Global Distribution of Nighttime MSTIDs and Its Association With E Region Irregularities Seen by CHAMP Satellite

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Abstract We investigate the correlation of sporadic E (Es) with the occurrence of medium-scale traveling ionospheric disturbances (MSTIDs) at night in middle latitudes (25°–40°N and 25°–40°S magnetic latitudes) by examining their occurrence climatology. The occurrence climatology of Es and MSTIDs is derived using the Challenging Minisatellite Payload satellite data acquired in 2001–2008 and 2001–2009, respectively. Electron density irregularities and radio scintillations are used as the detection proxies of MSTIDs and Es, respectively. The occurrence rate of MSTIDs shows a semi-annual variation with the primary peak during June solstices and the secondary peak during December solstices in both hemispheres. However, the occurrence rate of Es shows a seasonal variation with a pronounced peak in summer in both hemispheres. The occurrence of MSTIDs during local summer and equinoxes is correlated with the occurrence of local Es, but the high occurrence rate of MSTIDs in local winter is not correlated with local winter hemisphere Es. MSTIDs in the winter hemisphere are correlated with magnetically conjugate MSTIDs in the summer hemisphere; these summer hemisphere MSTIDs are correlated with the occurrence of Es in the summer hemisphere. The occurrence rate of MSTIDs clearly shows an increase with decreasing solar activity, but the solar cycle dependence of Es is not obvious from the data. This observation suggests that the generation of MSTIDs is significantly affected by factors other than Es such as the growth rate of the Perkins instability, atmospheric gravity waves, and the F region conductance.

1. Introduction

Traveling ionospheric disturbances (TIDs) are common electron density structures in the F region and are observed globally. TIDs are produced by various sources and appear as different forms depending on the sources. The most frequently observed TIDs in midlatitudes are medium-scale TIDs (MSTIDs). MSTIDs develop both on the dayside and at night, but the characteristics and generation mechanisms of daytime and nighttime MSTIDs are different (Kotake et al., 2007; Makela & Otsuka, 2011; Oliver et al., 1997; Otsuka et al., 2011). Our study is about the global behavior and sources of typical MSTIDs at night in midlatitudes.

MSTIDs at night (hereafter shortly MSTIDs) have typical characteristics. They have periods of ~1 h, phase velocities of ~100 m/s, and wavelengths of a few hundred kilometers (Amorim et al., 2011; Ding et al., 2011; Garcia et al., 2000; Huang et al., 2016; Martinis et al., 2011, 2019; Mendillo et al., 1997; Miller et al., 1997; Otsuka et al., 2011; Saito et al., 2001; Shiokawa et al., 2003; Taylor et al., 1998). In the Northern Hemisphere, MSTIDs are elongated in the northwest-southeast direction and propagate toward the southwest (Behnke, 1979; Ding et al., 2011; Martinis et al., 2010, 2019; Mendillo et al., 1997; Ogawa et al., 2009; Otsuka et al., 2004; Saito et al., 1998, 2001; Shiokawa et al., 2003; Tsugawa et al., 2007). In the Southern Hemisphere, MSTIDs are elongated in the northeast-southwest direction and propagate toward the northwest (Amorim et al., 2011; Figueiredo et al., 2018; Martinis et al., 2011). Thus, MSTIDs in the Northern and Southern Hemispheres are symmetric with respect to the magnetic equator, which is consistent with the conjugate property of MSTIDs (Martinis et al., 2010, 2019; Narayanan et al., 2018; Otsuka et al., 2004; Shiokawa et al., 2005; Stefanello et al., 2015).

The occurrence of MSTIDs has been investigated using various observations on the ground including airglow, total electron content (TEC), F region height, and spread F measurements (Amorim et al., 2011; Bowman, 1990; Ding et al., 2011; Duly et al., 2013; Figueiredo et al., 2018; Garcia et al., 2000; Huang et al., 2016;
Kotake et al., 2006, 2007; Martinis et al., 2011; Miller et al., 1997; Narayanan et al., 2014; Otsuka et al., 2013; Shiokawa et al., 2003; Taylor et al., 1998; Valladares & Sheehan, 2016). The common feature seen in all ground-based observations is the smaller occurrence rate of MSTIDs at the equinoxes compared to solstices. Differences exist between the magnitudes of the occurrence rates of MSTIDs in June and December solstices among different observations, but, on average, the occurrence rate of MSTIDs has the primary peak during June solstices and the secondary peak during December solstices. The semi-annual variation of the MSTID activity with two peaks during solstices is a global phenomenon as identified from satellite observations (Kil & Paxton, 2017). Note that because of the distribution of ground-observing sites, the Southern Hemisphere is much less well-characterized than the Northern Hemisphere; space-based observations, such as those discussed here, provide a unique vantage point. The other common feature in MSTIDs is the increase in MSTID activity with decreasing solar activity (Amorim et al., 2011; Martinis et al., 2010; Park et al., 2010; Shiokawa et al., 2003). Both ground-based and satellite observations show that MSTIDs occur most frequently in the Asian sector during June solstices.

Atmospheric gravity waves are understood to be involved in the generation of MSTIDs (Behnke, 1979; Hines, 1960; Kelley & Fukao, 1991; Mendillo et al., 1997), but the distinctive characteristics of MSTIDs indicate the operation of electrodynamical processes (Kelley & Fukao, 1991; Kelley & Miller, 1997; Miller et al., 1997). The Perkins instability (Perkins, 1973) predicts the growth of seed perturbations under specific conditions that are determined by the geometry of the magnetic field lines, propagation direction of waves, and effective background electric fields (Hamza, 1999; Kelley, Makela, et al., 2003; Kelley & Miller, 1997; Makela & Otsuka, 2011; Perkins, 1973; Zhou & Mathews, 2006). However, the growth rate of the Perkins instability is known to be too small to account for the observed amplitudes of MSTIDs (Garcia et al., 2000; Kelley & Fukao, 1991). The coupling effect of the $E$ and $F$ region in the generation of MSTIDs is suggested to explain the fast growth of the Perkins instability; polarization electric fields driven by the inhomogeneous electron density in sporadic $E$ (Es) promote the growth of the Perkins instability (Cosgrove & Tsunoda, 2002, 2004; Haldoupis et al., 2003; Kelley, Haldoupis, et al., 2003; Kelley & Fukao, 1991; Tsunoda, 2006; Tsunoda & Cosgrove, 2001). Numerical simulations (Yokoyama et al., 2004, 2009; Yokoyama & Hysell, 2010) and observations (Helmoldt, 2012, 2016; Helmboldt & Hurley-Walker, 2020; Narayanan et al., 2018; Otsuka et al., 2007, 2008) have shown the development of MSTIDs in association with Es.

The correlation between the occurrence of Es and MSTIDs over Japan (Narayanan et al., 2018; Otsuka et al., 2007, 2008), United States (Helmoldt, 2012, 2016), and Australia (Helmoldt & Hurley-Walker, 2020; Narayanan et al., 2018) provides supporting observational evidence of their connection, but their relationship has not yet been demonstrated globally. As described above, the occurrence of MSTIDs shows annual and longitudinal variations. We do not know yet whether these characteristics can be explained in terms of Es in both hemispheres. A rigorous comparison has not yet been made using the observations of both MSTIDs and Es.

This study addresses the relationship between Es and MSTIDs using their occurrence statistics derived from the Challenging Minisatellite Payload (CHAMP) satellite data in 2001–2009. Es and MSTIDs are derived using the observations of radio scintillation and electron density fluctuation, respectively. We note that Es is not the direct source of radio scintillations in the $E$ region. Scintillations are produced by the electron density irregularities that are believed to be associated with the electron density gradient caused by Es. We use the terminology Es as an indicator of $E$ region perturbations.

### 2. MSTIDs and Es Detection

The CHAMP satellite was launched on July 15, 2000 to an initial altitude of 454 km with an orbital inclination of 87.25°. After its orbit slowly decayed, the mission ended on September 19, 2010. This study uses the observations from two instruments: Planar Langmuir Probe (PLP) and a Global Positioning System (GPS) radio occultation (RO) receiver. The PLP measurements of the electron density with a data cadence of 15 s ($\sim$100 km spatial resolution) are used for the detection of MSTIDs. The measurements of the signal-to-noise ratio (SNR) on L1 (1.5 GHz) signal with 50 Hz sampling rate by the GPS RO receiver are used for the detection of perturbations in the $E$ region. The observations of PLP and GPS RO were not at the same spots because GPS RO observations were made along the line-of-sight to the GPS satellites.
The association of electron density irregularities in midlatitudes with MSTIDs is demonstrated by comparing satellite observations with ground-based observations (Kil & Paxton, 2017). MSTIDs are detected using either the absolute value (Park et al., 2010) or the normalization (or logarithm) (Kil & Paxton, 2017) of the electron density fluctuations from satellite observations. The absolute value can be a useful parameter when we are interested in the strength of MSTIDs, but this method can be affected by the background density. To minimize the effect of the background density, we use the logarithm of the density fluctuation as the detection proxy for MSTIDs. This method is relevant because we are interested in the occurrence of MSTIDs instead of the MSTID strength.

The detection method of MSTIDs is illustrated using a sample measurement shown in Figure 1. In Figure 1a, the electron density ($N$) observed by CHAMP is shown by a black line and the low-pass-filtered density ($F$) obtained using the Savitzky-Golay filter (Savitzky & Golay, 1964) is shown by a red line. The enlarged plots of them in green boxes are shown on right-hand side. The detection parameter ($\delta$) of MSTIDs shown in Figure 1b is defined as,

$$\delta = \log_{10}N - \log_{10}F$$

We use $\delta = 0.005$ as the detection threshold of MSTIDs to acquire a sufficient number of events while minimizing the detection of false alarms. The magnitude of the occurrence rate depends on the threshold, but the distributions of irregularities are not sensitive to the selection of the threshold. The absolute density fluctuation ($\Delta N$) is shown in Figure 1c for a comparison. We can detect the signatures of MSTIDs in both hemispheres in Figure 1b using a certain threshold, but they are difficult to detect in the Southern Hemisphere in Figure 1c because their amplitudes are small. We have validated our detection parameter by comparing with the detrended global navigation satellite system TEC maps over Japan (https://aer-nc-web.nict.go.jp/GPS/DRAWING-TEC/). We have randomly selected CHAMP orbits in different months and years and examined the correlated occurrence of irregularities with MSTIDs. The $\delta$ value was greater than the threshold on the days during which the development of MSTIDs was clearly visible from TEC perturbation maps, whereas the $\delta$ value was less than 0.002 when TEC perturbations did not occur. Of course, there were cases where we could not determine the development of MSTIDs because of the occurrence of weak TEC perturbations or of the occurrence of irregular shapes of TEC fluctuations in small areas. These features may be associated with MSTIDs or produced by other sources. We do not think that this uncertainty significantly affects our derivation of the morphology of MSTIDs from CHAMP data because the uncertainty would be distributed randomly. As we show in the following sections, the behavior of midlatitude irregularities is consistent with the behavior of MSTIDs identified from ground-based observations. This consistency is not explained, if the generation of midlatitude irregularities is dominated by sources other than MSTIDs. Our study has derived the occurrence statistics of MSTIDs using the CHAMP/PLP data acquired from May 15, 2001 to December 31, 2009.

Es is detected using the 50 Hz SNR profile of GPS L1 signal in the altitude range of 50–150 km. Examples of SNR values normalized by their mean values are shown in Figure 2a. The residuals of SNR values shown in Figure 2b are obtained using a high pass filter. We use 0.2 for the residual as the threshold for the detection of Es in the altitude range of 90–130 km. The global distribution of Es at night derived from the GPS RO data from May 19, 2001 to October 5, 2008 is shown in Figure 2c. Our study derives the occurrence statistics of Es using the data in ±25°–40° magnetic latitudes (yellow lines). The occurrence rates of Es in these latitude regions are greater than that in the equatorial region. From the longitudinal distribution, we can identify a smaller occurrence rate of Es over North America in the Northern Hemisphere and in the African
sector in the Southern Hemisphere compared with that in other longitudes. The latitudinal and longitudinal distributions of Es in Figure 2c are consistent with the results in Arras et al. (2008) and Wu et al. (2005). Both studies showed the concentration of Es at 100–110 km altitudes and the preferential occurrence of Es during summer in each hemisphere. The occurrence rate of Es at night is comparable to that on the dayside (Wu et al., 2005). These properties were also identified from our data (not shown). The detailed description of the CHAMP GPS RO data processing can be found in Wu et al. (2005) and Arras et al. (2008).

3. Observational Results

3.1. Seasonal and Longitudinal Distributions of MSTIDs and Es Layer at Night

The distributions of MSTIDs are obtained by processing the data in ±25°–40° magnetic latitudes to minimize the effect of other sources on the occurrence statistics of MSTIDs. Because equatorial bubbles are mostly confined to −20° to +20° magnetic latitudes (Choi et al., 2012; Haaser et al., 2012; Kil et al., 2020; Kil & Heelis, 1998; Stolle et al., 2006; Su et al., 2006) and midlatitude ionization troughs form mostly poleward of ±55° magnetic latitudes (He et al., 2011; Lee et al., 2011), their effects on our results are minor. We use the same magnetic latitude ranges for the occurrence statistics of both MSTIDs and Es. Because the difference of magnetic latitudes for the E and F regions is ∼2° and this difference does not affect the morphology of Es. The LT ranges used for the occurrence statistics of both MSTIDs and Es are 20–04 LT.

The distributions of MSTIDs and Es derived using the data in the magnetic North (25°–40°N) and magnetic South (25°–40°S) are shown in Figure 3. We define the occurrence rate as the ratio of number of events to the number of observations within a longitude and month bin. By comparing the MSTID distributions in the magnetic North and South (Figure 3a) we can identify hemispheric symmetry in the annual and longitudinal distribution of MSTIDs. On average, the primary peak occurs during June solstices (May, June, July, and August) and the secondary peak occurs during December solstices (November, December, January, and February). The occurrence rate reaches its maximum in the Asian-Pacific sector (90°–210°E) during June solstices in both hemispheres, but the occurrence rate in the Southern Hemisphere is greater than that in the Northern Hemisphere. These characteristics of the MSTID occurrence rate are almost the same as those identified from the Swarm satellite observations (Kil & Paxton, 2017). The distributions of the Es layer in Figure 3b show the seasonal variation; the peak occurrence rate is in summer (June solstices in the Northern Hemisphere and December solstices in the Southern Hemisphere). Thus, the annual behavior of Es is different from that of MSTIDs. The difference is pronounced in the Southern Hemisphere because the occurrence rate of Es is minimal in June solstices during which the occurrence rate of MSTIDs is maximal.

Figure 2. Detection of Es from the GPS RO data on April 23, 2003. (a) SNR normalized by the mean SNR. (b) Residuals obtained using a high pass filter. (c) The distribution of nighttime Es obtained from the GPS/RO data at 20–04 LT in 2001–2008. The yellow lines indicate ±25° and ±40° magnetic latitudes. The occurrence statistics of Es in each hemisphere are derived using the data within the yellow lines. GPS/RO, Global Positioning System radio occultation; MSTID, medium-scale traveling ionospheric disturbances.
To emphasize the difference in the annual behavior of MSTIDs and Es during solstices, their longitudinal distributions for the June and December solstices are compared using line plots in Figure 4: (a and b) Northern Hemisphere, (c and d) Southern Hemisphere, and (e and f) the sum of both hemispheres. The occurrence rates of MSTIDs during June and December solstices are comparable in both hemispheres, but the occurrence rates of Es in opposite solstices are significantly different. We can identify the similarity between the longitudinal distributions of MSTIDs and Es in summer in both hemispheres. This comparison is not effective in winter (December solstices in the Northern Hemisphere and June solstices in the Southern Hemisphere) because the occurrence rate of Es is too small. Thus, the behavior of MSTIDs and Es is consistent in summer, but it is not in winter.

The total occurrence rates of MSTIDs and Es during June (Figure 4e) and December (Figure 4f) solstices are obtained by combining the observations in both hemispheres. When we consider the occurrence of MSTIDs and Es without the distinction of the hemisphere, their longitudinal distributions show similar patterns. This result is expected because the longitudinal distribution of MSTIDs does not vary much with season and hemisphere and because the longitudinal distribution of Es is dominated by that in the summer hemisphere. The results in Figures 4e and 4f indicate that the annual and longitudinal behavior of MSTIDs in both hemispheres can be explained in terms of Es by assuming that Es in one hemisphere affects the generation of MSTIDs in both hemispheres. This assumption is directly related to the conjugacy in MSTIDs.

3.2. Solar Cycle Dependence of MSTIDs

The solar cycle dependence of the occurrence of MSTIDs has been identified from various ground-based and space-based observations (Aomorim et al., 2011; Martinis et al., 2010; Park et al., 2010; Shiokawa et al., 2003). These studies showed that the occurrence rate of MSTIDs is inversely proportional to the solar activity regardless of longitude and hemisphere. To examine the solar cycle dependence of MSTIDs, the global distributions of MSTIDs are divided into three periods in Figure 5: (a) 2001–2003 (solar maximum), (b) 2004–2006 (intermediate), and (c) 2007–2009 (solar minimum). The increase of the occurrence rate with
the decrease of the solar activity is clear. The semi-annual variation of the occurrence rate is a consistent feature over the solar cycle.

The dependence of the occurrences of (a) MSTIDs and (b) Es on the solar activity is compared in Figure 6. The occurrence rates of MSTIDs are calculated on each day independent of longitude, and their values are plotted as a function of the solar F10.7 index (a measure of the solar radio flux) on that day. Observations in June solstices (May, June, July, and August), December solstices (November, December, January, and February), and Equinoxes (March, April, September, and October) are distinguished by red, green, and black dots. The lines in the plots are the least square linear fits. The decreasing trend of the occurrence rate of MSTIDs with an increase of the F10.7 index is obvious. The decreasing trend is most pronounced in June solstices. For Es, the occurrence rates are calculated at eight ranges of the F10.7 index instead of on each day because the number of Es data is not sufficient for the calculation of its occurrence rate on each day. As Figure 6b shows, the occurrence of Es does not vary much with the F10.7 index.

An interesting feature in Figure 5 is the higher occurrence rate of MSTIDs in the Southern Hemisphere than in the Northern Hemisphere during June solstices. This hemispheric difference appears to be more significant during the solar maximum than during other periods. This behavior is more clearly visible with the hemispheric asymmetry index \( AI \) defined as

\[
AI = \frac{P_S - P_N}{P_S + P_N} \times 100\% 
\]
here $P_S$ and $P_N$ are occurrence rates of MSTIDs in the Southern and Northern Hemispheres, respectively. Figure 7 shows the longitudinal distributions of the asymmetry index obtained using the data in (a) all months and (b) June solstices during different periods of the solar cycle. The asymmetry is not pronounced over the course of the solar cycle when we use the data in all months, but the asymmetry is pronounced during the solar maximum when the months are limited to June solstices. As well as the variation of the asymmetry index with the solar cycle and month, there also exists the longitudinal difference in the asymmetry index. The hemispheric symmetry/asymmetry has a useful physical meaning regarding the conjugacy in

Figure 5. Solar cycle dependence of the MSTID activity in the (top) magnetic North (25°–40°N) and (bottom) magnetic South (25°–40°S). The years are divided into three periods of the solar cycle: solar maximum (2001–2003), intermediate (2004–2006), and solar minimum (2007–2009). MSTID, medium-scale traveling ionospheric disturbances.

Figure 6. Comparison of the solar cycle dependence of the MSTID and Es activities (a) Distribution of the occurrence rate of MSTIDs as a function of the solar F10.7 index. The observations in different months are distinguished with different colors. The lines are the least square linear fitting lines. (b) Distribution of Es as a function of the solar F10.7 index. The black dots are the mean occurrence rates and the vertical bars are the standard deviations. MSTIDs and Es derived using the CHAMP data in 2001–2009 and 2001–2008, respectively. CHAMP, Challenging Minisatellite Payload; MSTID, medium-scale traveling ionospheric disturbances.
MSTIDs. Based on our results, the conjugacy in MSTIDs is the weakest in June solstices during the solar maximum.

4. Discussion

The physical processes underlying the relationship between Es and nighttime MSTIDs is found in discussions of theoretical studies and numerical simulations (e.g., Cosgrove & Tsunoda, 2002, 2004; Haldoupis et al., 2003; Kelley & Fukao, 1991; Kelley, Haldoupis, et al., 2003; Tsunoda, 2006; Tsunoda & Cosgrove, 2001; Yokoyama et al., 2009; Yokoyama & Hysell, 2010). Here, we discuss the factors (growth rate of the Perkins instability, \(F\) region conductance, electric fields, and neutral winds) that may affect the generation of MSTIDs and the condition (conjugacy in MSTIDs) required for the support of the role of Es based on our results.

Let’s first consider the Northern and Southern Hemispheres separately and discuss whether the behavior of MSTIDs in each hemisphere can be explained in terms of Es in the local hemisphere. The behavior of MSTIDs and Es is consistent in summer. This argument is supported by the high occurrence rates of both MSTIDs and Es in summer and the similarity in their longitudinal distributions. The low activity of MSTIDs in equinoxes can also be attributed to the low activity of Es in equinoxes. Because the occurrence rates of both MSTIDs and Es are too small during the equinoxes, the comparison of their longitudinal distributions is not meaningful. We note that these observations do not corroborate the role of Es because other factors such as atmospheric gravity waves, the growth conditions for the Perkins instability, neutral winds, and electric fields would also affect the generation of MSTIDs. Knowledge of the global morphologies of these factors is necessary to determine the dominant role of Es in the generation of MSTIDs. Our assessment based on our results is that the behavior of MSTIDs in summer and equinoxes can be explained in terms of Es in the local hemisphere.

The situation in winter is totally different from that in other seasons because the occurrence rate of Es in winter is too small to explain the high occurrence rate of MSTIDs in the local hemisphere. The only way that we can explain the high occurrence rate of MSTIDs in winter in terms of Es is assuming the conjugacy in MSTIDs. As long as MSTIDs have strong conjugacy the probability that MSTIDs occur in both hemispheres increases, even if MSTIDs develop only in one hemisphere in association with Es. The conjugate property in MSTIDs is demonstrated by simultaneous observations of MSTIDs in both hemispheres (Martinis et al., 2010, 2019; Otsuka et al., 2004). The quasi-hemispheric symmetry in the longitudinal and annual distributions of MSTIDs in our results and in the results in Kil and Paxton (2017) supports the observation that conjugacy is a common property in MSTIDs. However, we do not know yet how often and under what conditions conjugacy is effective. Knowledge of the variability of the conjugate property is essential for the evaluation of the role of Es.

The solar cycle dependence of MSTIDs and Es are observed to be inconsistent. This observation indicates that the generation of MSTIDs is significantly affected by factors other than Es. Because we do not know whether other factors also affect the seasonal and longitudinal behavior of MSTIDs, our discussion focuses on other factors that may affect the solar cycle dependence. The plausible factors are the growth condition of the Perkins instability and the \(F\) region conductance.

The growth rate of the Perkins instability increases with the decrease of the ion-neutral collision rate (or neutral density) (Hamza, 1999; Kelley & Fukao, 1991; Makela & Otsuka, 2011; Perkins, 1973; Zhou & Mathews, 2006), and therefore, it is inversely proportional to the neutral density. The \(F\) region conductance is directly related to the role of Es. Electric fields associated with Es in the \(E\) region can affect the generation of MSTIDs in the \(F\) region when the \(E\) region conductance is significant compared to the \(F\) region conductance.

**Figure 7.** Solar cycle dependence of the hemispheric asymmetry in the MSTID occurrence rate. (a) The morphology of the asymmetry index obtained using the data in all months. (b) The morphology of the asymmetry index obtained using the data in June solstices. MSTID, medium-scale traveling ionospheric disturbances.
conductance. Because the $F$ region conductance is proportional to the plasma density, the effect of $E_s$ on the $F$ region is inversely proportional to the solar activity. If the generation of MSTIDs is determined by the combination of these factors and $E_s$, MSTIDs would develop more frequently during the period of lower solar activity.

We point out some aspects of our results that require further investigation. The hemispheric asymmetry in MSTIDs is pronounced during solar maximum compared with that during solar minimum. This phenomenon can be understood in terms of the solar cycle dependence of the Perkins instability and the $E$ and $F$ region coupling. The $F$ region conductance acts negatively to the development of MSTIDs at conjugate location because the current from the $F$ region weakens the polarization electric fields associated with the Perkins instability and the $E$ region instability. Thus, solar minimum periods provide better conditions for the development of conjugate MSTIDs and consequently for hemispheric symmetry in MSTIDs. Model simulations of the interhemispheric transmission of electric fields during different periods of the solar cycle are desirable for the validation of our interpretation.

The occurrence rate of MSTIDs in the Southern Hemisphere is greater than that in the Northern Hemisphere in June solstices. This is a puzzling observation on the aspect of the relationship between $E_s$ and MSTIDs because the Northern Hemisphere is the source region of $E_s$ during June solstices. The occurrence rate of conjugate MSTIDs in the Southern Hemisphere cannot be greater than that in the source region, if $E_s$ is responsible for MSTIDs in both hemispheres. This observation along with the solar cycle dependence of the MSTID activity indicates that other factors in the local hemisphere such as background electric fields and neutral winds affect the generation of MSTIDs. Narayanan et al. (2018) reported that the amplitudes of MSTIDs at conjugate locations could be different by the hemispheric difference in thermospheric neutral winds. Right now, we could not provide a good explanation for the determining factor of the hemispheric asymmetry in MSTIDs. Because uncertainties in our detection of MSTIDs may exist, our finding needs to be validated with other observations prior to further discussion of the variation of the hemispheric symmetry/asymmetry in MSTIDs.

The observed occurrence rate of $E_s$ is much smaller than that of MSTIDs. This observation does not directly imply that MSTIDs develop in the absence of $E_s$ because the magnitudes of the occurrence rates of $E_s$ and MSTIDs are subject to their detection proxies and detection thresholds. Our statistical results do not provide information of how often MSTIDs develop in association with $E_s$. This question can be addressed by investigating the coincident occurrence of $E_s$ and MSTIDs at the same location on a daily basis. There have been efforts to identify the simultaneous occurrence of $E_s$ and MSTIDs using ground-based observations (Hemboldt & Hurley-Walker, 2020; Narayanan et al., 2018; Otsuka et al., 2007, 2008), but long-term observations of them worldwide are required for the evaluation of the variability of their causal linkage with geographic and geophysical parameters.

For our observations, the key factor that supports the role of $E_s$ in the generation of MSTIDs is the similarity in their longitudinal distributions in summer. The preferential occurrence of $E_s$ during summer is consistent with ground-based observations (e.g., Whitehead, 1989), but ground-based observations are not sufficient for the validation of the longitudinal distribution of $E_s$. An explicit parameter related to the longitudinal distribution of $E_s$ is the magnetic field strength. $E_s$ is formed by the vertical convergence of ions by the shears in meridional and zonal winds (Axford, 1963; Axford & Cunnold, 1966; Haldoupis, 2011; Mathews, 1998; Whitehead, 1961, 1989). Because the zonal wind shear drives the vertical ion convergence through the Lorentz force which is proportional to the magnetic field strength, the effect of the zonal wind shear would also be proportional to the magnetic field strength (Haldoupis, 2011). The South Atlantic Anomaly located between South America and Africa in the southern midlatitude is the region where the magnetic field strength is the weakest. The magnetic field strength in North America is also smaller than that in other longitudes in the Northern Hemisphere. These features can be identified from the longitudinal morphology of $E_s$ derived from CHAMP data, but knowledge of the shears in zonal and meridional winds are essential for a complete understanding of the cause of the longitudinal distribution of $E_s$. As model simulations show, the global morphology of $E_s$ would also be affected by the redistribution of metallic ions by the combined effect of global electric fields and wind circulation (Huba et al., 2019).
5. Conclusions

We have investigated the role of Es in the generation of nighttime MSTIDs by comparing their occurrence climatology derived from CHAMP satellite observations in 2001–2008 and 2001–2009, respectively. Our results show that the seasonal and longitudinal behavior of MSTIDs in summer and equinoxes in each hemisphere can be explained in terms of Es in the local hemisphere. However, the high occurrence rate of MSTIDs in winter is not explained by Es in the local hemisphere because the occurrence rate of Es is too small in winter. The required condition for the explanation of winter hemisphere MSTIDs is the conjunction in MSTIDs. The activity of MSTIDs increases with decreasing solar activity. However, the solar cycle dependence of Es is not obvious. This observation indicates that other factors also significantly affect the generation of MSTIDs. Other factors that might affect the generation of MSTIDs, and its solar cycle dependence are the growth rate of the Perkins instability, background electric fields, neutral winds, and the $F$ region conductance. The solar cycle dependence of the propagation of atmospheric gravity waves should also be taken into account.

Data Availability Statement

CHAMP PLP and RO data are available in the website https://isdc.gfz-potsdam.de/champ-isdc/ and https://data.cosmic.ucar.edu/gnss-ro/champ/repro2016/, respectively.

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