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Difference in the Sporadic E Layer Occurrence Ratio Between the Southern and Northern Low Magnetic Latitude Regions as Observed by COSMIC Radio Occultation Data

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Abstract In this study, the difference in the sporadic E layer occurrence ratio between two low-magnetic-latitude (±5° to ±15°) regions is analyzed by using COSMIC scintillation observations covering the period from 2007.001 to 2017.365. Obvious longitudinal, seasonal, and LT dependencies of this phenomenon are found. Most features of the differences between two hemispheres could be explained by the difference in vertical wind shear between the two hemispheres induced by the difference between the magnetic and geographic latitudes of the studied regions. This result also indicates that the wind shear mechanism still dominates sporadic E layer formation in low-magnetic-latitude regions.

1. Introduction

Ionospheric sporadic E layers are irregularities with enhanced plasma density that occur in the ionosphere E region (∼80–120 km). A much higher electron density in thin layers and an associated density gradient lead to great impacts on satellite navigation, communication, radar systems and so on (Pavelyev et al., 2007; Yue, Schreiner, Pedatella, & Kuo, 2016). In recent studies, these layers also show complicated structures such as nonuniform wave layer structures and multiple layer structures (Yeh et al., 2012; Yue, Schreiner, Zeng, et al., 2015; Zeng & Sokolovskiy, 2010).

In the decades since the discovery of sporadic E layers, their formation mechanism has been investigated. In the mid-latitude region, the most accepted formation mechanism is the so-called wind shear theory (Axford, 1963; Chimonas & Axford, 1968; Mathews, 1998; Whitehead, 1961, 1970, 1989). Metal ions are forced into a thin layer by ion-neutral collisional coupling and geomagnetic Lorentz forcing induced by vertical wind shear. In the equatorial and high-latitude regions, gradient-drift instability and a large-scale convective electric field become the main sources of sporadic E layers, respectively (Macdougall & Jayachandran, 2005; Matsushita, 1951; Tsunoda, 2008; Whitehead, 1989).

Traditionally, sporadic E is observed by ground-based devices such as ionosondes, incoherent scatter radar, and VHF coherent scatter radar. Since the success of GPS/MET (Global Positioning System/Meteorology), radio occultation (RO) observations have been an effective data source for detecting sporadic E layers. With the development of RO technology, other RO missions, including CHAMP (Challenging Minisatellite Payload), GRACE (Gravity Recovery and Climate Experiment), and FORMOSAT-3 (Constellation Observing System for Meteorology, Ionosphere, and Climate, COSMIC), have provided a large amount of data with significantly improved spatial and temporal resolutions and global coverage (Reigber, 2006; Schreiner et al., 2007; Wickert, Beyerle, et al., 2005; Wickert, Reigber, et al., 2001).

Radio occultation data make it possible to investigate the sporadic E layer on a global scale. Some known features have been confirmed, such as a seasonal variation with the maximum occurrence ratio observed during hemispheric summer in the mid-latitude region, the magnetic equator depression, the South Atlantic anomaly depression and so on (Arras, Wickert, et al., 2008; Hocke et al., 2001; Niu, Weng, et al., 2019; Wu et al., 2005; Yeh et al., 2012).

There are also some new features that have been found in recent studies. For example, Hocke et al. (2001) confirmed the seasonal and latitudinal distribution of sporadic E layers based on GPS/MET RO data. Arras, Wickert, et al. (2008) analyzed the global distribution of the sporadic E layer occurrence ratio based on
CHAMP, GRACE and COSMIC RO data; in this study, the wind shear mechanism was first confirmed on a global scale. Chu et al. (2014) presented the general morphologies of sporadic E layers based on 1-Hz RO data with a stricter criterion compared with those used in former studies. The most important conclusion drawn in Chu et al. (2014) is the first modeling of the convergence of the Fe+ concentration flux and the accordance between the model results and the RO observations, both of which also support the wind shear mechanism.

In addition, the sporadic E layer intensity is obtained from RO data, which provide a new data source for quantitative analysis that is similar to ionosonde observations (Arras & Wickert, 2017; Niu, Fang, et al., 2015; Niu, Weng, et al., 2019; Yu et al., 2019). Tidal behavior has also been investigated in several studies. Arras, Jacobi, and Wickert (2009) investigated the semidiurnal tidal signature in the mid-latitude region and compared it with the zonal wind shear at Collm. Tsai et al. (2018) also presented diurnal and semidiurnal features based on COSMIC RO data. The results show semidiurnal tide behavior in mid-latitude hemispheric summers that generally starts at ~6 and 14 LT, as well as diurnal tide behavior in the mid-latitude and auroral zones. Fytterer et al. (2014) focused on terdiurnal tide behavior, which is mainly found at altitudes above 100 km. Other interesting phenomena have also been mentioned or investigated, such as the wavenumber 4 structure. Hocke and Tsuda (2001) first reported four enhanced occurrence ratio regions and attributed them to gravity wave activity. Niu, Weng, et al. (2019) also confirmed this phenomenon but attributed it to the nonmigrating DE3 tide.

In this study, the focus is an interesting phenomenon, the difference in the sporadic E layer occurrence ratio between two regions of low magnetic latitude (±5° to ±15°). Arras, Wickert, et al. (2008) and Arras, Jacobi, and Wickert (2009) mentioned this phenomenon and found that the occurrence rate is generally larger in the Northern Hemisphere. Here, the detailed features of this phenomenon, such as its spatial and temporal dependencies, are investigated. A possible reason for this phenomenon is also discussed based on the wind shear mechanism. In Section 2, the RO data and sporadic E layer detection method used in this study are briefly introduced. In Section 3, the spatial and temporal dependencies of the difference in the sporadic E layer occurrence ratio between two regions of low magnetic latitude are investigated. The discussion and main conclusions are presented in Sections 4 and 5, respectively.

2. Data

COSMIC is one of the most successful RO missions and is composed of six low Earth orbit (LEO) microsatellites. These microsatellites can provide ~2000 occultation observation profiles per day. The payloads onboard, consisting of occultation antennas and precise orbit determination (POD) antennas (Schreiner et al., 2007), provide observation profiles at 50 and 1 Hz, respectively. It should be noted that the upper boundaries of the 50-Hz profiles are limited, and the sporadic E layer occurrence ratio may tend to be systematically low for altitudes above 122 km (Chu et al., 2014).

In this study, the COSMIC S4 index values derived from scnLv1 files during the period from 2007.001 to 2017.365 are used for the sporadic E layer occurrence ratio calculation and analysis. These data are available on the COSMIC data analysis and archive center (CDAAC) website (http://cdaac-www.cosmic.ucar.edu/). COSMIC S4 is not measured directly due to receiver data format constraints and satellite downlink bandwidth limitations. Instead, the satellite measures signal-to-noise (SNR) intensity fluctuations from the raw 50-Hz L1 amplitude fluctuations, and these intensity measurements are recorded in the data stream at a 1-Hz rate. After these data are downloaded, the S4 indices are reconstructed in CDAAC ground processing. Therefore, the S4 index derived here might differ slightly from the real S4, but these differences would not influence the general climatological features.

To avoid the potential influence of geomagnetic disturbances, only data under quiet geomagnetic conditions, with the planetary 3-h-range index Kp ≤ 3, are included in the following analysis. The Kp index data are available at the National Oceanic and Atmospheric Administration (NOAA) website (https://www.ngdc.noaa.gov/geomag/indices/kp_ap.html). Finally, 3631777 profiles are obtained for further analysis.
3. Data Analysis

Previous studies have revealed that it is possible to identify the existence of sporadic E layers based on strong fluctuations in GPS amplitudes (both in SNR and phase data). Several approaches have been developed for sporadic E layer detection based on RO data. Hocke et al. (2001) and Dou et al. (2010) utilized the fluctuations of electron density profiles to identify the occurrence of sporadic E layers. Wu et al. (2005) and Arras, Wickert, et al. (2008) developed an identification criterion based on the standard deviations of normalized amplitude profiles. Chu et al. (2014) utilized both the amplitude and phase perturbations of L1 and L2 signals to avoid potential measurement errors. Tsai et al. (2018) used normalized amplitude standard deviations at both the L1 and L2 bands, similarly to Arras, Wickert, et al. (2008), with a narrow sliding window (1 km) to detect smaller-scale irregularities. Niu, Fang, et al. (2015) and Niu, Weng, et al. (2019) developed a method to identify sporadic E layers by calculating slant TEC perturbations along the signal paths between GPS and LEO satellites. Yue, Schreiner, Zeng, et al. (2015) and Yue, Schreiner, Pedatella, and Kuo (2016) also pointed out that the COSMIC S4 index derived from 50-Hz L1 amplitude samplings is accurate enough to be used to identify sporadic E layer occurrences. Although the results of these methods may slightly differ from each other, i.e., the absolute value of the occurrence ratio may differ for a fixed location, the general features are all in good accordance, which indicates that all these methods are reasonable for climate research.

In this study, a sporadic E layer is identified if the maximum S4 index in the height range of 80–120 km exceeds a threshold (0.3 in this study, the same as that used in Yue, Schreiner, Pedatella, and Kuo [2016]). The selected threshold represents moderate-to-strong scintillation, which may result in a lower occurrence ratio than the 50-Hz observations. The global geographical distribution of the sporadic E layer occurrence ratio (in %) with a spatial resolution of 5° × 5° is shown in Figure 1. Some already known features are found in Figure 1. Sporadic E layers are mainly found in the mid-latitude region of the summer hemisphere. Sporadic E layer activity is usually much lower in the winter. In addition to this seasonal dependency, a clear equatorial depression is found, which is caused by the horizontal magnetic field line within ±3° (magnetic latitude). A similar depression is also found over the South Atlantic region compared with other longitudinal sections in the same latitude band; this depression may be related to the distinct weak magnetic field intensity and large inclination angle in this region. All these results are in accordance with those of former studies (Arras, Wickert, et al., 2008; Haldoupis, 2012; Tsai et al., 2018; Wu et al., 2005), which indicates that it is feasible to investigate sporadic E layer features by using the method applied in this study.

Figure 1. Global geographical distribution of the sporadic E layer occurrence ratio (S4 > 0.3, in %), with a spatial resolution of 5° × 5°, for spring (top left), summer (top right), autumn (bottom left) and winter (bottom right).
Except for these already known features, the sporadic E layer occurrence ratio in the Northern Hemisphere is generally higher than that in the Southern Hemisphere. Sporadic E layer features in the mid-latitude region have been widely investigated and well-explained by the wind shear mechanism. Thus, the focus is difference in the sporadic E layer occurrence ratio between two low-magnetic-latitude regions in this study.

To analyze this difference in the occurrence ratio in a quantitative way, an asymmetry index is introduced in this study. First, S4 observations of low-latitude regions are obtained. Since the distribution of the sporadic E layer is greatly affected by the magnetic field, a magnetic latitude range from ±5° to ±15° is used for data selection. Second, the selected data are sorted according to different grids (such as longitude-LT and LT-month). Then, the occurrence ratio is calculated in each grid by using the criterion above. Thus, the occurrence ratio is obtained as a function of the hemisphere, longitude and time. The asymmetry index is defined as follows:

$$A_R = (R_S - R_N)$$

where $R_S$ and $R_N$ are the occurrence ratios in the Southern and Northern Hemisphere low-magnetic-latitude regions, respectively. Negative/positive $A_R$ values mean a larger occurrence ratio in the Northern/Southern Hemisphere. It should be noted that the occurrence ratio in the Southern Hemisphere is shifted 6 months later than that in the Northern Hemisphere to exclude the potential influence of seasonal variation.

4. Results

4.1. Seasonal Dependency

To investigate the seasonal dependency of the $A_R$ index, 1-month × 5° longitudinal grids are adopted, and the $A_R$ indices are obtained for each grid by using the method described in Section 2. The results are shown in Figure 2, and both seasonal and longitudinal dependencies are obviously found in this figure.

Obvious annual variations are found at almost all longitudes except for at longitudes from 120°W-180°W. For the longitudinal region between 30°W and 120°W, positive $A_R$ indices are found from approximately April to October, indicating a higher occurrence ratio (maximum ∼25%) in the Southern Hemisphere. Negative $A_R$ indices are found in other months, with a minimum of ∼−17%. For the longitudinal region between 30°W and 170°E, this annual variation is totally reversed, with negative $A_R$ indices (minimum ∼−32%).

![Figure 2. Seasonal variation in the $A_R$ index for different longitudes.](image_url)
occurring from March to October and positive $A_R$ indices (maximum $\sim 16\%$) occurring in other months. In general, the $A_R$ index shows an approximate annual variation and is most prominent from May to August. Clearly, a longitudinal dependency is also found. Two distinct longitudinal areas can be found in this figure: 180°W-30°W and 30°W-180°E. Larger $A_R$ indices are found at $\sim 100°W$, and small $A_R$ indices are found at $\sim 20°E$ and 90°E. $A_R$ indices nearly equal to zero occur at $\sim 30°W$ and 150°W. In general, the occurrence rate is larger in the Northern Hemisphere, which is in accordance with the findings of previous research (Arras, Wickert, et al., 2008). However, it is worth noting that the clear longitudinal dependency and seasonal variation shown in Figure 2 have not yet been reported or explained. These questions are discussed below.

4.2. LT Dependency

Considering the significant seasonal variation in the $A_R$ index, a 1-h $\times$ 1-month grid is adopted to investigate its LT distribution features in different seasons. The result is shown in Figure 3. Negative $A_R$ indices are mainly found from February to October. Positive $A_R$ indices are mainly found in winter. This seasonal variation shows agreement with the findings reported in the previous section.

Different LT dependency features are found in different months. An obvious diurnal variation is found in summer with minor $A_R$ indices observed from 12:00 to 16:00. Aside from this diurnal variation, semidiurnal variation is also found in winter, with two positive peaks at $\sim 13:00$–17:00 and 01:00–05:00. In addition, neither diurnal nor semidiurnal variations are prominent in spring or autumn.

4.3. Solar Activity Dependency

The use of data with coverage as long as 11 years enables us to investigate the solar activity dependency of the $A_R$ index in this study. The $A_R$ index is calculated based on a 1 month $\times$ 5° longitudinal grid, and the results are shown in Figure 4. The F10.7 index is available on the Natural Resources Canada website (https://www.spaceweather.gc.ca/solarflux/sx-5-en.php).

Thus, correlation coefficients between the $A_R$ index and F10.7 index are calculated for each longitudinal grid, as shown in Figure 5. The absolute values of these correlation coefficients are less than 0.25, which indicates no obvious solar activity dependency pattern. This result is in accordance with previous results. For
example, Pietrella and Bianchi (2009) pointed out no significant dependence of intense foEs occurrences on solar cycle variability by using ionosonde data obtained at a Rome station during the period from 1976 to 2007.

5. Discussions

As mentioned before, several features of the $A_R$ index should be explained to clarify the physical processes behind the occurrence of sporadic E layers. Here, an attempt is made to find reasonable explanations by using wind shear theory. It should be kept in mind that sporadic E layer formation is driven not only by neutral wind but also by other factors, such as the magnetic field. As revealed from the empirical model and observations (i.e., TIDI observations), the wind field in the E region is basically symmetrical along the geographic equator. However, the formation of sporadic E layers is also greatly controlled by the geomagnetic field. Therefore, differences between magnetic latitude and geographic latitude contribute to differences in vertical wind shear between two low-magnetic-latitude regions. For example, the magnetic latitudes +15° and −15° in the longitudinal sector 180°W-30°W correspond to the geographic latitudes of ~10°N and 20°S,
respectively. Thus, it is easily understood that the occurrence ratio in the Southern Hemisphere is higher than that in the Northern Hemisphere (indicated by positive $A_R$ indices).

To confirm this assumption, simulations are carried out based on the NRL Mass Spectrometer and Incoherent Scatter (MSIS-00) atmospheric model, horizontal wind model (HWM07) and International Geomagnetic Reference Field (IGRF-12) geomagnetic field model. According to wind shear theory, the vertical ion velocity of metal ions induced by neutral wind is described as follows:

$$w_i = \frac{r \cos I}{1 + r^2} V + \frac{\cos I \sin I}{1 + r^2} U$$

(2)

where $I$ is the magnetic inclination angle, $r$ is the ratio of the ion-neutral collision frequency to the ion gyro-frequency, and $V$ and $U$ are components of the zonal and meridional neutral winds, respectively.

The necessary condition for sporadic E layer formation is $\frac{dw_i}{dz} < 0$, which means a negative zonal wind shear or a positive meridional shear in the Northern Hemisphere. As pointed out in previous studies (Haldoupis, 2012), the effects of meridional wind shear on vertical ion motion become minimal below 115 km due to the large $r$ values. In addition, in low-latitude regions, the inclination angle is also small, which leads to much weaker meridional wind shear effects. Therefore, the second term of Equation 2 can be neglected, and only zonal wind is taken into consideration in the following analysis.

First, the distributions of $\frac{r \cos I}{1 + r^2}$ at 100 km, which is called the ion drift factor in this study, are presented in Figure 6 to investigate its effect on the studied phenomenon. The ion drift factor of Fe+ ions is simulated with a 5° × 5° × 1 h (latitude, longitude and time) resolution by using the MSIS-00 model and IGRF-12 geomagnetic field model (the details are the same as those presented in Chu et al. [2014]). It should be noted that the Fe+ is not the only ion species that contribute to the sporadic E layer formation. Other metal ions such as the sodium ions may be also related to the sporadic E layer. Its ion drift factor is also different with the Fe+ ions which will be discussed in the future investigations.

The results show that the ion drift factor presents almost the same distribution in different seasons (here, only spring in the Northern Hemisphere is presented). This result indicates that the ion drift factor cannot explain the seasonal dependency of the studied phenomenon. In addition, the difference in the ion drift factor between the Southern and Northern Hemisphere low-magnetic-latitude regions is in disagreement with the longitudinal features of the $A_R$ index. For example, the ion drift factor in the Southern Hemisphere is smaller than that in the Northern Hemisphere between 130°W and 140°E, with a minimum at ~30°W.

Figure 6. Distributions of the ion drift factor at 100 km for spring in the Northern Hemisphere (March to May). From top to bottom, the four red dashed lines indicate the magnetic latitudes of 15°, 5°, -5°, and -15°.
In general, the distribution of the ion drift factor shows obvious inconsistencies, compared with the longitudinal dependencies of $A_R$ index. However, this does not mean that the ion drift factor is not one of the key factors that controls the formation of sporadic E layers. In fact, the ion drift factor does not show an obvious contribution to this phenomenon because the magnetic latitude is used during the calculation. As seen from Figure 6, ion drift factor is more symmetrical along the magnetic equator than the geographic equator. Thus, differences in ion drift factor between the two hemispheres may be eliminated by using the magnetic latitude.

Second, the hourly zonal wind component is simulated with a spatial resolution of 5° latitude x 5° longitude x 1 km in the altitude range of 95–115 km (the same range as that used in Chu et al. [2014]) by using HWM07. The difference in negative zonal wind shear between two hemispheres, $A_W$, is defined as Equation 3, as follows:

$$A_W = W_s - W_n$$

where $W_s$ and $W_n$ are the occurrence ratios of negative zonal wind shear in the Southern and Northern Hemisphere low-magnetic-latitude regions, respectively. For a specific grid and altitude, wind shear is calculated by using the formula $V(i+1) - V(i)$, where $V(i)$ is the zonal wind velocity obtained from HWM07 and $i$ and $i+1$ are adjacent altitudes. $W_s$ and $W_n$ are defined as the ratio of the occurrence number of negative zonal wind shear and the total number in the Southern and Northern Hemispheres, respectively. It should be noted that $W_s$ was also shifted 6 months later.

The seasonal dependency of the mean $A_W$ index in the altitude range of 99–115 km is shown in Figure 7. The $A_W$ index in the altitude range of 95–98 km is not shown because it seems to have no obvious relation with the $A_R$ index distribution. Chu et al. (2014) noted that the occurrence of sporadic E layers at low latitudes generally coincides with neutral wind shear zones below 100 km. Our result differs from that conclusion because here, the occurrence ratio of negative zonal wind shear is used for the analysis.

The $A_W$ index distribution shows good agreement with the $A_R$ index in the longitude-month cross-section, including the longitudinal variation and annual variation over the 30°W-180°E longitudinal sector. Even good agreement is found for longitudinal dependency, but differences still exist, which indicates that the difference in zonal vertical wind shear between the two hemispheres may not be the only reason for this phenomenon. For example, this $A_W$ index distribution cannot explain the seasonal variation in $A_R$ in the region between 150°W and 30°W. The $A_R$ indices show negative values in winter and positive maximum
centers in summer, which was not found in the $A_p$ index distribution. Similar disagreement between wind shear and sporadic E layer occurrence ratio was also found in the mid-latitude region (Qiu et al., 2019).

The LT dependency of the $A_p$ index is shown in Figure 8. Basically, the distribution features of the $A_p$ index are in good agreement with the $A_r$ index, including the diurnal and semidiurnal variations in summer and winter, respectively. Two main disagreements are also found. (1) Minor $A_p$ indices are found at night (00:00–06:00) rather than during the afternoon in summer. (2) Although semidiurnal variation is also found in the $A_p$ indices in winter, the amplitude of the midnight peak is larger than that of the afternoon peak. In general, it seems that the difference in the negative zonal wind shear between the two hemispheres is very prominent around midnight, but this is not reflected in the sporadic E layer occurrence ratio.

In addition to wind shear, metal ions are extremely important in the sporadic E layer formation process and may be responsible for these disagreements. Chu et al. (2014) presented the monthly global distributions of Fe+ concentrations (Figure 12). Even though the difference in Fe+ concentrations between the two hemispheres is not analyzed, an extremely weak Fe+ concentration center is still easily found at $\sim 60^\circ$W during winter in the Southern Hemisphere. A similar weak center is not found during the Northern Hemisphere winter in the same longitudinal sector. This partially explains the lower sporadic E layer occurrence ratio found in the Southern Hemisphere than that in the Northern Hemisphere and validates the previous assumption.

It should be kept in mind that multiple formation mechanisms, such as electric fields, contribute to sporadic E layer formation, except for the wind shear mechanism in low-latitude regions. Hocke and Tsuda (2001) also reported four enhanced electron density fluctuation regions and showed a close relationship with gravity wave activity. Their contribution should be investigated in future research.

6. Conclusions

In this study, the difference in the sporadic E layer occurrence ratio between two regions of low magnetic latitude ($\pm 5^\circ$ to $\pm 15^\circ$) is analyzed by using COSMIC scintillation observations covering the period from 2007.001 to 2017.365. The difference in the sporadic E layer occurrence ratio between the two hemispheres is defined as $A_r$, and obvious longitudinal, seasonal, LT and solar activity dependencies of this phenomenon are analyzed.
(1) Two distinct longitudinal areas are found in this study: 180°W-30°W and 30°W-180°E. The seasonal dependency of the \( A_k \) index shows different features over these two longitudinal regions.

(2) Annual variation in the \( A_k \) index is also identified. Difference in the sporadic E layer occurrence ratio between two hemispheres is most prominent in summer for both longitudinal regions. For the longitudinal region between 30°W and 180°W, the occurrence ratio in the Southern Hemisphere is higher than that in the Northern Hemisphere in summer and lower in winter. Over other longitudinal regions, this variation is reversed.

(3) Obvious diurnal variation is found in summer, and semidiurnal variation is also found in winter. In addition, neither diurnal nor semidiurnal variations are prominent in spring or autumn.

By using the MSIS, IGRF and HWM07 models, the ion drift factor and zonal wind shear are briefly discussed to explain the observed \( A_k \) index features based on wind shear theory. The longitudinal, seasonal and LT dependencies of \( A_k \) index could be partly explained by the difference in vertical wind shear between the two hemispheres.

Nevertheless, there are still some questions that need to be answered in future research, such as several discrepancies in the LT variation and seasonal variation, which may be related to metal ion concentrations. Quantitative analysis based on wind shear theory will be carried out in future research to identify the roles of these factors.

**Data Availability Statement**

The COSMIC data analysis and archive center of the University Corporation of Atmospheric Research (http://cdaac-www.cosmic.ucar.edu/) are greatly thanked for the provision of the RO scintillation data.

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