Journal of Atmospheric and Solar-Terrestrial Physics xxx (2017) 1–11

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Infrasound in the ionosphere from earthquakes and typhoons

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ARTICLE INFO

Keywords:
Infrasound
Earthquake
Ionosphere
Nonlinear wave propagation
Typhoon
Remote sensing

ABSTRACT

Infrasound waves are observed in the ionosphere relatively rarely, in contrast to atmospheric gravity waves. Infrasound waves excited by two distinguished sources as seismic waves from strong earthquakes ($M > 7$) and severe tropospheric weather systems (typhoons) are discussed and analyzed. Examples of observation by an international network of continuous Doppler sounders are presented. It is documented that the co-seismic infrasound is generated by vertical movement of the ground surface caused by seismic waves propagating at supersonic speeds. The coseismic infrasound propagates nearly vertically and has usually periods of several tens of seconds far away from the epicenter. However, in the vicinity of the epicenter (up to distance about 1000–1500 km), the large amplitudes might lead to nonlinear formation of N-shaped pulse in the upper atmosphere with much longer dominant period, *e.g.* around 2 min. The experimental observation is in good agreement with numerical modeling. The spectral content can also be nonlinearly changed at intermediate distances (around 3000–4000 km), though the N-shaped pulse is not obvious. Infrasound waves associated with seven typhoons that passed over Taiwan in 2014–2016 were investigated. The infrasound waves were observed at heights approximately from 200 to 300 km. Their spectra differed during the individual events and event from event and covered roughly the spectral range 3.5–20 mHz. The peak of spectral density was usually around 5 mHz. The observed spectra exhibited fine structures that likely resulted from modal resonances. The infrasound was recorded during several hours for strong events, especially for two typhoons in September 2016.

1. Introduction

Acoustic-gravity waves represent an important coupling mechanism between the lower atmosphere and upper atmosphere as they transfer momentum and energy between different atmospheric layers; their presence in the ionosphere might also affect radio communications and signals from GPS satellites (Fritts and Alexander, 2003; Laštovička, 2006; Nishioka et al., 2013). The acoustic mode propagates at frequencies higher than the acoustic cut-off frequency ω_a; the mode propagating at frequencies lower than the buoyancy frequency ω_B ($\omega_a > \omega_B$) is called gravity waves (GWs) (*e.g.*, Fritts and Alexander, 2003; Kelley, 2009). Whereas the GWs are frequently observed in the ionosphere/thermosphere and have been broadly studied since the pioneering work by Hines (1960) as is documented by numerous reports (Vadas, 2007; Shiokawa et al., 2009; Otsuka et al., 2013 among many others), the observation of infrasound in the ionosphere is much rare. Only long-period infrasound, with periods longer than approximately 10 s, can reach the ionosphere; the shorter periods (higher frequencies) are significantly damped below the ionosphere (Blanc, 1985). The infrasound observed in the ionosphere mostly originated from strong ($M > 7$) earthquakes (Artru et al., 2004; Liu et al., 2016; Chum et al., 2016b and references therein) or severe tropospheric weather systems (Georges, 1973; Šindelářová et al., 2009). It is well documented that the coseismic infrasound is mainly generated by the vertical movement of the ground surface (*e.g.*, Watada et al., 2006; Chum et al., 2012). As the seismic waves propagate at supersonic speeds, the infrasound generated outside the epicenter propagates nearly vertically (Maruyama and Shinagawa, 2014; Liu et al., 2016; Chum et al., 2016b). Contrary, the generation and radiation pattern of long period infrasound waves from large convective systems, cyclones and gust fronts and their propagation to the ionosphere is much less understood.

Infrasound in the ionosphere is usually detected as perturbations of the total electron content (TEC) measured by dual-frequency GPS receivers (Calais and Minster, 1995; Lay et al., 2015) or as changes of Doppler shift observed by continuous Doppler sounders (Georges, 1973; Chum et al., 2016a, 2016b and references therein). There is a principle difference between these two remote sounding techniques. The GPS TEC represents an integrated value measured along the signal path between the GPS receiver and the satellite. The heights of TEC perturbations are

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http://dx.doi.org/10.1016/j.jastp.2017.07.022
Received 21 February 2017; Received in revised form 29 May 2017; Accepted 31 July 2017
Available online xxxx
1364-6826/

Please cite this article in press as: Chum, J., et al., Infrasound in the ionosphere from earthquakes and typhoons, Journal of Atmospheric and Solar-Terrestrial Physics (2017), http://dx.doi.org/10.1016/j.jastp.2017.07.022

not known; it is only assumed that the main contribution to the TEC variations is at the altitudes around the peak of maximum ionization, *i.e.*, in the F layer, approximately from 200 to 300 km. The GPS TEC perturbations observed by dense networks of GPS receivers are often used to study ionospheric responses to earthquakes (Liu et al., 2011; Astafyeva et al., 2011). Contrary, the continuous Doppler sounding provides information about variations at a specific altitude, at which the sounding radio signal reflects. The height of reflection varies during the day and season; however, it can be determined from a nearby ionospheric sounder or estimated from a model (*e.g.,* international reference ionosphere, IRI). The knowledge of ionospheric and atmospheric fluctuations at specific heights makes the comparison with numerical simulations much easier and straightforward than in the case of integral values obtained by GPS-TEC measurements.

The main purpose of this paper is to present and compare the character of infrasound in the ionosphere originating from seismic waves and typhoons (large convective systems) that represent the main sources of infrasound in the ionosphere. It will be also shown that character of coseismic infrasound depends on distance from the epicenters of strong earthquakes. Recent results obtained from observation of coseismic perturbations by an international network of continuous Doppler sounders (Chum et al., 2012, 2016a, 2016b) will be reviewed and also partly reanalyzed using numerical simulation. Namely, the infrasound waves related to three distinct earthquakes are compared and discussed a) *M* 9.0 that occurred near Japan on 11 March 2011, observed in the Czech Republic at about 9000 km distance from the epicenter. b) *M* 7.8 in Nepal on 25 April 2015 observed in the Czech Republic and Taiwan at about 6300 and 3700 km distance from the epicenter, respectively. c) *M* 8.3 near Chile on 16 September 2015, observed in Argentina at around 800 km distance from the epicenter. In addition, first results of analysis of infrasound that was observed in the ionosphere over Taiwan during passages of seven typhoons are presented and discussed. The paper is organized as follows: Section 2.1 provides short introduction to Doppler sounding with application to infrasound. Section 2.2 briefly describes numerical simulation used to distinguish between linear and nonlinear propagation of infrasound and to compare with observation. Section 2.3 presents analyses and comparison of different cases of coseismic infrasound observed by continuous Doppler sounders. Section 2.4 shows first results of the analysis of infrasound generated by typhoons that passed Taiwan from 2014 to 2016. Section 3 provides discussion and comparison with previous reports. Section 4 represents a brief summary.

2. Measurements and data analysis

Examples of co-seismic infrasound observed by multipoint continuous Doppler sounding systems (CDSSs) installed in the Czech Republic (~50.3° N, 14.5° E), Argentina (~26.8° S, 65.2° W), and Taiwan (~23.9° N, 121.2° E), and examples of infrasound generated by typhoons passing over Taiwan will be presented. The multipoint CDSS used in this study is composed of three transmitters forming approximately equilateral triangle with about 100 km side and one receiver (minimum configuration for each location). The CDSS was originally designed to study GWs; three spatially separated reflection points make it possible to determine horizontal propagation velocities and directions of GWs and of other ionospheric perturbations (Chum et al., 2014). The transmitted power is only 1 W. All the CDSSs are located close to an ionospheric sounder to determine the height of reflection. The sounding frequencies are 3.59 MHz in the Czech Republic (also 4.65 and 7.04 MHz since 2014), 4.63 MHz in Argentina, and 6.57 MHz in Taiwan. The low frequency CDSS data (after downward frequency conversion) are stored at 305 Hz sampling rate. Data are first visualized in the form of Doppler shift spectrograms (*e.g.* Fig. 1b) that are computed by successive spectral analyses using overlapping cosine time windows (usually 75% overlap is used) to get smooth spectrograms. The effective length of the time window can be set according the signal character; it is usually on the order of 10 s. For the purpose of the next data analysis, maxima of spectral

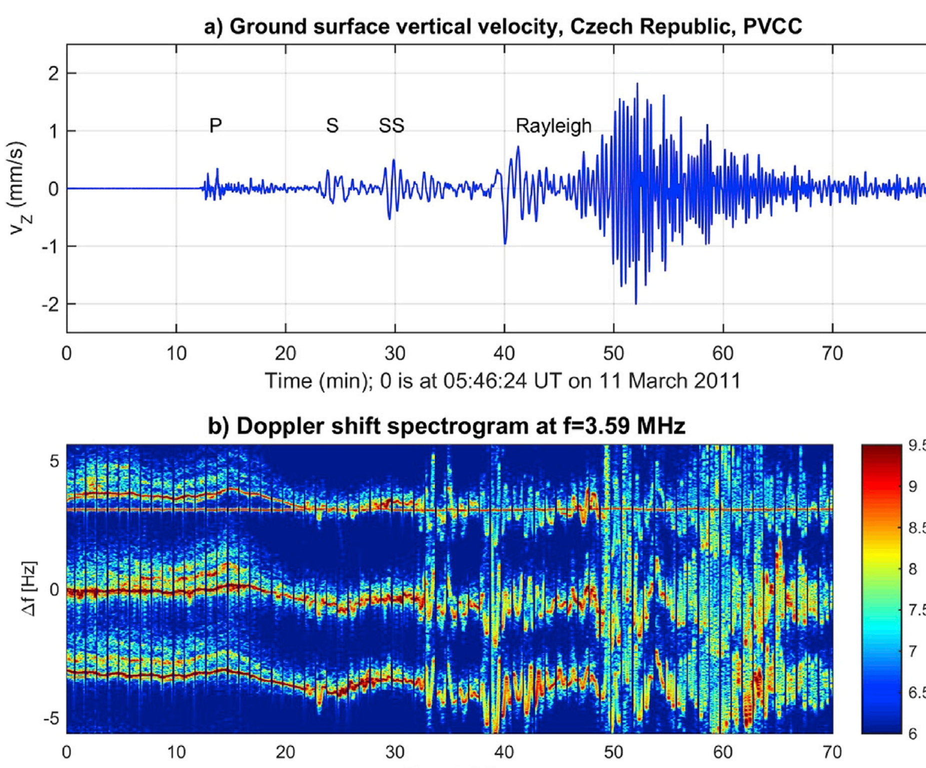

Fig. 1. Vertical velocity of ground surface motion (a) and Doppler shift spectrogram (b) recorded in the Czech Republic on 11 March 2011. Zero time corresponds to the beginning of earthquake at 05:46:24 UT. Colors in the Doppler shift spectrogram indicate common logarithm of received power spectral densities in arbitrary units (antenna is not calibrated). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)