

## RESEARCH ARTICLE



# An Investigation of Response of the Tropical Cyclone Ockhi in the Equatorial Ionosphere over the Indian region

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## Abstract

**Background/Objectives:** The ionospheric response to the tropical cyclone (TC) OCKHI of December 2017 in the equatorial region is presented in the study. **Methods/Statistical analysis:** The ionospheric response includes a change in Total Electron Content (TEC) is utilized using the stations of Tirunelveli and Bangalore. The critical frequency (foF2) from Ionosonde over Tirunelveli station also considered to study the TC effect in the F2 region of ionosphere. **Findings:** It has been observed that the significant changes in the equatorial ionosphere exhibits during the tropical cyclone (TC) OCKHI. They are: ionospheric parameter of vertical total electron content (VTEC) varies during the TC (i.e. from Day 332 to Day 336 of the year 2017) as the cyclone center is near to the Tirunelveli (8.7° N, 77.8° E) and the same follows for the IGS station of Bangalore. In addition, ionosonde measurements of foF2 perceived for the local night time support the TEC decrease noted over Tirunelveli when the cyclone attains its peak on 01 December 2017. **Novelty/Applications:** Using the ionosonde data over the equatorial ionosphere, such behavior may not be reported earlier to the best of my knowledge. The gravity wave induced by the TC Ockhi redistributes the element of the ionosphere due to strong convection and lightning activity.

**Keywords:** TEC; Cyclone; foF2; OCKHI; and gravity waves

## 1 Introduction

Mostly, the geomagnetic and solar activity affects the ionosphere region from above but the influence of the lower atmosphere also plays a role. Apart from this, its state is also influenced by the dynamical forcings of the lower atmospheric origin<sup>(1)</sup>. The meteorological events like cyclone, tsunamis, and others from the lower atmosphere also affect the ionosphere F region and reported by many researchers. The TC is

one of the strongest atmospheric disturbance originates in the troposphere over oceans and it rotates in the anticlockwise direction in the Northern Hemisphere and clockwise direction in the Southern Hemisphere due to the effect of Coriolis force<sup>(2)</sup>. Effects of tropical cyclone (TC) to the ionosphere have been emerging interest to the scientific community in recent years. The upward propagation of waves from troposphere to ionosphere is an essential source of energy and momentum for the ionospheric changes<sup>(3)</sup>. The changes in the ionosphere region is due to the mechanism of development of atmospheric turbulence by generation of internal waves such as tides, Rossby waves, Kelvin waves and gravity waves (GW)<sup>(4)</sup>. Also, the turbulence leads to transferring the energy influenced from lower atmosphere to ionosphere induced by tropical cyclone (TC)<sup>(5,6)</sup>. Besides, the gravity waves in the form of convective activity<sup>(7)</sup> and atmospheric tides generated by tropospheric weather systems<sup>(8)</sup> impacts on the variation of electron density in the ionosphere by analyzing the Total Electron Content (TEC)<sup>(9)</sup>. The GWs generated by TC have a time period with range of several minutes to hours depends on the intensity and duration of the event<sup>(10)</sup> and the waves can propagate in the horizontal direction for the several kilometers<sup>(11)</sup>. The variation of ionosphere is to be identified by the effect of considering both or either critical frequency of F2 (foF2) and virtual height of F2 region (h'F2)<sup>(12,13)</sup> and the impact of gravitational waves in the ionosphere due to the electrical, chemical and dynamical processes<sup>(14)</sup>.

In Indian region TC classified by different names depending on the wind speed and pressure difference such as low pressure area, depression, deep depression, cyclonic storm, severe cyclonic storm, very severe cyclonic storm, and super cyclonic storm. During the strong TC Mahesan and Hudhud passed over Indian sector observed to be decrease in TEC around equatorial region<sup>(11)</sup>. Nowadays, GNSS technique plays a vital role because of the increase in observing stations at different places for measuring the TEC and thereof the transmitter and receiver particularly used in different stations and also to study the ionospheric perturbations during the passage of tropical storms<sup>(15)</sup>. The ionospheric response of cyclones over Pacific Ocean observed to be an increase in TEC variations as the wind speed increases during the TC<sup>(16)</sup>. Due to the intense convection, the electric charge formed at the top of TC penetrates in the ionosphere increases the electron concentration in the F layer reveals the coupling of troposphere and ionosphere<sup>(17)</sup>. Whereas in another case the TEC tends to decrease while the tropical storm reaches the land and begins the trend of decreasing and then reverses when the storm effect gets reduced<sup>(18,19)</sup>. There is a possible change in the ionospheric parameter of foF2 of 10- 20% over the tropical cyclone zone at a distance from 3800 to 5500 km<sup>(20)</sup>. In the present study, for the first time, the ionospheric parameters are studied in the Equatorial region of Indian sector on the effect of Tropical Cyclone OCKHI during the period of November and December 2017.

## 2 Data analysis and Methodology

We have used GPS TEC observations from Scintillation Network Decision Aid (SCINDA) GPS receiver at Tirunelveli. To study the response of cyclone effects in the GPS TEC, International GNSS Service (IGS) TEC data for station IISC Bangalore were obtained from ftp://garner.ucsd.edu/pub/rinex/ (see http://www.igs.org/). We have also used our own Canadian Advanced Digital Ionosonde (CADI) data at equatorial station, EGRL, Tirunelveli. The ionosonde is a well-proven technique to study the ionosphere, and it provides useful information about various ionospheric layers and their temporal variations. CADI is widely used by many research groups across the globe<sup>(21)</sup>. Each GISTM can track up to 11 GPS C/A-code signals at the L1-frequency of 1.575 GHz and L2 frequency of 1.2 GHz. At the time of data analysis, the satellite biases should be corrected for the accurate measurement of TEC associated with GPS observations. Using ionospheric shell-model, vertical TEC were calculated and has been used in the present study<sup>(22)</sup>. The TEC data is collected for every one minute and the satellite and receiver bias correction be made to obtain the slant TEC directly.

The vertical TEC is obtained by using the following Eq. (1) model.

$$VTEC = (STEC - [Br + Bs])S(\theta) \tag{1}$$

Where, Br, Bs are receiver and satellite bias respectively,

$\varnothing$  Elevation angle of satellite in degrees, and

From Eq. (2),  $S(\varnothing)$  obliquity factor with zenith angle ( $\theta$ ) at IPP

$$S(\varnothing) = \frac{1}{\cos \theta} \frac{1}{\sqrt{\left[1 - \left(\frac{Re \cos(\theta)}{Re + h}\right)^2\right]}} \tag{2}$$

Where, Re is the Earth's mean radius in km, h is the height of the ionospheric Shell (in km) above the Earth's surface

The Dst (Disturbance storm time) data obtained from World Data Center (WDC) (<http://wdc.kugi.kyoto-u.ac.jp>) of 1-h temporal resolution and F10.7 data obtained from Space Physics Interactive Data Resource (SPIDR) of NOAA (<http://spidr.ngdc.noaa.gov/spidr/time.do>) of 1-day temporal resolution are used as indicators of the intensity of geomagnetic and solar activities, respectively. The Tropical Rainfall Measuring Mission (TRMM) was launched in 1997 with the precipitation radar in the observation satellite with the aim of measuring the rainfall and energy<sup>(23)</sup> (<http://trmm.gsfc.nasa.gov/>). To investigate convective activity during the observational period, we have utilized precipitation data available at 0.25x0.25 latitude and longitude grid provided by TRMM as the proxy.

### 3 Observation and Results

#### 3.1 Overview of Ockhi cyclone

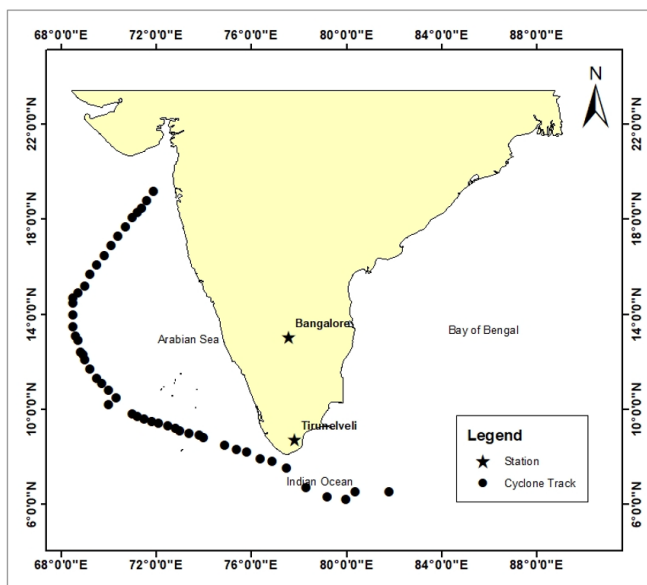


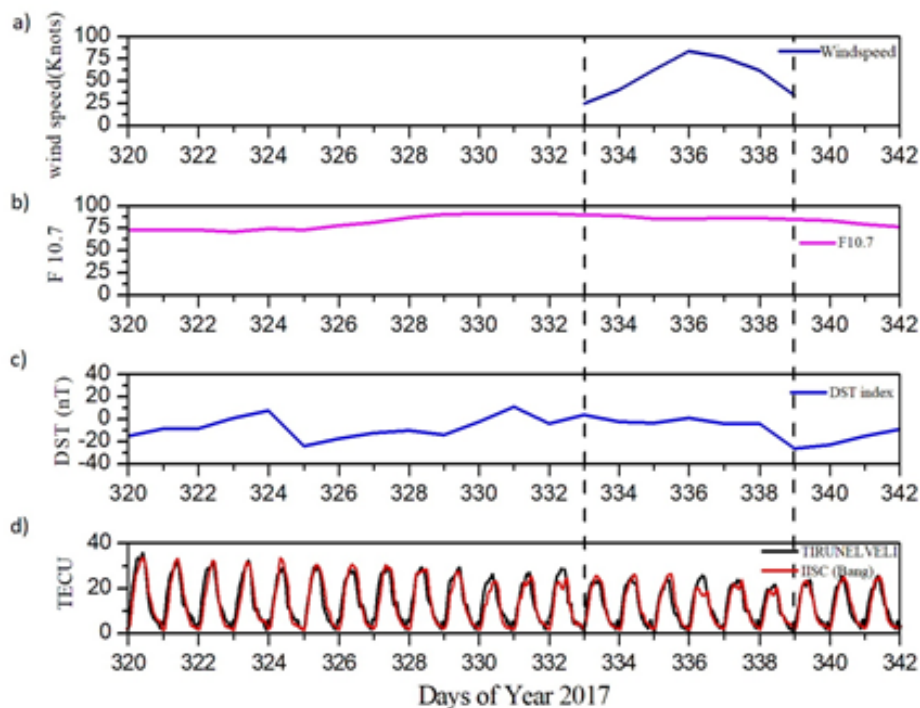
Fig 1. Path of the Cyclone OCKHI (Black color) and the location of stations at Tirunelveli and Bangalore (Black color Star symbol)

TC Ockhi occurred as a severe cyclonic storm (SCS) with its track length of about 2538 km and life span of ~162 hours (about 7 days) (Source: Indian Meteorological Department’s Regional Specialized Meteorological Centre for Tropical Cyclones, <http://www.rsmcnewdelhi.imd.gov.in>). On Drovak’s intensity scale, TC Ockhi attained the highest category of T5.4. Figure 1 presents the track of its eye from Indian Ocean to Arabian Sea during 29 November – 06 December 2017 (black color). GPS stations – Tirunelveli and Bangalore in India used in the present study are also shown in black star. TC Ockhi started with the formation of a depression on 29 November 2017 over southwest Bay of Bengal and centered at ~ 6.5° N latitude and 80.4° E longitude. Subsequently, this depression intensified into deep depression (DD) near the local sunset. Next, this DD moved west-northwestwards and promptly intensified into a cyclonic storm (CS) with centre at ~ 7.5° N, 77.5° E on 30 November at 0300 h UT. Within 6 hours, this CS underwent rapid intensification to become a severe cyclonic storm (SCS) almost close to the southern tip of the peninsular India near local noon of 30 November. Meanwhile its track moved from southwest Bay of Bengal to southeast Arabian Sea via the tip of the peninsular India. On early morning hours of 01 December, this storm attained the status of very severe cyclonic storm (VSCS) and moved north-eastwards thereby maintaining its intensity till the early morning hours of 3 December. Under the influence of strong upper level westerlies, this storm recurved from east-central Arabian Sea during 03 – 04 December. Gradually this cyclone weakened to a depression during midnight on course of its movement along the western coast of the Central India during 05 December and finally made a landfall on 06 December<sup>(24)</sup>.

#### 3.2 Meteorological and geomagnetic conditions during occurrence of TC Ockhi:

Figure 2 summarizes few meteorological and geomagnetic parameters noted during 16 November – 08 December 2017 along with the TEC measurements. The vertical black lines in the Figure depict the start and end of Ockhi cyclone. Wind speed

associated with the cyclone development is shown in Figure 2(a). During the severe cyclone activity, this wind speed reached the maximum of 80 – 85 Knots per hour. Figure 2(b) and (c) respectively represents Solar F10.7 cm radio flux and Dst index. Raw TEC measurements over Tirunelveli and Bangalore are shown in Figure 2(d). During this period, Ap index varied in the range of 01 - 28 units, Dst index varied from -45 nT to 22 nT, and F10.7 cm flux lay between 65 and 75 units. As such moderately quiet geomagnetic conditions were noted on few nights during the cyclone occurrence.



**Fig 2.** (a) Wind speed of the cyclone Ockhi (b) F10.7 solar indices (c) DST index (d) Diurnal variation of VTEC for Tirunelveli (Black) and for IISC (Red) for the period of 320 to 341 of year 2017.

### 3.3 Diurnal behavior of TEC over Tirunelveli and Bangalore:

During day number 333-335 when TC Ockhi was closer to the southern tip of the Peninsular India, we observed a significant decrease in TEC (about 5 Total Electron Content Unit, TECU) over both Tirunelveli and Bangalore (shown in Figure 2(d)). However, TEC decrease was more prominent over Tirunelveli in comparison to that over Bangalore. During this time, the wind speed reached its maximum. Most notable decrease in TEC was noted on day 338 over both stations. TEC values were found to recover back to their original values after this cyclone moved significantly away from the station. Figure 3 presents the diurnal variation of TEC over Tirunelveli (top panel) and Bangalore (bottom panel) during 29 November – 02 December 2017 corresponding to TC occurrence. In order to visualize the TEC changes during TC occurrence, we estimated mean TEC variation of four quiet days during 17 – 20 November over both stations and are shown in Figure 3. Quiet day variations of TEC over both stations are marked by an increase starting from local sunrise (~ 0000 – 0100 UT), followed by a maximum around noon (~ 1000 UT) and a decrease thereafter. Such diurnal trend is representative of TEC variations over the equatorial and low latitude ionosphere<sup>(25)</sup>. During the TC occurrence, a prominent decrease in TEC during 0400 – 1400 UT can clearly be seen at both the station. Generally TEC decrease of 3 – 4 TECU with reference to quiet day variation was noted. We found a maximum decrease of TEC of about 12 TECU around 0900 UT on 29 November over Bangalore. Further, we observed a well-marked decrease in TEC (~ 3 – 4 TECU) over Tirunelveli during 1600 – 2000 UT (corresponding to local midnight hours) on 29 - 30 November and 01 December. However, such decrease was less pronounced over Bangalore. Figure 3 also indicates that the decrease noted during the night was less evident over Bangalore.

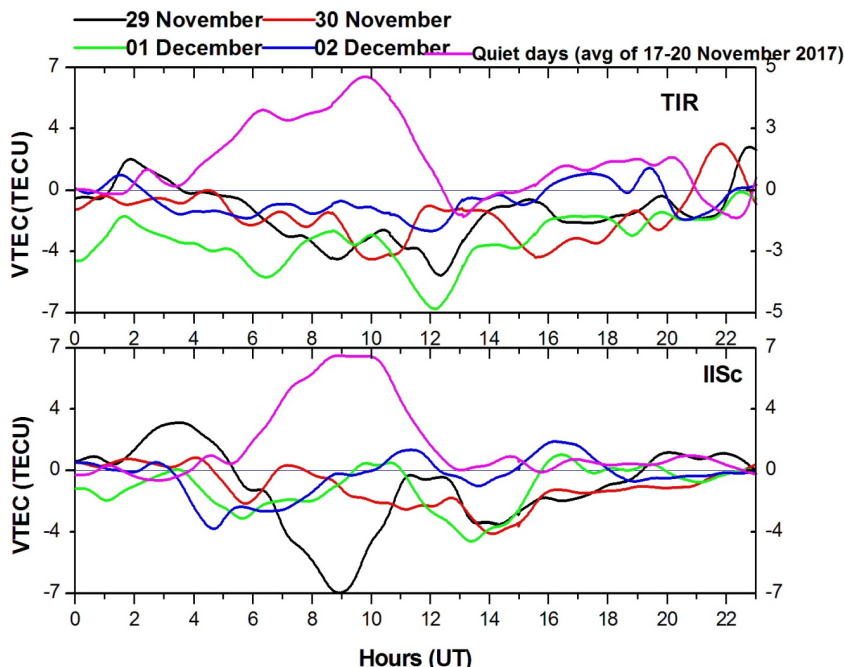


Fig 3. (a) Diurnal variation of VTEC during cyclone days (29 November to 2 December) and mean quiet days (Magenta color) of Station Tirunelveli and IISc Bangalore.

### 3.4 Observation of critical frequency (foF2) over Tirunelveli:

In order to see cyclone response in the ionospheric scaling parameters, the foF2 has taken with the sampling interval of 10 minutes for the period of 14 days (day number 329 to 342) with respect to the TC period. The Figure 4 depicts the temporal variation in foF2 during day time (top panel) and night time (bottom panel) for the station Tirunelveli. As seen in Figure 4, the foF2 noticed to be diminished at about ~ 2-3 MHz at 8-10 IST on day number 335 and 336 which is associated with severe cyclone occurred close to Tirunelveli. However, an enhancement in foF2 of about 8-10 MHz is also found in the early morning hours (3 - 4 IST) on day number 336. In general, foF2 rises after sunrise and it reaches peak in the early afternoon, there is a rapid fall shortly after sunset during quiet day conditions over low latitude region. It has also been suggested that gravity waves could be responsible for the night-time ionospheric density gradient enhancement and hence it has been the reason for the observed higher variability in foF2 at night-time rather than during daytime (12,26).

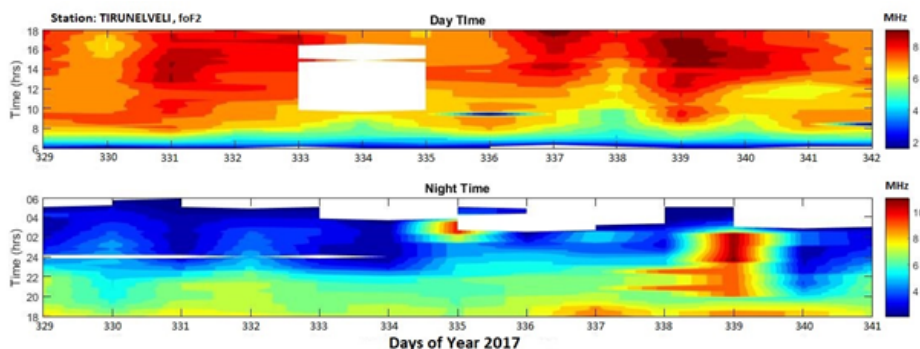


Fig 4. Variation of foF2 for Day time and Night time of Tirunelveli station for the period of 329 to 341 of year 2017

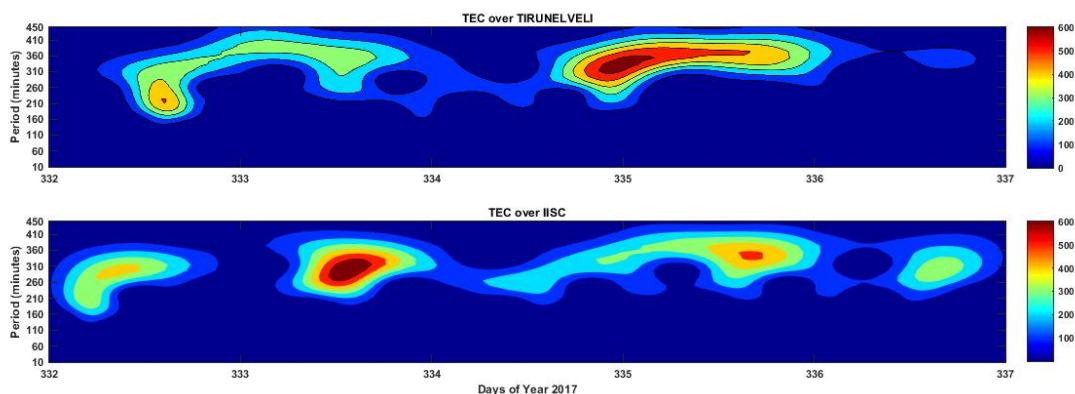
### 3.5 Observations of GWs in TEC measurements:

GWs are the important dynamical coupling elements of the mesosphere-lower thermosphere-ionosphere region. Owing to this, we interpret these wave-like variations as the signatures of GWs in the ionosphere and extended our study to identify these GWs. First, we calculated the residual TEC data for a particular day by subtracting daily mean TEC variation from original TEC data. Such removal of mean daily TEC trend was performed to enhance the GWs features embedded in TEC variations during the TC occurrence. Next, the wavelet analysis was performed to identify the GWs present in residual TEC data. Figure 5 depicts the wavelet analysis was carried out on residual TEC data over Tirunelveli (top) and IISC, Bangalore (bottom) during 28 November – 02 December 2017 i.e. starting from the day when TC Ockhi was deep depression, its subsequent development to a very severe cyclonic storm and till its decay to severe cyclonic storm. Table 1 summarizes the different wave periodicities identified during TC occurrence along with the time information when that particular wave was dominant. Table 1 clearly indicates that (i) GWs periodicities were common at both locations, and (ii) GWs were first seen at Tirunelveli and then noted at Bangalore. Wavelet analysis shows that the time period of observed GWs lay in the range of 1.4 – 6.5 h, and fell in two categories viz. 1 – 3 h and 4 – 6 h. Usually excited GWs with different frequencies occur when a typhoon is close to the coast or landfall causes disturbances in the ionosphere due to rapid loss of momentum and viscous interactions<sup>(27)</sup>.

**Table 1.** Gravity wave periodicities estimated from the wavelet analysis of residual TEC data during 29 November – 02 December 2017. Residual TEC has been obtained by detrending the daily mean TEC variation from original TEC data for a particular day. We have shown in braces the time when listed wave was the dominant component.

Date (2017)	GWs periodicity (in minute)	
	Tirunelveli	Bangalore
28 November	239.5 (0648 UT), 119.7 (0520 UT), 181.5 (0316 UT), 294.8 (0025 UT), 169.3 (1124 UT)	239.5 (1212 UT), 119.7 (0908 UT), 181.5 (0435 UT), 294.8 (0745 UT), 169.3 (1710 UT)
29 November	363.0 (1005 UT), 181.5 (0030 UT), 128.3 (1114 UT), 84.67 (0552 UT), 90.75 (1433 UT), 294.8 (2038 UT)	363.0 (2329 UT), 181.5 (0658 UT), 128.3 (1527 UT), 84.67 (0932 UT), 90.75 (1955 UT), 294.8 (0443 UT*)
30 November	128.3 (1054 UT), 84.67 (1532 UT), 111.7 (1422 UT), 316.0 (0749 UT)	128.3 (1548 UT), 84.67 (2121 UT), 111.7 (2340 UT), 316.0 (1251 UT)
01 December	389.1 (0025 UT), 275.1 (1652 UT), 169.3 (1642 UT), 90.75 (0338 UT), 194.5 (2252 UT)	389.1 (0724 UT), 275.1 (2335 UT), 169.3 (2148 UT), 90.75 (1329 UT), 194.5 (0047 UT*)
02 December	294.8 (0625 UT), 97.26 (1120 UT)	294.8 (0724 UT), 97.26 (1626 UT)

\*indicates the wave periodicity observed on next day



**Fig 5.** Wavelet spectra of TEC over Tirunelveli and IISC during 28 November – 2 December 2017

## 4 Discussions

General diurnal behaviour of TEC over Tirunelveli and Bangalore clearly indicates the influence of TC Ockhi in the equatorial ionosphere. When compared to control days, a decrease of TEC by about 3 – 4 TECU during the development of cyclone is noted. Time span of the observations are performed under quiet and low geomagnetic conditions yield favorable to investigate the ionospheric perturbations of large scale tropospheric disturbances. It clearly reveals that TEC variation and foF2 are positively correlated, which leads for some understanding of the ionospheric disturbances. Over the Indian low-latitudes, the F-region electron density or TEC is often marked by an increase due to increase in geomagnetic activity<sup>(18,28-30)</sup>. Over both Tirunelveli and Bangalore that are low-latitude stations, TEC decrease during the presence of TC Ockhi suggests a strong impact of the cyclone in the equatorial ionosphere. Several investigators have reported such a decrease in TEC during the tropical cyclone occurrence<sup>(2,11)</sup>.

Recently, the effect of Usagi cyclone on the TEC was reported during September 16-24, 2013, and noticed the ionosphere disturbances through Spectral Whitening Method (SWM) along the track of tropical cyclone<sup>(28)</sup>. Also, ionosphere could alter its behavior while cyclone approaching the continent and our results show that TEC anomaly deviates below the normal day on the landfall day is consistent with earlier report<sup>(18)</sup> noticed the deviation of 5 TECU before landfall and 3 TECU on the day of landfall of a typhoon using network of 50 GPS stations. The ionosphere parameters like foF2, electron concentration, and TEC decreases about a day after landfall of TC<sup>(11,31)</sup> and for some cases an increase in TEC observed<sup>(32)</sup>. In addition, decrease in foF2 marked during the onset of cyclone<sup>(12)</sup> while the same observed for the period of 2200 to 0300 in our study.

The anomalous TEC variation can be explained by several possible mechanisms. A sharp decrease of ionospheric TEC and foF2 over a wide zone of the cyclone track could be explained by the mechanism which fluctuate the ionosphere during the passage of a TC. TC is a strong hub of convective/lightning activity. Some studies suggest that lightning associated electric fields can bring about a decrease in the electron density by enhancing electron attachment to O<sub>2</sub><sup>(33)</sup>. Whereas for cyclone Phailin, energy released during the lightning activity perturbs the ionospheric TEC over the Indian region<sup>(34)</sup>. For cyclone Usagi, the ionosphere-related parameters had anomalous electron density variation on the second day after landfall near Hong Kong<sup>(32)</sup>.

Atmospheric waves act as a primary wave which propagates from low laying atmosphere to the thermosphere<sup>(35)</sup>. Due to the thunderstorms activity, modelling study reports the generated Acoustic Gravity Waves (AGW) which leads to the ionospheric perturbation<sup>(31)</sup>. Meteorological sources excite AGWs with periods close to the Väisälä-Brent period propagates from the excitation region vertically and reach the heights of thermosphere and ionosphere. Thus leads to the formation of local heating in the thermosphere region, due to the dissipation of waves, which affects the dynamics of the ionosphere region and its ionization recombination processes<sup>(36)</sup>. The E and F region of the ionosphere influence by the electrical effects of thunderstorms<sup>(37)</sup>. Often the tropical cyclone formation preceded by a convective burst of very deep and persistent cumulonimbus clouds and the updrafts of the convection can be extremely deep, wide, and intense. The convection generated stratospheric gravity waves due to the mechanical oscillator mechanism are based on the response to buoyancy oscillation forcing at the tropopause<sup>(38)</sup>. Also, the similar wave periodicities observed due to convective sources in the MLT region<sup>(39)</sup>. Furthermore, we found the meridional phase velocity of the TC Ockhi induced GWs in the range of 21 – 36 m/s during 29 – 30 November which are consistent with the thermospheric winds<sup>(40)</sup>.

We present in Figure 6 the TRMM precipitation data (a proxy of convective activity) over the Indian subcontinent during 28 November – 02 December. Clearly the precipitation starts on 28 November around 80° E during low pressure and gets intensified about 150 mm/day during 29 November - 01 December 2017 when TC Ockhi attains its peak near Tirunelveli. Later, the precipitation rate increases and persists within 60 - 70° E during 02 - 03 December 2017 and shows that convective activity moved away from Tirunelveli. The immense energy from the vortex formation of the tropical cyclone causes a convectational effect on the distribution of the chemical constituents of the Earth's atmosphere through the gravity waves which disturbed the F region of ionosphere. During the active period of TC, the chemical constituents redistribute at different ionospheric heights as well as the horizontal distances of the TC location. The TC generated energy from troposphere enhances the presence of dominant neutral particles from lower part of the atmosphere. We postulate that the decrease in TEC and foF2 may be due to the effect of TC-induced gravity wave, ejection of neutral particles from the terminator, and electric field generated by lightning may redistribute the chemical constituents of the ionosphere by raising the number of neutral particles at different height region in the track of the cyclone path.

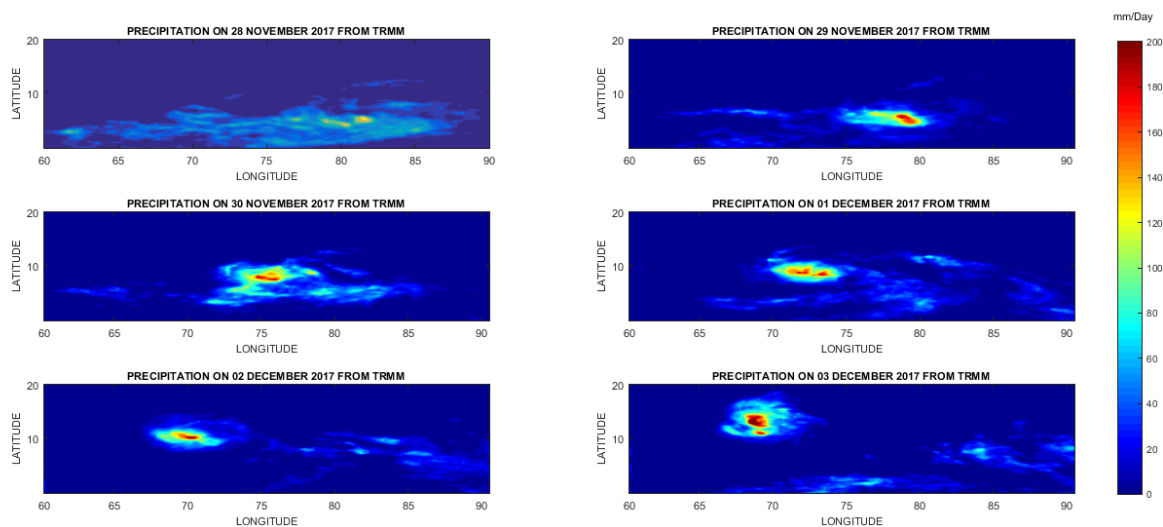


Fig 6. Longitude-latitude cross-section of rainfall rate derived from TRMM for the six days (28 November - 03 December 2017)

## 5 Conclusion

In this study, we presented TC Ockhi driven TEC anomalies and foF2 when the cyclone initiate and passes close to the station Tirunelveli. Our results show anomalous TEC variation and foF2 caused by gravity waves through the coupling process between the troposphere and ionosphere. When TC Ockhi was closer to these equatorial stations, significant changes in the equatorial ionosphere were noted viz. a decrease in TEC and the signatures of TC-induced GWs in diurnal variations of TEC. Ionosonde measurements of foF2 over Tirunelveli supported the decrease in TEC. Also, we have presented precipitation rate during intense TC Ockhi and it is noticed that the convective activity over the land region during the peak stage of TC. Intense GWs activity was noted over both stations when TC was closer to land during its development from deep depression to cyclonic storm. During 29 – 30 November when TC lay in the south of Tirunelveli, observed GWs had a phase speed of  $\sim 21 - 36$  m/s and propagated towards the north. However, continuous and comprehensive radar observations along with gravity wave ray-tracing algorithms are necessary to confirm typical ionospheric observations as the result of tropospheric forcing.

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