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An attempt to infer information on planetary wave by analyzing sporadic *E* layers observations

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In this paper we presented two typical global 6-day planetary wave oscillations occurring in sporadic E layers. By analyzing the f_oE_s time series observed from several ionosonde stations on the basis of the methods suggested by Haldoupis and Pancheva (2002), we computed estimates for the PW propagation direction, zonal wave number and phase velocity. We obtained results that the 6-day PW, with zonal wave number about 1, propagates westward, which are in agreement with those reported from radar and satellite neutral wind MLT measurements. The results provide experimental evidence for a close relationship between PWs and midlatitude E_s. In addition, the study proves the validity of E_s observations measured routinely and rather reliably with a dense global network of digital ionosondes used as an alternative means of studying large-scale neutral atmospheric dynamics in the MLT region.

Key words: Sporadic E layers, planetary waves, MLT dynamics.

1. Introduction

In general, the main factor involved in midlatitude sporadic E (E_s) formation is vertical neutral wind shears, associated with tides and/or gravity waves, which can compress the long-living metallic ions into a thin layer (e.g., see review articles by Whitehead, 1989; Mathews, 1998). Meanwhile, planetary waves (PWs) also play an important role on the formation of midlatitude E_s, as having been reported in many studies. Tsunoda *et al*. (1998) and Voiculescu *et al*. (1999) were the first to give evidence for planetary wave effects on midlatitide backscatter and the sporadic E layer occurrence. Furthermore, Voiculescu *et al*. (2000) analyzed measurements of midlatitude E region coherent backscatter obtained during four summers with SESCAT (Sporadic E SCATter experiment), a 50 MHz Doppler radar system operating in Crete, Greece, concurrent ionosonde recordings from the same ionospheric volume obtained with a CADI (Canadian Advanced Digital Ionosonde) for one of these summers and simultaneous neural wind data from the mesopause region around 95 km, measured in Germany. The results suggested that planetary wave effect on sporadic E is a viable option, which introduces a new element into the physics of midlatitude E region layering phenomena.

The first direct experimental evidence in favor of a PW role on E_s generation was provided by Haldoupis and Pancheva (2002). They analyzed f_oE_s data from a number of ionosonde stations covering a large longitudinal sector and found that a strong 7-day period oscillation in E_s was closely related with a simultaneous 7-day PW present in the mesosphere and lower thermosphere (MLT region) winds, which was detected with meteor radars and from space with satellites. Recently, Zuo and Wan (2008) also reported the evidence in the Wuhan ionosonde and MLT neutral wind observations on the existence of a close relationship between planetary wave oscillations and variations in sporadic E layer occurrence. The authors further confirmed that PW play an important role in the formation of mid-latitude sporadic E layers.

A possible mechanism for the explanation of the PW effects on E_s was proposed by Shalimov *et al*. (1999). This was followed by a theoretical model (Shalimov and Haldoupis, 2002) postulating a direct role for the PWs on E_s formation which relied on large-scale accumulation of metallic ions in the midlatitude E region ionosphere driven by PW horizontal wind shears. While Pancheva *et al*. (2003) and Haldoupis *et al*. (2004) suggested that the effects of PW on E_s were indirect through the PW modulation of the diurnal and semidiurnal tides in the MLT region. Also, the findings of Zuo and Wan (2008) favor an indirect PW role on E_s through a nonlinear process of PW modulation of the tidal wind amplitudes, which in line with the studies of Pancheva *et al*. (2003) and Haldoupis *et al*. (2004).

The idea for the present study originated from the paper by Haldoupis and Pancheva (2002) who suggested that E_s observational data can be useful for inferring information on PW. Haldoupis and Pancheva have computed estimates for the propagation direction, zonal wave number, and phase velocity of the 7-day PW by analyzing f_oE_s data from eight ionosonde stations. E_s observational data should have a global response with the occurring PW given that convincing experimental evidence showed that PW have a profound role in the physics of midlatitude E_s and they have

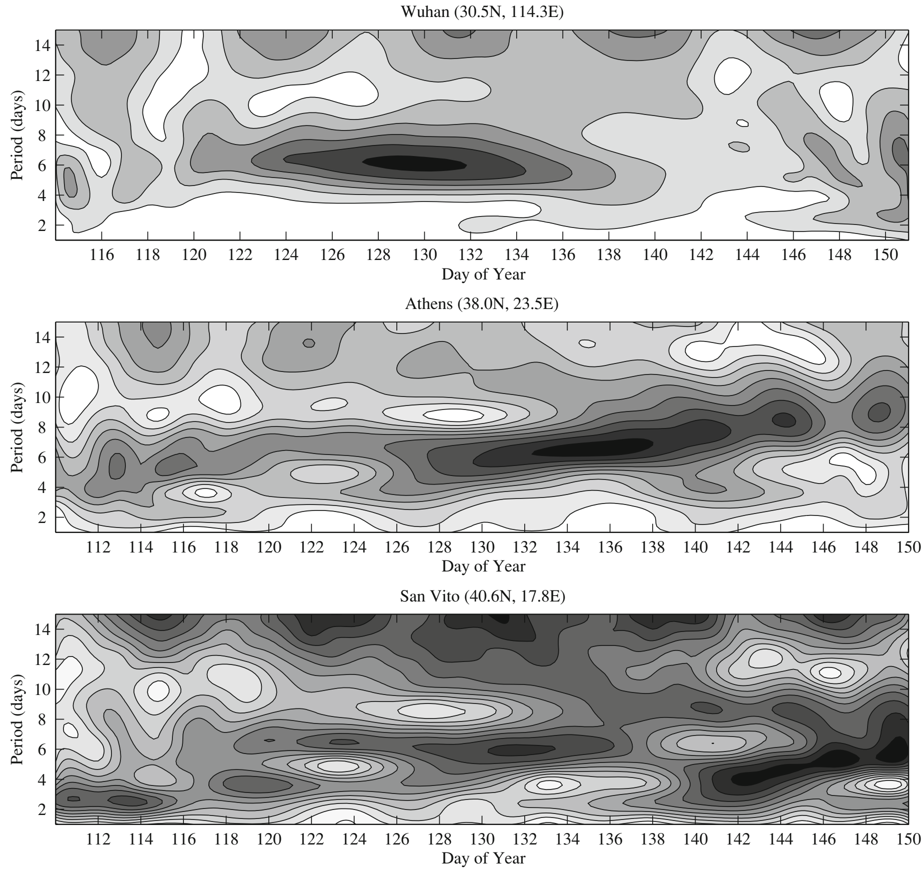

Fig. 1. Wavelet spectrograms for the time series of E_s occurrence during the period from day 110 to 150 of 2003 at Wuhan, Athens and San Vito.

global scales, although PWs are confined inside a limited altitude range in the MLT region. In the present study the observational data of E_s at different stations located in different areas were analyzed to provide further evidence of long-period disturbance exist in the E_s occurrence. Moreover, we also attempted to infer PW information utilizing ionogram E_s data following the methods in Haldoupis and Pancheva's paper (2002). The results argued the existence of a close relationship between PW and midlatitude E_s, and provided new support to the option of using the abundance of global E_s measurements in studying PW characteristics and dynamics.

2. The 6-day Planetary Wave Oscillations Occurring during May 2003

Quasi 6-day oscillation in E_s occurrence was observed to occur during May 2003 in relation with planetary wave activity at Wuhan, China (30.6°N, 114.5°E), as reported by Zuo and Wan (2008), who also found the same quasi 6-day planetary wave oscillation dominates the spectrum of concurrent wind data measured in the 80–100 km region by the meteor radar located also at Wuhan. The strong wave with quasi 6-day period in May 2003 has been also observed by the sounding of the atmosphere using broadband emission radiometry (SABER) instrument aboard the thermosphere-ionosphere-mesosphere energetics and dynamics (TIMED) satellite (Riggin *et al.*, 2006). Thus, this event with large amplitude and long duration was a typical global PW oscillation.

Since PWs have global scales and propagate approximately in zonal direction, we inspected E_s observational data at other stations locating in the latitudinal zone from 20 to 40 degree to examine if exist synchronous long periodicity oscillations. As expected, quasi 6-day planetary wave oscillations were found to occur in E_s occurrence at Athens (38.0°N, 23.5°E) and San Vito (40.6°N, 17.8°E) station locating in the European sector during the same period.

Following the method of Zuo and Wan (2008), we first obtained the daily occurrence of E_s layers (for conditions when $f_oE_s > 5$ MHz) at Wuhan, Athens and San Vito. The continuous Morlet wavelet analysis (e.g., Torrence and Compo, 1998) was then applied to the time series of E_s occurrence for the period from day 110 to 150 of year 2003, when E_s occurrence was fairly continuous. Figure 1 displays the period time spectrograms of the three stations. As shown in the figure, quasi 6-day (5∼7-day) oscillations can be seen clearly at all stations. The oscillations were present for the time interval from about day 123 to 136 at Wuhan, day 126 to 142 at Athens and day 127 to 137 at San Vito. The results reveal that a strong 6-day periodicity occurred approximately concurrently in E_s at the three stations.

In order to investigate the PW oscillations in the E_s occurrence in details, the time sequences of daily E_s occurrence for the three stations during the period from day 110 to 141 of year 2003, when the pronounced 6-day oscillations occurred, are shown in Fig. 2. It is immediately obvious that E_s occurrence at Wuhan is much higher than that at Athens and San Vito, which is subject to the "Far East

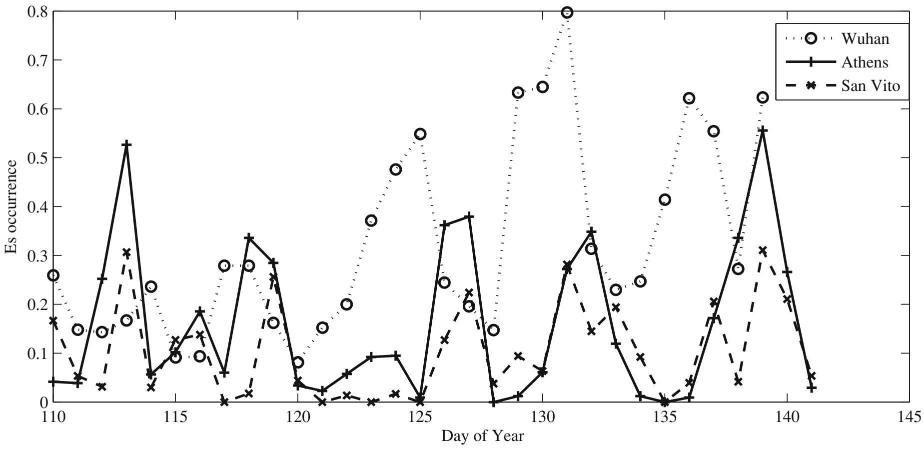

Fig. 2. Time sequences of E_s occurrence for the time interval from day 110 to 141 of 2003 at Wuhan, Athens and San Vito.

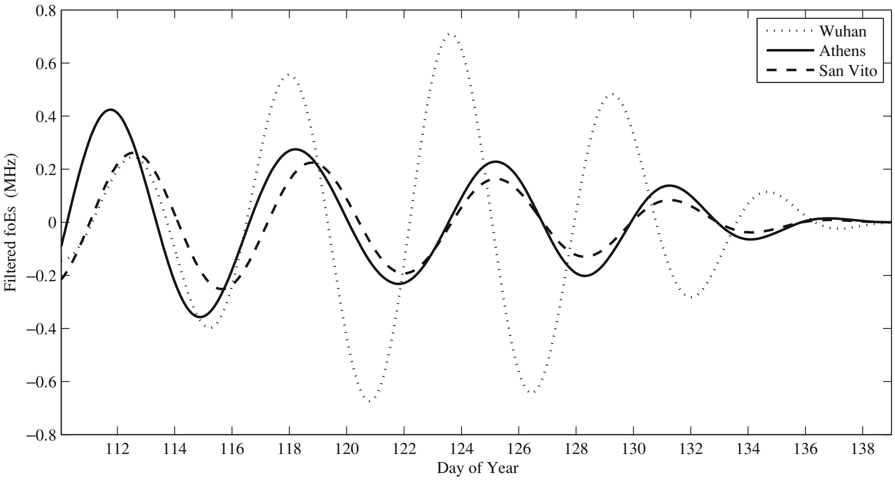

Fig. 3. The quasi 6-day band-pass-filtered hourly f_oE_s time series for the period from day 110 to 139 of 2003 at Wuhan, Athens and San Vito.

Table 1. Cross-correlation analysis for the filtered signals shown in Fig. 3.

Station pairs	Correlation coefficient	Time lag (h)	Zonal wave number	Phase velocity (m/s)
Wuhan-Athens	0.9256	−43	1.18	51.6
Athens-San Vito	0.9682	−1	\	\
Wuhan-San Vito	0.8863	−43	1.11	53.4

Anomaly" (e.g., Smith, 1957). Note that there is a close coincidence between the two time sequences for Athens and San Vito with a linear correlation coefficient 0.68, as is expected since Athens is close to San Vito. In addition, E_s occurrence at Wuhan also showed a coherent pattern with those at Athens and San Vito, but there was time shift with 2–3 days in E_s occurrence between Wuhan and other two stations. We estimated that the maximum correlation coefficient about 0.73 when the time lag is 2 days by applying cross-correlation analysis. This analysis reveals that the 6-day PW oscillations in E_s occurrences at Athens and San Vito are almost synchronous but lag behind that at Wuhan since the longitudinal separation between them is as large as 100°. The phase shift between the two stations and Wuhan indicates the westward propagation direction for the 6-day wave.

In the following we use two methods to estimate the wave propagation properties and zonal wave number (ZWN) by analyzing the f_oE_s data.

The First, a three-order Butterworth band-pass filter, which was centered on 6 days with a full width of 3 days, was performed on the f_oE_s time series for the three stations. The filter outputs are shown in Fig. 3. As depicted in Fig. 3, the 6-day wave oscillations occurred clearly at all stations, with the strongest amplitude appearing at Wuhan. In addition, the 6-day waves for Athens and San Vito are almost in phase, while phase differences are clearly between Wuhan and the other two stations. Cross-correlation analysis was applied to the filtered outputs, and then the cross-correlation coefficient and the time lag (in hours) were obtained. The zonal wave number and the phase velocity of the 6-day PW signature were calculated and the results are summarized in Table 1 for the station pairs. The results are not reliable for the station pair: Athens-San Vito because the two stations

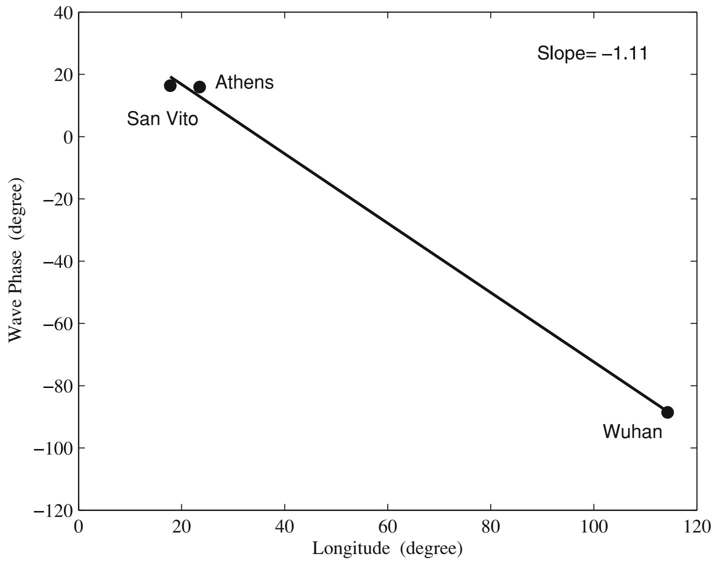

Fig. 4. Wave phase-longitude plot for Wuhan, Athens and San Vito. The slope of the line provides the planetary zonal wave number, where the minus sign means westward propagation.

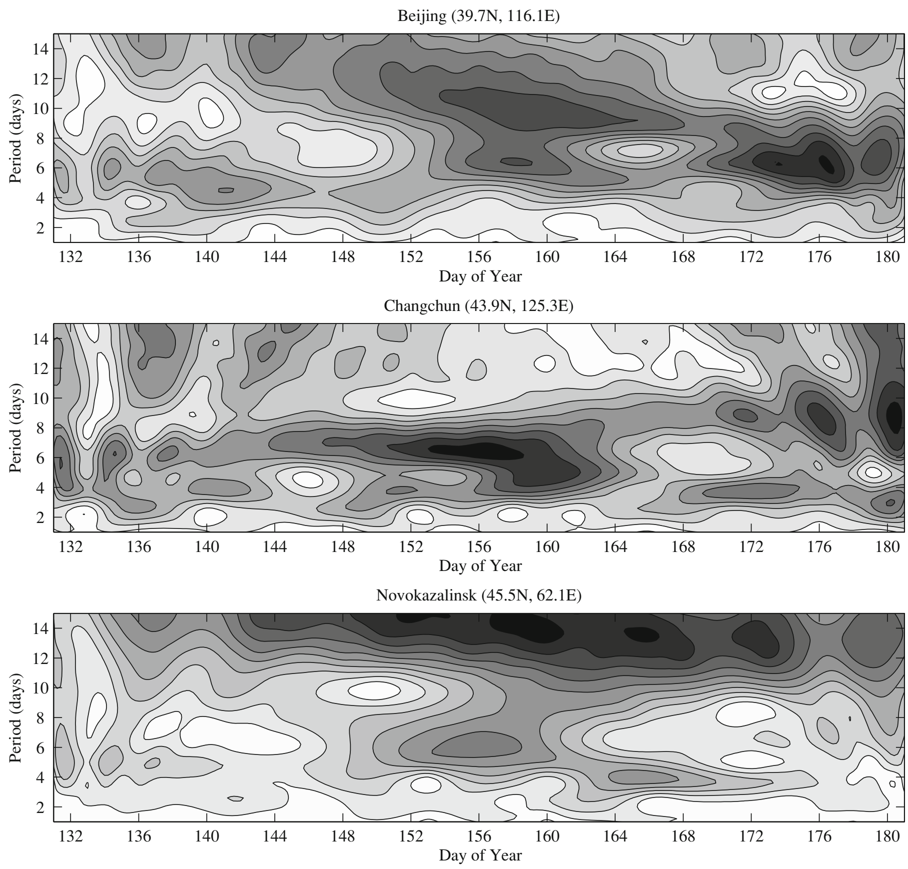

Fig. 5. Wavelet spectrograms for the time series of E_s occurrence during the period from day 131 to 181 of 1970 at Beijing, Changchun and Novokazalinsk.

are too close, and therefore they are not shown in the table. The mean zonal wave numbers was 1.1 and the westward mean phase velocity of the wave was 52 m/s.

The Second, every f_oE_s time series for the period from day 120 to 139 of year 2003, when the quasi 6-day PW activity was strongest, were analyzed by applying a least-square fitting algorithm (e.g., see Hocking *et al.*, 2001 for more details) to estimate the phases of the quasi 6-day PW. Subsequently, following standard methodology applied in PW analysis, the slope of the station points in the "phase-longitude plot" determines the zonal wave number of the propagating wave. The results of this analysis are displayed in Fig. 4. As seen, the zonal wave number is −1.11 (and a standard error 0.06), where the minus sign indicates west-

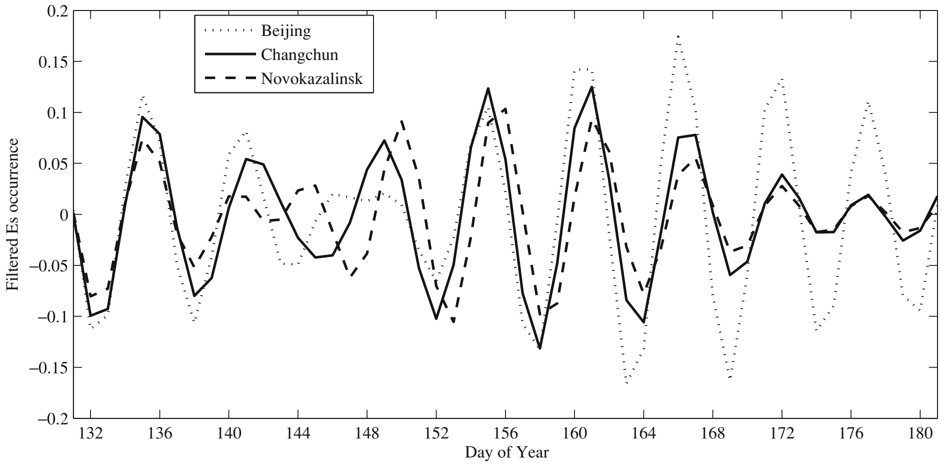

Fig. 6. The quasi 6-day band-pass-filtered daily E_s occurrence time series for the period from day 131 to 181 of 1970 at Beijing, Changchun and Novokazalinsk.

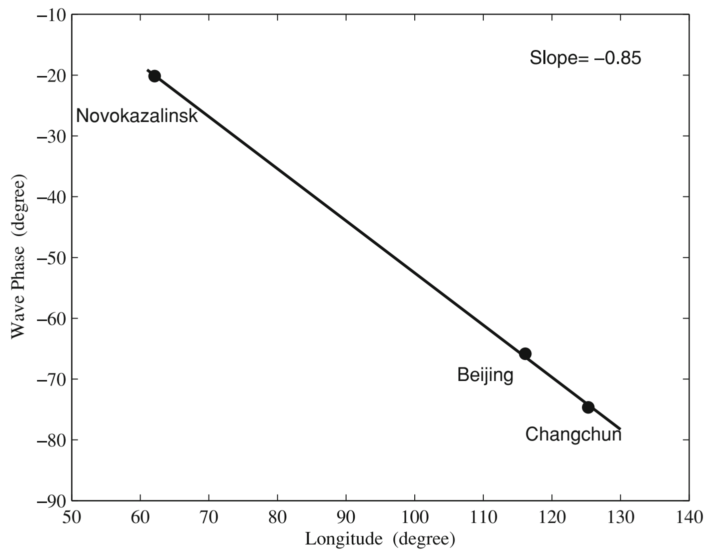

Fig. 7. Wave phase-longitude plot for Beijing, Changchun and Novokazalinsk. The slope of the line provides the planetary zonal wave number, where the minus sign means westward propagation.

ward propagation; the estimated mean phase velocity was 53.4 m/s.

In summary, the two methods used in the f_oE_s wave analysis provide nearly identical results for the zonal wave number, the propagation direction and the phase velocity of the 6-day wave.

3. The 6-day Planetary Wave Oscillations Occurring during June 1970

In addition, we also investigated another long periodicity oscillations occurring in E_s during June 1970. The f_oE_s time series for three stations, Beijing (39.7°N, 116.1°E), Changchun (43.9°N, 125.3°E) and Novokazalinsk (45.5°N, 62.1°E), separating about 60° longitudinal zone were analyzed. We presumed that E_s was affected by a 6-day planetary wave since strong quasi 6-day oscillations were obviously present in the time series of f_oE_s during the period though no data of radar or satellite measurements can be obtained at that time to prove there is really a global-scale wave occurred. Based on the reasonable assumption, we attempted to infer PW parameters by analysis E_s data following the above methods.

Figure 5 displays the period time spectrograms of the daily E_s occurrence for the period from day 131 to 181 of year 1970 at Beijing, Changchun and Novokazalinsk. Strong quasi 6-day oscillations occurred around day 156 at all stations, with the most pronounced peak at Changchun station. Note that quasi 6-day oscillations were also present around day 142 and day 176 at Beijing. Except the 6-day periodicity, a 10-day periodicity was also present around day 158 at Beijing and a brief 3-day oscillation occurred on day 165 at Novokazalinsk. The band-pass filter outputs, shown in Fig. 6, also reveal that the E_s occurrence manifests a strong quasi 6-day periodicity from day 152 to 168 at all stations, and the strongest peak of E_s occurrence is 0.2 present at Beijing.

Furthermore, the wave propagation properties were estimated utilizing f_oE_s data of the three stations following the methods introduced in Section 2. It should be noted that only the results estimated by using the second method are showed here since two methods provided almost identical results for the wave propagation properties. The f_oE_s time series at each stations for the period from day 150 to 170 of year 2003, when the quasi 6-day PW activity was strongest, was analyzed by applying the least-square fitting algorithm to estimate the phase of the quasi 6-day PW. As shown in Fig. 7, the slope of the station points, namely the zonal wave number, is -0.85 with a standard error 0.02. Again, the minus sign indicates westward propagation of the planetary wave. In addition, the estimated mean phase velocity was 64.3 m/s.

4. Discussion and Concluding Comments

We have reported two experimental cases in this study and found that planetary waves play a profound role in sporadic *E* layers. Two methods were applied to analyze the f_oE_s time series and then to estimate the propagation direction, zonal wave numbers and phase velocities of the 6-day PW. The obtained results are in agreement with those reported from radar and satellite neutral wind MLT measurements (Wu *et al.*, 1994; Clark *et al.*, 2002). More importantly, this work proves the validity of the use of f_oE_s data as an alternative studying means of PW activity. Therefore, f_oE_s time series may be very useful for inferring information on large scale neutral dynamics at altitudes above 100 km, where are usually higher than those covered by conventional (meteor and medium frequency) radar methods. By the way, the analysis methodology has its advantage because of the availability of the global E_s ionosonde network.

Finally, it should be noted that sometimes the long period variability in E_s is probably not to be directly caused by PW and only by the modulated tides, i.e. in case when the tidal amplitude modulation is generated by a nonlinear interaction with the PW which takes place at stratosphere levels and the generation of the secondary waves is fed by the energy taken from the PW, that is, the PW itself could not penetrate to the MLT region and together with the modulated tides to affect the sporadic *E* layer variability. If this is the case, the derived PW parameters by analyzing the E_s data may be different from the original zonal structure of the PW. This concern indicates that the application of this approach is limited and more suitable for the case that PW itself is observed in the MLT region.

In conclusion, in view of the very close relation between planetary waves and sporadic *E* layers, an alternative means of studying PW parameters by analyzing E_s observation data may be used. By the way, we only used the E_s data from three stations for each event in this work. A future study is planned that will investigate the PW activity in the E_s occurrence by collecting global ionosonde observations.

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