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Terdiurnal tidelike variability in sporadic *E* layers

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[1] Time series analysis was performed on a large database of ionosonde recordings taken over 12 years, for the 6-month period from the beginning of May to the end of October when sporadic *E* layer occurrence is frequent. The results show that in addition to the well known 24- and 12-hour tidal variations, there is also a weaker but regular 8-hour periodicity in midlatitude sporadic *E* layers (E_s). Statistically, this terdiurnal periodicity is significant and occurs in both the sporadic *E* layer critical frequency (*foEs*) and the layer virtual height ($h'Es$), becoming strongest around summer solstice and later in October after a minimum in September. At times a weak 6-hour periodicity can also be present in E_s but its effects are much less significant than those of the 8-hour oscillation. The 8-hour periodicity in E_s is attributed to the terdiurnal tide, presumably acting through its vertical wind shear forcing of the metallic ions in the lower thermosphere. The relation to the terdiurnal tide was inferred from simultaneous ionosonde recordings from three widely spaced stations in the same midlatitude zone, showing the 8-hour oscillation to be present simultaneously in all ionosonde stations and have phases which are consistent with a westward propagating terdiurnal wave of zonal wave number 3. The present study establishes the regular occurrence of a terdiurnal tidelike oscillation in E_s which needs to be incorporated into the physics and modeling of sporadic *E* layer formation and dynamics.

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1. Introduction

[2] The atmospheric tides in the lower thermosphere play a key role in the formation and vertical motion of midlatitude sporadic *E* layers (E_s) through their windshear action on the long-living metallic ions [e.g., see *Mathews*, 1998]. Arecibo incoherent scatter radar (ISR) observations [e.g., see *Mathews and Bekeny*, 1979] and ionosonde studies [e.g., see *MacDougall*, 1974; *Wilkinson et al.*, 1992; *Szuszczewicz et al.*, 1995; *Haldoupis et al.*, 2006] have shown that the pronounced variations in sporadic *E* are the 24- and 12-hour periodicities impacted upon by the action of the diurnal and semidiurnal tides. The sporadic *E* layers are controlled mostly by the diurnal tide which becomes dominant below 120 km, whereas the 12-hour periodicity in E_s is caused by the Descending Intermediate Layers (DILs) which are initiated by semidiurnal tides in the upper *E* region and move downward acting as a parenting process for E_s in the lower *E* region. Regarding shorter period tidelike variations in sporadic *E*, e.g., variations with periods of 8 and 6 hours, the existing published evidence is rather limited and circumstantial.

[3] The present paper is the first systematic study of the short period periodicities in midlatitude sporadic *E*. It comes as continuation of work we have done on tidal and planetary wave effects and variations on E_s layers [*Haldoupis and Pancheva*, 2002; *Pancheva et al.*, 2003; *Haldoupis et al.*, 2004, 2006]. In particular, this work was motivated by a case study reported by *Haldoupis et al.* [2004], showing that besides the strong 24- and 12-hour tidal periodicities in E_s there was present at times a weaker 8-hour oscillation as well. This was attributed to a terdiurnal tide in the lower thermosphere which apparently affected the windshear process of E_s formation. Previously, *Szuszczewicz et al.* [1995] were the first to find hints in favor of an 8-hour periodicity in E_s by analyzing sequential ionograms. On the other hand, and to our knowledge, there are no reports on ISR observations of 8-hour periodicities in sporadic *E*. The only Arecibo studies on short period tidelike oscillations in E_s, reported by *Tong et al.* [1988] and *Morton et al.* [1993], refer to 6-hour oscillations that have been attributed to quarterdiurnal tides in the upper *E* region. Such 6-hour periodicities in sporadic *E* were also found by *Lee et al.* [2003] who analyzed digisonde observations made, however, in the low-latitude equatorial anomaly region.

[4] In the present work, ionosonde observations obtained over many years were analyzed in order to identify the regular occurrence and assess the importance of the terdiurnal and quarterdiurnal periodicities in midlatitude sporadic *E* layers. In the following, we focus on the terdiurnal periodicity because this was found to be a regular characteristic in the variability of midlatitude sporadic *E*, critical

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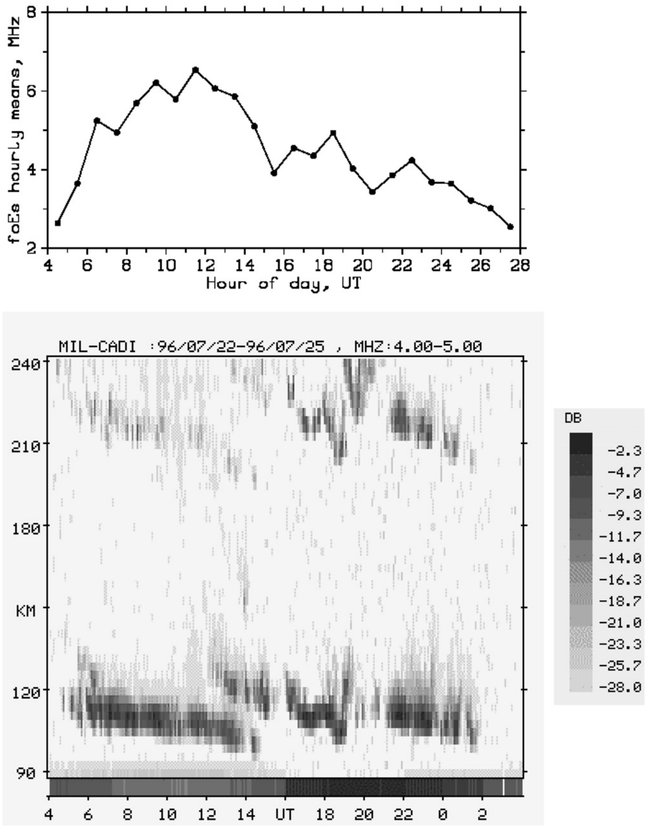

Figure 1. The top panel shows the composite 24-hour diurnal course of *foEs* hourly means observed by a digital ionosonde in Milos from 22 to 25 July 1996 when a strong 8-hour oscillation affected the sporadic *E* layers. The lower panel is the corresponding Height-Time-Intensity (HTI) plot for ionosonde frequencies between 4 and 5 MHz, averaged over the same time interval as the plot in the upper panel. See text for more details.

frequencies *foEs*, and layer heights *h′Es*, a fact which, so far, had escaped attention.

2. Observations of 8-Hour Periodicities in Sporadic *E*

[5] As mentioned, the presence of a tidelike 8-hour periodicity in E_s was initially recognized in a case study by *Haldoupis et al.* [2004]. In their approach, standard analysis techniques used in neutral dynamics were applied on sporadic *E* critical frequency, *foEs*, time series obtained with an ionosonde operating in the island of Milos (36.7°N, 24.5°E) during a summertime period of about 2 months. It was found that an 8-hour periodicity in *foEs* was weakly present throughout the observations while it intensified during an interval of several days. Figure 1 shows the 8-hour periodicity seen in the diurnal variation of *foEs* hourly means, and the E_s-reflected power as a function of (virtual) height and time of day, averaged over 4 days from 22 to 25 July 1996.

[6] The upper panel in Figure 1 shows the averaged *foEs* hourly means during the course of the day, characterized by three peaks separated in time by about 8 hours. The mean terdiurnal (three peaks per day) variability seen in the upper panel was present during each day from 22 to 25 July, as shown by *Haldoupis et al.* [2004] in their Figure 2. The lower panel in Figure 1 displays the corresponding Height-Time-Intensity (HTI) plot computed for the ionogram frequency band between 4.0 and 5.0 MHz (for more details on the HTI plots and their interpretation, see *Haldoupis et al.* [2006]). The HTI plot is dominated between 95 and 125 km by three sequential sloping traces of reflected power, distributed more or less evenly during the 24-hour day, which are in close correspondence with the three broad peaks seen in the upper panel. These sloping traces are attributed to descending E_s layers forming at sequential convergence nodes of vertical wind shears associated with the downward phase propagation of a terdiurnal tide. Note that the weaker traces in heights between 200 and 240 km in Figure 1 are sporadic *E* layer images due to ground-E_s double reflections.

2.1. Occurrence

[7] An objective of this study was to establish if the 8-hour periodicity in E_s is a regular and repeatable feature. To carry out this test, *foEs* and *h′Es* time series of hourly means measured by the Rome ionosonde (41.9°N, 12.5°E) were retrieved for analysis from the web page of the Colorado World Data Center. Note that *foEs* (expressed here in MHz with 0.1 MHz accuracy) is an estimate of the layer's maximum electron density and is used widely to quantify the layer's intensity and variability. As for *h′Es*, this is in kilometers and represents approximately the bottom height of the layer, which is especially true during nighttime when the lower ionosphere is depleted so that group velocity retardation and magnetoionic splitting becomes unimportant.

[8] The Rome ionosonde has been providing reliable data for many years. For our purposes it was possible to find and analyze (following the methodology of *Haldoupis et al.* [2004]) fairly continuous time series of hourly means for the 6-month period from 1 May to 31 October, when sporadic *E* activity in the northern hemisphere intensifies and becomes fairly regular. In the analysis we used observations for a total of 12 years, covering a complete solar cycle from the beginning of 1980 to the end of 1991.

[9] To investigate if the tidelike periodicites were regularly present in the sporadic *E* properties, the high-resolution spectral analysis method of the "correloperiodogram" by *Kopecky and Kuklin* [1971] was used to obtain the amplitude spectra. These were computed for both the *foEs* and *h′Es* time series of every year, for all 12 years under consideration. A typical example is shown in Figure 2, which displays in the top the time series of *foEs* and *h′Es* hourly means for the entire 6-month period from May to October, 1998, and in the bottom the corresponding amplitude spectra which are plotted, along with the 95% confidence level, up to periods of 36 hours. As seen from the times series in the top panels, there are also longer-term periodicities present which, as shown previously by *Haldoupis and Pancheva* [2002] and *Pancheva et al.* [2003], are attributable to planetary waves. These long-term variations are not of interest in this study.

[10] As seen from the bottom panels in Figure 2, the amplitude spectra for *foEs* and *h′Es* are marked by three

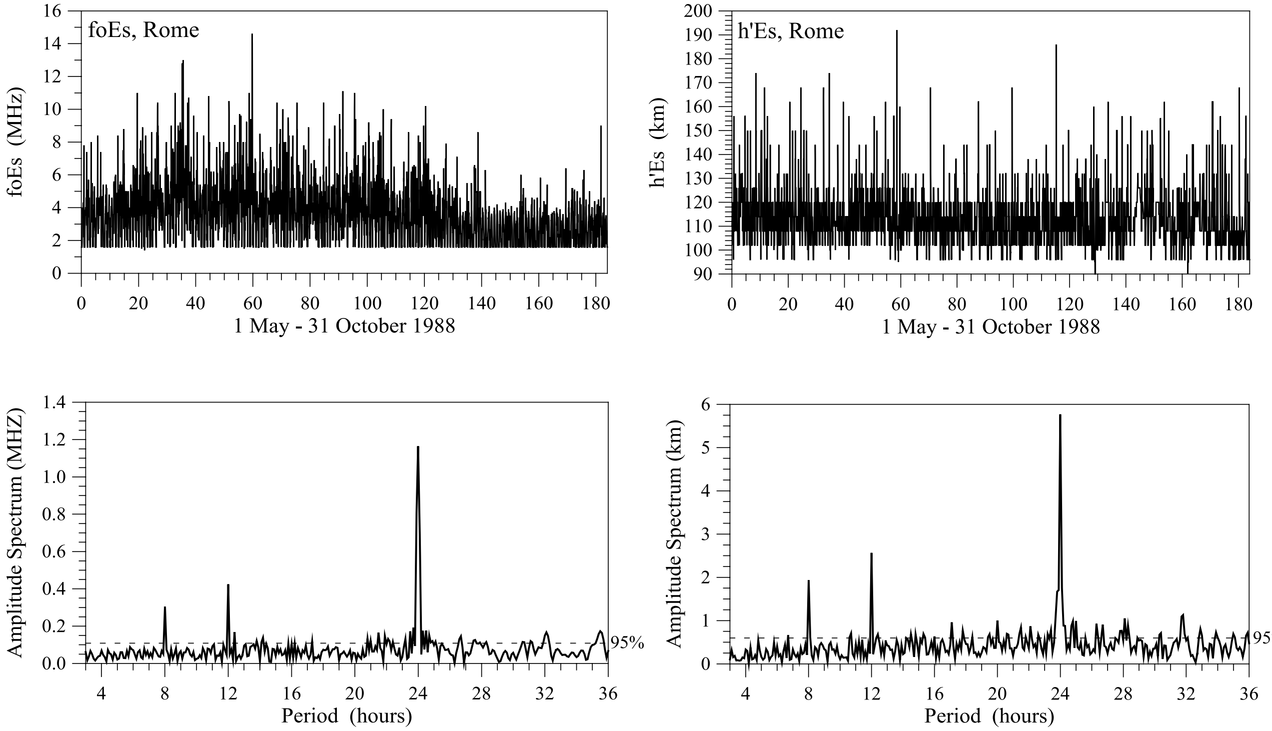

Figure 2. Times series of mean hourly values of *foEs* (top left) and *h′Es* (top right) obtained by the Rome ionosonde from 1 May to 31 October 1988, and the corresponding amplitude spectra shown in the bottom panels. These are dominated by three pronounced periodicities at 24, 12, and 8 hours.

narrow peaks located exactly at 24, 12, and 8 hours. The 24-hour periodicity is by far the strongest, whereas the 8-hour one is the weakest. As shown in previous studies by *Haldoupis et al.* [2004, 2006], the prevailing periodicities at 24- and 12-hours are mostly linked to the diurnal and semidiurnal tides in the lower thermosphere. The strongest support for the tidal origin of the 24-hour and 12-hour periodicities in midlatitude sporadic *E* comes from several Arecibo ISR studies, as discussed also by *Mathews* [1998]. On the other hand, one cannot also exclude the possibility that the strong 24-hour spectral peak in Figure 2 is also partly due to the diurnal course of photoionization, especially when the metallic layers are weak. In the case of stronger E_s layers, however, there are several studies [e.g., see *Whitehead*, 1989; *Mathews*, 1998] showing that the 24-hour periodicity in *foEs* originates on windshears related to the diurnal tide and not the diurnal variations of photoionization.

[11] As it will be shown later in the paper, the 8-hour periodicity seen in the spectra of Figure 2 is a genuine oscillation and not a harmonic caused by the distortion of the dominant 24-hour oscillation. Note that the situation depicted in Figure 2 is typical and applies for nearly all 12 years and that there was no clear solar cycle variability effects. Note also that, and in contrast to the 8-hour oscillation, the 6-hour peak is hardly identifiable in the spectra.

[12] In order to test the "coherent" nature and regular occurrence of the observed 8-hour periodicity, a superposed epoch analysis method was used. In this way, composite time series were obtained for the May to October time interval by superposing the time series of *foEs* and *h′Es* for all 12 years. The superposed epoch method has the advantage of suppressing signals with random phase, while it accentuates periodicites which are phase-coherent and thus having a deterministic character. The results of the superposed epoch analysis are shown in Figures 3 and 4 for *foEs* and *h′Es*, respectively.

[13] The upper panel in Figure 3 is the composite *foEs* time sequence from 1 May to 31 October, resulting from the point-to-point superposition of the corresponding times series from 1980 to 1991. The shape of this plot reflects basically the well-known seasonal occurrence of sporadic *E*, which maximizes around the summer solstice [e.g., see *Whitehead*, 1989]. The middle panel displays the amplitude spectrum of the composite time series plotted in the upper panel. Except for the well-known 24- and 12-hour periodicities, which dominate the spectrum and are attributable primarily to the diurnal and semidiurnal tides, the only other peak which exceeds clearly the 95% confidence level is that at exactly 8 hours. This recommends that the 8-hour periodicity in *foEs* is phase-coherent, thus it is a genuine oscillation and not the third harmonic which might have resulted from the distortion of the strong 24-hour oscillation. Finally, shown in the bottom panel of Figure 3 is a Fourier spectrogram obtained from the composite time series in the upper panel by running Fourier spectral analysis on a 30-day window which is shifted through the whole sequence with a step of 1 day. As seen, the 8-hour periodicity is a regular oscillation in *foEs*, being present for most of the time except for the month of September when its amplitude becomes minimum and is buried in the noise.

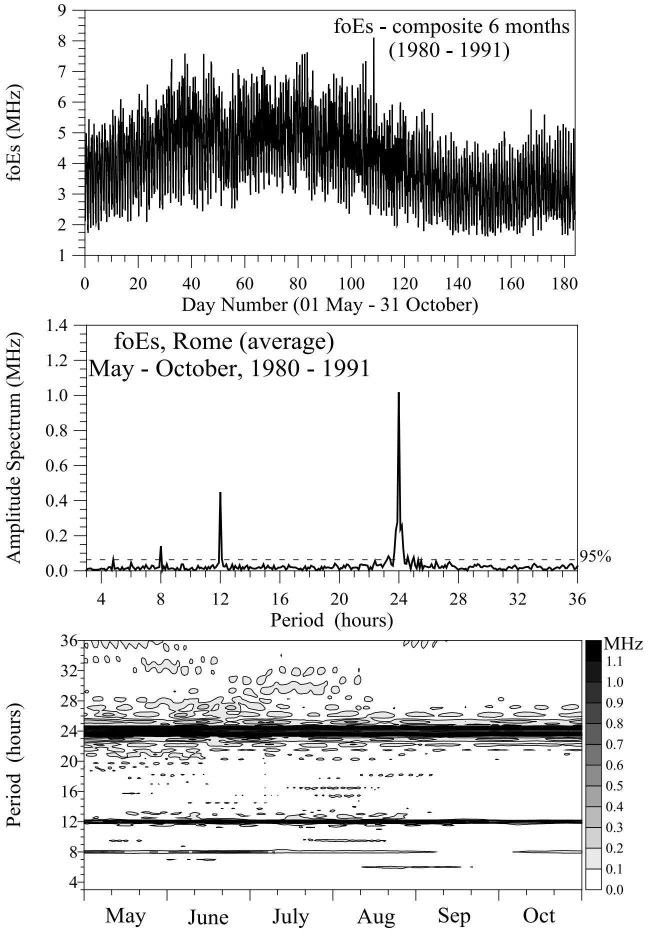

Figure 3. The upper panel shows the composite time series of mean hourly *foEs* values from 1 May to 31 October, obtained by the superposed epoch method using 12 years of data from 1980 to 1991. The corresponding amplitude spectrum and the Fourier spectrogram are shown in the middle and bottom panels, respectively.

Also shown in Figure 3 is that a 6-hour periodicity can also be weakly present at times but most of the time is absent or remains at noise levels.

[14] The superposed epoch analysis results for *h′Es* are shown in Figure 4. With respect to the dominant periodicites present in the 12-year composite time series for *h′Es*, the situation is similar to that in Figure 3, although not identical. The main difference is on the relative amplitudes of the dominant periodicities, particularly that of 8 hours whose peak in the amplitude spectrum is now nearly equal to that of the 12-hour oscillation. This means that the 8-hour periodicity affects more strongly *h′Es* than *foEs* and that its effect on *h′Es* is on the average the same as that of the 12-hour oscillation. We feel this has some physical significance and it will be brought up again later in the paper. Finally, the corresponding Fourier spectrogram in the lower panel of Figure 3, shows that the 8-hour oscillation is present all the time in *h′Es*; therefore it constitutes a regular characteristic. The 8-hour periodicity in *h′Es* is present during September, whereas it appears to be absent in *foEs* (e.g., see the bottom panel in Figure 3). This is apparently because the 8-hour oscillation is more pronounced in *h′Es* than *foEs*, as evidenced from the relative strength of the 8-hour spectral peaks in the middle panels of Figures 3 and 4.

2.2. Variability

[15] To gain information on the mean variability of the 8-hour periodicity during the 6-month period from May to October, the 12-year composite time series for *foEs* and *h′Es* shown in Figures 3 and 4 were used to obtain average days, by using again the superposed epoch method on sequential monthly and 10-day time intervals. Then, the 8-hour oscillation was extracted from the average days by applying a least squares fitting algorithm. This yielded monthly and 10-day means and standard deviations of the 8-hour oscillation for both the amplitude and phase of *foEs* and *h′Es*. For details on this methodology, which is used routinely in the analysis of mesosphere-lower thermosphere (MLT) wind observations, see for example *Pancheva et al.* [2002]. The results for *foEs* and *h′Es* are shown to the left and right panels of Figure 5, respectively. They are the mean amplitude (top) and phase (bottom) variations of the observed 8-hour periodicity from 1 May to 31 October.

[16] Figure 5 shows that the mean amplitude of the 8-hour periodicity in *foEs* maximizes around solstice, taking up a maximum mean value near 0.25 MHz in June. This is in line with the well-known summer maximum in E_s

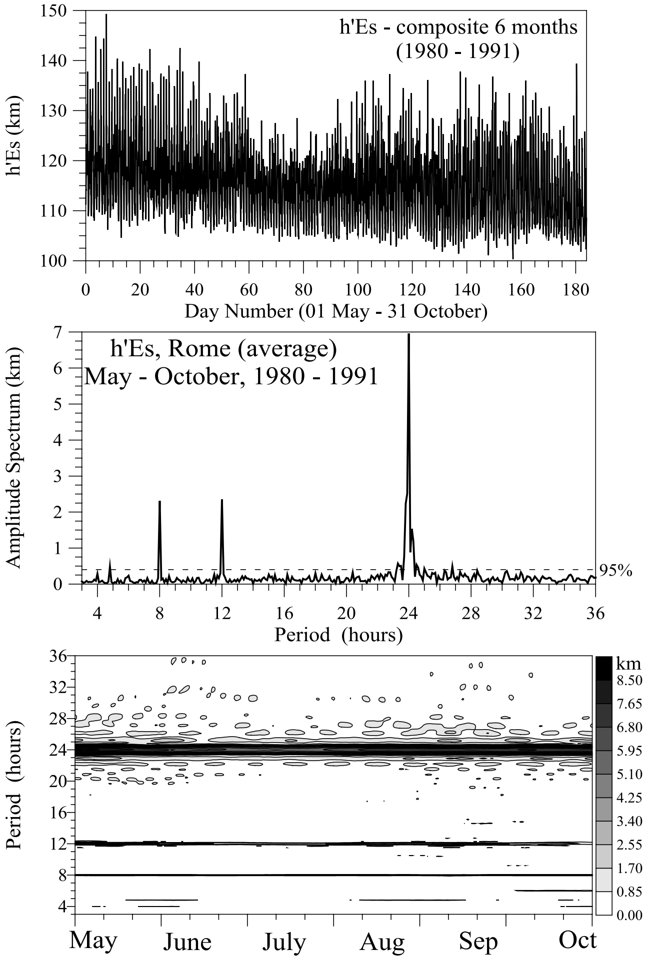

Figure 4. Same as Figure 3 but for *h′Es*.

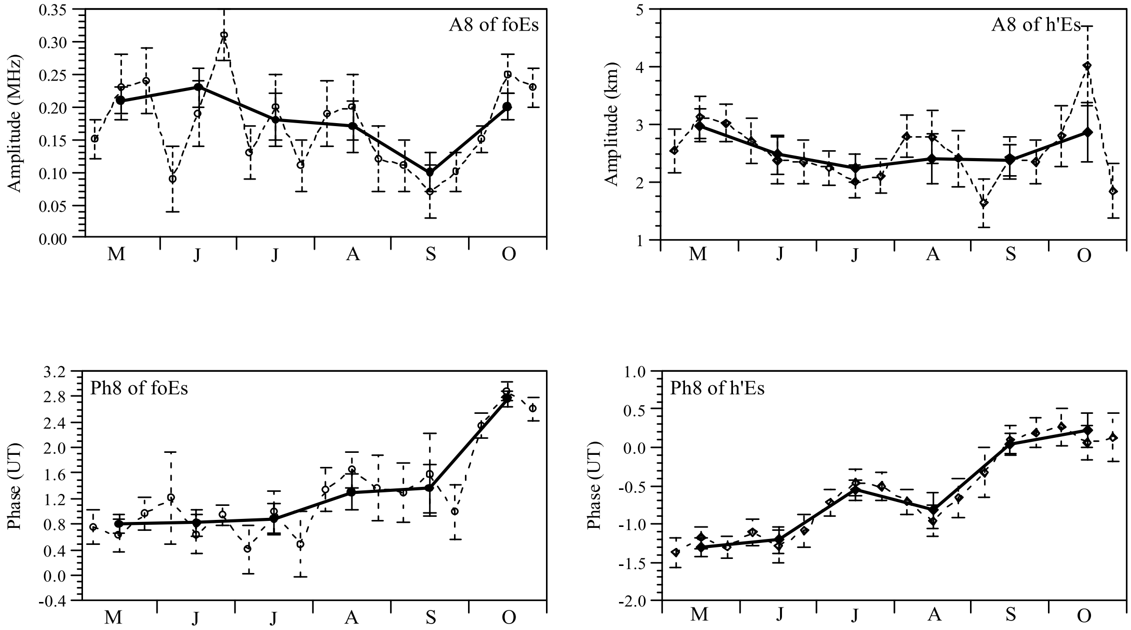

Figure 5. Monthly (solid line) and 10-day (dashed line) means and standard deviations marking the amplitude (top) and phase (bottom) variability of the 8-hour oscillation in *foEs* (left) and *h′Es* (right) from May to October. They are computed from the composite times series shown in Figures 3 and 4 which were based on 12 years of measurements. The error in the extracted 8-hour period is ±0.2 hours.

occurrence and in *foEs* (e.g., see review by *Whitehead* [1989]). The 8-hour amplitude decreases gradually toward equinox receiving its minimum monthly mean of about 0.1 MHz in September, while in October it increases again taking up a mean monthly value near 0.2 MHz, comparable to that in July. The 10-day mean amplitudes follow the trends of the monthly means and appear to be more variable when the amplitude is higher (solstice) than lower (equinox). As for the phase of the 8-hour periodicity in *foEs*, which is defined as the time of the day when the amplitude of the 8-hour oscillation becomes maximum, this increases steadily as time progresses from May to October by about 2 hours. It is interesting that the same phase shift is also present in *h′Es*, as shown in the bottom right panel of Figure 5. On the other hand, the mean amplitude in *h′Es* (upper right panel) remains rather invariable as time moves from May to October.

2.3. Relation to the Terdiurnal Tide

[17] Here, we present evidence suggesting that the 8-hour periodicities in E_s associate with the terdiurnal tide in the lower thermosphere. This came from the analysis of simultaneous ionosonde observations recorded at stations located at about the same latitude but at widely different longitudes. The idea was to investigate if the 8-hour periodicity had a global character and wavelike propagation characteristics. In this respect, good-quality time series were retrieved for two different years and two sets of three stations, as follows: (1) for *foEs*, a set of complete time series from 1 May to 31 October 1988 was found for Alma Ata (43.2°N; 74.5°E), Rome (41.9°N, 12.5°E), and Lannion (48.7°N; 3.4°W), with these three stations spanning ∼78° in longitude; and (2) for *h′Es*, simultaneous time series were found again from 1 May to 31 October of 1985, for Rome, Lannion, and Wallops (37.8°N; 75.5°W), which cover a longitudinal sector of 88°.

[18] Figure 6 shows the corresponding amplitude spectra of the *foEs* and *h′Es* time series of hourly means for all stations. As seen, the spectra are nearly identical showing that except for the dominant 24- and 12-hour peaks, the 8-hour periodicity is also present in *foEs* and *h′Es* for all stations despite that they are widely spaced in longitude. This argues in favor of a global character for the 8-hour oscillation and hints for a relationship with the terdiurnal tidal winds in the lower thermosphere. This is reinforced further by the observed variations in amplitude and phase of the 8-hour periodicity, displayed in Figure 7. Shown there in the four upper panels are the monthly means and standard deviations of amplitude and phase of the 8-hour oscillation obtained with the same methodology used to produce Figure 5. The monthly mean amplitude and phase variations in *foEs* (left panels) and *h′Es* (right panels) are similar for all stations under consideration, which means that the 8-hour oscillation is of global scale since the stations cover longitudinal distances as large as 8000 km. The phase changes for all three stations are shown for *foEs* and *h′Es* in the middle, left, and right panels, respectively. Note that except for the measured monthly means and standard deviations, shown also are straight lines of least squares fits representing the phase trends from 1 May to 31 October. As seen, these lines are approximately parallel to each other having systematic time shifts which signify a wavelike zonal propagation effect, apparently that of a migrating terdiurnal tide.

[19] Finally, the speculation for a terdiurnal tidal role is strongly supported by the corresponding "phase-longitude

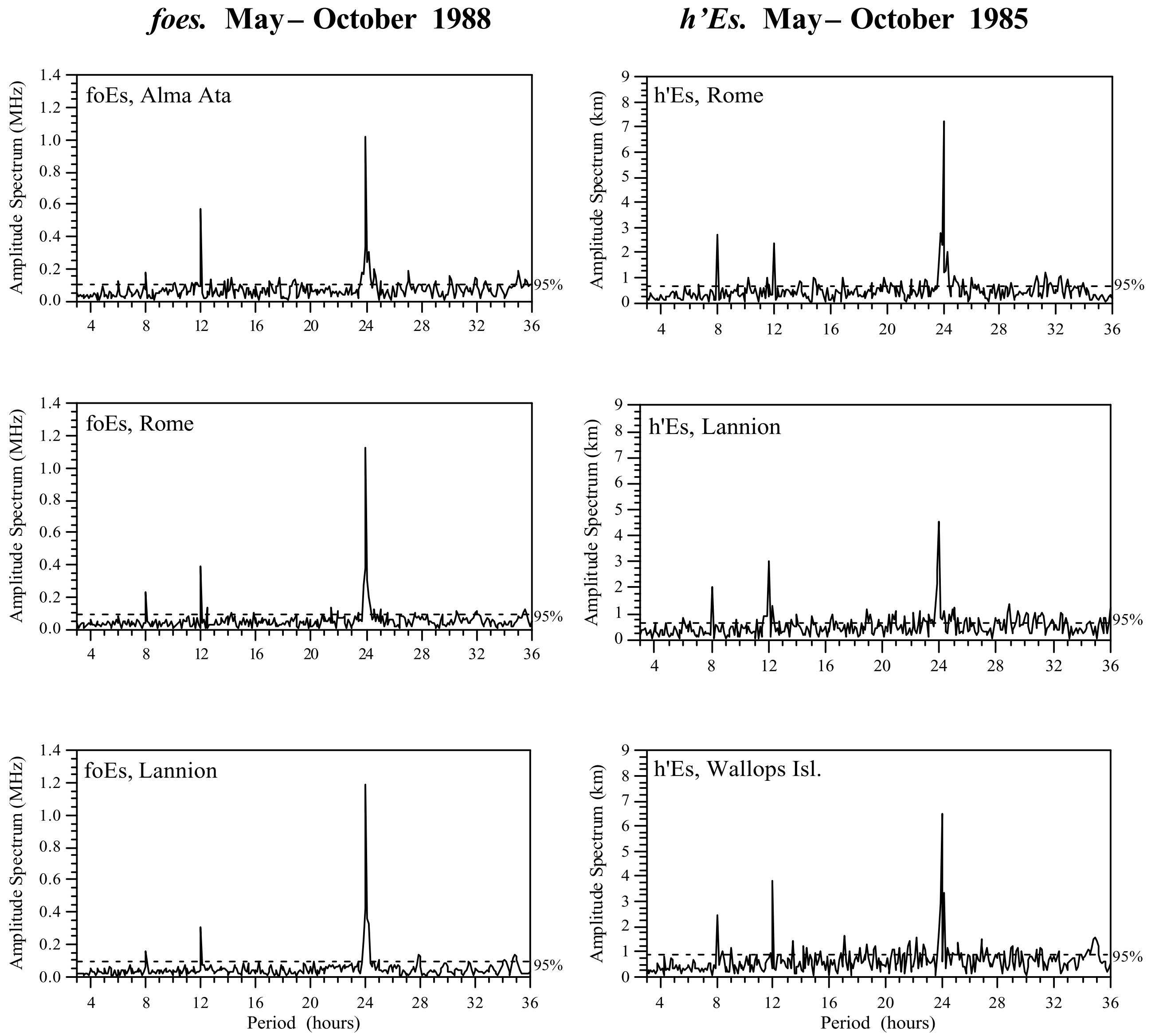

Figure 6. (left) Amplitude spectra of *foEs* hourly means from 1 May to 31 October 1988 corresponding to three ionosonde stations at Alma Ata, Rome, and Lannion, spanning 78° in longitude. (right) The same as before but for *h′Es* using now a different year (1985) and the ionosondes in Rome, Lannion, and Wallops, spreading over 88° in longitude.

plots" of the 8-hour oscillation, which were computed for both data sets. These are shown in the bottom panels of Figure 7 for both *foEs* (left) and *h′Es* (right). Such plots are computed routinely in MLT neutral dynamics because their least squares fitted slopes provide information on the propagation characteristics of tidal and planetary waves. As seen, both phase-longitude plots in Figure 7 have negative slopes which signify a wavelike westward propagation having a zonal wave number (ZWN) that is equal to 3.18 ± 0.16 for 1988 and 2.89 ± 0.19 for 1985. These results suggest that the 8-hour oscillation in E_s relates to a westward propagating wave of global scale with a ZWN 3. This agrees well with the propagation characteristics of terdiurnal tidal winds observed by the High-Resolution Doppler Interferometer (HRDI) on board the Upper Atmosphere Research Satellite (UARS), as reported by *Smith* [2000]. These results referred to a mid- to lower-latitude global structure of an 8-hour tidal wave averaged in time over a month and in height over several kilometers around 95 km, propagating westward and having a mean amplitude of 5 m/s in the meridional and 15 m/s in the zonal wind and a ZWN $\simeq$ 3.

3. Summary and Discussion

[20] Sporadic *E* time series of *foEs* and *h′Es* hourly means, measured with ionosondes during the May to October 6-month period and over many years, were analyzed in order to investigate the occurrence and character-

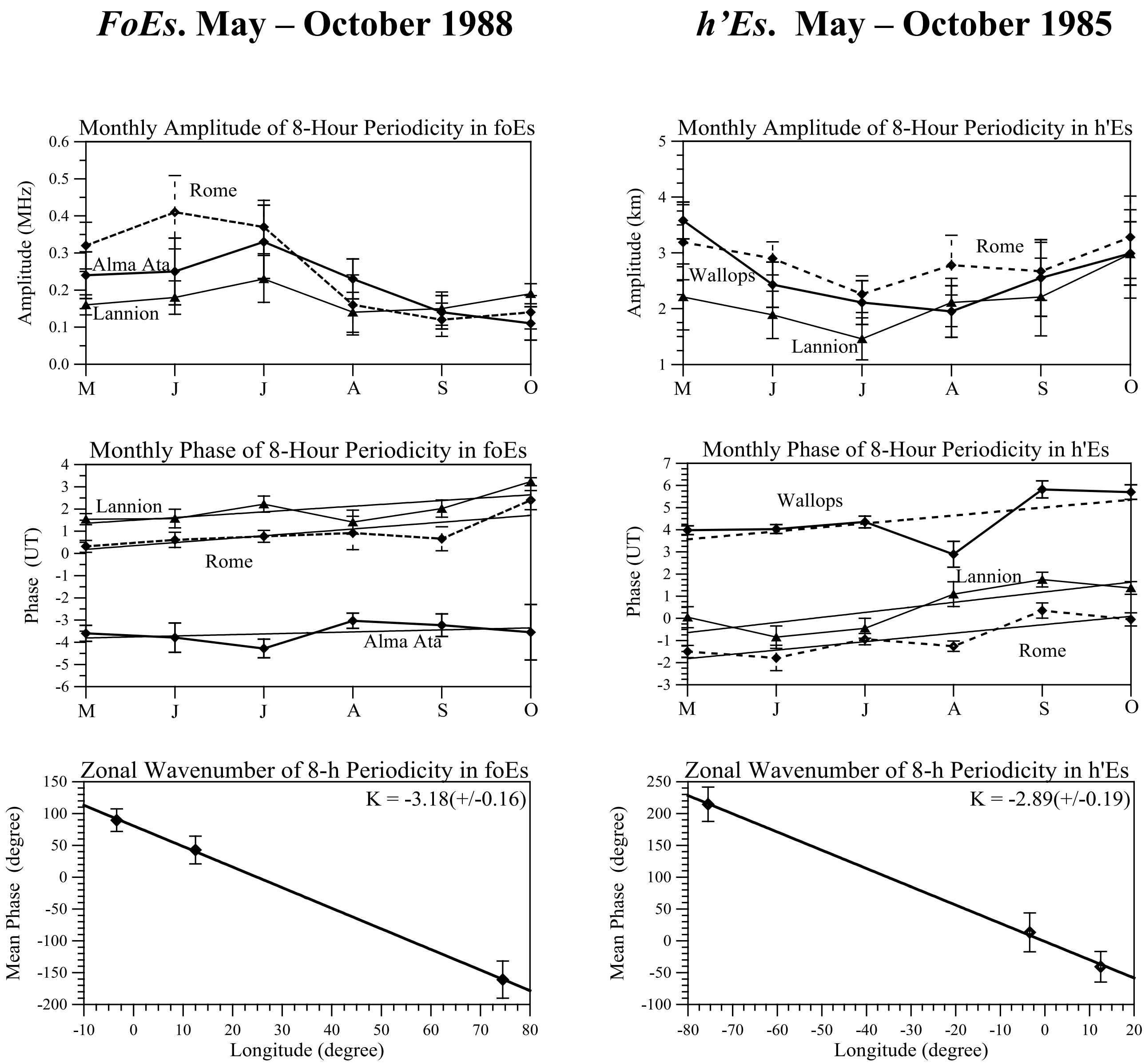

Figure 7. Monthly mean amplitude (top) and phase (middle) variations of the 8-hour oscillation in *foEs* (left) and *h′Es* (right) from 1 May to 31 October, for two different sets of three ionosonde stations and different years, as in Figure 6. The bottom panels are mean phase-longitude plots for each set of stations and the straight line are least squares fits whose slopes provide the zonal wave number (K), given in the top right corner. See text for more details.

istics of the 6- and 8-hour periodicities in midlatitude E_s. Our findings are summarized as follows:

[21] 1. In addition to the well-known diurnal and semidiurnal periodicities in E_s properties, a weaker but well-defined 8-hour wavelike oscillation is present also on a regular basis.

[22] 2. At times, the 6-hour periodicity is also weakly present in E_s, but overall and in relation to the 8-hour oscillation, it is much more weaker and less frequent.

[23] 3. The 8-hour periodicity is a genuine oscillation and not a harmonic generated by the distortion of the strong 24-hour variation in sporadic *E*.

[24] 4. The 8-hour oscillation is more pronounced in *h′Es* than in *foEs* and affects the layers' descend with time.

[25] 5. The amplitude of the 8-hour oscillation maximizes around summer solstice and becomes minimum in September, whereas its phase increases from May to October, approximately at ~0.3 h/month.

[26] 6. The 8-hour oscillation in E_s is of global scale, prevailing over large longitudinal sectors. It has wavelike properties characterized by a westward propagation and a zonal wave number near 3, which points to a close relation with the terdiurnal tidal winds in the lower thermosphere.

[27] The literature contains little reference to tidelike oscillations in sporadic *E* with periods shorter than 12 hours. Prior to our recent study by *Haldoupis et al.* [2004], *Szuszczewicz et al.* [1995] was the only paper referring briefly to a possible terdiurnal periodicity seen at times in

sequential ionograms, which was attributed to a descending meridional wind shear associated with a terdiurnal tide in the neutral wind. On the other hand, *Tong et al.* [1988] and later *Morton et al.* [1993] are the only Arecibo ISR papers to have reported an upper *E* region quarterdiurnal (6-hour) oscillation which affected the sporadic *E* in the lower *E* region through the descending intermediate layers (DILs). These data were explained in a realistic model atmosphere with a diurnal, semidiurnal, and quarterdiurnal tidal wind system. Although our present ionosonde measurements show the 8-hour periodicity in E_s to be much more regular and significant than that of 6 hours, the Arecibo E_s observations have somehow missed its detection. Possibly this is because the Arecibo E_s and DIL measurements are based on limited observational periods made mostly during winter when sporadic *E* is much weaker. Another reason could be the location of the Arecibo ISR, which is more close to the tropics rather than at midlatitudes.

[28] Our results show that a terdiurnal tide in the lower thermosphere with a ZWN = 3 is most likely the cause behind the 8-hour periodicity observed in both *foEs* and *h′Es*. This is to be expected given the well-known role of the diurnal and semidiurnal tides on the intensity and altitude descend of E_s with periods of 24 and 12 hours, respectively (e.g., see review paper by *Mathews* [1998]). The tides provide downward propagating wind shears of ion convergent nodes, which can account for the formation and vertical transport of the layers, as shown theoretically by *Axford* [1963], numerically by *Chimonas and Axford* [1968], and experimentally by *Mathews and Bekeny* [1979] who used Arecibo ISR observations, and recently by *Lee et al.* [2003] and *Haldoupis et al.* [2006] who used ionosonde recordings and a HTI (Height-Time-Intensity) analysis technique. The Arecibo ISR studies revealed a regular semidiurnal pattern for the descending intermediate layers in the upper *E* region, a dominant diurnal periodicity for the lower *E* region sporadic layers, and a confluence zone between about 120 and 100 km where both tidal modes are mixing. On the basis of the present results, this scenario needs to include, for midlatitude E_s, the action of the terdiurnal tides as well.

[29] With respect to the terdiurnal tide in the upper atmosphere, there are several studies on this topic relevant to the MLT region below 100 km [e.g., see *Manson and Meek*, 1986; *Thayaparan*, 1997; *Younger et al.*, 2002; *Beldon et al.*, 2006, and references therein]. These studies have shown that the 8-hour tide is a significant component in the MLT wind system, being an almost permanent feature with mean amplitudes increasing with height in the 80 to 100 km range and taking typical values $\leq$10 m/s. Given these facts and that higher frequency tides can easily penetrate well above 100 km into the lower and upper *E* region, it is not surprising that our results show the 8-hour periodicity to be a regular feature in the sporadic *E* layer properties. We need to mention, however, that the observed long-term variability of the 8-hour periodicites in E_s, which seem to have their amplitudes maximizing in June–July and minimizing in September, does not compare well with the seasonal behavior observed in the MLT terdiurnal tidal winds which show their largest amplitudes in September–October and their minimum in May [e.g., *Beldon et al.*, 2006]. In comparing such seasonal changes, however, one has to keep in mind that stronger (weaker) 8-hour tidal winds does not necessarily mean larger (smaller) amplitudes of the 8-hour periodicities in *foEs* and/or *h′Es*. This is because the key parameter in E_s formation is not the wind magnitude but the strength of the vertical (tidal) windshear that drives the E_s ionization layering process.

[30] The terdiurnal tide is believed to be generated either directly by solar heating, primarily in the upper stratosphere with its energy propagating upward, as shown by *Chapman and Lindzen* [1970], or in situ by EUV and UV absorption in the lower thermosphere, or through nonlinear interaction between the migrating semidiurnal and diurnal tides, as shown first by *Teitelbaum et al.* [1989]. Also, *Crary and Forbes* [1986] suggested another in situ mechanism for generation of terdiurnal tides, proposed originally by *Forbes and Garret* [1979] and *Mayr et al.* [1979]. This operates in the upper *E* and *F* regions and involves the interaction between the upward propagating semidiurnal tide and the diurnal component of the ion drag. Our findings suggest that systematic sporadic E_s measurements can provide insight on the origin of the terdiurnal tides in the lower thermosphere. For example, the seasonal variations shown in Figure 5 can be used to test if in situ EUV and UV absorption is the main mechanism for setting up the terdiurnal tides in the lower thermosphere. Alternatively, by comparing the properties of the 8-hour periodicities with those of 12 and 24 hours, one could evaluate if the terdiurnal periodcities result from nonlinear interaction of the diurnal and semidiurnal tides. The latter is a task we hope to pursue in a future study.

[31] In contrast with the MLT region observations of terdiurnal tides, there are very few studies reporting on the terdiurnal tide in the midlatitude lower thermosphere, that is, between 100 and 200 km. Note that the thermosphere above 100 km can be probed from the ground only by ISRs and from space with Doppler interferometer measurements of the oxygen green line (airglow) emission. *Zhang et al.* [2003] published a detailed study on the climatology of neutral winds in the lower thermosphere from 94 to 130 km over 42.6°N, using Millstone Hill ISR and WINDII (the space-based wind imaging interferometer, e.g., see *Shepherd et al.* [1993]) observations. Although these authors provide a great deal of information on the variability of the diurnal and semidiurnal tides and the mean winds, there is no reference on shorter period tidal components, that is, 8 and 6 hours, apparently because the experiments could not resolve such contributions.

[32] On the other hand, there exist a few papers reporting on 8-hour tides at *E* region heights detected in high latitudes with EISCAT (the European Incoherent Scatter experiment), e.g., see *Virdi et Williams* [1993], *Brekke et al.* [1994], and *Kofman et al.* [1996]. Also, among the many studies on the properties of the dominant semidiurnal and diurnal tides made with the Arecibo ISR at thermospheric heights above 100 km, there are very few reports on the presence of short period tides and especially the 8-hour tide. For example, *Harper et al.* [1981] were the first to report that the best harmonic fit to Arecibo ISR temperature data often has a period of 8 hours, whereas clear evidence was provided by

Zhou et al. [1997], who found during the 10-day Arecibo ISR campaign from 20 to 30 January 1993 that 8-hour oscillations in wind and temperature were also present at times in the altitude range from 94 to 144 km. In addition, the phase of the 8-hour oscillations showed remarkable consistence, suggesting the presence of (energy) upward propagating tides having a representative wavelength of about 30 km. Unfortunately, there are no reports of similar Arecibo observations made during summer when the observed 8-hour variability in E_s implies that the terdiurnal tide is a persistent component of the wind system in the thermosphere above 100 km.

[33] Our study suggests that the system of thermospheric winds, which is dominated by the action of the diurnal and semidiurnal tides, needs also to include a terdiurnal tide as well in order to account for the observed 8-hour oscillation in the E_s properties. It is not, however, clear from our data alone how the terdiurnal tide impacts its effects on E_s, that is, if the action is in the lower *E* region only, known also as confluence zone, or indirectly through the formation of DILs in the upper *E* region and their subsequent descend in the lower *E* region and into the confluence zone. Using the existing knowledge on the role of 12- and 6-hour tides [e.g., see *Tong et al.*, 1988; *Morton et al.*, 1993], it is likely that the terdiurnal tide affects the sporadic *E* in a similar way, that is, through a process which involves DILs. Some evidence for this postulation comes from the HTI plot in Figure 1, showing that the 8-hour periodicity relates to three sequential descending layers below about 120 km which seem to connect above to faint traces caused by DILs. In addition, the fact that the 8-hour periodicity is more evident in *h′Es* rather than *foEs*, also hints for a process that acts to modulate the layer's height, most likely through DILs. Certainly, additional work is needed, e.g., by means of obtaining more Arecibo ISR observations, in order to clarify better the role played by the terdiurnal tide on the E_s layering process.

[34] In conclusion, the present work established that the 8-hour periodicity in sporadic *E* is regular and significant and that this periodicity most likely relates to the terdiurnal tide in the lower thermosphere. We believe the present findings are useful for future investigations. Given that our knowledge on the properties and origin of the thermospheric terdiurnal tides is limited, one can take advantage of the large databases obtained with many ionosondes around the globe, which operate routinely for many years, in order to quantify the propagation properties and climatology of the terdiurnal tides in the lower thermosphere above 100 km, as well as its relationship to the diurnal and semidiurnal tides.

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