Evolution of ionosphere disturbances associated with the 1994 Shikotan earthquake

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Abstract

Earthquakes are known to produce infrasonic pressure waves in the atmosphere. Because of the coupling between neutral particles and electrons at ionospheric altitudes, these acoustic waves induce variations of the ionosphere electron density. However, the type of ionosphere response seems to depend on the focal mechanism of an earthquake. Thus, using GPS TEC measurements we found that TEC response to the Shikotan Island Earthquake (4 October 1994, M8.1) appeared as both “direct” and “inverted” N-waves excited at the uplifted and subsided segments, respectively. At that, the behavior of TEC changes differs essentially in the both initial and filtered TEC series.

High spatial resolution of the GEONET allowed us to observe the coseismic ionosphere disturbance (CID) at distance more than 1800 km and to track evolution of the propagated disturbance. This can provide us more information about the process of a wave transformation from the ground to the ionosphere (i.e., transformation of acoustic waves to shock-acoustic waves, SAW) and then to ionosphere disturbance: the amplitude and the shape of variations were found to change with distance from the source. In the records of the GPS receivers located within ~500 km from the epicenter the TEC response had a form of N-wave, whereas starting from ~500-600 km the negative phase of the N-wave seemed to separate from the “main” wave. Such observations of the evolution of waves in the ionosphere have been performed for the first time.

1. Introduction

Earthquakes are known to generate atmospheric and ionospheric disturbances [1]. Vertical displacements of the ground induce pressure waves in the neutral atmosphere that propagate upward and grow in amplitude by several orders of magnitude as they attain ionosphere heights, since the atmosphere density decreases with height. Such waves can initiate the ionosphere plasma motion due to the collisions between neutral and charged particles, and produce perceptible perturbations in the ionosphere electron density [2-6].

Coseismic ionosphere disturbances can be observed both near to the epicenter and far from it. However, the physical mechanisms of their generation are different and, therefore, their parameters (e.g. velocity of CID propagation, period, duration and shape of variations caused by CID propagation) differ markedly. The source of such CID can be the main quake itself (and propagating SAW, consequently), seismic surface Rayleigh waves, seismic air waves, Lamb waves etc.

Ionosphere response to SAW propagation can be detected in the vicinity of an earthquake’s epicenter 10-15 min after the main shock; CID caused by SAW were found to propagate with a velocity equal to the sound speed (~800-1000 m/s at the height of the ionosphere F-layer). The waveform of the ionosphere response in that case is usually described as an “N-type” wave, consisting of leading and trailing shocks connected by a smooth linear transition region. The waveform arises from non-linear propagation effects, the amplitude of N-waves depends on the magnitude of an earthquake, losses on shock fronts, neutral wind speed etc. [7]. The parameters of such CID were well examined using GPS TEC measurements [2-5].

One of the most interesting problems concerns the relation between an earthquake’s focal mechanism and the kind of the consequent ionosphere response. The majority of earthquakes occurred are of reverse fault type, so that observations in the above mentioned papers deal with an ionosphere response to such kind of earthquakes. However, the researchers’ attention seems never been paid to the tectonic information of earthquake, so dependence of an ionosphere response on focal mechanism of an earthquake was not studied before. Here we present observations of TEC response to the earthquake on 4 October 1994. We study the evolution of the observed ionosphere disturbance while propagating out from the source for more than 1800 km.

The GPS data used in this study, come from 30 s rate receivers of the Japanese GPS Earth Observation Network (GEONET, http://terras.gsi.go.jp), which has been in operation over a decade and contained 100 GPS stations in October 1994.

2. Observations

A major earthquake (magnitude M8.1) occurred at 13:23 UT near Shikotan Island, in the subducting Pacific Plate slab as a high-angle (~50 deg) reverse faulting resulting in both surface uplift and subsidence of comparable size (Figure 1). At Shikotan Island, there was approximately 50 cm of subsidence and major fissure formations were observed [8]. The corresponding coseismic crustal deformations due to the earthquake, calculated by the model of Okada [9], are presented on the right bottom panel in Figure 1. As one can see, both surface uplift and subsidence of comparable size occurred due to the earthquake.

TEC response to the earthquake on 4 October 1994 appeared 12-15 min after the main quake the closest to the epicenter GPS sites in the records of satellite 20 (Figure 1). The geometry of the satellite during the earthquake let us observe TEC response from the northwest and southwest of the epicenter (black thin lines show trajectories of sibionospheric points (SIP), asterisks indicate location of minimum of TEC response. Location of GPS receivers is shown by black dots, the certain code of station is indicated by numbers next to the dots). It is obvious that the shape of the response depends on the location of SIP relative to the epicenter: it is a N-type response from the southwest (sites 0027, 0031, 0036, 0038) and it is an “inverted” N-type wave on the northwest (sites 0004, 0005, 0006, 0010). Comparison with the areas of the coseismic crustal deformation shows that we observe the “inverted” N-type wave above the area of subsidence.

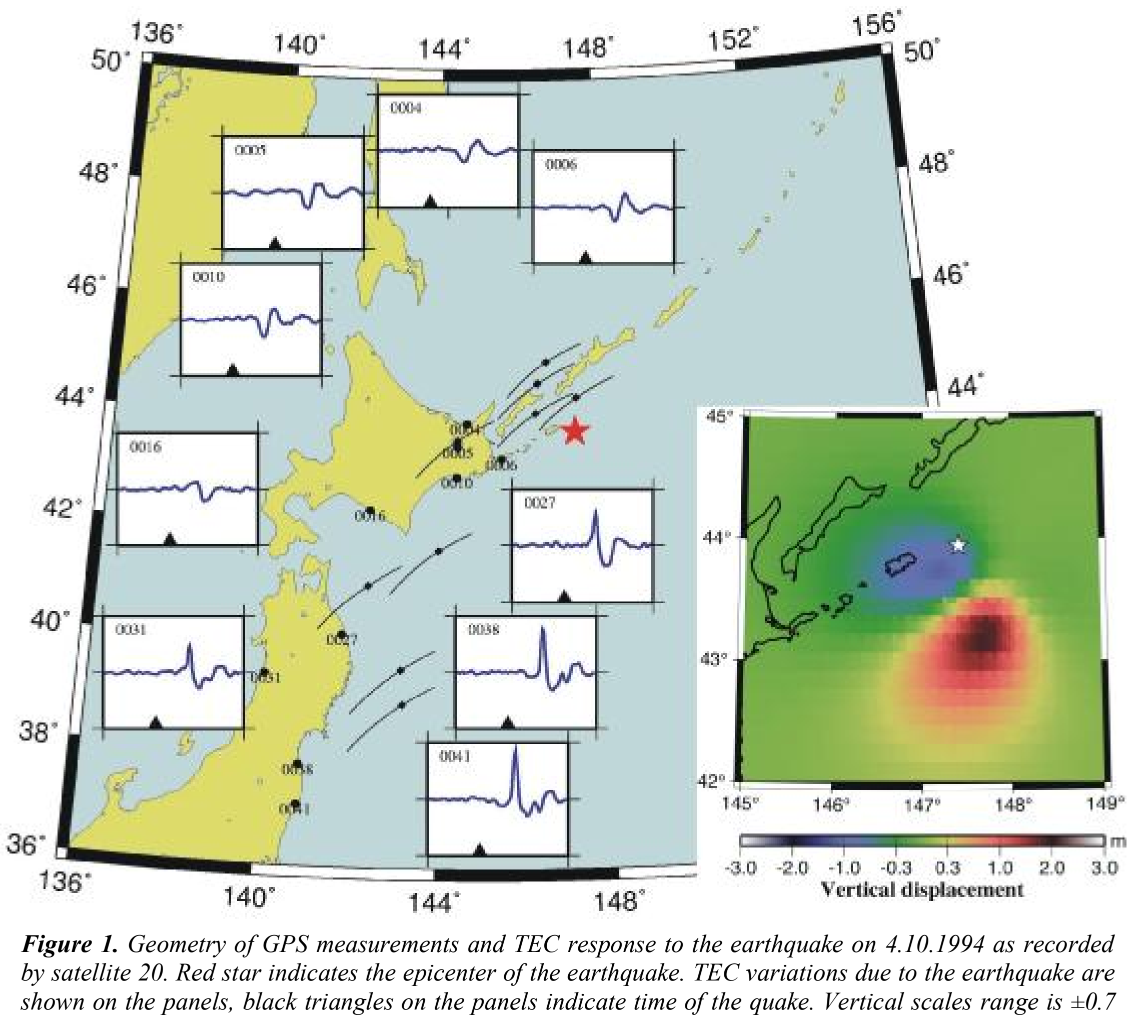

__Figure 1.__ Geometry of GPS measurements and TEC response to the earthquake on 4.10.1994 as recorded by satellite 20. Red star indicates the epicenter of the earthquake. TEC variations due to the earthquake are shown on the panels, black triangles on the panels indicate time of the quake. Vertical scales range is ±0.7 TECU, time scale corresponds to 13-14 UT. The panel in the right bottom corner shows vertical coseismic crustal movements due to the earthquake, subsidence (blue) and uplift area (red).

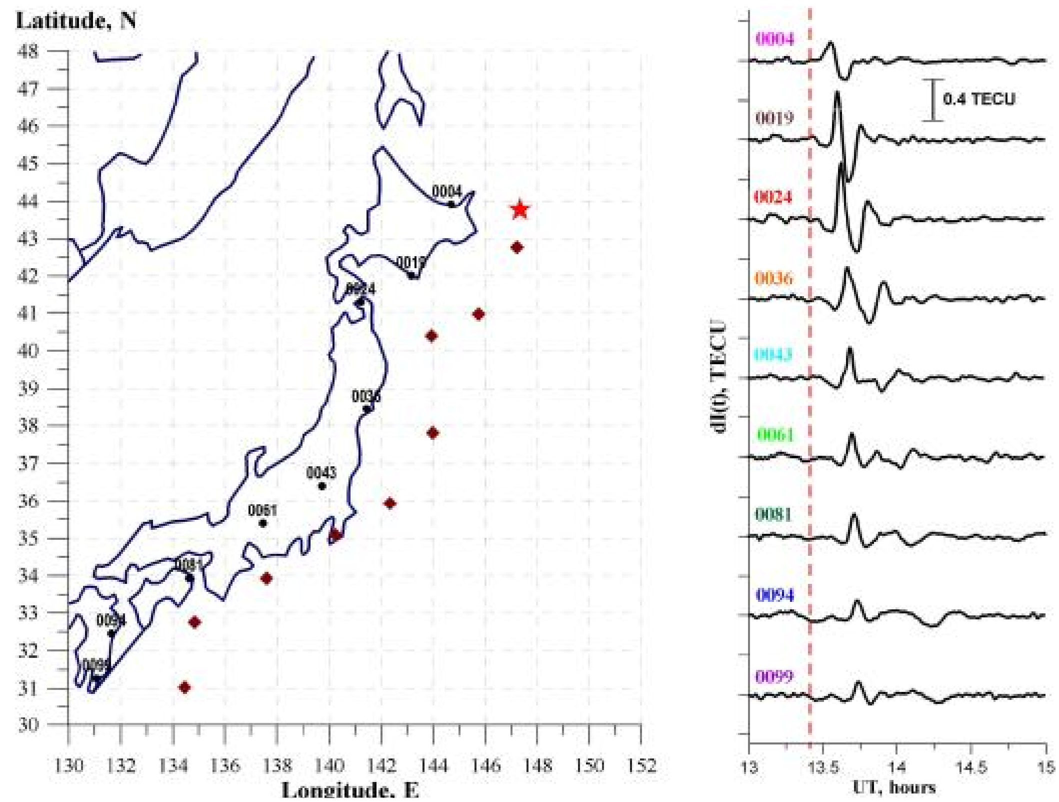

__Figure 2.__ TEC response to the earthquake on 4.10.1994 as recorded by satellite 06. Brown asterisks indicate location of maximums of TEC response. GPS receivers are shown by black dots, the certain code of station is indicated by numbers next to the dots. TEC variations are shown on the right panels, red broken line indicates the time of the quake.

Apart from that, TEC perturbations due to CID were recorded by satellite 06. In this case, the SIP were located on the south – southwest from the epicenter (Figure 2). Altogether, for satellite 06 the TEC response was recorded by 94 GPS receivers of the GEONET. Such high spatial resolution allowed us to observe the response at distance more than 1800 km and to track the evolution of the propagated wave.

It was found that the amplitude and the shape of variations changed with distance from the source. The amplitude of the signal was about 0.6 TECU for the records in the near-field (~100-200 km) of the source, at a distance of 200-350 km it increased to 1 TECU and in the far-field from the epicenter the amplitude decreased to 0.4-0.5 TECU.

In the records of the GPS receivers located within ~500 km from the epicenter the TEC response had a form of N-wave and the certain CID propagated with velocity ~1.3 km/s. Starting from ~500-600 km the negative phase of the N-wave seemed to separate from the “main” wave and those splitted waves further propagate with velocities that differ essentially in value: the positive phase of the N-wave propagates with the velocity about 1.7 km/s, while negative phase of the N-wave propagates with velocity about ~600 m/s and changes its shape considerably.

5. Conclusion

It was found that ionosphere response depends on the type of fault that ruptured in the earthquake. TEC response to the October 1994 earthquake showed both the “direct” and “inverted” N-waves excited from the uplifted and subsided segments, respectively.

The specific mechanism of the formation of the “inverted” N-type wave in TEC variations is not clear yet. On the one hand, experimental data show clear dependence of the response type on the focal mechanism of an earthquake, and the behavior of TEC changes differs essentially also in the initial TEC series (Figure 3), so the observed distinctions in the TEC fluctuations are not the consequence of the filtering process.

The “inverted” N-waves were observed about 70-130 km from the epicenter and exactly above the area of subsidence. Also, the fact that the shape of seismic P-waves depends on the focal mechanism of an earthquake, could confirm that such dependence is possible.

On the other hand, it is known [10] that "inverted" acoustic waves (i.e., rarefaction acoustic waves) cannot propagate for a long distance due to their instability and, therefore, most likely, cannot reach the ionosphere. Besides, the form of the ionosphere response might not follow the form of the certain acoustic wave. This depends on many factors, like phases of the "primary" and "secondary" waves, distance of the transformation area from the source of waves, etc. Thus, the particular mechanism of transfer of perturbation from acoustic wave to ionosphere is not well investigated yet.

The observed here long-distance propagation of the CID can provide us more information about the process of a wave transformation from the ground to the ionosphere (i.e., transformation of acoustic waves to SAW) and then to traveling ionosphere disturbance propagating for more than 1800 km. Such observations of the evolution of waves in the ionosphere have been performed for the first time. Our observations and ionosphere response parameters estimations are in agreement with results of modeling of ionospheric variations due to earthquakes [11].

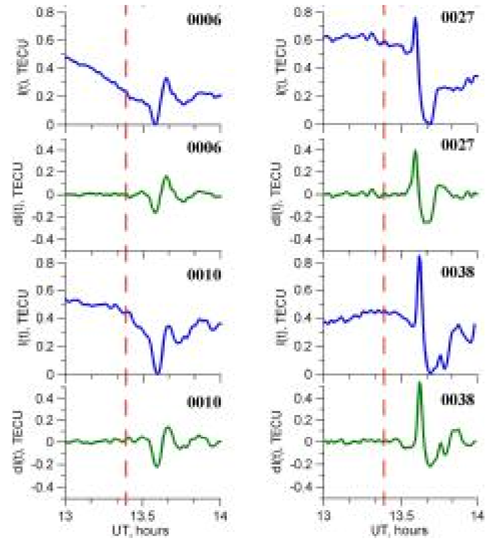

Figure 3*. Initial I(t) (blue curves) and filtered within 2-15 min dI(t) TEC series (green curves) recorded at GPS receivers from the northwest (panels on the left) and on the southwest (panels on the right) from the earthquake's epicenter, satellite 20.*

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