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Doppler observations of infrasonic waves of meteorological origin at ionospheric heights

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Abstract

Ionospheric effects of meteorological origin observed by the continuous HF Doppler sounder over the Czech Republic are reported in this paper. We focused on detection of waves of periods 1–10 min. We discuss the influence of dynamics and intensity of active weather systems on the occurrence of short period waves and dependence of the observed ionospheric effects on the height of reflection of the sounding radio wave. We observed 3–5 min waves during a severe weather event in summer and 2.5–4 min waves during a severe weather event in winter. We excluded possible geomagnetic origin of these oscillations by the analysis of fluctuations of the local geomagnetic field. In eight cases of 10, wave activity in the analysed period range was not significantly increased comparing to quiet days. The intensity of weather systems as well as the location of potential sources of waves towards the points of HF Doppler shift observation influence significantly the occurrence of infrasonic waves in the ionosphere. The results in Central Europe differ considerably from those previously obtained in North America. As a possible reason, we discuss different intensity and dynamics of weather systems in both regions.

Keywords: Infrasonic waves; Ionosphere; Meteorological activity

1. Introduction

Many kinds of waves originating from various natural and artificial sources have been observed in the upper atmosphere including infrasonic (acoustic) waves, gravity waves, planetary waves and tides (e.g. Yeh and Liu, 1974; Lastovicka, 2006). Periods of waves extend in the range from seconds to days. Active weather systems are considered to be a significant natural source of waves of various kinds, particularly, infrasonic and gravity waves. Waves generated in the lower atmosphere are transmitted up to the ionosphere. Observations and theoretical considerations of a possible influence of severe lower atmospheric weather on the average ionospheric variability have been discussed in the past (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; Lastovicka, 2006).

Infrasonic waves cover frequency range higher than the acoustic cut off frequency (f_a), $f_a \sim 0.002$ Hz. Infrasonic waves of meteorological origin detected at ionospheric heights have been emitted predominantly by convective storms (Georges, 1973; Raju et al., 1981; Walterscheid et al., 2003). Besides the meteorological activity, infrasound can also be generated by ocean waves, avalanches, earthquakes, volcanoes, and meteors or by man-made processes such as explosions, either chemical or nuclear (Krasnov et al., 2006). 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 and the main part of acoustic energy propagates to the upper atmosphere. Thus, infrasound is more efficient in energy transfer to ionospheric heights than other types of waves (Lastovicka, 2006).

During tropospheric convective storm activity, infrasonic waves with periods from 1 to 5 min have been

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observed in the ionosphere (Georges, 1973; Prasad et al., 1975; Blanc, 1985). They persisted for several hours. Ionospheric effects are usually observed when a convective storm is active within the radius of 250 km from ionospheric observation point (Prasad et al., 1975). Georges (1973) quoted the radius 300 km and pointed out that the ionospheric effects are rarely observable during the daytime due to decreased refractive index in the lower thermosphere after sunrise. Chimonas and Peletier (1974) observed waves with periods of 3.5–4.5 min in the nighttime F-region. Daytime monitoring showed waves with periods of 7–10 min in the lower F-region. The dynamics (mechanical motion) of storms is thought to be the source of the wave disturbances rather than acoustic effects associated with lightning (Blanc, 1985). Georges (1973) emphasizes particular efficiency in producing infrasound of those storms, during which the cloud tops penetrate the tropopause. The dependence of the observed ionospheric effects on geographical location and relative position of the convective storm and 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.

It is very well known that the ionosphere is strongly influenced by the geomagnetic field. Except of large disturbances during geomagnetic storms, the micropulsations of geomagnetic field can be detected in HF Doppler shift measurements.

Detection of high frequency waves requires sampling in very short intervals. Most instruments for ionospheric sounding, particularly ionosondes, do not enable such a sampling. The earlier experiments carried out in the 1950s and 1960s already showed that Doppler sounding can serve as a sensitive detector of natural and artificial atmospheric oscillations in the infrasonic range (e.g. Bauer, 1958; Davies, 1962; Georges, 1968). Continuous Wave (CW) Doppler sounders are able to measure signal with period larger than 10 s (e.g. Georges, 1968).

Georges (1973) reviewed collective experimental evidence of subaudible acoustic wave emission associated with certain severe convective storms for American region. For European region such kind of observation is still rare. Here, using geomagnetic, meteorological and ionospheric observations we focus on the detection of the wave spectrum generated by meteorological activity in the troposphere with emphasis paid on infrasonic waves.

2. Data and methods

The study is based on continuous HF Doppler shift measurements, ionosonde data, meteorological radar data, aerologic data, satellite images and data from the geomagnetic observatory Budkov (49°04′N, 14°01′E) of the Geophysical Institute (GI), Prague.

The continuous HF Doppler sounder including special software was developed in the Institute of Atmospheric Physics (IAP), Prague. 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 has been placed at the Pruhonice 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). At the beginning of April 2005, another transmitter has been installed at the Panska Ves observatory (50°32′N, 14°34′E). Two more transmitters, located at Dlouha Louka (50°39′N, 13°39′E) and Kasperske Hory (49°08′N, 13°35′E) observatories, were set in operation at the beginning of 2007. The frequencies of all four transmitters are mutually shifted by 4 Hz. The shift of sounding frequency enables using of only one receiver located at the IAP. A great advantage of this topological arrangement is the common volume measurement with a digisonde DPS-4 located at Pruhonice. Thus, we can determine the virtual height of reflection of the 3.59 MHz wave directly from ionograms.

The spectral content of the waves observed by continuous sounding was obtained in following way: First, 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 $\sim$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 complex Morlet wavelets. We focused on detection of waves of periods 1–10 min.

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). Location of the Doppler transmitters, receiver, digisonde DPS-4, meteorological radars and geomagnetic observatory Budkov is shown in Fig. 1. The radiolocators

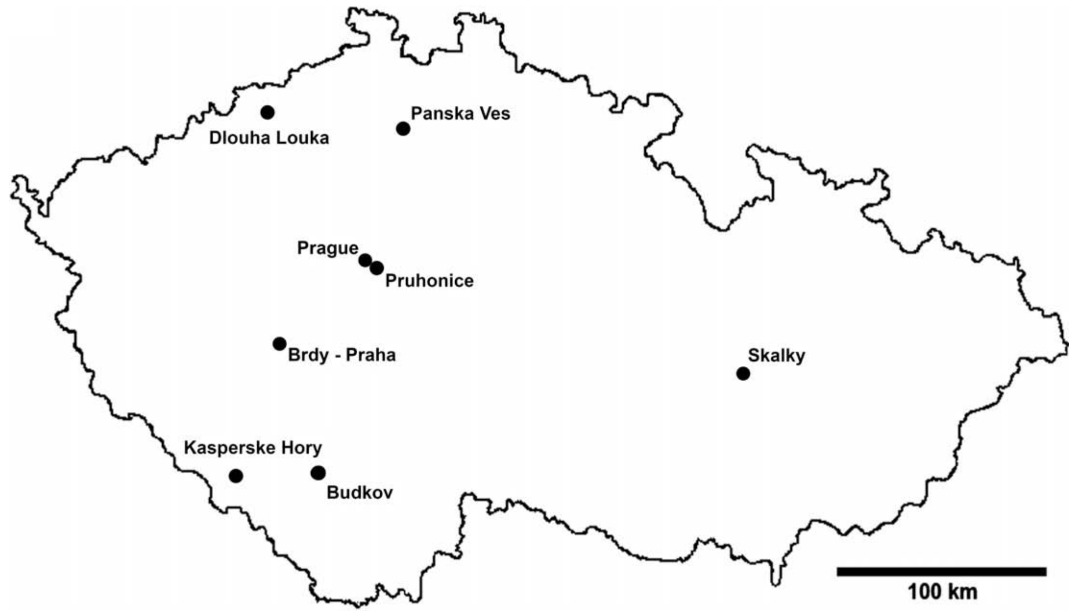

Fig. 1. Scheme of the Doppler system network (transmitters in Dlouha Louka, Panska Ves, Pruhonice and Kasperske Hory, receiver in Prague); locations of the Czech Republic meteorological radars (Brdy–Praha and Skalky) and geomagnetic observatory Budkov.

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 (Novak and Kracmar, 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 north–south direction and in west–east direction. The function of meteorological radar is based on the capability of particles in precipitation to backscatter microwaves. The position of the target is determined from the elevation angle and azimuth of the antenna and from the time delay between the transmission and reception of the signal. 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 $Z[\mathrm{dBZ}] = 10\log(Z[\mathrm{mm}^6/\mathrm{m}^3])$ (Novak, 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 (Pesice et al., 2003).

Satellite images and aerologic data give additional information on vertical extent of convective clouds. We use Meteosat Second Generation (MSG) images in the IR10.8 channel in 30-min intervals. The images cover the same area as radar measurements. Molecular absorption of heat radiation practically does not occur in the IR10.8 channel. Radiation temperature calculated from radiance values in the channel approximates the real temperature of the upper boundary of the cloud. The temperature is assumed to be in equilibrium with surrounding environment, except for overshooting tops, their temperature is lower owing to the adiabatic expansion. Aerologic measurements give information about vertical temperature profile up to the pressure level 100 hPa, which in the analysed days corresponds to the height about 16.5 km. Thus, we can assess the approximate height of cloud tops from images in the IR10.8 channel in combination with radar and aerologic data. The actual height of tropopause is obtained from aerologic data. The measurements at the upper air station Prague-Libus (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) aerologic stations.

The intensity of convective storms was evaluated using the extent of area of high radar reflectivity, the intensity of convection and the vertical extent of convective clouds. We took into account the extent of area of maximum radar reflectivity 52+ dBZ in the horizontal plane projection, the area of maximum radar reflectivity 52+ dBZ in heights over 10 km in the vertical plane projection and the height of clouds above tropopause. We assigned the equal weight to all three factors.

As there are no distinguishing wave form characteristics to identify infrasonic waves generated by severe tropospheric weather, it is difficult to define criteria by which it would be possible to identify infrasound signature originated from severe weather source (Georges, 1973). The only way to distinguish waves emitted by severe meteorological events is the elimination of other possible sources of observed oscillations. Fluctuations in HF Doppler shift records may be related to geomagnetic pulsations. Particularly, Pc5 might cause similar pattern in HF Doppler records like 3–5 min infrasonic waves emitted by convective storms. Therefore, we performed wavelet analysis of fluctuations of the north–south and west–east component of geomagnetic field at geomagnetic observatory Budkov to examine possible direct influence of geomagnetic activity on the ionosphere.

3. Results and analyses

We discuss here the ionospheric effects of convective storms in Central Europe under low to slightly increased geomagnetic activity. Since the most favourable atmospheric conditions for the convective storm activity are in summer, nine of ten analysed events occurred in June and July 2005–2006. We also included a winter severe weather event in our study, a passage of a distinct cold front and a windstorm on 18 January 2007. Selected cases involve six most intense convective storm events which occurred since the beginning of multipath HF Doppler soundings (in the time period from April 2005 to May 2007). Convective storms developed at weather fronts passing over the monitored region, except of two cases when convective storms appeared at instability lines in summer. During analysed summer convective storms, cumulonimbus clouds were of substantial vertical extent and reached to the tropopause or above. 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. We emphasize the extremity of the events on 29 July 2005 and 18 January 2007. 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 UT–01:00 UT on 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. Along the north western boarder of the Czech Republic a supercellular storm and four tornadoes, were observed between ~18:00 UT and 20:30 UT (analysis of the weather situation by Czech Hydrometeorological Institute, www.chmi.cz). Such intense convective storm activity has not repeated since the start of HF Doppler shift measurements in the Czech Republic. On 18 January 2007, deep cyclone Kyrill was passing over Europe. The large pressure gradient between Scandinavia and Mediterranean (~50 hPa) triggered an exceptionally strong air flow. The average wind speed in the Czech Republic was 15–20 m/s, in wind gusts over 40 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 passage of the cold front was accompanied by thunderstorms with exceptionally high lightning activity compared to usual winter thunderstorms. 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).

We observed an increased incidence of 2.5–5 min waves in HF Doppler shift records in two cases. On 29 July 2005, distinct infrasonic waves with characteristic periods of 3–5 min were recorded at both Panska Ves path and Pruhonice path already at about 18:00 UT and accompanied the convective storm activity in the monitored area, which had duration of several hours. Panel a of Fig. 2 shows the Doppler shift spectrogram for Panska Ves path between 18:00 and 23:59 UT, in panel b is the wavelet transform of the signal. On 18 January 2007, 2.5–4 min oscillations appeared at all four sounding path between 21:00 and 23:00 UT. This interval corresponds to the passage of the cold front over the HF Doppler system network. Panels a and b of Fig. 3 show the Doppler shift spectrogram and the wavelet transform of the signal at Dlouha Louka path. In the other eight events, such oscillations appeared only during short time intervals (several minutes); this pattern did not differ from the records obtained for quiet days.

Effects in the Doppler shift record similar to 3–5 min infrasonic waves may be caused by Pc5 geomagnetic pulsations. Therefore, we checked the oscillations of north–south and west–east component of the geomagnetic field at observatory Budkov during intervals when 2.5–5 min oscillations occurred in the Doppler shift records. The wavelet analysis of geomagnetic data and Doppler shift data from 29 July 2005 suggests that observed 3–5 min oscillations cannot be ascribed entirely to geomagnetism (Fig. 2b–d). We cannot exclude that geomagnetic pulsations are responsible for the observed 3–5 min waves within the time intervals from ~18:00 to 18:30 UT, from ~20:00 to 20:20 UT and from ~21:20 to 22:40 UT. However, the 3–5 min waves which occurred between ~18:30 and 20:00 UT and between ~20:20 and 21:10 UT are most probably of meteorological origin. We suppose they were emitted by convective storms. During the event of 18 January 2007, the wavelet analysis does not show geomagnetic pulsations that would correspond to the observed ~3 min oscillations in the ionosphere within the period from ~21:00 to 21:50 UT. On the other hand, ~4 min oscillations observed between ~21:30 and 21:40 UT might have been connected with geomagnetic pulsations, particularly with pulsations of the west–east component of the local geomagnetic field. Between ~21:50 and 22:30 UT, ~3-min oscillations appeared in HF Doppler shift records as well as in geomagnetic observations (Fig. 3b–d).

We examined possible influence of the reflection height of the sounding radio wave on results of Doppler shift measurements. We considered the influence of the Es layer. When the radio wave reflects from the Es layer, it might be difficult to detect the wave activity in the E- and F-region. Furthermore, at heights around 100 km is the region, where most of the acoustic energy is lost, it means deposited in the surrounding atmosphere or reflected back to the ground (Lastovicka, 2006). On 29 July 2005, the

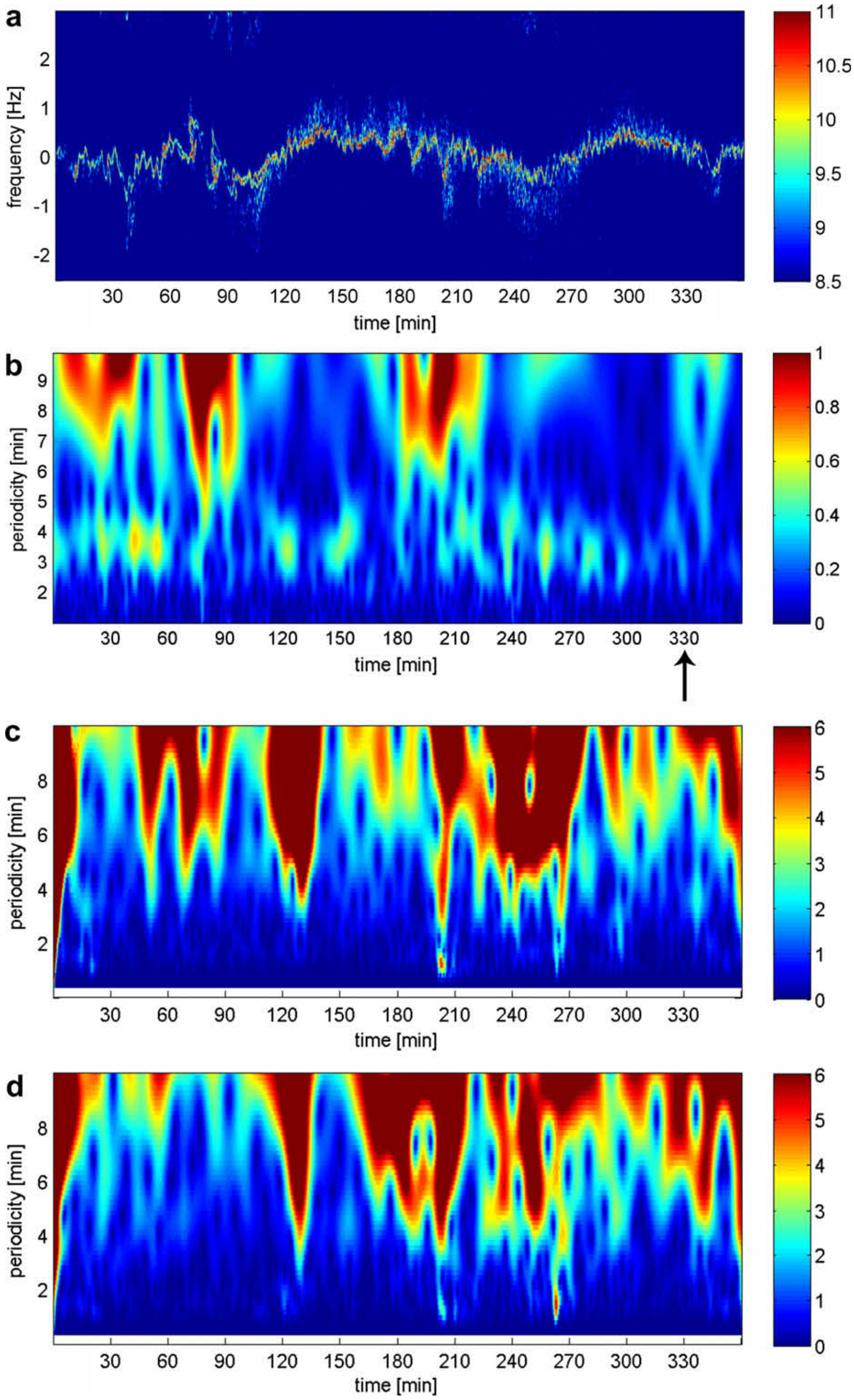

Fig. 2. (a) Doppler shift spectrogram at the Panska Ves sounding path during convective storm activity on 29 July 2005, start time at 18:00 UT; (b) wavelet transform of the signal; (c) wavelet transform of fluctuations of the north–south component of the geomagnetic field at observatory Budkov; (d) same as (c) but for west–east component. Convective storms passed from the west to the east over the Czech Republic. Arrow denotes the approximate time of passage of the squall line under the ionospheric observation point.

3.59 MHz wave reflected in the F-region (virtual height 200–300 km). On 30 July 2005 and on days in June–July 2006, the Es layer persisted on the sounding frequency during the whole interval of observation (1 day) or during the part of the interval (7 days) and the sounding wave was reflected at heights around 100 km. Infrasonic waves of a relatively large amplitudes were observed only on 29 July 2005. We did not register any increase of wave activity in the infrasonic range, when Es layer disappeared on 30 July 2005 and on the events in June–July 2006.

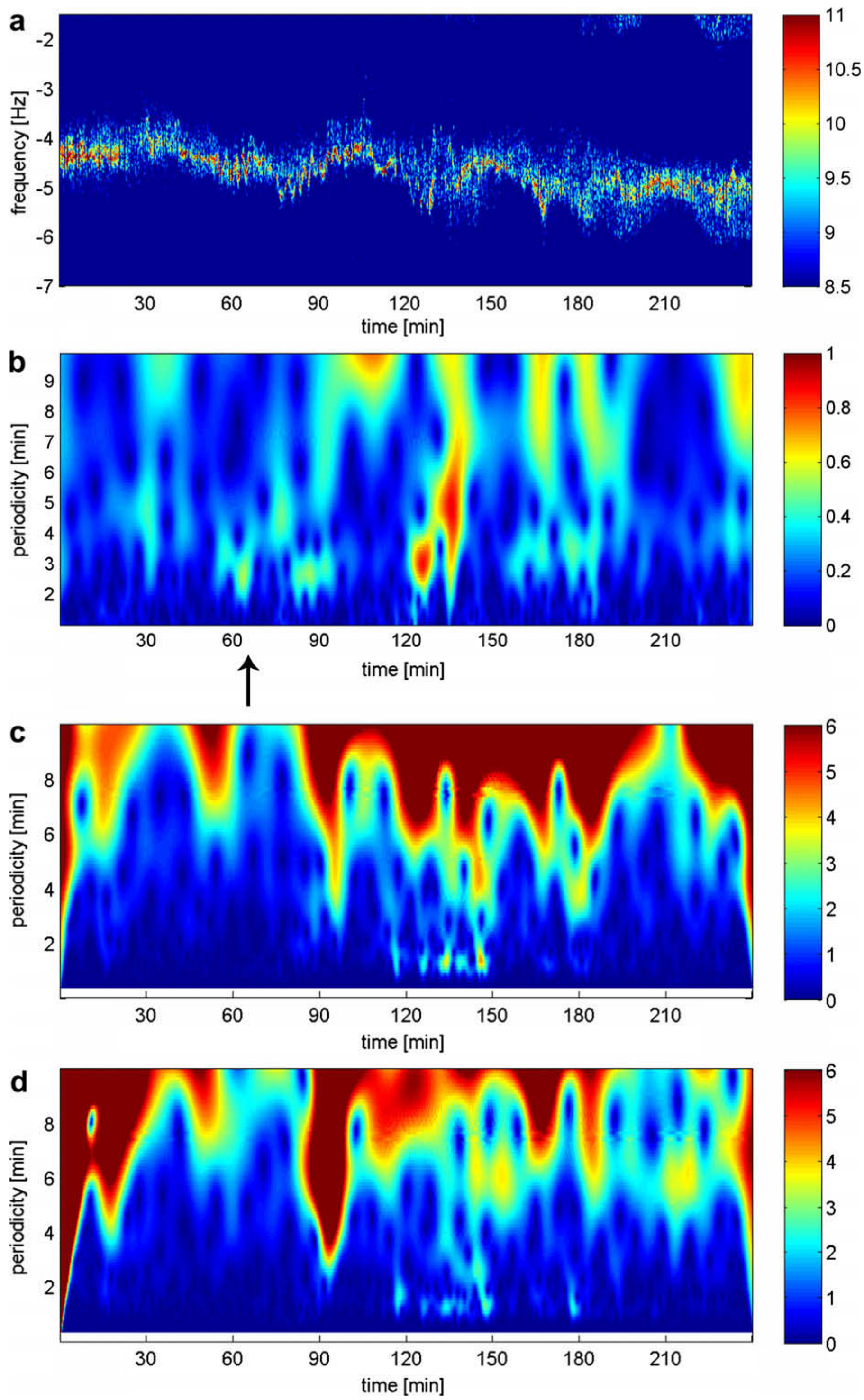

Fig. 3. (a) Doppler shift spectrogram at the Dlouha Louka sounding path during the windstorm and passage of the distinct cold front on 18 January 2007, start time at 20:00 UT; (b) wavelet transform of the signal; (c) wavelet transform of fluctuations of the north–south component of the geomagnetic field at observatory Budkov; (d) same as (c) but for west–east component. The cold front approached from northwest and moved to the southeast over the Czech Republic. Arrow denotes the approximate time of passage of the cold front under the ionospheric observation point.

We considered possible influence of the location of active weather systems towards the ionospheric observation points, which has already been discussed by Georges (1973) and Rind (1978). The intensity of convective storms was comparable on 29 July 2005, 30 July 2005 and 27 June 2006 between 17:00 and 20:00 UT. On 29 July 2005, severe convective storm activity including a supercellular storm and tornadoes was concentrated along the north western boarder of the Czech Republic between 17:00 and 20:00 UT; it means to the west of the Doppler system network.

On 30 July 2005, convective storms occurred to the south of the observation points. On 27 June 2006, convective storms passed the Doppler system network between 16:00 and 17:00 UT and moved further to the east during the interval of our observation. When convective storms had moved to the east of the observation point on 29 July 2005 (23:30 UT), we observed gradual decrease of wave activity in the ionosphere. Rind (1978) described different height of reflection of infrasonic waves depending on the direction of stratospheric winds. Easterly winds prevail in the stratosphere in summer. When the source of infrasonic waves is located easterly from the observation point, waves travel down the wind to the observation point and are reflected to the ground below the ionosphere. In case the source is located westerly, waves travel up the wind and propagate to higher levels. Georges (1973) states, that oscillation in the ionosphere are observed more often when assumed source is to the north of the ionospheric observation point than when it is to the south. This directional filtering effect is associated with the way the waves move the ionization under the influence of geomagnetic field.

The presence/magnitude of ionospheric effects caused by severe tropospheric weather is probably strongly affected by the intensity of active weather systems. A rapid passage of a distinct cold front on 18 January 2007 presumably caused strong vertical movements of the air at the frontal surface, which might have been the source of infrasonic waves observed in the ionosphere. On 29 July 2005, high meteorological radar reflectivity, particularly between 20:00 UT and 23:00 UT, in the whole monitored profile of the lower atmosphere indicates strong convection up to the tropopause region. Such strong extensive convection did not develop during the other events, although cumulonimbus clouds penetrated the tropopause in all studied cases.

The intensity of weather systems probably also explains significantly different results of observations of ionospheric effects of convective storm activity in Central Europe compared to previous studies made in North America. The observations of infrasonic waves emitted by convective storms were reported mainly in the central United States in summer, which is the region of frequent occurrence of tornadoes and supercellular storms. The thermal low above the continent in summer enables the inflow of tropical air from the Gulf of Mexico. The central part of United States is flat, there does not exists an orographic barrier for the air flowing in the north–south direction. The mixing of the warm moist air either with the dry polar air flowing from north or with the warm dry air which originates from the southern deserts, creates suitable conditions for the development of severe convective storms. In Central Europe western 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.) Further, the Alps constitute an orographic barrier for the meridional air flow. Therefore, suitable conditions for intense convection develop rarely in Central Europe.

4. Conclusions

We analysed wave activity in the period range 1–10 min during ten convective storm events in Central Europe. Only in two of the selected cases (29 July 2005 and 18 January 2007), 3–5 min waves and 2.5–4 min waves were observed in HF Doppler shift records. On the basis of wavelet analysis of fluctuations of geomagnetic field, 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. During the other eight analysed events, the incidence of infrasonic waves was low and did not differ significantly from the pattern on geomagnetically quiet day with low meteorological activity. Our results suggest that the penetration of tops of cumulonimbus clouds through the tropopause is not the only substantial condition for emission of infrasonic waves. We suppose that the intensity of updrafts/downdrafts in the troposphere, which of course is related to the vertical extent of convective clouds, may play an important role in generation of infrasonic waves. The results of observation in Central Europe significantly differ from the results obtained in the central part of the United States. The reason might be lower intensity of convective storms in Central Europe which can reasonably be assumed, if we consider the circulation of the troposphere in both regions and the orography of both continents.

Acknowledgments

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