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Ionospheric effects of the Mt. Kirishima volcanic eruption as seen from subionospheric VLF observations

A. Rozhnoi [a], M. Hayakawa [b,*], M. Solovieva [a], Y. Hobara [c], V. Fedun [d]

[a] Institute of Physics of the Earth, Russian Academy of Sciences, B. Gruzinskaya 10, Moscow 123995, Russia
[b] University of Electro-Communications (UEC), Advanced Wireless Communications Research Center, 1-5-1 Chofugaoka, Chofu Tokyo 182-8585, Japan
[c] UEC, Graduate School of Informatics and Communication Engineering, Chofu Tokyo, Japan
[d] Department of Automatic Control and Systems Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

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ABSTRACT

Data from the Pacific network of VLF receivers have been used to study the response of the lower ionosphere to the January 2011 Mt. Kirishima (South Japan) volcanic eruption. A major explosive eruption occurred on January 27, which was preceded by several small eruptions. Perturbations of nighttime subionospheric VLF signals have been detected on the day of the first small eruption on January 18 (UT) with the maximum observed about 1.5 h after the eruption. The nighttime signal remained disturbed during the subsequent pre-eruptive and eruptive activity of Mt. Kirishima. The daytime perturbations were not observed. The frequency of the maximum spectral amplitude was found to be in the range of periods of 6–30 min, which corresponds to the periods of internal gravity waves. These results suggest that the observed VLF ionospheric effects can possibly be produced by the penetration of gravity waves caused by the volcanic activity into the ionosphere.

1. Introduction

There has been recently reported a lot of convincing evidence on the presence of ionospheric disturbances as seen by subionospheric VLF/LF propagation caused by different kinds of agents including earthquakes, tsunami and volcano eruptions. Waves in the VLF frequency (3–30 kHz) and LF frequency (30–300 kHz) ranges are trapped between the lower ionosphere and the Earth and are reflected from the boundary between the upper atmosphere and lower ionosphere at altitudes of ~70 km in the daytime and ~90 km at night. When measured by a VLF/LF receiver, such signals inherently contain information on the reflection region of the ionosphere and its variability.

As for the seismo-ionospheric perturbations, there have been established a statistical correlation between the VLF ionospheric perturbations and earthquakes with large magnitude greater than 6 and with shallow depth (e.g., Molchanov and Hayakawa, 2008; Hayakawa et al., 2010; Hayakawa, 2011), which seems to be very promising for the short-term earthquake prediction. Then, the second topic of tsunami-associated ionospheric perturbation, Rozhnoi et al. (2012a) have reported the first report on the tsunami-related VLF perturbation, in which they have detected the VLF ionospheric perturbation in possible association with the tsunami of the 2011 Japan earthquake. The third topic is the VLF/LF ionospheric perturbation in association with a volcanic activity, which is the subject of this paper and to our knowledge there have been no report on VLF/LF study on this topic. Volcanic eruptions are likely to generate acoustic and gravity waves that propagate upward into the ionosphere where they induce electron density fluctuations which can be detected by electromagnetic waves in different frequency range.

The ionospheric response of the Mt. Pinatubo volcanic eruption in June 1991 was found from observations of the total electron content (TEC) variations in Taiwan (Cheng and Huang, 1992) and in Japan as well (Igarashi et al., 1994). Cheng and Huang (1992) studied signals from stations located to the north of the volcano. The period of the ionospheric disturbances was determined to be around 16–30 min. Ionospheric fluctuations with periods of about 20 min were found in the records of HF Doppler and TEC data by Igarashi et al. (1994). The surface pressure fluctuations due to the passage of atmospheric and gravity waves were confirmed by the microbarograph chain data in Japan. The similar period was also reported from the Doppler shift observation in the Beijing area (Hao et al., 2006).

Heki (2006) used data from the dense array of Global Positioning System (GPS) in Japan in order to estimate an explosive energy of the Asama Volcano eruption in September 2004. The disturbance had a period of one and a quarter minutes, which indicates its origin as the acoustic wave generated by the explosion. TEC

* Corresponding author at: University of Electro-Communications, Advanced Wireless Communications Research Center, 1–5–1 Chofugaoka, Chofu Tokyo 182–8585, Japan.
E-mail address: hayakawa@hi-seismo-em.jp182-8585 (M. Hayakawa).

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fluctuations have also been used for the detection of ionospheric perturbations after a major volcanic explosion at the Soufrière Hills volcano in July 2003 and for the further estimation of its energy release (Dautermann et al., 2009). Their spectral analyses revealed peaks centered at 17 and 4 min, which suggested both gravity and acoustic wave components.

The gravity wave activity was inferred from the investigation of nighttime LF radio wave absorption over the Central Europe after Mt. the Pinatubo volcanic eruption (Laštovička, 2003). An evident enhancement for waves with periods of about 2–3 h coinciding with the regional measurement of the optical depth of volcanic aerosols has been found in the LF wave at 270 kHz.

The works mentioned above reported on the co-eruptive and post-eruptive ionospheric effects, but such effects can be expected to also precede the volcanic eruption. Disturbances in the ionosphere observed before a volcanic eruption can be generated by magma migration resulting in changes in the air temperature, density and composition. Those changes take place in a thin near-ground layer. Extension of the influence above the ground layer is possible either by induced electric field (other variant is the modification of background electric field) or by the excitation of gravity waves transferring upward the power flux (for details of the mechanism of lithosphere–atmosphere–ionosphere coupling, see for example, Molchanov and Hayakawa, 2008; Sorokin and Hayakawa, 2013).

Investigation of ionospheric disturbances caused by a number of volcanic eruptions in North and South America, based on the critical frequency (foF2) and F layer virtual height (Ragone et al., 2004) revealed a decrease in foF2 and in its amplitude of variation, and an increase of h'F during the day before and after the eruption in 60% of cases studied.

Effects of volcanic eruptions in the ionosphere have been analyzed on the basis of DEMETER mission by Zlotnicki et al. (2010). It was found that 30 of the 74 eruptions recorded during the period of August 2004 through December 2007 were accompanied by 48 anomalies in the time window of 30 days preceding the onset of surface activity until 15 days after. For three volcanoes (Lopevi, Ambrym and Aoba) anomalies were observed only during their highest activity.

In the present paper, we will perform the first attempt to use subionospheric measurements of the Pacific network of VLF receivers, which was set up some time ago for the investigation of seismo-ionospheric perturbations, to study the response of the lower ionosphere to the January 2011 Mt. Kirishima volcanic eruption.

2. The January 2011 Mt. Kirishima eruptions

During 26–30 January 2011 strong explosive eruptions took place at the Kirishima volcano (31°55'N, 130°52'E) located in the Kyushu island of Japan. According to the Japan Meteorological Agency, the eruption began with a phreatomagmatic explosion from a mountain named Shinmoe-dake of the group of Kirishimayama volcanoes on the border between Miyazaki and Kagoshima prefectures at 1:27 LT on January 19 (16:27 UT January 18). After that, explosive eruptions continued with a big aerial vibration. It produced a shock wave detected 12 km north-east of the volcano, and an ash plume drifted south-east. Another explosion on January 22 ejected the material 200 m above the vent and it was reported that ash plumes rose up to altitudes of 1.8–2.1 km and drifted toward south-east.

Kirishima volcano erupted again on January 26 at 07:30 LT (22:30 UT January 25); at 14:50 LT (05:50 UT) it moved into the essential magma eruptions. Lava fragment emissions from the summit crater were confirmed by the visual camera at night on the same day. Night-time glow was also visible by a high-sensitivity camera since January 26. A major explosive eruption occurred on January 27 at 15:40 LT (06:40 UT), and its plumes rose as high as 2.5 km above the crater rim and went up into the clouds. Another eruption took place on January 28. Its volcanic ash was emitted continuously until January 30, when lava covered the crater floor.

Fig. 1 is taken from Ouzounov et al. (2012), which shows thermal anomalies detected above Mt. Kirishima during the period from December 1, 2010 to March 1, 2011 by the AVHRR (Advanced Very High Resolution Radiometer) sensor which is carried on NOAA polar-orbiting environmental satellites (http://www.cdc.noaa.gov/). The satellites were operating in orbits about 850 km above the earth. The orbits are timed to allow complete global coverage twice per day (daytime and nighttime). Space resolution of data is 4 km. The outgoing long wave radiation estimates calculated from the raw measurements between 10 and 13 μm have been used to integrate infrared data by separate algorithm (for details of methodology see e.g. Ouzounov et al., 2007).

The initial agent of thermal radiation is gas release at the ground surface resulting in changes in the air composition. Active

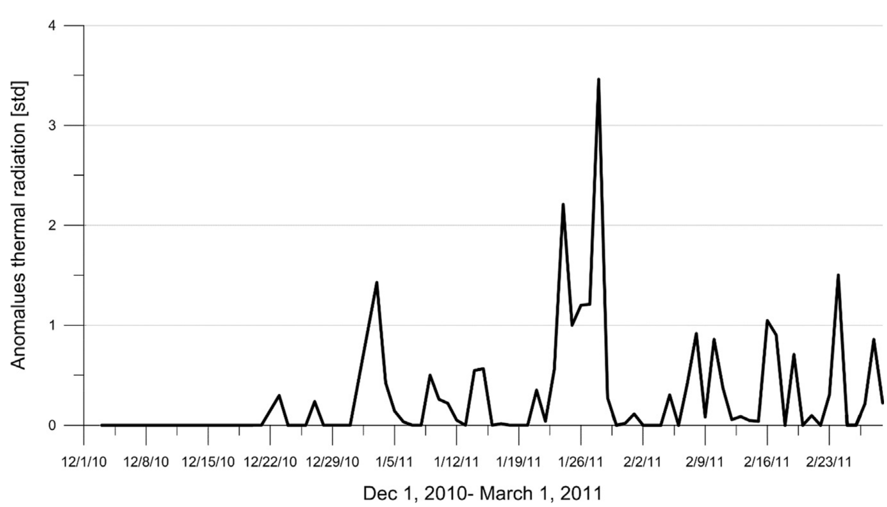

Fig. 1. Thermal radiation recorded on the satellite above the volcano Kirishima during a period from the beginning of December 2010 through the end of February 2011 (Ouzounov et al., 2012).

gases move into the atmosphere where heat release arises from chemical processes. The height of such hot spots detected by a sensor on the satellite is 8–12 km.

This figure indicates that some increase in the thermal radiation started on December 22, 2010 (about one month before the eruptions). A maximum in thermal radiation is observed from January 22 to January 30, which coincides with the maximum of volcanic activity. These observations confirm that intensive gas release took place during the pre-eruptive and eruptive period. The thermal radiation exceeds the background level by two standard deviations on January 23 and January 27–28, and even after that the active process continues until the end of the observation period.

3. Data analysis and results

Perturbations of subionospheric VLF signals during Mt. Kirishima activity were observed in the measurements of ground-based VLF/LF receiving stations in Petropavlovsk-Kamchatsky (PTK), Yuzhno-Sakhalinsk (YSH) and Chofu (CHF). These receivers have been developed in New Zealand (LF*EM Research, Ltd.) and they can record simultaneously both the amplitude and phase of MSK (Minimum Shift Key) modulated signals in the frequency range of 10–50 kHz from several VLF/LF transmitters. MSK signals have fixed frequencies in a narrow band of 50–100 Hz around the main frequency and adequate phase stability. AbsPal receivers have been installed in Chofu and Petropavlovsk-Kamchatsky about 15 years ago and a new receiver UltraMSK (http://ultramsk.com) is in operation now in Yuzhno-Sakhalinsk. The receiver station consists of the VLF antenna with a pre-amplifier, a GPS receiver with GPS antenna for accurate signal timing, an analog-to-digital converter and a computer with special software. The receiver can record signals with time resolutions ranging from 50 ms to 60 s. For our purpose we use a sampling frequency of 20 s.

The signal from the Japanese JJI (22.2 kHz) transmitter is analyzed here because this transmitter is located very close to the mountain. Sampling frequency of the signal is 20 s. Fig. 2 shows the relative geometry of various subionospheric VLF propagation paths together with the location of Mt. Kirishima and JJI transmitter. We only use the information on amplitude of the JJI signal in our analysis since it is not MSK modulated signal and its phase cannot be recorded by our receivers.

The data are processed by a method based on the difference between the real signal in nighttime and the model one (Rozhnoi et al., 2004). The model presents monthly averaged signals calculated using the data from quiet days. For our analysis we use a residual signal of amplitude dA: $dA = A - \langle A \rangle$; where A is the amplitude for the current day, and $\langle A \rangle$ is the corresponding model signal. The monitoring of the VLF signal was carried out from December 1, 2010 to the end of February 2011. Fig. 3 shows the residual amplitude (averaged over nighttime) of the JJI signal recorded at three stations during the period of monitoring. A significant decrease in amplitude is clearly seen in the period of January 18–24 at YSH and PTK stations and in a longer period of January 18–30 at CHF station which is the closest to the volcano. The maximum of the signal anomalies (5–6 dB) is observed on January 19–21. We have to note that the magnetic activity was very low during this period (Dst$\sim$0), so that the anomalies observed cannot be attributed to the geomagnetic environment. Another factor that can influence the behavior of the VLF/LF signals is fluctuations of atmosphere pressure (Rozhnoi et al., 2006). According to data from the meteorological stations in Tokyo, Kagoshima, Yuzho-Sakhalinsk and Petropavlovsk-Kamchatsky (http://rp5.ru) no sharp changes in atmosphere pressure were recorded during the period when anomalies in the JJI signal were detected.

We examined the spectral composition of the VLF signal during the days when such anomalies were observed. For the analysis we used the nighttime amplitudes of the signal filtered in the

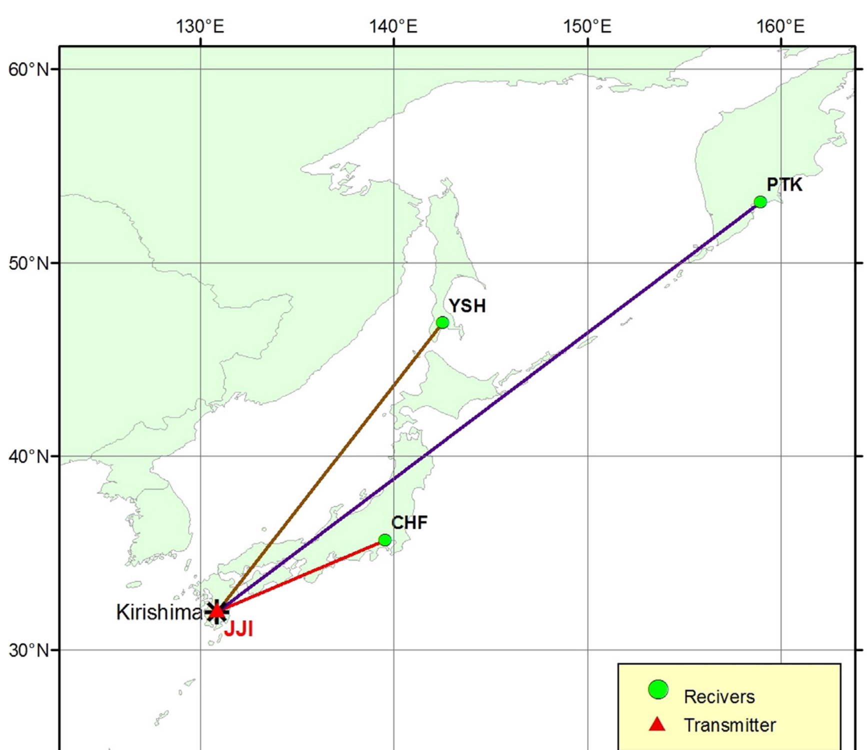

Fig. 2. A map showing the position of the volcano Kirishima together with the position of the VLF/LF receivers in Petropavlovsk-Kamchatsky (PTK), Yuzhno-Sakhalinsk (YSH) and Chofu (CHF) and the position of the Japanese VLF transmitter JJI (22.2 kHz).

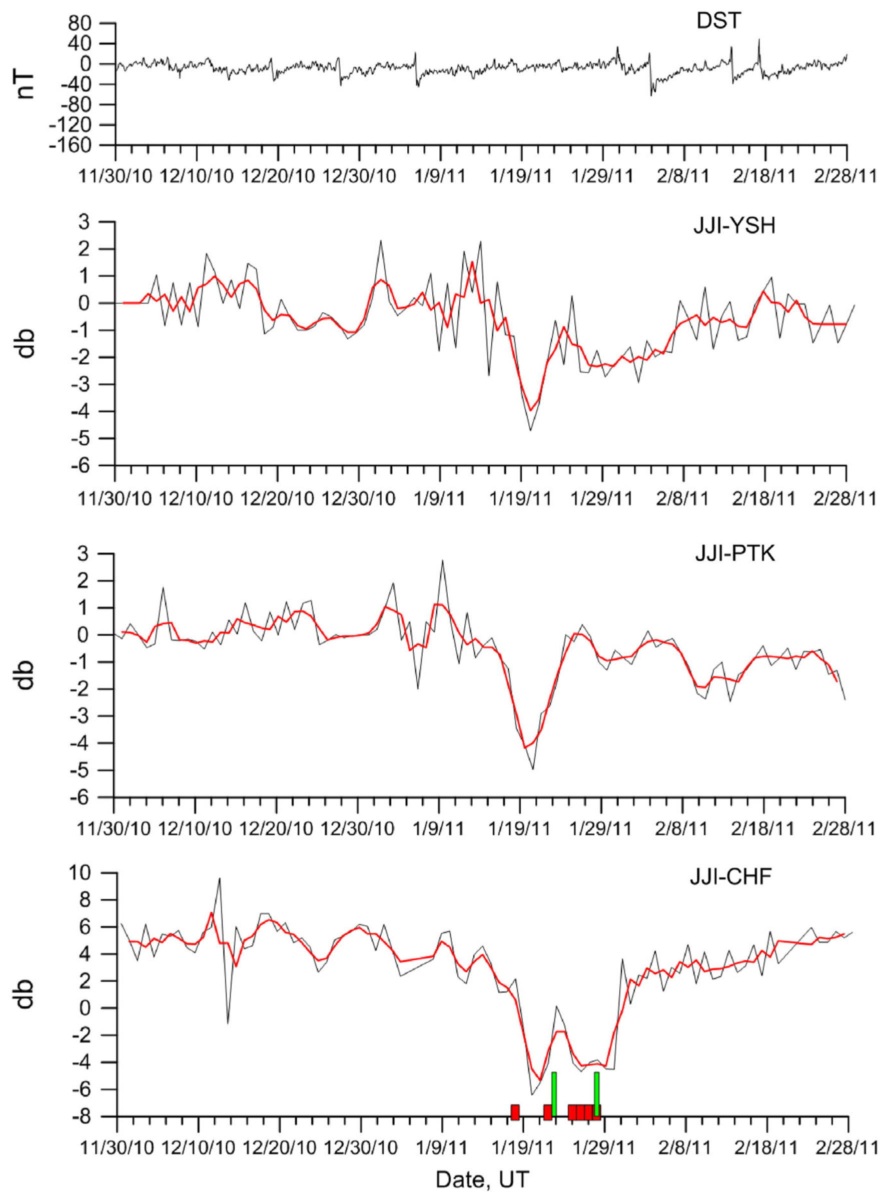

Fig. 3. Top panel shows the Dst index of magnetic activity. Next three panels show the residual amplitude (averaged over nighttime) of the JJI signal recorded at Yuzhno-Sakhalinsk (YSH), Petropavlovsk-Kamchatsky (PTK) and Chofu (CHF) stations during the period from December 1, 2010 to February 28, 2011. Black lines and red lines are the real and smoothed signals, respectively. The red bars on the bottom panel show the occurrence times of the volcano eruptions in January 2011, and the green bars show the peaks in the thermal anomalies.

frequency band 0.15–15 mHz which corresponds to wave periods in the range from 1 to 110 min. In this frequency range internal gravity waves whose periods are typically expected to be more than 6 min, can be observed in accordance with theoretical estimations. Some examples are given in Fig. 4. This figure shows the real amplitudes of VLF signal and their waveforms of the nighttime filtered data recorded in YSH on January 18, in PTK on January 19 and in CHF on January 21. Similar waveforms were obtained for all disturbed days at all the stations.

The first eruption occurred on January 18 at 16:27 UT. Maximum of the disturbances in the VLF signal is observed about 1.5 h after the event that is in good agreement with theoretical estimations concerning the interaction of internal gravity waves with the lower ionosphere (e.g., Hooke, 1977; Lizunov and Hayakawa, 2004). As is seen from the figure, the amplitude of the signal remained strongly disturbed during all night time on January 19 and January 21. The frequency of the maximum spectral amplitude is in the range of about 0.5–3 mHz (i.e. periods of about 6–30 min) which corresponds to the range of periods for internal gravity waves.

4. Discussion and conclusion

Our experimental results have revealed perturbations of nighttime subionospheric VLF signals before and during the maximum of Mt. Kirishima volcanic activity. Disturbances in the signals began several hours before the first small explosion on the night of January 19 (LT) and they became stronger after the explosion. The duration of these effects in VLF signals recorded in two distant Russian stations (PTK and YSH) is shorter than those recorded at the Japanese CHF station. Disturbances in the signal continued until January 24 at YSH and PTK and no effects were observed during major explosions on January 26–27. These anomalies can be

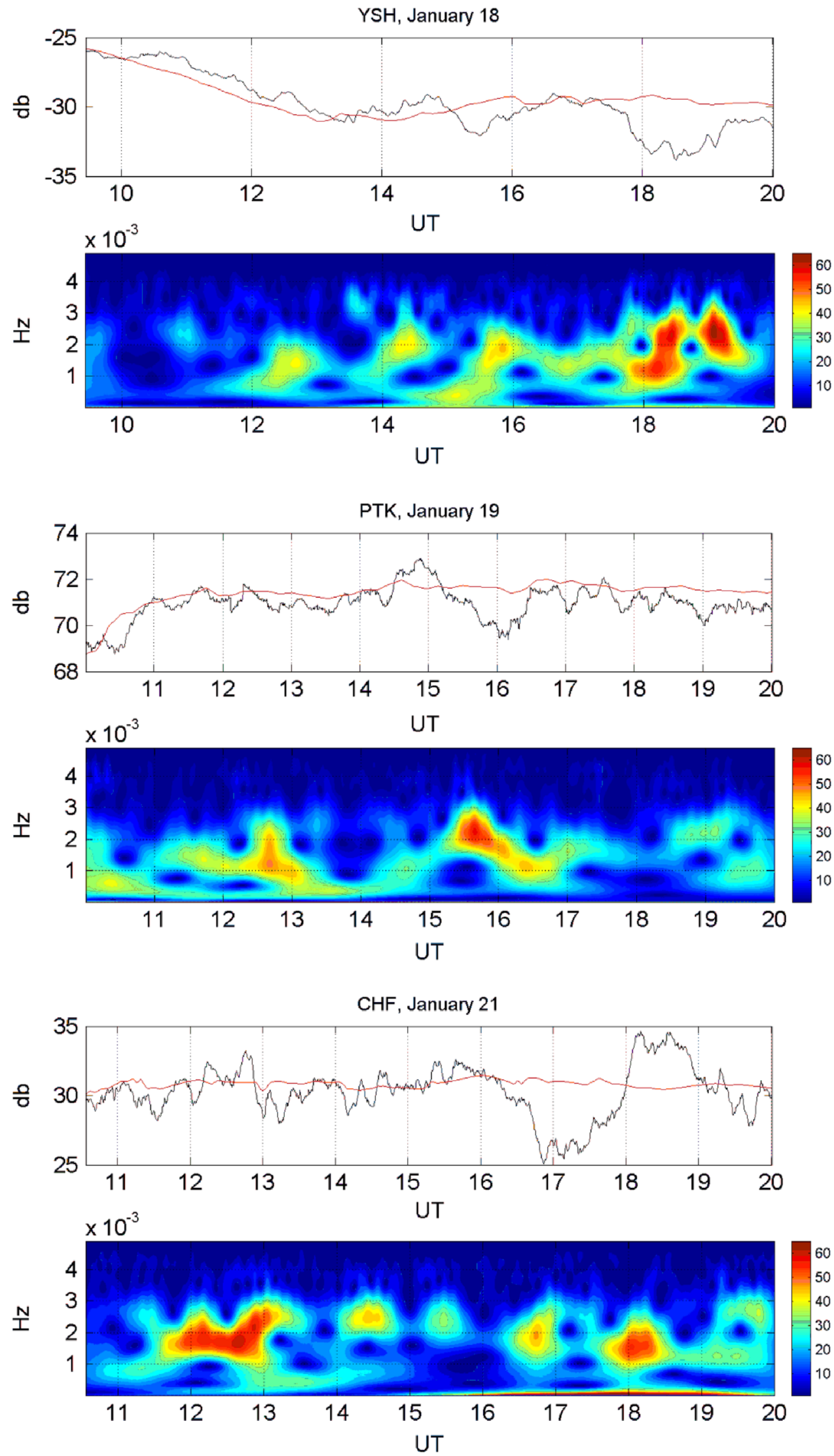

Fig. 4. The top panel shows the real amplitude (black line) recorded during local night in Yuzhno-Sakhalinsk on January 18 together with the monthly averaged signal calculated using data for quiet days (red line). The next panel shows wavelets of spectra of the filtered (0.15–15 mHz) signal. Next two panels are the same but for Petropavlovsk-Kamchatsky on January 19; two bottom panels are the same but for Chofu on January 21.

considered as pre-eruptive anomalies and they partly correspond to the first peak in the thermal anomalies. Though further study is required on this pre-eruptive anomaly.

Anomalies in the VLF signal began a little earlier on the day of the first small explosion after which volcanic tremor and steaming began. Volcanic tremor continued from January 18 to January 22. Vigorous steaming was observed at small vents on the crater bottom on January 21 (Nakada et al., 2013). After that, the first peak in the thermal anomalies was recorded. It is possible that the thermal radiation is not such sensitive to weaker gas release (not enough gases for chemical reactions), which can produce internal gravity waves detected by VLF signal. Disturbances in the signals received in CHF station continued until January 30 which coincides precisely with the maximum of thermal anomalies. Absence of the effects in the signals caused by the explosions themselves on January 26–27 can be explained by the fact that they occurred during local daytime and so could not influence the variations of VLF signal. VLF signals are very stable during daytime and they are unaffected by any external factors (even magnetic storms in mid-latitude paths) except by X-rays emitted during solar flares (Rozhnoi et al., 2012b, 2013). Nighttime, however, provides the optimal conditions for the detection of ionospheric disturbances (caused by magnetic storms, earthquakes, tsunami, etc.) by the VLF signals. So we can suppose that disturbances in the signal observed in CHF station in the period January 25–30 were caused by processes connected with magma migration which lead to venting of volcanic gases. A difference in the observed effects in this period in two distant stations and in Japanese station may be caused by the specificity of relative position of the transmitter and the receivers.

The frequency of the maximum spectral amplitude was found to be in the range of periods of 6–30 min, which corresponds to the periods of internal gravity waves. These results indicate that the observed effects during both pre-eruptive and eruptive activity of Mt. Kirishima can be possibly produced by the penetration of gravity waves into the ionosphere. This penetration leads to perturbations in the plasma in the lower ionosphere.

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