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Analysis of ionospheric disturbances associated with powerful cyclones in East Asia and North America

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ABSTRACT

East Asia and North America are the regions most heavily affected by powerful cyclones. In this paper we investigate the morphological characteristics of ionospheric disturbances induced by cyclones in different continents. The global ionosphere map supplied by the Center for Orbit Determination in Europe (CODE), International Reference Ionosphere Model (IRI) 2012, and Wallops Island ionosonde station data are used to analyse the ionospheric variations during powerful typhoons/hurricanes in East Asia and North America, respectively. After eliminating the ionospheric anomalies due to the solar-terrestrial environment, the total electron content (TEC) time series over the point with maximum wind speed is detected by the sliding interquartile range method. The results indicate that significant ionospheric disturbances are observed during powerful tropical cyclones in East Asia and North America, respectively, and that all the ionospheric anomalies are positive. In addition, the extent and magnitude of travelling ionospheric disturbances are associated with the category of tropical cyclone, and the extent of TEC anomalies in longitude is more pronounced than that in latitude. Furthermore, the maximum ionospheric anomaly does not coincide with the eye of the storm, but appears in the region adjacent to the centre. This implies that ionospheric disturbances at the edges of cyclones are larger than those in the eye of the winds. The phenomenon may be associated with the gravity waves which are generated by strong convective cells that occur in the spiral arms of tropical cyclones. This comprehensive analysis suggests that the presence of powerful typhoons/hurricanes may be a possible source mechanism for ionospheric anomalies.

1. Introduction

Solar radiation and geomagnetic activity play dominant roles in the formation and dynamic regime of the ionosphere (Sojka et al., 1981; Hargreaves, 1992; Schunk and Sojka, 1997; Breus et al., 2004), but there are still some ionospheric disturbances that cannot be explained except by perturbations associated with the solar-terrestrial environment (Chane-Ming et al., 2002; Kim et al., 2005; Guha et al., 2016). With the development of atmosphere-ionosphere coupling theory, scientists began to realise that some powerful meteorological disturbances (typhoons, hurricanes, thunderstorms, tornados, etc.) could cause acoustic gravity waves (AGWs), which can penetrate up to ionospheric heights and cause travelling ionospheric disturbances (TIDs) (Cowling et al., 1971; Sorokin et al., 2001; Afraimovich et al., 2008). Work to associate ionospheric disturbances with typhoon activity dates back to Bauer in the 1950s; he showed that the F2 layer critical frequency (foF2) increased as the typhoon approached and reached a maximum when the typhoon arrived at the ionosonde station (Bauer, 1958). Since then the morphological characteristics and coupling mechanisms of ionospheric perturbations, as they relate to tropical storms, have received increased attention. The ionospheric perturbations induced by 70 typhoons were detected by the Cosmos 1809 satellite array, Isaev et al. (2002, 2010) reported that the ion oscillation and electric field in an area of interest would increase with the intensity of the typhoon, and that these phenomena were caused by the transmission of charged aerosols and droplets. A real-time high frequency (HF) Doppler frequency shift sounding array was used to detect the ionospheric Doppler frequency shifts caused by an extreme tornado in 1974. The results indicate that significant ionospheric anomalies can be observed in the F layer due to the effect of the AGWs (Hung et al., 1978). However, some studies pointed out that HF Doppler sounders were not satisfactory instruments for distinguishing ionospheric disturbances induced by typhoons, because the means could lead to ionospheric

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perturbations by itself (Huang et al., 1985). In recent years, Global Navigation Satellite System (GNSS) techniques have played an important role in measuring the TEC between satellite and receiver. Rapid development of dense observation stations has allowed for 2D and 3D imaging of the dynamic regime in the ionospheric plasma, providing suitable data to investigate the TIDs during the passage of tropical storms (Lin, 2012). Zakharov and Kunitsyn (2012) proved that a ground based global positioning system (GPS) network, with a correlation method, was efficient at detecting the ionosphere responses to the natural hazards, that AGWs detected by the GPS interferometry were geographically associated with places of orographic disturbances, and that the waves were most effective at the high rates of typhoon growth or decay. Some studies show that the TEC tends to increase before a tropical storm reaches land, and afterwards the amplitude and extent of positive ionospheric anomalies begin to decrease, with the anomalies vanishing the next day (Mao et al., 2010; Rice et al., 2012; Liu et al., 2008). However, ionospheric responses to six cyclones in the north west Pacific Ocean show that the highest TEC variations appeared when the wind speed and the tropical cyclones (TC) are at a maximum, and that the TIDs can only be observed after the cyclones have reached typhoon intensity (Polyakova and Perevalova, 2013).

Tropical cyclones are the large-scale rotary storms that form over warm ocean waters in low latitudes, and the radius of influence can extend for more than 1000 km from the eye of the storm. In the Pacific, a mature tropical cyclone is called a typhoon, and in the Atlantic it is called a hurricane. East Asia and North America are the regions of the world that suffer most frequently from powerful typhoons/hurricanes. These regions also contain a large number of GPS stations and ionospheric ionosondes that are densely distributed (Zhang et al., 2009; Macias et al., 2009). Mass observational data in these areas support the investigation of ionospheric manifestations related to powerful typhoons/hurricanes, to provide a deeper understanding of the physical mechanism of atmosphere-ionosphere coupling. In this paper, we use the global ionosphere map (GIM), International Reference Ionosphere Model (IRI) 2012, and ionosonde observational data to investigate the ionospheric disturbances induced by power typhoons/hurricanes in East Asia and North America during 2004–2014. We discuss the morphological characteristics of ionospheric perturbations related to typhoons/hurricanes in different continents.

2. Data sources and methods

2.1. Space weather and typhoon/hurricane data

Many scientists make use of the data from the GIM assimilative model. This model takes data from more than 400 stations, then interpolates and smooths it to produce ionospheric TEC maps on one hour increments; it covers ±180° longitude and ±87.5° latitude with spatial resolutions of 5° and 2.5°, respectively (Hernández-Pajares et al., 2009). GIM data has been used to investigate the ionospheric disturbances associated with natural disasters such as typhoons, earthquakes, and volcanic eruptions, for example (Afraimovich et al., 2008; Guo et al., 2015; Li et al., 2016). Therefore, the GIM data are considered a useful tool to study the ionospheric perturbations induced by powerful typhoons. In this paper, the TEC maps from the Center for Orbit Determination in Europe (CODE) (ftp://ftp.unibe.ch/aiub/CODE/) are used to investigate the ionospheric disturbances during the passage of powerful typhoons and hurricanes. Slant total electron content (STEC) along the path from GPS receivers to GPS constellation satellites is estimated from the dual-frequency L1/L2 band signals (f_1 = 1575.42 MHz, f_2 = 1227.60 MHz) (Hofmann-Wellenhof et al., 1992; Naaman et al., 2001) as

$$STEC = \frac{\Delta\rho\cdot c}{40.3}\cdot\frac{f_1^2\cdot f_2^2}{f_1^2 - f_2^2}, \tag{1}$$

where c is the speed of light (m/s) and $\Delta\rho$ (m) is the distance covered at speed c multiplied by the difference between the time delays measured by f_1 and f_2.

Solar radiation and geomagnetic perturbations are the primary energy sources of travelling ionospheric disturbances, which means that the overwhelming majority of ionospheric anomalies are associated with the

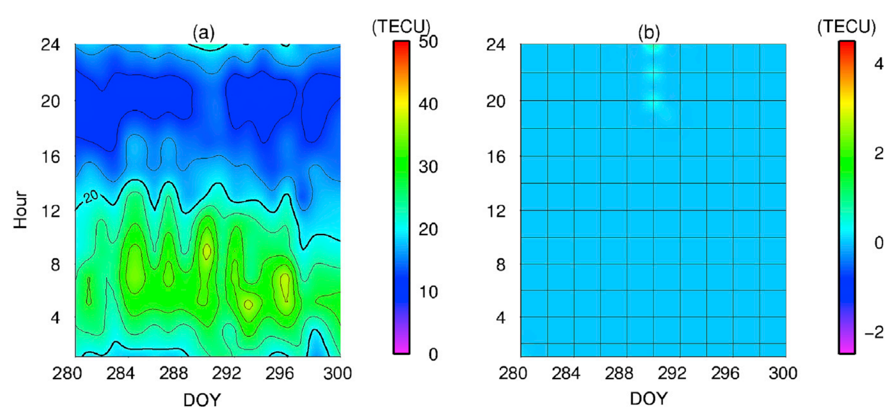

Fig. 1. The ionospheric TEC contour maps and TEC anomalies over the point (124.2°, -17.6°), no powerful cyclones occurred in the vicinities.

Table 1
The properties of six powerful typhoons originating in the Pacific.

Category	Name	Originating	Disappearance	Typhoon Properties at Peak Wind Speed				
				Time(UTC)	Lon(°)	Lat(°)	Pressure(hPa)	Speed(m/s)
5	Megi	2010101312	2010102318	2010101718	124.2	17.6	885	64
5	Usagi	2013091618	2013092306	2013091918	126.4	18.7	910	57
5	Haiyan	2013110400	2013111106	2013110712	129.1	10.2	895	65
4	Neoguri	2014070318	2014071100	2014070700	128.3	20.4	930	51
5	Halong	2014072900	2014081100	2014080212	135.1	14.9	920	54
4	Phanfone	2014092906	2014100612	2014100206	138.2	19.7	935	49