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Forcing of the ionosphere by waves from below

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Abstract

Meteorological processes in the lower-lying layers, particularly in the troposphere, affect the ionosphere predominantly through the upward propagating waves and their modifications and modulations. Those waves are planetary waves, tidal waves, gravity waves, and almost forgotten infrasonic waves. A part of wave activity can be created in situ at ionospheric heights as primary (e.g., diurnal tide, gravity waves) or secondary waves (e.g., some gravity or planetary waves), but this paper is focused on the upward propagating waves from below the ionosphere. They propagate into the ionosphere mostly directly but the planetary waves can propagate upwards to the F region heights only indirectly, via various potential ways like modulation of the upward propagating tides. The waves may be altered during upward propagation via non-linear interactions, particularly in the MLT region. A brief overview of effects on the ionosphere of upward propagating waves from lower-lying regions is given, separately for the lower ionosphere, for the E-region ionosphere, and for the F-region ionosphere. The upward propagating waves of the neutral atmosphere origin are important both from the point of view of vertical coupling in the atmosphere–ionosphere system, and for applications in radio propagation/telecommunications, as they are responsible for a significant part of uncertainty of the radio wave propagation condition predictions.
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1. Introduction

The ionosphere, that part of the upper atmosphere where free electrons formed by the solar X-rays and EUV radiation and other ionizing agents do exist, is first of all under solar control. Solar zenith angle, variability of solar ionizing radiation with the solar cycle, solar rotation, solar flares, and space weather phenomena mostly of solar origin are responsible for the extraterrestrial control of the ionosphere, i.e. control coming from above. However, there is also some coupling coming to the ionosphere from below, from lower-lying layers of the atmosphere.

Various processes in the lower-lying layers of the atmosphere, particularly in the troposphere, are summarized for simplicity under the term 'meteorological processes'. They can affect the ionosphere mainly through two channels: (i) electrical and electromagnetic phenomena, and (ii) upward propagating waves in the neutral atmosphere. The former category includes red sprites, blue jets and other lightning upward-induced phenomena, which play a role in the lower ionosphere below 100 km, changes in the global electric circuit, lightning-induced whistlers which can reach the magnetosphere, and a few other phenomena. However, these phenomena are not the scope of the paper, which

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deals with the latter category, with upward propagating waves in the neutral atmosphere, which are more important from the point of view of energy deposition and atmospheric modification than the phenomena under (i).

Various tropospheric and to a limited extent stratospheric and mesospheric "meteorological" processes and periodic solar heating and cooling excite waves in the neutral atmosphere. Upward propagating waves in the neutral atmosphere and their modifications, interactions and modulations affect the ionosphere, when and if they reach it. Those waves are planetary waves, tidal waves, gravity waves, and almost forgotten infrasonic waves. Most of the 'meteorological influences' on the ionosphere arise from the upward propagating gravity, tidal and planetary waves (e.g., Kazimirovsky et al., 2003). The meteorological influences play an important role in the overall ionospheric variability (e.g., Forbes et al., 2000; Rishbeth and Mendillo, 2001).

Planetary waves (periods of about 2–30 days) are very predominantly of tropospheric origin and can penetrate directly to heights slightly above 100 km. They have to propagate upwards into the F-region ionosphere via an indirect way. Their effects were observed in the lower ionosphere (e.g., Laštovička et al., 1994b), in the ionospheric E region in $h'E$ (e.g., Cavalieri, 1976) and sporadic-E (E_s) layer (e.g., Haldoupis et al., 2004), and in the F2 region (e.g., Forbes and Zhang, 1997; Altadill and Apostolov, 2001, 2003; Laštovička et al., 2003a, b). Mikhailov et al. (2004) studied ionospheric F2-layer disturbances not related to geomagnetic activity, which were of quite large amplitudes and looked like planetary waves with minimal deviations in the American sector and maximal deviations in the European sector.

Tides in the atmosphere are predominantly thermal, not gravitational tides. They are generated by the periodic solar heating. Dominant tidal periods in the ionosphere are 24, 12 and at high latitudes also 8 h. Their effects on the ionosphere were broadly studied by Fesen (1997) with emphasis to low-latitude F region, and briefly summarized by Laštovička (1997). Effects on the E_s layer were described, e.g., by Haldoupis et al. (2004). Tidal effects on N_{max} and h_{max} (electron density and height of the maximum of the ionosphere) may be of the order of 10–20% during the day and up to 40% at night at low latitudes, arising from perturbations to both the neutral composition and dynamics (Fesen, 1997). Hocke (1996) reported the dominant role of the terdiurnal (8 h) tide in the high latitude E region over EISCAT in the northern Scandinavia.

Gravity waves are oscillations with periods between several minutes and a few hours. Their lower cutoff period is given by the so-called Bruint-Vaisala frequency. They were observed in the lower ionosphere (e.g., Bošková and Laštovička, 2001) as well as in the E- and F-region ionosphere (e.g., Hocke and Schlegel, 1996; Matthews, 1998; Altadill et al., 2001a, b; Boška and Šauli, 2001; Boška et al., 2003; Šauli and Boška, 2001). Gravity waves are either of "meteorological" origin coming from below, or are of auroral origin coming quasi-horizontally from the auroral zone, or are excited in situ for instance by the solar terminator passage or solar eclipse.

Infrasound or infrasonic waves are oscillations with periods from about 1 s to a few minutes. Their effects on the ionosphere had been relatively extensively investigated in the 1960s to early 1980s, then they were almost forgotten, and such investigations re-appeared in recent years. Older results were reviewed by Blanc (1985) and Pokhotelov et al. (1996).

The paper is based on an invited review paper presented at the second IAGA/ICMA workshop "Vertical Coupling in the Atmosphere–Ionosphere System". It summarizes briefly our knowledge of effects of the above atmospheric waves on the ionosphere, on the lower ionosphere ($h < 100$ km), the E region, and the F region, and partly deals also with the utilization of ionospheric measurements to atmospheric wave studies and monitoring. The observational results are primarily treated, even though some results of modeling are included, as well. The paper is in no way a full review; the size of the paper does not make possible the full review. Therefore the author apologizes to those whose papers are not referred to in this work.

Section 2 describes the effects of tides on the ionosphere. Section 3 deals with the effects of planetary waves on the ionosphere. Section 4 treats the effects of gravity waves with emphasis to waves coming from below and excited in situ. Section 5 discusses almost forgotten ionospheric effects of infrasound and their utilization. The paper ends with concluding remarks in Section 6. Particular attention is paid to the effects of planetary and gravity waves on the ionosphere.

2. Tides

The term tides is used hereafter for the solar tides in the atmosphere/ionosphere. The minor lunar tides are not treated here. Tides are either migrating, those which follow the Sun, or non-migrating, those which do not follow Sun's motion. At ionospheric heights, tides are either excited in situ, or propagating from below, the latter being the tidal component contributing to vertical coupling in the atmosphere–ionosphere system, which is the scope of the paper. Tides have been broadly studied and modeled, and they are very important, in the neutral atmosphere. For example, the tidal amplitude in winds in the upper mesopause region at middle latitudes is larger than the prevailing wind. Tidal variations in the ionized component have been much less studied. They are to some extent overlapped by the solar zenith angle dependence of ionization rate.

As far as I know, no comprehensive investigations of tidal oscillations have been made in the lower ionosphere (essentially the D region) until now. The diurnal variation in the lower ionosphere is basically controlled by the solar zenith angle. On the other hand, the ionized component in the lower ionosphere is used for wind measurements via drift measurements (D1 method), meteor radar and partial reflection radar measurements. The ionized component serves as a tracer in tidal investigations in the upper middle atmosphere winds.

In the E region, the EISCAT incoherent radar measurements in the northern Scandinavia found the terdiurnal tide (8 h) to dominate among the E-region tides, particularly in ion and electron temperatures (Hocke, 1996). The incoherent scatter radar measurements already in the 1970s found tidal oscillations in the neutral atmosphere to be responsible for the remarkable difference between morning and afternoon electron concentrations in the E region (Monro et al., 1976), and detected a downward transport of long-lived ions in the upper E region due to the upward propagating tides (Wickwar and Carlson, 1999).

Tides in combination with planetary waves play an important role in the formation and development of the mid-latitude E_s layers. In our present understanding, the formation of the E_s layers at middle latitudes relies on vertical wind shears associated with atmospheric tides and gravity waves that force the long-living metallic ions into thin E_s layers (e.g., Matthews, 1998). At low latitudes, the Arecibo incoherent scatter radar observations established a fundamental role for the diurnal and semidiurnal tides in the E_s formation. Such E_s layers are often referred to as tidal ion layers (e.g., Matthews, 1998). The E_s layers were observed to be modulated by planetary waves and this modulation was explained by the planetary wave modulation of the E_s-forming tides (Pancheva et al., 2003; Haldoupis et al., 2004). This suggests that the ionosonde E-region data can be used as an alternative means of studying the tidal waves characteristics and climatology at lower thermospheric heights.

At F2 region heights ($h > 200$ km), both models and observations show a tendency of the neutral thermosphere tides to maintain constancy with height both in the amplitude and phase, mainly due to the dominance of molecular diffusion, and diurnal tidal winds exhibit less day-to-day variability than in the MLT region (e.g., Forbes, 1982). This is very important property of tides, because it makes possible to deduce from measurements at one height (e.g. at or near the F2 region maximum) the tidal pattern in the whole upper thermosphere/F2 region ionosphere.

Model calculations by Fesen (1997) revealed the effects of tides vertically propagating from the lower atmosphere on the F2 layer maximum electron density (N_mF2) and height (h_mF2) of the order of 10–20% during the daytime and as much as 40% during the nighttime at low latitudes. The lower atmosphere waves introduced also semidiurnal oscillations into h_mF2. Such strong effects were modeled for the low solar activity conditions. Under the high solar activity conditions, tides do not penetrate so deep into the thermosphere and a weaker effect in the F2 layer parameters is expected (Fesen, 1997). The N_mF2 perturbations are ultimately due to chemical effects, i.e. by changes in the concentration of N_2 and O_2 caused by displacement of the F layer by 10–20 km (Fesen, 1997).

The ionized component can again be used as a tracer for measurements of tidal motions in the neutral atmosphere. It is possible to infer the meridional component of wind (including tides) from ionosonde measurements (e.g., Titheridge, 1995), and the most recent Digisondes allow measure all three components of wind near the F2 region maximum. From such measurements the tidal components can be derived. An example of such application of ionosonde measurements is given in Fig. 1, which shows the evolution of diurnal and semidiurnal tides in the F2 region in

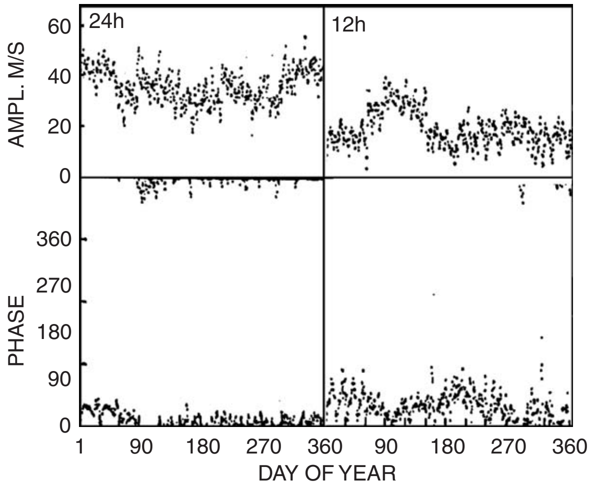

Fig. 1. Evolution of diurnal and semidiurnal tides in the F2 region in 1984 derived from ionosonde measurements at Kokobunji, Japan. Left panels—diurnal (24 h) tide, right panels—semidiurnal (12 h) tide; top panels—tidal amplitude, bottom panels—tidal phase. After Canziani (1994).

1984 derived from the ionosonde measurements at Kokobunji in Japan. The diurnal tidal phase is relatively stable compared to the semidiurnal tidal phase, and amplitudes are larger and less variable (except for annual variation) for the diurnal tide.

3. Planetary waves

Planetary waves of tropospheric origin have been observed in the neutral atmosphere to penetrate up to about 110 km at least in winter (e.g., Vincent, 1990), but they cannot penetrate directly to F-region heights. Several papers in this special issue describe planetary waves in the neutral atmosphere, particularly in the upper middle atmosphere, and their complex mutual non-linear interactions and interactions with tides.

Planetary wave-like oscillations of periods 2–30(35) days have been observed in all ionospheric layers:

- The lower ionosphere (radio wave absorption).
- E region ($h'E$, f_0E_s).
- F region (f_0F_2, h_mF_2, $h'F$).

Typical planetary wave periods or broad spectral peaks are about 2, 5, 10 and 16 (very broad spectral peak) days, but the planetary wave spectrum is very variable and on individual days it can be much different. They roughly correspond to eigenfrequencies of the atmosphere, which slightly differ for various modes; for instance for the wave with the zonal wave number 1 they attain values of 1.2, 5, 8 and 12 days (these periods are Doppler shifted by the prevailing wind). Around 27 days there is a strong solar rotation period, but there seems to occur also a planetary wave period. All planetary wave periods are quasi-periods with the exact period varying within a period range. Amplitudes of planetary waves are unstable, as well; planetary waves typically occur in bursts of a couple of waves.

3.1. Planetary waves in the lower ionosphere

For planetary wave investigations, long-term and continuous observations are required. Such data have been provided by the radio wave absorption measurements in the lower ionosphere. Data obtained by the A3 method in Europe (oblique incidence on the ionosphere, continuous wave transmission) at low (LF), medium (MF) and high (HF) frequencies between about 100 kHz and 10 MHz have been used. Pancheva and Laštovička (1989) and Pancheva et al. (1989) demonstrated for the daytime HF and MF, and nighttime LF absorptions that the planetary wave-like oscillations in absorption are related to similar oscillations in the neutral atmosphere, namely in wind, not to oscillations in solar or geomagnetic activity. It is worth noting that even the 27-day variation in absorption is not always of direct solar origin, relatively often it seems to be related rather to a planetary wave (Pancheva et al., 1991b). Laštovička et al. (1994a) performed model calculations that showed that the planetary waves in the neutral atmosphere were adequately transformed into planetary waves in the absorption, i.e. in the ionized component. Already Schwentek in the early 1970s (e.g., Schwentek, 1974) studied planetary wave-like structures in variations of the radio wave absorption in the lower ionosphere.

Scientific activities were focused mainly on studies of the long-term trends in the planetary wave activity (e.g., Laštovička et al., 1994a, b; Laštovička, 2001, 2002). Fig. 2 shows an example of long-term changes and trends in the planetary wave activity inferred from the A3 MF absorption in south-eastern Europe. A strong seasonal variation, particularly pronounced in the 1980s, is evident. Such a variation is expected. Much stronger filtering by stratospheric winds in summer is responsible for much smaller penetration of the tropospheric

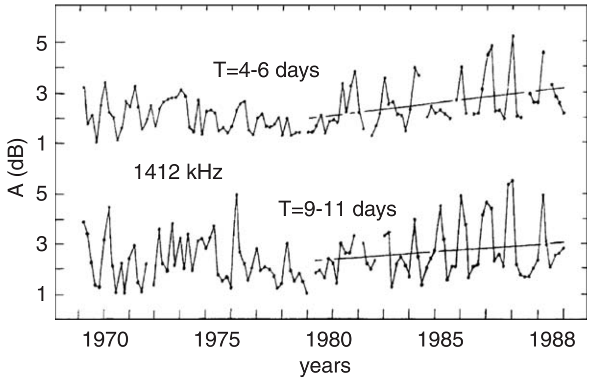

Fig. 2. Long-term development of planetary wave activity in the lower ionosphere at periods near 5 and 10 days as inferred from the A3 absorption measurements at 1412 kHz ($f_{eq} = 1.2$ MHz) in Bulgaria (southeastern Europe) during the 1970s and 1980s. After Laštovička (2002).

Table 1
Duration (number of wave cycles) of well-developed planetary wave events with periods around 5, 10 and 16 days in terms of the number of waves—mean, median and the most often occurring durations—for the planetary wave activity inferred from the absorption at 1539 and 6090 kHz measured at the Panska Ves Observatory

Period	5 days	10 days	16 days
1539 kHz			
Mean	4.8	4.0	3.7
Median	4.5	4	3.5
Most often	4, 4.5, 6	3, 3.5, 4	3
6090 kHz			
Mean	5.1	4.0	3.6
Median	5	3.5	3.5
Most often	5	3	3

Source: Laštovička et al. (2003a, b).

planetary waves to the lower ionosphere heights in summer, which reflects in the observed much smaller summertime planetary wave activity. As for trends, an increase of planetary wave activity is observed for the 1980s (since the very late 1970s), whereas no trend, only perhaps a wave-like variation is observed in the 1970s. Altogether nine radio wave absorption data sets (all available long-term absorption data sets) have been studied. They all revealed either positive (often statistically insignificant due to the large seasonal variation) or no trend, none of them revealed a negative trend. In general it may be said that there was no trend in the 1960s, early 1970s and 1990s, while there was a tendency to a positive trend (typical increase of the planetary wave type oscillation amplitude by 20–40%) in a part of the 1970s and in the 1980s (a bit earlier in the northern than southern Europe) (Laštovička, 2002).

Laštovička (1993) investigated possible effects of the quasi-biennial oscillation (QBO) on the planetary wave activity inferred from radio wave absorption. No significant effect of the QBO was found in the planetary wave activity. No significant effect of the 11-year solar cycle on the planetary wave activity was established, either.

Pancheva et al. (1991a) observed that the planetary wave activity in the lower ionosphere was enhanced at shorter periods during the periods of enhanced planetary wave two in the high latitude stratosphere at the 30 hPa level, while longer periods were enhanced during the periods of increased planetary wave one in the stratosphere.

Pancheva and Laštovička (1998) found very unusual behavior of planetary waves in the lower ionosphere in autumn 1994 (October–November) based on the radio wave absorption and $f_{\min}$ (indirect measure of absorption) data. Planetary waves at northern middle latitudes propagated dominantly eastward instead of the standard westward direction.

Planetary waves occur as bursts of activity. Therefore it is important to search for the persistence of the planetary wave activity. Laštovička et al. (2003a) did such a study. They analyzed absorptions along two radio paths in central Europe, which were representative for altitudes of about 85–100 km, by means of the wavelet technique. Only wave events of three or more wave cycles were considered. Averaged results are shown in Table 1. Waves with periods near 5 days reveal a typical persistence of wave events around 5 wave cycles. Waves with periods near 10 days are less persistent with a typical persistence of 3–4 cycles. The typical persistence of waves with periods around 16 days is no more than 3 cycles, taking into account that events of duration less than 3 cycles are not included in Table 1.

3.2. *Planetary waves in the E region*

Planetary waves have been studied in two E-region characteristics, in the critical frequency (i.e. in maximum electron density) of the E_s layers, f_0E_s, and in the apparent height of the E region maximum, $h'E$. Such studies have been based on the ionosonde network, VHF backscatter and other measurements.

As for the planetary wave activity in h'E, already Cavalieri (1976) reported the occurrence of planetary wave type oscillations in h'E for October–December 1970 from the northern hemisphere ionosonde network.

Planetary waves are believed to be responsible for a substantial part of modulation of the E-region wind-driven dynamo in the period range of about 2–30 days. Such oscillations are then observed in the ground-based measurements of geomagnetic field (Parish et al., 1994) and in geomagnetic activity indices (Kohsiek et al., 1995).

Tsunoda et al. (1998) reported measurements of radar echoes from the E_s layer in Japan, which displayed an evident 5-day periodicity coinciding with the 5-day periodicity in the neutral wind measured by a nearby partial reflection radar. Both oscillations were signatures of a 5-day period planetary wave occurrence.

Voiculescu et al. (2000) observed from simultaneous VHF backscatter and ionosonde measurements at Crete Island, Greece, planetary wave periods of 2–3 and 4–7 days in the E_s layer measurements, fairly related to wind oscillations as measured near 95 km at Collm, Germany, but not observed in geomagnetic activity. Haldoupis and Pancheva (2002) observed a strong 7-day wave event in simultaneous radar and satellite wind measurements and ionosonde network observations of an E_s layer as another observational evidence of the important role of planetary waves in formation of E_s layers. As already mentioned in Section 2, the E_s layer modulation by planetary waves can be explained by the planetary wave modulation of E_s-forming tides at heights below 100 km, because calculations show that the planetary waves experience difficulties with direct penetration into the upper E region, where the E_s layers are often formed and then descend to and below the E-region peak (Pancheva et al., 2003; Haldoupis et al., 2004). This, however, does not exclude some role of direct modulation of E_s layers at middle latitudes by planetary waves.

Fig. 3 illustrates the appearance of the planetary wave modulation of f_0E_s for Rome and Crete (Milos). f_0E_s data for the period 27 June–4 September 1996 display well-pronounced tidal peaks at 24-, 12- and 8-h (middle panel), and quite significant planetary wave spectral peaks at 5, 8–9, and 16–19 days (bottom panel). Similar planetary wave peaks were observed in the wind near 95 km at Collm, Germany.

Shalimov et al. (1999) considered formation of the E_s layers at middle latitudes through the E region plasma accumulation driven by the planetary wave-induced horizontal wind shears. Shalimov and Haldoupis (2002) modeled this mechanism as a mechanism capable to contribute to the E_s layers formation.

Kaladze et al. (2004) developed a hypothesis on magnetized Rossby waves in the E region ionosphere as an analog to planetary waves in the neutral atmosphere; they should be produced in the ionized component by the E region dynamo electric field.

3.3. Planetary waves in the F region

The planetary wave type oscillations in the F2 region have been studied more broadly than those in the E region and the lower ionosphere, for example by Forbes and Leveroni (1992), Yi and Chen (1994), Pancheva et al. (1994, 2002), Apostolov et al. (1995), Apostolov and Altadill (1996), Laštovička and Mlch (1996), Forbes and Zhang (1997), Forbes et al. (2000), Apostolov et al. (1998), Altadill and Apostolov (2001, 2003), Laštovička and Šauli (1999), Altadill et al. (2001a, b, 2003), Laštovička et al. (2003b); and references therein. Mainly the planetary wave type activity in f_0F2 (critical frequency—maximum electron density in the ionosphere), and to a limited extent also h_mF2 (height of the maximum electron density) and $h'F$ (apparent height of the F region) have been studied based mainly on the ionosonde network measurements. The planetary wave type oscillation studies have also practical impacts, because such oscillations affect ionospheric predictions on time scales of days.

For the purpose of predictions it is useful to know when we have to take the planetary wave-type oscillations into account and when we can neglect them. Fig. 4 shows for Kaliningrad (but the same is valid for all European stations) that it depends on the solar cycle and season. The 5-, 10- and 16-day planetary wave type oscillation amplitudes in f_0F2 display minima during the solar cycle minimum in summer, when it is not larger than the accuracy of the f_0F2 determination and, therefore, can be neglected for any practical purpose (Fig. 4, top panel). On the other hand, in the early phase of decline of solar activity after the solar cycle

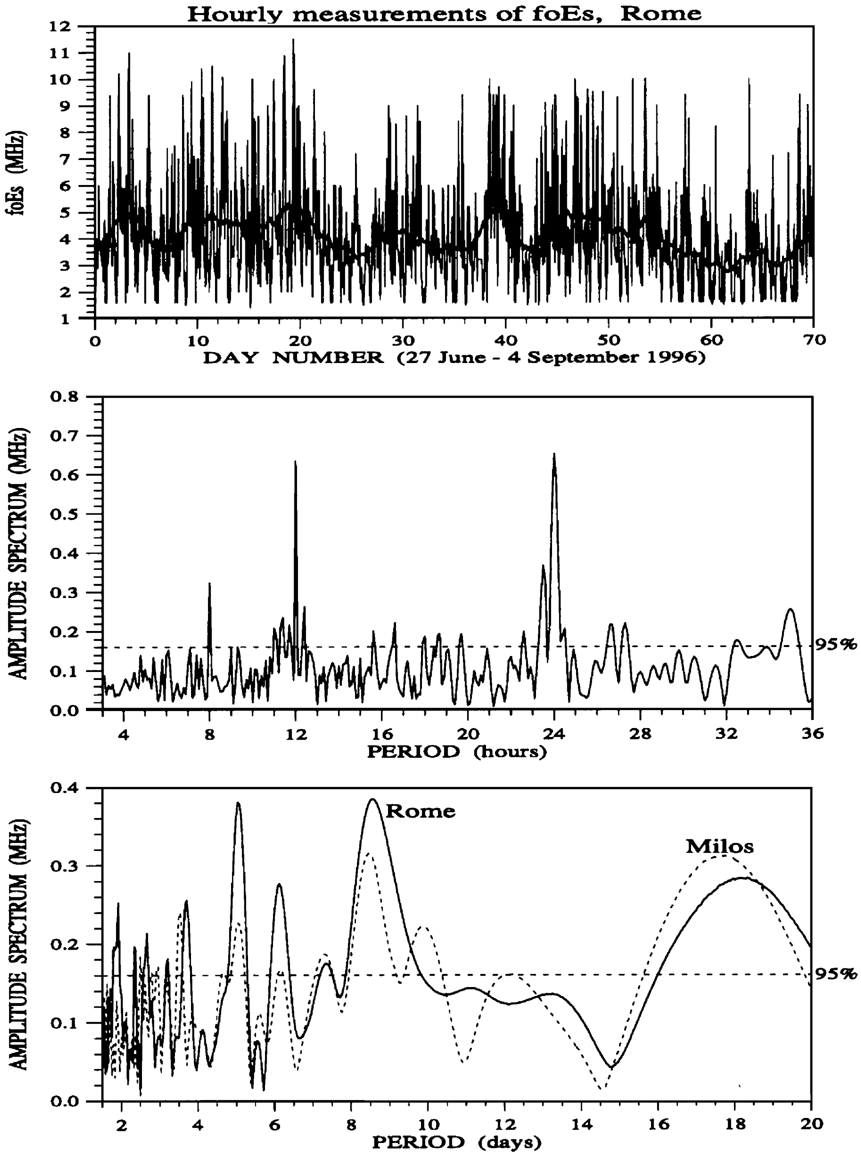

Fig. 3. Top panel: Time series of f_0E_s hourly means measured in Rome (41.9°N, 12.5°E) from 27 June to 4 September 1996; the thick solid line represents the smoothed behavior of f_0E_s obtained by a 75-h running mean. Middle panel: Amplitude spectra obtained by the correloperiodogram method for the period range of 3–36 h (tides) in Rome. Bottom panel: Amplitude spectra obtained by the correloperiodogram method for the period range of 1.5–20 days (planetary waves) in Rome and Milos (Crete, 36.7°N, 24.5°E. After Haldoupis et al. (2004).

maximum and in winter, amplitudes can be larger than 1 MHz, which means a very important effect. Fig. 4, top panel, also shows that there is a strong solar cycle dependence of the amplitude of the planetary wave type oscillations. Such dependence may be to a large extent induced by the strong solar cycle dependence of f_0F2 itself. Therefore Fig. 4, bottom panel, displays relative amplitudes (amplitude divided by f_0F2) of planetary wave type oscillations. The solar cycle effect in relative amplitudes is much smaller, if any at all, and reveals rather little dependence of the planetary wave activity on solar activity, as it is the case for the lower ionosphere (Section 3.1). The typical amplitude of planetary wave type oscillations in f_0F2 is about 5%, but extreme values reach almost 15% (each data point in Fig. 4 represents one spectrum over an interval 2-months long). The 13.5-day oscillations might have a solar/geomagnetic activity contribution (13.5 days = half of solar rotation).

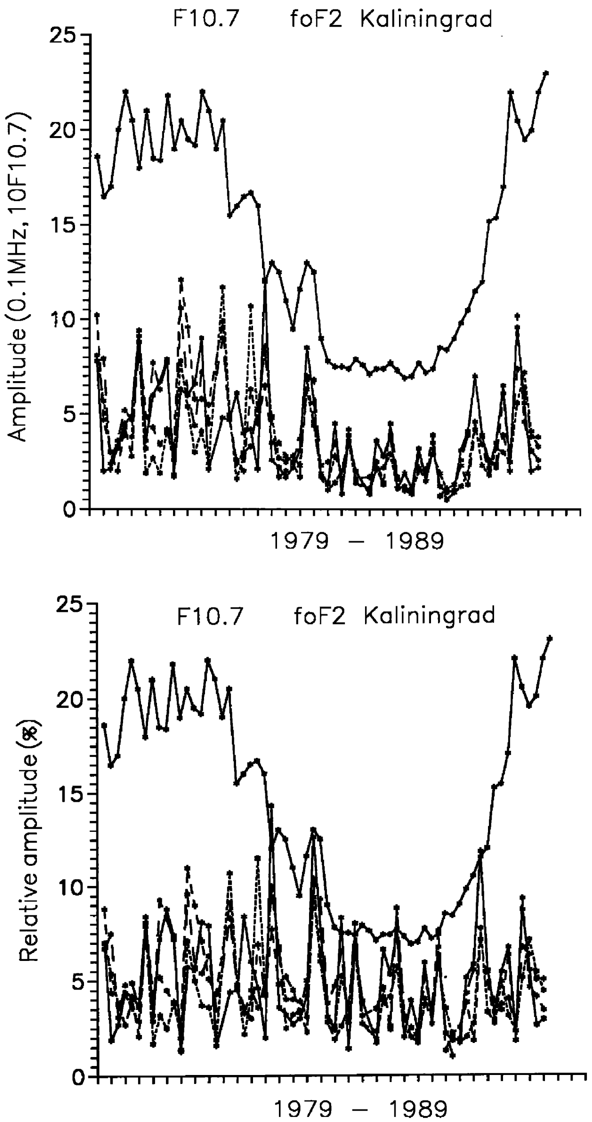

Fig. 4. Amplitudes of 5-day (short-dashed line), 10-day (medium-dashed line), 13.5-day (full line) and 16-day (long-dashed line) oscillations in f_0F2 for Kaliningrad; F10.7 represents solar activity; x-axis shows time since January 1979–December 1989. After Laštovička and Mlch (1996).

The results for h'F yield a pattern very similar to that for relative amplitudes of the planetary wave type activity in f_0F2 (Laštovička and Mlch, 1996).

Why do I use the term "the planetary wave type oscillation"? Altadill and Apostolov investigated origin of the planetary wave type oscillations in f_0F2 for several European stations over the period of 1983–2001. The drivers of oscillations may be the planetary wave activity in the MLT region, which is predominantly of tropospheric origin, the quasi-periodic geomagnetic activity, drivers of unknown origin 'independent' of the above two, and a very small contribution from solar flux variations (Altadill and Apostolov, 2003). The results are summarized in Table 2. The events caused by the planetary wave activity as observed in winds in the MLT region play an important role in the winter and during equinoxes, while summertime events are predominantly of the geomagnetic activity origin. Events of unknown origin form a significant fraction of all events. The authors used the prevailing wind in the MLT region, whereas it would be probably more adequate to use the tidal winds, whose planetary wave modulation differs to some extent from that in prevailing winds; then the role of events of the MLT origin could be larger. Altadill and Apostolov (2001) studied a couple of planetary wave type events with periods near 2 and 6.5 days at heights between 170 and 230 km above the Ebro Observatory (40.8°N, 0.5°E) in 1998. They found both upward and downward propagating events. The upward propagation indicates the planetary wave origin from below (MLT region/troposphere), whereas the downward propagation indicates another origin, e.g. the periodic geomagnetic activity.

Table 2
Percentages of seasonal occurrence of different planetary wave type oscillations in f_0F2 according to their possible origin

Period (days)	2	5	10	16
IND				
WIN	5	4	2	3
EQU	4	11	0	3
SUM	15	13	5	3
MLT				
WIN	5	8	11	10
EQU	14	6	5	11
SUM	13	7	4	5
GEO				
WIN	9	3	10	11
EQU	12	21	30	21
SUM	23	27	33	33

WIN means November–February, EQU means March, April, September and October, and SUM means May–August. MLT means oscillations driven by the planetary wave activity observed in the MLT region (i.e. of predominantly tropospheric origin). GEO means oscillations driven by the geomagnetic activity and IND means events 'independent' of the above two drivers. Adapted from Altadill and Apostolov (2003).

Fig. 4 and Table 2 show that the amplitudes of the planetary wave type oscillations in f_0F2 peak in winter, whereas the occurrence frequency of planetary wave type events reaches a maximum in summer. Fig. 5 displays the seasonal distribution of occurrence of the planetary wave type oscillations for various periods. The occurrence frequency is generally higher in the summer half of the year, particularly for short-period oscillations (2 and 5 days), while longer periods are distributed more uniformly throughout the year. Altadill and Apostolov (2003) found that the planetary wave type oscillations with periods around 2 days occurred for 12% of time, those with periods around 5 days occurred for 14% of time, 10 day oscillations for 24% of time, and those with periods around 16 days for 30% of time; for the rest of time they were not clearly discernible from noise.

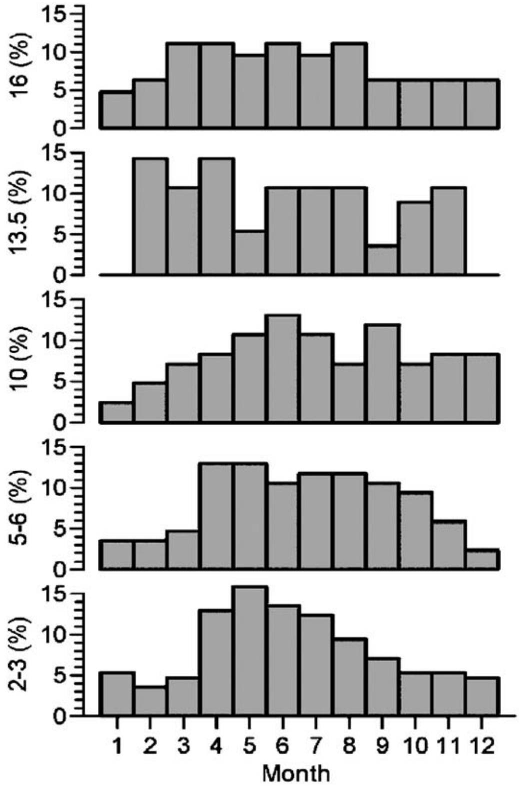

Fig. 5. Percentage of occurrence of the planetary wave type events as a function of month, 1983–2001. Figure shows how much of the overall yearly occurrence (100%) realizes in each month for periods around 2, 5, 10, 13.5 and 16 days. After Altadill and Apostolov (2003).

Since the planetary wave type oscillations occur as bursts of activity, it is important to search for the persistence of the planetary wave type activity bursts. Laštovička et al. (2003b) made such investigations for Europe by means of wavelet analysis, and more recently in a similar way for USA and Japan with the results very similar to those obtained for Europe.

Table 3 summarizes statistical characteristics of the persistence of the planetary wave type oscillations in f_0F2 for representative European stations. For the 5-day wave, a typical persistence of well-developed wave events is 4 wave cycles. For the 10-day wave, it is rather 3.5 wave cycles. For 16 days, the most frequent values provide typical persistence no more than 3 wave cycles. A similar persistence of the planetary wave type oscillation events is observed above Europe for the lower ionosphere (insignificantly longer—Section 3.1).

In terms of number of cycles in the planetary wave type events, the persistence decreases towards longer periods. However, the persistence of the planetary wave type events in terms of days increases towards longer periods. For the 5-day oscillation, 4 cycles means 20 days, for the 10-day oscillation 3.5 cycles means 35 days, and for the 16-day oscillation 3 cycles means 48 days. The planetary wave activity persistence characteristics for Europe are either identical or very little larger than such values from the USA and Japan (f_0F2).

Fig. 6 shows the spectral distribution of the duration of the planetary wave type oscillation events in terms of number of cycles for the 5-day wave, European station Juliusruh (northern Germany). The distribution is very broad, which means that from measurements of f_0F2 itself we cannot

Table 3
Statistics of persistence of the planetary wave type oscillations in f_0F2 over European stations Juliusruh, Slough, Průhonice and Rome—average values

	Period (days)	Number of events	Median value	Mean value	Most frequent value
Average values, Europe	5	40	4	4.3	4
	10	36	3.5–4	3.9	3.5
	16	32	3.5	3.7	3

Those for medians and the most frequent values are presented with step 0.5. Adapted from Laštovička et al. (2003b).

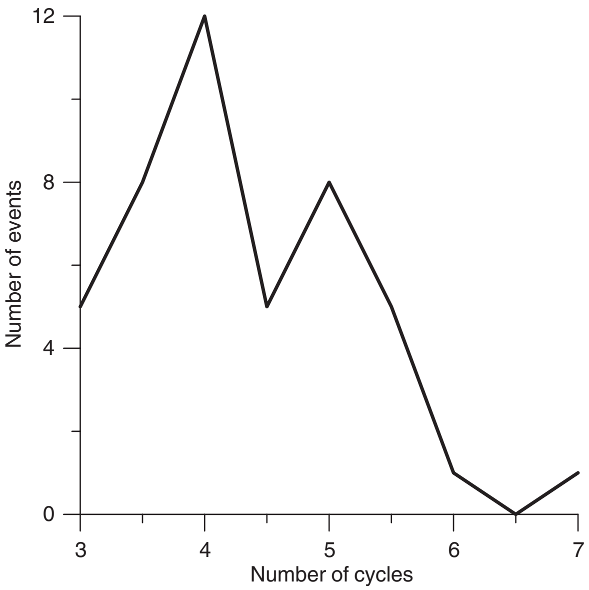

Fig. 6. Spectral distribution of the duration of the planetary wave type oscillation events in terms of number of cycles for the 5-day wave, station Juliusruh, 1979–1989. After Laštovička et al. (2003a, b).

predict the duration of wave events and, therefore, for the direct inclusion of the planetary wave type oscillations into ionospheric predictions we have to look for some predictive proxies out of the F2 region (e.g., in the mesopause region winds). The quasi 2-day wave differs somewhat from other waves. In f_0F2 it exists in three different forms (Apostolov et al., 1995): (a) westward traveling planetary wave type oscillation with $s = 1$, (b) stationary wave, (c) oscillations with well-developed characteristics of the quasi 2-day wave but with significant differences of the dominant period at well-separated locations. There is an evident controversy between the dominant zonal wave numbers 3 and 4 in the MLT region (the lower ionosphere) and 1 in f_0F2, which is in favor of non-MLT origin of the quasi 2-day wave in f_0F2.

Altadill and Apostolov (2003) found the typical longitudinal size of the planetary wave type events in f_0F2 to be: (a) for periods 5–6 days about 80° in average, for periods around 10 days about 100° in average, and (c) for periods around 16 days about 180° in average, with individual events covering up to the whole globe. This is consistent with our result (by-product of persistence investigations) of (a) full dissimilarity of the 5-day events in Europe, Japan and the USA, and very limited similarity of 7-day events, (b) 10-day events being also largely dissimilar, (c) 16-day events showing much higher degree of similarity between European, US and Japanese stations (f_0F2), which is consistent with their larger typical size.

Investigations of the persistence of the planetary wave type events (Laštovička et al., 2003a, b) makes possible a "vertical" comparison in Europe. The similarity is mostly poor, in agreement with Laštovička (1996), worse than expected from the results of some studies (e.g., Pancheva et al., 1994), which compared neutral wind oscillations in the MLT region with oscillations in f_0F2 or in the radio wave absorption in the lower ionosphere over selected shorter periods. The reason might be that the absorption fluctuations are related to fluctuations in the prevailing wind, while those in f_0F2 seem to be related more to fluctuations in the tidal winds (e.g., Laštovička and Šauli, 1999). Why and to what extent the fluctuations in prevailing and tidal wind differ should be examined, but observations show that they differ to some extent.

Pancheva et al. (2002) studied the planetary wave type oscillations in h_mF2 through analyzing 19 months of measurements by the Millstone Hill incoherent scatter radar (42.6°N, 71.5°W). They found a 16-day oscillation in h_mF2 generated probably by the 16-day modulation of the semidiurnal tide observed in the MLT region, and the quasi-2-day activity increase in h_mF2 during geomagnetic disturbances.

Planetary waves cannot penetrate directly to F region heights. Therefore, we have to assume an indirect upward propagation via the planetary wave modulation of various upward propagating agents at upper mesospheric/lower thermospheric heights:

- Vertical plasma drift—due to planetary wave modulation of the E-region dynamo (e.g., Pancheva et al., 1994).
- Tides—some role indicated observationally by e.g. Laštovička and Šauli (1999), Pancheva et al. (2002).
- Gravity waves (e.g., Meyer, 1999).
- Turbopause height and turbopause region properties or composition changes at the base of the thermosphere.

The relative importance of the above mechanisms is not known, but the modulation of tides definitely plays some role.

4. Gravity waves

Gravity waves are very important in the momentum and energy budget of the MLT region and for its wind system, as shown, e.g., in a review by Fritts and Alexander (2003). Gravity waves are either of "meteorological" origin coming to the ionosphere from below, or are of auroral origin coming quasi-horizontally from the auroral zone, or are excited in situ for instance by solar terminator or solar eclipse. Among them, those of auroral origin have been studied most broadly, but the scope of the paper is to deal with vertical coupling via atmospheric waves, therefore we deal only with the gravity waves of meteorological origin and to a limited extent of in situ origin.

4.1. Gravity waves in the lower ionosphere

Gravity waves in the lower ionosphere (and the MLT region) are predominantly those coming from below, even though during geomagnetic storms there is some contribution of gravity waves of auroral origin (e.g., Boška and Laštovička, 1996). The electron density profiles measured by rocket already in the late 1960s displayed well-developed gravity wave type vertical structures (e.g. profiles published by Mechtly and Smith, 1972). The rocket profiles make the determination of characteristics of individual gravity waves possible, but their small number and irregular geographic distribution do not allow for the determination of the gravity wave statistical characteristics and long-term changes. Studies of the latter type were made a few years ago with several years of the LF continuous nighttime digital radio wave absorption measurements in the Central Europe as summarized by Laštovička (2001).

Fig. 7 shows the development of gravity wave activity inferred from radio wave absorption measurements in the winter half of the year for the period 1988–1995. There is an evident decrease of the gravity wave activity with decreasing solar activity, which interferes with the effect of the Mt. Pinatubo volcanic eruption. The latter is well pronounced for long-period gravity waves (120–180 min), whereas it is not detectable in the shortest period range (10–30 min). On the other hand, the QBO does not seem to play a significant role in the gravity wave activity variations. Bošková and Laštovička (2001) observed absence of the seasonal variation of the gravity wave activity under

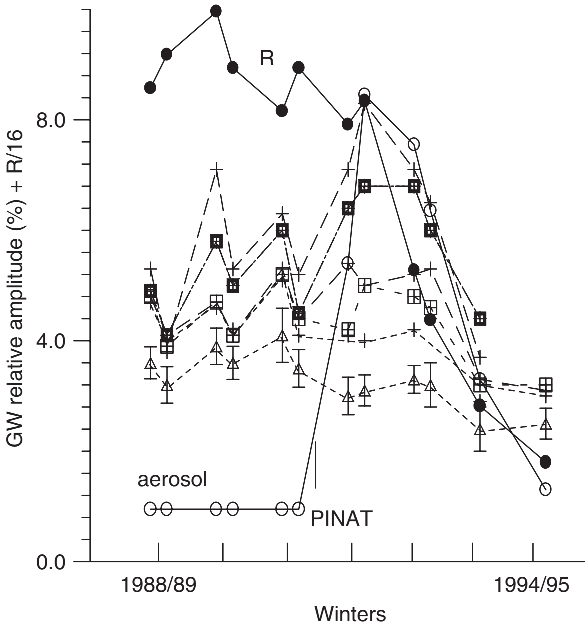

Fig. 7. Gravity wave activity (relative amplitudes in %) for period bands (from bottom to top)—10–30, 31–60, 61–90, 91–120, 121–150, and 151–180 min—in the winters of 1988/1989–1994/1995. R—sunspot number; aerosol—quasi-local aerosol optical depth; PINAT—Mt. Pinatubo volcanic eruption. Each winter is represented by two data points for October–December and January–March. After Laštovička (1999).

the high solar activity conditions, whereas a tendency to a summertime peak appeared under the lower solar activity conditions. However, they suggested that the shift of storm track in the North Atlantic–Europe sector with changing solar activity, i.e. a change in gravity wave sources, at least contributed to if not accounted for the observed dependence of the gravity wave activity on the 11-year solar cycle.

4.2. Gravity waves in the E region

In the E region the gravity wave investigation have been focused on the E_s layers, because gravity waves play some role in their formation (e.g., Matthews, 1998; Fukao et al., 1998; Kazimirovsky et al., 2003), probably via enhanced irregular neutral winds associated with gravity waves (Parkinson and Dyson, 1998).

Rao et al. (1978) observed very short gravity wave periods ($T \leqslant 18$ min) in echoes from blanketing E_s layers at Waltair (India). Woodman et al. (1991) found similar periodicities in the VHF backscatter observations of quasi-periodic striations of the

E_s layers. Lanchester et al. (1991) used the E_s layers as a tracer of atmospheric waves and found in the intensity and position of these layers evident effects of the gravity wave activity. Korsunova (1991) analyzed ionosonde soundings with 15 min repetition in days when airglow measurements near 90 km detected medium-scale gravity waves. She observed structures formed by a gravity wave passage both in f_0E_s and hE_s and found that gravity waves from below penetrate through the turbopause more often in winter than in summer. Gravity waves were found to cause vertical motions of E_s layers (Bourdillon et al., 1997).

EISCAT in the northern Scandinavia observed periodic ($T = 40-60$ min) enhancements of electron density in the E region attributed to a periodically modulated flux of precipitating electrons controlled by oscillations in the magnetospheric tail (Rinnert, 1996). This means that at high latitudes the gravity wave type oscillations may sometimes be of corpuscular origin.

4.3. Gravity waves in the F region

We deal only with the gravity waves of meteorological origin and to limited extent of in situ origin, not with those of auroral origin usually observed as traveling ionospheric disturbances (TID), because they do not contribute to the vertical coupling. A good even though not recent review of the F region gravity waves is that by Hocke and Schlegel (1996). They divided gravity waves into three groups according to their size—large-scale (horizontally propagating, predominantly of auroral origin), medium-scale (mainly coming from below), and small-scale. Ionosondes and radars have been used to study gravity waves in the F region; recently also the GPS technique has been used for the gravity wave detection and studies (e.g., Afraimovich et al., 2000). Climatological studies of gravity waves over the middle and upper atmosphere radar at Shigaraki, Japan reveal almost continuous presence of gravity waves in the F region ionosphere (Oliver et al., 1997). Optical and ionosonde observations during the SEEK campaign in Japan reveal signatures of ionospheric amplification of gravity waves propagating in selected directions possibly in relation to the Perkins plasma instability (Taylor et al., 1998).

Meteorological processes are a quasi-permanent source of gravity waves coming from below (mainly from the troposphere, partly also from the stratomesosphere). Cold fronts belong to the strongest midlatitude gravity wave sources. Deep tropical convection, mesoscale convective complexes, hurricanes, tornados, cyclones, upper troposphere jet, or flow over topography (mountain waves) are other members of the broad family of tropospheric meteorological sources of gravity waves. There are also sporadic sources of gravity waves coming from below like earthquakes, volcanic eruptions, big explosions, etc.

Fig. 8 based on 15 min ionosonde soundings presents an example of the enhancement of the gravity wave activity in the Central Europe associated with passage of a well-pronounced cold front. The gravity wave activity is enhanced in the whole period range of about 50–100(120) min (upper panel) compared with a quiet day (bottom panel). A similar response was observed in the gravity wave activity inferred from the collocated radio wave

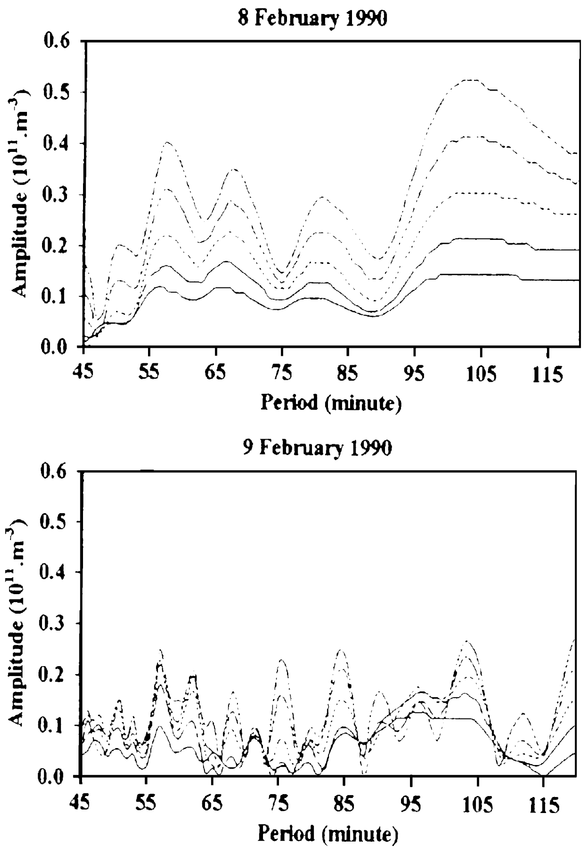

Fig. 8. Gravity wave activity (amplitude spectra) computed from ionosonde measurements at Pruhonice. Top panel—day of a cold front passage. Bottom panel—quiet day. Lines from bottom to top—180, 190, 200, 210, and 220 km. Adapted from Šauli and Boška (2001).

absorption measurements in the lower ionosphere (Šauli and Boška, 2001), which was an evidence supporting the tropospheric origin of the observed enhanced gravity wave activity. A couple of such events have been analyzed with very similar results. The cold front-related gravity wave activity always peaked at least 20 km (usually more) below the maximum of the F2 region (Boška and Šauli, 2001). This is in qualitative agreement with the results of modeling by Huang et al. (1998) that reveal a smaller amplitude of gravity-wave-induced ionospheric perturbations at higher heights in the F region in spite of the increasing amplitude of gravity waves in the neutral atmosphere as a consequence of action of plasma diffusion. Cold fronts cause a specific development of the shape of the electron density profile and ionograms, therefore experienced observer, who knows what to look for, is capable to detect cold fronts from ionograms.

Fig. 9 shows the vertical structure of a gravity wave event excited by a cold front as observed at Ebro (Spain). The left panel displays the vertical phase and group velocities of the cold front-related gravity wave. The phase velocity is negative and the group velocity positive, which means the upward propagation of the gravity wave in the whole interval of heights of 175–275 km.This finding is demonstrated in more explicite form in the right panel, which shows the disturbance excited by the gravity wave in the plasma frequency. The black line depicts the upward energy progression of the wave and/or the upward group velocity $+8\,\mathrm{m\,s^{-1}}$. White lines represent the downward phase progression with an average velocity of $-47\,\mathrm{m\,s^{-1}}$.

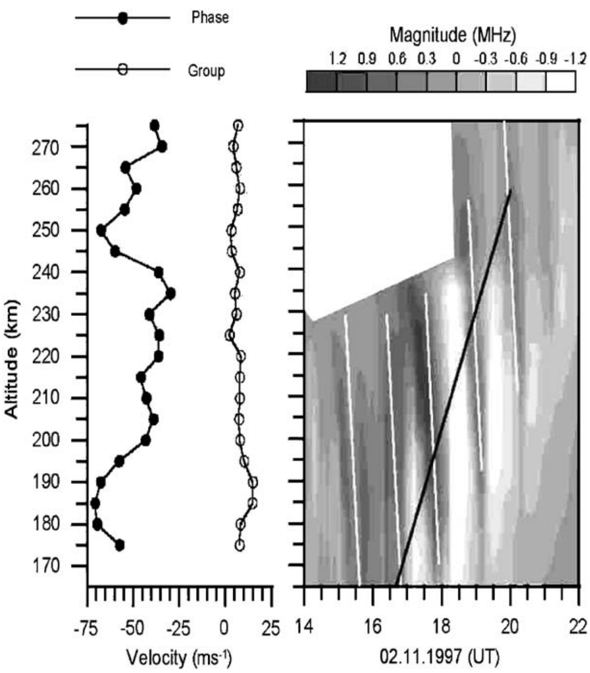

Fig. 9. Vertical structure of a gravity wave event excited by the cold front of 2 November 1997, Ebro (40.8°N, 0.5°E). Left panel—vertical phase and group velocities, wave packet with dominant period of 75 min. Right panel—the disturbance excited by the gravity wave in the plasma frequency; black line—energy progression of the wave, average velocity of $8\,\mathrm{m\,s^{-1}}$; white lines—phase progression of the wave, average velocity of $-47\,\mathrm{m\,s^{-1}}$. Adapted from Altadill et al. (1999).

Gravity waves with the dominant period of 50 min were observed in the F region in rocket experiments by Kelley (1997) in association with a storm front with thunderstorm cells of a broad spectrum of space scales. The measured electron density profiles were very structured.

One of the strongest meteorological sources of gravity waves seem to be the mesoscale convective complexes (MCC), which develop well among others above the South American pampas. Martinis and Manzano (1999) claim that gravity waves propagating from tops of clouds may be responsible for the observed MCC-related changes in electron density in the F region.

The two main in situ sources of gravity waves are the passage of solar terminator and solar eclipse. They both act in the same way, rapid change of the solar ionizing radiation and direct solar radiative heating. The solar eclipse of 11 August 1999 occurred in Europe and, therefore, it was well observed by the European network of ionosondes and by special measurements. Fig. 10 shows the vertical structure of the observed eclipse-related gravity wave event as measured at Průhonice (49.9°N, 14.5°E) in the form of vertical profiles of the phase and group velocities of a wave packet with a dominant period of 85 min. Below about 175 km, the phase velocity is positive and the group velocity is negative, which means the downward propagation of gravity waves. Above about 200 km, the phase velocity is negative and the group velocity is positive, which means the upward propagation of gravity waves. Thus, the gravity waves propagate from a region between about 180–200 km both upward and downward, which means that the heights of about 180–200 km are the source region for the eclipse-related gravity waves. The determination of source region heights from data of Spanish observatories Ebro and El Arenosillo revealed quite similar result, i.e. the transition

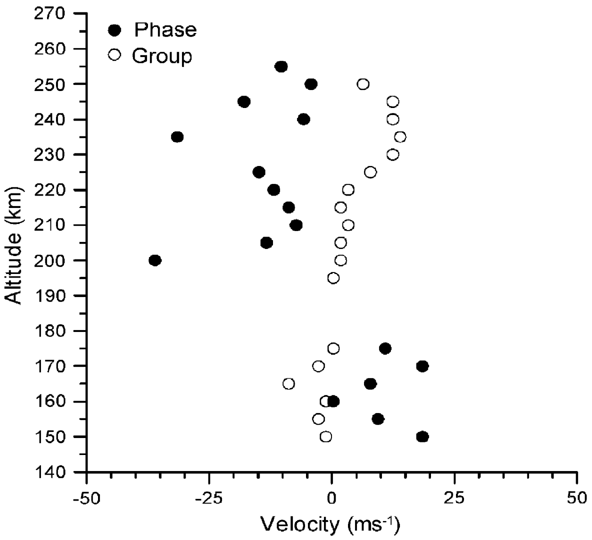

Fig. 10. Vertical structure of a gravity wave event observed during the solar eclipse of 11 August 1999 at Průhonice (49.9°N, 14.5°E). The plot shows the vertical phase and group velocities for the wave packet with a dominant period of 85 min as a function of altitude. After Altadill et al. (2004).

region between the F1 and F2 regions (Altadill et al., 2001a, b). The UK Doppler system and ionosonde network was used to determine the horizontal speed and direction of gravity waves during the eclipse period (Jones et al., 2004). The eclipse-generated gravity waves were consistent with a source region moving along the line of totality at the speed of the shadow region. Measurements at Tchaiwan during the solar eclipse of 24 October 1995 revealed very similar height region of the eclipse-related gravity wave excitation (Liu et al., 1998). More information about the ionospheric effects of the solar eclipse of 11 August 1999 may be found in Šauli et al. (2005).

While solar eclipses are very sporadic phenomenon, the solar terminator passes each location twice a day (except for the 24 h polar night or polar day). Boška et al. (2003) observed systematic occurrence of the terminator-related gravity wave events during sunrise, which lasted for several hours, and a generally enhanced level of gravity wave activity centered in the period range of about 60–90 min. The observed sunrise-related gravity waves were found to propagate with a significant vertical component through the ionosphere from a source located at altitudes of about 180–220 km, i.e. the same altitude region as that found for solar eclipses. The heating processes linked with the rapid increase of the solar radiation during sunrise can act as a source of atmospheric irregularities/instabilities and turbulence in the F region and generate gravity waves in the electron density (e.g., Somsikov, 1995). However, further research into mechanisms responsible for such gravity wave excitation is needed. The morning terminator passage-related gravity waves observed in Europe are excited quite regularly and may be, therefore, included into ionospheric predictions. On the other hand, the evening terminator passage excites less regular and weaker gravity wave effects (e.g., Altadill et al., 2004). Measurements by the incoherent scatter radar at Millstone Hill confirm higher efficiency of the morning terminator as a source of gravity waves (Galushko et al., 1998).

Gravity wave type ionospheric oscillations related to oscillations in the interplanetary magnetic field (IMF) under the northward IMF conditions have also been reported (Huang et al., 2000) but as rare events. They seem to remember similar events reported for the E region by Rinnert (1996), Section 4.2.

5. Infrasound

The infrasonic waves, briefly called infrasound, are those whose effects on the ionosphere were studied least among the ionospheric effects of atmospheric waves. In the past this research was put forward by possibility of application in remote detecting/monitoring of nuclear explosions. Therefore the main research activity was in the late 1950s–early 1980s. Then there was almost no scientific activity in this area (except for limited secret research for military purposes) until the last decade, when again some research activity re-appeared and the field became mostly unclassified. Nevertheless, the research activity in the field of infrasound is much lower than that concerning the planetary, tidal and gravity waves in the upper atmosphere and ionosphere, and infrasound has not been included into the upper atmospheric/ionospheric models. Older results were reviewed by Blanc (1985) and Pokhotelov et al. (1995). The aim of contemporary research activity is basically twofold: (i) contribution to remote detection of underground nuclear explosions, and (ii) search for the energy deposition by infrasound and its impact on processes in the upper atmosphere and ionosphere. More detailed information about explosion-oriented research may be found in Krasnov et al. (2003) or Krasnov and Drobzheva (2005). A review paper for Surveys in Geophysics is under preparation.

The contemporary activity is more in the field of ground-based monitoring and investigations of tropospherically and/or atmospherically propagating infrasound. At present there is a broad worldwide network of ground-based infrasound chains for such a purpose, build primarily as one of the means of the underground nuclear explosion monitoring. Hedlin et al. (2002) provided a brief description of tropospheric/atmospheric infrasound monitoring and research activities.

There are many different sources of infrasound, including:

- Meteorology—hurricanes, tornados, storms, cyclones, (cold) fronts, mesoscale convective complexes, flow over rough topography (mountains), etc.
- Nuclear and large chemical explosions.
- Volcanic explosions and earthquakes.
- Solar eclipses and lower-latitude (supersonic) solar terminator.
- Auroral activity.
- Bolides and meteorites.
- Supersonic jets and spacecraft launches.
- Industry, transport, big towns.

Most of them are sporadic but there is a more or less continuous infrasound noise of predominantly meteorological origin.

There is one very important feature of infrasound. Due to the shape of temperature profile in the lower and middle atmosphere, where the temperature is lower than at/near the surface, the coefficient of refraction is larger than unity. As a consequence of that, infrasound is focused upwards and the main part of radiated energy from any earth surface acoustic source propagates upward to the atmosphere and ionosphere. This property of infrasound was mentioned already by Blanc (1985). The infrasound pattern of a point source takes the form shown in Fig. 11. Even the acoustic ray with an initial takeoff angle of 3° can propagate upwards into the ionosphere up to heights around 100 km. The acoustic ray with initial takeoff angle of more than 70° can propagate well above 300 km. This means that infrasound is more efficient in transferring energy to ionospheric heights than the other types of waves (planetary, tidal and gravity waves). That property of infrasound is reflected also in the height profiles of energy transferred by acoustic pulses through cross-section of the cone for point and underground nuclear explosion as

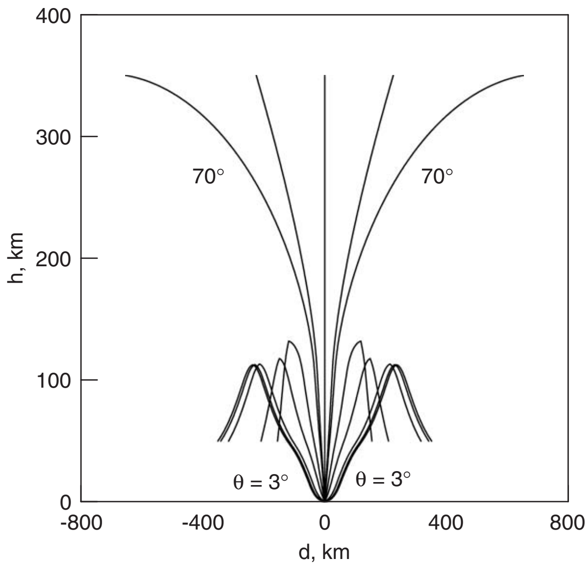

Fig. 11. Directional radiation pattern of a point infrasound source at surface for the real atmosphere. After Krasnov and Drobzheva (2005).

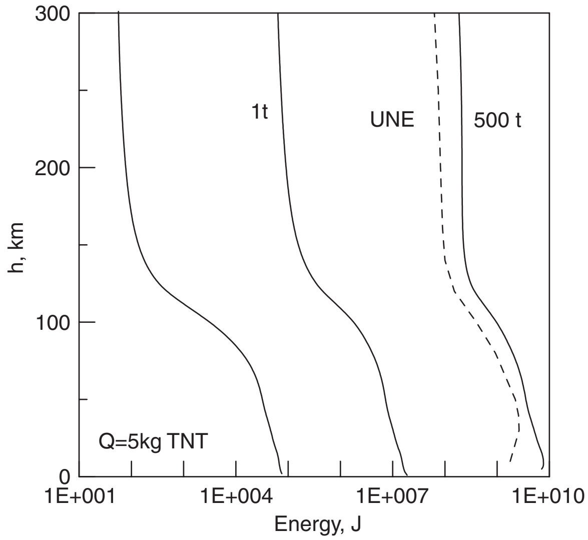

Fig. 12. Vertical profiles of energy transferred by acoustic pulse through a cross-section of the cone for a point (solid lines—three different explosion loads) and underground nuclear explosion (dotted line). After Krasnov and Drobzheva (2005).

shown in Fig. 12. Most of the energy is lost, which means deposited into the atmosphere or reflected, at heights around 100 km, where the atmospheric temperature rapidly increases and the coefficient of reflection rapidly decreases with height. Nevertheless a significant amount of energy (with respect to decreasing density) is transferred to altitudes above 300 km, i.e. well into the F region and even above the F-region maximum. Model calculations reveal that the infrasonic waves can locally heat the thermosphere/ionosphere quite significantly (Hickey et al., 2001).

6. Concluding remarks

Knowledge of the effects of waves coming from below into the ionosphere is very desirable for understanding the vertical couplings in the atmosphere–ionosphere system, for the energy budget of the ionosphere, for ionospheric dynamics, and for predictions of the state of the ionosphere for communication and other purposes. All four categories of the neutral atmosphere waves coming from below in the period range from a few weeks to a few seconds, planetary waves, tidal waves, gravity waves and infrasonic waves, are briefly treated. Much was done but still many questions became open.

The effects of tides coming from below are important for the behavior of the ionosphere. They play an important role in the process of formation of the E_s layers. Their contribution to the variability of f_0F2 is significant. However, they were less studied than the effects of gravity and planetary waves, particularly because the effects of tides are relatively regular compared with the effects of planetary and gravity waves and, therefore, they are to a substantial extent implicitly included in various empirical ionospheric prediction schemes based on large amounts of observational data. Further investigations are needed.

Planetary waves excite significant effects in the ionosphere. The planetary wave type oscillations in the ionosphere occur in the form of bursts of activity with relatively short persistence of typically 3–5 wave cycles (decreasing with increasing wave period). In the lower ionosphere the planetary wave type oscillations in the ionized component reflect the planetary waves in the neutral atmosphere, whereas in the F2 region a substantial part of such oscillations seems to be excited by similar periodicities in geomagnetic activity. The planetary waves significantly modulate the E_s layers and their formation. General understanding of planetary wave activity effects on the ionosphere is not yet sufficient in spite of remarkable progress.

Gravity waves play an important role in the behavior of the ionosphere. They are responsible for a substantial (often dominant) part of the ionospheric effects of various tropospheric meteorological phenomena like cold fronts, mesoscale convective complexes, etc. Gravity waves excited by the morning solar terminator passage are a quite regular phenomenon and can be included into ionospheric prediction/forecast models. The general qualitative knowledge of ionospheric effects of gravity waves is fairly good but more quantification is very desirable.

The effects of infrasound coming from below on the ionosphere are the least investigated and known part of lower atmosphere–ionosphere coupling via atmospheric waves. Its property of the upward focusing of energy is very promising. More investigations on their role in the energy budget and dynamical processes in the upper atmosphere and ionosphere are desirable.

The ionospheric infrasound is capable to serve as one of the methods of remote detection of large explosions including the nuclear underground explosions. Therefore the ionospheric infrasound research has also security aspects.

In spite of significant progress in recent years, various open questions remain, for example:

- Role/importance of infrasound.
- How planetary waves penetrate to F-region heights.
- Quantification of the role of gravity waves.

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