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Planetary waves and midlatitude sporadic *E* layers: Strong experimental evidence for a close relationship

Christos Haldoupis
Physics Department, University of Crete, Iraklion, Crete, Greece

Dora Pancheva
Department of Physics, University of Wales, Aberystwyth, Wales, UK

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[1] A large-amplitude, 7-day period westward propagating $S = 1$ planetary wave 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 planetary waves might play a role in the formation of midlatitude sporadic *E* layers (E_s), we have obtained and analyzed, for the period from August 1 to September 30, 1993, the sporadic *E* critical frequency (f_oE_s) time series from eight midlatitude ionosonde stations covering a large longitudinal zone from ~58°E to 157°W. The analysis revealed that all eight station f_oE_s data showed a strong 7-day periodicity, occurring concurrently with the 7-day planetary wave reported elsewhere. Using independent methods for the analysis of the f_oE_s time series, we computed identical estimates for the propagation direction, zonal wave number, and phase velocity of the 7-day wave, which are in agreement with those reported from radar and satellite neutral wind MLT measurements. The present findings provide the first direct evidence, proving that planetary waves play an important role in the physics of midlatitude sporadic *E* region layers. In addition, our results include an important implication, that the E_s parameters measured routinely and rather reliably with a dense global network of digital ionosondes, as well as the enormous ionogram databases existing in World Data Centers, may be used as an alternative means of studying large-scale neutral atmospheric dynamics in the MLT region. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); *KEYWORDS:* planetary waves, sporadic *E* layers, MLT dynamics, metallic ion plasma

1. Introduction

[2] The sporadic *E* layers are thin plasma layers of enhanced metallic ion concentration that form frequently, but not regularly, in the midlatitude *E* region ionosphere. They are monitored routinely by numerous ionosonde stations around the globe and less frequently by several coherent backscatter radars and the few incoherent scatter facilities, whereas occasionally they are observed in situ with rocket-borne sensors. In our present understanding [e.g., see reviews by *Whitehead*, 1989; *Mathews*, 1998], the main factor involved in midlatitude E_s formation is vertical neutral wind shears, associated with tides and/or gravity waves, which can compress the long-living metallic ions into a thin layer.

[3] In general, horizontal plasma transport has been ruled out as being unimportant in E_s formation, since the scales involved are much larger than the vertical ones. This conviction, however, had to be reconsidered recently in the light of new evidence, by *Tsunoda et al.* [1998] and *Voiculescu et al.* [1999], which suggested a link between E_s and planetary waves (PW). These papers reported PW periodlike modulations in the occurrence of *E* region coherent backscatter, observed with HF and VHF radars during strong sporadic *E* layer conditions in the summer nighttime. Subsequently, *Shalimov et al.* [1999] introduced a new mechanism for large-scale, horizontal convergence of metallic ions in the *E* region driven by PW energy. Planetary waves are quasiperiodic global scale oscillations in neutral wind, pressure, and density, which prevail and propagate zonally in the mesosphere and lower thermosphere (MLT) and have periods mostly near 2, 5, 10, and 16 days [e.g., see *Forbes*, 1994].

[4] If the postulation about a link between E_s and PW is valid, then this can open a new avenue in the ongoing research of layering plasma phenomena in the *E* region and the physics of the interaction of ionospheric plasma with large-scale dynamics in the neutral atmosphere. Obviously, the most pressing task at this stage is to substantiate the PW versus E_s relationship by means of additional experimental evidence. Some direct, but tentative, results in favor of a PW role on the unstable midlatitude *E* region were presented recently by *Voiculescu et al.* [2000], who compared ionosonde and 50-MHz coherent backscatter observations from southern Greece with simultaneous neutral winds at the mesopause region near 95 km measured from Germany.

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[5] The present paper uses E_s data from an extended longitudinal chain of ionosondes during a conspicuous, truly global, PW event to show clearly the existence of a close relationship between planetary waves in the MLT region and midlatitude sporadic *E* layers. Also, our findings introduce for first time the option of using the abundance of global E_s ionosonde measurements, and the existing large databases, in studying PW characteristics and dynamics.

2. A Global 7-Day Planetary Wave Event

[6] The idea for the present study originated from a recent paper by *Clark et al.* [2002] who presented mesospheric winds mostly from radar measurements in the North American sector and the UARS/High Resolution Doppler Imager (HRDI), showing the occurrence of a prominent 7-day planetary wave of global response. It lasted perhaps more than 20–25 days during the second half of August and into September 1993 and propagated westward, being especially pronounced in the meridional wind component with a peak to peak amplitude in excess of 20 m/s. The same event had been studied earlier by *Wu et al.* [1994], who used UARS/HRDI winds in the MLT region to identify a westward propagating 6–7 day period wave with zonal wave number 1 ($S = 1$), which appeared over a large ±40° latitudinal zone with possible extensions to higher latitudes. The characteristics and the origin of the same PW were also investigated by *Meyer and Forbes*, [1997] with the Global Scale Wave Model (GSWM). They estimated a 6.5-day, westward propagating $S = 1$ wave and interpreted it as an unstable mode triggered in the upper mesosphere but with a global response, rather than as a Doppler shifted 5-day Rossby wave.

[7] Figure 1 illustrates that this 7-day PW event was also dominant in the European sector during part of August and September 1993. Figure 1 (top) shows period time spectrograms (PTS) obtained by wavelet transforming the meridional hourly mean wind measured in the upper mesosphere by a meteor radar at Sheffield (53.5°N; 3.5°W), whereas Figure 1 (bottom) refers to the meridional daily mean wind measured near 95 km at Collm (52°N; 13°E) by means of using the D1 low-frequency radio wave method (e.g., see for details *Jacobi et al.* [1998]). Both PTS plots in Figure 1 show clearly a dominant 7-day oscillation to be present in the lower thermosphere wind that persists from about mid-August to mid-September. The meridional peak-to-peak wind amplitudes were, like in the American sector, rather large, nearing 20 m/s. The same oscillation was also seen farther to the east in Bulgaria by the meteor radar at Yambol (42.5°N, 26.6°E), but the Yambol PTS is not shown here because the measurements cover only the month of September.

[8] Finally, based on the fact that tides can be modulated by PW through nonlinear interactions, we also applied wavelet analysis on both components of the semidiurnal tide for the Sheffield wind data. Again, the results showed a strong 7-day modulation in the semidiurnal tidal amplitudes that was especially pronounced during the time when the 7-day wave in the meridional wind was about its maximum.

3. Ionosonde f_oE_s Data Set

[9] Given this dominant 7-day PW event in August-September 1993 and the need to prove (or disprove) the postulated PW-E_s relationship, the next step was to obtain for analysis, from the Colorado World Data Center via the Web, mean hourly E_s critical frequency (f_oE_s) time series for all the Northern Hemisphere midlatitude stations that made observations during August and September 1993. In this respect, we found usable data only from eight stations spanning from 58°E to 157°W, that is, covering ~215° in longitude around the globe. From east to west these stations include the following: Ashkhabad (37.9°N, 58.3°E), Belgrade (44.8°N, 20.5°E), Rome (41.9°N, 12.5°E), Poitiers (46.6°N, 0.3°E), Lannion (48.7°N, 3.4°W), Wallops (37.8°N, 75.5°W), Boulder (40.0°N, 105.3°W), and Maui (20.8°N, 156.5°W). Note that all stations are situated in middle latitudes except for the lower-latitude station in Maui, Hawaii.

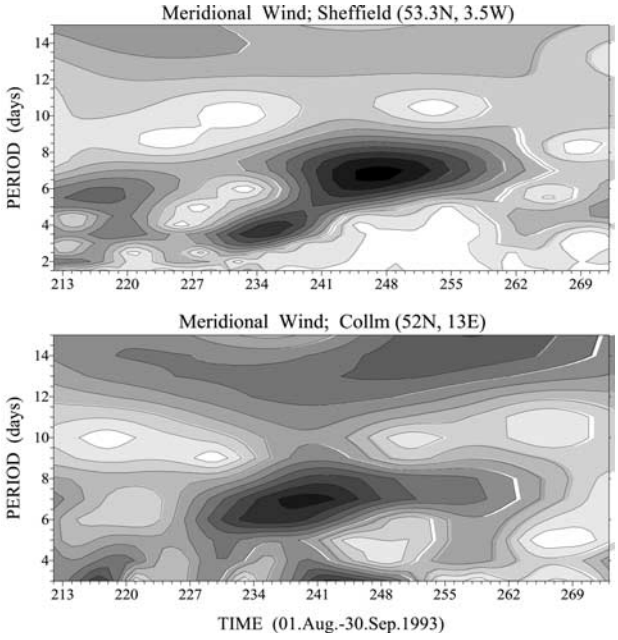

Figure 1. Period-time wavelet transform spectrograms for the meridional MLT wind over the European sector during August–September 1993.

[10] A first look inspection of the hourly mean f_oE_s times series has been surprisingly reassuring, as all stations appeared to have recorded a long-period modulation in f_oE_s during the time of the 7-day PW occurrence, discussed previously. As an example, Figure 2 illustrates the Rome ionosonde mean hourly f_oE_s times series from 1 August to 30 September 1993, where a pronounced periodicity is clearly seen to occur from about middle of August to middle of September with a period near 7 days.

4. Direct Evidence for PW Modulation of Sporadic *E* Layers

[11] In order to investigate the spectral dynamics in the f_oE_s time series, the continuous Morlet wavelet transform [e.g., see *Torrence and Combo*, 1998], which consists of a plane wave modulated by a Gaussian envelope, was applied. This technique decomposes a time series into the time-frequency (or time-period) space; thus one can deter-

mine both the dominant modes of variability (spectrum) and how those modes behave in time (dynamics). In the following, the wavelet coefficient, determined by the wavelet position in the time series, is presented as a function of period and time. The magnitude of the wavelet coefficient relates to the amplitude of the oscillations and therefore provides a qualitative estimate of the spectral composition of the wave field intensity. Before applying the wavelet transform, short data gaps in the time series were filled in by a widely used interpolation scheme which uses least squares fitting of the neighboring values by a second-degree polynomial with exponentially decreasing weights.

[12] The wavelet transform spectrograms show that a dominant 7-day periodicity is present, from about middle of August and into the first 10 to 15 days of September, in all eight ionosonde stations from the eastmost Ashkhabad to the westmost Maui. This is illustrated in Figure 3 with the wavelet transform PTS plots for all eight ionosonde stations stretching in longitude from 58.3°E to 156.5°W. As seen, the f_oE_s wavelike modulation maximizes everywhere around end of August, very much in agreement with the

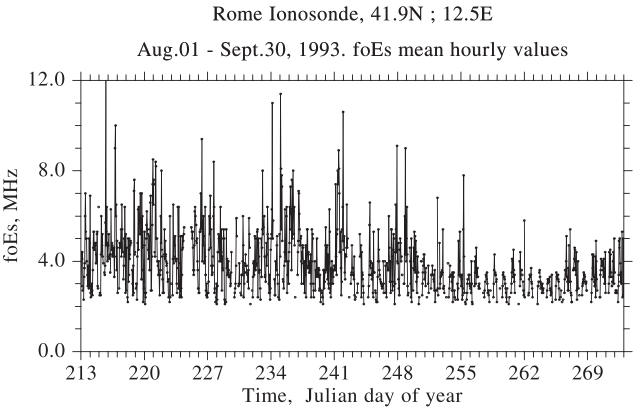

Figure 2. Mean hourly f_oE_s variations observed in Rome during August–September 1993. A strong 7-day periodicity is evident in the time series from about August 15 to September 15.

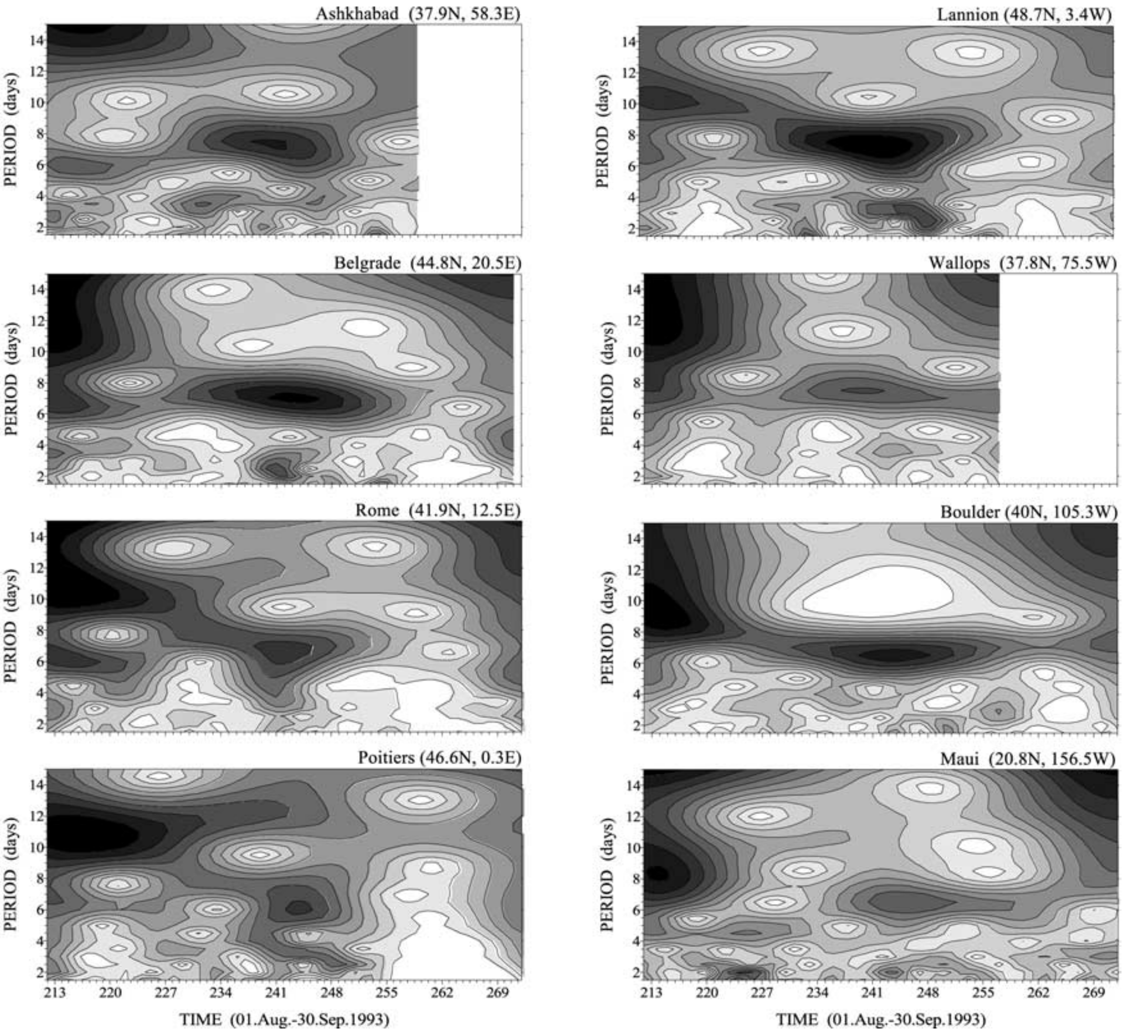

Figure 3. Period-time wavelet transform spectrograms for the mean hourly f_oE_s time series observed simultaneously in all ionosonde stations. All stations see a dominant 7-day oscillation during the second half of August 15 and into September 1993.

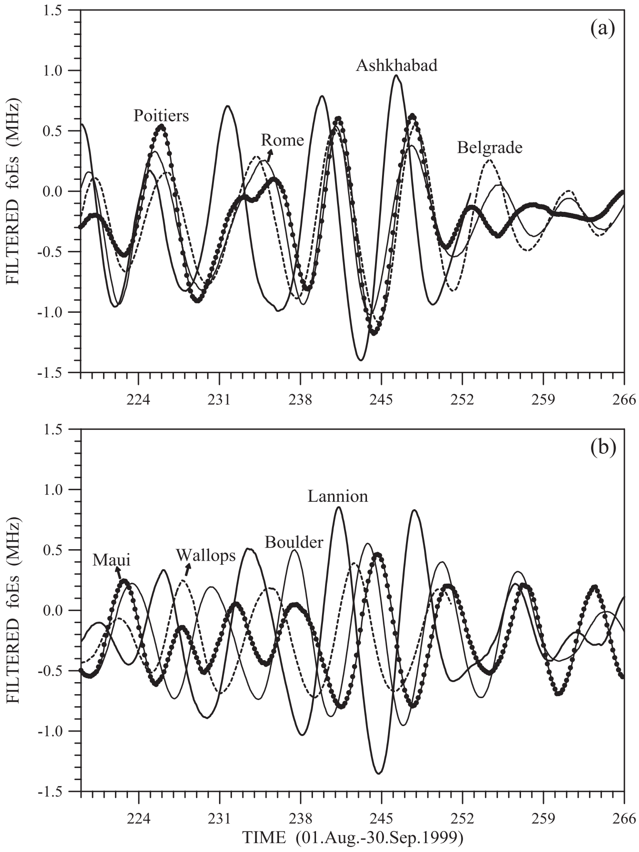

Figure 4. Band pass (T_0 = 7 days) filtered outputs for all eight ionosonde mean hourly f_oE_s time series.

maximum of the 7-day PW activity observed in the meridional component of the mesospheric neutral wind, e.g., see Figure 1 and results presented by *Clark et al.* [2002]. Note that all the 7-day wave peaks in Figure 3 correspond to confidence levels higher than 95%, when using a red noise spectrum to establish a null hypothesis for the significance of a peak in the wavelet power spectrum (for details, see *Pancheva and Mukhtarov* [2000]).

[13] We stress that this 7-day periodicity did not relate to a global geomagnetic activity. This was confirmed from similar wavelet transform analysis applied on 3-hourly *Ap* index time series. The *Ap* spectrogram (not shown here) did not show any 7-day periodicity during the second half of August and into September 1993.

[14] In order to investigate further the 7-day PW signature seen in all the f_oE_s time series over this huge longitudinal zone, we apply a linear phase bandpass filter as formulated by *Luzov et al.* [1965]. The filter is centered at period T_0 = 168 hours and is characterized by a damping value 0.1 for the second harmonic. The filter outputs are presented in Figure 4. Figure 4a shows the filtered f_oE_s time series for the four easternmost stations (Ashkhabad, Belgrade, Rome, and Poitiers) located between 58.3°E and 0.3°E, whereas the Figure 4b refers to the rest, the four westernmost stations (Lannion, Wallops, Boulder, and Maui) between 3.4°W and 156.5°W. All filtered outputs show a clear 7-day wave oscillation having peak-to-peak amplitudes from $\sim$1.0 to 2.0 MHz, with the strongest wave response appearing at the eastern longitude stations, that is, in Ashkhbad and Europe. In addition, also shown in Figure 4 are systematic phase differences between the various 7-day oscillations observed more clearly between stations that are distant in longitude. The resolved phase shifts between stations indicate westward propagation of this, global-scale, 7-day wave. This is in agreement with the data analysis of *Wu et al.* [1994] and *Clark et al.* [2002] and the GSWM estimates of *Meyer and Forbes* [1997] for the concurrent 7-day PW in the MLT region neutral wind.

5. Estimating PW Parameters from f_oE_s Data

[15] The observation of the PW periodicity in f_oE_s over a large latitudinal zone, introduces an alternative way for independent calculations of additional PW parameters. Next, we used the f_oE_s data set to estimate the wave propagation properties and zonal wave number (ZWN) with the following three methods.

1. A cross-wavelet analysis was applied that is suitable for measuring the strength and time of occurrence of any oscillation simultaneously present over any pair of stations. In this way, the estimated cross-wavelet spectrum is a complex quantity $C(T) = Pe^{i\Theta}$, where the amplitude P, that is, the cross-wavelet power at a given period, is a measure of the significance that an oscillation is simultaneously present in both time series, whereas the phase angle Θ represents the oscillation phase difference in the two time series. By applying cross-wavelet spectral analysis for all pairs of stations (more details and/or plots cannot be accommodated in this paper) we estimated a consistently westward propagation of the 7-day wave and found ZWN ranging between 0.87 and 1.29, with an overall mean 1.08 and a standard deviation 0.15. Also, the mean phase velocity of the 7-day wave was found on the average equal to $\sim$32.1 m/s and the standard deviation 5.0 m/s.

2. A conventional cross-correlation analysis was applied to the filtered outputs shown in Figure 4. The results of this analysis, which for a given station pair include (1) the cross-correlation coefficient, (2) the time lag (in hours), and (3) the calculated zonal wave number, are summarized in Table 1 for all possible station pairs formed between a given station and each of the rest to the west. Note that all the cross-correlation coefficients listed in Table 1 were computed at a confidence level higher than 99%. The zonal wave numbers shown there range between 0.80 and 1.26, having a mean 1.11 and a standard deviation 0.11; the westward mean phase velocity of the wave was 31.6 m/s and the standard deviation 3.8 m/s.

3. Finally, the mean amplitude and phase of the 7-day wave was estimated for every f_oE_s time series from the best fit of a sine wave to the filtered time sequences. Subsequently, following standard methodology applied in PW analysis, the slope of the station points in the "phase-longitude plot" determines the zonal wave number of the propagating wave. The results of this analysis are displayed in Figure 5. As seen, when only the seven midlatitude stations between 38°N and 48°N are included, the solid line slope yields a ZWN of -1.12 (and a standard deviation 0.12), where the minus sign indicates westward propagation;

Table 1. Cross-Correlation Analysis for the Filtered Signals Shown in Figure 4[a]

Station	Ashkhabad	Belgrade	Rome	Poitiers	Lannion	Wallops	Boulder	Maui
Ashkhabad		0.74	0.77	0.91	0.92	0.88	0.67	0.59
37.9°N, 58.3°E	1	+21	+26	+29	+31	+75	+89	+114
		1.19	1.21	1.07	1.07	1.20	1.16	1.13
Belgrade			0.88	0.84	0.96	0.93	0.76	0.68
44.8°N, 20.5°E		1	+3	+11	+13	+46	+69	+80
			0.80	1.16	1.16	1.03	1.17	0.97
Rome				0.93	0.89	0.82	0.66	0.69
41.9°N, 12.5°E			1	+6	+7	+43	+69	+81
				1.04	1.21	1.05	1.25	1.03
Poitiers					0.91	0.81	0.57	0.56
46.6°N, 0.3°E				1	+2	+39	+62	+74
					1.16	1.10	1.25	1.01
Lannion						0.93	0.69	0.67
48.7°N, 3.4°W					1	+37	+60	+77
						1.07	1.26	1.08
Wallops							0.71	0.51
37.8°N, 75.5°W						1	+17	+41
							1.24	1.08
Boulder								0.73
40°N, 105.3°W							1	+20
								0.84
Maui								
20.8°N, 156.5°W								1

[a] Results are shown for every possible ionosonde station pair between a given station in the leftmost column and the rest to the west. Starting from top, the set of three numbers represent: (1) the cross correlation coefficient, (2) time lag in hours with plus sign meaning that east station is leading, and (3) the corresponding planetary wave zonal wave number.

here, the estimated mean phase velocity was 30.6 m/s and the standard deviation 5.3 m/s. On the other hand, when all stations are included, the dashed line slope is near −1.20 but still, for all practical purposes, not far from −1.

[16] All three methods used in the f_oE_s wave analysis provide nearly identical results for the zonal wave number, the propagation direction and the phase velocity of the 7-day wave. Thus, by using f_oE_s time series from a longitudinal chain of ionosonde stations we calculated a 7-day period westward propagating $S = 1$ wave, which is in good agreement with the results of MLT neutral wind data analysis, published by *Wu et al.* [1994], and *Clark et al.* [2002] and the numerical estimates of *Meyer and Forbes* [1997].

6. Implications for PW Research

[17] As seen, f_oE_s time series from various stations stretching along an extended longitudinal sector were used to calculate key PW parameters that compare well with published results obtained from radar and satellite MLT wind measurements. Actually for this dominant 7-day wave event the PW parameters were estimated from f_oE_s by using three independent methods that gave identical results, a fact that strengthens the reliability of these estimates. This suggests that f_oE_s times series may be very useful for direct studies of large-scale neutral atmospheric dynamics. The analysis methodology and results of this paper, besides proving the existence of a direct relationship between PW and E_s, it also reveals the enormous capacity of the global E_s ionosonde recordings for the computation of PW parameters. This implication sounds especially promising, given the dense global coverage with numerous ionosonde stations as well as the reliability and compatibility of the ionosonde measurements. Perhaps, the most important contribution that can be made by including f_oE_s data in planetary wave analysis is the extension to altitudes higher than those covered by conventional radar methods. For example, extensive data in the 100- to 110-km altitude region are not usually available since it is above the altitude where meteor or medium-frequency radar data are deemed reliable.

[18] We conclude that in order for this new PW research option to become fully established and directly exploitable,

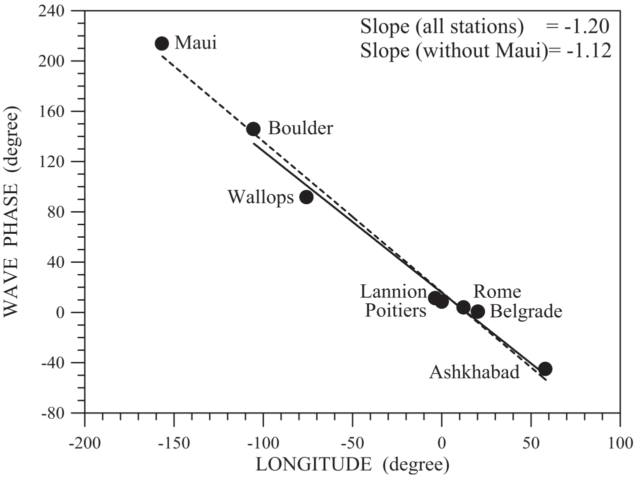

Figure 5. Wave phase - longitude plot for all the ionosonde stations. Wave phases were computed from the best sine wave fit to the filtered outputs shown in Figure 4. The slopes of the lines provide the planetary zonal wave number, where the minus sign means westward propagation.

the type of work presented in this paper needs to be continued and expanded, a task for us already on its way.

7. Discussion and Concluding Comments

[19] The present work provides, for first time, convincing experimental evidence showing that planetary waves have a profound role in the physics of midlatitude sporadic *E* layers. Since PW are confined inside a limited altitude range in the MLT region but have very large horizontal scales, our findings indicate that long-lasting, horizontal wind motions are important for the formation of strong E_s. This implies the existence of a new driving force that so far has been overlooked in the long-going research of E_s metallic ion layers. The present results substantiate the need for reconsideration of the midlatitude E_s theoretical modeling and suggest the formulation of a three-dimensional treatment. Also, the possibility exists that global-scale dynamics may have an indirect influence on plasma processes of much shorter scale, such as E_s layers, by affecting for example gravity waves and thus vertical wind shears.

[20] Our findings also imply that a new mechanism, introduced first by *Shalimov et al.* [1999] and formulated in detail more recently by *Shalimov and Haldoupis* [2002], maybe of fundamental importance in understanding the PW-E_s relationship. In this process a PW is viewed as composed of successive high- and low-pressure regions accompanied, under conditions of geostrophic wind balance, by large-scale anticyclonic and cyclonic vortices in neutral wind, respectively. In this picture the long-living, metallic ion plasma is Lorentz-forced to converge horizontally and thus accumulate inside areas of positive PW vorticity set up by the cyclonic neutral wind shears. In contrast, inside areas engulfed by anticyclonic PW winds, the metallic ions are gradually forced outward resulting to plasma depletion. Subsequently, a vertical wind shear acting in an area of negative PW vorticity is less probable to form a strong E_s layer, whereas the opposite would occur in an area of positive PW vorticity due to horizontally converging metallic ion transport and thus enhanced plasma densities there. In this way and for a zonally propagating PW, an ionosonde in the ground will observe a modulation in E_s strength and occurrence with a period comparable to that of the PW.

[21] As shown by *Shalimov and Haldoupis* [2002], the efficiency of the PW-driven horizontal plasma accumulation process can be complicated greatly by altitude effects and shorter scale PW-induced vertical plasma motions with contributions from additional dynamic neutral wind components, such as, gravity waves and tidal motions. Despite these anticipated complications, however, the present results indicate that the PW modulation of E_s does prevail fully during times of strong PW activity. This could reside on the fact that short-scale effects tend to average out, over the long scales (temporal and spatial) in the interaction between a PW and long-living metallic ion plasma.

[22] Finally, we suggest more studies of the type performed in the present paper, for example, during periods of strong quasi 2-day PW activity, which is known to intensify during summertime [e.g., see *Jacobi et al.*, 1998], when also E_s occurrence maximizes sharply [e.g., see *Whitehead*, 1989]. This could identify the cause for the well known, but not yet understood, E_s seasonal morphology that is completely inexplicable from classic wind shear theory. In addition, the present work needs to be expanded to include carefully done correlative studies between E_s ionosonde recordings and nearby radar measurements of MLT winds. This can test the validity of the *Shalimov and Haldoupis* [2002] mechanism and also establish the use of f_oE_s data as a diagnostic of PW activity.

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C. Haldoupis, Physics Department, University of Crete, Iraklion, Crete, Greece, 710 03. (chald@physics.uoc.gr)

D. Pancheva, Department of Physics, University of Wales, Aberystwyth, U.K. SY23 3BZ. (ddp@aber.ac.uk)