Lightning Evolution and VLF Perturbations Associated With Category 5 TC Yasa in the South Pacific Region

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Abstract

In this paper, we present the D-region ionospheric response during the lifespan (10–19 December 2020) of a severe category 5 tropical cyclone (TC) Yasa in the South Pacific by using the very low frequency (VLF, 3–30 kHz) signals from NPM, NLK, and JJI transmitters recorded at Suva, Fiji. Results indicate enhanced lightning and convective activity in all three regions (eyewall, inner rainbands, and outer rainbands) during the TC Yasa that are also linked to the wave sensitive zones of these transmitter-receiver great circle paths. Of the three regions, the outer rainbands showed the maximum lightning occurrence; hence convective activity. Prominent eyewall lightning was observed just before the TC started to weaken following its peak intensity. Analysis of VLF signal amplitudes showed both negative and positive perturbations (amplitudes exceeding $\pm 3\sigma$ mark) lasting for more than 2 hours with maximum change in the daytime and nighttime signal amplitudes of -4.9 dB (NPM) and -19.8 dB (NLK), respectively. The signal perturbations were wave-like, exhibiting periods of oscillations between ~ 2.2 –5.5 hours as revealed by the Morlet wavelet analysis. Additionally, the LWPC modeling of the signal perturbations indicated a 10 km increase in daytime D-region reference height, $H\phi$, and a 12 km decrease in nighttime D-region $H\phi$ during TC Yasa. The D-region density gradients (sharpness), b , showed small perturbations of 0.01 – 0.14 km^{-1} from its normal values. We suggest that the observed changes to the D-region parameters are due to the enhanced convection during TC Yasa which excites atmospheric gravity waves producing travelling ionospheric disturbances to the D-region.

1. Introduction

Tropical cyclones (TCs) are one of the leading natural disasters in the South Pacific Region. These immense and powerful convective storms have the potential to claim the lives of people, cause damages to physical structures and agriculture, and disrupt the overall socio-economic livelihood of the small and vulnerable Pacific Island Countries (PICs). A TC is a rapidly rotating storm system characterized by a low-pressure center, strong winds, and a spiral organization of thunderstorms that produce heavy rain. TCs can have total lifetimes from a few days to 2–3 weeks at most and generally spend most of their lifetime over the oceans.

Very Low Frequency (VLF, 3–30 kHz) navigational transmitters situated in different regions of the world radiate electromagnetic signals which propagate through the earth-ionosphere waveguide (EIWG) by multiple reflections with a low attenuation rate of 2–3 dB/Mm (Wait, 1962). The VLF signals from these transmitters have been widely used in several investigations relating to the D-region ionospheric effects associated with phenomena occurring from above the ionosphere, such as geomagnetic storms (Kerrache et al., 2021), solar flares (Selvakumaran et al., 2015), solar eclipses (Venkatesham et al., 2019), gamma ray bursts (Nina et al., 2015), and soft gamma ray repeaters (Mondal et al., 2012), as well as those occurring from below it, such as earthquakes (Hayakawa, 2015; Kumar et al., 2013), lightning discharges (Rodger, 2003; Kumar et al., 2008), and TCs (Rozhnoi et al., 2014). In particular, the use of VLF signals to investigate the D-region response to TCs is mainly based on monitoring sudden ionospheric disturbances during TCs which are observed in terms of signal perturbations over short time scales of 1–

100 seconds or few minutes. These VLF signal investigations can be broadly generalized as either determining the intensity of lightning flashes as a precursor to cyclone intensification/weakening (eg. Price et al., 2007) or analyzing the lightning activity surrounding TCs (eg. Thomas et al., 2010). Apart from lightning, atmospheric gravity waves (AGWs) and acoustic waves excited by TCs have also been reported as an alternate process whereby TCs influence variations in the D-region for which the VLF signals are sensitive to (Kumar et al., 2017; NaitAmor et al., 2018).

There have been studies relating to the possible D-region ionospheric response to the action of intense TCs beginning with the work by Bauer (1958). Isaev et al. (2002) and Thomas et al. (2010) suggested that the possible coupling between the lower ionosphere and TCs may be due to electrical and electromagnetic effects, particularly at low latitudes (temperate latitudes). Further investigations towards TC effects in the lower ionosphere done by Rozhnoi et al. (2014) have shown meteorological relationships after analyzing the VLF signals of navigational transmitters JJI, JJY, NWC, and NPM recorded in three far eastern stations in Russia. They looked at eight TCs of varying intensities and found negative nighttime anomalies in the signal amplitude for six events that were most probably caused by TC activity which significantly correlated with the variations of atmospheric pressure, temperature, humidity, and wind velocity. Kumar et al. (2017) studied the TC Evan when it was within the proximity of the transmitter-receiver links (NPM, NLK, NAA, and JJI) to Suva between 9 to 16 December 2012 and found signal amplitude perturbations associated with the decrease and increase in nighttime and daytime D-region reference height, h'_{p} . They also highlighted the very clear transition of wave-like signature events from quiet to TC disturbed days exhibiting characteristics similar to GWs. Similarly, based on investigations towards ionospheric disturbances during large meteorological systems (hurricanes and TCs), NaitAmor et al. (2018) observed TC anomalies in VLF signal amplitudes during both day and night and highlighted that the signal anomalies were detected even at the early stages of the TC (depression). They inferred that the signal anomalies may result from traveling ionospheric disturbances (TIDs) generated by TC/hurricane associated AGWs. In a more recent study, Das et al. (2021) determined D-region ionospheric disturbances due to TC Fani over the Indian Ocean based on three VLF transmitter signals (JJJ, NWC, and VTX) received at two low-latitude stations and found strong amplitude perturbations beyond 3σ mark which consistently correlated with the wind speed and central pressure of the TC. Although there has been great progress towards characterizing the coupling between TCs and the D-region, little has been done in determining the source origins of these coupling mechanisms, in particular, the convective sources of TC-induced AGWs which is the focus of this study.

In this paper, we present the lightning evolution pattern associated with TC Yasa which occurred during the 2020 cyclone season of the Southwest Pacific. We have used the World Wide Lightning Location Network (WWLLN) data to plot the lightning flash density for this cyclone from 12 to 19 December 2020. The wind speed measurements from National Oceanic and Atmospheric Administration (NOAA) have also been used to estimate the storm intensity of the TC. The VLF anomalies during TC Yasa have been modeled using the Long Wavelength Propagation Capability (LWPC) code to determine the associated ionospheric D-region perturbations. We attempt to determine the possible meteorological origins of AGWs during TC Yasa by analysing the lightning events during the active period of the storm.

2. Brief Description Of Tc Yasa

According to the National Disaster Management Office and Fiji Red Cross Society, three tropical depressions (TDs) formed from 10 to 13 December 2020, namely, TD01F, TD02F, and TD03F, with TC Yasa developing from TD02F. From the cyclone wind measurements by NOAA, TD02F developed into a category 1 strength on 14 December at about 6:00 UT. On 15 December, TC Yasa intensified to a category 2 TC (~0:00 UT), then developed into category 3 TC around 6:00 UT. TC Yasa then slowly intensified into a category 4 TC at about 15:00 UT after creating a loop west of Port Vila, Vanuatu (17.73°S, 168.33°E). Later, TC Yasa turned to the southeast direction and reached its peak intensity of category 5 TC around 21:00 UT. TC Yasa maintained its peak intensity for about 18 hours until it was classified back to category 4 TC on 16 December at 18:00 UT. TC Yasa then continued southeast and crossed over the second mainland (Vanua Levu) of the Fiji Islands. On 17 December, TC Yasa moved away from Vanua Levu and faded into category 3 TC at 15:00 UT. The storm intensity dropped to category 2 at 18:00 UT and later to category 1 at 21:00 UT. It weakened back to a TD on 18 December at about 21:00 UT and continued in its southern path. The storm path and intensity of TC Yasa are shown as an inset image in Figure 1.

3. Data And Analysis

The lightning data were obtained from the WWLLN database which is a global lightning location detection network. The WWLLN provides nearly real time lightning locations in terms of geographical location (latitude and longitude) and occurrence date and time (dd/mm/yyyy hh:mm:ss UT) of lightning strokes detected by this network. For a lightning stroke to be accurately detected with error analysis, the VLF radiation from a lightning discharge must be detected by a minimum of five of the network's over 80 receivers around the world (Holzworth et al., 2019). The WWLLN data processed using the upgraded (version 2) algorithm, which gives the network a location accuracy of less than 10 km and 10 ms (Rodger et al., 2009) for each lightning stroke, have been used. With the version 2 algorithm and the increase in the number of WWLLN stations over the years as of 2010, it is estimated that the network's detection efficiency has increased to 11% for all lightning strokes and > 30% for strokes with peak currents > ± 35 kA (Abarca et al., 2010; Bürgesser, 2017; Hutchins et al., 2012). The lightning flash density for each day (24 hours) for the period 12 to 19 December 2020 were plotted using Matlab codes to determine the daily spatial distribution and also used to study temporal evolution during the storm period. To help locate and identify the possible convective source regions within the storm, the lightning distributions were determined for three radial regions centered on the eye of the TC (Zhang et al., 2012); the eyewall (radius, $r = 60$ km), inner rainband ($r = 60$ to 80 km) and outer rainband ($r = 180$ to 500 km). In addition, the hourly counts of lightning flashes for the three radial regions were also determined during the lifetime of TC Yasa. This was done by first binning the lightning events in a $\frac{1}{4}^\circ \times \frac{1}{4}^\circ$ grid cells centered on the TC eye. The number of lightning events occurring inside each region within a 1-hour time window was then counted and recorded.

TC Yasa moved towards Fiji and intercepted the VLF paths from transmitters in Japan (JJI), Hawaii (NPM), and the USA (NLK). Over 16 days (from 10-25 December 2020) of subionospheric VLF data from the mid-latitude (JJI & NLK) and low-latitude (NPM) transmitters and recorded at the VLF receiver located at Suva, Fiji (18.14°S, 178.44°E) were used to analyze the TC Yasa's effect on the lower ionosphere (D-region). The relative location of the three VLF transmitters (JJI, NPM, and NLK), the receiving station, their transmitter-receiver great circle paths (TRGCPs), and the TC Yasa track are shown in Figure 1. The Suva receiving station uses software based amplitude and phase logger system termed as SoftPAL to record narrowband data at 10-100 ms. Here, we present the amplitude perturbation using 1 min averaged data from the recording at 100 ms resolution. To determine the signal perturbations, we first established the baseline amplitude values of the VLF signals by averaging the signal amplitudes during five international quiet days (Q-days) in December 2020. The five Q-days were obtained from the World Data Centre website <http://wdc.kugi.kyoto-u.ac.jp/> which provides information relating to the daily level of geomagnetic activity based on disturbance storm time (D_{st}) indices. Periods of high geomagnetic activity ($D_{st} < -50\text{nT}$) are known to strongly disturb the ionosphere at middle- and low-latitudes (Huang et al., 2005; Qian et al., 2019) and have been observed to significantly perturb VLF signals (eg. Choudhury et al., 2015). Hence, data from the World Data Centre has been used to recognize and remove such periods in our analysis to minimize the influence of high geomagnetic activity in the VLF signal variability. The averaged Q-day signal is then compared with the 16 days of real-time signal and signal amplitudes exceeding more than three standard deviations ($\pm 3\sigma$) for ≥ 2 hours are considered as TC associated VLF signal anomalies. The difference between the perturbed amplitude A_p during the TC and the baseline amplitude A_b of the signals defined as $\Delta A = A_p - A_b$ is also determined and is referred here as the reduced signal amplitude.

To find the response of the lower ionospheric D-region during TC Yasa, the Long Wave Propagation Capability V2.0 (LWPC) code was used to model the characteristics of detected VLF signal perturbations of the NPM transmitter (Ferguson, 1998). The code considers the EIWG to behave as a parallel-plate structure bounded below by an imperfect ground and above by ionospheric D-region plasma. For a given VLF wave propagation path, the code divides the path into segments and sequentially calculates at each segment the wave electric field starting from the transmitter and ending at the receiver by using the path conductivity and permittivity data embedded in the code. Wait model of the lower ionosphere which parameterizes the region in terms of the sharpness (β in km^{-1}) and reference height ($H\phi$ in km) (Wait and Spies, 1964) has been used. The disturbed segment is determined by projecting the TC eye onto the signal propagation path. The characteristics of the detected VLF signal perturbation in terms of amplitude and phase are then used to introduce a localized perturbation to the Wait parameters of the disturbed segment. In this analysis, the perturbation to the Wait parameters is assumed to display a Gaussian distribution and the process is iterated until a best-fit is found between the amplitude and phase of the real-time and code-simulated signals.

Finally, the signatures of the wave-like structures (WLS) present in the VLF signal amplitudes (NPM, NLK, and JJI) during 10 to 25 December were then estimated using the mother Morlet wavelet technique to

determine their association with AGWs (Mallat, 1999). Specifically, the spectra were determined only for the daytime and nighttime periods of the TRGCPs considering that solar terminator periods are known to generate AGWs (Nina and Čadež, 2013). For a given signal $x(t, z)$ with amplitude z and time series t , the wavelet transform $T_x(a, u, z)$ is defined as:

$$T_x(a, u, z) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t, z) \psi^* \left(\frac{t - u}{a} \right) dt \quad (1)$$

Where ψ is the mother Morlet wavlet function, a (positive value) is the scale of the analyzing wavlet, and u is the wavlet shift parameter. For further details regarding the wavelet transform, the reader is referred to Mallat (1999) and Addison (2017).

4. Results

4.1 Lightning evolution during TC Yasa

Figure 2 shows the daily spatial and temporal variation of lightning occurrences for three radial regions centered on the TC eye, namely, the eyewall (pink dots), the inner (orange dots) and the outer (blue dots) rainbands of TC Yasa from 12 to 19 December 2020. It can be observed that the majority of the lightning events took place in the outer rainband as seen from 12 to 17 December. The lightnings in the outer rainband populated along the JJI signal path during the early days of TC Yasa from 12 to 15 December and later along the NPM and NLK signal paths on 17 December. Comparatively fewer outer rainband lightnings can be seen during the weakening phase of TC Yasa from 18 to 19 December. Inner rainband lightnings occurred more frequently during the early days of TC Yasa from 12 to 14 December and decreased mainly to the right side of the JJI-Suva path. The inner rainband lightning density decreased as the days passed with a sudden increase at the end of TC Yasa on 19 December. Very few eyewall lightnings were observed throughout the lifetime of the storm. Prominent occurrence of eyewall lightning can be seen on 16 and 17 December during which TC Yasa reached peak intensity and slowly weakened with its movement towards the south of Fiji. If we relate the density of lightning locations with the regions of convective activity within TC Yasa, it can be inferred that convective activities were close to or were within the sensitive zones of the three VLF transmitters and that the density of convective activities are mostly in the outer rainband of the TC. The hourly variation of lightning activity within the three radial regions and for the total region as presented in Figure 3 showed a change in the intensity of the storm varying with maximum sustained wind speeds. The maximum peak in lightning activity for the outer rainband occurred approximately one day before the peak in maximum wind speed (Figure 3(c)). For the eyewall and inner rainband, however, the maximum peak in lightning activity occurred after the peak in maximum sustained winds. The peak in lightning activity in the eyewall occurred several hours after the cyclone started weakening (Figure 3(b)) whereas the peak in lightning activity in the inner rainband occurred approximately two days after (Figure 3(c)) when the TC was in its weakening phase.

4.2 VLF signal analysis during TC Yasa: December 2020

4.2.1 NPM signal amplitude analysis

The signal from the NPM transmitter (21.4 kHz) propagates across the geomagnetic equator over the ocean mainly in north to south direction and fairly less in east to west direction to Suva, with a complete path length of 5.07 Mm. Figure 4 shows the diurnal plots of the NPM signal amplitude (panels a-p) during the main phase of TC Yasa (12-19 December) along with two days before the cyclone (10-11 December) and six days post-cyclone (20-25 December). The time is in UT and the local time in Fiji is LT = UT + 12:00 hours. In each panel, the black line represents the mean signal amplitude on five international geomagnetic Q-days for the observed cyclone month and the red line is the real-time signal amplitude for the days indicated. The green and cyan dashed lines indicate the $\pm 2\sigma$ and $\pm 3\sigma$ Q-days signal amplitudes, respectively, which define the 95% and 99.7% confidence levels of signal variability, respectively. The threshold for the VLF anomalies due to the storm phase is marked with a blue arrow where perturbed amplitude exceeds $\pm 3\sigma$ level for more than 2 hours. The periods of transmitter being off-air are removed from the plots. From the NPM amplitude, anomalies are seen as signal amplitude went below the -3σ line during the daytime and nighttime.

Several clear anomalies for NPM signal amplitude below the -3σ line were observed during the TC. The first anomaly occurred when TC Yasa was a TD on 10 December. The daytime signal amplitude began decreasing -3σ line at 17:46 UT and approached -3σ line at 21:37 UT, where the maximum anomaly was observed at 19:30 UT ($\Delta A = -3.2$ dB). On 11-12 December, the amplitude was seen below the -3σ line from the period 22:24–2:22 UT, where the maximum signal anomaly was observed at 0:05 UT with $\Delta A = -2.6$ dB. On 12 December, the nighttime signal amplitude declined -3σ line for ~ 2 hours, where the maximum signal anomaly was observed at 12:41 UT with $\Delta A = -10.0$ dB. During the daytime on 12-13 December, the maximum amplitude anomaly beyond -3σ line was observed at 23:24 UT ($\Delta A = -2.5$ dB) from the period 23:01–1:06 UT. On 13 December, the nighttime amplitude from 10:23-13:54 UT was perceived below the -3σ line and the maximum change in signal amplitude of $\Delta A = -10.7$ dB was measured at 13:09 UT. On 14 December at approximately 6 UT, the system was classified as category 1 TC with wind speed of 118.5 km/h moving in the northwest direction. Due to change in the intensity and direction towards the receiver, a decline in the amplitude crossing below the -3σ line was observed at 10:25 UT and stabilized with the -3σ line at 13:59 UT, where the most pronounced $\Delta A = -14.3$ dB during the nighttime was measured at 13:21 UT. Again a drop in the daytime amplitude below the -3σ line was sensed from 19:13–23:49 UT, where the maximum $\Delta A = -3.1$ dB was recorded at 22:24 UT. TC Yasa completed a loop on 15 December (12:00 UT) and began to move towards Fiji (receiver) at 201.9 km/h. Perturbations in the signal amplitude below -3σ line were observed on 15 to 16 December from 19:13–5:06 UT, where the max. $\Delta A = -5.7$ dB occurred at 4:36 UT. On 16 December, the amplitude anomaly during the nighttime (7:41-11:31 UT) was seen below -3σ line and the maximum $\Delta A = -11.8$ dB at 10:47 UT. At 12:00 UT, category 5 TC Yasa continually moved towards receiver with a maximum wind speed of ~ 255.6 km/h and the signal amplitude went below the -3σ line at 22:48 UT. The signal amplitude returned to the -3σ line on 17 December at 5:45 UT, where the most pronounced daytime anomaly was observed at 5:44 UT ($\Delta A = -7.4$ dB). At this phase, the movement of TC Yasa was believed to cross Vanua Levu and the transmitter-receiver great circle path (TRGCP) of the NPM signal to Suva. TC Yasa was still a category 4 cyclone after

crossing the second mainland and transmitter-receiver link on 17 December (12:00 UT). VLF signal revealed nighttime amplitudes exceeding below -3σ line (10:27-12:43 UT) with a maximum anomaly observed at 11:07 UT ($\Delta A = -7.7$ dB). On 17 to 18 December, the daytime amplitude declined below -3σ line (17:37-2:11 UT) and the maximum anomaly was observed at 23:56 UT ($\Delta A = -4.9$ dB). On 18 December, TC Yasa (category 1) moved far from Fiji/VLF receiver in the south path, and the weakening of the TC strength and moving away from the NPM-Suva link showed no anomalies in the VLF propagation from 19 to 21 December. However, the signal amplitude on 22, 23 and 25 December were within the threshold range, most probably due to day-to-day signal variability.

4.2.2 NLK signal amplitude analysis

Similar to Figure 4, Figure 5 presents the NLK signal amplitude perturbations (panel a-p) during TC Yasa in December 2020. The diurnal amplitude variation in panels (a-p) designates that the signal propagation path is in complete daytime over 19:00-0:00 UT and complete nighttime over 7:00-16:00 UT. Considering the TD phase of the cyclone on 10 to 13 December, no significant rise or fall beyond $\pm 3\sigma$ criteria in the perturbed NLK signal amplitude was observed. It could be due to the NLK signal covering a larger path to Suva, its low radiation power (250 kW) and the signal path being reasonably far from the TC when compared to the NPM transmitter. However, ten clear anomalies were found to cross below -3σ for > 2 hours between 11 to 19 December during both the day and night periods of the TRGCP. The first nighttime amplitude anomaly was observed on 11 December from 11:37–14:08 UT when the signal went beyond -3σ line and the maximum $\Delta A = -11.3$ dB was measured at 12:48 UT. The second anomaly was observed on 12 December (12:00 UT) when the TD was approaching Fiji at 64.82 km/h. The amplitude decreased below -3σ line (9:37-14:00 UT), with the maximum $\Delta A = -12.2$ dB measured at 11:53 UT. On 13 December at 12:00 UT, the TD was heading southeast (away from Fiji) at 83.3 km/h, the amplitude went below -3σ line (11:22-13:41 UT) with the maximum anomaly observed at 11:33 UT ($\Delta A = -13.6$ dB). On 14 December (~6:00 UT), TC Yasa was classified as a category 1 cyclone and the NLK signal amplitude decreased below the -3σ line from 9:42–13:36 UT, where the maximum $\Delta A = -15.3$ dB was at 11:54 UT. After completing a loop on 15 December (12:00 UT), TC Yasa moved southwest at 201.9 km/h and the amplitude perturbations went below the -3σ line from 10:12–12:47 UT, with a maximum $\Delta A = -11.3$ dB at 4:36 UT. TC Yasa, by now a category 5, continually moved southwest with a maximum wind speed of ~255.6 km/h on 16 December (12:00 UT), causing the daytime amplitude to decrease below the -3σ line at 19:19 UT and recovered to the -3σ line on 17 December at 1:00 UT. A maximum $\Delta A = -5.6$ dB was observed at 23:59 UT. The TC Yasa changed to category 4 while crossing the Vanua Levu and NLK transmitter-receiver link on 17 December (12:00 UT). During this period, the NLK signal exceeded the -3σ line on two nighttime occasions, first, between 5:44-8:22 UT with the signal amplitude anomaly at 7:47 UT ($\Delta A = -19.8$ dB) and, second, between 11:21-13:36 UT with a maximum $\Delta A = -10.4$ dB at 12:35 UT. On 18 December at 12:00 UT, TC Yasa was characterized as a category 1 TC as it moved south away from Fiji and later became a TD the following day. A maximum ΔA of -10.9 dB was observed between 10:51-12:54 UT on 18 December. On 19 December, the signal exhibited a maximum ΔA of -9.9 dB between 7:14-14:01 UT. There were no anomalies present in the VLF propagation from 20 to 25 December because the TC moved away from the sensitive zone and its strength diminished.

4.2.3 JJI signal amplitude analysis

Panels (a-p) in Figure 6 presents the JJI signal amplitude variations during TC Yasa from 10 to 25 December 2020 for complete daylight during 22:00-6:00 UT and complete darkness during 9:00-17:00 UT. Four anomaly events were observed, three during daytime and one during nighttime. The first daytime amplitude anomaly occurred on 15 December when TC Yasa was approaching the JJI-Suva link (21:00 UT) in which the signal amplitude decreased below the -3σ line at 23:05 UT and recovered to the -3σ line at 6:26 UT on 16 December, where a maximum $\Delta A = -4.3$ dB was observed at 1:45 UT. Later into the day at 21:00 UT, TC Yasa intensified into a category 4 cyclone and began approaching the Suva receiver exhibiting wind speeds of ~ 242.6 km/h. This coincided with a decline in signal amplitude below the -3σ line at 22:32 UT and recovered to the -3σ line on 17 December at 6:26 UT. The maximum anomaly was observed at 1:35 UT with $\Delta A = -4.8$ dB. On 17 to 18 December, the signal amplitude anomaly seen between 22:40-5:20 UT showed a maximum $\Delta A = -4.1$ dB at 22:56 UT. Then, the anomaly during the nighttime was observed above the $+3\sigma$ line for ~ 2 hours with a maximum $\Delta A = 4.6$ dB at 13:02 UT. Later, the system was classified as a TD and began moving south away from the Suva receiver. No TC-related perturbations were observed from 19 to 21 December.

Figure 7 shows the *Dst* and *Kp* index during TC Yasa, revealing quiet *Dst* values varying above -22 nT and *Kp* values below 4 in December 2020 (http://wdc.kugi.kyoto-u.ac.jp/dst_realtime/202012/index.html). B-class solar flares were observed during the period 10 to 25 December except the C4.03-class flare at 14:35 UT on 14 December 2020 (<https://www.spaceweatherlive.com/en/archive.html>) during nighttime of the TRGCPs indicating no solar flare effect during the TC.

4.3 D-region perturbations during TC Yasa: LWPC modeling

To determine the perturbed values of the Wait parameters of reference height H' and sharpness factor β for each perturbation event, we first ran the LWPC code (V2.0) to obtain their ambient (unperturbed) values along the NPM signal path using the coordinates of the NPM transmitter and the Suva receiver (latitude and longitude) and the date and time (in UT) of the perturbation event. The ambient values obtained are assumed to be constant along the NPM signal propagation path except at the disturbed segment. This estimation of the unperturbed values of the Wait parameters is similar to the approach done by Kumar et al. (2017) and Pal et al. (2020). The values of H' and β were then varied from their unperturbed values until the modeled signal closely matched the real-time signal based on the magnitude of the maximum perturbation in signal characteristics of amplitude or amplitude and phase both. The resulting H' and β are identified as the perturbed values associated with the disturbed segment of the NPM signal path and are considered to vary as a Gaussian that extends up to 1000 km in either direction from the projected position of the TC eye on the signal path. A detailed explanation of this procedure can be further found in the work by NaitAmor et al. (2017). Figure 8 shows the results of the LWPC modeling of four clear NPM signal perturbation events (two daytime and two nighttime) selected from Figure 4. The four perturbation events modeled exhibited amplitudes exceeding the -3σ line for at least 2 hours. Modeling of the two daytime signal perturbations resulted in unperturbed values of $H' = 87$ km and $\beta =$

0.30 km⁻¹. Concerning the daytime unperturbed values, an increase in $H\zeta$ and a decrease in β by 10.6 km and 0.143 km⁻¹, respectively, were observed for the daytime signal perturbation on 13 December at 0:46 UT (panel a), whereas an increase in both $H\zeta$ and β by 9.7 km and 0.143 km⁻¹, respectively, were observed for the daytime signal perturbation on 14 December at 22:23 UT (panel b). Interestingly, the outer and inner rainband lightning can be observed to reach a local peak in activity prior to the times of both the daytime $H\zeta$ and β perturbations considered above as seen in Figure 3. Applying the same modeling used in the daytime perturbations to the nighttime perturbations, the nighttime unperturbed values of $H\zeta = 74$ km and $\beta = 0.43$ km⁻¹ were obtained. Compared to the daytime perturbations, both $H\zeta$ and β for the two nighttime perturbations considered decrease from their unperturbed values. For the signal perturbation on 16 December at 10:47 UT (panel c), $H\zeta$ decreased by 17.7 km while β decreased by 0.008 km⁻¹, whereas for the signal perturbation on 17 December at 11:07 UT (panel d), $H\zeta$ decreased by 13.2 km while β decreased by 0.011 km⁻¹. Notable local peaks in lightning activity can again be seen, in the eyewall region in this case, prior to the two nighttime perturbations in $H\zeta$ and β . Three more events (1 daytime and 2 nighttime) events were modeled using the LWPC code. Tables 1 and 2 provide a summary of the changes in Wait parameters associated with all seven selected events. It can be observed that the perturbed $H\zeta$ is more visible at night as compared to the day. In addition, we have further analyzed and determined the temporal changes (hourly) of the associated Wait parameters using LWPC modeling of a daytime NPM signal perturbation from 17 December at 18:00 UT to 18 December at 6:00 UT and is given in Figure 9. The time interval chosen covers the period that starts at the end of the sunrise terminator and finishes at the beginning of the sunset terminator. From the plots, wave-like variation of both the Wait parameters of $H\zeta$ and β may be attributed to the influence of propagating GWs from below, reaching up to ionospheric heights.

4.4. Gravity Waves associated with TC Yasa: Wavelet analysis

After analyzing the ionospheric high frequency Doppler shift data recorded at a station in Peking University during 24 typhoons from 1987 to 1992, Xiao et al. (2007) suggested that the corresponding changes in the lower ionosphere and electron content may be attributed to the influence of AGWs produced by the typhoons. To determine the TC-induced WLS present in the perturbed signals, the reduced amplitudes (ΔA) of the NPM, NLK, and JJI signals were used in the wavelet analysis to minimize and remove any diurnal variability in the signals. In doing so, the signals are expected to be free from variable influences induced by other sources such as topographic effects and auroral quasi-periodic oscillations (Boška and Laštovička, 1996; Laštovička, 2006) apart from waves associated with solar terminator (Nina and Čadež, 2013). Figure 10 presents the spectrums of the NPM, NLK, and JJI signals during TC Yasa from 10 to 25 December 2020 based on the wavelet analysis for separate daytime (left column) and nighttime (right column) periods. The x-axis represents the days of the month and the y-axis shows the frequency ranging from 0.05-0.65 mHz. Enhanced amplitudes of WLS at frequencies of 0.05-0.07 mHz corresponding to periods of 3.9-5.5 hours can be observed from 14 to 19 December in the daytime spectra of both the NPM (panel a, 20:00-3:00 UT) and NLK (panel c, 19:00-0:00 UT) signals and from 11 to 12 December in the daytime spectra of the JJI (panel e, 22:00-6:00 UT) signal. An increase in

WLS amplitude can also be observed from 21 to 23 December in the JJI daytime spectrum but this may not be relevant to TC Yasa which dissipated by 19 December. For the nighttime spectrums, a notable increase in amplitudes for WLS in the frequency range of 0.05-0.10 MHz corresponding to periods of 2.7-5.5 hours can be observed for all three signals. For the NPM signal (panel b, 7:00-16:00 UT), the nighttime WLS occurred on 10 and 15 to 19 December, while for the NLK signal (panel d, 7:00-16:00 UT), the nighttime WLS occurred on 10 and 16 to 18 December. The nighttime WLS in the JJI signal (panel f, 9:00-17:00 UT) similarly occurred between 16 to 18 December. Interestingly, the occurrence times of the enhancement in WLS amplitudes during both daytime and nighttime coincide with the periods when TC Yasa was developing into a TD (10-13 December) and when TC Yasa reached its peak intensity (15-16 December). Additionally, the amplitudes of the WLS in all the three signals during nighttime are observed to be comparatively higher than those during daytime.

5. Discussion

5.1 Lightning occurrence during TC Yasa

Lightning is one of the characteristic phenomena in convective cloud systems. Lightning strokes can be treated as indicators to detect the presence of significant convection (Molinari et al., 1999) and the intensity of convection within convective storms (MacGorman and Morgenstern, 1998). Monitoring of lightning within storms has since been studied as a feasible way of possibly forecasting storm intensification (Demaria et al., 2012; Molinari et al., 1994; Solorzano et al., 2008). At the same time, convective activity is considered as one of the dominant sources of GWs particularly in the tropics where TCs are known to be the strongest convective storms (Fritts and Alexander, 2003). After analyzing the WWLLN lightning location data during TC Yasa, our results indicated that the enhanced lightning activity and, hence, convective activity occurred in all three regions of TC Yasa and are observed to fall near or within the sensitive zones of the NPM, NLK, and JJI transmitter links. Of the three regions, the outer rainbands showed the highest density of convective activity which was reflected in terms of the high number of lightning events for the large number of days compared to the eyewall and inner rainband. It can be inferred that the high convective activity in the outer rainband may be the likely meteorological source of AGWs within TCs that potentially disturbs the lower ionosphere. However, it should be pointed out that our results do not rule out the possibility that GWs are also generated in the eyewall and inner rainband but merely suggests that the majority of the waves may have originated in the outer rainband. Moreover, by comparing the lightning data surrounding TC Yasa against the storm's maximum sustained winds, it was determined that there are multiple peaks in the total lightning activity throughout the storm's lifetime with the maximum peak in total lightning activity preceding the peak of the maximum sustained winds for a day (24 hours). An interesting observation is that the maximum peak in total lightning activity corresponds to the maximum peak in lightning activity of the outer rainband. In comparison, the maximum peaks in lightning activity for the eyewall and inner rainband occur several hours and days, respectively, after the peak in maximum sustained winds or during the weakening phase of TC Yasa. Our results showed that lightning activity peaked before TC Yasa reached its highest intensity based on maximum sustained winds and that this peak in lightning activity is attributed to lightning in the outer

rainband of the TC. This is consistent with the work by Demaria et al. (2012) where the authors examined lightning associated with TCs in the Atlantic and eastern North Pacific from 2005 to 2010 and observed high lightning density in the rainband regions (200-300 km) of cyclones that rapidly intensified 24 hours. Demaria et al. (2012) also observed high lightning density in the inner-core of TCs that rapidly weakened and suggested that inner-core lightning outbreaks signaled the end of the intensification phase. This is in agreement with our results showing a peak in eyewall lightning activity several hours into the weakening phase of TC Yasa. Xu et al. (2017) made similar findings after examining TCs in six TC-prone basins and determined that intensifying TCs showed significantly low inner core (0-100 km) and high outer rainband (200-400 km) lightning density compared to weakening and neutral TCs where the lightning density in the inner core and outer rainbands were high and low, respectively. The eyewall lightning outbreak during the weakening phase of TCs can be explained by the interaction between the inner core potential vorticity and incident vertical wind shear as determined by Davis et al. (2008) after conducting simulations of six Atlantic hurricanes. Davis et al. (2008) showed that the wind shear tilts the inner core potential vorticity resulting in asymmetric but intense convection.

5.2 VLF perturbations and D-region Changes Associated with TC Yasa

Upon analyzing the VLF signals received from the NPM, NLK, and JJI transmitters during TC Yasa, we have identified significant signal anomalies associated with the intensification and weakening of the TC where all the three signals showed strong perturbations beyond -3σ level (negative anomalies) lasting for at least 2 hours or more. Of the three signals, the JJI signal also showed a perturbation above the $+3\sigma$ level (positive anomaly) lasting for ~ 2 hours. For NPM-Suva path, only daytime anomalies were observed when the TD moved towards the TRGCP and a stable daytime signal was recorded and when the cyclone was a category 1 and was situated 317.8 km near the VLF receiving station. Both daytime and nighttime anomalies were revealed on NLK-Suva link which commenced during TD located 769.3 km west beside the TRGCP and the anomalies vanished after the TC crossed the TRGCP and weakened back to the TD about 611.9 km south of the receiver. Again, both daytime and nighttime perturbations on JJI-Suva path began when the category 5 system set 110.3 km west beside the JJI-Suva path and the anomalies faded upon category 1 classification about 359.7 km south the receiving station. The most significant perturbations were observed when the storm approached the transmitter-receiver path or the sensitive area, *i.e.*, during daytime for NPM, $\Delta A = -7.4$ dB and for JJI, $\Delta A = -4.8$ dB, whereas during nighttime for NLK, $\Delta A = -19.8$ dB. Our results show that signal amplitude anomalies can occur both during the daytime and nighttime. In our case, mostly the negative anomalies were revealed (one positive anomaly from JJI-Suva link) and the negative and positive magnitude in the perturbation are mainly due to the propagating distance of the received signal (NaitAmor et al., 2017) and distance between the storm to GCP which causes the constructive and destructive model interference at the receiver resulting in negative and positive anomaly (NaitAmor et al., 2018). Equivalent to our case, Kumar et al. (2017) observed negative daytime and nighttime anomalies in the NPM, NLK, and JJI signal amplitude when the TC Evan was inside the sensitive zone. Interestingly, our results revealed clear daytime perturbations with periods between 2-9 hours in NPM-Suva signal path, 2-6 hours in NLK-Suva signal path, and 2-7 hours in JJI-Suva

signal path while a clear nighttime perturbation of 2-4 hours in NLK-Suva signal path with different magnitude and the signal amplitude perturbations beyond -3σ mark.

We have used the LWPC v2.0 code to model TC-induced perturbations in the NPM signal observed during TC Yasa to estimate the associated disturbance in the lower ionosphere in terms of changes to its Wait parameters of reference height, $H\zeta$, and sharpness factor, b . The LWPC code has been used similarly in past research of the lower ionosphere which involved establishing parameters that characterize the region during daytime and nighttime conditions (Thomson et al., 2007; Thomson et al., 2011) and during times of perturbed conditions associated with geomagnetic storms (Kumar et al., 2015), lightning-induced electron precipitations (Poulsen et al., 1993), solar eclipses (Clilverd et al., 2001), solar flares (Thomson et al., 2005), and transient luminous events (NaitAmor et al., 2017). More recently, it was used to investigate ionospheric signatures of possible TC-ionosphere coupling where upward propagating GWs were suggested as the causes of the ionospheric disturbances (Bakul et al., 2021; Kumar et al., 2017). The results of our attempt to model the response of the lower ionosphere region in terms of estimated changes to $H\zeta$ and b with reference to their unperturbed values show that the behavior of the region is different during daytime and nighttime perturbations. For daytime perturbations, $H\zeta$ was observed to increase while b exhibited both increase and decrease, whereas for nighttime perturbations, both $H\zeta$ and b were observed to decrease. Moreover, a significant change in reference height, $DH\zeta$, with an appreciably small change in sharpness factor, $D\beta$, was observed from modeling of the daytime and nighttime signal perturbations. The changes to the reference height may be attributed to the motion induced by the propagation of upward GWs (Marshall and Snively, 2014) which lifts and sinks the background atmosphere and drags the D-region ionization with it given that the cyclone does not alter the source and loss mechanism of the lower ionosphere region. The largest changes to the daytime Wait parameters were $DH\zeta = +10.6$ km and $D\beta = -0.143$ km⁻¹, whereas the largest changes to the nighttime parameters were $DH\zeta = -19.2$ km and $D\beta = -0.050$ km⁻¹, indicating stronger D-region TC effect at the nighttime as compared to the daytime. In comparison, Kumar et al. (2017) reported a maximum decrease of ~ 5.2 km in nighttime D-region reference height and a maximum increase of 7.2 km in daytime D-region reference height after studying the perturbations of local origin in VLF signals of NPM, NLK, NAA, and JJI transmitters during TC Evan in the South Pacific. Bakul et al. (2021) also determined a maximum decrease in reflection height of the nighttime D-region by ~ 7.9 km after modeling the perturbations in VTX, NWC, and JJI signals recorded at two receiving stations (Kolkata and Cooch Behar, India) during TC Fani in the North Indian Ocean. Ionospheric fluctuations in D-region height were similarly found by Lay and Shao (2011) after carrying out a multi-station time-domain analysis of lightning waveforms associated with a large thunderstorm on 17 June 2005. The authors showed that nighttime perturbations to the D-region height can on average reach about 6 km due to the AGWs that arise from the convective storms overshooting the tropopause and disturbing the lower ionosphere. Our results for TC Yasa corroborates the findings of the studies above and show the stronger lower ionosphere perturbations particularly at the nighttime which can be associated with the susceptibility of the lower ionosphere to the meteorological influences from below in the absence of incident solar radiation at night.

The atmospheric gravity waves act as a carrier for the tropospheric disturbances to the ionosphere (Pal et al., 2020). A TD or TC perturbs the particles in the atmosphere from their equilibrium state and the gravity force pulls those particles back to the equilibrium (Das et al., 2012). We used Morlet wavelet analysis to three VLF transmitter signal amplitudes to examine wave-like spectra during day and night periods and found a clear transition from quiet days to TD/TC disturbed days with wave-like spectra associated with gravity waves. All the three transmitters had daytime wave-like events with periods between 3.9 and 5.5 hours when the TC approached the paths. While NPM, NLK, and JJI had nighttime wave-like events with periods starting from 2.2, 2.1, and 3.9 to 5.5 hours, respectively. In parallel to Kumar et al. (2017), we found a most similar signal spectrum for NPM and NLK, and they suggested this could be due to their paths which are close to each other. NaitAmor et al. (2018) studied VLF signal anomalies from August to November 2016 cyclones in the Atlantic Ocean using mother wavelet analysis of normalized signal amplitude and found nighttime wave-like events with periods between 2 and 3 hours. Pal et al. (2020) applied the wavelet analysis method to the residual perturbed VTX signal amplitude from the severe cyclone Fani of May 2019 and confirmed the major enhancement of AGWs spectrum with periods 10 min to 2 hours during landfall. Our outcomes correlate with these studies and show that wave-like oscillations of wider periods could be related to TCs.

We found that the perturbations occurred when the system was still a TD and when it strengthened into a TC. The perturbations were assumed to originate from TC Yasa because there were no geomagnetic storms or solar flares of class C and above. However, a total of six earthquakes occurred within the wave-sensitive area of the TRGCPs, *i.e.* within the fifth Fresnel zone during the period of TC Yasa. Using all known methods (Kumar et al. 2013), initial checks for any seismo-ionospheric signatures on the VLF signals were made. All the earthquakes were below magnitude 5, and hence their effect on the VLF propagation and D-region ionosphere could not be seen and are unlikely to occur.

6. Summary And Conclusions

It is evident from our results that there is a strong connection between the lightning activity (convective activity) and the observed perturbations in the VLF signals due to the D-region changes (parameters $H\phi$ and b) during the TC Yasa. WWLLN lightning data during TC Yasa revealed enhancement in lightning activity in all three regions of the TC that are observed to fall near or within the sensitive zones of the NPM, NLK, and JJI transmitter-receiver paths. Of the three regions, the outer rainbands showed the highest density of lightning activity, but each region showed distinct lightning evolution during different times of the TC which were observed to closely follow the detected VLF signal perturbations. Our VLF signal analysis showed both positive and negative signal perturbations during daytime and nighttime with the change in signal amplitudes for the quiet baseline values determined to reach up to -4.9 dB (JJJ) during the day and -19.8 dB (NLK) during the night. Additionally, VLF signal perturbations with long occurrence times were also determined during daytime (~2-9 hours) and nighttime (~2-7 hours) From the LWPC modeling of the NPM signal having purely low latitude path, the response of the lower D-region ionosphere for daytime perturbations showed an increase in the $H\phi$ and both increase and decrease in b , whereas for nighttime perturbations, both $H\phi$ and b decreased. The largest changes to the daytime Wait

parameters were $\Delta H' = +10.6$ km and $\Delta\beta = -0.143$ km⁻¹, whereas the largest changes to the nighttime parameters were $DH\zeta = -19.2$ km and $D\beta = -0.050$ km⁻¹. Finally, based on the mother Morlet wavelet analysis of the three VLF transmitter signals during the day and night periods, we found a clear transition of WLS from quiet days to TC disturbed days with the periods of the WLS in agreement with those of gravity waves. Daytime WLS with periods between 3.9 and 5.5 hours and nighttime WLS with periods between 2.1 and 5.5 hours were observed in all the spectrums of the three VLF signals.

Abbreviations

AGWs: Atmospheric gravity waves; EIWG: Earth-ionosphere waveguide; Dst: Disturbance storm time; LWPC: Long Wavelength Propagation Capability; NOAA: National Oceanic and Atmospheric Administration; PICs: Pacific Island Countries; Q-days: Quiet days; TCs: Tropical cyclones; TDs: Tropical depressions; TIDs: Travelling ionospheric disturbances; TRGCPs: Transmitter-receiver great circle paths; VLF: Very low frequency; WLS: Wave-like signatures; WWLLN: Worldwide Lightning Location Network.

Declarations

Availability of data and materials

The VLF data is available with PAALR and SK. The lightning data were obtained from the WWLLN database (WWNNL, <http://wwlln.net/>) which is a global lightning location detection network, while the wind speed data were obtained from National Oceanic and Atmospheric Administration (NOAA). The five Q-days were obtained from the World Data Centre website <http://wdc.kugi.kyoto-u.ac.jp/>.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The authors PAALR and SK₁ analyzed the lightning and VLF data for TC effects on VLF and carried out the D region modeling in consultation with AK and SK₂. The manuscript was jointly prepared by PAALR, SK₁, AK and SK₂. All authors read and approved the final manuscript.

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Tables

Table 1 The signal characteristic and D-region parameters for four daytime NPM signal anomaly events.

No. of events	Date (dd/mm/yy)	Time (hh:mm UT)	DAmplitude (dB)	Df (deg)	DH ζ (km)	Db (km ⁻¹)
1	13/12/20	00:46	-2.278	+12	+10.6	-0.143
2	14/12/20	22:23	-3.081	-90	+9.7	+0.010
3	16/12/20	02:36	-5.669	-100	+10.6	+0.005

Table 2 The signal characteristic and D-region parameters for eight nighttime NPM signal anomaly events.

No. of events	Date (dd/mm/yy)	Time (hh:mm UT)	DAmplitude (dB)	Df (deg)	DH ζ (km)	Db (km ⁻¹)
1	13/12/20	13:09	-10.664	+97	-18.0	-0.070
2	14/12/20	13:25	-14.297	+148	-19.2	-0.050
3	16/12/20	10:47	-11.831	+137	-17.7	-0.008
4	17/12/20	11:07	-7.710	+100	-13.2	-0.011

Figures

Figure 1

The relative location of the three VLF transmitters (JJJ, NPM, and NLK) in cyan diamond and a receiver station (Fiji) together with their transmitter-receiver great circle path (purple). The zoom portion shows the TC Yasa path (blue line) with different strengths and dates marked in red which were recorded at 12 UT on each day starting from 12 to 19 December 2020.

Figure 2

(a-h) Spatial and temporal variation of lightning during TC Yasa from 12 to 19 December 2020. Lightning activity is quantified in three radial regions centered on the eye of the TC; the eye wall (magenta), inner rainband (orange) and outer rainband (blue). The location of the TC eye at 15:00 UT on each day is indicated by the black star. The JJI, NPM and NLK signal paths to Suva receiver in green are also shown.

Figure 3

Hourly intensity variation of TC Yasa based on lightning activity and maximum sustained wind speeds from 12 (15:00 UT) to 19 (16:00 UT) December 2020. Lightning activity is quantified in three radial regions centered on the eye of the TC; (a) the eyewall, (b) inner rainband and (c) outer rainband. The total lightning activity in the three regions of the TC is shown in (d).

Figure 4

(a-p) NPM signal amplitude (red) during 10 to 25 December 2020 which includes TC Yasa days. The mean signal amplitude for five quiet days (black) along with the $\pm 2\sigma$ (green) and $\pm 3\sigma$ (cyan) are shown. Signal amplitude perturbations are marked with blue horizontal arrows.

Figure 5

(a-p) NLK signal amplitude (red) during 10 to 25 December 2020 which includes TC Yasa days. The mean signal amplitude for five quiet days (black) along with the $\pm 2\sigma$ (green) and $\pm 3\sigma$ (cyan) are shown. Signal amplitude perturbations are marked with blue horizontal arrows.

Figure 6

(a-p) JJI signal amplitude (red) during 10 to 25 December 2020 which includes TC Yasa days. The mean signal amplitude for five quiet days (black) along with the $\pm 2\sigma$ (green) and $\pm 3\sigma$ (cyan) are shown. Signal amplitude perturbations are marked with blue horizontal arrows.

Figure 7

Dst (purple) and Kp (green) indices during 10 to 25 December 2020 which includes TC Yasa days.

Figure 8

The variation of ionospheric Wait parameters, H' (first column, red) and β (second column, blue), based on the LWPC modelling of the following NPM signal perturbations: the daytime signal perturbations on (a) 13 December 2020 at 0:46 UT and (b) 14 December 2020 at 22:23 UT and the nighttime signal perturbations on (c) 16 December 2020 at 10:47 UT and (d) 17 December 2020 at 11:07 UT. The relative distance of the Suva receiver (Rx) from the NPM transmitter is indicated by the arrow pointing downwards.

Figure 9

Temporal variation of the ionospheric Wait parameters, H' (red) and β (blue), associated with the daytime NPM signal perturbation detected on 17 December 2020 at 18:00 UT to 18 December at 6:00 UT during TC Yasa.

Figure 10

The mother Morlet wavelet spectra of NPM (a-b), NLK (c-d) and JJI (e-f) signals during 10 to 25 December 2020. The daytime and nighttime spectra for each signals are shown in the left and right columns, respectively.

Supplementary Files

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