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Planetary wave oscillations in sporadic *E* layer occurrence at Wuhan

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Quasi 6-day oscillations in E_s occurrence were observed to occur in relation with planetary wave activity at Wuhan, China (30.6°N, 114.5°E). Wavelet analysis of E_s occurrence time series revealed that a strong 5- to 7-day oscillation was present during the period from about day 120 to 137 of 2003. The same quasi 6-day planetary wave oscillation was also found to dominate the spectrum of concurrent wind data measured in the 80- to 100-km region by a meteor radar, in agreement with the E_s occurrence. There is also a great deal of similarity between the 5- to 7-day band-pass filtered waveforms of E_s occurrence and the wind data. By estimating the wave phase changes with altitude, the quasi 6-day PW in the zonal wind was found to be in phase with the sporadic *E* layer critical frequency, f_oE_s, at about 115 km, close to the observed E_s height. The quasi 6-day PW modulation was also present in the amplitude of the 12-h and 24-h periodicities which existed in the f_oE_s time series. The present results provide new evidence in favor of a planetary wave indirect role on E_s formation through the modulation of tides, which in line with previous studies by Haldoupis and Pancheva (2002), and Pancheva *et al.* (2003).
Key words: Sporadic *E* layers, planetary waves, atmospheric tides, PW modulation of tides.

1. Introduction

Midlatitude sporadic *E* (E_s) layers, which are thin plasma layers of enhanced metallic ion concentration that form frequently in the midlatitude *E* region ionosphere, have been a topic of intensive research for quite a long time (see review articles by Whitehead, 1989; Mathews, 1998). The formation of the layers is explained by the wind shear theory (see Whitehead, 1961). On the other hand, several new results in the last decade suggest that the generation of sporadic *E* is not yet fully understood. A possible link between E_s and atmospheric planetary waves (PWs) has recently attracted considerable attention.

Planetary waves are global scale, quasi-periodic oscillations in temperature, pressure, density and wind of the atmosphere, with typical periods in the range of about 2–20 days. They are mainly of tropospheric origin and can affect the atmospheric dynamics in the lower thermosphere between 80 and 150 km (see Forbes, 1994). Tsunoda *et al.* (1998) and Voiculescu *et al.* (1999) were the first to provide 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. 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.

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 to find 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. Pancheva *et al.* (2003) took this work a step further to show that the effects of PW on E_s were indirect through the PW modulation of the diurnal and semidiurnal tides in the MLT region.

The eight ionosonde stations mentioned in the paper of Haldoupis and Pancheva (2002) were all located in the European and North American sectors. It is therefore useful to investigate a similar data set obtained in the Asia sector which is subject to the "Far East Anomaly" (e.g., Smith, 1957). Also, in the work of Pancheva *et al.* (2003), the analysis was based on concurrent mesospheric neutral winds and ionosonde f_oE_s data from nearby, but different, locations. We have studied the same problem as Pancheva *et* *al*. (2003) did, we have used a complete data set in which all (ionosonde f_oE_s and MLT wind) measurements were done at the same exactly location, that is, at Wuhan, China (30.6°N, 114.5°E). We believe this co-location of all instrumentation will certainly be more advantageous for this kind of correlative studies.

The present paper is organized as follows: the planetary wave periodicities in E_s occurrence at Wuhan are presented in Section 2, followed by the analysis of wind measurements in Section 3. Detailed comparisons of the quasi 6-day periodicities found in E_s and the wind data are made in Section 4, which is followed by a summary and discussion in Section 5.

2. Planetary Wave Periodicities in E_s Occurrence at Wuhan

We first obtained the daily occurrence of E_s layers (for cases when $f_oE_s > 5$ MHz) at Wuhan, and then Fourier analyzed the time series for the period from day 120 to 260 of 2002 in order to compute the corresponding spectrum. Note that small data gaps were filled by using a common cubic interpolation method. Figure 1 displays the time sequences of E_s occurrence in the top panel and the corresponding Fourier power spectrum in the bottom panel. It shows a pronounced daily variability in E_s occurrence with periods ranging from two to several days, as evidenced from the normalized Fourier power spectrum in the bottom panel. The spectrum shows two dominant periods at about 7 and 15 days, respectively, which are common prevailing periodicities in the planetary wave band.

To reduce data gaps, which are due to the absence of the layers at times, daily E_s occurrences was selected from day 114 to 151 of 2003, when E_s occurrence was fairly continuous. Continuous Morlet wavelet analysis was applied to the time series of E_s occurrence. The wavelet method has become a favored tool in geophysics for analyzing non stationary time series. By decomposing the time series into the time-period space, the wavelet analysis transform can determine both the dominant periodicities and their dynamic change (e.g., Torrence and Compo, 1998). As shown in Fig. 2, in the period time spectrogram seen in the bottom panel, a quasi 6-day (5–7 day) oscillation dominates the spectrum for the time interval from about day 120 to 137.

To investigate if the long-term periodicity owes its presence to geomagnetic activity, the time series of the daily averaged Kp and Ap index corresponding to the same time intervals were analyzed as well. The quasi 6-day oscillation under consideration did not occur in the Kp and Ap spectrograms (not show here). In addition, poor correlation between E_s occurrence and geomagnetic activity was found. The computed correlation coefficients of E_s occurrence with Kp and Ap were equal to −0.16 and −0.08, respectively. The lack of correlation between E_s and geomagnetic activity is a well-known fact (see Whitehead, 1989), whereas its absence has also been verified in previous PW-E_s studies by Voiculescu *et al*. (2000) and Haldoupis and Pancheva (2002).

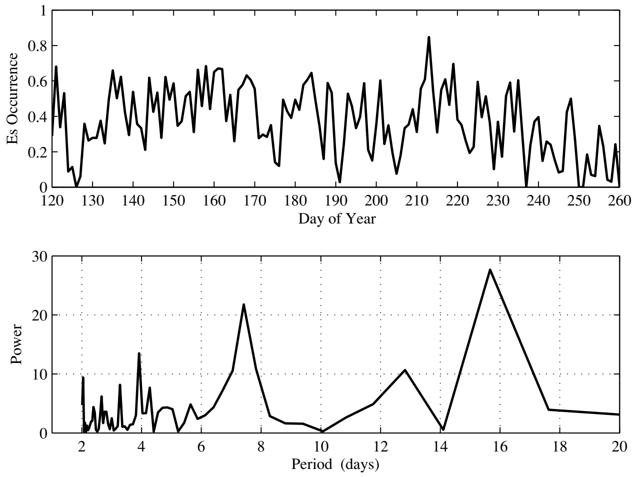

Fig. 1. Time sequence of E_s occurrence and the corresponding Fourier power spectrum for the time interval from day 120 to 260 of 2002 at Wuhan.

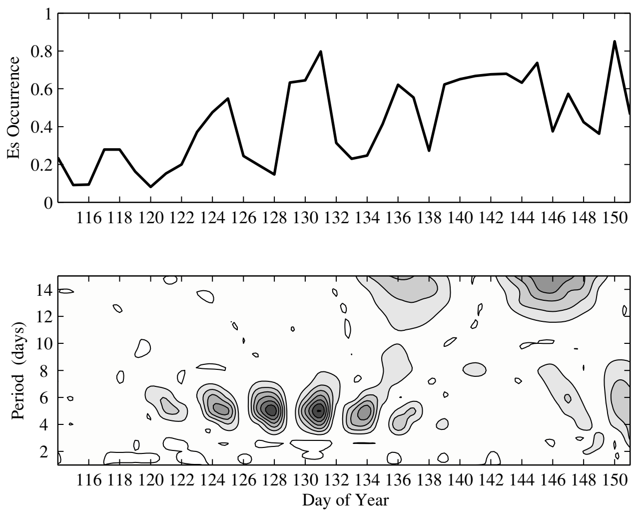

Fig. 2. Time sequence of E_s occurrence and the corresponding wavelet spectrogram for the time interval from day 114 to 151 of 2003 at Wuhan.

3. Quasi 6-day Period Variations in MLT Winds at Wuhan

Given this dominant quasi 6-day PW event in E_s occurrence and the need to search for a likely PW-E_s relationship, the next step was to analyze the concurrent wind observations over Wuhan. The wind data were obtained from an all sky interferometric meteor radar at Wuhan with a peak power of 7.5 kW, a duty cycle of 10% at a frequency of 38.7 MHz and a range sampling resolution of 2 km since January 2002, which commenced operation on 29 January 2002. The radar is a commercial VHF system manufactured by Atmospheric Radar Systems of Australia (ATRAD), and it is almost identical to the Buckland Park meteor radar in Australia and the earlier SKiYMET system in Canada (Hocking *et al*., 2001; Holdsworth *et al*., 2004). Almost continuous observations have been carried out from February 2002, apart from a 10-day interruption in February 2002 and a larger data gap of 56 days from February 26 to April 22 in 2003. The parameters used for routine observations

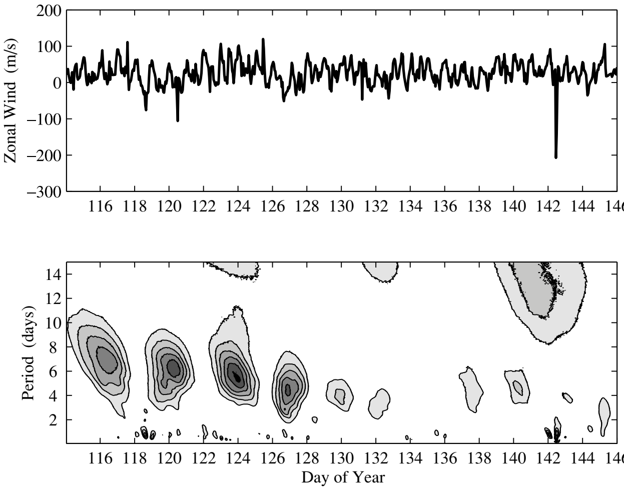

Fig. 3. Time sequence of hourly zonal wind at an altitude of 94 km and the corresponding wavelet spectrogram for the time interval from day 114 to 145 of 2003 at Wuhan.

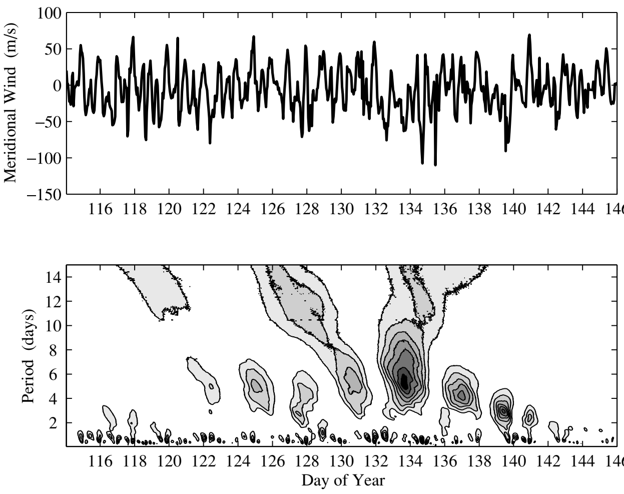

Fig. 4. Same as in Fig. 3 but for the meridional wind.

and the data analysis methodology are described by Xiong *et al.* (2004).

Although the quasi 6-day planetary wave oscillation is present in the wind data in the entire 80- to 100-km altitude range, here we select and show the observations at 94 km. Continuous time series wavelet analysis was performed on hourly mean wind speeds during the period from day 114 to 145 of year 2003. The analysis results of zonal and meridional wind are shown in Figs. 3 and 4, respectively, displaying in the upper panel the time series and in the lower panels the period versus time spectrograms. As seen, a dominant quasi 6-day period oscillation occurred on day 115 and persisted about 15 days in the zonal wind. Note that this appeared somewhat ahead of the oscillation present in E_s occurrence. A 6-day periodicity was also present in the meridional wind from day 124 to 138, being coincident with the quasi 6-day oscillation in the E_s occurrence. It is interesting to note that concomitant to the 6-day event, around day 139, a 3-day periodicity in the meridional wind was also present.

4. Comparison of Quasi 6-day Waves in E_s and Wind Data

In order to investigate the amplitude of the oscillations in both the E_s occurrence and the winds in more detail, a five-order Butterworth band-pass filter—as applied by Xiong *et al.* (2006)—was used which was centered on 6 days with a full width of 3 days. The band-pass filter analysis was performed on the time series of daily E_s occurrence and daily mean wind speeds covering the altitude range from 84 to 100 km, with a 4-km interval, for the period from day 100 to 200 of 2003.

As shown in Fig. 5, the E_s occurrence manifests a strong quasi 6-day periodicity from day 115 to 135, with the strongest peak located around day 125, while the gap seen in the figure is due to data losses. For comparison with the E_s occurrence, the band pass filtered waveforms of the zonal and the meridional component are shown in Figs. 6 and 7, respectively. The different altitudes are denoted as follows: $h = 84$ km, with thick solid line; $h = 88$ km, the thick dotted line; $h = 92$ km, the thick dash-dotted line; $h = 96$ km, the thin solid line; $h = 100$ km, with thin solid line and dots. As seen, the maximum amplitude of the zonal wind oscillation occurred at the altitude of 92 km, reaching about 18 m/s and lasting for two to three cycles from day 120 to 140. The waveforms at other altitudes displayed their largest amplitudes during the period from day 120 to 140 as well, but these were weaker than those seen at 92 km. Regarding the oscillation in the meridional wind, the largest amplitude occurred between day 120 and about day 140, with values nearing 13 m/s. The present results show that the quasi 6-day band-pass-filtered E_s occurrence has the same character with that of the neutral wind, which means that a common oscillation with a period inside the PW band is present simultaneously in both the winds and the sporadic E layer occurrence. This is in agreement with the August–September 1993 event studied by Haldoupis and Pancheva (2002).

Further, the time series of mean hourly wind speeds for the period from day 120 to 140 of year 2003, when the quasi 6-day PW activity was strongest, were analyzed by applying a least-square fitting algorithm (see Hocking *et al.*, 2001 for more details) to estimate the phase changes of the quasi 6-day PW for all altitudes from 84 to 100 km (every 2 km). Figure 8 summarizes the phase variation with altitude of the quasi 6-day PW in the zonal (left panel) and meridional wind (right panel), showing a phase decrease with increasing altitude in both components because of the downward phase propagation of the PW. The wave phase propagated vertically downward with a mean altitude rate of about 2–3 h/km.

Further, we also worked out the phase of the quasi 6-day periodicity in f_oE_s by analyzing the time series of hourly means for the same internal. Assuming that the quasi 6-day wave in zonal wind maintains about 2–3 h/km rate of phase change with altitude for heights above 100 km, we found that the PW in the zonal wind and E_s periodicities to be in phase at about 115 km. Note that no consideration was taken for the meridional component since the vertical plasma motion in the formation process is believed to be controlled mostly by the zonal wind shears below about

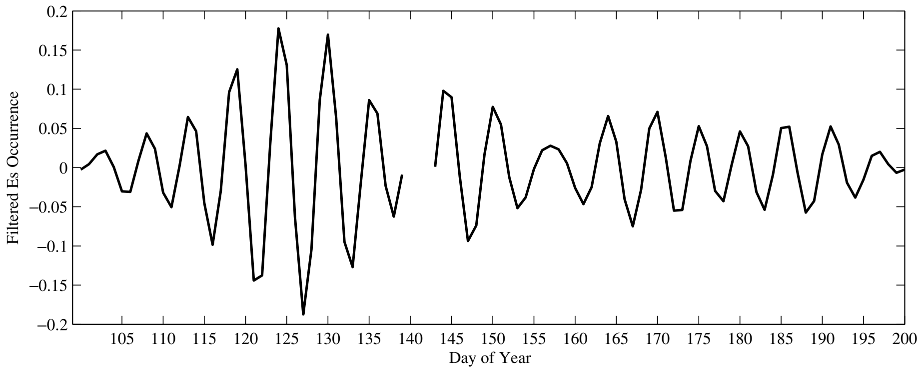

Fig. 5. The quasi 6-day band-pass-filtered daily E_s occurrence time series for the period from day 100 to 200 of 2003 at Wuhan.

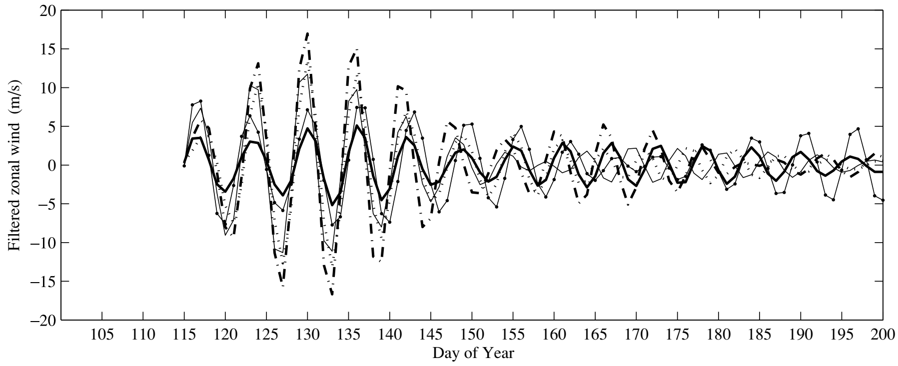

Fig. 6. The quasi 6-day band-pass-filtered daily mean zonal wind measured at five different altitude levels between 84 and 100 km for the period from day 114 to 200 of 2003 at Wuhan with a data gap from day 100 to 113. The different altitudes are denoted as follows: thick solid line, $h = 84$ km; thick dotted line, $h = 88$ km; thick dash-dotted line, $h = 92$ km; thin solid line, $h = 96$ km; thin solid line and dots, $h = 100$ km.

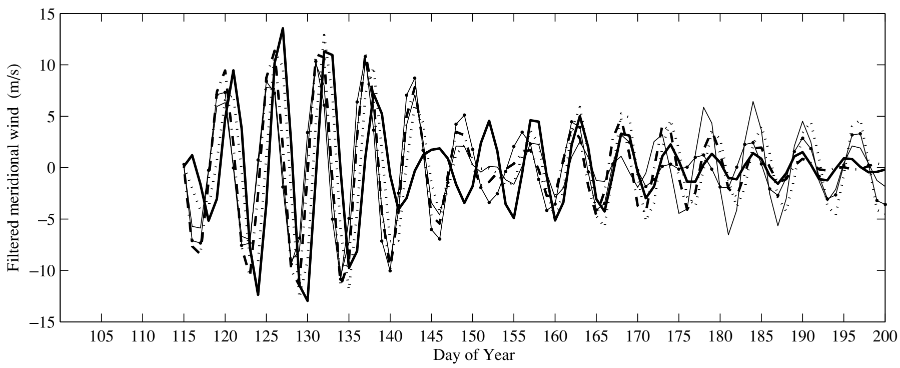

Fig. 7. Same as in Fig. 6 but for the meridional wind.

120 km (Pancheva *et al.*, 2003; Haldoupis *et al.*, 2004). Since the mean height of E_s for the period from day 120 to 140 of the year 2003 is estimated from the ionosonde data to be at about 111 km, the phase agreement mentioned above is fairly good. Although the agreement does not necessarily imply a direct effect of PW on E_s because the estimated results were rough and based on given premise, a direct PW role cannot apparently be excluded and might be at work just as the new mechanism proposed by Shalimov *et al.* (1999), which have been outlined in Section 1. However, in the present paper we hypothesized that PWs play an indirect role and then tested this hypothesis by using the methodology of Pancheva *et al.* (2003).

Given that atmospheric tidal winds play a fundamental role on E_s formation, it was postulated that a PW affects E_s by modulating the tidal wind amplitudes, apparently at lower altitudes. We have been directed to this postulation by the work of Pancheva *et al.* (2003) who used a detailed time series demodulation methodology to show that E_s is affected by the PWs indirectly through the PW-modulation of the tidal wind amplitudes. To test this in the present study, wavelet transform analysis was performed on the time series of the f_oE_s 12- and 24-h periodicity amplitudes for the interval from day 120 to 140 of 2003. The amplitudes were obtained from the f_oE_s time series by using the least-square fitting algorithm of Hocking *et al.* (2001). The results are presented in Fig. 9 which shows the wavelet spectrograms of the 12- and 24-h periodicity amplitudes. As seen, strong

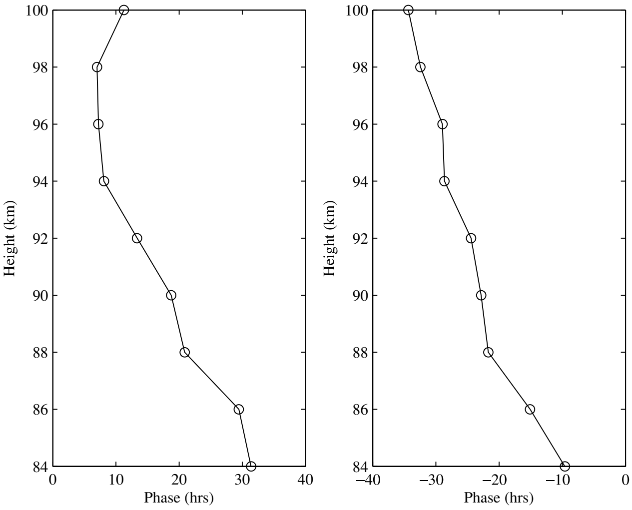

Fig. 8. The quasi 6-day wave phases for all altitudes of the zonal wind (left) and the meridional wind (right) for the period from day 120 to 140 of year 2003 at Wuhan.

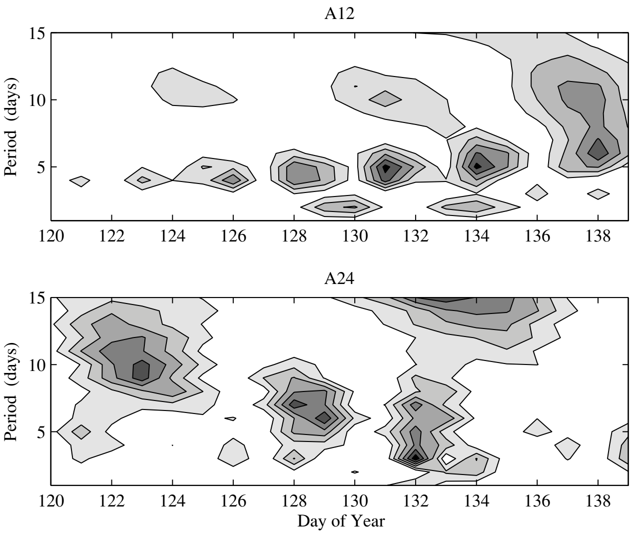

Fig. 9. Wavelet spectrograms for the amplitudes of the 12-h (top) and 24-h (bottom) periodicities in f_oE_s during the period from day 120 to 140 of 2003 at Wuhan.

6-day modulations are clearly present at both periodicities. As it is known, the semidiurnal and diurnal periodicities are imprinted on E_s layers because the layer occurrence and strength are controlled mostly by the semidiurnal and diurnal tidal waves in the altitude range from 90 to 160 km (see Mathews, 1998; and a recent study by Haldoupis *et al*., 2006). The present result provides strong reassuring evidence in favor of an indirect PW role on E_s formation through the modulation of atmospheric tides, which is in full agreement with the findings of Pancheva *et al*. (2003).

5. Summary and Concluding Comments

We report here the first evidence in the Wuhan ionosonde and MLT neutral wind observations on the existence of a relationship between planetary wave oscillations and variations in sporadic E layer occurrence. Here the characteristics of the long-term periodicities in E_s occurrence were studied to identify the prevailing periods and the duration of the dominant periodicities. Further, for the first time a direct comparison was attempted between the periodicities in E_s occurrence and simultaneous neutral winds, both measured at the same location (Wuhan). The wavelet spectrograms of both data sequences showed a very good agreement of the periodicities present concurrently in E_s occurrence and the MLT winds. Comparison of the 5- to 7-day band-pass filtered outputs of E_s occurrence and the wind data also show a good analogy. By investigating the phase changes with time of the quasi 6-day PW for all altitudes from 84 to 100 km, the quasi 6-day PW in the zonal wind was found to be in phase with E_s at about 115 km, an altitude that is near the observed mean E_s height of 111 km. We also found both the 12- and 24-h periodicities in the f_oE_s time series to undergo a strong quasi-6 day modulation. The present results reinforce the postulation that the reported PW effects on E_s are basically induced indirectly through tidal modulations.

Relying on our findings we can infer that the periodicities in E_s occurrence are likely due to large-scale planetary waves, which are known to exist in the midlatitude mesosphere and lower thermosphere (see Forbes, 1994). The present results provide more evidence that PW play an important role in the formation of mid-latitude sporadic E layers and support the findings of Haldoupis and Pancheva (2002), Pancheva *et al*. (2003), and Haldoupis *et al*. (2004). Also, the present findings favor an indirect PW role on E_s through a nonlinear process of PW modulation of the tidal wind amplitudes. The details of this mechanism need further study, in the framework of the wind shear theory, in order to be better clarified and understood. In addition, it is necessary to consider new driving forces in relation with PWs and their climatology are necessary in order to explain the E_s variability characteristics, such as, for example, the E_s annual occurrence. The thorough investigation of the PW physics on sporadic E layer formation and strength is an important task which hopefully will be undertaken in a future study.

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References

Forbes, J. M., Tidal and planetary waves, in *The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory*, edited by R. M. Johnson and T. L. Killeen, 67 pp, AGU, Washington, D.C., 1994.

Haldoupis, C. and D. Pancheva, Planetary waves and midlatitude sporadic E layers: Strong experimental evidence for a close relationship, *J. Geophys. Res.*, **107**(A6), 1078, doi:10.1029/2001JA000212, 2002.

Haldoupis, C., D. Pancheva, and N. J. Mitchell, A study of tidal and planetary wave periodicities present in midlatitude sporadic E layers, *J. Geophys. Res.*, **109**, A02302, doi:10.1029/2003JA010253, 2004.

Haldoupis, C., C. Meek, N. Christakis, D. Pancheva, and A. Bourdillon, Ionogram Height-Time-Intensity observations of descending sporadic E layers, *J. Atmos. Solar-Terr. Phys.*, **68**, 539–557, 2006.

Hocking, W. K., B. Fuller, and B. Vandepeer, Real-time determination of meteor related parameters utilizing modern digital technology, *J. Atmos. Solar-Terr. Phys.*, **63**, 155–169, 2001.

Holdsworth, D. A., I. M. Reid, and M. A. Cervera, Buckland Park all-sky interferometric meteor radar, *Radio Sci.*, **39**, RS5009, doi:10.1029/2003RS003014, 2004.

Mathews, J. D., sporadic E: Current views and recent progress, *J. Atmos. Solar.-Terr. Phys.*, **60**, 413–535, 1998.

Pancheva, D., C. Haldoupis, C. E. Meek, A. H. Manson, and N. J. Mitchell, Evidence of a role for modulated atmospheric tides in the dependence of sporadic *E* layers on planetary waves, *J. Geophys. Res.*, **108**(A5),1176, doi:10.1029/2002JA009788, 2003.

Shalimov, S. and C. Haldoupis, A model of mid-latitude E-region plasma convergence inside a planetary wave cyclonic vortex, *Ann. Geophys.*, **20**, 1193–1201, 2002.

Shalimov, S., C. Haldoupis, M. Voiculescu, and K. Schlegel, Midlatitude E region plasma accumulation driven by planetary wave horizontal wind shears, *J. Geophys. Res.*, **104**, 28207–28213, 1999.

Smith, E. K., Worldwide occurrence of sporadic *E*, NBS Circular 582, U.S. Govt. Printing Office, Washington, D.C., 1957.

Torrence, C. and G. Compo, A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, **79**, 61–78, 1998.

Tsunoda, R. T., M. Yamamoto, K. Igarashi, K. Hocke, and S. Fukao, Quasi-periodic radar echoes from midlatitude sporadic *E* and role of the 5-day planetary wave, *Geophys. Res. Lett.*, **25**, 951–954, 1998.

Voiculescu, M., C. Haldoupis, and K. Schlegel, Evidence for planetary wave effects on midlatitude backscatter and sporadic *E* layer occurrence, *Geophys. Res. Lett.*, **26**, 1105–1108, 1999.

Voiculescu, M., C. Haldoupis, D. Pancheva, M. Ignat, K. Schlegel, and S. Shalimov, More evidence for a planetary wave link with midlatitude E region coherent backscatter and sporadic *E* layers, *Ann. Geophys.*, **18**, 1182–1196, 2000.

Xiong, J. G., W. Wan, B. Ning, and L. Liu, First results of the tidal structure in the MLT revealed by Wuhan Meteor Radar (30°40′N, 114°30′E), *J. Atmos.-Terr. Phys.*, **66**, 675–682, 2004.

Xiong, J., W. Wan, B. Ning, L. Liu, and Y. Gao, Planetary wave-type oscillations in the ionosphere and their relationship to mesospheric/lower thermospheric and geomagnetic disturbances at Wuhan (30.6°N, 114.5°E), *J. Atmos.-Terr. Phys.*, **68**, 498–508, 2006.

Whitehead, J. D., The formation of the sporadic-E layer in the temperate zones, *J. Atmos.-Terr. Phys.*, **20**, 49–58, 1961.

Whitehead, J. D., Recent work on mid-latitude and equatorial sporadic E, *J. Atmos.-Terr. Phys.*, **51**, 401–424, 1989.

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