

Article

Investigation of the Ionospheric Response on Mother's Day 2024 Geomagnetic Superstorm over the European Sector

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Abstract: The present study examines the negative ionospheric response over Europe during two geomagnetic storms on 10–13 May 2024, known as the Mother's Day geomagnetic superstorm. The first storm, with a peak SYM-H value of -436 nT, occurred in the interval 10–11 May, while the second, less intense storm (SYM-H ~ -103 nT), followed in the interval 12–13 May. Using data from four European locations, temporal and spatial variations in ionospheric parameters (TEC, foF2, and hmF2) were analyzed to investigate the morphology of the strong negative response. Sharp electron density (Ne) depletion is associated with the equatorward displacement of the Midlatitude Ionospheric Trough (MIT), confirmed by Swarm satellite data. A key finding was the absence of foF2 and hmF2 values over all ionosonde stations during the recovery phase of the storms, likely due to the coupling between the Equatorial Ionization Anomaly (EIA) crests and the auroral ionosphere influenced by the intense uplift of the F layer. Relevant distinct features such as Large-scale Travelling Ionospheric Disturbance (LSTID) signatures and Spread F were also noted, particularly during the initial and main phase of the first storm over high midlatitude regions. Regional effects varied, with high European midlatitudes exhibiting different features compared to lower European latitude areas.

Keywords: Mother's Day 2024 geomagnetic super storm; midlatitude ionospheric response; midlatitude ionospheric trough; travelling ionospheric disturbances



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1. Introduction

The recent severe geomagnetic storm on 10–13 May 2024 was one of the six greatest recorded storms since 1957 (when the Dst index was first estimated, [1]) as seen in Table 1. Often referred to as the “Mother's Day Storm, 2024”, this intense space weather event has gathered considerable attention due to its profound ionospheric and geospace impact. The storm was so intense that it generated auroras visible as far as $\sim 35^\circ$ N [2] and $\sim 37^\circ$ S [3] at both hemispheres. Spogli et al., 2024 [4] were among the pioneers in documenting space weather effects in the Mediterranean region, with a focus on Italy. Their analysis highlighted a notable ionospheric impact following the geomagnetic storm, characterized by a significant drop in plasma density on 11 May. This led to a pronounced negative ionospheric storm, evident in foF2 and TEC measurements. The observed negative ionospheric

phases were linked to changes in the neutral composition of the thermosphere, reflected by a reduced [O/N₂] ratio. Remarkably, Gonzalez-Esparza et al., 2014 [5] even documented polar auroras over Mexican low latitudes on 10 May 2024. The Mexico Space Weather Service (SCIESMEX) and the National Space Weather Laboratory (LANCE) proved critical in monitoring this event. LANCE's extensive instrumentation recorded diverse phenomena, including solar chromospheric images, radio bursts, geomagnetic variations, Schumann resonances, ionospheric disturbances, and energetic particle flows. It also tracked Geomagnetically Induced Currents (GICs) at four strategic substations of the national electrical grid, offering unprecedented insight into severe space weather dynamics in North America's low-latitude regions. Foster et al., 2024 [2] used total electron content (TEC) data from Global Navigation Satellite System (GNSS) receivers, magnetometers, and citizen science auroral observations to map the ionospheric effect of the storm period. They provided a detailed view of an intense auroral breakup and westward surge during the storm's peak (10–11 May). They observed that over a 20 min interval, TEC increased unusually at low latitudes (~45°) and rapidly expanded azimuthally across the continent. The colocation of intense red auroras with the leading edge of the equatorward and westward TEC enhancement revealed that low-energy particle precipitation during substorm breakups drove these large-scale TEC increases. At higher latitudes, Themens et al., 2024 [6] analyzed the ionospheric evolution using TEC, Incoherent Scatter Radar, and ionosonde data. They observed plasma uplifting within the Storm Enhanced Density (SED) plume, with ionospheric peak heights rising by 150–300 km to nearly 630 km. Scintillations in the GNSS L-band emerged during the storm's expansion phase, spreading across the auroral oval. Singh et al., 2024 [7] focused on the Peruvian sector, utilizing Jicamarca incoherent scatter radar to examine equatorial and low-latitude ionospheric responses. Their findings showed a dramatic increase in electron density (Ne) within latitudes of ~20° S to 50° S during the onset of the storm. Bojilova et al., 2024 [8] studied the global ionospheric response, with a focus on the hemispheric asymmetries at mid and high latitudes, influenced by particle precipitation and neutral atmospheric temperature changes. They also investigated low-latitude effects related to the Equatorial Ionospheric Anomaly (EIA) and disturbed dynamo electric fields (DDEFs). Over the Indian equatorial sector, Thampi et al., 2024 [9] observed a pronounced super-fountain effect driven by prompt penetration electric fields (PPEFs) and pre-reversal enhancement (PRE) electric fields. They reported significant equatorial fountain intensification and, for the first time, in situ evidence of electron temperature increases in the evening equatorial ionosphere during an extreme geomagnetic storm, aligning with the latitudinal extent of the super-fountain effect. Gao et al., 2024 [10] conducted a detailed investigation of the F-region ionospheric storm effects predominantly over middle and low latitudes in the East Asian region during the Mother's Day superstorm 2024, utilizing various datasets such as GNSS TEC, an ionosonde network, Ne profiles from Radio Occultation (RO) measurements, [O/N₂] ratios, and other model observations. They identified the negative ionospheric storm effect as a substantial and prolonged Ne depletion, immediately after the Sudden Storm Commencement (SSC) on 10 May and persisting through the main and early recovery phases of the storm on 11 May. They observed positive regional storm effects on 11–12 May from post-midnight to sunrise, initially over eastern China and later over central regions followed by a pronounced negative storm during later recovery stages. In contrast, the western regions of China exhibited a positive storm effect on 12 May followed by a comparatively mild negative storm.

Table 1. List of severe and Great Geomagnetic storms since 1957.

<i>Date</i>	<i>Year</i>	<i>Dst (nT)</i>	<i>Class</i>
10–13 May 2024	2024	−412	Great
17–18 March 2015	2015	−234	Severe
20–21 November 2003	2003	−383	Severe
29–31 October 2003	2003	−353	Severe
6–7 November 2001	2001	−292	Severe
24–25 November 2001	2001	−221	Severe
6–7 April 2000	2000	−288	Severe
15–16 July 2000	2000	−301	Severe
8–9 November 1991	1991	−354	Severe
9–13 March 1989	1989	−589	Great
25–26 May 1967	1967	−387	Great
15–16 July 1959	1959	−429	Great
11 February 1958	1958	−425	Great
4–5 September 1957	1957	−324	Severe
13–14 September 1957	1957	−427	Great
21–23 September 1957	1957	−303	Severe
29–30 September 1957	1957	−246	Severe

In this context, the present analysis aims to provide insight into the May 2024 storm event over the European sector by exploiting ionospheric GNSS, ionosonde, and Swarm observations. The present article is organized into five sections. Section 1 provides a brief overview and highlights published studies on the 2024 Mother’s Day superstorm. Section 2 details the data sources and methodology. The results are presented in Section 3, while Section 4 provides a discussion of the findings w.r.t. physical processes driving storm-induced ionospheric variability. Finally, Section 5 concludes with a summary of key observations and insights.

2. Data and Methods

As the first step in our investigation, we used Solar and Solar Wind data from the Solar and Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronagraph (LASCO)/C2 (<https://soho.nascom.nasa.gov/data/data.html> accessed on 23 May 2024) for 10–13 May 2024 to examine solar activity.

Prevailing geomagnetic conditions during the storm were characterized by a high-resolution (1 min) OMNI dataset obtained from the Goddard Space Flight Center (<http://omniweb.gsfc.nasa.gov> accessed on 23 May 2024) and International Service of Geomagnetic Indices Centre (https://isgi.unistra.fr/indices_asy.php accessed on 23 May 2024).

We examined the temporal variation of foF2 and hmF2 ionospheric characteristics over four European Digisonde stations by exploiting ionospheric observations from the Digital Ionogram DataBase (DIDBase) of the Global Ionospheric Radio Observatory (GIRO) portal (<http://giro.uml.edu> accessed on 21 May 2024). We manually scaled ionograms extracting foF2 and hmF2 values during the event. In general, it is widely accepted in the ionospheric community that peak characteristics (foF2, hmF2) out of manual-scaled ionograms are more accurate than in the case of auto-scaled ionograms. However, the differences are not expected to exceed 0.7 MHz and 50 km, respectively, as a worst-case scenario [11]. Nevertheless, manual scaling was considered necessary as the error in some of the values of the auto-scaled characteristics was significant and could be misinterpreted as unrealistic disturbances. Based on past papers comparing manual and auto-scaled foF2-hmF2 values on a long time series on a monthly basis, statistically, the differences are insignificant, but since the present study addresses storm-time variations, we considered manual-scaling crucial.

Vertical TEC variation over GNSS stations collocated with Digisonde stations was also analyzed. RINEX files to estimate TEC data were retrieved from the International GNSS Service (IGS) (<http://igs.org/> accessed on 22 May 2024) and the EUREF Permanent Network (<http://www.epncb.oma.be/> accessed on 22 May 2024). TEC was estimated

with a calibration algorithm [12] based on phase delay between dual-frequency signals broadcasted from each Global Positioning System (GPS) satellite. Vertical TEC (hereafter TEC) was calculated at a 5 min resolution. Regarding TEC measurement maps, we have to point out that these are the result of an estimation process that depends on two aspects of uncertainties. The error is due to the interpolation of TEC data, which depends on the density of the stations and the error in estimating the exact TEC over a station, for which there is no standard technique to be known other than a number of comparison studies with the altimeter satellite mission used as a benchmark. Such studies define the possible errors in the order of a few TEC units. In our study, we are exploiting TEC maps over an area with thousands of stations over Europe, which means that possible errors will be at a minimum. Figure 1 shows a map of Digisonde and GNSS stations, with the respective coordinates presented in Table 2.

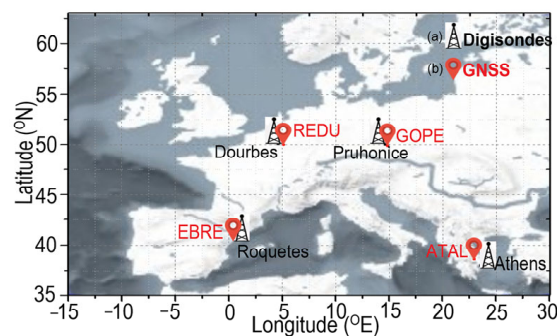


Figure 1. Map showing the locations of (a) Digisonde stations (black marker) and (b) the GNSS receiver stations (red marker).

Table 2. Coordinates of the Digisonde stations and collocated GNSS receivers.

Digisonde Stations			Collocated GNSS Receivers		
Station Name	Geographic Latitude (° N)	Geographic Longitude (° E)	GNSS Code	Geographic Latitude (° N)	Geographic Longitude (° E)
Pruhonice	50	14.6	GOPE	49.9	14.8
Dourbes	50.1	4.6	REDU	50.0	5.1
Roquetes	40.8	0.5	EBRE	40.8	0.5
Athens	38	23.5	DYNG	38.6	22.9

The spatial variation of TEC across an extended European area was analyzed using ionospheric maps by the Royal Observatory of Belgium (ROB). These maps leverage data from the dense EUREF Permanent GNSS Network (EPN). ROB generates vertical TEC maps over Europe, providing estimates of ionospheric variability in near real time. These maps are updated every 5 min on a $0.5^\circ \times 0.5^\circ$ grid using multi-GNSS (GPS + GLONASS + GALILEO) observations and are accessible online with a latency of approximately 3 min, either in IONEX format at www.gnss.be/SpaceWeather/Products/IONEX or displayed on the web pages at www.gnss.be/SpaceWeather/ (accessed on 22 May 2024). The accuracy of the ROB TEC maps has been validated against widely used post-processed products, such as those from IGS and ESA, with mean differences of 1.3 ± 0.9 TECu and 0.4 ± 1.6 TECu, respectively. A comprehensive description of the ROB-TEC mapping methodology and its applications is provided by Bergeot et al., 2014 [13].

Additionally, thermospheric composition data, specifically the ratio of atomic oxygen (O) to molecular nitrogen (N_2), from the GUVI instrument were used. These data, covering the period from 10–13 May, were accessed from the data repository (http://guvitimed.jhuapl.edu/data_products accessed on 23 May 2024).

In addition, we analyzed Swarm A and B satellite in situ Ne measurements from Langmuir probes provided through <https://vires.services/> (accessed on 23 May 2024).

The ESA Swarm mission comprises a constellation of three identical satellites (Swarm A, B, and C) at low-altitude polar orbits operating since 2014. The initial orbit heights were at ~465 km (Swarm A and C) and ~520 km (Swarm B) at an inclination of 87.35° for Swarm-A/C and 87.75° for Swarm-B. Regarding SWARM Ne datasets, there is evidence of uncertainties in their measurements, but only over low solar activity intervals and high- and low-latitude areas, which is not the case with our area or interval of interest [14–16].

To analyze Travelling Ionospheric Disturbance (TID) activity during the onset of the storm period, data from the Ionospheric Expert Weather Service Centre (I-ESC) portal of ESA (https://www.esa.int/Space_Safety/Space_weather accessed on 24 May 2024) were utilized. This portal provides data on the TechTIDE project. TechTIDE warning services, as described by Belehaki et al., 2020 [17], integrate several real-time detection methodologies, including Digisonde-based techniques such as the height-time-reflection intensity (HTI) [18], the Digisonde-to-Digisonde TID detection (HF-TID), HF Interferometry (HF-INT), Doppler Sounder detection (CDSS-MSTID), and the TaD ionospheric profiler model, which calculates the Large-Scale TID index (LSTIDx) using Digisonde and GNSS-TEC data. Additional methods, such as the Spatial and Temporal GNSS analysis for the MSTID index (MSTIDidx), GNSS TEC Gradient (TECgrad), and Along-the-Arc TEC Rate (AATR) indicators, rely solely on GNSS data to identify TEC variations. The HF-TID and HF-INT approaches are based on Digisonde characteristics, while CDSS-MSTID utilizes Doppler sounder data. By combining these advanced techniques, TechTIDE provides a robust framework for the real-time tracking of TID activity during geomagnetic storms. In this study, the impact of storm-induced TID activity, particularly during the onset of the first storm period, has been investigated using three identification methods: Gradient TEC, AATR, and HF Interferometry. The Gradient TEC method identifies the presence of TIDs in the ionosphere, while the AATR and HF Interferometry methods provide detailed insights into medium-scale TIDs (MSTIDs) and LSTIDs, respectively. Gradient TEC, AATR, and HF Interferometry maps were downloaded over Europe from <https://swe.ssa.esa.int> (accessed on 24 May 2024) from 18:00 to 23:00 UT on 10 May. It is important to note that these maps offer different latitude and longitude coverage. The Gradient TEC method [19] covers the longitude range of -30° to 50° E and the latitude range of 30° – 72° N. The AATR method [20], used for MSTID identification, spans -30° to 42° E in longitude and 20° – 82° N in latitude. Meanwhile, the HF Interferometry method [18], designed for LSTID identification, encompasses -10° to 40° E in longitude and 35° – 60° N in latitude.

3. Results

3.1. Solar Flare Effects on Mother's Day Storm

The Mother's Day event originated from the solar active region designated by the National Oceanic and Atmospheric Administration (NOAA) as AR13664. In the early morning of 10 May 2024, AR13664 was located at heliographic coordinates 18° S latitude and 17° W longitude. It was characterized by a complex topology according to the Hale classification, which assigns regions with two sunspots or sunspot groups of opposite intermixed polarity. This region generated multiple solar flares. The most powerful solar flares, classified as X-class based on their X-ray brightness in the 1 to 8 Å wavelength range, are often associated with Coronal Mass Ejections (CMEs). CMEs are substantial releases of plasma and magnetic fields from the Sun's corona, typically fast and wide when linked to large X-ray flares. Between 8 and 11 May 2024, several strong solar flares from AR13664 led to a sequence of rapid CMEs, causing the prolonged Mother's Day geomagnetic storm.

On 10 May 2024, AR13664 generated 10 M-class flares, 3 C-class flares, and one significant X3.98 flare, which began at 06:23 UT, maximized (with respect to GOES

X-ray flux temporal variation) around 06:55 UT, and faded away at 07:03 UT, as shown in Figure 2a,b (<https://www.spaceweatherlive.com/en/archive/2024/05/10/xray.html> accessed on 23 May 2024). This marked the onset of intense activity in AR13664 that continued for several days (8–11 May 2024). Figure 2a presents the full-disc continuum image of AR13664, captured by the Solar and Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronagraph (LASCO)/C2 at the peak of the X3.98 flare on 10 May. Images were taken in the Fe I spectral line at $6173 \text{ \AA}$ with a $1''$ spatial resolution, equivalent to 725 km on the solar surface. Figure 2b depicts solar activity on 10 May 2024. From Figure 2b, CME 1 first appeared on 10 May at 06:55 UT, almost concurrently with the X3.98 flare, which started at 06:23 UT. On 10 May 2024, several M-class and C-class eruptions were observed on the sun and caused several CMEs. Between 06:00 and 18:00 UT, 7 X-class, M-class, and C-class eruptions were recorded by SOHO/LASCO/C2 (as shown in Figure 2b). These CMEs merged into a single system and formed an interplanetary shock (IP) that reached L1 around 18:00 UT, followed by several IPs on 10 May.

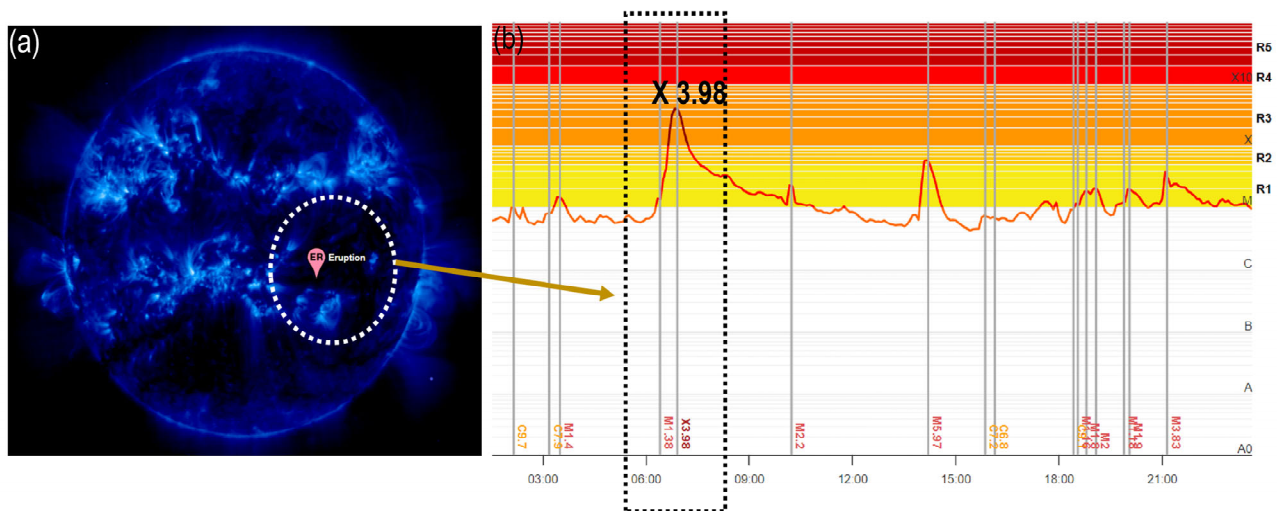


Figure 2. Solar flare effects recorded on 10 May 2024: (a) the location of AR13664 (pink marker) over the solar disc; (b) solar flares recorded (the yellow to red colours are used to indicate the intensity levels of the X-class solar flares).

3.2. Geomagnetic Activity on Mother's Day Storm

Figure 3 displays geophysical parameters recorded from 9 May to 13 May 2024. The IP shocks already discussed impacted the magnetosphere, with the first shock (IP1) causing the first Sudden Storm Commencement (SSC1) at 18:00 UT on 10 May 2024. At this time, the 1 min SYM-H index (which is equivalent to the hourly Dst index) was reduced from 40 nT to -61 nT, as shown with a brown arrow in Figure 2. This decrease is attributed to enhanced magnetopause currents associated with the observed SSC.

Following SSC1, the SYM-H index (SYM-H1) rapidly declined, marking the main phase of the geomagnetic storm, which persisted until SYM-H reached -436 nT around 02:00 UT on 11 May 2024. The index then began a gradual recovery, returning to pre-storm values by 06:00 UT on 12 May 2024. During the interval from SSC1 to around 18:00 UT on 11 May, the SYM-H index oscillated extensively. Detailed analysis of these oscillations reveals a correlation with variations in the Interplanetary Magnetic Field (IMF-Bz). Specifically, SYM-H increases align with positive IMF-Bz, indicating a closed magnetosphere, or abrupt changes in solar wind (SW) speed. Conversely, SYM-H decreases correlate with negative IMF-Bz, which signifies an open magnetosphere. Minor fluctuations observed after 18:00 UT on 11 May, during a period of near-zero or positive IMF-Bz, are attributed to variations in SW speed.

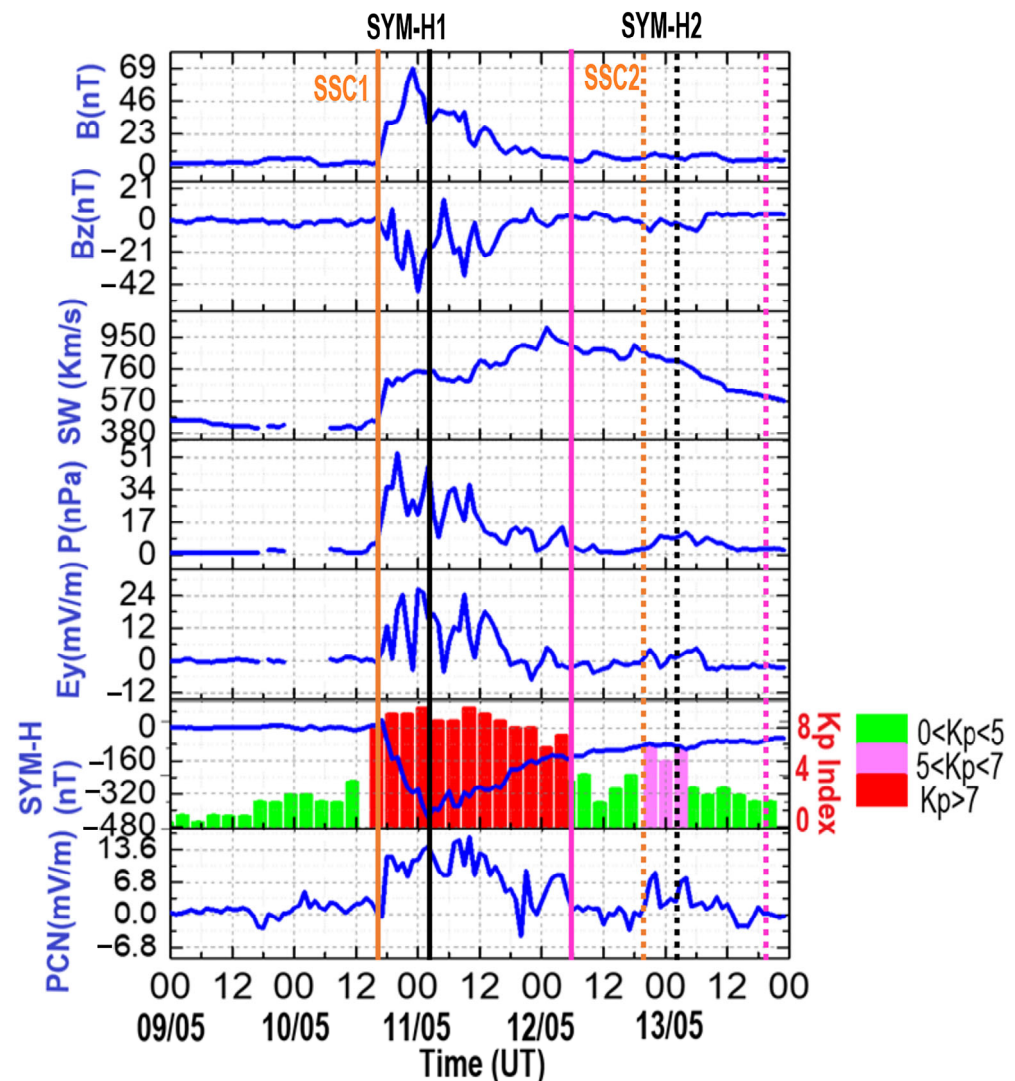


Figure 3. Geomagnetic conditions during the Mother's Day Storm event. The orange vertical lines represent the sudden storm commencement times (SSC1 and SSC2), the black vertical lines denote the time of the 1st and 2nd SYM-H index minima during the two successive storms, and the pink vertical lines represent the completion of the recovery phase of the ionosphere on Mother's Day Storm.

At 21:00 UT on 12 May, another shock (IP5) triggered the second sudden storm commencement (SSC2). Although there were no significant SYM-H index variations during SSC2, the main phase of the storm was marked by a decrease in the SYM-H index (SYM-H2), which reached -103 nT at 04:00 UT on 13 May, before the recovery phase concluded around 19:00 UT on the same day. To better understand the effects of the storm, Kp was also analyzed (Figure 3). The Kp index, which represents global geomagnetic activity on a scale from 0(0) to 9(+), first indicated strong geomagnetic activity on 10 May, between 12:00 and 15:00 UT, with a value of 5(−). This was followed by a rise to 8(0) and subsequent oscillations between 8(0) and 9(0) until late on 11 May. For the second storm event, the Kp index increased from 5(+) to 6(+) from 21:00 UT on 12 May to 03:00 UT on 13 May. Notably, during the SYM-H index recovery phases for both storms, the Kp index continued to rise (Figure 3).

Examining the PCN (Polar Cap Negative) indices (Figure 3) reveals that PCN tracks the Kp index during storm events. When Kp exceeds 6, there is a significant increase in PCN, indicating enhanced auroral electrojet due to the polar cap impact of IPs. On 10 May 2024, around 18:00 UT, a sharp increase in SW speed from 450 to 700 km/s was observed, coinciding with a decrease in SYM-H (Figure 3). This increase corresponds to the leading

edge of the CME linked to IP1. Concurrently, IMF-Bz shifted to large negative values, persisting for over a day (Figure 3), with an initial rise in IMF-B strength followed by successive increases, suggesting the passage of additional CMEs. A second shock (IP2) was detected at 21:39 UT on the same day, with SW speed peaking at 800 km/s, IMF-B reaching 74 nT, and IMF-Bz falling to -32 nT, associated with CMEs observed from 9–11 May. A third shock (IP3) appeared around 17:55 UT on 11 May, with IMF strength rising to about 20 nT and SW speed increasing to 895 km/s. As multiple CMEs and High-Speed Streams (HSSs) continued, the SW speed peaked at nearly 1000 km/s at 00:55 UT on 12 May. Additionally, a fourth shock (IP4) was noted at 08:59 UT on 12 May, featuring a modest IMF-B increase from 5 nT to 12 nT and a SW speed rise from 830 km/s to 900 km/s. After 12 May, IMF-Bz returned to near-zero values with a significantly reduced total intensity of about 8 nT. The prolonged and intense southward IMF-Bz component facilitated magnetic reconnection at the Earth's magnetopause, resulting in the most severe geomagnetic storm in the past two decades.

3.3. Spatio-Temporal Variations of Ionospheric Characteristics

The ionospheric response to the Mother's Day geomagnetic superstorm was examined through the variation of key ionospheric characteristics—foF2 (critical frequency of the F2 layer), hmF2 (height of the maximum electron density of the F2 layer), vertical TEC, and ion drift velocity—across an extended European area. Figure 4a–d present variations in foF2 and hmF2 over four Digisonde stations, while Figure 5a–d illustrate TEC variations over corresponding GNSS stations from 10 to 13 May. To establish a baseline, the geomagnetically quiet day of 9 May, was used as a reference.

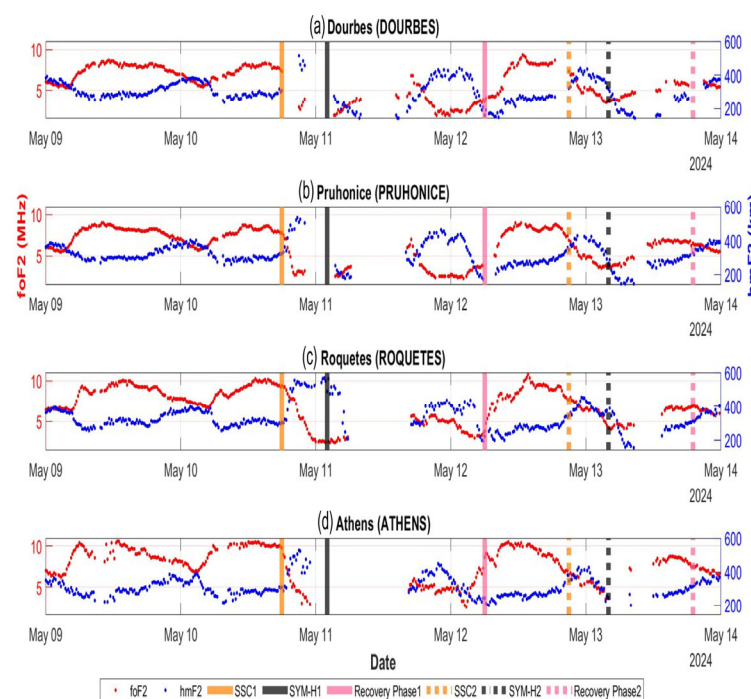


Figure 4. Variations in ionospheric characteristics (foF2 and hmF2) over (a) Dourbes, (b) Pruhonice, (c) Roquetes, and (d) Athens. The orange vertical lines represent sudden storm commencement times (SSC1 and SSC2), the black vertical lines denote the time of the 1st and 2nd SYM-H index minima during the two successive storms, and the pink vertical lines represent the end of the ionospheric recovery phases of the Mother's Day Storm.

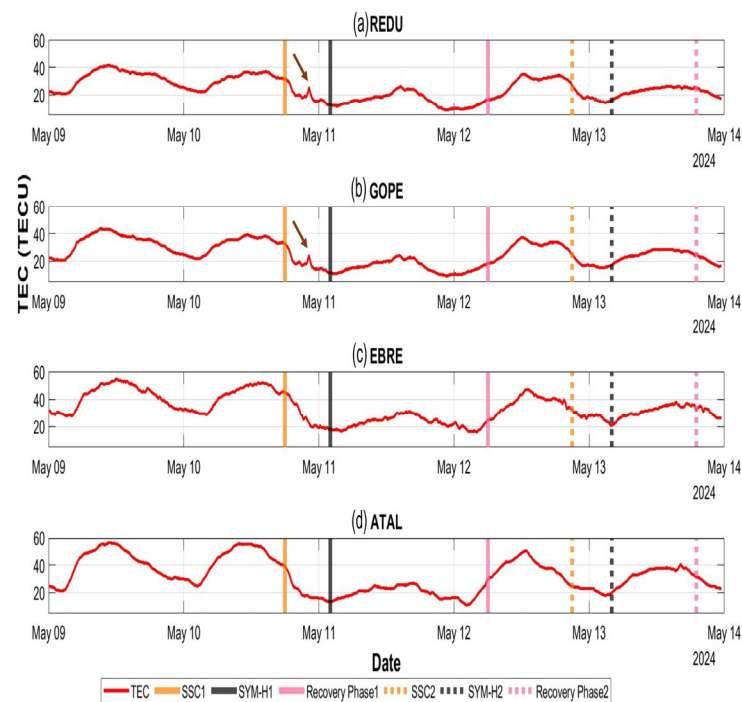


Figure 5. TEC recorded at (a) REDU, (b) GOPE, (c) EBRE, and (d) ATAL. Orange vertical lines represent the sudden storm commencement times (SSC1 and SSC2), the black vertical lines denote the time of the 1st and 2nd SYM-H index minima during the two successive storms, and the pink vertical lines represent the end of the ionospheric recovery phases of the Mother's Day Storm.

During the primary and recovery phases of both storm events from 10 to 13 May, significant excursions in foF2 and TEC were observed as compared to their quiet values under undisturbed geomagnetic conditions. Notably, a sharp decrease in foF2 was detected at all stations during the first storm. High midlatitude stations (Latitude $> 45^\circ$ N) recorded a decrease indicating a negative ionospheric storm following smooth, continuous foF2 variations observed during the geomagnetically quiet condition. Low midlatitude stations (Latitude $< 45^\circ$ N) exhibited a steep decrease in foF2 during the main phase of the first storm, preceded by fluctuations in foF2 from approximately 00:00 to 12:00 UT on 10 May. TEC depletion during the main and recovery phases was observed over all stations, showing no significant deviations from the quiet day values (Figure 5). Following the first storm, foF2 and TEC were restored to their quiet reference values. An interesting observation in Figure 5 is the abrupt increase in TEC values around 22:00 UT on 10 May during the main phase of the first storm, particularly over the REDU and GOPE stations. This sudden increase, marked by a brown arrow in Figure 5, can be attributed to the impact of a solar flare on the TEC data, as suggested by Ranjan et al., 2023 [21] (p. 10). As shown in Figure 2, an M3.83-class solar flare erupted at approximately 21:30 UT on 10 May, likely causing this TEC enhancement. Ranjan et al., 2023 [21] documented similar TEC increases during geomagnetic storms in the midlatitude ionosphere, attributing them to enhanced ionization from extreme ultraviolet (EUV) and X-ray radiation emitted during solar flares.

The impact of the second storm, while still significant, was less severe than the first. The SSC2 was noted at 21:00 UT on 12 May, marking the onset of the second storm event. Both foF2 and TEC profiles exhibited a decrease across all four stations following a prolonged positive storm response from approximately 06:00 to 21:00 UT on 12 May. A persistent positive ionospheric response was also observed the day before the first storm on 10 May (Figures 4 and 5) at all stations. In their analysis of the Mother's Day geomagnetic superstorm's impact on the European Mediterranean ionosphere, researchers from INGV [4] observed a pronounced ionospheric plasma depletion. This was reflected in

significantly reduced foF2 and TEC values over Italy, reaching as low as 2 MHz and 4 TECu, respectively—a ~70% decrease compared to quiet conditions. This depression persisted for two full days, on 11 and 13 May. Over the Asian low- to midlatitude ionosphere, a negative ionospheric storm effect was observed [10], marked by a sharp and prolonged drop in Ne profiles from RO data immediately after the SSC1 onset at 18:00 UT on 10 May. This reduction persisted through the main and early recovery phases of the first storm event on 11 May. During the later recovery phase on 12 May, the eastern Asian low-to-midlatitude ionosphere exhibited a sustained strong negative storm effect, except for some medium-scale local enhancements. This was later followed by a positive storm effect transitioning into a weak negative storm, possibly driven by enhanced northward winds [10].

During the Mother's Day storm, significant depletions in foF2 and TEC were linked to a pronounced reduction in the [O/N2] ratio, with values dropping as low as 0.2 [4]. The TEC depletion around 48° N on 10 May at 18:00 UT rapidly progressed lower to 36° N within a few hours. One critical finding was the absence of foF2 and hmF2 values over the stations during the recovery phases of the storm events due to the “disappearance” of F-region traces from ionograms (Figures 4 and 6). Over the two high midlatitude stations, the traces disappeared from 22:00 UT on 10 May to 03:00 UT on 11 May, and again from 07:00 to 16:00 UT on 11 May during the first storm. For the second storm, this was observed from 06:00 to 16:00 UT on 13 May. Over the two low midlatitude stations, this was manifested from 23:00 on 10 May to 16:00 UT on 11 May during the first storm event and from 05:00 to 13:00 UT on 13 May, during the second storm event (Figure 7). To examine these findings further, we analyzed ionograms from all four Digisonde stations, comparing geomagnetically quiet period ionograms (01:00–04:00 UT, 10 May) with disturbed recovery period ionograms (01:00–04:00 UT, 11 May) (Figure 8a,b). During the quiet period, the average altitude of the bottom-side F-region (h') was 287 km across all stations, whereas, during the recovery phase, h' values increased dramatically, at an average of 959 km over high midlatitude stations and 781 km over low midlatitude stations. Under the influence of the geomagnetic storm, this dramatic uplift of the F-layer was reflected in the absence of foF2 and hmF2 measurements. This represents a manifestation of the G-condition, which appears in the F region when the critical frequency of the F2 layer is equal to or lower than that of the F1 layer typical of disturbed geomagnetic conditions [22]. In their study of the geomagnetic storm in September 2017 over the European sector, Oikonomou et al., 2022 [22] observed G-conditions predominantly at high midlatitudes during high AE values. Similarly, in this event, the intense F-layer uplift coincided with high PCN values (Figure 3). The G condition arises due to a combination of the reduced atomic oxygen concentration and significant heating in the neutral atmosphere, as highlighted in previous studies [22] (pp. 22–24).

Our findings, supported by [3,4,6], underline a notable vertical drift enhancement over Europe during the storm. This enhancement was behind the partial disappearance of foF2 and hmF2 traces during the recovery phase of both storms. Figure 6a highlights a strong upward plasma drift velocity ($V_z \sim 140$ m/s) at Pruhonice around 18:00 UT on 10 May, immediately following SSC1, with strong fluctuations in the vertical drift velocity during the initial and main phase of the first storm event. Around 06:00 UT on 11 May, the F trace partially disappeared, likely due to the dramatic uplift of the F layer. The upward plasma drift velocity stabilized after the recovery phase of the first storm event. At Dourbes, which is located west of Pruhonice, the fluctuations in vertical drift velocity were weaker with $V_z \sim 50$ m/s. Both stations exhibited strong westward zonal drift ($V_{\text{east}} \sim -500$ to -800 m/s). Figure 6b compares Roquetes and Athens, showing fluctuations in V_z (~ 100 m/s) during the initial and main phases of the first storm. Weaker fluctuations in V_z were noted during the second storm. Unlike high midlatitude stations, no significant westward drift was observed at these low midlatitude locations. Foster et al., 2024 [2] linked strong westward and equatorward auroral surges during the main storm period (10–11 May) to low-energy

electron precipitation, which likely drove the observed westward drift at high midlatitude stations. Guo et al., 2024 [10] also reported east–west asymmetry, similar to Dourbes and Pruhonice, and suggested this as a typical pattern during supermagnetic storms, driven by large-scale storm-time thermospheric circulation.

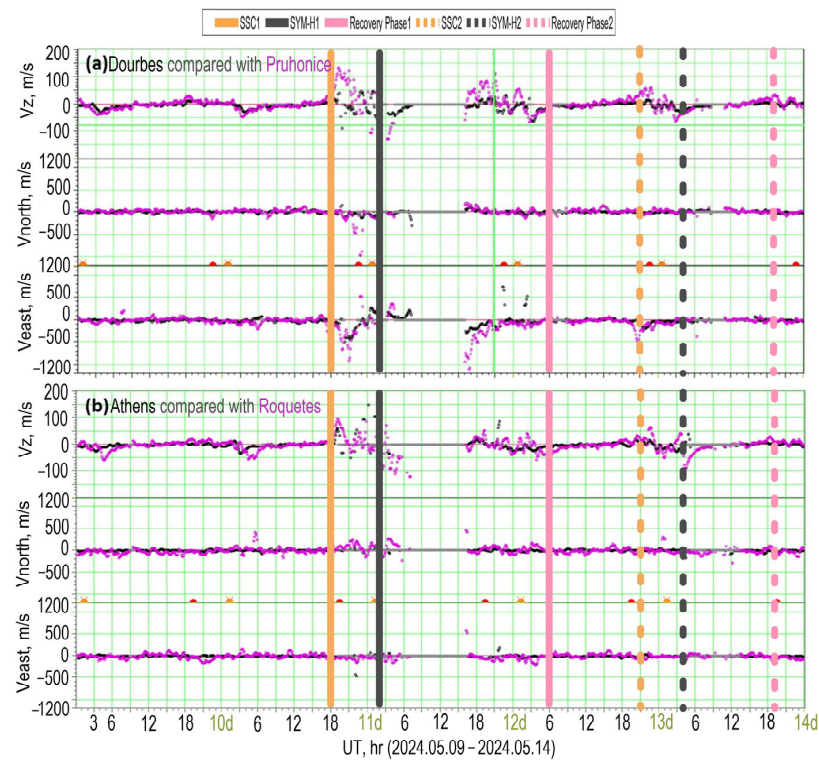


Figure 6. Vertical and zonal drift velocities over (a) high midlatitude (Dourbes as black dots and Pruhonice as purple dots) and (b) low midlatitude (Roquetes as purple dots and Athens as black dots) on 10 May. Orange vertical lines represent the sudden storm commencement times (SSC1 and SSC2), the black vertical lines denote the time of the 1st and 2nd SYM-H index minima during the two successive storms, and the pink vertical lines represent the end of the ionospheric recovery phases of the Mother’s Day Storm.

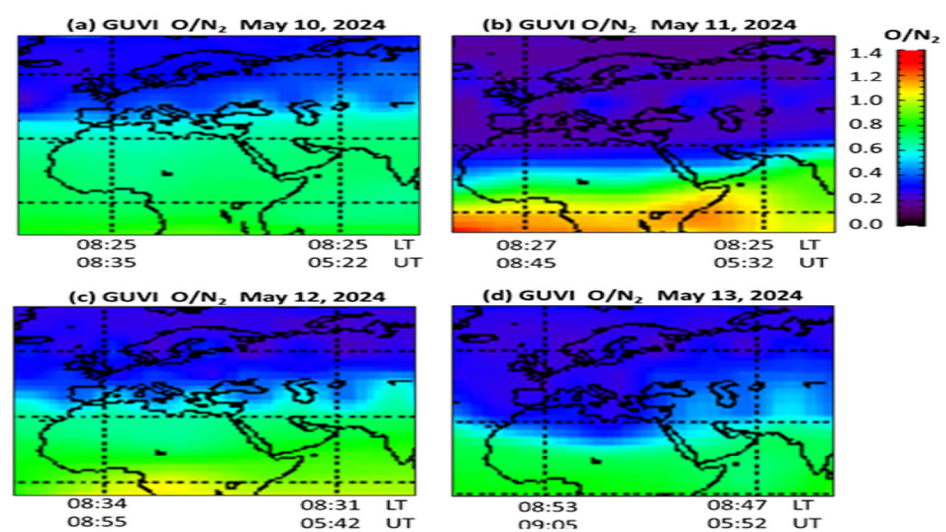


Figure 7. Diurnal variation of $[O/N_2]$ ratio observed over Europe in (a) 10 May; (b) 11 May; (c) 12 May and (d) 13 May.

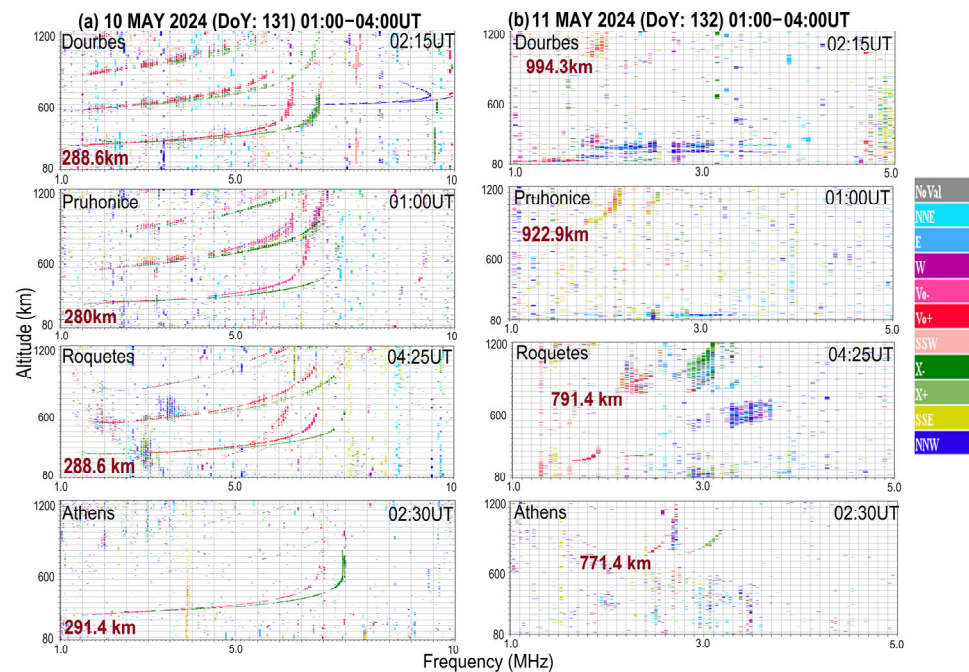


Figure 8. Ionograms recorded at Dourbes, Pruhonice, Roquetes, and Athens on 01:00–04:00 UT of (a) 10 May, a geomagnetically quiet period, and (b) 11 May, a geomagnetically disturbed period. Values inside the ionograms indicate the virtual altitude of the F layer (h').

The Global $[O/N_2]$ maps from the Global Ultraviolet Imager (GUVI) on the TIMED satellite demonstrated a substantial increase in the thermospheric density over low to mid-latitude regions on 11 May compared to 10 May, as shown in Figure 7. Negative phases in foF2 and TEC were attributed to changes in the neutral composition, specifically a decrease in the $[O/N_2]$ ratio [4], which increases the ion loss rate [23]. The energy dissipated by the solar wind raises the exospheric temperature, impacting the density structure of the polar upper atmosphere. During the second storm, a further decrease in the $[O/N_2]$ ratio led to another negative ionospheric storm. This was supported by the high auroral activity indices, likely due to the southward IMF Bz component and sudden changes in solar wind pressure (P).

Prölss 1995 [23] suggested that these changes can be attributed to TID activity and large-scale wind circulation changes, both triggered by significant energy input into the polar upper atmosphere. The TEC depletion over the European sector from 10 to 13 May was observed along with a rapid F region uplift during the main and recovery phases of the two successive storms (Figure 5), which also manifested in the significant increase in vertical plasma drift over Pruhonice and Roquetes as shown in Figure 6, reaching and exceeding drift velocities of 100 m/s. The most notable F-region uplift was recorded over Dourbes station during the main phase of the first storm, with hmF2 increasing from 288 km (quiet day) to approximately 990 km (Figure 8). The other three stations also registered significant hmF2 enhancements during the storm. During the main and recovery phases of the first storm, F region traces disappeared entirely from ionograms over the two high midlatitude stations, as well as over the two low midlatitude stations during the recovery period (Figure 4).

3.4. Storm Effects on the Midlatitude Ionospheric Trough (MIT)

High-energy deposition in polar and auroral regions during storms causes the southward expansion of the auroral oval, shifting the MIT equatorward [24]. Large convection returning flows equatorward of the Sub-Auroral Ion Drifts (SAIDs) region contribute to the formation of elongated troughs at high midlatitudes through enhanced recombination

in the F region [25,26]. SAIDs or Sub-Auroral Polarization Streams (SAPs) during disturbed conditions can trigger MIT formation [27].

The latitudinal Ne profiles of Swarm satellites over the European sector from 9–13 May 2024 were exploited in an effort to examine storm-induced MIT displacements. Figures 9–12 illustrate in situ Ne profiles from daytime and nighttime Swarm passes, respectively, with black, red, blue, green, and pink curves representing each day from 9 May to 13 May. The corresponding TEC maps in these figures show the TEC spatial distribution over Europe. Moreover, 9 May was a geomagnetically quiet day, which serves as the reference day for our analysis.

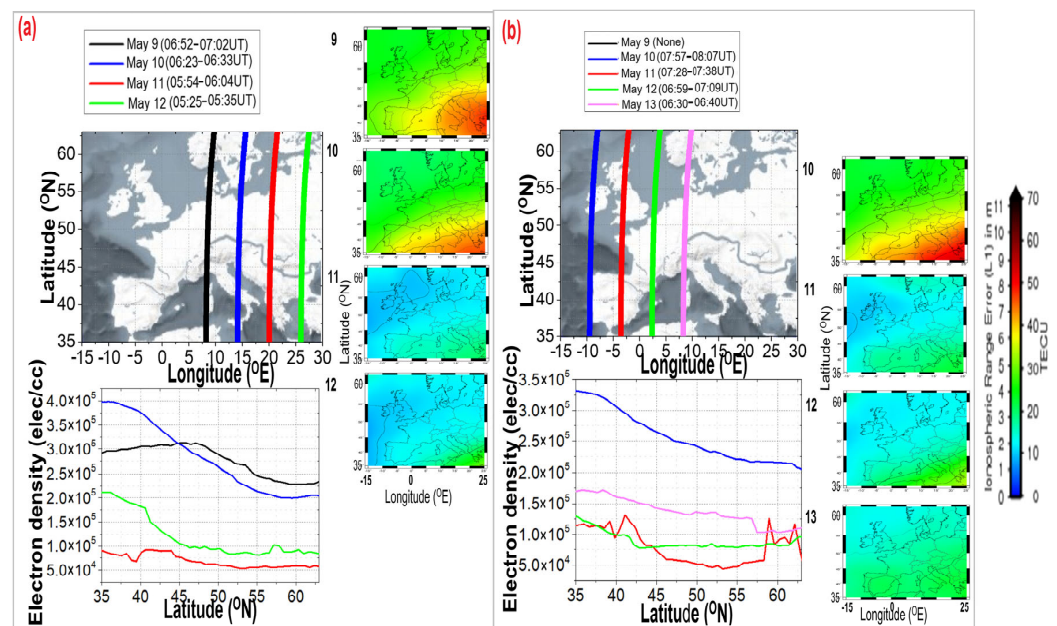


Figure 9. (a,b) Latitudinal Ne profiles for SWARM A from 00:00 to 07:00 UT on 9–13 May observed over Europe on Mother’s Day Storm (10–13 May). The black, red, blue, green, and pink tracks represent Ne profiles for 9, 10, 11, 12, and 13 May. The TEC Maps represent the Ne distribution over Europe during the same time interval when the SWARM pass was recorded.

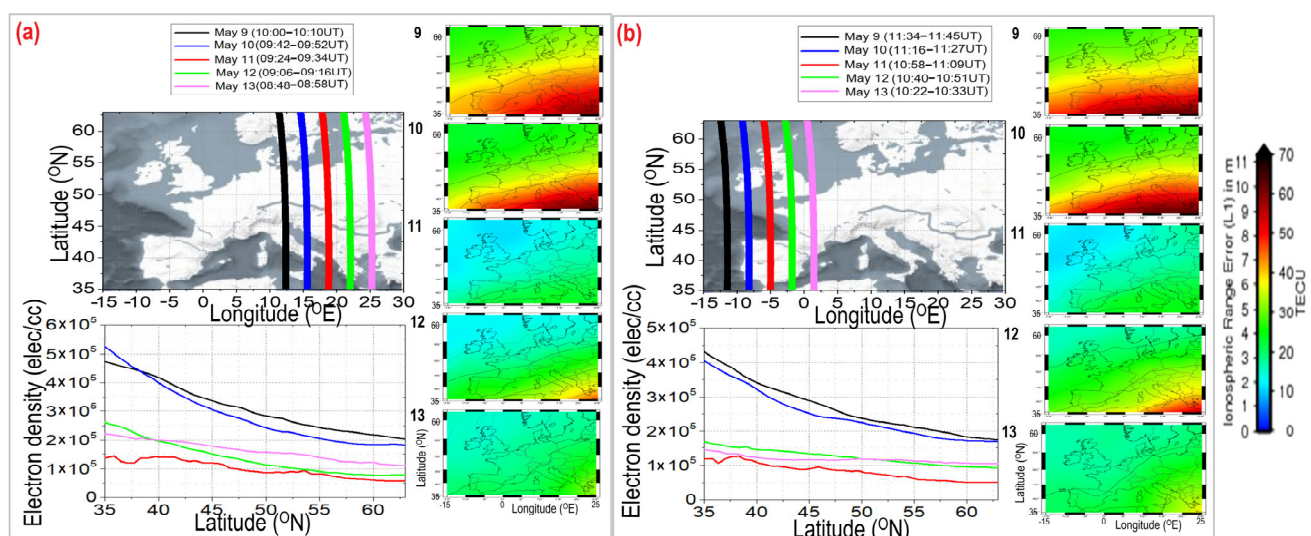


Figure 10. (a,b) Latitudinal Ne profiles for SWARM B from 06:00 to 12:00 UT on 9–13 May observed over Europe on Mother’s Day Storm (10–13 May). The black, red, blue, green, and pink tracks represent Ne profiles for 9, 10, 11, 12, and 13 May. The TEC-Maps represent the Ne distribution over Europe during the same time interval when the SWARM pass was recorded.

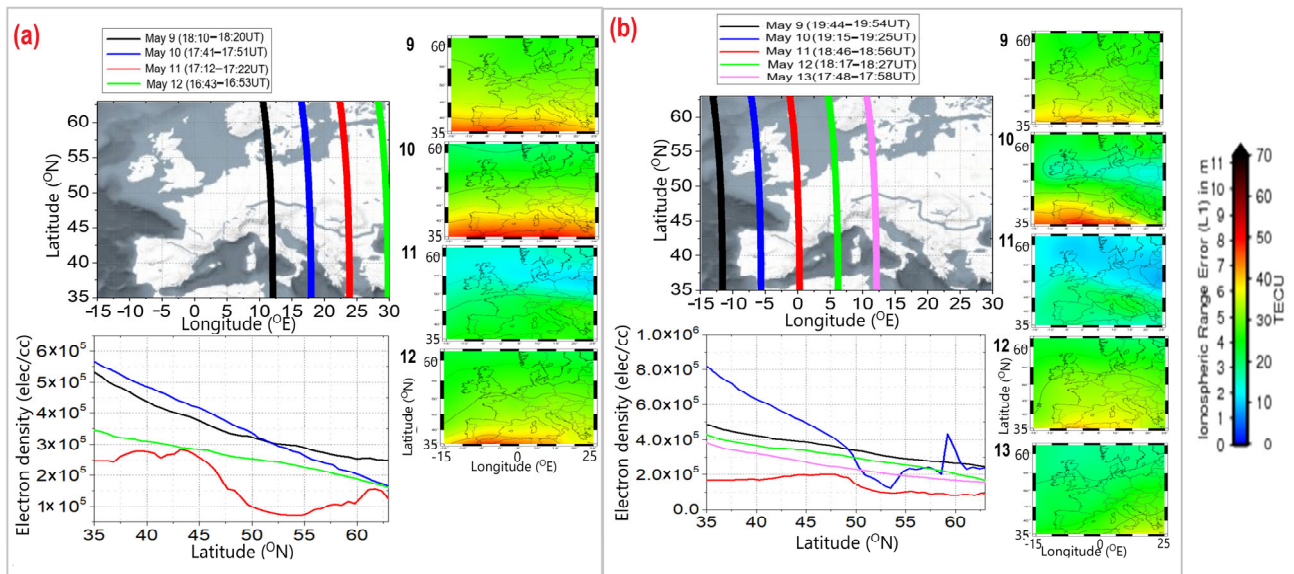


Figure 11. (a,b) Latitudinal Ne profiles for SWARM A from 16:00 to 24:00 UT on 9–13 May observed over Europe on Mother’s Day Storm (10–13 May). The black, red, blue, green, and pink tracks represent Ne profiles for 9, 10, 11, 12, and 13 May. The TEC Maps represent the Ne distribution over Europe during the same time interval when the SWARM pass was recorded.

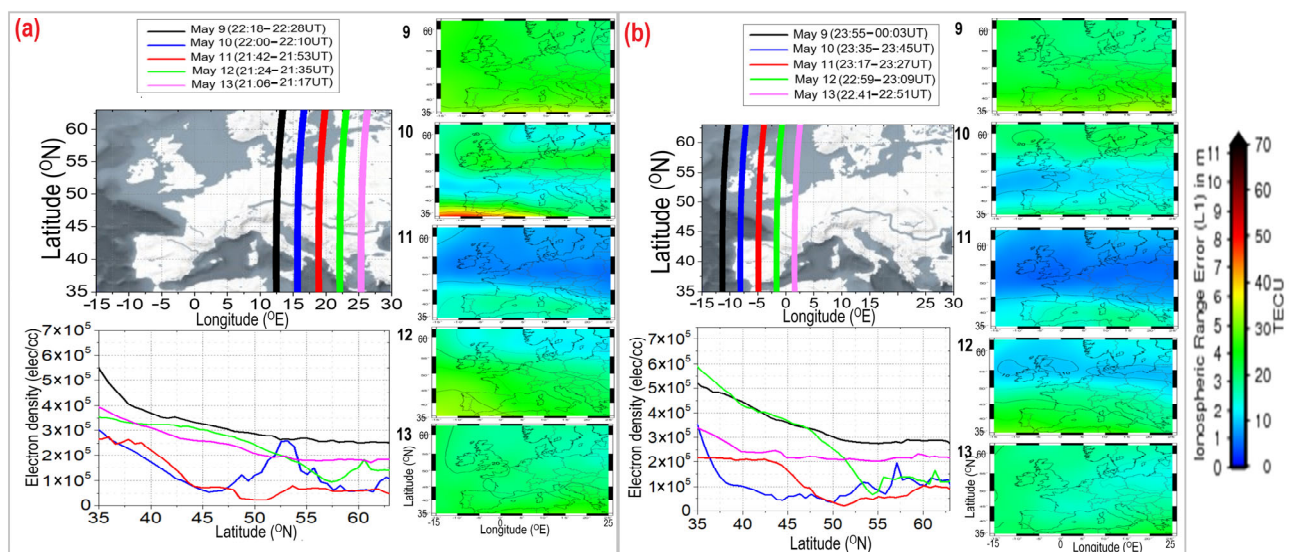


Figure 12. (a,b) Latitudinal Ne profiles for SWARM B from 18:00 to 24:00 UT on 9–13 May observed over Europe on Mother’s Day Storm (10–13 May). The black, red, blue, green, and pink tracks represent Ne profiles for 9, 10, 11, 12, and 13 May. The TEC Maps represent the Ne distribution over Europe during the same time interval when the SWARM pass was recorded.

Figure 9a,b shows Ne at Swarm A altitude between 00:00 and 07:00 UT over two longitude ranges (7° to 30° E and −10° to 7° E) within a latitude range of 35° to 63° N for 9–13 May. On 9 and 10 May, Swarm Ne exhibits insignificant fluctuations, indicating a quiet midlatitude ionosphere. On 11 May, fluctuations are observed around 38°–40° N near 20° E at 06:00 UT (near Athens/ATAL station) and around 59°–63° N near −5° E at 07:30 UT (near Roquetes/EBRE and Dourbes/REDU stations). As already discussed, during the recovery phase of the first storm event on 11 May (05:00–07:00 UT), strong TEC depletion was noted and was attributed to the poleward displacement of MIT [28]. This is corroborated by reduced TEC values in the TEC map (Figure 5). A similar pattern is observed in the Swarm A track on 13 May during the recovery phase of the second storm (06:30 UT).

Figure 10a,b displays the latitudinal Ne profiles recorded by Swarm B over the European longitude sector from 06:00 to 12:00 UT. On 11 May, fluctuations were noted during 09:00–11:00 UT near Athens/ATAL and Roquetes/EBRE stations, with the corresponding TEC maps indicating a TEC depletion, consistent with the observations in Figure 5.

Figures 11 and 12 present the nighttime response. The first geomagnetic storm commenced around 18:00 UT on 10 May, as illustrated in Figure 3. The Swarm A Ne captured the effects of the IP1 at 19:20 UT on the same day, showing significant TEC depletion in the corresponding TEC map (Figure 11b). On 11 May, during the recovery phase of the first storm, fluctuations in the Ne profile of Swarm A were observed at 17:20 UT, accompanied by a prominent depletion spanning the latitudinal range of 45° N to 60° N. This depletion pattern suggests a poleward shift of the MIT [28], typically located near 55° N. The corresponding TEC map from 11 May further supports this hypothesis by showing perturbations consistent with the suggested MIT displacement (Figure 11a). During the evening passes of Swarm A on 12 and 13 May, no fluctuations were observed in the Ne profile, and the TEC maps indicated no notable perturbations.

Figure 12a,b provide more detailed insights into the storm-induced disturbances during the main phases of the two storm events. Between 22:00 and 23:45 UT on 10 May, significant Ne depletions were recorded by Swarm B and validated by corresponding TEC maps. Around 22:00 UT, a pronounced depletion in the Ne profile indicated an equatorward movement of the MIT to approximately 45° N. This observation is validated by perturbations in the TEC map for the same period in agreement with the inferred MIT latitude. By 23:30 UT, as the geomagnetic storm intensified (referenced in Figure 3), the MIT shifted further equatorward to around 42° N, as shown in Figure 12b. On 11 May, during the recovery phase, Swarm B recorded Ne depletions between latitudes of 45° N and 50° N from 21:00 to 23:30 UT. This observation suggests a poleward shift of the MIT, as geomagnetic conditions started to recover. The TEC maps during this period reflected these changes, displaying corresponding perturbations in TEC profiles that support the inferred MIT dynamics (Figure 12a,b). On 12 May, during the SSC2 at approximately 21:00 UT, the MIT location was observed to shift equatorward once again, as depicted in Figure 12a. At 21:30 UT, the Ne profile of Swarm B demonstrated this equatorward movement, placing the MIT near 58° N. By 23:00 UT, the MIT had moved further equatorward to around 55° N, as evidenced in the Ne profile of Swarm B (Figure 12b).

The effects of the Mother's Day 2024 geomagnetic superstorm on the European MIT are detailed in Figures 9–12. On the quiet day of 9 May, the MIT latitude (~63° N) and electron concentration remained undisturbed. As the storm commenced around 18:00 UT on 10 May, the MIT shifted equatorward. A significant Ne depletion noted around 45°–50° N at 19:20 UT is supported by a reduction in TEC over REDU and GOPE from 18:00 UT on 10 May to 02:00 UT on 11 May (Figure 5). During the recovery phase on 11 May, midlatitude Ne decreased further, as shown in Figures 9 and 10. On the evening of 11 May, during the last phase of the recovery period, the MIT reappeared around 50°–55° N latitude (Figure 11), gradually shifting northward (Figure 12). On the morning of 12 May, the MIT moved beyond 60° N, shifting back to its original latitude range (Figure 9a). During the second storm event on the night of 12 May, the MIT shifted equatorward to 55° N around 23:00 UT (Figure 12b) and eventually reappeared back to its original latitude range by 21:00 UT on 13 May (Figure 12a,b). Evidently, all Swarm passes and TEC maps in Figures 9–12 confirm a clear equatorward displacement of the MIT followed by a poleward return during the recovery phase.

3.5. Travelling Ionospheric Disturbance Effects

In this study, we also looked for notable TID activity during the main phase of the first storm, from 18:00 UT on 10 May to 02:00 UT on 11 May. Based on periodicity, horizontal velocity, and wavelength, TIDs are broadly classified into two categories: MSTIDs and LSTIDs [29]. Data products from the I-ESC portal were downloaded and inspected for the period of 18:00 to 23:00 UT on 10 May. The descriptions for these products are detailed in Section 2. Based on data availability, four specific cases—at 18:00 UT, 20:00 UT, 20:50 UT, and 22:30 UT—were selected to underline TID activity during the main phase of the first storm, as depicted in Figures 13a–c, 14a–c, 15a–c and 16a–c.

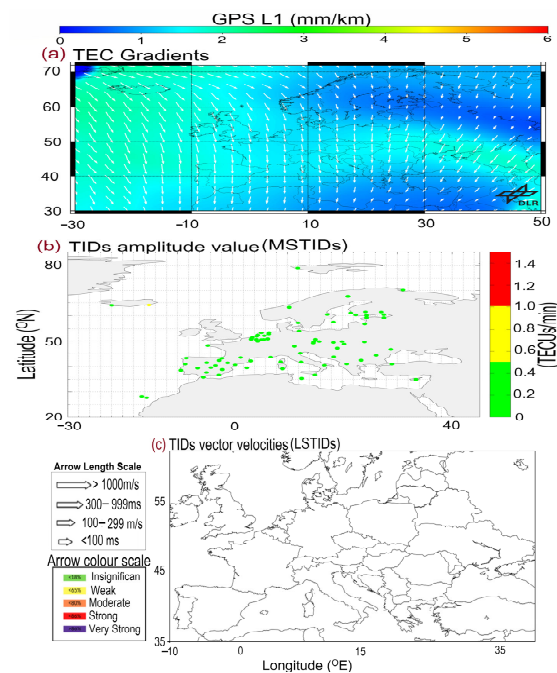


Figure 13. (a–c) No observations of TID activity at 18:00 UT of 10 May on any of the (a) Gradient TEC maps (b), AATR indicator for MSTID detection, or (c) HF-INT map for LSTID detection.

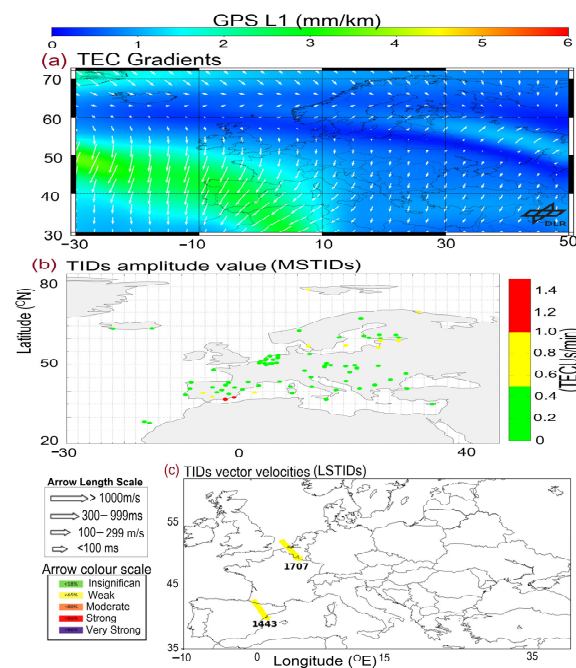


Figure 14. (a–c) TID activity at 20:00 UT of 10 May: (a) Gradient TEC maps, (b) AATR indicator for MSTID detection, and (c) HF-INT map for LSTID detection.

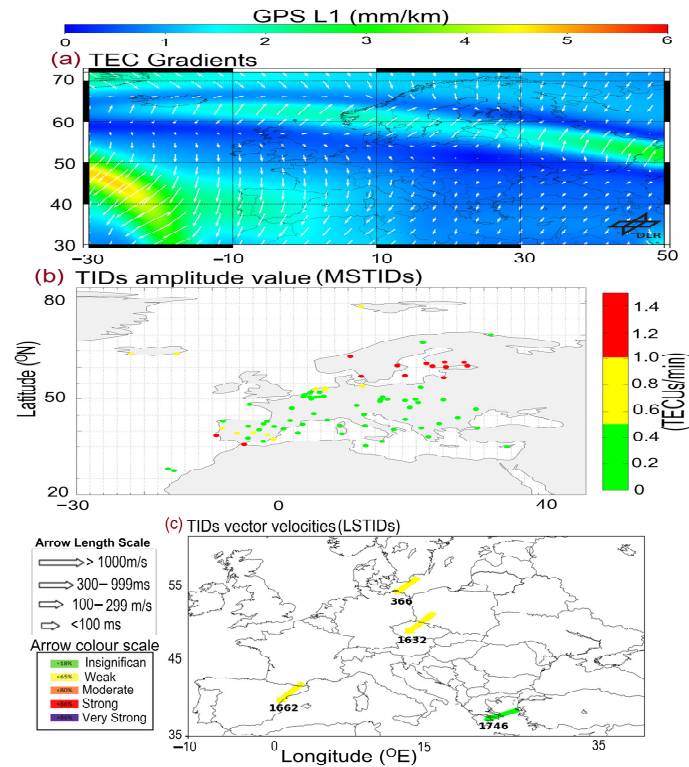


Figure 15. (a–c) Observation of TIDs at 20:50 UT of 10 May: (a) Gradient TEC maps, (b) AATR indicator for MSTID detection, and (c) HF-INT map for LSTID detection.

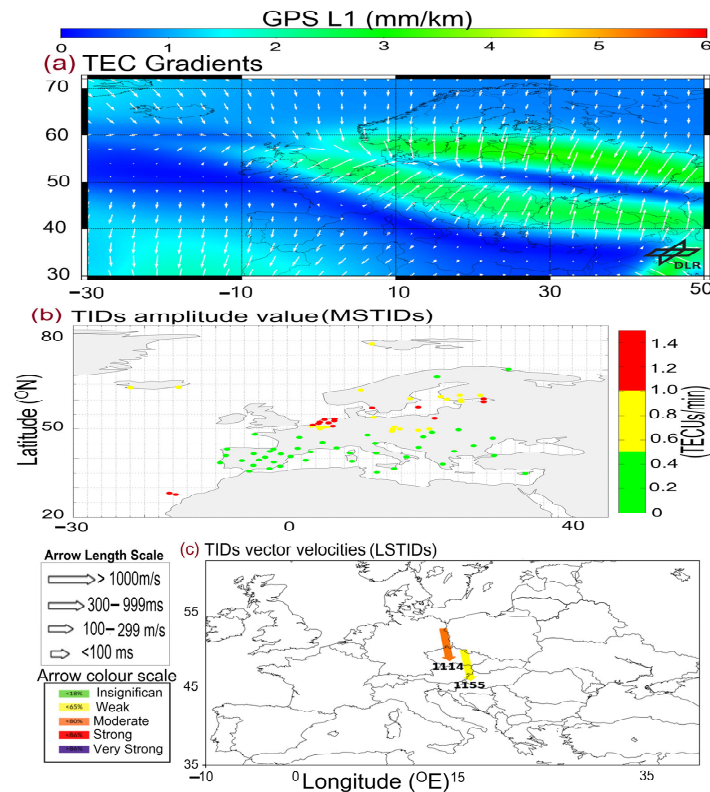


Figure 16. (a–c) TID activity at 22:30 UT of 10 May, based on (a) Gradient TEC maps, (b) AATR indicator for MSTID detection, and (c) HF-INT map for LSTID detection.

Figures 13a, 14a, 15a and 16a illustrate Gradient TEC maps during the main phase of the first storm on 10 May, employing the GNSS TEC gradient method proposed by Borries et al., 2017 [19]. This method calculates temporal and spatial TEC gradients from

TEC maps to detect potential areas under TID activity based on observed TEC perturbations, though gradients alone do not directly confirm MSTIDs/LSTIDs. At 18:00 UT, during the commencement of the storm, no notable TEC perturbations were observed. By 20:00 UT, a TEC depletion between 40° and 55° N latitude, within the −30° to 10° E longitude sector (Figure 14a), revealed a poleward movement of the EIA crest. This poleward shift intensified at 20:50 UT (Figure 15a), accompanied by an equatorward expansion of the auroral ionosphere in the 50°–60° N latitude range. By 22:30 UT (Figure 16a), coupling of the EIA crest with the auroral ionosphere was observed, coinciding with the absence of the midlatitude ionosphere, as discussed in Section 3.3. Additionally, Figure 16a highlights the equatorward shift of the MIT, identified between 45° and 55° N latitude.

The Spatial and Temporal GNSS analysis characterizes TIDs in terms of their velocity and period based on GNSS measurements. A critical first step is detrending the data to remove diurnal and elevation angle variations, enabling real-time calculation of the MSTID index (MSTIDidx). This index reports TID activity over the area in question and, for small networks, allows the estimation of propagation parameters. In this context, the AATR indicator [20] offers a metric for MSTID activity, particularly over mid- to high-latitude regions. In this study, we used the AATR indicator (MSTIDidx) to identify and characterize MSTID activity during the main phase of the first storm. Figures 13b, 14b, 15b and 16b illustrate storm-induced MSTID activity from 18:00 to 22:30 UT on 10 May 2024. At 18:00 UT, weak MSTID traces ($\text{MSTIDidx} < 0.4 \text{ TECUs/min}$) were observed. As the storm intensified, moderate ($0.4 \text{ TECUs/min} < \text{MSTIDidx} < 1 \text{ TECUs/min}$) and intense ($\text{MSTIDidx} > 1 \text{ TECUs/min}$) MSTID activity emerged. By 20:00 UT, intense MSTID activity signatures were observed around 35° N latitude. As the night progressed, the affected area expanded across European midlatitudes up to sub-auroral regions, as shown in Figures 15b and 16b.

Significant depletion and oscillations in TEC were observed during the initial storm period, particularly during the main phase, as shown in Figures 13a, 14a, 15a and 16a. The onset of the first storm event did not exhibit notable fluctuations or depletions (see Figure 13a). Simultaneously, the Swarm latitude Ne profiles also displayed fluctuations during this interval, illustrated in Figures 11a,b and 12a,b. The analysis in the preceding section, coupled with the observed deep depletions and fluctuations in the TEC profiles (Figures 14a, 15a and 16a), suggests the presence of equatorward-moving LSTIDs. To further investigate LSTID activity, HF-INT products were also examined [30]. This method identifies LSTIDs by detecting quasi-periodic oscillations of ionospheric characteristics across a network of HF sensors with spatially dense measurements ($\leq 1000 \text{ km}$ apart). It identifies coherent oscillations at multiple network sites and defines time intervals for their activity in a given region. Initially, no LSTID signatures were registered over the European midlatitude region during the early phase of the storm (Figure 13c). By 20:00 UT, however, LSTID signatures at higher midlatitudes ($\sim 50^\circ \text{ N}$) and lower midlatitudes ($\sim 43^\circ \text{ N}$) appeared, propagating southwestward with horizontal velocities of $\sim 1707 \text{ m/s}$ and 1443 m/s , respectively (Figure 14c). The associated wavefronts coincided with the positive phase of the storm and exhibited a zonal wavefront direction. As the storm progressed, around 20:50 UT, another set of LSTIDs emerged at the sub-auroral region. These signatures propagated equatorward along the northeast–southwest direction, with velocities ranging from $\sim 366 \text{ m/s}$ to 1746 m/s (Figure 15c). By 22:30 UT, the LSTIDs intensified, with moderate to strong signatures spanning the broad sub-auroral to midlatitudes. These LSTIDs propagated equatorward at velocities ranging from $\sim 1114 \text{ m/s}$ to 1556 m/s (Figure 16c). Similar storm-induced LSTID patterns were observed during the September storm of 2017 [22,31], where sub-auroral and midlatitude LSTIDs ($\sim 30^\circ$ – 50° N and 15° – 35° N) with wavelengths exceeding 5000 km were observed. These features were associated with sub-auroral polarization stream flow channels in the local dusk/evening sector.

During the 10 May 2024 storm, TID activity also manifested in the form of Spread F on ionograms. Figure 17a,b illustrates examples of Spread F occurrence, particularly during the main phase of the first storm. High midlatitude stations exhibited significant Spread F activity, in contrast to the lower midlatitude stations of Roquetes and Athens. However, during the recovery phase, particularly around dawn on 12 May (00:00–02:00 UT), substantial Spread F activity was recorded at both lower midlatitude stations. These observations align with findings by Oikonomou et al., 2022 [22] during the September storm of 2017. Borries et al., 2010 [29] noted a strong correlation between the AE index and LSTID amplitudes, suggesting that Joule heating near the auroral oval drives LSTID generation, affecting high midlatitudes and triggering Spread F formation.

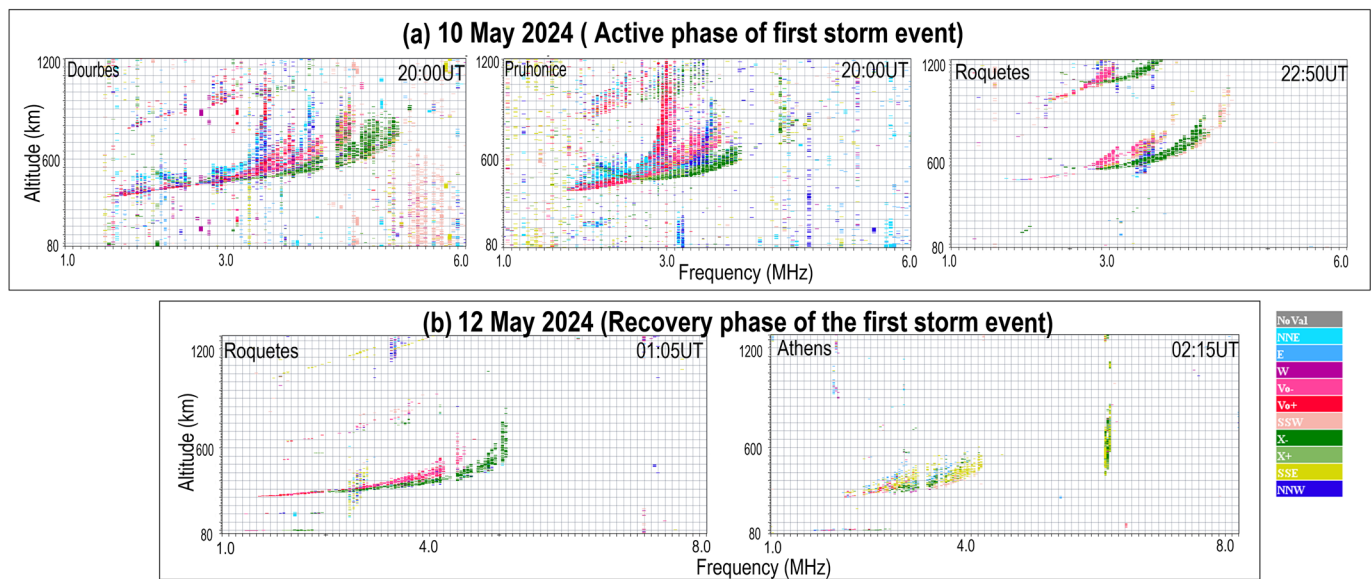


Figure 17. Observation of LSTIDs manifested as Spread F conditions in (a) the main phase (10 May) of the first geomagnetic storm, over Dourbes, Pruhonice, and Roquetes and (b) the recovery phase (12 May) over Roquetes and Athens.

Spread F was more pronounced at higher midlatitude stations and predominantly occurred during the main phase of the first storm, though it was also present during the recovery phase over low midlatitude stations. Frequency Spread F, caused by radio frequency pulses reflected off a range of densities at specific altitudes [32], was primarily observed at higher midlatitudes. This is in agreement with previous studies [33,34] that showed that during periods of high solar activity, Frequency Spread F dominates at higher midlatitudes, while Range Spread F is more prevalent at lower midlatitudes.

4. Discussions

The largest solar storm to hit Earth since the 2003 Halloween solar storms [35] in over 20 years occurred on 10–13 May 2024 (Mothers Day superstorm), resulting in a giant geomagnetic storm, classified as a G5-class geomagnetic storm ($K_p = 9$). A plethora of articles focused on the investigation of the ionospheric response to the 2003 event, which was the largest storm of the 23rd solar cycle (1996–2008). Mannucci et al., 2005 [36] observed a dramatic increase in TEC ($\sim 900\%$) above the CHAMP satellite (~ 400 km altitude) over the midlatitudes attributed to the sub-auroral PPEF [25]. In the equatorial and midlatitude ionosphere, Horvath et al., 2010 [37] identified TIDs during the Halloween 2003 storm, which created large plasma depletions over the dip equator in conjunction with equatorward winds and significant Ne enhancements at $\sim \pm 30^\circ$ N (geomagnetic), resulting in the development of early-morning EIA-like features. The impact of this superstorm on the GPS

was also investigated by Bergot et al., 2011 [35], reporting horizontal and vertical position outliers reaching 12 cm and 26 cm, respectively, for stations in northern Europe.

The next most significant geomagnetic storm after the Halloween 2003 storm event was the March 2015 storm (also referred to as the St Patrick's Day storm), which in fact was the strongest geomagnetic storm of the 24th solar cycle (2009–2015). The ionospheric response of this event was extensively reported through global-scale multi-instrument studies; for instance, Nava et al., 2016 [38] employed TEC measurements from GNSS along with magnetospheric and ionospheric observations to study the effects of the PPEF and the DDEF. Liu et al., 2016 [39] examined Ne profiles and spatio-temporal variations and the electrostatic potential during the storm using the Madrigal database, superDARN radars, and COSMIC satellite observations. Astafyeva et al., 2015 [40] vindicated a hemispheric asymmetry of the ionospheric storm effects during the recovery phase by exploiting data from ground-based GPS receivers, ionosondes, and several satellites (Swarm, TerraSAR-X, GRACE, TIMED). The physical processes driving the ionospheric storm effects have also been investigated by several researchers [41,42]. Borries et al., 2010 [29] identified three types of TIDs with quite different parameters in the partial recovery phase of the storm and during the second substorm by analyzing ionospheric TEC perturbations in the European–African sector. Moreover, the important role of polar and auroral activity in the formation of ionospheric irregularities has been discussed [43].

The investigation of solar wind driving the ionosphere-thermosphere responses during large ionospheric storms demonstrated that differences in solar wind factors led to different dynamical responses and preconditioning of the ionosphere-thermosphere system [44]. Three different southward IMF modes of the electric field provoked the ionospheric storm effects in March 2013 [45]. At the same time, during geomagnetic disturbances, the electric fields that characterize the auroral region expand equatorward, affecting sub-auroral latitudes [46]. Polar-orbiting satellite observations have detected a polarization jet or SAID often associated with the intensification of the MIT [47]. The MIT displacement during a geomagnetic storm has been identified during large geomagnetic storms (March 2013, 2015) [41] and less intense storms (September 2017, March 2023) as well [22,27].

In the present analysis, a negative ionospheric response in foF2 and TEC measurements (Figures 4 and 5) has been noted over European midlatitudes during the onset of the first storm. During the second storm, a less severe decrease in foF2 and TEC values was noted following a prolonged positive storm response. On 10 May, during the initial phase of the storm, the interaction between the solar wind and the geomagnetic field generates the magnetospheric electric convection field and the polar cap field. These electric fields extend into the thermosphere, particularly in auroral and polar regions, and drive electric currents that transfer heat to the neutral gas through Joule heating. Joule heating primarily produces a divergent irrotational wind field accompanied by significant pressure variations, while momentum forces generate rotational non-divergent winds with minimal pressure effects. The neutral gas constituents respond differently to these wind systems: divergent winds driven by Joule heating lead to the observed depletion of oxygen and helium at higher latitudes during magnetic storms, whereas rotational winds have a limited impact on compositional equilibrium. Volland, 1979 [48] demonstrated that Joule heating primarily drives solenoidal winds, characterized by strong vertical components associated with pressure and temperature changes. In contrast, momentum-driven irrotational winds lack vertical components and pressure variations. The solenoidal wind is thus the main factor behind compositional changes during the negative ionospheric response of the storm. Fuller-Rowell et al., 1994 [49] explained that the negative ionospheric response of the storm results from increases in molecular nitrogen, with their intensity during the

storm varying based on longitude and local time. They provided two drivers for negative ionospheric responses in the storm-induced nighttime ionosphere. First, since nighttime ion densities are naturally low and the F layer is initially at high altitudes, a slower decay rate has minimal impact. Second, thermal expansion of the ionospheric column spreads ions over a greater altitude range, reducing ion density without necessarily affecting TEC. However, TEC generally mirrors the changes in foF2. Previous studies [4,10] reported similar observations over midlatitude stations, as described in detail in Section 3.3.

The most significant observation during this superstorm was the absence of foF2 and hmF2 values at the stations during the recovery phases of the storm, attributed to the “disappearance” of F-region traces from ionograms. This event was primarily caused by the substantial uplift of the storm-induced F-layer. In their empirical study, Fuller-Rowell et al., 1994 [49] demonstrated that plasma motion along magnetic field lines, driven by meridional winds, produces a direct effect by elevating the F2 peak to a higher altitude with a different neutral composition. Additionally, the divergent global wind field causes an indirect effect, as upwelling accompanying wind divergence leads to alterations in the neutral composition. Another explanation for the pronounced F-region uplift during the Mother’s Day geomagnetic superstorm points to the coupling between the equatorial and polar ionosphere. Karan et al., 2024 [3] observed that the nightside southern crest of the EIA merged with the aurora near the southern tip of South America, as the southern crest of the EIA shifted poleward at speeds up to 450 m/s. They suggested that this poleward displacement, coupled with the equatorward expansion of the aurora, caused the dramatic ionospheric uplift, which resulted in the “disappearance” of the midlatitude ionosphere in the region. This was supported by increasing hmF2 and decreasing foF2 at the Cachoeira Paulista ionosonde, as well as increasing foF2 at the Bahia Blanca ionosonde, indicating enhanced upward plasma drift. They concluded that the poleward shift of the equatorial ionosphere and the equatorward expansion of the aurora merged these together, as observed by GOLD, resulting in the “disappearance” of the midlatitude ionosphere. They also noted that the EIA and aurora merged multiple times during the storm, each time causing significant changes to both structures. Our findings suggest a substantial F region uplift, reaching altitudes above 600 km (Figure 8). At higher latitudes, Themens et al., 2024 [6] documented a similar uplift within the initial SED region over North America, where hmF2 reached ~630 km, with plasma densities several times higher than background levels. Additionally, Spogli et al., 2024 [4] reported significant upward displacement of the ionosphere over Rome, with an F-region uplift during the storm period, verified by background plasma density measurements from Swarm B. These observations align with similar upward displacements registered during previous superstorms (Table 1). For instance, during the Halloween storm on October 30, 2003, the EIA expanded to approximately 28° magnetic latitude (Mlat), due to the combined effect of eastward penetration of electric fields and wind transport [36]. Similarly, auroral expansion from their typical quiet time zone (~70° Mlat) to ~40°–50° Mlat during extremely intense geomagnetic storms has been documented in the past [50]. During the 20–25 March 1940 geomagnetic storm, the auroral oval expanded to ~40° geographic latitude (Glat) [51]. Martinis et al., 2015 [52] studied a moderate geomagnetic storm and reported simultaneous incursions of Equatorial Plasma Bubbles into midlatitudes (~40° Mlat) and the presence of a stable auroral red (SAR) arc between ~45° and 50° Mlat, where the ionospheric trough was detected in GPS TEC maps, highlighting a negative ionospheric storm.

The negative ionospheric response and the F layer uplift during the two storms was closely linked to a significant intensification of the PPEF, as evidenced by the simultaneous increase in the Ey electric field component and hmF2 during the southward turning of IMF Bz ($B_z < 0$) [53]. PPEF represents interplanetary electric fields that rapidly propagate into

Earth's ionosphere and magnetosphere after being convected by the solar wind into the magnetosphere. These electric fields are observed in the magnetosphere and at Earth's ionospheric magnetic equator, with intensities typically ~5–10% of the interplanetary electric field intensities [54]. Vasyliunas, 1969 [55] was the first to describe a magnetospheric convection model based on PPEF. The model assumes that magnetic field lines from the polar caps, which either extend into interplanetary space or interact with a viscous drag boundary layer, partially move with the solar wind. This motion generates an electric field over the polar cap, known as the driving field, which is generally directed from dawn to dusk. Consequently, the electric potential along the polar cap boundary is positive on the dawn side and negative on the dusk side, assuming that variations in the convection pattern are slow enough to neglect induction fields. As shown in Figure 3, the IMF Bz component sharply decreased (~ -30 nT) around 18:00 UT on 10 May and remained negative (southward B), inducing a westward PPEF. This westward PPEF caused the F region uplift due to the enhanced upward $E \times B$ drift. A second significant southward IMF Bz turning occurred during the main phase of the second storm, reinforcing the eastward daytime PPEF inducing further uplift (Figure 3). Between the two storm periods, the positive IMF Bz resulted in a DDEF, affecting the ionosphere gradually during the second storm on 12 May. The ionospheric DDEF significantly influences storm-time ionospheric electric fields at middle and low latitudes. Blanc and Richmond 1980 [56] highlighted how thermospheric winds generated by auroral heating during magnetic storms create global dynamo effects that define the key features of DDEF. Auroral heating drives the formation of a Hadley cell, with equatorward winds forming above approximately 120 km altitude at midlatitudes. These winds transport angular momentum, causing sub-rotation or westward motion of the midlatitude thermosphere relative to the Earth. Westward winds generate equatorward Pedersen currents, which accumulate charge near the equator and produce a poleward electric field, a westward $E \times B$ drift, and an eastward current. At low latitudes, both the electric field and current reverse their typical quiet-day behavior. This disturbance pattern in winds, electric fields, and currents is superimposed on the usual quiet-day dynamics. When neutral winds are artificially restricted to the nightside, the primary pattern of predominantly westward $E \times B$ plasma drifts persists on the nightside but no longer extends into the dayside. This DDEF, coupled with the PPEF during both storms, signified different physical processes as drivers of the negative ionospheric response and the F-layer uplift during the two successive storms. This conclusion aligns with [22] varying ionospheric responses to different triggering processes, magnetic and ionospheric background conditions, and local time.

During the commencement of the first storm, an equatorward shifting of the MIT was also noted. During the main phase, the MIT was detected around 45° N. During the recovery phase, the MIT gradually shifted north and was finally restored to its original latitude range. The second storm event also caused an equatorward MIT displacement as presented in Figures 9–12. Fuller-Rowell et al., 1994 [49] reported the relocation of a trough manifests as a depletion, while the auroral oval expansion and the tongue of ionization (TOI) are observed as increases. The diurnal variation in the ionospheric response to the storm arises from the composition bulge interacting with the background wind field. During the initial and main phases of the storm, the wind field drives the composition bulge equatorward, reaching its maximum latitude penetration, which prompts the equatorward movement of the MIT. In the recovery phase, poleward winds gradually push the bulge poleward, restoring the MIT to its pre-storm latitude range. Paul et al., 2024 [28] documented a significant equatorward and subsequent poleward displacement of the MIT during the 24 March 2023 storm over the European sector, based on Swarm Ne measurements. They attributed the intensification of the trough to a thermospheric density increase and a strong

eastward PPEF observed during the main and recovery phases of the storm. Previous studies [24,26] have identified two primary factors contributing to MIT intensification: neutral composition changes and eastward PPEF. The observed thermospheric density increase [55] and strong eastward PPEF during the main and recovery phases significantly impacted the trough. Similar depletion was observed over the USA during the 2015 St. Patrick's Day storm [40], attributed to thermospheric composition disturbances, asymmetric hemispheric response, and IMF Bz variations.

TID excitation (both MSTID and LSTID) and spread F activity were also registered during the main phase of the first storm. The storm-induced irregularities, reflected in the temporal variations of foF2 and TEC, are attributed to changes in the neutral atmospheric composition, particularly a reduction in the [O/N2] ratio (Figure 7), which increases the ion loss rate [23]. Prölss, 1995 [23] explained that the energy dissipated by the solar wind raises the exospheric temperature, altering the density structure of the polar upper atmosphere. These compositional changes are associated with TID activity and shifts in large-scale wind circulation, both triggered by substantial energy input into the polar ionosphere. The energy and momentum deposited into the polar and auroral regions during geomagnetic storms, through particle precipitation and Joule heating, contributed to the observed Ne decrease over Europe and AGWs observed as TIDs. Borries et al., 2010 [29] identified a strong correlation between the AE index and LSTID amplitudes, suggesting that Joule heating near the auroral oval plays a key role in generating LSTIDs, impacting high midlatitudes and facilitating the formation of Spread F.

5. Conclusions

The present study investigated the ionospheric response over the European midlatitude sector during two consecutive giant geomagnetic storms from 10–13 May 2024—among the strongest since 1957, with a minimum SYM-H index of approximately -436 nT. During the initial phase of the storm, Joule heating at high latitudes elevated the upper thermosphere temperature, while ion drag induced high-velocity neutral winds. This heating generated a global wind surge from both polar regions, propagating toward mid and low latitudes with the characteristics of a large-scale gravity wave. Following the surge, a global circulation was established at midlatitudes, indicating that the wave and the onset of global circulation were integral aspects of the same event. The main conclusions of the present study are as follows:

- a. The strong Ne depletion during the main phases of both storms was primarily attributed to the negative ionospheric response. During the first storm, the depletion was driven by increased thermospheric density, enhanced PPEF, and potentially strong SAPs in auroral regions. Joule heating drives solenoidal winds with strong vertical components, causing pressure and temperature changes. In contrast, momentum-driven irrotational winds lack vertical components and pressure variations. Thus, solenoidal winds are the primary cause of compositional changes and the negative ionospheric response during storms. In contrast, the sharper Ne depletion as observed in the second storm resulted from DDEF superimposed on already disturbed conditions, rendering it more intense overall.
- b. A notable observation was the absence of foF2 and hmF2 characteristics over the midlatitude ionosphere during the recovery phases of both storms, observed over high midlatitude stations from 22:00 UT on 10 May to 03:00 UT and again from 07:00 to 16:00 UT on 11 May during the first storm event. For the second storm, the disappearance was noted from 06:00 to 16:00 UT on 13 May. At lower midlatitudes, this was extended from 23:00 to 16:00 UT during the first storm and from 05:00 to 13:00 UT during the second. This event was characterized by the plasma motion along magnetic field lines, driven by meridional winds, which produced a direct

effect by raising the F2 peak to higher altitudes. This upward movement of plasma also resulted in a change in the neutral composition at the higher altitudes. In addition to this direct effect, the event also involved an indirect effect caused by the divergent global wind field. As the winds diverged, upwelling occurred, which led to significant alterations in the neutral composition of the ionosphere.

- c. The Ne depletion over northern midlatitudes during the main and recovery phases of both storm events reflects the relocation of the trough, while the auroral oval expansion and the movement of a tongue of ionization appear as Ne increases. The diurnal variation in the ionospheric response to the storm was influenced by the interaction between the composition bulge and the background wind field. During the main phase, the wind field drives the composition bulge equatorward, reaching its maximum latitude penetration and causing the equatorward displacement of the MIT. In the recovery phase, poleward winds gradually push the composition bulge poleward, initiating the restoration of the MIT to its pre-storm position. This equatorward shift of the MIT can be attributed to changes in the neutral composition, particularly the reduced [O/N₂] ratio, and the influence of eastward PPEFs.
- d. Intense spatial and temporal variations in the ionosphere were driven by MIT displacement during the storms, coupled with LSTID signatures. LSTIDs, generated at high latitudes, propagated equatorward during the initial and main phases of the first storm. These were accompanied by Spread F conditions, observed exclusively over high midlatitude regions.

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List of Abbreviations

Abbreviations

AATR
AGWs
CMEs
CDSS-MSTID
DDEF
DIDBase
EPBs
EPN
foF2
GICs
GIRO
GNSS
GPS
GUVI
hmF2
HF-INT
HF-TID
HTI
IGS
IMF-B/Bz
INGV
IP
LANCE
LASCO
LSTIDs
LSTIDx
MIT
MSTIDs
MSTIDidx
Ne
P
PCN
PPEF
PRE
RO
ROB
SAIDs
SAPs
SAR
SCIESMEX
SED
SOHO
SSC
SW
SYM-H
TEC
TECgrad
TIDs
Veast
Vnorth
Vz

Definitions

Along-the-Arc TEC Rate
Atmospheric Gravity Waves
Coronal Mass Ejections
Doppler Sounder detection of TIDs
Disturbance Dynamo Electric Field
Digital Ionogram DataBase
Equatorial Plasma Bubbles
EUREF Permanent GNSS Network
Critical frequency of the F2 layer
Geomagnetically Induced Currents
Global Ionospheric Radio Observatory
Global Navigation Service System
Global Positioning System
Global Ultraviolet Imager
Height of the maximum Ne of the F2 layer
High Frequency Interferometry
Digisonde-to-Digisonde TID detection
height-time-reflection intensity
International GNSS Service
Interplanetary Magnetic Field
National Institute of Geophysics and Volcanology
InterPlanetary shock
National Space Weather Laboratory of Mexico
Large Angle and Spectrometric Coronagraph
Large-scale Travelling Ionospheric Disturbances
Large-Scale TID index
Midlatitude Ionospheric Trough
medium-scale TIDs
Spatial and Temporal GNSS analysis for the MSTID index
Electron Density
solar wind pressure
Polar Cap Index Negative
Prompt Penetration Electric Field
Pre-reversal Enhancement
Radio Occultation
Royal Observatory of Belgium
Sub Auroral Ion Drifts
Sub Auroral Polarization streams
Stable Auroral Red
Mexico Space Weather Service
Storm enhanced Densities
Solar and Heliospheric Observatory
Sudden Storm Commencement
Solar Wind
Systematic Horizontal Magnetic Field
Disturbance
Total Electron Content
GNSS TEC Gradient
Travelling Ionospheric Disturbances
East-west horizontal ion drift/plasma velocity
North-south horizontal ion drift/plasma velocity
Ion drift/plasma velocity in the vertical direction

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