

Interdecadal variation of tropical cyclone genesis and its relationship to the convective activities over the central Pacific

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Received: 31 October 2016 / Accepted: 20 April 2017 / Published online: 24 April 2017
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Abstract Using the outgoing longwave radiation (OLR) data from the National Oceanic and Atmospheric Administration archives, this paper analyzes the interdecadal variation of convective activities over the central Pacific (CP) from July to October of 1979–2013 and its impact on tropical cyclone (TC) genesis in the western North Pacific (WNP). Concurrent with the interdecadal decrease of TC genesis, the tropical convection underwent a significant interdecadal change in the late 1990s. Overall, the first leading empirical orthogonal function mode of the tropical OLR during July–October turned from a zonal dipole pattern during 1979–1997 to a tripole pattern during 1998–2013. Concomitant to this change, the boreal part of the Walker circulation shrank westward, with its downdraft branch located over the CP. The downward motion anomalies over the CP increased after the late 1990s, as did the trade easterlies. Consistent with the CP convective activity anomalies, the negative low-level relative vorticity anomalies and upper-level divergence anomalies, positive vertical wind shear anomalies and anomalous abundant water vapor can be observed over the southeastern part of the WNP. Additionally, the tropical depression (TD)-type waves associated with the CP convective activities are significantly different before and after the late 1990s. Before the late 1990s, the off-equatorial TD-type waves could be distinctly observed, with clear transitions located along the WNP monsoon trough. However, these transitions were vague after the late 1990s. Therefore, the convective activities

over the CP may have played an important role in affecting the interdecadal change of TC genesis by affecting the genesis of TD-type waves.

Keywords Tropical cyclone genesis · Interdecadal variation · Convective activities · Central Pacific.

1 Introduction

The interdecadal changes of the Pacific have been an important scientific topic, thought to be carrying profound climatological implications. In the last century, the Pacific has gone through several significant interdecadal shifts, including the 1920s, 1940s and 1970s (Wang 1995; Zhang et al. 1997; Chao et al. 2000). During these relatively short periods, the Pacific thermal states shifted from one relative stable state to another. Meanwhile, the regional climate shifted to a different climatic state (Chang et al. 2000; Yun et al. 2010; Zhang et al. 2016, 2017). Affected by the interdecadal changes of Pacific thermal states, tropical cyclone (TC) activities over the western North Pacific (WNP) would shift between active and inactive periods accordingly (Chan and Shi 1996; Yumoto and Matsuura 2001; Matsuura et al. 2003; Chan 2005; Hong et al. 2016).

Recent studies suggested that the Pacific underwent another regime shift in the late 1990s (McPhaden et al. 2011; Xiang et al. 2013). It was found that a significant cooling (warming) took place over the tropical eastern (western) Pacific and the major pattern of Pacific sea surface temperature had turned to the central Pacific (CP) El Niño type in the later period (Chung and Li 2013). Accompanying this regime shift, studies conducted on TC showed that their activities entered an inactive period, with less TCs generated over the western North Pacific (WNP) (Liu

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and Chan 2008; Kubota and Chan 2009). In addition, the TC paths showed a northwestern shift in the latter period (Tu et al. 2009; Yokoi and Takayabu 2013).

Previous studies have devoted significant effort to reveal the causes of the interdecadal shift of WNP TC activity in the late 1990s. Liu and Chan (2013) reported that the interdecadal decrease of TC activity was related to the larger vertical wind shear and stronger subtropical high in the eastern part of the tropical WNP in the latter period. He et al. (2015) showed a decrease (increase) of TC genesis to the south (north) of 20°N and ascribed the north–south interdecadal changes in TC activity to the decadal change in tropical Indo-Pacific sea surface temperature. Huangfu et al. (2016) showed that the spatial distribution of the interdecadal decrease of the WNP TC genesis ran northwest-southeast and attributed it to the monsoon trough (MT). All of these studies noticed that the most noticeable decrease in the overall TC activities was located in the southeastern part of the WNP, which may be connected to the systematic interdecadal changes of the CP areas.

In the last few decades, convectively coupled tropical depression (TD) type waves, also known as easterly waves, have been proved to be highly connected to TC genesis in the Pacific from the synoptic-scale and climatological perspectives (Frank and Roundy 2006; Kiladis et al. 2009). TD-type waves can provide seedlings of initial disturbances for tropical cyclone genesis (Chen and Chou 2014). Hence, we may find some clues for the interdecadal changes of the TC genesis from TD-type waves. Previous works have documented that one important way to initiate TD-type waves is the transition from MRG waves as they propagate northwestward (Takayabu and Nitta 1993). The transitions are most observed over the CP (Kiladis et al. 2009; Wu et al. 2014). Hence, the convective activities over the CP may have played an important role in affecting the generation of the convectively coupled TD-type waves, which may have contributed to the interdecadal decrease of TC activity.

Thus, the convective activities over the CP are key climate variables, which may play an important role in linking Pacific thermal state and atmospheric circulation anomalies to the interdecadal variation of the WNP TC genesis. It's important to investigate the interdecadal changes of the CP convective activities, the related atmospheric circulation, environmental factors and the convectively coupled TD-type waves, which may help reveal the dynamic process of the interdecadal decrease in TC activity in the late 1990s. This paper is organized as follows. The datasets and methodologies are described in Sect. 2. The interdecadal changes to the CP convection are presented in Sect. 3. Section 4 analyzes the atmospheric circulation anomalies associated with the convective activities over the CP. Section 5 investigates the role of the CP convection in the transition of TD-type waves and the interdecadal changes of its eddy

kinetic energy (EKE). Finally, a summary of the results and possible future work are presented in Sect. 6.

2 Datasets and methodologies

2.1 Datasets

The TC best track data obtained from the International Best Tracks Archive for Climate Stewardship project (Knapp et al. 2010) for the years 1979–2013 are used for analyzing the TC genesis frequency. Relative humidity, monthly winds and geopotential height are extracted from the European Centre for Medium-Range Weather Forecasts Interim (ERA-Interim) Reanalysis dataset (Simmons et al. 2007). In addition, the daily and monthly mean outgoing long-wave radiation (OLR) data with $2.5^\circ \times 2.5^\circ$ resolution are employed and obtained from the National Oceanic and Atmospheric Administration archives (Liebmann 1996), which is considered a good proxy for tropical deep convective activities.

2.2 Methodologies

The peak season of TCs over the WNP starts in July and ends after October (He et al. 2015). Therefore, this study would focus on the July–October as the studied period during 1979–2013. The Lepage test and Moving *t* test are employed as the long-term change detection method (Lepage 1971; Liu et al. 2011), using a 11-year window. Additionally, this study employs the empirical orthogonal function (EOF) method to extract the dominant spatial patterns of the tropical Pacific. Next, a regression analysis is used to reveal the atmospheric circulation anomalies associated with the convective activities over the CP. Finally, a two-tailed Student's *t* test is used to estimate the statistical significance of the regressed fields.

One of major ways TD-type waves develop is through the transition of MRG waves. Using a Butterworth filter, OLR and 850 hPa horizontal wind fields were filtered to extract a 3–6-day cutoff period to isolate the tropical disturbance of interest, including both the TD-type waves and the MRG waves. This method is always used to analyze as an illustration of the MRG-to-TD transition process (e.g., Feng et al. 2016). The regression analysis was performed to examine the transition of MRG waves to TD-type waves under different states of the CP convection. In addition, the zonal space–time spectral analysis and filtering method (Wheeler and Kiladis 1999) is employed on the OLR data to determine the distribution of power in the wavenumber–frequency domain associated with zonally propagating convectively coupled equatorial waves. This method has been successfully applied on the OLR dataset in previous

studies (Kiladis et al. 2009; Huang and Huang 2011). Figure 1 shows the resulting wavenumber-frequency spectrum, including all wave bands, from July to October for the period of 1979–2013. The filter captures the major peaks of the convectively coupled equatorial waves, including the mixed Rossby-gravity (MRG) waves, TD-type waves, Kelvin waves and $n=1$ equatorial Rossby waves. The most prominent higher frequency westward-propagating waves

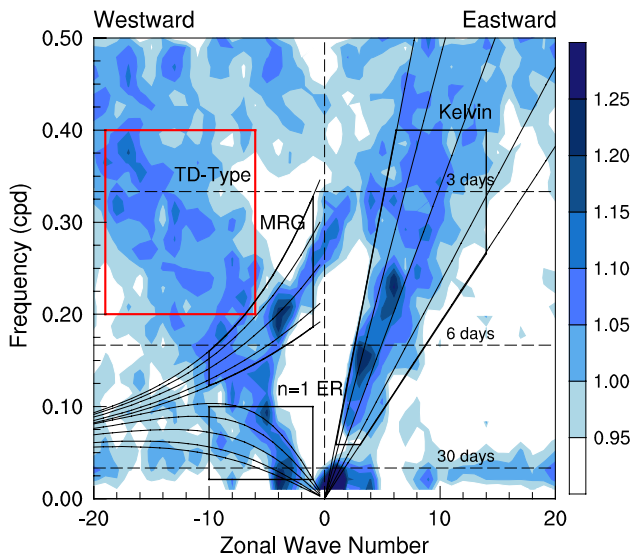


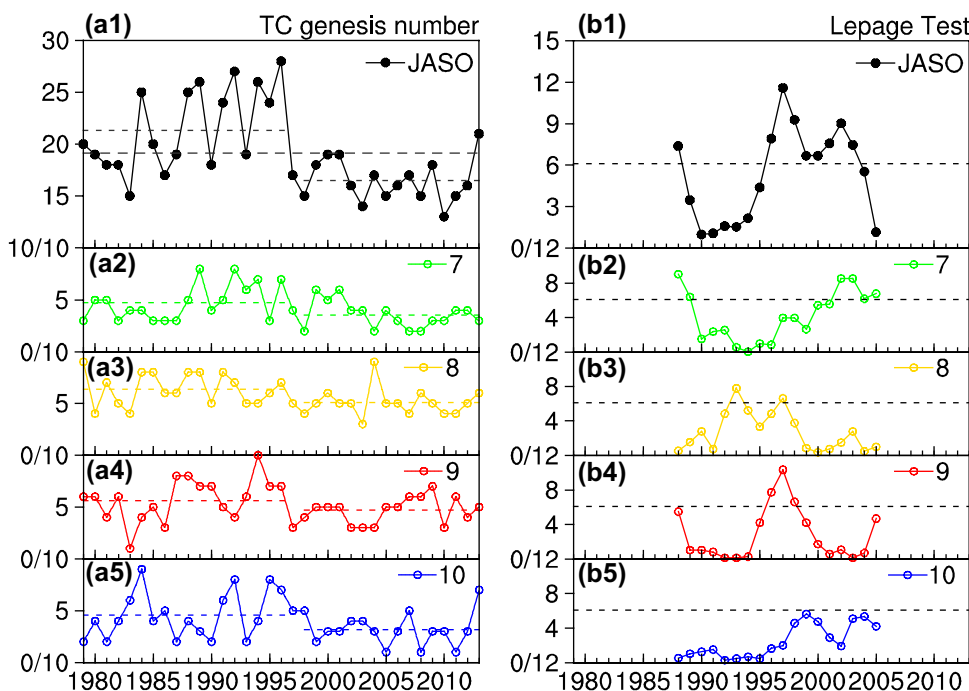
Fig. 1 Wavenumber-frequency spectrum of the OLR over the Northern Hemisphere during JASO from 1979 to 2013. The filter band for TD-type wave is indicated by the thick red box

are MRG and TD-type waves. TD-type waves can be separated from MRG waves with this method because TD-type waves have the relatively larger zonal wave number and higher frequency. In the present study, the wavenumber-frequency band of TD-type waves are determined over a period of 2.5–5 days, with negative zonal wave numbers ranging from -6 to -19 , and with equivalent heights of 8–90 m. This spectrum can separate TD-type waves from both MRG and the westward inertia-gravity waves (Feng et al. 2016). The MRG waves are filtered with a period of 3–10 days, the zonal wave numbers of -1 to -10 and the equivalent heights of 8–90 m. The vertical wind shear in this study (followed Feng et al. 2014) is defined as the difference between the 200 and 850 hPa zonal and meridional winds, and can be expressed using the equation $\sqrt{(u_{850hPa} - u_{200hPa})^2 + (v_{850hPa} - v_{200hPa})^2}$, where (u, v) are the horizontal zonal winds and meridional winds, respectively. In some cases, the contribution of the meridional winds cannot be neglected. Therefore, the above measurement is adopted.

3 The interdecadal variation of tropical cyclone genesis and its relationship to the convective activities over the CP

Based on the 1979–2013 data, the interannual variations of the WNP TC genesis numbers during JASO are analyzed (Fig. 2). Approximately 19 TCs are generated annually

Fig. 2 Time series of TC genesis numbers over the WNP (0° – 30° N, 120° E– 180° E) from 1979 to 2013 during (a1) JASO (black line), (a2) July (green line), (a3) August (yellow line), (a4) September (red line) and (a5) October (blue line), with its average values for the two epochs: 1979–1997 and 1998–2013 (the horizontal dashed line) and for 1979–2013 during JASO (the horizontal dashed thin line in a1); Lepage tests of the WNP TC genesis number during (b1) JASO (black line), (b2) July (green line), (b3) August (yellow line), (b4) September (red line) and (b5) October (blue line). The horizontal dashed line represents significance at the 5% level



during the peak season in the period of study (Fig. 2a1). The time series of the WNP TC genesis numbers shows an interdecadal change in the late 1990s, with the significant decrease in WNP TC genesis numbers after the 1990s. Furthermore, the interdecadal changes of the WNP TC genesis numbers are analyzed from July to October (Fig. 2a2–a5). As shown by the horizontal dashed lines in Fig. 2a2–a5, the comparisons of two periods (1979–1997 and 1998–2013) month by month reveal that the interdecadal changes are rather consistent in each month, and there are fewer TCs generated after the late 1990s. The most active months during TC peak season are August and September. Our analysis indicates that the contributions of each month are comparable across years.

Employing a 9-year test window, Fig. 2b1 shows the Lepage test results of the time series of the WNP TC genesis numbers during the TC peak season, with a significant interdecadal change during the late 1990s, under the 5% significance. The interdecadal shift point occurred around 1997/1998, is consistent with the recent regime shift of the equatorial Pacific (Xiang et al. 2013), and has been reported in Liu and Chan (2013). Here we detected the long-term variations of the TC genesis numbers during JASO with the Lepage test (Fig. 2b2–b5). The results suggest that the interdecadal shift around 1997/1998 can be mainly attributed to the interdecadal change in August and October, with some change detected in September during this period. Hence, our analysis used 1997/1998 as the turning point of the interdecadal shift of the late 1990s.

As mentioned above, the interdecadal change of the tropical convective activities might play an important role in linking the oceanic thermal state to WNP TC genesis. The present study employs the EOF to extract the dominant spatial pattern of the tropical convection over the Pacific for the period of 1979–2013. The first leading EOF mode of the monthly OLR during July–October is presented in Fig. 3a. The EOF1 pattern captures a spatial distribution with a zonal dipole pattern. This mode explains about 42.5% of the tropical Pacific OLR variability. The western and central tropical Pacific OLR anomalies have loadings of the opposite sign. The magnitudes of the loadings are comparable, while the eastern part covers a broader area over the tropical Pacific, with its center located around the tropical CP. The PC1 time series is shown in Fig. 3b. It's noticed that the interannual change of the PC1 variability exhibited an interdecadal change in the late 1990s, with more positive phases found in the latter period. This means that the convective activity anomalies over the CP would become less active after the late 1990s. Additionally, the Lepage test is applied to the PC1 time series to examine its long-term change (Fig. 3c). The result shows that the PC1 time series experienced a significant interdecadal change around the 1997/1998. To further verify this interdecadal

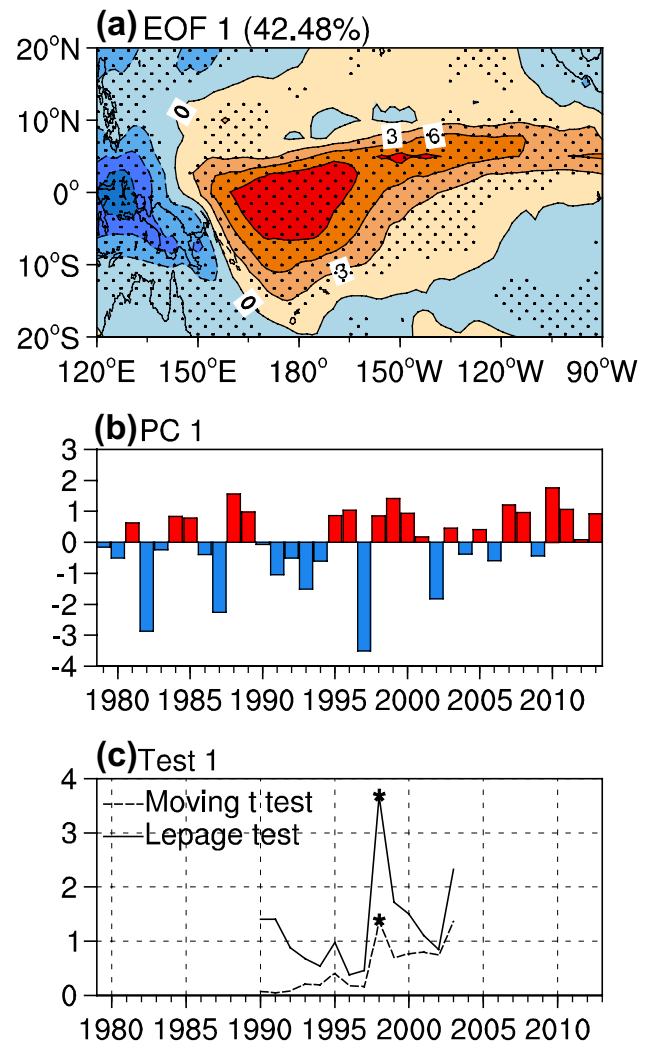


Fig. 3 **a** The first leading EOF mode of OLR (unit: Wm^{-2}) during JASO based on the period of 1979–2013. Stippling denotes significant anomalies significantly at the 90% confidence level, according to Student's *t* test. **b** Time series of PC1 (bars). **c** Lepage and moving *t* tests of the PC1. The asterisks represent tests exceed significance at the 90% confidence level

change point, the moving *t* test is applied to this PC1 time series. The significant interdecadal variation signal around 1997/1998 can also be detected, indicating that this changing point is robust. This interdecadal shift point is consistent with that of the Pacific thermal state (Xiang et al. 2013).

Moreover, the EOF method was applied to the two periods before and after the late 1990s to examine the changes of the dominant spatial patterns. As shown in Fig. 4a, the EOF1 pattern captures a spatial distribution with a zonal dipole pattern. This mode explains approximately 38.9% of the tropical Pacific OLR variability for the period of 1979–1997. The western and central tropical Pacific OLR anomalies have similar distribution as the finding in Fig. 3a, but shown as its opposite phase. However, the magnitude

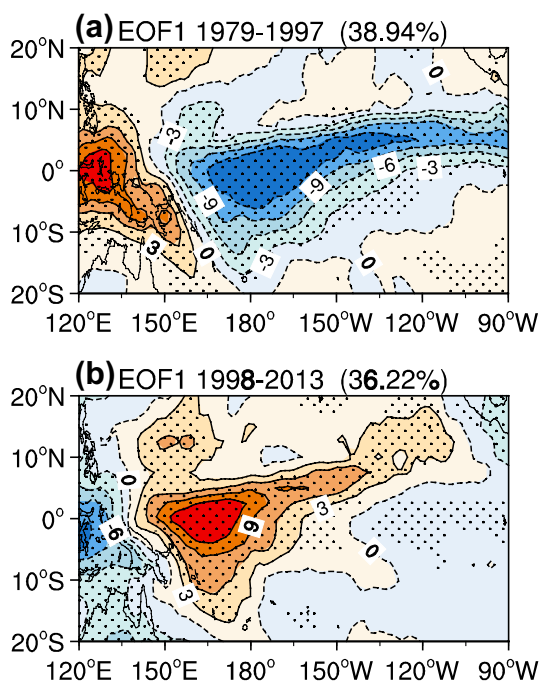


Fig. 4 The first leading EOF mode of OLR (unit: Wm^{-2}) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013. Stippling denotes significant anomalies significantly at the 90% confidence level, according to Student's t test

of the loadings in Fig. 4a are larger in both central and eastern tropical Pacific. Oddly enough, we found that the EOF1 pattern of 1998–2013 shifts westward significantly and explains 36.2% of the OLR variability. Accompanied by the westward shift of the positive anomalies areas, the tropical Pacific exhibits a zonal tripole pattern. Both eastern and western tropical Pacific OLR anomalies have loadings of the same sign, while those of the CP are opposite. Yet, the magnitudes of the loadings in the central and western Pacific are comparable, while the eastern part shows much weaker signals. It is reasonable to expect that these two patterns represent different modes of climate variability. Therefore, it's meaningful to investigate the influence of the convective activities on the interdecadal variation of tropical cyclone genesis.

4 Atmospheric circulation anomalies associated with the convective activities over the CP

As mentioned above, the convective activities over the CP shifted to a more weakened state in the late 1990s. Additionally, the leading mode of the tropical convection has turned to a zonal tripole pattern, with the inactive convection over the eastern Pacific shifted to the CP. The results indicate that the strength of the CP convection is

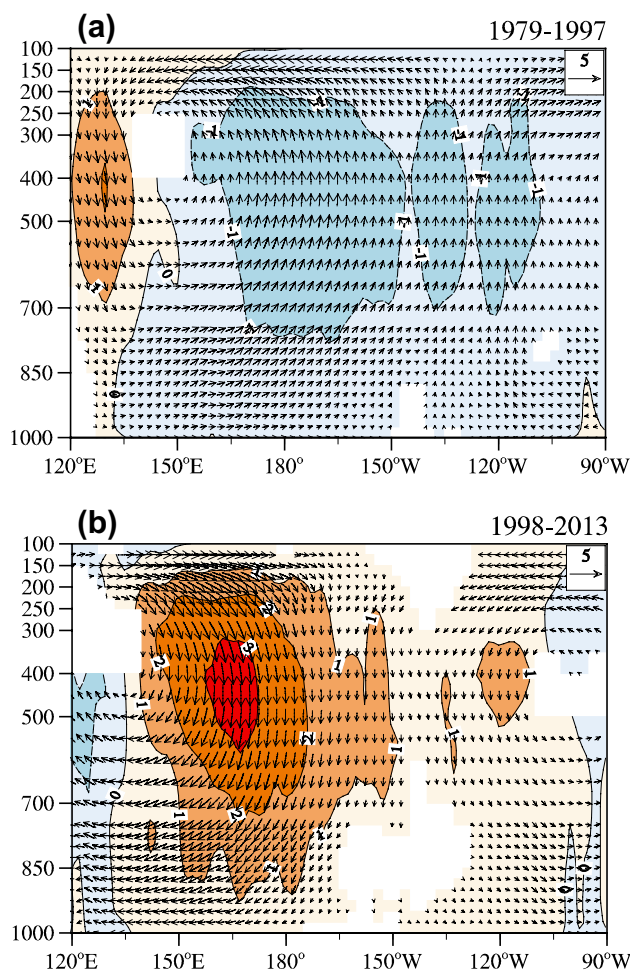


Fig. 5 Anomalies of zonal and vertical velocity (vector, units are m s^{-1} for u and $5 \times 10^{-3} \text{ Pa s}^{-1}$ for ω) averaged between 0° and 15°N during JASO based on the period of **a** 1979–1997 and **b** 1998–2013, obtained by regression on the normalized OLR time series at $(0^\circ, 180^\circ)$. The vectors shown and stippling denote anomalies significant at the 90% confidence level according to Student's t test

significantly different before and after 1997/1998. These changes of the CP convective activities are concurrent with the interdecadal decrease of TC genesis number. Therefore, it's interesting to investigate that what role the convective activities over the CP might have played in affecting the interdecadal changes of TC genesis through the associated atmospheric circulation and environmental factors. In this section, we examine large-scale atmospheric circulation and the environmental factors closely associated with the CP convective activities for the development of TC genesis.

4.1 Atmospheric circulation anomalies

The zonal and vertical circulations averaged along the latitudinal band of 0° – 15°N are shown in Fig. 5. In this figure, the zonal and vertical wind fields are regressed

onto the standardized OLR time series at a reference point (0° , 180°) (where the OLR variance center is located, as depicted in Fig. 3a). The standardized OLR time series at (0° , 180°) is significantly positively correlated with the PC1 of OLR and their correlation coefficient is 0.94. The significant interdecadal change around the 1997/1998 can also be identified in the OLR time series at (0° , 180°). Here this reference point is used to represent the convective activities over the central Pacific. The regressions based on the standardized OLR time series at (0° , 180°) are supposed to be able to explain the changes of the associated atmospheric environmental conditions induced by the interdecadal variation of the convective activities over the central Pacific. Considering the mean value of the standardized OLR time series at the reference point is negative before 1997/1998 (figure not shown), the corresponding regressed fields are shown as their opposite phases to improve clarity. Compared with the negative anomalies in Fig. 5a, significant positive anomalies can be observed in Fig. 5b. Additionally, the active center of the vertical motions shift westward after the late 1990s. Consistent with the leading modes of tropical convection for the two periods shown in Fig. 4, the zonal dipole and tripole patterns can also be found in the vertical circulations in Fig. 5. Note that the enhanced downward motion in the period after 1997/1998 is located over the eastern part of the WNP, which is the key area for the development of TCs. It is shown that the vertical motion anomalies change from enhanced to suppressed over the tropical CP since the late 1990s, which may lead to weakened TC genesis.

To further clarify the interdecadal change of the tropical circulation, the low level (850 hPa) horizontal wind anomalies are regressed onto the standardized OLR time series at (0° , 180°). As shown in Fig. 6a, the significant westerly anomalies are found around the eastern WNP, meaning the eastward expansion of the MT, which was favorable to TC genesis. However, the trade wind anomalies are significantly stronger after 1997/1998 (Fig. 6b), meaning the westward shift of the MT. These low-level changes are coupled with the stronger downward motion in the eastern WNP (Fig. 5b). In addition, the active regions shifted westward by approximately 10 longitudinal degrees. Hence, the interdecadal changes of the atmospheric circulation anomalies associated with the convective activities over the CP could be described as follows: the stronger downward motion over the tropical CP may lead to stronger trade easterlies, and the easternmost location of the MT would shift westward, which creates an unfavorable environment for TC genesis.

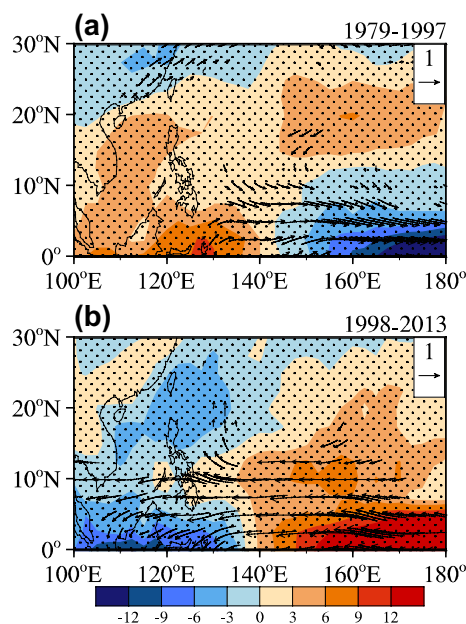


Fig. 6 Anomalies of 850 hPa horizontal wind field (vector, units: m s^{-1}) and OLR (shading, unit: Wm^{-2}) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013 obtained by regression on the normalized OLR time series at (0° , 180°). The vectors shown and stippling denote anomalies significant at the 90% confidence level, according to Student's *t* test

4.2 Environmental factor anomalies

We explored the related environmental factor anomalies associated with the CP convective activities. Among them, the low-level relative vorticity is the most relevant factor for the development of TC activity (Cheung 2004). Corresponding to the standardized tropical CP convection (0° , 180°), the regressed low-level (850 hPa) relative vorticity anomalies over the WNP in the period prior to 1997/1998 display a zonal dipole pattern (Fig. 7a). The significant positive anomalies located to the east of 140°E indicate strong low-level relative vorticity anomalies. In contrast, the significant negative anomalies band during 1998–2013 extends westward from the CP to the South China Sea, running northwest-southeast (Fig. 7b). The negative low-level relative vorticity anomalies covering the tropical regions may contribute to the decrease of TC genesis.

The upper-level divergence pumping action played an important role in TC genesis. Strong upper-level (200 hPa) divergence would enhance the midlevel vorticity generation progress, and thus create larger TC genesis numbers (Cheung 2004). The distribution of the upper-level divergence anomalies bears some resemblance to that of the low-level relative vorticity anomalies (Figs. 7, 8). The significant positive anomalies in the earlier period are located to the east of 140°E , a feature similar to the low-level relative vorticity anomalies. However, in the years after the late

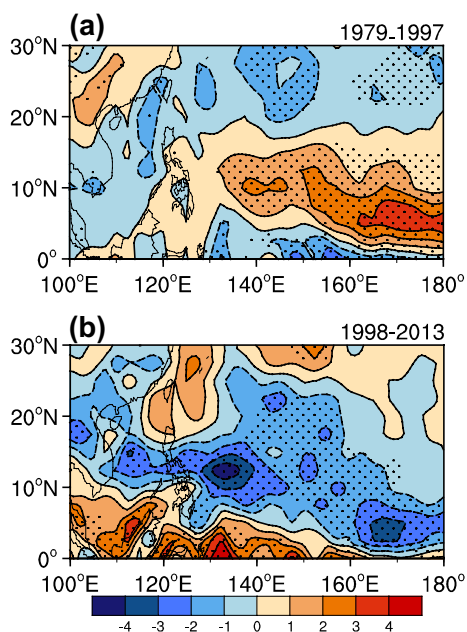


Fig. 7 Anomalies of 850 hPa relative vorticity (unit: 10^{-6} s^{-1}) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013 obtained by regression on the normalized OLR time series at (0° , 180°). Stippling denotes anomalies significant at the 90% confidence level, according to Student's *t* test

1990s, the significant negative anomalies not only grow stronger in the southeastern WNP but also extended westward to the South China Sea (Fig. 8b). Weak upper-level divergence would lead to weak pumping, which coupled with the weak low-level vorticity over the significant area around the southeastern WNP, would have negative contributions to the development of TCs.

Small vertical wind shear, considered an important environmental factor in TC genesis, can help develop large vorticity and build up a mid- to upper-level warm core (DeMaria 1996; Chu 2002). Liu and Chan (2013) related the interdecadal decrease of TC genesis in the late 1990s to the enhanced vertical wind shear in the area (10° – 17.5° N, 150° E– 180°). Their work revealed that there would be less TCs generated when the vertical wind shear shows positive anomalies. Our regression results exhibit a similar distribution (Fig. 9). As shown in Fig. 9a, significant negative anomalies are observed over the aforementioned key area, which indicate smaller vertical wind shear. In comparison, the larger vertical wind shear over that area is enhanced significantly after the late 1990s (Fig. 9b). The amplified vertical wind shear may restrict the formation of TCs.

Sufficient mid-tropospheric (500–700 hPa) relative humidity has long been shown as a necessary condition for TC genesis (Gray 1968). Similarly, the 500–700 hPa relative humidity anomalies are regressed onto the standardized OLR time series at (0° , 180°), as shown in Fig. 10.

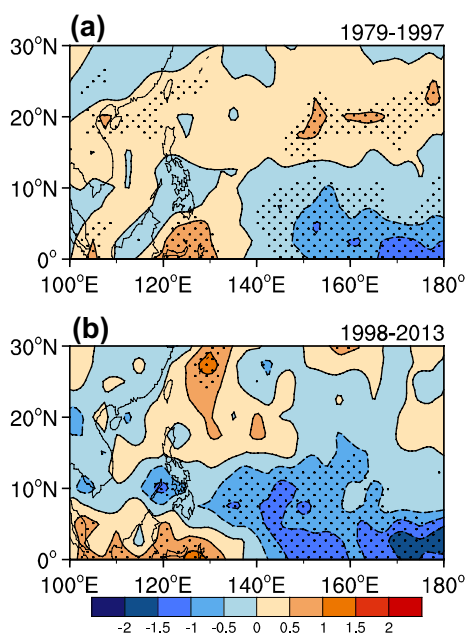


Fig. 8 Anomalies of 200 hPa divergence (unit: 10^{-6} s^{-1}) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013, obtained by regression on the normalized OLR time series at (0° , 180°). Stippling denotes anomalies significant at the 90% confidence level, according to Student's *t* test

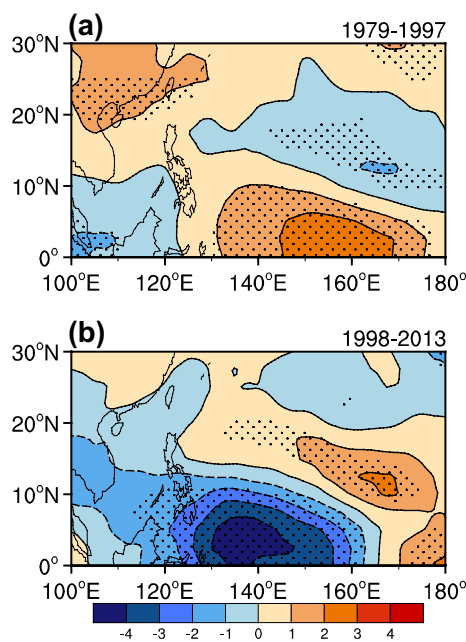


Fig. 9 Anomalies of 200–850 hPa vertical wind shear (unit: m s^{-1}) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013, obtained by regression on the normalized OLR time series at (0° , 180°). Stippling denote anomalies significant at the 90% confidence level, according to Student's *t* test

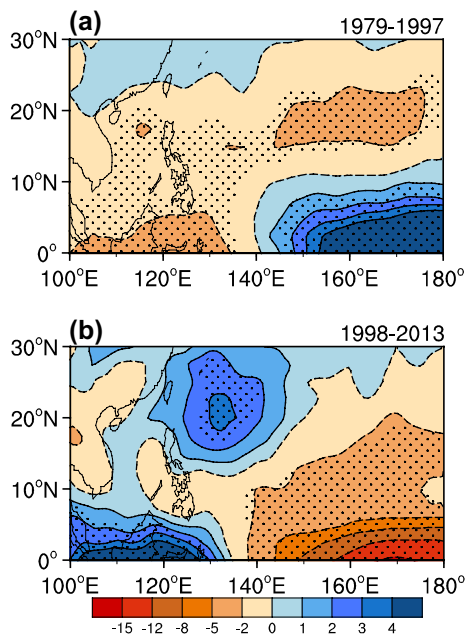


Fig. 10 Anomalies of 700 to 500 hPa relative humidity (unit: %) during JASO based on the period of **a** 1979–1997 and **b** 1998–2013, obtained by regression on the normalized OLR time series at (0° , 180°). Stippling denotes anomalies significant at the 90% confidence level, according to Student's t test

The intervals of this figure are non-linear, especially when exhibiting the negative anomalies. In the latter period, the drier region can extend both westward to the South China Sea and northward to the higher latitude. Additionally, the equatorial areas over the southeastern WNP exhibited stronger anomalies, showing that there was less water vapor supported to the tropical turbulences. According to previous studies (Briegel and Frank 1997; Chu 2002; Cheung 2004; Feng et al. 2014), these large-scale changes would contribute to suppressed TC genesis over the southeastern WNP in the period after the late 1990s.

5 Role of the CP convection in the transition of TD-type waves and their interdecadal changes

Previous works (Frank and Roundy 2006; Chen and Chou 2014) have documented that TD-type waves provide important seeds for WNP TC genesis. In this section, we examine the role of the CP convection in the transition of TD-type waves and their interdecadal changes. Here TD-band filtered OLR and 850 hPa horizontal wind fields are used to represent TD-type waves.

Most of the transition from MRG waves to the off-equatorial TD-type waves are related to the MT, which provides an environment conducive to this process (Lander 1994;

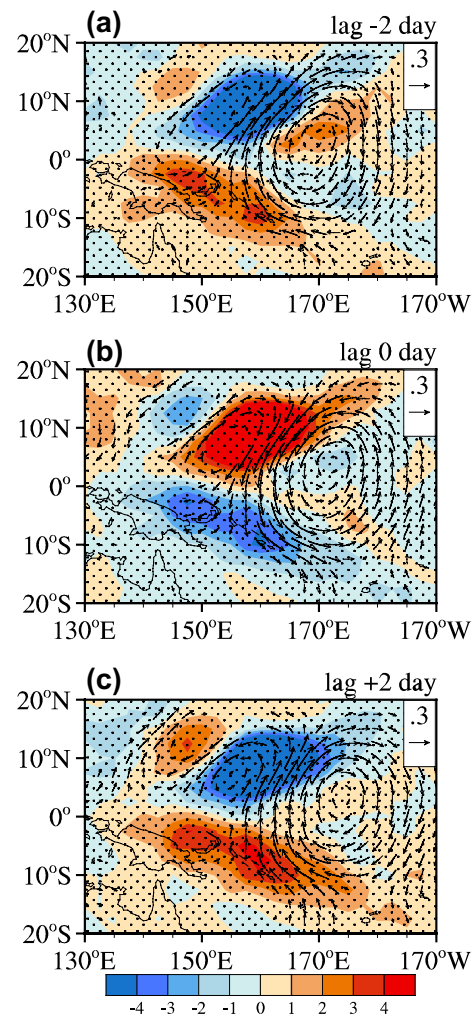


Fig. 11 Regression of OLR (shaded) and 850 hPa horizontal wind field (vector) on lag days **a** -2 , **b** 0 , and **c** $+2$ during JASO from 1979 to 1997. Regression is based on the filtered OLR at (10°N , 160°E). The vectors shown and stippling denote anomalies significant at the 90% confidence level, according to Student's t test

Chen and Chou 2014). The MT provides the EKE for TD-type waves to grow into TCs (Feng et al. 2014; Wu et al. 2015a). Hence, a different base point (10°N , 160°E) (where the strong MT can extend to) was applied in the regression analyses. To better reveal the structure and propagation characteristics of TD-type waves over the WNP before and after the late 1990s, we plotted a day sequence (lag days -2 , 0 , and $+2$) of horizontal structure of TD-type waves in Figs. 11 and 12. Based on the time series of the filtered OLR at (10°N , 160°E), the filtered OLR and 850 hPa wind fields were regressed.

As shown in Fig. 11, from 1979 to 1997, a clear transition of MRG wave to TD-type wave train is observed. At lag day -2 , a clockwise circulation disturbance was found around (0° , 170°E). The center of the vortex circulation is located between the strong and weak OLR centers, almost

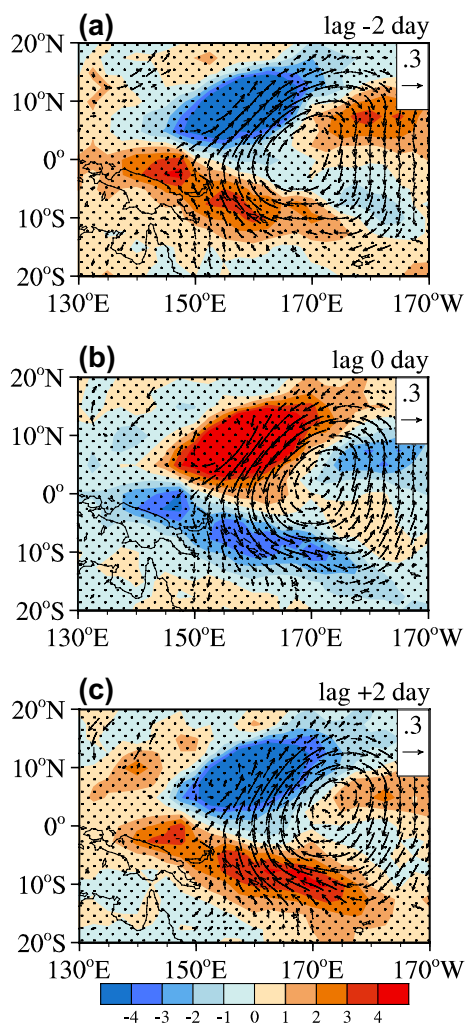


Fig. 12 Regression of OLR (*shaded*) and 850 hPa horizontal wind field (vector) on lag days **a** -2, **b** 0, and **c** +2 during JASO from 1998 to 2013. Regression is based on the filtered OLR at (10°N, 160°E). The vectors shown and stippling denote anomalies significant at the 90% confidence level, according to Student's *t* test

leading the filtered OLR anomalies a half-wavelength distance, which resembles a theoretical solution of an equatorial MRG wave (Wu et al. 2015b). At day 0, this vortex circulation shifted to (10°N, 160°E), with the amplitude the OLR center increased and the scale of the anti-cyclone vortex decreased. Meanwhile, the centers of the OLR and vortex circulation associated with the CP convective activities were coincident, which is thought to be an important feature of TD-type waves (Takayabu and Nitta 1993; Feng et al. 2016). This feature implies that circulation and convective diabatic heating are strongly coupled. At day +2, the amplitude of the OLR center decreased and its scale narrowed further. In addition, the cyclonic circulation located around (0°, 170°E) at day 0 and the new anti-cyclonic circulation located around 0°, 175°E at day+2

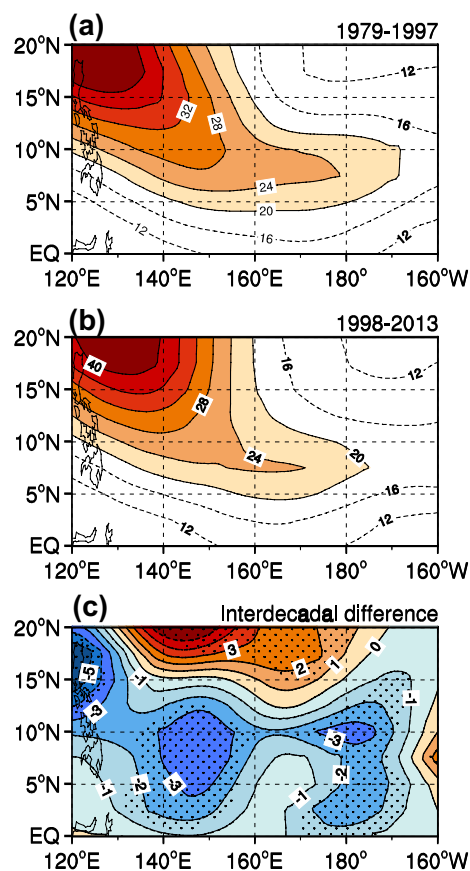


Fig. 13 850 hPa horizontal TD-band EKE (unit: $m^2 s^{-2}$) during JASO for **a** 1979–1997, **b** 1998–2013 and **c** interdecadal difference (latter minus former). *Red dots* in figures **a** and **b** indicate the average locations of TCs. *Stippling* in **c** denotes anomalies significant at the 90% confidence level, according to Student's *t* test

continued to move northwestward, and thus more TD-type waves could be created, which could lead to more TC genesis. This process suggests the transition of MRG waves to TD-type waves which is associated with the CP convection state before the late 1990s could be observed clearly along the monsoon trough.

In contrast, from 1998 to 2013, as shown in Fig. 12, MRG wave structure can be identified around (0°, 170°E) at day -2. However, only weak TD-type waves could be found at day 0 and the extent of the OLR center was larger than that of the former period. Additionally, no significant northwestward propagation signal of TD-type wave was found at day+2. Our analysis suggests that the transition of MRG waves to TD-type waves after the late 1990s is vague, which may lead to the interdecadal decrease of the generation of TD-type waves.

Furthermore, the interdecadal changes of TD-band EKE, i.e., $\frac{1}{2}(u_{TD}^2 + v_{TD}^2)$, are analyzed from July to October in the two epochs (1979–1997 vs. 1998–2013). As shown in Fig. 13, the EKE of TD-type waves shrank westward in

the latter period by approximately 10 longitudinal degrees. More important, the EKE of TD-type waves over the tropical WNP was suppressed significantly, which may directly lead to the reduction of TC genesis. Hence, this finding may further confirm that the convective activities over the CP may have played an important role in affecting the transition from MRG waves to TD-type waves and thus TC genesis.

6 Summary and discussion

This paper examined the interdecadal variation of convective activities over the central Pacific and its impact on tropical cyclone genesis in the western North Pacific. Using the ERA-Interim Reanalysis dataset and the TC best track data from July to October for the years 1979–2013, the interdecadal changes of the WNP TC genesis numbers are analyzed month by month. The results showed that the interdecadal changes are quite consistent in each month and there are less TCs generated in the latter epoch. In addition, the results suggest that the interdecadal shift around 1997/1998 can be mainly attributed to the interdecadal change in August and October.

Concurrent with the interdecadal decrease of TC genesis, the tropical convection underwent a significant interdecadal change in the late 1990s. Our analysis showed that the convective activity anomalies over the CP are more unstable than those over other areas in the equatorial Pacific. The convective activities over the CP were weakened after the late 1990s. Moreover, this study found that the first leading EOF mode of the tropical OLR during July–October turned from a zonal dipole pattern during 1979–1997, accounting for 38.9% of the variance, to a tripole pattern during 1998–2013, accounting for 36.2% of the variance. In the latter period, the magnitudes of the loadings in the central and western Pacific are comparable, with the eastern part showing weaker signals. This interdecadal change is consistent with that of the Pacific thermal state (Xiang et al. 2013).

According to the interdecadal change of the convective activities over the CP, we further examined the large-scale atmospheric circulation. The results showed that the boreal part of the Walker circulation shrank westward, with its downdraft branch located over the CP. Consistent with the leading modes of the tropical convection for the two epochs, the zonal dipole and tripole pattern can also be found in the vertical circulations, respectively. Note that the enhanced downward motion anomalies in the latter epoch were located over the eastern part of the CP, which is the key area for the development of TCs. The trade easterlies are enhanced significantly in the latter period, coupled with the stronger downward motion over the eastern WNP. In

addition, the negative anomalies region shifted westward by approximately 10 longitudinal degrees. This analysis agrees with a previous study considering the interdecadal zonal shift of the MT (Huangfu et al. 2016). Hence, the interdecadal changes of the atmospheric circulation anomalies associated with convective activities over the CP support an unfavorable environment for TC genesis in years 1998–2013.

Moreover, the most related environmental factor anomalies associated with the CP convective activities are analyzed. Our results showed that the significant negative low-level relative vorticity anomalies in the latter epoch covered the tropical WNP, with similar distribution of the upper-level divergence anomalies. The interdecadal weakened pumping action may have played an important role in TC genesis. Additionally, significant positive vertical wind shear anomalies are observed over the key area, which may restrict the formation and development of the TCs. This analysis is similar to the study by Liu and Chan (2013). Additionally, the negative mid-tropospheric relative humidity anomalies were found over the southeastern WNP, showing that there was less water vapor supported to the tropical turbulences. These large-scale changes would contribute to the suppressed TC genesis over the southeastern WNP in the period after the late 1990s.

Furthermore, this study investigated TD-type waves, which are highly related to TC genesis in the WNP. It was noted that TD-type waves are significantly different before and after the late 1990s. In the former epoch, the off-equatorial TD-type waves could be distinctly observed, with clear transitions located along the WNP monsoon trough. However, these transitions were vague in the latter epoch. The interdecadal changes of the convective activities over the CP and the related large-scale atmospheric circulation and environmental factor anomalies, may have contributed to this process. Our analysis showed that the EKE of TD-type waves over the tropical WNP was suppressed significantly, which may directly lead to the reduction of TC genesis.

The central Pacific cooling can enhance the anti-cyclonic anomalies over the tropical WNP by shifting the Walker circulation (Wang et al. 2013). Additionally, the zonal SST gradient can produce an anomalous tropical easterlies over the central-western Pacific (Zhan et al. 2013). The anomalous easterlies further produce local equatorial upwelling and seasonal cooling in the central Pacific, which may lead to a weakened monsoon trough over the WNP, suppressing the WNP TC genesis. He et al. (2015) showed that the epochal SST differences in the late 1990s, with a cooling over the tropical central Pacific and a warming over the warm pool, can be treated as the oceanic cause of the inactive TC period after the late 1990s. The interdecadal decrease of TC genesis over the WNP in the

late 1990s has been studied considering the thermal state of the Pacific, the large-scale atmospheric circulation and the environmental factors in many previous studies (Liu and Chan 2013; Xiang et al. 2013; Huangfu et al. 2016). The present study investigated not only the influence of the CP convective activities on the environment for TC genesis but also its impact on affecting the formation of TD-type waves from MRG waves. The synoptic-scale wave activity may offer a physical explanation of why less TCs are generated in the southeastern WNP after the late 1990s. However, simply analyzing TD-type waves is insufficient for explaining the interdecadal change of TC genesis. More studies are required to investigate the joint contribution of the convectively coupled equatorial waves, including TD-type waves, equatorial Rossby waves and Madden–Julian oscillation.

Acknowledgements This work was supported by the National Key Research and Development program (2016YFA0600603) and the National Natural Science Foundation of China (Grant Nos. 41461164005, 41661144016, 41375065 and 41230527).

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