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Interdecadal changes in the genesis activity of the first tropical cyclones over the western North Pacific from 1979 to 2016

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Abstract

This study analyzes time series data on the genesis latitude, longitude, and date of the first tropical cyclone (TC) each year during the 38 years between 1979 and 2016. Statistical change-point analysis applied to these three variables shows that a shift in climate regime occurred around 1998. More specifically, the first TCs in the western North Pacific (WNP) tend to occur later and more northwest area since 1998. Also, we compared differences between 1998 and 2016 (post-1998) and between 1979 and 1997 (pre-1998) in terms of outgoing longwave radiation (OLR), total cloud cover, precipitable water, precipitation, vertical wind shear, 850 hPa relative vorticity, and sea surface temperature. Our results show that a favorable environment for TC genesis formed near the South China Sea (SCS) and the Philippines, and an unfavorable environment for TC genesis formed in the southeastern portion of the WNP during the post-1998. Analysis of stream flow shows that an anomalous cyclonic circulation at 850 hPa formed in the SCS, and a large, anomalous, anticyclonic circulation formed in the North Pacific. From these circulations, a ridge extended to the east sea of the Philippines, and consequently, anomalous trade winds strengthened in the equatorial Pacific. Such an anomalous atmospheric circulation seems to be associated with the cold Pacific Decadal Oscillation (PDO) phase. At 200 hPa, the anomalous anticyclonic circulation strengthened in the SCS, and an anomalous cyclonic circulation formed in the east sea of the Philippines, which strengthened anomalous westerlies in the equatorial Pacific. Furthermore, this circulation pattern is related to a strengthening of the Walker circulation. Therefore, post-1998, when trade winds strengthened from development of the Walker circulation, the cold PDO phase strengthened, the locations for TC genesis moved toward the northwestern portion of the WNP, and the TC genesis day tended to be delayed.

Keywords TC genesis · Statistical change-point analysis · Pacific decadal oscillation · Walker circulation

1 Introduction

Tropical cyclones (TCs) such as typhoons and hurricanes, which are among the most devastating meteorological phenomena. As this disaster not only causes loss of lives but also has enormous societal and economic damage with only one entry, preparing for it in advance is absolutely necessary. In particular, the Western North Pacific (WNP) has the warmest sea surface temperature (SST) on the globe with active TC genesis (Mcbride 1995; Elsberry 2004) where more than one third of TCs worldwide are generated. Hence, the activity of TCs in the WNP has been a focus of interest.

Climatologically, TCs occur frequently, become stronger and move further north near mid-latitude region in warm season between June and November. Therefore, while most of previous studies on TCs were focused on the main season, there were relatively fewer studies regarding other seasons. Basconcillo and Moon (2021) compared the characteristics of activities of Christmas typhoons (TCs from December of the previous year to February) between two periods (Period 1: 1991–2012, Period 2: 2012–2020). They demonstrated that Christmas typhoons in recent years (Period 2) increased distinctly in the WNP, particularly in the Philippines, and attributed the finding to the favorable change of the TC

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generation environment due to the transition of positive phase of PDO mode. The study stated that expansion of the western North Pacific subtropical high (WNPSH) and high pressure over Southeast Asia associated with the Siberian High caused TCs to move to the Philippines, which is located in the south of the WNPSH (approximately 10°N). Choi and Wang (2020) studied the yearly latest TC activities and discovered that the latest TC genesis exhibited a strong negative correlation with Antarctic Oscillation (AAO), and tended to be more in the western part of the WNP from 1998 to 2015.

There are a few studies that investigated the length and start date of TC activity period in the WNP (Dwyer et al. 2015; Kim and Kim 2017; Corporal-Lodangco ang Leslie 2017). Kim and Kim (2017) argued that the length of TC activity period in the WNP depends largely on their initiaton timing and found out that the timing for the initiation of typhoon season is closely associated with SSTs over the Indian Ocean and the eastern Pacific in the preceding winter and early spring through a numerical experiment. Corporal-Lodangco and Leslie (2017) generated the climatology regarding the TCs that affected the Philippines during 1945–2011 by dividing the period between more active season (MAS; June to December) and less active season (LAS; January to May). Through a comparison of mean annual frequencies, landfalls, TC days, season lengths, season earliest and latest start and end dates, genesis locations, and tracks between the two periods, they discovered an existence of quiescent season (TC free) between LAS and MAS. Their study also showed that ENSO is the dominant mode affecting Philippine TCs and TC frequency is low from January to March and high from April to June in cold ENSO (La Niña) years.

Reviewing these previous studies, we realized that analysis on the initiation of TC season is most important in studying the quiescent season (TC free) before TCs act in earnest and the length of entire TC activity period. Furthermore, we confirmed that early TC genesis is closely related to the SST variability mode in the WNP, such as ENSO and PDO.

Many previous studies have investigated the correlation between TC development in the WNP and ENSO. In particular, it was proven that TC genesis frequency is affected by the ENSO although their correlation is in nonlinear form (Chan 2000; Chen et al. 1998; Wang and Chan 2002; Chand and Walsh 2011; Li and Zhou 2012; Kang et al. 2019; Tan et al. 2019; Kim et al. 2020). Furthermore, it has been reported that the locations of TC occurrences in strong warm ENSO (El Niño) years lean toward the southeast WNP, and the frequency of TC genesis in the central Pacific region increases in warm ENSO years (Wang and Chan 2002; Clark and Chu 2002).

The PDO is an SST-based mode like ENSO, but the most obvious difference between the PDO and ENSO is the time scale. Whereas ENSO events tend to persist on the order of one year, the PDO signature can last up to 30 years (Mantua 2001). Hence, PDO is used as a main signal when studying the interdecadal variability activities of TCs (Liu and Chan 2008; Kubota and Chan 2009; Zhao et al. 2018; Liu et al. 2019; Shan and Yu 2020). Among the relevant studies, Wang et al. (2015) and Lee et al. (2021) raises important issues regarding the PDO mode. Wang et al. (2015) investigated the relationship between multidecadal variability of RI (rapidly intensifying) TCs and PDO during a period from 1951 to 2008 and demonstrated a partial contribution to the increase of the RI TC during negative PDO phase (1998–2008). Lee et al. (2021) conducted a correlation analysis between TC and PDO in the WNP from 1982 to 2018 and showed that TCs affect broader region to cover higher latitude (around the Korean Peninsula and Japan) during negative PDO phase.

One thing to notice is that the exposure of TCs in the WNP is decreasing at low latitudes and increasing at mid-latitude compared to the past due to climate change (IPCC, 2021). And the results of Corporal-Lodangco and Leslie (2017) that the first start date clearly has delayed during the LAS and the latest end date has been earlier during the MAS since 1980, imply lengthening TC free term between the MAS and the next LAS and shortening the entire TC activity period. One extreme case is 2016. That year, the first TC occurred in July, which was extraordinary, and moved north of the 26°N. Ten people in China died from the TC and it was recorded as the strongest first TC in 61 years. Also, unlike no TC in the first half year, 26 TCs generated in a row only during the second half year, which was more than the average.

The changing pattern of the first TC occurrence that notifies the start of the TC season implies that TCs can unexpectedly strike in regions and periods that typically received trivial influence from TCs. Hence, research on such possibility and preparation is necessary at present. Our study attempted to examine the characteristics of the change of the first TC occurrence in the long-term (time span over a decade) and correlation with the Pacific Decadal Oscillation from 'interdecadal' perspectives. In Sect. 2, data and methodologies are introduced. Section 3 provides an overview of variations and mechanisms responsible for the annual first TCs. Finally, Sect. 4 summarizes the findings of this study.

2 Data and methodology

2.1 Data

We used best-track data produced by the Regional Specialized Meteorological Center (RSMC) Tokyo – Typhoon Center. RSMC Tokyo was designated by the WMO (WMO 1988) and provides information (latitude, longitude, central pressure, maximum sustained wind speed (MSWS) and so on) in six-hour intervals from TCs that have occurred in the WNP since 1951. However, we used the TC data from 1979 to 2016 that the real-time monitoring capability of TCs has been greatly improved with reliable satellite observations (WMO 1979; WMO 2004; Velden et al. 2017). In this study, a TC that occurred in the WNP is defined as a TC with an MSWS $\geq 17\ ms^{-1}$, that is, one that developed to more than tropical storm (TS) strength. In order to consolidate the results of this study, RSMC best-track data were compared with data produced by the Shanghai Typhoon Institute (STI) of the China Meteorological Administration and the Joint Typhoon Warning Center (JTWC). For the JTWC best-track, we only used the data since 1999, when the level of TC development began to be provided. The time series of the first TC-genesis latitude, longitude, and day for each year showed that RSMC and STI data were similar (a positive correlation of 0.99 was observed between the two time series) (Fig. 1). However, JTWC best-track data differ slightly from the other two time series. This is the result of reflecting the fact that different determination criteria (the timing of the first TC genesis was determined as somewhat later or earlier) were applied, because the JTWC measures the intensity of tropical cyclones based on the 1 min-averaged maximum wind speed unlike the other two institutions (which use the 10 min-averaged maximum wind speed). Data of the three institutions were similar in tendency of the TC genesis date and locational change patterns, and the RSMC best-track data were deemed appropriate to use.

To analyze large-scale environments with respect to the cause of TC activity, we used Reanalysis-2 (R-2) monthly average data issued since 1979 by the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) (Kanamitsu et al. 2002). The data show a grid interval of 2.5° × 2.5° (latitude–longitude) and 17 vertical layers. For SST data, we used Extended Reconstructed SST (ERSST) V3b (Smith et al. 2008). ERSST data contain monthly averages from 1854 to the present with a grid interval of 2° × 2°. Outgoing longwave radiation (OLR) data were utilized for the analysis of convective activity (Liebmann and Smith 1996).

In this study, several related climate indices were used to determine the causes of long-term changes in the first TCs. Trade wind and 200 hPa zonal wind indices were obtained from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (https://www.cpc.ncep.noaa.gov/data/indices/). These indices are averaged zonal winds over the central Pacific (5°N–5°S, 175°W–140°W). The Walker circulation index is defined as the difference in 500 hPa omega velocities between the eastern equatorial Pacific (160°W–80°W, 5°S–5°N) and the western equatorial Pacific (80°E–160°E, 5°S–5°N) (Vecchi et al. 2006). The January to May Pacific Decadal Oscillation (PDO) indices were obtained from the website of the University of Washington (http://jisao.washington.edu/pdo) (Mantua et al. 1997). PDO is a robust, recurring pattern of ocean–atmosphere climate variability centered over the mid-latitude Pacific basin. PDO is detected as warm or cool SST in the North Pacific Ocean above 20°N.

2.2 Methodology

This study analyzes time series data on the genesis latitude, longitude, and day for the first TCs in each year during the 1979–2016 period.

Vertical wind shear (VWS), which was used to diagnose large-scale conditions, was calculated as follows:

$$VWS = \sqrt{(u_{200-850})^2 + (v_{200-850})^2}$$

where u and v indicate zonal and meridional flows, respectively, at 200 hPa and 850 hPa, respectively (Wingo and Cecil 2010). VWS is a good variable for seeing the change in intensity of a TC by examining the difference in wind directions between the upper and lower troposphere.

Genesis potential indices (GPI) were calculated using the equation derived by Camargo et al. (2007). The occurrence of the first TC in each year is defined as the first day a TC reaches TS strength. Figure 2a shows the overall frequency of TCs that have occurred from January to December over the past 66 years (1951–2016). The frequency of TC genesis from January to May was low with 11% of all TCs. The number of TC genesis is less than once per month in this period, which may be of great significance depending on whether a TC occurred or not during the given month. Figure 2b shows the proportion of first TC genesis for each month within the same period. The first TCs occurred from January to July, with January accounting for the majority at 38%. The proportion of the first TC genesis for June-July was quite low at less than 5%. To determine the significance of the results, we used the two-tailed Student's t test (Wilks 1995). Confidence intervals are preferable to p-values. Conventionally, if a p-value is less than or equal to 0.05 ($p \leq 0.05$), it is declared a statistically significant at the 95% confidence level. And to examine the existence of a climate regime shift in the time series, we applied statistical change-point analysis to the time series (Elsner et al. 2000; Chu 2002; Ho et al. 2004). Climate regime shift was defined

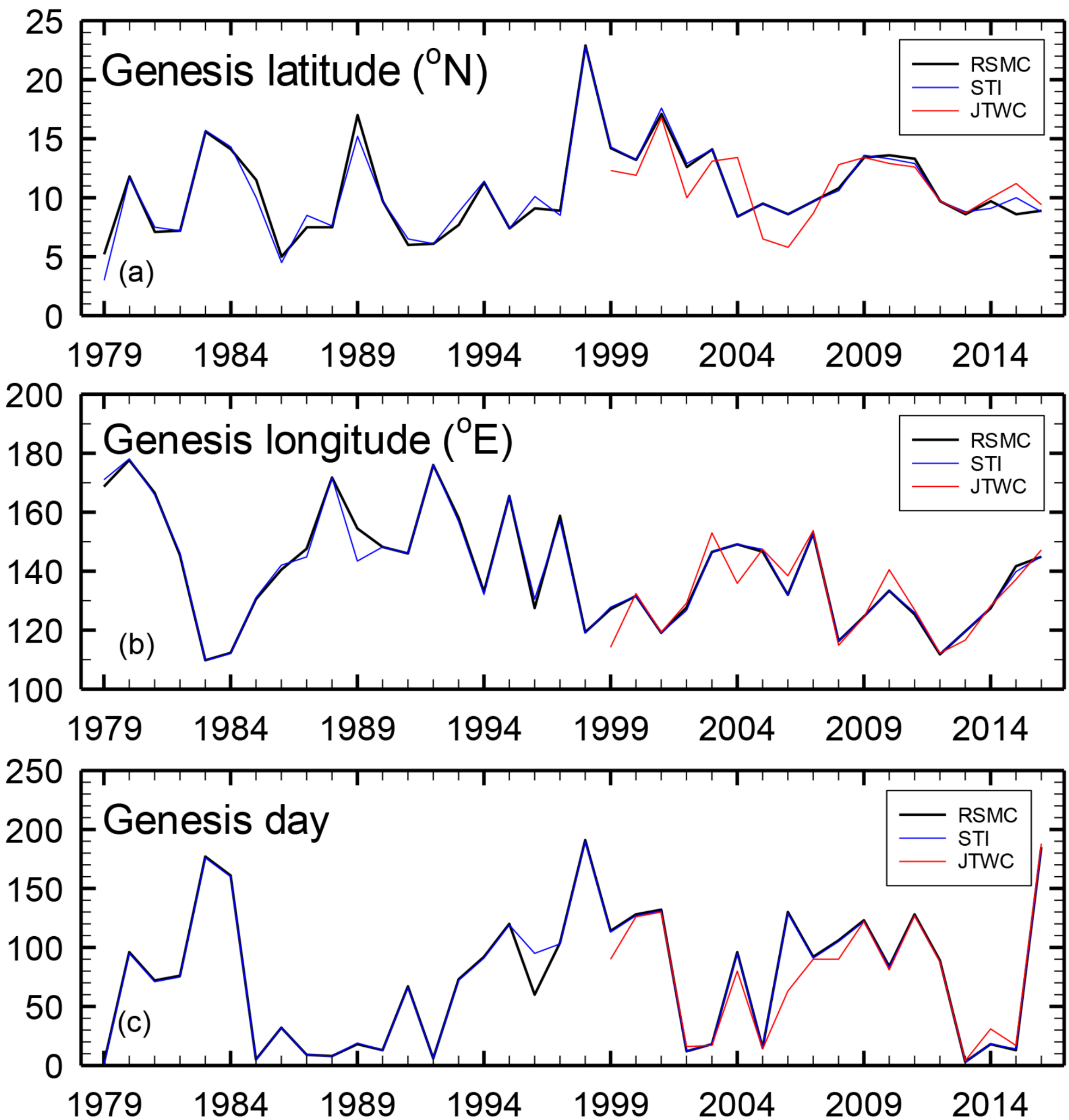

Fig. 1 Time series of (a) genesis latitude, (b) genesis longitude, and (c) genesis day (Julian day) of the yearly earliest tropical cyclone (TC) in the western North Pacific (WNP)

as the time when the absolute t-value obtained greater than 2.101 at the 95% conficence level ($p \leq 0.05$).

3 Results

3.1 Statistical change-point analysis

Figure 3 shows the 'normalized' time series charts of latitude, longitude, and day of the yearly earliest TC in the WNP. For statistical change-point analysis, these time series are generated from the standard normal distribution with a mean of zero and a s.d. of one (Beaulieu et al., 2012).

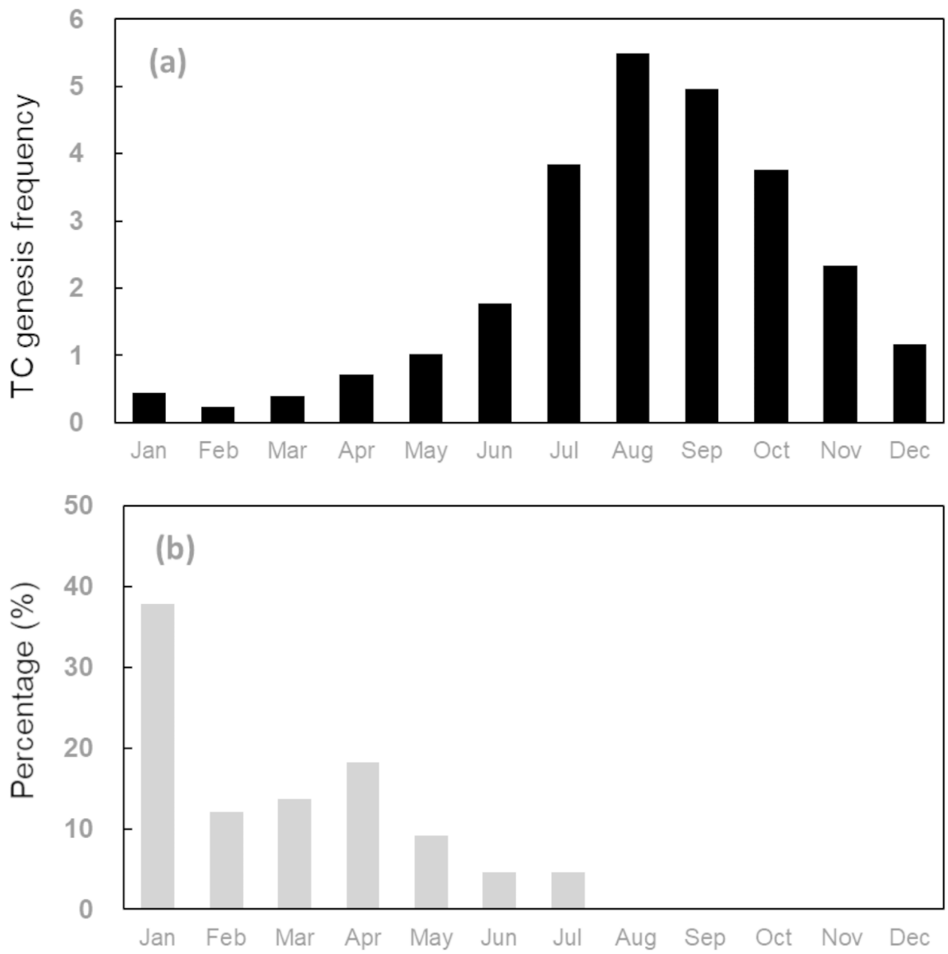

Fig. 2 . (a) Monthly mean distribution on the genesis frequency of all TCs in the WNP and (b) monthly percentage of the first TC genesis frequency based on 1951-2016

Normalizing provide good chances to construct confidence intervals for quantities (or magnitudes) associated with stationary time series. Thus, if normalized deviation is used, it is easy to find a signal indicating + or – changes (especially for an abrupt shift), and it is also easy to compare the data with other time series. First, in the time series of first TC genesis latitude, a distinct interdecadal variation was observed (Fig. 3a). The linear trend has shifted slightly to the north over 38 years, but it is not significant. However, if we focus on the climate regime shift rather than the long-term trend, it shows a statistically obvious difference. Statistical change-point analysis was applied to the TC genesis latitude data. The smallest t-value was observed in 1998, indicating the existence of a climate regime shift in TC genesis latitudes. The average TC genesis latitude during 1979–1997 was 9.2°N, whereas the average TC genesis latitude during 1998–2016 was 11.9°N—an increase of 2.7° from 1998. This means the genesis latitudes of TCs have moved 2.7° north on average. This difference in TC genesis latitude between these two periods is significant at the 95% confidence level ($p \leq 0.05$). The time series of TC genesis longitudes shows a distinct interdecadal variation, and hence, exhibits a distinct linearly decreasing trend, significant at the 95% confidence level ($p \leq 0.05$). Statistical change-point analysis was applied to this time series and showed the largest t-value occurred in 1998, which indicates the existence of a climate regime shift in TC genesis longitude. The average TC genesis longitude during 1979–1997 was 149.4°E, whereas the average during 1998–2016 was 131.4°E. This difference between the two periods of 18.0° is significant at the 95% confidence level ($p \leq 0.05$). This means the genesis longitude of TCs has moved 18.0° west on average. In the time series of TC genesis days, a distinct interdecadal variation exists. Although this time series showed an increasing linear trend, it is not statistically significant. Statistical change-point analysis was applied and showed the lowest t-value occurred in 1998, which indicates a climate regime shift in TC genesis day. The average TC genesis day during

1979–1997 was March 2, whereas the average TC genesis day during 1998–2016 was March 29, a difference of 27 days. Furthermore, this difference is significant at the 95% confidence level ($p \leq 0.05$), which means that TC genesis days have recently occurred later in the year. It is similar to that Corporal-Lodangco and Leslie (2017) confirmed the less active season start dates of Philippine TCs have been delayed as the substantially sharper trend slope since 1980. In summary, the first location for TC genesis has been moving northwest in the WNP, and TC genesis days after 1998 have been later in the year. Therefore, differences were analyzed between averages during 1998–2016 (hereinafter referred to as post-1998) and averages during 1979–1997 (hereinafter referred to as pre-1998).

The spatial distributions of the first TCs' genesis locations and the first TCs' full tracks were analyzed for each year from 1979 to 2016 (Fig. 4a and b). Here, the full track refers to the path for the TC activity duration with TS or higher intensity (TS). For spatial distributions of the first TC genesis locations by year, those TCs showed a tendency to occur over limited region between 0°N and 20°N in boreal winter and spring (Fig. 4a). Meanwhile, TCs post-1998 tended to occur mainly in the South China Sea (SCS) and near the Philippines, whereas TCs pre-1998 tended to occur in the southeast portion of the WNP. Thus, recent TCs have occurred more in the northwest portion of the WNP.

A TC full-track analysis showed TCs pre-1998 shifted west toward the Indochina Peninsula, whereas TCs post-1998 showed a strong tendency to shift toward the mid-latitude region of East Asia (Fig. 4b). Therefore, we analyzed the time series for the TS days, the duration which the yearly first TC was active with TS or higher intensity (Fig. 4c). The smallest TS-day value appeared in 1979, and the largest value was in 1998. Furthermore, this time series showed a distinct interdecadal variation. Consequently, the time series of TS-day values shows an increasing linear trend, and this linear trend is significant at the 95% confidence level ($p \leq 0.05$). This is believed to have occurred because TCs post-1998 moved further toward the mid-latitude region of East Asia. When statistical change-point analysis was applied to this time series, the lowest t-value occurred in 1998, indicating the existence of a climate regime shift in TS-days in 1998. The average TS-day value pre-1998 was 4.3 days, whereas the average post-1998 was 6.0 days. The difference between the two periods (1.7 days) is significant at the 90% confidence level ($p \leq 0.1$). This means that TCs have been stronger post-1998 compared to pre-1998.

3.2 Large-scale environments

To examine the cause of the recent shift in TC genesis locations toward the northwest portion of the WNP, the large-scale environments in these two periods were analyzed (Fig. 5). The period from January to May was divided into winter (January and February) and spring (March to May). Initially, we analyzed thermodynamic factors that influence TC genesis. OLR analysis showed that in winter, convection is active in the northwestern parts of the WNP, including the SCS and the Philippines, but is not active in the southeastern WNP (left panel of Fig. 5a), and this trend appeared to be stronger in spring (right panel of Fig. 5a). This result suggests environmental factors favored TC development in the northwestern WNP post-1998. OLR analysis provided information on total cloud cover (Fig. 5b). In winter, there is a positive anomaly that extends from the SCS and the northeast region of the Philippines to the mid-latitude region of the WNP, whereas in the southeastern WNP, there is a negative anomaly (left panel of Fig. 5b). This spatial distribution becomes more distinct in spring (right panel of Fig. 5b). Differences between the spatial distributions of precipitable water in these two periods (Fig. 5c) were similar to the spatial distributions of total cloud cover; that is, a positive anomaly existed from the SCS and near the Philippines to the mid-latitude region of the WNP, and a negative anomaly was present in the southeastern WNP. Thus, our analysis of differences in winter and spring precipitations between the two periods (Fig. 5d) showed a positive anomaly in the SCS and near the Philippines, and a negative anomaly in the southeastern WNP.

Dynamic factors that influence TC genesis were also analyzed. In spring, VWS showed a negative anomaly in the SCS and the northern Philippines and a positive anomaly in the southeastern WNP (right panel of Fig. 5e). A smaller VWS value stabilizes the upper and lower layers of the troposphere, which provides a more favorable environment for TC genesis. The different spatial distributions of VWS in the northwestern and southeastern WNP became more distinct in spring (right panel of Fig. 5e). Analysis of 850 hPa relative vorticity showed a positive anomaly in the SCS and near the Philippines and a negative anomaly in the southeast part of the WNP in both winter and spring (Fig. 5f).

In January-May, warm SST anomaly appears in the southwest-northeast of WNP from the warm pool region to the central North Pacific, while cold SST anomaly showed in the southeast portion of WNP (Fig. 5 g). This spatial distribution provided a marine environment post-1998 that favored TC development in the northwestern WNP associated with the cold phase of PDO.

GPI analysis, which included all thermodynamic and dynamic factors that influence TC genesis, showed that in winter, a positive anomaly exists from the east sea of the Philippines to the southern portion of the SCS, and a negative anomaly exists in the southeastern parts of the WNP (left panel of Fig. 5h). These results show that the GPI

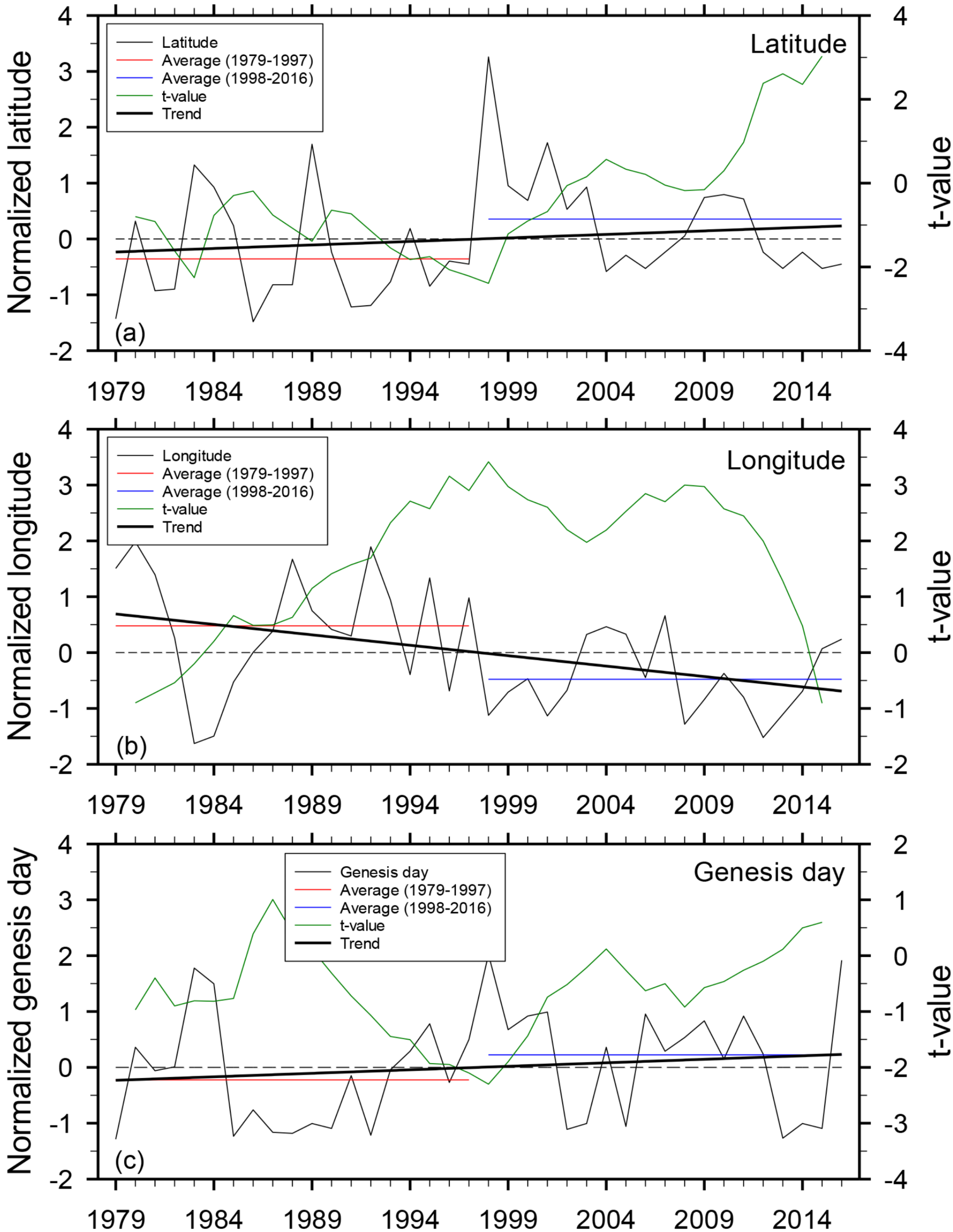

Fig. 3 The results of statistical change-point analysis on (a) normalized genesis latitude, (b) normalized genesis longitude, and (c) normalized genesis day of the first yearly TC in the WNP

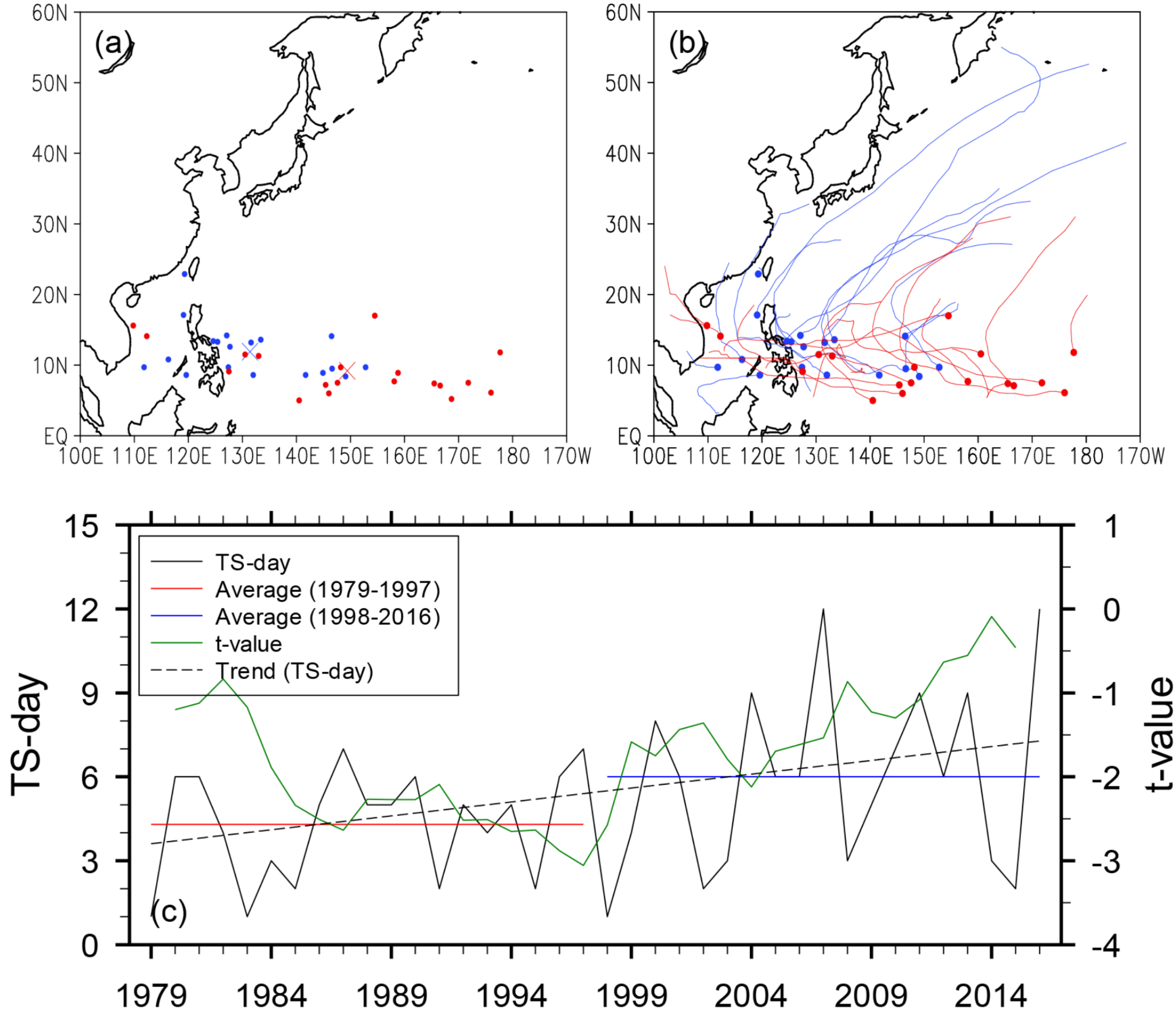

Fig. 4 (a) TC genesis location, and (b) TC full tracks, with pre-1998 data shown with blue dots and blue tracks and post-1998 data shown with red dots and red tracks. In (a), red and blue crosses denote mean TC genesis locations pre-1998 (9.2°N, 149.4°E) and post-1998 (11.9°E, 131.4°E), respectively. (c) The time series of tropical storm (TS) days from the period 1979–1997

spatial contrast between the northwestern and southeastern parts of the WNP in winter becomes more evident in spring (right panel of Fig. 5h).

In addition, horizontal divergence between lower and upper levels in boreal winter and spring were analyzed (Fig. 6). At 850 hPa, in both winter and spring, there was a negative anomaly in the western portion of the WNP and a positive anomaly in the eastern portion (Fig. 6a). In contrast, at 200 hPa, there was a positive anomaly in the SCS and northern Philippines and a negative anomaly in the eastern WNP (Fig. 6b). This suggests that anomalous upward flows strengthened in the western WNP post-1998, and anomalous downward flows occurred in the eastern WNP.

A time series of factors influencing TC genesis, averaged for the SCS and near the Philippines (10°N–20°N, 110°E–130°E) and the southeastern WNP (5°N–15°N, 140°E–180°E) were also analyzed (Fig. 7). These factors were averaged for the period from January to May. The OLR and VWS showed a decreasing linear trend in the SCS and the seas near the Philippines, whereas SST and GPI showed an increasing linear trend, and these trends for all four factors are significant at the 95% confidence level ($p \leq 0.05$). In contrast, in the southeastern WNP, OLR and VWS showed an increasing linear trend, whereas SST and GPI showed a strong decreasing linear trend, and these trends are also significant at the 95% confidence level ($p \leq 0.05$). The above results indicate that a favorable environment for

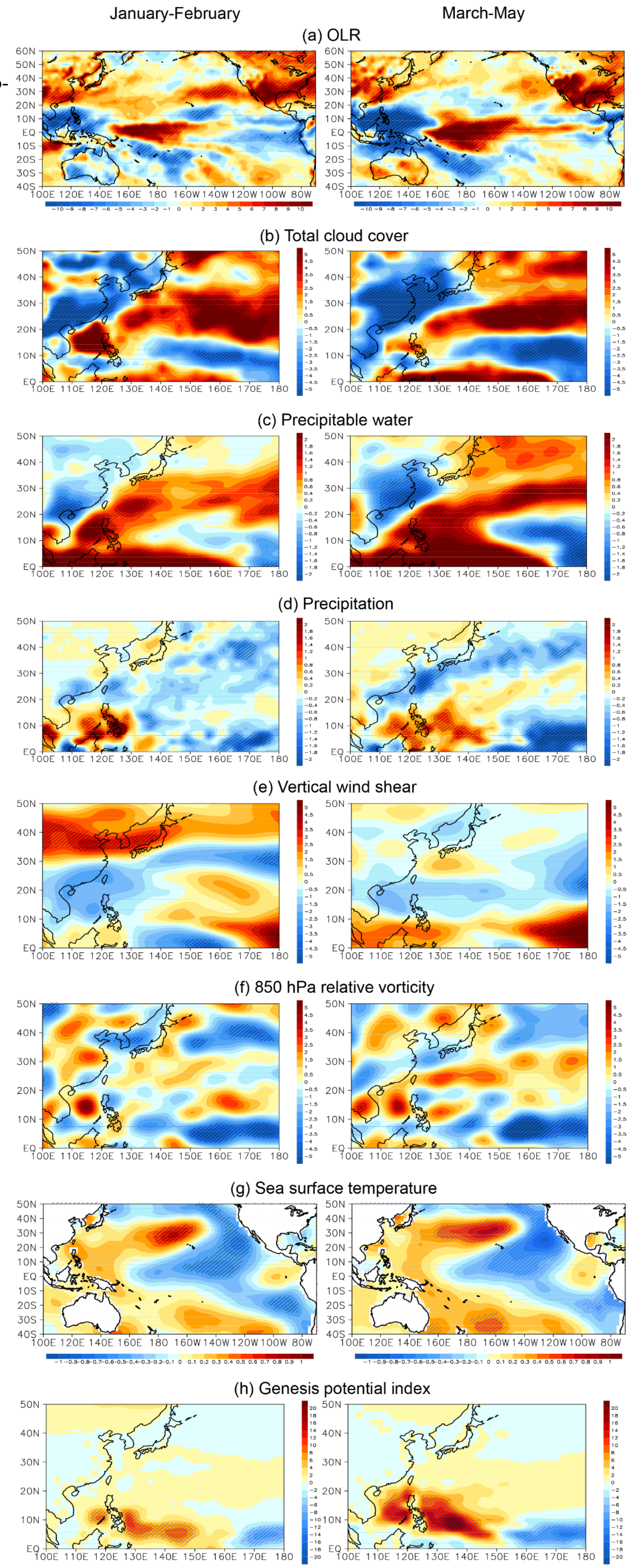

Fig. 5 Composite differences in (a) OLR, (b) total cloud cover, (c) precipitable water, (d) precipitation, (e) vertical wind shear (VWS), (f) 850 hPa relative vorticity, (g) SST, and (h) genesis potential index (GPI) post-1998 and pre-1998 for January and February (left panels) and for March to May (right panels). Hatched lines are significant at the 95% confidence level

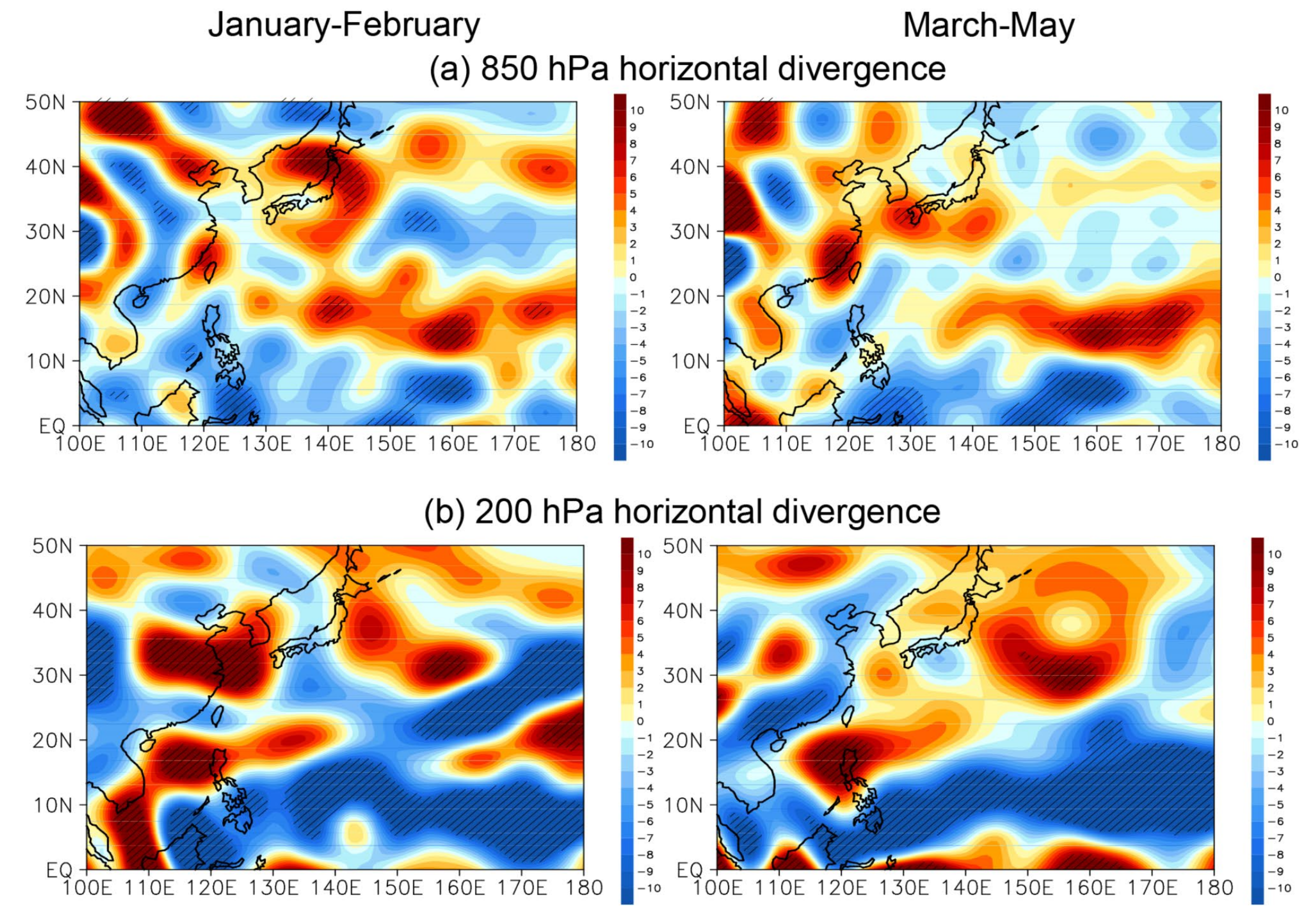

Fig. 6 Composite differences in (a) 850 hPa and (b) 200 hPa horizontal divergence (units: $s^{1} \times 10^{7}$) post-1998 and pre-1998 in January and February (left panels) and for March to May (right panels). Hatched lines are significant at the 95% confidence level

TC genesis recently formed in the SCS and near the Philippines, whereas an unfavorable environment for TC genesis recently formed in the southeastern portion of the WNP. Because the time series of these four factors in these two regions exhibit a distinct interdecadal variation, we applied statistical change-point analysis to each time series. Notably, all tvalues had the largest or smallest values in 1998, thus indicating the existence of a climate regime shift in the time series of the four factors in 1998 associated with the movement of the first TC genesis location to the northwestern portion of the WNP.

3.3 Atmospheric circulations

We also analyzed differences in lower- and upper-level stream flows in boreal winter and spring pre- and post-1998 (Fig. 8). At 850 hPa in winter, an anomalous cyclonic circulation formed in the SCS (left panel of Fig. 8a). In contrast, a huge anomalous anticyclonic circulation formed in the North Pacific with a ridge extending to the east seas of the Philippines, which strengthened anomalous trade winds in the equatorial Pacific, and this anomalous atmospheric circulation pattern was associated with the cold PDO phase. In spring (the right panel of Fig. 8a), the spatial distribution of atmospheric circulation was similar to that observed in winter. Anomalous cyclonic circulation was strengthened from the SCS to the East China Sea (ECS), and anomalous anticyclonic circulation formed northeast to southwest, from the North Pacific to the east seas of the Philippines. As a result, anomalous trade winds strengthened in the equatorial Pacific. At 200 hPa in boreal winter and spring, an anomalous anticyclonic circulation strengthened in the SCS, whereas anomalous cyclonic circulation formed in the east seas of the Philippines (Fig. 8b), and as a result, anomalous westerlies were strengthened in the equatorial Pacific. Thus, we can see that an anomalous cyclone and an anomalous anticyclone formed in the lower and upper levels, respectively, in the SCS and near the Philippines, whereas opposite anomalous pressure systems formed in the lower and upper levels of the southeastern parts of the WNP.

The above results regarding SST differences during the two periods show that the spatial pattern observed was

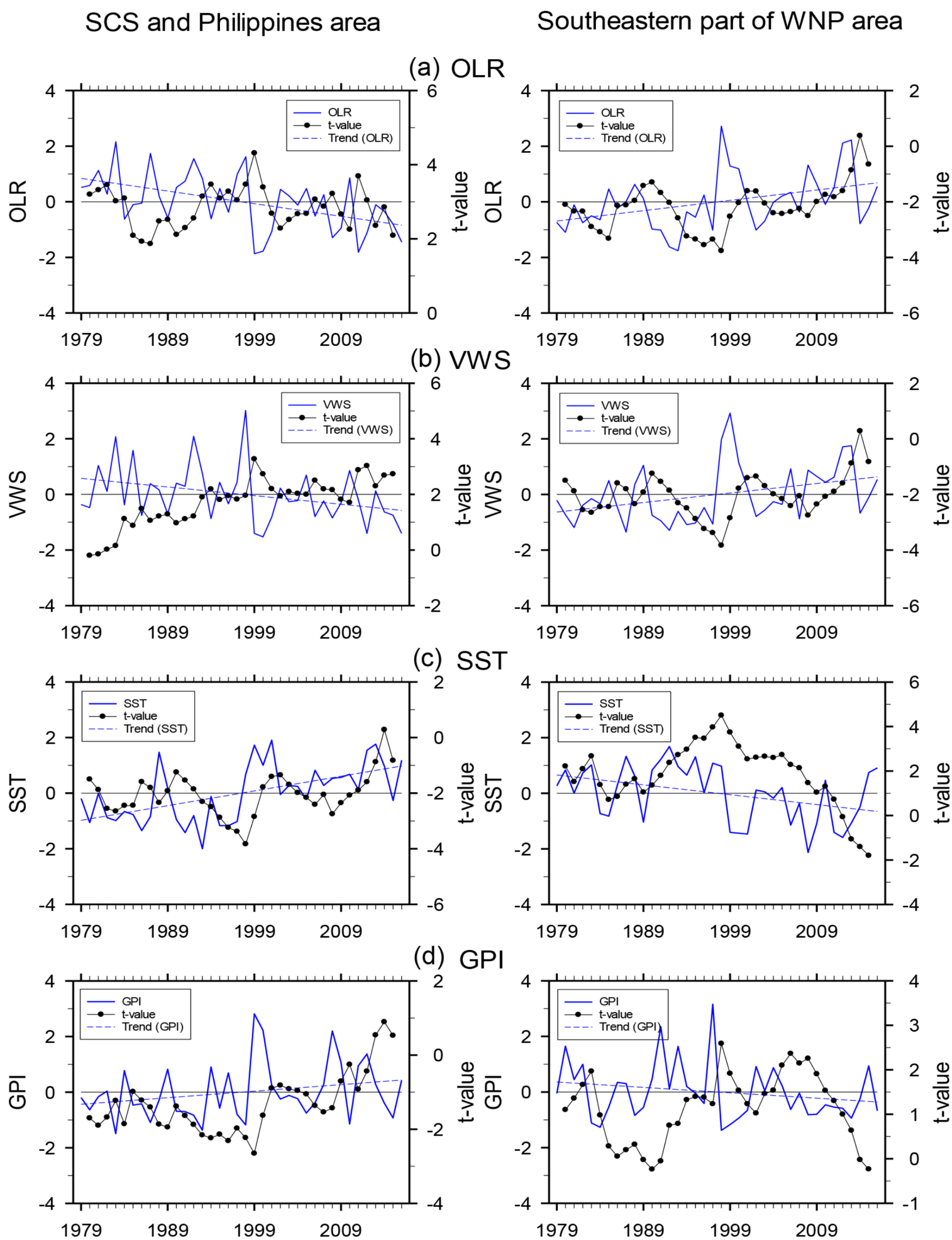

Fig. 7 The results of statistical change-point analysis on normalized (a) OLR, (b) VWS, (c) SST, and (d) GPI in the South China Sea (SCS) and the Philippines (left panels), and the southeastern portion of the WNP (right panels)

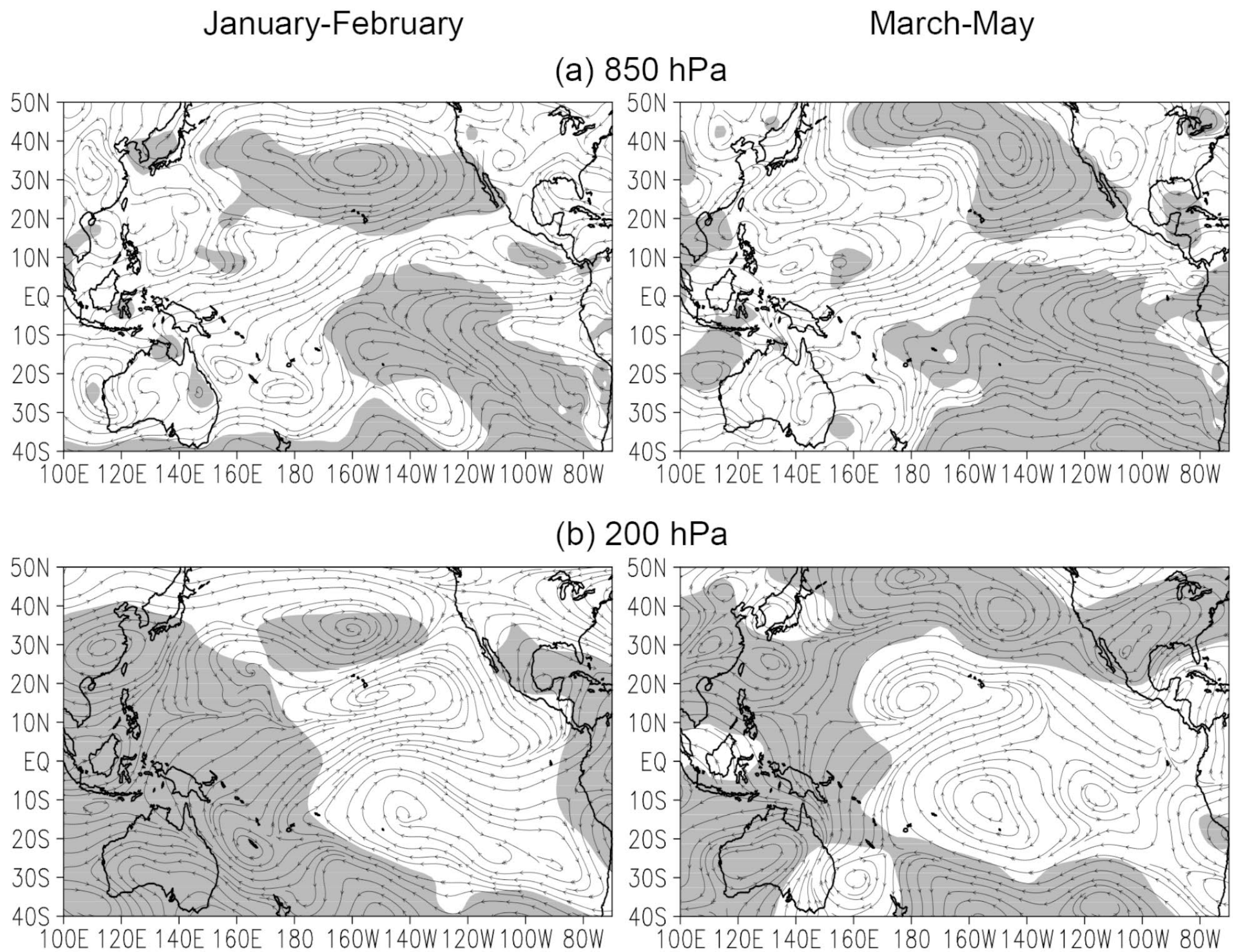

Fig. 8 Composite differences in (a) 850 hPa stream flow and (b) 200 hPa stream flow post-1998 and pre-1998 for January and February (left panels) and for March to May (right panels). Shaded areas are significant at the 95% confidence level

associated with PDO. In addition, analysis results of atmospheric circulation differences also showed that the anomalous circulation was associated with PDO, and thus, we analyzed correlations among PDO averaged from January to May and TC genesis latitude, TC genesis longitude, and TC genesis day (Fig. 9). A negative correlation (0.54) was observed between PDO and TC genesis latitude (Fig. 9a), which is significant at the 99% confidence level ($p \leq 0.01$). Since PDO shows a strong linear trend with the cold phase, the correlation was reanalyzed after removing the linear trend from the two variables, and the correlation did not differ significantly from the first correlation (r = -0.53; significant at the 99% confidence level, $p \leq 0.01$). This means that the stronger (or weaker) the PDO cold phase, the greater the tendency for TC genesis locations to move north (or south). Furthermore, a positive correlation of 0.57 was observed between PDO and TC genesis longitude (Fig. 9b), which is significant at the 99% confidence level ($p \leq 0.01$). The correlation was analyzed again after removing the linear trend from the two variables, and the correlation did not significantly differ from the first correlation ($r = 0.54$; significant at the 99% confidence level, $p \leq 0.01$). This means that the stronger (or weaker) the PDO cold phase, the greater the tendency for TC genesis locations to move west (or east). A negative correlation (-0.48) was observed between PDO and TC genesis day (Fig. 9c), and this correlation is significant at the 99% confidence level ($p \leq 0.01$). The correlation was reanalyzed after removing the linear trend from the two variables, and again was not significantly different from the first correlation (r = -0.46; significant at the 99% confidence level, $p \leq 0.01$). This means when the PDO cold phase is stronger (or weaker), TC genesis occurs later (or sooner). In other words, the above results show that in the PDO's cold (or warm) phase, TCs have a strong tendency to occur in the northwestern (or southeastern) region of the WNP, and TC genesis tends to occur later (or sooner). Statistical change-point analysis was applied to the PDO time series. The highest t-value occurred in 1998, and a climate regime

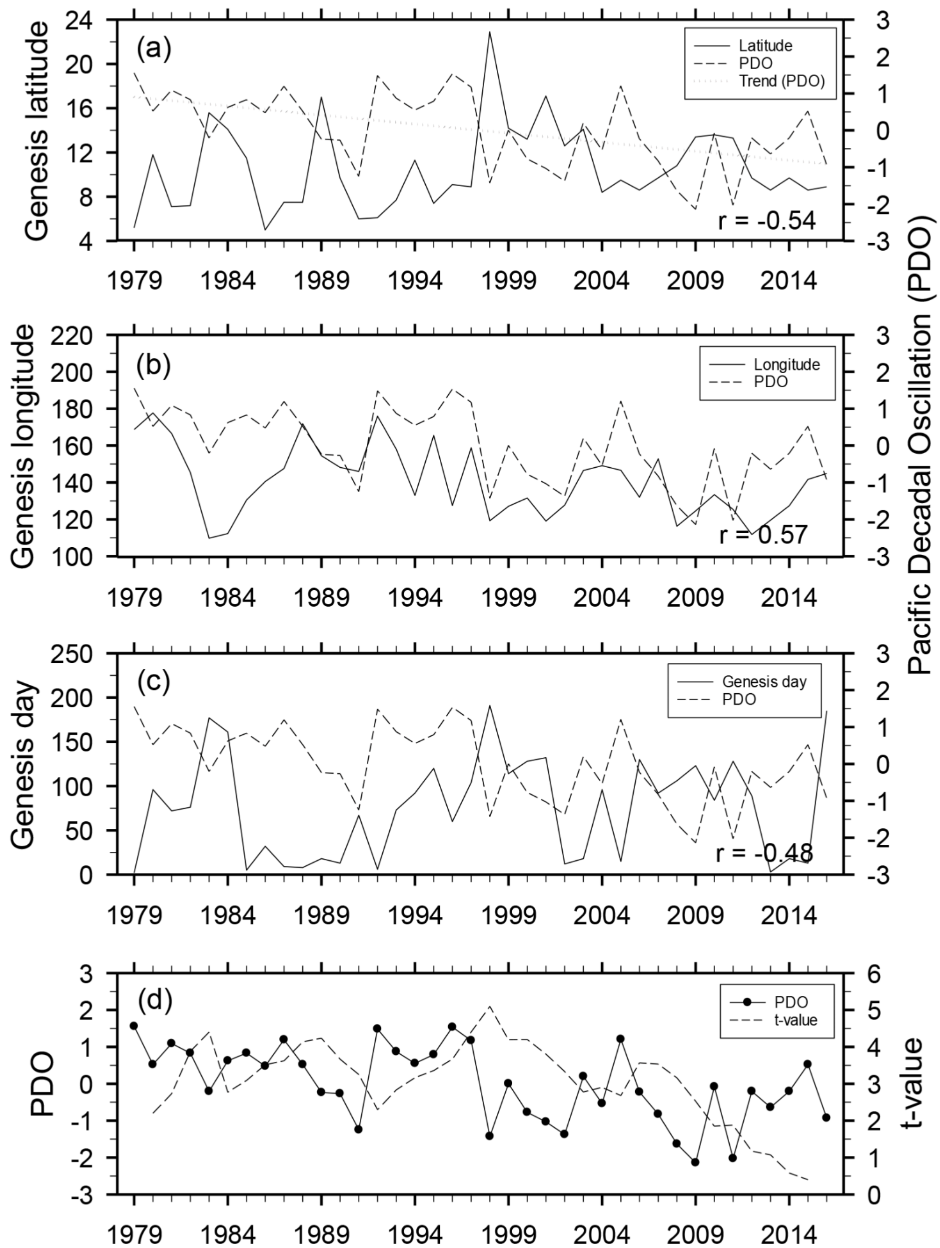

Fig. 9 Relationships between (a) TC genesis latitude and Pacific Decadal Oscillation (PDO), (b) TC genesis longitude and PDO, and (c) TC genesis day (Julian day) and PDO. (d) The results of statistical change-point analysis on PDO

shift in the PDO time series also occurred during 1998. Furthermore, PDO showed a high correlation with interdecadal and interannual variations in the TC genesis locations and TC genesis days.

Post-1998 in the equatorial Pacific, anomalous trade winds strengthened at 850 hPa, and the anomalous westerlies strengthened at 200 hPa (see Fig. 8), which suggests that Walker circulation strengthened post-1998. Thus, we analyzed vertical zonal circulation averages for 0°N–20°N (Fig. 10a). In both winter and spring, anomalous upward flows developed at 130°E–150°E, whereas anomalous downward flows developed at 170°E–160°W, and these anomalous upward flows and anomalous downward flows are significant at the 95% confidence level ($p \leq 0.05$). This means that anomalous Walker circulation caused air to rise in the tropical western Pacific and descend in the tropical equatorial Pacific post-1998. Such strengthening of anomalous Walker circulation post-1998 was also observed in an analysis of 850 hPa velocity potential during the two periods (Fig. 10b). In boreal winter and spring, anomalous convergence developed in the tropical western Pacific, whereas anomalous divergence strengthened in the tropical central

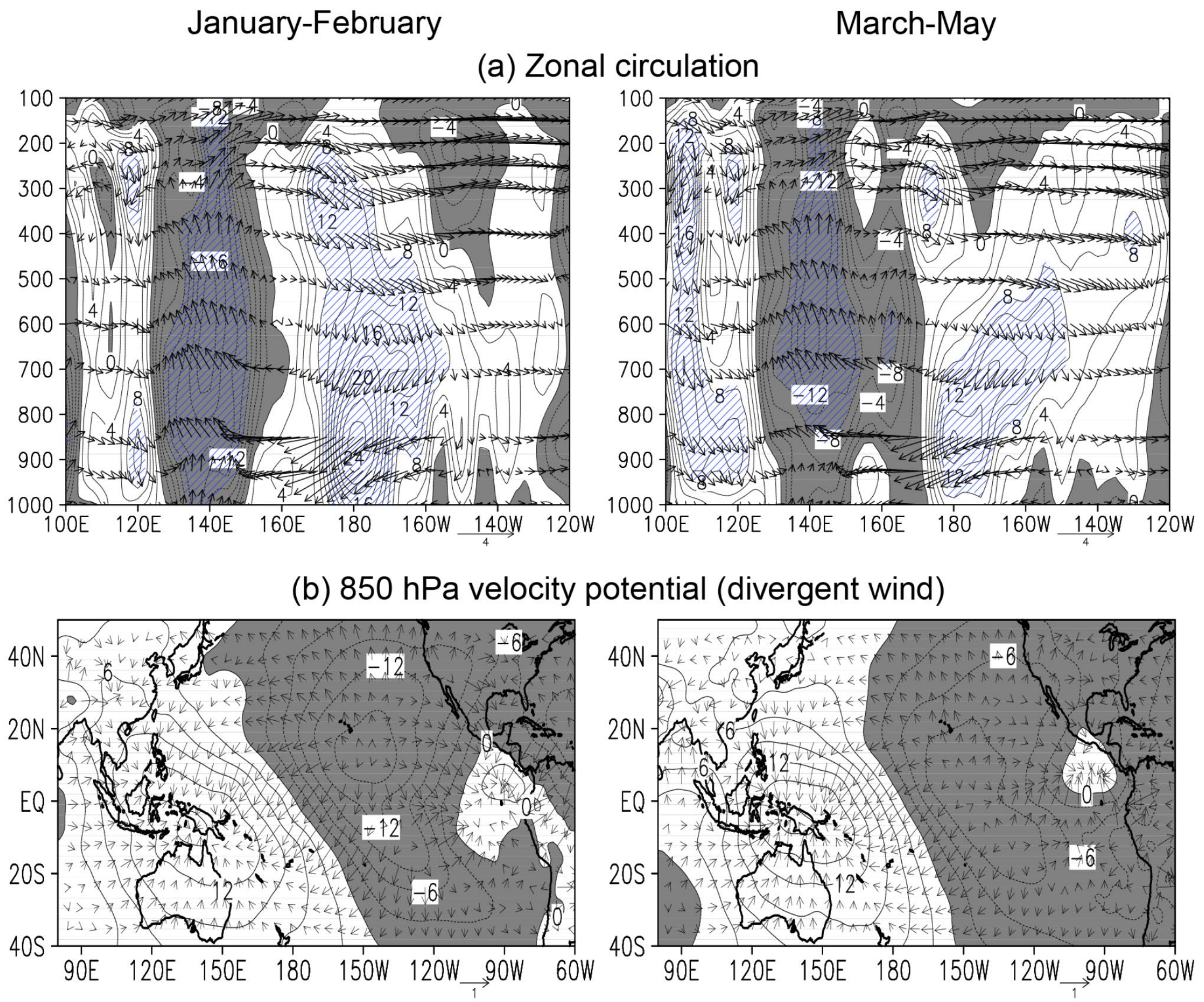

Fig. 10 Composite differences in a longitude–pressure cross section of (a) vertical velocity (contours) and zonal circulation (vectors) averaged along 0°N–20°N and (b) 850 hPa velocity potential post-1998 and pre-1998 for January and February (left panels) and for March to May (right panels). In (a), the values of vertical velocity are multiplied by – 100, dashed lines are significant at the 95% confidence level, and contour intervals are 2^{-2} hPa s^{-1}. In (b), shaded areas denote negative anomalies, and the contour interval is 3 $m^2s^{-1}10^{-6}$

and eastern Pacific. This means that anomalous Walker circulation, whereby air rises in the tropical western Pacific and descends in the tropical equatorial Pacific, was enhanced post-1998.

Therefore, we analyzed correlations between the 850 hPa trade wind index and the 200 hPa zonal wind index (averaged for January to May) and TC genesis latitude, TC genesis longitude, and TC genesis day (Fig. 11a and c). The time series for the trade wind index and TC genesis latitude showed distinct interannual and interdecadal variations (left panel of Fig. 11a). The trade wind index showed a linear weakening trend, and this linear trend is significant at the 90% confidence level ($p \le 0.1$). Since there was a distinct out-of-phase tendency between the two time series, we examined the correlation between the two and found a negative correlation (-0.48), which is significant at the 99% confidence level ($p \le 0.01$). This negative correlation did not change significantly when the linear trend was removed from the two time series (r = -0.47; significant at the 99% confidence level, $p \le 0.01$). This result means that as the trade wind strengthened (or weakened), TC genesis occurred more in the south (or north). The time series for the trade wind index and TC genesis longitudes also showed distinct interannual and interdecadal variations, and these two time series exhibited an in-phase trend (left panel of Fig. 11b). Therefore, the correlation between the two variables was analyzed, and it showed a positive correlation of 0.46, which is significant at the 99% confidence level

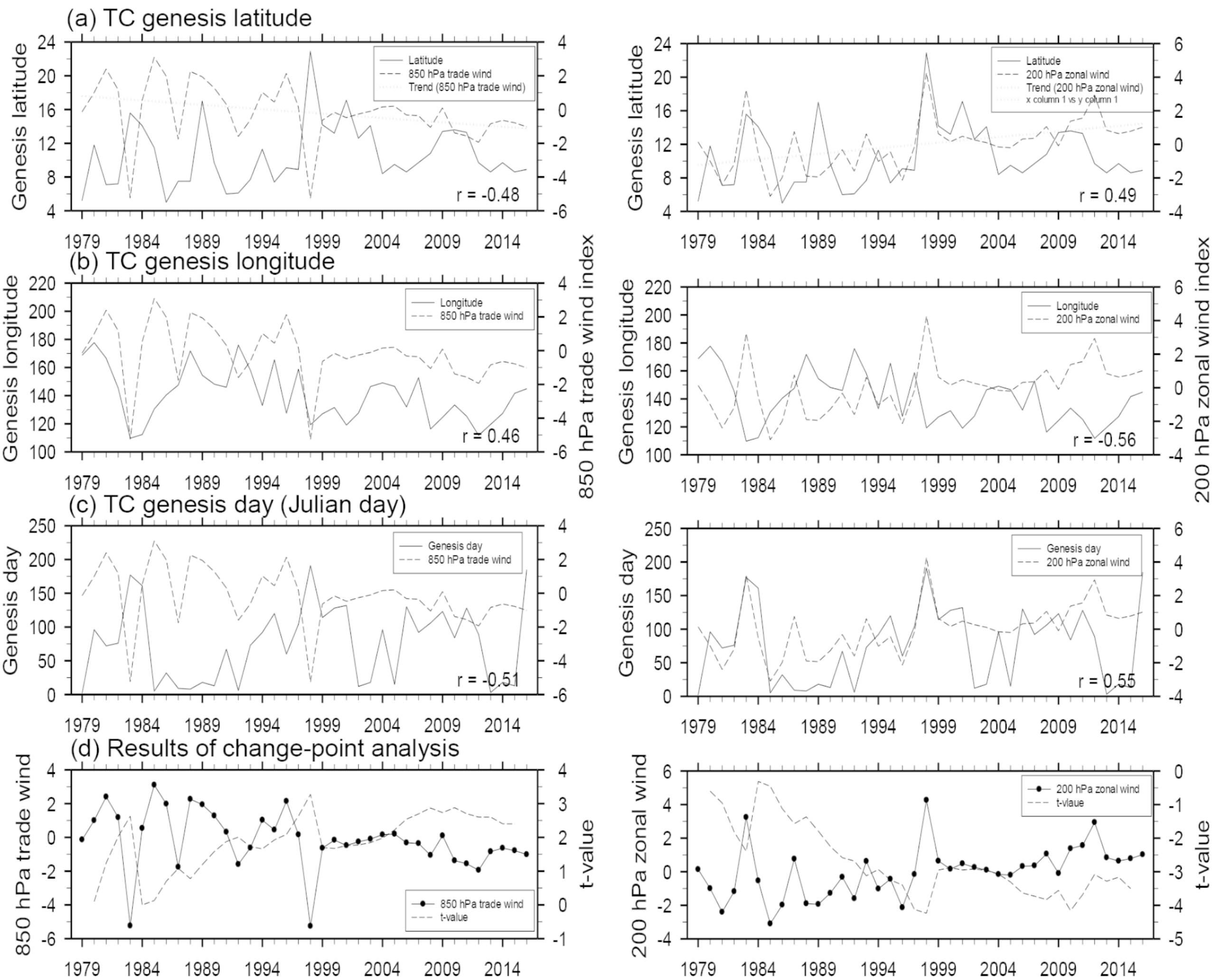

Fig. 11 Relationships in the 850 hPa trade wind index (left panels) and the 200 hPa zonal wind index (right panels) between (a) TC genesis latitude, (b) TC genesis longitude, and (c) TC genesis day (Julian day). (d) Results of statistical change-point analysis in the 850 hPa trade wind index (left panel) and 200 hPa zonal wind index (right panel)

($p \leq 0.01$). Since these two variables showed a large linear trend, the correlation was analyzed again after the linear trend was removed, and this resulted in a positive correlation of 0.51, which is greater than the first correlation and significant at the 99% confidence level ($p \leq 0.01$). This means that as the trade wind strengthened (or weakened), TC genesis occurred more in the west (or east). The time series for the trade wind index and the TC genesis day also showed distinct interannual and interdecadal variations, and a distinct out-of-phase trend between the two (left panel of Fig. 11c). Therefore, the correlation between the two variables was analyzed and it showed a high negative correlation (-0.51), which is significant at the 99% confidence level ($p \leq 0.01$). Removal of the linear trend had little effect on the correlation (r = -0.52; significant at the 99% confidence level, $p \leq 0.01$). This means that as the trade wind strengthened (or weakened), TC genesis occurred later (or sooner). Thus, statistical change-point analysis was applied to the trade wind index time series (left panel of Fig. 11d). The trade wind index also had its largest t-value in 1998, indicating the existence of a climate regime shift in 1998.

Correlations among the 200 hPa zonal wind index and the TC genesis latitude, TC genesis longitude, and TC genesis day showed opposite correlations to those observed in the trade wind index. The 200 hPa zonal wind index and the TC genesis latitude showed a positive correlation of 0.49 (right panel of Fig. 11a), while the 200 hPa zonal wind index and the TC genesis longitude showed a high negative correlation of -0.56 (right panel of Fig. 11b). The 200 hPa zonal wind index and the TC genesis day showed a high positive correlation of 0.55 (right panel Fig. 11c). All three correlation results are significant at the 99% confidence level ($p \leq 0.01$).

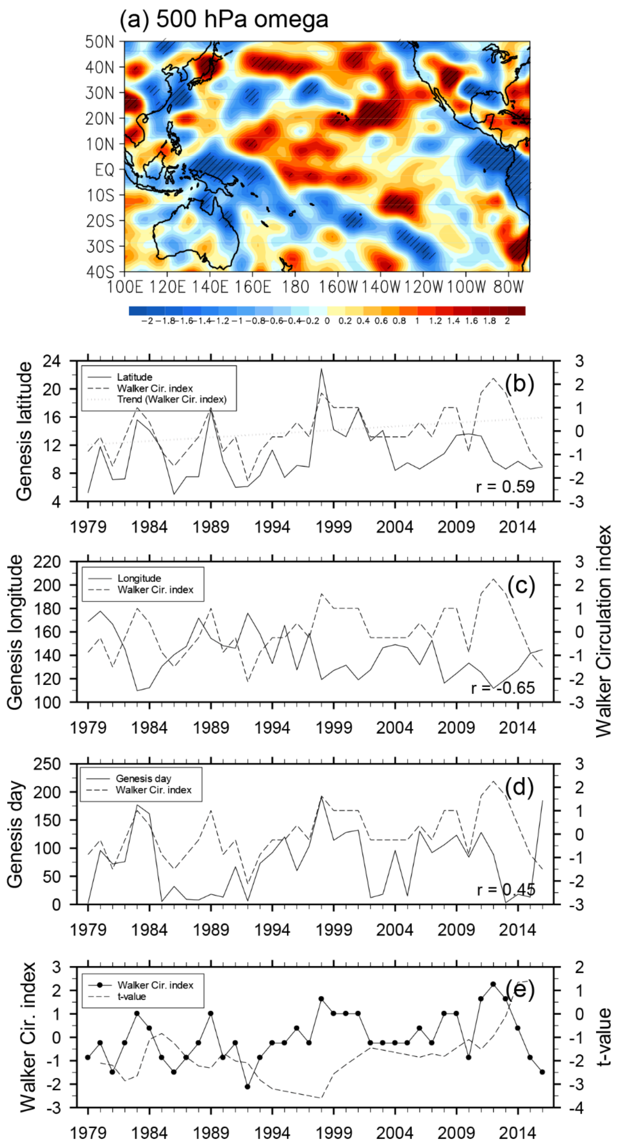

Fig. 12 Composite difference in (a) 500 hPa omega post-1998 and pre-1998 for January to May. Parts (b) to (d) show relationships between the Walker circulation index and (b) TC genesis latitude, (c) TC genesis longitude, and (d) TC genesis day (Julian day). (e) Results of statistical change-point analysis on the Walker circulation index

When correlations were reanalyzed after removing linear trends from the time series, results did not differ appreciably, with all three correlations significant at the 99% confidence level ($p \leq 0.01$). This means that when the 200 hPa zonal wind strengthened, TC genesis showed a strong trend to occur in the northwest portion of the WNP, and TC genesis days were delayed. The 200 hPa zonal wind index continued to show a significant increasing linear trend (significant at the 90% confidence level, ($p \leq 0.1$)). Because it showed a distinct interdecadal variation, statistical change-point analysis was applied (right panel of Fig. 11d). This analysis showed the t-value was lowest in 1998, indicating the existence of a climate regime shift in the 200 hPa zonal wind index time series in 1998.

To examine the strengthening of Walker circulation post-1998, we analyzed 500 hPa omega differences between the two periods (Fig. 12a). The negative anomaly strengthened in the equatorial western Pacific, the SCS, and near the Philippines, whereas a positive anomaly formed in the subtropical and tropical central Pacific. This means the Walker circulation, whereby air rises in the tropical western Pacific and descends in the tropical central Pacific, strengthened. We analyzed correlations between the Walker circulation index and the TC genesis latitude, TC genesis longitude, and TC genesis day (Fig. 12b and d). The time series of the Walker circulation index and of the TC genesis latitude show distinct interannual and interdecadal variations (Fig. 12b). The Walker circulation index continued to show an increasing linear trend, and this trend is significant at the 90% confidence level ($p < 0.02$). A distinct in-phase trend is observed between these two time series. Correlation analysis showed a high positive correlation of 0.59 between the two variables, which is significant at the 99% confidence level ($p \leq 0.01$), and this correlation was unaffected after removing the linear trend from the two variables ($r = 0.57$; significant at the 99% confidence level, $p \leq 0.01$). This means that when the Walker circulation strengthens (or weakens), TC genesis shows a strong tendency to move north (or south).

The Walker circulation index and TC genesis longitudes show a high negative correlation (-0.65) (Fig. 12c), which is significant at the 99% confidence level ($p \leq 0.01$). Since the linear trends of these two variables had large variations, their correlation was analyzed again after removing the linear trend from the two time series, which resulted in a higher negative correlation ($r = -0.68$; significant at the 99% confidence level, $p \leq 0.01$). This means that when the Walker circulation strengthens (or weakens), TC genesis occurs more in the west (or east). The Walker circulation index and the TC genesis day show a positive correlation of 0.45, which is significant at the 99% confidence level ($p \leq 0.01$) (Fig. 12d). Furthermore, when the linear trend was removed from the two time series, this correlation was virtually unaffected ($r = 0.46$; significant at the 99% confidence level, $p \leq 0.01$). This means that when the Walker circulation strengthens, TC genesis is delayed. Since the Walker circulation index also shows considerable interdecadal variations, we applied statistical change-point analysis to that time series (Fig. 12e). The t-value was lowest in 1998, indicating the existence of a climate regime shift in the Walker circulation index in 1998.

3.4 Monthly variations of OLR and WNPSH

To examine in more detail why TCs post-1998 occurred more in the northwestern portion of the WNP, differences between OLR post-1998 and in the overall climatology (1979–2016), and differences between OLR pre-1998 and the climatology were analyzed for the months from January to May (Fig. 13). Overall, the analysis results show opposite monthly spatial patterns. Regarding differences post-1998 and in the climatology, a strong negative anomaly was observed in the northwestern portion of the WNP, with a strong positive anomaly in the southeastern WNP (left panels of Fig. 13). By contrast, the differences pre-1998 versus the climatology revealed a strong positive anomaly in the northwestern WNP and a strong negative anomaly in the southeastern WNP (right panels of Fig. 13). These characteristics of spatial distribution were more distinct in the January to May monthly averages (Fig. 13f). Pattern correlation analysis was applied to the spatial distribution of differences post-1998 and in the climatology for each month, to the spatial distribution of the differences pre-1998 and in the climatology for each month, and for January to May monthly averages. The results showed a high negative correlation (≥ -0.75). Furthermore, pattern correlation analysis of the two spatial distributions for January to May averages showed a high negative correlation (-0.92). Therefore, these results show TCs pre-1998 tended to form in the southeastern portion of the WNP, whereas TCs post-1998 tended to form in the northwestern WNP.

To determine the reason for the recent delays in TC genesis, we examined the characteristics of the monthly spatial distributions in the average western North Pacific subtropical highs (WNPSHs) from January to May pre- and post-1998 (Fig. 14a and e). Here, a WNPSH is defined as a region larger than 5,870 gpm. Monthly WNPSHs post-1998 developed in more east-to-west and south-to-north directions than pre-1998. This characteristic was also more distinct for the January-to-May averages (Fig. 14f). The WNPSH expansion is a factor that can curb the occurrence of the first TC. In particular, the PDO-related mixed layer and surface heat flux are characterized by maximum variance in boreal winter and early spring and tend to weaken from late spring to early autumn (warm season) (Alexander et al. 1999; Wang et al. 2012). Therefore, the marked expansion of the WNPSH in boreal winter created an unfavorable condition for TC genesis, and the unfavorable condition was diminished in March-May. Hence, the genesis of TCs post-1998 was reduced in the WNP when WNPSHs were more developed, which delayed TC genesis and reduced TC genesis frequency (TCGF) (Fig. 14g). In fact, TCGF from January to May continued to follow a linear decreasing trend throughout the study period. Furthermore, average TCGF pre-1998 was 3.4 TCs, whereas average TCGF post-1998 was 1.9 TCs, and this difference of 1.5 TCs is significant at the 95% confidence level ($p \le 0.05$).

4 Summary and conclusions

This study analyzed time series data for genesis latitude, genesis longitude, and genesis day for the first TCs in each year over the period 1979–2016. Statistical change-point analysis indicated the existence of a climate regime shift in 1998 for all three variables. In other words, recent TCs have shown a stronger tendency to occur more frequently in the northwestern portion of the WNP. Therefore, we analyzed differences pre-1998 and post-1998 in terms of thermodynamic and dynamic factors.

To examine the cause of the occurrence of more TCs recently in northwestern WNP, large-scale environments were analyzed pre-1998 and post-1998. The period from January to May was divided into winter (January and February) and spring (March to May). Initially, we analyzed thermodynamic factors that influence TC genesis. OLR analysis showed that convection was active in the northwestern portion of the WNP, including the SCS and near the Philippines, whereas convection was not active in southeastern WNP.

Next, we analyzed dynamic factors that influence TC genesis. VWS showed a negative anomaly in the northern region of the Philippines and the SCS, and a positive anomaly in the southeastern portion of the WNP. However, 850 hPa relative vorticity results showed a positive anomaly in the SCS and near the Philippines but a negative anomaly in southeastern WNP.

SSTs showed a warm anomaly from the southwest to the northeast and from the warm WNP pool region to the mid-latitude region of the central Pacific, but showed a cold anomaly from southeastern WNP to the tropical central Pacific and the east coast of the U.S. Furthermore, this spatial distribution of SST anomaly was associated with the cold phase of PDO.

We also analyzed differences between lower- and upper-level stream flows in boreal winter and spring, pre- and post-1998. Figure 15 shows schematic diagram of 850 hPa anomalous atmospheric circulation in cold PDO phase in post-1998. At 850 hPa, an anomalous cyclonic circulation was observed in the SCS along with a huge, anomalous anticyclonic circulation in the North Pacific. From this circulation, a ridge extended to the east sea of the Philippines (Fig. 15). Consequently, anomalous trade winds were strengthened in the equatorial Pacific. This anomalous atmospheric circulation was associated with the cold PDO phase. At 200 hPa, an anomalous anticyclonic circulation

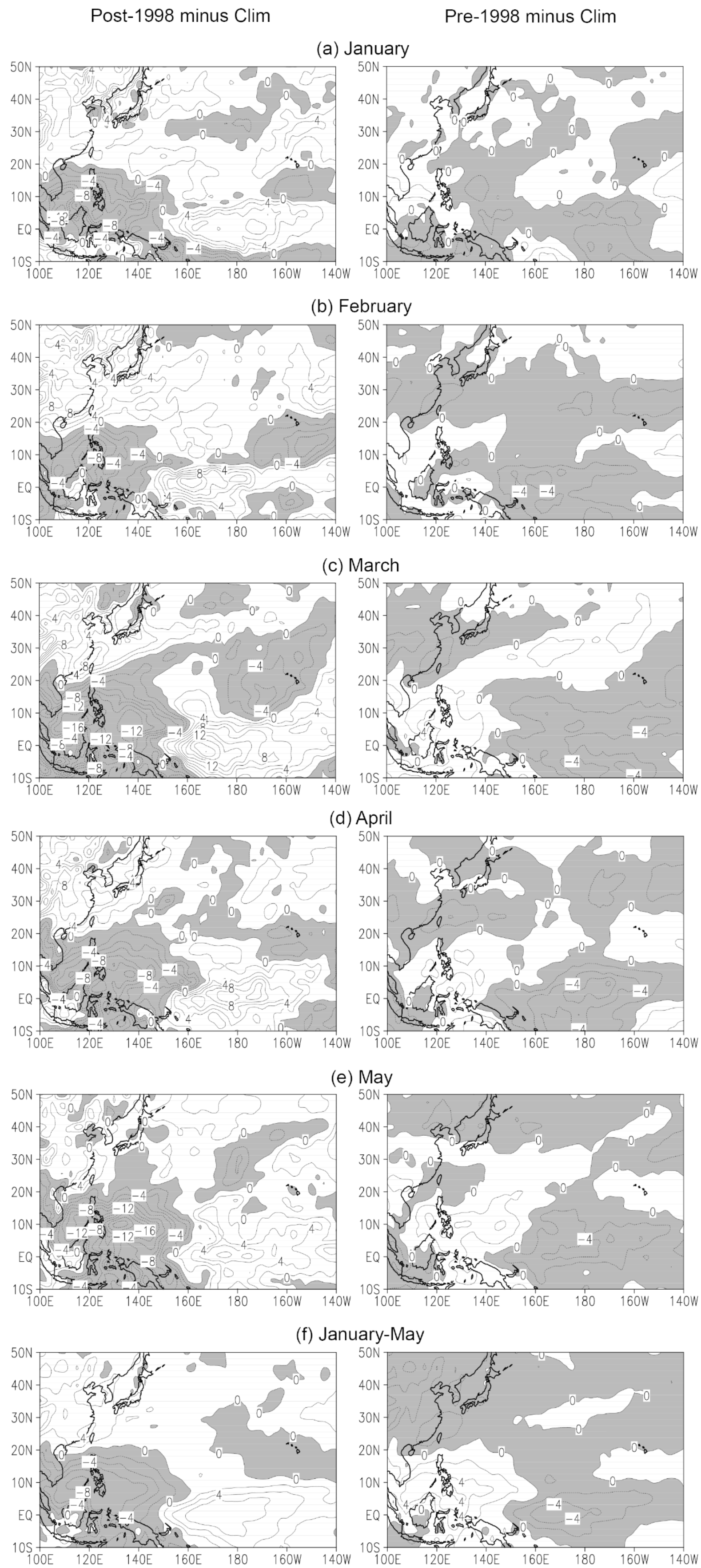

Fig. 13 Composite differences in OLR between (left panels) post-1998 and the climatology (1979–2016) and between (right panels) pre-1998 and the climatology for (a) January, (b) February, (c) March, (d) April, (e) May, and (f) January to May averages. Contour interval is $2Wm^{-2}$. Shaded areas denote negative values

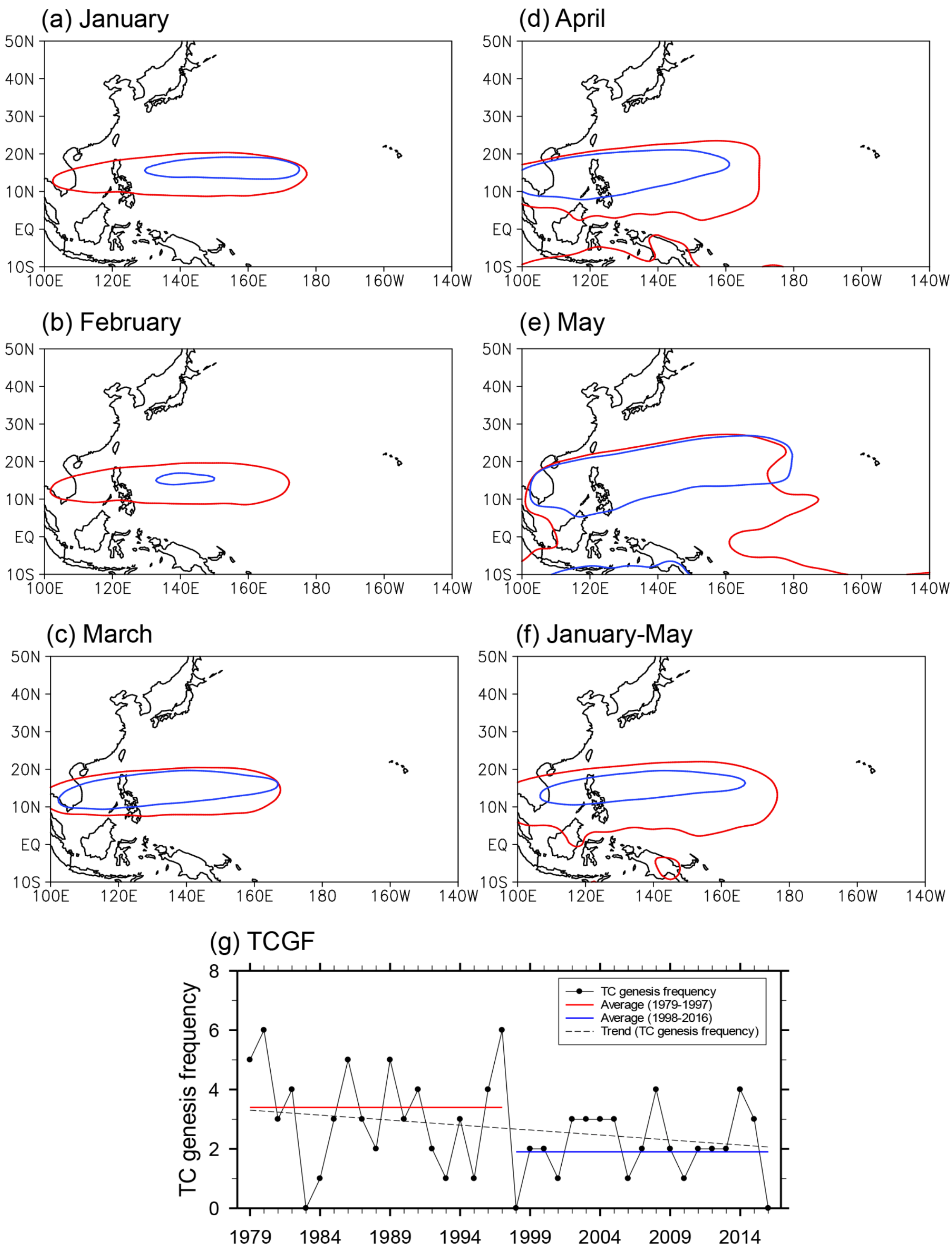

Fig. 14 Parts (a) to (f) show monthly variations in WNPSH (5,870 gpm contour). Red and blue lines denote WNPSHs post-1998 and pre-1998, respectively. (g) Time series of TCGF for January to May

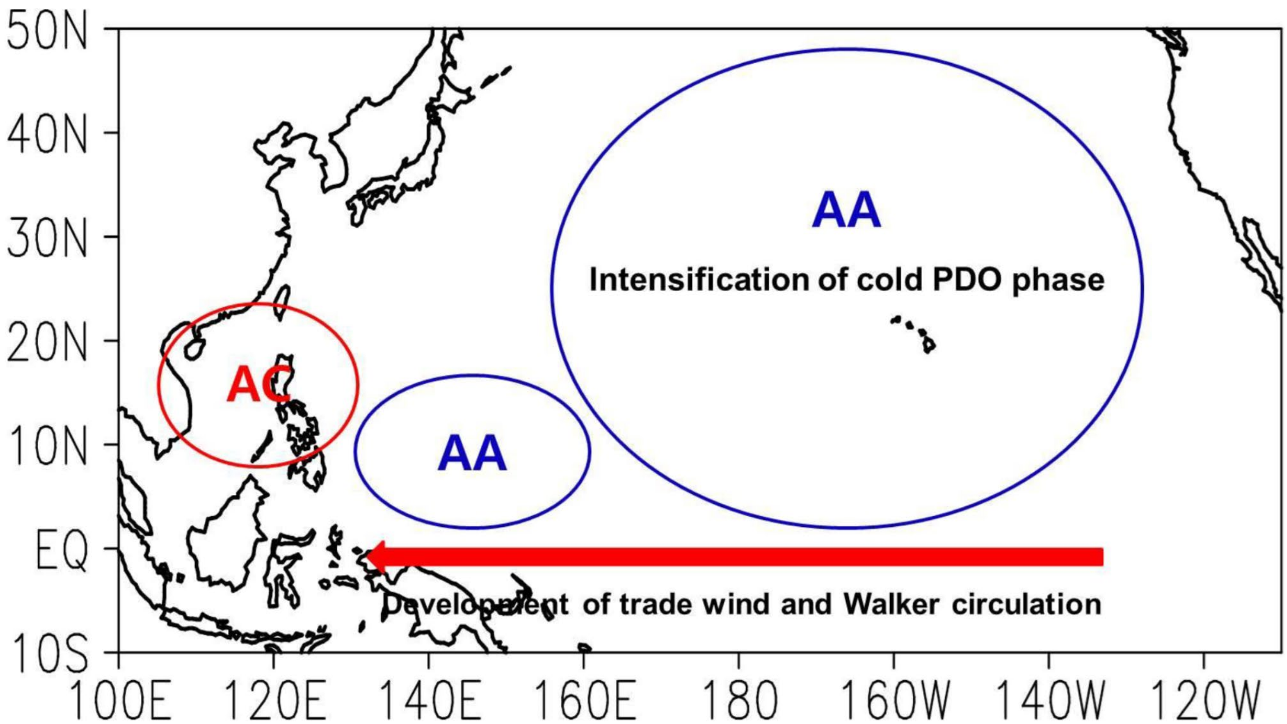

Fig. 15 Schematic diagram of 850 hPa anomalous atmospheric circulation in the PDO cold phase post-1998. AA and AC indicate anomalous anticyclone and anomalous cyclone, respectively

strengthened in the SCS, and an anomalous cyclonic circulation formed in the east seas of the Philippines. As a result, anomalous westerlies strengthened in the equatorial Pacific.

The correlations between the average PDO index for the period from January to May and the TC genesis latitudes, TC genesis longitudes, and TC genesis days were also analyzed. The PDO index and the TC genesis latitude were negatively correlated, meaning that as the PDO cold phase strengthened (and weakened), TC genesis location tended to move north (or south). The PDO index and TC genesis longitude were positively correlated, implying that as the PDO cold phase strengthened (and weakened), TC genesis location tended to move west (or east). The PDO index and TC genesis day correlated negatively, indicating that as the cold PDO phase strengthened (and weakened), TC genesis occurred later (or sooner). These results show that in the PDO cold and warm phases, TCs showed a strong tendency to occur in the northwestern and the southeastern portions of the WNP, respectively, and TC genesis days tended to occur later (or sooner). Furthermore, the results of statistical change-point analysis applied to the PDO time series showed that the PDO time series exhibited a climate regime shift in 1998.

We also analyzed vertical zonal circulation averages from 0°N to 20°N. In both winter and spring, anomalous upward flows developed at 130°E–150°E, whereas anomalous downward flows developed at 170°E–160°W. This result suggests the development of an anomalous Walker circulation involving rising air in the tropical western Pacific and descending air in the tropical equatorial Pacific post-1998. This strengthening of the anomalous Walker circulation post-1998 was also observed during the analysis of 850 hPa velocity potential differences between the two periods.

Correlations between the Walker circulation index and these three variables were also analyzed. The Walker circulation index and TC genesis latitudes exhibited a high positive correlation, meaning that as the Walker circulation strengthened or weakened, TC genesis showed a strong tendency to occur in the western and eastern WNP, respectively. The Walker circulation index and TC genesis longitude showed a strong negative correlation; as the Walker circulation strengthened and weakened, TC genesis occurred more in the western and eastern WNP, respectively. The Walker circulation index and the TC genesis day correlated positively, showing that when Walker circulation strengthened, TC genesis was delayed. Statistical change-point analysis applied to the Walker circulation index time series also demonstrated a climate regime shift in 1998.

To examine in more detail the reason that TCs post-1998 occurred more in the northwest region of the WNP, the monthly OLR differences post-1998 compared to the climatology, and the monthly OLR differences pre-1998 compared to the climatology from January to May were analyzed. The differences post-1998 versus the climatology revealed a strong negative anomaly in the northwestern portion of the WNP and a strong positive anomaly in the southeastern portion of the WNP. Interestingly, the differences in the pre-1998 period showed the opposite pattern. Therefore, TCs pre-1998 tended to form in the southeastern WNP, whereas TCs post-1998 tended to form in the northwestern portion.

Finally, to examine the reason for the delay of recent TC genesis, characteristics in the spatial distribution of average WNPSHs for each month from January to May pre-1998 and post-1998 were examined. We found that in every month, WNPSHs post-1998 tended to develop in east-to-west and south-to-north directions, whereas WNPSHs pre-1998 tended to weaken. Therefore, TC genesis was delayed, and TCGF was smaller post-1998 when WNPSHs were more developed in the WNP, because WNPSH makes TC genesis more difficult.

In this study, we found that there was a climate regime shift in 1998 and the location and timing of the first TC genesis have changed since 1998. Moreover, the corresponding period matched the time when the PDO was switched from the warm to the cold phase. Through various analyses related to the PDO, we confirmed that the changes in SST and atmospheric environment caused by this transition to the cold PDO phase brought the change of the first TCs genesis pattern in long-term. The northwest shift of the first TC genesis locations and the delay in the timing of TC genesis observed in the post-1998 suggested the approach possibility by unexpected TCs and a change in the duration of their activity (or impact on subsequent TCs), which has a significant meaning for the countries near the Northwest Pacific coast.

However, it is regrettable that the sampling period of 38 years was rather short for testing long-term (over more than 10 years) fluctuations. If more than 30 years data are accumulated before and after 1998, more distinct analysis will be possible. In the future, it is also necessary to look at the relationship between the first TCs and the ENSO in the perspective of interannual variability. However, it is difficult to regard the PDO and the ENSO as independent phenomena (Stuecker, 2018). Recent studies have mentioned the asymmetry in the frequencies of the occurrence of the PDO and ENSO (El Niño and La Niña) modes (Lin et al. 2018; Liu and Chan 2013; Zhao et al. 2018; Liu et al. 2019). In fact, when the frequencies of strong ENSO events were examined for the same period as used in this study, both phenomena occurred five times each, of which, strong La Niña event occurred only once (1988–1989) in the pre-1998 and strong El Niño event occurred only once in the post-1998 (2015–2016). However, this asymmetry disappeared when the range was extended to the weak ENSO events (8 El Niño and 8 La Niña events after 1998).

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