Weak upstream westerly wind attracts western North Pacific typhoon tracks to west

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Abstract
The steering flow of the large-scale circulation patterns over the western North Pacific and North East Asia, constrains typhoon tracks. Westerly winds impinging on the Tibetan Plateau, and the resulting flow uplift along the slope of the mountain, induce atmospheric vortex flow and generate stationary barotropic Rossby waves downstream. The downstream Rossby wave zonal phase is determined by the upstream zonal wind speed impinging on the Tibetan Plateau. Negative anomaly of westerly wind forcing tends to induce a westward shift of the large-scale Rossby wave circulation pattern, forming an anti-cyclonic circulation anomaly over North East Asia. In this study, we show that the Tibetan Plateau dynamically impacts the tracks of western Pacific typhoons via modulation of downstream Rossby waves. Using the topographically forced stationary Rossby wave theory, the dynamical mechanisms for the formation of the North East Asian anti-cyclonic anomaly and its impact on the typhoon tracks are analyzed. The westward shift of typhoon tracks caused by the southeasterly wind anomaly, or track density increase over the western flank of the North East Asian anti-cyclonic circulation anomaly is robust in June, August and September, but it is not statistically significant in July. The physical understanding of the large-scale circulation pattern affecting typhoon trajectories has large implications not only at the seasonal prediction of the high impact weather phenomena, but also at the right understanding of the long-term climate change.

1. Introduction

Typhoons are one of the most serious natural disasters, causing both loss of life and property damage. Typhoons are accompanied by intense winds, heavy rainfall, extreme oceanic waves, and storm surges. However, they also have some positive aspects, such as dissipating pollutants and red tides by causing vertical mixing in oceans and lakes, and water resource supply to the land. Every year from spring to fall, several western North Pacific (WNP) typhoons impact Asian countries. In addition, in North East Asia, the extreme winds and heavy rainfall accompanied by typhoons have been gradually increasing over the past few decades (Park et al 2011). Therefore, the northward migration trajectories of these typhoons, and their intensity, are important concerns for North China, Korea, and Japan. To reduce potential damage along the tracks of typhoons in these regions, it is important to understand the critical factors that control them.

Typhoon intensity is related to large-scale atmospheric conditions (e.g. Wang 2009, Hendricks et al 2010, Ge et al 2013), oceanic thermodynamic characteristics (e.g. Emanuel 1986, Yun et al 2012, Gao et al 2016), and the internal dynamics of the typhoon (e.g. Montgomery and Kallenbach 1997, Sikowski et al 2011). Typhoon tracks are mainly determined by steering flow and beta drift (Holland 1983, Chan 2005a, Shan and Yu 2020). The importance of steering flow has been reported in numerous previous studies (e.g. Chan 1985, Archambault et al 2013, Zhao and Wu 2014, Tang and Chan 2016, Zhang et al 2018). The large-scale steering winds regulating typhoon trajectories over the WNP are influenced by the seasonal march and interannual fluctuation of the subtropical high (Liu and Chan 2008), and anomalous atmospheric wave trains.
forced by global climate factors such as the El Niño–Southern Oscillation, Madden-Julian oscillation, and stratospheric quasi-biennial oscillation (e.g. Chan 2005b, Camargo et al 2007, Archambault et al 2015, Kim and Seo 2016). In addition to the dominant role of steering flow, warm sea surface temperature anomalies and eastward increasing sea surface temperature gradients can lead to positive potential vorticity tendencies to the northeast of the typhoon center, inducing the northeastward movement of the typhoon (Yun et al 2012, Choi et al 2013). Moreover, typhoons tend to be attracted by warmer land surfaces owing to moist monsoonal flow (Xu et al 2013). Topographic effects modulate typhoon tracks through the barotropic beta effect of topography (Kuo et al 2001), friction-induced asymmetry in large-scale flows (Wong and Chan 2006, Szeto and Chan 2010), asymmetric horizontal and vertical advection of the potential vorticity, and diabatic heating around mountain regions caused by typhoon cyclonic flow (Tang and Chen 2014, Tang and Chan 2015).

As described above, typhoon tracks are determined by complex physical processes; however, in this study, we focused on the interannual variability of the environmental steering flow near North East Asia. Recent papers (Son et al 2019, 2020) showed that the dynamic effect of the Tibetan Plateau is one of the most dominant physical mechanisms modulating prevailing monsoonal circulation. The lower level westerly wind impinging on the Tibetan Plateau deflects south and north, but higher-level wind uplifts along the mountain slope. The flow uplift increases the air thickness with the anti-cyclonic vortex flow. Once the vortex is formed, the barotropic Rossby wave propagates to the downstream region by conserving potential vorticity. The downstream East Asian region is directly influenced by the stationary Rossby wave train, and the surrounding circulation pattern is modulated by the intensity change and phase shift of Rossby waves. However, the responses of typhoon trajectories to this large-scale dynamic effect forced by upstream zonal wind is not yet understood. Therefore, using the topographically forced stationary Rossby wave theory, we address the effects of anomalous steering flow on typhoon trajectory caused by the interannual fluctuation of upstream zonal wind velocity.

2. Datasets and methods

Data from 1979 to 2019 were extracted from the best track product of the Joint Typhoon Warning Center of the US Naval Pacific Meteorology Oceanography Center in Hawaii (in Guam before 1999) and the fifth generation of the atmospheric reanalysis dataset (Hersbach et al 2020) from the European Center for Medium-Range Weather Forecasts (ERA5). Here we used monthly averaged zonal and meridional winds in ERA5 with horizontal resolution of 2.5° from 850 to 200 hPa. In addition, ETOPO5 5 min gridded elevation data (National Geophysical Data Center 1988) were downloaded from www.ngdc.noaa.gov/mgg/global/etopo5.HTML and interpolated to a 2.5° × 2.5° horizontal resolution for the theoretical prediction of geopotential height.

The dynamic response to orographic forcing can be expressed as the following theoretical solution, derived from the vorticity equation. Through the midlatitude beta plane approximation, and the introduction of Rayleigh friction, the forced topographic wave solution, \( \phi_n \), (Held 1983) is given by:

\[
\phi_n = \frac{f_0^2 h_n}{gH \left(K^2 - K_s^2 - i\nu k^2 / \bar{u} \right)},
\]

where \( \phi_n \) is the geopotential height, \( f_0 \) is the Coriolis parameter, \( h_n \) is the topographical height, \( g \) is gravity, \( H = 8 \) km is the scale height, \( K^2 = k^2 + \ell^2 \) is the total wavenumber where \( k \) is the zonal wavenumber and \( \ell \) is the meridional wavenumber, \( K_s^2 = \beta / \bar{u} \) is the stationary wavenumber, \( i = \sqrt{-1} \), \( r = 1/5 \) d\(^{-1} \) is the inverse of the spin-down time, and \( \bar{u} \) is the zonal wind speed at the higher level measured over the region immediately upstream of the mountain. The forced topographic wave is determined by calculating \( h_n \), using the Fourier transform (Held 1983). As described by Son et al (2020), the geopotential height \( \phi_n \) is only a function of \( \bar{u} \) if \( h_n \) is determined from the topography and \( r \) is fixed.

In addition to this theoretical method, an observational composite analysis was performed using the normalized upstream zonal wind index averaged over 60°E–80°E and 27.5°N–35°N at 200 hPa, to clarify the dynamic effect of the Tibetan Plateau and the role of upstream zonal wind forcing. The composite analysis is performed with strong (\( \geq 0.75 \) standard deviation: STD) and weak upstream westerly wind (\( \leq -0.75 \) STD) years (table 1). To calculated the typhoon track density, the duration of typhoon track within each 10° × 10° grid were counted on June, July, August, and September, respectively (Mei et al 2014). Preliminary results using the smaller grid box were similar to the results in the present study.

3. Results

3.1. Theoretical perspective of the environmental wind structure

The theoretical prediction of geopotential height, forced by zonal wind from 10 to 25 m s\(^{-1} \) at 30°N, showed a peculiar geopotential anomaly pattern in which low–high pressure appears sequentially to the east of the Tibetan Plateau. As shown in figure 1(a), the stronger westerly wind induced the Rossby wave phase to shift eastward and caused vigorous amplitude; in contrast, weaker wind forcing caused a westward phase shift and small amplitude. These
Table 1. Strong and weak upstream westerly wind years in June, July, August, and September. The strong westerly wind years are defined by criteria with wind speed $\geq 0.75$ STD, and weak years are $\leq 0.75$ STD.

|         | Strong westerly wind                          | Weak westerly wind                          |
|---------|-----------------------------------------------|---------------------------------------------|
| June    | 1982, 1983, 1992, 1995, 2009, 2012, 2014,      | 1979, 1980, 1984, 1990, 1991, 1996, 2000,     |
|         | 2016, 2017, 2019                              | 2004, 2013                                  |
| July    | 1979, 1980, 1982, 1983, 1986, 1993, 2003,      | 1981, 1984, 1994, 1995, 2000, 2001, 2004,    |
|         | 2007, 2014                                    | 2010, 2011, 2013, 2017, 2018                |
| August  | 1980, 1986, 1987, 1993, 2001, 2015             | 1984, 1985, 1994, 1995, 2007, 2010, 2012,    |
|         |                                               | 2018                                         |
| September | 1981, 1984, 1986, 1996, 1997, 2009, 2014,    | 1989, 1999, 2000, 2003, 2004, 2005, 2007,    |
|         | 2015, 2017                                    | 2010, 2011, 2012, 2019                      |

Figure 1. Theoretical prediction of geopotential height anomaly at 30°N using 10–25 m s$^{-1}$ zonal wind speed (a). Each geopotential height line in (a) is subtracted by a 3 m s$^{-1}$ larger line in (b). The Eurasian topography used in the theoretical calculation is shown in (c). HGT, height; TOPO, topography.

Characteristics of the stationary Rossby wave, induced by the mechanical effect of the huge mountain (Son et al. 2019), were projected onto the climatological seasonal changes of monsoonal circulation over the downstream areas of the Tibetan Plateau (Son et al. 2020). However, the geopotential height deviation from the climatology caused by this wind forcing anomaly, and its impact on the tracks of tropical cyclones, could not be fully addressed using this theoretical approach.

Geopotential height differences between cases of weak and strong zonal wind forcing can represent the response of the geopotential height anomaly forced by variations in zonal wind speed. In figure 1(b), the geopotential height anomaly difference calculated by weak minus strong westerly wind forcing (wind speed discrepancy between them is 3 m s$^{-1}$) showed the positive geopotential height anomaly around the East Asian region, and the negative anomaly to the east. Interestingly, this sequential high–low zonal pressure pattern was shifted eastward by the strengthening of higher wind speed in the 3 m s$^{-1}$ difference calculation. Here, for example, the higher wind speed was assumed as climatology and 3 m s$^{-1}$ weaker zonal wind speed represented weak wind case. When the climatological mean zonal wind speed was 19 m s$^{-1}$,
the high- and low-pressure anomaly were further eastward than they were at climatological zonal wind speeds of 10 m s\(^{-1}\). In addition, the intensity of the high-pressure anomaly tended to be stronger in instances with strong climatological zonal wind speeds, despite having the same \(-3\) m s\(^{-1}\) anomalous wind forcing.

To illustrate the characteristics of the westerly wind speed impinging on the Tibetan Plateau in the observations, the zonal wind was averaged across the domain (60\(^\circ\)E–80\(^\circ\)E, 27.5\(^\circ\)N–35\(^\circ\)N) at 200 hPa (figure 2). The zonal wind domain selected in this study was slightly different from the original domain at Son et al (2020). The main reason was that a horizontal domain of the westerly wind correlated with the downstream Rossby wave response was not identical between the climatological seasonal cycle and interannual variation. Interannually correlated westerly wind region was confined at immediate upstream region of the Tibetan Plateau (not shown). Over the Tibetan Plateau, the boundary layer was known to reach up to 300 hPa in boreal summer (Chen et al 2013, 2016), therefore the wind is used at 200 hPa. In general, over the mid-latitude, the upper level zonal wind is balanced with the surface meridional temperature gradient by the thermal wind relationship. Therefore, the westerly wind speed was stronger in winter than in summer owing to seasonal changes in the meridional temperature gradient. During July and August, the westerly wind speed was approximately 10 m s\(^{-1}\), the weakest of the year. In June and September, the wind speed was approximately 20 m s\(^{-1}\).

3.2. Tropical cyclone trajectory response to upstream westerly wind forcing
Northern East Asian countries, including north-east China, Korea, and Japan, are mainly affected by typhoons from June to September. Poleward-propagating typhoons passing through 30\(^\circ\)N are important to Northern East Asia (figure 3). These regions are mostly affected by typhoons in August, and the number of typhoons is lowest in June. Typhoon tracks are generally governed by the background horizontal wind distribution or steering flow (Holland 1983, Chan 1985, 2005a). Without any steering wind, such as the anti-cyclonic circulation induced by the WNP subtropical high, typhoons propagate only northwestward by planetary and relative vorticity advection. Therefore, the interannual and decadal variation of the circulation anomaly around the WNP is vital for determining extratropical typhoon trajectories (e.g. Chan 2005b, Kim and Seo 2016, Tang and Chan 2016).

The composite difference of the 850–400 hPa averaged streamfunction (figure 4), between zonal westerly wind index with \(\leq -0.75\) STD and those with \(\geq 0.75\) STD, represents the large-scale circulation anomaly induced by the downstream barotropic Rossby wave response. By weak zonal wind forcing, a high-pressure cyclonic circulation anomaly is formed over 120\(^\circ\)E–140\(^\circ\)E from June to September. In detail, the anti-cyclonic circulation anomaly extends eastward to 150\(^\circ\)E or 160\(^\circ\)E in June and September; moreover, the anti-cyclonic circulation is strong in June and September, while it is weak or marginally statistically significant in July and August. These results are associated with the fact that the climatological zonal wind speed impinging on the Tibetan Plateau is stronger in June and September than in July–August, as shown in figure 2. These overall circulation anomaly features correspond to the theoretical results in figure 1.

In figures 5 and 6, typhoon tracks and track density with weak and strong zonal wind forcing are illustrated in June, July, August, and September. In June, weak westerly wind force pushes the typhoon tracks toward Korea, but strong westerly wind forces
Figure 3. Typhoon tracks passing through 30 °N in June, July, August, and September during 1979–2019. The dots denote the tropical cyclone generation points.

Figure 4. Composite difference of horizontal wind and stream function averaged over 850–400 hPa using a ±0.75 standard deviation of zonal wind index (weak minus strong westerly wind years) for June, July, August, and September. Black arrows, and dots over shading show statistically 95% significant signal.

The typhoon tracks toward Japan. Here, the anomalous westward movement of the typhoon is related to the anti-cyclonic circulation anomaly at approximately 130 °E and 30 °N, as shown in figure 4(a).

The southeasterly wind anomaly over the southwest of the anti-cyclonic circulation works as an anomalous steering flow, inducing the westward shift of the typhoon trajectories. In July, the anti-cyclonic
circulation over North East Asia has weak statistical significance. Instead, the formation of cyclonic circulation was evident to the east at 150°E–160°E (figure 4(b)). Because of this cyclonic circulation, the far eastern typhoon track density was increased (figure 6(b)), and therefore, the mean trajectory moved eastward in response to weak wind forcing (figure 5). However, there were no significant differences in the typhoon tracks affecting Northeast Asia between those with positive and negative wind anomaly forcing. In August, weak zonal wind forcing and the anti-cyclonic circulation at 135°E with the associated southeasterly wind anomaly induced significant westward shift of the typhoon tracks. In contrast, under the strong westerly wind forcing, the typhoon tracks were not shown over northeastern China and Korea. In September, the anti-cyclonic circulation anomaly formed over 130°E–150°E, and the typhoon tracks tend to be confined in 125°E–135°E along the western flank of the anti-cyclonic anomaly (figures 5 and 6(d)). Meanwhile, the mean typhoon track was shifted westward by negative zonal wind anomaly forcing, and the discrepancy between the weak and strong wind forced typhoon tracks was approximately 10° in the zonal direction.

Figure 5. Typhoon tracks sorted by zonal wind index. (a) Weak westerly wind, and (b) strong westerly wind cases are shown in June, July, August, and September. Black line is the mean tropical cyclone track for each map. Dots denote the generation points of the tropical cyclone.
4. Summary and discussion

The average WNP typhoon track tends to shift westward owing to weak upstream westerly wind and downstream anti-cyclonic circulation anomaly, which is influenced by the zonal phase shift of the topographically forced stationary barotropic Rossby wave. The westerly wind impinging on the Tibetan Plateau acts on the forcing of the downstream Rossby waves, and therefore, the interannual variation of the westerly wind velocity can cause circulation anomalies over North East Asia. Owing to the westerly wind forcing anomaly, a high-pressure anomaly occurred in the right-hand downstream region in the theoretical model. Corresponding with the theoretical results, in the observational analysis, the formation of anti-cyclonic circulation anomalies and the subsequent changes in the typhoon tracks were statistically significant in June, August and September; however, the typhoon track shifts were relatively vague in July. In July and August, the downstream Rossby wave response can be weak due to the relatively weak climatological zonal wind velocity. The westerly wind speed in the climatology data was approximately 20 m s$^{-1}$ in June and September, but approximately 10 m s$^{-1}$ in July–August.

Under global warming, a future weakening of the meridional temperature gradient is expected over the subtropical or mid-latitudes. If this occurs, typhoon trajectories are more likely to be directed toward China and Korea than toward Japan. Therefore, it is necessary to carefully monitor the upstream zonal wind speed impinging on the Tibetan Plateau to predict and understand future typhoon activity. It is worth noting that the formation of the anti-cyclonic circulation anomaly in North East Asia is important for the westward shift of typhoon tracks; however, not every circulation anomaly over this region in the monthly dataset indicates environmental steering flow causing typhoon track changes. The frequent migration of intense typhoons to the mid-latitudes can be projected onto the monthly field as cyclonic circulation; therefore, the sources of anomalous pressure events should be carefully analyzed when using the monthly averaged dataset.

As concluding remarks, the typhoon trajectories seem to change linearly influenced by the upstream westerly wind speed and the circulation anomaly around East Asia. However, the typhoon tracks and surrounding steering winds are modulated by various climate factors such as continental diabatic heating, oceanic thermodynamical conditions, and other effects of Asian huge mountains (e.g. Chou et al, Abe et al 2003, Kitoh 2004, Wu et al 2007, Molnar et al 2010, Chen and Bordoni 2014, Chiang et al 2015, 2017); therefore, a further in-depth study using the dynamical model is needed to clarify the dominant dynamical process.
Data availability statement

All data that support the findings of this study are included within the article. Original datasets used in this study are publicly available. The data can be obtained from the ECMWF and NCEP-NCAR websites, and the Naval Oceanography Portal.

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Conflict of interest

The authors declare no competing interests.

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Author contributions

J S, J K, K H conceptualized the paper. J S undertook the analysis. All authors contributed to the analysis and writing of the paper.

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