Ionospheric F2-layer Perturbations Observed After the M8.8 Chile Earthquake on February 27, 2010, at Long Distance from the Epicenter

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The F2-layer critical frequency (foF2) data from several ionosondes are employed to study the long-distance effect of the M8.8 Chile Earthquake of February 27, 2010, on the F2 layer. Significant perturbations of the peak F2-layer electron density have been observed following the earthquake at two South African stations, Hermanus and Madimbo, which are located at great circle distances of ~8,000 and ~10,000 km from the earthquake epicenter, respectively. Simplified estimates demonstrate that the observed ionospheric perturbations can be caused by a long-period acoustic gravity wave produced in the F-region by the earthquake.

Keywords: seismo-ionospheric coupling, ionospheric F2 layer, acoustic gravity wave, ionospheric perturbation

1. INTRODUCTION

The F-region ionosphere is highly variable due to a whole number of influences from below (severe meteorological and seismic events) and from above (solar ionizing EUV flux, solar wind conditions, magnetospheric and auroral activities) (e.g., Forbes et al. 2000; Rishbeth & Mendillo 2001; Laštovička 2006; Kim & Hegai 2015; Chung et al. 2016; Kim & Hegai 2016). An ionospheric response to a major earthquake is still far from being fully investigated, although early studies on the subject have been carried out more than 50 years ago when Davies & Baker (1965), Leonard & Barnes (1965), and Row (1966) presented an evidence of perturbations in the F2 layer caused by the M8.4 Alaska Earthquake of March 28, 1964. Row (1967) showed that the ionospheric perturbations could be attributed to the F2-layer electron density of acoustic gravity waves (AGWs) produced by the earthquake in the F-region. A more detailed theoretical treatment of AGWs launched into the ionosphere by seismic shocks was presented by Liu & Yeh (1971) and Yeh & Liu (1974) for the case of an isothermal and dissipationless neutral atmosphere. The data were extrapolated for a realistic neutral atmosphere in a number of studies (e.g., Francis 1973, 1975; Liu & Klostermeyer 1975; Mayr et al. 1984; Maeda 1985; Liang et al. 1998; Sun et al. 2007; Ma 2016). At long distances from an earthquake epicenter, ionospheric perturbations in the F-region due to AGWs of seismic origin are observed as medium- and large-scale traveling ionospheric disturbances (TIDs; Francis 1973, 1975). Seismic TIDs have been registered at distances of more than 3,000 km from epicenters using ionosonde measurements of the F2-layer critical frequency (foF2; Leonard & Barnes 1965; Hegai et al. 2011). The TIDs associated with earthquakes have also been studied using ionospheric total electron content (TEC) data measured by GPS receiver networks (e.g., Calais & Minster 1995; Astafyeva & Afraimovich 2006; Liu et al. 2006; Tsugawa et al. 2011; Cahyadi & Heki 2013).

Another type of ionospheric perturbations detected in the F-region after earthquakes is small amplitude variations in the electron density caused by vertically propagating acoustic waves that were excited by seismic Rayleigh waves traveling along the Earth’s surface with respect to an epicenter. Rayleigh wave signatures in the ionosphere following earthquakes have been measured by Doppler sounding (e.g., Yuen et al. 1969; Tanaka et al. 1984; Artru et al. 2004; Chum...
et al. 2016) using TEC measurements (e.g., Ducic et al. 2003; Astafyeva et al. 2009; Rolland et al. 2011) and the inspection of ionograms (Maruyama et al. 2012, 2016a, 2016b).

In this work, ionosonde foF2 data are utilized to study perturbations of the peak F2-layer electron density following the M8.8 Chile Earthquake of February 27, 2010, at long distances from its epicenter.

2. DATA ANALYSIS AND DISCUSSION

As reported by the U.S. Geological Survey, the major earthquake with a magnitude of 8.8 and depth of 35 km occurred at 06:34:14 UT on February 27, 2010, at a distance of 335 km from Santiago, the capital of Chile. The epicenter of the earthquake was located at a geographic latitude of 35.9°S and longitude of 72.7°W.

We examine the foF2 values [proportional to (NmF2)^1/2] recorded at several ionospheric stations listed in Table 1. The foF2 data were taken from the NGDC SPIDR website (http://spidr.ionosonde.net/spidr/). The index Kp is used to represent the geomagnetic activity around the earthquake. The solar and geomagnetic activities were low in February 2010; the monthly F10.7 and Ap indices were as small as 82.7 and 5, respectively.

Fig. 1 shows the time variation of the observed critical frequency foF2 (a, b, and c) at three ionosonde stations (Hermanus, Madimbo, and Port Stanley) over the period 00:00 to 24:00 UT on February 27, 2010. The average foF2 (\langle foF2\rangle) of ten quiet days in February 2010, during which the Kp index did not exceed 2 (February 7, 10, 11, 19, 20, 21, 22, 23, 24, and 28, 2010), is superposed to provide reference curves. The vertical lines consequently indicate the moment of the earthquake onset (t_Q), which means the estimated time of arrival of the seismic atmospheric disturbance traveling in the F-region from the epicenter to the ionosonde site along the great circle path (t_ar). The great circle distances from the epicenter of the earthquake to the selected ionosonde stations are given in Table 1. We estimate the arrival times t_ar in the simplest way by using the formula \( t_{ar} = t_{eq} + L/V \), where \( L \) is the value of the great circle distance and \( V \) is the speed of the horizontal propagation of the seismic atmospheric disturbance in the F2 layer. The speed of medium- and large-scale seismic atmospheric disturbances, \( V \), is \( \approx 800 \) m/s (e.g., Row 1967; Francis 1973, 1975).

The geomagnetic activity was very low on February 27, 2010, and the Kp index did not exceed 1, while the Kp index did not exceed -3 during the three previous days, which means that the geomagnetic conditions were favorable to identify ionospheric perturbations unrelated to geomagnetic disturbances. After the earthquake, at \( t_{ar} \), the foF2 at the South African stations Hermanus and Madimbo started to decrease; soon became smaller than \( \langle foF2\rangle \), by more than

| Table 1. A list of ionospheric stations |
|----------------------------------------|
| Station | Geog. Lat. (°N) | Geog. Long. (°E) | Δt (min) | L (km) |
|---------|----------------|-----------------|---------|-------|
| PORT STANLEY | -51.7 | 302.2 | 30.0 | 2,100 |
| HERMANUS | -34.4 | 19.2 | 15.0 | 8,000 |
| NORFOLK IS | -29.0 | 168.0 | 60.0 | 10,400 |
| MADIMBO | -22.4 | 30.9 | 30.0 | 9,700 |
| KWAJALEIN | 9.1 | 167.2 | 5.0 | 13,300 |
| WALLOPS IS | 37.9 | 284.5 | 15.0 | 8,200 |
| ROME | 41.8 | 12.5 | 15.0 | 12,200 |
| WAKKANAI | 45.2 | 141.8 | 60.0 | 16,900 |

Δt is the time interval between ionospheric sounding impulses, L is the great circle distance from the earthquake epicentre to a station.
perturbation in the ionospheric electron density at long distance, predominantly between altitudes of 180 and 280 km, which is in agreement with Francis (1973).

3. CONCLUSIONS

The present study showed that the M8.8 Chile Earthquake of February 27, 2010, likely produced a long-distance impact on the ionospheric F2 layer at a distance > 8,000 km from the epicenter. Seismic perturbations (reduction) of foF2 have been observed for several hours at the South African stations Hermanus and Madimbo. They exceeded 20 % with respect to quiet time values. We suggest that the mechanism responsible for these perturbations is associated with large-scale AGWs excited in the F-region ionosphere by the earthquake.

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