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ORIGINAL PAPER

Inter-decadal change of the lagged inter-annual relationship between local sea surface temperature and tropical cyclone activity over the western North Pacific

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Abstract

This study documents the inter-decadal change of the lagged inter-annual relationship between the TC frequency (TCF) and the local sea surface temperature (SST) in the western North Pacific (WNP) during 1979–2014. An abrupt shift of the lagged relationship between them is observed to occur in 1998. Before the shift (1979–1997), a moderately positive correlation (0.35) between previous-year local SST and TCF is found, while a significantly negative correlation (− 0.71) is found since the shift (1998–2014). The inter-decadal change of the lagged relationship between TCF and local SST over the WNP is also accompanied by an inter-decadal change in the lagged inter-annual relationship between large-scale factors affecting TCs and local SST over the WNP. During 1998–2014, the previous-year local SST shows a significant negative correlation with the mid-level moisture and a significant positive correlation with the vertical wind shear over the main development region of WNP TC genesis. Almost opposite relationships are seen during 1979–1997, with a smaller magnitude of the correlation coefficients. These changes are consistent with the changes of the lagged inter-annual relationship between upper- and lower-level winds and local SST over the WNP. Analyses further suggests that the inter-decadal shift of the lagged inter-annual relationship between WNP TCF and local SST may be closely linked to the inter-decadal change of inter-annual SST transition over the tropical central-eastern Pacific associated with the climate regime shift in the late 1990s. Details on the underlying physical process need further investigation using observations and simulations.

1 Introduction

Tropical cyclones (TCs) are one of the most devastating weather phenomena on earth. The western North Pacific (WNP), the most active basin over the global oceans, experiences on average about 26 TCs each year, accounting for nearly 1/3 of the global annual total TC counts (Chan 2005). TCs that form over the WNP basin often bring about huge loss of life and property damage to China and adjacent countries (Zhang et al. 2009; Zhang et al. 2013). Studies suggest that damages associated with TC activity show an increasing trend during recent decades (Zhang et al. 2009; Mendelsohn et al. 2012; Peduzzi et al. 2012), which has led to concerns on the relationship between climate change and TC activity. Therefore, an enhanced understanding of the variability of WNP TC activity and associated physical mechanisms can lead to a deeper recognition of the socio-economic impact of these storms as well as their scientific significance.

It has been well documented that changes of WNP TC activity are closely associated with various modes of climate variability. The two dominant intra-seasonal modes of variability, the Madden-Julian oscillation (Madden and Julian 1971) with an approximately 30–60-day period and the quasi-biweekly oscillation (Kikuchi and Wang 2009; Chen and Sui 2010) with an approximately 10–30-day period, are

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likely to be significant contributors to intra-seasonal changes of TC activity in WNP and other regions (Gray 1979; Liebmann et al. 1994; Kim et al. 2008; Huang et al. 2011; Li and Zhou 2013a, 2013b; Zhao et al. 2015a, 2015b, 2016, 2017a; Zhao and Wu 2017). On the inter-annual time scale, the El Niño-Southern Oscillation (ENSO) is regarded as one of the major factors in modulating variability of WNP TC activity (Lander 1994; Chan 2000; Wang and Chan 2002; Camargo and Sobel 2005; Zhao et al. 2010, 2011, 2014a; Zhao and Raga 2014). During El Niño years, the TC formation location tends to shift more southeastward than during La Niña years. Combined with the changes in large-scale circulations induced by ENSO forcing, more TCs tend to have northwestward tracks and thus have longer duration and higher intensity. Nevertheless, these studies have suggested that ENSO has no significant impact on TC frequency (TCF) over the WNP basin. The quasi-biennial oscillation (QBO) (Chan 1995; Ho et al. 2009), east Indian ocean (EIO) sea surface temperature (SST) (Zhan et al. 2011), SST anomalies (SSTAs) east of Australia (Zhou and Cui 2011) and SST gradient (SSTG) between the southwest Pacific east of Australia and the western Pacific warm pool in boreal spring (Zhan et al. 2013) have all been reported to contribute to the inter-annual changes of TCF over the WNP basin. Studies have also shown a significant decadal/inter-decadal variation in WNP TC activity and further suggest that it is mainly due to the change of the climate mean state, associated with the phase shift of the Pacific Decadal Oscillation (PDO) (Yumoto and Matsuura 2001; Ho et al. 2004; Chan 2005; Chan 2008; Liu and Chan 2008; Xiang et al. 2013; Zhao and Wu 2014; Zhao et al. 2014b; Zhao and Wang 2016). The possible explanations of the variability on various time scales in most of the aforementioned studies mainly focused on the changes in environmental conditions affecting WNP TC activity accompanied with the specific SST anomaly (SSTA) pattern. The changes in large-scale conditions corresponding to the remote impact of specific SSTA pattern were emphasized in these previous studies, while the direct association between WNP local SST and TC activity was relatively less studied.

A vigorous debate has currently focused on the relationship between increasing TC activity and increasing SST (Knutson et al. 2010). Although studies have argued that TC frequency and intensity are closely linked to the local SST (Emanuel 2005; Webster et al. 2005; Trenberth 2005), given that high SST is one of the main factors for TC genesis and intensification (Gray 1968), it is still unclear whether such a relationship is robust (Landsea et al. 2006; Pielke et al. 2006; Knutson et al. 2010). If the TCF were to increase with increasing SST, an increased TCF should have been expected during the past few decades. Over the North Atlantic, a significant increase of TCs has been observed since 1995, consistent with increasing SST (Goldenberg et al. 2001; Murakami et al. 2011; Zhao et al. 2017b). However, over the WNP basin, a significant decrease of TCF has been observed since 1998 (Liu and Chan 2013; Lin and Chan 2015; Zhao and Wang 2016). Global TCF has showed a similar reduction since the late 1990s (Maue 2011). Change of TCF over the past few decades does not appear to be consistent with changes in local SST. Observational analyses further pointed out that there is no significant correlation between the TCF and local SST over the WNP basin (Chan 2006; Yeh et al. 2010). Meanwhile, an inconsistent relationship between TCF and local SST can be seen from numerical simulations in a warming climate (Bengtsson et al. 1996; Knutson et al. 2010; Murakami et al. 2011). Such an unclear relationship between WNP local SST and TCF is possibly one of the main reasons for not considering the direct impact of local SST over the WNP in most current statistical models for forecasting TCF in the basin (Camargo et al. 2007).

Much attention has been payed to the hiatus in the global warming trend observed since 1998 (Kosaka and Xie 2013; Trenberth and Fasullo 2013; England et al. 2014; Karl et al. 2015). Possibly associated with the hiatus, extreme weather events in many regions around the globe showed a significant change (Lin and Chan 2015). Specifically over the WNP basin, Zhao and Wang (2016) found that the inter-decadal change of the inter-annual relationship between PDO and ENSO had a strong impact on the abrupt shift in late season TC activity observed in 1998. Similarly, the inter-annual relationships of WNP TCF with the north Atlantic Oscillation (NAO) (Zhou and Cui 2014) and the Arctic Oscillation (AO) (Cao et al. 2015) have been revealed to experience a significant inter-decadal shift. A possible explanation for these decadal shifts has been given based upon the inter-decadal change of simultaneous large-scale factors affecting WNP TC genesis in association with the inter-decadal change in mean-state climate. However, these studies mainly examined the changes of simultaneous remote impact of specific SSTA pattern (e.g., NAO, AO, ENSO, and PDO) on the WNP TC activity along with the current climate regime shift, while the question of how climate change would affect the association between the WNP local SST and TCF remains unclear. So an interesting question arose naturally: does the inter-annual relationship between the local SST and TCF over the WNP basin experience a similar inter-decadal shift due to this climate regime shift? An attempt to answer this question will further enhance understanding of the impact of climate change on WNP TC activity, which would be helpful for the climate predictions and climate projections of WNP TC activity.

The main objective of this study is to examine whether the inter-annual relationship of WNP local SST and TCF undergoes an inter-decadal change and, if so, to further explore the possible cause of such an inter-decadal change. The remainder of this study is organized as follows: Section 2 describes the data and methodology used. Section 3 documents the inter-decadal change of the inter-annual relationship between WNP local SST and TCF during the TC season from

July to November (JASON) during 1979–2014. Relationships between the WNP local SST and the large-scale environmental factors affecting WNP TCF are compared between the different inter-decadal regimes. Possible explanations for these relationships are discussed in Section 4, followed in Section 5 by a summary of the major findings.

2 Data and methodology

2.1 TC data

The TC data used in this study is obtained from the Joint Typhoon Warning Center (JTWC) best track dataset. It provides information on the TC latitude, longitude, and maximum sustained wind speed at a 6-h interval. Note that other studies have often used the best track datasets from the China Meteorological Administration-Shanghai Typhoon Institute (CMA_STI) and Japan Meteorological Agency (JMA) to study the possible impact of climate change on the WNP TC activity. However, several studies have shown inconsistent or even contradictory results using the different TC best track datasets (Kamahori et al. 2006; Song et al. 2010; Wu and Zhao 2012). The uncertainty in TC data among these agencies was mainly associated with the inconsistent intensity estimate techniques and different computation methods (Emanuel 2005; Wu and Zhao 2012). Using the intensity model developed by Emanuel et al. (2006), Wu and Zhao (2012) recently derived a dynamically consistent basin-wide WNP TC intensity data and further suggested that the TC intensity data from the JTWC is more reasonable than those from the JMA and the CMA_STI. Therefore, the JTWC best track dataset is selected for this study, which covers the TC season (JASON) from 1979 to 2014. For completeness, the same analyses presented here were performed using the TC datasets from the CMA_STI and JMA and almost consistent results on the relationship between TCF and local SST over the WNP were found. The occurrence of TC genesis is counted for each 2.5° × 2.5° grid box over the WNP domain. The TC genesis location is defined as the first position at which the maximum sustained winds exceed or equal to 35 knots.

2.2 Large-scale field data

The atmospheric fields used in this study, e.g., relative humidity and winds, were obtained from the National Center for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) monthly Reanalysis II dataset in a 2.5° × 2.5° grid (Kanamitsu et al. 2002). The vertical wind shear in this study is computed as the magnitude of the vector difference between winds at 850 and 200 hPa. The monthly mean SST was obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstruction SST version 3b (ERSSTv3b) at a horizontal resolution of 2° × 2° (Smith et al. 2008). In the analysis presented in Section 3.2, the local WNP SST is computed as the averaged SST over the main development region of WNP TC activity [5° N–25° N, 100° E–180° E].

2.3 Detection of abrupt shift and statistical significance

The Bayesian change-point analysis approach proposed by Chu and Zhao (2004) is applied to the time series of TC counts to detect any abrupt shift in the annual WNP TCF. In this approach, the annual TCF is considered as a discrete Poisson process. The Poisson intensity is the only parameter and is coded by a conjugate gamma distribution. The Bayesian inference provides the probability estimate of the shifts, rather than a deterministic estimate of the change-point location. Such change-point analysis has been extensively used in previous studies (Tu et al. 2009; Zhao and Chu 2010; Hsu et al. 2014; Zhao and Wang 2016; Zhao et al. 2017b). More details of this methodology can be found in Chu and Zhao (2004) and Zhao and Chu (2010). Once a change-point is identified, the resulting two sub-periods are then considered for further analyses, before and after the change-point. The non-parametric Mann-Kendall test (Mann 1945; Kendall 1975) and the Wilcoxon-Mann-Whitney test (Wilcoxon 1945; Mann and Whitney 1947) are used to assess the statistical significance of the correlations and differences between the two sub-periods identified, before and after the change-point.

3 Inter-decadal change of local SST-TCF relationship

3.1 Abrupt change of WNP TCF

Large inter-annual variability of WNP TCF during the 1979–2014 period can be seen in Fig. 1a. The highest TCF occurred in 1996 with 26 TCs, which was more than twice the lowest value (11 TCs) observed in 1999. This significant inter-annual variation of WNP TCF has been extensively documented and some important factors have been mentioned as possibly responsible, such as the QBO (Chan et al. 1998), EIO SST (Zhan et al. 2013), East Australia SST (Zhou and Cui 2011), North Atlantic SST (Huo et al. 2015; Cao et al. 2015), and SSTG between southwest Pacific East of Australia and the western Pacific warm (Zhan et al. 2013). Further detailed investigation of the inter-annual variability of the WNP TCF is beyond the scope of this study.

In addition to the large inter-annual variability, the time series of WNP TCF during JASON appears to show an inter-decadal shift around 1998 (Fig. 1a). Systematically, more TCs formed over the WNP basin during the first sub-period

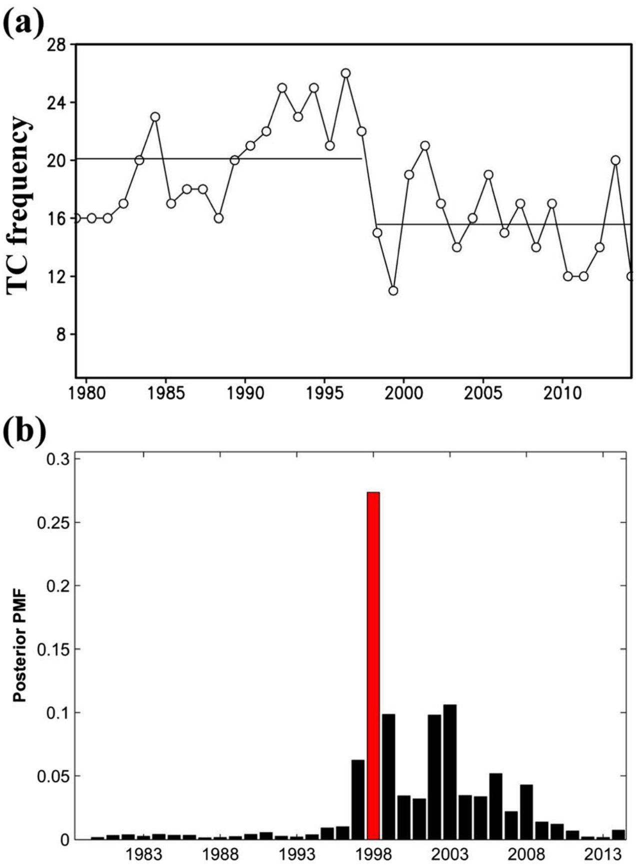


Fig. 1 **a** Time series of the TC frequency during July to November (JASON) over the WNP basin for the whole period (1979–2014). The horizontal lines in (**a**) represent the mean TC frequency during 1979–1997 and 1998–2014, respectively. **b** The conditional posterior probability mass function of change-points as a function of time. The red bar in (**b**) indicates the specific year 1998 with the abrupt shift in JASON TC frequency

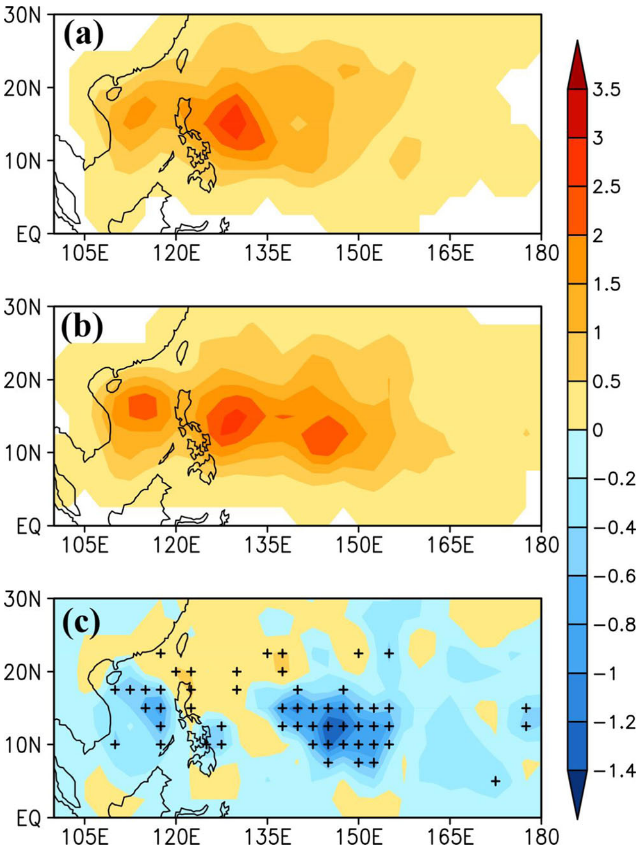


Fig. 2 Occurrence of TC genesis for **a** 1998–2014, **b** 1979–1997, and **c** the composite difference (**a**–**b**). The plus sign indicates that the difference is statistically significant at the 95% confidence level

1979–1997 with an annual average of 20 TCs, than during the second sub-period 1998–2014 that had 15.5 TCs on average each year. The recent reduction in WNP TCF during the second sub-period is significant at a 95% confidence level. A change-point analysis of the annual WNP TCF over the whole period 1979–2014 suggests an abrupt shift in 1998 (Fig. 1b), in agreement with the climate regime shift identified in previous studies (Kosaka and Xie 2013; Trenberth and Fasullo 2013; England et al. 2014; Karl et al. 2015).

To further investigate the link between the spatial distribution of TC formation and the recent reduction in frequency of TCs over the WNP basin, we compare the difference of TC formation distribution between the two periods, before and after the change-point. During the second sub-period (1998–2014), two main TC genesis regions can be readily seen (Fig. 2a): one in the South China Sea and the other one in east of the Philippines. Those two regions are also present during the first sub-period (1979–1997), but an additional active genesis center is seen over the southeastern part of WNP basin (Fig. 2b). The spatial distribution of the difference in TC activity is shown in Fig. 2c, indicating that the recent significant decrease in WNP TCF is mainly due to the significant decrease of TCs over the southeastern region of the WNP basin, consistent with previous studies (Liu and Chan 2013; Wu et al. 2015; Zhao and Wang 2016). Over the northwestern part of the WNP [17° N–30° N, 120° E–135° E], 3.4 TCs occur during 1998–2014, and 2.6 TCs during 1979–1997. Their difference of 0.8 is not statistically significant at a 95% confidence level. In contrast, over the southeastern WNP basin [0–17° N, 135° E–180° E], 7.3 TCs occur each year on average during 1979–1998, significantly decreasing to only 4.0 TCs during 1998–2014. These changes of WNP TCF between the two sub-periods correspond well with the changes of large-scale factors shown in Fig. 3. Compared to conditions observed during 1979–1997, enhanced vertical wind shear and decreased 850 hPa relative vorticity during 1998–2014 are found especially over the southeastern WNP (Fig. 3a, b), associated with the recent decrease in TCs in that region. The larger relative humidity over the western WNP basin during 1998–2014 (Fig. 3c) may play a role in contributing to more TCs over the northwestern WNP.

The TCs that develop over the southeastern part of the WNP have more chances of attaining higher intensity (Wang and Chan 2002; Camargo and Sobel 2005; Wu et al. 2008; Wu

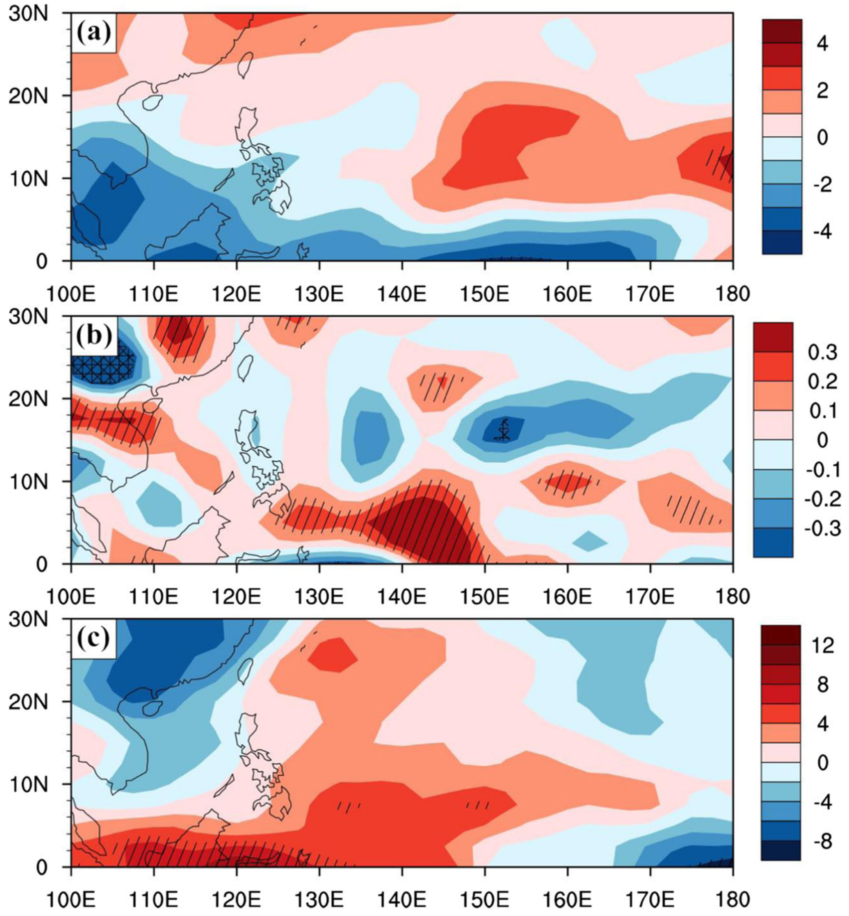


Fig. 3 Composite differences of large-scale factors between the two sub-periods (1998–2014 minus 1979–1997) for **a** vertical wind shear (m/s), **b** 850 hPa relative vorticity (10e-5 s^{-1}), and **c** 600 hPa relative humidity (%). The strip-line represents that the difference is statistically significant at a 95% confidence level

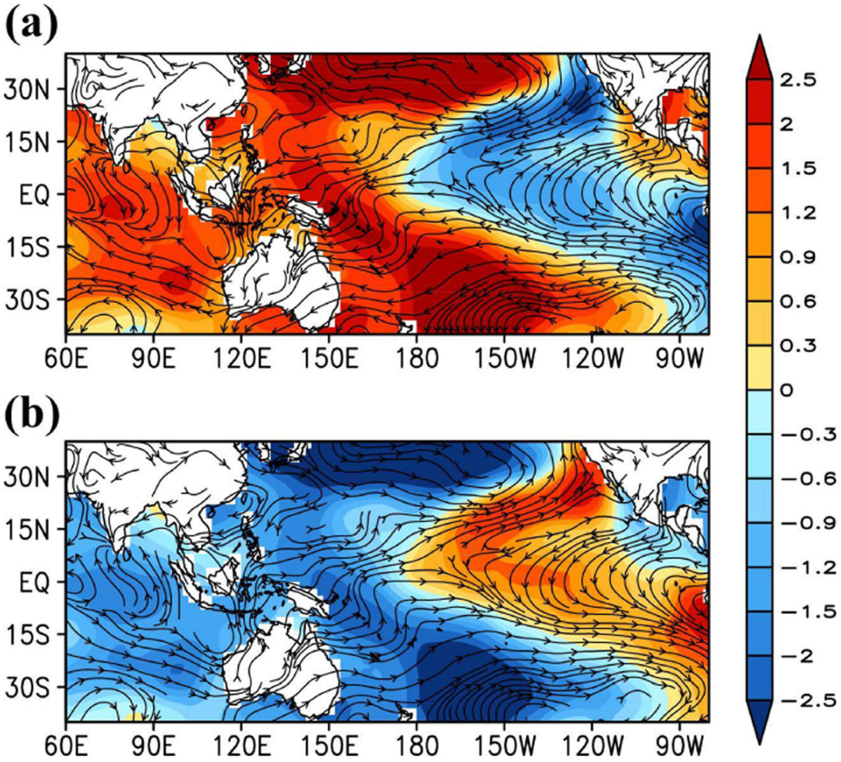
and Wang 2008; Zhao et al. 2011; Wu and Zhao 2012; Zhao 2016). During 1979–1997, more intense TCs (with annual average of 7.8 Cat.3–5 TCs, with intensity greater than or equal to 96 knots) are observed compared to those observed during 1998–2014 (annual average of 6.4 Cat.3–5 TCs). The difference of 1.4 between the two sub-periods is statistically significant at a 95% confidence level. Especially, a significantly larger difference in the number of intense TCs (i.e., 1.8) is seen over the eastern part of the WNP basin [5° N–20° N, 140° E–180° E] between the two sub-periods. On average, 5.2 Cat.3–5 TCs are observed over this region during 1979–1997, compared to 3.4 Cat.3–5 TCs during 1998–2014. These results are consistent with a westward shift of TC genesis location over the WNP basin over the past few decades (Lin and Chan 2015; Wu et al. 2015).

A similar recent reduction of TC frequency was observed in the WNP basin and of global TC activity was observed by Liu and Chan (2013) and Maue (2011). They qualitatively explained the decrease in frequency of TCs as inter-decadal changes in atmospheric conditions affecting TC genesis associated with the shift in the mean-state climate. The cold PDO phase is observed during the second sub-period (Fig. 4a) and the warm PDO phase is seen during the first sub-period (Fig. 4b). This change of PDO phase affects the large-scale factors that modulate TC activity. During the warm (cold) PDO phase, anomalous westerlies (easterlies) can be found over the equatorial WNP basin and, thus, an intensified (weakened) monsoon trough, and an increased (decreased) TC activity.

3.2 Inter-decadal change of the lagged relationship between local SST and TCF

Most previous studies have focused on the impact of remote SST on the WNP TCF (Wang and Chan 2002; Zhou and Cui 2011; Zhan et al. 2011, 2013; Zhao et al. 2014a), with less emphasis on the direct association between local SST and WNP TCF. No significant simultaneous correlation between the local WNP SST and TCF was found by Chan (2006), and likewise we find only a weak negative correlation ($r = -0.17$), when evaluating the whole period 1979–2014 (Fig. 5a). We evaluated the potential impact of the shift in the mean-state climate on the inter-annual relationship between local WNP SST and TCF by computing the correlation between these two parameters for the periods before and after the change-point: 1979–1997 and 1998–2014. The statistically insignificant correlation coefficients (0.28 and 0.22, respectively) imply no

Fig. 4 Composites of SST anomalies and streamlines at 850 hPa for **a** 1998–2014 and **b** 1979–1997



significant inter-decadal change of annual simultaneous correlation between WNP local SST and TCF.

An interesting result can be observed, however, by studying Fig. 5a. During the JASON period over the WNP, the local SST in the preceding year significantly correlates with the current frequency of TCs at the 95% confidence level ($r = -0.31$) during the whole period 1979–2014. Hereafter, the preceding, current and following years are denoted as − 1, 0, and + 1, respectively. Analyses of the 11-year sliding correlation between local WNP SST (− 1) and TCF (0) shows a transition from being in-phase to being out-of-phase relationship with a weak negative correlation observed after 1998 (Fig. 5b). This implies that the significant inter-annual relationship between WNP SST (− 1) and TCF (0) during the 1979–2014 is mainly due to the inter-decadal shift of the lagged relationship between local WNP SST and TCF. The lagged inter-annual relationship between them shows a moderately positive correlation during 1979–1997 with correlation coefficient 0.35 (Fig. 5c), which is not significant at the 95% confidence level. In contrast, a significantly negative correlation at the 95% confidence level can be found between them, with correlation coefficient − 0.71, during 1998–2014 (Fig. 5c).

In summary, the decadal shift of the mean-state climate has no significant modulation of the *simultaneous* relationship between local WNP SST and TCF; however, there is an abrupt inter-decadal change of the *lagged* inter-annual link between them at the change-point (Fig. 5c). The following section explores the associated large-scale patterns and a possible explanation for the inter-decadal-shift in the inter-annual relationship between the local SST (− 1) and TCF (0) over the WNP basin in association with the current climate regime shift of mean-state climate.

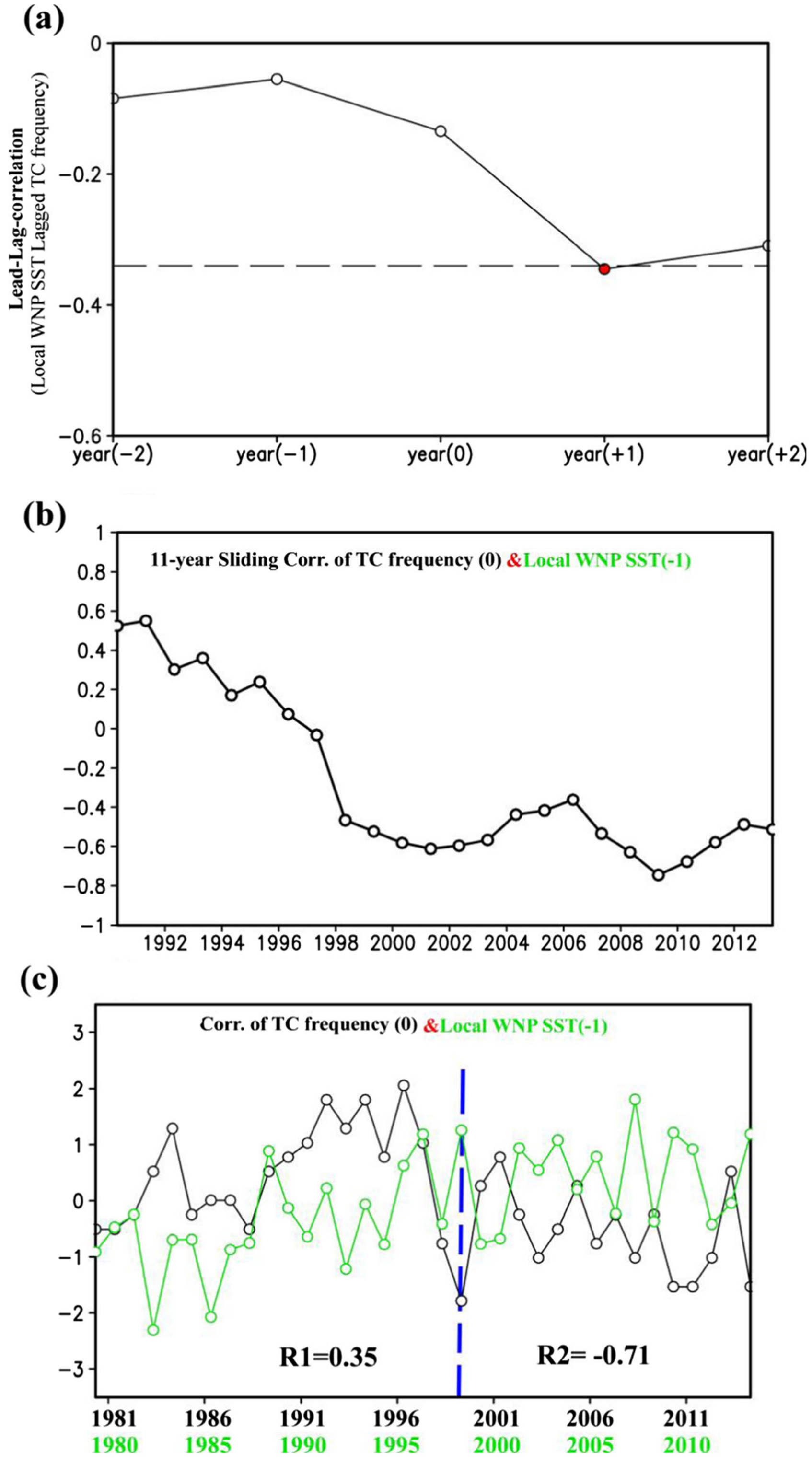
4 Associated changes of large-scale patterns

4.1 Inter-decadal change of the lagged inter-annual relationship between large-scale atmospheric factors and local SST

Previous studies have documented that TC genesis is generally dominated by favorable, concurrent environmental conditions (Gray 1968). In this section, analyses of the inter-annual relationship between the local WNP SST (− 1) and 600 hPa relative humidity (0), vertical wind shear (0), and 200 and 850 hPa winds (0) are performed to better attempt to understand the possible cause of the inter-decadal change in the lagged inter-annual relationship between the local WNP SST and TCF.

Figure 6 shows the changes in the inter-annual correlation pattern between the WNP local SST (− 1) and 600 hPa relative humidity (0) and vertical wind shear (0), as spatial distributions of the correlation coefficients. The “+” symbols indicate correlation coefficients that are statistically significant at the 95% confidence level. Over the main development region of WNP TC genesis, the 600 hPa relative humidity (0) is negatively correlated with the local WNP SST (− 1) during 1998–2014 (Fig. 6a), while a positive correlation between them can

Fig. 5 Lead-lag correlation between **a** the WNP local SST and TC frequency, **b** 11-year sliding correlation between TCF(0) and local SST(01), and **c** the annual TC frequency (0) and local WNP SST (− 1). The correlation between TCF (0) and local SST (− 1) shows a phase shift (indicated by the vertical dashed line) with correlation coefficient 0.35 during 1979–1997 and − 0.71 during 1998–2014



be found especially over the southeastern part of WNP basin during 1979–1997 (Fig. 6b). The lagged correlation maps between local SST and vertical wind shear over the WNP basin for the two sub-periods are shown in Fig. 6c, d. A significantly positive correlation area is observed over the southeastern region of WNP basin during 1998–2014, while a moderately negative correlation area over the southeastern part of WNP basin can be found during 1979–1997.

The lagged relationships between the upper- and lower-level winds with local WNP SST are further examined. The correlation map between 850 hPa wind (0) and local SST (− 1) shows a strong anti-cyclonic pattern over the main

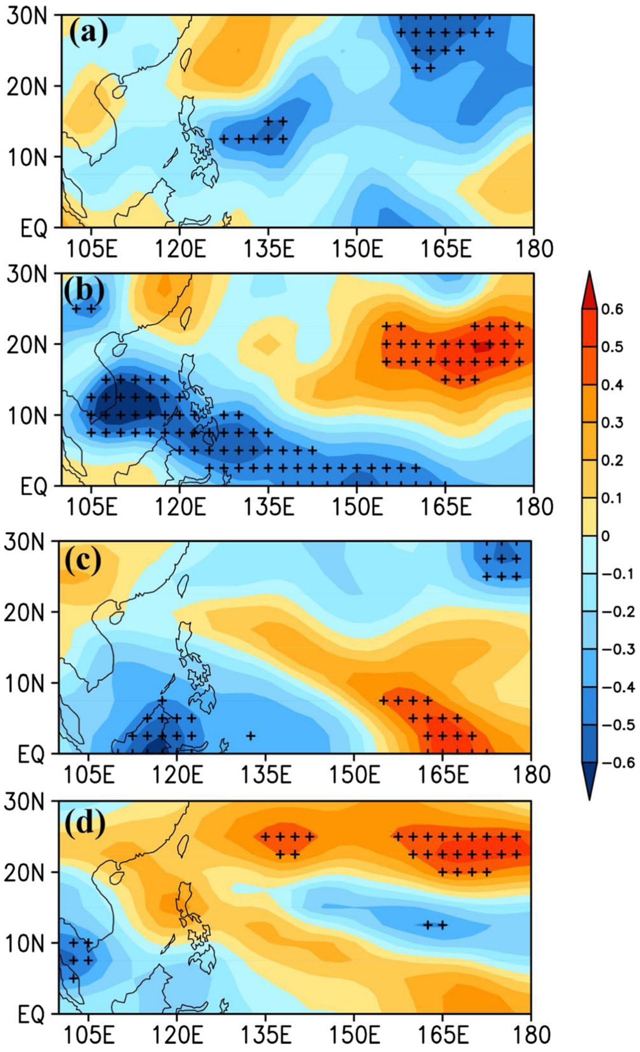


Fig. 6 Correlation of **a** previous-year JASON WNP local SST and 600 hPa relative humidity during 1998–2014, **b** same as (**a**) but for 1979–1997, **c** previous-year JASON WNP local SST and vertical wind shear during 1998–2014, and **d** same as (**c**) but for 1979–1997. The plus sign indicates that the difference is statistically significant at the 95% confidence level

development region during 1998–2014 (Fig. 7a), while a relatively moderate cyclonic lagged correlation is found during 1979–1997, especially over the southeastern part of WNP, (Fig. 7b). The anti-cyclonic (cyclonic) correlation map corresponds to the weakened (intensified) WNP monsoon trough and, thus, unfavorable (favorable) for the WNP TC genesis during the second (first) sub-period. A more distinct difference can be found for the correlation map between the upper-level wind (0) and local SST (− 1) as displayed in Fig. 7c, d. A relatively weak anti-cyclonic pattern during the first period and a strong cyclonic correlation pattern during the second period can be found. The cyclonic pattern during the second period is statistically significant over the southeastern region of the WNP basin, consistent with fewer TCs formed over the WNP during 1998–2014 compared to 1979–1997.

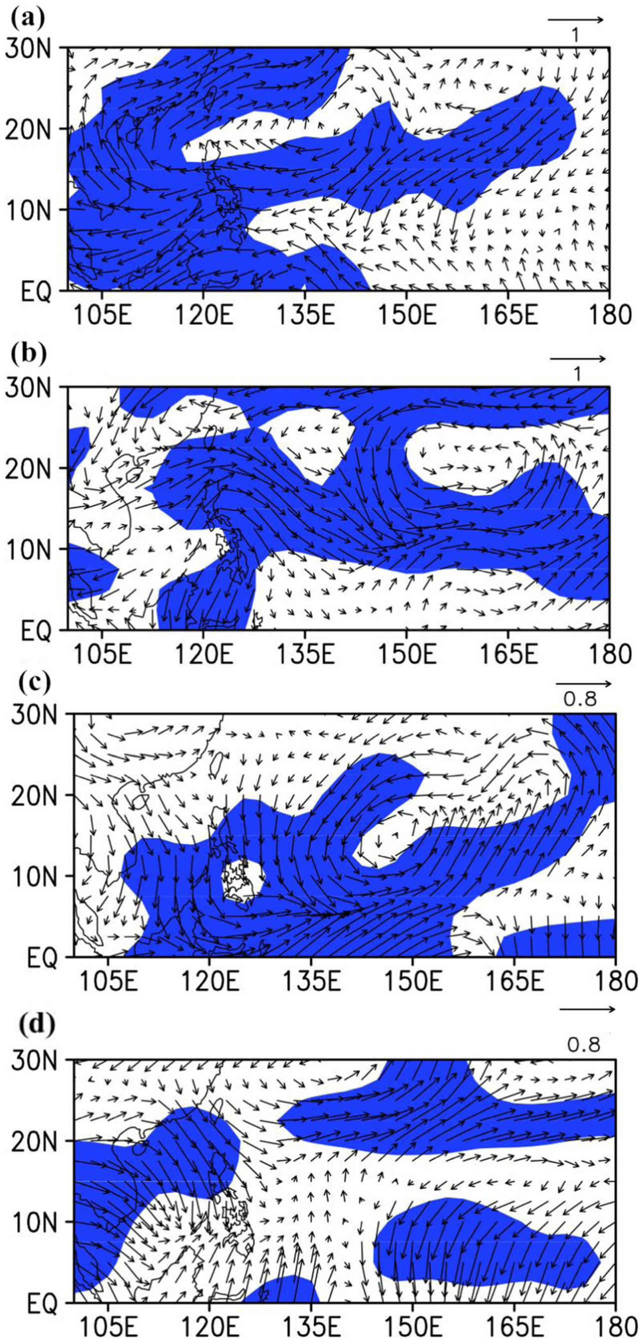


Fig. 7 Correlation of **a** previous-year JASON WNP local SST and 850 hPa winds for 1998–2014, **b** same as (**a**) but for 1979–1997, **c** previous-year JASON WNP local SST and 200 hPa winds for 1998–2014, and **d** same as (**c**) but for 1979–1997. Shading indicates that the difference is statistically significant at the 95% confidence level

As suggested by Wu et al. (2015), changes in the location of the tropical upper troposphere trough (TUTT) have a significant impact on TC formation location over the WNP basin. The correlation pattern between 200 hPa winds (0) and WNP local SST (− 1) indicates that the TUTT tends to shift more westward and thus decreasing low-level relative vorticity, increasing vertical wind shear, and decreasing 600 hPa relative humidity over the southeastern part of WNP basin during 1998–2014 compared to 1979–1997 (Fig. 3). The unfavorable conditions associated with the upper-level circulation during 1998–2014 results in fewer TCs generated over the southeastern region of the WNP basin.

In summary, the lagged inter-annual relationship between large-scale factors affecting TCs and their frequency experiences an inter-decadal change around the change point-year 1998. This is consistence with the inter-decadal shift of the lagged inter-annual relationship between the WNP local SST and TCF. During 1998–2014 (1979–1997), a significantly negative (moderately positive) correlation between previous-year local SST and 600 hPa relative humidity is observed concurrent with a significantly positive (moderately negative) correlation with vertical wind shear especially over the southeastern WNP. Moreover, the correlations between preceding local SST and the upper- and lower-level winds also show a corresponding inter-decadal change.

4.2 Inter-decadal change of the inter-annual difference of the SSTA pattern

To better clarify the results in the previous section, we have selected four cases for further consideration. Based upon the moderately positive correlation during the first sub-period and significantly negative correlation during the second sub-period, four cases are selected so that local WNP SST (− 1) and TCF (0) over the WNP basin are in-phase during the first period and out of phase during the second period. The selected cases are (i) low local SST (− 1) and low TCF (0) over the WNP basin during the first sub-period, hereafter labeled them LSLT-1; (ii) high local SST (− 1) and high WNP TCF (0) during the first sub-period, HSHT-1; (iii) low local SST (− 1) and high WNP TCF (0) during the second sub-period, LSHT-2; and (iv) high local SST (− 1) and low WNP TCF (0) during the second sub-period, HSLT-2. According to this classification, 3 years are selected for each of the four cases: (i) LSLT-1: 1980, 1981, and 1997; (ii) HSHT-1: 1995, 1996, and 1998; (iii) LSHT-2: 1999, 2000, and 2012; (iv) HSLT-2: 2005, 2009, and 2013. The change in the difference of SST between the selected years and the corresponding following years for each of four cases are compared, in order to understand the distinct difference in the inter-annual relationship between the local WNP SST (− 1) and TCF (0) during the two sub-periods. As an example, for the case of low SST and low TC frequency in the first sub-period, LSLT-1 (1980, 1981, and 1997), the composite SST difference is computed as the difference between average SST of the selected years (1980, 1981, and 1997) and the average SST of the years following the selected years (1981, 1982, and 1998) (i.e., composite following years SST minus composite current years SST).

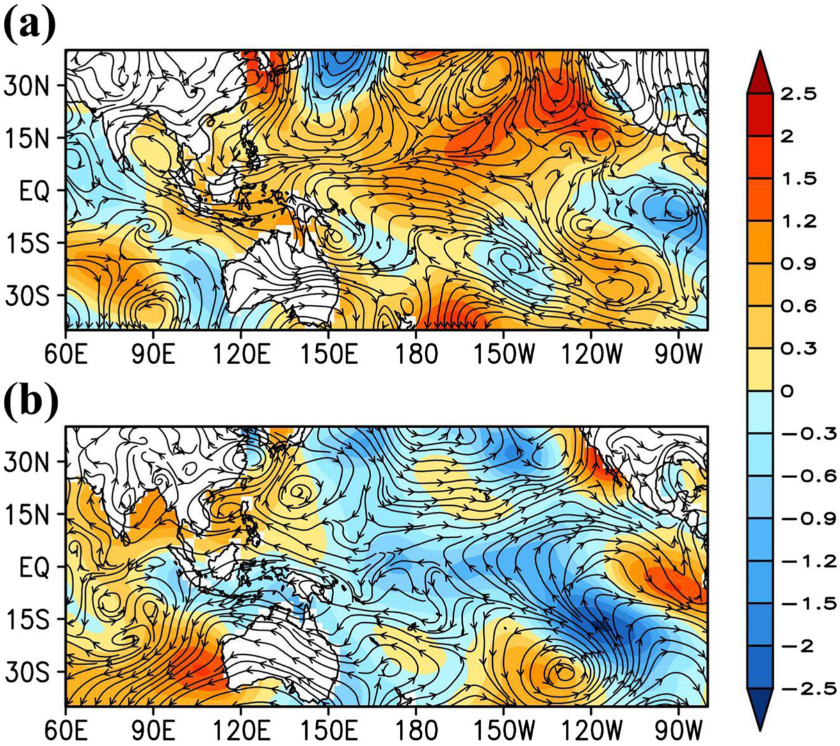
The SST difference between the years of LSHT-2 and the corresponding following years during the second sub-period is displayed in Fig. 8a. The composite SST differences show a central Pacific (CP) El Niño-like pattern, which is closely associated with the anomalous westerlies over the WNP basin and thus an intensified WNP monsoon. These changes will lead to an increase of TC frequency in the years following periods of low local SST over the WNP. In contrast, a somewhat CP La Niña-like pattern can be found for the SST difference between the years of HSLT-2 and the corresponding following years (Fig. 8b). Anomalous easterlies are seen over the WNP basin associated with a weakened WNP monsoon, which is unfavorable for WNP TC genesis. Note that there is a positive anomaly in the North Indian Ocean in Fig. 8. As suggested by previous studies (Zhan et al. 2011; Tao et al. 2012), a warm (cool) SST anomaly over the North Indian Ocean will weaken (enhance) the WNP monsoon that suppresses (enhances) WNP TCF. In addition, studies have also suggested that the SST over the North Atlantic and East Australia regions can modulate WNP TC activity (Yu et al. 2016; Zhou and Cui 2011). Nevertheless, the relative importance of SST anomalies in other oceanic basins and WNP on the WNP TCF remains unclear and needs further investigation.

A similar analysis for the first sub-period (1979–1997) yields an almost opposite SST difference pattern from the one obtained for the second sub-period (Fig. 9). The composite SST difference for the LSLT-1 case, corresponding to cool local SST and low TCF, shows a conventional eastern Pacific (EP) La Niña-like pattern. A conventional EP El Niño-like pattern is seen for the HSHT-1 case, corresponding to warm local SST and low TCF. These agree well with anti-cyclonic (cyclonic) anomalous circulation over the WNP basin and thus suppressed (enhanced) WNP TC activity in the years following years with low (high) local SST during the first sub-period.

To further confirm the important role of the CP-ENSO SSTA pattern in modulating the WNP TC frequency, the correlation between WNP local SST (− 1) and CP-ENSO index difference between year(0) and year(− 1) is computed. The CP index is calculated using the regression-EOF method following Kao and Yu (2009) and Yu and Kim (2010) from ERSSTv3b. The results of this computation are presented in Fig. 10 and show a moderately positive correlation (0.30) during the first sub-period (1979–1997) and a significantly negative correlation (−0.65) during the second sub-period (1998–2014), implying that the correlation between WNP local SST and inter-annual SST transition over the tropical central-eastern Pacific also undergoes an inter-decadal change. Almost identical results can be found using the index computed following the Modoki El Niño index by Ashok et al. (2007).

Based upon the discussion presented above, the difference of the inter-annual transition of the tropical central-eastern Pacific SST between the two periods plays an important role in the lagged inter-annual relationship between the local WNP SST and TCF. During the first sub-period, the difference of SST between the years (0) with high (low) local SST and the

Fig. 8 Composite differences of SST anomalies and streamlines at 850 hPa during the period 1998–2014 for **a** years with low SST and high TC frequency and the corresponding following years and **b** years with high local SST and low TC frequency and the corresponding following years



following year (+ 1) shows an EP El Niño-like (EP La Niña-like) pattern. In contrast, during the second sub-period, the difference of SST between the years (0) with high (low) local SST and the following year (+ 1) shows a CP La Niña-like (typical CP El Niño-like) pattern. These changes correspond well to the inter-decadal changes of the lagged inter-annual relationship between large-scale factors and local WNP SST at the change-point 1998. In summary, during the second sub-period, the inter-annual tropical SST transition generally shows a CP El Niño-like (La Niña-like) pattern when the local

Fig. 9 Composite differences of SST anomalies and streamlines during the period 1979–1997 for **a** years with low local SST and low TC frequency and the corresponding following years and **b** years with high local SST and high TC frequency and the corresponding following years

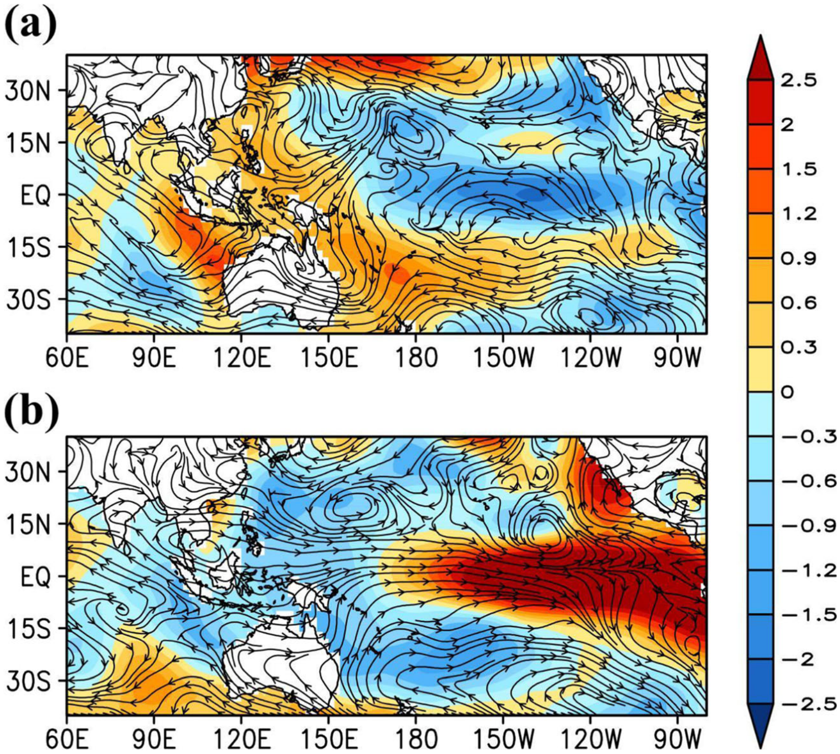
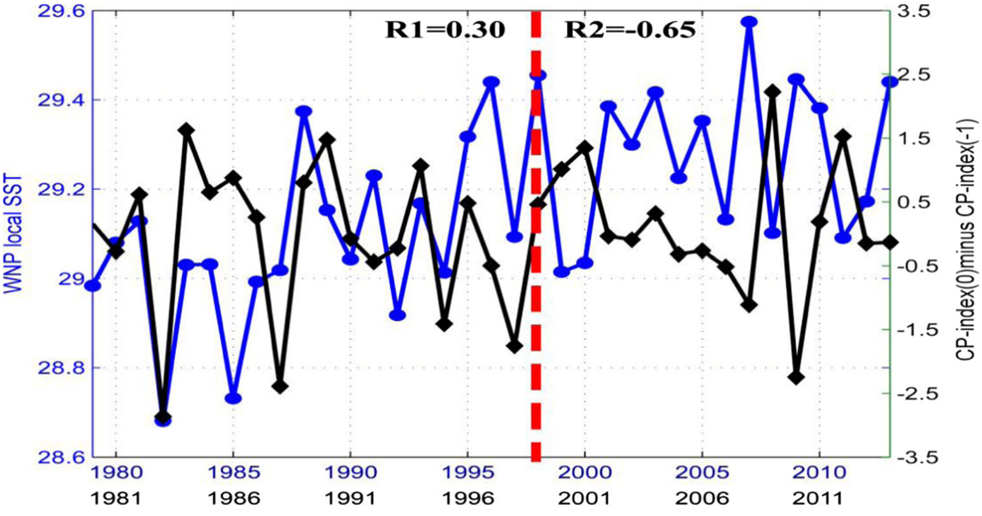


Fig. 10 The annual TC CP index difference (year (0)–year (− 1)) and local WNP SST (− 1).The correlation between them shows a phase shift (indicated by the vertical dashed line) with correlation coefficient 0.30 during 1979–1997 and − 0.65 during 1998–2014



WNP SST is relatively low (high). In contrast, the inter-annual tropical SST transition generally captures a typical eastern Pacific ENSO SSTA pattern during 1979–1997. These results imply that the inter-decadal shift of tropical Pacific climate appears to play an important role in contributing to the inter-decadal change of inter-annual SST transition.

The climate regime shift of tropical Pacific climate around 1998 has been well documented and is associated with significant changes of circulations and teleconnections over various regions of globe (Xiang et al. 2013; McPhaden 2012; Horii et al. 2012; Hu et al. 2013; Cao et al. 2015; Zhao and Wang 2016). Associated with this shift, a shifting ENSO and changing ENSO-associated teleconnections have also been observed (McPhaden 2012; Xiang et al. 2013). For example, McPhaden (2012) speculated that the breakdown of the ENSO and warm water volume relationship may be linked to a shift toward more CP versus EP El Niños in the past decade. Hu et al. (2013) found a weakened inter-annual variability in the tropical Pacific since 2000 characterized by a cool PDO phase. An and Wang (2000) also pointed out that an ENSO regime change occured in the late 1970s, when the ENSO period lengthened from 2 to 4 years during 1962–1975 to 4–6 years during 1980–1993. Together with these studies, one would expect that such an inter-decadal shifts of inter-annual transition of SST over the tropical Pacific between the two sub-periods as highlighted in this study should be closely associated with weakened inter-annual variability in tropical Pacific Ocean since the late 1990s. Details on the underlying physical mechanisms need further theoretical and observational study.

5 Summary

This study documents the inter-decadal change of the lagged inter-annual relationship between the local SST and TCF over the WNP basin during the period of 1979–2014. An abrupt shift in TC frequency is observed in 1998, when the lagged inter-annual relationship between the WNP local SST and TCF experiences a corresponding inter-decadal shift. During the first sub-period (1979–1997), there is a moderately positive correlation (0.35) between previous-year local SST and current year TC frequency, while a significantly negative correlation (− 0.71) is found between them during the second sub-period (1998–2014).

The corresponding lagged inter-annual relationship between the large-scale factors affecting TC activity and local SST over the WNP basin is further investigated for the two sub-periods. Consistent with the inter-decadal shift of the lagged inter-annual relationship between WNP local SST and TCF, the lagged inter-annual relationship between WNP local SST and large-scale factors in controlling TCF also displays an inter-decadal change. During the first sub-period, the previous-year local SST is positively correlated with the current year 600 hPa relative humidity and negatively correlated with the current year vertical wind shear over the main development region of TC genesis over the WNP basin. In contrast, the previous-year local SST is significantly negatively correlated with the current year 600 hPa relative humidity and significantly positively correlated with the current year vertical wind shear during the second sub-period, especially over the southeastern region of WNP basin. These changes are consistent with the changes of the lagged inter-annual relationship between previous-year local SST and current year upper- and lower-level winds over the WNP basin. During the second sub-period, there is an anti-cyclonic correlation pattern, which corresponds to the more westward shift of the TUTT and WNP monsoon trough and, thus, a decrease in 600 hPa relative humidity and an increase in vertical wind shear. These lead to a decrease in WNP TCF, especially over the southeastern region of WNP basin during the second sub-period. The opposite patterns are seen for the first sub-period, consistent with the observed higher TCF over the WNP basin.

Further analyses suggest that the changes of the lagged inter-annual relationship between large-scale factors and WNP local SST are closely associated with the different inter-annual SST transitions over the tropical central-eastern Pacific during the two sub-periods. During the second sub-period, the SST difference between years of HSLT (LSHT) and the following years show a somewhat CP La Niña-like (CP El Niño-like) pattern, which corresponds to the decrease (increase) of WNP TCF. In contrast, the SST difference between years with both high SST and TCF or low SST and TCF and the following years shows a conventional EP El Niño-like (EP La Niña-like) pattern during the first sub-period, which corresponds to the increase (decrease) of TCF over the WNP basin. The physical mechanism of the difference of inter-annual SST transition during the two sub-periods should be closely associated with the decadal changes in the inter-annual variability of SSTA over the tropic central-eastern Pacific along with the tropical Pacific climate shift and a shifting ENSO in 1998. Note that in this study, we focus on the inter-decadal shift of the lagged inter-annual relationship between WNP local SST and TCF by emphasizing the remote influence of inter-annual SSTA transition over the tropical central-eastern Pacific, while the quantitative role of the other respective basin SST change in contributing to the inter-decadal shift of the lagged relationship is not discussed in this study. Details on the underlying physical mechanism need further study based upon observations and simulations. As a final remark, this study mainly focuses on the inter-decadal shift of lagged inter-annual correlation between the local WNP SST and TCF, and thus, we should be cautious to attempt to explain the TC activity over the WNP using only correlation analyses and need to understand it from the combined changes in the magnitudes of large-scale factors and their correlations with TC activity in a changing climate.

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