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A detailed investigation of low latitude tweek atmospherics observed by the WHU ELF/VLF receiver: 2. Occurrence features and associated ionospheric parameters

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Key Points:

- Detailed analysis of low-latitude tweek events in February 2016 reveals that the occurrence rate varies considerably — from 800 to 6000 tweeks per day
- The majority (~ 92%) of the low latitude tweeks originate from the lightning activity within a radius of 4000 km
- The tweek reflection height varies mainly between 70 and 88 km

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Abstract: As a companion paper to Zhou RX et al. (2020), this study describes application of the automatic detection and analysis module to identify all the tweek atmospherics detectible in the WHU ELF/VLF receiver data collected at Suizhou station during the period of 3 February through 29 February 2016. Detailed analysis of the identified low-latitude tweek events reveals that the occurrence rate varies considerably — from 800 to 6000 tweeks per day, and exhibits a strong diurnal and local time dependence, the peak occurring before local midnight. The diurnal variation of identified tweeks was similar to that of the lightning data obtained by the World-Wide Lightning Location Network (WWLLN).. Estimates of the propagation distance and ionospheric reflection height of tweek atmospherics suggest that the majority (~92%) of the low latitude tweeks originate from the lightning activity within a radius of 4000 km and that they are very likely to reflect from the lower ionospheric D-region at the height range of 75–85 km. At these lower ionospheric reflection altitudes, ~74% of the corresponding electron densities from the tweek spectral measurements are within 24.5–27.5 cm^{-3}. The daily variation of estimated D-region electron densities in the considered period (February 2016) also exhibits a small overall increasing trend from early to later in the month.

Keywords: ionospheric D-region; electron density; tweek atmospherics

1. Introduction

As a kind of dispersive electromagnetic phenomenon naturally propagating in space between the Earth and the lower ionosphere, tweek atmospherics are produced by lightning strikes that may be many thousands of kilometers away (Helliwell, 1965). Hence, analyses of tweek atmospherics provide a useful means to monitor the lower ionospheric D region.

Based on waveguide mode theory, Outsu (1960) investigated the relation between propagation time and frequency characteristics of tweeks and proposed a graphical procedure to determine propagation distance. Kumar et al. (1994) studied the propagation of tweek atmospherics in the Earth-Ionosphere Wave Guide (EIWG) and provided preliminary results showing that in India the height of EIWG varies between 83 and 89 km. To estimate the distances of lightning strikes, Hepburn (1959) assumed that the smooth oscillatory waveform was quasi-periodic and proposed an equation to reveal the relation between a strike distance, lower ionosphere height h, and their delay times, which was further simplified by Ramachandran et al. (2007) to evaluate the statistics of lightning strike distances for validation with WWLLN data. Utilizing the tweeks recorded in Fiji, Kumar et al. (2008, 2009) studied the propagation features and reflection heights of tweek atmospherics, showing that 90% of tweeks propagate for distances ranging from 1000 to 5000 km with reflection heights range from 83 to 92 km. Ohya et al. (2008) presented an automated procedure to estimate the reflection height, the horizontal propagation distance, and the propagation time of tweek atmospherics recorded in Japan. Their following study (Ohya et al., 2011) further reported that the average reflection height of tweeks in Japan is 95.9 km

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with standard deviation of 3.1 km.

A number of interesting studies have also been performed to explore the potential effect of total solar eclipse on occurrence of tweek atmospherics. Ohya et al. (2012) found that during solar eclipse events, the appearance of tweeks indicated a decrease in the electron density in the D- and lower E regions. Singh et al. (2011) proposed that partial obscuration of the solar disc can lead to daytime occurrence of tweeks. Yusop et al. (2013) presented the nighttime D-region ionosphere characteristics of tweek atmospherics recorded in North America. They reported that the equivalent electron densities associated with observed tweeks vary between 23 and 27 cm^{-3} at the D-region altitudes of 77 to 91 km. Maurya et al. (2010) also found that the reflection height associated with the tweeks recorded at the Allahabad station varies between ~80 and 90 km and that the electron density varies within the range of ~20 to 25 el/cm^3. Their following study (Maurya et al., 2012a) further investigated the seasonal dependence of tweek atmospherics, finding that ~63% of the tweeks occur during the summer season, ~18% during the winter season, and ~19% during the spring equinox.

Yi et al. (2019) proposed the importance of electron density of the lower ionosphere to the VLF signal propagation properties. Apparently, measurements of tweek atmospherics are important to monitor the electron density and the ionospheric D-region locally. However, there is very limited information about the tweek features at low latitudes over central China. Therefore, the present study uses a one-month data set from the WHU ELF/VLF receiver at Suizhou station (GLAT 31.75°N, GLON 113.32°E) tolook at tweek occurrence features and associated ionospheric parameters.

2. Instrumentation and Data

The WHU ELF/VLF receiver is designed and developed for sensitive reception of low-latitude broadband ELF and VLF radio waves (Chen YP et al., 2016). This system consists of a magnetic loop antenna, low-noise analog front-end, digital receiver and transmission, and time keeping and synchronization. To meet the requirements of low frequency and high sensitivity, an isosceles right triangle B-field loop antenna is selected as the signal receiver, with turns = 7, wire diameter = 1.4 mm, area = 7.29 m^2, and height = 2.7 m. Two orthogonal magnetic loop antennas are aligned in the north-south (N-S) and east-west (E-W) directions to collect broadband wave data continuously and separately. The impedance of the low-noise analog front-end is designed to match the antennas so that received signals can get better amplification with the preamplifier. To receive data of our interest, a band-pass filter with a bandwidth from 1 kHz to 50 kHz is designed to filter out interference from other frequencies. This receiver system uses a 16-bit A/D converter chip with throughput of 250 kSPS (kilo samples per second).

In the present study we adopt the WHU ELF/VLF receiver data at Suizhou station for comprehensive investigation because it holds an ideally clean electromagnetic environment to provide high quality measurements for our research purpose. We focus on the 27-day period from 3 February to 29 February 2016. Due to the orthogonal configuration of the two magnetic loop antennas, we further choose the spectrogram data of the E-W channel for our analysis. Based on the automatic detection and analysis module developed by Zhou RX et al. (2020), only tweeks whose intensity is a minimum of 20 dBFS above averaged background noise are identified.

3. Analysis Results

3.1 Occurrence Features of Low-latitude Tweeks

Our ELF/VLF receiver operates routinely and continuously to measure tweeks at both daytime and nighttime; all the data are recorded and stored. Figure 1 displays the variation of tweek events within one day, i.e., 12 February, and each data point represents the occurrence rate (tweeks per hour); the time of local sunrise and sunset is marked. We notice that the occurrence rate of daytime tweeks is much less than that of nighttime tweeks, because the attenuation for daytime is greater than for nighttime. Ohya et al. (2015) proposed that the typical attenuation for daytime is in excess of −70 dB/MM (dB per Megameter), compared to −3 dB/MM for nighttime. As a consequence, in this study we concentrate on the analysis of nighttime tweeks.

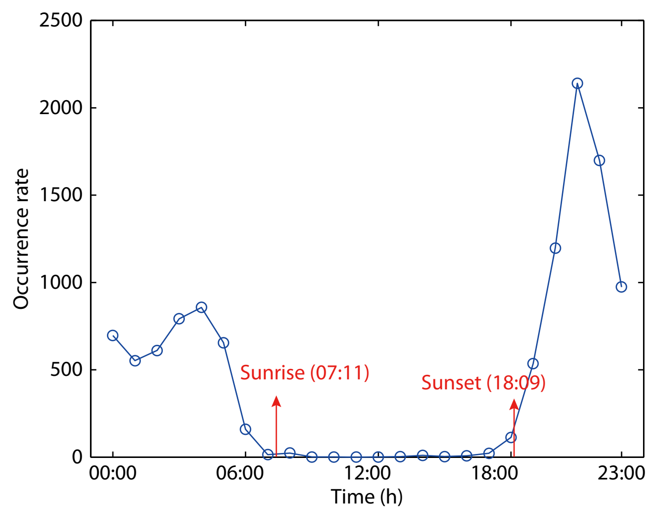

Figure 1. Hourly variations of the occurrence rate of identified tweeks at Suizhou station on 12 February 2016.

Kumar et al. (2008) and Maurya et al. (2012a) have studied the occurrence of tweeks and conclude that the tweek rate peaks at midnight. To further verify the result, Figure 2 illustrates the occurrence rate of tweek events per hour automatically identified at Suizhou station between 18 and 06 LT for three days in February 2016. In Figure 2, the blue, red, and black lines denote the occurrence rates of tweeks from 18 LT on 3 February to 06 LT on 4 February, from 18 LT on 11 February to 06 LT on 12 February, and from 18 LT on 12 February to 06 LT on 13 February, respectively. For the blue line, the rate increases rapidly during 18 to 01 LT and then decreases at ~03 LT. While a similar trend takes place on 12 February (red line), the majority of the tweeks on 11 February (black line) are concentrated between 21 and 02 LT. It is evident that with an average occurrence rate of hundreds of times per hour, the low latitude tweeks are more likely to occur around midnight (i.e., 22–02 LT). This tendency is attributed mainly to the presence of much larger electron densities at daytime than nighttime, owing to solar radiation, that can result in enhanced attenuation of tweek emissions and thus strongly reduce the number detected at the receiver in daytime. In addition, the tweek signals received between 22 and 02 LT have the advantage of minimizing the emission mixture from daytime and nighttime propagation. Therefore, in the following analysis we concentrate on low latitude tweeks observed between 22 and 02 LT.

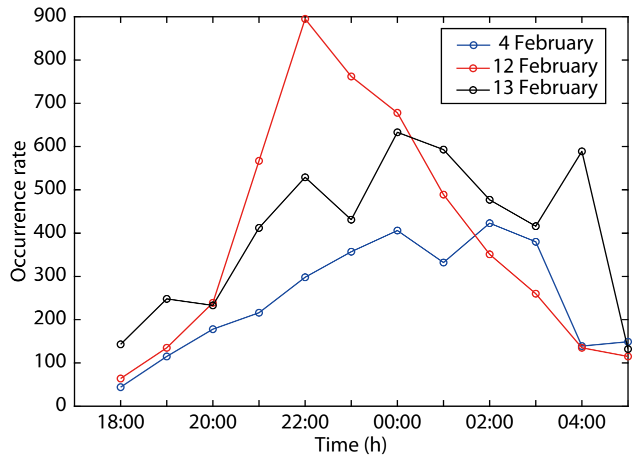

Figure 2. Temporal variations of occurrence rate of identified tweeks per hour at Suizhou station for three days in February 2016.

A total of 158471 tweeks were identified, in the the E-W channel wave data acquired by the WHU ELF/VLF receiver at Suizhou station, as having occurred in the interval of 22 to 02 LT during the period from 3 February to 29 February 2016. Of these, 50909 tweeks with clear dispersive traces were selected to establish a robust database for detailed investigation. About 87% of these tweeks exhibit unambiguous structures of the first and second modes (n = 1–2). In contrast, only 5% of the tweeks have higher modes (with n = 4–6).

Figure 3 displays the numbers of detected tweeks and lightning events from WWLLN for each day from 3 February to 29 February

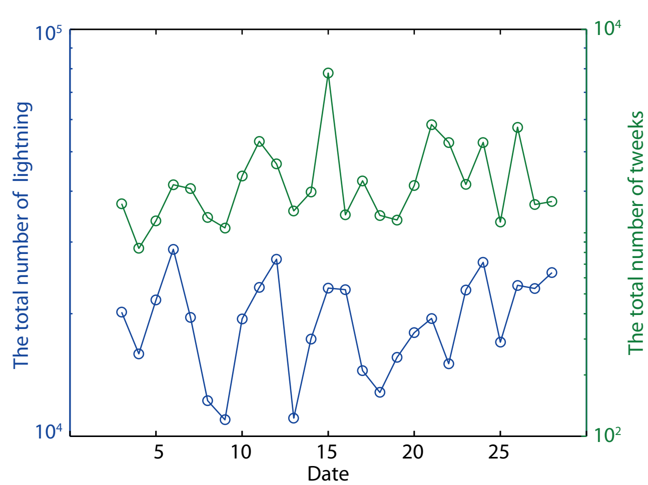

Figure 3. The numbers of identified tweeks (right, in green) at Suizhou station and of lightning events (left, in blue) from WWLLN for each day during the period from 3 February to 29 February 2016.

2016. Each point represents the total number of tweeks and WWLLN lightning events registered from 22 LT of the corresponding day to 02 LT of the next day. The tweek number maximizes at the midnight of 15 February, reaching a value of 6096, and minimizes at the midnight of 4 February, reaching a value of 838, which clearly manifests a significant degree of daily variation. The WWLLN data include only lightning events located within 8000 km of Suizhou, and only for which at least 5 detection stations are involved so that their locations can be known to an accuracy of 20 km or less. As can be seen from this figure, tweek numbers vary consistently with number of lightning events; the cross-correlation between them is 0.5033. The number of identified tweeks is highest on 15 February, corresponding well to the largest number of lightning events captured by WWLLN in February 2016. This strong correlation suggests that the enhanced lightning activity on February 15 was an important contributor to the peak tweek events observed on that same day, compared to other days in February 2016.

Ohya et al. (2015) also studied the occurrence rate of tweeks and reported about 15–35 tweeks per minute at nighttime and 0–5 during daytime. Agreement before midnight between our finding and theirs is good; after midnight, our results diverge to some degree. The possible reasons can be multifold: (1) our studies employeddifferent intensity thresholds in selecting unambiguous tweeks to be included in our analyses (refer to Zhou RX et al., 2020 for details); (2) multiple factorsaffect the propagation and detection of tweeks, including the location of receivers.

We then evaluate the low latitude tweek propagation distance from the lightning source. As described above in Zhou RX et al. (2020), there are two ways to calculate the propagation distance on the basis of fits to the dispersive power spectrum profiles. Theoretically and ideally, the results from the two methods should be identical, which however is unlikely in practice. By comparing the results of these two methods and excluding the data outliers, we improve the data reliability and finally decide to adopt, for subsequent investigation, the results obtained using the slope method.

Figure 4 shows the distribution of evaluated propagation distance for the 50909 low latitude tweeks clearly identified at Suizhou station; we observe that the propagation distances of tweek atmospherics are mainly within 1000–4000 km. In other words, these tweeks detected by our ELF/VLF receiver originate primarily from the lightning strikes that occur about 1000–4000 km away from Suizhou station: 9469 tweeks are traced to sources 2000–2500 km away; 9203 tweeks propagated from distances of 2500–3000 km. Only a very small number (363) of tweeks appeared to originate from distances above 6000 km, accounting for just 0.7% of the total. As electromagnetic emissions with duration usually between 10 ms and 100 ms, the low latitude tweeks with longer duration time correspond to larger propagation distances from the lightning source.

We compare the WWLLN lightning locations with the tweek propagation distances derived from our analysis of WHU ELF/VLF receiver data. In Figure 5, the occurrence times of tweeks are compared with WWLLN lightning locations, limited to those known to

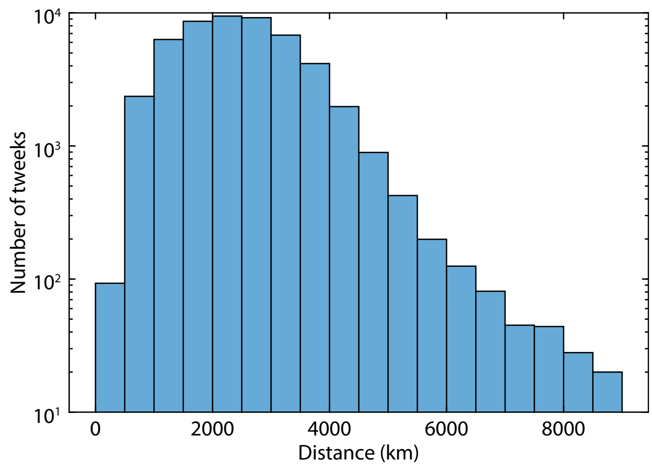

Figure 4. The number of low latitude tweeks detected at Suizhou station, as a function of propagation distance from lightning source.

within spatial accuracy of roughly 20 km or better. The red markers indicate the WWLLN lightning locations; the magenta circles indicate distances of 2000 km, 4000 km, 6000 km, and 8000 km from Suizhou. It is apparent that a large number of the propagation distances of observed tweeks are in the range of 3000–6000 km. Compared with our propagation distance results, shown in Figure 4, the WWLLN data include more lightning events with further distances from Suizhou (i.e., > 4000 km). The reasons can be many-fold. For instance, influenced by the equatorial anomaly, a low-latitude ELF/VLF receiver such as the one located at Suizhou may be more likely to record tweeks with smaller propagation distances (i.e., < 4000 km). In addition, since the global detection efficiency of WWLLN for strong strikes is approximately 30% (Hutchins et al., 2012; Abarca et al., 2010; Rodger et al., 2004), it is possible that our ELF/VLF receiver detects tweek signals produced by relatively weak strikes that occur relatively close to Suizhou station. Furthermore, we discuss the difference of low-latitude tweek features obtained in this study from the results reported in other local regions, e.g., Suva, Fiji (Kumar et al., 2008) and Gakona, Alaska (Yusop et al., 2013). The propagation distances are found to be mainly within 1000–5000 km for tweeks recorded at Suva and within 737–5689 km for tweeks recoded at Gakona, which are roughly consistent with results of tweek propagation distances at Suizhou produced by our model.

Figure 6a displays further, with the superposition of error bars, the variation of daily averaged tweek propagation distance as a function of time. Each specific time bin's error bar denotes the standard deviation of the propagation distance for that bin. Note that the present study focuses on the data for 22–02 LT; hence, four points of averaged propagation distance are considered each day. For average values between 2000–3000 km, the maximum tweek propagation distance error bar is 1417.2772 km at 00–01 LT on 12 February; the minimum is 794.9643 km at 01–02 LT on 11 February. Figure 6b presents the scatter plot of the low latitude tweek propagation distance as a function of local time (say, between 22–02 LT), it is shown that the propagation distances of most tweeks are less than 4000 km. The red curve of the mean value profile suggests that, on average, the tweek atmospherics observed by the WHU ELF/VLF receiver at Suizhou station originate from lightning activities ~2500 km away. Occasionally, received

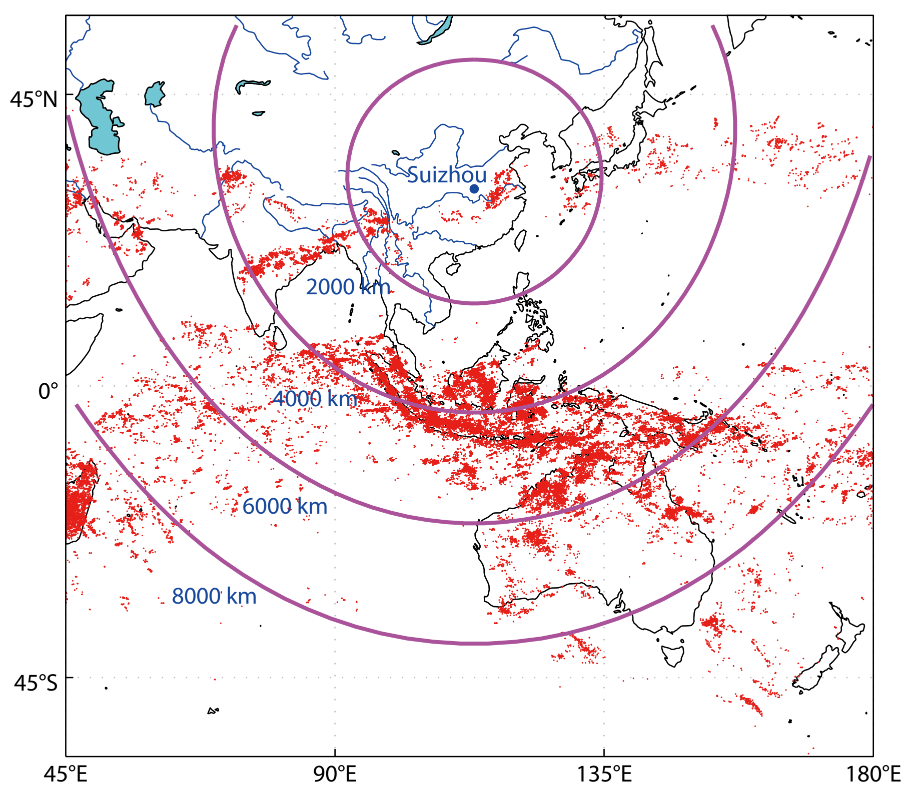

Figure 5. Lightning locations detected by WWLLN from 3 February to 29 February 2016 in the local time interval of 22–02 LT. Red markers indicate lightning locations; magenta circles indicate distances from Suizhou.

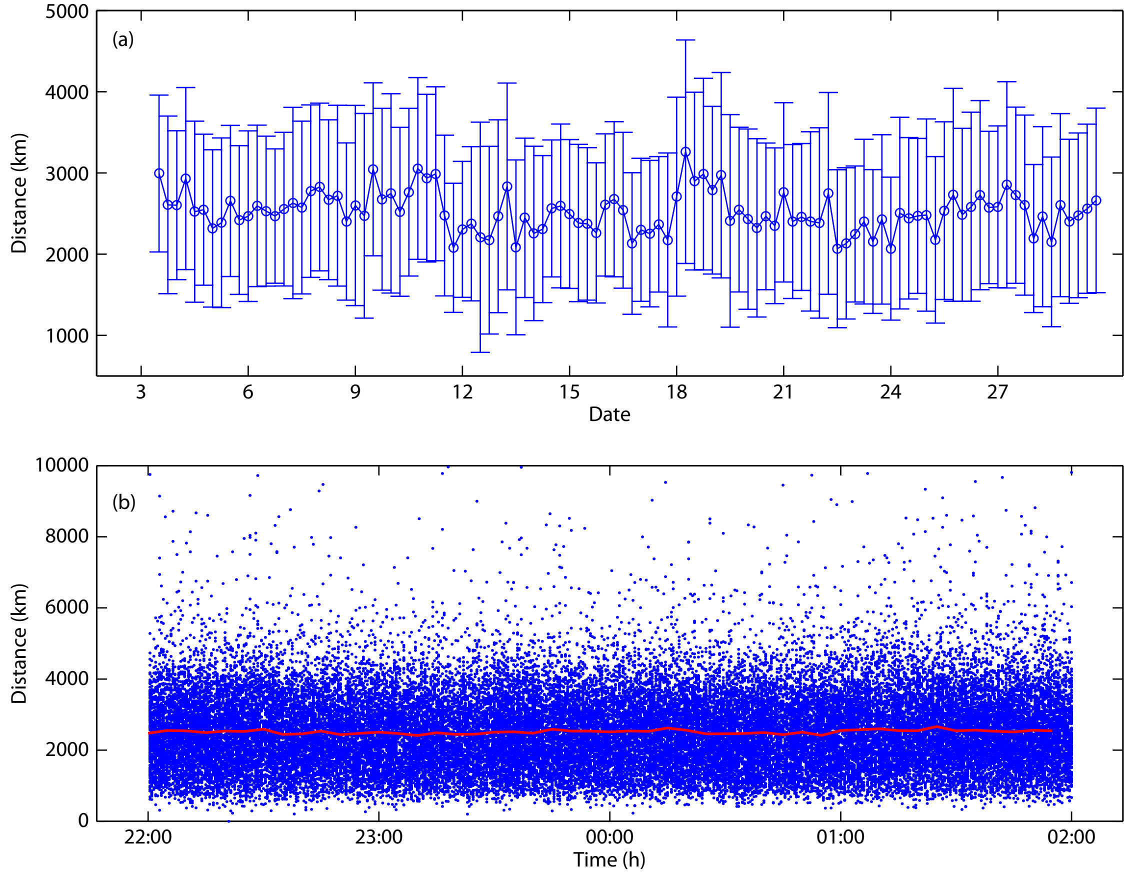

Figure 6. (a) Variation of daily averaged tweek propagation distance at Suizhou station as a function of time between 3–29 February 2016 with the superposition of error bars, and (b) corresponding scatter plot of the low latitude tweek propagation distance as a function of local time (say, between 22–02 LT).

tweek signals may result from a source as distant as approximately 10000 km. Overall, the propagation distances of the low latitude tweeks tend to exhibit insignificant dependence on local time.

3.2 Estimates of Associated Ionospheric D-region Parameters

The acquisition of characteristic cut-off frequencies of tweek atmospherics from ground-based ELF/VLF receiver measurements provides valuable information to estimate associated ionospheric parameters, in particular for the lower ionospheric D-region that cannot be monitored by conventional high-frequency sounding radars. The tweek cutoff frequency of the n^{th} mode, f_{cn}, is given by (Budden, 1961; Shariff et al., 2011; Yano et al., 1991)

$$f_{\text{cn}} = \frac{nc}{2h}, \tag{1}$$

where h is the tweek reflection height. The corresponding ionospheric electron density n_{e} at the reflection height h is subsequently estimated using the following equation (e.g., Chen YP et al., 2017; Maurya et al., 2012b; Ohya et al., 2003; Shvets and Hayakawa, 1998)

$$n_{\text{e}} = 1.39 \times 10^{-2} f_{\text{cn}} \left(\text{cm}^{-3}\right). \tag{2}$$

Although the reflection heights of tweeks are related to their incident angles to the ionosphere and the electron density gradient in the D region, for simplicity the present investigation adopts the cut-off frequencies of the first mode tweeks to evaluate the tweek reflection heights and associated D-region electron densities at Suizhou station during the period of 3–29 February 2016.

Figure 7a further shows the variation of daily averaged tweek reflection height as a function of time with the superposition of error bars. Each error bar denotes the standard deviation of the tweek reflection height for the specific time bin. The daily values average between 75–85 km; the maximum error bar for tweek reflection heights is 7.5 km, occuring at 00–01 LT on 12 February; the minimum is 3.0 km at 00–01 LT on 16 February. Overall, the variation of reflection heights shows a gradual decline from early February to late February, which may be related to seasonal variation (Maurya et al., 2012a). Figure 7b shows the overall local time variation of tweek reflection height from 3 to 29 February. Figure 6b presents the scatter plot of the low latitude tweek propagation distance as a function of local time (say, between 22–02 LT), indicating that the propagation distances of most tweeks are within 4000 km.

The reflection height of the tweeks studied by Shariff et al. (2011) is in the range of 73–87 km. Ohya et al. (2011) found the average reflection height of tweeks in Japan to be 95.9 km. Yusop et al. (2012) reported that the reflection height of tweeks recorded at

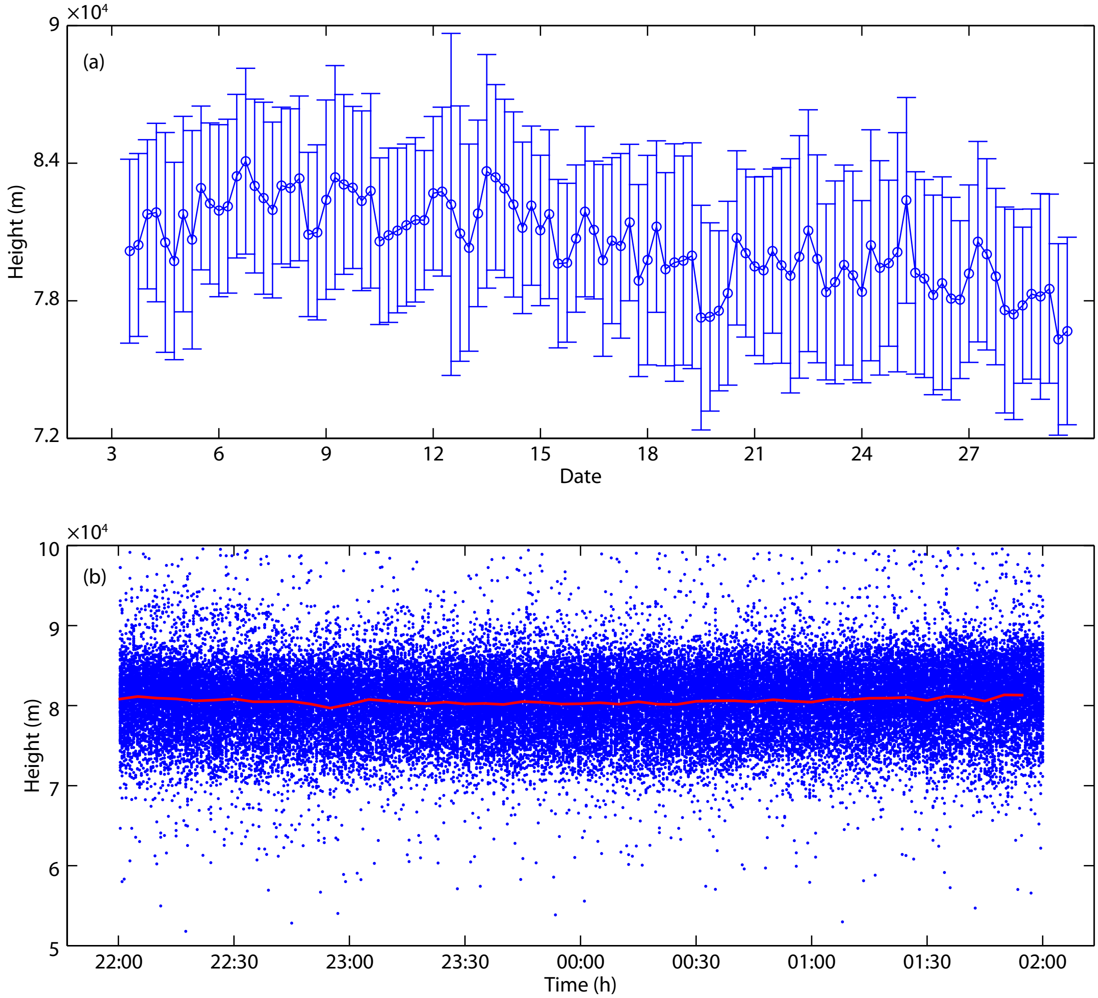

Figure 7. Corresponding to Figure 6, (a) variation of daily averaged tweek reflection height at Suizhou station as a function of time between 3–29 February 2016 with the superposition of error bars, and (b) scatter plot of the low latitude tweek reflection height as a function of local time (say, between 22–02 LT).

Gakona station varies between 77 km and 91 km. The comparison of reflection height between this and previous studies shows small differences, which may result from features of the different locations at which the data were collected.

Figure 8a shows the variation of daily averaged D-region electron density at the tweek reflection height as a function of time, with the superposition of error bars. The daily values average between ~24–27 cm^{-3}; the maximum error bar of estimated electron densities is 2.7 cm^{-3} at 01–02 LT on 12 February; the minimum is 1.0 cm^{-3} at 22–23 LT on 12 February. The D-region electron densities show a moderately increasing trend from early February to late February, contrary to that of the tweek reflection height. Figure 8b shows the overall local time variation of electron density at the D-region reflection height from 3 to 29 February. This scatter plot of D-region electron densities at the tweek reflection height as a function of time illustrates that the electron density of tweeks varies between 23–29 cm^{-3} and an average value ~26 cm^{-3}.

4. Discussion

This study analyzes tweeks recorded in a one-month period at the low-latitude station located at Suizhou in central China. It presents a number of important features of tweek propagation and the associated D-region ionosphere profile. As for a longer-time (e.g., monthly, seasonal and annual) analysis, it will be our future work to accumulate more datasets to investigate the statistical distribution features of low-latitude tweeks in central China and compare them with those in other regions.

The orthogonal configuration of the two magnetic loop antennas at the Suizhou station provides data that allow calculation of arrival directions. We are still developing the related analysis method. Therefore, for the sake of simplicity the present study utilizes only one channel (i.e., E-W) of data to establish the tweek database. We leave use of two-channel data to future work. In addition, evaluation of mixed day/night path tweeks would require a good understanding of wave propagation properties and background ionospheric conditions, which were not readily obtainable for this study, and thus would have added complexity to our current analysis, the aim of which is to explore observational aspects of the available data.

Finally, as mentioned in Section 3, our data include a small num-

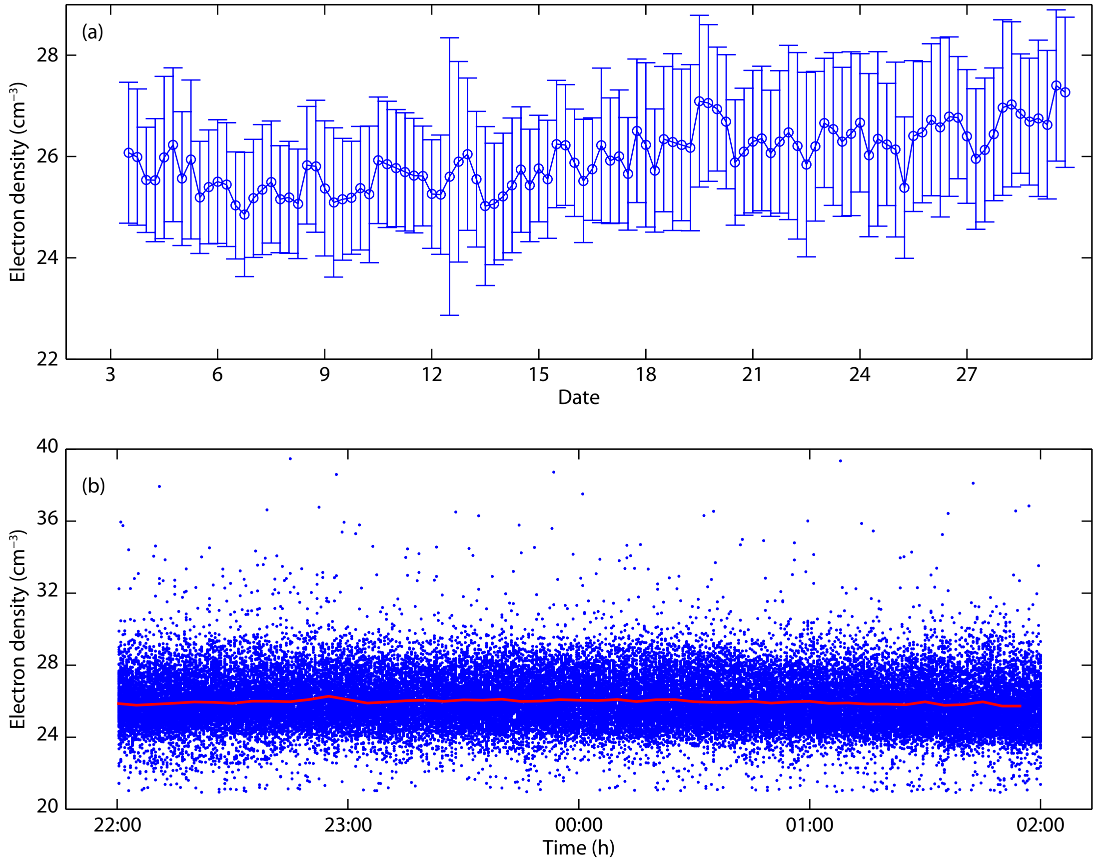

Figure 8. Corresponding to Figure 6, except for the ionospheric electron density at the tweek reflection height is estimated from Equation (2).

ber of higher order mode tweeks. The analysis of tweeks of higher order modes relates to a large number of aspects, such as the occurrence rate of higher mode tweeks and the propagation mechanism of tweeks, which need further investigation. Since not all the observed tweeks have the second-mode profile, and since the parameters derived from the first mode of tweeks are enough to support this study, we evaluate t only results of the first mode of tweeks in order to determine the cut-off frequency and propagation distances; future studies will use data from our WHU ELF/VLF receiver system to look into features of higher order modes of low-latitude tweeks.

5. Conclusion

Adopting the automatic detection and analysis module developed by Zhou RX et al. (2020), we have performed a comprehensive analysis of the occurrence features of low latitude tweek atmospherics and associated ionospheric parameters, using the high quality ELF/VLF signal spectrogram data acquired at 22–02 LT in February 2016 by the Suizhou station of the WHU ELF/VLF receiver system. To improve knowledge of the characteristic low latitude tweek atmospheric over central China, we have investigated in detail the temporal and local time dependence of a number of important parameters, including the tweek occurrence rate, tweek propagation distance, tweek reflection height, and associated D-region electron density.

Our major conclusions are summarized as follows:

(1) The occurrence rate of low latitude tweeks at Suizhou station varies largely between ~800–6000, showing a strong daily and local time dependence. Observed tweeks and WWLLN lightning strikes are closely correlated. The tweek occurrence rate peaks at 22–22.5 LT, minimizes at 23–23.5 LT, and subsequently elevates and changes slightly after midnight.

(2) For low latitude tweek atmospherics observed at Suizhou station, 58% of the events propagate within 2000–4000 km from the lightning source, in contrast to 34% for propagation distances < 2000 km, 7% within 4000–6000 km and < 1% well above 6000 km. Compared with WWLLN lightning strikes, the tweeks focus closer to Suizhou. The tweek propagation distance also tends to exhibit insignificant dependence on the considered interval of local time (i.e., 22–02 LT).

(3) In February 2016 the tweek reflection heights varied mainly between 70 and 88 km; the average daily height ranged between 75 and 85 km, showing a gradual decline from early to later in the month.

(4) Corresponding to the tweek reflection altitudes, ~74% of estimated D-region electron densities are within 24.5–27.5 cm^{-3}, exhibiting over the period of time under consideration a small overall increasing trend with the date.

Acknowledgments

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