

Statistical characteristics and classification of ionospheric mid-latitude trough as revealed by the observations of DMSP-F18

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Key Points:

- Mid-latitude troughs and its auroral edges are precisely identified by the in-situ density and electron spectrum of DMSP-F18.
- The troughs, along with higher ion temperature, occur at higher latitudes than those with elevated electron temperature.
- The troughs with T_i or V_i -maximum tend to locate closer to the auroral edge on the nightside and in the southern hemisphere.

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Abstract: Statistical characteristics and the classification of the topside ionospheric mid-latitude trough are systemically analyzed, using observations from the Defense Meteorological Satellite Program F18 (DMSP-F18) satellite. The data was obtained at an altitude of around 860 km in near polar orbit, throughout 2013. Our study identified the auroral boundary based on the in-situ electron density and electron spectrum, allowing us to precisely determine the location of the mid-latitude trough. This differs from most previous works, which only use Total Electron Content (TEC) or in-situ electron density. In our study, the troughs exhibited a higher occurrence rate in local winter than in summer, and extended to lower latitudes with increasing geomagnetic activity. It was found that the ionospheric mid-latitude trough, which is associated with temperature changes or enhanced ion drift, exhibited distinct characteristics. Specifically, the ionospheric mid-latitude troughs related to electron temperature (T_e) peak were located more equatorward of auroral oval boundary in winter than in summer. The ionospheric mid-latitude troughs related to T_e -maximum were less frequently observed at 60–70°S magnetic latitude and 90–240°E longitude. Furthermore, the troughs related to ion temperature (T_i) maximums were observed at relatively higher latitudes, occurring more frequently in winter. In addition, the troughs related to ion velocity (V_i) maximums could be observed in all seasons. The troughs with the maximum- T_i and maximum- V_i were located closer to the equatorward boundary of the auroral oval at the nightside, and in both hemispheres. This implies that enhanced ion drift velocity contributes to increased collisional frictional heating and enhanced ion temperatures, resulting in a density depletion within the trough region.

Keywords: topside ionosphere; mid-latitude trough; ionospheric main trough; auroral oval boundary; temperature maximum

1. Introduction

The mid-latitude trough is a phenomenon characterized by a significant depletion of ionospheric plasma density in the mid-latitude region, close to the equatorward boundary of auroral precipitation (Rodger, 2008). The plasma density depletion, along with the large density gradient at the equatorward and poleward edges of the trough region, can significantly affect the propagation of radio waves (Spogli et al., 2009). Various physical processes could contribute to the formation of the mid-latitude troughs, including nighttime plasma depletion due to lack of sunlight, auroral convection and co-rotation patterns (Spiro et al., 1978; Evans et al., 1983), sub-auroral ion drift (SAID) (Spiro et al., 1979; Rodger et al., 1992; Rodger, 2008), and density enhancement at

polar regions (Rodger et al., 1986).

Since the first work of the ionospheric mid-latitude trough conducted by Muldrew (1965), many studies have revealed the characteristics of such troughs. These include seasonal variations, local time differences, and solar and geomagnetic activities affecting the position and occurrence rate of mid-latitude troughs. Higher rate of occurrence of the mid-latitude trough in winter or equinox is commonly observed; the troughs are primarily observed during winter, and exhibit a higher occurrence rate in local winter compared to local summer (Moffett and Quegan, 1983; Voiculescu et al., 2006; Lee et al., 2011; Ishida et al., 2014; Aa et al., 2020). In some cases, the occurrence rate reaches its maximums at the equinox rather than in winter (Moffett and Quegan, 1983; Aa et al., 2020). The trough position also greatly depends on local time, occurring at relatively higher and lower magnetic latitudes in pre-midnight and post-midnight sectors (Karpachev, 2019). This local time variation is more pronounced in summer than in winter (Yang N et al., 2016). Furthermore, trough positions are significantly influenced by geomagnetic activity, with the

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trough minimum moving equatorward with increased geomagnetic activity (Muldrew, 1965; Köhnlein and Raitt, 1977; Karpachev et al., 1996; Yang N et al., 2015; Aa et al., 2020).

Although the characteristics of the ionospheric mid-latitude trough and its formation process are well studied, the classifications and detailed descriptions of ionospheric mid-latitude troughs and their correspondence to different physical parameters and processes are not fully explored. Rodger et al. (1992) provided the relationship between the ionospheric mid-latitude troughs and the characteristic temperatures, ion velocity, and composition for each trough type. However, the statistical characteristics of these troughs and their association with different physical parameters were not well understood. Moreover, previous studies have tended to use only TEC or in-situ electron density to determine the location of the mid-latitude trough, a method that carries significant uncertainty and does not take into account information from the auroral boundary. In this study, we utilized the electron energy spectrum data from auroral particle spectrometer Special Sensor J (SSJ), along with electron density, electron and ion temperature, and ion drift velocity from the topside thermal plasma monitor Special Sensor for Ion and Electron Scintillation (SSIES) of the Defense Meteorological Satellite Program F18 (DMSP-F18) satellite. These data allowed us to accurately identify the auroral boundary of the mid-latitude troughs, and investigate their characteristics as well as their relationship with different physical parameters and processes.

2. Dataset

The DMSP is a series of satellites with polar orbits. Each DMSP satellite operates in a sun-synchronous, near-polar orbit ($\sim 98.9^\circ$ inclination), with a period of approximately 101 minutes at an altitude of around 860 km. This inclination enables the observation of the auroral oval and the mid-latitude trough at higher latitudes. The DMSP spacecraft carries space environment sensors, including the Special Sensor J (SSJ), the Special Sensor Magnetometer (SSM), the Special Sensor for Ion and Electron Scintillation (SSIES) instruments, the Special Sensor Ultraviolet Spectrographic Imagers (SSUSI), and the Special Sensor Ultraviolet Limb Imager (SSULI) (Ober et al., 2014). In our dataset, the SSJ and SSIES data from the DMSP-F18 are chosen. DMSP-F18 was launched on October 18, 2009, and carried the sensors including SSJ5 and SSIES3. In 2013, during the periods of higher solar activity, the DMSP-F18 was at around 08 and 20 local time (LT), when mid-latitude troughs could be frequently observed. SSJ could provide a complete spectrum of the low-energy particles associated with the aurora and other high-latitude phenomena. Both the ion and electron spectrum and the energy flux from 30 eV to 30 keV, with a time resolution of one second, are used. Because we could observe clear, discontinuous boundaries of the electron spectrum in the dataset, electron spectrums were chosen which define the auroral oval boundary. Whenever the spectrum data of the SSJ is not available, or no clear auroral boundary is observed, a constant limit of the magnetic latitude from 40° to 65° is applied. SSIES provides the electron density (N_e), the electron temperature (T_e), ion temperature (T_i), ram drift ion velocity (V_x), horizontal crosstrack ion velocity (V_y), and the vertical crosstrack ion velocity (V_z) from its retarding potential analyzer (RPA) and the ion drift

meter (IDM). This approach enables us to identify the trough position based on the auroral oval, and simultaneously analyze abnormal temperature changes or velocity peaks within the vicinity of the mid-latitude trough. This allows for classification of different troughs and investigation into their possible relationships.

3. Instances of the Ionospheric Mid-latitude Trough

Figure 1 shows an example of the mid-latitude trough, observed from the DMSP-F18 on December 25, 2013. The mid-latitude trough is generally defined as the depletion of plasma density in regions located between the mid-latitude and the auroral oval. Aa et al. (2020) used the magnetic latitude range of 45° to 75° , while Yang N et al. (2018) used a magnetic latitude range of 40° to 80° to define the locations of mid-latitude troughs. In this study, we defined the troughs as occurring between a lower magnetic latitude of 40° and the equatorward boundary of the auroral oval. We identified the equatorward boundary of the auroral oval using the SSJ electron energy spectrum, rather than assuming a fixed magnetic latitude. As shown in Figure 1a, the electron spectrum ranges from 30 eV to 30 keV. Newell et al. (1996) identified the auroral boundary using the two lowest energy channels of the SSJ instrument. Moving from lower to higher latitudes, an increase in energy flux by a factor of 2 indicates the location of the boundary. However, background noise can sometimes be strong in these channels. Therefore, more channels and a higher detection threshold are adopted in this work. When more than four energy channels from 30 eV to 1 keV showed a clear discontinuity (with differential energy flux exceeding 10^6 eV/(cm²-s-sr-eV)), we identified this as the equatorward boundary of the auroral oval. This boundary was then taken as the poleward boundary of the trough position. As shown in Figure 1a, the electron spectrums were significantly enhanced in most energy channels at 6:38 UT in the northern hemisphere, and at 7:28 and 7:37 UT in the southern hemisphere, all of which clearly show the auroral boundaries. Additionally, the SSJ could provide information on auroral precipitation. We observed a clear increase in the electron spectrum inside the auroral oval around 6:39 UT, which is consistent with the simultaneously observed increase of electron density (shown in Figure 1b). The auroral precipitation, represented by the increased electron spectrum, clearly contributes to formation of the poleward edge of the mid-latitude trough.

In addition to auroral precipitation, the increased temperature and enhanced ion drifts also could contribute to trough formation. Figures 1b, c, and d depict the mid-latitude troughs observed from SSIES data, along with temperature and ion drift speeds. The quality flags of SSIES data were noted as 'bad' whenever the data was deemed invalid (according to the quality flags described in the SSIES-3 introduction document: <https://spdf.gsfc.nasa.gov/pub/data/dmsp/documents/>). Invalid data flagged as 'bad' or 'cautious' were removed, along with discontinuous or abnormal data (e.g. the abnormal electron temperatures in the northern hemisphere). To identify the troughs from the electron density data (Figure 1b), we set the threshold of trough depth to at least 1.6 times the density of the trough minimum. Trough depth is expressed as the density drop from the lower density maximum to the trough minimum. In cases where multiple troughs are observed, the most prominent one (that with the largest

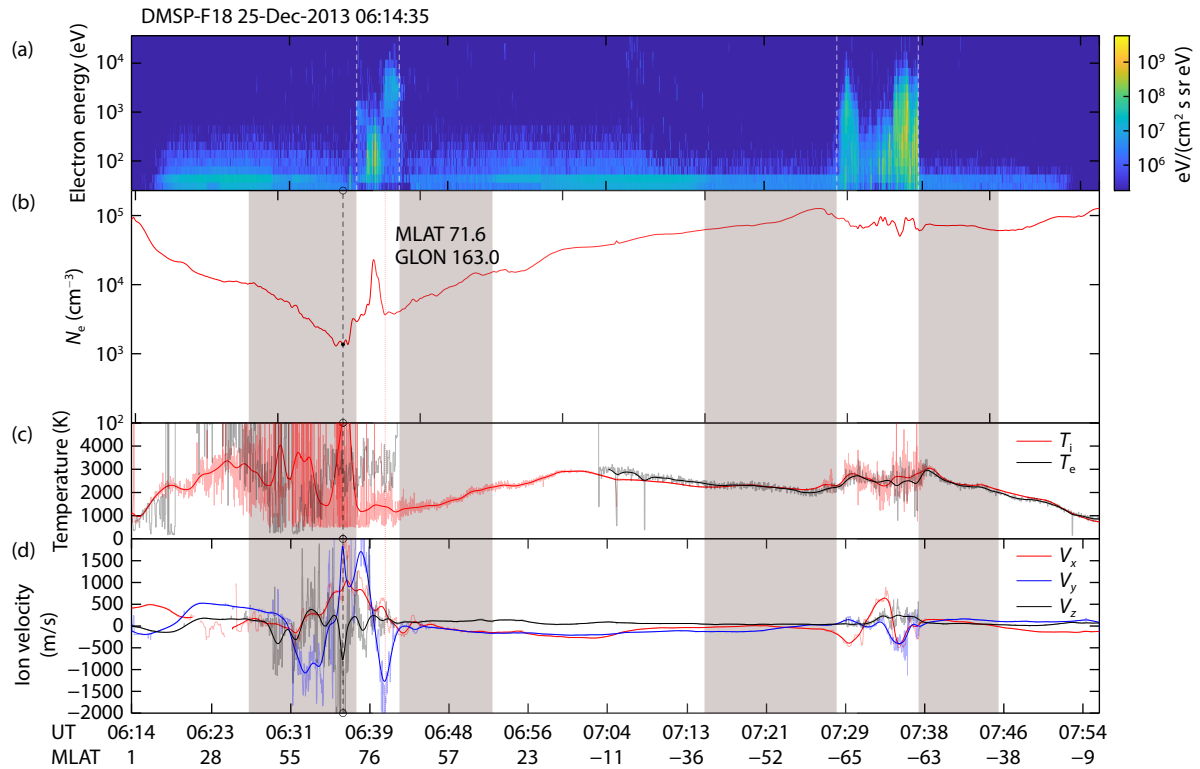


Figure 1. An example of trough identification. (a) displays the electron energy spectrum observed by the SSJ instrument on the DMSP satellite, where auroral boundary is clearly visible and its position identified. (b–d) show data from the SSIES instrument, also on DMSP. (b) plots the ion density, where two troughs are detected in the northern hemisphere: one in the mid-latitude region (mid-latitude trough) and another within the auroral oval (high-latitude trough). (c) illustrates the electron (black) and ion (red) temperatures, while (d) presents the ion drift velocities. Both the mid-latitude and high-latitude troughs were associated with simultaneous temperature increase or fast ion drift.

width $\times$ depth) was selected. After the automatic scan, we then scan manually, to ensure the validity of the trough identification. As shown in Figure 1b, a significant mid-latitude trough was observed at 6:36 UT and 71.6° MLAT.

Ion temperature (T_i), electron temperature (T_e), and ion velocities (Figure 1c and 1d) were used to analyze the relationship between the mid-latitude trough, abnormal temperature change, and fast ion drifts. As shown in Figures 1b and 1c, a substantial increase in the ion temperature (reaching 5000 K) occurred within the trough valley. Simultaneously, the trough was accompanied by increased ion drift velocity. V_x , V_y , and V_z near the trough reached 1000, 1500, and 700 m/s, respectively, compared to the 0 m/s at 55° MLAT and less than 500 m/s from the equator to 55° MLAT. These significant increases in temperature and ion drift velocities were observed near the trough minimum, coinciding with the increased electron spectrum.

Figure 2 presents another case where the trough was observed without significant temperature change or enhanced ion drift velocity. In this case, the ion temperature remained at around 1000 K, with only a slight decrease in the trough region. The ion drift velocity stayed below 500 m/s, showing no notable increase. The trough was detected just equatorward of the region with the enhanced auroral precipitation. These two cases showed that different factors could contribute to trough formation, indicating that the classification of troughs is quite complex.

After manually scanning and classifying the data, we further identified prominent peaks and valleys in electron or ion temperature, and the velocity peaks, within 2° of the trough minimum. Temperature threshold was defined as temperature changes exceeding 500 K while the velocity threshold was set for the peaks exceeding 500 m/s. These events are further labeled as T_e - & T_i -maximum (and minimum) and V_i -maximum for convenience. We assume that these factors could potentially be related to trough formation, and this classification will be discussed in detail later.

4. Statistical Results

4.1 Statistical Variations of the Mid-Latitude Trough

First, we conducted a statistical analysis of the mid-latitude trough characteristics. Figure 3 depicts the temporal distribution of the occurrence rate and magnetic latitude position of the mid-latitude troughs, observed from DMSP in 2013. A clear annual variation of the trough occurrence rate, with a higher occurrence rate in local winter, was observed at 08 and 20 LT in both hemispheres. In the northern hemisphere, the troughs were primarily observed from January to March, and from October to December at 20 LT (the local winter), with the occurrence rates exceeding 0.8 in January and December. By contrast, during local summer (April to August), the troughs rarely occurred. This winter-dominant pattern was also observed at 08 LT in the southern hemisphere.

Although the occurrence rate was consistently higher in local winter at both local times, there was a significant difference

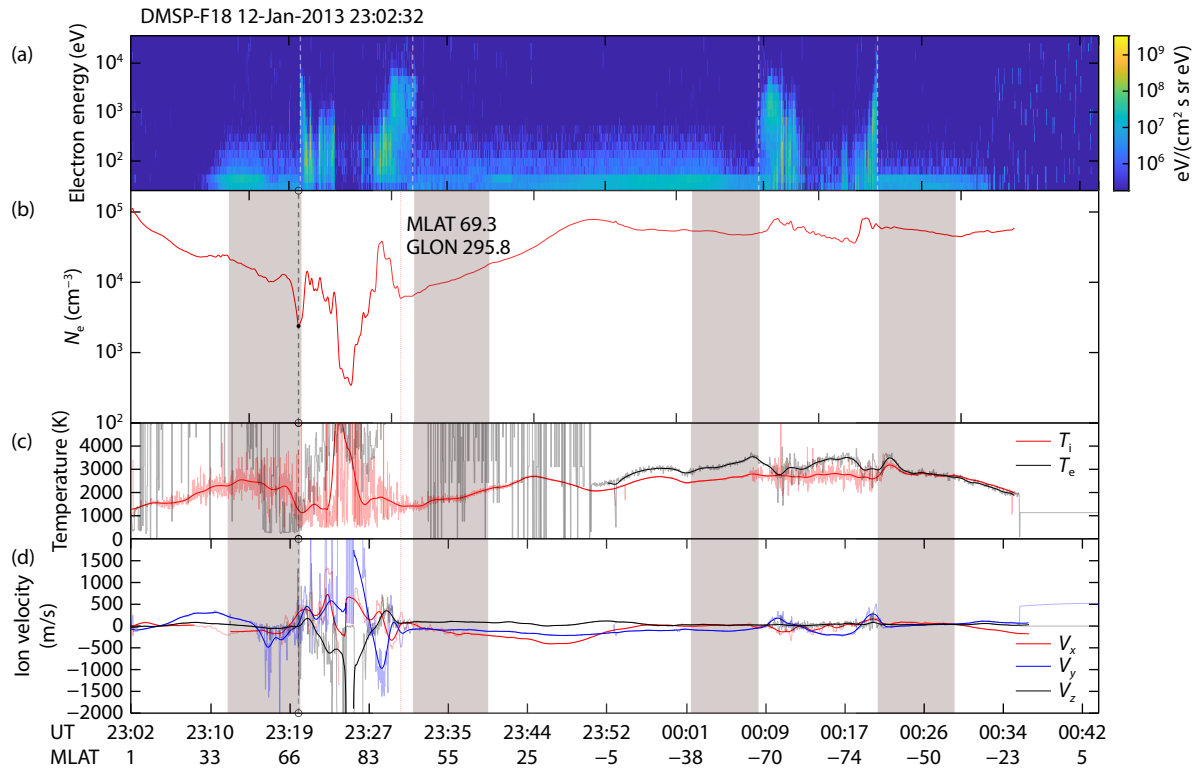


Figure 2. Another example of the trough, but without obvious temperature maximum and minimum or the ion drift velocity peak around the mid-latitude trough.

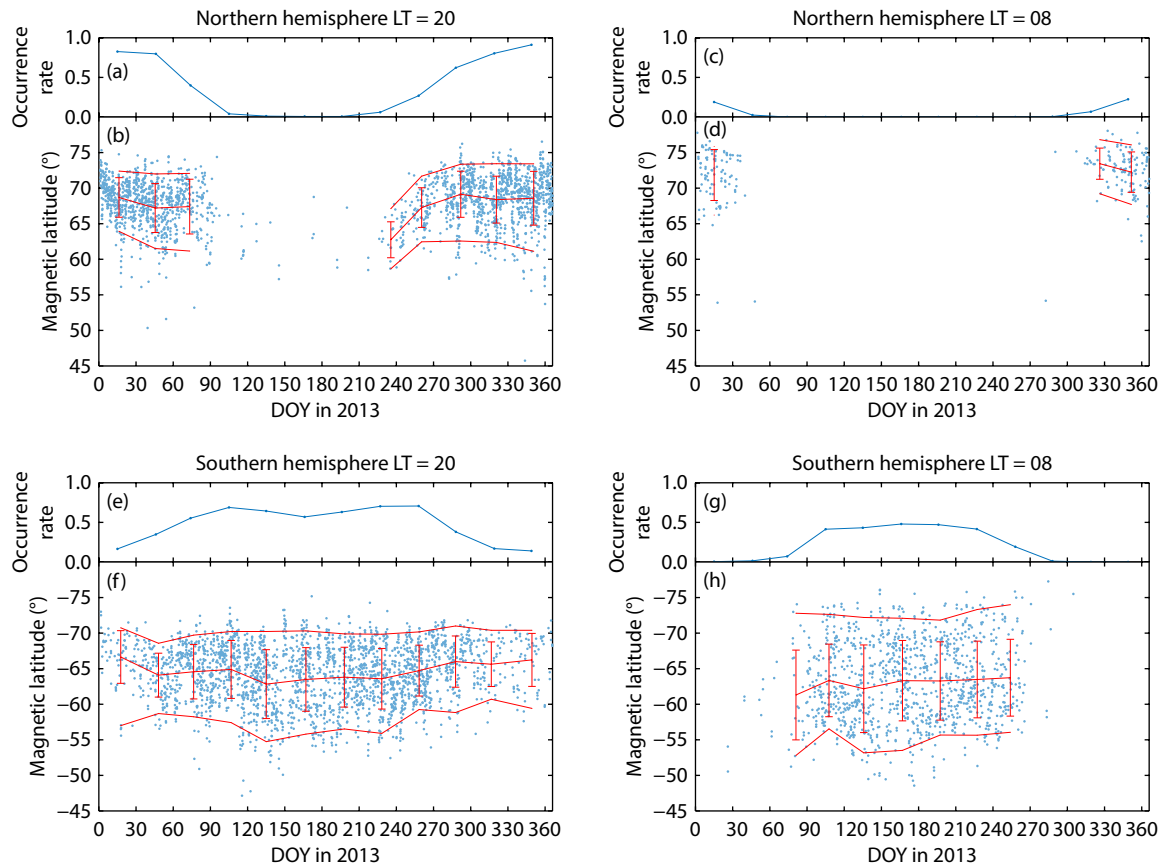


Figure 3. Variation of the occurrence rate (a, c, e, and g) and the latitude position (b, d, f, and h) of the mid-latitude trough during 2013. The top and bottom panels are for northern and southern hemispheres, respectively.

between two local times. At 08 LT in the northern hemisphere, troughs were observed almost exclusively in January and December, with occurrence rates of around 0.2, significantly lower than the nighttime observation at 20 LT. This pattern of lower trough occurrence at dayside was also observed in the southern hemisphere. At 20 LT in the southern hemisphere, the occurrence rate peaked at around 0.7–0.8 during the equinoxes. This could result from the higher relative geomagnetic activity during equinoxes (Aa et al., 2020). At 08 LT, the trough occurrence rate reached 0.4 during local winter, and dropped to nearly 0 in the local summer.

The higher occurrence rate during local winter is consistent with previous studies (Lee et al., 2011; Ishida et al., 2014; Aa et al., 2020). Meanwhile, the significantly lower trough occurrence rate at 08 LT in both hemispheres is consistent with earlier findings. Our dataset is based on in-situ observation at an altitude of around 860 km in the topside ionosphere during 2013 (a period of relatively higher solar activity during which the ionosphere expanded due to the increased temperature and scale height). Meanwhile, Aa et al. (2020) used the SWARM data collected at around 500 km. Additionally, as we discuss later, differences in the ion drift velocity peak between 08 and 20 LT may also contribute to this difference in occurrence rate.

Additionally, we analyzed the variation in trough position throughout 2013. In the northern hemisphere, at around 20 LT (Figure 3b), the magnetic latitude of the trough was approximately 70° during local winter, extending to lower latitudes in the local summer. However, the trough position determination in the local summer is challenging due to the low rate of occurrence. These seasonal and latitudinal variations in trough observations in the northern hemisphere align with the findings of Aa et al. (2020). At 08 LT on the dayside, the occurrence rate was too low to establish a clear trend over the year. By contrast, the southern hemisphere exhibited less pronounced seasonal variations of the observed trough position. At 20 LT, the average trough position ranged from around 63° magnetic latitude in the local winter, to 67° in the local summer. The troughs in the southern hemisphere spanned a wider range of the geomagnetic latitudes in the local winter as compared to summer. At 08 LT, the troughs also covered a broader magnetic latitude range, with no significant differences from month to month.

Figure 4 presents the distribution of mid-latitude troughs in terms of magnetic latitude and longitude. We compared trough positions during periods of relatively lower and higher geomagnetic activities, represented by K_p indices from 0–3 and 3–6, respectively. In Figure 4a, the northern hemisphere shows a longitudinal difference in the magnetic latitude position of the trough. At most longitudes in the eastern hemisphere, the trough was observed around 66° magnetic latitude, while it was near 70° at around 270° longitude (western hemisphere). When the K_p index increases from 0–3 to 3–6, a similar variation pattern is observed, with the trough's highest averaged magnetic latitude being around 62° at 270° longitude, and the lowest around 59° at 0° longitude. The trough shifted approximately 8° equatorward as the K_p index increased.

A similar pattern of longitudinal and magnetic-latitudinal variation was observed in the southern hemisphere when comparing lower

and higher geomagnetic activity. On the nightside (Figure 4c), the trough was near 60°S MLAT and 270° longitude, shifting poleward to around 67°S MLAT at 60° longitude. The trough position moved equatorward by about 7° across all longitudes when the K_p index increased from 0–3 to 3–6. On the dayside (Figure 4d), the trough reached its maximum (70°S MLAT) and minimum magnetic latitude (58°S MLAT) at 180°E and 330°E, respectively. Despite some data gaps at higher K_p values, the equatorward shift of the trough during increased geomagnetic activity was evident. These results are consistent with previous studies (Karpachev et al., 1996, 2019; Karpachev, 2019), showing that the trough was more poleward around 180° longitude, and shifted equatorward at the longitude near 330°.

Figure 5 illustrates the trend of the mid-latitude trough minimum and the auroral equatorward boundary as a function of geomagnetic activity. As the K_p index increases, both the trough minimum and the auroral equatorward boundary shift equatorward. However, the trough moved faster than the equatorward boundary, resulting in an increasing magnetic latitude gap between the trough minimum and the auroral equatorward boundary as geomagnetic activity intensified. A possible link between the trough and the plasmapause has been proposed (Yizengaw et al., 2005; Yizengaw and Moldwin, 2005). Typically, the trough maps to the plasmapause, and the auroral particle precipitation originates primarily from the plasma sheet. This widening gap, illustrated in Figure 5, implies that the separation between the ionosphere projections of the plasmapause and the plasma sheet is increasing with geomagnetic activity.

4.2 Relationship Between the Trough and Ionospheric Parameters

The physical mechanisms underlying the mid-latitude trough are complex. Rodger et al. (1992) proposed a rough classification of these troughs based on the characteristics of ion velocity (V_i), electron temperature (T_e), ion temperature (T_i), and ion composition. Stagnation troughs are associated with high T_e and normal V_i and T_i ; High E-field troughs are characterized by both high V_i and high T_i . SAID troughs display simultaneously high V_i , T_e , and T_i . Other troughs between patches do not exhibit enhancements in V_i , T_e , or T_i . Since variations of the V_i , T_e , and T_i can indicate different physical processes, we performed a statistical analysis of the relationship between the mid-latitude trough and these parameters.

Figure 6 shows the seasonal and longitudinal variations of the mid-latitude trough in relation to various physical parameter changes, as observed by the DMSP. The southern hemisphere data at the nightside (20 LT) from DMSP-F18 was used due to the higher trough occurrence rate during this period. After manually scanning the mid-latitude troughs, we noticed that they were often accompanied by either elevated electron temperature, high ion temperature with increased ion drift speed, or occasionally lower electron or ion temperature. Based on this, we categorized the troughs according to whether abnormal T_e , T_i , and V_i were present. Troughs without any noticeable T_e , T_i , and V_i changes were classified as “normal troughs”.

As seen in Figure 6a, the T_e -maximum troughs occurred at relatively lower latitudes (around 60°S) during local winter (from May to

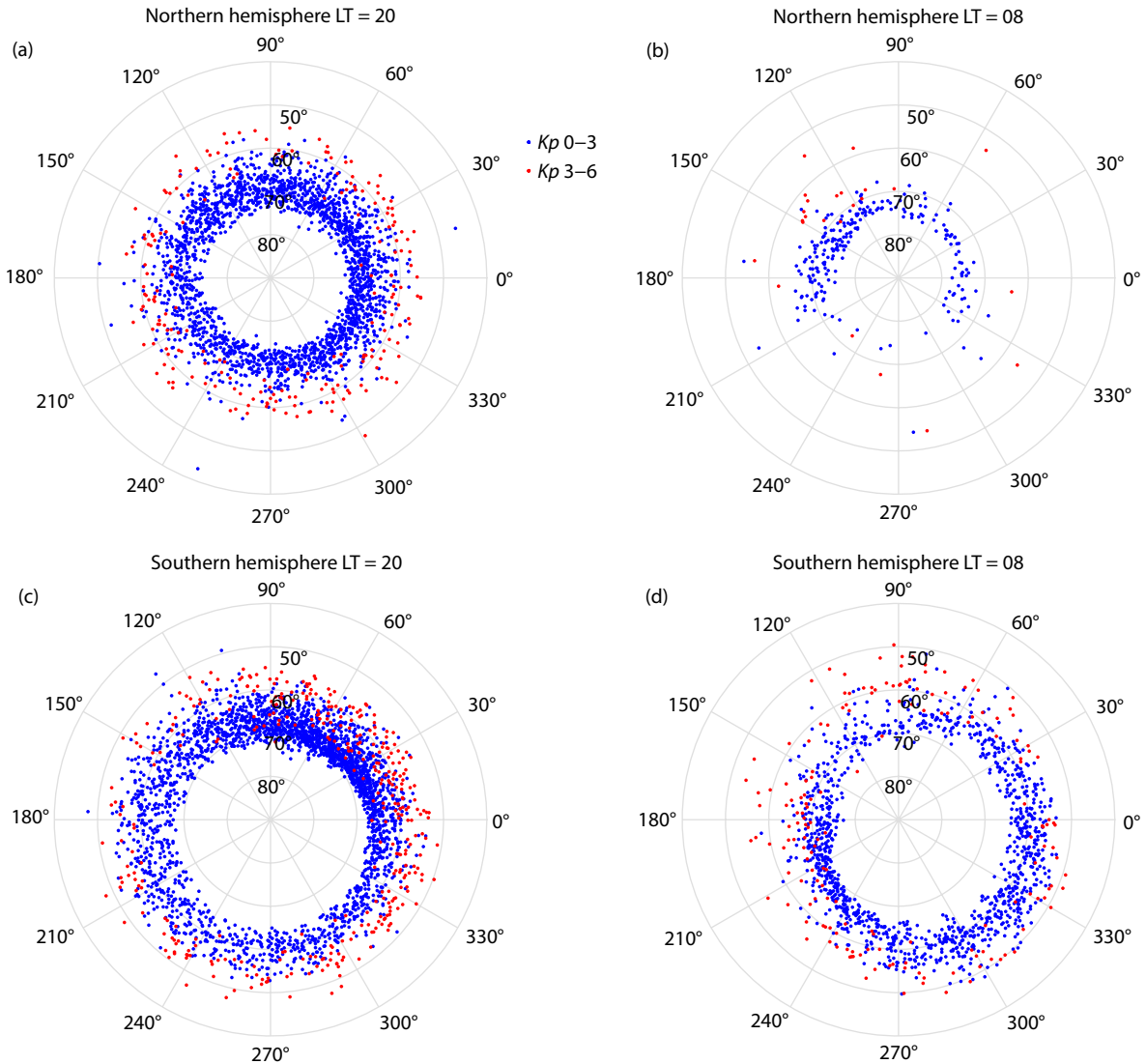


Figure 4. Longitudinal variation of the magnetic latitude position of the mid-latitude trough for the relatively quiescent condition (Kp from 0 to 3, blue dots) and higher geomagnetic activity (Kp from 3 to 6, red dots).

August), and shifted poleward in local summer. By contrast, the T_e -minimum troughs were observed at higher latitudes (between 60°S to 70°S), and showed a seasonal preference: they appeared more frequently during the equinoxes, and were mostly absent in December and January.

Figure 6b shows the distribution of the troughs in terms of magnetic latitude and geographic longitude. The T_e -minimum troughs appear at all longitudes and latitude ranges. By contrast, the occurrence of the T_e -maximum troughs exhibited a distinct preference for specific longitudes and magnetic latitudes. Notably, T_e -maximum troughs were completely absent in the longitude range of 90° to 240° and magnetic latitude range of 60° to 70° in the southern hemisphere. These troughs with T_e enhancements were found in other longitudes and magnetic latitude regions.

Figure 6c and 6d illustrate the distribution of the troughs related to ion temperature maxima and minima. T_i -maximum troughs were predominantly observed between April and October (local

winter in the southern hemisphere), and occurred at a relatively higher magnetic latitude, ranging from 60° to 70° . Interestingly, this region was complementary to where T_e -maximum troughs were found, with T_e -maximum troughs being located at lower latitudes (around 60°) during the same period. T_i -minimum troughs were more frequently observed than T_i -maximum troughs, and followed a similar magnetic latitude and temporal distribution pattern to all troughs. Figure 6d shows the latitudinal and longitudinal distribution of these troughs. Notably, T_i -maximum troughs were concentrated within the longitudinal range of approximately 0° to 60° , and between 60° to 70° magnetic latitude. While the data from 90° to 240° longitude also covered the magnetic latitude range from 60° to 70° , the T_i -maximum troughs were absent in this region, a distribution similar to that of the T_e -maximum troughs. The T_i -minimum troughs, however, were distributed across all longitudes, with higher occurrences between longitudes 300° and 120° , and fewer observed from 120° to 300° .

Both T_i and V_i could be associated with mid-latitude troughs. Rodger (2008) indicated that the magnitude of electric field has

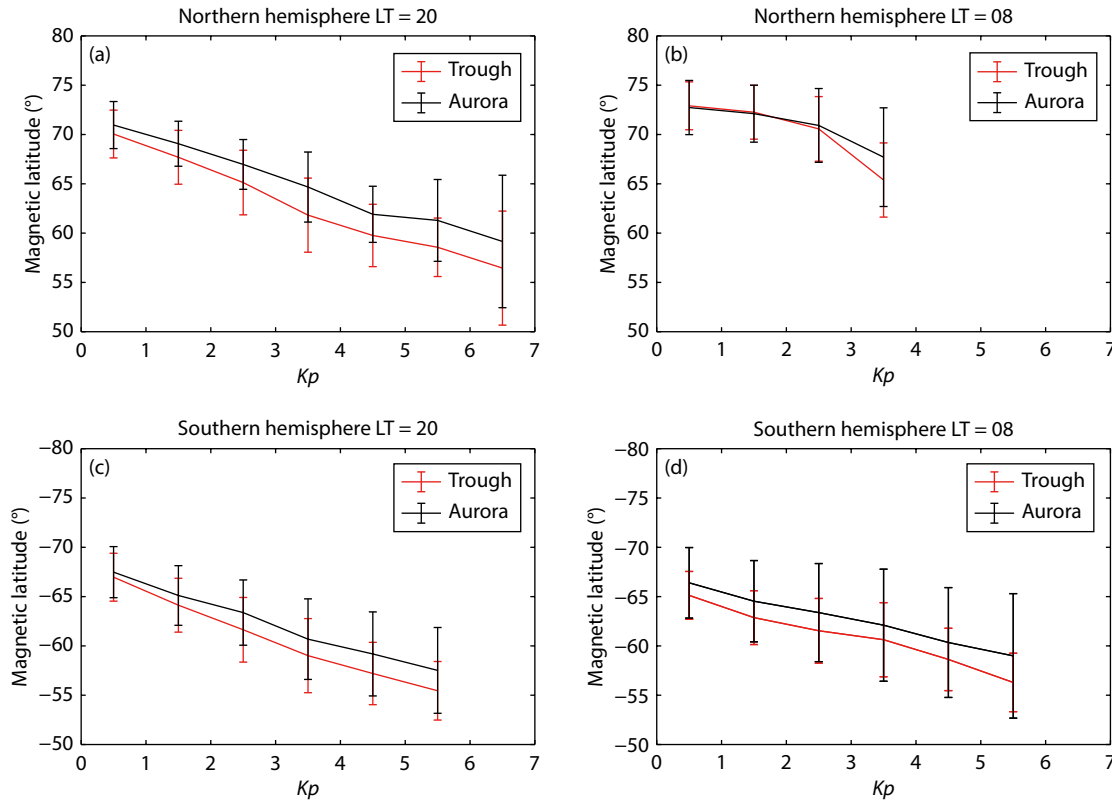


Figure 5. Variation of the magnetic latitude position of the mid-latitude trough with geomagnetic activity index Kp . Both the magnetic latitude position of the auroral oval (black error bar) and the mid-latitude trough (red error bar) are given here.

significant impact on ion temperature T_i . For instance, within the SAID, T_i could exceed 3000 K, accompanied by a plasma velocity of over 1 km/s. The enhanced electric field leads to a larger ion drift, which in turn increases T_i . Additionally, energy transfer from ions to electrons could further enhance electron temperature T_e . To explore this relationship, Figures 6e and 6f illustrate the distribution of troughs related to the velocity and ion temperature peaks. It can be clearly seen that the troughs associated with V_i peaks occurred throughout the year, predominantly within the geomagnetic latitude range of 60° to 70°. As shown in Figure 6f, V_i -maximum-related troughs were mainly observed from 330° to 120° longitude, and within 60° to 70° magnetic latitude range in the southern hemisphere at 20 LT. T_i -maximum-related troughs, compared with V_i -maximum-related troughs, displayed a similar pattern in both longitude and latitude distribution. Nevertheless, the V_i -maximum-related troughs do not always collocate to those with maximum- V_i .

We further examine the relationship between the T_i - and V_i -maximum-related troughs at 20 LT in the northern hemisphere. As the T_e data is unavailable, only T_i and V_i results are presented in Figure 7. Out of 2065 troughs identified at 20 LT in the northern hemisphere, there were 1148, 453, and 381 troughs correlated with V_i -maximum, T_i -maximum, or both, respectively. By comparison, 2489 troughs were observed at 20 LT in the southern hemisphere; however, the numbers of troughs corresponding to V_i -maximum, T_i -maximum, or both are only 297, 288, and 131, respectively. Further investigation is required to understand why the characteristics of troughs related to T_i and V_i variations differ

so greatly between the two hemispheres.

5. Discussion

In Figure 3, we analyzed the temporal variations in the occurrence rate and magnetic latitude positions of mid-latitude troughs. We observed higher trough occurrence rates in the local winter, which aligns with previous studies (Ishida et al., 2014; Aa et al., 2020). The trough occurrence rates on the dayside (08 LT) are significantly lower than on the nightside (20 LT), which is consistent with other observations. For example, Aa et al. (2020), using in-situ observation from the SWARM constellation, reported a significantly higher occurrence rate of the mid-latitude trough at 20 magnetic local time (MLT) as compared to 08 MLT.

The higher occurrence rate of trough on the nightside than dayside may be related to the differing physical processes on the duskside as compared to the dayside. At the pre-midnight sector, the westward convection and the eastward corotation create a stagnation zone, leading to continuous plasma density loss at night. By contrast, on the post-midnight zone and dawnside, both convection and corotation are eastward, which could push the trough from pre-midnight to other local times (Spiro et al., 1978). Additionally, in our dataset, we found that the nightside troughs were more frequently associated with high-speed ion drifts, as shown in Figure 6f. By contrast, high-speed ion drifts were rarely observed on the dayside, and were only present at very high geomagnetic latitudes, near the equatorward boundary of auroral oval. This absence of high-speed ion drift may explain the relatively lower occurrence rate of dayside mid-latitude troughs.

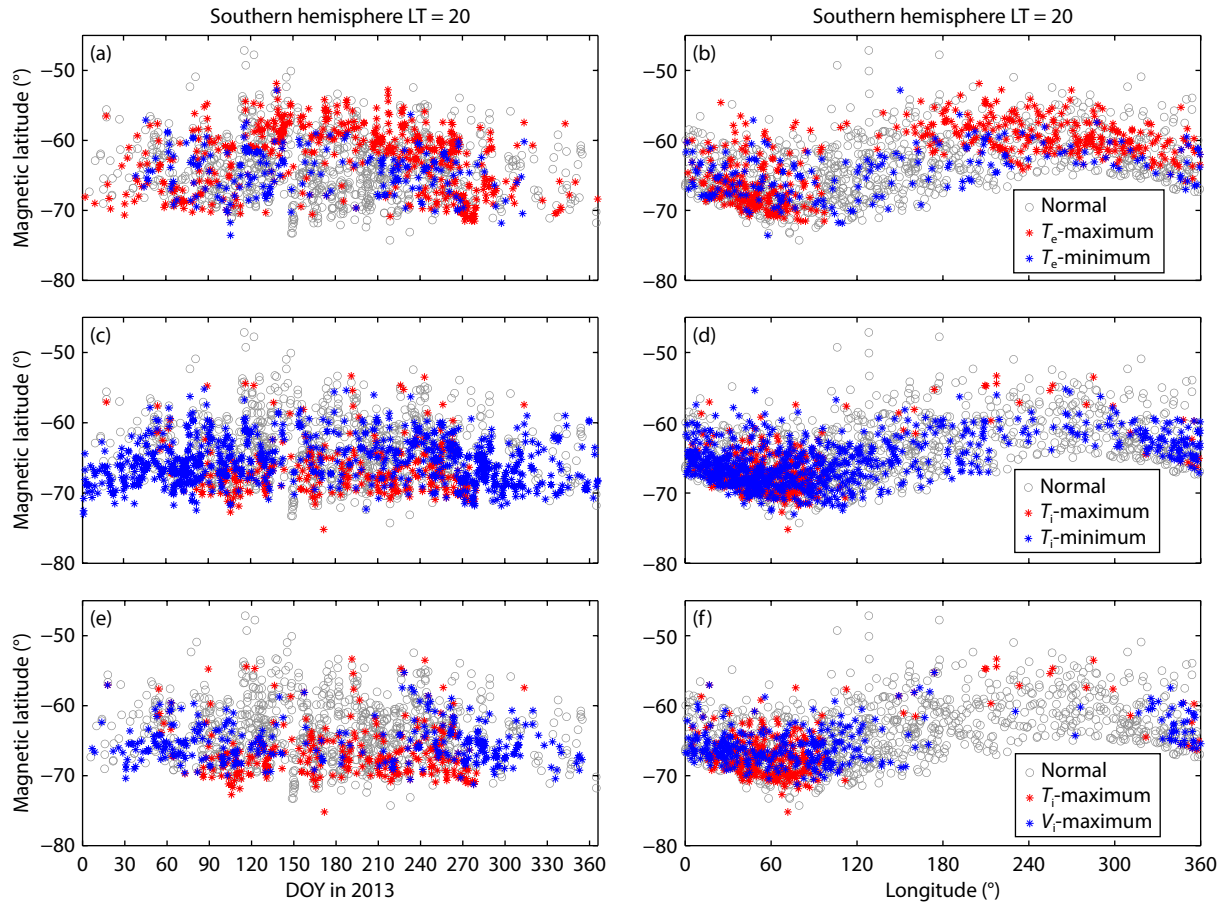


Figure 6. The seasonal (left) and the longitudinal (right) distribution of the magnetic latitude position of the mid-latitude trough, and the association with different ionospheric physical parameters (T_i , T_e and V_i), in the southern hemisphere. (a, b) The distribution of the T_e -maximum-related, T_e -minimum-related, and the normal trough (red dots, blue dots, and gray dots). (c, d) Same as panels a and b, for T_i . (e, f) Comparison of T_i -maximum-related troughs and the velocity-maximum-related troughs.

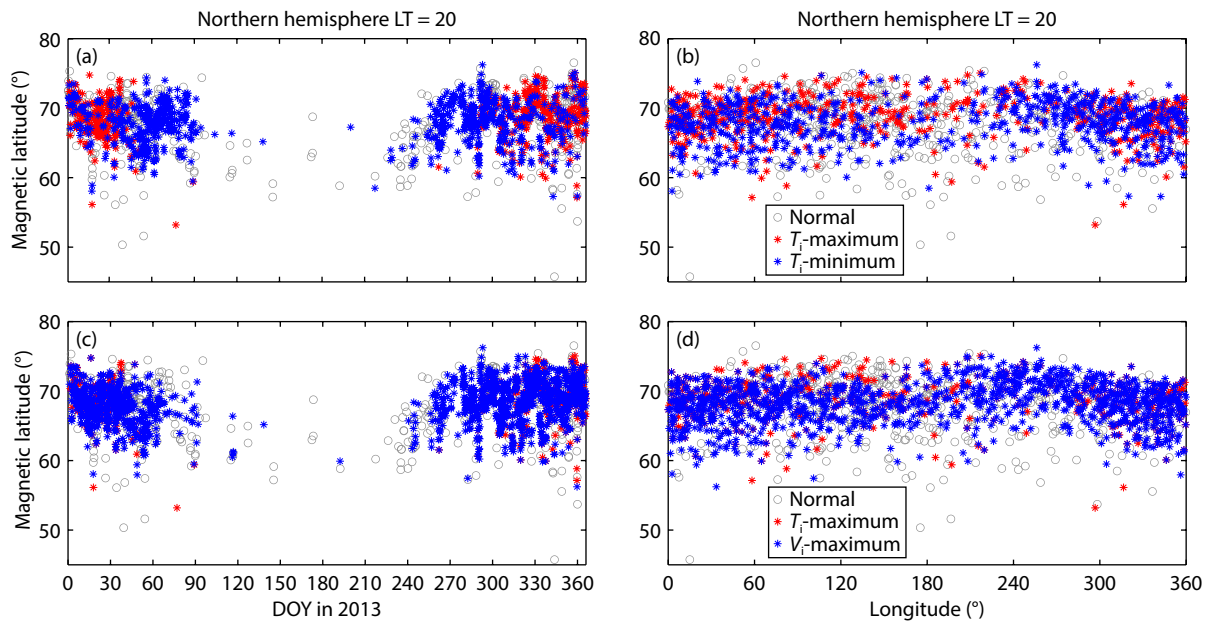


Figure 7. The seasonal (left) and the longitudinal (right) distribution of the magnetic latitude position of the mid-latitude trough, and the association with different ionospheric physical parameters (T_i , and V_i) in the northern hemisphere. (a, b) The distribution of the T_i -maximum-related, T_i -minimum-related, and normal trough (red dots, blue dots, and gray dots). (c, d) Comparison of T_i -maximum-related troughs and the velocity-maximum-related troughs.

In Figure 6, we categorize the trough observations from the DMSP SSIES instrument, based on the simultaneous presence of abnormal T_e , T_i , and V_i within the trough. The phenomenon of T_e -enhancement at sub-auroral latitudes has been previously studied by researchers (Fok et al., 1991; Prölss, 2006). The subauroral electron temperature enhancement can be attributed to the heat transfer from the ring current (Prölss, 2006), or the influx during the magnetic storm in the vicinity of the plasmopause (Fok et al., 1991). At the trough, where plasma density is low and more easily influenced, it is reasonable to observe a T_e peak at the trough minimum, if the influx is relatively constant. However, in our study, we observed troughs with electron temperature enhancement located close to the equator during the local winter in the southern hemisphere. Interestingly, these troughs were predominantly located at specific magnetic latitudes in the western hemisphere. Further investigation into the seasonal and hemispheric variations of these troughs is needed to better understand this phenomenon.

Additionally, we observed instances where the T_e -minimum coincided with the mid-latitude trough. This decrease in electron temperature likely results from the absence of external energy sources, including solar radiation and magnetospheric inputs. The distribution of the T_e -minimum occurred at nearly all latitudes, suggesting that there might not be a unique reason for this T_e drop, given its scattered occurrence. We also identified V_i -maximum troughs, and their statistical pattern showed some similarities to T_i -maximum troughs. For example, both were observed at relatively higher magnetic latitudes. While T_i -maximum troughs were more frequently detected during the local winter, V_i -maximum troughs were present across all seasons. Despite this seasonal

difference, the spatial distribution of both the T_i -maximum and V_i -maximum troughs were notably similar.

This similarity between the T_i -maximum and V_i -maximum troughs is more evident in the northern hemisphere (Figures 7c and 7d). A higher number of troughs were observed where both maximum- T_i and maximum- V_i occurred simultaneously. T_i -maximum troughs are more pronounced during winter, while the V_i -maximum troughs could also be observed during equinox period. The troughs associated with the ion temperature enhancement are probably similar to the SAID troughs described by Rodger et al. (1992). Figure 6f shows that the troughs with T_i and V_i enhancement appear in similar magnetic latitude and longitude sectors. According to Rodger et al. (1992), SAID troughs are characterized by an enhanced electric field greater than 25 mV/m (while $V_i > 500$ m/s), and a significant increase in T_i within the SAID. Some of the T_i and V_i enhancements observed in overlapping region (Figure 6f and Figure 7d) occurred simultaneously (Figure 6e and Figure 7c), suggesting a possible association with the SAID. The distribution of the SAID is found adjacent to the poleward boundary (Providakes et al., 1989), or sometimes overlapping the equatorward edge of the diffuse aurora (Anderson et al., 1991). In our statistics (Figure 6f, Figure 7d, and Figure 8), it is interesting to note that the T_i -enhancement-related troughs and V_i -maximum-related ones were observed over a relatively broad area, equatorward of the auroral oval at the nighttime (20 LT). This contrasts with a more confined area near the auroral oval at the daytime (08 LT). In some cases, troughs with enhanced ion drift and ion temperature were observed at higher latitudes, even inside the auroral oval at 08 LT (Figure 1). This suggests that SAID troughs at 08 LT may reach a higher magnetic latitude, and might not be

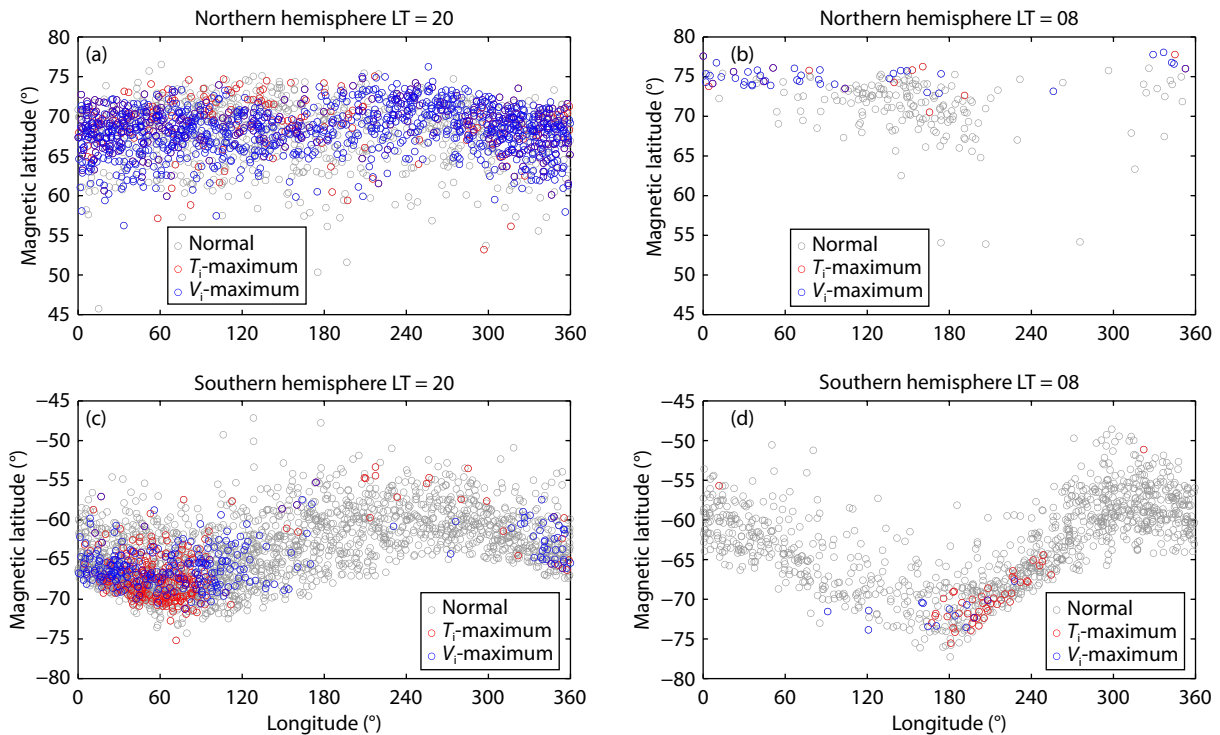


Figure 8. The longitudinal distribution of the magnetic latitude position of the troughs associated with T_i -maximum and V_i -maximum, in the northern hemisphere (top panels) and southern hemisphere (bottom panels), at 20 LT (left panels) and 08 LT (right panels).

classified as mid-latitude troughs, due to their magnetic latitude limit. Therefore, SAID-associated troughs can occur at either mid-latitude or high-latitude.

It should be noted that the SAID contributes to significant plasma depletion, depending on the drift velocity, while the auroral precipitation shapes the density enhancement (auroral oval boundary). Further investigation is needed to better understand how these two factors contribute to the formation and structure of both the mid-latitude and high-latitude troughs.

6. Conclusion

In this study, we statistically analyzed the characteristics of mid-latitude troughs and their relationships with various physical parameters using in-situ electron density and multiple-parameter observations from DMSP throughout 2013. We found that troughs had a higher occurrence rate during local winter, and extended to lower latitudes with increasing geomagnetic activity.

Ionospheric mid-latitude troughs associated with different potential physical parameters exhibited distinct features. In the southern hemisphere, troughs related to T_e enhancements were frequently observed at lower magnetic latitudes during local winter, while those with T_i enhancements were observed at higher magnetic latitudes around 60° – 70° . These T_i enhancements showed a complementary relationship with T_e . V_i -maximum troughs were also observed inside the mid-latitude region around 60° – 70° at the nightside (~ 20 LT), with their positions overlapping those of the T_i enhancement. A correlation between T_i - and V_i -maximum troughs was found in the northern hemisphere, indicating the possible presence of SAID troughs, which are characterized as both high V_i and high T_i .

The relationship between the troughs and the different physical parameters could deepen our understanding of mid-latitude troughs and their underlying mechanisms. However, in this work, only one year's worth of data is used. Future work will extend this analysis over a longer period to further explore the variations and the detailed mechanisms of the mid-latitude troughs.

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References

Aa, E., Zou, S. S., Erickson, P. J., Zhang, S. R., and Liu, S. Q. (2020). Statistical analysis of the main ionospheric trough using swarm in situ measurements. *J. Geophys. Res.: Space Phys.*, 125(3), e2019JA027583. <https://doi.org/10.1029/2019ja027583>

- /2019ja027583
- Anderson, P. C., Heelis, R. A., and Hanson, W. B. (1991). The ionospheric signatures of rapid subauroral ion drifts. *J. Geophys. Res.: Space Phys.*, 96(A4), 5785–5792. <https://doi.org/10.1029/90JA02651>
- Evans, J. V., Holt, J. M., Oliver, W. L., and Wand, R. H. (1983). The Fossil Theory of nighttime high latitude F region troughs. *J. Geophys. Res.: Space Phys.*, 88(A10), 7769–7782. <https://doi.org/10.1029/JA088iA10p07769>
- Fok, M. C., Kozyra, J. U., Warren, M. F., and Brace, L. H. (1991). Seasonal variations in the subauroral electron temperature enhancement. *J. Geophys. Res.: Space Phys.*, 96(A6), 9773–9780. <https://doi.org/10.1029/91JA00791>
- Ishida, T., Ogawa, Y., Kadokura, A., Hiraki, Y., and Häggström, I. (2014). Seasonal variation and solar activity dependence of the quiet-time ionospheric trough. *J. Geophys. Res.: Space Phys.*, 119(8), 6774–6783. <https://doi.org/10.1002/2014ja019996>
- Karpachev, A. T., Deminov, M. G., and Afonin, V. V. (1996). Model of the mid-latitude ionospheric trough on the base of Cosmos-900 and Intercosmos-19 satellites data. *Adv. Space Res.*, 18(6), 221–230. [https://doi.org/10.1016/0273-1177\(95\)00928-0](https://doi.org/10.1016/0273-1177(95)00928-0)
- Karpachev, A. T. (2019). Variations in the winter troughs' position with local time, longitude, and solar activity in the Northern and Southern Hemispheres. *J. Geophys. Res.: Space Phys.*, 124(10), 8039–8055. <https://doi.org/10.1029/2019ja026631>
- Karpachev, A. T., Klimenko, M. V., and Klimenko, V. V. (2019). Longitudinal variations of the ionospheric trough position. *Adv. Space Res.*, 63(2), 950–966. <https://doi.org/10.1016/j.asr.2018.09.038>
- Köhnlein, W., and Raitt, W. J. (1977). Position of the mid-latitude trough in the topside ionosphere as deduced from ESRO 4 observations. *Planet. Space Sci.*, 25(6), 600–602. [https://doi.org/10.1016/0032-0633\(77\)90069-1](https://doi.org/10.1016/0032-0633(77)90069-1)
- Lee, I. T., Wang, W., Liu, J. Y., Chen, C. Y., and Lin, C. H. (2011). The ionospheric midlatitude trough observed by FORMOSAT-3/COSMIC during solar minimum. *J. Geophys. Res.: Space Phys.*, 116(A6), A06311. <https://doi.org/10.1029/2010ja015544>
- Moffett, R. J., and Quegan, S. (1983). The mid-latitude trough in the electron concentration of the ionospheric F-layer: A review of observations and modelling. *J. Atmos. Terr. Phys.*, 45(5), 315–343. [https://doi.org/10.1016/s0021-9169\(83\)80038-5](https://doi.org/10.1016/s0021-9169(83)80038-5)
- Muldrew, D. B. (1965). F-layer ionization troughs deduced from Alouette data. *J. Geophys. Res.*, 70(11), 2635–2650. <https://doi.org/10.1029/JZ070i011p02635>
- Newell, P. T., Feldstein, Y. I., Galperin, Y. I., and Meng, C. I. (1996). Morphology of nighttime precipitation. *J. Geophys. Res.: Space Phys.*, 101(A5), 10737–10748. <https://doi.org/10.1029/95JA03516>
- Ober, D. M., Holeman, E., Rich, F. J., Gentile, L. C., Wilson, G. R., and Machuzak, J. A. (2014). The DMSP Space Weather Sensors Data Archive Listing (1982–2013) and File Formats Descriptions. Air Force Research Laboratory Kirtland AFB, AFRL-RV-PS-TR-2014-0174.
- Pröls, G. W. (2006). Subauroral electron temperature enhancement in the nighttime ionosphere. *Ann. Geophys.*, 24(7), 1871–1885. <https://doi.org/10.5194/angeo-24-1871-2006>
- Providakes, J. F., Kelley, M. C., Swartz, W. E., Mendillo, M., and Holt, J. M. (1989). Radar and optical measurements of ionospheric processes associated with intense subauroral electric fields. *J. Geophys. Res.: Space Phys.*, 94(A5), 5350–5366. <https://doi.org/10.1029/JA094iA05p05350>
- Rodger, A. (2008). The mid-latitude trough—Revisited. In P. M. Kintner Jr, et al. (Eds.), *Midlatitude Ionospheric Dynamics and Disturbances* (Vol. 181, pp. 25–33). Washington, DC: American Geophysical Union. <https://doi.org/10.1029/181GM04>
- Rodger, A. S., Brace, L. H., Hoegy, W. R., and Winningham, J. D. (1986). The poleward edge of the mid-latitude trough—its formation, orientation and dynamics. *J. Atmos. Terr. Phys.*, 48(8), 715–728. [https://doi.org/10.1016/0021-9169\(86\)90021-8](https://doi.org/10.1016/0021-9169(86)90021-8)
- Rodger, A. S., Moffett, R. J., and Quegan, S. (1992). The role of ion drift in the formation of ionisation troughs in the mid- and high-latitude ionosphere—a review. *J. Atmos. Terr. Phys.*, 54(1), 1–30. [https://doi.org/10.1016/0021-9169\(92\)90082-v](https://doi.org/10.1016/0021-9169(92)90082-v)
- Spiro, R. W., Heelis, R. A., and Hanson, W. B. (1978). Ion convection and the

- formation of the mid-latitude *F* region ionization trough. *J. Geophys. Res.: Space Phys.*, 83(A9), 4255–4264. <https://doi.org/10.1029/JA083iA09p04255>
- Spiro, R. W., Heelis, R. A., and Hanson, W. B. (1979). Rapid subauroral ion drifts observed by Atmosphere Explorer C. *Geophys. Res. Lett.*, 6(8), 657–660. <https://doi.org/10.1029/GL006i008p00657>
- Spogli, L., Alfonsi, L., De Franceschi, G., Romano, V., Aquino, M. H. O., and Dodson, A. (2009). Climatology of GPS ionospheric scintillations over high and mid-latitude European regions. *Ann. Geophys.*, 27(9), 3429–3437. <https://doi.org/10.5194/angeo-27-3429-2009>
- Voiculescu, M., Virtanen, I., and Nygrén, T. (2006). The F-region trough: seasonal morphology and relation to interplanetary magnetic field. *Ann. Geophys.*, 24(1), 173–185. <https://doi.org/10.5194/angeo-24-173-2006>
- Yang, N., Le, H. J., and Liu, L. B. (2015). Statistical analysis of ionospheric mid-latitude trough over the Northern Hemisphere derived from GPS total electron content data. *Earth Planets Space*, 67(1), 196. <https://doi.org/10.1186/s40623-015-0365-1>
- Yang, N., Le, H. J., and Liu, L. B. (2016). Statistical analysis of the mid-latitude trough position during different categories of magnetic storms and different storm intensities. *Earth Planets Space*, 68(1), 171. <https://doi.org/10.1186/s40623-016-0554-6>
- Yang, N., Le, H. J., Liu, L. B., and Zhang, R. L. (2018). Statistical behavior of the longitudinal variations of the evening topside mid-latitude trough position in both Northern and Southern Hemispheres. *J. Geophys. Res.: Space Phys.*, 123(5), 3983–3997. <https://doi.org/10.1029/2017JA025048>
- Yizengaw, E., Wei, H., Moldwin, M. B., Galvan, D., Mandrake, L., Mannucci, A., and Pi, X. (2005). The correlation between mid-latitude trough and the plasmopause. *Geophys. Res. Lett.*, 32(10), L10102. <https://doi.org/10.1029/2005gl022954>
- Yizengaw, E., and Moldwin, M. B. (2005). The altitude extension of the mid-latitude trough and its correlation with plasmopause position. *Geophys. Res. Lett.*, 32(9), L09105. <https://doi.org/10.1029/2005gl022854>