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Persistence of the planetary wave type oscillations in *fo*F2 over Europe

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Abstract. Planetary waves are oscillations of very predominantly tropospheric origin with typical periods of about 2–30 days. Their dominant zonal wave numbers are 1, 2 and 3, i.e. the waves are of large-scale (global) character. The planetary wave type oscillations have been observed in the lower and middle atmosphere but also in the ionosphere, including the ionospheric F2-layer. Here, we deal only with the oscillations analyzed for four European stations over a solar cycle with the use of the Meyer and Morlet wavelet transforms. Waves with periods near 5, 10 and 16 days are studied. Only events with a duration of three wave-cycles and more are considered. The 5-day period wave events display a typical duration of 4 cycles, while 10- and 16-day wave events are less persistent, with a typical duration of about 3.5 cycles and 3 cycles, respectively. The persistence pattern in terms of number of cycles and in terms of number of days is different. In terms of number of cycles, the typical persistence of oscillations decreases with increasing period. On the other hand, in terms of number of days the typical persistence evidently increases with increasing period. The spectral distribution of event duration is too broad to allow for a reasonable prediction of event duration. Thus, the predictability of the planetary wave type oscillations in *fo*F2 seems to be very questionable.

Key words. Ionosphere (ionosphere-atmosphere interaction, mid-latitude ionosphere, ionospheric disturbances) – Meteorology and atmospheric dynamics (waves and tides)

1 Introduction

Planetary waves are oscillations with typical periods of about 2–30 days. Their dominant zonal wave numbers are 1, 2 and 3, i.e. the waves are of large-scale (global) character, and they are very predominantly of tropospheric origin (e.g. Vincent, 1990). The planetary waves are divided into two groups, the stationary planetary waves, associated with the quasi-stable meteorological structures, such as the Icelandic pressure low, etc., and the transient planetary waves, which propagate predominantly westward, even though sometimes (rarely) the eastward propagation dominates (Pancheva and Laštovička, 1998). The planetary waves, together with the tidal and gravity waves, appear to be the most important and persistent components of the effects on the ionosphere from "below".

The planetary waves propagating upwards from the troposphere have to pass through the lower ionosphere ($h < 100$ km). Investigations of the transient planetary wave activity in the lower ionosphere (in its ionized component) are based on the long-term measurements of the radio-wave absorption in the lower ionosphere over Europe by the A3 method (continuous wave, oblique incidence on the ionosphere). The planetary wave activity has been studied in the period range of 3–15 days. The best-developed and most persistent spectral peaks in the range of 3–15 days over the 1980s occurred near 5 and 10 days (Laštovička and Pancheva, 1991). They are consistent with the eigenperiods of the atmosphere of about 2, 5, 10 and 16 days. The planetary wave type oscillations were shown to be caused by the planetary wave type oscillations in the neutral atmosphere, and not by solar or geomagnetic activity (Pancheva et al., 1989; Pancheva and Laštovička, 1989). Model computations confirmed adequate transformation of planetary wave type oscillations in the neutral atmosphere into waves in the radio-wave absorption (Laštovička et al., 1994). The planetary wave type oscillations in the lower ionosphere have been studied in a series of papers, e.g. Laštovička and Pancheva (1991), Laštovička et al. (1994), Laštovička (1997, 2001 and references herein), Pancheva and Laštovička (1998). The planetary wave activity in the lower ionosphere is higher in winter than in summer due to the different conditions of the upward penetration of planetary waves, and it exhibits a slight trend of increasing amplitude (e.g. Laštovička, 2001)

The planetary wave type oscillations in the F-region of the ionosphere have been studied in a couple of papers,

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e.g. Forbes and Leveroni (1992), Canziani (1994), Pancheva et al. (1994), Apostolov et al. (1995, 1998), Altadill and Laštovička (1996), Laštovička and Mlch (1996), Laštovička (1997), Meyer and Forbes (1997), Laštovička and Šauli (1999), Forbes et al. (2000), Altadill et al. (2001). Altadill and Apostolov (1998, 2001) analyzed six events of both the upward propagation and the downward propagation of the wave-type oscillations with periods of 2 and 6.5 days. They attributed all three upward propagating events to planetary waves observed simultaneously in the mesosphere/lower thermosphere region. The downward propagating events had a different relation between group and phase velocities. One of these events was attributed to a periodic geomagnetic activity. Thus, not every oscillation in the period range 2–30 days in the F-region can be considered a planetary wave oscillation, even though the majority of such oscillations can be attributed to planetary waves. There is a strong solar-origin oscillation with periods near 27 days (the solar rotation), and partly also at 13–14 days (half of the solar rotation), therefore, these periods are not analyzed herein.

Some studies report simultaneous observations of planetary waves in the lower and upper ionosphere, as, for instance, Pancheva et al. (1994), for some 2-day events (but not all events) and Yi and Chen (1994) for low latitudes. However, such observations create a problem for theory, because the planetary waves in the neutral atmosphere cannot propagate directly upwards to the F2-region peak heights due to the atmospheric viscosity and other factors. Therefore, we need to look for indirect ways of propagation. One possibility is the planetary wave modulation of the upward propagating tides in the mesosphere and lower thermosphere (MLT) region. Such a modulation has been observationally confirmed to occur in the wind in the MLT region in correspondence with theoretical expectations (Mitchell et al., 1996; Beard et al., 1999; Pancheva, 2001 and references herein). Laštovička and Šauli (1999) investigated the variability of *fo*F2 from two Central European stations, Juliusruh and Průhonice, and the tides inferred from wind measurements in the MLT region at nearby station Collm. They found that the planetary wave modulation of the upward propagating tides in the MLT region did not play a dominant role, but it might contribute to the planetary wave type oscillations in *fo*F2.

Another possibility is the planetary wave modulation of the upward propagating gravity waves (Meyer, 1999). Observational confirmation and quantification of the role of the "gravity wave" mechanism remains difficult due to data problems; we need to find a gravity wave parameter which is persistent on time scales of days (Laštovička, 1999). Other possibilities of an indirect upward propagation via planetary wave modulation of various upward propagating agents at the upper mesospheric/lower thermospheric heights are: (i) the vertical plasma drift due to the planetary wave modulation of the E-region dynamo (Pancheva et al., 1994), and (ii) modulation of the turbopause height and turbopause region properties.

The quasi-two-day oscillations in *fo*F2 have some specific features that are different from longer periods. Their behaviour was studied , for example, by Apostolov et al. (1995) and Pancheva et al. (1994). One of these specific features is a combination of three different types of oscillations: the westward travelling wave with the wave number one (this oscillation has the wave number three in the MLT region), the stationary planetary wave, and more local oscillations. Therefore, we shall deal with the 5-, 10- and 16-day oscillations, and not with the 2-day oscillations. If we assume that spectral peaks of the F2-region ionizing radiation are similar to those of the Lyman-alpha flux, then the three selected periods cannot be caused by solar radiation variability, as follows from the results of Pancheva and Laštovička (1989). Some oscillations near $T = 5$ days might be of geomagnetic activity origin (Pancheva et al., 1989; Altadill and Apostolov, 1998, 2001). However, we analyze only oscillation events of duration of at least three wave-cycles, where the probability of oscillations of other than the planetary wave origin is very low, practically negligible.

All observed planetary wave periods are unstable and/or quasi-periods, therefore, we use data from the period bands of 4–6, 9–11 and 15–18 days as representative for the 5-, 10- and 16-day periods, respectively. This migration of periods was also confirmed by wind measurements at similar heights (e.g. Williams and Avery, 1992; Beard et al., 2001). The background wind is probably responsible for the migration of periods (Beard et al., 2001).

The transient planetary waves in the atmosphere and ionosphere seem to occur in the form of bursts of a couple of waves with limited persistence. Potential predictability of planetary wave effects for the sake of predictions of the ionospheric radio-wave propagation conditions needs some information about the persistence of the planetary wave type events in the ionosphere. In the stratosphere, the waves with periods of 4–5 days occur as bursts of several cycles, as deduced from satellite measurements of temperature fields. In the mesosphere, satellite measurements of winds at altitudes of 50–100 km reveal the transient 5-day wave with a lifetime of 10–20 days (Wu et al., 1994). In the mesopause region the tidal winds observed in Central Europe (Collm) in the first half of 1984 were dominated by oscillations with typical periods of 5–6 days, with a typical persistence of 6 cycles for meridional and 4 cycles for zonal component (Laštovička and Šauli, 1999). Also, meteor radar wind measurements from Sheffield confirm the episodic nature of planetary waves (Beard et al., 2001). An analysis of two long data sets of the radio-wave absorption in the lower ionosphere over Central Europe showed that in the lower ionosphere, the typical persistence of waves with period (T) of about 5 days was about 5 cycles, $T = 10$ days for 3–4 cycles, and for periods around 16 days no more than 3 cycles (Laštovička et al., 2002). In the F2-region ionosphere in the critical frequency *fo*F2, Laštovička and Šauli (1999) found at Průhonice (Central Europe) for 1984 in the first four months the dominance by the 5–6 day oscillations with a typical persistence of 5–6 cycles. Altadill et al. (2001) analyzed two planetary wave events observed at the Ebro Observatory (northeastern Spain). They found the persistence of 4–6 cycles for oscilla-

Table 1. Coordinates of ionospheric stations

Station	Geographic latitude	Geographic longitude	Geomagnetic latitude
Juliusruh	54.6°C	13.4° E	54.3° N
Slough	51.5°C	0.6° W	51.5° N
Průhonice	50.0° N	14.6° E	49.7° N
Rome	41.8° N	12.5° E	42.3° N

tions with a period of 6.5 days. It should be mentioned that Lindzen et al. (1984) already suggested that the existence of propagating external Rossby modes in the atmosphere was episodic.

We investigate the persistence of the planetary wave type oscillations over Europe, among others, in order to clarify the possible predictability of such oscillations with applications to the radio-wave propagation conditions (e.g. in project COST271), and for a better understanding of the coupling of the lower and upper atmosphere. A brief description of data and methods in Sect. 2 is followed by the Meyer wavelet analysis results in Sect. 3 and the Morlet wavelet analysis results in Sect. 4. The results are briefly discussed in Sect. 5 and summarized in Conclusions.

2 Data and method

As the analyzed ionospheric parameter we use the basic characteristics of the F2-region, the widely available critical frequency *fo*F2. Data from four stations, which are typical for the European area (except Russia), Juliusruh, Slough, Průhonice and Rome, are used over the period 1979–1989 (from maximum to maximum of the solar cycle). The coordinates of those four stations are listed in Table 1. Noontime (10:00–14:00 UT) average values of *fo*F2 are used. Sometimes there are problems with the quality and availability of *fo*F2 data with some stations for some periods (Burešová, 1997). The above stations and the analyzed period were selected by taking such problems into account. Therefore, good quality data with minimum gaps are used in the paper. Single data gaps were interpolated with the use of data of the same station at other local times and/or from neighbouring stations at the same time, or a combination of both, based on the availability of data. Nevertheless, Rome, January–June 1979 and Průhonice 1989 data have not been taken into analysis due to more data gaps.

In our previous study of the persistence of the planetary wave type oscillations in the F2-region (Laštovička and Šauli, 1999) we used the autocorrelation method. The autocorrelation can yield information about the persistence only for a dominant wave, if a well-dominant wave exists. If not, this method does not reveal reasonable information about the persistence. To overcome this problem, the wavelet analysis applied to consecutive 1-year long intervals, shifted by half a year, was used in searching for the persistence of the planetary wave oscillation events in the lower ionosphere by Laštovička et al. (2002). Time series were analyzed by a continuous wavelet transform. The Meyer wavelet was used from the family of wavelet functions.

The wavelet analysis is a powerful tool for analysing localised variations of power within a time series. The method allows for the decomposition of one-dimensional series into the time-period space, where it is possible to determine both the dominant modes of variability and how those modes vary in time. The wavelet analysis can be used to analyze time series that contain non-stationary power at many different frequencies. The continuous wavelet transform is defined as the convolution of signal with a scaled and translated version of wavelet function. By varying the wavelet scale and translating along the localised time it is possible to construct a picture showing both the amplitude of any feature versus the scale and how this amplitude varies with time. In the paper we apply two types of continuous wavelet analysis, the Meyer wavelet and the Morlet wavelet analyses. The Meyer wavelet is an infinitely regular orthogonal symmetric wavelet. Its definition and scaling functions are more complicated than for most of the other famous wavelets, so interested readers should look for details in Daubechies (1994). A commercial MATLAB-Wavelet software has been used to compute Meyer wavelet transform.

The Morlet wavelet consists of a plane wave modulated by Gaussian (Torrence and Compo, 1998). The Morlet wavelet function is a complex function and the corresponding wavelet transform is also complex. The Morlet wavelet with parameter 7 is used. As a source Matlab code the wavelet software for Morlet wavelet computations provided by Torrence and Compo was used. Matlab codes are available at URL: http://paos.colorado.edu/research/wavelets/.

The wavelet analysis is applied to consecutive 1-year long intervals, shifted by half a year (January–December 1979, July 1979–June 1980, January–December 1980, etc.). Thus, for Slough and Juliusruh we have 21 partly overlapping intervals for the period 1979–1989, for Rome 20 intervals and for Průhonice 19 intervals.

3 Results of the Meyer wavelet analysis

Figures 1–3 show examples of the results of the Meyer wavelet transform. Altogether, 81 such pictures have been obtained for the four stations. Figures 1 and 2 represent the periods of high solar activity, while Fig. 3 is for the solar cycle minimum year. Figures 1 and 3 are for January-

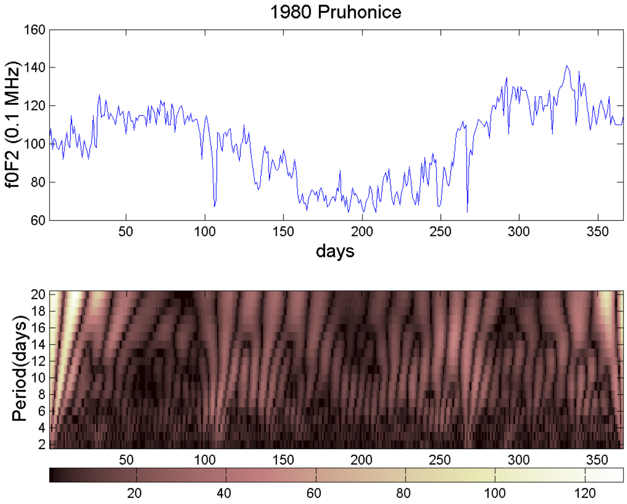

Fig. 1. Planetary wave activity inferred from *fo*F2 for Průhonice, January–December 1980, Meyer wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom panel, wavelet transform of the planetary wave activity changing by colour from black-brown (minimum value) to white (maximum value).

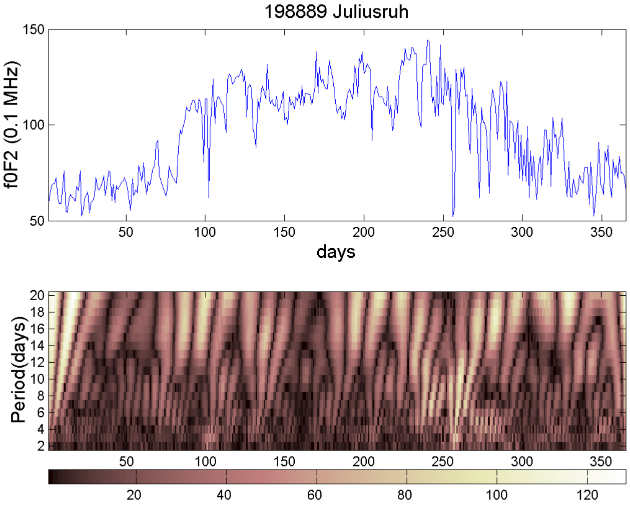

Fig. 2. Planetary wave activity inferred from *fo*F2 for Juliusruh, July 1988–June 1989, Meyer wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom panel, wavelet transform of the planetary wave activity changing by colour from black-brown (minimum values) to white (maximum values).

December, whereas Fig. 2 is for July–June. Top panels in Figs. 1–3 show time series of the raw *fo*F2 data with a well-developed seasonal variation with summer minimum, particularly under high solar activity conditions (Figs. 1 and 2). Bottom panels in Figs. 1–3, the results of the Meyer wavelet analysis, must be interpreted taking into account the seasonally variable level of the background *fo*F2 shown in top panels. Two planetary waves of the same amplitude in the neutral atmosphere will transfer into two planetary waves in *fo*F2 with different amplitudes due to the different level of the background *fo*F2. In other words, we need to consider the kind of "relative" amplitudes and/or power.

The most pronounced feature of Figs. 1–3 is a large temporal and partly spectral variability of the planetary wave activity. The migration of periods of planetary wave activity is also well visible. The large temporal variability of the planetary wave activity means, in other words, the limited persistence of the individual planetary wave events. Furthermore, we focus on well-developed wave events, i.e. events with a persistence of at least 3 wave cycles. The colours in Figs. 1–3 represent the events of relative brightening of a duration of at least three cycles with respect to their vicinity. This is a bit of a non-precise definition, but in view of the above effect of variable background *fo*F2, it seems to be better than to fix a level of brightness for such a search. We have to consider relative brightening with respect to the vicinity of the events. The brightening at the edges of Figs. 1–3 are artifacts caused by border effects.

The statistics of duration of individual events of the enhanced planetary wave activity for all yearly intervals and period bands centred at 5, 10 and 16 days is summarized in Table 2: number of events together with their mean, median and the most often occurring number of cycles for individual stations and the average values for all four stations. Due to the overlap of half-year shifted intervals, the majority of the events occur twice in these statistics.

For the 5-day wave, its mean, median and the most often occurring number of cycles provide an identical typical persistence of well-developed wave events to be of 4 cycles (Table 2). This is somewhat less than the persistence found

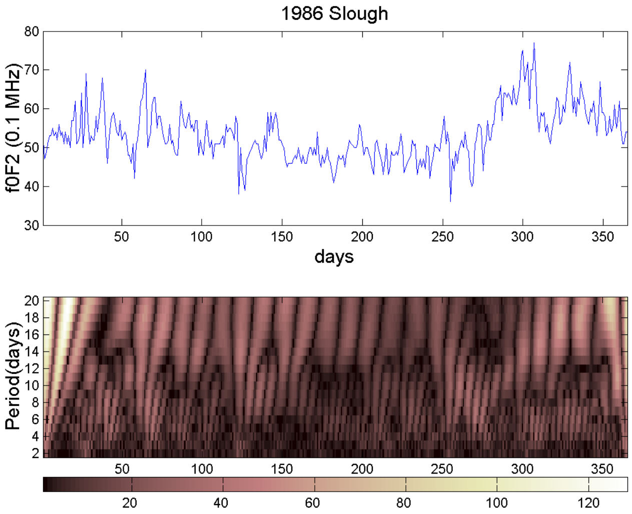

Fig. 3. Planetary wave activity inferred from *fo*F2 for Slough, January–December 1986, Meyer wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom panel, wavelet transform of the planetary wave activity changing by colour from black-brown (minimum values) to white (maximum values).

Table 2. Statistics of persistence of planetary wave type oscillations in *fo*F2 over Europe, 1979–1989, based on the Meyer wavelet transform. The average values for medians and the most frequent values are presented with step 0.5

Station	Period (days)	Number of events	Median value	Mean Value	Most frequent value
Juliusruh	5	45	4	4.5	4
	10	39	4	4.0	3 + 4
	16	35	3.5	3.8	3–3.5
Slough	5	37	4	4.3	4
	10	29	3.5	3.6	3.5
	16	34	3.5	3.6	3–3.5
Průhonice	5	49	4.5	4.7	4
	10	42	4	4.1	3
	16	33	3.5	3.8	3
Rome	5	31	4	4.0	3.5–4
	10	33	3.5	3.7	3.5
	16	25	3	3.5	3
Average values	5	40	4	4.3	4
	10	36	3.5–4	3.8–3.9	3.5
	16	32	3.5	3.7	3

by Laštovička and Šauli (1999) for a very limited data set. The coincidence of mean, median and the most often occurring number of cycles is slightly worse for the longer periods of 10 and 16 days, where all these characteristics provide the persistence smaller than 4 cycles. For 10 days, the median value and the most frequent occurrence point to a typical persistence of 3.5 cycles. For 16 days, all values point to a typical persistence of 3–3.5 cycles. However, if we consider the most frequent value of 3 cycles and we also imagine the occurrence of events shorter than 3 cycles, then the typical persistence of events with periods around 16 days seems to be no more than 3 cycles. The spectrum of duration of the planetary wave events peaks near its lower cutoff duration of 3 cycles and has a relatively long tail in longer duration; therefore, the mean duration cannot be considered representative and/or close to the typical duration.

Thus, in terms of the number of cycles in the planetary wave events, the 5-day period wave events display the typical duration of 4 cycles, while 10- and 16-day events display 3.5 and no more than 3 cycles, respectively. However, in terms of days it means that there is a typical duration of 20 days for $T = 5$ days, about 35 days for $T = 10$ days and no more than 48 days for $T = 16$ days. In other words, the duration of wave events in terms of days is not shorter for longer periods, but rather it seems to be longer. We are not going to analyze bursts shorter than 3 cycles, since the physical understanding of such variations and/or events as waves may be questioned. On the other hand, one season (90 days) is equal to 5.5 cycles with $T = 16$ days. This means that for long periods we can hardly expect a long persistence in terms of the number of

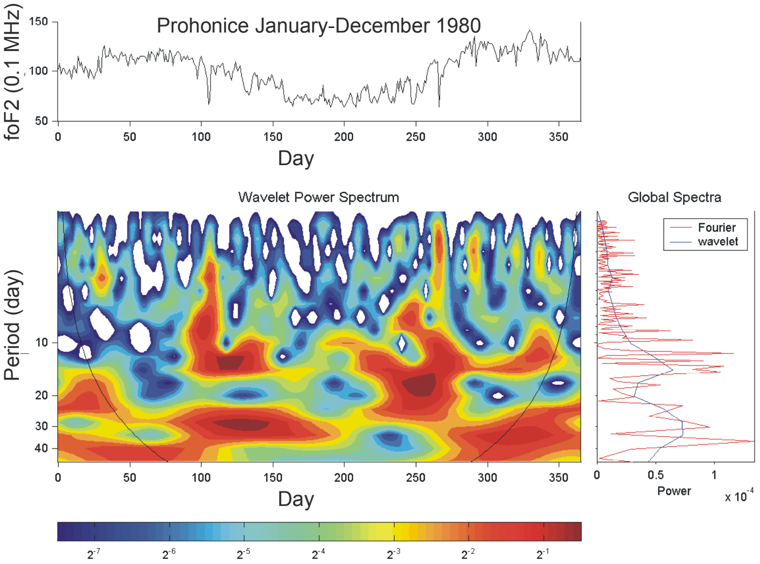

Fig. 4. Planetary wave activity inferred from *fo*F2 for Průhonice, January–December 1980, Morlet wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom left panel, wavelet transform power spectrum of the planetary wave activity changing by colour from white and black-blue (minimum values) through green to red and black-red (maximum values). Power spectrum is normalized to 1. Bottom right panel, global (over 365 days) Morlet wavelet and Fourier spectrum; horizontal axis – power; vertical axis – period of oscillations in days.

cycles. It has to be destroyed by the seasonal variation of the atmosphere and by various sporadic effects.

4 Results of the Morlet wavelet analysis

Figures 4–6 show examples of results of the Morlet wavelet power spectra normalized to a peak amplitude equal to 1. Again, 81 such pictures have been obtained for the four stations. Figures 4, 5 and 6 are for the same intervals and stations as Figs. 1, 2 and 3. Figures 4 and 5 represent periods of high solar activity, while Fig. 6 is for the solar cycle minimum year. Figures 4 and 6 are for January–December, whereas Fig. 5 is for July–June. Top panels in Figs. 4–6 show time series of the raw *fo*F2 data with a well-developed seasonal variation with summer minimum, particularly under high solar activity conditions.

Bottom left panels in Figs. 4–6 provide the results of the Morlet wavelet analysis. While the Meyer wavelet transform results (Figs. 1–3) are more suitable for the evaluation of the relative amplitudes/power with respect to the vicinity of the analyzed interval, the Morlet wavelet transform results are more suitable for the evaluation of the normalized absolute amplitude/power, i.e. a search for intervals with values larger than a fixed value. Even though the values shown in Figs. 4–6 are normalized, their interpretation with respect to a fixed level, and not to vicinity of the given interval, is hereafter called “absolute amplitudes”. This allows us, among others, to compare the results of the relative and absolute amplitude/power approach to interpretation of the results. Bottom right panels in Figs. 4–6 show global (over 365 days) Morlet wavelet transform and Fourier transform spectra, with the horizontal axis representing the power and the vertical axis representing the period of oscillations in days. The Morlet wavelet analysis reveals much better resolution in time and allows for the study of events of a (very) limited persistence/duration. The Fourier spectral analysis has in global values better resolution in periods but does not enable one to study events of limited duration and to localize their position.

The most pronounced feature of Figs. 4–6 is again a large temporal and spectral variability of the planetary wave activity. The migration of periods of planetary wave activity is visible, even better than in Figs. 1–3. We again deal only with the well-developed wave events, i.e. events with a persistence of at least 3 waves. With Morlet wavelets we consider the normalized absolute amplitudes. In Figs. 4–6 we are not interested in the change in colour. We only consider intervals with a yellow or red colour of the duration of at least three wave cycles. Only results inside of the conus of significance (black thin curve) are taken into account. The border effects affect the information out of the thin curve. Figures 4–6 display a well developed and reasonably persistent ∼27-day variation (particularly Fig. 5), which, however, is of solar origin and, therefore, out of the scope of the paper.

The statistics of the duration/persistence of individual events of enhanced planetary wave activity for all yearly intervals and period bands centred at 5, 10 and 16 days is summarized in Table 3, as is the Meyer wavelet in Table 2: number of events together with their mean, median and the most often occurring number of cycles for individual stations, and average values for all four stations. Numbers of events in Table 3 versus Table 2 differs due to the difference in their definition.

Table 3 reveals for the 5-day wave the typical persistence of well-developed wave events to be of 4 cycles or a little bit

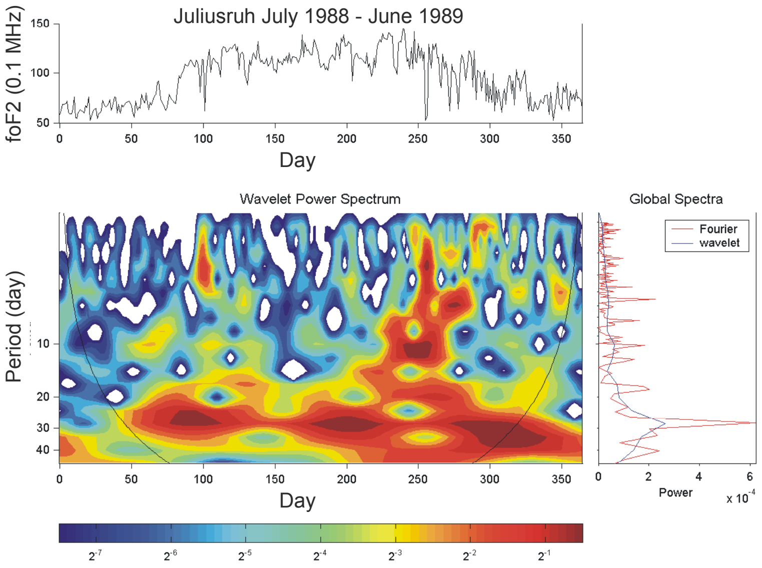

Fig. 5. Planetary wave activity inferred from *fo*F2 for Juliusruh, July 1988–June 1989, Morlet wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom left panel, wavelet transform power spectrum of the planetary wave activity changing by colour from white and black-blue (minimum values) through green to red and black-red (maximum values). Power spectrum is normalized to 1. Bottom right panel - global (over 365 days) Morlet wavelet and Fourier spectrum; horizontal axis - power; vertical axis – period of oscillations in days.

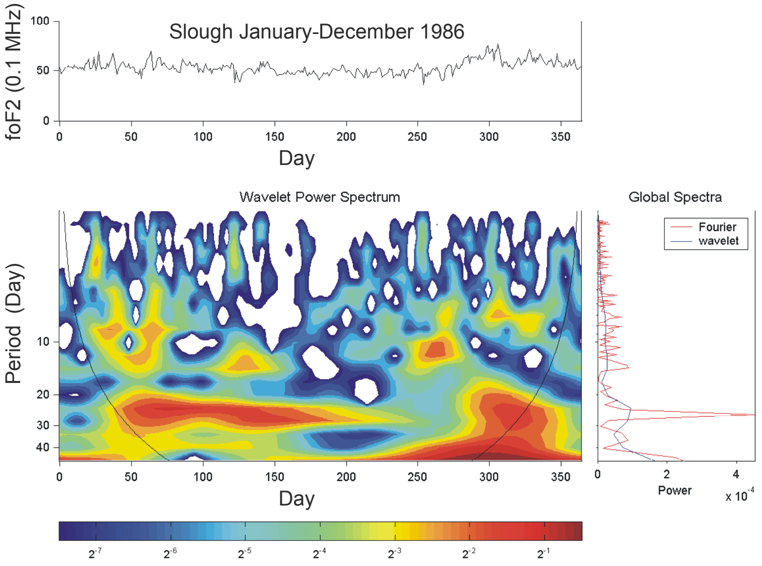

Fig. 6. Planetary wave activity inferred from *fo*F2 for Slough, January–December 1986, Morlet wavelet transform. Top panel, time series of raw *fo*F2 data. Bottom left panel, wavelet transform power spectrum of the planetary wave activity changing by colour from white and black-blue (minimum values) through green to red and black-red (maximum values). Power spectrum is normalized to 1. Bottom right panel - global (over 365 days) Morlet wavelet and Fourier spectrum; horizontal axis - power; vertical axis – period of oscillations in days.

more, based on median and the most frequent values. This is consistent with the persistence obtained from the Meyer wavelet transform by another way of evaluation, "relative" instead of "absolute" amplitudes. For the 10-day wave, both the median value and the most frequent occurrence provide the typical persistence of just 4 cycles. For the 16-day wave, the median and most frequent values point to a typical persistence of 3.5 cycles or slightly more. Thus, the persistence in terms of the number of cycles slightly decreases with increasing period, but less than that for the Meyer wavelet transform interpreted in terms of relative brightness in Figs. 1–3. In other words, the persistence interpreted from Figs. 1–3 ("relative" amplitudes) and 4–6 ("absolute" amplitudes) is not the same. The latter interpretation requires sufficiently large power but does not consider its changes with time, which may include changes of phase. The former considers changes of power with time but does not require the power to be always higher than a fixed limit. Therefore, Table 3 reveals one

Table 3. Statistics of persistence of planetary wave type oscillations in *fo*F2 over Europe, 1979–1989, based on the Morlet wavelet transform. The average values for medians and the most frequent values are presented with step 0.5

Station	Period (days)	Number of events	Median value	Mean value	Most frequent value
Juliusruh	5	55	4	4.8	4
	10	39	4.5	4.6	4.5
	16	30 + 1*	4	4.8	3
Slough	5	52	4.5	4.8	3–4
	10	38	4–4.5	4.6–4.7	3.5
	16	35	4	4.3	3
Průhonice	5	33	4	4.6	4
	10	42	4	4.4	3
	16	31	4.5	4.7	4
Rome	5	55	4.5	4.9	3.5–4
	10	52	4	4.2	4.5
	16	38	4	4.6	4
Average values	5	49	4–4.5	4.8	4
	10	43	4	4.4	4
	16	34	4	4.6	3.5

1* – ∼220 day long period of persistent occurrence in 1980

extremely long (≈220 days) event, which is not the case for the Meyer wavelet analysis (Table 2).

In terms of days the typical duration for the Morlet wavelet transform is 20 days or a little bit more, for $T = 5$ days, about 40 days for $T = 10$ days and about 54 days or a little bit more for $T = 16$ days. In other words, the duration of wave events in terms of days is not shorter for longer periods, but rather it again seems to be longer. We are not going to analyze bursts shorter than 3 cycles, since the physical understanding of such variations and/or events as waves may be questioned.

In order to exclude the possibility of some difference in the results due to a difference between the Meyer and Morlet wavelet techniques, the results of the Morlet wavelet transform (Figs. 4–6) are also interpreted in the same way as the results of the Meyer wavelet transform, i.e. in terms of relative changes in power. For the 16-day wave, the results are the same as in Table 2. For shorter periods, particularly for $T = 5$ days, the number of wave events is slightly lower and the average duration is slightly lower for the Morlet wavelet transform results, whereas median values are mostly identical, with some by 0.5 lower, and the most typical values for the Morlet wavelet transform results are identical to those in Table 2. Thus, the overall pattern remains the same for both the Meyer and Morlet wavelet transform results. The minor differences observed might result from partly subjective evaluation in the "relative" amplitude approach. The difference between the "absolute" amplitude and "relative" amplitude interpretation of the results is even slightly higher when we use the Morlet wavelet transform results instead of the Meyer wavelet transform results for the "relative" amplitudes. Nevertheless, the gross features of the results obtained by both means of interpretation are generally consistent.

5 Discussion

The *fo*F2 data of four stations representative for the mid-latitudinal Europe, Juliusruh, Slough, Průhonice and Rome, were used to study the persistence of planetary wave events in the maximum of the F2-region of the ionosphere. The general pattern of persistence of the planetary wave type oscillations is similar for all four stations in Tables 2 and 3 and, therefore, may be considered representative for European middle latitudes (except Russia). Slight differences may be caused by a slightly different data set, a limited amount of the analysed data, perhaps some local effects, as well as a different approach to the persistence evaluation in Tables 2 and 3. However, these differences appear to be within the accuracy of determination of persistence of the planetary wave type events.

Some planetary wave events have a sharp beginning and end. Then, the accuracy of the determination of persistence is given basically by the resolution of the software used. However, the beginning and end of most events is not so sharp and the accuracy of the determination of persistence in such cases is between half and one wave cycle. Therefore, we can consider that the accuracy of determination of the typical persistence of planetary wave events is not worse than one wave cycle, but rather close to half a cycle. We are aware of the fact that such determination of accuracy does not look very scientific but by taking into account a partly vague definition of persistence and the accuracy of the input data, such an approach that is a bit like "fuzzy mathematics" seems to be the right approach.

The typical persistence of the 5-day wave in *fo*F2 is 4 cycles. This is slightly less than the typical persistence of 5 cycles for the 5-day wave in *fo*F2 found by Laštovička and

Šauli (1999) and Altadill et al. (2001) for very limited data sets. Also, in the lower ionosphere the typical persistence was found to be 5 cycles by Laštovička et al. (2002). This indicates the possibility of the persistence of 4–5 cycles to be typical for the 5-day wave oscillations in the upper atmosphere and ionosphere over Central Europe. Wu et al. (1994) reported shorter persistence for the 5-day wave events in the mesospheric winds as observed by HRDI/UARS. This might be caused either by different criteria for persistence, or by a difference in latitudes (UARS observations of planetary waves concern predominantly low latitudes). On the other hand, Laštovička and Šauli (1999) found the typical persistence of the 5-day wave events in the tidal wind in the mesopause region in Central Europe to be 4 cycles for the zonal component and 6 cycles for the meridional component. As for the persistence of oscillations with periods near 10 and 16 days, we have no available information about the persistence of such oscillations in other parameters.

The pattern for the persistence in terms of number of cycles and in terms of number of days is different. In terms of number of cycles, the persistence of oscillations decreases with increasing period. On the other hand, in terms of number of days, the persistence increases with increasing period. Both these results may be intuitively expected, taking into account seasonal variation that creates a problem mainly for the longer periods, and the occurrence of sporadic events, which disturb the shorter periods more.

We investigate the persistence of the planetary wave type oscillations over Europe, among others, in order to clarify the possible predictability of such oscillations with applications to the predictions of the radio-wave propagation conditions. For the sake of predictions, not only typical values of the persistence of planetary wave type events, but also spectral distribution of persistence (= event duration) is necessary. An example of the spectral distribution of event duration is shown in Fig. 7. The spectral distribution is too broad to allow for a reasonable prediction of event duration. Moreover, Figs. 1–6 display many events with a duration shorter than three cycles, which was the lower limit of events studied. Thus, the predictability of the planetary wave type oscillations in *fo*F2 seems to be very questionable. Unfortunately, we will probably be unable to separate these effects from the prediction noise, thereby improving the quality of radio-wave propagation predictions in such a way.

6 Conclusions

The basic characteristics of the F2-region, the critical frequency *fo*F2, was analyzed for four European stations, Juliusruh, Slough, Průhonice and Rome over the period 1979–1989 (one solar cycle). Noontime average values (10:00–14:00 UT) of *fo*F2 were used. The persistence of the planetary wave type oscillations at periods near 5, 10 and 16 days was studied with the use of the Meyer and Morlet wavelet transforms. Only events with a duration of three cycles or more were considered.

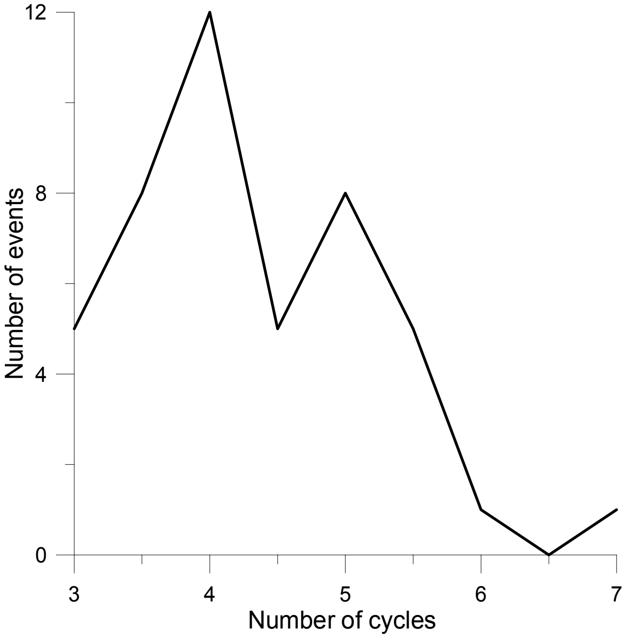

Fig. 7. Spectral distribution of the duration of the planetary wave type oscillation events (= persistence) in terms of number of cycles for the 5-day wave, station Juliusruh, 1979–1989.

The Meyer wavelet transform results were evaluated from the point of view of the relative enhancement of oscillation intensity with respect to surrounding “background” level (i.e. relative amplitudes of oscillations). The 5-day period wave events displayed a typical duration of 4 cycles, while 10- and 16-day wave events displayed 3.5 and no more than 3 cycles, respectively.

The Morlet wavelet transform results evaluated in the same way as the Meyer wavelet transform revealed almost identical results. However, the Morlet wavelet transform results were also evaluated from another point of view, as the increase in oscillation intensity above a fixed level (i.e. normalized absolute amplitudes of oscillations). Such evaluation provides for the 5-day wave a typical persistence of 4 cycles or a little bit more. For the 10-day wave, the typical persistence seems to be just 4 cycles. For the 16-day wave, the typical persistence is 3.5 cycles or slightly more. Thus, the persistence slightly decreases with increasing period, but less than that for the Meyer wavelet transform interpreted in terms of relative, not absolute amplitudes.

The pattern of the persistence in terms of the number of cycles and in terms of the number of days is different. In terms of tha number of cycles, the typical persistence of oscillations decreases with increasing period. On the other hand, in terms of the number of days, the typical persistence evidently increases with increasing period.

The spectral distribution of event duration is too broad to allow for a reasonable prediction of the event duration. Moreover, Figs. 1–6 display many events with a duration shorter than three cycles, which was the lower limit of events studied. Thus, the predictability of the planetary wave type oscillations in *fo*F2 seems to be very questionable. We will probably be unable to predict them for improving the quality of the radio-wave propagation predictions.

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