Journal of Atmospheric and Solar-Terrestrial Physics 102 (2013) 71–80

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

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

Subionospheric VLF perturbations observed at low latitude associated with earthquake from Indonesia region

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ARTICLE INFO

Article history:
Received 3 July 2012
Received in revised form
14 March 2013
Accepted 19 April 2013
Available online 9 May 2013

Keywords:
VLF propagation
Ionospheric perturbations
Earthquakes

ABSTRACT

Subionospheric propagation from a Very Low Frequency (VLF) transmitter (VTX, 18.2 kHz) received at a low latitude station Suva, Fiji over a Transmitter–Receiver Great Circle Path (TRGCP) length of 11,400 km has been utilized to identify any possible ionospheric perturbations associated with the earthquakes that occurred in the Indonesia region during the period December 2006–October 2010. Out of five earthquakes that occurred with their epicenter in the fifth Fresnel zone, only an earthquake on 18 December 2006, in the North Sumatra region, has shown convincing evidence of lower ionospheric perturbations on the VTX transmission. The magnitude of this earthquake was 5.8 measured on the Richter scale and occurred at a depth of 53 km with its epicenter located 45 km off the TRGCP. The VLF amplitude data for this earthquake was analyzed using (1) terminator time (TT), (2) average nighttime and daytime amplitude variation, and (3) nighttime fluctuation (NF) methods. The results show that the sunrise TTs deviated considerably in the period 14–22 December 2006 measuring up to ~20 min on the day of the earthquake. The results also show that the average nighttime as well as the average daytime signal amplitudes decreased by about 5 dB and 3 dB, respectively, during the period of the earthquake. The NF method revealed a decline in the trend at least 2 days before the earthquake though not exceeding the 2σ criteria and enhancements in the NF exceeding 2σ mark, however, the normalized values of the trend, NF and dispersion did not reveal an increase above the 2σ marks as reported by previous researchers. This could be due to the very long path length and the prevalence of lightning activity along the TRGCP in the Asia-Oceania Region.

1. Introduction

There is considerable interest in radio wave propagation in the Extremely Low Frequency (ELF, 3–3000 Hz) and the Very Low Frequency (VLF, 3–30 kHz) bands due to their importance in navigational communication, positioning, timing and research arising from the comparatively large skin depths and very low attenuation. At VLF, the Earth's surface and the lower ionosphere act as good electrical conductors and form an atmospheric waveguide called the Earth-ionosphere waveguide in which signals are guided along the conducting structures through multiple reflections. Measurement of the amplitude and phase of the VLF signals generated by navigation transmitters is a novel technique to study the morphology of VLF propagation over wide regions and for remote sensing the lower ionosphere (D and E-regions). These regions may in turn be affected by thunderstorms, solar flares, cosmic gamma rays, earthquakes, terrestrial gamma ray flashes, and geomagnetic storms.

There is accumulating evidence that the ionosphere may be sensitive to seismic effects, and the detection of ionospheric perturbations associated with earthquakes is an interesting proposition for short-term earthquake prediction. The first attempts of VLF/LF radio sounding for seismo-ionospheric effects were made by Gokhberg et al. (1989) and Gufeld et al. (1992), who studied VLF propagation over a long distance (~5000–9000 km) from Reunion (Omega transmitter) to Omsk in Russia to detect any effect of an earthquake in the Caucasian region. Gokhberg et al. (1989) reported nighttime perturbations in the VLF amplitude and/or phase associated with earthquakes. Gufeld et al. (1992) found a significant propagation anomaly a few days before the famous Spitak earthquake in Armenia (7 December 1988, magnitude 7.1, depth 5 km) over the two long distance paths from Reunion to Moscow and Omsk.

Evidence of seismo-ionospheric perturbations was reported by Hayakawa et al. (1996) for the famous Kobe earthquake (17 January 1995, magnitude 7.3, depth 20 km) by means of shifts in the terminator times in VLF amplitude data from the Omega transmitter received at Inubo, Japan (great circle path length of ~1000 km).

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http://dx.doi.org/10.1016/j.jastp.2013.04.011

A Japanese VLF/LF network was therefore established within the framework of NASDA's earthquake Remote Sensing Frontier Project (Hayakawa and Molchanov, 2004), and a similar VLF/LF observation network was established in Europe (Rozhnoi et al., 2009).

Research on this subject is typically based on (1) case studies e.g. for specific and huge earthquakes, such as the Niigata-Chuetsu earthquake (Hayakawa et al., 2006), the Sumatra earthquake (Horie et al., 2007) and so forth, and (2) statistical studies of the correlation between VLF/LF propagation anomalies (i.e., perturbations in the lower ionosphere) and earthquakes (Shvets et al., 2002, 2004; Rozhnoi et al., 2004; Maekawa et al., 2006; Kasahara et al., 2008).

Two methods for analyzing the effects of earthquakes on subionospheric VLF/LF propagation have been proposed so far. The first one is called the terminator time (TT) method, in which the TTs are traced around sunrise and sunset to find any anomalous shifts in these times. This method has been widely used for studying short ($\sim$1000 km) E–W propagation paths (e.g., Molchanov and Hayakawa, 1998; Maekawa and Hayakawa, 2006). The second method is the nighttime fluctuation (NF) method, in which particular attention is given to data during local nighttime and the mean amplitude, dispersion, and level of fluctuations are estimated (e.g. Shvets et al., 2002, 2004; Rozhnoi et al., 2004). This method has also been used in the statistical studies to determine the correlation between ionospheric perturbations and earthquakes (Maekawa et al., 2006; Kasahara et al., 2008, 2010; Hayakawa et al., 2011).

Hayakawa et al. (2011), based on the 2010 Haiti earthquake, using VLF data from NAA received in Peru (N–S propagation), found that a clear precursory ionospheric perturbation was detected about 12 days before the main shock. This was characterized by the simultaneous decrease in the trend (explained later in Section 4.3) and increases in the dispersion and nighttime fluctuation. Similar results were also reported by Kasahara et al. (2010) from a study on ionospheric perturbations associated with Asian earthquakes for VLF transmissions from NWC (19.8 kHz) received at Japanese stations (Moshiri, Chofu, and Kochi). Kasahara et al. (2010) also suggested that the propagation anomaly can only be detected when the earthquake magnitude is greater than 6.0 and the depth is shallow with the earthquake epicenter located within the wave sensitive area (or fifth Fresnel zone) of the propagation path.

As mentioned by Kasahara et al. (2010), much of the above research has used observations over relatively short propagation paths (great circle distance from 1000 km to a few thousand kilometers). The shift of the TT was investigated by Clilverd et al. (1999) for a long ($>$10,000 km) North–South (N–S) propagation path and they concluded that there existed no seismo-ionospheric perturbation, and hence the TT method is not useful for detecting seismo-ionospheric perturbations. However, Kasahara et al. (2010) stated that it was reasonable for them to have detected no terminator time anomaly on their long propagation path because the perturbed region was too small relative to the whole propagation path. Maekawa and Hayakawa (2006) also stated that N–S propagation itself was not so suitable generally to detect any TT effect.

In this paper we describe effects of the 18 December 2006 Sumatra earthquake on a long subionospheric VLF propagation path with Transmitter–Receiver Great Circle Path (TRGCP) of 11,400 km for VTX (18.2 kHz) received at Suva, Fiji (geo. long. 178.4°, geo. lat. 18.1°). The VTX-Suva great circle path is mostly over the sea but crosses over Sumatra, a region prone to earthquakes. A number of earthquakes were recorded around the Indonesia region during the period December 2006–October 2010. Our narrowband data recording started in October 2006 and there were no earthquakes reported along the VTX-Suva TRGCP during October–November 2006. The VTX amplitude data from December 2006 to October 2010 have been analyzed to study any effects of such earthquakes occurring near the TRGCP. Since VTX is a phase unstable transmitter, phase data could not be utilized. There occurred 15 earthquakes with magnitudes ≥5.8 during the period studied, out of which five were within the fifth Fresnel zone. Of these, only the earthquake which occurred on 18 December 2006 in the North Sumatra region showed effects on VLF transmissions from the VTX transmitter. The magnitude of this earthquake was 5.8 measured on the Richter scale, the lowest strength earthquake to cause VLF perturbations reported so far. We have used all the recognized methods to identify seismo-ionospheric effects: (1) TT changes, (2) nighttime and daytime average amplitude variation, and (3) the nighttime fluctuation, previously used by other researchers (e.g. Maekawa et al., 2006; Kasahara et al., 2008, 2010; Hayakawa et al., 2011). We present results suggesting that the observed subionospheric VLF changes were indeed due to earthquake-associated changes in the lower ionosphere. However, this is a subject of continued debate and understanding how this occurs requires more experimental data and analysis.

2. Earthquakes examined

A total of 15 earthquakes which occurred during the period December 2006–October 2010 were studied for any subionospheric VLF signatures on the VTX signal received at Suva. Table 1 gives

Table 1
The details of the earthquakes that occurred in the Indonesia region with any causative effect on the VTX signal.

No.	Earthquake information			Distance from the TRGCP (km)	Depth (km)	Any effect on VLF signal
	Date YY/M/D	Place	Magnitude			
1	2006/12/18*	North Sumatra	5.8, 6	$\sim$45	53	Effects on TT shifting, average day and night amplitude changes, and enhancement in Nighttime fluctuation noticed
2	2007/03/06	Sumatra	6.4, 6.3			No VLF data
3	2007/08/09	Java	7.5[2]	700	290	No effect
4	2007/09/12	Sumatra	8.5, 7.9, 7.1			No VLF data
5	2008/02/20	Simeulue	7.4	90	35	No effect
6	2008/02/25	Kepulauan Mentawai Region	7.0, 6.4, 6.6	350	35	No effect
7	2008/11/16	Sulawesi	7.5, 5.6	880	30	No effect
8	2009/01/04	West Papua	7.6, 4			
9	2009/02/12	Talaud Islands	7.2			
10	2009/08/16	Siberut, Mentawai Islands	6.7			No effect—very far from TRGCP
11	2009/09/02	Java	7.0			
12	2009/09/30	Sumatra	7.6	220	81	No effect
13	2010/04/06	Sumatra	7.8			VTX transmitter inactive
14	2010/05/19	Sumatra	7.2			
15	2010/10/25	Sumatra	7.7			

details of these earthquakes including the time and place of occurrence, the earthquake magnitude as recorded on the Richter scale, the distance off the VTX-Suva TRGCP and the depth for the earthquakes within the fifth Fresnel zone, and any possible effect observed on VLF propagation. Out of the five earthquakes within the fifth Fresnel zone, only the one which occurred on 18 December 2006 was found to show anomalous effects on propagation of the 18.2 kHz VTX signal. As reported by the Meteorology and Geophysics Agency (BMG) in Indonesia, an earthquake measuring 5.8 on the Richter scale occurred in the North Sumatra Province on 18 December 2006 at 21:39:20 UT at a depth of 53 km. The epicenter (0.82°N and 99.88°E) of this earthquake was approximately 30 km southeast of Muarasipongi Sub-district, Mandailing Natal District, North Sumatra Province. This earthquake killed at least 4 people, injured 50 people and destroyed 160 houses. Fig. 1 shows the position of the VTX transmitter, receiving station Suva, the TRGCP, wave sensitive area (fifth Fresnel zone) and the earthquake epicenter. Also shown in the figure are the locations of the other four earthquakes within this Fresnel zone which did not produce any effects on the VTX amplitude.

3. Experimental data and analysis

We use a software based VLF phase and amplitude logger known as "SoftPAL" to record the amplitude and phase of VLF transmitter signals that are Minimum Shift Key (MSK) modulated (Dowden and Adams, 2008). The transmitter signals are recorded continuously with a time resolution of 0.1 s using GPS based timing, but 1 s resolution data are utilized here for analysis purposes. Due to the high occurrence rate of earthquakes around the Indonesia region, it was decided to use the VTX signal to investigate any seismo-ionospheric effects. We considered earthquakes which occurred within the fifth Fresnel zone (marked by an ellipse) around the TRGCP, as shown in Fig. 1. The Fresnel zone is an elliptical area for which the VLF transmitter and receiver are foci. As seen in Fig. 1 the epicenter of the Sumatra earthquake was about 45 km off the TRGCP but inside the fifth Fresnel zone. According to Molchanov and Hayakawa (1998), seismogenic perturbations of the atmosphere and lower ionosphere may influence VLF signal propagation in this zone.

The three methods of data analysis used to identify possible seismo-ionospheric effects are described as follows. In the TT method, we traced the times of occurrence of the sunrise amplitude minima four days prior and four days after the earthquake. We did not consider sunset minima since they are not clearly identifiable, and examined only amplitude data as the phase is unstable for VTX signal. The VTX signal was intermittently off air for more than four days before and 4 days after the earthquake, hence longer duration of sunrise minima data are not presented.

In the nighttime and daytime average amplitude variation method, we analyzed the VLF signal amplitude data when the TRGCP was in complete darkness (12–18 UT), and when the TRGCP was in complete daylight (01–06 UT). We compared the difference between these with average values calculated prior to and after the earthquake day.

Under the nighttime fluctuation method, the fluctuation level in the nighttime signal amplitude is obtained using the formula, $dA(t) = A(t) - A_{av}(t)$, where $dA(t)$ is the variation in the signal amplitude from a standard running average, $A(t)$ is the VLF amplitude at any time, and $A_{av}(t)$ is the running average amplitude value for over ± 15 days at time t. Using the quantity $dA(t)$ (sometimes called residual), other statistical quantities including the trend (T), nighttime fluctuation level (NF), and dispersion (D) and their respective normalized values (explained later in section 4.3) are calculated and compared with the two standard deviation (2σ) criterion for the identification of any seismo-ionospheric effects.

4. Results

The results of the VLF data analysis using three methods; TT, average nighttime and daytime amplitude variations, and nighttime fluctuations, are presented here for the 18 December 2006 earthquake.

4.1. Terminator-time (TT) method

As shown in Fig. 1, the VTX-Suva propagation path is largely in the E–W meridian plane, so according to Maekawa and Hayakawa (2006) the TT method is expected to be effective in identifying any seismo-ionospheric perturbation. Fig. 2 shows the diurnal VLF amplitude variation for the period 14–22 December 2006, in the form of stacked 24 h amplitude-time series spanning the period for four days prior to and four days after the earthquake. The diurnal amplitude variation shows that the propagation path was in complete daylight over 01–06 UT and in complete darkness over 12–18 UT. This diurnal pattern is very similar from day to day. The average nighttime amplitude is larger than the average daytime amplitude. The sunrise and sunset transition (time during which the sunrise/sunset terminator moves between the transmitter and receiver producing minima in the received signal amplitude) is identified using vertical arrows in Fig. 2. At least four such signal minima can be clearly identified, which have been

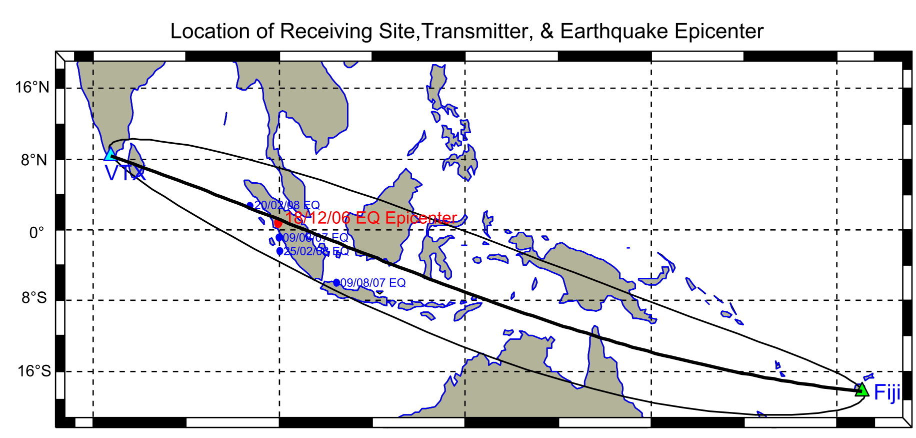

Fig. 1. The relative locations of the VTX transmitter, the receiving station Suva, Fiji, along with the TRGCP. The wave sensitive area (defined by fifth Fresnel zone) is also plotted with an ellipse. The 18 December 2006 earthquake epicenter is marked with solid red circle. Four other earthquakes that did not show any effect on VTX amplitude are marked by solid blue circles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

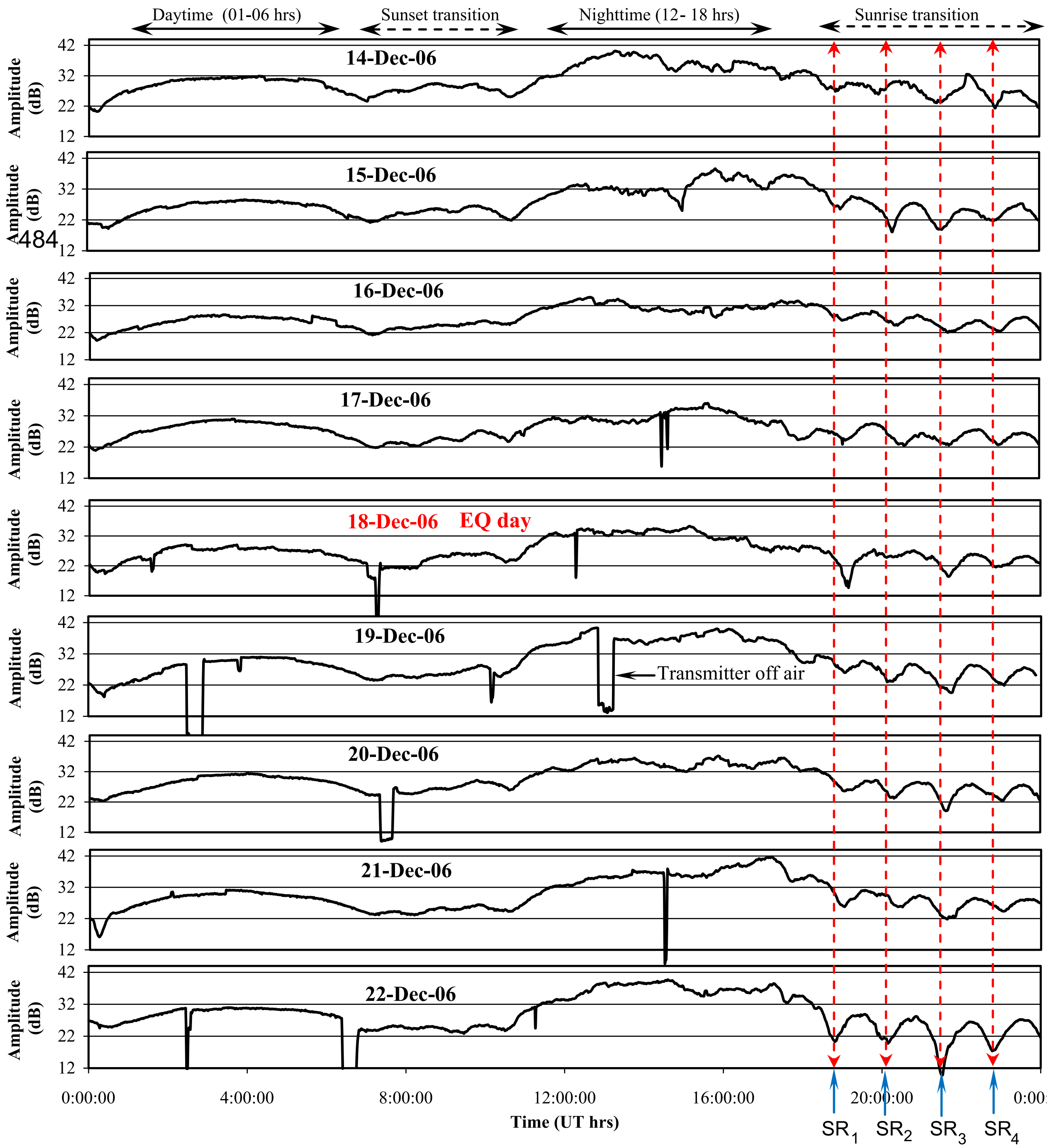

Fig. 2. Diurnal variation of the VTX (18.2 kHz) amplitude received at Suva, Fiji, during the period 14–22 December 2006. The horizontal axis corresponds to UT time while the vertical axis in each panel gives the signal amplitude in dB. The dashed vertical lines labeled SR_1, SR_2, SR_3, and SR_4, show the shifts in the sunrise minima times.

labeled SR_1, SR_2, SR_3, and SR_4. However, the sunset minima are not very clear, and so the sunset terminator shift timing has not been measured. Sudden large drops in the signal amplitude are due to the transmitter being off air for that duration.

Typically, the TTs are good measures of sunrise and sunset transition and tend to be consistent from day-to-day. TTs change gradually and vary seasonally due to changes in the sunrise and sunset times at lower ionospheric altitudes (60–85 km) and the changing angle of the terminator for fixed locations (Ries, 1967; Clilverd et al., 1999).

The times of the sunrise minima were analyzed for 15 days (outside the earthquake occurrence period) for the month of December 2006, and the maximum deviation in the time of occurrence of these minima was found to be about 5 min. However, in the VTX amplitude data at Suva, the times of sunrise minima were shifted up to 20 min during the 4 days before and 4 days after the Sumatra earthquake on 18 December 2006. The occurrence times of the sunrise minima were observed to be delayed by a certain amount each day starting at least 3 days prior to this earthquake. In this case the sunrise minima started to become delayed on 15 December 2006 and shifted gradually to a maximum delay on the day of the earthquake. On the day of the earthquake a delay of $\sim$20 min was observed between the times of occurrence of the minima to that on 14 December as shown in Fig. 2. After the earthquake, the minima started shifting back to their normal positions and finally settled to the same positions on 22 December as on 14 December. Thus, at sunrise at which the VLF signal showed minima, anomalous shifts in TTs were observed, as if the nighttime had been prolonged by 20 min on the day of earthquake as seen in our data.

4.2. Average nighttime and daytime amplitude variation method

In the second method of data analysis, the average amplitudes of the VTX signal were analyzed when the TRGCP was in complete darkness (12–18 UT) and in complete daylight (01–06 UT) for the period 9–22 December 2006. The mean signal amplitudes for these days are presented in Fig. 3. Intervals when the transmitter was off have been removed to avoid any discrepancies in the mean values. The day of the earthquake is identified by an arrow on the bar graph. It can be seen that the average signal strength is generally higher in the nighttime than the daytime. However, the average nighttime signal strength began to decline from 15 December, reaching a minimum of around 31 dB on 17–18 December and then increasing after the day of the earthquake to reach the previous level of just over 36 dB on 21 December. This decrease of about 5 dB is clearly evident on 18 December as compared to that on 14 December. Similarly, the daytime average signal strength decreased from about 30 dB on 14 December to around 27 dB on 15 December, and returned to the pre-event level on 22 December.

These declines in the average signal strengths indicate a decrease in the ionospheric reflection height both during the night and day starting at least 3 days before the earthquake and recovering to the pre-earthquake levels in about 3–4 days after the earthquake. The decrease in the signal strength is due to higher attenuation to VLF propagation in the Earth-ionosphere waveguide, as the attenuation depends upon the reflection height of the VLF signals, where higher height corresponds to lower attenuation (Kumar et al., 2008). The fractional change in the average signal amplitude is higher in the nighttime than the daytime; therefore, we assume that the nighttime reflection height is lowered more when compared to the daytime reflection height. In this analysis of nighttime and daytime signal strengths, any apparent significant variations in the signal amplitude due to phenomena such as lightning-associated electron density perturbation events in the lower ionosphere of typically 10–100 s duration (usually referred to as early VLF events/Trimpis) and solar flares typically of few minutes to an hour cannot cause the decrease in daily averaged amplitude and have been ruled out in comparison to earthquake associated effects.

4.3. Nighttime fluctuation (NF) method

A statistical analysis of nighttime signal fluctuation was conducted to check for any change in the nighttime signal fluctuation around the time of earthquake occurrence, as previously reported by researchers (Maekawa et al., 2006; Kasahara et al., 2008, 2010; Hayakawa et al., 2011). We used for our analysis the method suggested by Hayakawa et al. (2010a, 2010b) and described in Section 3. The nighttime $dA(t)$ values for the period 14–22 December have been plotted in Fig. 4. As the signal strength at any time can fall below or go above an average value, the $dA(t)$ values, represented by the shaded regions in the graph, varied in both directions. The level of $dA(t)$ can thus be interpreted from the depth of the shaded regions in either direction prior to and after the earthquake day. However, only the quantity $dA(t)<0$ is essential for seismogenic effects because the mean nighttime amplitude is found to decrease around the day of the earthquake (Rozhnoi et al., 2004; Hayakawa et al., 2011). Inspection of Fig. 4 reveals an increase in the occurrence of $dA(t)<0$ values between 15–19 December but this reduces after 19 December. The increases in $dA(t)<0$ are marked by dashed ellipses in Fig. 4 to show the periods when enhanced fluctuation was evident.

For statistical analysis, we have used $dA(t)$ values to estimate the following three parameters; (1) trend (T), which is the average of nighttime $dA(t)$ values for each day; (2) nighttime fluctuation (NF), estimated by integrating $[dA(t)]^2$ values over the respective nighttime hours; and (3) dispersion (D), which is the standard deviation of $dA(t)$ values for each day. Hayakawa et al. (2010b) proposed additional statistical quantities for better analysis of VLF data to avoid variability in different propagation paths, called the normalized values of trend (Trend*), normalized nighttime fluctuation (NF*), and normalized dispersion (D^*). The normalized trend is calculated using the formula $T^*=(\text{trend}-\langle\text{trend}\rangle)/\sigma_T$, where the trend is calculated for each day, $\langle\text{trend}\rangle$ is the average trend for $\pm$ 15 days around the earthquake day, and σ_T is standard deviation of the trend for the selected days. In a similar way the NF* and D^* are calculated.

The statistical results are presented in Fig. 5(a–f). The trends for the days during the period 14–22 December do not exceed the 2σ mark, however, a notable decline is noticed for 16–18 December in Fig. 5a. Fig. 5b indicates significant enhancement in NF during 16–19 December (at least 3 days before the earthquake) which exceeds the 2σ criterion indicative of seismo-ionospheric effects as pointed out by Hayakawa et al. (2010a). The dispersion during this period remains above the 2σ mark for each day because of its high variability from a standard mean value. As can be seen from Fig. 5

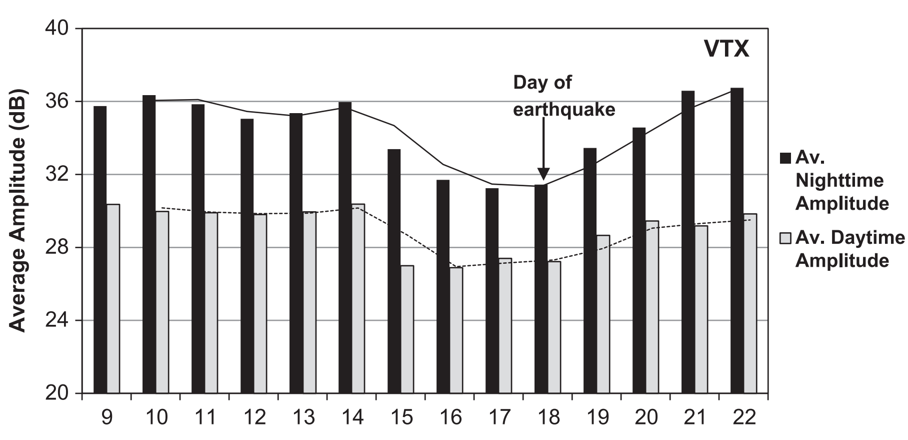

Fig. 3. Average values of the nighttime and daytime VTX signal amplitudes for the period 09–22 December 2006. The day of the earthquake is marked by an arrow.

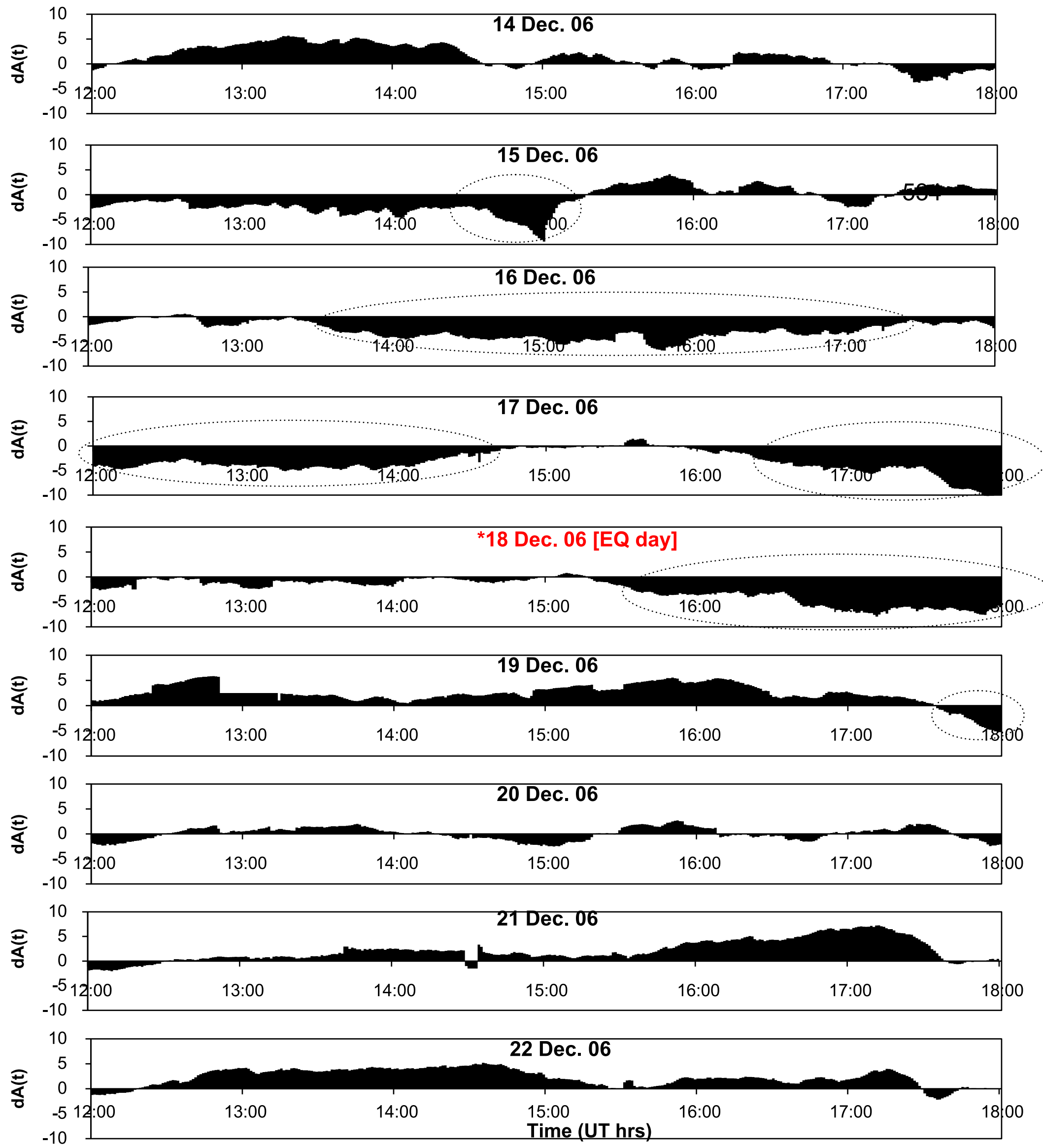

Fig. 4. Plots showing the fluctuation in the nighttime signal strengths (in dB plotted on the y-axis) during the period 14–22 December 2006. An increase in the occurrence of $dA(t) < 0$ conditions is apparent from 15 to 19 December 06 during certain times of the nights (marked by dashed ellipses).

(d–f) the normalized values, Trend*, NF*, and Dispersion* do not increase above the 2σ mark for any day during the selected period of data analysis. Therefore, this method does not prove very promising in identifying any seismo-ionospheric effects in our case. A possible reason for ineffectiveness of this method could be the high signal variability of VTX signal received at Suva over the very long propagation path. The rate of occurrence of strong lightning around the VTX-Suva TRGCP and the earthquake epicenter is relatively high; hence, the signal variability due to lightning cannot be completely ruled out. The World-Wide Lightning Location Network (WWLLN) detected lightning events which are identified with blue spots in Fig. 6 for the period 14–21 December 2006. WWLLN data provides the time and location of global lightning events with return stroke currents of more than ~50 kA (only strong lightning) with spatial and temporal accuracy of roughly 10–20 km and 10 μs, respectively (Rodger et al., 2006). The plots of the WWLLN detected lightning reveal a high occurrence of strong events which continue to evolve throughout the period of data analysis around the VTX-Suva TRGCP and close to the Indonesia region. Some of these lightning events may have caused short-term VLF perturbations as a result of lightning induced electron density enhancement in the D-region ionosphere, thereby producing high signal variability.

5. Discussion

The VLF propagation anomalies reported here are consistent with previous reports, showing possible seimo-ionospheric effects at least 3 days before a major earthquake and lasting for at least few days after the earthquake. Maekawa et al. (2006) reported such effects starting 2–6 days prior to an earthquake, Kasahara et al. (2008) reported ~5 days, and Hayakawa et al. (2010b) obtained 5 days for trend, 3 days for dispersion, and 6 days for nighttime fluctuation.

Other phenomena which may affect VLF propagation include solar flares with durations <30 min, gamma ray flashes (similar in duration to the solar flares), direct effects of lighting induced perturbation with short durations (as early/fast Trimpis) (Dowden et al., 1994; Inan et al., 1996; Rodger, 1999). These effects, however,

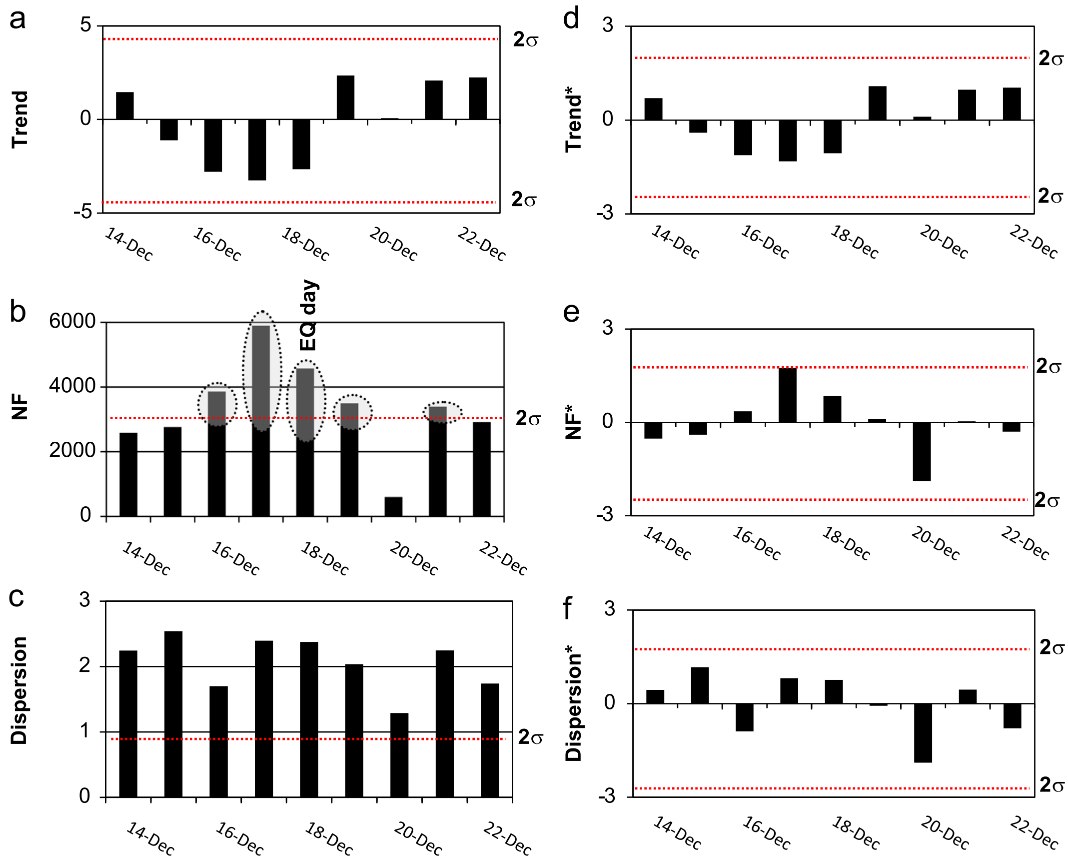

Fig. 5. Statistical test results for the trend (panel a), nighttime fluctuations, NF (panel b), and dispersion (panel c) during the period 14–22 December 2006. The 2σ criterion is represented by dashed red horizontal lines. The NF shows an increase over the 2σ mark as indicated by shaded ellipses in panel (b). The panels (d–f) on the right side give the normalized values of the trend, NF, and dispersion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

can easily be identified and removed while analyzing the data because we know the exact time and duration of these phenomena. The other factor to complicate the situation might be geomagnetic storms.

A geomagnetic storm (Kp=8+, Dst∼−155 nT) occurred during the period of data analysis, commencing on 15 December 2006 and completely subsided by the end of 16 December. To ensure that the effects reported here were seismo-ionospheric and not related to this storm, two further VLF transmitter signals were analyzed for the same days presented here. These were from NWC (19.8 kHz, lat. 21.8°S, long. 114.2°E) and NPM (21.4 kHz, lat. 21.4°N, long. 158.2°W), both received at Suva with great circle paths far away from the earthquake epicenter. The NWC-Suva propagation path is mostly west–east and passes over land and sea at low latitudes, whereas the NPM-Suva path has north–south as well as east–west components traversing the equator mainly over the sea in the low latitude region. There were no TT shifts noticed for NWC and NPM signals during the period of data analysis (though not shown here). The average daytime and nighttime signal strengths for NWC and NPM are plotted in Fig. 7 for the period 14–22 December, which may be compared with Fig. 3 for VTX. As a result of the storm the average daytime signal strength decreased on 15 December by ∼2.5 dB and ∼1 dB for NWC and NPM, respectively. This decrease exceeds the daytime day-to-day variability (∼0.2 dB) both for NWC and NPM signals. However, the signal amplitude recovered partially on 16 December and completely by the start of 17 December. No apparent changes in the average nighttime NWC and NPM signal strengths were observed.

To check the effect of the recovery phase of any storm on the VTX signal amplitude, the amplitude data of VTX, NWC and NPM signals during another geomagnetic storm which occurred on 05–06 April 2010, but in the absence of any earthquake, were also analyzed. No effect was seen on the amplitudes of these signals, indicating that there is no effect of the recovery phase of storms on the lower ionospheric VLF reflection heights.

Kleimenova et al. (2004) studied storm effects on VLF propagation of the NWC signal received at Kamchatka (lat. 53.1°N, long. 158.9°E), Russia, with a transequatorial path in the north-east direction during six magnetic storms in 2000. They found that the VLF phase and amplitude decreased mainly in the nighttime during the main phase of the storm, indicating that the effective altitude of wave reflection was lowered. However, in our case both the average daytime and nighttime VTX signal amplitudes remained low until 18 December as shown in Fig. 3 and only recovered fully on 21 December. The amplitude decrease of ∼1 dB on the transequatorial NPM signal due to the 15–16 December geomagnetic storm could have had a similar effect on the VTX signal but the decline in the average signal strength of the VTX signal (3 dB in the daytime, 5 dB in the nighttime) on 17–18 December recovering completely on 21 December indicates that this amplitude decline was most likely earthquake related. The 15–16 December geomagnetic storm could have played some role in changing the average signal amplitudes for all three signals during the period 15–16 December only, but the absence of any shift in TTs on NWC and NPM signals compared to a maximum shift of ∼20 min on VTX lends further support to the argument that this effect is mainly seismo-ionospheric related. It is also important to note that a number of earthquakes with strengths greater than 7.0 occurred during the period of data analysis but with no effects on VLF propagation, as shown in Table 1. The distinguishing feature of the 18 December 2006 earthquake is that its epicenter was the closest to the VTX-Suva TRGCP (∼45 km)

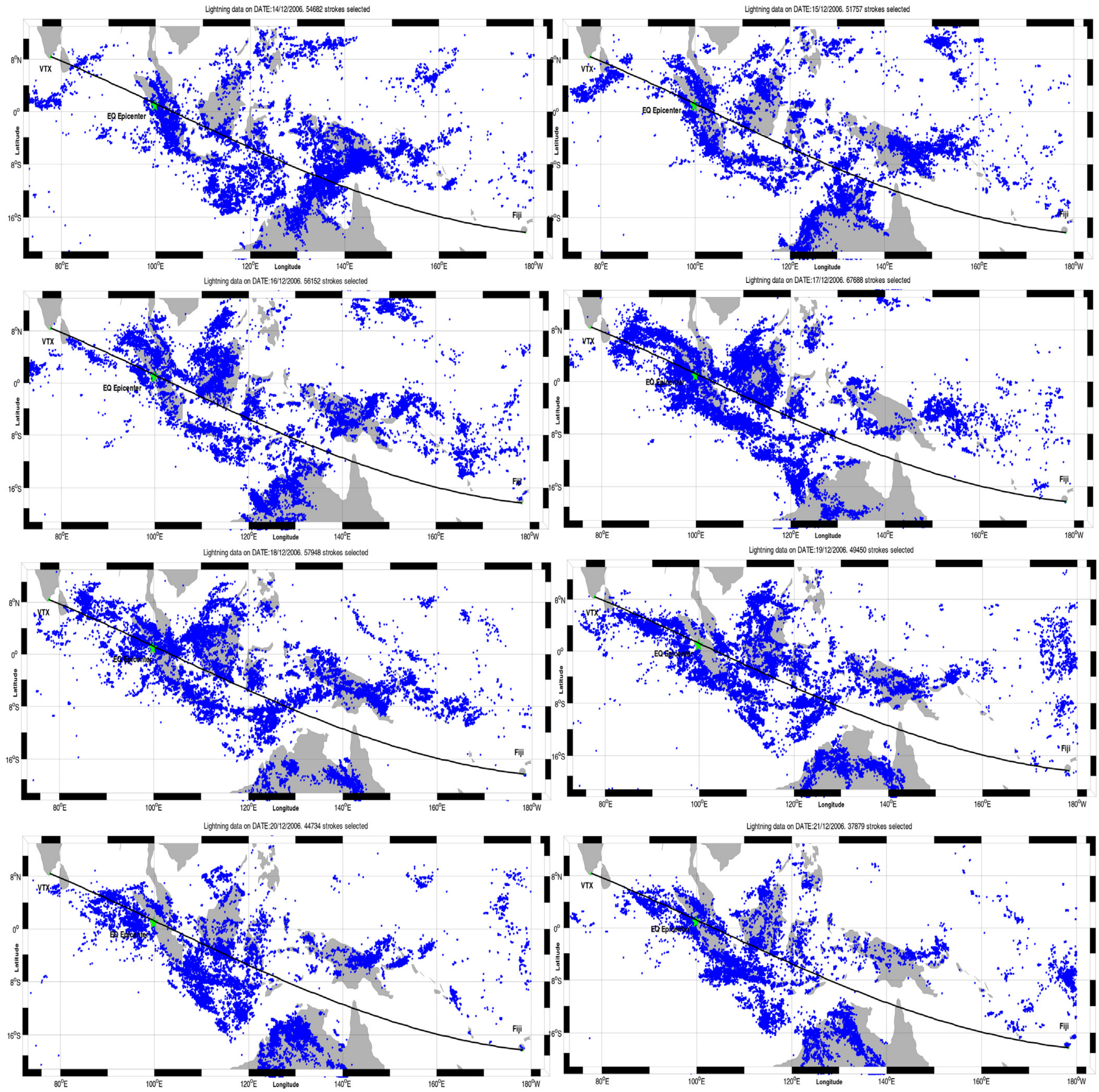

Fig. 6. World-Wide Lightning Location Network detected lightning locations are plotted (blue spots) for each day for the period 14–21 December 2006. The evolution of strong lightning around the VTX-Suva TRGCP during this period could be responsible for high signal variability during nighttime resulting in indistinguishable statistical nighttime fluctuations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

when compared to the other earthquakes. The next closest earthquake, which occurred on 20 February 2008, was located about 90 km away from the TRGCP but did not show any effect on the VLF propagation. Similarly, all other earthquakes also did not show any anomaly perhaps because their epicenters were far away from the TRGCP (> 200 km) or their depth of occurrence was large. An earthquake at a depth of 53 km such as the one reported here may be considered a deep earthquake (> 40 km) (Hayakawa et al., 2010b), but this depth can be considered a marginal value for producing ionospheric perturbations (Maekawa et al., 2006) and effects of earthquakes at greater depths (depth = 108 km, magnitude = 6.8) have been previously reported by Hayakawa et al. (2010a). Therefore, it seems likely that for any earthquake effects to be observed on very long VLF propagation paths such as the VTX-Suva, the epicenter of the earthquake has to be located close (< 50 km) to the TRGCP and the earthquake has to be shallow. However, this is still an area of further experimental research.

Finally, we speculate on possible mechanisms by which ionospheric perturbations are formed due to seismic activity. This is not the main point of the paper and we restate hypotheses previously proposed by Hayakawa et al. (1996) and Molchanov and Hayakawa (2008). The three likely mechanisms are: (1) chemical processes (and electric field effects) in the ionosphere; (2) acoustic and gravity

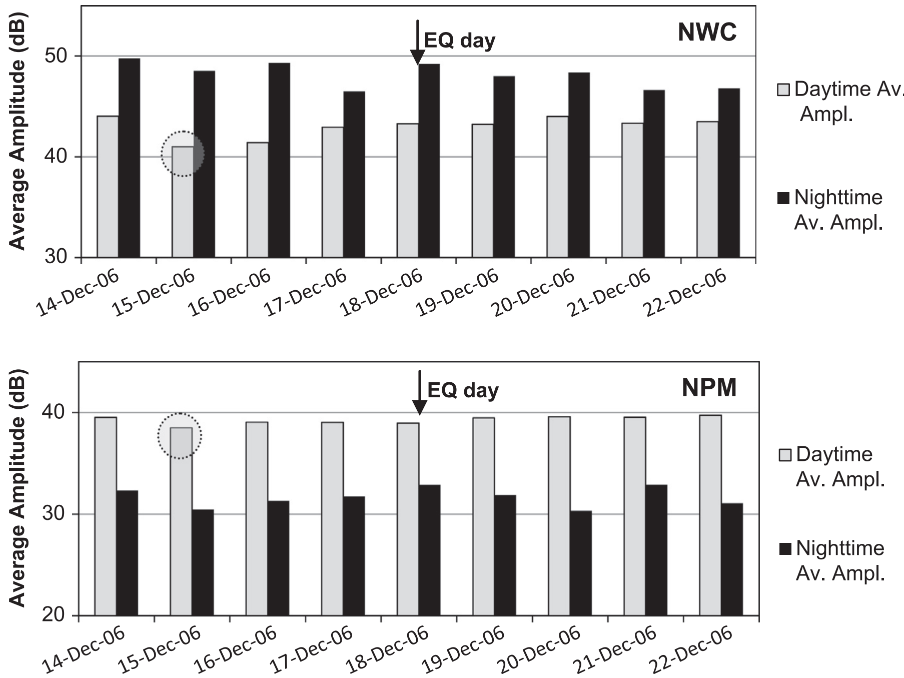

Fig. 7. Average values of the nighttime and daytime signal amplitudes for the period 14–22 December 2006 for NWC and NPM. No apparent change in the average daytime and nighttime signal strengths can be noticed on the day of the earthquake marked by an arrow. A slight decrease in the average daytime signal strength on 15 December is shown using shaded circles; this can be attributed to the geomagnetic storm of 14–15 December 2006. Compare with Fig. 3 for the VTX-Suva path which passed near the earthquake epicenter.

wave channels; and (3) electromagnetic channels. Regarding the first process, geochemical quantities (e.g., surface temperature, radon emanation) may induce perturbations in the conductivity of the atmosphere which leads to ionospheric modification through the atmospheric electric field (e. g., Pulinets and Boyarchuk, 2004; Sorokin et al., 2006). Xu et al. (2011) have shown that there was an anomalous enhancement of electric field in the ionosphere close to the epicenter with maximal amplitude $\sim$2 mV/m (about 10 times the background) going up to the F2-region in relation to the Wenchuan earthquake in China.

The second method concerns the role of atmospheric oscillations in the lithosphere–atmosphere–ionosphere coupling and perturbations of the Earth's surface (e.g., temperature, pressure) in a seismo-active region which excites the atmospheric oscillations traveling up to the ionosphere and coupling to ionospheric density perturbations (e.g., Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2004). Hao et al. (2012) reported evidence of earthquake-excited infrasonic waves by a multi-instrument observation of Japan's Tohoku earthquake (magnitude 9.0). The effects of surface oscillations were observed by local infrasonic detectors suggesting that these effects were due to surface oscillation-excited infrasonic waves instead of the direct influence of seismic vibration. The local excited infrasonic waves propagated both horizontally and upward and caused ionospheric disturbances as observed by Doppler shift and GPS/TEC measurements.

The third mechanism deals with electromagnetic radio emissions (in any frequency range) generated in the lithosphere and propagating up to and modifying the ionosphere, thereby heating and/or ionizing it. We think the electric field effect and acoustic and gravity wave processes to be more likely responsible for VLF perturbations observed here, as suggested by Hayakawa et al. (2010b). The last mechanism of electromagnetic wave generation is less likely because of the weak intensity of lithospheric radio emissions (Molchanov et al., 1993). Further analysis (either experimental or theoretical) should be carried out before arriving at any conclusions as to which mechanism would be more probable in the lithosphere–ionosphere coupling.

6. Summary

VLF amplitude data for the 18.2 kHz VTX transmission received at Suva, Fiji, during December 2006–October 2010 has been analyzed to study any possible seismo-ionospheric effects due to earthquakes occurring along the great circle path, mainly around the Indonesia region. This is the first time that the effect of earthquakes on a very long VLF propagation path ($\sim$11,400 km) has been observed, at least for one earthquake event. The 18 December 2006 earthquake (magnitude = 5.8), for which the VLF propagation anomaly has been identified, occurred only $\sim$45 km off the TRGCP at a depth of 53 km. Based on our data analysis we summarize our findings as follows:

1) The sunrise TTs for this long propagation path were delayed by about 20 min on the day of the earthquake and the effect of TT shifting began at least 3 days before the earthquake and lasted for at least 3 days after.
2) The average nighttime signal strength decreased by $\sim$5 dB and the average daytime signal strength decreased by $\sim$3 dB with the effect taking place 3 days prior to the earthquake and subsiding by at least 3 days after the earthquake.
3) An increase in nighttime signal fluctuation was noticed as depicted by the increase in the quantity $dA(t) < 0$ at least three days before the earthquake event. Enhancements were noticed in NF during 16–19 December (at least 3 days before the earthquake) which exceeded the 2σ criterion indicative of seismo-ionospheric effects. The trend also declined during 16–18 December though it did not exceed the 2σ mark, while the dispersion remained above the 2σ. However, the normalized statistical parameters did not reveal any increase above the 2σ mark.
4) This analysis indicates that the earthquake effects on very long VLF propagation paths can be observed if the earthquake epicenter is located close ($<$50 km) to the TRGCP with a small depth, however, more investigations are required to verify this further.

Based on the results presented here, we conclude that the VLF propagation anomalies observed during the 18 December 2006 earthquake were indeed seismo-ionospheric related. Such effects may therefore be detected on very long propagations paths such as the one under study for earthquakes with magnitudes less than 6.0.

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