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Ionospheric turbulence from ground-based and satellite VLF/LF transmitter signal observations for the Simushir earthquake (November 15, 2006)

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ABSTRACT

Signals from very low frequency (VLF)/ low frequency (LF) transmitters recorded on the ground station at Petropavlovsk-Kamchatsky and on board the French DEMETER satellite were analyzed for the Simushir earthquake (M 8.3; November 15, 2006). The period of analysis was from October 1, 2006, to January 31, 2007. The ground and satellite data were processed by a method based on the difference between the real signal at night-time and the model signal. The model for the ground observations was the monthly averaged signal amplitudes and phases, as calculated for the quiet days of every month. For the satellite data, a two-dimensional model of the signal distribution over the selected area was constructed. Preseismic effects were found several days before the earthquake, in both the ground and satellite observations.

1. Introduction

Seismo-induced electromagnetic effects in the ionosphere were first reported in Russia [Migulin et al. 1982] from observations by satellite Intercosmos-19. A lot of studies were then carried out on satellite recordings of wave-plasma disturbances that were possibly associated with individual earthquakes or with several strong earthquakes [for reviews, see Parrot et al. 1993, Hayakawa 1997, Molchanov et al. 2002].

A new opportunity to investigate ionospheric perturbations that might be associated with seismic activity arose with the DEMETER satellite mission. The first study that showed examples of unusual ionospheric observations made by the DEMETER satellite over seismic regions at the beginning of the mission was published in 2006 [Parrot et al. 2006]. Later on, statistical investigations using data from more than 3.5 years confirmed the existence of very small, but statistically significant, decreases in wave intensity a few hours before earthquakes, at a frequency around 1.7 kHz [Nemec et al. 2009].

These DEMETER observations also provided the very interesting possibility to analyze ground transmitter signals detected by the satellite above seismic regions. The first results from these analyses were reported by Molchanov et al. [2006]. Clear drops in the subionospheric transmitter signals around the time of several strong earthquakes were recorded in 2004, including for the catastrophic Sumatra earthquake. The method applied estimated the changes in the reception zone of the transmitter signals using the signal-to-noise ratio (SNR). Further analyses of the Sumatra earthquakes were made on the data collected over one and half years of observations [Solovieva et al. 2009]. Evident effects before and during the great Sumatra earthquakes were confirmed, with long-term durations of about one month. These results led to the conclusion that the size of the perturbation area in the ionosphere was of the order of several thousand kilometers. After these first publications, the effects of this influence of seismic activity on very low frequency (VLF)/low frequency (LF) signal propagation were further reported from observations of the DEMETER satellite [Boudjada et al. 2008, Muto et al. 2008, Slominska et al. 2009].

In our earlier studies [Rozhnoi et al. 2007, 2010], we presented a correlated analysis of VLF/LF signals radiated by ground transmitters and collected both at ground receivers and by the DEMETER satellite. In these analyses, we used the night-time data from the alternative electric field receiver of Instrument Champ Electrique (ICE) [Berthelier et al. 2006] in LF (20 Hz to 20 kHz) and high frequency (3 kHz to 3.3 MHz) ranges. The discretization of the power spectrum density in the LF range was 19.53 Hz, and in the high frequency range it was 3.255 kHz. Effects in the VLF/LF signal were found in both the ground and satellite observations.

In the present study that analyzes the Simushir earthquake (M 8.3; November 15, 2006), we used the signal from the Australian NWC transmitter (19.8 kHz) for the satellite observations, and in addition, for the ground analysis, we used signals from two Japanese transmitters: JJI (22.2 kHz) and JJY (40 kHz). The NWC transmitter signal is the most powerful in the VLF range, so that we can analyze the signal in a large area for satellite observations. Signals from the Japanese transmitters are local and can be used for satellite analysis only if the epicenters of the earthquakes are located in the maximum signal zone.

2. Data processing

Data from the VLF/LF station in Petropavlovsk-Kamchatsky and data from the ICE receiver collected by the DEMETER satellite were used for the analysis. The monitoring of the VLF/LF signals was carried out from October 1, 2006, to the end of January, 2007. A very strong earthquake with M 8.3 occurred near Simushir Island of the Central Kuril region (Russia) on November 15, 2006. Following this, a series of strong aftershocks (M 5.0-6.5) was observed over several months.

The position of the station at Petropavlovsk-Kamchatsky and the VLF/LF transmitters, together with the epicenter of this earthquake and its aftershocks, are shown in Figure 1. The earthquake epicenter was in the sensitivity zone of wave paths JJY–Petropavlovsk-Kamchatsky, JJI-Petropavlovsk-Kamchatsky and NWC-Petropavlovsk-Kamchatsky. For the DEMETER data, we analyzed the signals in the part of the night-time orbits when the satellite passed above the earthquake area. The zone of analysis had a width of 25°, which provided one orbit every day. The time averaging of the dynamic spectrum was about 2 s, and the space resolution along the orbit was about 10 km to 15 km.

The ground and satellite data were processed by a method based on the difference between the real signal in the night-time and the model signal [Rozhnoi et al. 2004, 2007]. The model for the ground observations was the monthly averaged signals of amplitudes and phases calculated for the quiet days of every month. For our analysis we use the residual signals of phase dP or amplitude dA:

$$dA = A - \langle A \rangle; \quad dP = P - \langle P \rangle \tag{1}$$

where A and P are the amplitude and phase for the current day, and <A> and <P> are the corresponding averages.

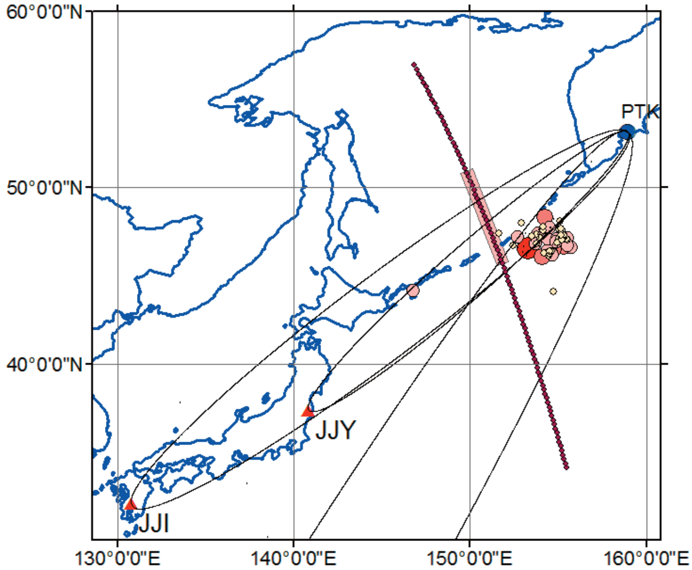

Figure 1. Map showing the positions of the Petropavlovsk-Kamchatsky (PTK) station and the JJI and JJY VLF/LF transmitters, together with the epicenters of the earthquake on November 15, 2006, and its aftershocks (after the US Geological Survey catalog). The ellipses show the sensitivity zones for the JJI, JJY and NWC transmitters. Part of a night-time orbit of the DEMETER satellite that passes above the earthquake area is indicated. Pink rectangle, section where effects are observed.

For the satellite observations, we calculated the model of the signals for every real orbit based on a two-dimensional model with regular signal distributions over the selected area. The modeling consists of the following procedure:

a) Computation of a polynomial expression for the surface as a function of the longitude and latitude. We applied the method of local polynomial interpolation, which uses multiple regression methods on data within a localized window to fit a set of trends. The window can be moved around and the surface value at the center of the window, $\mu_0(x, y)$, is estimated at each point, based on a weighted least squares fit to the data points $Z(x_i,y_i)$ as follows:

$$\sum_{i=1}^{n} w_i (Z(x_i, y_i) - \mu_0(x_i, y_i))^2, \tag{2}$$

where n is the number of points within the window, and w_i is a weight defined as:

$$w_i = \exp(-3d_{i0}/a), \tag{3}$$

where d_{i0} is the distance of the point from the center of the window, and a is a parameter that controls how fast the weights decay as a function of distance. Finally, $\mu_0(x_i,y_i)$ is the value of the polynomial.

For the first-order polynomial:

$$\mu_0(x_i, y_i) = \beta_0 + \beta_1 x_i + \beta_2 y_i \tag{4}$$

For the second-order polynomial:

$$\mu_0(x_i, y_i) = \beta_0 + \beta_1 x_i + \beta_2 y_i + \beta_3 x_i^2 + \beta_4 y_i^2 + \beta_5 x_i y_i \,, \quad (5)$$

and so on. The minimization occurs for the parameters $\{\beta_i\}$. The parameters are re-estimated whenever the center point, and consecutively, the window move [Gandian 1963].

b) Construction of a regular latitude and longitude grid of 0.32°.

c) Computing of a net point model.

The models were calculated for the SNR defined as the ratio of the signal spectrum density near the transmitter frequency F_0 with the minimum value in the frequency band (SNR = A_{F_0}/A_{min}). Using this model, we can define the instantaneous variations in the VLF/LF signal intensity in the active region at any time and for any longitude and latitude as the difference between the measured SNR of the signal (longitude, latitude, t) and the reference signal (longitude, latitude).

3. Results

Results of ground observations for the wavepaths JJY-Petropavlovsk-Kamchatsky and NWC-Petropavlovsk-Kamchatsky are shown in Figure 2. For both wave paths, there were disturbances in the signals (Figure 2, yellow and brown colors). These started about two weeks before the earthquake and continued during the aftershock activity, to the middle of December, 2006. The effects were more evident in the 40 kHz signal.

Figure 3a shows the spectra of the VLF signals recorded by the DEMETER satellite along part of the night-time orbits that passed above the earthquake area on the disturbed day of November 2, 2006. For comparison, we give here the quiet day of October 29, 2006 (Figure 3b). The signals from several powerful VLF transmitters (the Russian Alfa [11.8, 12.6 and 14.88 kHz], and the Australian NTS [18.6 kHz] and NWC [19.8 kHz] transmiters) are clearly observed in Figure 3. A signal at almost 18 kHz can be seen in Figure 3b, although this was out-of-operation in Figure 3a. Changes in the NTS and NWC signals (decreases in the amplitudes, and spectral broadening of the signals) occurred in the region of 149-152°E, 45-50°N, just above the area of the seismic activity (Figure 1, pink rectangle along the DEMETER pass). The same effects were observed in the dynamic spectra of the VLF signals (Figure 4). The signals of the same transmitters are easily noted here as the horizontal lines. Spectral

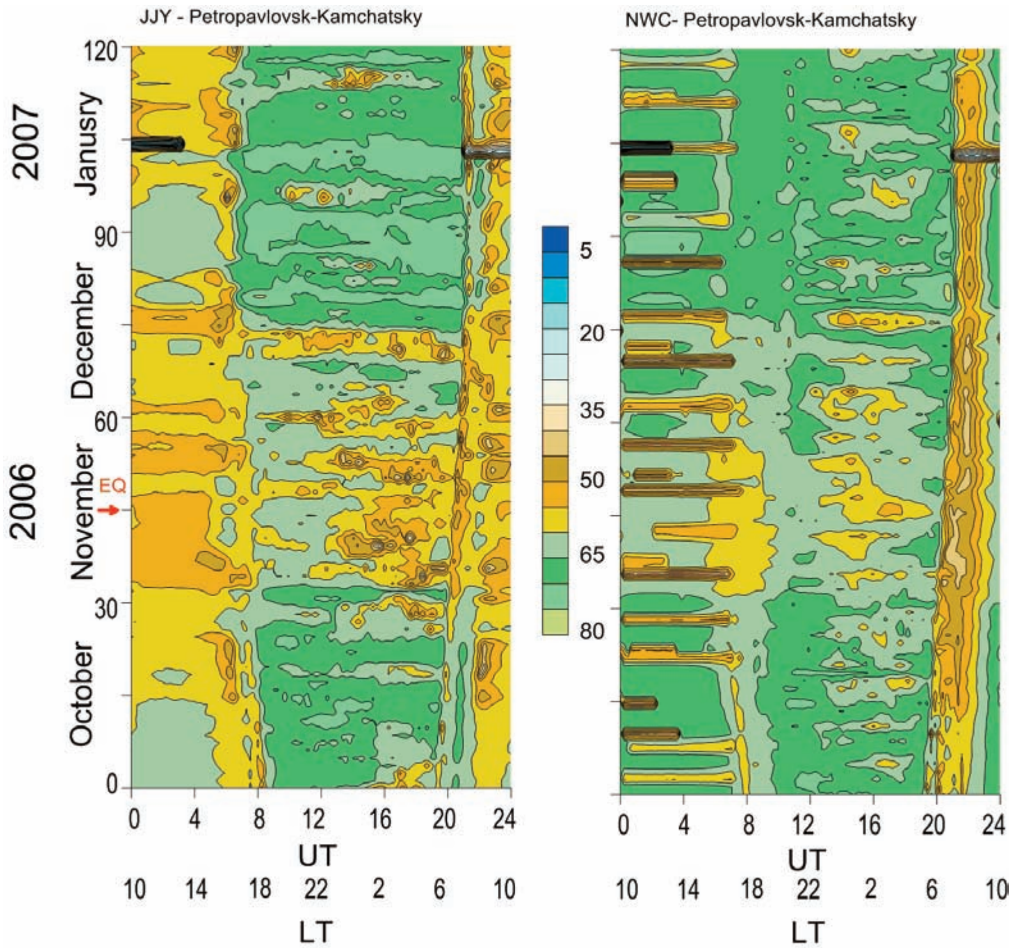

Figure 2. Contour map of the diurnal variations of the VLF/LF signal amplitudes at Petropavlovsk-Kamchatsky from October 1, 2006, to January 31, 2007. Left panel: Wave path JJY (40 kHz)-Petropavlovsk-Kamchatsky. Right panel: Wave path NWC (19.8 kHz)-Petropavlovsk-Kamchatsky.

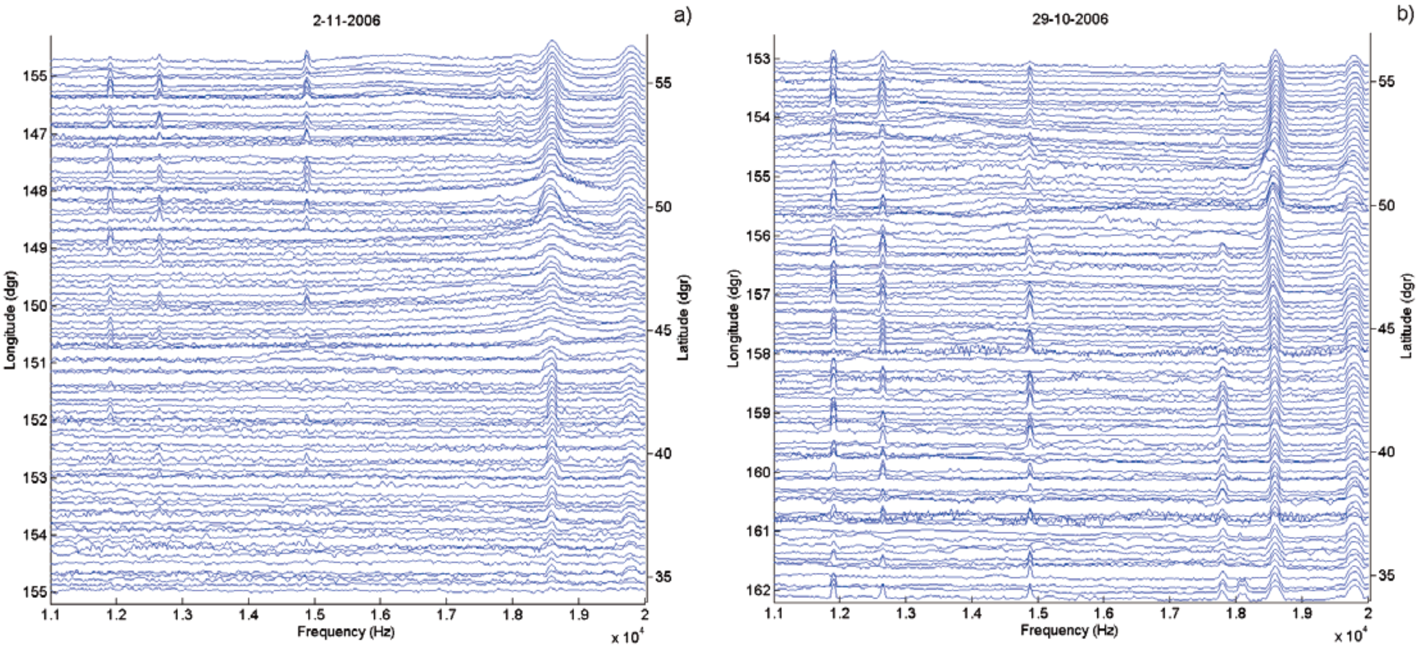

Figure 3. VLF signal variations recorded by the DEMETER satellite along parts of the orbits for the frequency range 11 kHz to 20 kHz. Upper panel: Disturbed day of November 2, 2006. Bottom panel: Quiet day of October 29, 2006. Left Y axis, longitude; right Y axis, latitude, for points of the orbits.

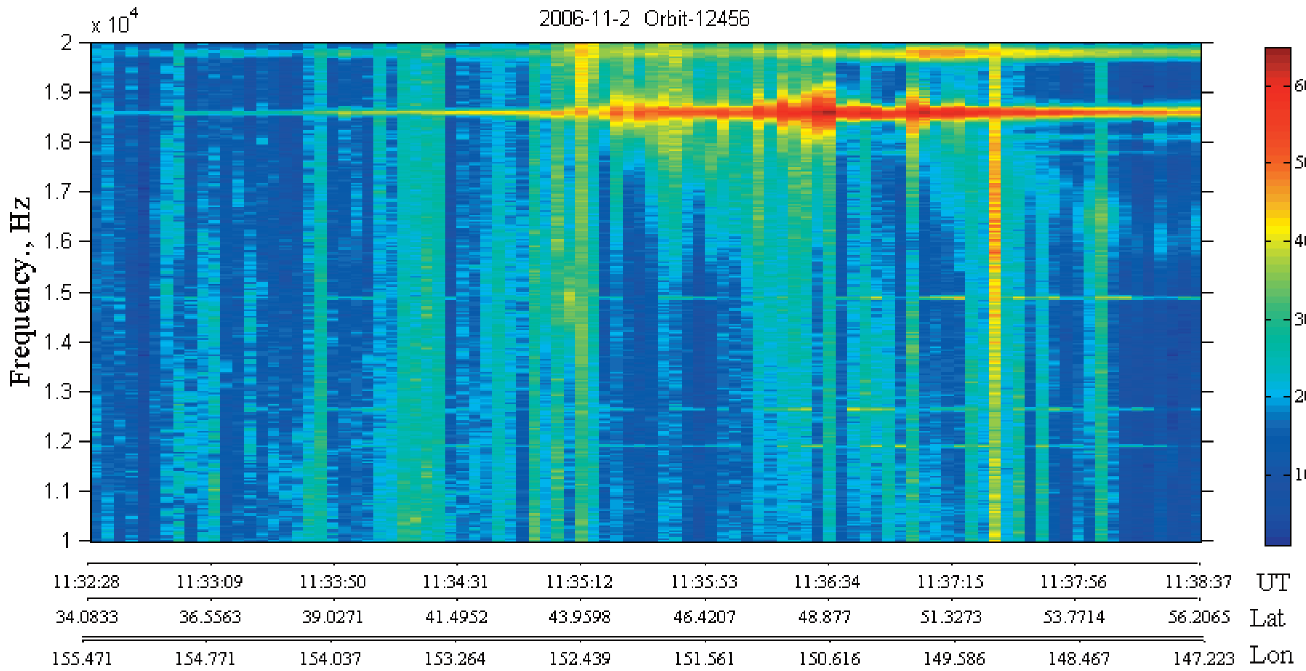

Figure 4. Dynamic spectra of the VLF signal variations for parts of the orbits passing above the earthquake area, for the frequency band 10 kHz to 20 kHz. The disturbed day of November 2, 2006, is shown.

broadening of the NWC and NTS signals can be seen above the earthquake region.

Finally, a comparison of the results of the satellite and ground observations is shown in Figure 5. Here, we used the differences averaged over the night-time for the ground reception, and the differences averaged along the part orbit crossing the seismic area for the satellite data. There is an evident decrease in the amplitude of the VLF/LF signals in both the ground and satellite data that is associated with the seismicity. The amplitude anomalies are always negative for both magnetic storms and seismic activity, because of the loss of the signal in the ionosphere irregularity during the propagation. Phase anomalies can be both positive and negative; these depended on the length of the path. In the present case, the anomalies in the phase of the JJY signal were positive.

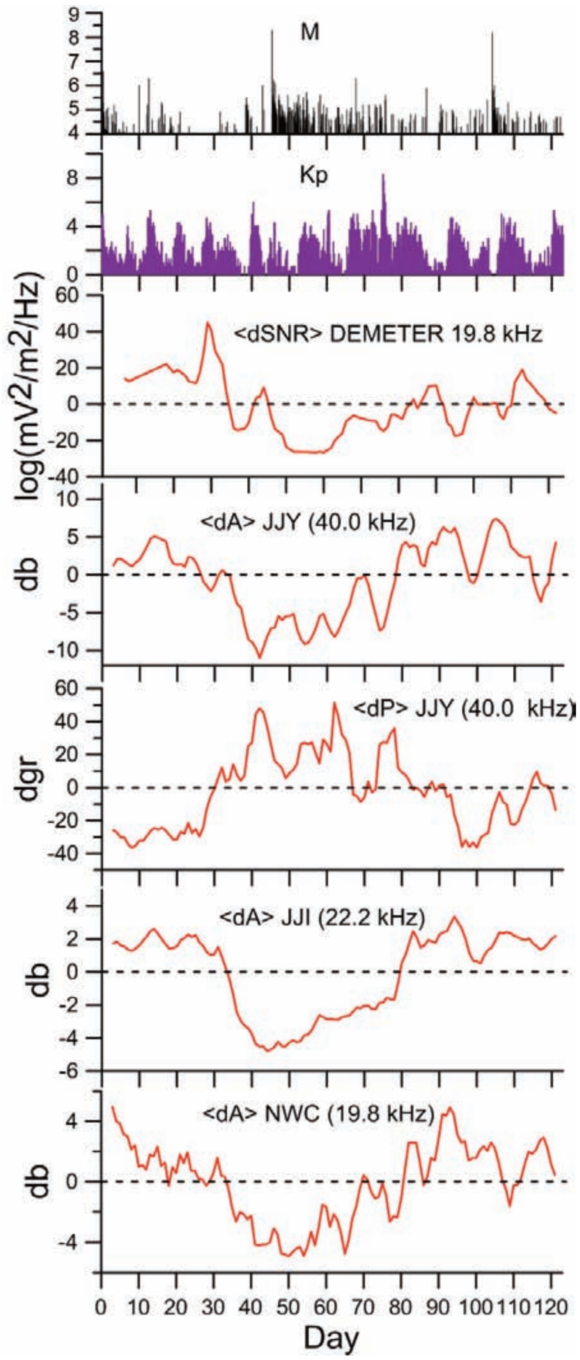

Figure 5. Comparison of the ground and satellite observations during October 2006 to January 2007. For the satellite observations averaged along parts of the orbits, the VLF signal differences from the reception of the NWC transmitter signal are shown. For the ground observations averaged through the night-time, the VLF/LF signal differences are shown for the wave paths: JJY-Petropavlovsk-Kamchatsky (amplitude and phase), JJI-Petropavlovsk-Kamchatsky and NWC-Petropavlovsk-Kamchatsky. The X axis shows the days beginning from October 1, 2006. Two upper panels, earthquake magnitudes, and Kp indices of the magnetic activity.

4. Discussion and conclusions

We have presented here a further comparison of ground and satellite data during periods of seismic activity. These simultaneous analyses provide cross-validation of the results, and they are more reliable for earthquake precursor studies.

As a mechanism of the observed effects, we suggest the following:

Such long-term and large-scale perturbations in the ionosphere cannot be produced by the seismic shock itself (durations of minutes), and so we need to assume a long-lasting agent that influences the ionosphere around the date of an earthquake.

We believe that this initial agent is an upward energy flux of atmospheric gravity waves that are induced by gas–water release in the earthquake preparatory zone.

Penetration of atmospheric gravity waves into the ionosphere leads to modifications in the natural (background) ionospheric turbulence, especially over space scales of ~1 km to 3 km and wave numbers kT of $\sim 10^{-4}$-10^{-3} m^{-1}. These weak, but reliable, effects can be revealed by direct satellite observations [e.g. Molchanov and Hayakawa 2007].

Resonant scattering of the VLF signals is possible under the following conditions of frequency–wave number synchronism: $\omega_0 = \omega_s + \omega_T$, $\mathbf{k_0} = \mathbf{k_s} + \mathbf{k_T}$, where ω_0 and $\mathbf{k_0}$ are for the incident VLF waves, ω_T and $\mathbf{k_T}$ are for the turbulence, and ω_s and $\mathbf{k_s}$ are for the scattered waves. Here, the amplitude of the incident wave A_0 decreases exponentially during the course of propagation through the perturbed medium: $A_0 \sim \exp(-\alpha_n A_T H)$, where an is the coefficient of nonlinear interaction, which depends on A_s and A_T, and H is the length of the interaction region. In our case with VLF signals: $\omega_T << \omega_0 \sim \omega_s$, and the interaction is especially efficient because $k_0 \sim k_s \sim k_T$ [Molchanov 1985]. Therefore, even though the amplitude of the turbulence A_T is small, the scattering can be significant if the length H is large.

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Data and sharing resources

The earthquake catalog used in this study can be found at the site: http://neic.usgs.gov/neis/epic/epic_global.html

The Kp data are from the site: http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html

The DEMETER data are from the site: http://demeter.cnrs-orleans.fr/

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