Increasing TCHP in the Western North Pacific and Its Influence on the Intensity of FAXAI and HAGIBIS in 2019

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Abstract

In the 2019 tropical cyclone season in the western North Pacific, Typhoons FAXAI and HAGIBIS made landfall in Japan while keeping the intensity, resulting in serious disasters. This study addresses the influences of an increasing trend and variations in the upper ocean heat content above 26°C (tropical cyclone heat potential: TCHP) from January 1982 to June 2020 on FAXAI and HAGIBIS. TCHP beneath FAXAI and HAGIBIS in 2019 was higher than the climatological mean except for a part of mature phase of HAGIBIS due to HAGIBIS-induced sea surface cooling. TCHP significantly increased with the interannual oceanic variations (IOVs) in the subtropical (15°N–20°N, 140°E–150°E) and midlatitude (30°N–35°N, 130°E–140°E) areas where FAXAI and HAGIBIS intensified or kept the intensity. From an empirical orthogonal function (EOF) analysis of TCHP, we demonstrate that the leading three EOF modes of TCHP explain approximately 76.8% of total variance, but the increase in TCHP along the tracks of FAXAI and HAGIBIS particularly in the early intensification of HAGIBIS cannot be explained only by the IOVs included in the leading three EOF modes but rather by the warming trend irrespective of the IOVs.

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1. Introduction

In the 2019 tropical cyclone (TC) season in the western North Pacific (WNP), the number of TCs was relatively low before July. However, the situation drastically changed after August. Strong winds caused by Typhoon FAXAI on September destroyed the houses and the power supply system while torrential rains accompanied by Typhoon HAGIBIS in October caused river flooding over a broad area in Japan along its track. Whether global warming and long-term variations in the ocean have an impact on these typhoons is therefore of great interest.

TC activity in the WNP seems to have undergone some changes in recent years. TCs have reached their lifetime maximum intensity at higher latitudes (e.g., Kossin et al. 2014). The movement speed of TCs appears to have become slower (Kossin et al. 2018), and the number of category 4 and 5 TCs in the Saffir-Simpson hurricane scale has been increasing (Holland and Bruyère 2014). Decadal-scale fluctuations and increases in sea surface temperature (SST) are considered to be a factor that causes the increase in destructive TCs (Song and Klotzbach 2018) due to the modulation of El Nino-Southern Oscillation (ENSO) associated with non-linearity between atmospheric convection and SST (Capotondi et al. 2014; Williams and Patricola 2018).

Tropical cyclone heat potential (TCHP), a measure of the oceanic heat content from the surface to the 26°C isotherm depth, has been widely used for TC climatological studies (e.g. Wada and Chan 2008) and statistical intensity forecasting. Wada and Chan (2008) reported from an empirical orthogonal function (EOF) analysis of monthly mean TCHP that the number of super typhoons increased in mature El Niño years. However, it has not been investigated how the increase in TCHP underneath a TC in recent years is associated with global warming and interannual oceanic variations (IOVs).

The purpose of this study is to demonstrate that TCHP from September to October 2019 increased from the climatological mean around the area underneath FAXAI and HAGIBIS and to identify the factors such as global warming and IOVs that caused the increases.

2. Data and method

The Regional Specialized Meteorological Center (RSMC) Tokyo best track data set (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html) was used to examine the history of FAXAI and HAGIBIS in 2019. This study used the Four-dimensional variational Ocean ReAnalysis data set for the WNP (FORA-WNP30; Usui et al. 2017) and the subsequent oceanic analysis data operationally analyzed in the Japan Meteorological Agency (JMA) from January 2016 to June 2020 to calculate TCHP. The horizontal resolution of the North Pacific version of the data set was 0.5° in the longitude-latitude coordinate system. TCHP is calculated based on the data and the methodology of Wada (2015):

\[ Q = \sum_{i=0}^{26} \rho C_{p} (T_i - 26) \Delta z_i \]  

(1)

where \( Q \) is the value of tropical cyclone heat potential (kJ cm⁻²), \( z_{26} \) the 26°C isotherm depth, \( C_{p} \) the specific heat at constant pressure, \( T_i \) water temperature in °C at the \( i \)-th level (\( z_i \)), \( \Delta z \Delta z \) a layer thickness of water at the \( i \)-th level, and \( \rho \) density of water at the \( i \)-th level.

Climatological mean TCHP was determined by daily mean TCHP averaged from 1993 to 2018 because satellite altimeter data began to be used for ocean analysis in 1993. In the empirical orthogonal function (EOF) analyses, data of 00UTC on 1st, 6th, 11th, 16th, 21st, 26th (every 5 days) in each month were used. The domain of the analysis was a square of 0°N–60°N, 100°E–100°W. The 6-month running mean used in the EOF analysis was applied for TCHP data to remove the fluctuations equal to and shorter than a year.

Oceanic monitoring indices such as the difference in SST from the reference averaged over 5°N–5°S and 150°W–90°W (NINO3), Pacific Decadal Oscillation (PDO) index are obtained from the JMA webpage (Japan Meteorological Agency 2020a, b). The ENSO Modoki index (EMI) and dipole mode index (DMI) are obtained from the Application Laboratory (APL) virtual earth webpage (Japan Agency for Marine-Earth Science and Technology 2020). The Pacific Meridional Mode (PMM) SST index (Chiang and Vimont 2004) is obtained from the Physical Sciences Laboratory website (Physical Sciences Laboratory 2020).

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3. Results

Figure 1a shows the horizontal map of monthly mean TCHP and 500-hPa geopotential height obtained from the Japanese 55-year reanalysis (JRA-55) 6-hourly product with the horizontal resolution of 1.25° × 1.25° (Kobayashi et al. 2015) in September 2019. The highest TCHP area (over 100 kJ cm⁻²) was located off east of the Philippines, where HAGIBIS passed along the western edge of Pacific high. FAXAI and HAGIBIS had similar trajectories before landing in Japan, where TCHP exceeded 50 kJ cm⁻² underneath the tracks during the intensification phase. Figure 1b shows the time-series of TCHP averaged over the square box of 30°N–35°N, 130°E–140°E (region N in Fig. 1a) and 15°N–20°N, 140°E–150°E (region S in Fig. 1a). The increase in TCHP in region S where HAGIBIS passed over in the early intensification phase is greater than in region N although there is a significant trend in TCHP in both regions at the 99% confidence level based on t-test.

Figure 2 shows the time series of TCHP underneath FAXAI (Fig. 2a) and HAGIBIS (Fig. 2b). The TCHP and its climatological mean were averaged over a 6° × 6° square centered at the TC center. HAGIBIS passed over the highest TCHP area in the intensification phase (Fig. 2b), while moving westward. In addition, FAXAI (Fig. 2a) and HAGIBIS (Fig. 2b) passed over the area of which TCHP is higher than the climatological mean around the Kuroshio south of Japan before their landfall. The TCHP in September and October 2019 is higher than climatological mean, while no clear difference from the climatological mean is found in the other environmental factors such as 200–850 hPa vertical wind shear (Fig. S1) and 600-hPa relative humidity (Fig. S2).

Figure 3 shows the horizontal maps of the standard deviation (Fig. 3a) and the linear trend of TCHP (Fig. 3b) with the average from January 1982 to June 2020. Although the average is lower than the climatological mean (Fig. 2), the difference does not affect the horizontal distribution of TCHP. The trend is highest in the equatorial central Pacific and off east of the Philippines where the average TCHP is climatologically high (Wada and Chan 2008). The standard deviation is highest in the equatorial central Pacific, while that off east of the Philippines is relatively low.

Figure 4a shows the timeseries of three leading amplitudes normalized by the temporal standard deviation of TCHP. Table 1
shows the correlation coefficient of IOVs with the three leading normalized loading amplitudes (NLAs) for TCHP. The first leading EOF mode (EOF1) explains approximately 43.1%, the second mode (EOF2) approximately 21.9%, and the third mode (EOF3) approximately 11.8% of total variance. The sum of the three leading EOF modes explains approximately 76.8% of total variance. The linear regression function of EOF2 shows that the value of the negative slope is greater than that of EOF1 and EOF3 (not shown). EOF2 includes the significant trend at the 99% significance level, but it is different from the linear trend (Fig. 3b). Since the trend included in the TCHP data is not removed in the EOF analysis, the obtained EOF modes are possibly affected by the linear trend of TCHP. The evolution of the three leading NLAs in Fig. 4a is not always consistent with that obtained from the EOF analysis for TCHP data after the removal of the linear trend (Fig. S3).

The horizontal map of EOF1 (Fig. 4b) shows the east-west TCHP contrast between the western and the eastern North Pacific Oceans, and EOF1 is significantly correlated with various IOVs particularly Nino3 (or ENSO) (Table 1). The horizontal map of EOF2 (Fig. 4c) shows a negative correlation in most North Pacific Ocean except east of the Mindanao island and the Equatorial East Pacific, which is significantly correlated with EMI and PMM. The horizontal map of EOF3 (Fig. 4d) shows a positive correlation in the equatorial Pacific, while it is negative in the eastern and western North Pacific Oceans, which is significantly correlated with Nino3 (or ENSO), EMI, and PMM.

In Fig. 4a, the NLA of EOF2 in September and October 2019 is negative and the absolute value is much greater than the NLAs of EOF1 and EOF3. However, Fig. 4a does not include the information of correlation shown in Figs. 4b, 4c, and 4d. Therefore, the composite map that represents the normalized TCHP variation is created in Fig. 4e by summing of the products of EOF1-3's explanatory ratio, correlation, and the NLA of 1 October 2019. The NLA of EOF2 is negative, while the NLAs of EOF1 and EOF3 are close to zero in September and October 2019 (Fig. 4a). However, Fig. 4e suggests that the TCHP field in September and October 2019 is formed by the offsetting of IOVs explained by EOF1-3. In particular, the increase in TCHP in region S is not explained

### Table 1. Correlation coefficients between the NLAs of the leading three EOF modes of TCHP and induces associated with IOVs (see supplement 2) from January 1982 to June 2020. Bold fonts indicate that the correlation is significant at the 99% confidence level based on the t-test. Underlines show that the correlation is also significant in Table 2.

|       | Nino3 | EMI  | PDO  | DMI  | PMM  |
|-------|-------|------|------|------|------|
| EOF1  | 0.79  | 0.62 | 0.58 | 0.20 | 0.18 |
| EOF2  | 0.06  | -0.40| 0.01 | -0.12| -0.44|
| EOF3  | -0.23 | 0.49 | -0.12| 0.06 | 0.35 |
| EOF123| 0.66  | 0.48 | 0.47 | 0.13 | 0.05 |
by the composite normalized TCHP variation, indicating that the increase in TCHP in region S is explained not by the IOVs but by the linear trend (Fig. 3b). However, the increase in TCHP in region N is explained by both the warming trend and the IOVs in EOF2 (Fig. 4c) because Fig. 4e shows that the normalized TCHP variation is positive in region N (Fig. 4e). The result is also obtained from the EOF analysis for TCHP data after the removal of the linear trend (Fig. S4).

Although the increasing trend in TCHP is related to TC intensification of HAGIBIS in the early intensification phase, there is little difference in TCHP underneath HAGIBIS in the mature phase between 2019 and climatological mean (Fig. 2b) due to TC-induced sea surface cooling and the decrease in TCHP caused by enhanced TC activity east of Philippines (Wada and Chan 2008). This feature is also associated with relatively low standard deviation east of Philippines (Fig. 3a).

4. Concluding remarks

This study focuses on the increases in TCHP in the WNP and its influence on FAXAI and HAGIBIS in 2019 that made landfall in Japan. This study demonstrates from the EOF analysis that the increase in TCHP around 15°N–20°N, 140°E–150°E, which helped intensify HAGIBIS in the early intensification phase, is explained by an increasing trend in TCHP rather than IOVs. In addition, the increase in TCHP around 30°N–35°N, 130°E–140°E is explained by both an increasing trend in TCHP and IOVs such as EMI and PMM. This study only addresses the IOVs in TCHP, but the seasonal or decadal TCHP variations may also affect TC activity.

Regarding the effect on changes in the preexisting oceanic environment, the impact of increasing TCHP has been investigated by numerical simulations on FAXAI initiated before the landfall (Wada 2020a) and HAGIBIS in the early intensification phase (Wada 2020b). The results suggest that there is an impact on the maximum wind speed and central pressure, but no impact on the tracks. Since these are only one simulation result, it is necessary to obtain robustness in each TC by conducting ensemble experiments with multiple initial conditions.

It is important to understand that the factors that increase TCHP are different and that the warming trend itself affects the increase in TC intensity. In addition, the other environmental factors such as vertical wind shear and moist mid-troposphere should be considered to understand TC intensity and intensification in an ongoing global warming.

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Supplement

The supplementary material provides the timeseries of 200–850 hPa vertical wind shear (Fig. S1) and 600-hPa relative humidity (Fig. S2) in the cases of FAXAI and HAGIBIS and the result of empirical orthogonal function (EOF) analysis for TCHP data after the removal of linear trend from January 1982 to June 2020 (Figs. S3–S4).

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