Impacts of tropical cyclones on the meridional movement of the western Pacific subtropical high

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Movements of the western Pacific subtropical high (WPSH) are an important factor dominating the synoptic weather and climate over East Asia. In this study, characteristics of the WPSH meridional movement are statistically analysed for the tropical cyclone (TC) peak months (July–September) from 2001 to 2010. The results show that the WPSH meridional movement is consistent overall, namely, its ridge line moves synchronously with its main body centroid, with a correlation coefficient of 0.70 between the ridge line and main body centroid. Moreover, the sensitivity experiment with the Weather Research and Forecasting Model (WRF) for super typhoon Megi (2010) demonstrates that TCs can affect the WPSH meridional movement by stimulating abnormal perturbations that disperse and propagate outwards. Specifically, the WPSH ridge line would shift northwards at an average of 0.64° latitude and a maximum of 1.44° latitude for the period when TC Megi moves to the south of the WPSH. In summary, the meridional movement of the WPSH ridge and centroid are well-correlated and are strongly influenced by TC activity. This study proposes a possible way by which TCs over western North Pacific could affect the weather and climate in East Asia.

KEYWORDS composite analysis, sensitivity experiment, tropical cyclone, western Pacific subtropical high

1 | INTRODUCTION

The western Pacific subtropical high (WPSH) is an important atmospheric circulation system in the middle and low latitudes of the northwestern Pacific. The WPSH strengthens and covers a large area in summer, imposing pronounced influences on weather and climate systems over East Asia.

Movement of the WPSH exhibits zonal and meridional features (Huangfu et al., 2015; Yang et al., 2017) and is under the influence of multiple factors and weather/climate systems such as the sea surface temperature (SST; He and Gong, 2002; Wu and Zhou, 2008), the summer monsoons (Rodwell and Hoskins, 2001) and tropical cyclone (TC; Sun et al., 2015; Wang et al., 2017). In their statistical research on the effect of sea surface temperature on WPSH, Zhou et al. (2009) indicates that the rising SST in the Indian and west Pacific Ocean basins can promote the development of convection heating in the equatorial Indian Ocean/Maritime Continent, which subsequently leads to the western extension of the WPSH. Based on reanalysis products for the period of 1979–2008, Su and Xue (2011) discussed the two annual northwards jump regularities of the WPSH and found that the first northwards jump is associated with SST anomalies (SSTA) in the tropical central Pacific and that the second northwards jump is related to SSTA in the Indian Ocean. About the impacts of precipitation on the WPSH, Liu et al. (2001) and Si et al. (2008) proposed that the zonal movement of the WPSH is highly correlated with precipitation.
around because stronger divergence in the upper troposphere would happen due to the latent heat release by the precipitation of the East Asian summer monsoon, and the accompanied outflows and downdrafts subsequently promote the westwards extension of the WPSH. In addition, a statistical study of precipitation influences on the zonal movement of the WPSH suggests that corresponding to persistent precipitation in the Yangtze River basin, positive geopotential height anomalies at 500 hPa occur over East Asia, causing the westwards extension of the WPSH (Ren et al., 2013). Besides, a numerical study of TC Megi (2010) indicated that when the TC is located to the south of the WPSH, the upper troposphere warming due to the condensation in anvil clouds coupled with the lower troposphere cooling due to raindrops evaporation would cause a weakening of the southern WPSH (Sun et al., 2014). On the other hand, Hoskins (1996) speculated that the interaction between the equatorial Rossby waves and the westerly flows may result in descent, and below the maximum descent there is a strong equatorwards motion, which is equivalent to the anticyclonic vorticity generated in region to the west of the descent, favouring the subtropical anticyclone to extend westwards. Therefore, the variability of tropical waves (Raghavendra et al., 2019) can also affect the position of WPSH.

To date, most studies on WPSH zonal movement have focused on the impacts of precipitation. However, it is argued that TCs in a specific area in the northwestern Pacific can induce Pacific–Japan teleconnection pattern wave trains that propagate northwards and reach the mid-latitude areas (Kawamura and Ogasawara, 2006; Yamada and Kawamura, 2007). This finding indicates that TC activities can stimulate wave-like fluctuations that propagate meridionally, which will inevitably affect the position and strength of the WPSH. In the present study, a statistical method and a composite analysis are adopted first to analyse the features of the overall consistent meridional movement of the WPSH in the northwestern Pacific TC peak months (July–September) (Wang et al., 2008), and then, TC Megi is used as an example for sensitivity numerical experiments to explore the impacts of the TC on the WPSH meridional movement.

# DATA AND METHOD

The National Centers for Environmental Prediction (NCEP) 1° resolution global gridded Final Analysis (FNL) data set (http://rda.ucar.edu/datasets/ds083.2) is widely used in studies of TC influences on other weather and climate systems in East Asia (Harr and Dea, 2009; Pan et al., 2018), and the 1° resolution FNL data set is sufficient in representing WPSH movement, so the statistical data used in the present study are derived from the NCEP FNL data set at 6-hr intervals for July–September from 2001 to 2010, and the daily mean geopotential height and wind vector data for the statistical analysis are calculated with the original data at 6-hr intervals to remove the semi-diurnal oscillation feature in the FNL data set.

The mean latitude of the WPSH ridge line can well represent the meridional position of the WPSH. To calculate the WPSH ridge line, the grids between 120°–160°E with zonal wind $u$ satisfying the criteria $u = 0$ and $\frac{\partial u}{\partial y} > 0$ are identified as ridge line grids (Liu and Wu, 2004), and the mean latitude of the WPSH ridge line is obtained by averaging the latitudes of the ridge line grids.

Here, we define the WPSH geopotential height centroid as the centre of its main body. To exhibit the WPSH meridional movement, the latitude of the WPSH main body centroid is also calculated with a geopotential height greater than the threshold value $S$ (unit: geopotential metre, gpm) within the longitude range of the ridge line grids. For statistical analysis, $S$ is set as $S = S_{\text{max}} - 60$, and $S_{\text{max}}$ is the maximum geopotential height value of the WPSH ridge line grids at the corresponding time. The average $S_{\text{max}}$ for TC peak months from 2001 to 2010 is approximately 5,920 gpm, and the average $S$ is approximately 5,860 gpm. For the composite analysis and TC case study, $S$ is set to 5,860 gpm. In the statistical study, the macro features of the WPSH movement and the responses of the WPSH movement to TC influences can be well reflected.

However, the analysis products include the interactions between TCs and large-scale circulation; therefore, only the sensitivity experiment by numerical modelling can provide simulated circulations without a TC effect (Zhong and Hu, 2007). In addition, it is hard for numerical models to accurately capture the multiple TC features and to remove the influence of each TC for a long simulation period. As a compromise method, a case study is more appropriate for the purpose of the present study. Since TC Megi is one of the most intense TCs on record and its sharp turn was not forecasted by any leading operational centres because of its strong interaction with the WPSH (Qian et al., 2013), the sensitivity experiment for super typhoon Megi (2010) with the non-hydrostatic Weather Research and Forecasting Model (WRF; Skamarock et al., 2008) is carried out to verify the impacts of the TC on the meridional movement of the WPSH. Two experiments are conducted in the present study, that is, the TC Megi simulation experiment (Megi-sim) and the TC Megi removed experiment (Megi-rem). According to Sun et al. (2014), the initial and boundary conditions are derived from the 1° resolution FNL data set, and the model domain in the present study is centred at (30°N, 130°E) with $240 \times 260$ grids in the east–west and north–south directions, respectively. The horizontal grid interval is 20 km, and there are 36 levels in the vertical grid. The main physics schemes include the WSM 3-class microphysical scheme (Hong et al., 2004), the Mellor–Yamada–Janjić boundary layer scheme (Mellor and Yamada, 1982; Janjić, 2001), and the Grell–Dévényi cumulus parameterization scheme (Grell and Dévényi, 2002). The model is initialized at 0000 UTC on...
October 15, 2010 and run for 168 hr ending at 0000 UTC on October 22, 2010. In the Megi-rem experiment, TC Megi vortex in the initial field is removed as the first step using the TC bogus scheme (Fredrick et al., 2009), and all other model configurations are the same as those in the Megi-sim experiment.

TC Megi track observation and TC activity feature for July–September from 2001 to 2010 are extracted from the best track data set of the Joint Typhoon Warning Center (JTWC, http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.html).

### RESULTS

#### 3.1 Overall consistency of the WPSH meridional movement

Temporal evolutions of daily mean latitudes of the WPSH ridge line and the WPSH main body centroid between 130°E and 160°E during July–September from 2001 to 2010 are displayed in Figure 1. Although the relative positions of the WPSH ridge line and main body centroid are determined by the distribution pattern of the WPSH to some degree, the results in Figure 1 show that the WPSH ridge line is almost always located to the north of the WPSH main body centroid, and the average difference in the daily mean latitude between the WPSH ridge line and the WPSH main body centroid for July–September from 2001 to 2010 is 3.30° latitude. The correlation coefficients between the two latitude time series for each year are listed in Table 1 and all exceed the 99% confidence level, with an average value of 0.70. The statistical results above indicate that the meridional movement of the WPSH is consistent overall, that is, the meridional movement of the WPSH ridge line seldom deviates from that of the WPSH main body centroid. Therefore, when the WPSH intensifies at its northern (southern) flank due to dynamic and thermodynamic effects and the WPSH main body centroid moves northwards (southwards), then the WPSH ridge line would also move northwards (southwards), and vice versa.

The 920 daily samples for July–September from 2001 to 2010 are then divided into three groups for composite analysis according to their WPSH ridge line latitudes: the 300 samples with the highest WPSH ridge latitudes (HLAT), the 300 samples with the lowest WPSH ridge latitudes (LLAT) and the remaining 320 samples (MLAT). Figure 2 displays the average geopotential height field and the corresponding WPSH centroid position and ridge line in HLAT, LLAT and MLAT. The average WPSH ridge line latitudes from 130°E to 160°E in HLAT, MLAT and LLAT are 32.39, 28.77 and 24.71°N, and the corresponding WPSH main body centroid latitudes are 24.93, 21.14 and 18.76°N, respectively, which indicates that, as in Figure 1, when the WPSH main body centroid moves to the south/north, the WPSH ridge line would also move towards the same direction. Furthermore, the statistical results from the JTWC best track data at 6-hr intervals from 2001 to 2010 show that the number of 6-hr interval samples (i.e., 0000, 0600, 1200 and 1800 UTC) with TC activity in HLAT, MLAT and LLAT are 908, 864 and 728, respectively, accounting for 76, 68 and 61% of the whole 6-hr interval sample number in each group (1,200 times in HLAT, 1,280 times in MLAT and 1,200 times in LLAT). Therefore, it can be inferred that the position of the WPSH is related to TC activities, and high TC activities always correspond to a more northwards WPSH position.

Moreover, the composite geopotential height and the corresponding WPSH ridge line and centroid centre position for the TC-active period and TC-free period in the peak months (July–September) from 2001 to 2010 are displayed in Figure 3, and the number of 6-hr interval samples for the TC-free and TC-active periods are 1,180 and 2,500.

#### Table 1 Annual correlation coefficients between the daily time series of the WPSH ridge line latitude and WPSH main body centroid latitude each year for TC peak months from 2001 to 2010

| Year | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | Mean |
|------|------|------|------|------|------|------|------|------|------|------|------|
| r    | 0.71 | 0.81 | 0.73 | 0.69 | 0.72 | 0.59 | 0.73 | 0.72 | 0.56 | 0.76 | 0.70 |
respectively. Additionally, the movement of the WPSH ridge line and the WPSH main body centroid are consistent overall, namely, when the WPSH main body centroid moves further north (south) with high (low) TC activities, the WPSH ridge line also moves northwards (southwards).

### 3.2 Numerical experiment results of the impacts of TC Megi on the WPSH meridional movement

The simulated track in the present study (Figure S1, Supporting Information) is almost identical to the observed track at 6-hr intervals, with a mean bias of only 54 km during the integration period, and specifically, the model can realistically reproduce the abrupt northwards recurving of TC Megi in the South China Sea after it passed over the Philippines, as shown in Sun et al. (2014, fig. 1).

Figure 4 displays the 500-hPa geopotential height and wind from the FNL analysis and Megi-sim and Megi-rem simulations, as well as the differences between Megi-sim and Megi-rem. A comparison of the FNL analysis (Figure 4a,c) and Megi-sim simulation (Figure 4d,f) indicates that the simulated positions of TC Megi and the 500-hPa characteristic geopotential height contours of the WPSH are consistent with those of the FNL analysis, which suggests that the model can well describe the interactions between the WPSH and TC Megi, and that is the reason why the model can reasonably simulate the TC track. However, it should be noted that the strength of the TC in Megi-sim is much weaker than that in FNL analysis, and the reason for the discrepancy may be that the numerical simulation at a relatively low horizontal resolution (20 km in this study) cannot precisely represent the physical processes important to TC intensity (Gentry and Lackmann, 2010). In addition, a TC vortex no longer exists in the simulated geopotential height field (Figure 4g,i) after TC Megi vortex is removed from the initial field (in Megi-rem), as proposed by Dzung and Yamada (2017). The differences between the two simulation experiments show that the abnormal signals induced by TC Megi can propagate and disperse outwards (Figure 4j, l), and by the time TC Megi made landfall in the northern

**FIGURE 2** Composited geopotential height (contour, unit: dagpm), WPSH ridge lines (red line) and WPSH centroid positions (red cross) for (a) HLAT, (b) MLAT and (c) LLAT

**FIGURE 3** Composited geopotential height (contour, unit: dagpm), WPSH ridge lines (red line) and WPSH centroid positions (red cross) for (a) the TC-active period and (b) the TC-free period
Philippines at 0000 UTC on October 18, the geopotential height anomalies related to TC Megi already extended northwards to eastern China and the East China Sea, resulting in negative geopotential height anomalies and abnormal cyclonic circulations in these areas. Meanwhile, affected by the northwards propagation of perturbations induced by TC Megi, positive geopotential height anomalies and abnormal anticyclonic circulations appear from north of the Sea of Japan to the ocean to the east of Japan (Figure 4l), which is consistent with previous studies (Kawamura and Ogasawara, 2006; Yamada and Kawamura, 2007). In fact, as a thermodynamic and dynamic forcing source, TCs can interact with...
the environmental fields by stimulating Rossby wave trains (Nitta, 1987), so TCs can affect the atmospheric circulation outside the TC centre area via triggering abnormal signals that propagate outwards and make changes to the weather and climate systems in the corresponding area.

To better reflect the interaction between TC Megi and WPSH, the WPSH ridge lines within 120°–130°E are selected for discussion. In addition, considering that TC Megi turned from westwards movement to northwards movement after approximately 1400 UTC on October 19 and, consequently, the interactions between TC Megi and WPSH before and after that time were completely different, in this study, analysis for the period before 1400 UTC on October 19 was conducted to discuss the influence of TC Megi on the WPSH when TC Megi was moving westwards. The temporal evolutions of the 500 hPa mean latitudes of the WPSH ridge line and the WPSH main body centroid between 0000 UTC on October 15 and 1400 UTC on October 19 in Megi-sim and Megi-rem are displayed in Figure 5, which shows that the Megi-rem simulated WPSH ridge line and WPSH main body centroid are always located to the south of those in Megi-sim, consistent with the statistical results shown in section 3.1. It can be estimated that the mean and maximum latitude differences in the ridge line in Figure 5 are 0.64 and 1.44° from 0000 UTC on October 17 to 1400 UTC on October 19, and those in the WPSH main body centroid are 1.50 and 4.08°, respectively.

In their numerical experiments to remove the TC, Zhong and Hu (2007) found that although the TC activity is under the strong influence of the WPSH, it can also feedback to the atmospheric circulation and lead to changes in the position of the WPSH. The present study of TC Megi further clarifies that when the TC is located to the south of the WPSH and moves westwards, it could lead to a northwards shift in the WPSH.

One interesting phenomenon is that the meridional movement of the WPSH main body centroid exhibits regular semi-diurnal variation in both Megi-sim and Megi-rem during the period when TC Megi is located to the south of the WPSH and moves westwards (Figure 5b). Wang et al. (2017) also found a similar phenomenon in their numerical sensitivity study of the impacts on the WPSH for various initial intensities and sizes of TCs. Analysis of the temporal evolution of the WPSH intensity derived from the analysis data set reveals a regular semi-diurnal variation; therefore, it is concluded that the regular semi-diurnal variation in the meridional movement of the WPSH main body may be related to the semi-diurnal variation in the WPSH intensity.

4 CONCLUSIONS

The characteristics of the WPSH meridional movements during the TC peak months in the northwestern Pacific are statistically analysed, and TC Megi is used as an example to investigate the feedback of TCs on the WPSH meridional movement in the present study, revealing a possible way by which TCs could affect the weather and climate in East Asia. The major conclusions are as follows.

1. Temporal evolution of the mean latitude of the WPSH ridge line is correlated with that of the WPSH main body centroid. Therefore, the meridional movement of the WPSH is consistent overall, which means that when the WPSH intensifies at its northern (southern) flank and the main body centroid moves northwards (southwards), the WPSH ridge line would also move northwards (southwards), and vice versa.

2. TCs can induce abnormal perturbations that disperse and propagate outwards, and these perturbations can subsequently lead to the meridional movement of the WPSH. Specifically, when the TC moves westwards or northwestwards to the south of the WPSH, it can lead to a northwards shift in the WPSH. For the case of super typhoon Megi, the sensitivity experiment suggests that the WPSH ridge line would shift northwards at an average of 0.64° latitude and a maximum of 1.44° latitude for the period when TC Megi moves to the south of the WPSH.

It should be noted that the relatively low horizontal resolution in the present sensitivity experiment leads to a weaker TC than the analysis data set, and numerical experiments at higher horizontal resolutions should be conducted to further verify the conclusion of this study. In addition, experiments...
concerning the influence of TCs with different initial intensities and sizes on the WPSH movement will be helpful for a deeper understanding of the interaction between TCs and the WPSH. Moreover, considering that the tropical waves are important for TC activities (Done et al., 2011), it is worthwhile to verify the relationship among tropical waves, TCs and movement of WPSH for a better understanding of the WPSH movement mechanism.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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