Persistent longitudinal features in the low-latitude ionosphere


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Various longitudinal wave patterns exist in the low-latitude ionosphere, but the investigation has been limited to the wave number (WN) 3 and 4 patterns. This study extends the investigation to the wave patterns that have not yet been explored. The persistent ionospheric wave patterns are investigated by using the measurements of the ion density during March 1999–June 2004 by the first Republic of China satellite. The investigation is performed with data sets in the magnetic south (20°S–0°) and magnetic north (0°–20°N). The dominant wave features in plasma density are the WN1, WN2, WN3, and WN4 patterns. Among them, the WN1 pattern in the magnetic south during the June solstice is the most pronounced feature. Except for this component, the WN3 pattern is the most persistent and pronounced feature. Fundamental difference exists between the WN1 and WN2 patterns and the WN3 and WN4 patterns. First, the wave phases in the south and north are the same in the WN3 and WN4 patterns, but they are opposite in the WN1 and WN2 patterns. Second, the amplitudes of the WN3 and WN4 patterns show similar annual variation in the south and north, but those of the WN1 and WN2 patterns show opposite annual trends in the opposite hemispheres. These observations indicate that the WN1 and WN2 patterns and the WN3 and WN4 patterns are created by different mechanisms. We discuss the creation of the WN1 and WN2 patterns in association with the geomagnetic field configuration.


1. Introduction

When the plasma distribution in the low-latitude F region is viewed at a fixed local time, different wave patterns appear in different seasons. The most striking wave patterns are the wave number 4 (WN4) and wave number 3 (WN3) patterns [Kil and Paxton, 2011, and references therein]. The WN4 pattern has been investigated extensively by using various observations. The common characteristics of the WN4 pattern are (1) the occurrence of the amplitude maximum during July–September and the amplitude minimum during the December solstice and (2) the eastward phase shift close to a rate of 90° per 24 h local time (LT) [Ren et al., 2009; Kil et al., 2008, 2010; Lühr et al., 2008; Fang et al., 2009; Kil et al., 2008; Scherliess et al., 2008; Wan et al., 2008]. These characteristics support that the creation of the WN4 pattern is associated with the diurnal eastward-propagating nonmigrating WN3 tide (DE3). DE3 winds modulate the E-region dynamo electric field; the E-region dynamo electric field modulates the vertical plasma drift in the F region; and the longitudinal modulation of the vertical plasma drift creates the WN4 pattern in the F-region plasma density [England et al., 2006; Immel et al., 2006; Jin et al., 2008; Kil et al., 2007]. This mechanism is supported by the observations of a good correlation between the WN4 patterns in plasma density and the vertical plasma drift [Kil et al., 2007, 2008, 2011]. Model simulations further verified the linkage between DE3, vertical plasma drift, and WN4 pattern in plasma density [Fang et al., 2009; Hagan et al., 2007; Oh et al., 2008; Ren et al., 2009, 2010].

The WN3 pattern is also a persistent feature in the ionosphere. The WN3 pattern is apparent only during the months near the December solstice, although the WN3 pattern is a pronounced feature in all months. This is because the WN3 pattern is hidden under the superposition of the WN3 and WN4 patterns during the months when the WN4 pattern is pronounced [Kil et al., 2011]. Similar to the creation of the WN4 pattern, the creation of the WN3 pattern in plasma density is explained by the longitudinal modulation of the E-region dynamo electric field [Kil et al., 2010]. The diurnal eastward-propagating nonmigrating wave number 2 tide (DE2) is suggested as the source of the WN3 pattern in the E-region dynamo electric field [England et al., 2009;
3. Results and Discussion

To identify the primary longitudinal wave features in the ionosphere, we have calculated the percentage wave amplitudes using the data in three magnetic latitude intervals: 20°S–0° (south), 0°–20°N (north), and 20°S–20°N (average) for the 32 data sets. The percentage wave amplitude is obtained by applying a Fourier analysis to the data divided by the longitudinal average density. Throughout this study, we use the percentage wave components. The LT interval was chosen between 1200 and 1600 LT. Figure 1 presents the percentage amplitudes (solid dots) and standard deviations (vertical bars). The amplitudes of the high wave number components ($\geq 5$) are small (<4%). Because those components are considered minor features in the ionosphere, our investigation of the persistency of the wave components is limited to the WN1–WN4 components. The WN1 component in the magnetic south has the largest amplitude. The large standard deviation of this component is related to the large seasonal variation of this component (see Figure 3). Except for this WN1 component, the WN3 amplitude is the largest.

In Figure 2, we examine the recurrence of the (a) WN1, (b) WN2, (c) WN3, and (d) WN4 components during the 32 periods. The wave components in the south and north are shown by red and blue colors, respectively. In the plots, the observation month and year are not distinguished. The thick black curve in Figure 2a denotes the geographic latitude of the magnetic equator. For the WN1 component, the WN1 amplitude in the south is much greater than that in the north, as is shown in Figure 1. In a comparison of the southern WN1 component with the magnetic equator location, we can identify the creation of the crest and trough of the WN1 component in the longitude regions where the magnetic equator is located in the geographic north and south, respectively. This tendency appears to be reversed in the northern WN1 component. The opposite phases between the southern and northern components also appear in the WN2 component. In Figure 1, the WN2 amplitude obtained from the average data in the magnetic south and north (black dots) is smaller than the amplitudes obtained from the data in each hemisphere (blue and red dots). This behavior is related to the opposite phases of the WN2 components in the opposite hemispheres. The wave components in the opposite hemispheres do not show any notable difference in the WN3 and WN4 components. Among the four wave components,

2. Data Description

ROCSAT-1 was launched on 27 January 1999 into a circular orbit at an altitude of 600 km. Its orbital inclination was 35° and the orbital period was 97 min. The Ionospheric Plasma and Electrodynamics Instrument onboard ROCSAT-1 [Yeh et al., 1999] made the measurements of the ion density and ion velocity from March 1999 to June 2004. For this study, we processed the ROCSAT-1 data at the times of low and moderate levels of the Earth’s magnetic field disturbance ($Kp$ index $\leq 3$). The persistency of wave patterns is investigated by using the data between 1200 and 1600 LT. This time interval was chosen because the longitudinal modulation in plasma density is most pronounced in the afternoon [e.g., Kil et al., 2008]. The wave components in plasma density were extracted by applying a Fourier analysis to the average density in the magnetic south (20°S–0°) and magnetic north (0°–20°N). The observation data are divided into six periods (January–February, March–April, May–June, July–August, September–October, and November–December) of each year. Because the ROCSAT-1 data are available during March 1999–June 2004 (64 months), the wave components were extracted from 32 data sets.

Figure 1. The percentage wave amplitude distribution. The wave amplitudes are calculated by using the ROCSAT-1 ion density data between 1200 and 1600 LT in the magnetic latitude interval 20°S–0° (red dots), 0°–20°N (blue dots), and 20°S–20°N (black dots). The average amplitudes (solid dots) and standard deviations (vertical bars) are obtained from the 32 period data sets described in the text.

Pedatella et al., 2008], but Kil et al. [2010, 2011] argued that the DE2 characteristics do not appear in the WN3 patterns in the vertical plasma drift and plasma density. The source of the WN3 pattern is still an open question.

A significant portion of the longitudinal plasma distribution is described by the WN3 and WN4 patterns, but other wave features also exist in the ionosphere. Not much attention has been paid to the wave number 1 (WN1) and wave number 2 (WN2) patterns. Those low wave number patterns are not easily perceived when they co-exist with the WN3 and WN4 patterns. The characteristics and sources of the WN1 and WN2 patterns have not yet been investigated.

In this study, we determine which wave patterns are persistent and dominant features in the ionosphere by examining the measurements of the ion density during March 1999–June 2004 by the first Republic of China satellite (ROCSAT-1). A typical method to investigate the wave characteristics in the ionosphere is to extract the wave amplitude and phase by applying a Fourier analysis. However, the wave components extracted by this method are mathematical outputs. Only the wave components whose characteristics repeatedly occur would be considered persistent and physically meaningful features in the ionosphere. Because the characteristics of the WN3 and WN4 patterns have been reported by many studies, the main interest of this study is to understand the characteristics and source of the WN1 and WN2 patterns.
the WN3 component shows the most consistent phase during the 32 periods. The WN4 component also shows a consistent phase during the periods when the WN4 amplitude is large. During the periods when the WN4 amplitude is small, however, the phase of the WN4 component is not consistent. The WN1 and WN2 components show opposite phases in the opposite hemispheres, but those components are consistent in each hemisphere.

The fundamental difference between the WN3 and WN4 components and the WN1 and WN2 components is the phase of the southern and northern wave components. They are in-phase in the WN3 and WN4 components and opposite phase in the WN1 and WN2 components. This result provides insight into the source of the ionospheric wave patterns. The creation of the opposite wave patterns in the opposite hemispheres is not explained by the effect of the vertical plasma drift (or dynamo electric fields). Thus WN1 and WN2 patterns are created by a mechanism that is different from the creation mechanism (i.e., dynamo electric fields) of the WN3 and WN4 patterns.

The annual and yearly variations of the percentage wave amplitudes are shown in Figure 3. The results obtained with the data sets in the north and south are presented in Figures 3a–3d and Figures 3e–3h, respectively. Note the use of different amplitude scale in the WN1 component. In general, repeatable annual patterns exist in all wave components.

Figure 2. Persistency test of the (a) WN1, (b) WN2, (c) WN3, and (d) WN4 components. The wave components in the magnetic south (red) and north (blue) are obtained from the 32 data sets. The geographic latitude of the magnetic equator is shown with a thick black curve in Figure 2a.

Figure 3. The annual and yearly variations of the percentage wave amplitude. (a–d) Wave components in the magnetic north. (e–h) Wave components in the magnetic south.
Figure 4. Comparison of the longitudinal plasma distribution and the magnetic equator location. The red curves show the average plasma density \( (N) \) normalized by the longitudinal mean density \( (N_0) \) in the magnetic south (20°S–0°) during June–July of each year. The magnetic equator location is denoted with a black dashed curve.

The absence of an increasing or decreasing trend of the wave amplitude as a function of year may indicate that the wave amplitude does not depend on the solar cycle. The WN1 component in the south shows a clear annual variation; the amplitude maximum occurs during the June solstice and the amplitude minimum occurs during the December solstice. This annual trend appears to be reversed in the north. The annual variation of the WN2 amplitude is small. A minor tendency that we can identify in the WN2 component is the greater amplitude during the spring equinox than during the fall equinox in the south and the reversal of this tendency in the north. For the WN3 component, the amplitude during solstices is greater than that during equinoxes. The amplitude of the WN4 component shows a clear annual variation; the maximum amplitude occurs during July–August and the minimum amplitude occurs near the December solstice. The correlated annual variation of the wave amplitudes in the southern and northern data in the WN3 and WN4 components is contrasted to their anti-correlated variation in the WN1 and WN2 components.

[11] The WN1 component in the magnetic south during the June solstice is the most pronounced feature in the ionosphere. We interpret this phenomenon in association with the geomagnetic field configuration. The red curves in Figure 4 show the average plasma density in the magnetic south (20°S–0°) acquired during June–July. The plasma density of each year is normalized by the longitudinal average density. The geographic latitude of the magnetic equator is shown with a black dashed curve. Ignoring the high-frequency wave features, the longitudinal variation of the plasma density shows a good correlation with the location of the magnetic equator. Creation of the large WN1 amplitude during the June solstice is related to the low plasma density in the longitude near 300°E, where the magnetic equator is located farthest distance from the geographic equator. The solar zenith angle at the magnetic equator is the largest near 300°E during the June solstice. Thus the low photoionization rate near 300°E during the June solstice is presumably the primary cause of the WN1 feature. Photoionization rate is proportional \( \exp (-K / \cos \mu) \). Here \( K \) is a variable expressed by the optical depth, scale height, and height, and \( \mu \) is the solar zenith angle. The variation of the photoionization rate is greater for large solar zenith angles than for small solar zenith angles because of the \( \cos \mu \) term. Therefore, the magnitude of the solar zenith angle as well as its longitudinal difference causes the seasonal and hemispheric difference of the WN1 component amplitude. Neutral winds and neutral composition at the same magnetic latitude vary with longitude in association with the geomagnetic field configuration. These factors would also cause a large-scale longitudinal asymmetry in plasma density.

[12] The WN1 feature is associated with a longitudinally asymmetric plasma distribution. Although the clarification of the source of the large-scale longitudinal asymmetry in plasma density requires further investigation by model simulations, creation of the WN1 feature in the ionosphere might be predictable by the reasons described above. However, the source of the WN2 feature is clueless. The WN2 component and the location of the geomagnetic equator do not seem to show any correlation. The observation of the opposite phases between the southern and northern WN2 components rules out the possibility that the tidal modulation of the E-region dynamo electric fields is the source. We deduce the possible connection of the WN1 and WN2 components from their similar behavior: the opposite phases of the longitudinal wave patterns and the opposite annual patterns of the wave amplitudes in the opposite hemispheres.

[13] To test the connection between the WN1 and WN2 components, we examine the wave components embedded on a schematic model ionosphere that resembles the plasma distribution shown in Figure 4 (ignoring the high-frequency features). The model ionosphere in Figure 5a is produced with a half sine curve to represent the low plasma density in the longitude 180°E–360°. The wave components extracted...
from the model ionosphere are shown in Figure 5b. As expected, the WN1 component has the largest amplitude. The WN2 amplitude is the second largest and is about 40% of the WN1 amplitude. The WN4 amplitude is about 10% of the WN1 amplitude. The WN3 amplitude is zero. The WN1 and WN2 components obtained from the simple model ionosphere are similar to those obtained from the magnetic south data in Figures 2a and 2b (red curves). This comparison provides insight into the source of the WN2 component. The large-scale longitudinal asymmetry in plasma density might be the source of the WN2 component as well as the WN1 component. In the southern hemisphere during the June solstice, the WN2 component may be considered a subordinate feature of the WN1 component. However, the WN2 amplitude is not proportional to the WN1 amplitude. In Figure 2, the WN2 amplitude in the north is comparable to that in the south, although the WN1 component in the north is much smaller than that in the south. In this case, the WN2 component is not a subordinate feature of the WN1 component. The relative amplitude of the WN1 and WN2 component depends on the morphology of the large-scale longitudinal asymmetry. The reduction of the longitude range of the density drop in the schematic model ionosphere causes the increase of the WN2 amplitude. The seasonal and hemispheric variations of the WN1 and WN2 amplitudes shown in Figure 3 further demonstrate that the WN2 amplitude is not proportional to the WN1 amplitude. We note that our result partially explains the creation of the WN2 component in association with the WN1 component. The longitudinal and hemispheric asymmetries of the plasma density induced by other factors such as the magnetic declination would also affect the WN2 amplitude.

[14] The WN4 amplitude is nonzero in Figure 5b, although the schematic model ionosphere does not have the WN4 feature. This result indicates that some wave components with small amplitude in observation data are not real features. During the December solstice, the WN4 component in plasma density has a small amplitude and the phase of the WN4 component is variable year to year. The eastward phase shift at a rate of $90^\circ/24$ h LT did not appear in the WN4 component during the December solstice [Fang et al., 2009; Kil et al., 2011; Wan et al., 2008]. Thus the WN4 components identified during the December solstice may not be the physically meaningful features created by the effect of DE3.

4. Conclusions

[15] We have investigated the persistency of the longitudinal wave features in the low-latitude ionosphere by using the plasma density data during March 1999–June 2004 provided by ROCSAT-1. Our results show that the longitudinal plasma distribution in the low-latitude $F$ region can be described primarily by the wave number 1–4 patterns. Among them, the WN3 pattern shows the most persistent behavior with significant amplitude in all months.

[16] Fundamental difference exists between the WN1 and WN2 components and the WN3 and WN4 components. The wave components in the magnetic southern and northern hemispheres are in-phase in the WN3 and WN4 components, but they are opposite phases in the WN1 and WN2 components. The annual patterns of the wave amplitude in the magnetic south and north are similar in the WN3 and WN4 components, but those show opposite trends in the WN1 and WN2 components. These results indicate that the WN1 and WN2 components are created by a mechanism that is different from the creation mechanism of the WN3 and WN4 components. In other words, the WN1 and WN2 components are not created by the modulation of the $E$-region dynamo electric field. The creation of the WN1 component might be explained by the longitudinal variation of the solar zenith angle at the magnetic equatorial region, neutral winds, and neutral composition in association with the magnetic field configuration. The large-scale longitudinal asymmetry also produces the WN2 component. It would be adequate to understand the WN1 and WN2 components as longitudinal asymmetry features rather than as wave features.


