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DECADAL CHANGES IN WESTERN NORTH PACIFIC TROPICAL CYCLONES ASSOCIATED WITH MADDEN–JULIAN OSCILLATION

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Abstract: This study focuses on the decadal variability of tropical cyclones (TC) over the Western North Pacific (WNP) and how these changes are related to the Madden-Julian Oscillation (MJO). It was done with the help of the Real-time Multivariate MJO index from the Australian Government Bureau of Meteorology of the Centre for Australian Weather and Climate Research, TC data from the Joint Typhoon Warming Center best track datasets, and daily and monthly datasets from the NCEP/NCAR reanalysis center. The results show that the TC frequency in the WNP exhibited a statistically significant decrease during 1998-2010 compared to during 1979-1997. The decrease in TC frequency in the WNP mainly occurred during MJO active phases (i.e., phases 4, 5, 6, and 7). Further investigation of the climate background and the propagation differences of the MJO between 1979–1997 and 1998–2010 was performed. The La Niña-like tropical sea surface temperature cooling caused stronger Walker circulation and thus induced unfavorable atmosphere conditions for WNP TC genesis including a low-level easterly anomaly, a negative relative vorticity anomaly, an increase in sea-level pressure, and stronger vertical wind shear. Moreover, shortening of the MJO cycle, decline in the duration of the active phases in the WNP, and easterly anomaly and shrinkage of the convection area during MJO active phases may also partly explain the decadal variation of TC.

Key words: climate; EOF; tropical cyclone; MJO; Western North Pacific; decadal change
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1 INTRODUCTION

The Western North Pacific (WNP) basin is the most active region of tropical cyclone (TC) activity over the global ocean, accounting for almost 30% of global TCs each year (Chen and Huang [1]; Zhao et al.[2]). Important factors in the genesis and development of TCs on synoptic scale are the dynamical and thermal conditions such as sea surface temperature (SST), vertical wind shear, low-level relative humidity, low-level vorticity, and convective instability (Grey[3]). On decadal or longer time scales, whether TC activity is active or inactive is also largely dependent on the changes in these environmental conditions (Zhao[4]; Zhao and Wu[5]).

Over the past few decades, the decadal variation of TC over WNP has received much attention. Most previous studies considered that long-term changes of TC frequency over the equatorial western Pacific is closely associated with coupled atmosphere-ocean process. Matsuura et al.[6] demonstrated that decadal changes of TC are related to SST changes of the central Pacific and the westerly anomaly caused by changes in the monsoon trough. Liu and Chan[7] pointed out that the relative lack of TC activity during 1998–2011 was partly due to the enlarged local wind shear and strengthened subtropical high. Hsu et al.[8] also found that the abrupt decline of TC number in the late season after 1995 could be attributed to the unfavorable dynamic conditions that existed in the southeast of the WNP. The majority of these previous studies mainly focused on how environmental conditions directly influence TC activities on the decadal scale, but not on the contribution of other time-scales of oscillation and their relationship with TC activities; for example, the tropical intraseasonal oscillation called the Madden-Julian Oscillation (MJO) has received less attention.

The MJO is one of the most significant tropical intra-seasonal modes, which was first recognized by Madden and Julian and has a period of 30–60 days (Maloney and Hartmann [9]). The MJO-TC relationship and the mechanism of how MJO modulates TC activity have been examined in many previous studies (Charney and

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Eliassen[10]; Nakazawa et al.[11]; Zhao et al.[12, 13]). Most researchers have agreed that the number of TC origins during MJO active phases is usually much greater than that during MJO inactive phases (Liebmann et al.[14]; Hall et al.[15]; Cao et al.[16, 17]). For the mechanism, Chen and Huang[1] suggested that MJO modulation of TC over the WNP basin is closely associated with conversion between high-frequency synoptic fluctuations and low-frequency fluctuations through zonal wind shear. For example, the westerly winds in the westerly phase (MJO active phase) are stronger and the increase in TC number is more evident compared to the decline in TC number in the easterly phase (MJO inactive phase). Moreover, Huang and Chen [18] found that equatorial mixed Rossby gravity waves are prone to shift to a tropical-depression-type disturbance that has a larger wave number and shorter wavelength due to the convergence of the monsoon trough during the MJO active phase.

Recently, the causes of the global warming hiatus that have operated since the late 1990s have attracted much attention (Lovett[19]; Kosaka and Xie[20]). Although different studies have provided a variety of explanations from different aspects, there is no doubt that the global climate background has changed during this interval. Many studies have posited that the physical properties of the MJO can be affected by the background of climate change, which in turn may affect the modulation process of TC activity by the MJO (Zhou et al.[21]). Thus, we chose to investigate changes in the MJO and TC activities, and how these changes are related.

The structure of this paper is as follows. Data and methodology are described in section 2. Section 3 discusses the interdecadal changes in TC frequency and some background conditions including vertical wind shear, sea-level pressure, relative vorticity, and 850-hPa wind. The changes in environmental circula tion during the lifecycle of MJO evolution are examined in section 4. A discussion and conclusions are provided in section 5.

2 DATA AND METHODS

In this study, we focus on the TC peak season (June-October) during the period 1979–2010. TC best track data were obtained from the Joint Typhoon Warming Center (JTWC). Only TCs that reached tropical storm intensity, with maximum wind speeds greater than 17.2 m/s, are considered and their positions of origin are regarded as the place at which their maximum wind speed reached 17.2 m/s for the first time. Environmental factors including daily and monthly reanalysis sea surface temperature (SST), wind, and outgoing longwave radiation (OLR) datasets (version 2) from NCEP/NCAR with a horizontal resolution of 2.5°×2.5°, were used to analyze oceanic thermal condition, lower-level atmospheric circulation, and large-scale convective conditions, respectively. The vertical wind shear was computed as the difference in wind between 850 and 200 hPa.

We divided the MJO into eight successive phases using the Real-time Multivariate MJO Index (RMM index) provided by the Australian Government Bureau of Meteorology, which is commonly used to divide MJO phases at present (Wheeler and Hendon [22]). This MJO index is based on the multivariable empirical orthogonal functions of the combined fields of near-equatorial averaged 850- and 200-hPa zonal winds, and satellite-observed OLR data (Simms[23]). The index describes well the processes of MJO propagation without annual cycles and annual variability. The obtained time series of the first and second EOF modes are termed RMM1 and RMM2 respectively. According to this MJO index, the strong convective centers in different regions correspond to different MJO phases, including the Indian Ocean (phases 2–3), the Maritime Continent (phases 4–5), the Western Pacific Ocean (phases 6–7), and the Western Hemisphere (phases 8–1). To illustrate the different active and inactive phases, Simms used grids wherein the OLR values exceeded 230 W/m^2 to obtain the area average, and phases wherein the average result exceeded a specific number were defined as MJO active phases[23]. In this study, MJO active phases in the Western North Pacific Ocean are defined as phases wherein the amount of grids (band-pass OLR < 0) exceeded 200 in a specific region of the WNP: these were phases 4, 5, 6, and 7. Other phases were identified as MJO inactive phases in the WNP: these were phases 8, 1, 2, and 3.

This study identifies the decadal abrupt shift in TC frequency in 1979–2010 using the Student's *t*-test. The TC frequency and its relationship with MJO propagation in two different time intervals is compared. Spectrum analysis and a band-pass filter (30–60 days) were adopted to verify the significant peak period of the RMM index and extract the intra-seasonal signal of atmospheric circulation, respectively.

3 ATMOSPHIRIC AND OCEANIC CONDITIONS

Figure 1 shows the decadal shift of TC frequency in the WNP during the period 1970–2010 and the result of the Student's t-test of annual TC number with a significance level of 0.05. It is observed that the decadal variation of TC frequency during 1979–2010 is significant, and the abrupt shift in 1998 is evident in Fig.1b. The average annual TC frequency is 21 during 1979–1997, which decreases to 17 during 1998–2010. The annual TC frequency evidently declined during the later time period compared to the earlier one. On the basis of the results of the abrupt analysis and the global warming hiatus since 1998, we divided the period 1979–2010 into two intervals—1979–1997 and 1998–2010—to analyze possible decadal changes in relationship between MJO and TC frequency during different periods.

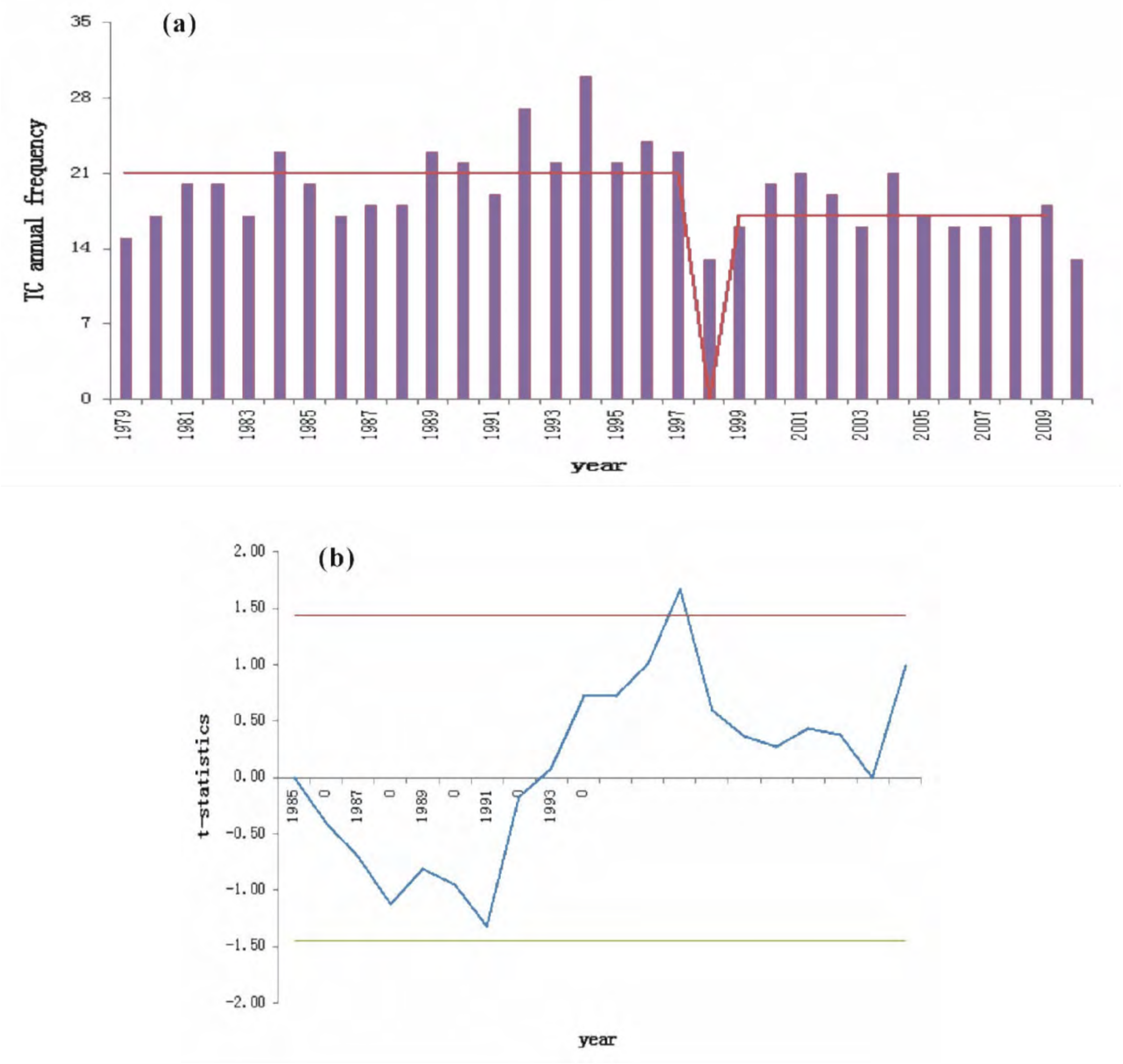

Figure 1. (a) Annual TC frequency in WNP during 1979–2010; (b) Slip-t test with significant level 0.1.

TC activity largely depends on large-scale atmospheric and oceanic conditions on a decadal time scale. Fig.2 shows the tropical SST anomaly during 1979–1997 and 1998–2010 and their differences. During 1979–1997, the SST of the tropical Central Pacific and East Pacific shows a warm anomaly, whereas a cold SST anomaly occurs in the West, which exhibits an El Niño-like pattern. In contrast, the SST of the tropical Central and East Pacific has a cold anomaly, while a warm anomaly occurs in the West, which shows a La Niña-like pattern during 1998–2010. Overall, the SST is lower in most areas of the Central and East Pacific Ocean and shows warming in the shape of a "C" in the Western Pacific in the later time interval, which resembles a La Niña-like pattern and the cold-phase pattern of the Pacific decadal oscillation (PDO), as suggested in previous studies (Liu and Chan[7]; Hsu et al.[8]; Zhao and Raga[24]; Zhao and Chu[25]).

The Walker circulation is enhanced by the convergence and upward motion caused by warmer SST in the tropical Western Pacific and the divergence and downward motion caused by colder SST in tropical Eastern Pacific. In the later time interval, the background condition of the Walker circulation shifts westward in the later time interval compared to the earlier. The original wind at the level of 850 hPa, relative vorticity, sea-level pressure, and difference of wind shear (200–850 hPa) in the period 1979–1997 are illustrated in Fig.3. During 1998–2010, an easterly anomaly of the lower wind field, which is simulated by the enhanced Walker circulation, generates an anticyclone circulation anomaly, leading to a decrease in the cyclonic relative vorticity and an increase in the anti-cyclonic relative vorticity. At the same time, large wind shear also occurs. These conditions are all relatively unfavorable for TC genesis and development.

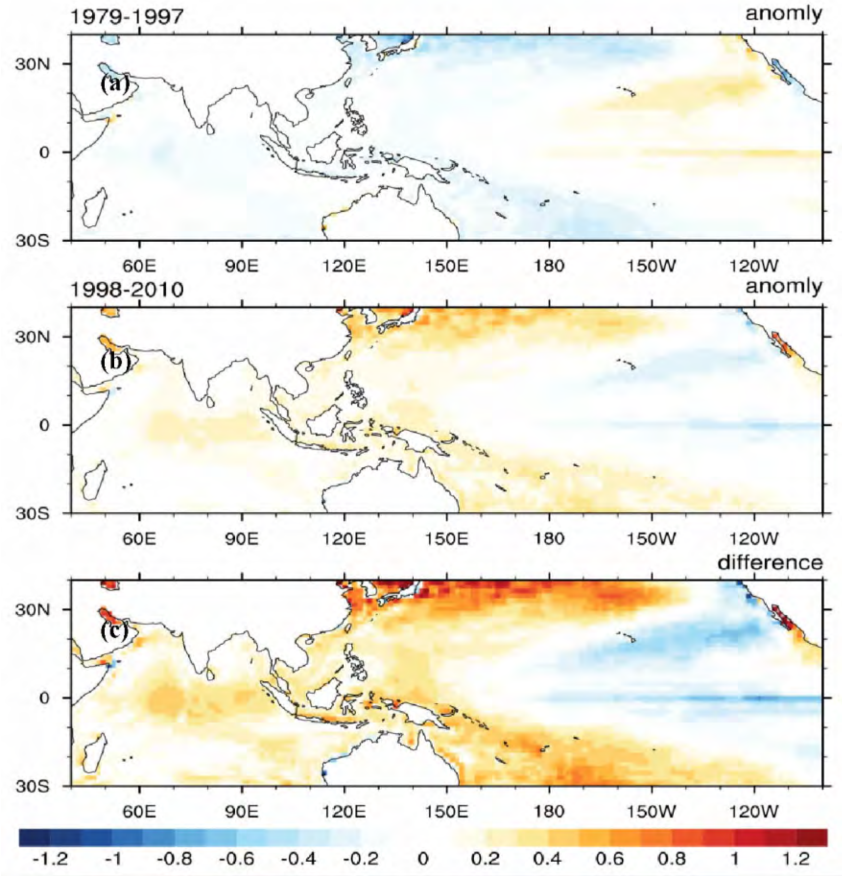

Figure 2. Spatial distribution of tropical SST anomaly in June-October (unit: ℃): (a) 1979−1997; (b) 1998−2010; (c) difference between 1998−2010 and 1979−1997.

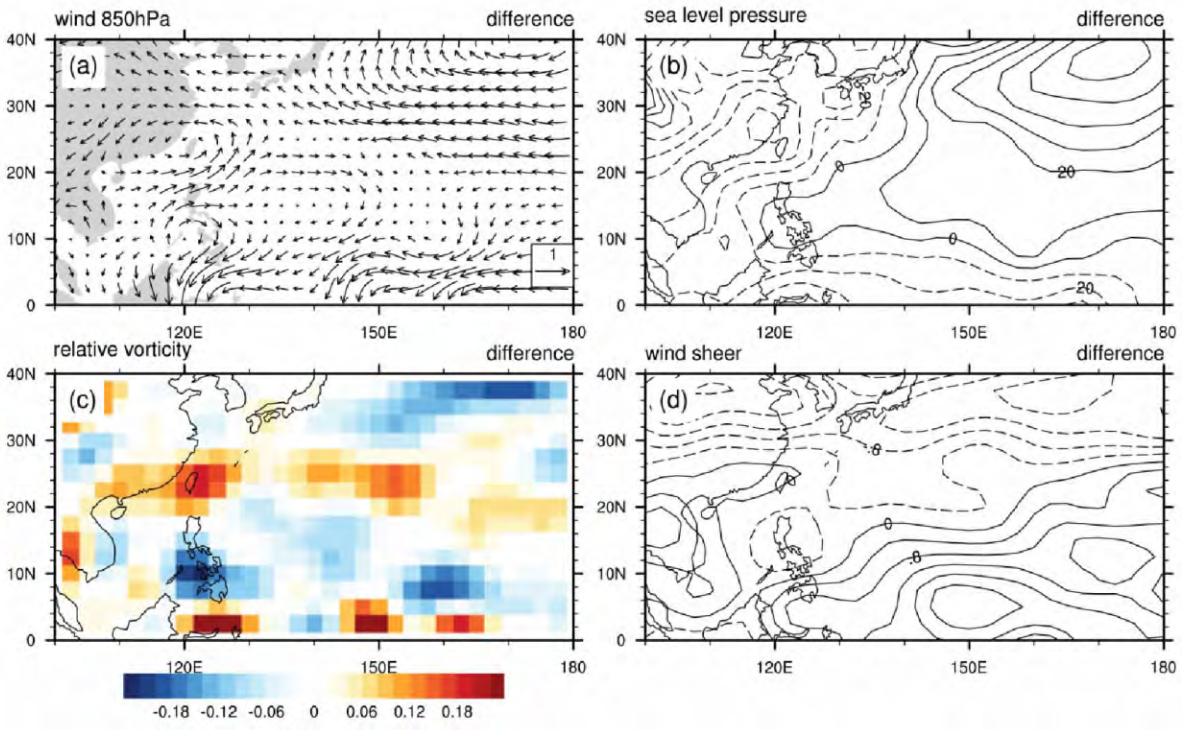

Figure 3. Circulation condition (difference between 1998−2010 and 1979−1997): (a) original wind of 850 hPa(unit: :m/s); (b) relative vorticity of 850 hPa (expanded for 105); (c) sea level pressure (unit: Pa); (d) vertical wind sheer of 850 hPa.

4 DECADAL CHANGES IN MJO PROPAGATION AND ITS RELATIONSHIP WITH TC

Based on the decadal variations of lower circulation and oceanic thermal conditions analyzed in section 2, possible explanations for the MJO characteristics and its relationship with TC are investigated in terms of both spatial and temporal evolution in this section.

Figure 4 shows the average annual TC frequency of each MJO phase in the two time intervals. The annual TC frequency in most MJO phases is decreased, except for phases 2 and 8. Compared to the earlier period (1979–1997), the averaged annual TC frequency in MJO inactive phases (i.e., phases 8, 1, 2, and 3) declined by 0.97 per year, while that in MJO active phases (i.e., phases 4, 5, 6, and 7) declined by 2.88 per year, which is almost three times more than the decrease during MJO inactive phases. Thus, the total decrease in TC number in the WNP during 1998–2010 mainly resulted from the decrease during MJO active phases.

4.1 *Change of MJO cycle*

In order to analyze the changes in the MJO cycle in the two time intervals, power spectral analysis is applied to the RMM1 series (Fig.5). There are two main peaks in the power spectrum during 1979–1997: the first is around 35–54 d with the largest spectral density being 0.025 W/Hz; the second peak is about 55–74 d with a largest spectral density value of about 0.035 W/Hz. In contrast, there is only one major peak in the power spectrum of the later period (1998–2010) with a period of 35–55 d and a spectral density of 0.065 W/Hz. The oscillation energy of MJO during 1998–2010 is relatively concentrated in a shorter cycle, which means that the averaged MJO period is shorter, as suggested in a previous study (Yoshiyuki and Xie[26]).

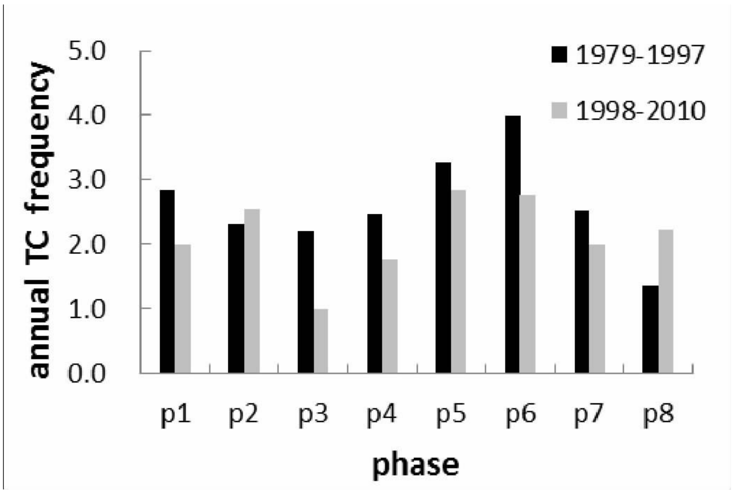

Figure 4. Annual averaged TC number of MJO phases during 1979–1997 and 1998–2010.

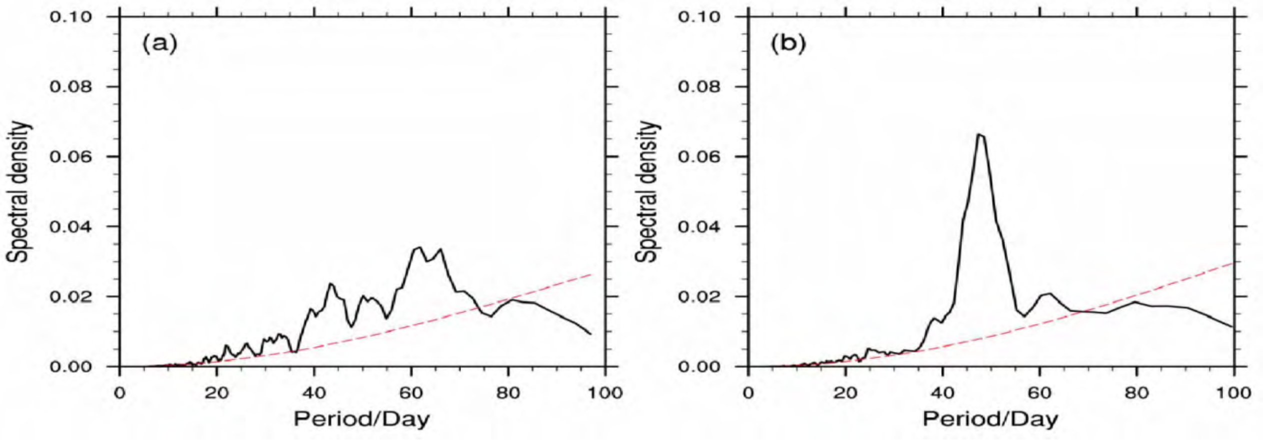

Figure 5. Spectrum analysis of RMM1 during 1979–1997 (a) and 1998–2010 (b). Unit of spectral density: W/Hz; unit of period: day. Spectrum above the dot line pass though the red noise test (significant level: 0.5).

To further evaluate the effect of shortening of the MJO cycle on TC frequency over the WNP, we calculate the percentage of MJO active days (amplitude > 1.0) in the active and inactive phases. As can be seen in Table 1, the percentage of active days decreases in phases 3, 5, 6, and 7, whereas in the other phases the percentage shows an increasing trend. On average, the percentage of active days in MJO active phases (4, 5, 6, and 7) shows an obvious increase but that of MJO inactive phases (8, 1, 2, and 3) decreases, especially in phases 6 and 7. The TC number is indeed significantly reduced in phases 6 and 7 and increased in phases 4 and 5 at the 5% confidence level (Fig.4) during 1998–2010. Overall, the reduced duration of MJO active phases in the WNP caused by the accelerated MJO in this area is a possible reason for the significant decrease in TC number in MJO active phases between 1998 and 2010.

Table 1. Percentages of MJO active days (amplitude>1.0) in each of the phases.

phase	1979–1997	1998–2010
1	17.2	18.1
2	13.1	18.4
3	9.7	7.1
4	10.2	11.1
5	17.0	15.5
6	15.5	10.3
7	9.3	7.6
8	8.1	13.0
m	52.0	43.4

4.2 *Change of environmental conditions*

Figure 6 illustrates the low-frequency wind at 850 hPa in MJO active phases during 1979–1997 (left-hand line) and the difference between 1979–1997 and 1998–2010 (right-hand line). The red dots represent locations of TC genesis. A notable easterly anomaly covered most of the WNP in phases 4 and 5 during 1998–2010. The zonal easterly wind tends to transfer barotropic energy conversions from high-frequency waves to low-frequency waves, which is unfavorable for TC genesis; however, in phases 6 and 7 the conditions are different and even reversed. The lower wind can partly explain the decrease in TC number in phases 4 and 5, but not in all phases. Furthermore, the monsoon trough (figure omitted) in phases 4 and 7 shows a notable contraction in the period of 1998–2010, which is not conductive to the genesis and development of TC, which is also one of the factors involved in the decline in the number of TCs.

The propagation of MJO is actually the propagation of the cumulus convective center (Pan et al.[27]). The relationship between large-scale convection and decadal variation of TC activity is examined in Fig.7. The area (5°–30°N; 110°–180°E) marked by a black box represents the active TC genesis region. From the genesis location and TC number, TCs in MJO active phases tend to concentrate in convective areas where the OLR anomaly is negative, but this pattern is not perfectly consistent with the strong convective area (absolute OLR > 12 W/m^2). Meanwhile, most TCs are relatively concentrated to the west of 150°E because of the existence of the monsoon trough, but to the east of 150°E, TCs are relatively scattered and fewer. In phases 5 and 6, the decrease of TC number mainly occurs to the east of 150° E; in phase 7, the decrease is to the west of 150°E.

In order to examine specifically the relationship between convection associated with MJO and TC number, a convective area index is defined, which calculates the number of negative OLR anomaly grids inside the black box. A higher index value denotes than an area is more convective, and hence more conducive to TC genesis. Fig.8 compares the area index of MJO active phases in the two intervals. In phases 4 and 5, the convective area index is obviously less in the period 1979–1997 than in 1998–2010, indicating that the convection over the WNP was weaker in these two phases, and thus unfavorable conditions for TC genesis. Additionally, the convective area index in phases 6 and 7 is higher during 1998–2010, indicating expansion of convection, which favors TC genesis, but the TC number actually declined.

In general, the TC frequency during the MJO active phases over the WNP basin is related both to the low-frequency circulation and convective environment and is also closely associated with how long the large-scale convection brought by MJO active phases is maintained in the area. Thus, the changes result from variations in both temporal and spatial factors.

5 CONCLUSION AND DISCUSSION

This study addressed decadal variations of TCs over the WNP during 1979–2010 and its relationship with MJO propagation. On the basis of a series of data including the RMM index, TC data from the JTWC best track dataset, daily and monthly data of the NCEP/NCAR reanalysis, and statistical methods including abrupt analysis, band-pass filter, and composite analysis, the following conclusions were obtained.

(1) The study period (1979–2010) can be divided into two parts on the basis of the abrupt analysis method: an active TC period (1979–1997) and an inactive TC period (1998–2010).

(2) The oceanic conditions and circulation environment were different between 1979–1997 and 1998–2010, providing different backgrounds for TC genesis in the two time periods. During 1998–2010, the tropical sea surface temperature showed a La Niña-like pattern, warming in the east Pacific and cooling in the west Pacific, leading to a stronger Walker circulation. The easterly anomaly caused by strengthened Walker circulation further stimulated an anti-cyclonic anomaly, negative relative vorticity, increase in sea-level pressure, and en-

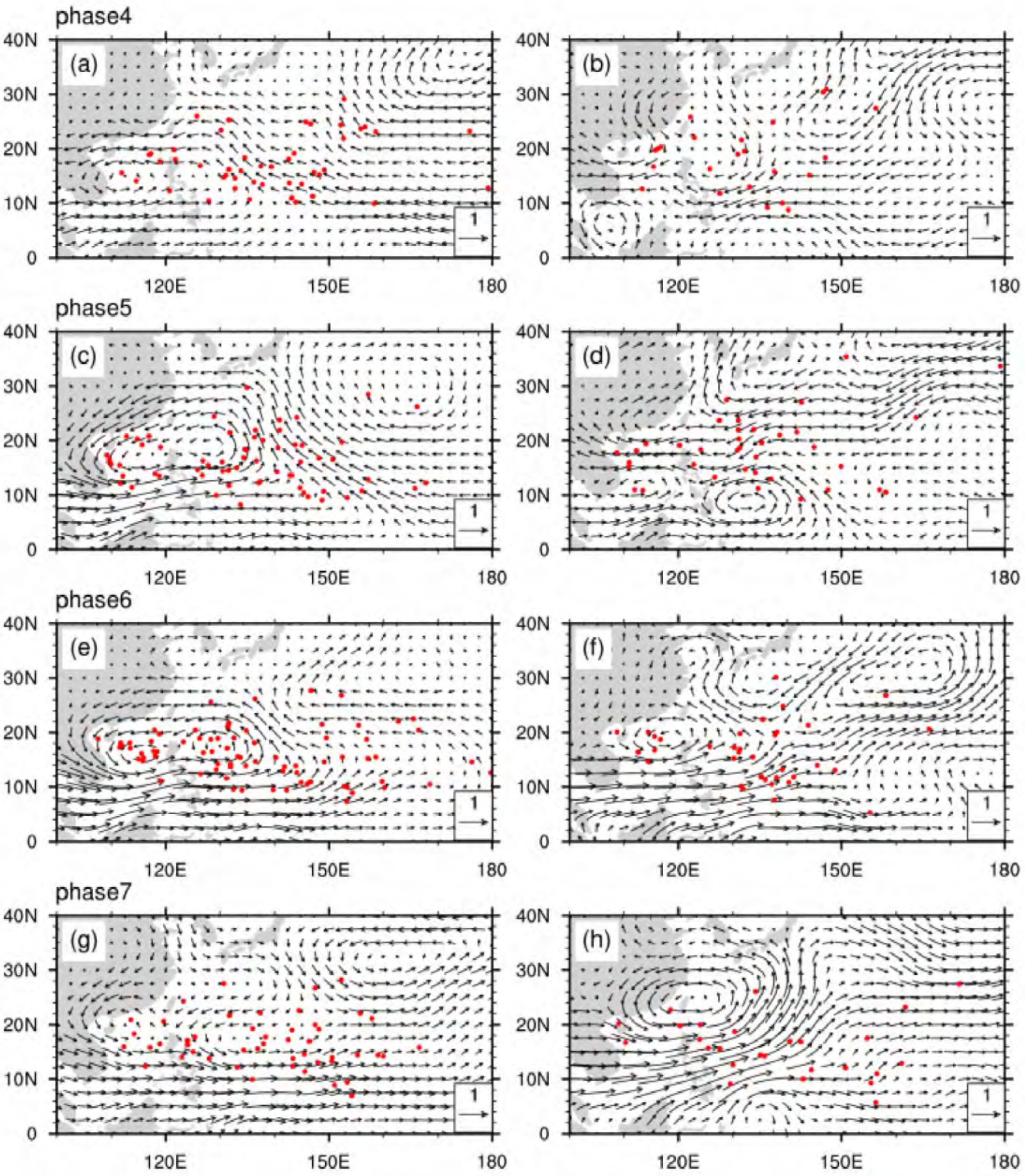

Figure 6. Filtered wind of 850 hPa in MJO active phases (unit: m/s): 1979−1997 (left panels); difference between 1979−1997 and 1998−2010 (right panels), red solid dots represent the locations of TC genesis.

hanced vertical wind shear. All these large-scale conditions are unfavorable to TC genesis and resulted in the decrease of TC number in the period 1998−2010.

(3) The main contribution to the decrease in TC frequency during 1998−2010 was the decrease of TC genesis during MJO active phases (phases 4, 5, 6, and 7), which was the combined effect of various environmental factors. These included: (a) the shorter duration of the convective center, wherein the MJO cycle was shortened and the duration of the active phases in the WNP was prolonged, and (b) shrinkage of low-level circulation and convection, with the easterly anomaly and contraction of the convective area over the WNP being unfavorable for the genesis and development of TCs.

According to observations, the Pacific decadal oscillation changed to the cold phase and ENSO cold events increased after 1998, which may also partly explain why TC numbers declined during 1998−2010. Tam and Lau [28] demonstrated that the MJO tends to accelerate in ENSO cold events and decelerate in ENSO warm events. Meanwhile, the observations of ENSO events indicate that the cold events increased and strengthened during 1998−2010. In those conditions, the propagating speed of MJO was possibly connected with the changes in ENSO. Further investigations of the exact mechanism for how the decadal change of MJO frequency affects the decadal variation of TC activity are required.

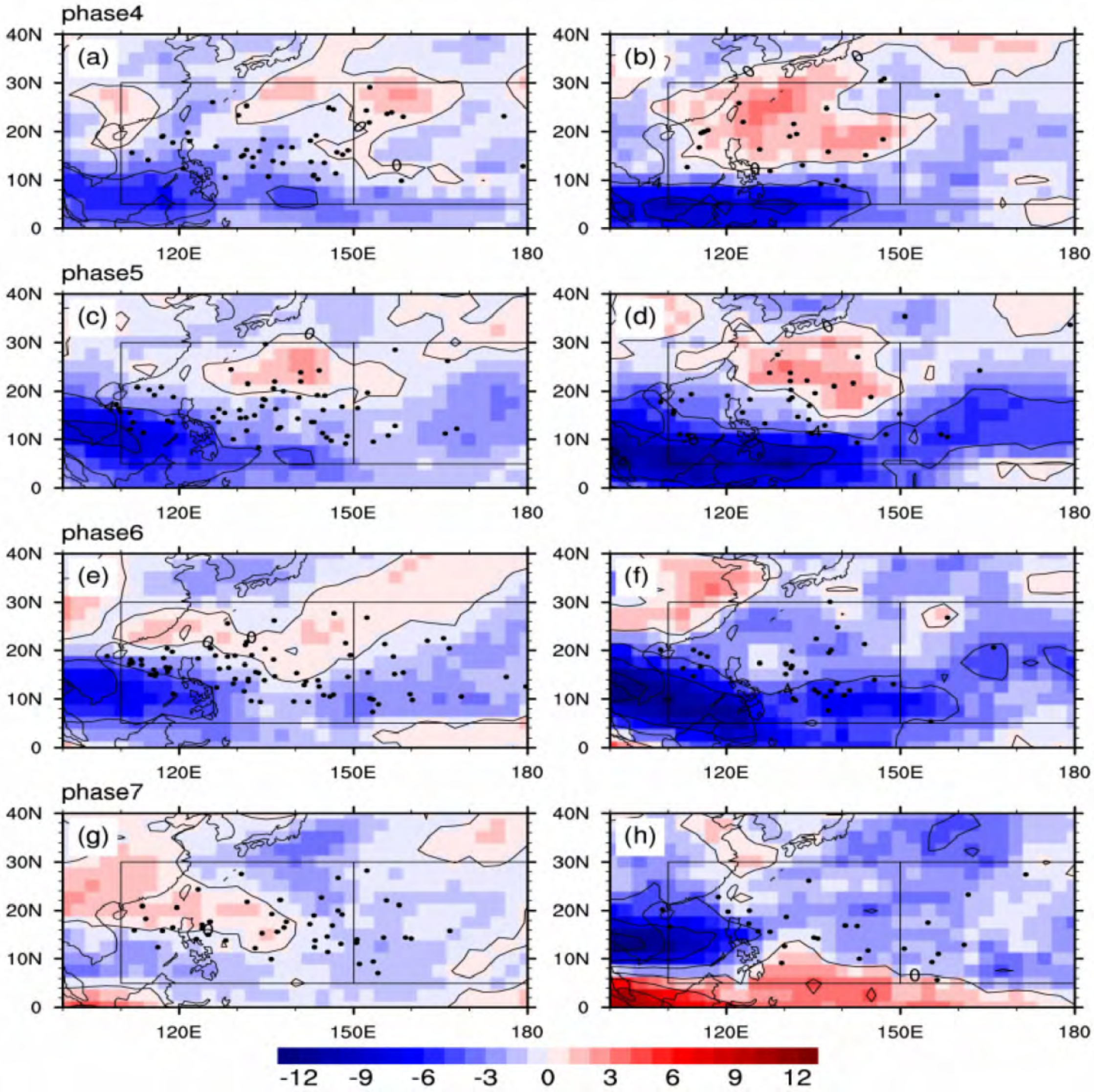

Figure 7. Filtered OLR composition in MJO active phases (unit: W/m^2): 1979–1997 (left panels); 1998–2010 (right panels), black dots represent locations of TC genesis.

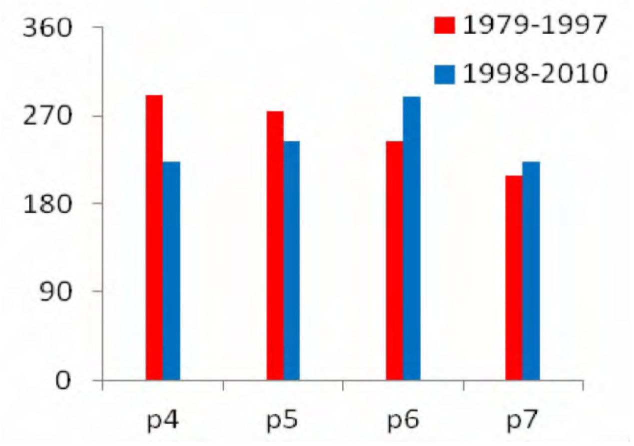

Figure 8. Comparison of OLR area index (x axis) of MJO active phases (y axis) during 1979–1997 and 1998–2010.

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