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Evidence of a role for modulated atmospheric tides in the dependence of sporadic *E* layers on planetary waves

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[1] A large amplitude, 7-day period westward propagating S = 1 planetary wave (PW) of global response has been reported from ground radar and satellite wind measurements in the mesosphere-lower thermosphere (MLT) during the second half of August and well into September 1993. Following recent suggestions that PW might play a role in the formation of midlatitude sporadic *E* layers (E_s), *Haldoupis and Pancheva* [2002] found a strong 7-day periodicity present in all stations concurrently with the 7-day planetary wave reported elsewhere, by analyzing sporadic *E* critical frequency (*foEs*) time series from eight midlatitude ionosonde stations covering a longitudinal zone from about 58°E to 157°W. This study provided the first direct proof in favor of a PW role on E_s formation. In the present paper we further investigate this role by considering the same PW event and correlating the 7-day periodicity in *foEs* directly with concurrent variations in the mesospheric neutral wind measured with atmospheric radars in Saskatoon, Canada, and in Sheffield, United Kingdom. Although our analysis cannot exclude a direct PW role on E_s formation, it shows clearly that E_s is affected indirectly by the PW through the action of the diurnal and semidiurnal tides which are strongly modulated by the same PW, apparently through a nonlinear interaction process at altitudes below 100 km. This 7-day PW modulation was found to be clearly present simultaneously in the amplitude of the zonal 12-hour tidal wind, the meridional 24-hour tidal wind, and in both, the 12-hour and 24-hour periodicities which existed in the *foEs* time series. The results here provide a new physical explanation for the observed relation between sporadic *E* layers and planetary waves. *INDEX TERMS:* 2427 Ionosphere: Ionosphere/atmosphere interactions (0335); 2439 Ionosphere: Ionospheric irregularities; 3384 Meteorology and Atmospheric Dynamics: Waves and tides; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); *KEYWORDS:* ionosphere-atmosphere interactions, metallic ion layers, MLT dynamics, waves and tides, nonlinear interactions

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1. Introduction

[2] The sporadic *E* layers (E_s), which are thin layers of dense plasma forming in the midlatitude *E* region ionosphere, have been the subject of numerous investigations over many years (e.g., see review by *Whitehead* [1989]). Their formation is believed to be governed by the complexity of neutral wind dynamics in the mesosphere and lower thermosphere (MLT). In particular, the diurnal and semidiurnal tides, and the vertical wind shears carried by them, are of fundamental importance to E_s, which sometimes are referred to as "tidal ion layers" [e.g., see *Mathews*, 1998]. In addition to the undisputed role of atmospheric tides, recent results suggested that planetary waves (PW) play a role on E_s formation as well, a fact that went unnoticed in the long-going research of sporadic *E*. The first evidence for a link between E_s and PW was provided by the field-aligned backscatter observations of *Tsunoda et al.* [1998] and *Voiculescu et al.* [1999], who reported PW period like modulations in the occurrence of magnetic aspect-sensitive *E* region radar echoes that associate closely with strong sporadic *E* layers [e.g., see *Hussey et al.*, 1998]. Note that planetary waves are very large horizontal scale atmospheric oscillations in neutral wind, pressure and density, which propagate zonally and vertically in the MLT region and have quasi-periods near 2, 5, 10, and 16 days [e.g., see *Forbes*, 1994].

[3] The first direct evidence in favor of a PW role on E_s generation was provided recently by *Haldoupis and Pancheva* [2002]. They used sporadic *E* layer critical frequency (*foEs*) data from an extended longitudinal chain of several ionosondes during a conspicuous, truly global, PW event that occurred in August–September 1993, to show that all stations displayed the same 7-day periodicity in *foEs* concurrently with the 7-day period PW detected independently in MLT ground radar and satellite wind measurements [*Wu*

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et al., 1994; *Meyer and Forbes*, 1997; *Clark et al.*, 2002; *Pogoreltsev et al.*, 2002]. Using independent methods for the analysis of the *foEs* time series, *Haldoupis and Pancheva* [2002] computed identical estimates for the propagation direction, zonal wave number, and phase velocity of the 7-day wave, all in agreement with those reported from radar and satellite MLT winds.

[4] This paper comes as a continuation of the work of *Haldoupis and Pancheva* [2002] (hereinafter referred to as paper A). In the present study, we perform a detailed correlative analysis between concurrent radar MLT wind and neighboring ionosonde *foEs* time series for the same 7-day PW event of August–September 1993. This is done with the purpose of gaining new physical insight into the nature of interaction and a better understanding of the relationship between layering plasma processes in the *E* region and large scale neutral wind oscillations in the lower thermosphere. Our findings showed that planetary waves can affect E_s formation indirectly through nonlinear interaction and modulation of the semidiurnal and diurnal atmospheric tides.

2. Wind Shear Theory Basics

[5] Before presenting our experimental results, in this section we summarize some key points behind the *E* region vertical plasma convergence caused by the $\mathbf{V}_n \times \mathbf{B}$ action, where $\mathbf{V}_n$ and $\mathbf{B}$ are the neutral wind and magnetic field vectors respectively. This is useful for assessing in our analysis the significance of the zonal and meridional wind components on vertical plasma transport and sporadic *E* layer forming.

[6] Our basic physical understanding of sporadic *E* relies on the so called "wind shear theory" first proposed by *Whitehead* [1961]. This theory shows that vertical wind shears with a proper polarity can cause, by the combined action of ion-neutral collisional coupling and geomagnetic Lorentz forcing, the long-lived metallic ions to move vertically and converge into dense plasma layers. At its simplest form, when electric field and diffusional effects are neglected, the steady state ion momentum equation yields for the vertical drift velocity of ions (positive upward):

$$w_z = \frac{\cos I \sin I}{1 + (\nu_i/\omega_i)^2} U + \frac{(\nu_i/\omega_i) \cos I}{1 + (\nu_i/\omega_i)^2} V. \quad (1)$$

Following the notation of *Mathews* [1998], here *U* and *V* are the geomagnetic southward and eastward components of the neutral wind (representing in general the meridional and zonal wind components, respectively), *I* is the magnetic dip angle, and $(\nu_i/\omega_i) = r$ is the ratio of ion-neutral collision frequency to ion gyrofrequency. Note that the process is fully controlled by ion dynamics therefore the vertical ion drift w_z is in fact representing the plasma drift, since the electrons simply follow the ions by moving along the field lines to maintain charge neutrality. Also note that vertical winds are ignored as being too small to have a significant effect on vertical transport.

[7] The vertical plasma drift becomes collision-dominated below about 125 km because $r^2 \gg 1$; thus the first term in equation (1) becomes small and is negligible below say 120 km. This means that below about 120 km the vertical plasma motion is controlled solely by the zonal wind, with a downward (upward) drift caused by a westward (eastward) wind. In this case the plasma convergence into a layer becomes most effective in the presence of a vertical wind shear with a westward wind above and an eastward, or smaller westward, wind below. On the other hand, the meridional wind (first) term in equation (1) dominates over the zonal wind (second) term, above say 130 km where *r* becomes increasingly smaller than unity as the ions become gradually more and more magnetized with increasing altitude. Therefore in the upper *E* region the meridional winds play the dominant role in vertical plasma convergence with layers forming most effectively in the presence of a suitable meridional wind shear, that is, with a northward wind above and a southward, or smaller northward, wind below. Note that the meridional effects as described apply for the Northern Hemisphere.

[8] Since most E_s layers are centered below 110 km, their frequent presence there is sustained solely by a vertical shear in the zonal wind, or even a steady westward wind that pushes the plasma downward till it is nearly stopped by collisions. On the other hand, above 125 km a northward meridional wind pushes ions down in the upper *E* region, acting as a source of metallics for layer forming at lower *E* region altitudes. Finally, as shown by *MacDougall* [1974], no wind component will cause plasma drift below 95 km because the vertical Lorenz forces diminish there. In addition, E_s layers start to deplete quickly below this altitude because of sharp increases in the metallic ion recombination rates.

3. Data Sets and Methods of Analysis

[9] Paper A was motivated by the work of *Clark et al.* [2002], who presented mesospheric wind measurements showing the occurrence of a westward propagating 7-day PW of zonal wave number *S* = 1,which lasted more than 20–25 days during the second half of August and well into September 1993. This wave was present mostly in the meridional wind with a peak to peak amplitudes in excess of 15 m/s. Paper A dealt only with the analysis of sporadic *E* critical frequency (*foEs*) time series from a number of midlatitude ionosonde stations spanning a large range of longitudes in the Northern Hemisphere and focused on the detection and investigation of the properties of the anticipated 7-day periodicity in E_s. In the present paper the investigation of the PW - E_s relationship is carried one step further by means of correlating concurrent mesospheric neutral winds and *foEs* data from neighboring locations.

[10] In this study, the neutral wind data were hourly mean values of zonal and meridional winds measured, during the entire August–September 1993 period, by the medium frequency (MF) radar in Saskatoon, Canada (52°N, 107°W), and the meteor wind radar (MR) in Sheffield, United Kingdom (52°N, 2°W). The wind measurements were compared with available *foEs* observations made with ionosondes located as near to the radars as possible, that is, we used Boulder, Colorado (40°N, 105°W), *foEs* data for the American sector (Saskatoon), and Lannion, France (49°N, 3°W) data for the west European sector (Sheffield). Since the Saskatoon MF radar provides measurements with 3-km height resolution, time series of wind speeds covering the

altitude range from 91 to 103 km were used. On the other hand, the MW radar in Sheffield provides height integrated measurements of a weighted wind profile centered approximately at about 90 to 92 km.

[11] The wavelet transform was used in order to obtain representative spectrograms for the wind and *foEs* time series. The wavelet method has become a favored tool in geophysics for analyzing non stationary time series. By decomposing the time series into the time-frequency (or time period) space, the wavelet transform can determine both the dominant periodicities and their dynamic change [e.g., see *Torrence and Compo*, 1998]. In the present analysis the Morlet wavelet was applied, which consists of a sine wave modulated by a Gaussian envelope and is used widely with ionospheric data and MLT wind time series [e.g., see *Pancheva and Mukhtarov*, 2000]. A refinement of this analysis has also been used to investigate concurrent periodicities being present in two or more time series. In this case, a cross-wavelet analysis was applied that produced cross wavelet spectra. For each periodicity T, the cross spectral estimate is a complex quantity $C(T) = Pe^{j\Theta}$, where the amplitude P is a measure of the significance that the periodicity is present in both time series, whereas the angle Θ represents the phase difference between the periodicity in each time series. In addition, the high resolution spectral analysis method of the correloperiodogram, as described by *Kopecky and Kuklin* [1971], was also applied to compute amplitude spectra.

[12] The wavelet transform used here requires regularly spaced data points in the time series under consideration, i.e., there should be no gaps in the data. In the present work, small data gaps of 2–4 hours duration were filled by an interpolation scheme based on data points on either side of the gap and using a least squares fit of a second-degree polynomial with exponentially decreasing weights as one moves away from the gap. Larger data gaps of 4 to 8 hours were filled by first applying a daily tidal fit. The gaps are filled with the fitted values plus a random error distributed uniformly in the range of ±1 standard deviation. If the length of the gap was longer than 24 hours, as there were only a few of those in our data, the following procedure was used, which applies when the frequency of the dominant signals in a given time series is known in advance (as is for example in the case of 12- and 24-hour tides). First, the data points neighboring the gap, but for an interval at least two times longer than the gap, were used to determine the mean amplitudes and phases of the strongest periodic components in that segment. Second, the gap was filled with data derived from these values, under the constraint that the variance of the data used to fill the gap must be the same as that of the neighboring time intervals.

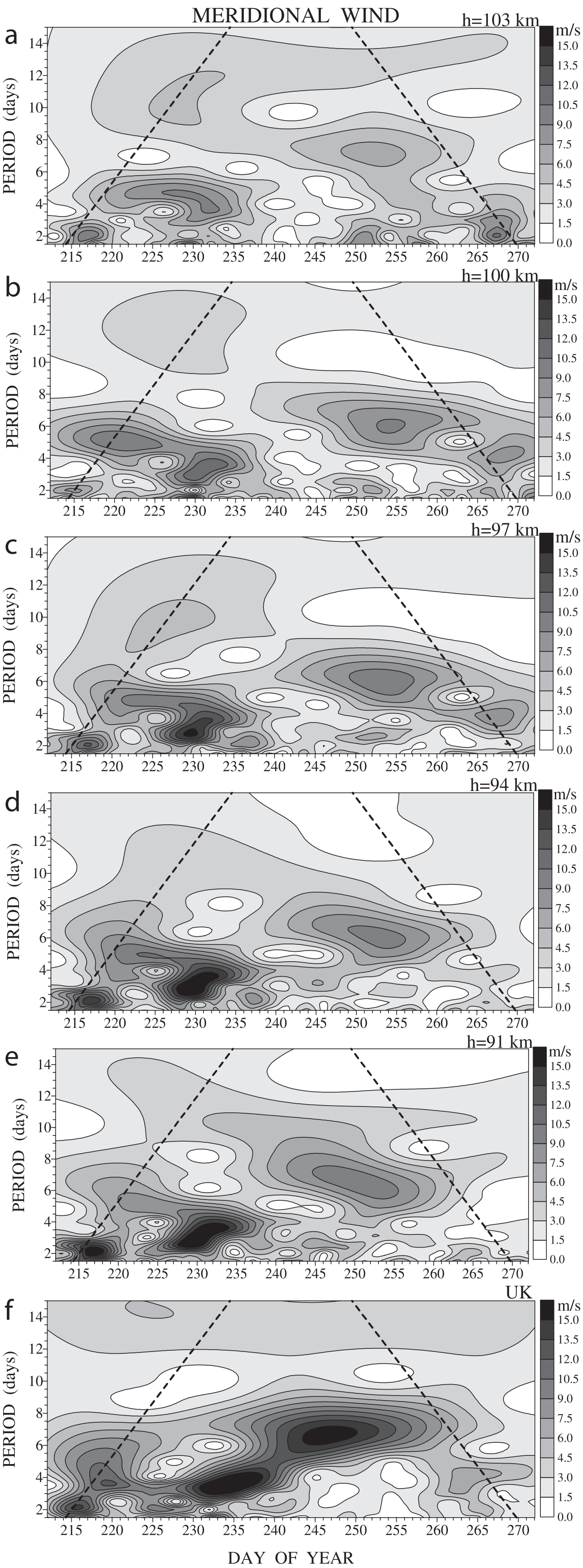
[13] Since the objective of this work was to study in detail the PW-E_s relationship through incorporating a possible role for the modulated atmospheric tides, the underlying winds and tides were uncovered by using appropriate techniques for analysis, that included a best fit procedure to extract the periodicities from the time series. In brief, the raw data were analyzed by means of using a linear least squares fit method which included the mean wind, and the 24-, 12-, and 8-hour harmonic components. The data points were weighted in the fitting process according to the number of individual measurements contributing in each hourly mean. For the Saskatoon measurements, each height was treated separately and the harmonic components were determined in segments of 24-hour duration. Next, the mean wind and tidal components were obtained only when the daily time segment consisted of more than 16 hours. Then this segment was incremented through the time series in steps of 1 hour and the analysis was repeated, yielding hourly spaced values for the mean wind, the 24-, 12-, and 8-hour tidal amplitudes and phases. To estimate the confidence levels, the Student T test was used under the assumption that the residual error in the fit was representative of Gaussian white noise.

4. MLT Winds and *foEs* 7-Day Period Variations

[14] As shown by *Clark et al.* [2002], the 7-day PW periodicity under consideration occurred in the second half of August and into September 1993 and was evident overwhelmingly in the meridional wind. Also, it propagated westward and was stronger in the European than the American sector. This is also verified by the wavelet spectrograms shown in Figure 1 for the meridional wind measured in Sheffield (Figure 1f) and Saskatoon (Figures 1a–1e for the five altitude levels from 91 to 103 km). As seen, the 7-day PW dominates the spectrum from about day 235 to 265, having amplitudes near 16 m/s for the United Kingdom and 10–12 m/s for Saskatoon. The Saskatoon records show that above 97 km the PW amplitude tends to decrease with altitude. It is interesting to note also that prior to the 7-day event, from about day 225 to 240, both stations see a strong 4 day periodicity whose amplitude, as evidenced by the Saskatoon data, is again decreasing with altitude.

[15] As shown in paper A, the 7-day periodicity seen in the meridional wind, was also present in the sporadic *E* critical frequency *foEs* for a number of midlatitude ionosonde stations stretching in longitude from 58°E to 157°W. For completeness we include here the spectrograms for the ionosonde stations Boulder and Lannion used in the present study. These are the nearest ones to the radar sites in Saskatoon and Sheffield, respectively. Figure 2 (top) shows the Boulder *foEs* spectrogram and Figure 2 (bottom) shows the Lannion one for the same time interval of August–September 1993. As seen, the 7-day periodicity in *foEs* is stronger in the Lannion measurements where it reaches an amplitude of 1.4 MHz as compared to 0.9 MHz seen in the Boulder data. This is in line with the mesospheric wind observations suggesting that the observed PW is stronger over Europe than North America. Finally, note that the strong 4-day periodicity seen in the meridional winds prior to the 7-day PW event is absent from the *foEs* time series.

[16] The next logical step is to compare the 7-day (PW) periodicities seen in the meridional wind with those in *foEs*, keeping in mind of course that these variations were measured at different altitude. To achieve this, a linear phase band-pass filter, centered at T_0 = 7 days, was used and applied to all available time series. Most of the filtered outputs are compared in Figure 3 during the PW occurrence, from day 235 to 265. The dashed lines represent the *foEs* 7-day periodicity which is superimposed on the filtered meridional winds at Sheffield (Figure 3c) and Saskatoon (Figures 3a and 3b, with Figure 3a referring to 94 and 97 km



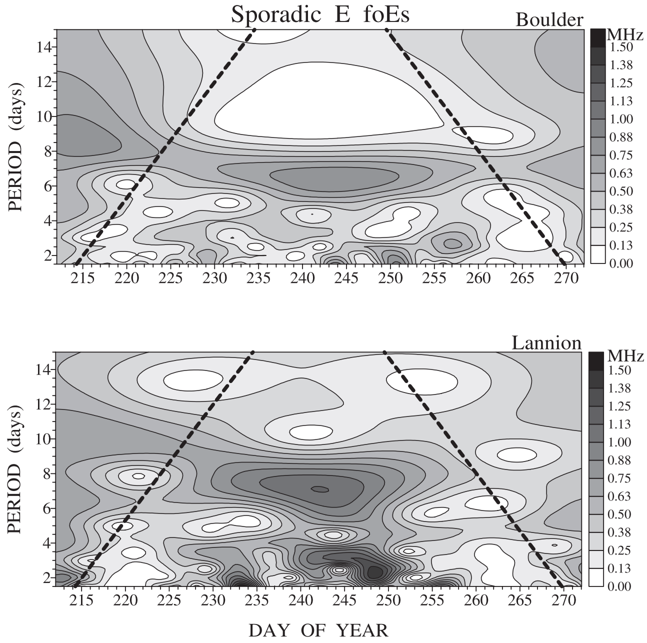


Figure 2. Wavelet spectrograms for sporadic *E* layer critical frequency, *foEs*, time series measured in Boulder (40°N, 105°W) and Lannion (49°N, 3°W) during August–September, 1993.

wind and Figure 3b referring to 100 and 103 km wind). As expected, there is a good deal of agreement between the *foEs* variations and 7-day periodicity in the meridional wind. Also there is a systematic time difference, with the variation in *foE* leading the 7-day wave-like variations in the meridional wind.

[17] Inspection of Figure 3 shows that the phase difference between *foEs* and the 7-day wave in the meridional wind appear to decrease with increasing altitude, apparently because of a downward phase propagation of the PW. This is clear in the Saskatoon measurements which are summarized in Figure 4. Figure 4 (left) shows the filtered waveforms for all altitudes from 91 to 103 km showing a systematic phase difference with the wave front progressing with time from higher to lower altitudes. This was confirmed by computing the phase gradient of the wave from about 92 to 102 km, expressed in hours per kilometer and shown in Figure 4 (right). The phase gradient estimates were obtained by two independent methods: the solid line phase gradients resulted from cross-correlation analysis of the filtered waveforms in Figure 4 (left), whereas the dashed line ones from wavelet cross spectral analysis of different altitude time

Figure 1. (opposite) (a–e) Wavelet spectrograms of the neutral meridional wind measured by the MF radar in Saskatoon, Canada (52°N, 107°W) at five different altitude levels (marked at the top right side of each plot), and (f) the wavelet spectrogram for the meridional wind measured by the meteor radar in Sheffield, United Kingdom (52°N, 2°W), during August–September 1993. The slanted thick dashed lines indicate the regions where the edge effects may become important. See text for more details.

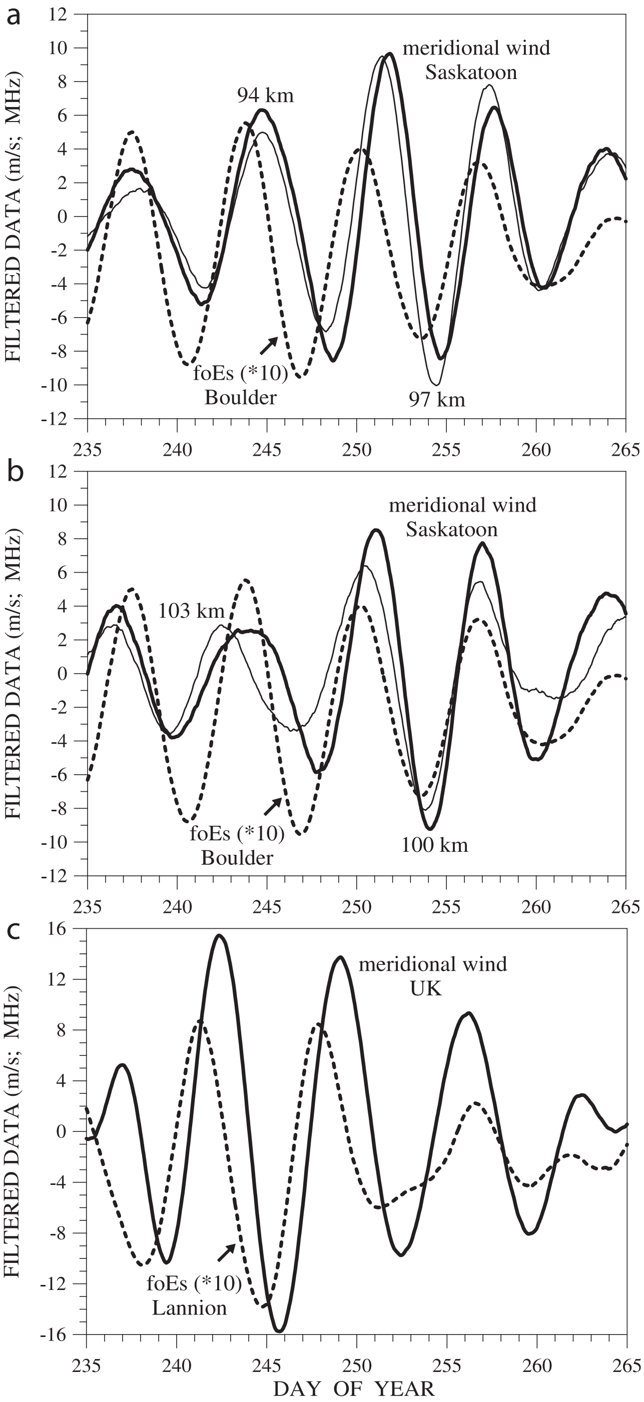


Figure 3. (a) Comparison of the 7-day band-pass-filtered meridional wind at h = 94 km (thick solid line) and at h = 97 km (thin solid line) observed in Saskatoon with the 7-day band-pass-filtered *foEs* periodicity (dashed line) observed in Boulder. (b) Same as Figure 3a but for the meridional wind measured in Saskatoon at 100 km and 103 km. (c) Comparison of the 7-day band-pass-filtered meridional wind observed in Sheffield, United Kingdom (thick solid line), with the 7-day band-pass-filtered *foEs* periodicity (dashed line) observed in Lannion, France.

series in the meridional wind. As seen both methods yielded similar results suggesting a vertical wave phase propagation with a mean altitude rate of about −2.5 h/km. Finally, as seen from Figure 4 (left), the wave amplitude does also decrease with altitude at about −0.3 m/s per kilometer.

[18] In an effort to assess the implications of this PW/*foEs* comparison, we make the assumption that the 7-day wave maintains the same −2.5 h/km rate of phase change with altitude for heights above 100 km. In this case, we find the PW and *foEs* periodicities to be in phase at about 107 km, that is, the maximum northward PW wind coincides with the *foEs* maximum. This good degree of agreement, however, does not necessarily imply a direct relationship between the two periodicities. This is because, as discussed in section 2, a northward wind will have no effect in transporting ions downward below 120 km, therefore it cannot play a direct role on E_s formation. On the other hand, and if we assume that the PW can propagate at a gradient of −2.5 h/km well into the upper *E* region, say above 130 to 140 km where a meridional wind can cause vertical ion transport, the PW meridional wind will be more or less out of phase with *foEs*, which again argues against a direct role for this 7-day PW on the E_s layering process. Furthermore, it is questionable if PWs can penetrate efficiently into the upper *E* region [e.g., see *Forbes et al.*, 1995], and if they do apparently their amplitudes must be greatly reduced, which is in line with the measured amplitude attenuation rate of −0.3 m/s per kilometer.

[19] Although the wind shear theory does not favor a direct role of this 7-day PW on E_s, such a direct PW role cannot be entirely excluded because there might be a different mechanism at work not represented in the simplified basic theory outlined in section 2. For example, *Shalimov et al.* [1999] proposed a new mechanism for horizontal convergence of metallic ions in the *E* region driven by PW winds. In this process, which was formulated in more detail recently by *Shalimov and Haldoupis* [2002], the long-living metallic ions are Lorentz-forced to converge horizontally and accumulate inside areas of positive PW vorticity set up by cyclonic neutral wind shears associated with the PW. In this way, vertical wind shears acting inside these areas can form stronger E_s layers than in areas of negative vorticity. Unfortunately the present, single station, wind measurements cannot be used to provide vorticity estimates, therefore our data alone cannot test the validity of the Shalimov and Haldoupis mechanism.

5. PW Influence on E_s via Modulation of Tides

[20] On the basis of our analysis, we conclude that for the strong PW event under consideration there is no convincing evidence in favor of a direct PW role on $\boldsymbol{E_s}$ generation. This points to the possibility for an indirect PW role, probably through the modulation of atmospheric tides. We arrived at this speculation because of the nonlinear interactions between tides and planetary waves which are known to take place in the middle atmosphere [*Cevolani and Kingsley*, 1992; *Rüster*, 1992; *Beard et al.*, 1999; *Jacobi*, 1999; *Pancheva*, 2000, 2001], and the conviction that PWs modulate upward propagating tides and through them mediate their signatures in the ionosphere [e.g., see *Forbes*, 1996]. In addition, the role of atmospheric tides on E_s formation is

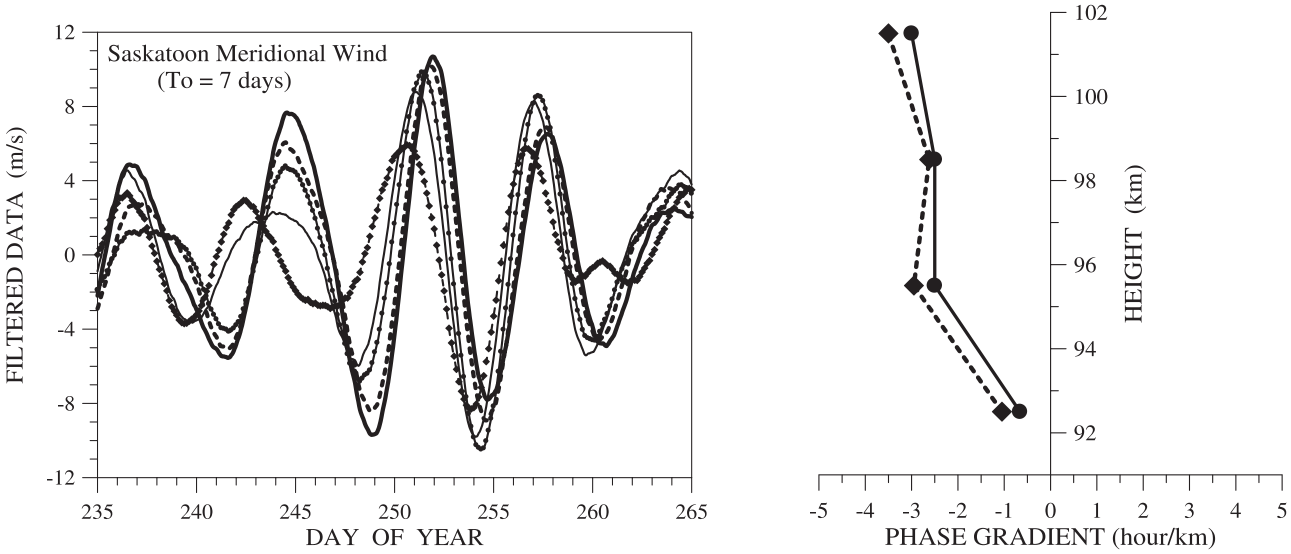


Figure 4. (left) The 7-day band-pass-filtered meridional wind measured in Saskatoon at five different altitude levels between 91 and 103 km. The different altitudes are denoted as follows: h = 91 km, thick solid line; h = 94 km, thick dashed line; h = 97 km, solid line with dots; h = 100 km, thin solid line; and h = 103 km, dashed line with diamonds. (right) The 7-day wave phase gradient measured in hours per kilometer for the meridional wind in Saskatoon, as determined by two methods: (1) cross-correlation analysis performed on the filtered data between days 235 and 265 when the 7-day wave activity was strongest (solid line with dots), and (2) cross wavelet analysis (dashed line with diamonds).

well established and considered to be of fundamental importance in the physics of midlatitude sporadic *E* layers, e.g., see review by *Mathews* [1998, and references therein].

[21] In the following, we investigate the option of PW-driven modulatory effects on the diurnal and semidiurnal tides measured in Saskatoon and Sheffield during the August–September PW event, and examine if similar effects are concurrently evident in the *foEs* time series. This, if true, would suggest a new mechanism for the observed relationship between PWs and sporadic *E* layers.

5.1. PW Modulation of 12- and 24-Hour Atmospheric Tides

[22] Here the wind data are analyzed in order to detect if the tides observed in Saskatoon and Sheffield are also modulated with a period of ~7 days during the time interval from day 235 to 265, 1993, when the 7-day PW was dominant. The interaction between PWs and atmospheric tidal waves is a nonlinear process [*Teitelbaum and Vial*, 1991] which resembles, for example, amplitude modulation (AM) in communication systems. As a result of this interaction, one would expect to find in the data two secondary waves having frequencies respectively equal to the sum and difference of the frequencies of the interacting primary waves, that is, $\omega_T \pm \omega_{PW}$ for the interacting tidal and planetary waves. In terms of periods, this means for the 7-day PW modulation that the secondary waves must have periods: (1) for the 12-hour tide near 11.1–11.2 hours and 12.9–13 hours, and (2) for the 24-hour tide near 21.0 and 28.0 hours, respectively. In the following we search for such secondary waves in both the Saskatoon and Sheffield semidiurnal and diurnal tides.

[23] As shown in Figure 5, the 7-day tidal modulation was found to be present in both amplitude spectra of the zonal (Figure 5, left) and meridional (Figure 5, right) winds measured in Saskatoon (Figure 5, top) and in the United Kingdom (Figure 5, bottom). The amplitude spectra were computed by the correloperiodogram method for the period range between 3 and 36 hours. The spectra are calculated only for the time series between days 235 and 265 when the 7-day PW activity was strongest. The two arrow pairs in each plot indicate the position in the spectrum of the secondary peaks discussed previously if their amplitudes exceed the 95% confidence level. As evidenced in Figure 5, in both, the Saskatoon and the United Kingdom (Sheffield), longitudinal sectors the measured tides are 7-day amplitude modulated, with the secondary waves being stronger in the zonal component of the semidiurnal tide and the meridional component of the diurnal tide. Note that the two secondary waves are also present in the Saskatoon meridional component of the semidiurnal tide but not as clearly as in the zonal component. Apparently this is because of interference with nearby peaks, most likely relating to the interaction with the strong 4- to 5-day PW that was also present in the data for part of the time interval under analysis (e.g., see Figure 1). Figure 5 shows both the Saskatoon and Sheffield diurnal tide to be much stronger in the meridional rather than the zonal component. In addition, the meridional diurnal tides are more deeply modulated by the 7-day (modulation levels are between 50 to 80%) than the zonal semidiurnal tides (modulation levels are less than 30%).

[24] To confirm the previous results and locate in time the tidal modulations, wavelet transform analysis was performed on the time series of the tidal amplitudes. Before doing this, we first removed the 7-day wave from the data in order to avoid any artificial coupling between the tidal amplitudes and the mean wind (because of some nighttime gaps in the original data). In this way we show that the tidal

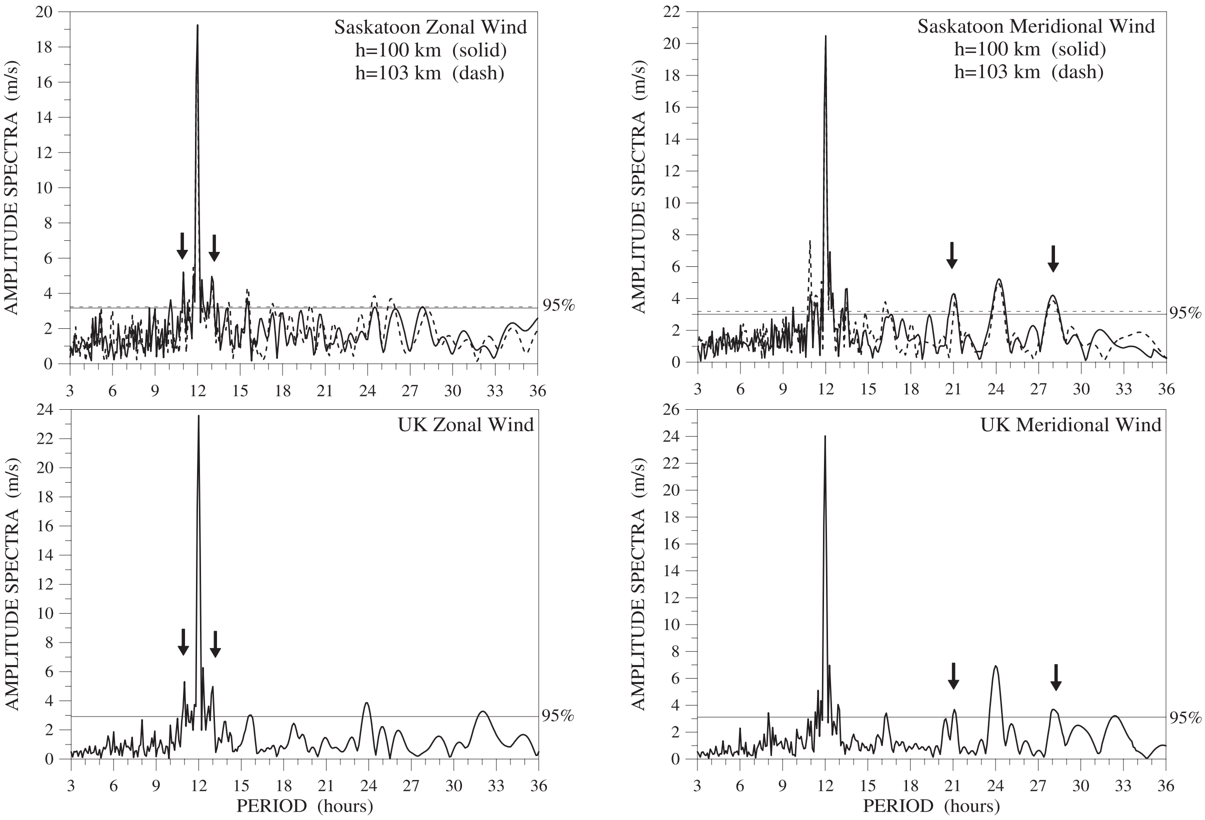


Figure 5. Amplitude spectra of the (left) zonal and (right) meridional winds measured at h = 100 and 103 km (top) in Saskatoon and (bottom) in Sheffield, United Kingdom, obtained by the correloperiodogram method for the period range between 3 and 36 hours. The spectra are calculated only for the interval between days 235 and 265, when the 7-day PW activity in the meridional wind is strongest. The pairs of arrows shown in the plots indicate the secondary waves, resulting from the nonlinear interaction between the 12- and 24-hour tides and the 7-day PW.

characteristics (or in this case the tidal modulations) is not an artefact of the data analysis itself. As expected, the wavelet spectral analysis confirmed the 7-day PW modulation detected in the correloperiodograms of Figure 5. The wavelet spectrograms are shown in Figures 6 and 7, for the meridional diurnal tide and the zonal semidiurnal tide, respectively, in full analogy with Figure 5. Figures 6 (top) and 7 (top) correspond to the Saskatoon 100 and 103 km MF radar winds, whereas Figures 6 (bottom) and 7 (bottom) correspond to the Sheffield meteor radar winds. As seen, strong modulations with period 6–7 days are clearly present in the tides at each altitude. Again, these are amplified in the time interval between days 235 and 265 when the 6–7 day PW dominated the wind.

5.2. PW Modulation of *foEs* 12- and 24-Hour Periodicities

[25] The next logical step was to search if the 7-day PW modulation was also present in the *foES* 12- and 24-hour periodicities. As discussed by *Mathews* [1998] in his review paper, the semidiurnal and diurnal periodicities are imprinted on sporadic *E* layers because the layer occurrence and strength are controlled mostly by the semidiurnal and diurnal tidal waves in the altitude range from 100 to 160 km. This knowledge was obtained with the incoherent scatter radar at Arecibo, which can monitor accurately midlatitude sporadic *E* layers. The same periodicities in E_s were also confirmed from high resolution ionosonde measurements reported by *Wilkinson et al.* [1992], and *Szuszczewicz et al.* [1995]. Obviously, if the 7-day modulation is also present in the diurnal and semidiurnal variations of *foEs*, then this constitutes reassuring evidence in favor of an indirect PW role on E_s through the modulation of atmospheric tides. A similar line of reasoning was also applied in the analysis of *Pancheva et al.* [2002] in order to prove that the observed 16-day variability in *hmF*2 measured during the summer of 1999, was probably generated by the global-scale 16-day modulation of the semidiurnal tide measured in the MLT region during the PSMOS (Planetary Scale Mesopause Observing System) campaign.

[26] In search for the 7-day modulation in *foEs* we applied the same methodology used in the wind data, that is, correloperiodogram and wavelet spectral analysis, and looked for spectral peak pairs about the 12-hour periodicity near 11 and 13 hours, and about the 24-hour periodicity near 21.0 and 28.0 hours. Figure 8 shows the *foEs* amplitude correloperiodograms for Boulder (Figure 8, top) and Lannion (Figure 8, bottom). As seen, there is a very good deal of agreement in the two spectra despite that the stations are more than 100° apart in longitude. The 12- and 24-hour periodicities in *foEs* are present at both stations, but the diurnal periodicity is by far the dominant. This differs when

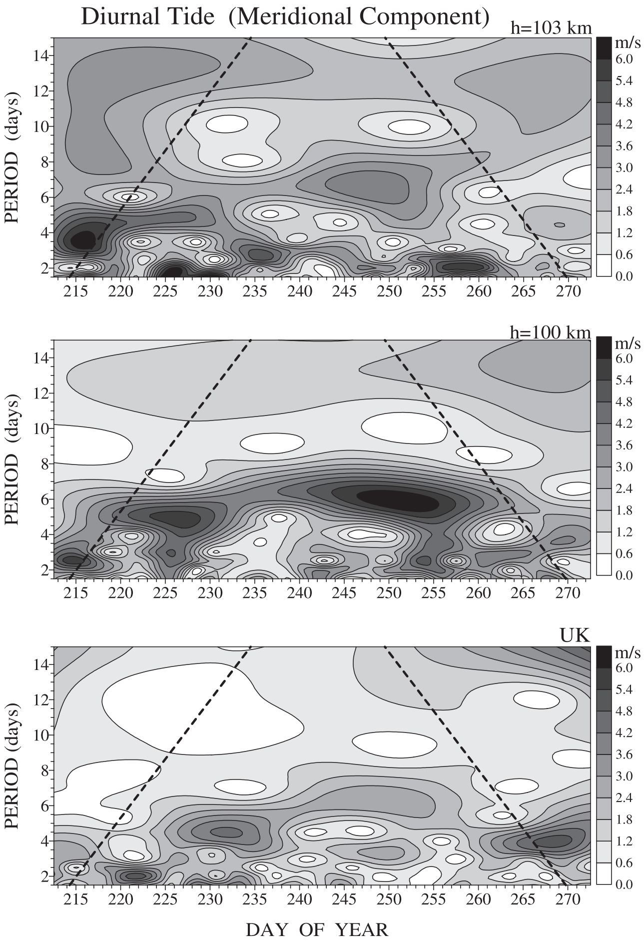


Figure 6. Wavelet transform spectrograms for the amplitudes of diurnal tide (meridional component) measured in Saskatoon at (top) 103 km and (middle) 100 km, and (bottom) in Sheffield, United Kingdom, during August–September 1993.

it is compared to the MLT wind spectra shown in Figure 5 for Saskatoon and Sheffield, where the semidiurnal tide is dominating over the diurnal one. The latter is commonly found for high midlatitudes. This difference may be understood if we take into consideration the Arecibo radar measurements of E_s [e.g., see *Mathews*, 1998] which show that the semidiurnal tides affect mostly the descending intermediate layers in the upper *E* region whereas the diurnal tides are most effective at lower *E* region altitudes to which the E_s ionosonde data are heavily biased.

[27] Figure 8 shows clearly that the 24- and 12-hour periodicities in *foEs* are both 7-day amplitude modulated. As seen, the strong peaks at each side of the 24-hour periodicity with periods exactly at 21 and 28 hours are obviously present in both ionosonde stations, standing out well above the 95% confidence level. As for the 11 and 13 hours peaks about the semidiurnal periodicity, these are also present (especially in Lannion), but they are weaker than those seen in the diurnal periodicity. Note that the strong 7-day modulation measured in the *foEs* 24-hour periodicity is also in line with the deep 7-day modulation seen in both the Saskatoon and Sheffield 24-hour meridional tide.

[28] Finally, Figure 9 shows the wavelet spectrograms for the 12- and 24-hour periodicity amplitudes for Boulder (Figure 9, left) and Lannion (Figure 9, right). These amplitudes were obtained from the *foEs* time series in the same way as the tidal amplitudes in the neutral wind. The wavelet analysis here confirmed the results of the correloperiodograms shown in Figure 8. As seen, the 24-hour periodicity undergoes a much stronger 7-day modulation at both stations, while the 12-hour periodicity modulation is weaker but present in both stations, especially Lannion. Note that the same analysis was performed for all eight ionosonde stations used in paper A and yielded similar results, namely, (1) the 7-day modulation in the 24-hour periodicity was the strongest and was present in every station except in the low latitude station of Maui, and (2) the 7-day modulation in the 12-hour periodicity was weaker but seen clearly in all stations.

6. Summary and Concluding Comments

[29] The study by *Haldoupis and Pancheva* [2002] during a 7-day period global PW event, which relied on multistation ionosonde data covering a large longitudinal sector, proved that there is a dependence of midlatitude sporadic *E* layers on planetary waves. The present paper has taken this recent work a step further by considering the same PW event and performing a detailed correlative analysis between simultaneous MLT radar wind measurements made in central

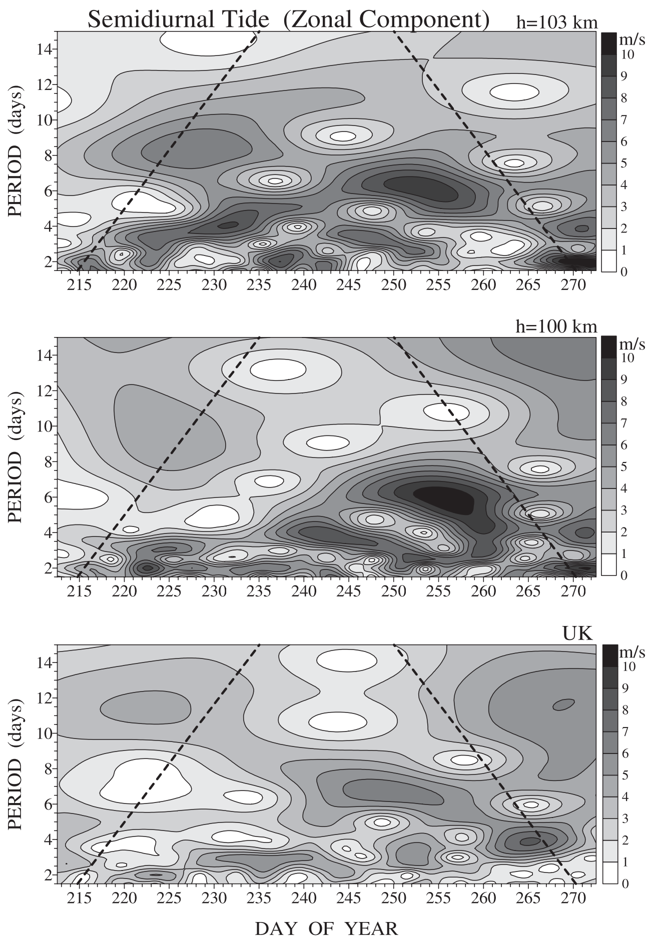


Figure 7. Same as in Figure 6, but for the amplitudes of the zonal component of the semidiurnal tide.

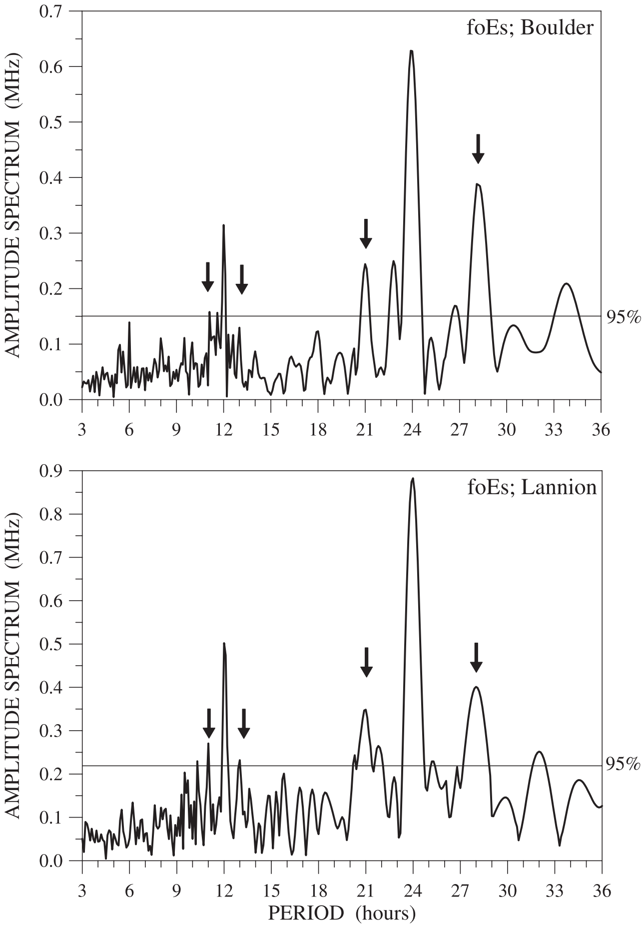


Figure 8. Correloperiodogram spectra, as in Figure 5, but for *foEs* measured (top) in Boulder and (bottom) in Lannion.

Canada and western Europe, and nearby ionosonde sporadic *E* layer *foEs* time series. The purpose was to use sophisticated analysis methods in order to obtain some physical insight into the working mechanism behind the observed relationship between planetary waves and sporadic *E* layers.

[30] By computing the PW phase and amplitude rates of change with altitude, it was concluded that the PW itself is unlikely to propagate in the upper *E* region and thus could not play a direct role on E_s formation which would be in line with the vertical plasma transport predictions of the basic wind shear theory. Consequently, this led to the search for an indirect PW role on E_s, possibly through the PW modulation of atmospheric tides which are known to intensify with altitude and penetrate into the upper *E* region. Our analysis revealed, for the PW event under consideration, that there is a clear 7-day amplitude modulation of the semidiurnal and diurnal tides, seen in both the European and the American sectors, caused apparently by a nonlinear interaction process between planetary and tidal waves below 100 km. This modulation is much stronger in the diurnal rather than the semidiurnal tides, whereas it prevails more on the 24-hour meridional and 12-hour zonal components. Given that atmospheric tides play a fundamental role on E_s formation, it was postulated that the reported PW effects on E_s are basically induced indirectly through the 7-day modulated tides. This postulation was reinforced greatly by the results of the same analysis applied also on the concurrent *foEs* time series, which showed that the existing *foEs* 12- and 24-hour periodicities, caused presumably by the wind shear action of the semidiurnal and diurnal tides, were also clearly amplitude modulated by the same 7-day PW period.

[31] Although our present analysis cannot exclude the mechanism of *Shalimov and Haldoupis* [2002], which proposes horizontal metallic plasma convergence within areas of positive PW vorticity as an additional cause for

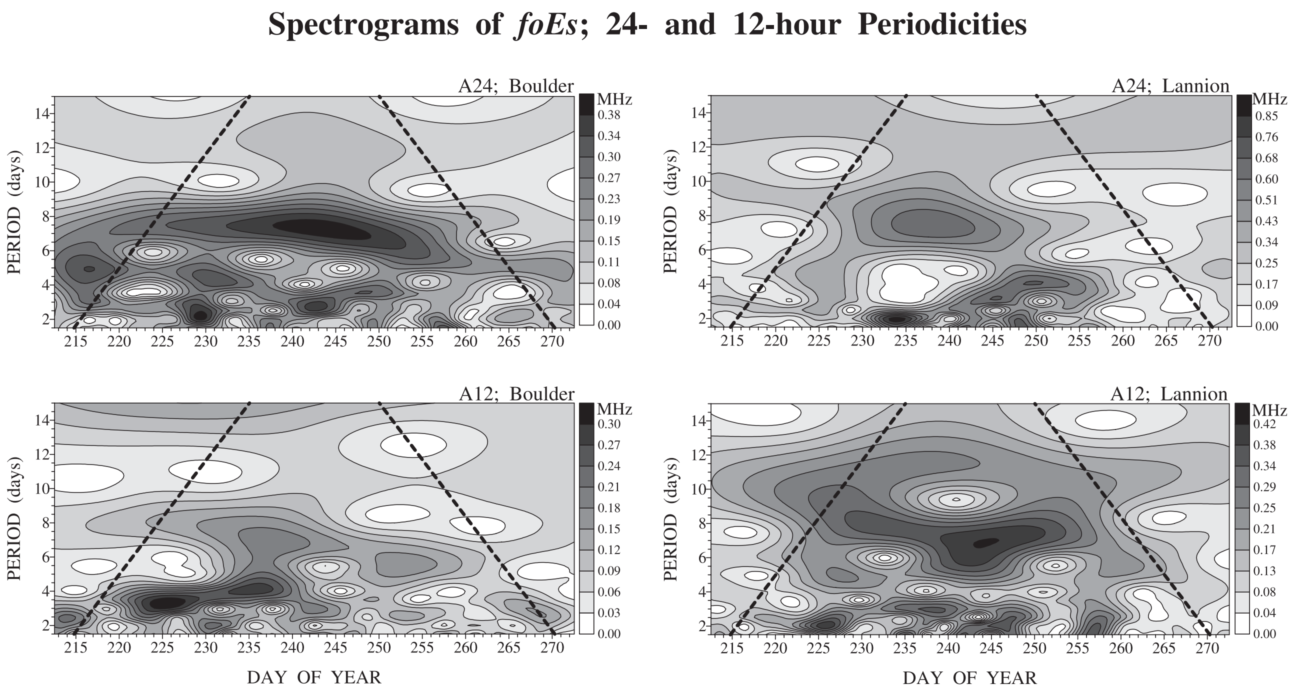


Figure 9. Wavelet spectrograms for the amplitudes of the (top) 24-hour and (bottom) 12-hour periodicities in *foEs*, for (left) Boulder and (right) Lannion during August–September 1993.

the sporadic *E* layer PW dependence, it provides convincing evidence in favor of an indirect PW role on E_s formation through the PW-modulated tides and vertical plasma convergence along the lines of the classic wind shear theory. This is a new finding which can account, at least partially, for the observed dependence of midlatitude sporadic *E* layers on planetary waves.

[32] Finally, it should be mentioned that the details of the tidal effects on E_s formation are not easily discernible from the available data. This is because the wind measurements, and thus the observed PW modulation of tides, are made at altitudes below about 100 km whereas the formation of E_s is taking place at higher altitudes in the range from about 100 to 160 km, considering also contributions from the intermediate descending layers in the upper *E* region. This means that, in order to assess the importance of the modulated 12- and 24-hour tides in the framework of the wind shear theory, we need to know their altitude propagation properties, particularly their vertical wavelength, phase velocities and polarization. We feel it is outside the scope of this paper to speculate on the altitudinal tidal characteristics and discuss the various scenarios on tidal E_s layer forming at different altitudes, for example to examine how the measured 12-hour modulated zonal tidal component at 100 km acts at 150 km in transporting vertically metallic ions. The present paper aims only in reporting our findings on a new mechanism for the observed dependence of sporadic *E* layers on planetary waves. To investigate the details of this process is a major task which it is hoped to be undertaken in a future study. This will attempt to model the 7-day PW effects on E_s layer forming through nonsteady state solutions of the generalized wind shear theory, taking also into consideration the altitude propagation characteristics of the PW-modulated diurnal and semidiurnal tides.

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