RESEARCH ARTICLE OPEN ACCESS

An Investigation into Height Variation of Ionospheric Signature Due To the Cyclonic Storm Formation Using COSMIC-RO Measurements

Gopal Mondal*, Manojit Gupta** and Goutam Kumar Sen***
**(Department of Mathematics, Vivekananda Mission Mahavidyalaya, Haldia, 721645, gopalmondal18@gmail.com)*
***(Departments of Mathematics, Jadavpur University, Kolkata 700032, manojitgupta@hahoo.co.in)*
****(School of Oceanographic Studies, Jadavpur University, Kolkata, 700032, gksju@yahoo.co.in)*
Corresponding author:Gopal Mondal

ABSTRACT
Here the height dependence of ionospheric signature due to the existence of low pressure systems, like, Cyclonic Storms (CSs) at the lower atmosphere, have been studied using COSMIC-RO satellite measurements on the example of two deleterious cyclones – Mahasen (10-16th May 2013) and Phailin (8-14th October 2013). These two CSs were generated over the Bay of Bengal (BOB) in 2013. Day-to-day variations of four different physical parameters, namely, IEC, NmF2, HmF2 and the NOAA Outgoing Long Wave Radiation (OLR) have been retrospectively analyzed during the Cyclone Genesis Period (CGP). For the first time, five 50 km width ionospheric layers have been considered to rectify the dominant perturbation zone linked to the considered lower atmospheric convective activities. All the ionospheric parameters exhibit excellent correlation between themselves whereas OLR exhibit little correlation with the ionospheric parameters. Both, pre-cursor and post cursor signatures have been registered at the ionospheric F2 layer in the pre and post Cyclone Life Cycle (CLC). Here, the dominant perturbations were mostly confined in the layers associated to lower F region of the bottom side Ionosphere and it is gradually decreasing for the upper layers. Moreover, few discrepancies which were detected in case of two CSs were mainly due to dissimilar strength of CSs and difference of sampling size of ionospheric data. Atmospheric Gravity Waves (AGWs) is assumed to be the main responsible coupling agent between lower atmosphere and Ionosphere during this type of lower atmospheric convective activities, like CSs.

Keywords:CS, COSMIC-RO, IEC, OLR

Date of Submission: 07 -07-2017 Date of acceptance: 20-07-2017

I. INTRODUCTION

In the Earth's atmosphere various geophysical processes are happening. Out of which maximum are confined in lower most layers of the atmosphere (i.e. Troposphere). A cyclone is a convective process, characterized by the rotation around a low pressure area, something not typical in smaller storms. It is one of the strongest devastating phenomenon in the lower atmosphere generated due to thermal misbalance. The period in between generation and precipitation of any Cyclone is called the Cyclone Life Cycle (CLC). Generally, Cyclone of longer life cycle is of more intensity and more devastating in nature (Sharkov, 2012). Any low pressure system characterized in the lower atmosphere can sensitively influence different layer of the atmosphere through different mechanisms (Vinay Kumar *et al*. 2016). Scientists of various disciplines are busy to filtered out the mechanisms which are reasonably influencing the Ionosphere during different lower atmospheric convective phenomena, like thunderstorm, cyclone etc and from there make a prediction mechanism of ionospheric modulation. In this connection it should be mentioned that, in 1948 Erik Palmen first observed that the tropical cyclones required ocean temperatures of at least 80°F (26.5°C) for their formation and growth. Above this temperature deep convection can occur, but below this value the atmosphere is too stable and no thunderstorm activity can be found (Graham and Barnett, 1987 and references there in). As early as in 1950s, Bauer (1958), for the first time, observed ionospheric signature in the passage of hurricanes and found that maximum enhancement in foF2 occurred when hurricanes were closest to the observation station. Also, Huang *et al.* (1985) researched about 15 typhoons throughout 1982 and 1983 near Taiwan region using High Frequency (HF) Doppler radar to detect Frequency Shifts (FS) at ionospheric height induced by typhoons and reported that two typhoons, Wayne (21-26th July 1983)and Andy (22-30th July 1982), caused significant ionospheric variations.

In fact, most of the previous studies have been reported about two responsible mechanisms which affect the ionosphere mostly during different lower atmospheric meteorological phenomena, these are: (i) Electrical and Electromagnetic process (Harrison *et al.* 2010, Sorokin *et al.* 2005), and (ii) Upward propagating waves generated in the neutral atmosphere (Lastovicka, 2006; Su *et al.* 2014), such as the planetary waves, the tidal waves and the AGWs (Killeen and Johnsson, 1995; Bhattacharya and Das, 2013). However, the former option is out of the scope of this study and ionospheric signature due to the evolution in AGWs is of our main concern. In general,AGWs, generated by tropospheric disturbances (may be due to CS generation), under favourable conditions can propagate up to MLT region (i.e.50-180 km) where wave breaking taken place through growth of wave amplitude with height or through reduction of vertical wave length by Doppler-shifting. Hence, energy and momentum sustained by the wave deposited which produce field-aligned current (Didebulitze *et al.,* 2015;Killeen and Johnsson, 1995) in the ionospheric F region helping to appear sprites and other transient luminous events (Didebulitze, 1997), TEC perturbation (Zhao *et al.,* 2008) and quasi-periodic Ne density perturbation known as AGW-TID (Hines, 1972; Eun and Gross, 1976; Fritts *et al.,* 2008; Kazimirovsky, 2002; Lastovicka, 2006; Su *et al.,* 2014; Vlasov *et al.,* 2011; Vincent, 2009). Another study, Sorokin *et al.* 2005 have shown that the electric field disturbances arises due to perturbation in atmosphere–ionosphere electric circuit, generated by the upward transport of charged water drops and aerosols, in the hurricane convection zone may causes the generation of ionospheric plasma irregularity. In 2006, using CROSS-2 satellite (Indian satellite) data, Rai *et al.* (2006) observed that the electron and ion temperature enhance consistently during active thunderstorm period and it was slightly higher in case of electron temperature. Recently, Polyakova and Perevalova (2011, 2013) estimated the ionospheric responses due to CSs generation, observing the variations in Total Electron Content (TEC) obtained from International network of dual-frequency ground-based GPS receivers and assured that intense TEC variation occurred when CSs reached its maximum intensity.

Again, OLR estimation is vitally important to monitor the evolution in different convective activities in the Earth-atmosphere system. In general, decrease in OLR is associated with an enhanced activity of precipitation i.e. increasing cloud amount and releasing latent heat, whereas its increase is associated with decrease in cloud amount (Jin *et al.* 2005; Xiong *et al.* 2010). There are some studies (Vinay Kumar *et al.* 2016; Jin *et al.* 2005; Xiong *et al.* 2010) where the researchers have analysed the swing in OLR to addressed different characteristic of lower atmospheric dynamic. Such as, Jin *et al.* (2005) tried to predict the CS moving direction analysing the swing in OLR whereas, Vinay Kumar *et al.* (2016) estimated the impact of cyclone Nilam on lower atmospheric dynamics in the tropical region in which OLR play vital role.

Afraimovich*et al.* 2008; Lin, 2012(a), 2012(b); Polyakova and Perevalova, 2011, 2013 and Tian *et al.* 2010 have been presented different characteristic of ionospheric responses due to the CS generation and/or its passage, none of the studies reported about variations in Ne concentration at different height levels, mainly variation in TEC were analysed. In our previous study (Mondal *et al.* 2014) it has been reported by analysing the Electron Content ratio (ECR) that during Cyclone Genesis Period (CGP) Ne concentration in the bottom side ionosphere increased by significant amount which help to get lower ECR during CGP compared to normal period. However, lack of sufficient number of scientific resources about ionospheric precursor and/or post-cursor signature during this type of convective phenomenon, encourages us to give insight into investigating the delicate evolution in Ne concentration at different height levels. In recent years, the intensity and lifecycle of CS in the tropical region considerably increasing (Elsner *et al.* 2008; Park *et al.* 2014) which encourages the research community to estimate its evolution**.** Again, as the Coriolis force ($f = 2\Omega \text{Sin}\phi$) at the Equator ($\phi = 0$) and low latitude region is very weak (actually zero at equator) the tropical region exhibit unique type of dynamics in case of both atmospheric and ionospheric activities compared to other latitudes.

Till date the acquisition of ionospheric parameters, particularly the parameters from space-based observations, in the Indian Equatorial Region (IER) is considerably limited. In this respect, Low Earth Orbiting (LEO) satellite Radio Occultation (RO) information could be an apposite alternative source to evolve the evolutions in ionospheric layers during different geophysical phenomenon, like, thunderstorm, cyclone etc. In this study, COSMIC-RO observation profiles have been used to determine and estimate the precursor and/or post-cursor signature, if any, at ionospheric heights due to the existence of two CSs: Mahasen (10-16th May 2013) and Phailin (8-14th October 2013). This kind of study, using space based measurements, is first over this region. Here, section II and III are devoted to data acquisition and methodologies. Results and

Discussions were given in section IV, and the Conclusions are given in section V.

II. DATA ACQUISITION

For both the cyclonic activities we have chosen separate 15 days observational periods including their CLCs (Sharkov, 2012). For ionospheric information during the observational periods, COSMIC-RO satellite data have been downloaded from the mission website. Detailed descriptions about this mission and its data format have been addressed in its official website (http://www.cosmic.ucar.edu). Several previous studies (Aragon-Angel *et al.* 2009; Mondal *et al.* 2014, 2015; Sripathi, 2012, etc) have been imposed different realistic quality control criteria according to their need. Similarly, here also, precise restrictions have been imposed to filter out suitable data sets for better quality and applicability of this study. Finally, 111 VED profiles (80 and 31 for CS1 and CS2) for the selected 15 days observational periods have been filtered out to analyze. In addition to this, all the information about considered Cyclonic activities including their track, intensity, lifecycle (Figure 1) etc were obtained from Indian Meteorological Department (IMD) website(http://www.imd.gov.in/).Also, the solar activity (Liu *et al.* 2006) and Earth's geomagnetic field (Dabas *et al.* 1980) activity were checked during the respective observational periods with the help of solar F10.7 flux and geomagnetic $\sum \mathrm{Kp}$indices information, obtained from http://www.ukssdc.ac.uk of UKSSDC, UK and http://wdc.kugi.kyoto-u.ac.jpof Kyoto, Japan. Daily mean OLR, over the selected region, were taken from NOAA website (http://www.esrl.noaa.gov/psd/data/gridded).

III. METHODOLOGIES

Each satellite in the COSMIC-RO mission rotates one round of Earth in ~100 min. So, it is not possible to have the daily variability in any ionospheric parameter at any specific location for a particular time which is necessary to draw any conclusion about short and/or long term trend in it. To overcome this inconvenience, data of those orbits which pass through a 15° box size region including respective cyclone tracks, presented in Fig. 1(A) and Fig. 1(B), have been considered to cover less spatial variability in the parameters. Here, the Local Time (LT) is obtained by adding 5.5 hrs to the Universal Time (UT).

It was already reported in one of our previous studies (Mondal *et al.* 2014) that during Cyclone Genesis Period (CGP) (Sharkov, 2012) significant Ne perturbations were mostly confined in bottom side Ionosphere. Now, a question naturally arises: what is the altitudinal dependency of this perturbation in this bottom side part? This issue has been addressed in this study with the help of correlation analysis between considered ionospheric parameters. Most of the studies (Afraimovich*et al.* 2008; Lin, 2012(a), 2012(b); Polyakova and Perevalova, 2011, 2013; Tian *et al.* 2010) linked to ionospheric signature due to the existence of lower atmospheric convective phenomena, comprised of TEC variation only. However, to detect the height levels where sensible Ne perturbations taken place, the height range 150-400 km have been divided in five 50 km sub-intervals. Note that, according to α Chapman function (Chuo *et al.* 2013) for vertical electron density profile, the magnitude of scale height (H_T) is 50-55 km near the height of peak electron density which motivates us to take 50 km width ionospheric layer. The Integrated Electron Content (IEC is equivalent to TEC and$1\mathrm{TECU} = 10^{16}\ \mathrm{el}/m^2$) in each sub-interval has been calculated using the equation;

$$\mathrm{IEC} = \int \mathrm{Ne}(z)\mathrm{dz} \qquad (1)$$

In the above equation (Eq. 1), Balt and Talt are the Mean Sea Level Altitude (MSL_Alt) at the bottom and top point of each sub-interval. Actually, from equation (1) six different IECs were calculated on the basis of six different pair of lower and upper limits tabulated in Table 1. To curtail the effect of diurnal variability in the ionospheric signature to be detected, if any, we finally calculate daily weighted mean and standard deviation of each parameter using equation (2). In this regard, each day (i.e. 24 hours) is being divided in four equal length (six hours) LT sub-intervals:$0 \le \mathrm{LT} < 6$, $6 \le \mathrm{LT} < 12$, $12 \le \mathrm{LT} < 18$and $18 \le \mathrm{LT} < 24$ and thereafter all the parameters associated to these four sub-intervals have been assigned the weights; 4, 3, 2 and 1 respectively.

$$P(\mathrm{ave}) = \frac{(4N_4P + 3N_3P + 2N_2P + N_1P)}{(4N_4 + 3N_3 + 2N_2 + N_1)} \qquad (2)$$

Where P(ave) is the average of parameter P. N4, N3, N2 and N1 are number of data in respective time periods.

IV. RESULTS AND DISCUSSIONS

4.1. Daily Variation in OLR and vertical Ne concentration

The variations in spatial averaged OLR (W/m^2) and the weighted averaged Ne concentration during the considered 15 days observational period, including respective CLC, have been depicted in Fig. 2(a-b) and Fig. 3(a-b). In both the Figs. the upper panels are associated to CS1 (Mahasen), whereas the lower panels are for CS2 (Phailin). The OLR variability in both the panels exhibit more or less similar trend. However, during the incipient stage of these low pressure systems (CS1 and CS2) the OLR values primarily decreases (see Fig. 2(a-b)) up to a certain level (170 on 11^{th} May and 181 on 11^{th} October for CS1 and CS2) mainly due to initial trend of enhanced precipitation or increasing cloud amount (Jin *et al.* 2005) in the lower atmosphere. Interestingly, just before the precipitation of the low pressure systems one acute fall, actually the lowest, in OLR concentration occurred and thereafter, it increases sharply till reaching the normal level (12-16^{th} May for CS1 and 12-14^{th} October for CS2). On giving insight into the variation of vertical Ne concentrations (for example see Fig. 3) during the observation period; we have seen that at the initial stage (i.e. 9-10^{th} May for CS1 and 5-6^{th} October for CS2) of the formation of these low pressure systems, a noticeable diminishing trend in Ne concentration mainly at the F2 layer (especially at 200 km and above) detected for both the CSs and thereafter, this trend is totally opposite till the maximum intensified state of the CLCs, such as, for CS1 (Mahasen) this trend continued to persist in till the maximum intensity day on 15^{th} May 2013 (see Fig. 3a and Fig. 1a), whereas, for CS2 (Phailin) that happen on 12^{th} October 2013 (see Fig. 3b and Fig. 1b). Also in the lower F region an apparent trend of increasing Ne concentration exhibits a significant ionospheric evolution due to the presence of CS activities at the lower atmosphere. Evidently, the gradual intensification of CSs and their associated higher EMSSW during different phases of CLCs, as given in Fig. 1(a) and Fig. 1(b), must have proportional influence to the ambient atmosphere. During the last phase of CLCs when the low pressure systems generally entered to the adjacent coastal area with heavy to very heavy rainfall and EMSSW, higher Ne concentration detected in the F region, which partially admits the Bauer's (1958) conclusion. Also, in case of CS2, both NmF2 and HmF2 were considerably higher during its last phase of life cycle in comparison to CS1, perhaps due to their dissimilar strength or intensity and slow rate of weakening (i.e. state change from high intensified state to low intensified state) in this phase of life cycle. During the last phase of CLCs (i.e. Cyclone Life Cycle) when (on 18^{th} May and 16^{th} October for CS1 and CS2 respectively) the low pressure systems gradually weakening due to precipitation, another noticeable fall in Ne concentration (see Fig. 3(a-b) and Fig. 4 (a-b)) at the Ionospheric F2 layer could be attributed as the post-cursor ionospheric signature, as no unusual geomagnetic and/or solar activity occurred during this period. Here, the major discrepancies in variation pattern of vertical Ne concentration for CS1 and CS2, as displayed in Fig. 3a and Fig. 3b, primarily due to their dissimilar strength at different stage of CLC (Sharkov, 2012). This evolution in Ne concentration at the ionospheric heights helps to infer that the ionosphere have close link with the lower atmosphere.

4.2. Correlation analysis

The main approach of this study is to address sensible variations of ionospheric signature at different height levels due to CS generation at the lower atmosphere which is the major difference from other studies (Afraimovich*et al.* 2008; Lin, 2012(a), 2012(b); Polyakova and Perevalova, 2011, 2013; Tian *et al.* 2010; Mondal *et al*. 2014). To select the ionospheric disturbances which are most likely to be associated with the perturbation generated due to existence of low pressure system like, CSs, the correlative variations between IECs have been analyzed. Fig. 4(a-b) shows the evolution in IECs associated to different ionospheric height layers (150-200, 200-250, 250-300, 300-350 and 350-400 km) during the respective observational periods. The gaps are due to non-availability of data during the respective day. On the other hand, Table 2-4 show the correlation coefficients of different pairs of ionospheric parameters. Of which, Table 3 and Table 4 are devoted for the estimation of correlation between IECs for CS1 and CS2 respectively. In this regard, it should be noted here that the correlation coefficient between any two parameters helps to determine whether any linear relationship between them exist or not. Interestingly, here, above 91% cases, the pairs of the parameters were highly positive correlated which help to infer that their correlative variations, could have linear relationship, were reasonably controlled by same geophysical phenomenon. As, no unusual geomagnetic (Dabas *et al.* 1980) and/or solar activity (Liu *et al.* 2006; Sripathi, 2012) occurred during the considered observational periods, the disturbance due to CSs generation at lower atmosphere might be the sole responsible agent to control this type variations at ionospheric heights. Clearly the correlation coefficients between IEC1 and IEC2 in both the table (Table2 and Table 4, in2×2 principal minor matrix) is extremely high (above 90%) which imply that their correlative variation matches in most of the cases. Similarly, if we consider IEC3 along with IEC1 and IEC2 (in 3×3 principal minor matrix of Table 3 and Table 4) their correlation coefficients are also very high (above 75%) which again assert that their correlative variation undergoes through the collateral propensity in most of the cases. Hence, the variation in bottom three ionospheric layers (i.e. 150-200, 200-250 and 250-300) is showing similar pattern throughout the observational period. In the same way when all the coefficients of these two tables were considered it could be seen that any two adjacent ionospheric layers were highly correlated but correlations of IEC1 with that of upper layers are gradually decreasing, same for other layers also. Again, each of IEC2, IEC3 and IEC4 maintain higher level correlation with their respective lower layer IECs in comparison to upper layer. From this point of view, it could be concluded that each lower layer is influencing the respective upper layer considerably and it is gradually decreasing for upper layers. Now, if we separately inspect the Table 3 and Table 4 then it will be cleared that IEC5 for Phailin (i.e. Table 4 for CS2) exhibits low association with other IECs which could be attributed to the fact that the ionosphere in between 350 km to 400 km height might be less influenced by the so called coupling mechanism with the other layers bellow it. The fact is that the AGWs generated at the lower atmosphere due to the presence of convective activities, like thunderstorm, cyclone etc, under favourable condition can propagate up to the height of lower ionosphere (Killeen and Johnsson, 1995; Bhattacharya and Das, 2013) where they deposit the sustained energy and momentum through the mechanism of breaking and absorption. The associated wave instability generates related field-aligned currents and plasma density irregularities in the upper ionosphere (Bhattacharya and Das 2013 and references therein) which is termed as AGW-TID.

Thereafter, the correlation coefficients between OLR and ionospheric parameters for both the cyclonic activities, Mahasen and Phailin, are tabulated in Table 5. Evidently, the IECs ($1\text{IECU} = 10^{16}\ \text{el}/m^2$) and OLR (W/m^2) are two completely different types of geophysical parameters; one (i.e. OLR) is electromagnetic radiation emitted from the Earth and its atmosphere out to space in the form of thermal radiation and other is the line integral of electron concentration in the Ionosphere (see Eq.(1)). Interestingly, here, the ionospheric parameters are generally anti-correlated with OLR (more than in 81% cases) with considerable low association ($-0.3<R<0.2$), except three cases for CS2 where OLR maintain highly negative correlation with IEC1, IEC2, IEC3. The low correlation coefficients primarily indicate that the associated pair of parameters has little, if any (linear), relationship in their correlative variation. But, for CS2, the occurrence of highly negative correlation coefficient in case of some IECs with OLR is a sensitive issue to the general nature of correlation, which might be due to the difference of sampling size of Ionospheric data. Note that for CS2 the sampling size was 31 whereas for CS1 it was 80.

V. CONCLUSIONS

We have carried out an observational study to understand the ionospheric variability due to the generation of CS in the lower atmosphere using COSMIC-RO satellite information. Here, the ionospheric evolution has been studied with the example of two severe CSs: CS1 (Mahasen, 10-16th May 2013) and CS2 (Phailin, 8-14th October 2013), generated over BOB in the year 2013. The result shows that these CSs profoundly affect the state of the ionosphere during their lifecycle. In summary, the major features of the present study are outlined as follows:

1) At the incipient stage when the so called low pressure systems were forming in the lower atmosphere, an acute dip in Ne concentration at the ionospheric F2 layer has been detected (see Fig. 3(a-b) and Fig. 4(a-b)). This characteristic may be attributed as an acute pre-cursor ionospheric signature primarily due to the generation of lower atmospheric convective activities (here CSs), as no unusual geomagnetic and/or solar activity occurred during this period.

2) During the last phase of CLCs (i.e. Cyclone Life Cycle) when the low pressure system gradually weakening due to precipitation, another noticeable fall in Ne concentration (see Fig. 3(a-b) and Fig. 4(a-b)) at the Ionospheric F2 Layer may be attributed as the post-cursor ionospheric signature, as no unusual geomagnetic and/or solar activity occurred during this period.

3) Correlation analysis asserts that maximum Ne perturbation confined in bottom side part of the Ionosphere which is exhibited through accumulating relatively higher Ne concentration in the concern region. This phenomenon admits the result of our previous study reported in Mondal *et al.*, 2014. But here, as it is displayed in Fig. 3(a-b) and Fig. 4(a-b), the ionospheric responses due to the presence of low pressure system of different intensity were mostly confined in the layers associated to lower F region (i.e. 150 km and above) of the bottom side Ionosphere and it is gradually decreasing for the upper layers which partially contradict Bauer (1958) study

4) The low association of ionospheric parameters with OLR, during the cyclone genesis period, provides anyway some valuable reference information for the future efforts to clearly unfold the mystery behind this and to learn more about the dominating AGW-TID control to it.

AGWs (Fritts *et al.* 2008; Kazimirovsky, 2002; Lastovicka, 2006) generated from the top of the convective systems (like CS1 and CS2) and their modifications during the upward propagation through different atmospheric layers are the principal agent of perturbations at the ionospheric heights (Killeen and Johnsson, 1995; Bhattacharya and Das, 2013).

ACKNOWLEDGEMENTS

COSMIC satellite data were downloaded from website http://www.cosmic.ucar.edu. Cyclone related information has been taken from IMD website http://www.imd.gov.in/.The authors would like to thanks WDC Geomagnetic Data Centre, Kyoto University, Japan for providing geomagnetic indices and UKSSDC, UK for providing F10.7 cm solar flux data. The authors are also grateful to NOAA for their OLR information. The authors would also like to acknowledge the reviewers for their earnest comments.

REFERENCES

[1]. E. L. Afraimovich, S. V. Voeykov, A. B. Ishin, N. P. Perevalova, and Y. A. Ruzhin, Variations in the total electron content during the powerful typhoon of August 5-11, 2006, near the southeastern coast of China. *Geomagnetism and Aeronomy*. *48 (5)*, 674-679, doi: 10.1134/S0016793208050113, 2008.

[2]. Aragon-Angel, M. Hemandez-Pajares, J. M. Juan, J. Sanz, Obtaining more accurate electron density profiles from bending angle with GPS occultation data: FORMOSAT-3/COSMIC constellation. *Advance in Space Research*, *43*, 1694–1701, doi:10.1016/j.asr.2008.10.034,2009.

[3]. S. J. Bauer, The apparent ionospheric response to the passage of hurricanes. *Journal of Geophysical Research*, *63*, 1958.

[4]. B. Bhattacharya and T. Das, Tropospheric-Ionospheric Coupling by Electrical Processes of the Atmosphere.*International Journal of Application or Innovation in Engineering & Management (IJAIEM), 2(5)* 2013.

[5]. Y. J. Chuo, C. C. Lee, W. S. Chen, and B. W. Reinisch, Comparison of the characteristics of ionospheric parameters obtained from FORMOSAT-3 and digisonde over Ascension Island.*Annales Geophysicae*, *31*, 787–794, doi: 10.5194/angeo-31-787-2013, 2013.

[6]. R. S. Dabas, J. B. Lal, T. R. Tyagi, Y. V. Somayajulu, Variations in TEC and other parameters associated with magnetic storms. *Indian Journal of Radio & Space Physics*, *9*, 1-6, 1980.

[7]. J. B. Elsner, J. P. Kossin, T. H. Jagger, The increasing intensity of the strongest tropical cyclones. *Nature*, 455(4), doi: 10.1038/nature07234, 2008.

[8]. H. Eun, and S. H. Gross, Ionospheric Disturbances and Gravity Waves. *Journal of Geophysical Research*. *8(3), 81(19)*, 1976.

[9]. D. C. Fritts, S. L. Vadas, D. M Riggin, M. A. Abdu, I. S. Batista, H. Takahashi, A. Medeiros, F. Kamalabadi, H. L. Liu, B. G. Fejer, M. J. Taylor, Gravity wave and tidal influences on equatorial spread F based on observations during the Spread F Experiment (SpreadFEx), *Annales Geophysicae*, *26*,3235–3252, 2008.

[10]. N. E. Graham, and T. P. Barnett, Sea surface temperature, surface wind divergence, and convection over tropical oceans, *Science*, *238*, 657-659, doi: 10.1126/science.238.4827.657, 1987.

[11]. R. G. Harrison, K. L. Aplin, and M. J. Rycroft, Atmospheric electricity coupling between earthquake regions and the ionosphere, *Journal of Atmosphere and Solar-Terrestrial Physics*, *72*, 376-381 http://dx.doi.org/10.1016/j.jastp.2009.12.004, 2010.

[12]. C. O. Hines, Gravity wave in the Atmosphere, *Nature*, *239*, 73-78, 1972.

[13]. Y. N. Huang, K. Cheng, and S. W. Chen, On the detection of acoustic gravity waves generated by typhoon by use of real time HF Doppler frequency shift sounding system, *Radio Science*, *20*, 897–906, 1985.

[14]. W. Jin, J. Ji-xi, and K. Zong-jian, An Investigation into tropical cyclone moving direction prediction based on OLR data, *Journal of Tropical Meteorology*, Article ID: 1006-8775(2005) 02-0178-09, 2005.

[15]. E. S. Kazimirovsky, Coupling from below as a source of ionospheric variability: a review, *Annales Geophysicae*, 45(1), 1-29, 2002.

[16]. E. Kerry, Increasing destructiveness of tropical cyclones over the past 30 years, *NATURE* 436(4), doi: 10.1038/nature03906, 2005.

[17]. J. Lastovicka, Forcing of the ionosphere by waves from below, *Journal of Atmosphere and Solar-Terrestrial Physics*, 68, 479–497, 2006.

[18]. J. W. Lin, Ionospheric total electron content anomalies due to Typhoon Nakri on 29 May 2008: A nonlinear principal component analysis, *Computers and Geosciences*, 46, 189-195, doi:10.1016/j.cageo.2011.12.007, 2012a.

[19]. J. W. Lin, Study of ionospheric anomalies due to impact of typhoon using Principal Component Analysis and image processing, *Journal of Earth System Science*, 121 (4), 1001-1010, 2012b.

[20]. J. Y. Liu, C. H. Lin, Y. I. Chen, Y. C. Lin, T. W. Fang, C. H. Chen, Y. C. Chen, and J. J. Hwang, Solar flare signature of the ionospheric GPS total electron content, *Journal of Geophysical Research*, (USA) 111A5, A05308, 2006.

[21]. P. Kenpankho, K. Watthanasangmechai, P. Supnithi, T. Tsugawa, and T. Maruyama, Comparison of GPS TEC measurements with IRI TEC prediction at the equatorial latitude station, Chumphon, Thailand, *Earth Planets Space*, 63, 365–370, and 2011.

[22]. T. L. Killeen, and R. M. Johnson, Upper atmospheric waves, turbulence, and winds: Importance for mesospheric and thermospheric studies, *Review of Geophysics*, 33(S1), 737–744, 1995.

[23]. G. Mondal, M. Gupta, and G. K. Sen, Variations in Electron Content Ratio and Semi-thickness Ratio during LSA and MSA periods and some Cyclone Genesis Periods using COSMIC satellite observations, *Advance in Space Research*, 54, 2151–2158, 2014.**

[24]. D. S. R. Park, C. H. Ho, and J. H. Kim. Growing threat of intense tropical cyclones to East Asia over the period 1977–2010, *Environmental Research Letters*, 9, 014008, (7pp), doi:10.1088/1748-9326/9/1/014008, 2014.

[25]. S. Polyakova, and N. P. Perevalova, Investigation into impact of tropical cyclones on the ionosphere using GPS sounding and NCEP/NCAR Reanalysis data, *Advance in Space Research*, 48**,** 1196–1210, 2011.

[26]. S. Polyakova, and N. P. Perevalova, Comparative analysis of TEC disturbances over tropical cyclone zones in the North–West Pacific Ocean, *Advance in Space Research*, 52, 1416–1426, 2013.

[27]. H. S. Porter, and T. F. Tuan, On the behaviour of the F-layer under the influence of the gravity wave, Journal *of Atmospheric and Terrestrial Physics*, 36, 135-157, 1974.

[28]. J. Rai, D. K. Sharma, R. Chand, K. Suda, and M. Israil, Effect of active thunderstorms on ionospheric electron and ion temperatures as obtained by the SROSS-C2 satellite measurements, *19th International Lightning Detection Conference* 24-25 April • Tucson, Arizona, USA and *1st International Lightning Meteorology Conference* 26-27 April • Tucson, Arizona, USA, 2006.

[29]. Rozhnoi, M. Solovieva, B. Levin, M. Hayakawa, and V. Fedun, Meteorological effects in the lower ionosphere as based on VLF/LF signal observations, Natural *Hazards Earth System Science Discuss*, 2, 2789–2812, doi: 10.5194/nhessd-2-2789-2014, 2014.

[30]. E. A. Sharkov, Global Tropical Cyclogenesis, Springer Praxis Books, p. 604, Springer Berlin Heidelberg, 2012.

[31]. V. M. Sorokin, N. V. Isaev, A. K. Yaschenko, V. M. Chmyrev, M. Hayakawa, Strong DC electric field formation in the low latitude ionosphere over typhoons, *Journal of Atmosphere and Solar-Terrestrial Physics*, *67* 1269–1279, 2005. doi:10.1016/j.jastp.2005.06.014

[32]. S. Sripathi, COSMIC observations of ionospheric density profiles over Indian region: Ionospheric conditions during extremely low solar activity period, Indian*Journal of Radio & Space Physics*, *41,* 98-109, 2012.

[33]. S. Y. Su, C. L. Wu, C. H. Liu, Correlation between the global occurrences of ionospheric irregularities and deep atmospheric convective clouds in the inter-tropical convergence zone (ITCZ), *Earth Planets and Space 66*, 134, doi:10.1186/1880-5981-66-134, 2014.

[34]. M. Tian, W. JingSong, Y. GuangLin, Y. Tao, P. JinSong, S. YuCheng, Effects of typhoon Matsa on ionospheric TEC, *Chinese Science Bulletin. 55(8),* 712–717, doi: 10.1007/s11434-009-0472-0, 2010.

[35]. P. Vinay Kumar, G. Dutta, M. V. Ratnam, E. Krishna, B. Bapiraju, B. V. Rao, and S. Mohammad, Impact of cyclone Nilam on tropical lower atmospheric dynamics, *Advances in Atmospheric Sciences*, *33(8),* 955–968, doi: 10.1007/s00376-016-5285-x, 2016.

[36]. R. A. Vincent, Gravity wave coupling from below: A review. Climate and Weather of the Sun-Earth System (CAWSES), *Kyoto Symposium*, 279–293, 2007.

[37]. Vlasov, K. Kauristie, M. van de Kamp, J. P. Luntama, A. Pogoreltsev, A study of Traveling Ionospheric Disturbances and Atmospheric Gravity Waves using EISCAT Svalbard Radar IPY-data, *Annales Geophysicae*, 29, 2101–2116, doi: 10.5194/angeo-29-2101-2011, 2011.

[38]. P. Xiong, X. H. Shen, Y. X. Bi, C. L. Kang, L. Z. Chen, F. Jing, Y. Chen, Study of outgoing long wave radiation anomalies associated with Haiti earthquake, *Natural Hazards Earth System Science*, 10,2169–2178, doi: 10.5194/nhess-10-2169-2010, 2010.

Figure Captions

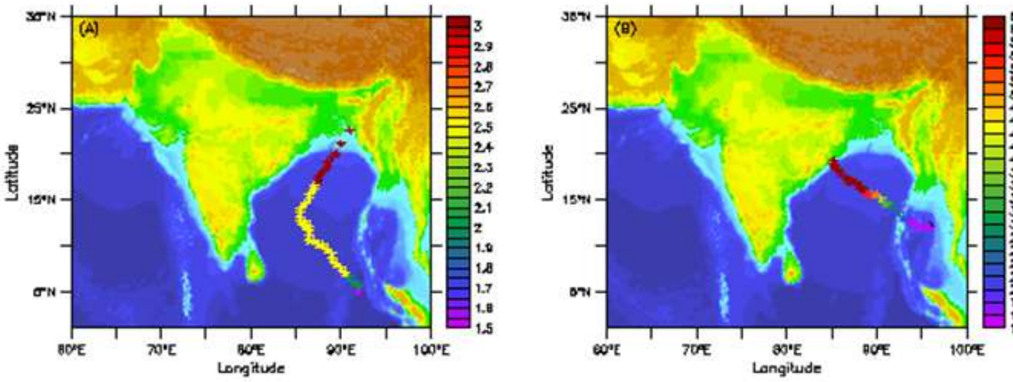

Figure 1. The track and intensity of Cyclone (a) Mahasen (10-16th May 2013) and (b) Phailin (8-14th October 2013) over BOB.

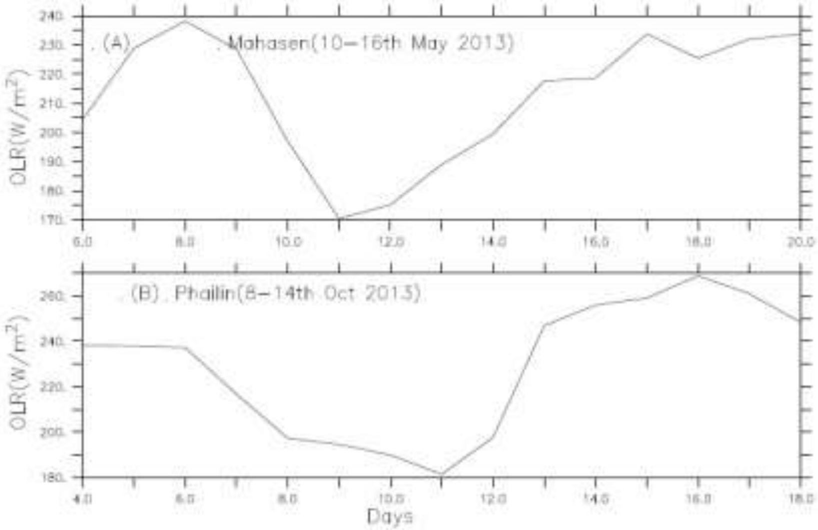

Figure 2. The OLR (averaged) variations during 15 day's observational period including respective life cycle of (a) Mahasen (10-16th May 2013) and (b) Phailin (8-14th October 2013).

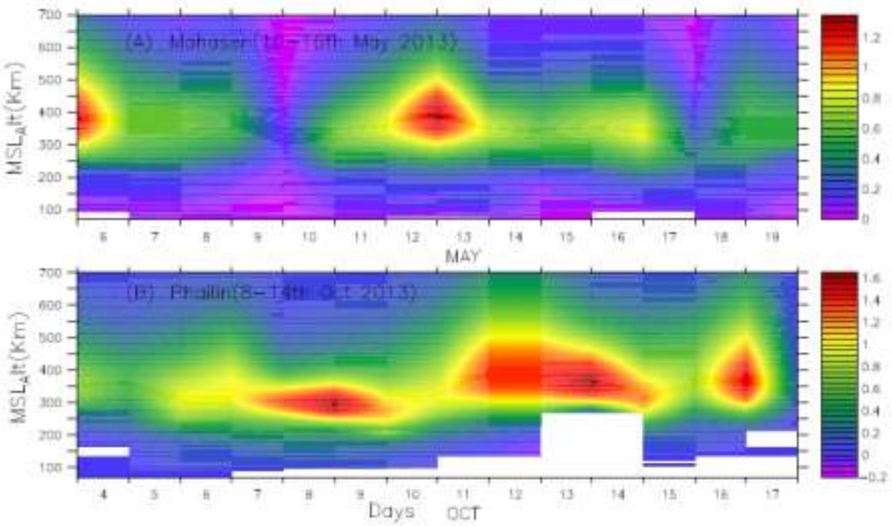

Figure 3. The altitude variations of Ne (weighted averaged) concentration for 15 days observational period including the cyclone life cycle of (a) Mahasen(10-16th May 2013) and (b) Phailin(8-14th Oct 2013). For convenience data gap on 13th October in case of Phailin is filled by that of 14th October in bottom panel.

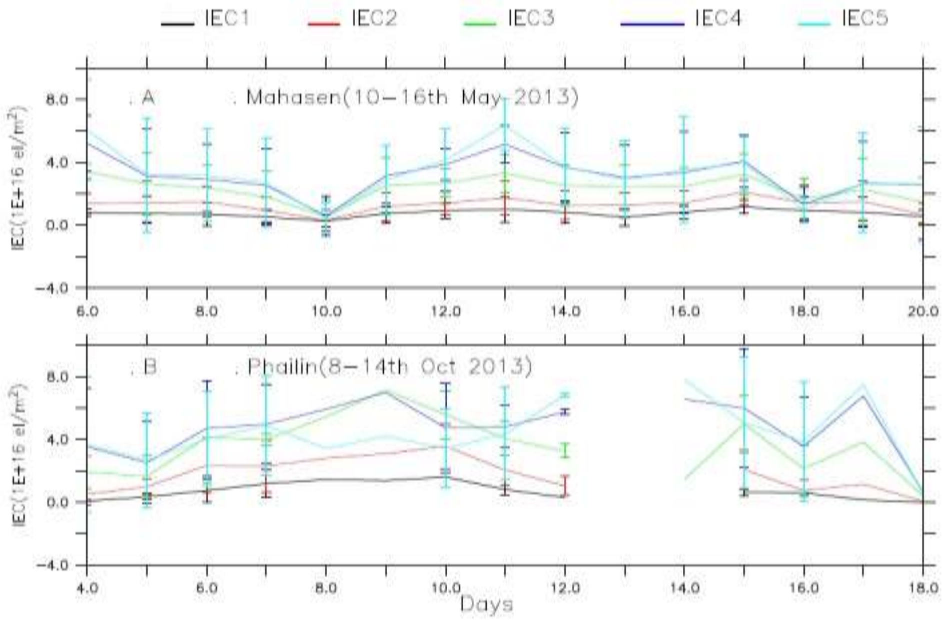

Figure 4. The time series plot of IECs: IEC1 (black), IEC2 (Red), IEC3 (Green), IEC4 (Blue) and IEC5 (Cyan) associated to cyclones: (a) Mahasen(10-16th May 2013) and (b) Phailin(8-14th Oct 2013) are depicted in above figure. The data gaps are due to non-availability of data during the respective day

Table 1 Upper and lower limits of the definite integral in Equation (1).

Parameter name	Balt(KM)	Talt(KM)
IEC	70	700
IEC1	150	200
IEC2	200	250
IEC3	250	300
IEC4	300	350
IEC5	350	400

Table 2: The correlation coefficients (R) of ionospheric parameters NmF2 (N), HmF2 (H) and IEC (I) between each other for the two Cyclonic Storms (CTs).

	R(N,H)	R(N,I)	R(H,I)
TC1	0.86	0.97	0.84
TC2	0.23	0.85	0.58

Table 3: The correlation coefficients (R) between the IECs associated to TC1. In this table IEC1, IEC2, IEC3, IEC4 and IEC5 are associated to five 50 km width ionospheric layers.

	IEC1	IEC2	IEC3	IEC4	IEC5
IEC1	1	0.90	0.75	0.61	0.55
IEC2	0.90	1	0.83	0.64	0.57
IEC3	0.75	0.83	1	0.94	0.88
IEC4	0.61	0.64	0.94	1	0.98
IEC5	0.55	0.57	0.88	0.98	1

Table 4: The correlation coefficients between the IECs associated to Cyclonic storm, Phailin (8-14th October 2013). In this table IEC1, IEC2, IEC3, IEC4 and IEC5 are associated to five 50 km width ionospheric layers.

CT2	IEC1	IEC2	IEC3	IEC4	IEC5
IEC1	1	0.94	0.81	0.47	-0.04
IEC2	0.94	1	0.92	0.62	0.13
IEC3	0.81	0.92	1	0.68	0.14
IEC4	0.47	0.62	0.68	1	0.80
IEC5	-0.04	0.13	0.14	0.80	1

Table 5 The correlation coefficients of OLR with the IECs associated to two Cyclonic storm activities (Mahasen and Phailin).

	NmF2	HmF2	IEC	IEC1	IEC2	IEC3	IEC4	IEC5
OLR(CT1)	-0.27	-0.19	-0.21	-0.06	0.13	-0.16	-0.26	-0.27
OLR(CT2)	-0.32	0.23	-0.12	-0.64	-0.62	-0.58	-0.22	0.11

International Journal of Engineering Research and Applications (IJERA) is **UGC approved** Journal with Sl. No. 4525, Journal no. 47088. Indexed in Cross Ref, Index Copernicus (ICV 80.82), NASA, Ads, Researcher Id Thomson Reuters, DOAJ.

Gopal Mondal. "An Investigation into Height Variation of Ionospheric Signature Due To the Cyclonic Storm Formation Using COSMIC-RO Measurements." International Journal of Engineering Research and Applications (IJERA) 7.7 (2017): 76-85.