Modulation of winter precipitation associated with tropical cyclone of the western North Pacific by the stratospheric Quasi-Biennial oscillation

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Abstract
Tropical cyclone precipitation (TCP) has increasing impacts on many coastal regions under global warming. Causes of TCP variation have been principally explored in the troposphere. This study identifies the significant modulation of the stratosphere Quasi-Biennial oscillation (QBO) on the winter TCP in the coastal regions of the western North Pacific (WNP). In the westerly QBO winter, the zonal wind vertical shear anomalies in the stratosphere strengthen (weaken) convective activities around the East China Sea (the Philippines) and cause middle-level easterly (westerly) anomalies of the middle (low) latitudes in the troposphere, leading to more (less) TC activities around the East China Sea (the Philippines). Consequently, a TCP dipole pattern can be observed. The TCP increases in East China, Korean peninsula, Japan and Russian Far East, but decreases in Indo–China Peninsula, South China and the Philippines. These results not only improve the knowledge of QBO-TCP relationship but also provide a potential indicator for the seasonal prediction of the TCP in the coastal regions of the WNP due to the high predictability of the QBO.

1. Introduction
Precipitation associated with tropical cyclone (TC) is an important component of total rainfall in many coastal regions (e.g. Englehart and Douglas 2001, Ren et al 2006). Over the west coast of the tropical Pacific, TC precipitation (TCP) occurs very frequently so as to cause enormous flood disasters. In the Philippines, the contribution of TC to rainfall increases 29.8% in summer while decreases 27.9% in fall during El Niño developing years from the mean contribution (Lyon and Camargo 2009). In China, TCP plays an important role in the trends of extreme rainfall (Chang et al 2012, Chen et al 2012). TCP can account for about 20%–40% of the total precipitation during summer in southeast China (Li and Zhou 2013). Besides, there are inverse variations between TCP and monsoon precipitation in Taiwan, which is caused by the difference of circulation anomalies regulating TC activity and moisture transport (Chen et al 2010, Chen and Chen 2011).

TCP variation can be attributed to some dynamical and thermodynamical conditions, which greatly influence TC activity that is closely related to TC genesis and track. TC genesis is principally decided by environmental fields such as low-level relative vorticity and sea surface temperature (SST) (Gray 1979, Emanuel 2003, Li and Zhou 2014). TC track is largely modulated by large-scale steering flow (Ho et al 2004, Choi et al 2016). These conditions are significantly adjusted by many factors, such as the El Niño–Southern Oscillation (ENSO), the Pacific–Japan teleconnection pattern, Japan–South China Sea wave patterns, and intraseasonal oscillations (Kim et al 2012, Li et al 2012, Feng et al 2013, Li and Zhou 2013a, 2013b, Ko and Liu 2016).

It is worth noting that more studies investigated factors in the troposphere that impact the TCP variations, but not those in the stratosphere. The stratospheric Quasi-Biennial oscillation (QBO) not only influences stratospheric dynamics globally but also can modulate the troposphere (Barnston and
Livezey 1989). Previous studies has surveyed the linkage between the QBO and TC activity in Pacific, Atlantic and Indian Ocean (e.g. Jury 1993, Chan 1995, Whitney and Hobgood 1997, Balachandran and Guhathakurta 1999, Ho et al 2009, Camargo and Sobel 2010). Although the influence of the QBO on TC genesis and track has been addressed, the influence of the QBO on TCP has received less attention, especially on a seasonal scale. In this study, we attempt to explore the modulation of the QBO on the TCP in the coastal regions of the western North Pacific (WNP) and its physical process with a specific focus on boreal winter, when the TCP shows the significant response to the QBO.

2. Data and methodology

The 3-hourly TC dataset from the International Best Tracks Archive for Climate Stewardship (IBTrACS) project (Knapp et al 2010) combines information from numerous TC datasets and has been used widely to survey the WNP TC activities from 1979 to 2015. During the same period, TCP characteristics are depicted by the gridded data (0.5° × 0.5°) from Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation of the water resources project (Yatagai et al 2012). In order to avoid missing data and be compatible with the period of above-mentioned data, 10,534 grids are selected during 1979–2015. The monthly ERA-Interim data (2.5° × 2.5° horizontal resolution) from the European Centre for Medium-Range Weather Forecasts (Dee et al 2011) is used to calculate the QBO index and investigate large-scale circulation changes. The monthly mean of the SST dataset from Met Office Hadley Centre (Rayner et al 2003) is used to calculate the Niño-3.4 index, which is a SSTA (derived from the 1981–2010 SST climatology) averaged over the Niño-3.4 region (120°–170° W, 5° S–5° N). The outgoing longwave radiation (OLR) data is from the National Oceanic and Atmospheric Administration (Liebmann and Smith 1996).

TC-related precipitation is often measured by the recorded precipitation within a circular region of different radius from the TC center (e.g. Jiang et al 2008, Lau et al 2008, Chen et al 2012, Dare et al 2012). According to the mean rainfall distribution at different distances from the TC center, the influence of a TC might be limited to the radius in the range of 800–1000 km (Kubota and Wang 2009, Li and Zhou 2015). Following Wang et al (2020), 8° (approximately 888 km) is selected as the effective radius of the circular region on the globe surface influenced by a TC. As shown in figure 1, the TCP of a grid in a day is defined as the daily precipitation in the grid which falls into the effective radius of a TC. The QBO is characterized by significant intrinsic nonlinearity and asymmetric vertical structure, leading to various definitions of the phases of the QBO. Some studies divide the westerly and easterly phases of the QBO according to the zonal wind anomaly at a particular level (e.g. 30, 50, or 70 hPa) or the average among different levels (Holton and Tan 1980, Gray 1984, Liess and Geller 2012, Inoue and Takahashi 2013, Watson and Gray 2014). Others are according to the vertical shear of zonal wind. The shear facilitates comparison of variable fields such as zonal wind and geopotential height (Huesmann and Hitchman 2001), and has dynamic meaning because it is an important term in both the mean zonal momentum equation and the thermal wind equation (Lindzen and Holton 1968). Aiming at different targets, previous studies
isolate the QBO phases based on the various QBO indices such as the 50–70 hPa and 10–70 hPa zonal wind shear (Fadnavis et al. 2014, Xue et al. 2015). To identify the modulation of the TCP by the QBO, we propose a QBO index to isolate the QBO phases. The QBO index is measured by the difference between the boreal winter tropical-mean (10° S–10° N) zonal wind at 30 hPa and that at 70 hPa. The winter is regarded as the westerly (easterly) phase winter if the anomaly of the QBO index is positive (negative). Based on these criteria, 18 out of 37 winters are selected as the QBO westerly phase winters and 19 as the QBO easterly phase winters. This study defines winter from October to December, because not only boreal winter can be observed in October (Zhuang et al. 2018) and has been defined beginning with October (e.g. Wang et al. 2018), but also the number of TC genesis over the WNP is merely about 0.9 from January to February according to the statistics during the period 1979–2015. The regression and composite analyses are performed to reveal the changes of environmental fields associated with the QBO phases.

3. Results

3.1. The distribution of the winter TCP in coastal regions of the WNP corresponding to the QBO

Figure 2(a) shows the difference of the spatial distribution of the winter TCP between the westerly phase of the QBO (WQBO) and easterly phase of the QBO (EQBO). Apparently, the difference shows a dipole pattern. The TCP increases in East China, Korea, Japan and Russian Far East, which is denoted by the northern region (NR; 25°–55° N, 115°–145° E). On the contrary, the TCP decreases in South China, Vietnam, Laos, Cambodia and the Philippines, which is denoted by the southern region (SR; 5°–25° N, 100°–130° E). In particular, the TCP in central Philippines is reduced by 100 mm at least. Although small increased TCP in the SR and decreased TCP in the NR are also observed, the reversed situation of the TCP in coastal regions of the WNP is meridionally obvious. Furthermore, in the cases of the TCP calculated via different radius from the TC center, the dipole pattern is still recognizable albeit with changes in the TCP amount.

Previous studies suggested the possible connection between the QBO and ENSO (e.g. Xue et al. 2015, Nishimoto and Yoden 2017). During the period 1979–2015, some strong El Niño and La Niña events exist in the QBO phases. Given that ENSO events play an important role in TC activity (e.g. Chan 2000, Camargo et al. 2007, Wang et al. 2020), one may argue that the variation of the TCP may be dominated by ENSO events. To survey this possibility, we remove ENSO signals in the TCP during the QBO winters by the linear regression of the TCP with respect to the Niño-3.4 index for 1979–2015. The TCP removing ENSO signals (TCP_r) is computed based on the following formula:

$$TCP_r = TCP - (ax + b)$$

where $a$ is the regression coefficient of the TCP with respect to the Niño-3.4 index, $x$ is the Niño-3.4 index, $b$ is the regression intercept of the TCP with respect to the Niño-3.4 index.

Figure 2(b) shows the result removing ENSO signals. A meridional TCP pattern is still recognizable although with changes in the amplitude. Therefore, the TCP change modulated by the QBO is not strongly influenced by ENSO.

Table 1 shows amounts of the TCP in different QBO phases. In the WQBO, the amount of the TCP in the NR accounts for 30.9% of that in the SR.
Figure 3. Difference of the WQBO minus the EQBO for latitude-pressure cross section of averaged (110°E–180°E) (a) vertical velocity (10^{-2} Pa s^{-1}), and (b) zonal wind (m s^{-1}) in winter (OND) during 1979–2015. Contour denotes regions where the differences are significant at the 90% confidence level according to the student’s t test.

### Table 1

The annual mean of the QBO index and annual sum of the TCP in the different QBO phases from October to December during 1979–2015.

| QBO index | TCP in NR (mm) | TCP in SR (mm) |
|-----------|----------------|----------------|
| WQBO 4.6  | 2.1 × 10^4     | 6.8 × 10^4     |
| EQBO −19.7| 1.4 × 10^4     | 9.6 × 10^4     |

In the EQBO, the amount of the TCP in the NR only accounts for 14.6% of that in the SR. Both the WQBO and the EQBO winters show obvious meridional difference of the TCP amount. Compared with the EQBO winter, more TCP appears in the NR while less TCP in the SR in the WQBO winter. The TCP in the WQBO winter is 1.5 times that in the EQBO winter in the NR, and the TCP in the WQBO winter is 0.7 times that in the EQBO winter in the SR. This TCP distribution feature causes a obvious meridional dipole pattern between the WQBO and the EQBO winters (figure 2(a)). Besides, the TCP sum of NR and SR in the WQBO accounts for 80.9% of that in the EQBO.

### 3.2. Possible physical process

The vertical shear of zonal wind in the stratosphere over the equator induces a meridional circulation anomaly between the stratosphere and the tropopause, modulating upper-tropospheric wind in the tropics (Plumb and Bell 1982, Huesmann and Hitchman 2001). These may adjust convective activities via producing vertical motion anomaly and horizontal wind shear anomaly in the tropical troposphere (Collimore et al 2003). These anomalies can significantly influence TC activities. To examine the effect of the QBO measured by the zonal wind vertical shear on the TCP, the seasonal mean flow over the WNP corresponding to the different QBO phases is compared. Figure 3 shows differences of vertical structures of vertical motion and zonal wind between the WQBO and the EQBO. In the WQBO, descent motion can be observed from the stratosphere to the troposphere over tropics, while ascent motion around 40° N. Meanwhile, westerly anomalies appear from the stratosphere to the troposphere over the low latitudes (around 15° N), while easterly anomalies over the middle latitudes (30°–45° N). These features imply that anomalous horizontal wind shear and anomalous vertical motion exist over the WNP. As shown in figure 4(a), lower-level anticyclonic shear anomalies can be observed around the Philippines and northern Japan, while lower-level cyclonic shear anomalies over the East China Sea and the southeastern WNP. These lower-level circulation anomalies induce lower-level relative vorticity anomalies. There are evident positive relative vorticity anomalies over the southeastern WNP and regions around Japan and Kalimantan Island. Negative relative vorticity anomalies appear over regions around the Philippines. Corresponding to these lower-level circulation anomalies, apparent negative (positive) OLR anomalies can be observed over the southeastern WNP and regions around the Philippines. However, positive (negative) relative humidity anomalies can be observed over the southeastern WNP and regions around the East China Sea (regions around the Philippines), as shown in figure 4(b). Meanwhile, positive (negative) relative humidity anomalies can be observed over the southeastern WNP and regions around the East China Sea (regions around the Philippines). These dynamic and thermodynamic conditions are favorable (unfavorable) for TC genesis over the southeastern WNP and regions around the East China Sea (regions around the Philippines).

Moreover, middle-level easterly anomalies sweep from the WNP to East Asia in the latitudes (30°–40° N), while westerly anomalies go from the South China Sea to the northern Philippines (figure 4(c)). These facilitate to steer TC to Japan,
Korea and Northeast China, and to suppress TC to the Philippines, South China and Indo–China Peninsula. As demonstrated in figure 4(c), TC frequency shows remarkable negative anomalies from the South China Sea to the east of the Philippines. These are unfavorable for the TCP in the regions around the South China Sea. In contrast, the positive anomalies of TC frequency are observed from Taiwan to Japan, being favorable for the TCP in the regions around the East China Sea.

The above-mentioned features indicate a possible physical process of the influence of the QBO on the TCP in coastal regions of the WNP. The zonal wind vertical shear anomalies in the stratosphere induce horizontal wind shear anomalies and vertical motion anomalies from the stratosphere to the troposphere over the WNP, leading to atmospheric circulation anomalies in the troposphere in situ. In the WQBO, the westerly anomaly prevails in the troposphere in the low latitudes of the WNP, while the easterly anomaly in the middle latitudes. This wind shear causes circulation anomalies over the WNP. Around the East China Sea, there are lower-tropospheric cyclonic shear and positive relative vorticity anomalies which induce anomalous convective activities with increasing relative humidity. Around the Philippines, there are reverse situations. These dynamic and thermodynamic conditions are favorable (unfavorable) for TC genesis around the East China Sea (the Philippines). Moreover, steering flows are westerly in the low latitudes and easterly in the middle latitudes over the WNP, which is favorable (unfavorable) for TC moving to the north (south) regions to Taiwan. As a result, a dipole pattern of the TCP in coastal regions of the WNP is observed.

Data availability statement

The data that support the findings of this study are all openly available on the websites. The TC data are available at https://www.ncdc.noaa.gov/ibtracs/index.php?name=ib-v4-access; the precipitation data are available at http://aphrodite.st.hirosaki-u.ac.jp/products.html; the ERA-Interim data are available at https://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=pl/; the SST data are available at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html; and the OLR data...
are available at (https://psl.noaa.gov/data/gridded/data.interp_OLR.html).

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