Abstract

The western North Pacific (WNP) exhibited markedly enhanced tropical cyclone (TC, typhoon) activity during the boreal summer (June–August) of 2018; 18 named typhoons were generated and 13 of these approached near Japan, causing serious damage and disruption in the country. During the summer of 2018, warm sea surface temperature persisted over the tropical Northeastern Pacific, which are typical oceanic conditions of a positive phase of the Pacific meridional mode (PMM), while no El Niño condition was observed. The Japan Meteorological Agency seasonal forecast system successfully predicted the enhanced TC activity in the WNP as well as associated seasonal characteristics such as a deep monsoon trough and active convection. Results of sensitivity experiments clearly indicate that the positive phase of the PMM played a major role in establishing the active TC conditions in the WNP during the summer of 2018 and reveal predictable seasonal processes of TC activity (genesis and tracks) during the summer of 2018, when there was no El Niño.

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1. Introduction

During the boreal summer (June–August) of 2018, the western North Pacific (WNP) exhibited markedly enhanced typhoon (tropical cyclones with maximum wind exceeding 17.2 m s⁻¹) activity associated with active convection and anomalous cyclonic circulation in the lower troposphere (Fig. 1). According to the best track analysis of the Regional Specialized Meteorological Center (RSMC) Tokyo-Typhoon Center, during the season, 18 named typhoons were generated and 13 of these approached to within 300 km of Japanese coastlines (Fig. 1c); both numbers were remarkably high in the historical best track analysis. In particular, August 2018 ranked third in monthly typhoon genesis number (9 typhoons) in the WNP since 1951. In early July, Typhoon Prapiroon (T1807) hit Japan and it was followed by an intensified Baiu front. An unprecedented amount of accumulated rainfall due to these consecutive events caused widespread floods and landslides in Western Japan (Shimpo et al. 2019; Tsuguti et al. 2018; Takemi 2018). Typhoon Jebi (T1821), which made landfall in September 2018, caused severe damage as a result of strong winds and storm surges (Takemi et al. 2019). Given the severe disasters associated with tropical cyclones (TCs) in the summer of 2018, it would be valuable to identify the underlying climate processes related to these extremes and to explore capabilities to predict them.

The TC variability in the WNP is controlled mainly by synoptic- and meso-scale atmospheric circulation, and the intra-seasonal variability (Madden–Julian oscillation). However, the basin-scale interannual oceanic conditions at least partly control seasonal-scale atmospheric circulation that, in turn, influences TC genesis through various environmental factors (Fudeyasu and Yoshida 2018). The equatorial Pacific and Indian Ocean are recognized as key basins that affect WNP TC activity (Chen et al. 1998; Chan 2000; Kim et al. 2011; Du et al. 2011; Kosaka et al. 2013; Takaya et al. 2017). The El Niño–Southern Oscillation (ENSO) is the primary modulator of the interannual variability of TCs (basin-wide TC genesis number, genesis location and tracks) in the WNP (Camargo and Sobel 2005; Takaya et al. 2010; Wang and Chan 2002). Recently, the Indian Ocean has attracted much attention as a mediator of delayed ENSO effects on the WNP TC activity (Du et al. 2011; Kosaka et al. 2013; Takaya et al. 2017).

Recent studies have revealed that the Pacific meridional mode (PMM; Chiang and Vimont 2004) in the tropical North Pacific has a remote influence on WNP TC activity (Zhang et al. 2016; Gao et al. 2018; Zhan et al. 2017). Zhang et al. (2016) analyzed a long-term (1000-year) climate model simulation and found that the positive PMM phase enhances TC genesis in the WNP, while the negative PMM phase inhibits TC genesis there. Zhan et al. (2017) analyzed observed WNP TC conditions in 1998 and 2016, and pointed out that a positive phase of the PMM in 2016, despite a weak La Niña condition, contributed to the enhancement of WNP TC activity during the peak typhoon season (August–September) by driving an anomalous cyclonic circulation and reducing vertical wind shear over the WNP. Since the PMM is closely associated with the Central-Pacific ENSO (CP-ENSO, Kao and Yu 2009), they often occur together (Stuecker 2018). For this reason, the limited length of satellite observations (late 1970s to present) makes it difficult to perform observationally based analyses to disentangle the role of the PMM from those of other major drivers such as the ENSO. The summer of 2018 is a unique test case in the historical TC record, as it presented the remarkable sea surface temperature (SST) pattern of the positive PMM phase (warm SST in the central–eastern tropical North Pacific) with a neutral ENSO condition in the equatorial Pacific (Fig. 1a). This study investigates the underlying mechanisms of the enhanced TC activity in the summer of 2018 by conducting and analyzing sets of large ensemble sensitivity experiments using an operational seasonal prediction system.

2. Data and methods

The latest operational climate prediction system of the Japan Meteorological Agency (JMA), JMA/MI-JPS (Takaya et al. 2018) was employed to examine the PMM influence in the summer of 2018. Three sets of 52-member ensemble simulations starting from the end of April 2018 were run with realistic atmospheric and oceanic initial conditions following experimental settings described by Takaya et al. (2017). A control experiment (CTRL) is an ensemble prediction started from the observed initial conditions as used in operational seasonal predictions (Takaya et al. 2018). Historical CTRL experiments (hindcasts) with 52 members during the 30-year period (1981–2010) were also performed to obtain a model climatology. In addition, two sensitivity experiments (referred to as the noPMM and noENSO experiments) were conducted to evaluate the impact of SST conditions. In the noPMM experiment, SST in the PMM region (5°N–25°N, 150°E–100°W) was strongly nudged to the climatological SST. In the two sensitivity experiments, the influence of anomalous SST conditions observed in the summer of 2018 was artificially removed in
the targeted regions with the SST nudging. In this study, TCs with maximum wind speed exceeding 17.2 m s\(^{-1}\) (tropical storm strength) are analyzed. Simulated TCs are detected and tracked by applying an objective algorithm to 6-hourly model outputs (Appendix; Takaya et al. 2010; Takaya et al. 2017). The TC detecting algorithm considers the difference in TC intensity between observations and model simulations (Walsh et al. 2007; Takaya et al. 2010). In this study, a TC genesis number is defined as a total count of the detected TC genesis in a 4.5° × 4.5° box during summer (June–August), and TC density is defined as the total number of TC existing time steps in a 4.5° × 4.5° box in 6-hourly outputs during summer.

Several analysis datasets are used as reference data: atmospheric analysis of the 55-year Japanese Re-Analysis (JRA-55; Kobayashi et al. 2015), monthly precipitation analysis of the Global Precipitation Climatology Project (GPCP; Adler et al. 2018) version 2.3, SST analysis of Centennial in situ Observation-based Estimate (COBE-SST; Ishii et al. 2005), and TC best track analysis of the RSMC Tokyo (JMA).

3. Results and discussion

In the CTRL experiment, the model predicted well the dominant seasonal characteristics of the summer of 2018 including the PMM-like positive SST anomalies in the tropical Northeastern Pacific, anomalous lower-tropospheric cyclonic circulation (deeper monsoon trough) over the WNP, and active rainfall from the WNP to the central tropical North Pacific (Figs. 2a and 2c). The WNP monsoon trough is the primary environmental condition controlling the seasonal TC activity in the WNP (Wu et al. 2012), and the predicted deeper monsoon trough favors enhanced TC activity (Figs. 2a and 2c).

In contrast to the CTRL experiment, the noPMM experiment presents weakened or opposite anomalies for the lower-tropospheric circulation (850-hPa relative vorticity), sea-level pressure (SLP), and rainfall (Figs. 2b and 2d); these conditions weaken the TC activity in the summer of 2018. SSTs outside the nudged region (box in Fig. 2b) are similar to those of the CTRL experiment except for a discernible weakened positive anomaly in the equatorial central Pacific (Figs. 2a and 2b), suggesting that differences between the CTRL and noPMM experiments are mostly the result of the PMM-like SST anomaly. The weakened transition to the central-Pacific El Niño (CP-El Niño) in the noPMM experiment might result from a lack of the PMM effect to force the CP-El Niño (Stuecker 2018).

These results suggest that the PMM-like SST pattern in the summer of 2018 enhanced the TC activity in the WNP. To confirm this, simulated TCs were directly detected and tracked with an objective method (Appendix; Takaya et al. 2010; Takaya et al. 2017), and the TC genesis numbers and TC density were evaluated. Figure 3 displays the spatial distributions of simulated TC genesis and TC density anomalies for the CTRL and noPMM experiments, where the anomalies were computed with respect to the model climatology of the CTRL experiment during the 1981–2010 period. The CTRL experiment captured well the observed measures of the TC activity: TC genesis and TC density. Unsurprisingly, TC activity, both genesis and density, was greatly reduced with removal of the PMM-like SST anomaly (Figs. 3b and 3d). The suppressed TC activity in the noPMM experiment compared with the CTRL model climatology is presumably attributable to the slightly warmer SST conditions in the Indian Ocean (Fig. 2a; Du et al. 2011). Note also that the TC genesis was enhanced around 15°N, which is about 10° farther north than a typical enhanced region in El Niño years in model simulations, reflecting the northward shift of the TC genesis region. The region of anomalously positive TC density in the CTRL experiment appears to be consistent with that obtained in a previous modeling study (Zhang et al. 2016), suggesting that the location of the PMM influence is a meaningful (neither model-dependent nor case-dependent) feature.

Figure 4 summarizes the impacts of the PMM-like SST on the WNP TC genesis in the summer of 2018. The CTRL experiment reproduced well an observed climatology of total TC genesis in the WNP during 1981–2010. The CTRL experiment presents a statistically significant larger number of total TC genesis for the summer of 2018 (TC genesis number: 12.7) than for the model climatology (TC genesis number: 11.2) based on the two-tailed Student’s t-test (p < 0.05), although it is still lower than the observed 2018 genesis number. The underestimate of the CTRL
The experiment for the summer of 2018 is due presumably to the large uncertainty of ensembles (reduction of anomaly amplitudes by ensemble averaging) and insufficient response of the TC activity to the PMM-like SST pattern, unpredicted intraseasonal tropical variability and extratropic circulation variability. In the noPMM experiment, the total TC genesis significantly decreased (two-tailed Student’s t-test, \( p < 0.05 \)) from the CTRL experiment (TC genesis number: 9.8), indicating the impact of the PMM-like SST on the WNP TC. As discussed above, the noPMM experiment showed weakening of the CP–El Niño transition. Therefore, the noENSO experiment was run and analyzed to assess SST impacts of the central–eastern equatorial Pacific only. The noENSO experiment presented a smaller and statistically insignificant decrease in TC genesis from the CTRL experiment (TC genesis number: 11.8).

These results affirm that the PMM-like SST accounts for a greater part of the TC activity modulation arising from SST conditions.

The rest of this paper briefly discusses the atmospheric condi-
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Fig. 5. Simulated (a, c) vertical shear of horizontal wind (200−850 hPa) [m s$^{-1}$] (contours, contour interval: 5) and its anomaly (colors), (b, d) 850-hPa wind [m s$^{-1}$] (black vectors) and wind anomaly (red vectors) for summer 2018. Results for (a, b) CTRL and (c, d) noPMM experiments.

4. Summary and conclusions

This study has examined impacts of the PMM-like SST conditions on the remarkably enhanced TC activity in the summer of 2018. Initialized coupled predictions and sensitivity experiments with a partial SST nudging to the climatology were conducted and analyzed. The results clearly indicated that the positive phase of the PMM played a major role in triggering the enhanced TC activity. The underlying processes are summarized as follows. The PMM-related SST pattern enhanced convection (rainfall) from the WNP to the central tropical North Pacific. In turn, this enhanced convection formed a lower-tropospheric cyclonic circulation anomaly in the WNP, and induced westerly anomaly in the lower troposphere around 10°N. These circulation changes then created favorable conditions for TC genesis and development by weakening the vertical wind shear and strengthening the lower-tropospheric cyclonic anomaly (WNP monsoon trough). Through these processes, the PMM-like SST pattern synergistically induced the sizable enhancement of WNP TC activity in the summer of 2018. The summer of 2018 exemplifies how the PMM can be a source of the seasonal TC predictability including TC genesis and TC density (tracks) in the WNP, in addition to other key sources of predictability such as the ENSO and Indian Ocean conditions.

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Appendix

(1) TC detection and tracking method

The objective method used to detect and track TCs is briefly described here. An algorithm was adapted from one originally developed by Takaya et al. (2010), which is similar to other algorithms used in previous studies (Walsh et al. 2007). Thresholds in the algorithm were adjusted so that the model reproduces reasonably well an observed TC genesis climatology (maximum wind
exceeding 17.2 m s\(^{-1}\)) and are the same as those used by Takaya et al. (2017). Six-hourly simulation data with a 1.5° × 1.5° resolution were used. The steps in the detection method are as follows.

1. Search grid cells with a local sea level pressure (SLP) minimum in a 6° × 6° box over the ocean between the equator and 20°N to determine the center of a candidate TC.

2. Check if relative vorticity at 850 hPa is below 5 × 10\(^{-5}\) s\(^{-1}\) in at least one grid cell in a 3° × 3° box surrounding the center of the candidate TC.

3. Check if geopotential height thickness between 200 and 500 hPa at the center of the candidate TC is more than 7 gpm higher than the averaged thickness in a 9° × 9° box surrounding the center of the TC excluding the center of the candidate TC (24 grids).

4. Check if the horizontal wind speed at 200 hPa is lower than that at 850 hPa at the center of the candidate TC.

5. If the conditions 1−4 are satisfied for at least 12 hours (two consecutive 6-hourly data), the candidate TC is determined to be a TC in the model.

For tracking TCs, TCs are searched within a 9° × 9° box of a previous location of the detected TCs 6 hours before. TCs with a lifetime longer than 12 hours are exempt from the conditions 3 and 4.

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