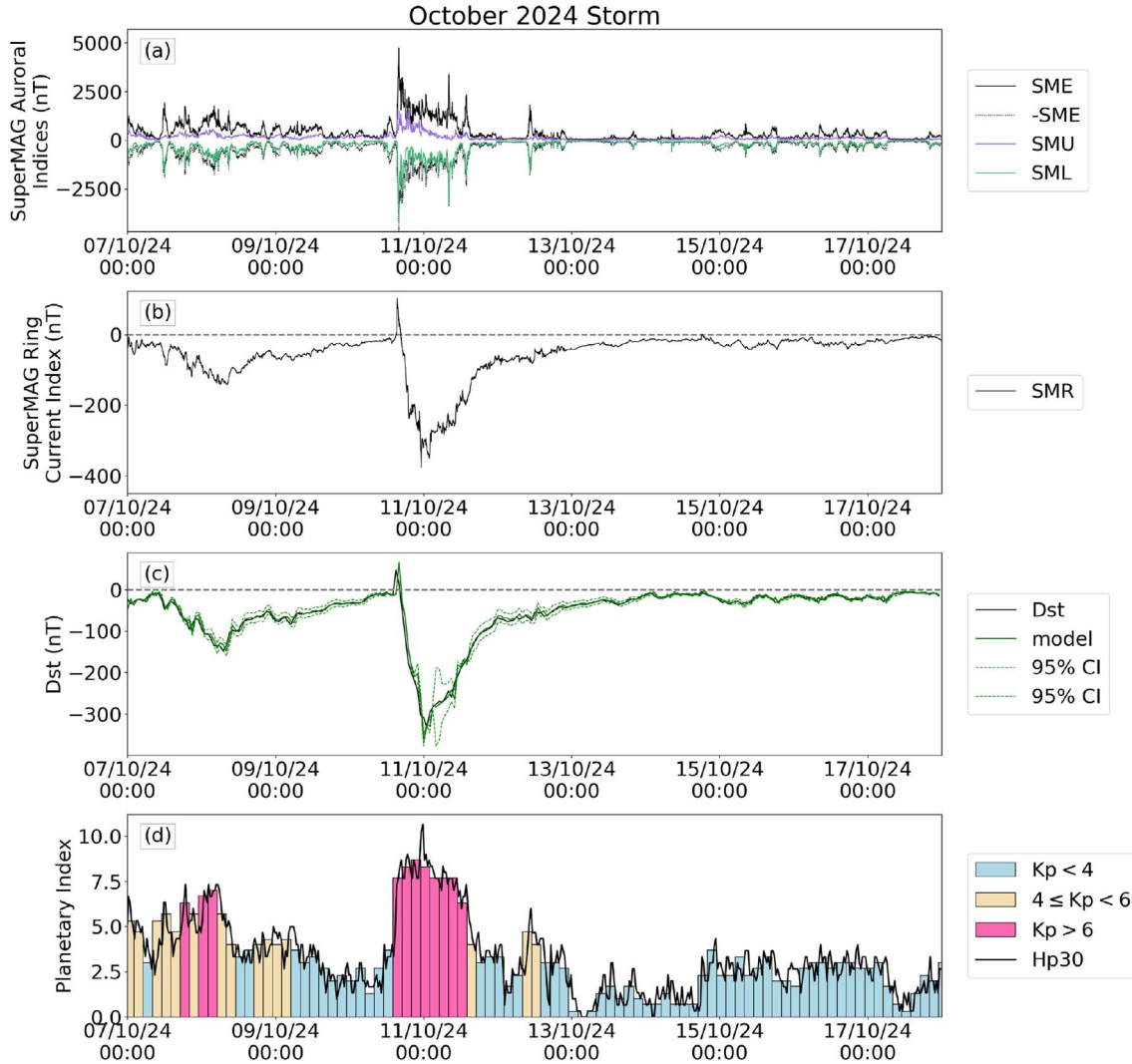
comparison, the precursor activity leading up to the October storm includes observations across the latitudes (i.e., SME to SMR and  $K_p$ ), indicating what would already be considered moderate-strong activity. With only a short period in between this and the arrival of the October CME, the magnetosphere was still recovering from enhanced electrodynamics. For example, SMR/Dst are still slightly negative at storm onset. Ultimately, this precursor activity means that the magnetosphere is more active than if there were no precursor activity. Another way to look at it may be that there is more energy in the magnetosphere following this precursor activity than without it. Hence, the magnetosphere is closer to an active state, and less energy, or a ‘less strong’ driving event, may be needed to trigger a geomagnetic storm (or other phenomenon) of a certain level. Therefore, despite the relative simplicity of the single CME event, which had lower  $P_{SW}$  than the multiple CME-CME event of May, the geomagnetic impact was able to reach a similar level.

#### 4.1 NARX predictive Dst model

Events such as the May and October storms provide an opportunity to test the extremes of our predictive capability, which is important for space weather preparedness. When predictive models are trained on large quantities of observational data, they may capture the bulk properties of the system, but struggle to characterise extremes in magnitude, gradient of change, and so on. Here we present a new approach to predicting the Dst index, and test its capability over the May and October storms, utilising these dramatic events as a sandbox for prediction techniques.

There are many different approaches to predict the Dst index, such as neural networks (and various teaching algorithms, e.g., Lazzús et al., 2019; Sierra-Porta et al., 2024), explicit models (e.g., Temerin & Li, 2002, 2006), and polynomial models (e.g., Billings, 2013; Boynton et al., 2018; Yatsenko et al., 2019). For example, Temerin & Li (2006) used a trial





**Figure 9.** Time series of geomagnetic conditions observed during the October storm, displaying observations from 0000 UT 7th to 0000 UT 18th October 2024. (a) SuperMAG Auroral Indices SME (black), SMU (purple) and SML (green); (b) SuperMAG Ring Current index SMR; (c) Dst (black), NARX-predicted Dst (green, solid) and 95% confidence interval (green, dashed); (d) planetary  $K$  index  $K_p$  (bars coloured according to magnitude, see legend) and  $H_p30$  (black line).

and error approach to find the parameters that best predicted Dst, by optimising the root mean square error. Boynton et al. (2011) note that Temerin & Li (2006) validated their model with a correlation coefficient and prediction efficiency, showing good predictive ability. In fact, Temerin & Li (2002) demonstrate a high correlation coefficient of 0.94, and 0.956 for Temerin & Li (2006). However, Boynton et al. (2011) note that trial and error cannot guarantee the best model, or that there is a relationship with the underlying physics. Furthermore, the model of Temerin & Li (2006) includes many parameters, which can be computationally expensive.

One of the most promising approaches to predicting the Dst index is to consider this indicator as a nonlinear dynamic system with input parameters from the solar wind and the output being the Dst index itself. To identify this system, it is proposed to use the physically interpretable NARX type (Nonlinear AutoRegressive eXogenous model), which is a part of the NARMAX model (Nonlinear AutoRegressive Moving Average

with eXogenous inputs) without noise (Billings, 2013; Boynton et al., 2018).

The NARX model can be formulated as

$$y(t) = F[y(t-1), y(t-2), \dots, y(t-n_y), u(t-d), u(t-d-1), \dots, u(t-d-n_u)] + e(t), \quad (2)$$

where  $y(t)$ ,  $u(t)$ , and  $e(t)$  are the system output, input, and independent noise sequences (i.e., the prediction error), respectively.  $n_y$  and  $n_u$  are the maximum lags for the system output and input,  $F[\cdot]$  is some nonlinear function, and  $d$  is a time delay typically set to  $d = 1$  hour. This model can also be presented with multiple inputs (Billings, 2013).

The main objective of system identification using NARX (NARMAX) is to find a nonlinear mapping, i.e., the functional form that describes the relationship between inputs (solar wind, etc) and outputs (Dst). The power-form polynomial model (Billings, 2013) is the most widely used mapping

representation; these polynomials are smooth functions (Billings, 2013). According to the Stone-Weierstrass theorem (e.g., Groenewegen & van Rooij, 2016), any continuous function defined on a closed interval can be uniformly approximated by a power-form polynomial.

OMNI hourly data (Weimer et al., 2002, 2003; King & Papitashvili, 2005; Weimer & King, 2008; Papitashvili NE & King JH, 2020) is retrieved for this predictive model. The solar wind velocity  $V$  multiplied by  $B_S$  is used as input to the model.  $B_T$  is the hourly average of the magnetic field magnitude with three components  $B_X$ ,  $B_Y$ , and  $B_Z$ .  $B_S$  is the southward component of the IMF (all GSM). The southward component  $B_S = -B_Z$  for  $B_Z < 0$ ; otherwise  $B_S = 0$ .  $V$  is the solar wind velocity in  $\text{km s}^{-1}$  (Yatsenko et al., 2019).

To identify the model in equation (2), we consistently add the previous values of the Dst index, input ( $VB_S$ ), and the degree of the polynomial equation (4) to find the best value of the multiple R-squared coefficient. To simplify the problem, the variables in equation (2) are renamed as follows:

$$\hat{y} = F[x_1, x_2, \dots, x_m, x_{m+1}, x_{m+2}, \dots, x_n] + e, \quad (3)$$

where  $\hat{y}$  is the model Dst index at time  $t$  (output). Note that  $\hat{y}$  is the “predicted” or “model” Dst, and  $y$  is the observed Dst. Hence  $x_1 = y(t-1)$  (i.e., Dst at  $t = t-1$ ),  $x_2 = y(t-2)$ ,  $\dots$ ,  $x_m = y(t-m)$ ,  $x_{m+1} = u(t-1)$ ,  $\dots$ ,  $x_n = u(t-n)$ , where  $u(t-1)$ ,  $\dots$ ,  $u(t-n)$  is the coupling function  $VB_S$  at time  $t-1$ ,  $\dots$ ,  $t-n$  (input). Finally, the prediction error  $e = y(t) - \hat{y}(t)$  (i.e., the difference between the predicted and observed Dst), where  $y(t)$  is the observed Dst index at time  $t$ .

The polynomial model describing Dst is described with free parameters in equation (4):

$$\begin{aligned} \hat{y} = & b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n \sum_{j=i}^n b_{ij} x_i x_j \\ & + \sum_{i=1}^n \sum_{j=i}^n \sum_{h=j}^n b_{ijh} x_i x_j x_h + \dots \end{aligned} \quad (4)$$

Using the parameters described in equation (3), a least-squares algorithm is used to determine the parameters of the model by minimising the difference between observed and predicted Dst.

Hence, the one-hour-ahead predictive model is found, and is presented in equation (5). This model was trained on OMNI hourly data (Papitashvili NE & King JH, 2020) from the first 4000 hours of 2020, and it was tested during the May and October geomagnetic storms in 2024.

$$\begin{aligned} \text{Dst}(t) = & 0.06277539 + 0.04821709 * \text{Dst}(t-5) \\ & - 0.00498567 * \text{Dst}(t-4) + 0.07599911 * \text{Dst}(t-3) \\ & - 0.47555687 * \text{Dst}(t-2) + 1.28897030 * \text{Dst}(t-1) - \\ & - 0.00033561 * VB_S(t-5) + 0.00019865 * VB_S(t-4) \\ & + 0.00025180 * VB_S(t-3) + 0.00105244 * VB_S(t-2) \\ & - 0.00285495 * VB_S(t-1) + 0.00003581 * (\text{Dst}(t-5))^2 \\ & + 0.00000001 * (VB_S(t-5))^2 \end{aligned} \quad (5)$$

The multiple R-squared coefficient ( $R^2 = 0.9429$ ) and the correlation coefficient ( $r = 0.9710$ ) with the 0.05 confidence level

and a probability of  $P = 95\%$  are statistically significant. The  $P = 95\%$  confidence interval is calculated using the regress function in the MATLAB system, as shown in Table A1 of Appendix A. Since the aim is to predict the Dst index, multicollinear terms are not considered (e.g., Siegel, 2012).

NARX predicted Dst values are presented in Figures 8c and 9c for the May and October storms, respectively. The NARX-Dst matches the observed Dst very well for both storms, with a tight confidence interval in both cases (excluding some regions in the peaks of the storms).

With this predictive model, we achieve a correlation coefficient of 0.9710 between our predictive model and the true, observed Dst. This demonstrates good agreement, indicating the quality of our model. Additionally, it shows that our NARX-based approach is able to perform well under a variety of conditions: it predicts both the quiet, pre-storm Dst and the dynamic storm-time Dst well. This capability can be hard to achieve with traditional empirical models. Referring to the NARX model parameters presented in Table A1, we observe that the coefficient on  $\text{Dst}(t-1)$  is higher than that for earlier Dst measurements. This suggests, perhaps unsurprisingly, that Dst at a given time is most similar to the most recent measurements. Finally, since we use  $VB_S$  to predict Dst, our results show that the ring current system that is measured by Dst is strongly controlled by upstream  $VB_S$ .

## 4.2 Comparison of storms

Peak, median, and median absolute deviation (MAD, a measure of variability, e.g., Fogg et al., 2023a) values for the entirety of 2024, and the May and October storms are presented in Table 1. More extreme values are coloured darker for illustrative purposes, normalised for each row individually. In general, the median values during the storms are greater than those for the whole year, demonstrating a generally active period. Often, the annual peak is observed during the May storm, although this is not true for  $V_{SW}$ ,  $N_{SW}$ , and SME.

## 5 Local geomagnetic response: Ireland

Utilising the Magnetic Network of Ireland<sup>12</sup> (previously the Magnetometer Network of Ireland), the local geomagnetic response in Ireland is examined in this section, exploiting magnetometers at Dunsink and Valentia (see yellow crosses in Fig. 14d).

### 5.1 Ground magnetometer data

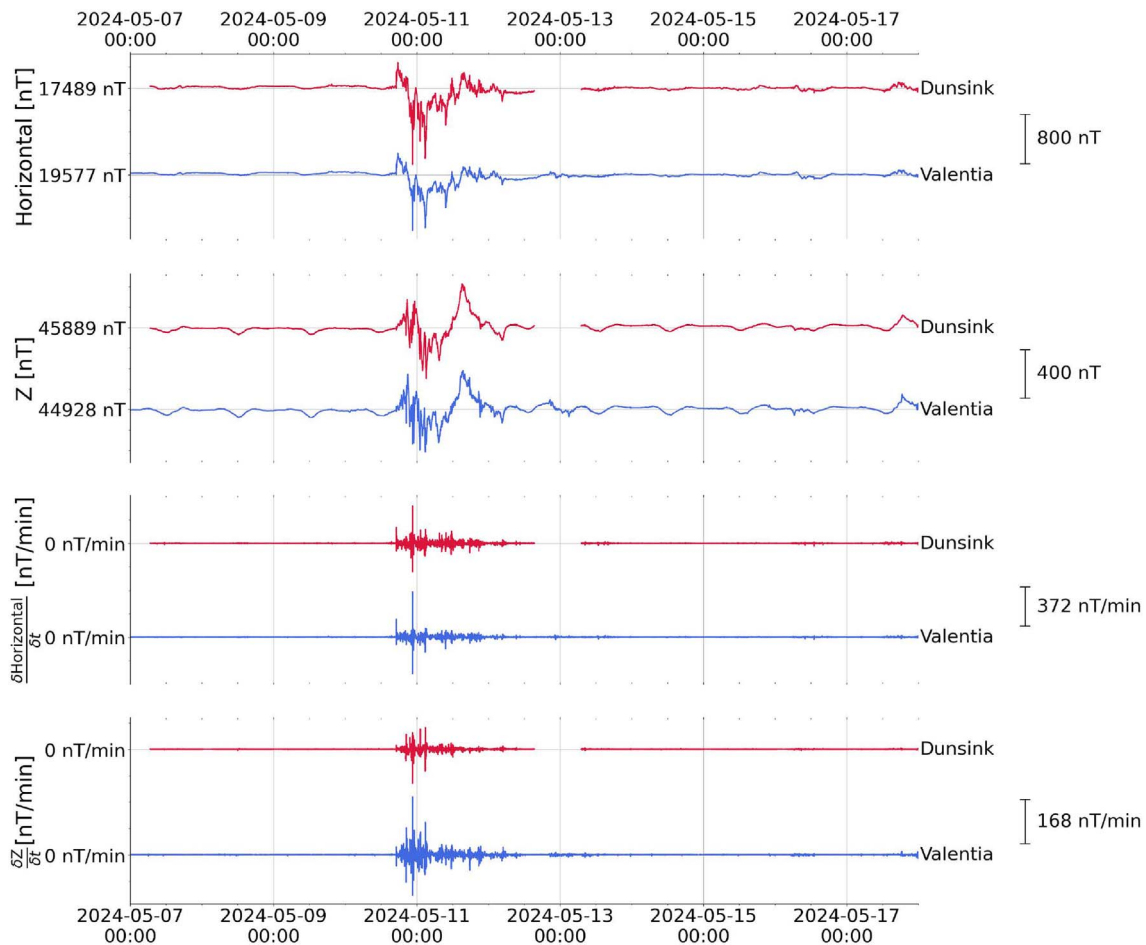
Figures 10 and 11 show the magnetic field measured at MagIE stations Dunsink and Valentia for the May and October events, respectively. From top to bottom, Figures 10 and 11 show: horizontal/H and down/Z components, followed by their time derivatives; red traces show observations at Dunsink, and blue at Valentia. A number of processing steps are applied to observations at Dunsink, which are detailed in Appendix B.

Examining Figures 10 and 11, there are some similarities between the storms. In both events, Irish magnetometers see a positive excursion (indicative of the CME compression-driven

<sup>12</sup> <https://www.magie.ie/data/>.

**Table 1.** Table of maximum, median, and median absolute deviation (MAD) values 2024, May storm (12 UT 10th May–00 UT 12th May inclusive) and October storm (12 UT 10th October–00 UT 12th October inclusive). Cells are coloured darker for more extreme values, normalised to the values in each row; these colours are purely illustrative, to highlight higher magnitude. The maximum is for positive values for all rows except  $B_Z$  and SML.

| Parameters                     | 2024 Max | 2024 Median | 2024 MAD | May Max | May Median | May MAD | Oct Max | Oct Median | Oct MAD |
|--------------------------------|----------|-------------|----------|---------|------------|---------|---------|------------|---------|
| $B_T$ (nT)                     | 70.1     | 6.14        | 1.7      | 70.1    | 23.43      | 13.85   | 47.96   | 20.44      | 10.41   |
| $B_Y$ (nT)                     | 69.9     | 0.35        | 3.22     | 69.9    | 1.18       | 7.07    | 36.67   | 1.93       | 5.05    |
| $B_Z$ (nT)                     | -47.85   | -0.01       | 2.43     | -47.85  | -8.38      | 11.32   | -47.04  | -4.74      | 9.43    |
| $P_{SW}$ (nPa)                 | 70.01    | 1.69        | 0.57     | 70.01   | 14.29      | 8.65    | 45.16   | 4.87       | 2.06    |
| $V_{SW}$ (km s <sup>-1</sup> ) | 1051.0   | 386.0       | 40.6     | 955.0   | 728.05     | 54.45   | 842.9   | 679.7      | 26.8    |
| $N_{SW}$ (cc <sup>-1</sup> )   | 72.08    | 5.89        | 2.29     | 70.07   | 13.02      | 8.02    | 41.81   | 5.28       | 1.74    |
| $\phi_D$ (kV)                  | 1049.01  | 8.37        | 8.15     | 1049.01 | 204.07     | 201.2   | 953.81  | 102.3      | 101.52  |
| SME (nT)                       | 4741.0   | 138.0       | 67.0     | 4692.0  | 1706.0     | 482.0   | 4741.0  | 1069.0     | 556.0   |
| SMU (nT)                       | 2280.0   | 64.0        | 30.0     | 2280.0  | 534.0      | 238.0   | 1665.0  | 217.0      | 148.0   |
| SML (nT)                       | -4058.0  | -67.0       | 39.0     | -4058.0 | -979.0     | 475.0   | -3927.0 | -661.0     | 414.0   |
| SMR (nT)                       | 161.6    | -4.1        | 8.5      | 161.6   | -267.2     | 87.7    | 102.1   | -186.8     | 87.1    |
| Kp                             | 9.0      | 1.7         | 0.7      | 9.0     | 8.3        | 0.5     | 9.0     | 8.3        | 0.5     |
| Hp30                           | 11.33    | 1.67        | 0.67     | 11.33   | 8.67       | 0.67    | 11.33   | 8.67       | 0.67    |

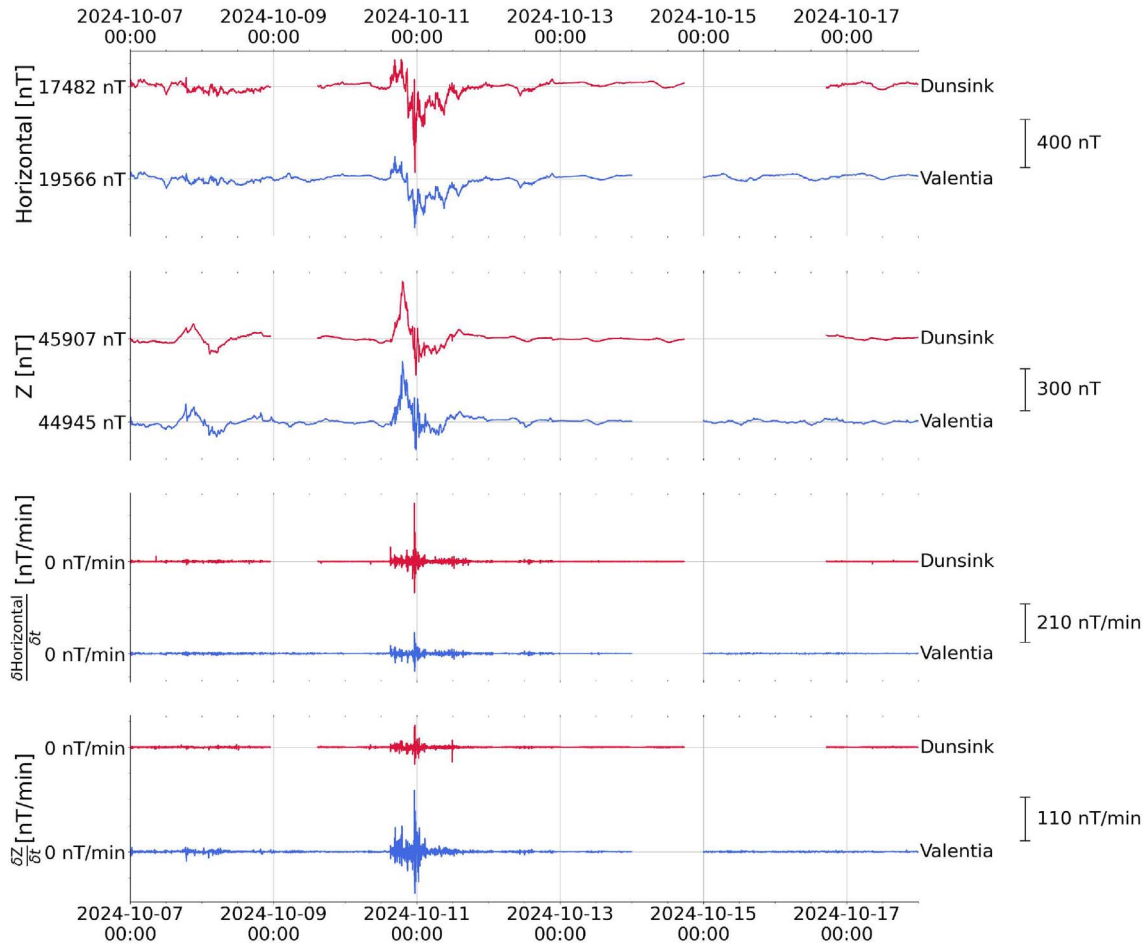


**Figure 10.** MagIE Magnetometer Stack Plot for the 5th to the 17th of May 2024 inclusive. The magnetic field components in red and blue are recorded by Dunsink and Valentia, respectively; top to bottom: horizontal/H, down/Z component, followed by the time derivative of H and Z. Ticks on the left show the Huber mean of each parameter for the plotted period and the scale of each panel is shown by whiskers on the right.

SC) followed by a negative excursion (indicative of storm time). However, as indicated by the scale of the y-axis in Figure 11 (top), the deviations in H as a result of the October storm are lower in magnitude. As with the geomagnetic indices, the October storm is preceded by some activity observed by both stations' observations of H and Z.

For  $\frac{\delta H}{\delta t}$ , the May storm appears to exhibit greater variability, indicated by the larger scales in Figure 10 (third, fourth). Again, the October storm is preceded by some variability in  $\frac{\delta H}{\delta t}$  and  $\frac{\delta Z}{\delta t}$  at both stations, indicating that the precursor activity reached Irish latitudes. It is important to note, however, that the magnitude of the precursor activity in the October storm is much lower than





**Figure 11.** MagIE Magnetometer Stack Plot for the 7th to the 17th of October 2024 inclusive. The magnetic field components in red and blue are recorded by Dunsink and Valentia, respectively; top to bottom: horizontal/H, down/Z component, followed by the time derivative of H and Z. Ticks on the left show the Huber mean of each parameter for the plotted period and the scale of each panel is shown by whiskers on the right.

the main event in MagIE, unlike similar magnitudes seen in geomagnetic indices between the precursor and storm activity (see Fig. 9). We propose that while there may be more open flux in the magnetosphere during the October storm than its precursor activity (according to the expanding and contracting polar cap paradigm, e.g., Cowley and Lockwood, 1992; Lockwood and Cowley, 1992; Milan et al., 2003, 2007), the precursor activity is not expanding the auroral oval as close to Irish latitudes as the main storm. Simply put, the polar cap expanded further down during the October storm than during its precursor activity; hence, greater activity is observed at Irish latitudes during storm time.

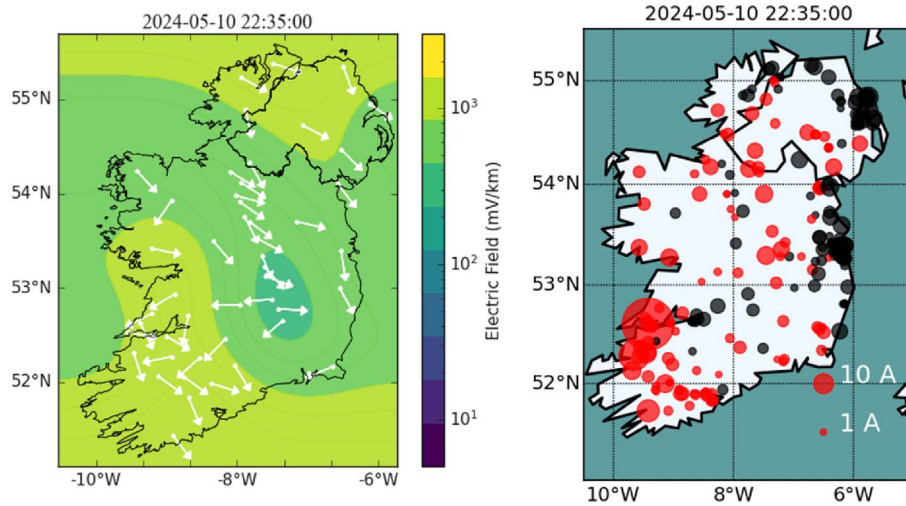
For both magnetometers during both storms, there is a strong westward electrojet after the sudden commencement at around premidnight in magnetic local time. This is indicated by a weakening of the horizontal field compared to the storm average. The radial field measured at Dunsink and Valentia during the two events indicates that for the majority of the storms the magnetometers are on the equatorward side of the main electrojet current (i.e., the auroral electrojet is poleward of the magnetometers). In the October storm, the electrojet weakens, roughly returning the observed magnetic field to the storm average by the 12th. Conversely, in the May storm, the

electrojet signature remains beyond the 12th but with a weaker current compared to the premidnight peak on the 11th.

## 5.2 Geoelectric and GIC maps

Building on work by Campanyà et al. (2019); Malone-Leigh et al. (2024); Malone-Leigh (2024), here we model the geoelectric field and geomagnetically induced currents (GICs) over the island of Ireland during the May and October storms. Using ground magnetometers from MagIE (Dunsink and Valentia) and INTERMAGNET (including Eskdalemuir, Lerwick, Hartland and Chambon-la-Forêt), the magnetic field is interpolated to create a map over Ireland. Three-dimensional transfer functions are used to convert this map to an electric field. Finally, electric fields are applied across a network map of power lines to estimate the GICs. GICs were modelled using an adapted version of Blake et al. (2018), which updated a thin-sheet one-dimensional geoelectric field model to three dimensions using the 3D Earth model of Campanyà et al. (2019), mapped in Figure 13. For full details, the reader is directed to Malone-Leigh et al. (2023, 2024); Malone-Leigh (2024).

Maps of the geoelectric field and its associated GICs during the peak of the May storm are presented in Figure 12 (left), and



**Figure 12.** (Left) Electric field model snapshot for 10th May 2024 at 22.35 UT (time of peak GIC during May storm) over the island of Ireland. Colour shows the estimated electric field, and arrows denote the direction of the electric field at each site. (Right) bubbles show the GIC strength at different locations: size indicates magnitude according to scale in bottom right, red (black) indicates positive (negative) current.

again for the October storm in Figure 13 (left). At the peak of the May storm,  $620 \text{ mV km}^{-1}$  was estimated, while  $420 \text{ mV km}^{-1}$  was estimated at the peak of the October storm. This was significantly higher than the estimated maximum of  $9 \text{ mV km}^{-1}$  for the November 1991 storm (Malone-Leigh et al., 2024). The south-west of Ireland is most affected (as is the case for most storms) due to the underlying resistive structure here relating to the main power generation facility at Moneypoint.

The sustained activity in both the May and October storms led to a moderately high GIC. For the May event, a snapshot of the GICs modelled in the power grid over the island of Ireland is presented in Figure 12 (right). Each circle on the map represents the amplitude of the GIC (see scale in bottom right), while red (black) denotes positive (negative) polarity. Generally, larger GICs are observed along the coastlines (e.g., Parkinson & Jones, 1979), and in this event the largest GIC of 69 A is estimated at the Moneypoint power station in the South-West of the island. For the October storm, a very similar GIC pattern is observed in Figure 13 (right) in terms of sites affected, with a maximum amplitude of 46 A estimated, again at the Moneypoint power station in the South-West of the island. GIC for these storms ranked as the 4th and 5th largest storms since the March 1989 storm (with a maximum of 120 A, Malone-Leigh, 2024).

The large GIC and electric field observations in the south-west of the island, and specifically at Moneypoint, are heavily influenced by the power generation facility. Moneypoint power station sits at the end of the longest high voltage power line in Ireland. Another important point to note is that between both GIC snapshots in Figures 12 (right) and 13 (right), there is only a small UT difference, and hence a small difference in magnetic local time (which could otherwise influence results).

Interestingly, these two storms result in the 4th and 5th largest peak GICs for Ireland since 1989, surpassed only by the November 1991, March 1989 and Halloween 2003 storms (Malone-Leigh et al., 2024). Finally, it is important to note that both of the peaks in GIC shown here may occur during substorms due to the local time of the observations.

### 5.3 Auroral observations

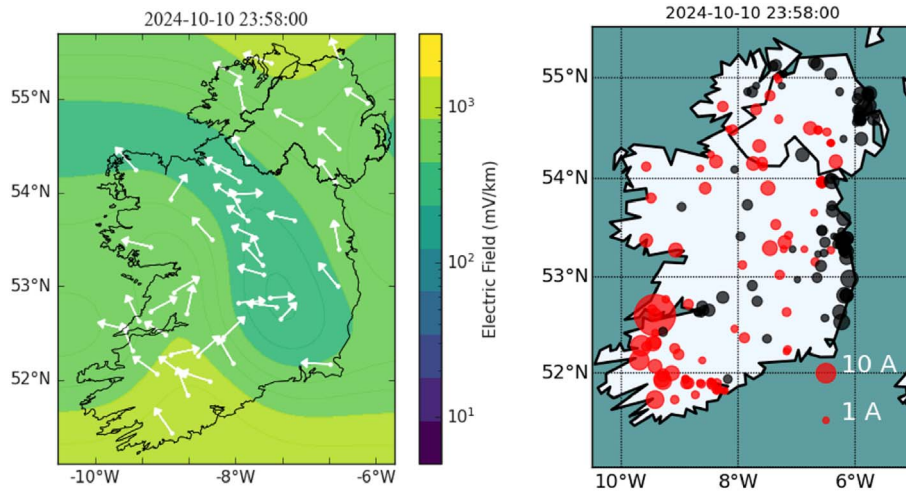
For completeness, some auroral observations from the island of Ireland are presented here to highlight the historic and social impact of the storm. Aurorae were reported across Ireland for both storms, even within urban areas (Burns/The Irish Times<sup>13</sup>, McGreevy/The Irish Times<sup>14</sup>). Figure 14 contains a summary of some images taken by S. R. Leahy in central Ireland over both storms. These photos were taken using non-specialist equipment (i.e., mobile phones), and are not photometrically calibrated. They are included here to illustrate the visible impact of the storm at mid-latitudes, specifically highlighting the obvious auroral displays observed from Ireland. Therefore, these images serve as qualitative illustrations rather than sources for quantitative analysis of auroral intensity or colour.

The approximate location of the observations is indicated with a purple star in Figure 14d, and their timing in a timeseries of SMR in Figure 14c for the May storm and Figure 14d for the October storm.

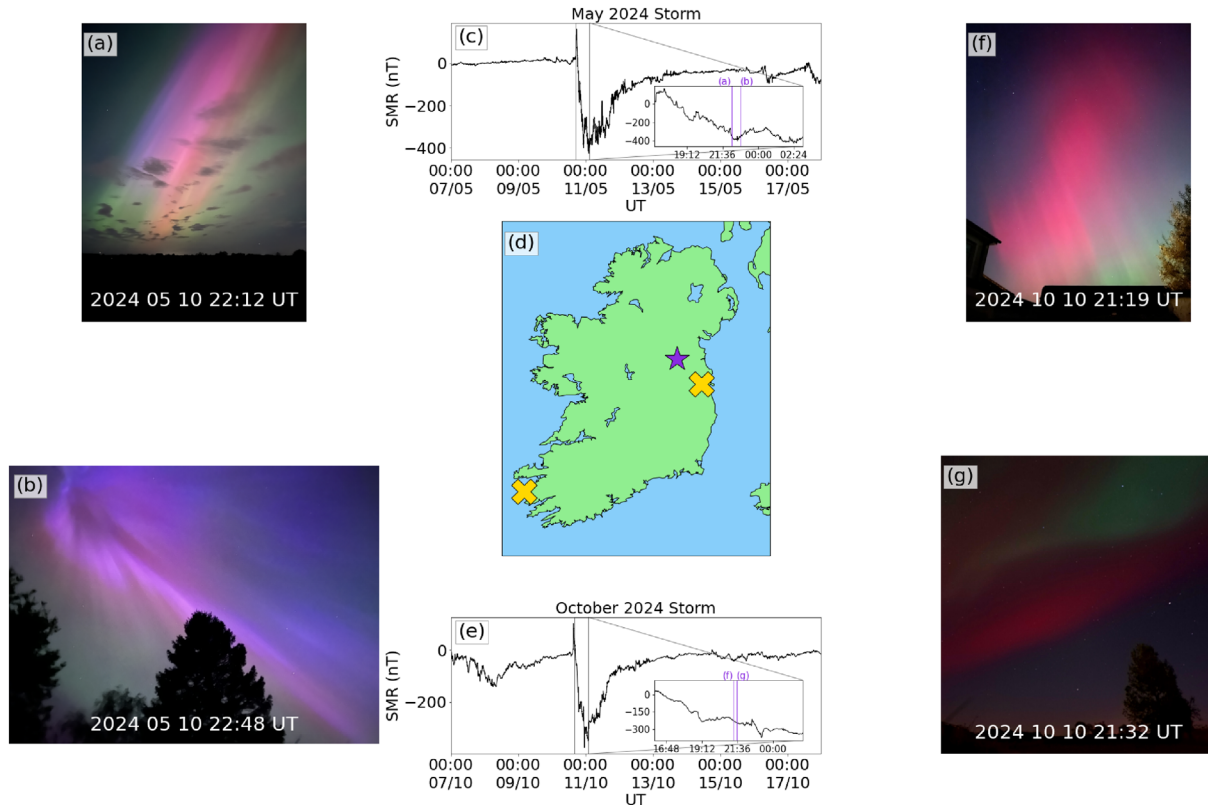
Figures 14a and 14b show two images from the May storm, taken within about half an hour. The structure of the aurora is quite different in the two photos. At 22:12 UT, shown in Figures 14a, curtain aurora (e.g., Herlingshaw et al., 2024) is observed, in green, pink and some purple. Curtain aurorae are a series of pillars, which are streaks following magnetic field lines; hence this image is looking more side-on than the subsequent image. In the later photo in panel 14b, the aurorae are pink-purple, and appear morphologically as a corona, like a crown overhead; this indicates the aurorae are directly overhead (e.g., Herlingshaw et al., 2024). Hence the polar cap must have expanded to much lower latitudes than normal.

<sup>13</sup> <https://www.irishtimes.com/ireland/2024/10/11/northern-lights-visible-across-ireland-on-thursday-night/>, accessed on 26/03/2025.

<sup>14</sup> <https://www.irishtimes.com/ireland/2024/05/10/northern-lights-expected-to-be-visible-across-ireland-tonight-amid-intense-solar-storm/>, accessed on 26/03/2025.



**Figure 13.** (Left) Electric field model snapshot for 10th October 2024 at 23.58 UT (time of peak GIC during October storm) over the island of Ireland. Colour shows the estimated electric field, and arrows denote the direction of the electric field at each site. (Right) bubbles show the GIC strength at different locations: size indicates magnitude according to scale in bottom right, red (black) indicates positive (negative) current.



**Figure 14.** Collection of images of the Aurora taken during both storms in Ireland. All photos were taken near Kells, Co. Meath, approximately indicated by the purple star on the map of Ireland in panel (d). The approximate locations of the MagIE magnetometers at Dunsink (north east) and Valentia (south west) in utilised [Section 5.1](#) are indicated with yellow crosses in panel (d). (a, b, f, g) show photos taken with an iPhone 13 by S. R. Leahy. (c, e) show time series of SMR for the May and October storms, respectively, with purple vertical lines on inset panels indicating the timings of each photo.

For the October storm, in [Figures 14f](#) and [14g](#), again within almost 15 min, the structure of the aurora has changed. Again in panel [14f](#), a curtain aurora is observed, suggesting a side-on view; the aurora has dominant pink, with some green

components. Thirteen minutes later, at 21.32 UT, the aurora presented in panel [14g](#) is much more dim, and contains red and green components which may resemble *arcs* (e.g., [Herlingshaw et al., 2024](#)).



## 6 Conclusions

In this manuscript, we have presented Sun-to-Mud observations of the solar sources and ground effects of the May and October storms of 2024, with a focus on the island of Ireland. Near the peak of solar cycle 2025, these storms occurred in an era of a broad range of space and ground-based observations, and indeed the era of widespread mobile imaging, meaning aurora-chasers and scientists alike are observing the space weather effects like never before.

We highlight some of the key differences between the two storms here:

- Multiple CMEs were ejected from the Sun in May, resulting in a high likelihood of CME-CME interaction during propagation. In October, only one halo CME propagated to the Earth, likely much more cleanly.
- The solar active region in May exhibited a more complex Fkc McIntosh class than the October region, which had a Dki McIntosh class.
- The May solar drivers were associated with stronger X-ray flares.
- In May, the CME arrival at the Earth was preceded by a more quiescent, calm IMF and solar wind than in October.
- The May geomagnetic storm activity was preceded by a quiet interval in both auroral and equatorial geomagnetic activity. Whereas in October, the storm was preceded by strong-moderate activity in all geomagnetic indices.
- Magnetometer stations in Ireland observed sudden storm commencements related to both storms, but the October storm was preceded by some moderate activity in line with global geomagnetic indices.
- Irish magnetometer observations indicate the auroral electrojets are poleward of Ireland.
- Both storms generate high geoelectric fields over Ireland; the south-west of the island is most susceptible due to a significant power generation facility in this region.
- Sustained activity led to moderately high GICs for both storms: The 4th and 5th largest since March 1989.
- Aurora was visible across Ireland in both storms, including observations in urban regions despite light pollution.

While the May geomagnetic storm was driven by multiple, dramatic solar eruptive events impacting a quiet magnetosphere, the single CME driving the October geomagnetic storm encountered a magnetosphere that was already primed by previous activity. Hence, we emphasise here that the time history of priming of the magnetosphere plays a very important role in the ultimate impact of transient solar wind / IMF phenomena.

This “Sun-to-Mud” study demonstrates how observations of the Sun, in interplanetary space, or global geomagnetic indices propagate down to local, ground effects for the island of Ireland. As society becomes increasingly dependent on technology, space weather resilience becomes more important, and local studies such as this aid space weather preparedness.

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## Data availability statement

CME propagation profiles were downloaded from the SOHO LASCO CME Catalog Version 2 ([https://cdaw.gsfc.nasa.gov/CME\\_list/](https://cdaw.gsfc.nasa.gov/CME_list/)) on 16th July 2025. This CME catalog is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA.

Solar wind, IMF, and geomagnetic index data were obtained via OMNIWeb at hourly Papitashvili NE & King JH (2020) and minute Papitashvili N (2023) resolution. We gratefully acknowledge use of NASA/GSFC’s Space Physics Data Facility’s OMNIWeb service, and OMNI data. The Dst index used in this paper was provided by the WDC for Geomagnetism, Kyoto (<http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>) via OMNIWeb. The Kp index was provided by GFZ Potsdam (<https://kp.gfz-potsdam.de/en/>) via OMNIWeb. SuperMAG indices SME, SMU, SML and SMR were obtained from <https://supermag.jhuapl.edu/indices/>. We gratefully acknowledge the SuperMAG collaborators (<https://supermag.jhuapl.edu/info/?page=acknowledgement>). We gratefully acknowledge the use of Hp30 data (Matzka et al., 2024).

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## Appendix A

### NARX Model fitted parameters and confidence interval

For completeness, the fitted model parameters and confidence intervals are presented here in [Table A1](#).

**Table A1.** The NARX model parameters  $b$  and the confidence interval  $\{b_-, b^+\}$  with a probability of  $P = 95\%$ .

| Term              | $b$         | $b_-$       | $b^+$       |
|-------------------|-------------|-------------|-------------|
| (Intercept)       | 0.06277539  | -0.07097901 | 0.14614361  |
| $Dst(t - 5)$      | 0.04821709  | 0.02168318  | 0.08457906  |
| $Dst(t - 4)$      | -0.00498567 | -0.06928210 | 0.03446675  |
| $Dst(t - 3)$      | 0.07599911  | 0.03875983  | 0.14738881  |
| $Dst(t - 2)$      | -0.47555687 | -0.54763898 | -0.44356382 |
| $Dst(t - 1)$      | 1.28897030  | 1.26695640  | 1.33049600  |
| $VB_s(t - 5)$     | -0.00033561 | -0.00058067 | -0.00008639 |
| $VB_s(t - 4)$     | 0.00019865  | -0.00007244 | 0.00033247  |
| $VB_s(t - 3)$     | 0.00025180  | 0.00010445  | 0.00050581  |
| $VB_s(t - 2)$     | 0.00105244  | 0.00047903  | 0.00087840  |
| $VB_s(t - 1)$     | -0.00285495 | -0.00257170 | -0.00223099 |
| $(DST(t - 5))^2$  | 0.00003581  | -0.00040117 | 0.00043135  |
| $(VB_s(t - 5))^2$ | 0.00000001  | -0.00000003 | 0.00000007  |

## Appendix B

### MagIE Data Processing

Here, the preprocessing steps applied to the Dunsink magnetometer data, including filtering to 1-minute are detailed (Valentia data are retrieved directly from INTERMAGNET):

1. A sliding window of size 300 data points is used to identify anomalous data points within each measured component.
  - (i) If the window has a standard deviation greater than 2 nT and the maximum deviation from the mean is greater than two times the standard deviation, it is checked for anomalies.
  - (ii) Each element within this window is then checked, assessing the of magnitude of deviation from the mean. If it deviates more than two times the standard deviation from the mean, then the window is moved to have its start on this element.
  - (iii) If in this second window the element either meets this “deviation from the mean” criteria again or has the largest deviation from the mean in the this window then it is removed from the dataset.
  - When criteria (i) are no longer met by the first window or an iteration is performed with an anomalous data point being checked but not removed by criteria (ii), the window slides one data point forward.
2. Finally, the INTERMAGNET 1-min centred Gaussian filter is applied on the 1-sec resolution magnetic field components ([St-Louis B & Intermagnet Executive Council and Intermagnet Operations Committee, 2024](#)).