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Observational evidence of thermospheric wind and composition changes and the resulting ionospheric disturbances in the European sector during extreme geomagnetic storms

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Abstract—On November 1st and 2nd, 2021, four Halo coronal mass ejections were ejected from the Sun, releasing billions of tons of high-energy particles into interplanetary space. These were directed towards the Earth and reached our planet on November 3rd and 4th, 2021, generating the first G3-level extreme geomagnetic storm since the beginning of the 25th solar cycle. In this study, we investigate the thermospheric and ionospheric responses in the European sector to a G3-level storm using various observational data from Fabry-Perot interferometer, Ionospheric Connection Explorer/Michelson Interferometer for Global High-resolution Thermospheric Imaging (ICON/MIGHTI), and Thermosphere Ionosphere Mesosphere Energetics and Dynamics/Global Ultraviolet Imager (TIMED/GUVI). The results show positive ionospheric storms in the middle and low latitudes of Europe which may be associated with the equatorward and westward neutral winds induced by heating in the polar region. In contrast, negative storms were detected at high latitudes in association with the increase in thermospheric density (upwelling). These two antithetical responses were confirmed by using European ionosonde and total electron contents (TEC) observation chains distributed over a wide range of latitudes. Finally, we, for the first time, attempt to identify the imaginary boundary line between the two responses.

Keywords: Ionosphere responses / Geomagnetic storm / CMEs / Zonal and meridional winds / TID induced by TAD

1. Introduction

Geomagnetic storms can occur when solar coronal mass ejections (CMEs) have a profound impact on the space environment surrounding the Earth because of the strong solar winds and interplanetary magnetic field (IMF) interacting with the Earth's magnetic field. In particular, when the north-south component (B_z) of the IMF points southward near the Earth, it can lead to a phenomenon called magnetic reconnection, which causes high-energy particles to precipitate strongly into the Earth's ionosphere. Geomagnetic storms can alter field-aligned currents (FAC), which affect the electrodynamics of the polar ionosphere. These magnetospheric energy inputs occurring during these storm events can lead to the heating of the polar upper atmosphere, which propagates to lower latitudes to have global

effects (Rishbeth, 1975, 1998; Fuller-Rowell et al., 1994, 1997; Buonsanto, 1999; Wang et al., 2010).

The heating of the polar thermosphere is of great significance. As the thermosphere heats due to Joule heating or auroral heating, the Earth's atmosphere expands, transporting neutral molecular components from lower to higher altitudes. Consequently, the O/N₂ ratio is reduced, and the loss process of ionospheric plasma in the polar region dominates. Therefore, at high latitudes, the ionosphere statistically produces negative ionospheric storms during geomagnetic storms (Shinbori et al., 2022). Furthermore, expansion due to heating in the thermosphere is not limited to altitude but extends in the latitudinal direction as well. The result of this expansion is wave-like propagation in the form of traveling atmospheric disturbances (TADs), due to which, the ionosphere can also propagate in the form of waves called traveling ionospheric disturbances (TIDs) (Rishbeth, 1975; Richmond & Matsushita, 1975;

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Fuller-Rowell et al., 1994; Shiokawa et al., 2007; Borries et al., 2009; Prölss, 2012).

From another perspective, when the high-latitude thermosphere is heated, neutral atmospheric winds blow toward the equator, triggering a global cyclic convection process. Therefore, the equatorward component of the neutral wind may be dominant and then change westward because of the Coriolis force in the middle latitudes (Blanc & Richmond, 1980). At this point, plasmas of the ionosphere in the middle latitudes (bound by the Earth's magnetic field lines) can be transported to higher altitudes by equatorward neutral winds from high latitudes (Lin et al., 2005; Lu et al., 2008). Plasma transported to higher altitudes can persist for relatively longer periods, causing positive storms in mid-latitude regions. Moreover, in sunlit equatorial regions, strong fountain effects due to enhanced eastward equatorial electrojet currents during geomagnetic storms are added, and a significant positive storm can occur at middle latitudes (Scherliess & Fejer, 1997).

Although many studies (Thayer et al., 1995; Knipp et al., 2004; Deng et al., 2011; Zhu et al., 2022) on the ionospheric responses to the expansion of the thermosphere have been conducted in the past, most have detected and analyzed only one aspect of the ionospheric storm. In addition, the propagation of thermospheric winds has been widely studied through sounding rocket observations in the past (Smith, 1968; Haerendel, 1972; Rishbeth et al., 1972; Fagundes et al., 1995). It has been reported that the equatorward wind is dominant at a speed of approximately -150 to 500 m/s during geomagnetic storms. However, most studies analyzed wind data from only one location. Therefore, observational data have spatiotemporal limitations.

In this study, we simultaneously report the thermosphere and ionosphere responses over Europe during the G3 geomagnetic storm on November 4, 2021. We cross-checked the strength of wind blowing in the equatorial direction after polar heating using Fabry-Perot interferometer (FPI) observations at high latitudes and an Ionospheric Connection Explorer/Michelson Interferometer for Global High-resolution Thermospheric Imaging (ICON/MIGHTI) observations at middle latitudes. In addition, through the European Ionosphere Observation Network, the tendency for negative storms at high latitudes and positive storms at middle latitudes could be confirmed simultaneously. Furthermore, this tendency was confirmed to propagate to lower latitudes through TID waves.

Unlike previous studies, we simultaneously confirmed thermospheric changes and their resulting ionospheric responses during extreme geomagnetic storms over a wide latitudinal area using various observational data. In addition, we were able to delineate the boundary between two ionospheric storms that exhibited contradictory behaviors. Section 2 presents the data and analysis methods used and Section 3 presents the results of the ionosphere and thermosphere reactions. Finally, Section 4 summarizes the study.

2 Data and methods

2.1 Solar and near-Earth space environment data

We provide a brief overview of the four halo CMEs that occurred on the western limb of the solar disk from November 1–2, 2021. We utilized four CME images from the Solar and

Heliospheric Observatory (SOHO)/Large Angle and Spectrometric Coronagraph (LASCO)-C2 coronagraph and the CME catalog available at https://cdaw.gsfc.nasa.gov/CME_list/. Figure 1 and Table 1 summarize the characteristics of four halo CMEs. In Table 1, the first column, “halo type”, distinguishes the size of halo CMEs based on their angular width. CMEs with an angular width over 90° were labeled Type II, those over 180° as Type III and those over 270° as Type IV. The second column indicates the time when the CME occurred, and the third column displays the “Central Position Angle (CPA)” which is measured counterclockwise from solar north at 0° to the center of the angular width where the CME originated. This angle provides a means to locate the region where the CME occurred. The fourth column, “angular width,” represents the angular span of the CME in the plane of the sky. Lastly, the “linear speed” is obtained by fitting a first-order polynomial to the height-time measurements and representing the velocity of the CME as a function of time.

We also examined the space environment data based on the CME characteristics to obtain information about the geomagnetic storms that occurred on November 3rd and 4th, 2021. Figure 2 shows the solar wind velocity, flow pressure, solar wind-induced interplanetary electric field (IEFy), symmetric disturbance of H components (SYM-H), IMF Bz, and Auroral Electrojet (AE) index. The AE index was obtained from the Kyoto University website (<https://wdc.kugi.kyoto-u.ac.jp/aedir/>), and the remaining space environment information was downloaded from the OMNI webpage (https://omniweb.gsfc.nasa.gov/form/omni_min_def.html).

2.2 Observational data over the European sector

Observational data were used to ascertain the thermospheric and ionospheric responses of Europe to geomagnetic storms. First, we utilized data from the FPI installed in Kiruna (67.8°N , 20.4°E geographic coordinates, and 65.42°N geomagnetic latitude) to check the thermospheric wind changes. It was installed by the Korea Polar Research Institute (KOPRI) and has been in operation since 2016. Because Kiruna (red star symbol) is located mainly in the auroral oval region, as in Figure 3a, we can clearly observe the responses of the thermospheric zonal and meridional winds over this region when geomagnetic storms occur.

Observing thermospheric wind data near middle latitudes is also necessary to confirm the change in thermospheric winds from high to middle latitudes during geomagnetic storms. However, we could acquire no ground-based observational wind data near the mid-latitudes in the European sector. Therefore, we selected and secured thermospheric wind data from the ICON/MIGHTI satellite as an alternative. The ICON/MIGHTI data was available for download from the following FTP public server (<ftp://icon-science.ssl.berkeley.edu/pub/>). In Figure 3a, the positions marked with the ‘x’ are the points observed by the satellite. The ICON/MIGHTI measures neutral wind velocities from 88 km to 300 km by observing oxygen atom emission lines (green line – 557.7 nm & red line – 630.0 nm) through limb scanning. We used only red-line data with altitudes between 253 and 301 km obtained from the region spanning 20° to 40°N , encompassing the European continent and the Atlantic Ocean. Although the ICON/MIGHTI observation location is slightly biased towards the western side, away from the

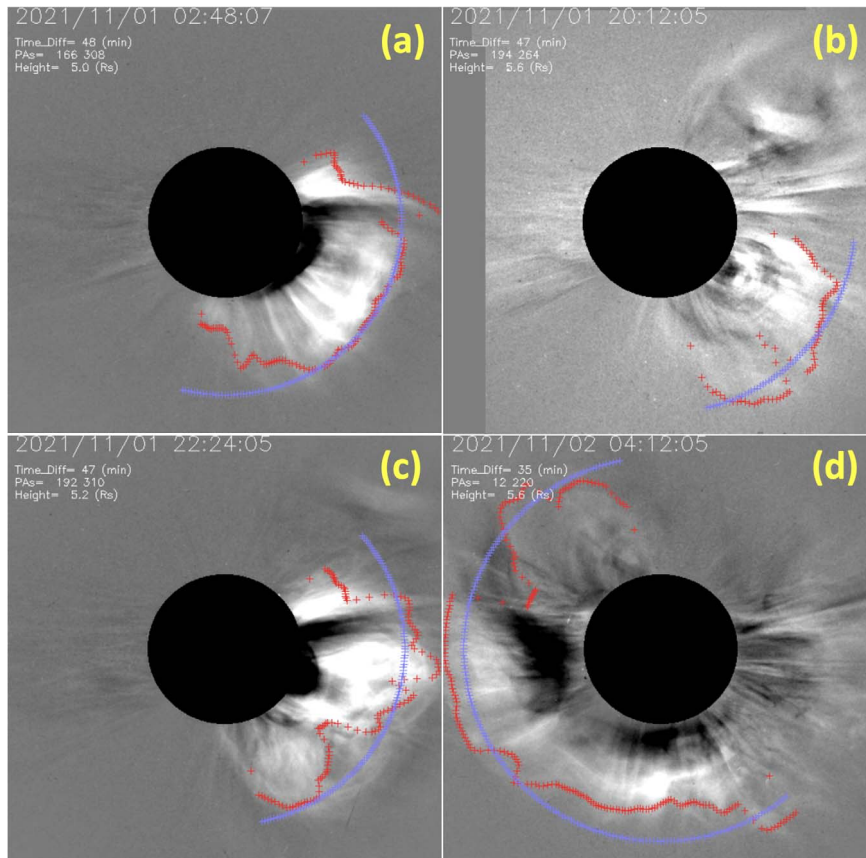


Figure 1. Images of four CMEs between November 1st and 2nd 2021 from SOHO/LASCO C2. The individual images in (a)–(d) represent sequentially occurring events; detailed information can be found in Table 1.

Table 1. Characteristics of four CMEs from SOHO/LASCO C2.

No.	Halo type	Start time (UT)	Central PA (°)	Angular width (°)	Linear speed (km/s)
(a)	Type II	2021/11/01/UT 02:00:06	201	274	753
(b)		2021/11/01/UT 18:24:05	228	116	461
(c)		2021/11/01/UT 21:24:05	246	162	830
(d)	Type IV	2021/11/02/UT02:48:05	Halo	360	1473

upper atmosphere over the European continent, we considered the possibility of using their data because, during geomagnetic storms, the overall direction of the macroscopic atmospheric circulation does not change significantly.

To utilize ICON/MIGHTI wind data in our study, we employed version 4 and selected data with a quality standard greater than 0.5 (=caution). Although it is generally recommended to use data with a quality standard of 1.0 (=Good), we had to use caution standard data because we required spatiotemporal data in the mid-latitude region. When we analyzed the data, we could only obtain 11 to 37 data points per altitude for the 1.0 level quality data from November 2nd to November 5th. Moreover, on November 4th, which is the day with the strongest geomagnetic storm according to the Kp index, there were no observations available at the 1.0-level. However, for the 0.5-level data, we were able to secure a much larger number of data points, ranging from 114 to 223 per

altitude. Forbes et al. (2022) similarly utilized data with a quality standard of 0.5 and noted that it can be used adequately with proper caution flag verification. Before using the 0.5-level data, we analyzed the caution codes for each individual dataset from the ICON/MIGHTI wind data. The caution codes for the ICON/MIGHTI data can be found in the official documentation, and each dataset includes various caution flags ranging from 0 to 33. Upon analyzing the caution codes for the 0.5-level data, we observed the presence of some noticeable caution codes. Among them, we utilized all data except those with no calibration performed or with bad calibration codes.

In addition, to check the thermospheric composition change, we utilized O/N₂ ratio data from the Thermosphere Ionosphere Mesosphere Energetics and Dynamics/Global Ultraviolet Imager (TIMED/GUVI), which was developed by the Johns Hopkins University/Applied Physics Laboratory (JHU/APL). The O/N₂ ratio data may allow us to infer drivers of the change

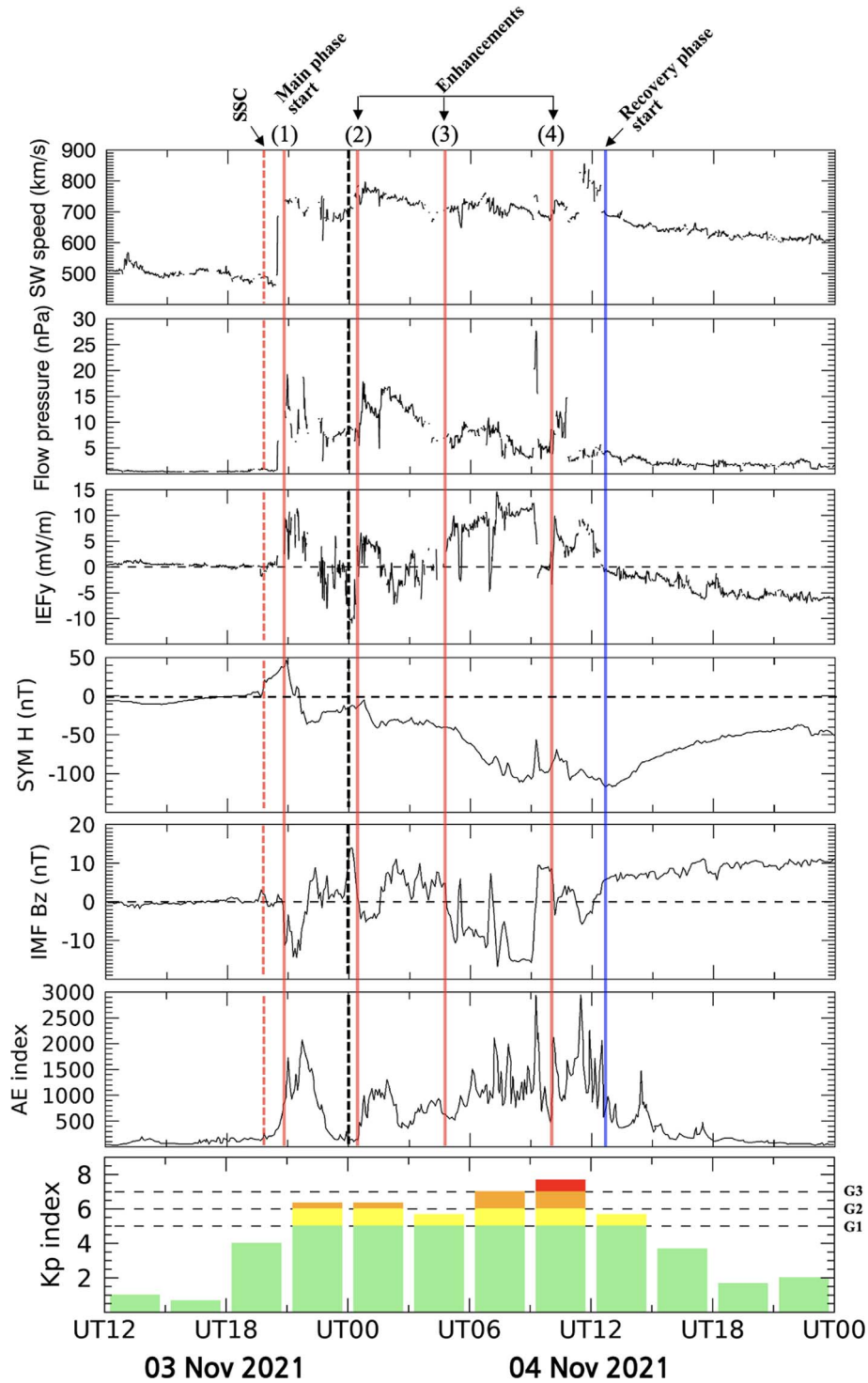


Figure 2. The state of the space environment during the period November 3–4, 2021, when the G3 geomagnetic storm occurred. The panels from top to bottom display the solar wind speed, flow pressure, IEFy, SYM-H, IMF Bz, AE index, and Kp index. The red vertical dashed line indicates the SSC. The first red vertical solid line (1) indicates the main phase start of the geomagnetic storm triggered by type IV halo CME occurred on November 2nd. Three red vertical solid lines (2–4) indicate the enhancements of the geomagnetic storm due to subsequently arriving CMEs. The blue vertical solid line marked the recovery phase start of the storm. The black dashed vertical line indicates the date change.

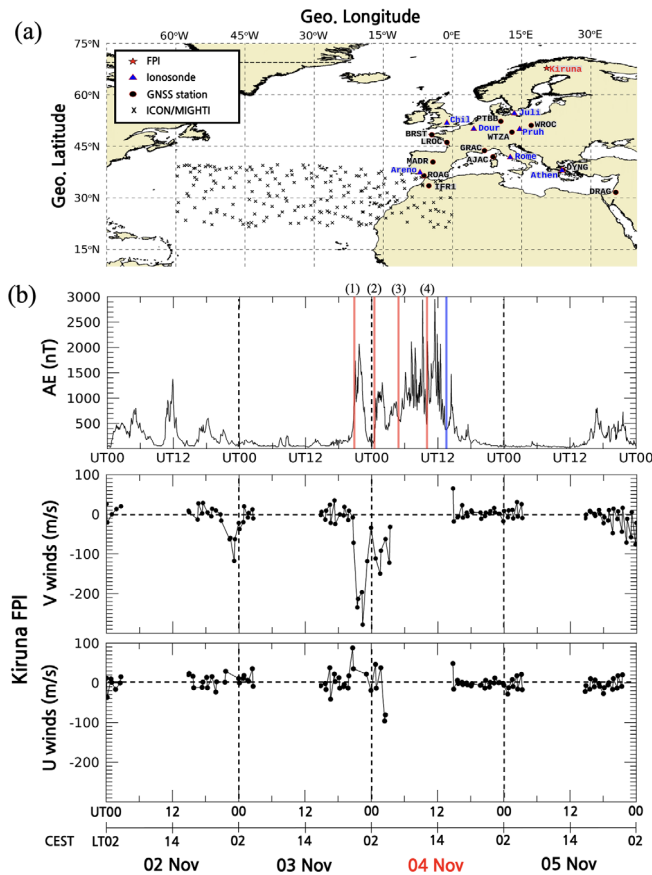


Figure 3. (a) Locations of thermospheric and ionospheric observations conducted in Europe and the North Atlantic region. (b) Meridional (V) and zonal (U) wind components derived from Kiruna FPI observations. Also, the annotations corresponding to (1)–(4) in (b) represent the same meanings as the numbers in Figure 2.

in the ionospheric plasma during geomagnetic storms. Furthermore, since the O/N_2 ratio data were available on a global map, it is possible to delineate the difference in the composition of the thermosphere in the European region we are targeting.

Next, we utilized data from the European Ionosonde Service (EIS)/European Digital Upper Atmosphere Server (DIAS), a European ionosonde observation network, to estimate the ionospheric changes over Europe by latitude (Belehaki et al., 2015). This network contains many ionosonde data from northern to southern Europe and can be accessed on a web page (<http://dias.space.noa.gr/>). Also, we obtained the hmF2 values from the Global Ionospheric Radio Observatory (GIRO) network (Reinisch & Galkin, 2011) using the SAO-X program database server and analyzed the variation of the hmF2. In this study, we used seven European ionosonde datasets (Arenosillo, Athens, Chilton, Dourbes, Juliusruh, Pruhonice, and Rome), as indicated by the blue triangular symbols in Figure 3a. We also selected the international quiet days (IQD) to use the quiet period as a reference and confirmed the ionosphere storm pattern on the event day.

Finally, we utilized the vertical total electron content (VTEC) data from the Global Navigation Satellite System (GNSS) receiver indicated by the black circle symbol in

Figure 3a. GNSS data (<https://www.unavco.org/data/gps-gnss/gps-gnss.html>) from 12 sites were selected to track latitudinal changes in the ionosphere over Europe. Table 2 summarizes the locations of the ionosondes and GNSS receivers used to investigate the distribution of ionospheric storms according to latitude and longitude in Europe and their propagation during geomagnetic storms. To mitigate errors caused by low satellite altitudes, we utilized only data with elevation angles greater than or equal to 30° . The VTEC data allow us to determine the boundary line between the positive and negative ionospheric responses to the geomagnetic storms.

3 Results and Discussions

3.1 Responses of Near-Earth Space Environment

As shown in Table 1, three partial halo CMEs occurred sequentially on November 1st, 2021, at 02:00, 18:24, and 21:24 UT. The fourth CME, which was the largest and fastest type-IV halo CME, occurred on November 2nd, 2021, at 02:48 UT. In particular, the last halo CME appears to have played a decisive role in directly affecting the Earth. Li et al. (2022) reported that the last halo CME caught up with the three preceding CMEs just before reaching the Earth. Additionally, they described the potential for stronger turbulence due to CME-CME interactions among these four halo CMEs. Therefore, it appears that the most recent Type IV halo CME (referred to as (d) in Table 1) arrived near Earth at UT 19:36 on November 3rd, 2021, which triggered the onset of the Sudden Storm Commencement (SSC), which is indicated by the red vertical dashed line in Figure 2. Here, the SSC refers to the abrupt increase in the Earth's magnetic field, which occurs when a fast solar wind associated with the aforementioned halo CME reaches Earth (Oyedokun & Cilliers, 2018). When a fast solar wind reaches the leading edge of the Earth's magnetosphere, the magnetopause is compressed, resulting in a sudden elevation of the Earth's dayside magnetic field. We identify the point at which the SYM-H index in Figure 2 begins to increase as the starting point of the SSC and have indicated it accordingly.

The main phase of a geomagnetic storm triggered by the arrival of the most recent halo CME on Earth began, marked by the red vertical solid line (1) in Figure 2, immediately after the SCC caused by the solar wind colliding with the Earth's magnetosphere. From this point onward, the AE index also starts to increase rapidly, which means that not only are high-energy particles deposited into the auroral oval region, but also the interplanetary electric field is injected there, resulting in strong auroral electrojet currents (Baumjohann & Kamide, 1984; Wei et al., 1985). During the main phase of the storm, the high-latitude thermosphere can be heated by both Joule heating and auroral precipitation. It is worthwhile noting that the AE index increased as the IMF Bz stayed southward. In this storm period, the Kp index reached 7, which was recorded as a G3 storm.

After the main phase started (1), it can be observed from all indicators that the intensity of the storm increases again at points (2), (3), and (4). The three red solid lines (2), (3), and (4) represent periods when the subsequent arrival of CMEs adds to their impact on Earth, that is when they further intensify the geomagnetic storms caused by earlier arriving CMEs. The criteria

Table 2. Locations of the ionosondes and GNSS receiver stations.

Station	Geog. Lat. (°N)	Geog. Lon. (°E)	Geom. Lat. (°N)
Ionosonde			
Juliusruh	54.60	13.40	54.30
Chilton	51.60	358.7	47.70
Dourbes	50.10	4.60	51.07
Pruhonice	50.00	14.60	49.35
Rome	41.90	12.50	41.81
Athens	38.00	23.50	36.24
Arenosillo	37.1	353.3	27.28
GNSS receivers			
PTBB	52.29	10.46	52.24
WROC	51.11	17.06	50.04
WTZA	49.14	12.88	48.80
BRST	48.38	355.50	50.87
LROC	46.16	358.78	48.19
GRAC	43.75	6.92	44.52
AJAC	41.93	8.76	42.45
MADR	40.43	355.75	43.08
DYNG	38.08	23.93	36.25
ROAG	36.46	353.79	39.51
IFR1	33.51	354.87	36.45
DRAG	31.59	33.39	28.42

for defining points (2)–(4) may vary based on different indicators, but our primary approach was to check when the IMF Bz value transitions into negative. In Figure 2, the fifth panel from the top displays the IMF Bz values, and we observed the beginning of the negative transition at points (2)–(4) as defined by us. Although occasional abrupt switches between positive and negative values are evident, interpreting all of these variations can be challenging. For points (2)–(4), we assumed that a large portion of the impact had surrounded the Earth. A negative IMF Bz value indicates a southward orientation of the interplanetary magnetic field, which is favorable for magnetic reconnection with the Earth's magnetic field. Simultaneously, if accompanied by strong solar wind speed, it can generate a powerful electric field throughout the Earth. We refer to this as the interplanetary electric field extending from dawn to dusk (IEFy), and we are actually calculating it using the formula $V \times B_z$. Some studies have shown that during such events, a strong dawn-to-dusk electric field envelopes the entire Earth, triggering the Prompt Penetration of Electric Fields (PPEF) phenomenon almost instantly (Singh et al., 2022; Idosa & Shogile, 2023).

Moreover, the first and second panels of Figure 2 show the characteristics of the solar wind. The solar wind has already covered the Earth with fast and strong pressure after the main phase. Despite some variations in magnitude, the solar wind continues with rapid and strong pressure. In other words, even if the solar wind progresses continuously with relatively minor changes, its impact on geomagnetic storms can vary depending on the direction of the IMF Bz. It can either strengthen or weaken the storms. Particularly, at point (3), the speed or pressure of the solar wind does not show any significant enhancement. However, the IEFy exhibits a sharp increase at this point. This response is largely influenced by the IMF Bz. The AE index, which indicates the intensity of geomagnetic storms, also shows a subsequent increase after this point. Therefore, while considering the variations in the solar wind and other

indicators, we primarily focused on the direction of the IMF Bz to identify the intensification point of this event.

Regarding this event, Li et al. (2022) found that a plasma sheath structure passes through points (1) to (4), and after point (4), a magnetic cloud passes through the Earth. Here, a magnetic cloud is one of the phenomena resulting from CMEs, characterized by enhanced magnetic field strength, smooth rotation of the magnetic field vector, and low proton density and temperature observations (Burlaga et al., 1981, 1982). As the confirmation of the observed magnetic clouds during this event falls outside the scope of our study, we did not provide detailed explanations. For further details, please refer to the study by Li et al. (2022). Based on their analysis (Li et al., 2022), it was difficult to determine the cause of the sudden intensification of the storm at Points (2) and (3). Verifying the structures of CMEs that changed due to CME-CME interactions using observational data is particularly challenging. Tentatively, we understand that the changes at points (2) and (3) were caused by the CMEs shown in Tables 1 (a) and 1 (c), which arrived after the CME-CME interaction and had a relatively weaker impact. Lugaz et al. (2017) comprehensively reviewed the effects of CME interactions, including complex magnetic reconnection, momentum exchange, and shock propagation, which can lead to various outcomes. In addition, Scolini et al. (2020) reported multiple occurrences of interplanetary shocks (IPs) and magnetic ejecta resulting from CME-CME interactions during the main phase of a geomagnetic storm that occurred in September 2017. Their studies provided insight into the impact of CME-CME interactions on geomagnetic storms. We speculate that the events reported here also involve such complex responses. It is almost impossible to interpret fully the characteristics of changes in the near-Earth space environment due to CME-CME interactions based on only one event. Therefore, we suggest that collecting more event cases of CME-CME interactions and tracking the resulting changes in the near-Earth space environment should be pursued in future studies.

3.2 Changes in the thermospheric winds

The second and third panels of Figure 3b show the meridional and zonal wind components, respectively, from the FPI observations at Kiruna. We present the AE index information along with these figures to clarify the impact of geomagnetic storms. Markings (1), (2), (3), and (4) at the top of the AE index are the same as those in Figure 2. At the onset of the geomagnetic storm, the thermospheric meridional wind (V) also switched to a negative value with a slight time difference (approximately 50 min). This pattern was repeated twice, indicating changes in thermospheric winds due to Joule and auroral heating over the auroral oval region (Prölss, 2012; Lu et al., 2012). A negative value of meridional wind indicates the wind blowing toward the equatorial direction (southward). We can confirm a velocity of about -280 m/s after the first energy inflow, marked with (1).

When geomagnetic storms occur, the equatorward winds intensify, as observed in many previous studies. The meridional winds in the middle latitudes measured by sounding rockets were reported to have a velocity of 100 to 200 m/s in the equatorward direction (Smith, 1968; Haerendel, 1972; Rishbeth et al., 1972; Fagundes et al., 1995). Similar equatorward winds have been reported in FPI observations over high

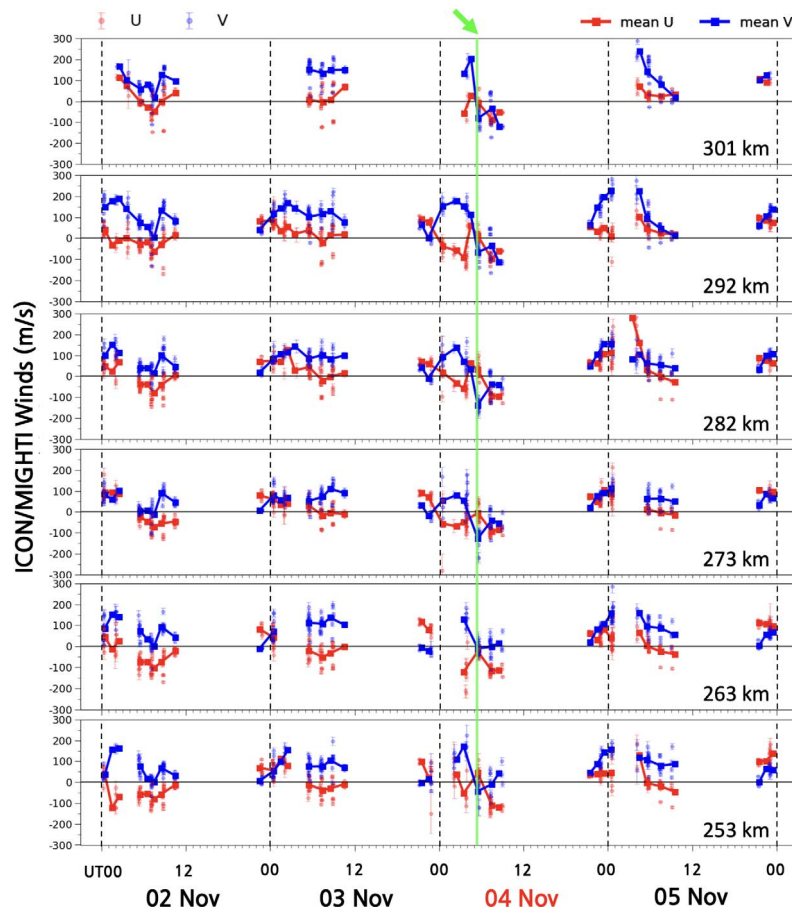


Figure 4. The thermospheric winds presented include error bars at 253–301 km altitudes, as observed near middle latitudes by ICON/MIGHTI satellite. The square symbols represent the hourly averaged values. The vertical black dashed lines denote the points where the dates change, while the horizontal lines indicate 0 m/s for each altitude. Additionally, the green vertical line and arrow indicate significant change points in the meridional wind (U) fields.

(Rishbeth et al., 1972) and mid-latitude regions (Malki et al., 2018; Loutfi et al., 2020). As shown in the FPI wind data in Figure 3b, we can clearly see that the wind turned to the equatorial direction (approximately -280 m/s) after a geomagnetic storm occurred, consistent with the previous studies. Meanwhile, although there was a clear change in the equatorward wind of the FPI after a geomagnetic storm, it was difficult to find a large change in the zonal wind, and the observation results during the geomagnetic storm periods were similar to those of other days. In other words, although accurate interpretation is difficult because of data gaps caused by the nature of optical observations, the change due to geomagnetic storms in the middle latitudes is considerably weaker in the case of zonal winds than in meridional winds.

Another goal of this study is to examine how changes in the thermospheric wind generated in the auroral oval region propagate to the middle latitudes. The ICON/MIGHTI wind observations at middle latitudes are presented in Figure 4. Based on the ICON/MIGHTI results, it was revealed that a strong equatorward wind was blowing in the thermosphere on the day of the geomagnetic storm compared to other days and that the westward wind was blowing in the zonal direction. Strong equatorward winds are speculated to be influenced by global circulation blowing from polar regions. Previous studies

(Fagundes et al., 1995; Yagi & Dyson, 1985; Burnside et al., 1991) have also reported wind changes in the westward and equatorward directions near middle latitudes; therefore, our results are reasonable. Compared to the response seen in the FPI wind data shown in Figure 3b the ICON/MIGHTI observations appeared to have propagated to the mid-latitudes after approximately 5 h. At this time, the speed of the propagating wave was approximately 245 m/s, which is similar to the propagation speeds reported in previous studies as mentioned earlier.

An Important feature of this study is that the change in thermospheric wind according to the energy input over the auroral regions was successfully tracked using observational data at high and middle latitudes. Most previous studies used data observed at one location to estimate wind changes or did so through global model simulations (Lu et al., 2001; Wang et al., 2008). Therefore, we are confident that our observational results provide strong evidence for estimating changes in global thermospheric winds related to geomagnetic storms.

3.3 Changes in the thermospheric composition

Figures 5a and 5b show the global distribution of the O/N₂ ratio from TIMED/GUVI on the quiet day, November 3, before the geomagnetic storm occurred, and on the G3-level

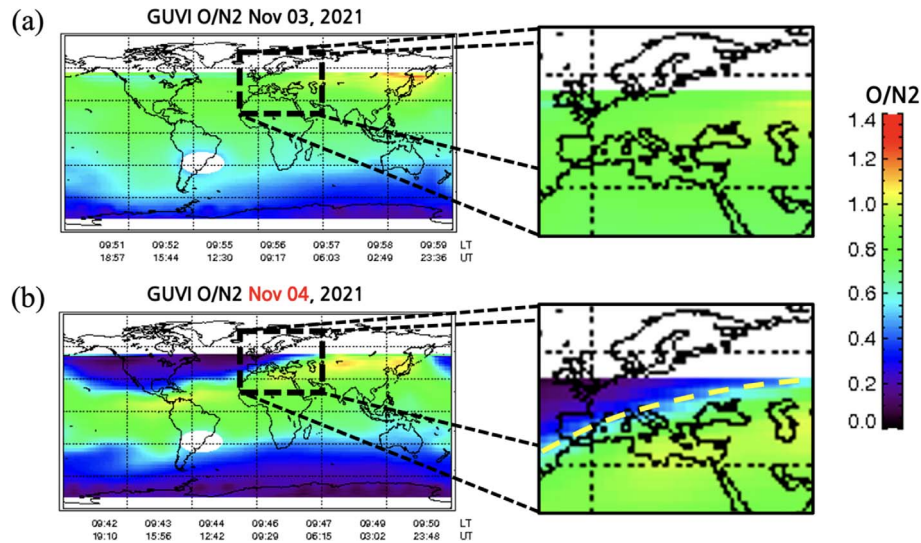


Figure 5. O/N_2 ratio values observed by TIMED/GUVI. (a) The day before the geomagnetic storm; (b) the day the geomagnetic storm occurred.

geomagnetic storm day, November 4, respectively. It is evident that the value of the O/N_2 ratio decreased during the geomagnetic storm in all high-latitude regions of the northern and southern hemispheres. The decrease in the O/N_2 ratio may result from a rapid increase in the density of N_2 because the thermosphere at high latitudes heated up and expanded the atmosphere to higher altitudes. The increase in N_2 makes a major contribution to the depletion of the ionospheric plasma via the fast recombination of molecular ions, resulting in a lower-than-usual electron density in the high-latitude ionosphere. The decreased O/N_2 ratio values observed by TIMED/GUVI are clear indications that the thermosphere responded to the geomagnetic storm.

A detailed examination of the O/N_2 ratio data in the European region revealed that the thermospheric composition changed rapidly along a specific latitude line, as shown in the right panel of Figure 5b. At latitudes lower than this particular line, values similar to the ordinary O/N_2 ratio were observed, while considerably lower values were observed at higher latitudes. We speculated that these changes in thermospheric density may have had a significant effect on the conditions of the ionosphere.

3.4 Evidence from the ionospheric responses

Finally, we analyzed ionospheric changes over Europe using an observation network distributed by latitude. Figure 6a shows the ionosonde and the GNSS receive stations from which we obtained the critical frequency of the F2 layer (f_oF_2), the peak height of the F2 layer (h_mF_2) data, and the VTEC data, respectively. To facilitate the understanding of the timing of geomagnetic storms for each phase, we have marked them as (1)–(4) and R at the top of Figure 6b–6d, which corresponds to the markings shown in Figure 2. In addition, we have shown the reference line of the quiet period, which is the average of the diurnal variations in f_oF_2 , h_mF_2 , and VTEC corresponding to the IQD dates, as a black solid line and the changed value on the day of the geomagnetic storm as a red solid line. We placed

the high-latitude data at the top and arranged them in sequential latitude order so that the characteristics of the latitude-specific changes could be easily captured. For h_mF_2 , there was no reliable data from the Rome ionosonde's SAO dataset, so we did not include it in Figure 6.

If the f_oF_2 value of the red solid line in Figure 6c is greater (less) than that of the black solid line, it can be said that a positive (negative) ionospheric storm has occurred. It is challenging to precisely interpret the sudden changes in f_oF_2 and VTEC shown in the figures and pinpoint their exact origins among points (1)–(4). The complexity arises from the time it takes for energy to move from high to mid-latitudes and the interactions of various factors. In this study's scope, determining the exact starting point for these changes remains difficult. However, a possible scenario is that these effects began accumulating during the main phase's onset (point 1) and continued to impact lower latitudes thereafter.

We note from Figure 6c that the two opposing ionospheric storms appeared simultaneously at different latitudes with a border between Pruhonice and Rome stations. Similarly, 12 GNSS VTEC datasets are plotted in Figure 6d, and two opposing ionospheric storms also appear, centered at specific latitudes (between the LROC and GRAC stations). Based on these observations, we drew a virtual blue dashed line in Figure 6a, which is the boundary or reference line for opposing ionospheric storms. In other words, based on this boundary, negative storms occurred at higher latitudes, and positive storms were observed at lower latitudes. Notably, the blue dashed line in Figure 6a and the yellow dashed line in Figure 5b are located at very similar latitudes. The maximum electron density values of the F2 layer and the GNSS VTEC values indicated the same location with respect to the boundary between the two ionospheric storms. This boundary line is not coincidental but provides extraordinary evidence for separating the two opposing ionospheric storms.

It has been suggested that the upwelling of the thermosphere at high latitudes leads to a reduced O/N_2 ratio, resulting in a negative ionospheric storm that lowers the electron density in

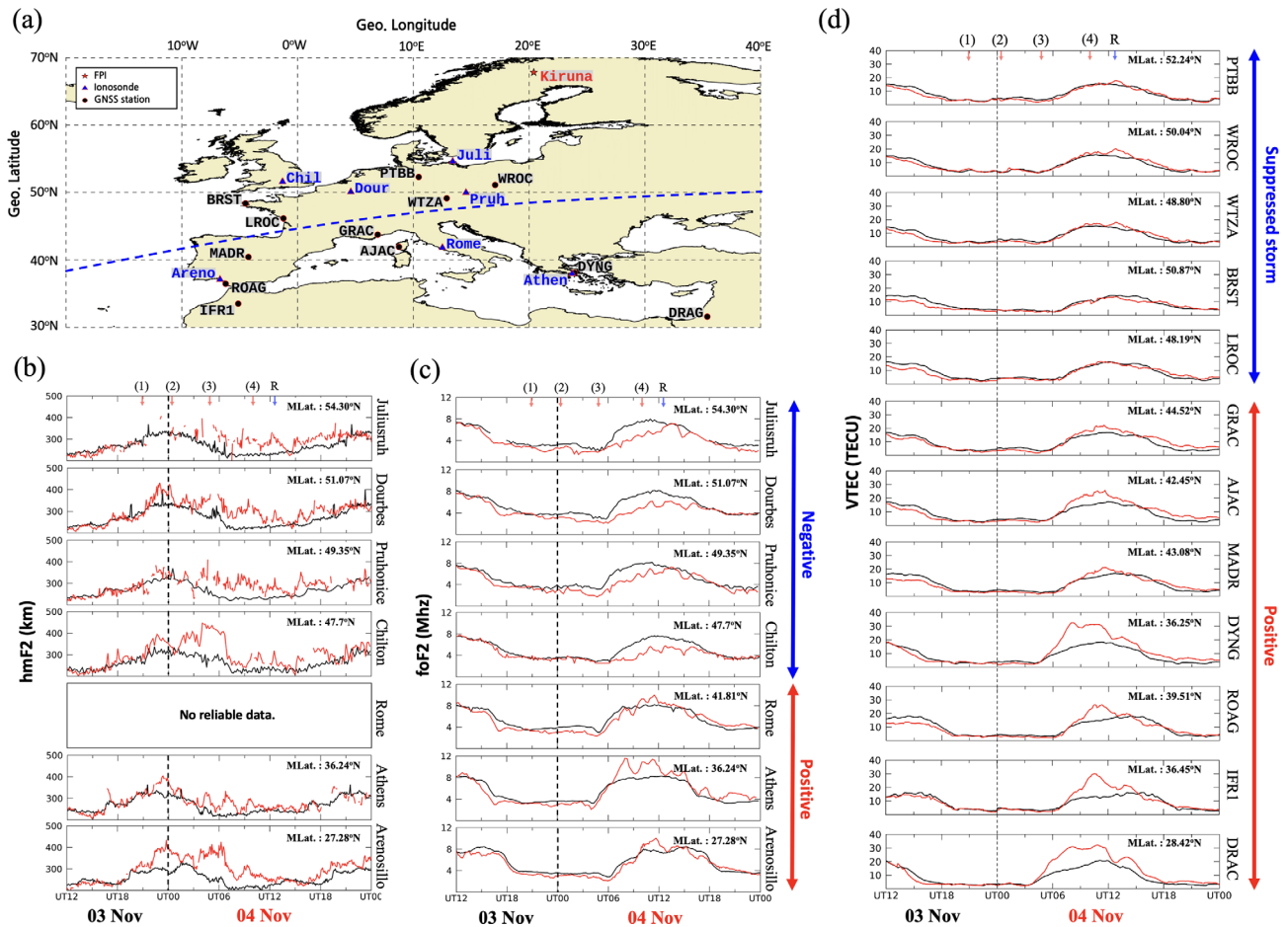


Figure 6. (a) Locations of observation equipment used over Europe. The blue dashed line is the imaginary boundary where the pattern of the ionosphere storm changes. (b) and (c) Variations in hmF2 and foF2 values from ionosondes. The black solid lines represent the IQD reference day and the red ones are those on the event days. (d) Variations in VTEC values from GNSS receivers. The (1)–(4) and R markers indicated at the top of (b)–(d), along with the storm phases used in Figure 2 illustrate the state of geomagnetic storms.

the ionosphere (Rishbeth, 1998). On the other hand, at middle latitudes equatorward of the boundary line, the thermospheric expansion is not effective, but thermospheric winds blow in the equatorial direction, resulting in a positive ionospheric storm that increases the electron density in the ionosphere. When the equatorward wind blows in the middle latitude region, ions move to higher altitudes due to collisions with plasmas bound to the Earth's magnetic field lines. Based on the model study with a thermospheric equatorward wind of 100 m/s from the Horizontal Wind Model (HWM), Balan et al. (2009) realized that the super-fountain effect can occur at low and middle latitudes. They reported that during a geomagnetic storm, the equatorward wind and fountain effect combine to generate a strong positive ionospheric storm at low and middle latitudes. In short, the lifetime of the plasmas becomes prolonged at high altitudes, increasing electron density in the low- and middle-latitude ionosphere.

As we speculated and anticipated, the F2 layer from high to mid-latitudes appears to be significantly elevated, as clearly observed in Figure 6b. However, it is worth noting that at high latitudes, the heating effect of the thermosphere could cause its expansion, which might result in the higher altitudes of the

F2 layer. At lower latitudes, the effect of the thermospheric expansion on the elevation of the F2 layer becomes less significant compared to the influence of the wind pattern. The fact that the F2 layer remains at higher altitudes in mid-latitudes indicates, it is conceivable that the equatorward wind played a substantial role in displacing the plasma to higher altitudes along the magnetic field lines, as supported by the observational evidence we presented. Hence, although the increase in hmF2 was observed across all latitudes, the specific causes of the elevation might vary regionally. Interestingly, the abrupt change in the O/N₂ ratio along the blue dashed boundary line we envisioned suggests that both the thermospheric expansion and the wind-induced effect might have occurred simultaneously in the European region.

In addition, the model of Bravo et al. (2019) demonstrated that wave-like perturbation of foF2 propagates from high latitude to low latitude at a speed of about 300 m/s. Various studies have reported the propagation of wave-like perturbations (Richmond & Matsushita, 1975; Shiokawa et al., 2007; Borries et al., 2009; Prölss, 2012). In fact, Figure 6c shows wave-like perturbations that have a pattern of gradual propagation from high latitudes to lower latitudes. As observed from the variation

in the AE index in the top panel, the intensity of the storm weakened and strengthened three times from (2) to (4) after the start of the main phase of the geomagnetic storm (1). Repetitive changes in the energy input at high latitudes may have provided optimal conditions for wave-like perturbations to propagate to the middle latitudes, which may be directly reflected onto the ionosphere. Hence, it can be inferred that repetitive fluctuations in storm intensity contribute to wave-like perturbations created in this manner. Furthermore, by tracking the wave-like perturbation from Juliusruh to Athens, we estimated a propagation speed of ~ 300 m/s which is a very similar velocity to previous research results. Therefore, the foF2 peak perturbations from the ionosonde latitudinal chain presented in this study can be regarded as sufficient evidence for wave propagation. However, wavelike perturbation propagation was not clearly observed in the VTEC data, as shown in Figure 6d. This is likely due to the longitudinal distribution of the GNSS stations in which the local time influence contributed strongly. In fact, the furthest east (DRAG) and west (IFRI) stations are about 40 degrees apart in longitude. Upon examining the positive storm occurrence time in Figure 6d, it was observed that a positive storm appeared in the DRAG station data approximately three hours earlier despite the two stations being relatively close in latitude. This effect is likely due to the longitudinal difference and may explain why wave-like perturbations do not appear to propagate southward in the VTEC data plot. Another possibility is that wave-like perturbations may be attenuated during the process of mapping slant TEC observed by GNSS receivers into VTEC. Due to the different satellite observations of wave phases, such phase differences might conceal perturbations. Furthermore, according to some recent studies (Zakharenkova et al., 2016; Ren et al., 2022), wave-like perturbations such as TID (Traveling Ionospheric Disturbances) generated during geomagnetic storms have been observed with TEC variations on the order of approximately 1 TEC unit. Given the significant variations on such a small scale, it is also plausible that these perturbations were masked or obscured.

The high-latitude ionosonde (Juliusruh, Dourbes, Pruhonice, and Chilton) foF2 data indicated a clear negative storm from 06:00 to 15:00, November 4 (Fig. 6c). In contrast, the VTEC data of the high-latitude GNSS stations (PTBB, WROC, WTZA, and BRST) showed a suppressed positive storm rather than a clear negative storm (Fig. 6d). Since the VTEC data contain the electron densities along the full ionosphere-plasmasphere, the plasmaspheric contribution may have erased the negative storm feature in the ionosphere. During this period, it is speculated that the O/N_2 ratio decreased due to the expansion of the thermosphere, causing a negative ionospheric effect in the F2 layer, whereas the plasma density in the plasmasphere may have increased. Nishimura et al. (2022) reported a proportional relationship between the plasma plume density variations during magnetic storms and VTEC variations. Additionally, some studies have reported the structure and evolution of plumes using VTEC values (Foster et al., 2002, 2014; Goldstein & Sandel, 2005). Although we could not track the plume density variations in the plasmasphere in this study, we speculate that the high-latitude VTEC results were suppressed because of the related impact of plume density variations.

Among the VTEC stations located at relatively lower latitudes, as seen in Figure 6d, the data from DYNG and DRAC

showed a remarkably similar pattern of intense positive storms despite being geographically distant from each other by approximately 8 degrees in latitude. In contrast, data from ROAG and IFG1 between the two stations (DYNG and DRAC) showed completely different patterns. This difference is probably due to their location, as ROAG and IFG1 are the easternmost stations. Notably, the intensity of the positive storms in DYNG and DRAC appeared to be considerably stronger than the data from other stations at different locations.

To obtain a more accurate interpretation, we examined the VTEC maps (Fig. 7) generated from the data of five ionosonde stations obtained from the DIAS database as snapshots. Beleghaki et al. (2015) presented a methodology for obtaining a TEC (Total Electron Content) map of the European region. They used the Topside Sounders Model (TaD) to determine the topside ionospheric profile from the altitude of the maximum electron density observed in the ionosphere with reference to the ionosonde values. Additionally, the real-time state of the ionosphere was adjusted by collecting the surrounding TEC parameters calculated from the GNSS (Global Navigation Satellite System) receiver at the ionosonde location, rather than relying solely on ionosonde data. The topside ionospheric profiler used in this process is based on an empirical formula derived from topside-sounding data observed by the Alouette/ISIS satellite. The performance of the resulting TEC map was reported to have an error of 3 TECU ($1 \text{ TECU} = 10^{16} \text{ m}^{-2}$) when compared with the GNSS data and 98.8% accuracy when compared with the ISIS1 topside ionospheric profile values. Despite potential slight discrepancies with actual GNSS observations, the EIS/DIAS TEC data incorporates both ionosonde and GNSS data, rendering it highly valuable for inferring and referencing the overall characteristics of the entire European region. Consequently, we have chosen to utilize the validated EIS/DIAS TEC dataset for the European sector in our study.

Figure 7a shows the VTEC maps taken every 2 h from UT 02:00 to UT 12:00 on November 3, 2021, before the storm. Figure 7b shows a snapshot captured during the main phase on November 4, 2021, for the same UT period. Some maps include markers indicating the locations of the ionospheric stations to aid in understanding their positions. In the maps during the main phase of the storm, it was found that from UT 08:00 to UT 10:00, an intense positive storm occurred at the DYNG and DRAC stations. Therefore, it is reasonable to conclude that the strong increases in the GNSS VTEC features observed at DYNG and DRAC (Fig. 6d) are valid.

Moreover, this intense positive storm in the region can be attributed to the combined effects of the positive ionospheric storm caused by the TID with the TAD, and the equatorial ionospheric anomaly (EIA) extending from the equator to higher latitudes during the main phase of the geomagnetic storm. This phenomenon, also known as the super-fountain effect, has been observed in various studies (Kelley et al., 2004; Abdu et al., 2007; Balan et al., 2009; Lu et al., 2013; Fagundes et al., 2016) as a cause of intense positive storms around middle latitudes. Especially, during geomagnetic storms, the Prompt Penetration Electric Field (PPEF) can have an immediate global effect, which can enhance the eastward electric field in the sunlit region. This effect ultimately strengthens the $E \times B$ drift motion in the dayside ionosphere, and the equatorward neutral wind during storm periods can further contribute to a more powerful

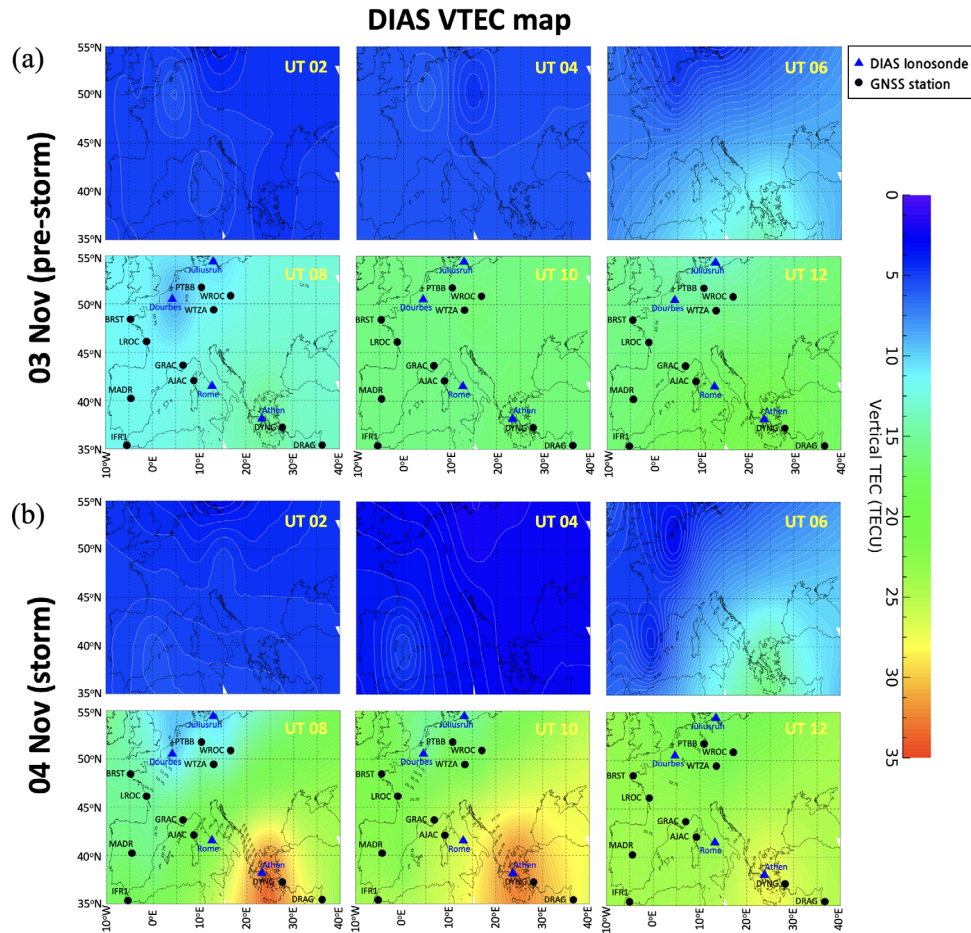


Figure 7. The DIAS VTEC map from UT 02:00 to 12:00, derived from DIAS ionosonde data, shows the VTEC values for two different days. (a) The VTEC values on November 3, 2021, before the storm period. (b) The VTEC values during the geomagnetic storm on November 4, 2021. The blue triangle (black circle) symbols mean the DIAS ionosonde (GNSS receivers) locations.

Equatorial Ionization Anomaly (EIA) formation (Lu et al., 2013). As a result of the mechanism behind the occurrence of this super-fountain effect, we conclude that a strong positive ionospheric storm occurred in the relatively low-latitude regions.

4 Summary and conclusion

Numerous studies have examined the responses of the thermosphere and the ionosphere to geomagnetic storms. However, most of these studies have been limited to specific regions or focused only on the thermospheric density or wind response as well as on the ionospheric responses. In this study we utilized observational data from high to middle latitudes, to confirm that thermospheric winds and neutral compositions exhibit significant variation during geomagnetic storms. Moreover, it was also observed that there exist opposite negative and positive ionospheric storms in the European longitudinal sector and the border between these storm responses was identified. Remarkably, all observational responses of the thermosphere and ionosphere converged in the same border location between the two opposing ionospheric storms. This finding revealed a previously

unknown regional connectivity between two opposing ionospheric storms, challenging previous assumptions that such storms could only appear in distant regions. Therefore, while negative and positive ionospheric storms may appear as separate events when observed at individual stations, this study proposes that in the examined events, changes in thermospheric composition and wind effects from high to mid-latitudes occur simultaneously, indicating they cannot be considered entirely distinct events and are suggested to be interconnected.

Thus, our study provides a new insight into how the thermosphere and ionosphere respond to geomagnetic storms and the potential for opposite ionospheric storms to appear in specific regions. Furthermore, by analyzing thermospheric wind data from high to mid-latitudes during geomagnetic storms, we were able to provide further verification for existing theories. Future studies will focus on further verifying the existence of the opposite storm phases in specific regions through the statistical analysis of the observational data on the thermospheric and ionospheric responses to geomagnetic storms.

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References

- Abdu MA, Maruyama T, Batista IS, Saito S, Nakamura M. 2007. Ionospheric responses to the October 2003 superstorm: longitude/local time effects over equatorial low and middle latitudes. *J Geophys Res Space Phys* **112**(A10): A10306. <https://doi.org/10.1029/2006JA012228>.
- Balan N, Shiokawa K, Otsuka Y, Watanabe S, Bailey GJ. 2009. Super plasma fountain and equatorial ionization anomaly during penetration electric field. *J Geophys Res Space Phys* **114**(A3): A03310. <https://doi.org/10.1029/2008JA013768>.
- Baumjohann W, Kamide Y. 1984. Hemispherical Joule heating and the AE indices. *J Geophys Res Space Phys* **89**(A1): 383–388. <https://doi.org/10.1029/JA089iA01p00383>.
- Belehaki A, Tsagouri I, Kutiev I, Marinov P, Zolesi B, et al. 2015. The European Ionosonde Service: nowcasting and forecasting ionospheric conditions over Europe for the ESA Space Situational Awareness services. *J Space Weather Space Clim* **5**: A25. <https://doi.org/10.1051/swsc/2015026>.
- Blanc M, Richmond AD. 1980. The ionospheric disturbance dynamo. *J Geophys Res Space Phys* **85**(A4): 1669–1686. <https://doi.org/10.1029/JA085iA04p01669>.
- Borries C, Jakowski N, Wilken V. 2009. Storm induced large scale TIDs observed in GPS derived TEC. *Ann Geophys* **27**(4): 1605–1612. <https://doi.org/10.5194/angeo-27-1605-2009>.
- Bravo MA, Batista IS, Souza JR, Foppiano AJ. 2019. Ionospheric response to disturbed winds during the 29 October 2003 geomagnetic storm in the Brazilian sector. *J Geophys Res Space Phys* **124**(11): 9405–9419. <https://doi.org/10.1029/2019JA027187>.
- Buonsanto MJ. 1999. Ionospheric storms – a review. *Space Sci Rev* **88**(3–4): 563–601. <https://doi.org/10.1023/a:1005107532631>.
- Burlaga L, Sittler E, Mariani F, Schwenn AR. 1981. Magnetic loop behind an interplanetary shock: Voyager, Helios, and IMP 8 observations. *J Geophys Res Space Phys* **86**(A8): 6673–6684. <https://doi.org/10.1029/JA086iA08p06673>.
- Burlaga LF, Klein L, Sheeley NR Jr, Michels DJ, Howard RA, Koomen MJ, Schwenn R, Rosenbauer H. 1982. A magnetic cloud and a coronal mass ejection. *Geophys Res Lett* **9**(12): 1317–1320. <https://doi.org/10.1029/GL009i012p01317>.
- Burnside RG, Tepley CA, Sulzer MP, Fuller-Rowell TJ, Torr DG, Roble RG. 1991. The neutral thermosphere at Arecibo during geomagnetic storms. *J Geophys Res Space Phys* **96**(A2): 1289–1301. <https://doi.org/10.1029/90JA01595>.
- Deng Y, Fuller-Rowell TJ, Akmaev RA, Ridley AJ. 2011. Impact of the altitudinal Joule heating distribution on the thermosphere. *J Geophys Res Space Phys* **116**(A5): A05313. <https://doi.org/10.1029/2010JA016019>.
- Fagundes PR, Sahai Y, Bittencourt JA, Takahashi H. 1995. Observations of thermospheric neutral winds and temperatures at Cachoeira Paulista (23 °S, 45 °W) during a geomagnetic storm. *Adv Space Res* **16**(5): 27–30. [https://doi.org/10.1016/0273-1177\(95\)00169-F](https://doi.org/10.1016/0273-1177(95)00169-F).
- Fagundes PR, Cardoso FA, Fejer BG, Venkatesh K, Ribeiro BA, Pillat VG. 2016. Positive and negative GPS-TEC ionospheric storm effects during the extreme space weather event of March 2015 over the Brazilian sector. *J Geophys Res Space Phys* **121**(6): 5613–5625. <https://doi.org/10.1002/2015JA022214>.
- Forbes JM, Oberheide J, Zhang X, Cullens C, Englert CR, Harding BJ, Harlander JM, Marr KD, Makela JJ, Immel TJ. 2022. Vertical coupling by solar semidiurnal tides in the thermosphere from ICON/MIGHTI measurements. *J Geophys Res Space Phys* **127**(5): e2022JA030288. <https://doi.org/10.1029/2022JA030288>.
- Foster JC, Erickson PJ, Coster AJ, Goldstein J, Rich FJ. 2002. Ionospheric signatures of plasmaspheric tails. *Geophys Res Lett* **29**(13): 1–1–1–4. <https://doi.org/10.1029/2002GL015067>.
- Foster JC, Erickson PJ, Coster AJ, Thaller S, Tao J, Wygant JR, Bonnell JW. 2014. Storm time observations of plasmasphere erosion flux in the magnetosphere and ionosphere. *Geophys Res Lett* **41**(3): 762–768. <https://doi.org/10.1002/2013GL059124>.
- Fuller-Rowell TJ, Codrescu MV, Moffett RJ, Quegan S. 1994. Response of the thermosphere and ionosphere to geomagnetic storms. *J Geophys Res Space Phys* **99**(A3): 3893–3914. <https://doi.org/10.1029/93JA02015>.
- Fuller-Rowell TJ, Codrescu MV, Roble RG, Richmond AD. 1997. How does the thermosphere and ionosphere react to a geomagnetic storm?. In: *Magnetic Storms*, vol. 98 *geophysical monograph*, Tsurutani BT, Gonzales WD, Kamide Y, Arballo JK (Eds.), American Geophysical Union, Washington, DC. pp. 203–225. ISBN: 9781118664612. <https://doi.org/10.1029/GM098p0203>.
- Goldstein J, Sandel BR. 2005. The global pattern of evolution of plasmaspheric drainage plumes. In: *Inner magnetosphere interactions: new perspectives from imaging*, vol. 159, *geophysical monograph series*, Burch J, Schulz M, Spence H (Eds.), American Geophysical Union, Washington, DC. pp. 1–22. ISBN: 9781118666128. <https://doi.org/10.1029/159GM02>.
- Haerendel G. 1972. Electric fields and their effects in the ionosphere. In: *The Upper Atmosphere: Part IV of Solar-Terrestrial Physics/1970 Comprising the Proceedings of the International Symposium on Solar-Terrestrial Physics Held in Leningrad, USSR87-116*, Bowhill SA, Dyer ER, (Eds.), Springer Netherlands, pp. 87–116. https://doi.org/10.1007/978-94-010-3132-5_6.

- Idosa C, Shogile K. 2023. Variations of ionospheric TEC due to coronal mass ejections and geomagnetic storm over New Zealand. *New Astron* **99**: 101961. <https://doi.org/10.1016/j.newast.2022.101961>.
- Kelley MC, Vlasov MN, Foster JC, Coster AJ. 2004. A quantitative explanation for the phenomenon known as storm-enhanced density. *Geophys Res Lett* **31**(19): L19809. <https://doi.org/10.1029/2004GL020875>.
- Knipp DJ, Tobiska WK, Emery BA. 2004. Direct and indirect thermospheric heating sources for solar cycles 21–23. *Solar Phys* **224**(1): 495–505. <https://doi.org/10.1007/s11207-005-6393-4>.
- Li X, Wang Y, Guo J, Lyu S. 2022. Solar energetic particles produced during two fast coronal mass ejections. *Astrophys J Lett* **928**(1): L6. <https://doi.org/0.3847/2041-8213/ac5b72>.
- Lin CH, Richmond AD, Heelis RA, Bailey GJ, Lu G, Liu JY, Yeh HC, Su SY. 2005. Theoretical study of the low-and midlatitude ionospheric electron density enhancement during the October 2003 superstorm: relative importance of the neutral wind and the electric field. *J Geophys Res Space Phys* **110**(A12): A12312. <https://doi.org/10.1029/2005JA011304>.
- Loutfi A, Bounhir A, Pitout F, Benkhaldoun Z, Makela JJ. 2020. Thermospheric neutral winds above the Oukaimeden Observatory: effects of geomagnetic activity. *J Geophys Res Space Phys* **125**(7): e2019JA027383. <https://doi.org/10.1029/2019JA027383>.
- Lu G, Richmond AD, Roble RG, Emery BA. 2001. Coexistence of ionospheric positive and negative storm phases under northern winter conditions: A case study. *J Geophys Res Space Phys* **106**(A11): 24493–24504. <https://doi.org/10.1029/2001JA000003>.
- Lu G, Goncharenko LP, Richmond AD, Roble RG, Aponte N. 2008. A dayside ionospheric positive storm phase driven by neutral winds. *J Geophys Res Space Phys* **113**(A8): A08304. <https://doi.org/10.1029/2007JA012895>.
- Lu G, Goncharenko L, Nicolls MJ, Maute A, Coster A, Paxton LJ. 2012. Ionospheric and thermospheric variations associated with prompt penetration electric fields. *J Geophys Res Space Phys* **117**(A8): A08312. <https://doi.org/10.1029/2012JA017769>.
- Lu G, Huba JD, Valladares C. 2013. Modeling ionospheric super-fountain effect based on the coupled TIMEGCM-SAMI3. *J Geophys Res Space Phys* **118**(5): 2527–2535. <https://doi.org/10.1029/jgra.50256>.
- Lugaz N, Temmer M, Wang Y, Farrugia CJ. 2017. The interaction of successive coronal mass ejections: a review. *Solar Phys* **292**: 1–37. <https://doi.org/10.1007/s11207-017-1091-6>.
- Malki K, Bounhir A, Benkhaldoun Z, Makela JJ, Vilmer N, Fisher DJ, Kaab M, Elbouyahyaoui K, Harding BJ, Laghriyeb A, Daassou A. 2018. Ionospheric and thermospheric response to the 27–28 February 2014 geomagnetic storm over North Africa. *Ann Geophys* **36**(4): 987–998. <https://doi.org/10.5194/angeo-36-987-2018>.
- Nishimura Y, Goldstein J, Martinis C, Ma Q, Li W, Zhang SR, Coster AJ, Mrak S, Semeter JL, Nishitani N, Ruohoniemi JM. 2022. Multi-scale density structures in the plasmaspheric plume during a geomagnetic storm. *J Geophys Res Space Phys* **127**(3): e2021JA030230. <https://doi.org/10.1029/2021JA030230>.
- Oyedokun DT, Cilliers PJ. 2018. Geomagnetically induced currents: A threat to modern power systems. In: *Classical and recent aspects of power system optimization 2018 Jan 1*, Zobaa AF, Abdel Aleem SHE, Abdelaziz AY, (Eds.), Academic Press. pp. 421–462. <https://doi.org/10.1016/B978-0-12-812441-3.00016-1>.
- Prölss G. 2012. *Physics of the Earth's space environment: an introduction*. Springer Science & Business Media. ISBN: 9783642971235.
- Reinisch BW, Galkin IA. 2011. Global ionospheric radio observatory (GIRO). *Earth Planets Space* **63**: 377–381. <https://doi.org/10.5047/eps.2011.03.001>.
- Ren X, Mei D, Liu H, Zhang X. 2022. Investigation on horizontal and vertical traveling ionospheric disturbances propagation in global-scale using GNSS and multi-LEO satellites. *Space Weather* **20**(5): e2022SW003041. <https://doi.org/10.1029/2022SW003041>.
- Richmond AD, Matsushita S. 1975. Thermospheric response to a magnetic substorm. *J Geophys Res* **80**(19): 2839–2850. <https://doi.org/10.1029/JA080i019p02839>.
- Rishbeth H, Rees D, Kaiser TR. 1972. Winds and temperatures in the auroral zone and their relations to geomagnetic activity: discussion. *Philos Trans Royal Soc A* **271**(1217): 573–575. <http://www.jstor.org/stable/74114>.
- Rishbeth H. 1975. F-region storms and thermospheric circulation. *J Atmos Terr Phys* **37**(6–7): 1055–1064. [https://doi.org/10.1016/0021-9169\(75\)90013-6](https://doi.org/10.1016/0021-9169(75)90013-6).
- Rishbeth H. 1998. How the thermospheric circulation affects the ionospheric F2-layer. *J Atmos Sol Terr Phys* **60**(14): 1385–1402. [https://doi.org/10.1016/S1364-6826\(98\)00062-5](https://doi.org/10.1016/S1364-6826(98)00062-5).
- Scherliess L, Fejer BG. 1997. Storm time dependence of equatorial disturbance dynamo zonal electric fields. *J Geophys Res Space Phys* **102**(A11): 24037–24046. <https://doi.org/10.1029/97JA02165>.
- Scolini C, Chané E, Temmer M, Kilpua EK, Dissauer K, Veronig AM, Palmerio E, Pomoell J, Dumbović M, Guo J, Rodriguez L. 2020. CME–CME interactions as sources of CME geoeffectiveness: The formation of the complex ejecta and intense geomagnetic storm in 2017 early September. *Astrophys J Suppl Ser* **247**(1): 21. <https://doi.org/10.3847/1538-4365/ab6216>.
- Singh R, Lee YS, Song SM, Kim YH, Yun JY, Sripathi S, Rajesh B. 2022. Ionospheric density oscillations associated with recurrent prompt penetration electric fields during the space weather event of 4 November 2021 over the East-Asian sector. *J Geophys Res Space Phys* **127**(6): e2022JA030456. <https://doi.org/10.1029/2022JA030456>.
- Shinbori A, Otsuka Y, Sori T, Tsugawa T, Nishioka M. 2022. Statistical behavior of large-scale ionospheric disturbances from high latitudes to mid-latitudes during geomagnetic storms using 20-yr GNSS-TEC data: dependence on season and storm intensity. *J Geophys Res Space Phys* **127**(1): e2021JA029687. <https://doi.org/10.1029/2021JA029687>.
- Shiokawa K, Lu G, Otsuka Y, Ogawa T, Yamamoto M, Nishitani N, Sato N. 2007. Ground observation and AMIE-TIEGCM modeling of a storm-time traveling ionospheric disturbance. *J Geophys Res Space Phys* **112**(A5): A05308. <https://doi.org/10.1029/2006JA011772>.
- Smith LB. 1968. An observation of strong thermospheric winds during a geomagnetic storm. *J Geophys Res* **73**(15): 4959–4963. <https://doi.org/10.1029/JA073i015p04959>.
- Thayer JP, Vickrey JF, Heelis RA, Gary JB. 1995. Interpretation and modeling of the high-latitude electromagnetic energy flux. *J Geophys Res Space Phys* **100**(A10): 19715–19728. <https://doi.org/10.1029/95JA01159>.
- Wang W, Burns AG, Wiltberger M, Solomon SC, Killeen TL. 2008. Altitude variations of the horizontal thermospheric winds during geomagnetic storms. *J Geophys Res Space Phys* **113**(A2): A02301. <https://doi.org/10.1029/2007JA012374>.
- Wang W, Lei J, Burns AG, Solomon SC, Wiltberger M, Xu J, Zhang Y, Paxton L, Coster A. 2010. Ionospheric response to the initial phase of geomagnetic storms: Common features. *J Geophys Res Space Phys* **115**(A7): A07321. <https://doi.org/10.1029/2009JA014461>.

- Wei S, Ahn BH, Akasofu SI. 1985. The global joule heat production rate and the AE index. *Planet Space Sci* **33**(3): 279–281. [https://doi.org/10.1016/0032-0633\(85\)90059-5](https://doi.org/10.1016/0032-0633(85)90059-5).
- Yagi T, Dyson PL. 1985. The response of the mid-latitude thermospheric wind to magnetic activity. *Planet Space Sci* **33**(4): 461–467. [https://doi.org/10.1016/0032-0633\(85\)90090-X](https://doi.org/10.1016/0032-0633(85)90090-X).
- Zakharenkova I, Astafyeva E, Cherniak I. 2016. GPS and GLONASS observations of large-scale traveling ionospheric disturbances during the 2015 St. Patrick’s Day storm. *J Geophys Res Space Phys* **121**(12): 12–38. <https://doi.org/10.1002/2016JA023332>.
- Zhu Q, Lu G, Deng Y. 2022. Low- and mid-latitude ionospheric response to the 2013 St. Patrick’s Day geomagnetic storm in the American sector: global ionosphere thermosphere model simulation. *Front Astron Space Sci* **9**: 124. <https://doi.org/10.3389/fspas.2022.916739>.

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