

# A Canadian perspective on the May 2024 space weather event

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**Abstract**—The May 2024 space weather disturbance is the latest (as of the time of writing) in a series of space weather events going back to 1859 that have documented impacts on critical infrastructure and technologies. Impacts on these systems range from minor degradation (e.g., static or noise in a communication link) to major, which was demonstrated by a complete blackout of the Hydro-Québec power system on 13 March 1989. This event heightened international awareness of space weather and motivated efforts toward enhanced resilience. This paper presents the May 2024 space weather event from a unique Canadian perspective, demonstrating the Canadian Space Weather Forecast Centre (CSWFC) approach to monitoring, forecasting, and alerting to characterize space weather phenomena and mitigate their impacts. Satellite data, numerical modelling of solar wind disturbances, and ground-based magnetometer and riometer data from instruments located in Canada demonstrate the progression of the event. In response to observations of enhanced solar activity, the CSWFC issued a major geomagnetic storm WATCH spanning an almost 3-day period, a major geomagnetic storm WARNING for more than 1 day that began at auroral latitudes but quickly expanded to cover all of Canada, and a solar proton WARNING for more than 2 days. Impacts to high-frequency communications and Global Navigation Satellite System positioning, navigation, and timing over Canada are evaluated using Transport Canada's Civil Aviation Daily Occurrence Reporting System entries and reported outages of the Wide Area Augmentation System. This paper compares the May 2024 event with the March 1989 event and evaluates the latitude and magnetic local time distribution of the geomagnetic perturbations. In general, geomagnetic activity increased from southeastern to north-western North America.

**Keywords:** Space weather / Hazards / Solar activity / Geomagnetism / Ionosphere

## 1 Introduction

Space weather hazards affect a wide range of technology and critical infrastructure. Due to its distinct high-latitude location and proximity to the North Magnetic Pole, Canada is particularly susceptible to these effects, as they are more concentrated within the polar and auroral regions. The auroral region stretches across Canada's high and central latitudes, from the east to the west coast and moves to lower latitudes during intense space weather events. Due to this enhanced exposure, Canada is also in an excellent position to observe space weather. The Canadian Space Weather Forecast Centre (CSWFC) (Canadian Hazards Information Service, Natural Resources Canada) researches and forecasts space weather and its impacts on technology. The CSWFC is a Regional Warning Centre of the International Space Environment Service, and in a consortium with Australia, France, and Japan, provides space weather services to the International Civil Aviation Organization (ICAO).

Solar Cycle 25 has proven to be one of the most interesting solar cycles in more than two decades, producing some of the largest solar, geomagnetic, and ionospheric activity seen since the space weather event that caused the famous March 1989 Hydro-Québec blackout (e.g., Allen et al., 1989; Yeh et al., 1992; Boteler, 2019) and the October/November 2003 “Halloween Storm” (e.g., Barbieri & Mahmot, 2004). Comparison of the current solar cycle with past events could provide insight into the potential effects of space weather on critical infrastructure and technology as Solar Cycle 25 progresses (e.g., Eastwood et al., 2017; Hapgood et al., 2021).

According to the Solar Cycle 25 Prediction Panel, Solar Cycle 25 is predicted to peak with a maximum monthly average solar 10.7 cm flux (F10.7) of 115 ( $\pm 10$ ) sfu in July 2025 ( $\pm 8$  months)<sup>1</sup>. With a maximum average monthly F10.7 of 245.6 sfu in August 2024 (as of the time of publication), Solar Cycle 25 exceeds predictions and is already larger than

<sup>1</sup> <https://www.swpc.noaa.gov/news/solar-cycle-25-forecast-update> (last accessed 06 August 2025).

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Solar Cycle 24, which peaked at 170.13 sfu in February 2014. For comparison, the monthly mean sunspot number reached a peak of 216.0 in August 2024 during Solar Cycle 25, and the Solar Cycle 24 peak monthly mean sunspot number was 146.1 in February 2014<sup>2</sup>.

Solar activity, as gauged by the number and size of solar X-ray flares, was intense in 2024. Based on the events reported by the Bureau of Meteorology's Australian Space Weather Forecasting Centre<sup>3</sup>, 51 X-class solar X-ray flares were observed from the Earth-facing side of the sun in 2024. Over the last 44 years (~4 solar cycles) similar or greater yearly levels have only been reached in 1982 (42 events), 1989 (59 events), and 1991 (54 events). Solar flares are often accompanied by Coronal Mass Ejections (CMEs), which drive geomagnetic disturbances. While CMEs are not always easy to identify, due to observational gaps or CME properties (faint, narrow), most X-class solar flares have associated CMEs. For example, a statistical study of solar events from 1996 to 2001 by Yashiro et al. (2005) shows that 91% of X-class solar flares had associated CMEs.

Geomagnetic disturbances caused by CMEs can have adverse effects on critical infrastructure. In 1982, disturbances on 13–14 July caused 4 transformers and 15 power lines to trip in Sweden (Elovaara et al., 1992) and railway signals to be turned to red by the induced voltage (Wallerius, 1982). During 1991, protective relay misoperations occurred in North American power systems on 22–24 March, 28 April, 16 May, 04–05 June, 10 June, and 28–29 October (Bozoki et al., 1996). During 08–09 November 1981, strong geomagnetically induced potentials were measured in Sweden's gas pipeline system (Lundstedt, 2006).

Solar activity in March 1989 caused the largest magnetic storm during the space age with major socioeconomic impacts. Between 06 and 19 March 1989, a complex sunspot group NOAA (National Oceanic and Atmospheric Administration) active region (AR) 5395 produced 11 X-class and a number of M-class solar flares. During 13–14 March 1989, strong geomagnetic disturbances caused widespread effects across North American power systems, ranging from minor voltage fluctuations to tripping out of lines and capacitors, with the largest impact being a nine-hour blackout of the 21,000 MW Hydro-Québec power system that affected 6 million people (Hruska et al., 1990; Boteler, 2019). While other Canadian power utilities did not experience blackouts, they observed high levels of geomagnetically induced currents (GIC).

Space weather activity during May 2024 stands out due to the prolonged duration of strong geomagnetic and ionospheric activity observed. In early May 2024, a large active region (AR 3664) became visible at central solar latitudes (~20° south). The active region persisted for >1 solar rotation, reaching a peak area of 3400 millionths of the Sun's visible hemisphere, placing its size just above that of the Carrington event's sunspot group<sup>4</sup>. During 08–09 May 2024, a series of at least 5 CMEs erupted from AR 3664 (located near the central solar disk) with

an Earth-directed trajectory. The CMEs began to reach the L1 point at 16:37 UT on 10 May 2024 (Weiler et al., 2025) denoted by a sharp jump of >200 km/s in the solar wind speed and a change in the IMF  $B_z$  to negative values. The IMF  $B_z$  remained negative for ~24 h with prolonged periods of <−40 nT. The first shock front reached the Earth roughly 30 min later at 17:05 UT, compressing the magnetopause to 5.04  $R_E$  (Hayakawa et al., 2025). Geomagnetic activity became severely disturbed with  $K_p \geq 8$  for 24 consecutive hours, causing space weather centres, including the CSWFC, to issue space weather alerts. The geomagnetic storm was preceded, accompanied, and followed by several moderate solar proton events. The event spurred enormous public interest, with the media reporting aurora observed on 10–11 May as far equatorward as Puerto Rico<sup>5</sup> (~18°N geographic latitude, last reported in 1859 and 1921) in the northern hemisphere and New Zealand<sup>6</sup> (~41°S geographic latitude) in the southern hemisphere. Based on a citizen science approach, Hayakawa et al. (2025) report naked-eye observations of the aurora to an even larger extent, reaching 22°N geographic latitude in the northern hemisphere and 17°S geographic latitude in the southern hemisphere.

This paper presents the May 2024 event from a Canadian perspective to demonstrate the CSWFC's approach to monitoring, forecasting, and alerting to characterize space weather phenomena and mitigate their impacts. Section 2 describes the data sets contributing to this work. A description of solar activity and observations at and near the Earth is provided in Section 3. Section 4 details actions taken by the CSWFC in response to the event. Section 5 presents impacts on Canadian infrastructure. Discussions in Section 6 offer insight into the similarities and differences between the May 2024 and March 1989 space weather events and present an extreme value analysis of the geomagnetic data. A summary and conclusions are provided in Section 7.

## 2 Data

### 2.1 Ground-based observatory networks

Canada provides an ideal landscape for space weather observations due to its large geographic extent, which stretches across ~90° of geographic longitude and >40° of geographic latitude. Natural Resources Canada (NRCan) operates a network of geomagnetic and ionospheric stations across Canada<sup>7</sup> (Lam, 2011; Fiori et al., 2023a) with stations located within the (1) polar cap, where magnetic field lines are “open” to the penetration of solar protons and polar cap patches are observed, (2) auroral zone, where penetrating electrons cause both the aurora and severe ionospheric disturbances, and (3) sub-auroral regions. The sub-auroral region is generally the most benign, but during large geomagnetic disturbances, the auroral zone expands, bringing geomagnetic and ionospheric disturbances to southern Canada.

<sup>2</sup> <https://doi.org/10.24414/qnza-ac80> (last accessed 05 August 2025).

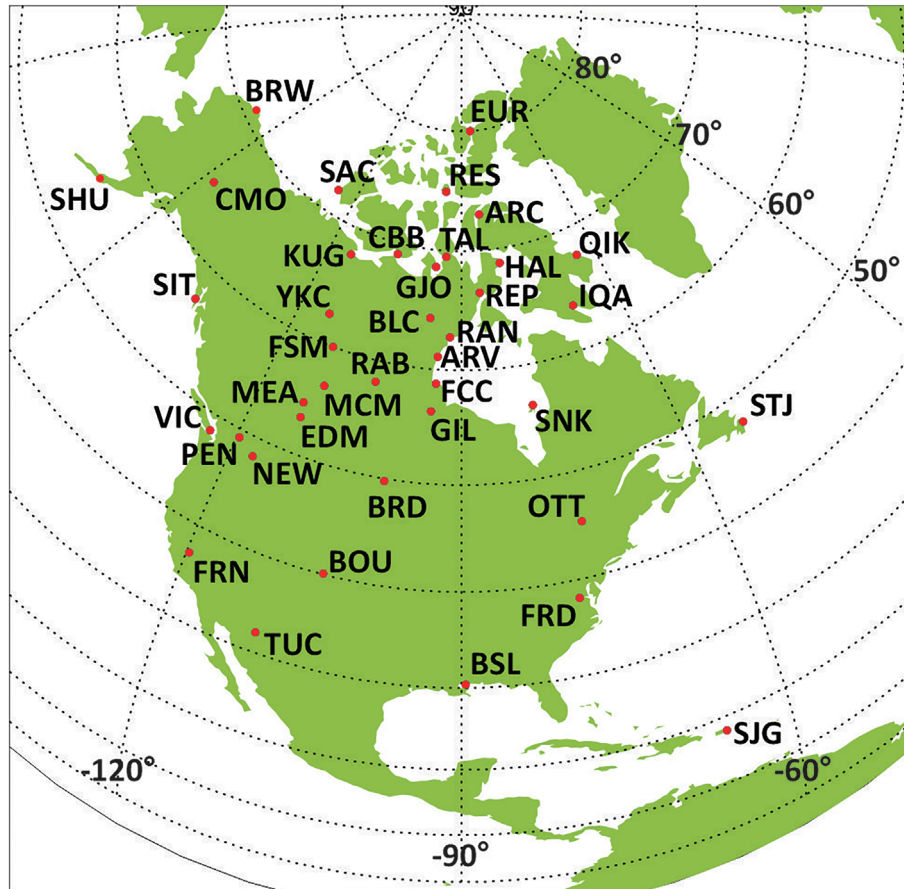
<sup>3</sup> <https://www.sws.bom.gov.au/Solar/1/8> (last accessed 06 August 2025).

<sup>4</sup> [https://britastro.org/journal\\_contents\\_ite/the-size-of-the-carrington-event-sunspot-group](https://britastro.org/journal_contents_ite/the-size-of-the-carrington-event-sunspot-group) (last accessed 06 August 2025).

<sup>5</sup> <https://www.sanjuandailystar.com/post/northern-lights-seen-in-pr-over-the-weekend> (last accessed 23 October 2024).

<sup>6</sup> <https://www.rnz.co.nz/news/national/516583/solar-storm-aurora-dazzles-over-new-zealand-skies> (last accessed 06 August 2025).

<sup>7</sup> <https://webapp.csrscs-nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en> (last accessed 05 August 2025).



**Figure 1.** Ground-based magnetometer, riometer, and GNSS stations considered in this study. Stations are operated by NRCan, CHAIN, and USGS, as indicated in Table 1.

The Canadian stations host one or more instruments, including magnetometers, riometers, and scintillation receivers. NRCan's magnetic observatories consist of a fluxgate magnetometer and a proton magnetometer (see [Data availability statement](#)). The CSWFC characterizes and forecasts geomagnetic activity using the hourly range (Hruska & Coles, 1987; Trichtchenko et al., 2009). The hourly range is defined as the maximum of the X and Y component magnetic field variation evaluated from 1-minute magnetic field values over a 1-hour period. Evaluation over a 1-hour interval removes or minimizes longer-term magnetic field variations such as secular variation and changes due to the solar quiet or Sq current system (e.g., Danskin & Lotz, 2015). Magnetic field observations are also used in combination with conductivity models to calculate the geoelectric field (see Sect. 3.2).

The riometer stations used in this study consist of an antenna and a La Jolla Sciences riometer instrument (Chivers & Maggoe, 1974) measuring signal attenuation at 30 MHz. Signal voltage, measured by the riometer at a 1-second resolution, is evaluated against a quiet day curve to derive absorption, expressed in dB, before being filtered and downsampled to a 1-minute resolution (Fiori et al., 2023a).

Scintillation data are provided by the University of New Brunswick CHAIN network of Global Navigation Satellite System (GNSS) receivers (<http://chain.physics.unb.ca/chain/>). Scintillations are monitored using GNSS receivers at a 50 or

100 Hz rate from multiple satellite links to a given station. Scintillation is typically quantified by two values: amplitude (S4) and phase scintillations ( $\sigma_\phi$ ). Scintillations at high latitudes, including Canada, are predominantly phase scintillations. Phase scintillation data from Global Positioning System (GPS) satellites with a carrier signal at the L1 frequency (1575.42 MHz) derived in a one-minute window are used here to evaluating scintillation activity during the May event. An elevation cut-off angle of  $15^\circ$  is applied to minimize the multipath effect (e.g., Spogli et al., 2009; Jin et al., 2016).

The Canadian ground-based stations considered in this study are indicated in Figure 1 and Table 1. Also included are several United States Geological Survey (USGS) magnetic observatories, which contribute data used to generate geoelectric fields (Sect. 3.2) and to perform an extreme value analysis of magnetic data (Sect. 6).

## 2.2 Satellite data

We used data from the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) Geostationary Operational Environmental Satellite (GOES) network to evaluate the March 1989 and May 2024 events. We used solar X-ray flux from the X-Ray Sensor instrument (Garcia, 1994). Only the soft X-rays (0.1–0.8 nm) were considered, and data for the March 1989

**Table 1.** List of ground-based instruments considered in this study.

| Station        | Abbreviation | Geographic latitude (°) | Geographic longitude (°) | Operator | Instrument    | Region                               |
|----------------|--------------|-------------------------|--------------------------|----------|---------------|--------------------------------------|
| Arctic Bay     | ARC          | 73.0                    | 275.0                    | CHAIN    | GNSS receiver | Polar cap                            |
| Arviat         | ARV          | 61.1                    | 265.9                    | CHAIN    | GNSS receiver | Auroral                              |
| Baker Lake     | BLC          | 64.3                    | 264.0                    | NRCan    | Magnetometer  | Auroral                              |
| (Point) Barrow | BRW          | 71.3                    | 203.4                    | USGS     | Magnetometer  | Polar cap                            |
| Boulder        | BOU          | 40.1                    | 254.8                    | USGS     | Magnetometer  | Sub-auroral                          |
| Brandon        | BRD          | 49.8                    | 260.0                    | NRCan    | Magnetometer  | Sub-auroral                          |
| Cambridge Bay  | CBB          | 69.1                    | 255.0                    | NRCan    | Riometer      | Transition<br>(polar cap to auroral) |
|                |              |                         |                          | NRCan    | Magnetometer  |                                      |
|                |              |                         |                          | CHAIN    | GNSS receiver |                                      |
| College        | CMO          | 64.9                    | 212.1                    | USGS     | magnetometer  | Auroral                              |
| Eureka         | EUR          | 80.0                    | 274.1                    | CHAIN    | GNSS receiver | Polar cap                            |
| Fort Churchill | FCC          | 58.8                    | 265.9                    | NRCan    | Magnetometer  | Auroral                              |
|                |              |                         |                          | CHAIN    | GNSS receiver |                                      |
| Fort McMurray  | MCM          | 56.6                    | 248.8                    | CHAIN    | GNSS receiver | Auroral                              |
| Fort Smith     | FSM          | 60.0                    | 248.1                    | CHAIN    | GNSS receiver | Auroral                              |
| Fredericksburg | FRD          | 38.2                    | 282.6                    | USGS     | magnetometer  | Sub-auroral                          |
| Fresno         | FRN          | 37.1                    | 240.3                    | USGS     | magnetometer  | Sub-auroral                          |
| Gillam         | GIL          | 56.4                    | 265.4                    | CHAIN    | GNSS receiver | Auroral                              |
| Gjoa Haven     | GJO          | 68.6                    | 264.2                    | CHAIN    | GNSS receiver | Polar cap                            |
| Hall Beach     | HAL          | 68.8                    | 278.8                    | NRCan    | Riometer      | Polar cap                            |
|                |              |                         |                          | CHAIN    | GNSS receiver |                                      |
| Iqaluit        | IQA          | 63.8                    | 291.5                    | NRCan    | Magnetometer  | Auroral                              |
|                |              |                         |                          | NRCan    | Riometer      |                                      |
|                |              |                         |                          | CHAIN    | GNSS receiver |                                      |
| Kugluktuk      | KUG          | 67.8                    | 244.9                    | CHAIN    | GNSS receiver | Auroral                              |
| Meanook        | MEA          | 54.6                    | 246.7                    | NRCan    | magnetometer  | Transition (auroral to sub-auroral)  |
| Ministik Lake  | EDM          | 53.3                    | 247.0                    | CHAIN    | GNSS receiver |                                      |
| Newport        | NEW          | 48.3                    | 242.9                    | USGS     | Magnetometer  |                                      |
| Ottawa         | OTT          | 45.4                    | 284.4                    | NRCan    | Magnetometer  | Sub-auroral                          |
|                |              |                         |                          |          | Riometer      |                                      |
| Penticton      | PEN          | 49.3                    | 240.4                    | NRCan    | Riometer      | Sub-auroral                          |
| Qikiqtarjuaq   | QIK          | 67.6                    | 296.0                    | CHAIN    | GNSS receiver | Auroral                              |
| Rabbit Lake    | RAB          | 58.2                    | 256.3                    | CHAIN    | GNSS receiver | Auroral                              |
| Rankin Inlet   | RAN          | 62.8                    | 267.9                    | CHAIN    | GNSS receiver | Auroral                              |
| Repulse Bay    | REP          | 66.5                    | 273.8                    | CHAIN    | GNSS receiver | Auroral                              |
| Resolute       | RES          | 74.9                    | 265.1                    | NRCan    | Magnetometer  | Polar cap                            |
|                |              |                         |                          | NRCan    | Riometer      |                                      |
|                |              |                         |                          | CHAIN    | GNSS receiver |                                      |
| Sachs Harbour  | SAC          | 72.0                    | 234.7                    | CHAIN    | GNSS receiver | Polar                                |
| San Juan       | SJG          | 18.1                    | 293.9                    | USGS     | Magnetometer  | Sub-auroral                          |
| Sanikiluaq     | SNK          | 56.5                    | 280.8                    | NRCan    | Magnetometer  | Auroral                              |
| Shumagin       | SHU          | 55.3                    | 199.5                    | USGS     | Magnetometer  | Sub-auroral                          |
| Sitka          | SIT          | 57.1                    | 224.7                    | USGS     | Magnetometer  | Sub-auroral                          |
| St Johns       | STJ          | 47.6                    | 307.3                    | NRCan    | Magnetometer  | Sub-auroral                          |
| Stennis        | BSL          | 30.4                    | 270.4                    | USGS     | Magnetometer  | Sub-auroral                          |
| Taloyoak       | TAL          | 69.5                    | 266.4                    | CHAIN    | GNSS receiver | Polar cap                            |
| Tucson         | TUC          | 32.2                    | 249.3                    | USGS     | Magnetometer  | Sub-auroral                          |
| Victoria       | VIC          | 48.5                    | 236.6                    | NRCan    | Magnetometer  | Sub-auroral                          |
| Yellowknife    | YKC          | 62.5                    | 245.5                    | NRCan    | Magnetometer  | Auroral                              |
|                |              |                         |                          |          | Riometer      |                                      |

event were calibrated according to descriptions in the GOES X-ray Sensor (XRS) Operational Data report<sup>8</sup>. Solar proton data were obtained from the GOES energetic particle sensor for the March 1989 event and from the solar and galactic proton sensor

(SGPS) for the May 2024 event (Kress et al., 2021). The SGPS measures proton flux for protons with energies ranging from >1 to >500 MeV in several distinct channels.

Solar wind and interplanetary magnetic field (IMF) data, including IMF components ( $B_x$ ,  $B_y$ ,  $B_z$ ) in the Geocentric Solar Magnetospheric (GSM) coordinate system, magnitude ( $B_t$ ), and azimuthal angle ( $\phi$ ), and the solar wind density, speed, and

<sup>8</sup> [https://www.ngdc.noaa.gov/stp/satellite/goes/doc/GOES\\_XRS\\_-readme.pdf](https://www.ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_-readme.pdf) (last accessed 05 August 2025).



temperature, are captured from graphics produced by NOAA SWPC<sup>9</sup>.

### 2.3 Numerical modelling of solar wind disturbances

To simulate propagation of CMEs in the background solar wind and forecast their arrival times, a 3D numerical framework has been developed at the CSWFC (Narechania et al., 2021). This Sun-to-Earth solar wind – CME simulation framework employs a semi-empirical approach to describe the solar corona and a magnetohydrodynamic model of the heliosphere. The coronal magnetic field is derived using the potential field source surface (PFSS) and Schatten current sheet models, and the background solar wind is derived using a semi-empirical solar wind relation to associate the solar wind parameters with the magnetic field. To drive the PFSS model, Global Oscillation Network Group (GONG) zero-point corrected synoptic maps of the magnetic field are used. Observations of the solar corona by the Large Angle and Spectrometric Coronagraph Experiment (LASCO) instrument on board the Solar and Heliospheric Observatory<sup>10</sup> (SOHO) satellite, and observations of the corona by the Solar Terrestrial Relations Observatory<sup>11</sup> A (STEREO-A) and Solar Dynamics Observatory<sup>12</sup> (SDO) Satellites are used to obtain information about CMEs. To estimate parameters such as CME velocity, angular width, and location, CME information provided by the Computer-Aided CME Tracking<sup>13</sup> (CACTus) Software, Solar Influences Data Analysis Center, Royal Observatory of Belgium, is used. For additional descriptions, including information on the models used, see Narechania et al. (2021). Comparisons with previous events and observations, including those listed in the SOHO LASCO CME catalog<sup>14</sup>, are used to make more appropriate parameter estimates. To access the data used to drive the solar wind-CME simulations, see the [Data availability statement](#).

## 3 Observations

This section presents the satellite and ground-based observations characterizing solar, interplanetary, geomagnetic, and ionospheric conditions considered by the CSWFC. These data were used to develop Sun-to-Earth simulations to evaluate the geoeffectiveness and arrival of CMEs during the May event and to assist in creating space weather alerts.

### 3.1 Sun-to-Earth

A series of solar phenomena led to the disturbed geomagnetic and ionospheric activity observed during the May 2024 space weather event. The event occurred during a period of

strong solar activity, primarily produced by AR 3364 as it rotated across the visible solar disc. [Figure 2a](#) shows the GOES 18 solar X-ray flux for 08–18 May 2024. During this period, the background solar X-ray flux was high, exceeding  $10^{-6} \text{ Wm}^{-2}$ , and most flares exceeded the M-class flare threshold ( $10^{-5} \text{ Wm}^{-2}$ ). In addition to many M-class flares, 12 X-class ( $>10^{-4} \text{ Wm}^{-2}$ ) flares observed from early May 08 to early May 15 are attributed to AR 3664, with the largest flare of the period reaching X8.7 at 16:51 UT on 14 May 2024. All these intense solar flares erupted during the transition of AR 3664 across the western part of the solar disc, starting from location S22W11 (X1.0 on May 08, 05:09 UT) to the west limb location S18W89 (X3.5 on May 15, 08:37 UT) (see, e.g., the SolarSoft latest events archive<sup>15</sup>).

CMEs are frequently associated with high M and X-class flares (Yashiro et al. 2005). Several CMEs were observed from 08 May to 15 May, 2024. However, it is not an easy task to assess their geoeffectiveness. In [Figure 2a](#), blue arrows indicate events with potentially geoeffective CMEs, which could produce significant geomagnetic disturbances. Geoeffectiveness was evaluated using the Sun-to-Earth simulations presented in [Section 4](#). While some CMEs did not have strong signatures in the LASCO coronagraph images, their proximity to the central meridian elevates their importance.

A CME associated with the X2.2 solar flare observed on May 09, 09:13 UT, was accompanied by a solar energetic particle (SEP) event, particularly visible in the  $\geq 10$  MeV solar proton flux, with an energetic storm particle (ESP) signature at the time of the shock arrival on May 10, 17:30 UT. This is seen in [Figure 2b](#), where the proton flux observed by the GOES 18 satellite during May 08–15 is shown for the  $\geq 10$  MeV,  $\geq 30$  MeV,  $\geq 50$  MeV, and  $\geq 100$  MeV energy levels. Strong enhancement of the  $\geq 10$  MeV solar proton flux began near 12 UT on May 10, reaching a peak of 206.9 pfu at 17:45 UT before dropping to a minimum value of 7.0 pfu at 01:45 UT May 11. After this time, a rapid increase was observed in all proton flux energy channels, with the  $\geq 10$  MeV flux reaching 23.8 pfu at 02:45 UT, indicating an impulsive SEP event which followed an X5.8 solar flare (01:23 UT) from S17W44. This solar flare was also accompanied by a CME. The more gradual SEP behavior after the impulsive signature suggests SEP generation by a CME-driven shock. The broad profile of this SEP event shows a slow decrease over the course of  $\sim 36$  h until  $\sim 12$  UT May 13, when another SEP event began. The latter SEP event follows a west limb M6.7 solar flare and associated CME from AR 3664. This event is particularly pronounced in the  $\geq 10$ ,  $\geq 30$ , and  $\geq 50$  MeV energy spectrum, with  $\geq 10$  MeV solar proton flux peaking at 121 pfu on May 14 and not dropping to background levels for more than 3 days.

[Figure 3](#) shows the IMF and solar wind data captured from the NOAA Space Weather Prediction Center (SWPC) real-time solar wind plot<sup>16</sup> for the period from 10:41 UT on 10 May 2024 until 13:14 UT on 12 May 2024. Notably, there is a strong interplanetary shock in the data at 16:37 UT on 10 May 2024, observable as a jump in the solar wind velocity from  $<500$  km/s to  $\sim 700$  km/s and an increase in the total magnetic

<sup>9</sup> <https://www.swpc.noaa.gov/products/real-time-solar-wind> (last accessed 06 August 2025).

<sup>10</sup> <https://soho.nascom.nasa.gov/data/data.html> (last accessed 06 August 2025).

<sup>11</sup> <https://stereo-ssc.nascom.nasa.gov/> (last accessed 06 August 2025).

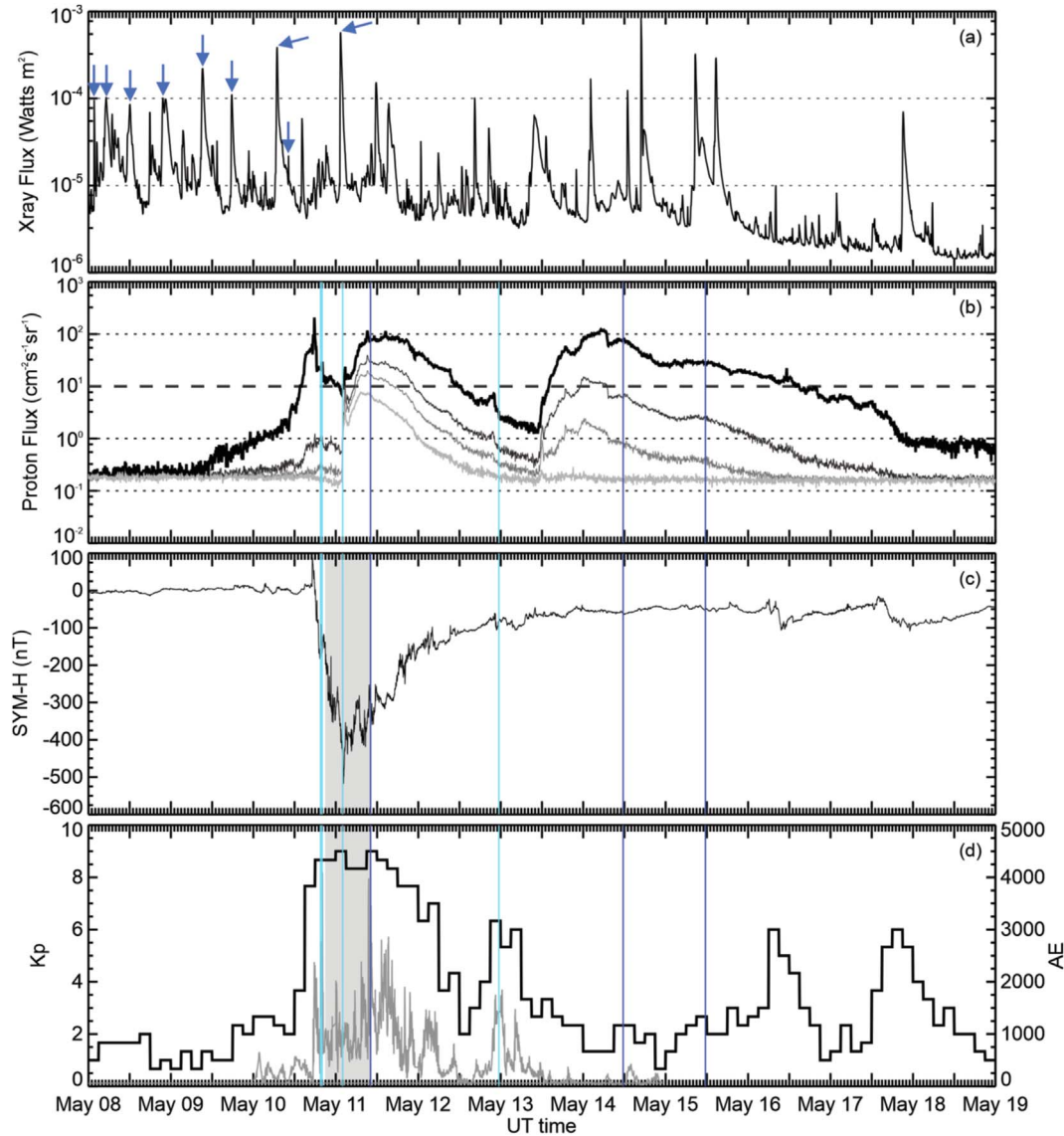
<sup>12</sup> <https://sdo.gsfc.nasa.gov/data/> (last accessed 06 August 2025).

<sup>13</sup> <https://www.sidc.be/cactus/> (last accessed 06 August 2025).

<sup>14</sup> [https://cdaw.gsfc.nasa.gov/CME\\_list/](https://cdaw.gsfc.nasa.gov/CME_list/) (last accessed 06 August 2025).

<sup>15</sup> [https://www.lmsal.com/solarsoft/latest\\_events\\_archive.html](https://www.lmsal.com/solarsoft/latest_events_archive.html) (last accessed 06 August 2025).

<sup>16</sup> <https://www.swpc.noaa.gov/products/real-time-solar-wind> (last accessed 06 August 2025).



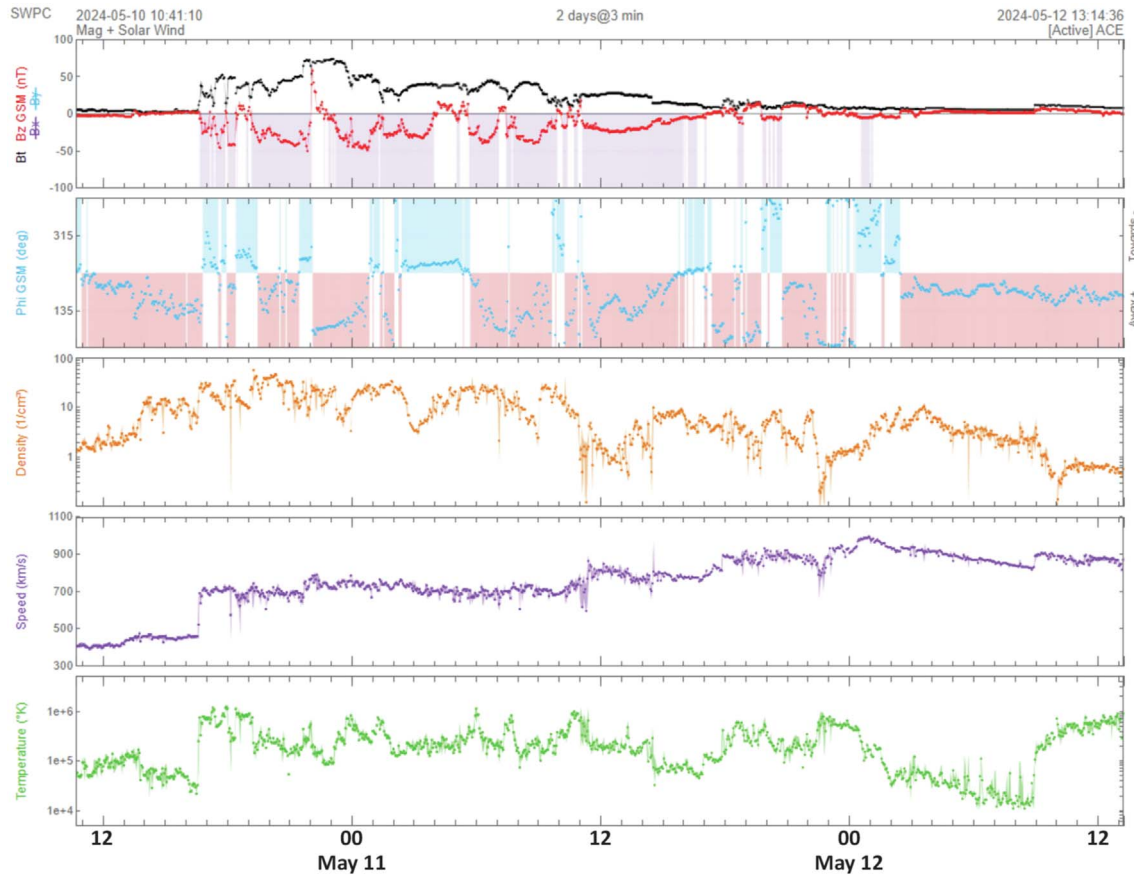
**Figure 2.** (a) GOES 18 solar X-ray flux. Horizontal lines at  $10^{-5}$  Wm $^{-2}$  and  $10^{-4}$  Wm $^{-2}$  indicate thresholds for M-class and X-class flares, respectively. Blue arrows indicate CMEs considered in the event forecasting. (b) GOES 18 solar proton flux in the  $>10$  MeV (thick black line),  $>30$  MeV (thin black line),  $>50$  MeV (thin dark grey line), and  $>100$  MeV (thick light grey line) channels. Horizontal dashed line indicates the  $10 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  typically used to indicate the onset of a solar proton event based on the  $>10$  MeV solar proton flux. (c) SYM-H index. (d) Kp index (heavy black line) and AE index (grey line). All data are for 08–19 May 2024. Vertical lines in (b), (c), and (d) indicate times of HF COM (dark blue) and GNSS (light blue) degradation reported in CADORS reports (see Sect. 5). Grey shading in panels (c) and (d) indicates an outage of the Wide Area Augmentation System (WAAS; see Sect. 5).

field from near 0 nT to  $\sim 40$  nT. The solar wind speed slowly increased to a maximum value of  $\sim 1000$  km/s close to 01 UT May 12. Most notably, over the  $\sim 4$ -hour period following the shock, the IMF  $B_z$  was strongly negative, exceeding  $-40$  nT for hours at a time.

### 3.2 Geomagnetic and geoelectric

Geomagnetic activity can be characterized by several different geomagnetic activity indices. Although not all indices were available in near-real time during the event, they can provide a global context for local geomagnetic and geoelectric

observations. Figures 2c and 2d shows the SYM-H, Kp, and AE index for the 09–18 May 2024 period. SYM-H reached a peak of 88 nT at 17:15 UT on May 10, 30 min before the peak  $\geq 10$  MeV solar proton flux. Values quickly dropped, reaching a minimum of  $-518$  nT by 02:14 UT May 11. The Dst index (not shown) reached a minimum value of  $-412$  nT. Kp index increased rapidly from 4- to 8- between the 12–15 and 15–18 UT periods of May 10 and continued at levels above Kp = 8 for exactly 24 h beginning 18:00 UT May 10 and remained above Kp = 6 until 06 UT May 12. A second peak of Kp  $> 5$  was observed between 21 UT May 12 and 06 UT May 13. During the extended period of Kp  $> 8$ , Kp saturated



**Figure 3.** Screenshot of the total ( $B_t$ ) and Z-component ( $B_z$ ) of the IMF, solar wind speed, density and temperature near the L1 point from 10 May 2024 10:41 UT until 12 May 2024 13:14 UT.

at 9 from 00–03 UT and 09–12 UT on May 11, which could be attributed to the expansion of the auroral zone to typically sub-auroral locations such that the sub-auroral magnetometers used to derive Kp observed geomagnetic field variations stronger than expected by the Kp scale (e.g. Allen et al., 1989; Sojka et al., 1994). Yamazaki et al. (2024a) assessed a series of strong ( $K_p \geq 9$ ) events using the Hp30 and Hp60 indices, which are similar to Kp but are based on a 30- and 60-minute evaluation period, respectively, and are not limited to an upper limit of 9 (Yamazaki et al., 2024b). They found the May event reached Hp30 = 11+ and Hp60 = 11– on May 10, peaking shortly before 24 UT. For comparison, the March 1989 event peaked at Hp30 = 13+ and Hp60 = 13–.

A sudden storm commencement was observed at the ground at 17:05 UT<sup>17</sup> on 10 May 2024. NRCan polar cap and auroral zone magnetometers immediately began registering significant geomagnetic variations of more than 1000 nT, as seen in Figure 4<sup>18</sup>. Equatorward expansion of the auroral oval was evident in Canadian auroral and sub-auroral magnetometers over the following 48 h. Enhancements of geomagnetic activity associated with substorms were also evident. Isolated periods of

geomagnetic variations exceeding 1000 nT were recorded in the auroral zone and sub-auroral magnetometers between 07 and 20 UT on 11 May 2024. Near-continuous disturbed geomagnetic conditions persisted through to 05 UT on 12 May 2024. Further isolated periods of heightened geomagnetic activity were also observed in nightside Canadian magnetometers from 12 to 13 May, 2024 (not shown).

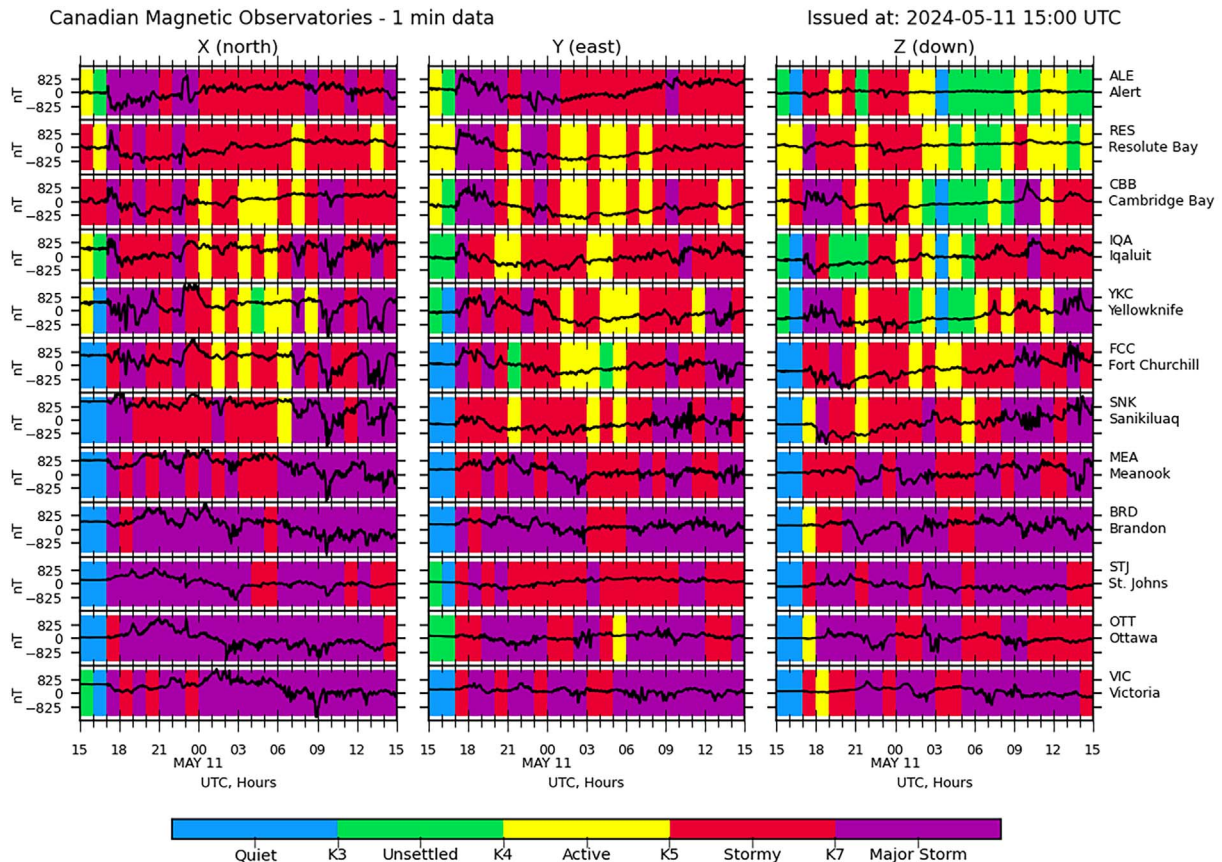
The upper panels in Figure 5 show snapshots of the geoelectric field across North America at key times during the storm. In general, geoelectric fields depend on local geomagnetic field variations in combination with regional conductivity characteristics. Geoelectric fields are calculated from magnetic field observations recorded at 18 NRCan and United States Geological Survey (USGS) observatories. Magnetic field observations are detrended and interpolated to a  $0.5^\circ \times 0.5^\circ$  grid using the spherical elementary current systems technique (Amm & Viljanen, 1999; Pulkkinen et al., 2003), before being differentiated and convolved with impulse responses corresponding to regional conductivity models across North America to calculate the geoelectric field. Due to the lack of Earth conductivity models in the Canadian Territories, geoelectric fields were only mapped up to  $60^\circ$  geographic latitude.

The geoelectric field changes illustrated in Figure 5 show a quick progression of enhancement across North America. At 12 UT on 10 May 2024 (Fig. 5a), before the arrival of the CME, geoelectric fields across North America were small

<sup>17</sup> <https://www.obsebre.es/en/variaciones/rapid> (last accessed 06 August 2025).

<sup>18</sup> <https://spaceweather.gc.ca/data-donnee/geomag/ssp-1-en.php> (last accessed 06 August 2025).





**Figure 4.** Review plot of magnetic field variations (black line) for the previous 24 h issued 11 May 2024 at 15:00 UT by the CSWFC. The black line represents one-minute variations of the X, Y and Z magnetic field components for NRCan’s geomagnetic observatories. The observatories are ordered according to their geographic latitude, from the north (top) to the south (bottom). Color denotes geomagnetic activity characterized by the hourly range of magnetic field variations. The plot captures the start of the storm on May 10 at 17–18 UT and the most intense part of the storm during May 10–11, including significant X component field variations around 9–10 UT on May 11. Geomagnetic activity colour is coded according to the colour bar at the bottom of the Figure which also denotes NRCan’s activity level descriptors (“Quiet”, “Unsettled”, “Active”, “Stormy”, “Major Storm”) and roughly equivalent K values.

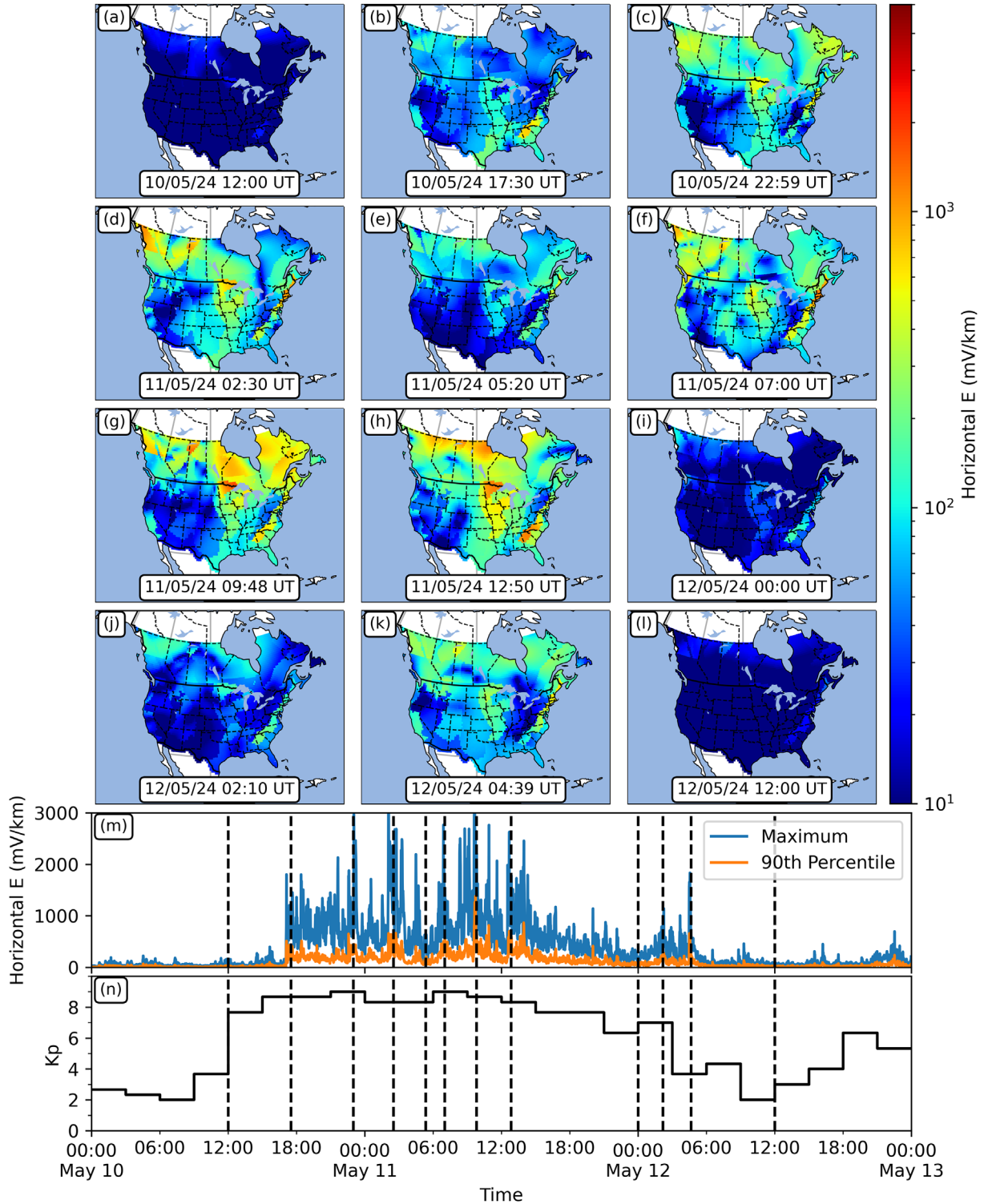
(90% of values  $<20$  mV/km, maximum value of 37 mV/km). Just after the onset of geomagnetic activity at 17:30 UT (Fig. 5b),  $>100$  mV/km geoelectric fields were produced in north-western Canada, and the south-east US. Throughout the storm, local conductivity features in the southeast US caused geoelectric field enhancements that were larger than in the immediately surrounding regions. Geoelectric field activity expanded southward for the rest of the UT day. By 22:59 UT (Fig. 5c), this southward expansion resulted in geoelectric fields of up to  $\sim 600$  mV/km being measured across Canada and in the northern and southeastern parts of the US. Geomagnetic intensifications, peaking at  $\sim 03$  UT on May 11 in the X-component of the BRD, STJ, and OTT magnetic stations and the Y-component of the MEA magnetic station (see Fig. 4), produced the local peak geoelectric fields at 02:30 UT on 11 May 2024 (Fig. 5d). At this time, some regions in northwest Canada and northeast US experienced geoelectric fields of  $>1000$  mV/km, and geoelectric field variations of  $\sim 300$  mV/km were observed into the southernmost US (Texas). Geoelectric field variations continued until roughly  $\sim 12$  UT on 11 May 2024 (Figs. 5e–5h), undergoing intensifications coincident with geomagnetic field variations. For example, the

strong geomagnetic field enhancement observed in the X-component of almost all the geomagnetic observatories at  $\sim 10$  UT on May 11, shown in Figure 4, results in geoelectric fields that exceed 500 mV/km at 09:48 UT (Fig. 5g) across the eastern auroral zone.

Geoelectric fields across North America slowly decayed from  $\sim 14$  UT onward on May 11. By 00:00 UT on 12 May 2024 (Fig. 5i), fields were quiet ( $<50$  mV/km), except for the northwestern tip of British Columbia and parts of the southeastern US. A second, smaller intensification of the geoelectric field was observed on 12 May 2024. At 02:10 UT (Fig. 5j), fields in parts of northern Canada and southeastern US had intensified again to 100s of mV/km, and by 04:39 UT (Fig. 5k), geoelectric fields of 100s of mV/km had expanded southward to cover most of Canada and parts of the southern US. This second intensification of the geoelectric field ended around 06:00 UT, and by 12:00 UT (Fig. 5l), geoelectric activity was quiet again across North America. A video showing the full evolution of the electric field data between 00:00 UT May 10 and 23:59 UT May 12 is available in the [Supplementary material S1](#).

Figure 5m is a time series of the maximum (blue) and 90th percentile (orange) geoelectric field across the entire mapped

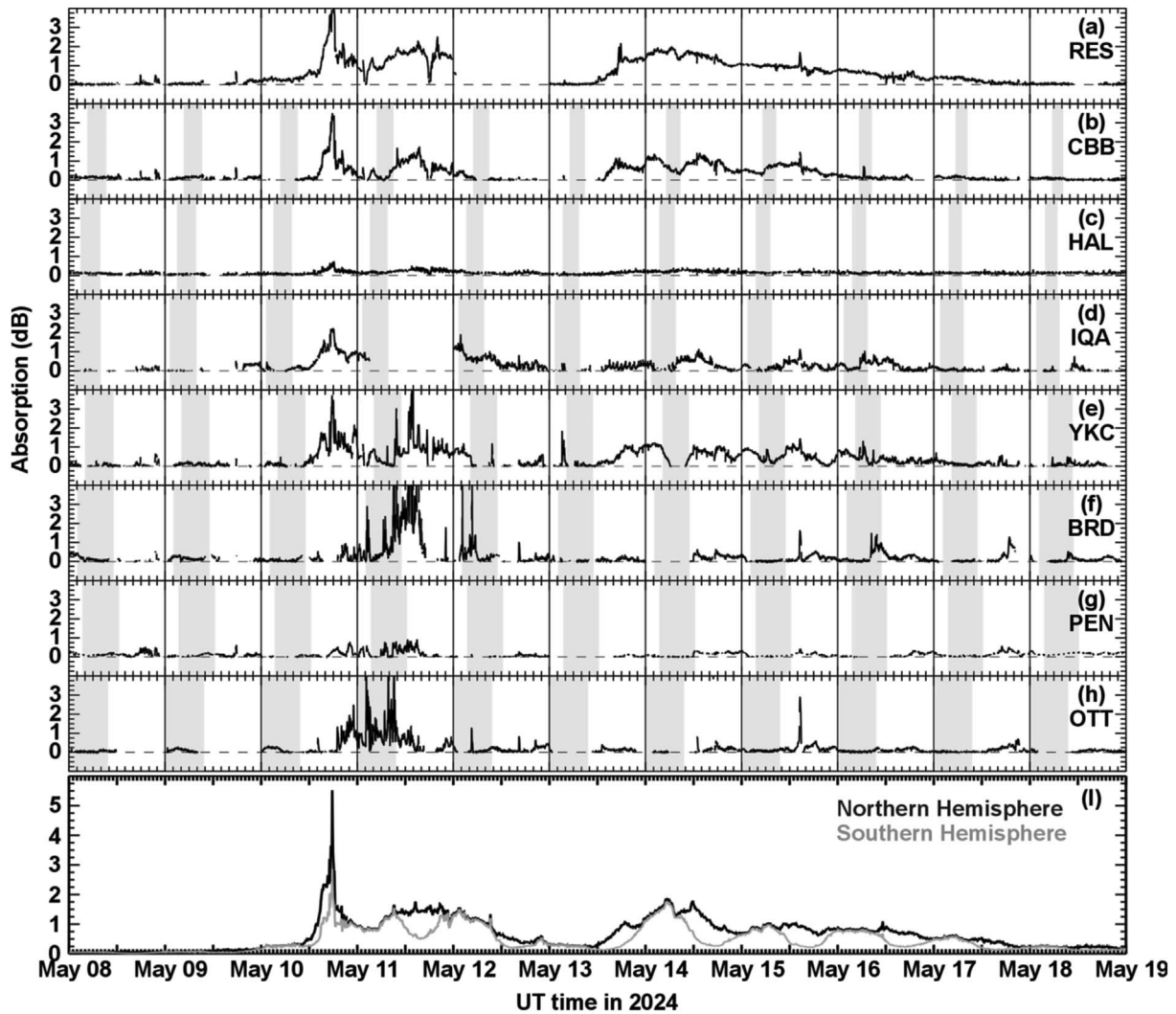




**Figure 5.** (a–l) Maps of geoelectric fields across North America at notable times during the 10–12 May 2024 geomagnetic storm. (m) Time series of maximum (blue) and 90th percentile (orange) geoelectric fields across North America from 10–12 May 2024. Times mapped in panels (a–l) are indicated with vertical dashed lines. (n) Kp index as plotted in Figure 2d, but for 10–12 May 2024.

region for 10–12 May 2024. Vertical dashed lines indicate periods mapped in the upper panels of Figure 5, for reference. From minute to minute, large changes were observed in the strength of the geoelectric field. Maximum geoelectric fields exceeded

1000–1500 mV/km for an almost 24-hour period beginning at 17:07 UT and exceeded 2500 mV/km for brief periods between 23:03 UT May 10 and 12:41 UT May 11 at geographic regions with geological features that produce larger geoelectric fields.



**Figure 6.** (a–h) Absorption at 30 MHz derived from the NRCan riometer array for 08–18 May 2024. Data have been downsampled to a 1-minute median value. Stations are ordered by descending geographic latitude (see Table 1) according to the station label in the upper right portion of the panel. Grey shading indicates when the station was located on the nightside. (i) Maximum northern hemisphere (black) and southern hemisphere (grey) polar cap absorption at 30 MHz modelled using the Fiori & Danskin (2016) “non-optimized” model at 5-minute increments.

Variations in the maximum and 90th percentile geoelectric field match variations in the geomagnetic activity as represented by Kp-index in Figure 5n.

### 3.3 Ionospheric

Ionospheric disturbances were also observed during the May 2024 event. Figure 6 shows the 30 MHz ionospheric absorption observed by the NRCan riometer network. The solar proton event beginning May 09 reached high enough levels to be visible in the riometer data beginning ~14 UT on May 10. Enhancements were observed in the RES, CBB, IQA, and YKC riometers with peaks of 2.2–4.4 dB absorption observed at ~17:50 UT, coincident with the peak  $\geq 10$  MeV solar proton flux observed by GOES. Dayside enhancements of 1–2 dB were observed by the RES, CBB, and YKC riometers on the first day

of the May 11–12 proton enhancement, and the first 4 days of the May 13–17 proton enhancement.

Several dayside X-class solar X-ray flares were observed by the network as evidenced by sharp peaks in absorption coinciding with the time of peak solar X-ray flux indicated in Figure 2a. The strongest response was from the X3.0 flare peaking at 14:38 UT on May 15, where  $>3.0$  dB absorption is observed at OTT. Absorption signatures were observed across the network, reaching  $>1$  dB at RES, CBB, IQA, and BRD. For the RES, CBB, and YKC stations, these enhancements were observed in addition to polar cap absorption. Note that although the NRCan riometer network was on the dayside during the X8.7 solar X-ray flare that peaked at 16:51 UT on 14 May 2024, the flare was accompanied by solar radio noise that saturated the riometer voltage measurements, preventing an accurate characterization of absorption.

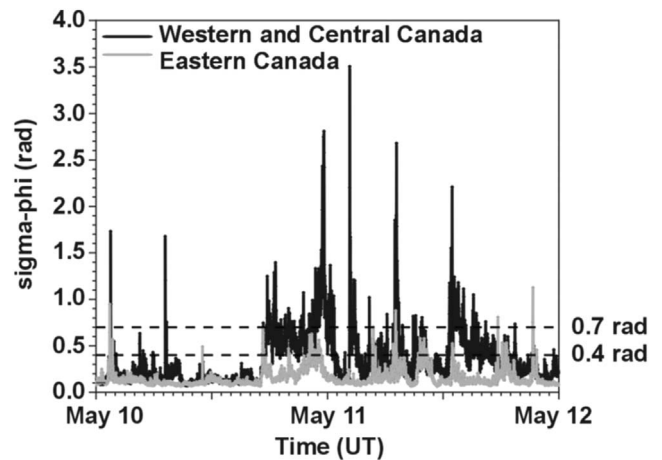
In addition to polar cap absorption and shortwave fadeout, the riometer data show significant periods of elevated absorption beginning at ~19 UT on May 10 until ~06 UT May 12. Enhancements were first observed in the low-latitude OTT riometer, with peak absorption exceeding 3 dB, and then at BRD and YKC beginning ~06 UT May 11. The enhancements occurred during a period when the 3-hour Kp index exceeded 6 from 18 May 10 to 06 May 12 and are attributed to auroral absorption.

As the data in Figure 6 are limited to the Canadian sector, a model was used to evaluate global trends. The lower panel of Figure 6 shows the maximum northern and southern hemisphere polar cap absorption modeled using the Fiori & Danskin (2016) “non-optimized model”. The magnitude of absorption predicted by the model agrees well with absorption observed by the RES and CBB riometer stations, with a peak absorption of >3 dB on May 10 and peaks of 1–2 dB observed on May 11 and May 14. The maximum northern and southern hemisphere absorption have similar peaks. Note that drops in the southern hemisphere absorption are caused by the tilt of the Earth, causing longer night-time periods in the southern hemisphere.

Ionospheric disturbances were also observed in the sigma-phi scintillation observed across Canada, see Figure 7. Data were categorized as western, central, and eastern based on their location. Each minute, all data collected by all stations in each region were evaluated to determine the second maximum of sigma-phi for May 10–11. The second peak was used to avoid spikes. Activity is strongest in the western and central parts of Canada where sigma-phi increases from quiet levels to >0.4 rad (moderate) shortly after 17 UT on May 10, remaining >0.4 rad and peaking at >0.7 rad (severe) for large periods of time until ~01 UT on May 11. Bursts of activity are also observed throughout May 11 with a prolonged enhancement shortly after 12 UT. Peak scintillations were observed within a few hours of 00 UT on May 11. Similar enhancements were observed in eastern Canada, but with lower activity levels predominantly <0.4 rad.

#### 4 CSWFC forecasts and alerts

The CSWFC provides forecasts and alerts based on expected and observed space weather conditions. In addition to regular forecasts, alerts are issued to heighten awareness about unusual conditions. Alerts include special space weather statements, major geomagnetic storm WATCH and WARNINGS, solar energetic particles (SEP) WARNINGS, and ionospheric advisories. The special space weather statements notify users about solar activity and disturbances that are or could be geoeffective. For example, special space weather statements are used to inform users about CMEs, solar flares, and coronal holes, which could produce disturbed conditions. The “watch” and “warning” terminology is consistent with the terminology used by Environment and Climate Change Canada to describe terrestrial weather<sup>19</sup>. A major geomagnetic storm WATCH is used to inform users that significant geomagnetic disturbances with the potential to



**Figure 7.** One-minute maximum sigma-phi scintillation based on western and central (black) and eastern (grey) scintillation receivers. Dashed horizontal lines indicate moderate and severe thresholds. Data are for 10–11 May 2024.

adversely affect technological systems are possible, but not necessarily imminent. When such disturbances are occurring or imminent, the CSWFC issues a major geomagnetic storm WARNING. A SEP WARNING is issued to indicate the arrival of energetic particles that can affect space technology, cause ionospheric disturbances, and increase the intensity of radiation at commercial aircraft altitudes in the polar region. The ionospheric advisories are used to inform specialized users about polar cap and auroral absorption, short-wave fadeout, and GNSS scintillations.

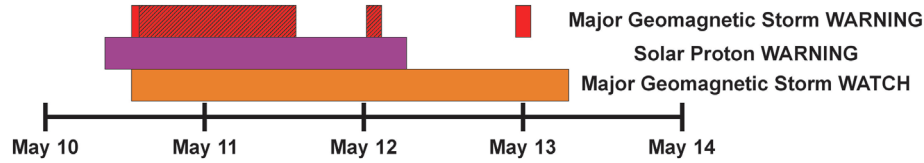
Due to the unique magnetic environment in Canada, alerts about geomagnetic activity<sup>20</sup> can be issued for the auroral zone only, or for all three zones (polar cap, auroral, and sub-auroral). Typically, major geomagnetic storm conditions in the sub-auroral zone require a larger driver of geomagnetic disturbances, than for major geomagnetic storm conditions in the auroral zone.

The May 2024 event prompted the CSWFC to issue several alerts, as shown in Figure 8. Note that CSWFC alerts are issued in Eastern Daylight Time (EDT) or Eastern Standard Time (EST). Times in this section are therefore provided in EDT, with the corresponding UT times noted. At 13:52 EDT (17:52 UT) on 09 May 2024, the impending arrival of the CMEs prompted issuance of a major geomagnetic storm WATCH across Canada from 10 May 2024 19:00 EDT (23:00 UT) to 11 May 2024 19:00 EDT (23:00 UT). Prompted by the early arrival of the CME, the start time of the major geomagnetic storm WATCH was subsequently shifted earlier to 13:00 EDT (17:00 UT) and was periodically extended throughout the event, eventually ending at 09:00 EDT (13:00 UT) May 13. Shortly after the CME arrived, observed geomagnetic variations became so large that a major geomagnetic storm WARNING was issued for the auroral region beginning 13:17 EDT (17:17 UT), and then at 14:42 EDT (18:42 UT), expanded to cover the entirety of Canada. This corresponded to the onset of enhanced geomagnetic activity in the auroral zone, and its subsequent expansion to sub-auroral latitudes. The warning was adequate for 24 h

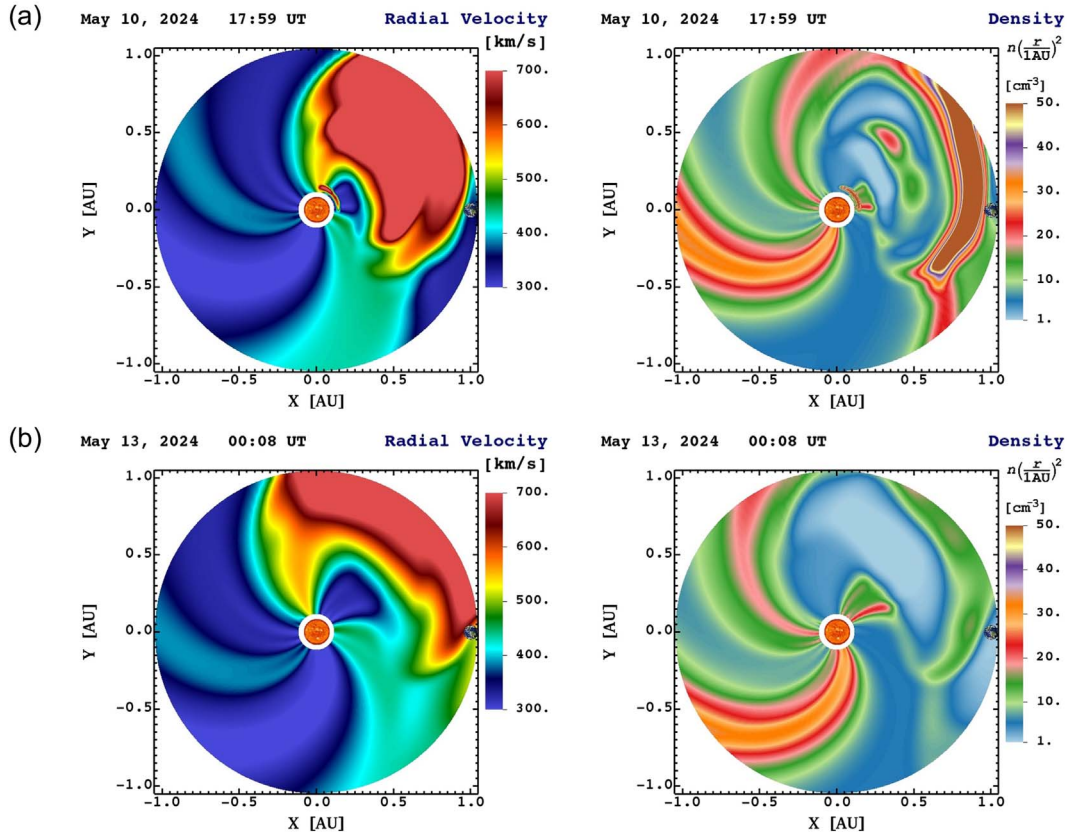
<sup>19</sup> <https://www.canada.ca/en/environment-climate-change/services/weather-general-tools-resources/glossary.html#wsglossaryA> (last accessed 06 August 2025).

<sup>20</sup> <https://www.spaceweather.gc.ca/forecast-previous/short-court/desc-en.php> (last accessed 06 August 2025).





**Figure 8.** Timeline illustrating when CSWFC watches and warnings were in effect. Shown in local Eastern Daylight Time (EDT; EDT = UT – 4 hours). Major Geomagnetic Storm WARNING was issued either for the auroral region (red) or for all of Canada (red, black hatching).



**Figure 9.** Simulations of the CME propagation through the background solar wind in the interplanetary space during the May 2024 event. The solar wind speed (left) and density (right) for (a) 10 May and (b) 13 May 2024. The scales for the velocity, and density are saturated at 700 km/s, and 50 cm<sup>-3</sup>, respectively. Earth is located at the right edge of the simulation domain.

ending at 14:42 EDT (18:42 UT) 11 May 2024. A separate major geomagnetic storm WARNING was briefly in force from 00:37 EDT to 02:37 EDT (04:37 UT to 06:37 UT) for the entire Canadian region and 23:17 EDT 12 May 2024 to 01:17 EDT 13 May 2024 (03:17 – 05:17 UT 13 May 2024) in the auroral region, associated with observed magnetic substorm activity across Canada.

Space weather alerts were also issued based on the magnitude of the solar proton flux. Solar energetic proton flux was observed to steadily increase from May 09, before sharply increasing at 17 UT on May 10 with the arrival of the first CME shock. Once the  $\geq 10$  MeV solar proton flux exceeded 10 pfu at 09:45 EDT (13:45 UT) on May 10, a solar energetic proton WARNING was issued that persisted until 09:00 EDT (13:00 UT) on May 12. Both  $\geq 10$  MeV (100 pfu) and  $\geq 100$  MeV (1 pfu) thresholds for solar protons were exceeded during this event.

To estimate the geoeffectiveness and times of arrival of CMEs during the May 2024 event, Sun-to-Earth simulations were used, see described in Section 3.1. Figure 9 illustrates the simulations, which include nine CMEs observed during May 8–11 (see Table 2 and blue arrows in Fig. 2). Instruments used to observe the solar corona and assess the CMEs and their geoeffectiveness are described in Section 2.3. Unfortunately, not all parameters could be derived from the observations and qualitative assessment, and parameter assumptions were used. Inspection of SDO images following the X1.0 solar flare on 08 May (01:41 UT) showed that the source of this flare was AR 3663 (N26W58). No CME associated with this flare was identified in the LASCO images. However, soon after this flare, a M3.4 flare erupted from AR 3664 (02:27 UT). A faint, slow southwest-moving CME was attributed to this flare. Since the eruption was close to the central meridian ( $\sim 18^\circ$ W), this CME was considered geoeffective. This eruption marked the

**Table 2.** CMEs observed from AR 3664 08–11 May 2024. Approximate time of eruption, associated solar flare, CME location, speed, mass, angular width, radial width, and magnetic flux used in the simulations. The CME geoeffectiveness and parameters were assessed using SDO, SOHO/LASCO, and STEREO observations of the solar corona, CACTus CME detection, and the SOHO LASCO CME catalog. Not all parameters could be derived from the observations and qualitative assessment, and parameter assumptions were used, particularly for the CME mass and magnetic flux.

|   | Time [UT]    | Solar flare | Location | Speed [km/s] | Mass [ $10^{12}$ kg] | Angular width [ $^{\circ}$ ] | Radial width [ $R_0$ ] | Magnetic flux [ $10^{20}$ Mx] |
|---|--------------|-------------|----------|--------------|----------------------|------------------------------|------------------------|-------------------------------|
| 1 | 08 May 03:00 | M3.4        | S15W13   | 600          | 25                   | 90                           | 2                      | 30                            |
| 2 | 08 May 06:00 | X1.0        | S15W14   | 700          | 25                   | 90                           | 2                      | 20                            |
| 3 | 08 May 12:00 | M8.7        | S15W14   | 550          | 10                   | 90                           | 2                      | 30                            |
| 4 | 08 May 21:30 | X1.0        | S15W19   | 800          | 35                   | 90                           | 2                      | 40                            |
| 5 | 09 May 09:30 | X2.3        | S15W29   | 1700         | 25                   | 90                           | 2                      | 30                            |
| 6 | 09 May 18:30 | X1.1        | S15W29   | 1100         | 25                   | 90                           | 2                      | 30                            |
| 7 | 10 May 07:30 | X4.0        | S10W35   | 650          | 35                   | 90                           | 2                      | 30                            |
| 8 | 10 May 11:00 | M2.2        | S19W40   | 700          | 15                   | 90                           | 2                      | 30                            |
| 9 | 11 May 02:30 | X5.8        | S17W50   | 1400         | 35                   | 90                           | 2                      | 30                            |

beginning of the CME chain, which caused significant geomagnetic disturbances. Soon after the first CME signatures in the LASCO images, another CME was observed. This CME followed an X1.0 solar flare with the peak at 05:09 UT. Two more CMEs were noted on 08 May. These CMEs were associated with an M8.7 (12:04 UT) and X1.0 (21:40 UT) flares. All CMEs from 08 May had speeds of <1000 km/s. Two CMEs with speeds of more than 1000 km/s were observed on 09 May. The first CME was followed by SEP and was associated with an X2.3 (09:13 UT) flare, and the second was associated with an X1.1 (17:44 UT) flare. On 10 May, two CMEs were noted associated with X4.0 and M2.2 solar flares (06:54 and 10:14 UT, respectively), and on 11 May, a fast CME was observed following an X5.8 solar flare (S15W44) which peaked at 01:23 UT. The CME from early 11 May was the last CME considered in the CME simulation chain. Due to the location of AR3663, closer to the west limb, the CSWFC did not consider further eruptions likely to be geoeffective.

Figure 9 captures the solar wind speed and density in the XY plane of the interplanetary space on 10 May at 17:59 UT (Fig. 9a) and 13 May at 00:08 UT (Fig. 9b). The coordinate system is Heliocentric Earth Equatorial (HEEQ), and Earth is located close to the right edge of the simulation domain. As Figure 9a shows, the 17:59 UT arrival time of merged CMEs on 10 May is close to the observed CME impact, based on the shock arrival at the L1 point at 16:37 UT and the sudden commencement observed at 17:05 UT. Figure 9b shows the expected arrival of the last CME included in the simulations from 11 May 02:30 UT, associated with the X5.8 solar flare at 01:10 UT (see Fig. 2a) and suggests a glancing blow. These simulations were used to evaluate the geoeffectiveness of the CMEs and to inform arrival times for the dissemination of alerts. A video illustrating CME propagation for the May 2024 event is available in the [Supplementary material S2](#).

## 5 Impacts to HF communication and GNSS in Canada

Reports of impacts in Canada were limited to high-frequency (HF) radio wave propagation, affecting communications, and GNSS positioning. Based on an evaluation of HF

radio wave propagation in the 5.4–14 MHz range, Fiori et al. (2023b) recommended a threshold of 0.5 dB absorption at 30 MHz to indicate possible degradation of HF radio communications, and 1.0 dB as an indicator of more widespread and severe degradation. Evaluating the riometer data shown in Figure 6, the 1.0 dB threshold was crossed for long periods of time between 14 UT May 10 and 04 UT May 12, and again for a ~48-hour period beginning roughly 12 UT May 13. The strongest enhancements, and therefore the greatest possibility for more and widespread signal degradation, occurred during the peak of the polar cap absorption event May 10 at the higher latitude stations (RES, CBB, IQA, YKC) and the peak geomagnetic activity (auroral absorption) May 10–11 at the lower latitude stations (BRD, OTT).

Impacts to GNSS and HF radio communications services in Canada are not widely reported due to the lack of a widespread reporting system. However, some information was found in Transport Canada's Civil Aviation Daily Occurrence Reporting System<sup>21</sup> (CADORS), which collects information on incidents reported by the aviation community. Canada's CADORS reports were searched for reports of communication failure. Table 3 details three such incidents reported in northern (Nunavut, Yukon) and Pacific (British Columbia) Canada. One incident occurred on May 11 during periods of likely polar cap and auroral absorption, and two northern incidents occurred on May 14–15 during a period of polar cap absorption. Radio communication was also reportedly disrupted in Japan, the US, and South Africa<sup>22,23</sup>.

Canadian scintillation receivers detected strong sigma-phi scintillation activity exceeding both moderate (0.4 rad) and severe (0.7) thresholds used to describe impact levels expected on GNSS navigation used by the aviation industry<sup>24</sup>. Single-frequency GNSS receivers, such as those used by aviation, are vulnerable to propagation errors caused by variations in

<sup>21</sup> <https://www.wapps.tc.gc.ca/saf-sec-sur/2/cadors-screaq/> (last accessed 06 August 2025).

<sup>22</sup> [https://www.unoosa.org/documents/pdf/psa/activities/2024/ISWI2024/ISWI2024\\_11\\_06.pdf](https://www.unoosa.org/documents/pdf/psa/activities/2024/ISWI2024/ISWI2024_11_06.pdf) (last accessed 06 August 2025).

<sup>23</sup> <https://www.swpc.noaa.gov/news/g5-conditions-reached-yet-again> (last accessed 06 August 2025).

<sup>24</sup> <https://store.icao.int/en/annex-3-meteorological-service-for-international-air-navigation-1> (last accessed 06 August 2025).

**Table 3.** CADORS report number, date, time, location, and narrative for issues attributed to space weather impacts to HF radio communications. Narrative entries have not been modified from the CADORS report.

| CADORS number | Date time (UT) | Location # aircraft     | Narrative                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|---------------|----------------|-------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2024C2966     | 20240511 10:07 | Nunavut<br>(1 aircraft) | A Societe Air France Boeing 777-300 (FGZNU/AFR163) from Tokyo/Haneda, Japan (RJTT) to Paris/Charles de Gaulle, France (LFPG) showed radio failure on automatic dependent surveillance - broadcast (ADS-B) and then climbed without a clearance.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| 2024C4190     | 20240514 11:38 | Nunavut<br>(1 aircraft) | A Lufthansa German Airlines Boeing (DLH717) from RJTT to EDDF was observed on surveillance display climbing from FL330 to FL350 without a clearance from air traffic control (ATC), and in close proximity to a boundary between Edmonton Area Control Center and Reykjavik Control Center. The event occurred when the flight was approximately 70 miles from entering Reykjavik Control Area. High Frequency (HF) conditions were very poor or blackout during this period. The flight may not have had any contact with ATC for several hours during this period. No data link connection was present, too far North. The aircraft may have been following North Atlantic Traffic (NAT) communication failure procedures.                                                                                                                       |
| 2024C4189     | 20240515 11:35 | Nunavut<br>(1 aircraft) | A Societe Air France Boeing (AFR291) from RJBB to LFPG was observed on surveillance display climbing from FL350 to FL370 without a clearance from air traffic control (ATC), and in close proximity to a boundary between Edmonton Area Control Center and Reykjavik Control Center. The event occurred when the flight was approximately 70 miles from entering Reykjavik Control Area. High Frequency (HF) conditions were very poor or blackout during this period. The flight had previously had positive data link connection with Edmonton area control centre (ACC). The aircraft may have been following North Atlantic Traffic (NAT) communication failure procedures. The obtained positive HF contact with Iceland Radio at the boundary or shortly after, with Reykjavik Control Center. (Second entry, 2024C4188, 20240515, 11:37 UT) |

the ionospheric electron density profile caused by space weather (e.g., Fisher et al., 2010). Mitigation is possible using satellite-based augmentation systems (e.g., El-Arini et al., 2001). In North America, corrections are provided by the Wide Area Augmentation System (WAAS) service, which estimates the ionospheric propagation delay using a network of dual-frequency reference stations using data for the GPS satellite constellation. WAAS is especially important during the flight approach phase by supporting vertically guided precision approach services such as localizer performance (LP), localizer performance with vertical guidance (LPV), and LPV to 200-foot decision height (LPV 200). Vertical approach guidance systems assist pilots in safely flying toward a runway to complete the approach to land visually. Strong ionospheric disturbances, such as those observed during the May 2024 event, can render these services useless, forcing aircraft crews to switch to alternative systems such as Lateral Navigation (LNAV), which can only guide a plane to 400–600 ft above the runway. When the cloud ceiling is low during such conditions, the pilot may miss their approach or be unable to land safely, resulting in the flight being rerouted, causing increased fuel usage and delays. Such impacts are especially serious in the Canadian north, where weather conditions frequently produce a low cloud ceiling, and flights are both infrequent and necessary to provide critical goods and services.

WAAS report #89<sup>25</sup> describes the 01 April – 30 June 2024 period of WAAS operation. According to this report, during a large period extending from 10–11 May 2024, the WAAS Extreme Storm Detector (ESD) tripped out for the first time since its inception in 2007. This caused loss of the WAAS vertical service between 20:55 UT 10 May 2024 and 10:22 UT

<sup>25</sup> [https://www.nstb.tc.faa.gov/reports/FAA\\_WAAS\\_PAN\\_Report\\_89\\_v1.0.pdf](https://www.nstb.tc.faa.gov/reports/FAA_WAAS_PAN_Report_89_v1.0.pdf) (last accessed 06 August 2025).

**Table 4.** Onset and end of periods of significant degradation to WAAS LPV and LPV 200 services over the continental US (CONUS), Alaska, and Canada during the May 2024 space weather event as reported by WAAS report #89.

| Region | Service | Onset, 10 May 2024<br>(UT) | End, 11 May 2024<br>(UT) |
|--------|---------|----------------------------|--------------------------|
| CONUS  | LPV     | 18:45                      | 10:45                    |
| CONUS  | LPV200  | 18:35                      | 10:40                    |
| Alaska | LPV     | 18:35                      | 10:35                    |
| Alaska | LPV200  | 18:25                      | 10:40                    |
| Canada | LPV     | 18:30                      | 10:30                    |
| Canada | LPV200  | 18:10                      | 10:30                    |

11 May 2024. Periods of significant degradation to the LPV and LPV 200 are listed in Table 4. Table 5 reports four instances where CADORS reports capture LPV degradation. The first three were observed May 10 at 19:33 UT over Saskatchewan and 20:00 UT over Nunavut and on May 11 at 02:00 UT over Nunavut. An additional instance at 23:28 UT on May 12 over Manitoba occurred likely due to the residual ionospheric activity. Impacts to the WAAS service and GNSS accuracy in general were also reported in the United States in relation to agriculture<sup>26</sup> and in other countries<sup>27,28</sup>.

<sup>26</sup> <https://www.deere.com/en/stories/featured/solar-storm/> (last accessed 06 August 2025).

<sup>27</sup> [https://www.unoosa.org/documents/pdf/psa/activities/2024/ISWI2024/ISWI2024\\_11\\_06.pdf](https://www.unoosa.org/documents/pdf/psa/activities/2024/ISWI2024/ISWI2024_11_06.pdf) (last accessed 06 August 2025).

<sup>28</sup> <https://www.farmprogress.com/planting/this-spring-s-solar-storm-could-cost-american-farms-500-million> (last accessed 06 August 2025).



**Table 5.** CADORS report number, date, time, location, and narrative for issues attributed to space weather impacts to GNSS, specifically localizer performance with vertical guidance (LPV). Narrative entries have not been modified from the CADORS report.

| CADORS number | Date time (UT) | Location # aircraft                      | Narrative                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|---------------|----------------|------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 2024C3562     | 20240510 19:33 | La Ronge, Saskatchewan (1 aircraft)      | A Rise Air de Havilland (C-FDGV/RS630T) from CYVC to CYVC and a Government of Canada, Royal Canadian Mounted Police Pilatus (C-GMPA) from CZWL to CYVC reported global navigation satellite system (GNSS) issues, loss of localizer performance with vertical guidance (LPV). Area Control Centre Shift Manager (CSM) advised.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| 2024C3141     | 20240510 20:00 | Rankin Inlet, Nunavut (multiple flights) | A Canadian North Boeing 737-406 (C-FFNF/AKT118) from Yellowknife, NT (CYZF) to Rankin Inlet, NU (CYRT) and a Nolinor Aviation Boeing 737-2B6C (C-GNLN/NRL947) from Meadowbank, NU (CMB2) to Rankin Inlet, NU (CYRT) reported a global navigation satellite system (GNSS) downgrade from localizer performance with vertical guidance (LPV) to lateral navigation (LNAV) on the area navigation (RNAV) Runway 31 and Runway 13 approaches, respectively. The beginning was at 30NM northwest of ONDOS on the latter approach. A Calm Air Aerospatiale ATR 42-320 (CAV234) from Yellowknife, NT (CYZF) to Rankin Inlet, NU (CYRT) and a Calm Air Aerospatiale ATR 42-320 (C-FMAK/CAV235) from Rankin Inlet, NU (CYRT) to Nauyasat, NU (CYUT) reported similar occurrences at CYUT and a Nolinor Aviation Boeing 737-200 (NRL946) from Rankin Inlet, NU (CYRT) to Meadowbank, NU (CMB2) at CMB2, between 1851Z and 2041Z. A Canadian North Boeing 737-400 (AKT152) from Winnipeg/James Armstrong Richardson, MB (CYWG) to Rankin Inlet, NU (CYRT) reported the same issue at 2325Z and stated they heard multiple aircraft with same issue at other airports on other frequencies. |
| 2024C2977     | 20240511 02:00 | Rankin Inlet, Nunavut (1 aircraft)       | A Calm Air Aerospatiale ATR 42-320 (C-FECI/CAV667) from Arviat, NU (CYEK) to Rankin Inlet, NU (CYRT) reported a global navigation satellite system (GNSS) downgrade from localizer performance with vertical guidance (LPV) to lateral navigation (LNAV) at 0146Z on the area navigation (RNAV) Runway 13 approach into CYRT.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| 2024C3097     | 20240512 23:28 | Thompson, Manitoba (3 aircraft)          | A Keewatin Air Beech B200 (C-FSAO/KEW214) from The Pas, MB (CYQD) to Thompson, MB (CYTH) reported a GNSS downgrade of localizer performance with vertical guidance (LPV) to lateral navigation (LNAV) after commencing the area navigation (RNAV) Runway 06 approach. Two subsequent aircraft reported similar experiences from 2328Z to 2343Z, including a Mississippi Air-Care Beech 200 (C-FICU/MA04) from Gods River, MB (CZGI) to Thompson, MB (CYTH) and a North Star Air Ltd. ATR-GIE ATR 72-212A (C-FNSN/BF502) from Rankin Inlet, NU (CYRT) to Thompson, MB (CYTH). All aircraft completed their approaches without incident. The centre shift manager was notified, advised no further action due to ongoing pertinent NOTAM. <i>[Notice to Airman is a notice filed with an aviation authority to alert aircraft pilots of potential hazards along a flight route or at a location that could affect the flight.]</i>                                                                                                                                                                                                                                                |

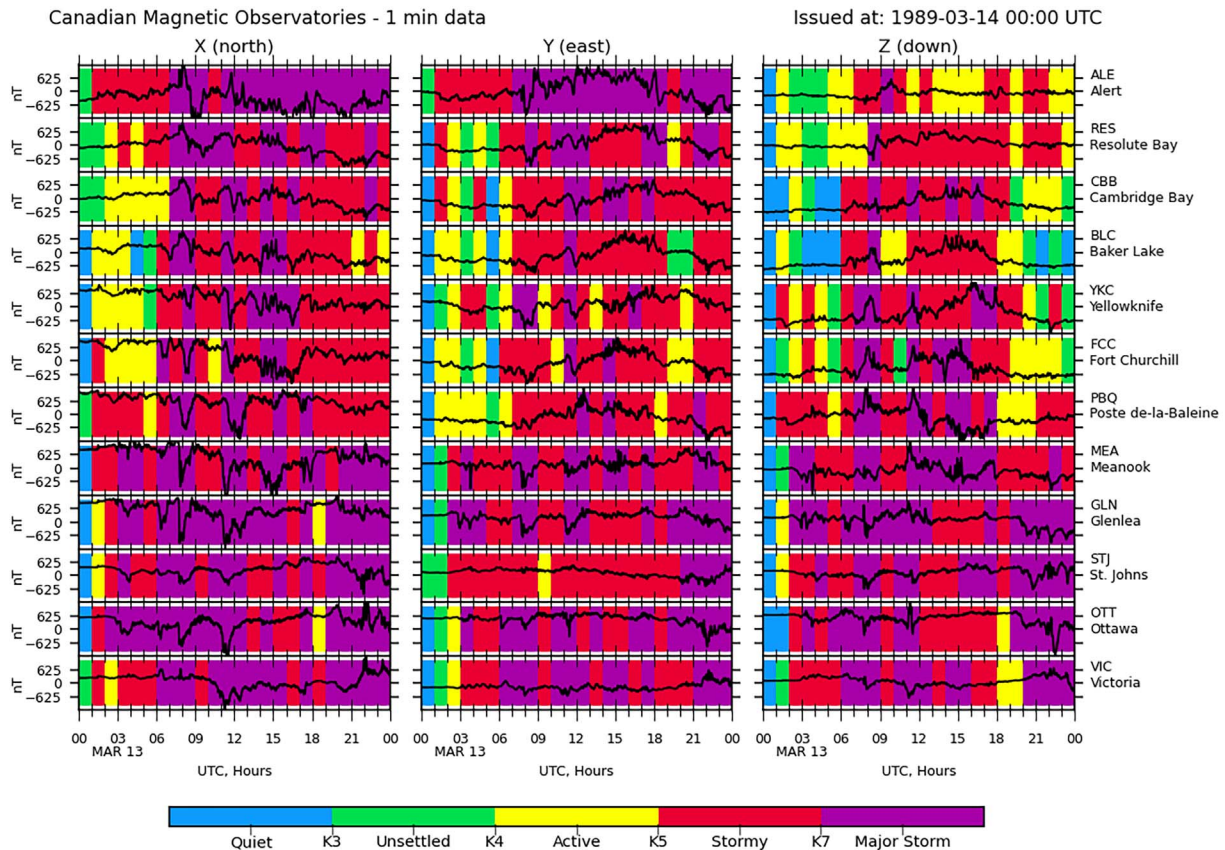
Some aircraft mitigate the need for satellite-based augmentation systems, such as WAAS, using multi-frequency GNSS receivers. However, these are also prone to space weather effects, such as loss of lock, that do not benefit substantially from augmentation systems.

## 6 Discussion

This paper describes the May 2024 space weather event from a Canadian perspective, detailing observations from Canadian space weather sensor networks and models, actions taken by the CSWFC, and observed impacts to HF radio communications and GNSS in Canada. Given the widespread impacts, it is interesting to contrast this event with the March 1989 space weather event affecting power systems. The March 1989 event spurred a huge amount of awareness, education,

research, and development, and collaborative efforts between space weather scientists and service providers with power utility companies around the world. Due to these efforts, power system operators in many countries were able to take precautionary measures during the May 2024 event, preventing system outages and impacts to the public.

There are many similarities between the space weather events in May 2024 and March 1989, as well as some key differences. Both events involved a series of solar flares being observed on the Sun and multiple coronal mass ejections being directed towards Earth. At the L1 point, the CMEs in May 2024 had solar wind speeds around 800 km/s and southward interplanetary magnetic fields up to 50 nT. Both these values are similar to those estimated for the March 1989 storm. These parameters indicate that conditions existed that enabled a strong transfer of energy between the solar wind and the Earth's magnetosphere.



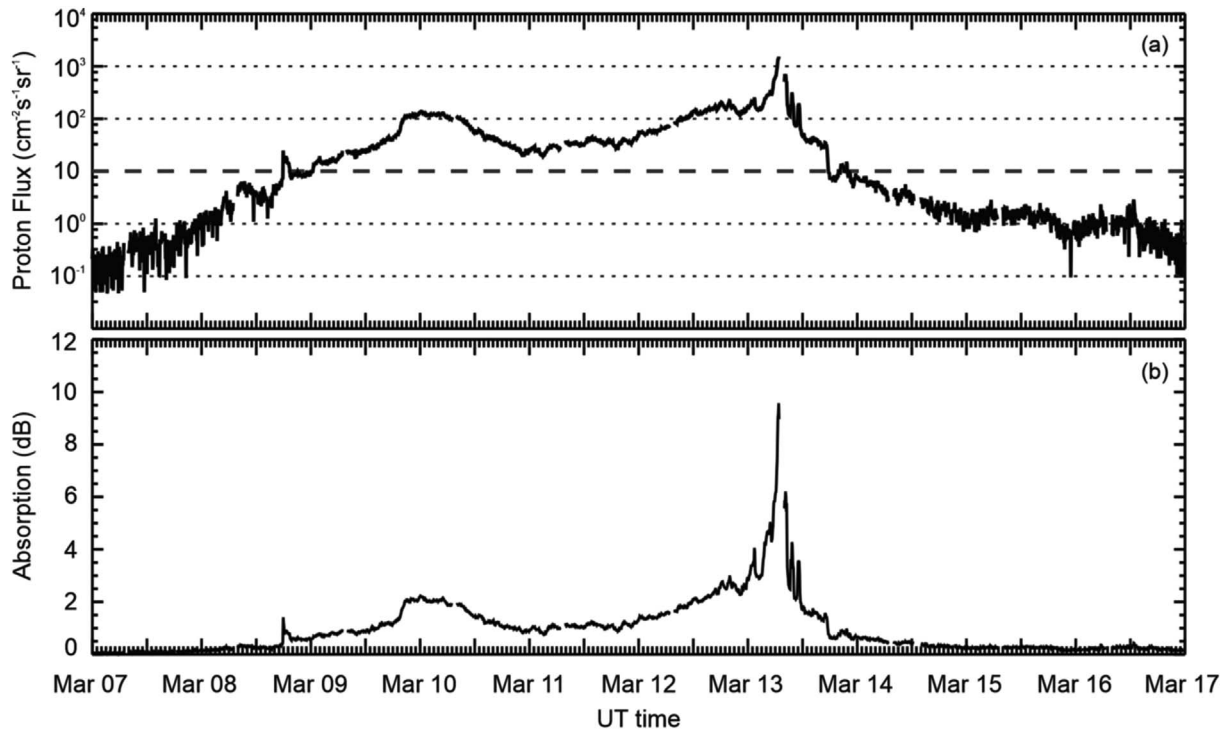
**Figure 10.** Review plot of magnetic field variations (black line) for 13 March 1989. The black line represents one-minute variations of X, Y and Z magnetic field components for NRCan's geomagnetic observatories. The observatories are ordered according to their geographic latitude, from the north (top) to the south (bottom). The color in the plot denotes geomagnetic activity where the activity is associated with the hourly range of magnetic field variations.

Based on several geomagnetic indices, the March 1989 event was stronger than the May 2024 event. The peak Dst, SYM-H, Kp, Hp30, and Hp60 were  $-589$  nT,  $-720$  nT, 9, 13+, and 13– for the March 1989 event and  $-412$  nT,  $-518$  nT, 9, 11+, and 11– for the May 2024 event. For both, Kp exceeded 8 for >20 h and saturated at Kp = 9 for ~3 h. With such strong activity observed for each storm, the major concern is the impact on power systems. The key parameter for impacts on electric power supply is the local magnetic disturbance and the geoelectric field experienced by a power system. Figures 4 and 10 show the geomagnetic variation during the peak of the May 2024 and March 1989 storms, respectively.

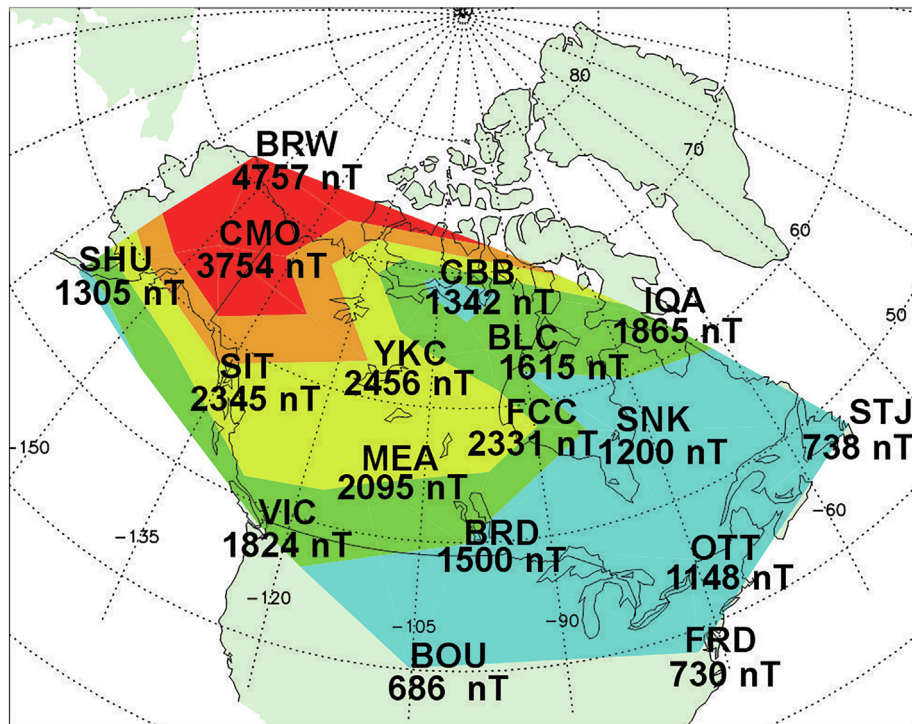
In March 1989, the early part of the disturbance was centred over the Hydro-Québec power system and produced geoelectric fields exceeding 1100 mV/km (Boteler, 2015). These caused GICs in the power system that saturated multiple transformers and created disturbances on the system that caused a system collapse (i.e., a power blackout; Guillon et al., 2016). In the evening of 10 May 2024, magnetic disturbances of similar size to those of March 1989 were observed at the Ottawa magnetic observatory; however, this is estimated to have only produced geoelectric fields of 800 mV/km. More significantly, though, this disturbance was produced by an auroral electrojet south of the NRCan magnetometer network, and therefore south of Canada. This means the peak disturbance was not centred over

the Hydro-Québec power system as it was in March 1989. It also shows that the auroral oval had expanded significantly and had taken the peak of the magnetic disturbance into the United States. A similar thing happened later in the March 1989 storm, and the resulting GIC burnt out several power transformers at substations on the east coast of the US (Balma, 1992).

GNSS was not a widely used technology in 1989, and its impacts are therefore not well documented. Impacts to HF radio communications can be compared between the March 1989 and May 2024 events, both of which featured significant polar cap absorption. Figures 2 and 11 show the >10 MeV solar proton flux for the May 2024 and March 1989 events, respectively. Both events are multi-peaked and are attributed to multiple solar proton eruptions. The March 1989 event was notably bigger, peaking at >1000 pfu, compared to 206.9 pfu for the May 2024 event, with absorption exceeding the >1 dB threshold for most of the time, 09–14 March 1989. Although there are no corresponding CADORS reports indicating impacts on aviation, there are several anecdotal examples reported in the literature. Allen et al. (1989), for example, report degradation to HF radio communications systems used by the US Coast Guard and US Navy. Based on these reports, it is a reasonable expectation that communications would have been impacted at northern latitudes in Canada.



**Figure 11.** (a) GOES 07 solar proton flux in the  $>10$  MeV channel. Horizontal dashed line indicates the  $10 \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$  typically used to indicate the onset of a solar proton event based on the  $>10$  MeV solar proton flux. (b) Maximum northern hemisphere polar cap absorption at 30 MHz modelled using the Fiori & Danskin (2016) “non-optimized model” at 5-minute increments. Data are for 07–16 March 1989.



**Figure 12.** (a) Maximum geomagnetic field variation observed during the May 2024 event. See also Table 6.



**Table 6.** Geographic and geomagnetic latitude and maximum hourly range variation observed during the May 2024 event for NRCan and USGS magnetometer stations. Also provided are the maximum hourly range for solar cycles 21 (March 1976 – August 1986), 22 (September 1986 – July 1996; which includes the March 1989 event), 23 (August 1996 – November 2008), 24 (December 2008 – November 2018), and 25 (December 2018 – June 2024; noting that this is only a half solar cycle).

| Latitude (°) |            | Station     |      | Maximum hourly range (nT) |             |      |      |      |    |
|--------------|------------|-------------|------|---------------------------|-------------|------|------|------|----|
| Geomagnetic  | Geographic |             |      | May 2024 event            | Solar cycle |      |      |      |    |
|              |            |             |      |                           | 21          | 22   | 23   | 24   | 25 |
| 47.4         | 38.2       | FRD (USGS)  | 730  | –                         | –           | 1211 | 230  | 730  |    |
| 47.9         | 40.1       | BOU (USGS)  | 686  | –                         | –           | 680  | 348  | 686  |    |
| 53.8         | 48.5       | VIC (NRCan) | 1824 | 1590                      | 1200        | 1323 | 537  | 1824 |    |
| 54.4         | 55.3       | SHU (USGS)  | 1305 | –                         | –           | 736  | 883  | 1305 |    |
| 54.6         | 54.6       | MEA (NRCan) | 2095 | 3448                      | 2110        | 3026 | 1511 | 2304 |    |
| 54.9         | 45.4       | OTT (NRCan) | 1148 | 1928                      | 2047        | 2178 | 766  | 1148 |    |
| 56.4         | 47.6       | STJ (NRCan) | 738  | 2245                      | 1163        | 1178 | 627  | 738  |    |
| 58           | 49.8       | BRD (NRCan) | 1500 | 2222                      | 2102        | 2043 | 1325 | 1500 |    |
| 60.1         | 57.1       | SIT (USGS)  | 2345 | –                         | 1986        | 2051 | 2067 | 2420 |    |
| 65.5         | 64.9       | CMO (USGS)  | 3754 | –                         | –           | 3401 | 2689 | 3754 |    |
| 65.9         | 56.5       | SNK (NRCan) | 1200 | –                         | 2414        | 3058 | 2109 | 1200 |    |
| 67.3         | 58.7       | FCC (NRCan) | 2331 | 2728                      | 2588        | 3443 | 1736 | 2331 |    |
| 68.6         | 62.5       | YKC (NRCan) | 2456 | 2555                      | 2255        | 2204 | 2431 | 2617 |    |
| 69.86        | 71.3       | BRW (USGS)  | 4757 | –                         | –           | 4632 | 3237 | 4757 |    |
| 72.7         | 64.3       | BLC (NRCan) | 1615 | 2267                      | 2670        | 2575 | 2334 | 1615 |    |
| 73.3         | 63.8       | IQA (NRCan) | 1865 | –                         | –           | 4894 | 1890 | 1865 |    |
| 76.2         | 69.1       | CBB (NRCan) | 1342 | 1927                      | 2182        | 2652 | 1964 | 1791 |    |

The severity of the May 2024 event can be described using extreme value statistics. [Elvidge & Themens \(2024\)](#) present such an analysis based on several geomagnetic indices. They conclude the storm's magnitude and duration were 1-in-12.5 and 1-in-41-year events, respectively.

Geomagnetic activity during the May event was evaluated by comparing the maximum hourly range against the maximum value in observed each solar cycle. [Figure 12](#) and [Table 6](#) indicate the maximum hourly range for the May event observed by NRCan and USGS stations. Roughly speaking, the maximum geomagnetic perturbation for the May event increases from southeast to northwest. Also listed in [Table 6](#) are the maximum hourly range observed during solar cycles 21 (March 1976 – August 1986), 22 (September 1986 – July 1996; which includes the March 1989 event), 23 (August 1996 – November 2008), 24 (December 2008 – November 2018), and 25 (December 2018 – June 2024; noting that this is only a half solar cycle).

Geomagnetic variations during the May 2024 event were enhanced for the central ( $\sim 50^\circ$ – $70^\circ$ ) geomagnetic latitudes. The strongest perturbations of  $>3000$  nT were observed at the Alaskan CMO (3754 nT) and BRW (4757 nT) stations at  $65.5^\circ$  and  $69.9^\circ$  geomagnetic latitude, respectively. These values are higher than the maximum values reported for solar cycles 23 and 24 and represent maximum values for the partial solar cycle 25. Values exceeding 2000 nT were observed at the YKC (2456 nT), SIT (2345 nT), FCC (2331 nT), and MEA (2095 nT) stations south and east of the strongest perturbations. Each of these four stations observed maximum perturbations during the May 2024 event that were below the maximum values observed in previous cycles. At MEA, the maximum perturbation was observed in solar cycle 21, and values greater than the May event were observed in solar cycles 22, 23, and 25. The maximum hourly range for the May event observed

at the SIT station exceeded values for solar cycles 22–24, but not solar cycle 25. At FCC, the May event observed the maximum hourly range for partial solar cycle 25, but larger values were observed in solar cycles 21–23. At YKC, hourly ranges during solar cycles 21 and 25 exceeded the May event maximum.

Stations located in the western sub-auroral parts of Canada and the US observed somewhat lower maximum perturbations during the May event. The SHU, VIC, and BOU stations observed peak values of 883 nT, 1824 nT, and 686 nT, respectively. Although lower than the perturbations observed across the auroral zone, these values exceed the maximum perturbation observed during solar cycles 23–24 at BOU and SHU and solar cycles 21–24 at VIC.

Geomagnetic variations are attributed to local ionospheric current enhancements and energetic particle precipitation and generally have both a latitude and MLT dependence with local maximum values observed near 00 MLT under the auroral oval. The 08–09 UT hour on May 11, when the maximum geomagnetic activity was observed at most stations, corresponds to the 23–24 MLT hour at VIC. VIC, SHU, SIT, CMO, and BRW are located between 21 and 24 MLT and observed maximum perturbations during the May event that exceed previous solar cycle maxima. The only other station with similar observation is the BOU station located at sub-auroral latitudes. Maximum values at the low latitude VIC (1824 nT) and BOU (686 nT) stations stand out as these are atypical values at sub-auroral latitudes, as demonstrated by the past solar cycle maxima. Such values are more commonly observed at auroral zone stations such as, for example, BLC, FCC, and SNK, which are located under typical auroral latitudes and observed maximum magnitude variations of 1200 nT – 2331 nT. Although these perturbations are considered strong for the sub-auroral region, they are typical for the auroral region.

An extreme value analysis, like that already done based on geomagnetic indices, would be interesting to perform based on the geomagnetic hourly range. However, because of the latitude and MLT dependencies demonstrated by the maximum hourly range values, it is likely that such an analysis would result in independent statistics (e.g., rate of recurrence) for each station, rather than a single statistic for the entire event. A review of Table 6 shows that for the seven stations that observed peak activity in the first half of solar cycle 25 during the May event, this peak represents the highest value observed in at least the previous 2.5 (BOU, SHU, CMO, BRW), 3.5 (SIT), or 4.5 (VIC, YKC) solar cycles indicating the event recurrence ranges from roughly 1-in-28 to 1-in-50 years, although a shorter recurrence cycle could be possible for other stations. Normalization of extreme value analysis studies by MLT is a recommended topic for future consideration and could assist in developing a single return period based on local geomagnetic activity.

Operational space weather services like those provided by the CSWFC play an important role in supporting critical infrastructure and industry to protect against and mitigate the effects of space weather on technologies. This is done by nowcasting and forecasting geomagnetic and ionospheric disturbances, enabling situational awareness and planning, and distributing alerts, watches, and warnings to notify users when impacts are most likely. The Canadian power industry, having experienced problems, including a blackout of the Hydro-Québec power system during the magnetic storm of March 1989, is an excellent example of the development of user-driven space weather services. That event spurred a huge amount of awareness, education, research, and development, and collaborative efforts between space weather scientists and service providers with the power utility companies in North America and elsewhere. Because of these efforts, power system operators in many countries were able to take preventive measures during the May event, avoiding system outages and impacts to the public.

Canadian systems primarily impacted during the May 2024 event were HF radio communications and GNSS positioning and navigation, including LPV approaches reliant on WAAS. Country-wide riometer and GNSS networks exist, see Figure 1, to provide an overall characterization of ionospheric conditions affecting these technologies. Due to harsh environmental conditions and low population density in some regions, stations are too sparsely distributed to support observation of some small-scale features or instantaneous modelling of the phenomena. However, the data are useful to constrain existing models based on geomagnetic indices or satellite data and for the development of climatological models that can fill in the gaps. Increasing Arctic activity reliant on HF radio communications and GNSS for positioning, navigation, and timing, including marine traffic and circumpolar flight paths, has escalated the need for more reliable situational awareness and network densification at high latitudes. Future work is also needed to develop more accurate forecasts of the duration of absorption and GNSS scintillation events, and to forecast activity likely to impact HF radio communications and GNSS signals. Also, of increasing importance to GNSS users is the development of techniques to assess the impacts (e.g., position error) and the identification of space weather events versus jamming/spoofing to better ensure safe

flight paths, maritime navigation, military surveillance, and emergency response.

## 7 Summary and conclusions

This paper presents the May 2024 event from a Canadian perspective, demonstrating how the CSWFC monitors, models, and analyzes space weather data to characterize space weather phenomena and generate space weather forecasts and alerts to mitigate space weather impacts. Canada's geographic extent and geomagnetic location put it in a unique position to observe a wide range of space weather phenomena spanning the polar cap, auroral, and sub-auroral regions across roughly 6 h of magnetic local time. Both geomagnetic and ionospheric disturbances were observed by Natural Resources Canada's sensor networks. Strong geomagnetic perturbations were observed 11–13 May 2024 in the auroral and sub-auroral regions, with isolated intervals of geomagnetic variations  $>1000$  nT. The resulting geoelectric field variations of  $\sim 300$  mV/km were calculated to extend into the southern US (Texas) during the peak of the storm, with parts of northwest Canada and northeast US experiencing  $>1000$  mV/km. The riometer network observed responses to shortwave fadeout, auroral absorption, and polar cap absorption with absorption at 30 MHz exceeding 1 dB for  $\sim 48$  h beginning midday May 10 and  $\sim 24$  h beginning the afternoon of May 13. Enhanced phase scintillation was observed with values exceeding 0.4 rad, and often  $>0.7$  rad beginning at  $\sim 17$  UT May 10 for roughly 24 h, with the strongest enhancements observed in the western and central parts of Canada. The geoeffectiveness of nine CMEs that erupted on 08–11 May was evaluated using Sun-to-Earth simulations. Model runs predicted an initial 17:59 UT impact on May 10, very close to the actual arrival at 17:05 UT. The arrival of the final CME was predicted to be at 02:30 UT on May 11. Based on observations from ground-based riometers, reports found in Transport Canada's Civil Aviation Daily Occurrence Reporting System and the loss of the Wide Area Augmentation System (WAAS), impacts to HF radio communications and GNSS-reliant services occurred throughout Canada, with the strongest impacts observed during the peak of the solar proton event and highest geomagnetic activity 10–11 May.

The CSWFC issued several space weather statements, major geomagnetic storm WATCH and WARNINGS, a solar energetic particle WARNING, and several ionospheric advisories throughout the event. Based on observed and anticipated geomagnetic activity, a major geomagnetic storm WATCH was issued on May 09, beginning 17:00 UT May 10. The initial WATCH ended at 19:00 UT May 11, but was extended throughout the event, eventually ending at 13:00 UT May 13. A major geomagnetic storm WARNING was issued at 17:17 UT May 10 for the auroral region and was expanded to cover all of Canada at 18:42 UT, persisting for 24 h. Shorter 2-hour warnings were issued beginning at 04:37 UT May 12 for the entire Canadian region and 03:17 UT May 13. Additionally, a solar energetic proton WARNING was issued from 13:45 UT May 10 until 13:00 UT May 12. Several ionospheric advisories were also issued to note degradation to HF radio communications and GNSS accuracy.

Geomagnetic activity during the May event across Canada and the US was considered using the magnetic field hourly range. Geomagnetic variations were shown to increase from the southeast to the northwest. Based on a comparison of the maximum hourly range observed during both the May event and during solar cycles 21–24 and the first half of solar cycle 25 (until June 2024), the geomagnetic variations were shown to have a rate of recurrence that varied across North America due to the latitude and magnetic local time dependence on the phenomenon driving the geomagnetic perturbations.

Although the May 2024 event was less intense than the March 1989 event, such events do contribute to large event statistics, allowing the establishment of operational benchmarks to work toward building resiliency in critical infrastructure and technologies to space weather.

## Acknowledgments

The authors thank NAV CANADA for providing additional context regarding impacts to HF radio communications and GNSS reported in CADORS. The work utilizes data obtained by the Global Oscillation Network Group (GONG) Program, managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofísica de Canarias, and Cerro Tololo Interamerican Observatory. Data from the Deep Space Climate Observatory (DSCOVR), Advanced Composition Explorer (ACE), Solar Dynamics Observatory (SDO), and Solar and Heliospheric Observatory (SOHO) satellites are acknowledged. The editor thanks Christian Möstl and an anonymous reviewer for their assistance in evaluating this paper.

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## Data availability statement

Geomagnetic data from NRCan observatories can be retrieved from <https://www.spaceweather.gc.ca/data-donnee/geomag/sd-en.php>, or from the International Real-time Magnetic Observatory Network (INTERMAGNET) at <https://intermagnet.org>. US magnetic observatories are operated and maintained by the US Geological Survey (USGS), and data may be retrieved from INTERMAGNET.

The geoelectric field maps presented in this paper were created through the US-Canada-1D electric field mapping project, which is a joint effort between NOAA and NRCan. Maps presented in this paper were generated by NRCan and are similar to geoelectric field maps generated in near real time that can be retrieved from <https://www.swpc.noaa.gov/products/geoelectric-field-models-1-minute>.

Monthly averages of the 10.7 cm solar radio flux were retrieved from <https://www.spaceweather.gc.ca/forecast-prevision/solar-solaire/solar-flux/sx-5-mavg-en.php>. The 10.7 cm solar radio flux is provided as a service by the National Research Council of Canada, with the participation of Natural Resources Canada and support by the Canadian Space Agency.

Statistics on the occurrence of historic solar X-ray flares were obtained from the GOES X-Ray Sensor reports (<https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/>), after having calibrated the flare magnitude according to the GOES X-ray Sensor (XRS) Operational Data report version 1.5 ([https://ngdc.noaa.gov/stp/satellite/goes/doc/GOES\\_XRS\\_readme.pdf](https://ngdc.noaa.gov/stp/satellite/goes/doc/GOES_XRS_readme.pdf)).

GOES data were retrieved from the NOAA National Centers for Environmental Information (<https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html>) for the March 1989 event and from NOAA Space Weather Prediction Center's json service (<https://services.swpc.noaa.gov/json/>) for the May 2024 event.

IMF and solar wind parameters were captured from graphics produced by NOAA SWPC here: <https://www.swpc.noaa.gov/products/real-time-solar-wind>.

Canadian regional conductivity models are described in Trichtchenko et al. (2019a, 2019b). US regional conductivity models were provided by the Electric Power Research Institute (EPRI Product ID 3002019435, June 08, 2020, Use of magnetotelluric measurement data to validate/improve existing Earth conductivity models).

The GONG synoptic maps, used for the solar wind – CME simulations, are available from <https://magmap.nso.edu>.

Information about CMEs was obtained using the SOHO LASCO instrument (<https://soho.nascom.nasa.gov/data/data.html>), CACTus automated CME detection software (<https://www.sidc.be/cactus/>), observations of the solar corona by the SDO (<https://sdo.gsfc.nasa.gov/data/>) and STEREO (<https://stereo-ssc.nascom.nasa.gov>) satellites. Further, the SOHO LASCO CME catalog ([https://cdaw.gsfc.nasa.gov/CME\\_list/](https://cdaw.gsfc.nasa.gov/CME_list/)) was used for the CME comparison. The CACTus CME catalog is generated and maintained by the SIDC at the Royal Observatory of Belgium.

Transport Canada's CADORS reports were obtained from <https://wwwapps.tc.gc.ca/saf-sec-sur/2/cadors-screaq/>. Daily maps of the WAAS service coverage over North America and quarterly performance analysis reports, including periods of service degradation, are available from the Federal Aviation Authority at <https://www.nstb.tc.faa.gov/>.

Sudden commencement timing was obtained from the international service on rapid magnetic variations, housed at Ebre Observatory as part of the International Service of Geomagnetic Indices (ISGI). <https://www.obsebre.es/en/variaciones/rapid>. SC list for 1989 and 2024 (last accessed July 2025).

## Supplementary material

*S1: Model of geoelectric field 10–12 May 2024:* Model of geoelectric field 10–12 May 2024.mp4 movie shows geoelectric fields mapped across North America for 10–12 May 2024. The maximum calculated electric field and the number of contributing magnetic observatories at each time step are indicated in the top right and the bottom right of each frame, respectively. Geoelectric fields were calculated from interpolated NRCan and USGS magnetic field measurements combined with regional conductivity models for geologically distinct regions across North America.

*S2: Propagation of CMEs through the background solar wind in interplanetary space:* CME-Simulations-Velocity-XY.mp4 movie shows the solar wind speed in the XY plane (HEEQ coordinate system) of the interplanetary space during 06–14 May. 9 CMEs from 08–11 May (Table 2) were used in the simulations. Earth is located close to the right edge of the simulation domain. The solar wind speed scale is saturated at 700 km/s.

The supplementary material of this article is available at <https://www.swsc-journal.org/10.1051/swsc/2025037/olm>.

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