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Response of the mesosphere and lower ionosphere to the Extremely Severe Cyclone 'Fani' of 2019 over the North Indian Ocean

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Abstract

We present new observations of lower ionospheric disturbances due to the extremely severe cyclonic storm 'Fani' over northeastern part of the Indian Ocean. Very Low Frequency radio signals received from two places Kolkata and Cooch Behar, India revealed disturbances in the lower ionosphere namely in the D-region ionosphere. Mesospheric temperature and Ozone concentration data from the NASA's TIMED satellite were also used to diagnose the disturbances in the lower ionosphere. Significant wave-like oscillations and strong amplitude anomalies in daytime and nighttime VLF signal were observed during the intense phase of the cyclone. Both the mesospheric Ozone concentration and temperature showed maximum anomalies beyond 3σ during the cyclone period. Mesospheric temperature enhancement around VLF reflection heights indicates changes in the chemical composition and electron-neutral balance in the D-region ionosphere. Wavelet analysis of the VLF amplitudes indicates a strong anti-correlation of the total wavelet power in the wave-band of periods 10-30 min with the cyclone pressure which suggests a possibility of monitoring cyclone intensity from mesospheric gravity waves using VLF radio measurements.

1 Introduction

Tropical cyclones are important sources of non-stationary atmospheric gravity waves (AGWs) in the troposphere that propagate upward and outward from deep moist convection of the storm center (Wang et al., 2019). The AGWs generated from the cyclones can propagate upward transporting energy and momentum flux from the source region to upper atmosphere. It is now believed that these upward propagating AGWs in the neutral atmosphere are the key factor in coupling the different layers of the atmosphere. Various works using satellite, radar, radio, GPS TEC and optical airglow methods clearly showed the upward propagation of a broad spectrum of gravity waves through the troposphere to mesosphere-ionosphere via the stratosphere (Sato, 1993; Dhaka et al., 2003; Guha et al., 2016; Singh & Pallamraju, 2016 and references therein). Recent works also showed that the amplitudes of the AGWs at the troposphere, stratosphere or mesosphere detected at longer distances from the source location are correlated with the intensity of cyclone

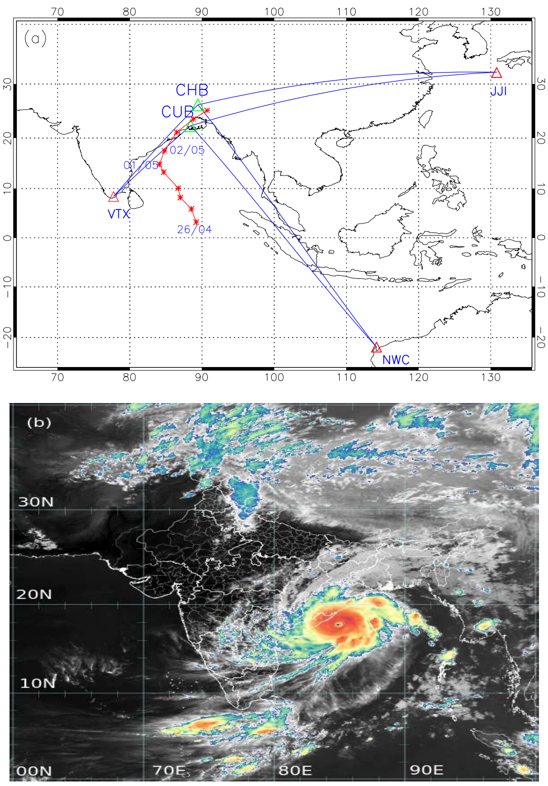

Figure 1. Great circle paths (GCPs) between the VTX transmitter and the receivers (Kolkata-CUB, Cooch Behar-CHB) are shown by the blue line. Red line shows the cyclone path from April 26, 2019 to May 05, 2019 and the asterisks show the location of the cyclone center on each day around 1200 UT. (b) The MSG satellite image (obtained from the www.imd.gov.in) shows the colorized infrared clouds of the Extremely Severe Cyclone Fani over the Bay of Bengal on 02 May, 2019 at 1400 UT before landfall.

(Hoffmann et al., 2018; Pal et al., 2020) and thus can be used to monitor cyclone intensity from remote measurements.

Here in this article, we briefly summarize the effects of the extremely severe cyclone 'Fani' of 2019 on the upper mesosphere and lower ionosphere using the very low frequency radio signals received at two tropical stations. Tropical cyclones are formed almost throughout the years in the North Indian Ocean above the equator. The Northeastern part of the Indian Ocean named as the Bay of Bengal is the source of many strongest tropical cyclones. The cyclone 'Fani' formed from a depression on April 26, 2019 over the Bay of Bengal and turned into an extremely severe cyclone on Ma 01, 2019 which made landfall on May 03, 2019. The propagation paths of the radio signals and track of the cyclone are shown in Figure 1(a). The satellite image of the cyclone on May 02, 2019 around 1400 UT when the cyclone intensity was maximum is shown in Figure 1(b).

2 Results and Discussion

In Figure 2, we present diurnal variations of signal amplitude of VTX transmitter (red) from 01 May to 04 May, 2019 along with the reference signal (black) and two $\pm 3\sigma$ deviation curves (green) for Kolkata (first panel) and Cooch Behar (second panel). Daytime signal amplitude from about 0200 UT to $\sim$1100 UT at Kolkata is very stable with less variability characterized by lower value of σ compared to the daytime signal at Cooch Behar. While the daytime signal at Kolkata showed a beautiful solar zenith angle variation, signal at Cooch Behar is flat which could be due to the complex interference pattern among the daytime waveguide modes in the earth-ionosphere waveguide. From 2300 UT in night to next day morning 0200 UT, signal amplitude is affected by destructive interference among the waveguide modes due to passage of sunrise terminator through the receiver to transmitter propagation paths. Similarly from 1100 UT to 1300 UT, VTX signal is affected by sunset terminator indicating disappearance of D-region ionosphere over the propagation path. The signal amplitude decreased beyond 3σ level between 1300-1600 UT (shown by the blue circle) on 02 May and 03 May indicating strong anomaly at both places. The deviation is more on 02 May than on 03 May as the cyclone intensity was maximum on 02 May, 2019 with maximum 1-minute sustained winds of 250 km/h (according to the United States Joint Typhoon Warning Center (JTWC)). The wave-like oscillations are present in the nighttime signal amplitude from 01 May to 04 May with maximum oscillation on 02 May at both places. The daytime signal amplitude also crossed the 3σ level on 03 May (0200 UT to 0700 UT) at Kolkata but not at Cooch Behar as Kolkata was nearer to the landfall area. Similar disturbances were observed on the NWC signals at both places though the intensity of the disturbances were less at Cooch Behar. On the other hand, the JJI signal at Kolkata was affected lately on May 03, 2019 and May 04, 2019 while the JJI signal at Cooch Behar showed no disturbances as the propagation path is far away from the cyclone affected area. Simulation of VTX signal received at Kolkata using the Long Wave Propagation Capability (LWPC) v2.1 code (Ferguson, 1998) showed that electron density at the D-region heights during the time of maximum perturbation (i.e., at 1400 UT on 02 May) is increased by almost $\sim$11 times with respect to the unperturbed value of 1400 UT on any normal day (Pal et al., 2020).

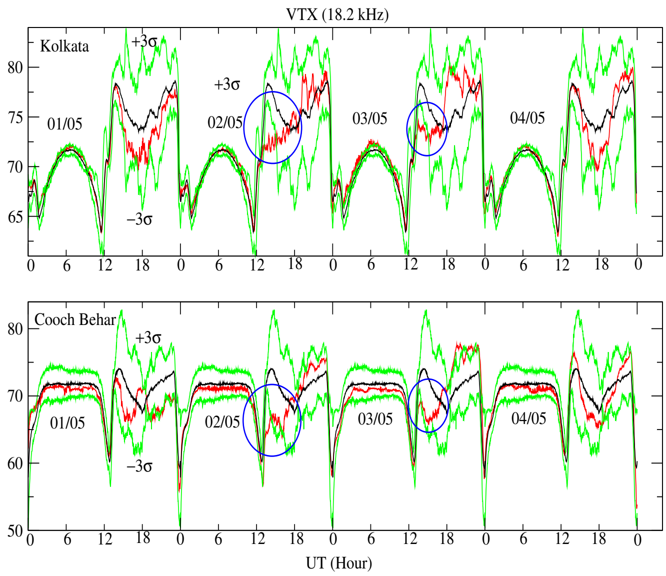

Figure 2. Diurnal variations of signal amplitude of VTX transmitter (red) from 01 May to 04 May, 2019 along with the reference signal (black) and two $\pm 3\sigma$ deviation curves (green) for Kolkata (first panel) and Cooch Behar (second panel).

We have used mesospheric temperature and Ozone concentration data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA's TIMED satellite during cyclone period over the Bay of Bengal region within a $12^\circ \times 12^\circ$ grid (10°N–22°N, 81°E–93°E). We choose the grid size so that at least one satellite pass is obtained daily. Then we plot the daily average mesospheric temperature and Ozone concentration time series to compare with the cyclone central pressure and VLF amplitude data. Figure 3(a) shows the atmospheric temperature variation (color map) for the altitude range 15-100 km during the above mentioned period obtained from the SABER/TIMED measurements. Daily-averaged temperature (red) for the altitude range of 75-85 km (white dashed rectangular box) is overlapped on the color map with axis label shown on the right-hand side in red. The daily averaged temperature time-series is calculated for the altitude range of 75-85 km, typical reflection heights of the VLF waves. Maximum of this temperature has been observed on 03 May, while the maximum disturbances in the VTX amplitude were seen on 02 May when the cyclone intensity was maximum. Figure 3(b) presents the mesospheric temperature (upper panel) and Ozone concentration (lower panel) anomalies before, during and after the cyclone period. These variations of mesospheric temperature and Ozone concentration during tropical cyclone may be explained by ion chemistry changes due to upward propagation of atmospheric gravity waves which require further investigations. In general, stratospheric Ozone, changes in CH4, mesospheric NOx and water vapor concentration can lead to changes in Ozone level in the mesosphere and lower thermosphere connected through various chemical channels.

Wavelet analysis of the residual VLF amplitudes has been carried out which shows wave-like oscillations in two significant wave-bands with periods 10-15 min and 30 min-2 h respectively. Total wavelet power calculated from the post-sunset and pre-sunrise period in the wave-bands with periods 10-30 min is found to be strongly anti-correlated with the central cyclone pressure (Pal et al., 2020). This suggests a possibility of using the mesospheric gravity waves from VLF signal measurements to remotely monitor the tropical cyclone activity.

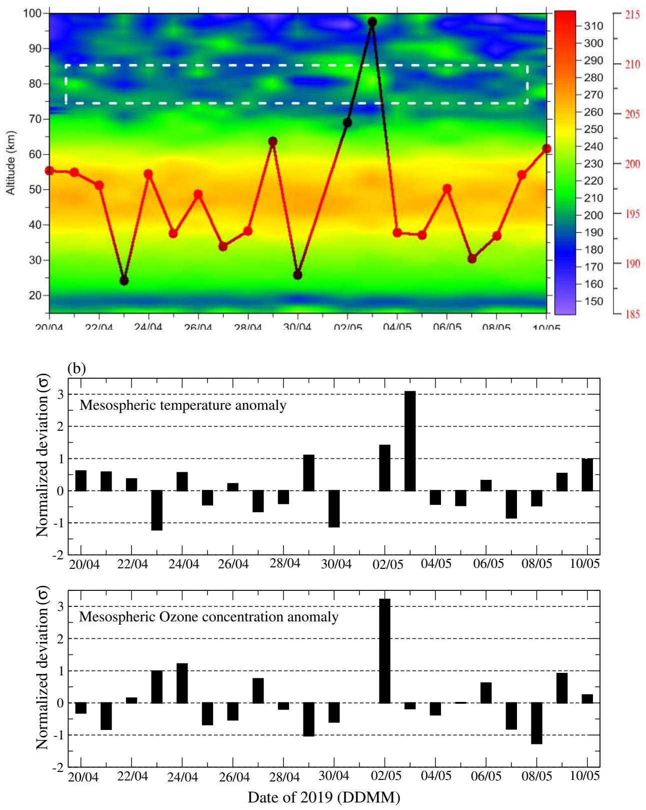

Figure 3. (a) The color map represents the variation of atmospheric temperature (Kelvin) in the altitude range of 15-100 km. White rectangular box covers the mesospheric temperature in the altitude range of 75-85 km. The average temperature at this heights (red circles connected by lines) are plotted over the color map corresponding to a third y-axis labeled in red. (b) Anomalies in the mesospheric temperature (upper panel) and Ozone concentration (lower panel) in the 75-85 km altitude range are shown before, during and after the cyclone period.

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References

[1] Dhaka, S. K., M. Takahashi, Y. Shibagaki, M. D. Yamanaka, & S. Fukao, "Gravity wave generation in the lower stratosphere due to passage of the typhoon (Orchid) observed by the MU radar at Shigaraki (34.85N, 136.10E)", *Journal of Geophysical Research*, **108(D19)**, 2003, 4595. https://doi.org/10.1029/2003JD003489

[2] J. A. Ferguson, "Computer programs for assessment of long-wavelength radio communications, version 2.0", *Tech. Document 3030, Space and Naval Warfare Systems Center*, 1998, San Diego, California.

[3] A. B. Guha, M. Paul, M. Chakraborty, and B. K. De, "Tropical cyclone effects on the equatorial ionosphere: First result from the Indian sector", *J. Geophys. Res. Space Physics*, **121**, 2016, 5764–5777, doi:10.1002/2016JA022363.

[4] Hoffmann, L., X. Wu, & M. J. Alexander, "Satellite observations of stratospheric gravity waves associated with the intensification of tropical cyclones", *Geophysical Research Letters*, **45**, 2018, 1692. https://doi.org/10.1002/2017GL076123

[5] S. Pal, S. Sarkar, S. K. Midya, S. K. Mondal and Y. Hobara, "Low latitude VLF radio signal disturbances due to the Extremely Severe Cyclone Fani of May, 2019 and associated mesospheric response," accepted for publication in *J. Geophys. Res. Space Physics*, January 2020.

[6] K. Sato, "Small-scale wind disturbances observed by the MU radar during the passage of typhoon Kelly", *Journal of the Atmospheric Sciences*, **50(4)**, 1993, 518.

[7] R. P. Singh and D. Pallamraju, "Effect of cyclone Nilofar on mesospheric wave dynamics as inferred from optical nightglow observations from Mount Abu, India", *J. Geophys. Res. Space Physics*, **121**, 2016, 5856–5867, doi:10.1002/2016JA022412.

[8] Y. Wang, L. Zhang, Y. Zhang, & J. Guan, "Effects of tropospheric vertical wind shear on gravity waves generated by tropical cyclones", *Geophysical Research Letters*, **46**, 2019, 4523.