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Response of the low-latitude *D* region ionosphere to extreme space weather event of 14–16 December 2006

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Key Points:
- Strong reduction in the H′ by 15.6 km due to X1.5-class flare
- Storm time values of H′ and β were reduced by 1.2 km and 0.06 km^{-1}
- Morlet wavelet analysis shows no strong signatures of storm time gravity wave

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Abstract The response of the *D* region low-latitude ionosphere has been examined for extreme space weather event of 14–16 December 2006 associated with a X1.5 solar flare and an intense geomagnetic storm ($Dst = -146$ nT) using VLF signals from Northwest Cape, Australia (NWC) (19.8 kHz) and Lualualei, Hawaii (callsign NPM) (21.4 kHz) transmitters monitored at Suva (Geographic Coordinates, 18.10°S, 178.40°E), Fiji. Modeling of flare associated amplitude and phase enhancements of NWC (3.6 dB, 223°) and NPM (5 dB, 153°) using Long-Wave Propagation Capability code shows reduction in the *D* region reflection height (H') by 11.1 km and 9.4 km, and enhancement in ionization gradients described by increases in the exponential sharpness factor (β) by 0.122 and 0.126 km^{-1}, for the NWC and NPM paths, respectively. During the storm the daytime signal strengths of the NWC and NPM signals were reduced by 3.2 dB on 15 and 16 December (for about 46 h) and recovered by 17 December. Modeling for the NWC path shows that storm time values of H' and β were reduced by 1.2 km and 0.06 km^{-1}, respectively. Morlet wavelet analysis of signal amplitudes shows no clearly strong signatures of gravity wave propagation to low latitudes during the main and recovery phases. The reduction in VLF signal strength is due to increased signal attenuation and absorption by the Earth-ionosphere waveguide due to storm-induced *D* region ionization changes and hence changes in *D* region parameters. The long duration of the storm effect results from the slow diffusion of changed composition/ionization at *D* region altitudes compared with higher altitudes in the ionosphere.

1. Introduction

Extreme *space weather* events are a confluence of natural phenomena in different regions of Earth's environment and can have significant adverse effects on increasingly sophisticated ground- and space-based technological systems [*Baker and Allen*, 2000; *Laštovička*, 2002] as well as on subionospheric communication. Solar flares and geomagnetic storms are associated with such space weather phenomena. Solar flares affect the entire daytime ionosphere, whereas geomagnetic storms mainly affect the high-latitude ionosphere with their effects propagating toward the equatorial latitudes. Under normal conditions the solar X-ray flux is too small to be a significant source for ionizing the lowest part of ionosphere (*D* region), ranging from ~60 to 75 km altitude in the daytime and ~75–95 km at the nighttime [*Hargreaves*, 1992]. However, when solar flares occur, the X-ray flux increases significantly at wavelengths below 1 nm, penetrating into the daytime *D* region and markedly increasing the ionization of neutral constituents (particularly nitrogen and oxygen) hence increases the electron density. The *D* region ionosphere can be characterized by two parameters; reference height H' in kilometer (km) and the exponential sharpness factor β in km^{-1} [*Wait and Spies*, 1964] which can be significantly changed by solar flares [*Thomson et al.*, 2004, 2005].

The *D* region is too high for balloons to probe and too low for satellite measurements but can be diagnosed using very low frequency (VLF: 3–30 kHz) electromagnetic waves which are guided within the naturally formed spherical waveguide formed between the Earth and the *D* region boundary known as Earth-ionosphere waveguide (EIWG). The *D* region response to geomagnetic storms using VLF and low frequency (LF: 30–300 kHz) radio wave amplitude and phase measurements has been studied at middle and high latitudes [e.g., *Kikuchi and Evans*, 1983; *Kleimenova et al.*, 2004]; and absorption measurements at medium frequency (MF: 0.3–3 MHz) and high frequency (HF: 3–30 MHz) have also shown storm time daytime *D* region ionospheric effects. *D* region

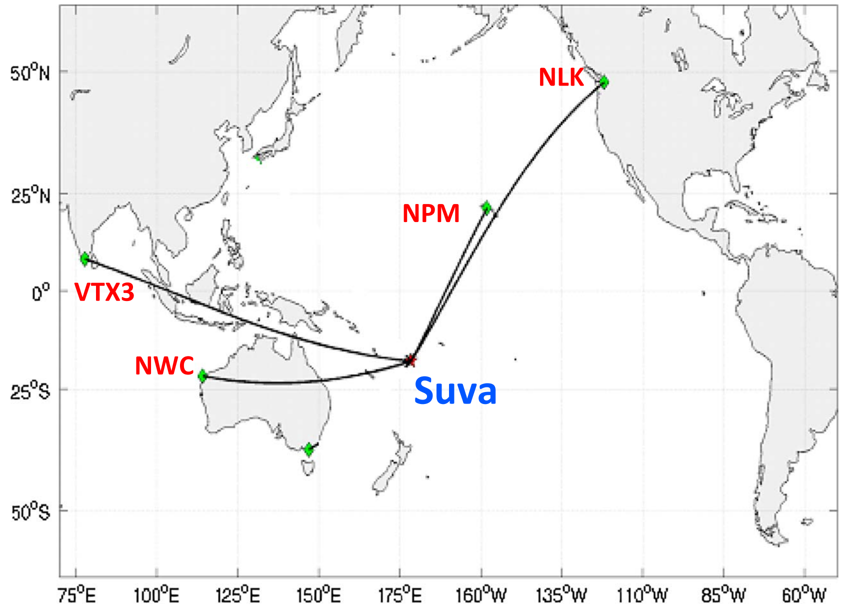

Figure 1. Map showing the positions of the four VLF transmitters, the receiving station, and their transmitter-receiver great circle paths.

storm effects can be characterized as a "primary storm effect" when occurring during the main phase onset of the storm and as a "storm after effect" when occurring during the storm recovery phase [*Araki*, 1974]. *Araki* [1974] analyzed the relative phase of Northwest Cape (NWC) (Geog. latitude 21.82°S, longitude 114.17°E; geomagnetic latitude 32.30°S) VLF signal (22.3 kHz) received at Uji (Geog. latitude 34.54°N'), Japan, during September 1967, and found that anomalous phase decreased during nighttime associated with the main phase of two large geomagnetic storm groups. The NWC-Uji path mostly lies at low latitudes with only a small component in the middle latitude region. Spectral analysis of the NWC signal (19.8 kHz) received at Kamchatka (Geog. latitude 53.15°N), Russia, for six geomagnetic storms during 2000 by *Kleimenova et al.* [2004] found negative phase and amplitude variations of the VLF signal during day and night during the main phase of intense storms, but the nighttime variations were more pronounced. The NWC-Kamchatka path lies at low latitudes with a significant component at middle latitudes. Thus, geomagnetic storm-associated changes in *D* region parameters and its response to geomagnetic storms for completely low latitude paths are still not well known.

In this work we discuss an unusual decrease in the amplitude of VLF signals from North West Cape (NWC), Australia, and NPM, Hawaii (Geog. 21.42°S, 158.15°W; geomagnetic 17.30°S) recorded at Suva (Geog. 18.1°S, 178.4°E), Fiji, a low-latitude station, during the intense geomagnetic storm ($Dst = -146$ nT) of 14–16 December 2006. A storm with $-200 \leq Dst < -100$ nT is classified as intense storm [*Gonzalez et al.*, 1994]. The NWC-Suva and NPM-Suva paths lie purely in the low-latitude region of $L < 1.5$, where electron precipitation is very unlikely to occur [*Voss et al.*, 1998]. The intense storm of 14–16 December was associated with a X1.5-class solar flare and halo coronal mass ejection (CME) on 14 December 2006. The changes in *D* region parameters associated with this storm and the X1.5 solar flare have been estimated using the Long-Wavelength Propagation Capability (LWPC) code version 2.1. Morlet wavelet analysis of storm time amplitude of NWC and NPM signals has also been performed to look for the signatures of gravity waves at low latitudes associated with this storm. We find short-lived flare effects and longer duration storm effects during the storm main and recovery phases.

2. Data Sources and Analysis

Subionospheric VLF signals from the NWC (19.8 kHz) and Lualualei, Hawaii (NPM) (21.4 kHz), MSK VLF transmitters were monitored at Suva, Fiji, with a time resolution of 0.1 s using GPS-based timing and the Software-based Phase and Amplitude Logger (termed "SoftPAL"). In this paper we present 1 min averaged amplitude and phase data. The positions of these VLF transmitters, the Suva receiving station, and the respective transmitter-receiver great circle paths (TRGCPs) are given in Figure 1. The TRGCP propagation distances are 6.67×10^6 m for NWC and

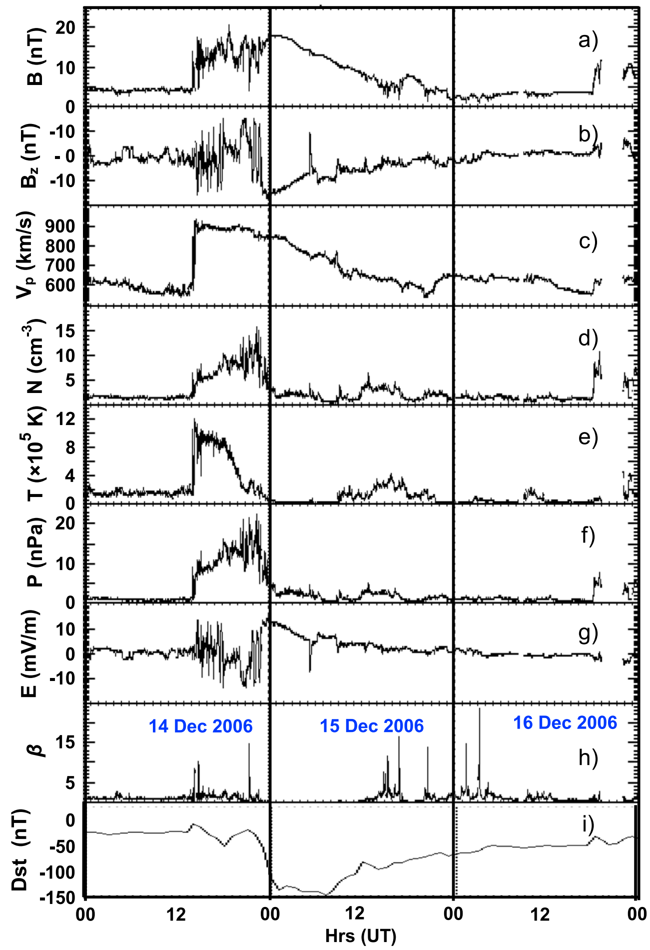

Figure 2. Geophysical conditions for the 14–16 December 2006 magnetic storm, caused by a shock compression, southward turning of *Z* component of interplanetary magnetic field (IMF) and followed by a magnetic cloud. Interplanetary parameters are (a) interplanetary magnetic average field *B* (nT), (b) *Z* component of IMF B_Z (nT) in GSM coordinates, (c) solar wind flow velocity V_p (km/s), (d) solar wind proton density N_p/cc, (e) solar wind thermal temperature *T*, (f) solar wind flow pressure *nPa*, (g) solar wind electric field *E*, and (h) plasma β. (i) The *Dst* variation.

5.08×10^6 m for NPM transmitters to Suva. The TRGCPs of VTX3 (18.2 kHz) and NLK (24.8 kHz) to Suva are also shown in Figure 1 on which effects of X1.5 solar flare are presented here.

Solar flare-induced perturbations in the amplitude (ΔA) of these VLF transmissions were determined using the method given by *Todoroki et al.* [2007]. The value of ΔA is obtained by $\Delta A = A_{\text{peak}} - A_{\text{background}}$, where A_{peak} is the value of peak amplitude during the solar flare and $A_{\text{background}}$ is the monthly mean value of amplitude at the time of peak amplitude. The flare-induced perturbation in the phase ($\Delta\phi$) is obtained by $\Delta\phi = \phi_{\text{peak}} - \phi_{\text{background}}$, where ϕ_{peak} is the value of peak phase during the solar flare and $\phi_{\text{background}}$ is the phase just before occurrence of flare.

Solar X-ray fluxes are recorded in two wavelength bands by the X-ray imager on the Geostationary Operational Environmental Satellites (GOES): (1) 0.1–0.8 nm, referred to as “long” or “XL,” and (2) 0.05–0.4 nm, referred to as “short” or “XS”. Solar flares are classified in A, B, C, M, and X classes according to the peak flux (in W/m^2) in the XL band, with class-A flares being the weakest and class X the strongest. For this study solar flux data in the XL band were obtained from the website http://spidr.ngdc.noaa.gov/spidr/dataset.do as 1 min averages.

Interplanetary magnetic field and solar wind parameters were obtained from the National Space Science Data Center, NASA/Goddard (http://nssdc.gsfc.nasa.gov/omniweb). In addition the geomagnetic indices *Dst* and *Kp* were obtained from the World Data Center (http://wdc.kugi.kyoto-u.ac.jp/), Kyoto University, Kyoto, Japan. The hourly values of f_oF_2 and *h′F* recorded with the ionosonde at Niue (Geog. 19.06°S, 169.93°W) and Townsville (Geog. 19.63.2°S, 146.85°E) were downloaded from the Ionospheric Prediction Service (IPS) Radio and Space Services (http://www.ips.gov.au/World_Data_Centre), Australia.

3. Results

3.1. Interplanetary Origin of the Geomagnetic Storm of 14–15 December 2006

The intense magnetic storm of 14–16 December 2006 was associated with a CME and a shock compression followed by a magnetic cloud [*Lei et al.*, 2008]. The shock occurred on 14 December at 1410 UT when the solar wind increased abruptly from 650 km/s to 980 km/s. Figure 2 shows the time history of various interplanetary parameters and geomagnetic activity associated with this storm, adjusted for travel time to the bow shock nose. A sudden storm commencement occurred at 1414 UT on 14 December. Figure 2b shows that this day B_Z turned northward at about 1805 UT and then clearly turned southward (negative)

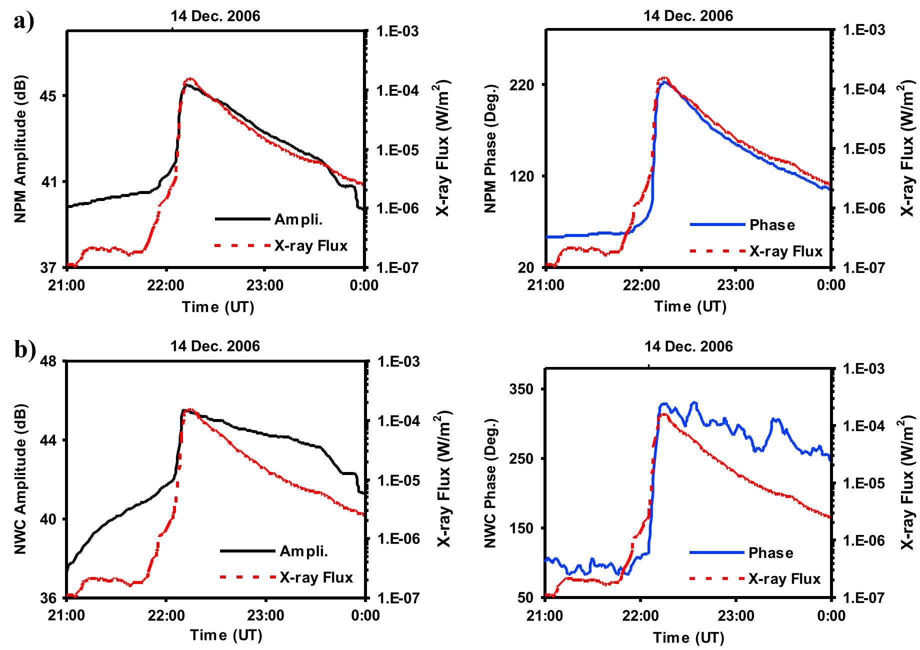

Figure 3. Variation in the amplitude (black lines) and phase (blue) of low-latitude VLF signals, and GOES X-ray flux (red), during the solar flare on 14 December 2006. (a) The NWC-Suva path. (b) The NPM-Suva path.

around 2100 UT and attained a value of −17 nT at around 2310 UT. There were rapid northward and southward fluctuations of B_Z between 18 and 19 UT. B_Z then sharply turned southward and remained southward for more than 24 h with a gradual recovery. Minimum *Dst* (= −147 nT) occurred at 0800 UT on 15 December, indicative of an intense storm, and *Kp* value reached a maximum of 8 at 0300 UT on 15 December. Several workers have studied the interplanetary parameters associated with this 14–15 December storm [e.g., *Lei et al.*, 2008; *Wang et al.*, 2010].

The subionospheric VLF perturbations (NWC, NPM) due to the solar flare on 14 December 2006, and associated *D* region perturbations estimated from NWC and NPM signal perturbations, are presented in sections 3.2 and 3.3, respectively. The longer duration perturbations in the amplitude of subionospheric *D* region signals from the NPM and NWC transmitters associated with this storm are presented in section 3.4.

3.2. VLF Perturbations Associated With the Solar Flare on 14 December 2006

The X1.5-class solar flare occurred on 14 December 2006 at 2107 UT and ended at 2226 UT, with its peak flux at 2215 UT. The effect of this flare was apparent on the amplitudes of four transmitter signals (NWC, NPM, VTX3, and NLK) and the phases of NWC and NPM. Since the phases of VTX3 and NLK signals are unstable, no clear effect could be identified on their phases. During this solar flare, the TRGCP of the VTX3 signal was partly in daylight but the TRGCPs of NPM, NWC, and NLK were in complete daylight. We present here the amplitude and phase perturbations (ΔA, $\Delta\phi$) only for the NWC and NPM signals, whose TRGCPs lie in the low-latitude regions (Figure 1). These are shown with the corresponding solar flux intensity in Figures 3a and 3b. The values of ΔA were found to be 3.6 and 5 dB for NWC and NPM signals, respectively. The changes in phase were $\Delta\phi = 223°$ and 153° for NWC and NPM, respectively.

It can be seen that the amplitude and phase signals rose in proportion with the flux intensity but do not return to the preevent level linearly with the decrease in flux. This indicates that the ionization enhancement can remain for some time even if the X-ray flux is decreased before the ionosphere settles back to its initial state through attachment and recombination processes. These ΔA and $\Delta\phi$ values for the NWC and NPM transmitters have been used to estimate the *D* region changes associated with the solar flare on 14 December 2006.

3.3. *D* Region Changes Associated With the Solar Flare on 14 December 2006

To determine the *D* region electron density changes associated with the solar flare, the observed VLF amplitude and phase perturbations are modeled using the Long-Wavelength Propagation Capability (LWPC)

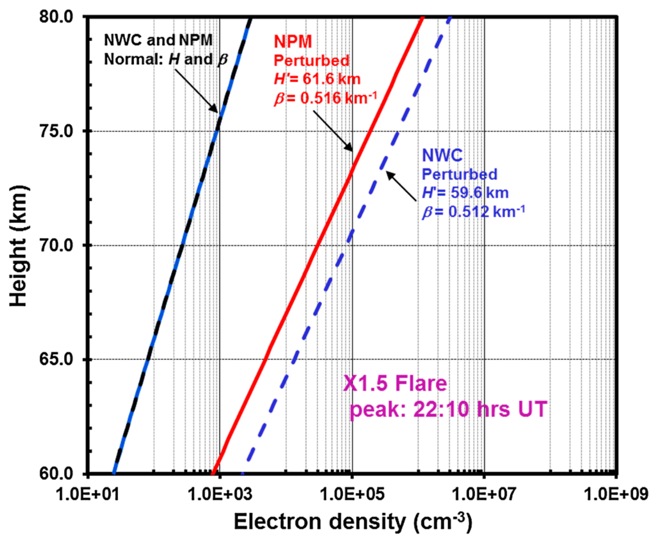

Figure 4. The perturbed electron density determined by LWPC VLF modeling for the X1.5 solar flare on 14 December 2006 with peak at 22:10 UT for NPM (solid red line) and NWC (dashed blue line) compared with normal unperturbed electron density for NPM (solid blue line) and NWC (dashed black line) to Suva paths. The electron density is almost the same under normal condition for both the paths.

model V2.1 for Wait's model of the lower ionosphere characterized by two parameters: the sharpness (β in km^{-1}) and reflection height (H' in km). The solar zenith angle values for mid-TRGCPs for both signals at the time of peak occurrence of solar flare, at 2215 UT, were calculated and then used to estimate the values of H' and β by using the relationship given by *McRae and Thomson* [2000]. This gives $H' = 70.7$ km and $\beta = 0.390$ km^{-1} for the NWC-Suva path and $H' = 71.0$ km and $\beta = 0.390$ km^{-1} for the NPM-Suva path, respectively, for the unperturbed daytime ionosphere and the corresponding amplitude (A) and phase (ϕ).

By varying the values of β and H' as to match the observed perturbed amplitude ($A + \Delta A$) and phase ($\phi + \Delta\phi$), new values of H' and β for solar flare perturbed ionosphere were obtained with the LWPC 2.1 code. These values are H' = 59.6 km and $\beta = 0.512$ km^{-1} for the NWC-Suva path and $H' = 61.6$ km and $\beta = 0.516$ km^{-1} for the NPM-Suva path, respectively. This gives decrease in H' ($\Delta H'$) by 11.1 km and 9.4 km, and increase in β ($\Delta\beta$) by 0.122 and 0.126 km^{-1}, for the NWC and NPM paths, respectively. *McRae and Thomson* [2004], using LWPC modeling for X3.0-class flare, on NLK to Dunedin path, New Zealand, estimated the decrease in unperturbed H' from 71 to 59 km ($\Delta H' = 12$ km) and increase in β from 0.39 km^{-1} to 0.52 km^{-1} ($\Delta\beta = 0.13$ km^{-1}). They also found that the H' lowered from 71 to 58 km ($\Delta H' = 13$ km) and β increased from unperturbed value of 0.39 km^{-1} to a saturation level of 0.52 km^{-1} ($\Delta\beta = 0.13$ km^{-1}) for X5-class flare. Thus, our results for X1.5-class flare on the NPM to Suva path with the $\Delta H' = 9.4$ km and $\Delta\beta = 0.126$ km^{-1} and for NWC to Suva path with the $\Delta H' = 11.1$ km and $\Delta\beta = 0.122$ km^{-1} are very similar to the results of *McRae and Thomson* [2004]. *Tan et al*. [2014], using amplitude observations of NWC signal in Vietnam, modeled the D region during solar flares and found that H' lowered from 74 to 60 km and β increased from unperturbed value of 0.3 km^{-1} to a level of 0.434 km^{-1} for X1.2 class flare. By extrapolating the phase profiles during the strong solar flares, *Thomson et al*. [2005] estimated the peak value of the X-ray flux that corresponded to solar flare of X45 class. They estimated that during this great flare (X45), the H' lowered to 53 km from the normal midday value of 70 km and β increased from 0.39 km^{-1} to 0.57 km^{-1}. Thus, D region could be used as solar flare strength detector for the flares above X17 class for which GOES detector saturates.

The D region electron density height profiles $N_e(h)$ in cm^{-3} for our situation have been constructed using the Wait profile, valid up to about 100 km altitude [*Wait and Spies*, 1964], following $N_e(h) = 1.43 \times 10^7$ [exp($-0.15H'$)exp[$(\beta - 0.15)(h - H')$]. This equation has been used by several researchers for determining the electron density of D region (both day and night) ionosphere using the lightning-generated ELF-VLF sferics and the VLF signals from navigational transmitters [e.g., *McRae and Thomson*, 2004; *Thomson et al*., 2005; *Cheng et al*., 2006; *Maurya et al*., 2012; *Tin et al*., 2014]. Figure 4 shows $N_e(h)$ in the altitude range of 60–80 km both for unperturbed (blue/black) and perturbed (red solid line for NPM and blue dashed line for NWC) values of the Wait parameters are given for both paths. The electron density is almost same under normal conditions both for NWC and NPM to Suva paths. The electron density is clearly larger under solar flare conditions compared to normal conditions, which is responsible for the increase in amplitude of the signals. Also, solar flare-associated electron density is higher for NWC-Suva path as compared to NPM-Suva path.

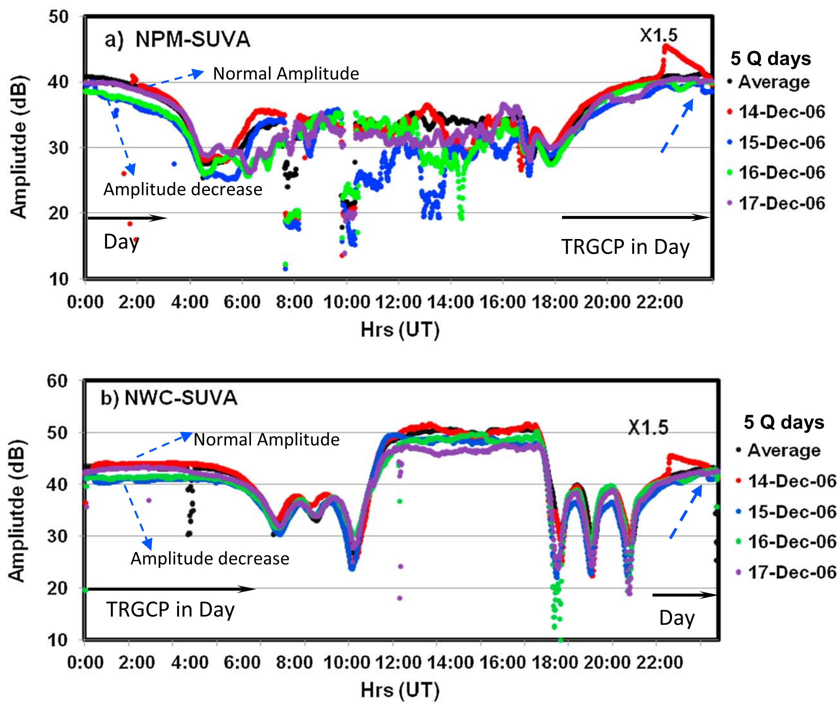

Figure 5. Diurnal variation of the amplitude of (a) NPM and (b) NWC signals for the average of 5 magnetically quiet days in December 2006 and during the 14–17 December magnetic storm. The sudden rise in amplitude at 22 UT on 14 December is due to an X1.5-class solar flare. VLF amplitude decreased on 15 December at 2310 UT indicated by dashed lines with arrow with a slow recovery until the end of 16 December.

3.4. Effect of 14–15 December 2006 Storm on Subionospheric VLF Propagation

In order to detect geomagnetic storm effect on subionospheric propagation along low-latitude paths, the amplitudes of the NWC and NPM signals recorded at Suva during the intense geomagnetic storm of 14–16 December 2006 were analyzed. Under normal conditions the amplitude of both the NWC and NPM signals over daytime TRGCPs is remarkably stable at Suva. The analysis showed that the intense geomagnetic storm of 14–16 December 2006 associated with $Dst > -146$ nT produced a significant reduction in the daytime NWC and NPM signal amplitudes of about 3.2 dB relative to the average value of amplitude over five international quiet days.

The variation of NPM and NWC signal amplitudes over 14–17 December along with average for five international quite days recorded at Suva is shown in Figure 5. Red lines represent average amplitudes over 5 quiet days. The flare enhancement effect is seen near 2210 UT on 14 December, followed by storm-related reduction in the amplitude over the next 2 days. The decrease in the amplitude (indicated by dashed lines with arrows (Figure 5)) started on 15 December at 0030 UT (1230 LT) during the main phase of the storm and the amplitude remained low until around 0800 UT on 16 December, then recovering slowly by the end of 16 December. There was no change in terminator times as the VLF modal minima were coincident both for the average quiet days and storm days both for day-night and night-day transition times.

The nighttime reduction in the signal strength cannot be seen clearly in Figure 5 because of large day-to-day variability of the *D* region. However, preliminary analysis of the average day and nighttime signal strength of the NWC signal for this storm carried out by *Kumar and Kumar* [2014] showed a reduction in the average nighttime signal strength by about 2.5 dB. The changes in the phase could not be identified as the transmitters went momentarily off air at about 02 UT (NWC) and at about 04 UT (NPM), and phase does not follow the same values as before the momentary switch off.

In summary, Figures 5a and 5b show a 2 day decrease with a maximum of about 3.2 dB, in the storm time daytime signal amplitude for both NWC and NPM, indicating a long timescale perturbation of low-latitude *D* region ionosphere. This *D* region effect persisted throughout much of the storm recovery phase shown in

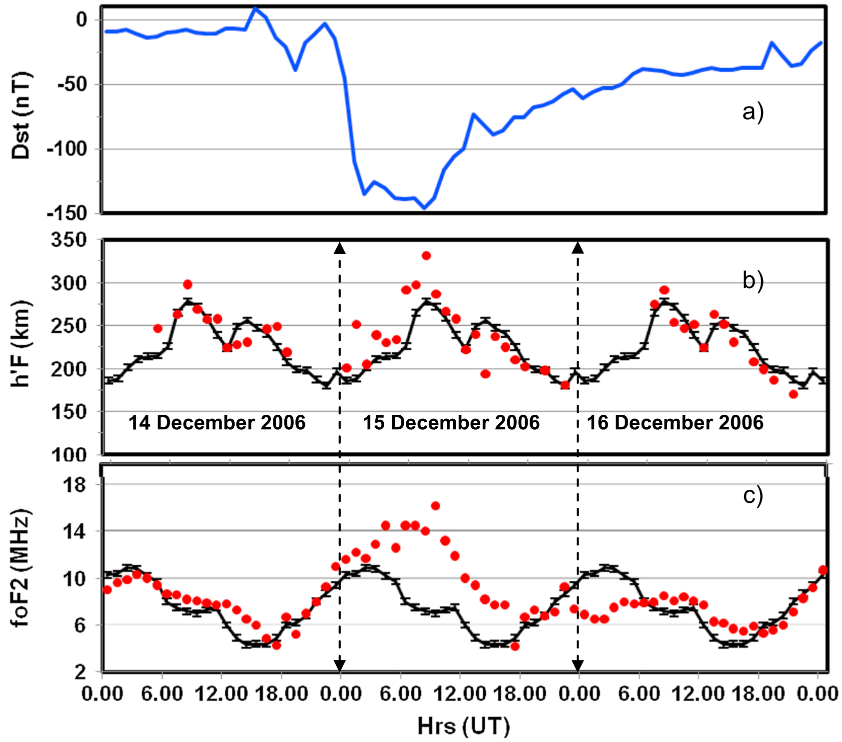

Figure 6. (a) Variation in *Dst* index for the geomagnetic storm of 14–16 December 2006. (b, c) Corresponding hourly variation of *h′F* and f_oF_2 (red solid points) over Niue (19.06.2°S, 169.93°W). The monthly median values of these parameters with standard errors are shown by solid lines.

Figure 2i. These *D* region perturbations suggest that the *F* region ionosphere in this longitude belt would also have been disturbed by this storm. *Ohya et al*. [2006] for great geomagnetic storm of October 2000 ($Dst = -182$ nT) using various radio wave techniques (including tweeks) found the lowering of the *D* region VLF reflection height coupled with vertical motion of the *F* region. To check *F* region conditions, ionosonde data for low-latitude stations, Niue (Geog. 19.06°S, 169.93°W) and Townsville (Geog. 19.63°S, 146.85°E) located near Suva's latitude, were collected from the Australian Government-Bureau of Meteorology, IPS Radio and Space Weather Services (http://www.ips.gov.au/). Both the stations did show variations in the hourly values of virtual height of *F* layer (*h′F*) and critical frequency of F_2 layer (f_oF_2) over this storm and more clearly at Niue. The variation in the hourly values of *h′F* and f_oF_2 at Niue over 14–16 December 2006 is shown by solid red points in Figures 6b and 6c. The monthly median values of these parameters with standard errors are represented by solid lines. The *Dst* index is presented in Figure 6a for comparison. An increase in f_oF_2 started near the beginning of the main phase, at about 23 UT on 14 December, with a maximum increase from 7.5 MHz to 14.5 MHz over 04–07 UT on 15 December, a 93% increase from the median value. This increase in f_oF_2 was accompanied by an increase in *h′F* with a maximum of 331 km from 281 km, at 02 UT, an 18% increase from median value. This enhancement in f_oF_2 indicates a long duration positive storm phase.

The f_oF_2 then decreased from 20 UT on 15 December and recovered at 06 UT on 16 December. The main point is that the enhancement in f_oF_2 over the median values started at 23 UT on 14 December and lasted until 19 UT on 15 December indicating a long duration positive storm phase in f_oF_2. Enhanced $\mathbf{E} \times \mathbf{B}$ vertical plasma drifts are responsible for such positive storm effects observed during the daytime. The f_oF_2 then decreased from 20 UT on 15 December and recovered at 06 UT on 16 December. So this particular storm showed both positive and negative storm phases in f_oF_2 for long durations of about 20 and 10 h, respectively, an unusual feature but may be explained due to strong and long duration changes in $\mathbf{E} \times \mathbf{B}$ plasma drift. Thus, the ionosphere was lifted at low latitudes to heights where recombination was weak allowing the plasma to exist for a long period resulting in long duration ionospheric effects, as also reported by *Wang et al*. [2010].

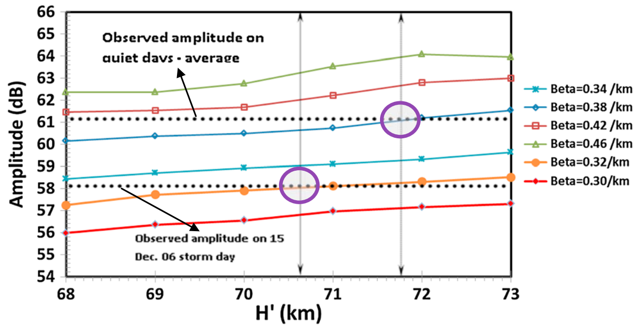

Figure 7. *D* region parameters estimated for the NWC to Suva path using LWPC VLF amplitude modeling for the 14–16 December 2006 geomagnetic storm.

Having confirmed that the entire ionosphere including the *D* region was disturbed by the 14–16 December 2006 geomagnetic storm at low latitudes in the longitudinal belt including Suva, we estimated the changes in the *D* region Wait ionospheric parameters (β in km^{-1}, H' in km) for the daytime *D* region ionosphere for NWC-Suva path using the LWPC 2.1 code as shown in Figure 7. The average amplitude on geomagnetically quiet days during the complete daylight NWC-Suva path was modeled, giving quiet daytime values of about $H' = 71.8$ km, $\beta = 0.38$ km^{-1}. To avoid any effect of transequatorial propagation anomalies, the NPM-Suva path has not been considered. To estimate the storm time H' and β, the observed value of the daytime NWC amplitude was reduced by 3.2 dB (61 dB to 57.8 dB), and correspondingly the perturbed values were estimated as $H' = 70.6$ km, $\beta = 0.32$ km^{-1} as also shown in Figure 7. Thus, associated with this storm, the values of H' and β were reduced by 1.2 km and 0.06 km^{-1}, respectively. The previous two studies [*Araki*, 1974; *Kleimenova et al.*, 2004] on geomagnetic storm effects on the *D* region ionosphere using NWC observations at Uji, Japan and Kamchatka, Russia, for low-latitude and midlatitude paths have also shown longer-term amplitude and phase changes but did not estimate the changes in H' and β.

4. Discussion

An intense geomagnetic storm associated with a solar flare and halo CME occurred on 14 December 2006. Geomagnetic storms associated with solar flares can disturb Earth's entire atmosphere and affect satellites, navigation, and communication networks. The main phase of this particular storm developed in three steps; the first step produced a minor storm with minimum *Dst* of −39 nT at 19 UT on 14 December, the second step produced an intense storm with minimum *Dst* of −135 nT at 02 UT on 15 December, further intensified by the third step to a minimum *Dst* of −146 nT at 08 UT on 15 December (Figure 2i).

An X1.5-class solar flare occurred at 2107 UT on 14 December 2006 with peak flux at 2215 UT during the first step of the main phase. The geomagnetic disturbance at this time (*Dst* −39 nT) is not expected to produce any change in the *D* region ionosphere. For example, none of the other six moderate strength storms studied by *Kumar and Kumar* [2014] produced any noticeable changes in the subionospheric signals received at this station. Therefore, the increases in the amplitude and advances in phase observed on 14 December were solely due to the X1.5-class solar flare.

The enhancement in the amplitude of VLF signals with increasing solar flare intensity can be explained qualitatively as follows. As the flare flux increases, two phenomena may take place: an increase in *D* region electron density and redistribution of electron density with height, lowering the *D* region [*Grubor et al.*, 2005]. The upper boundary of the Earth-ionosphere waveguide (EIWG) might become more sharp and lower; and as a result, VLF signals are reflected at a sharp boundary with comparatively less penetration into the *D* region and hence undergo less attenuation/absorption than under the normal propagation conditions. The LWPC modeling of the increase in the NWC and NPM signal amplitudes over normal values shows that H' decreased by 11.1 km and 9.4 km and sharpness β increased by 0.122 and 0.126 km^{-1}, respectively. Thus, the *D* region change due to the X1.5-class solar flare on 14 December is consistent to that for an X3.0-class flare discussed by *McRae and Thomson* [2004] and for an X3.2-class solar flare on 13 May 2013 analyzed by *Tan et al.* [2014]. The relatively higher effect of the X1.5-class flare could be due to the low solar activity when the 14 December flare occurred, since the *D* region ionosphere is more sensitive to solar flares [*Raulin et al.*, 2013] during low solar activity when compared with high-solar activity periods.

We now consider the observed storm time changes. The *D* region of the ionosphere has been reported to be disturbed at high latitude to midlatitude due to magnetic storm-induced energetic electron precipitation

(EEP), but this is highly unlikely for low-latitude paths such as NWC-Suva and NPM-Suva. This is supported by observations of several hundred EEP bursts by the low-altitude S81-1 satellite, with no events detected below $L \sim 1.8$ [*Voss et al.*, 1998]. Also, the EEP-induced precipitation does not last long and produces short timescale VLF perturbations [*Helliwell et al.*, 1973]. Therefore, we consider that the decrease of 3.2 dB in amplitude of the NWC and NPM signals during 14–16 December geomagnetic storm was indeed a storm effect and not related to precipitation.

The storm of 14–16 December 2006, and its consequences on ground-based technological systems and the upper ionosphere, is one of the most studied space weather events. The storm was associated with major and unusual fluctuating solar energetic particle events observed by several near-Earth spacecraft [*Rosenvinge et al.*, 2009]. *Watari* [2009] examined geomagnetically induced currents (GICs) in Hokkaido, Japan, due to 18 storms with ΔH between 82 and 272 nT over December 2005 to December 2007 and found that the most intense GIC of 3.85 A was associated with the storm of 14 December 2006. Solar radio bursts were associated with flares on 6, 13, and 14 December which drastically reduced the carrier-to-noise ratio of Global Positioning System (GPS) signals [*Carrano et al.*, 2009; *Tretkoff*, 2010]. From analysis of global ionospheric maps of total electron content and ionosonde data at four stations, *Lie et al*. [2008] reported a positive ionospheric storm in the Atlantic and American sectors during the initial phase of 14–16 December 2006. *Jesus et al*. [2010] observed ionospheric plasma bubbles after an unusual uplifting of the F region on the disturbed night of 14 and 15 December 2006, at several stations in the South American sector. Thus, the storm of 14–16 December 2006 significantly affected ground-based technological systems and the F_2 region.

Earlier observations of unusual storm effects on the D region ionosphere [e.g., *Belrose and Thomas*, 1968; *Araki*, 1974; *Kleimenova et al*., 2004] were not for purely low latitude paths. Our observations (Figure 4) show that NWC and NPM transmissions were affected significantly for about 46 h. This is a long duration but shorter than storm effects at middle and high latitudes, which can last for several days [e.g., *King and Fooks*, 1968; *Kikuchi and Evans*, 1983; *Kleimenova et al*., 2004]. These long lasting higher-latitude effects have been attributed to intense absorption due to energetic particle precipitation, which is highly unlikely along the low-latitude paths selected for this study.

Our modeling of daytime NWC amplitude during this magnetic storm shows that the D region reference height (H') of EIWG and electron density gradient (β) were reduced by 1.2 km and 0.06 km^{-1}, respectively. Attenuation by the EIWG increases with decreasing VLF reflection height [*Kumar et al*., 2008], and a decrease in the electron density gradient (i.e., decrease in β) would have caused additional attenuation resulting in a substantial decrease in the signal strength due to storm-induced D region compositional changes. Potential mechanisms for such compositional changes could be prompt penetration of the high-latitude electric fields to low latitudes during the main phase and the electric fields generated by the disturbance dynamo. The disturbance dynamo electric field is less effective in the daytime [*Blanc and Richmond*, 1980]. Considering the geomagnetically disturbed nights of 14 and 15 December, *de Jesus et al*. [2010] reported strong traveling ionospheric disturbances to the low-latitude F region at Sao Jose dos Campos (23.2°S, 45.9°W; dip latitude 17.6°S), Brazil, and Port Stanley (51.6°S, 57.9°W; geomagnetic latitude 41.6°S), due to Joule heating in the auroral region.

Atmospheric gravity waves are quasi-periodic oscillations with periods ranging between several minutes to few hours. Gravity waves in the D region are mainly of meteorological origin, but during geomagnetic storms there could be some contribution of auroral origin propagating quasi-horizontally [*Laštovička*, 2006]. *Hunsucker* [1982] in his review paper suggested that gravity waves can be generated during geomagnetic disturbances in the auroral region by the auroral electrojet and Joule heating and can propagate from high latitude to midlatitude or even to the equatorial latitudes. In order to examine the signatures of TIDs/gravity waves in the low-latitude D region associated with this storm, we have performed wavelet analysis of the NPM and NWC signal amplitudes using the Morlet wavelet technique [*Sauli et al*., 2006a; *Maurya et al*., 2014]. Figure 8 shows Morlet wavelet spectra of NPM and NWC signal amplitudes observed on 15–17 December 2006 and on one quiet day during daylight (08–15 LT) for the same TRGCPs. Nighttime periods are not considered because of the large temporal and day-to-day variability of signal amplitude in which storm-associated changes in signal amplitude are not visible. There appears to be some enhancement in intensity of wavelet spectra in the period range of gravity waves at around 10 and 1240 LT on 15 December (2200 UT on 14 December to 0010 UT on 15 December) and at ~1140 LT on 16 December on both TRGCPs, but significantly strong wave-like signature (WLS) which are manifestations of gravity waves are not evident. This may be

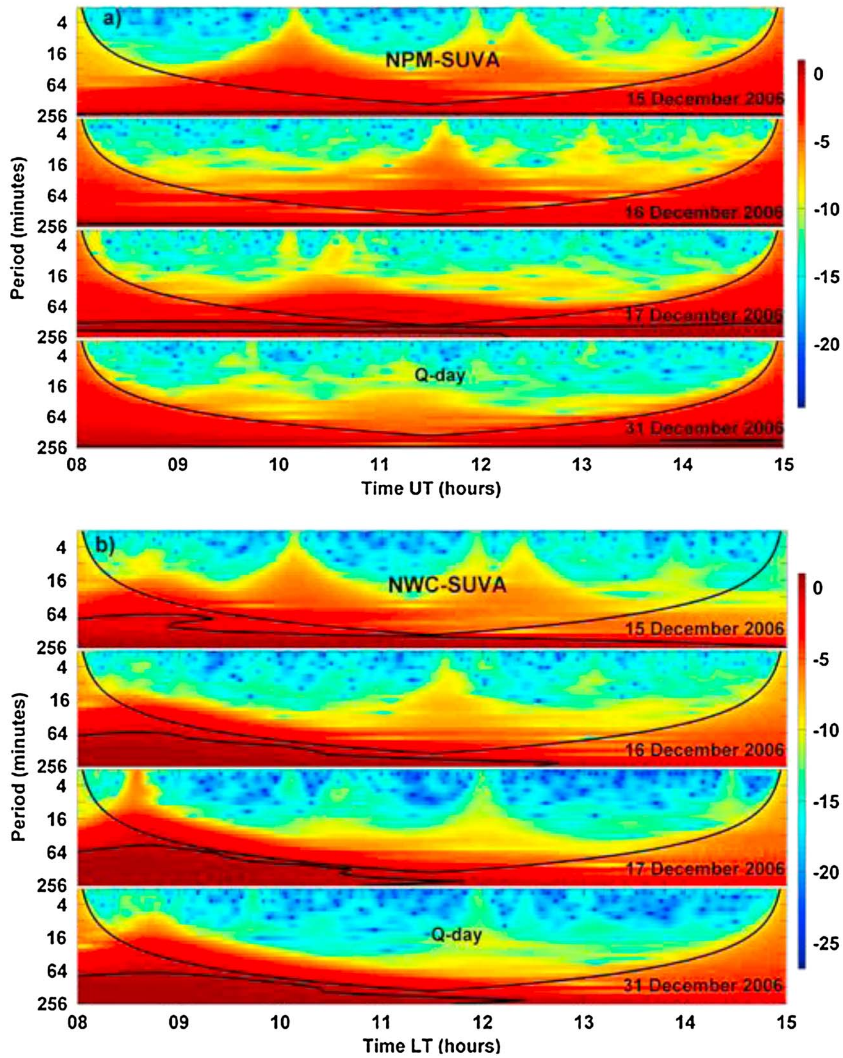

Figure 8. Morlet wavelet spectra for the daylight of TRGCPs: (a) NPM and (b) NWC signal amplitudes observed on 15–17 December 2006, and on a quiet day in December over the same paths. The black thick contours show 95% confidence line of the period, and the bowel shape contours show the cone-of-influence, anything below is dubious. Hence, the period lying between two curves is significant.

due to weakening of gravity waves while propagating from high to low latitudes. The significant WLS in the wavelet spectra is the wave periods lying between the black thick contour line of 95% confidence line of the period, and the bowel shape contour called as the cone-of-influence. *Sauli et al*. [2006b] detected WLS in the *F* region electron density using ionosonde at midlatitude stations, Ebro (Spain, Geog. latitude 40.8°N, longitude 0.5°E) and Průhonice (Czech Republic, Geog. latitude 49.9°N, longitude 14.5°E) for geomagnetic storm event on 23–29 April 2001.

This analysis suggests that the observed storm time *D* region changes may not be mainly related to the propagation of atmospheric gravity waves. This indicates that the major contribution to change in the *D* region could be due to changes in $\mathbf{E} \times \mathbf{B}$ drifts due to the prompt penetration of the auroral electric field to low latitudes [*Araki*, 1974] apart from the changes in the neutral gas composition of entire ionosphere due to storm-induced circulation (gravity waves). The prompt penetration of electric field does not affect ionospheric drifts over a long duration. But short perturbations in the composition associated with storm (prompt penetrating field) in the lower ionosphere would recover slowly since diffusion is lower at low altitudes, e.g., diffusive time is about 1 day at 125 km, and 1 h at 240 km [*Richmond and Lu*, 2000]. The decrease in storm time signal amplitude is due to the decrease in VLF reflection height and the sharpness factor (vertical electron density gradient), resulting from the change in the ionization profile as shown by LWPC modeling for the NWC signal. The long duration (46 h, Figure 5) decrease in the VLF amplitude during the main phase of the storm arises from the slow recovery of storm-associated ionization changes or redistribution due to slow molecular diffusion at *D* region altitudes. The storm effect in the *D* region seems more complicated than for *F* region ionospheric storms, particularly when considering why only certain intense storms like that of 14–16 December 2006 are associated with *D* region perturbations in the low-latitude region.

5. Summary

A detailed investigation of the ionospheric *D* region has been conducted for the extreme space weather event of 14–16 December 2006 associated with an intense magnetic storm ($Dst < -146$ nT) and an X1.5-class solar flare. We examined the propagation of subionospheric VLF signals from NWC (19.8 kHz) and NPM (21.4 kHz) monitored at Suva (Geog. 18.1°S, 178.4°E), Fiji. The solar flare increased the NWC and NPM signal amplitudes by 3.6 and 5 dB, respectively, and significantly lowered the *D* region ionosphere reference heights by about 11.1 km (NWC) and 9.4 km (NPM) at the maximum of the solar flare. This is similar to that estimated for an X5-class solar flare by *McRae and Thomson* [2004].

During the geomagnetic storm there was a significant long duration reduction in the daytime NWC and NPM signal amplitude of about 3.2 dB relative to the average value over five international quiet days. This storm has been previously reported to have caused global upper ionospheric perturbations. Our modeling results using LWPC indicate that lower ionosphere (*D* region) reference height and sharpness factor were reduced by 1.2 km and 0.06 km^{-1}, respectively. Wavelet analysis of NPM and NWC signals using the Morlet wavelet technique does not show clearly strong signatures of gravity wave propagation to these low latitudes over 15–17 December (i.e., during the storm main and recovery phases). However, there appeared to be some enhancement in wave-like signatures at around 10 and 1240 LT on 15 December (2200 UT on 14 December to 0010 UT on 15 December) and at ~1140 LT on 16 December. The prompt penetration of electric field and storm-induced circulations would have changed the composition of the *D* region ionosphere giving rise to long duration effects due to the slow recovery of the composition in the lower ionosphere compared to the upper ionosphere. Such storm effects on the low-latitude *D* region are still an area for further experimental and theoretical investigations.

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