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Investigating the Impacts of Tropical Cyclones in Hong Kong Region using GNSS Techniques

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ABSTRACT

A tropical cyclone (TC) is a severe weather phenomenon over the equatorial and subequatorial ocean areas. During the TC period, the intense air convection often forms and progresses in the lower atmosphere, i.e. troposphere. One of TC's energy sources is water vapor, which is evaporated from the sea surface and released in the form of rainfalls and rainstorms. That is why TC is often in company with heavy rainfalls, strong winds, and frequent lightning. These weather phenomena often cause severe damage to coastal regions during the landfall period. Furthermore, the deep convection in the troposphere can trigger ionospheric disturbances. Sequentially, the abnormal variation of the total electron content (TEC) in the ionosphere will affect the performance of radio communication applications, e.g. the Global Positioning System (GPS) or the Global Navigation Satellite System (GNSS). Therefore, it is essential and meaningful to investigate the characteristics and impacts of TCs on the troposphere, ionosphere, and GPS performance. Deep investigation of TCs can help further improve the understanding of the TC's mechanism and the capacity of TC forecasting.

Since the emergence of GNSS technology in the 1970s, it has been widely used in modern lives, e.g. navigation and positioning. Apart from its basic function, GNSS is also a powerful tool in the meteorological community. Based on GPS observations, the zenith wet delay (ZWD) can be precisely calculated as GPS signals travel through the troposphere. Then, ZWD can be further converted into the precipitable water vapor (PWV) content by multiplying a factor. PWV is a critical parameter in atmospheric research, which is used for measuring the amount of water in a column of the atmosphere if all the water in that column was precipitated as rain. On the other hand, the total electron content (TEC) estimated from GPS observations can be used as an indicator of ionospheric conditions and, at the same time, is a crucial parameter affecting the reliability and stability of space-ground communications. The tropospheric and ionospheric conditions play a critical role in the GNSS applications.

Therefore, this study aims to investigate the TC impacts on three aspects, 1) PWV in the troposphere; 2) TEC in the ionosphere; 3) the GPS performance. First, the long-term trend (2008-2020) of TC-surrounding PWV on a global scale is studied and discussed based on GNSS radio occultation (RO) data. After this, we focused on the TC events in the Hong Kong region because Hong Kong is located on the south coast of China and faces towards the west of the Western North Pacific (WNP) ocean. Additionally, Hong Kong has suffered an average of six TCs each year in the past 50 years. The main findings from this study can be summarized as the following:

Based on the space-based GNSS RO data, PWV can be calculated by integrating meteorological profiles, including temperature, humidity, and pressure. The global PWV variation during TC events between 2008 and 2020 was studied. We selected RO events within 600 km from the TCs' center and analyzed the PWV values in the upper atmosphere at the altitude of 1.6 – 40.0 km. The results suggest that the TC-surrounding PWV shows a significant increase trend from 2008 to 2020. In detail, the increase rate is 0.7, 0.5, 0.3, 1.3, and 0.8 $kg \cdot m^{-2} \cdot decade^{-1}$ for radius bands of 0-200 km, 200-300 km, 300-400 km, 400-500 km, and 500-600 km from the TC center, respectively. Such an increase

trend attributes to the large influx of PWV towards coastal areas in recent years. In addition, the PWV spatial gradient in the TC's radial direction shows an enhancing trend for the eastern and western parts of the North Pacific Ocean (ENP and WNP) and the South Pacific (SP). In contrast, the spatial gradient shows a weakening trend for the North Atlantic Ocean (NA), the North Indian Ocean (NI), and the South Indian Ocean (SI).

For the Hong Kong region, we examined the PWV variation based on ground-based GPS observations. After PWV values were estimated from GPS, the continuous wavelet transform (CWT) was applied to differential PWV between two GPS stations to investigate the temporal characteristics of the PWV variation during the TC period. Moreover, the PWV spatial gradient was calculated based on the fifth generation of European Centre for Medium-Range Weather Forecasts (ECMWF) Re-analysis (ERA5) PWV data to investigate the spatial characteristics. Based on the method, the temporal and spatial properties of PWV during the Super TC event Hato (20-24 August 2017) are discussed, and the results show that PWV above Hong Kong varied significantly in both temporal and spatial domains. When Hato was around 1,000 km from Hong Kong, PWV above Hong Kong experienced a sudden increase. On the landfall day (22 August 2017), the CWT wavelet power of the differential PWV indicates that PWV above Hong Kong frequently fluctuated with a period of 2-5 hours, and the spatial gradient of PWV above Hong Kong increased magnificently. Additionally, we also applied the discrete Fourier transform (DFT) to the positioning errors of GPS baseline solutions. The results suggest that the positioning errors varied with a consistent period of 2-5 hours on the same day.

To study the impact of TC events on the ionosphere, we retrieved vertical TEC (VTEC) values along each GPS satellite observing arc. Then, we combined the VTEC value of the GPS satellite with the highest elevation at each epoch and generated a new VTEC time series, namely the highest elevation vertical TEC (HeVTEC). By comparing the daily maximum of reconstructed HeVTEC time series during the TC event, namely Hato (20-24 August 2017), we find that TEC in the ionosphere above the Hong Kong region showed an abnormal variation. The daily maximum of HeVTEC reached up to 62.0 TEC unit (TECU) on the landfall day (23 August 2017), while the daily maximum was about 33.0 TECU on the no-TC-impacted days. Furthermore, the VTEC mean bias (with respect to that on the normal day of 16 August 2017) on the landfall day shows different increase levels during different periods: 1) an increase of about 20 TECU during the period of 11:00 LT – 21:00 LT; 2) an increase of about 5 TECU during the period of 21:00 LT- 11:00 LT. At the same time, the significant increase in VTEC mean bias is situated in the west of Hong Kong, the same as the TC movement's direction.

The impact of TC events on GPS data quality and positioning performance is also studied. The GPS data quality can be assessed by these parameters, such as scintillation index S_4, the occurrence rate of cycle slips, and TEC rate (TECR). The S_4 index is calculated from the GPS signal intensity, which is output by the ionospheric scintillation monitoring receiver (ISMR). The cycle slips and TECR can be detected and computed based on the GPS pseudorange and carrier phase measurements. We find that the GPS signals were significantly contaminated by examining these parameters and assessing the positioning performance during Super TC events, namely Usagi in 2013 and Hato in 2017. In detail, the parameters share a consistently changing pattern in both temporal and spatial domains. Their values experienced a sudden increase during the sunset period (20:00 LT – 02:00 LT) on the second day (24 September 2013) after the TC made landfall near Hong Kong. The values fluctuated up and down in a wavelike form with a decreasing magnitude on the following days. Meanwhile, the abnormal values of these parameters shared the same location along the GPS trajectory. During the Usagi period, the root mean square (RMS) of the precise point positioning (PPP) errors on TC-impacted day (24 September 2013) was degraded by 138%, 181%, and 461% in the components of east, north, and up, compared with that on the non-TC-impacted day (19 September 2013). The RMS of the relative positioning errors on the TC-impacted day was 7.1, 7.8, and 12.2 times as large as that on the non-TC-impacted days. During the Hato period, the RMS of the relative positioning errors on the TC-impacted day (22 August 2017) increased by 255% with respect to that on the non-TC-impacted days.