OBSERVATIONS OF ACOUSTIC-GRAVITY WAVES IN THE IONOSPHERE GENERATED BY SEVERE TROPOSPHERIC WEATHER

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ABSTRACT

Atmospheric waves influence the dynamics and energetic budget of the upper atmosphere. Using the continuous HF Doppler sounder, we study the wave activity in the ionosphere during tropospheric convective storms in western and central part of the Czech Republic. The study is focused on acoustic-gravity waves in the period range 2−30 minutes. We discuss possible methods of distinguishing the waves emitted by meteorological sources from waves of different origin, particularly waves of geomagnetic origin. In two cases out of twenty-five analysed, we found waves in the infrasonic period range which might be generated by exceptionally intense meteorological activity in the troposphere. The results differ considerably from those previously obtained in North America. In the central part of the United States, infrasonic waves were frequently observed during convective storms. As a possible reason, we discuss different intensity and dynamics of weather systems in both regions.

Key words: acoustic-gravity waves; ionosphere; convective storms

1. INTRODUCTION

The state and dynamics of the upper atmosphere is mainly driven by extraterrestrial sources, particularly by the Sun. Nevertheless, the influences coming from below also substantially contribute to the upper atmosphere variability. One of the broadly discussed phenomena is the meteorological activity in the troposphere (e.g. *Georges, 1973*; *Chimonas and Peletier, 1974*; *Yeh and Liu, 1974*; *Prasad et al., 1975*; *Gossard and Hooke, 1975*; *Blanc, 1985*; *Kazimirovsky and Kokourov, 1991*; *Kazimirovsky et al., 2003*; *Rishbeth, 2006*; *Laštovička, 2006*).

Meteorological processes in the troposphere are a source of strong internal waves of a broad period spectrum which carry energy and momentum upward through the atmosphere. Waves of periods longer than the Brunt-Vaisala period are termed gravity waves. Gravity waves, emitted besides meteorological activity by a number of various sources including auroral activity, the passage of solar terminator, solar eclipse, earthquakes, and eruptions (*Laštovička, 2006*), play an essential role in the thermal regime

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and composition of the middle and upper atmosphere and contribute significantly to its general circulation, structure and variability (*Kazimirovsky et al., 2006*). *Vadas and Fritts (2004)* emphasize the potential of gravity waves to influence very high atmospheric altitudes because of their relatively large vertical wavelengths and their propagation, at least initial, in all directions from the source. Climatological studies of gravity waves in the middle and upper atmosphere over Japan revealed almost continuous presence of gravity waves in the F region (*Oliver et al., 1997*). In the E region, gravity waves contribute to the formation of the Es layer (*Matthews, 1998*; *Fukao et al., 1998*; *Kazimirovsky et al., 2003*); probably due to the enhancement of irregular neutral winds associated with gravity waves (*Parkinson and Dyson, 1998*). Zones of the deep tropical convection are the dominant sources of convectively generated gravity waves and possibly the most important sources of high frequency gravity waves on the Earth (*Vadas and Fritts, 2004*). As the most efficient meteorological source of gravity waves in mid latitudes are considered passages of cold fronts (*Laštovička, 2006*). *Šauli and Boška (2001)* described increased wave activity in the period range 50–100 min during the passage of weather fronts over the Czech Republic. The observations of gravity waves were also reported during tornadoes. *Hung et al. (1979)* described observations of 13–15 min and 27–30 min waves in the ionospheric *F* region during an extreme tornado outbreak. *Zuo Xiao et al. (2007)* observed medium scale travelling ionospheric disturbances with periods near 20 min which gradually grow longer and spread F after sunset as a response to a typhoon.

Waves of periods up to a few minutes are termed acoustic waves. The spectrum is at long periods restricted by the acoustic cut-off period. Acoustic waves are strongly absorbed and only waves in the low frequency band of the acoustic spectrum may propagate to ionospheric heights. *Blanc (1985)* states that only waves of frequencies lower than 1 Hz are observed in the upper atmosphere. Due to the profile of refractive index (n) in the lower and middle atmosphere, n is indirectly proportional to the square root of absolute temperature, infrasound is focused upwards in the troposphere and in the mesosphere and the main part of acoustic energy propagates up to the base of the ionosphere. Thus, infrasound is more efficient in energy transfer to ionospheric heights than other types of waves (*Laštovička, 2006*). On the other hand, infrasonic waves affect due to the focusing only spatially constricted region in the upper atmosphere. Infrasonic waves are emitted by artificial as well as natural processes. Most of the infrasound sources can be described as occasional or sporadic. They include volcanic eruptions, earthquakes, solar eclipses, passage of the solar terminator in lower latitudes, auroral activity, bolides and meteorites, nuclear and chemical explosions, supersonic jets and spacecraft launches. Meteorological activity and ocean waves are considered as a continuous source of infrasound (*Laštovička, 2006*; *Rind, 1978*). Infrasonic waves were frequently observed during severe convective storms in the central part of the USA. Numerous authors dealt with this topic, particularly in 1960s and 1970s. Observations of infrasonic waves with periods from 1 to 5 min in the ionosphere during nearby tropospheric convective storms were repeatedly reported (*Georges, 1967*; *Baker and Davies, 1969*; *Chimonas and Peltier, 1974*; *Davies and Jones, 1973*; *Georges, 1973*; *Prasad et al., 1975*). Spectral analysis revealed peaks near the periods 3.5 and 4.5 min. One event lasted several hours; *Baker and Davies (1969)* found in their study most typical duration from 2 to 4 h. Ionospheric effects were usually observed when a convective storm was active within the radius of ~ 250 km from ionospheric observation point (*Prasad et al., 1975*). *Georges (1973)* emphasized particular efficiency in producing infrasound of those storms, during which the cloud tops penetrated the tropopause. The dependence of the observed ionospheric effects on geographical location and relative position of the convective storm towards the point of ionospheric observation were mentioned by *Georges (1973)* and *Prasad et al. (1975)*. On the other hand, *Georges (1973)* reported a number of convective storms which contrary to reasonable expectations produced no observable ionospheric effects.

The present paper describes results of observation of acoustic-gravity waves at ionospheric heights which occurred during periods of increased meteorological activity in the troposphere, particularly during convective storms. The emphasis is paid on waves of periods up to 30 min. Using ionospheric, meteorological and geomagnetic data, we also discuss a method of distinguishing the origin of observed waves.

2. DATA AND METHODS

The data used in our study include continuous HF Doppler shift measurements at ionospheric heights, ionosonde data, meteorological radar data, aerological data, satellite images, data from the surface meteorological station Milešovka (50°33′N, 13°56′E) of the Institute of Atmospheric Physics (IAP), Prague, and data from the geomagnetic observatory Budkov (49°04′N, 14°01′E) of the Institute of Geophysics (IG), Prague. Convective storm events were selected on days with quiet to active geomagnetic conditions. The *Dst* index was not lower than −30 nT and the maximum *Kp* index was 4.

The continuous HF Doppler sounder including special software was developed at IAP. The transmitted frequency of 3.5945 MHz is derived from the 10 MHz Oven Controlled Crystal Oscillator (OCXO) by means of direct digital synthesis (DDS). In 2004, the first transmitter was placed at the Průhonice observatory (49°59′N, 14°33′E), which is at about 7 km distance from the receiver, located at IAP (50°02′N, 14°28′E). A great advantage of this topological arrangement is the common volume measurement with a digisonde DPS-4 located at Průhonice. Thus, we can determine the virtual height of reflection of the 3.59 MHz wave directly from ionograms. At the beginning of April 2005, another transmitter was installed at the observatory Panská Ves (50°32′N, 14°34′E). Two more transmitters, located at Dlouhá Louka (50°39′N, 13°39′E) and Kašperské Hory (49°08′N, 13°35′E) observatories were set in operation at the beginning of 2007. The frequencies of transmitters are mutually shifted by 4 Hz. The shift of sounding frequency enables using of only one receiver located at the IAP.

The spectral content of observed waves was obtained in following way: the received signal was converted (shifted) to low frequencies, and a spectral analysis was performed resulting in Doppler shift spectrograms. To achieve high frequency-time resolution of the observed Doppler shift, the successive spectra were obtained by shifting Gaussian window of the width ~ 10 s by a time step less than the width of the window in the time domain. That means the successive time intervals, in which spectra were calculated, overlap each other. Therefore, the resulting spectrogram has a smoother character comparing to the analysis with no overlap in time. In further analysis, we selected time intervals, in which we received signal containing one frequency - we observed one clear trace in the Doppler shift spectrograms. That means we excluded time intervals, during which we received two different frequencies for extraordinary and ordinary waves with comparable amplitudes or any kind of multi-ray reflection, relatively broad-band spectrum of Doppler shift owing to reflection from a spread layer etc. In the selected time intervals we found one value of the Doppler shift which fits best the observation in each time step, thus obtaining an unambiguous function of Doppler shift on time. Analysing the spectral content of this function, we got information about typical periods of the observed waves at each time. To obtain simultaneously a maximum frequency and time resolution for different periods, we applied a Continuous Wavelet Transform (CWT) based on the complex Morlet wavelet.

The Fourier transform was used in addition to the wavelet transform. Gravity waves originating from different sources are nearly always present in the upper atmosphere and gravity waves generated by severe weather do not carry any label which would enable their identification. Therefore, we first analysed gravity wave spectra on quiet days. A quiet day means a day with quiet or unsettled geomagnetic field ($Kp \leq 3$, $Dst \geq -20$ nT) and low meteorological activity in the troposphere. It means weather in Central Europe was governed by a high air pressure system or a flat low. Due to known different effects of the morning and evening passage of the solar terminator on the ionosphere (*Boška et al., 2003*; *Altadill et al., 2004*), the night and early morning part of the day (~ 00:00 to 06:00 UT) and the period from afternoon till midnight (~ 16:00 to 24:00 UT) were analysed separately. During the daytime (~ 06:00 to 16:00 or to 18:00 UT), the HF signal is usually reflected in the E region and experiences low Doppler shift close to zero. Median, upper and lower quartiles were calculated from wave spectra obtained for individual quiet days and serve as a reference Fourier spectrum. Due to a low number of cases in the data set, the above mentioned statistics are supposed to be more representative than the mean and the standard deviation, particularly due to the influence of extreme values. We compared the reference Fourier spectrum with the Fourier spectrum of the Doppler shift measurements during individual cases of nearby convective storms. In this way, we checked whether the amplitudes of waves detected in the previous step by the wavelet transform exceed significantly mean values for quiet days, it means exceed the upper quartile.

A possible geomagnetic origin of waves was verified using the data from geomagnetic observatory Budkov. The wavelet transform of fluctuations of horizontal and vertical components and the amplitude of the local geomagnetic field was computed and compared with wavelet transform of the Doppler shift measurements. Cross-correlations between the Doppler signal and geomagnetic field components were computed as well. Cross-correlation analysis is able to reveal a possible direct relationship between ionospheric and geomagnetic oscillations, which was previously described between short period ionospheric waves and geomagnetic micropulsations (e.g. *Marshall and Menk, 1999*). On the basis of wavelet analysis, we found the time interval of occurrence of waves and using band pass filter, we filtered wave periods shown by the wavelet analysis. Thus processed signals were used for the computation of the cross-correlation. In the case that ionospheric waves occured simultaneously with geomagnetic oscillations of corresponding periods (according to the wavelet transform) and/or the cross-correlation values were $|c| \geq 0.5$, it is in our opinion necessary to consider geomagnetic origin of the waves.

The height of reflection of 3.59 MHz radio wave was checked, since the results of Doppler shift observations are substantially influenced by the reflection height of the sounding wave, furthermore Doppler shifts possibly caused by sudden changes of the reflection height between Es and F layer could have been revealed.

To follow dynamics and actual location of weather systems, we used meteorological radar data. The Czech radar network operated by the Czech Hydrometeorological Institute (CHMI) consists of radiolocators located at Brdy-Praha (49°39′N, 13°49′E) and at Skalky (49°30′N, 16°47′E). The radiolocators are able to monitor dynamics of active weather systems up to the horizontal distance 256 km. The radar volume data are updated every 10 min (*Novák and Kračmar, 2000*). We use quasi-three-dimensional projections of maximum radar reflectivity in 30-min intervals, which show projection of column maximum reflectivity on the horizontal plane and on two vertical planes up to the height 14 km in the north-south direction and in the west-east direction. The reflectivity Z of meteorological targets is proportional to the sum of the sixth power of particle diameters in the unit volume. The unit of reflectivity is 1 mm^6/m^3. For practical purposes, the logarithmic unit dBZ is used, where $Z[\text{dbZ}] = 10\log\left(Z\left[\text{mm}^6/\text{m}^3\right]\right)$ (*Novák, 2000*). From radar reflectivity, the precipitation intensity can be computed and subsequently the strength of convective phenomena can be deduced. There are two threshold values of maximum radar reflectivity routinely used in the Czech Hydrometeorological Institute to evaluate the intensity of convective phenomena: 40 dBZ and 52 dBZ for convective phenomena (showers, rain, thunderstorms) and severe convective events (heavy rain, hail), respectively (*Pešice et al., 2003*).

Additional information on vertical extent of convective clouds was obtained from combination of the Meteosat Second Generation (MSG) images in the IR10.8 channel in 30-min intervals and aerological data - vertical temperature profile up to the pressure level 100 hPa (corresponds to height ~ 16.5 km in the analysed days). The actual height of tropopause is obtained from aerological data as well. The measurements at the upper air station Prague-Libuš (50°01′N, 14°27′E) are scheduled daily at 00:00, 06:00, 12:00, 18:00 UT. The station is operated by the CHMI and is one of the regular World Meteorological Organization (WMO) aerological stations.

Wind speed at the station Milešovka complete the information about meteorological conditions on analysed days. The observatory is located on an isolated peak (837 m a.s.l.) with vertical distance towards its surroundings up to 400 m. The wind speed and direction thus approaches the wind flow in the free atmosphere.

To compare the meteorological activity during summer convective storm events, we use an index which is based on the wind speed at Milešovka observatory, the vertical extent of convective clouds, the extent of area of high radar reflectivity, and the intensity of convection. We computed the extent of the area of maximum radar reflectivity 52+ dBZ in the horizontal plane projection and in vertical plane projections in the north-south direction and in the east-west direction at heights above 10 km and summarized the extents (R). R was obtained for each event in 30 min time step. We found the maximum and minimum value (R_{max} and R_{min}) for each event. We found the maximum hourly average wind speed for reach event (W). The extents of areas of maximum radar reflectivity 52+ dBZ and the hourly average wind speeds were always expressed as a ratio to the corresponding maximum value of all the events. The height of clouds was evaluated as follows: When the clouds penetrated the tropopause during the event, we assigned $C = 1$. When clouds reached to the tropopause region, we assigned $C = 0.5$. When the height of cloud tops was lower than the tropopause, we assigned $C = 0$. The index (I) was then computed as $I = R_{min} + R_{max} + W + C$.

3. RESULTS

Most of the data were collected from May 2006 to September 2006. We considered only convective storms in the late afternoon and evening of local time (~ 16:00–00:00 UT), because the most intense convective storms usually occur in that part of day. Twelve quiet days according to the criteria described in Section 2 were found and used to calculate the reference Fourier spectrum. Days with the Es layer occurrence and days without Es layer were not treated separately.

Twenty-three events were selected during convective storm season 2006. We also analyse a case of exceptionally intense summer convective storms which developed on 29 and 30 July 2005 and a severe weather event on 18 January 2007. In most cases, convective storms developed at a cold front which was passing over the Czech Republic.

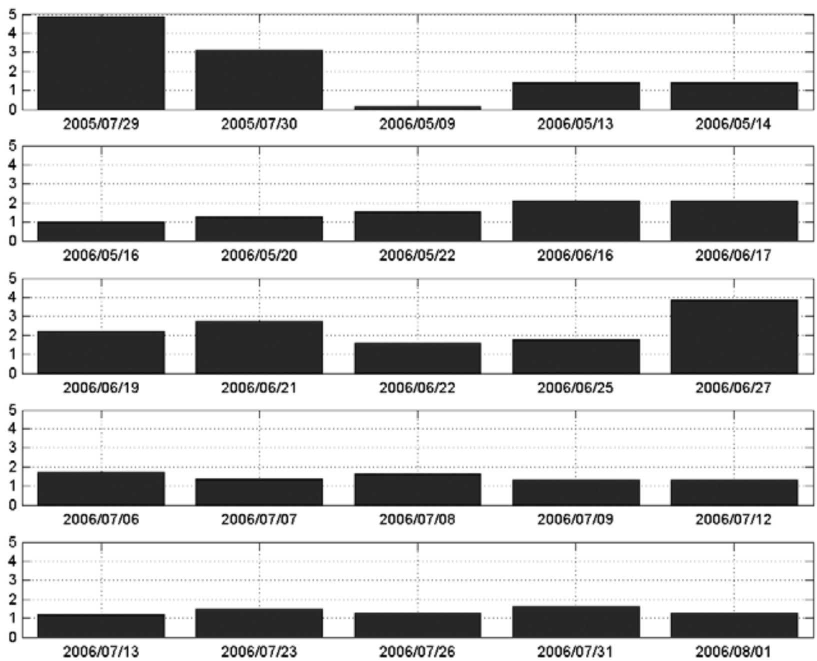


Fig. 1. Index to compare meteorological activity in the troposphere during summer convective storm events. The intensity of convective storms on 29 July 2005 stands out.

The height of convective clouds varied between ~ 10 km and 16 km. In nine cases, convective clouds penetrated the tropopause whose height was in the range ~ 10–13 km. The intensity of summer convective storms is compared using the index (Fig. 1).

We focused on the detection of waves of periods 2–30 min. Fourier analysis showed increased wave amplitudes during convective storm events compared to wave amplitudes on quiet days. However, the waves occurred simultaneously with geomagnetic field fluctuations of corresponding periods. Acoustic-gravity waves of significant amplitudes (higher than 0.1 Hz) and significant duration (longer than the period of the wave) which could be unambiguously ascribed to the meteorological activity in the troposphere were not found in analysed events in 2006. We often observed a spread or smeared Doppler signal. The Doppler trace was in several cases S-shaped. However, all these effects were observed also on quiet days. The occurrence and origin of S-shapes in the Doppler record were discussed by Chum *et al. (2008)*. Spread and smeared signal occurred particularly in time intervals when an Es layer was present.

Next, we will focus on the days of 29 and 30 July 2005 and 18 January 2007, since the intensities of meteorological processes which developed in the troposphere on these days were exceptional for Central Europe.

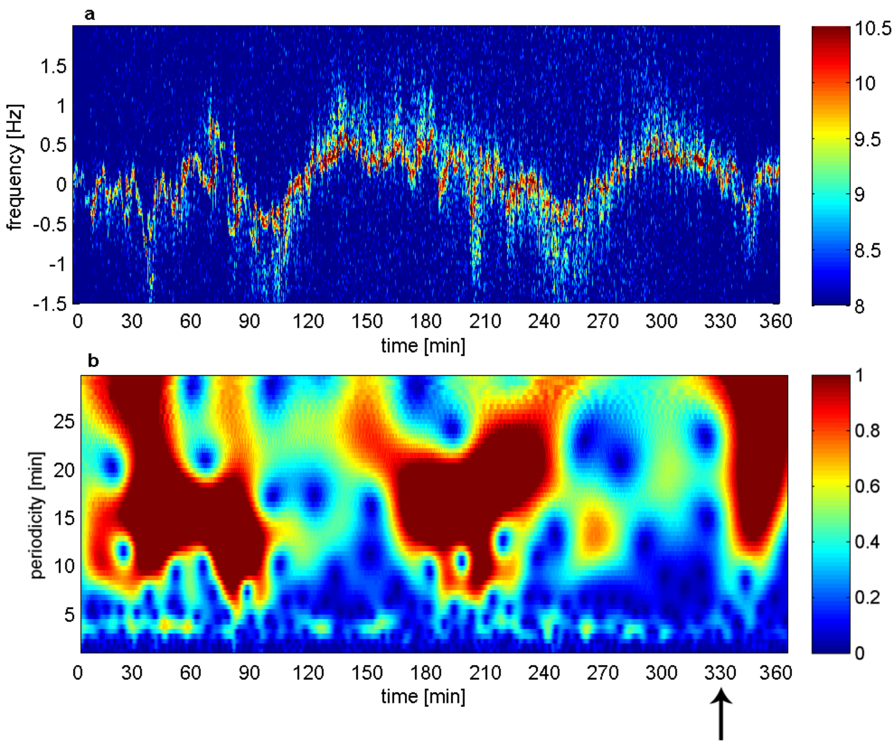


Fig. 2. a) Doppler shift spectrogram at the Panská Ves sounding path during convective storm activity on 29 July 2005, start time at 18:00 UT; **b)** Wavelet transform of the signal. Arrow denotes the approximate time of passage of the squall line under the ionospheric observation point (*Šindelářová et al., 2009*, © COSPAR and Elsevier Ltd.).

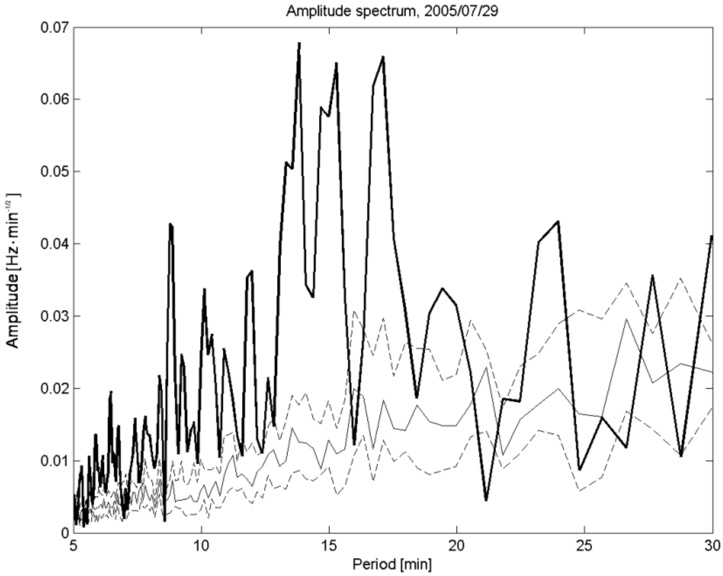


Fig. 3. Fourier spectrum show much higher wave activity on 29 July 2005 than on quiet days. Red line: amplitude spectrum on 29 July 2005. Black solid line: median of Fourier spectra on quiet days. Black dashed lines: lower quartile and upper quartile of Fourier spectra on quiet days.

During the day of 29 July 2005, suitable conditions for strong convection developed in wet warm air flowing to Central Europe in front of the cold front. The actual passage of the cold front in the evening hours (~ 18:00–01:00 UT on 29/30 July 2005) was accompanied by intense convective storms with convective cloud tops reaching to heights ~ 15–16 km and wind gusts 20–40 m/s. The squall line passed the Doppler system measuring path between ~ 22:40 and 23:30 UT. Along the north western boarder of the Czech Republic, a supercell storm and four tornadoes were observed at ~ 18:00–20:30 UT (analysis of the weather situation by Czech Hydrometeorological Institute, *www.chmi.cz*). On 30 July 2005, the intense convective storm activity continued. In the afternoon, convective storms started developing in Southern Bohemia and moved towards north-east. They reached the highest intensity around 20:00 UT. The height of convective clouds exceeded 16 km as follows from MSG satellite images and vertical temperature profiles. Probably a supercell storm was observed between ~ 17:00 and 19:00 UT in Southern Bohemia. On 29 July 2005, distinct infrasonic waves with characteristic periods of ~ 2.5–5 min superimposed on gravity waves were recorded in the F region already at about 18:00 UT (Fig. 2). The wave activity in the infrasonic range was ceasing after midnight as convective storms were passing further to the east and were abating. The Fourier spectrum of the Doppler record shown in Fig. 3 (thick black line) indicates much higher wave activity on 29 July 2005 compared to quiet days (reference Fourier spectrum is represented by thin black lines). On 30 July 2005, a relatively weak wave activity was recorded in the late afternoon and evening hours (Fig. 4). Unlike the day before, the Es

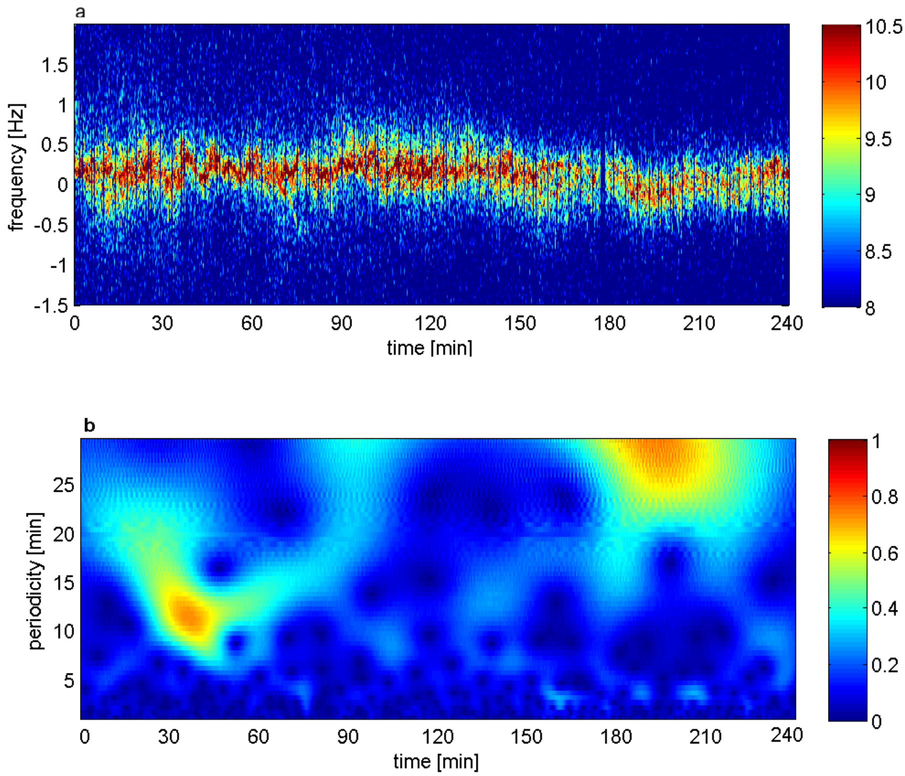
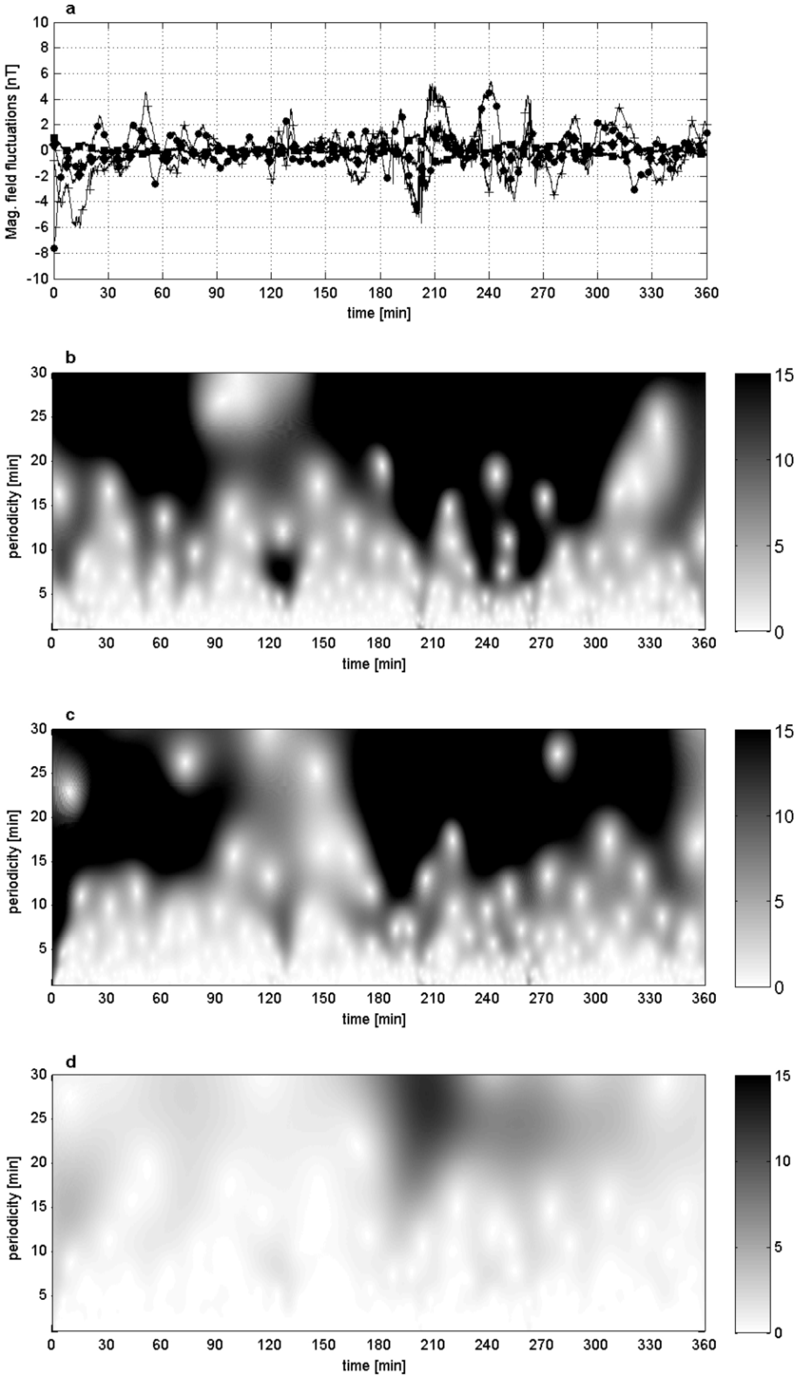


Fig. 4. a) Doppler shift spectrogram at the Panská Ves sounding path during convective storm activity on 30 July 2005, start time at 20:00 UT; **b)** Wavelet transform of the signal. Relatively low wave activity was observed. Infrasonic waves if significant amplitudes did not occur.

layer occurred during the whole studied interval with critical frequency higher than 3.6 MHz. We should note that a negligible Doppler shift and/or a spread trace are usually observed when the reflection occurs from the Es layer.

Wave effects in the Doppler shift record may be caused not only by acoustic-gravity waves propagating in the neutral atmosphere, but also by magneto-hydrodynamic waves. Therefore, we checked the oscillations of the north-south, west-east and vertical component of the geomagnetic field at observatory Budkov. Comparing the wavelet analysis of the Doppler records (Fig. 2) and wavelet analyses of components of the local geomagnetic field (Fig. 5) and computing the cross-correlations between the signals, we conclude that ~ 2.5–5.5 min waves observed on 29 July 2005 at ~ 18:00–19:00 UT (Fig. 6), ~ 20:20–20:40 UT, and ~ 23:10–23:30 UT are not of geomagnetic origin. We assume that they were emitted by convective storms in the troposphere. We cannot exclude that geomagnetic pulsations are responsible for the observed 2–5.5 min waves


a
Mag. field fluctuations [nT]
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within the time intervals from ~ 19:50 to 20:10 UT and from ~ 20:45 to 22:55 UT. The oscillations of periods over 6 min which occurred at 18:00–24:00 UT are correlated with fluctuations of the geomagnetic field (not shown). Simultaneous occurrence of ionospheric and geomagnetic fluctuations was observed also on 30 July 2005.

On 18 January 2007, a deep cyclone was passing over Europe. The large pressure gradient between Scandinavia and Mediterranean (~ 50 hPa) triggered an exceptionally strong air flow. The average wind speed measured in the Czech Republic was 15–20 m/s, and in wind gusts it was over 40 m/s. Wind speed at Milešovka reached over 30 m/s; (to compare, the average wind speed in January for years 1961–1990 was 9.6 m/s). Strong wind reaching up to 12° of the Beaufort scale was blowing before the passage of the frontal system of the cyclone as well as after the passage. The cold front was passing over the Doppler system network between ~ 20:15 and 23:45 UT. Its passage was accompanied by thunderstorms with exceptionally high lightning activity compared to usual winter thunderstorms. Due to different stratification and energetic potential of the lower atmosphere in winter, the vertical extent of clouds during the January event was significantly less comparing with summertime events and clouds did not reach to the tropopause. 18 January 2007 is a case of very strong winter convection in connection with a strong turbulence (weather situation analysis by Czech Hydrometeorological Institute, *www.chmi.cz*). Increased wave activity in the ionosphere was observed during the whole analysed interval 20:00–23:59 UT (Fig. 7). Doppler records at the Průhonice path and Panská Ves path were spread and disturbed by a strong ground wave (Průhonice). Waves of periods ~ 2–4 min which occurred in the records from Dlouhá Louka path at ~ 20:50–21:35 UT and at 22:00–22:10 UT and waves of periods ~ 2.5–4 min observed on the Kašperské Hory path at ~ 21:40–21:50 UT are not related to geomagnetic oscillations. In our opinion, these oscillations are infrasonic waves generated in the troposphere. Waves of periods longer than 5 min occurred in Doppler shift records as well as in geomagnetic records.

The current analysis, based on a larger number of cases, has so far confirmed the results of our previous study focused on the detection of infrasonic waves in the upper atmosphere during convective storms (*Šindelářová et al., 2009*). That is, infrasound emitted by meteorological activity is rarely observed in the upper atmosphere over the Czech Republic and accompanies only exceptionally severe troposheric weather (in conditions of Central Europe).

Fig. 5. (Facing page) a) Fluctuations of the local geomagnetic field at the observatory Budkov on 29 July 2005, start time at 18:00 UT. Red: north-south component. Green: west-east component. Blue: vertical component. Magenta: amplitude. Periods over 30 min have been filtered. **b)** Wavelet transform of fluctuations of the north-south component of the geomagnetic field at observatory Budkov; **c)** the same as b) but for west-east component; **d)** the same as b) and c) but for vertical component.

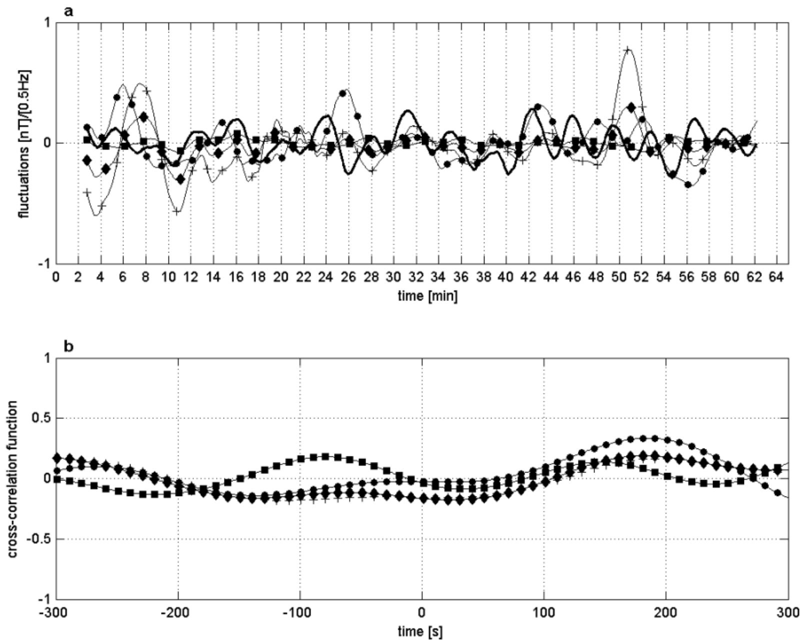

Fig. 6. **a)** Short period waves observed in the ionosphere and fluctuations of the local geomagnetic field at observatory Budkov on 29 July 2005, start time 18:00 UT. Yellow: the Doppler shift record. Red: north-south component of the geomagnetic field. Green: west-east component. Blue: vertical component. Magenta: amplitude of the geomagnetic field. Band-pass filter with pass band 2–5 min was used. **b)** Cross-correlation functions between the Doppler shift record and components of the geomagnetic field. Meaning of colours follows the colour system in panel a).

4. DISCUSSION

The Doppler shift observations of wave activity in the ionosphere are significantly influenced by the presence of the Es layer. On quiet days, a very low or no wave activity was observed when the Es layer, particularly non-transparent Es, was present. On 30 July 2005, wave activity in the period range 2–30 min observed by the Doppler measuring system was weak despite intense convective storms in the troposphere, which is in contrast to observations made the day before. On 29 July 2005, the Doppler sounding wave was reflected from the F layer whereas on 30 July 2005, the Es layer persisted throughout the day; in some intervals, it was non-transparent.

On several days, the Es layer was not present over the whole period of observation. However, we did not found increased occurrence of infrasonic waves in the intervals when the Doppler system sounding wave reflected from the F layer. It leads to an assumption, that convective storms in Central Europe are not as efficient in emitting infrasonic waves as convective storms in North America.

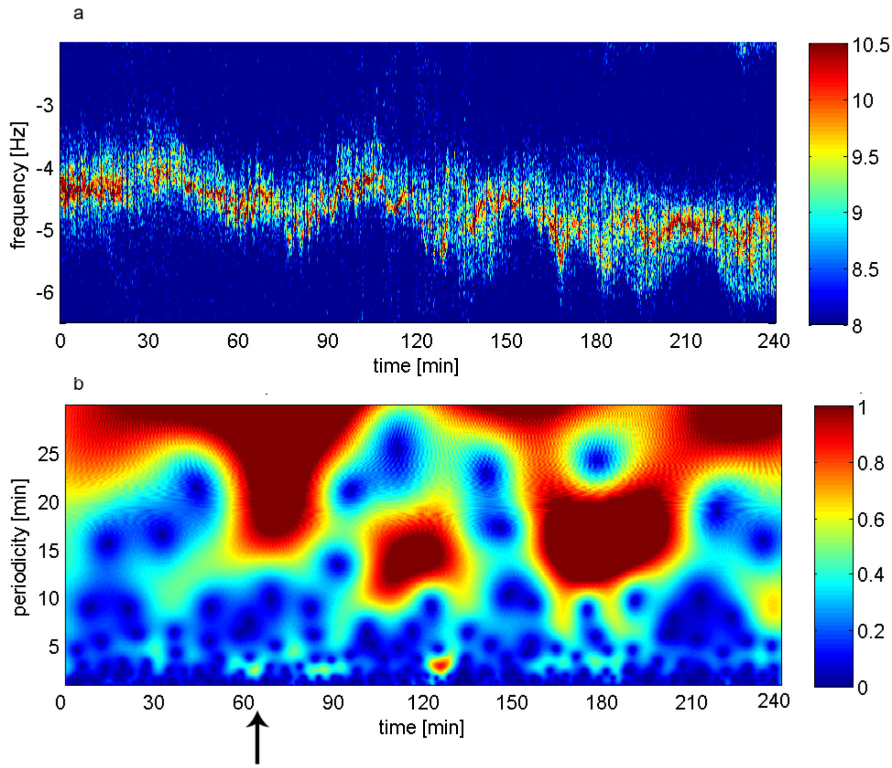

Fig. 7. **a)** Doppler shift spectrogram at the Dlouhá Louka sounding path during the windstorm and passage of the distinct cold front on 18 January 2007, start time at 20:00 UT; **b)** wavelet transform of the signal (*Šindelářová et al., 2009*, © COSPAR and Elsevier Ltd.).

The observations of infrasonic waves emitted by convective storms were reported mainly in the central United States in summer. A thermal low develops above the continent during the summer time and enables the inflow of wet tropical air from the Gulf of Mexico. In the central USA, no significant orographic barrier exists for the meridional air flow. The high terrain of the Rocky Mountains generates steep lapse rates in the Plains of the United States. The moist air together with high lapse rate air creates an ideal location for development of severe thunderstorms and tornadoes in the central United States (*Brooks et al., 2003*). In Central Europe, zonal air flow prevails throughout the year. (The circulation is determined by the permanent centres of action in the troposphere, Azores anticyclone in the south and Island cyclone in the north.) The Mediterranean Sea is not as warm most of the year as the Gulf of Mexico and is relatively small to modify significantly the air masses (*Brooks et al. 2003*). Further, the Alps constitute an orographic barrier for the meridional air flow. Therefore, suitable conditions for intense convection do not frequently develop in Central Europe.

Waves of periods which correspond to periods of gravity waves were observed in time intervals when the Doppler system sounding wave reflected from the F layer. Wave activity on days with convective storms was higher than on quiet days. However, the ionospheric waves occurred simultaneously with fluctuations of local geomagnetic field. Therefore, geomagnetic origin of the waves must be considered. Multipoint measurements which started in 2007 will contribute to more precise determination of the origin of waves. In future, we will also focus on the analysis of propagation speed of observed waves and enlarge the number of cases for better statistics.

5. CONCLUSIONS

We presented the results of the wave activity analysis based mainly on observations during the convective storms of 2006. Two severe weather events in July 2005 and January 2007 were presented as well. We analysed wave activity at ionospheric heights with periods from 2 to 30 minutes. Effects of summer and winter convective storms of different intensity were studied. In two cases, we found increased wave activity in the infrasonic period range. On 29 July 2005, 2.5−5.5 min waves were observed in the ionospheric F region. On 18 January 2007, 2−4 min waves were detected. On the basis of wavelet analysis of fluctuations of the local geomagnetic field and cross-correlations between the Doppler signal and geomagnetic data, we are convinced that the observed oscillations cannot be entirely assigned to the pulsations of the geomagnetic field. Therefore we consider exceptionally strong meteorological activity as a source of these waves. Oscillations of periods ~ 5−30 min observed on these two days were most probably of geomagnetic origin. During the other analysed events, wave activity which could be unambiguously attributed to tropospheric meteorological processes was not found in the analysed period range. The oscillations either were possibly connected with fluctuations of the geomagnetic field or the pattern did not differ significantly from the pattern on geomagnetically quiet days with low meteorological activity. The results of observation in Central Europe significantly differ from the results obtained in the central part of the United States, where observations particularly of infrasonic waves were frequently reported. The reason might be lower intensity of convective storms in Central Europe which can be assumed, if we consider the circulation of the troposphere in both regions, the orography of both continents and the position of the continents and seas.

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References

Altadill D., Apostolov E.M., Boška J., Laštovička J. and Šauli P., 2004. Planetary and gravity wave signatures in the F region ionosphere with impact to radio propagation predictions and variability. *Annals of Geophysics*, **47** (Suppl.), 1109−1119.

Baker D.M. nad Davies K., 1969. F2-region acoustic waves from severe weather. *J. Atmos. Sol.-Terr. Phys.*, **31**, 1345−1352.

Blanc E., 1985. Observations in the upper atmosphere of infrasonic waves from natural or artificial sources: A summary. *Annales Geophysicae*, **3**, 673−688.

Boška J., Šauli P., Altadill D., Solé G. and Alberca L.F., 2003. Diurnal variation of the gravity wave activity at midlatitudes of the ionospheric F region. *Stud. Geophys. Geod.*, **47**, 579–586.

Brooks H.E., Lee J.W. and Craven J.P., 2003. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, doi: 10.1016/S0169-8095(03)00045-0.

Chimonas G. and Peletier W.R., 1974. On severe storm acoustic signals observed at ionospheric heights. *J. Atmos. Terr. Phys.*, **36**, 821–828.

Chum J., Laštovička J., Šindelářová T., Burešová D. and Hruška F., 2008. Peculiar transient phenomena observed in the infrasound range. *J. Atmos. Sol.-Terr. Phys.*, **70**, 866–878, doi: 10.1016/ j.jastp.2007.06.013.

Davies K. and Jones T.B., 1973. Acoustic waves in the ionospheric F2-region produced by severe thunderstorms. *J. Atmos. Terr. Phys.*, **35**, 1737–1744.

Fukao S., Yamamoto M., Tsunoda R.T., Hayakawa H. and Mukai T., 1998. The SEEK (Sporadic-E Experiment over Kyushu) campaign. *Geophys. Res. Lett.*, **25**, 1761–1764.

Georges T.M., 1967. *Ionospheric Effects of Atmospheric Waves*. *ESSA Technical Report IER 57-ITSA 54*. Institute for Telecomunication Sciences and Aeronomy, Boulder, USA.

Georges T.M., 1973. Infrasound from convective storms: Examining the evidence. *Rev. Geophys. Space Phys.*, **11**, 571–594.

Gossard E.E. and Hooke W.H., 1975. *Waves in the Atmosphere. Atmospheric Infrasound and Gravity Waves - their Generation and Propagation*. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Hung R.J., Plan T. and Smith R.E., 1979. Coupling of ionosphere and troposphere during the occurrence of isolated tornadoes on November 20, 1973. *J. Geophys. Res.*, **84**, 1261–1267.

Kazimirovsky E.S. and Kokourov V.D., 1991. The tropospheric and stratospheric effects in the ionosphere. *J. Geomagn. Geoelectr.*, **43**, 551–562.

Kazimirovsky E.S., Herraiz M. and De la Morena B.A., 2003. Effects on the ionosphere due to phenomena below it. *Surv. Geophys.*, **24**, 139–184.

Kazimirovsky E.S., Kokourov V.D. and Vergasova G.V., 2006. Dynamical climatology of the upper mesosphere, lower thermosphere and ionosphere. *Surv. Geophys.*, **27**, 211–255, doi: 10.1007 /s10712-005-3819-3.

Laštovička J., 2006. Forcing of the ionosphere by waves from below. *J. Atmos. Sol.-Terr. Phys.*, **68**, 479–497, doi: 10.1016/j.jastp.2005.01.018.

Marshall R.A. and Menk F.W., 1999. Observations of Pc 3-4 and Pi 2 geomagnetic pulsations in the low-latitude ionosphere. *Ann. Geophys.*, **17**, 1397–1410.

Matthews J.D., 1998. Sporadic-E: current views and recent progress. *J. Atmos. Terr. Phys.*, **60**, 413–435.

Novák P., 2000. *Meteorological Interpretation of Doppler Weather Radar Measurements.* PhD Thesis. Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic.

Novák P. and Kráčmar J., 2000. Using data from the Czech weather radar network for detection of convective storms. 1st European Tornadoes and Severe Storms Conference, Toulouse, France (www.chmi.cz/meteo/rad/pub/ssc2000/).

Oliver W.L., Otsuka Y., Sato M., Takami T. and Fukao S., 1997. A climatology of F region gravity wave propagation over the middle and upper atmosphere radar. *J. Geophys. Res.*, **102**, 14499–14512.

Parkinson K.L. and Dyson P.L., 1998. Measurements of mid-latitude E-region, sporadic-E and TID-related drifts using HF Doppler-sorted interferometry. *J. Atmos. Sol.-Terr. Phys.*, **60**, 509–522.

Pešice P., Sulan J. and Řezáčová D., 2003. Convection precursors in the Czech territory. *Atmos. Res.*, **67–68**, 523–532, doi: 10.1016/S0169-8095(03)00070-X.

Prasad S.S., Schneck L.J. and Davies K., 1975. Ionospheric disturbances by severe tropospheric weather storms. *J. Atmos. Terr. Phys.*, **37**, 1357–1363.

Rind D., 1978. Investigation of the lower thermosphere results of ten years of continuous observations with natural infrasound. *J. Atmos. Terr. Phys.*, **40**, 1199–1209.

Rishbeth H., 2006. F-region links with the lower atmosphere? *J. Atmos. Sol.-Terr. Phys.*, **68**, 469–478, doi: 10.1016/j.jastp.2005.03.017.

Šauli P. and Boška J., 2001. Tropospheric events and possible related gravity wave activity effects on the ionosphere. *J. Atmos. Sol.-Terr. Phys.*, **63**, 945–950.

Šindelářová T., Burešová D., Chum J. and Hruška F., 2009. Doppler observations of infrasonic waves of meteorological origin at ionospheric heights. *Adv. Space Res.*, **43**, 1644–1651, doi: 10.1016/j.asr.2008.08.022.

Vadas S.L. and Fritts D.C., 2004. Thermospheric responses to gravity waves arising from mesoscale convective complexes. *J. Atmos. Sol.-Terr. Phys.*, **66**, 781–804, doi: 10.1016/j.jastp.2004.01.025.

Xiao Z., Xiao S.G., Hao Y.Q. and Zhang D.H., 2007. Morphological features of ionospheric response to typhoon. *J. Geophys. Res.*, **112**, A04304, doi: 10.1029/2006JA011671.

Yeh K.C. and Liu C.H., 1974. Acoustic-gravity waves in the upper atmosphere. *Rev. Geophys. Space Phys.*, **12**, 193–215.