Chapter 2

Influence of Climate Regime Shift on the Abrupt Change of Tropical Cyclone Activity in Various Genesis Regions

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Additional information is available at the end of the chapter

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Abstract

In this chapter, we reported the effect of basin-scale climate regime shift (CRS) on the abrupt change of tropical cyclone (TC) activity in various genesis basins, including the Pacific, Atlantic, and Indian Oceans. An analysis of regime shift index reveals that the worldwide TC activity experienced four significant abrupt changes during 1960–2014, including (i) an abrupt increase/decrease in the eastern North Pacific (ENP)/western North Pacific (WNP) in the early 1970s, (ii) an abrupt increase in the ENP and WNP in the early 1980s, (iii) an abrupt increase in the North Atlantic and ENP in the middle 1990s, and (iv) an abrupt decrease in the WNP and western South Pacific in the late 1990s. Three of them are identified concurrent with a significant CRS. The possible influence of a CRS on the abrupt change of TC activity in various genesis regions is addressed. We demonstrate that a CRS induced time mean state shift results in a rapid change in the large-scale dynamic and thermodynamic conditions, which substantially contributes to the abrupt change of TC activity in various genesis regions. In addition the CRS, the effect of interdecadal variability, such as the interdecadal Pacific Oscillation and Atlantic Multidecadal Oscillation, on the abrupt change of TC activity was discussed.

Keywords: climate regime shift, abrupt change, tropical cyclone, interdecadal Pacific Oscillation, Atlantic Multidecadal Oscillation

1. Introduction

The activity of tropical cyclones (TCs) substantially affected by large scale thermal and dynamic conditions fluctuates with multiple time scales. For example, the TC genesis number in the western North Pacific (WNP), the TC occurs most frequently in this region of the worldwide, exhibits an interannual and interdecadal fluctuation [1–6]. The interannual variation of TC activity in the WNP has been shown to be associated with large scale circulation anomalies caused by El Niño and Southern Oscillation [2, 7], as well as by stratospheric quasi-biennial oscillation [6, 8]. However, thermal conditions play a more dominant role than dynamic conditions in the interannual variation of TC activity in the North Atlantic [9–11].

In the view of interdecadal time scale, the TC genesis frequency in the WNP was high in mid-1960s and late 1980s but relatively low in 1970s and late 1990s [8, 12, 13]. It was noted a significant decrease in TC activity over the WNP after 1998 [8]. They attributed this decrease to the change in large scale vertical wind shear and 500-hPa geopotential height fields, which is likely associated with Pacific decadal Oscillation (PDO). In contrast to WNP, the TC activity in the North Atlantic Ocean showed an interdecadal increase since mid-1990s [10, 14, 15], which is likely a response to the interdecadal warming in the tropical Atlantic due to the Atlantic Multidecadal Oscillation (AMO) [10, 15].

Whereas the interdecadal variation of TC activity in various genesis regions had been widely discussed, most of previous studies are focused on specific genesis region. The TC activity in various genesis regions possibly had experienced an interdecadal change simultaneously, and so far, this issue was not thoroughly investigated yet. Recently, Hong et al. [16] reported that the tropical Pacific Ocean experienced a basin-scale climate regime shift (CRS) during the middle to late 1990s (approximately 1996/1997). This CRS, characterized by a negative sea surface temperature anomaly (SSTA) in the tropical central Pacific, generated a pair of anticyclone in the tropical western Pacific and that resulted in the interdecadal decrease of TC activity in the WNP and western South Pacific (WSP) in the late 1990s [17]. In this chapter, we extended the previous work [17], the possible influence of a CRS on the abrupt change of TC activity in various regions was investigated. Because a CRS is generally accompanied with atmospheric or oceanic low frequency variability, such as PDO and interdecadal Pacific Oscillation (IPO), the contribution of low frequency variability of climate system on the abrupt change of TC activity was discussed.

2. Data and methodology

Data from the International Best Track Archive for Climate Stewardship (IBTrACS; [18]) from the Regional Specialized Meteorological Center of the World Meteorological Organization and various agencies (e.g., Joint Typhoon Warning Center, JTWC, and the Japan Meteorology Agency, JMA) during the period of 1960–2014 were used to analyze TC frequency change. Because the observation of tropical depression-associated wind speed was not available until 1980 in the southern hemisphere, the analysis of TC activity in the Indian Ocean (IO) and western South Pacific (WSP) starts from the 1980s. Besides, the typhoon season (October to April) in the southern hemisphere covers two calendar years, the TC genesis number was measured from July to next June. Monthly atmospheric datasets of NCEP/NCAR Reanalysis I [19] and monthly SST field data obtained from the Met Office Hadley Centre [20] were used for diagnosing large scale circulation anomalies. The TC is defined as the maximum sustained wind speed of tropical cyclone reaches 34 knots. The TC is further separated to three scales, TS,

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TY and ST, which is approximately corresponding to the TS, C1–C2, C3–C5 of Saffir-Simpson typhoon-scale [21] respectively (**Table 1**). A singular vector decomposition (SVD) analysis by pairing up the SST and 850 hPa stream function fields was conducted to investigate the climate regime shift (CRS) of coupled climate system. Because the global SST, especially in the Indian Ocean (IO), exhibits a remarkable warming trend, the linear trend of SST during 1950–2010 had been removed off in the SVD analysis. A regime shift index (RSI; [22]) was them applied to the time series of first two SVDs to detect the specific time of climate regime shift. A cut-off length of 10 years was applied for climate regime shift (CRS) diagnosis, and only the RSI exceeding significant test at 0.05 significance level was considered.

3. Abrupt change of TC activity in various genesis regions

Figure 1 shows the time series of the annual TC count in various genesis basins. The TC genesis number in the WNP shows an interdecadal variation, indicating that the TCs were active approximately in the periods of 1960–1970 and 1980–1997, but were inactive in 1970–1980 and 1998–2014. This interdecadal variation of TC activity was consistent with the previous study [8]. The RSI calculation shows that the TC number underwent three significant abrupt changes in 1972, 1983 and 1997 during the 55-year period (1960–2014). Note that the RSI value in 1983 is in the margin of 5% significant level, and therefore is not clearly seen in **Figure 1**. Among the RSI, an abrupt decrease in TC activity after 1998 was particularly pronounced; the annual mean TC number was near 30 in the active period of 1988–1997, but decreased dramatically to 25 in the inactive period of 1999–2008. Time series of different TC scales (**Figure 2a**) reveals that the abrupt drop of TC number after 1998 is primarily caused by the decrease in TY. The number of TS and ST do not exhibit significant change prior and after the change point in 1998.

The TC genesis number in the eastern North Pacific (ENP) was low in 1960–1970 but was high in 1980–1990 and was approximately normal in 1970–1980 and after mid-1990s (**Figure 1**). The RSI calculation shows that the TC number in the ENP underwent three significant abrupt changes in 1969, 1981, and 1992 during 1960–2014. **Figure 2** further shows that the number of

Type of TC	Sustained wind speed (units: Knots)	Saffir-Simpson hurricane wind scale
Td	17–33	Tropical depression
TS	34–63	Tropical storm
TY	64–104	C1 (64–82) C2 (83–95)
ST	≧105	C3 (96–112) C4 (113–136 t) C5 (≧137)

The TY (typhoon) is approximately corresponding to category 1 + 2, and ST (sever typhoon) is corresponding to category 3 + 4 + 5 of Saffir-Simpson hurricane wind scale [21]. The TC number is defined as the summation of TS, TY, and ST numbers.

Table 1. Definition of the different tropical cyclone scale in this study.

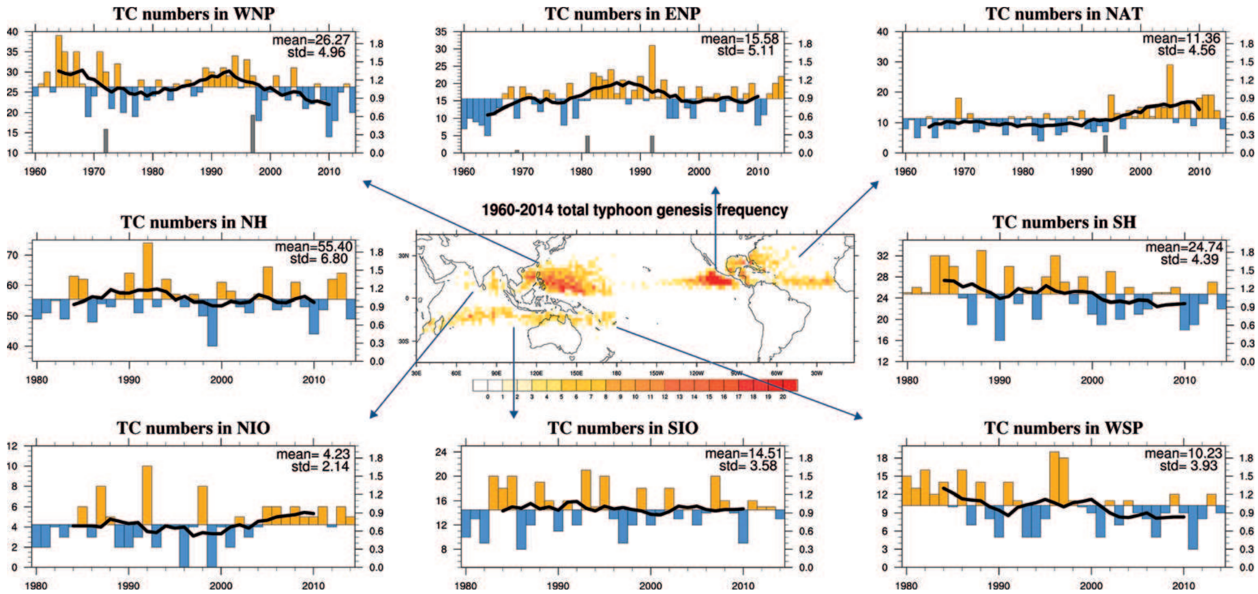

Figure 1. Time series of annual (filled bar) and 9-year running mean (black line) TC genesis number in various basins. The numbers in the upper corner indicate the mean and one standard deviation of the relevant to time series. The gray bar at the bottom shows the regime-shift index (RSI) [22] with 10-year cutoff length. Only the RSI exceeding 95% confidence is plotted. The central plot is the climatology of the spatial distribution of TC genesis density during 1960–2014.

all the TC scales (TS, TY, and ST) in the ENP increased simultaneously in the active period (1984–1993), however, the genesis number of the TY and ST exhibited a decrease in the inactive period in 1995–2004. The abrupt increase of TC activity in the North Atlantic (NAT) in middle 1990s was evident, that is, the TC genesis number exhibited a significant interdecadal increase after 1994/1995 [10, 14, 15]. In contrast to the ENP, the TC number in the NAT only experienced once abrupt change in 1994 (**Figure 1**). This abrupt change is primarily resulted from the number increase in TS and especially in ST, however, the contribution of TY is relatively weak (**Figure 2c**). It is clear that the abrupt increase of TC number in the ENP in the early 1980s is concurrent with the abrupt increase in the WNP. Whereas the abrupt decrease of TC number in the ENP in mid-1990s is synchronized with the abrupt increase in the NAT.

The time series of TC activity in the WSP shows that the TC genesis number was high in 1980–1990 and low throughout the 2000s. Whereas the total TC number decreases since 2000, the number of ST shows a gradual increase (**Figure 2d**). The decrease since 2000 was approximately synchronized with the abrupt decrease of TC number in the WNP in the late 1990s. The TC activity in the North Indian Ocean (NIO) was low during the 1990–2000, but was high, especially for the specific scale of TS, during the early 2000s (**Figure 2e**). Conversely, the TC activity in the South Indian Ocean (SIO) was high during middle 1980s to middle 1990s (**Figure 2f**). In contrast to North Hemisphere, the TC activity in South Hemisphere does not show significant abrupt change. Only the TC number in the WSP shows an abrupt decrease approximately in 2000 with a lower confidence level at 80%.

Overall, the total TC number in all the genesis regions in each year is approximately the same. Approximately 80 TCs forms each year in the global (**Figure 3a**). That is, the global TC number

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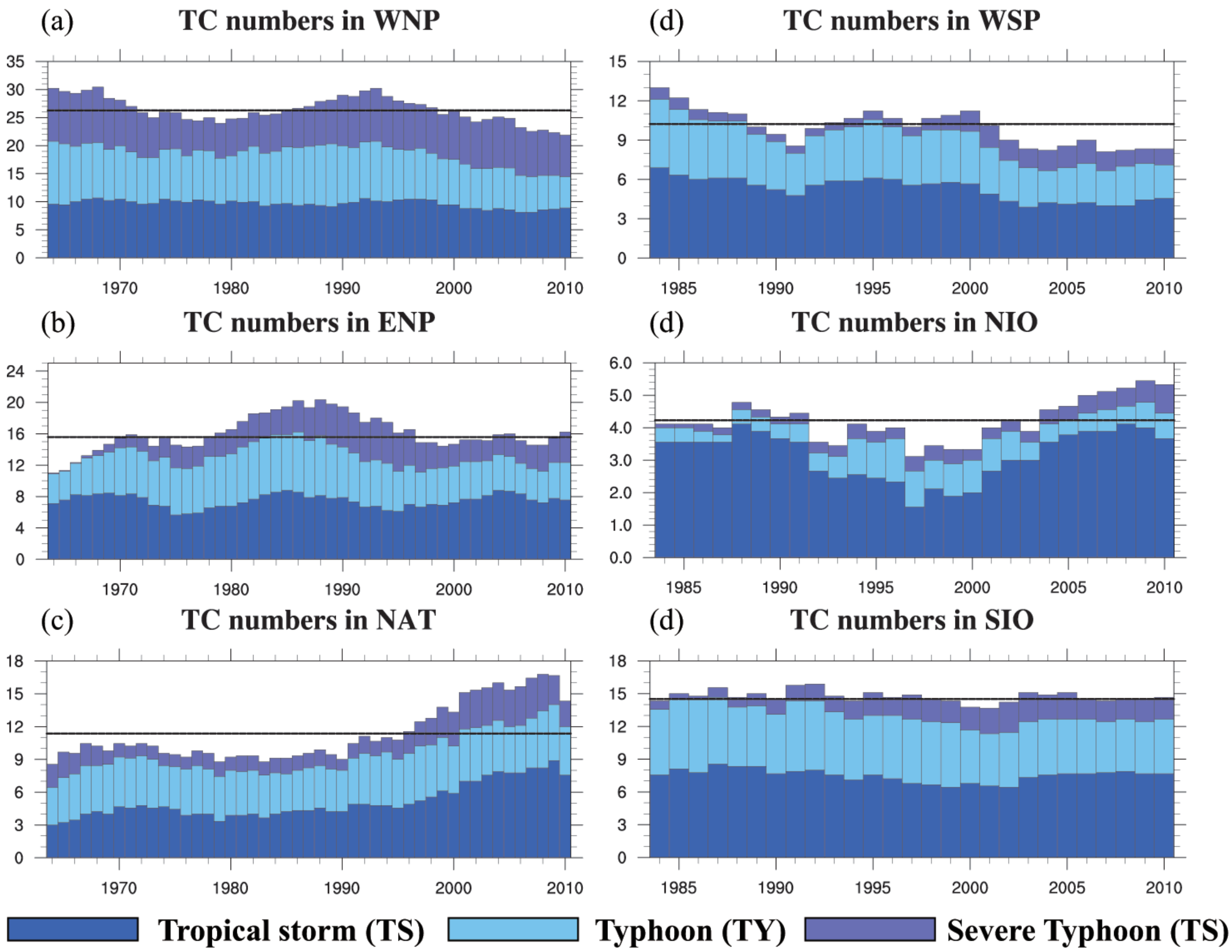

Figure 2. Time series of 9-year running mean (filled bar) of TC genesis number in various basins. Colorful fill bar represent the genesis number of different scale of TCs, including TS, TY and ST (**Table 1**). The horizontal dot line denotes the climatological mean of the TC genesis number.

does not exhibits interdecadal variation as identified in specific genesis region, such as in the WNP. The annual mean TC number in North Hemisphere also approximately remains the same since the late 1990s (**Figure 3b**) because that the decrease of TC number in the WNP is nearly compensated by the increase of TC number in the NAT (**Figure 2**). By contrast, the annual mean TC number in South Hemisphere shows an interdecadal decrease since the late 1990s, and the decrease is primarily resulted from the decline in specific scale of TY (**Figure 3c**). We note that the time series of TS and TY number for both Hemispheres are approximately opposite since the late 1990s. That is the TS and TY genesis number exhibits gradually increase and decrease respectively since the late 1990s. The interdecadal variation of the ST number in both Hemispheres is not so pronounced compared with that of TS and TY. The opposite relationship between the TS number and TY number is clearly seen in the ratio of specific scale of TC number to the total TC number: the ratio of TS and ST number to the total TC number in North Hemisphere and global exhibit gradually increase trend conversely, the ratio of TY number to the total TC number shows decrease trend since the late 1990s (**Figure 3d–f**).

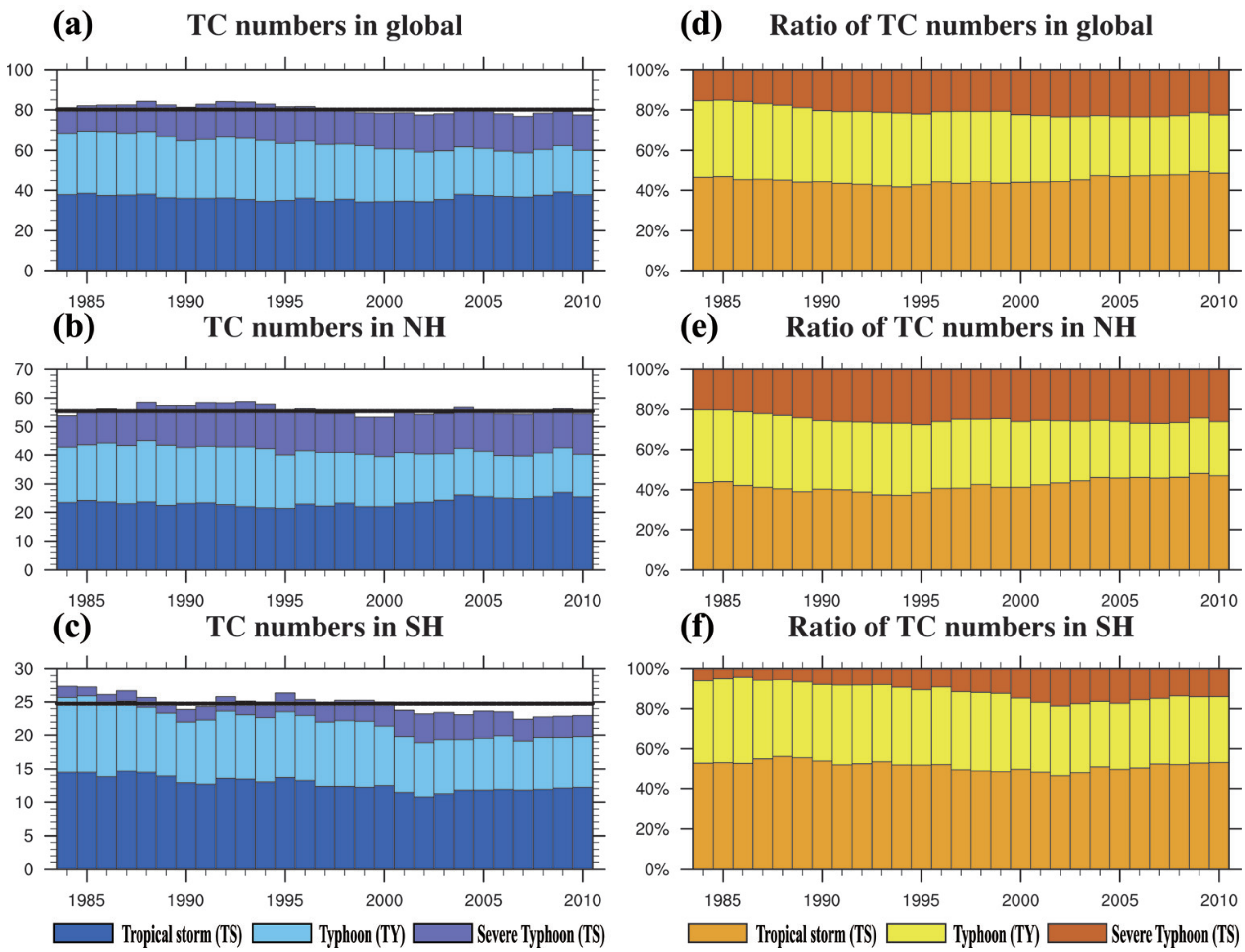

Figure 3. (Left) Same as in **Figure 2** except for the TC number in global, North and South Hemispheres. (Right) Same as in left panels except for the ratio of TC number of specific scale to the total TC number.

Based on the analysis of RSI in TC (TS + TY + ST) number, four significant abrupt changes of TC genesis number in various regions are identified during 1960–2014 (**Table 2**), including (i) an abrupt decrease (increase) in the WNP (ENP) in the early 1970s, (ii) an abrupt increase in the ENP and WNP in the early 1980s, (iii) an abrupt increase (decrease) in the NAT (ENP) in the middle 1990s, and (iv) an abrupt decrease in the WNP and WSP in the late 1990s. In the first abrupt change, the annual mean TC number in the WNP (ENP) decreases (increases) approximately 15% year^{-1} after the abrupt change in the late 1990s; In the second abrupt change, the TC number in the ENP increases approximately 40% year^{-1}; the TC number in the ENP (NAT) decreases (increases) approximately 36% year^{-1} in the third abrupt change; The last change is especially pronounced, the TC number in the WNP (WSP) decreases approximately 20% year^{-1}, and the TC number in the ENP (NAT) decreases (increases) approximately 15% (42%) year^{-1}. Whereas the TC number in the NIO also exhibits a remarkable increase (26% year^{-1}) after the mid-1990s, this increase is not significant because that the climatology of annual mean TC number is quite low (approximately 4), a small deviation of TC number could lead to a larger change.

Time of an abrupt change of TC activity		WNP Mean = 26.27 Std. = 4.96		ENP Mean = 15.58 Std. = 5.11		NAT Mean = 11.36 Std. = 4.56		NIO Mean = 4.23 Std. = 2.14		WSP Mean = 10.23 Std. = 3.77		SIO Mean = 14.40 Std. = 3.26	
1971	1961–1970	29.1	−4.1 (15.4%)	12.1	2.3 (14.8%)	9.7	−0.2 (1.8%)	—		—		—	
	1972–1981	25		14.4		9.5							
1982	1972–1981	25	2.4 (9%)	14.4	6.1 (39.2%)	9.5	−0.2 (1.8%)	—		—		—	
	1983–1992	27.4		20.5		9.3							
1994	1984–1993	28	−1.6 (6%)	19.9	−4.8 (30.8%)	9.8	3.3 (29%)	4.5	−1.1 (26%)	10.4	−0.1 (1%)	15.3	−0.9 (6.3%)
	1995–2004	26.4		15.1		13.1		3.4		10.3		14.4	
1998	1988–1997	29.7	−4.8 (18%)	17.6	−2.3 (14.8%)	10.8	4.8 (42.3%)	3.6	0.5 (11.8%)	10.7	−2.3 (22.5%)	15.2	0 (0%)
	1999–2008	24.9		15.3		15.6		4.1		8.4		15.2	

A regime shift index [22] was used to investigate an abrupt change of TC genesis number. Ten-years mean is used to indicate the time mean (background) state.

Table 2. Difference of the annual mean of TC number in various genesis regions after and prior the abrupt change of TC activity in 1971, 1982, 1994 and 1998.

4. Influence of climate regime shift on abrupt change of TC activity

In this section, we will demonstrate that the possible effect of a CRS on the abrupt change of TC genesis number. A CRS is featured by an abrupt transition from one quasi-steady climate state (or time mean state) to another quasi-steady state, and its transition period is relative shorter than the duration of each climate state. Using an analysis of experience orthogonal function (EOF) on SST, Yasunaga and Hanawa [23] reported that the North Hemisphere winter experienced three significant CRSs in 1971/1972, 1976/1977, and 1988/1989, during 1960–1997. The first CRS in 1971/1972 resembles the Central-Pacific or Modoki-El Niño SST anomaly [24–27], and the CRS in 1976/1977 and 1988/1989 are referred to a positive PDO or IPO pattern.

	PC1	PC2	AMO	PDO	CP	IPO
PC1	—					
PC2	−0.10	—				
AMO	−0.55	−0.54	—			
PDO	0.60	0.05	−0.09	—		
CP	0.25	−0.69	0.45	0.36	—	
IPO	0.73	−0.24	−0.03	0.85	0.58	—

A 9-year running mean is applied to the index before the calculation. The PCs are the principle component of SVDs. It indicates the SVD1 (SVD2) is closely related with the IPO (CP), and both SVD1 and SVD2 are correlated with AMO. The AMO, PDO and IPO indices are obtained from the website at https://www.esrl.noaa.gov/psd/data/timeseries/AMO/, https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/PDO/, https://www.esrl.noaa.gov/psd/data/timeseries/IPOTPI/ res pectively. The CP index is calculated by the previous study [28].

Table 3. Correlation coefficient table among the indices of SVDs, AMO, IPO, PDO and CP during 1960–2010.

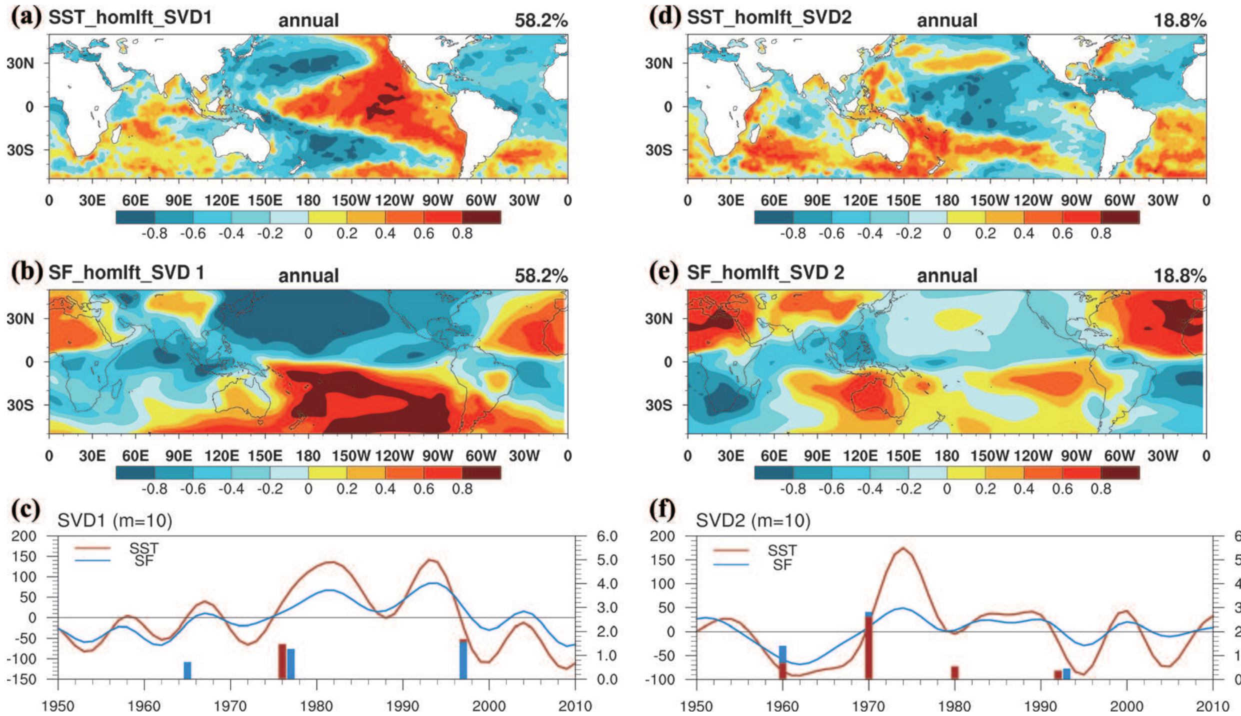

Figure 4. (Left) The leading SVD pattern of (a) SST and (b) 850 hPa stream function fields and (c) the corresponding principle components (PCs). The bars in (c) indicate the PCs experienced a significant abrupt change detected by regime shift index [22]. (Right) Same as in the left panels but for the second SVD mode.

These three CRSs are further identified by SVD analysis by paring the global SST and low-level circulation (850 hPa stream function) [16], indicating these CRSs are regime shifts of the air-sea coupled climate system. The SVD analysis reveals that leading SVD mode, with spatial pattern resembling the IPO (**Table 3**), showed a significant abrupt change in the 1976/1977 and 1996/1997 (**Figure 4a**); nevertheless, the second SVD mode, characterized by a CP La Niña-like [28] or Pacific Meridional Mode (PMM)-like [29, 30] SSTA in the Pacific (i.e., a southwest-northeast tilted negative SSTA in the central-eastern North Pacific, as well as a cooling in the tropical Atlantic), exhibited an abrupt change in the 1970/1971. A comparison between **Table 2** and the CRSs indicates that the three abrupt changes of TC activity in the Pacific basin, including the early 1970s, early 1980s and late 1990s, were approximately synchronized with the CRSs in the 1971/1972, 1976/1977 and 1996/1997 respectively (**Figure 5**). Whereas the abrupt TC increase in the NAT in the 1993/1994 was not corresponding to a specific CRS, it was concurrent with the interdecadal change of AMO.

4.1. Effect of CP-like SST on the abrupt change of TC activity in the early 1970s

The CRS in the early 1970s is primarily determined by the second SVD, which is characterized by a CP La Niña-like SSTA (**Figure 4d**). **Figure 5** shows that the CRS in the early 1970s is concurrent with the abrupt decrease/increase of TC number in the WNP/ENP in the early 1970s, suggesting that both are related. Because the TC activity is substantially affected by the large-scale factors (e.g., low-level vorticity, vertical wind shear and mid-atmosphere relative humidity), the effect of CRS on the abrupt change of TC activity can be understood by regressing these large-scale factors on the SVD. Because the first two SVDs are closely related

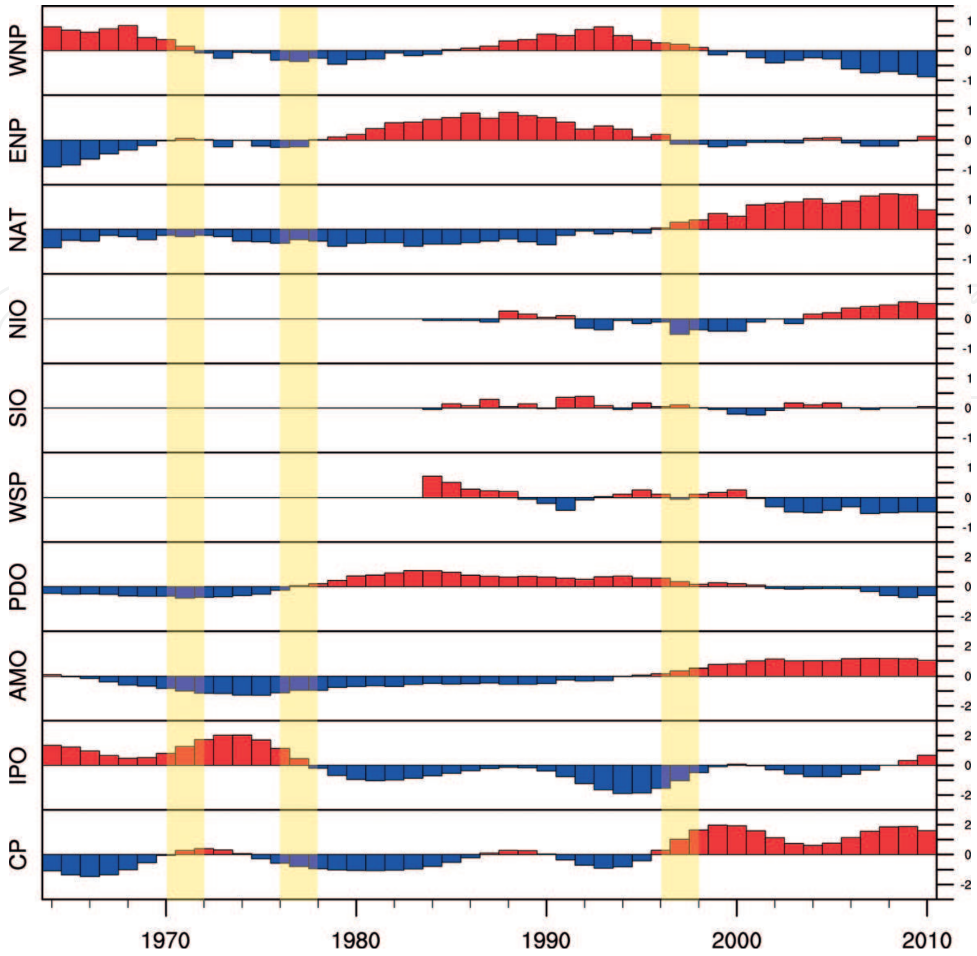

Figure 5. The bars indicate the normalized TC genesis number in various genesis regions and PDO, AMO, IPO and CP indices. The vertical yellow shaded indicates that the climate regime shift in 1971/1972, 1976/1977 and 1996/1997. The climate regime shift is identified by the regime shift index of leading SVDs by coupling the SST and 850 hPa stream function (**Figure 4c** and **f**).

with the AMO (**Table 3**), the partial regression by removing the effect of AMO is applied to investigate the net effect of SVD on the large-scale conditions. It shows that the second SVD is associated with a pair of cyclonic anomalies in the tropical eastern Pacific, as well as an anticyclonic circulation anomaly in the WNP and WSP (**Figure 6d** marked with H and L, respectively). This anticyclonic circulation creates a low-level easterly anomaly and a positive zonal wind shear in the WNP (**Figure 6e**), which provides unfavorable large-scale conditions for TC activity. Conversely, the cyclonic circulation creates a favorable large-scale environment for TC genesis in the ENP. In contrast to the dynamic factors, the regression of thermodynamics (700 hPa relative humid) does not exhibit significant signal in the WNP and ENP (**Figure 6f**). That indicates the CP La Niña-like SSTA associated dynamic conditions determine the abrupt decrease (increase) of TC genesis number in the WNP (ENP) in the early 1970s.

4.2. Effect of IPO-like SST on the abrupt change of TC activity in the early 1980s

The CRS in the early 1976/1977 is determined by the leading SVD, featured by a positive IPO SSTA. The TC activity-related large-scale factors regressed on the leading SVD reveals that the

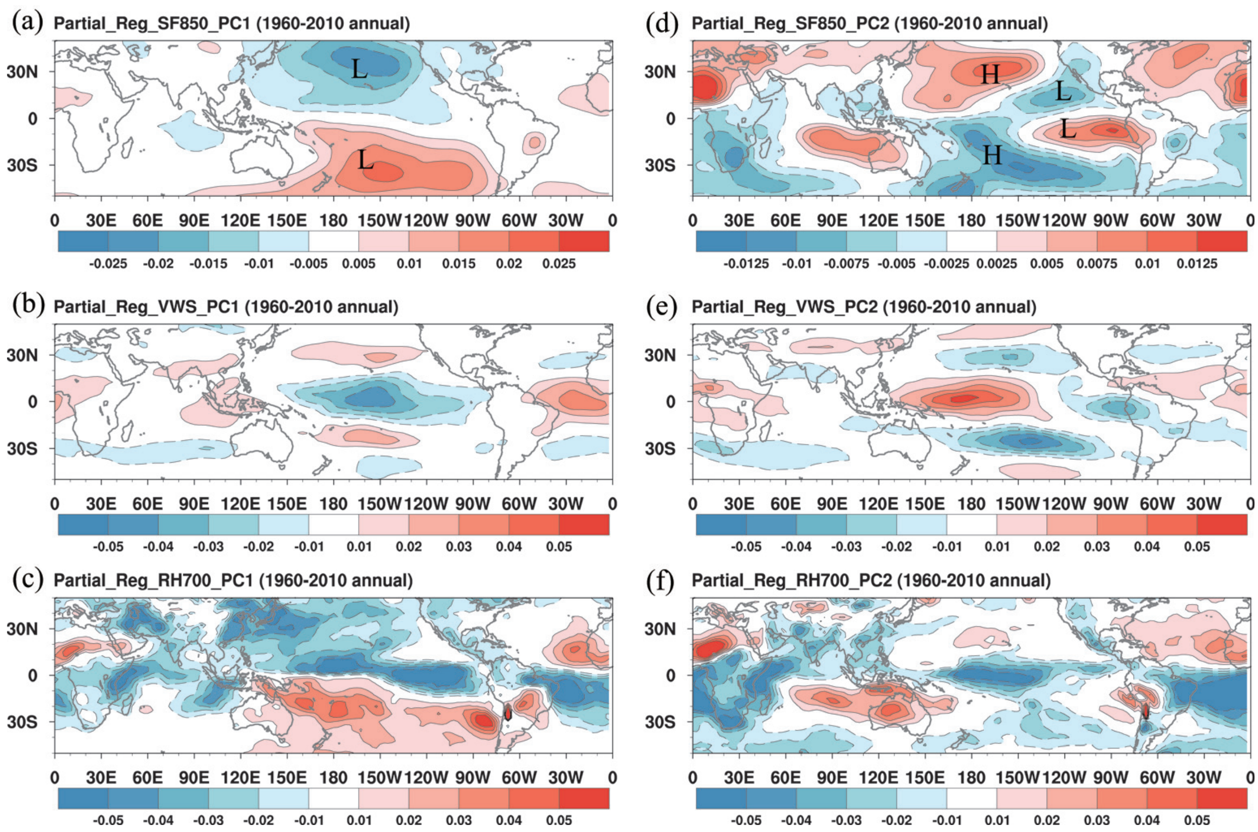

Figure 6. The partial regression (with AMO index fixed) of TC activity associated large-scale dynamic and thermal conditions on the first SVD (IPO-like SST): (a) 850 hPa stream function (b) vertical zonal wind shear, and (c) 700 hPa relative humidity. (d–f) Same as in (a–c) except for the second SVD (CP-like SST).

first SVD (i.e., IPO or PDO) was accompanied by a pair of basin–scale cyclonic anomaly, a Matsuno-Gill response [31, 32] to the positive SSTA in the tropical eastern Pacific (**Figure 6a**). The pair of cyclonic anomaly creates a negative vertical zonal wind shear anomaly in the tropical eastern Pacific (**Figure 6b**), which provides a favorable dynamical condition for TC genesis. There has no evidence indicates that the mid-level relative humid contributes to the abrupt increase of TC genesis number in the WNP and ENP in the early 1980s. In contrast to the dynamic factors, the positive IPO phase is associated with a negative 700 hPa relative humidity anomaly in the WNP (**Figure 6c**), which is unfavorable for TC genesis. Because the effect of dynamics on enhancing the TC activity in the WNP partially offsets by the effect of thermodynamics, the magnitude of abrupt increase of TC number in the WNP in the early 1980s is much weaker than that in the ENP. Again, the IPO-related large-scale change in the dynamics determines the abrupt increase of TC number in the ENP and WNP in the early 1980s.

4.3. Combined effect of IPO and AMO on the abrupt change of TC activity in the late 1990s

The CRS in 1996/1997 is also primarily determined by the leading SVD except that the amplitude is negative. That is the CRS-induced time mean state change exhibits a negative IPO-like (or Mega La Niña-like) SSTA pattern, which is accompanied by a pair of anticyclone and

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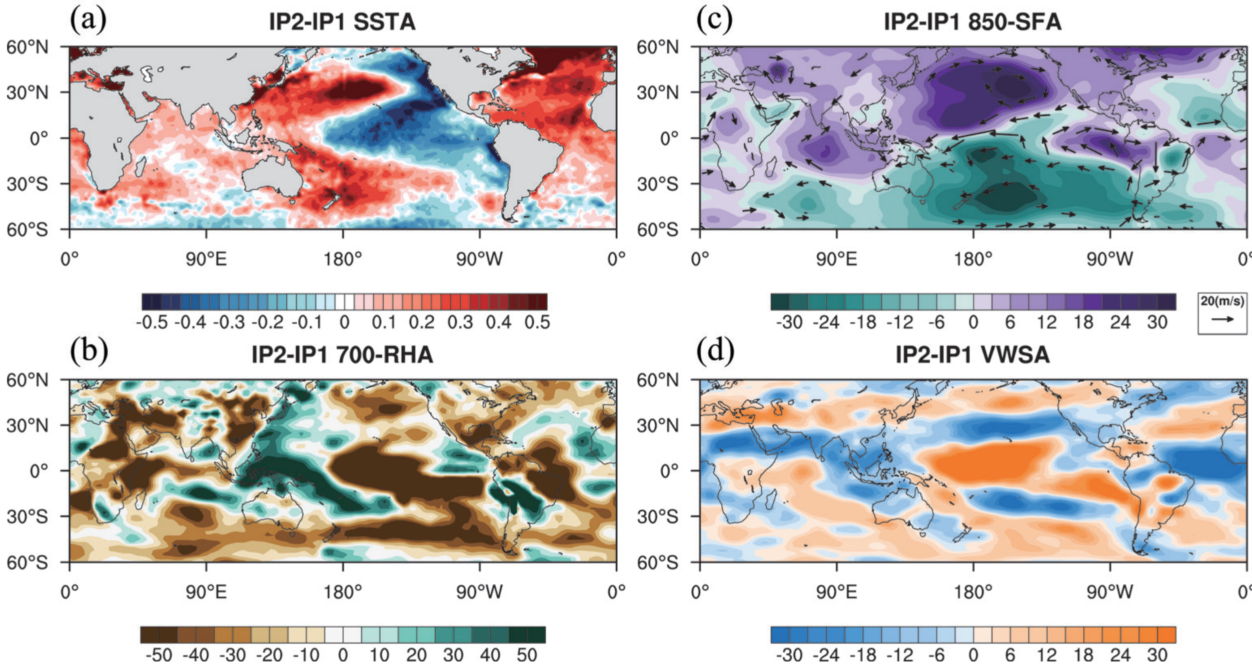

Figure 7. The time mean-state difference relevant to the climate regime shift in 1996/1997 ([IP2: 1999–2008 minus IP1: 1989–1997). (a) SST (°C), (b) 700 hPa relative humidity (%), (c) 850 hPa stream function (10^{-6} m^2 s^{-1}), (d) vertical zonal wind shear (m s^{-1}) (U_{200}–U_{850}).

cyclone anomalies in the western Pacific and eastern Pacific respectively (**Figure 7**). The anticyclone associated positive vertical zonal wind shear anomaly in the western Pacific is not favorable for the TC activity in the WNP and WSP. The influence of the basin-wide CRS in 1996/1997 on the TC activity in the late 1990s could be interpreted as outlined in follows: the global SST experienced a significant regime shift approximately in 1996/1997. Prior to this climate regime shift, a positive SSTA appeared in the equatorial central-eastern Pacific as well as a negative SSTA appeared in the tropical Atlantic and western Pacific. In response to this positive SSTA, a Matsuno-Gill-type [31, 32] of low-level cyclonic circulation anomaly occurred in the WNP. This large-scale anomalous cyclone, together with reduced vertical zonal wind shear, favored TC genesis, which explains why TC number in the WNP were above normal before the CRS. However, these anomalous thermodynamic and dynamic conditions reversed after 1996/1997. That is, the SSTA in the equatorial central-eastern Pacific turned from positive to negative, and vice versa in the equatorial western Pacific, after the CRS in 1996/1997. In response to the phase change of the SSTA in the central-eastern equatorial Pacific, an anticyclone anomaly was observed in the WNP/WSP after 1996/1997. Meanwhile, the anticyclone associated low-level easterly wind anomaly creates a positive vertical zonal wind shear anomaly in the western Pacific. Both of these changes in the background state suppressed TC activity in the WNP and WSP.

A comparison between the time mean state change prior and after the CTS in 1996/1997 (**Figure 7**) and the leading SVD (**Figure 4a** and **b**) reveals that a pair of cyclonic anomaly in the ENP (**Figure 7**) is not detected in **Figure 4a** and **b**. This distinction is primarily caused by the effect of the interdecadal change of AMO, which terminated phase in 1994/1995 and was approximately

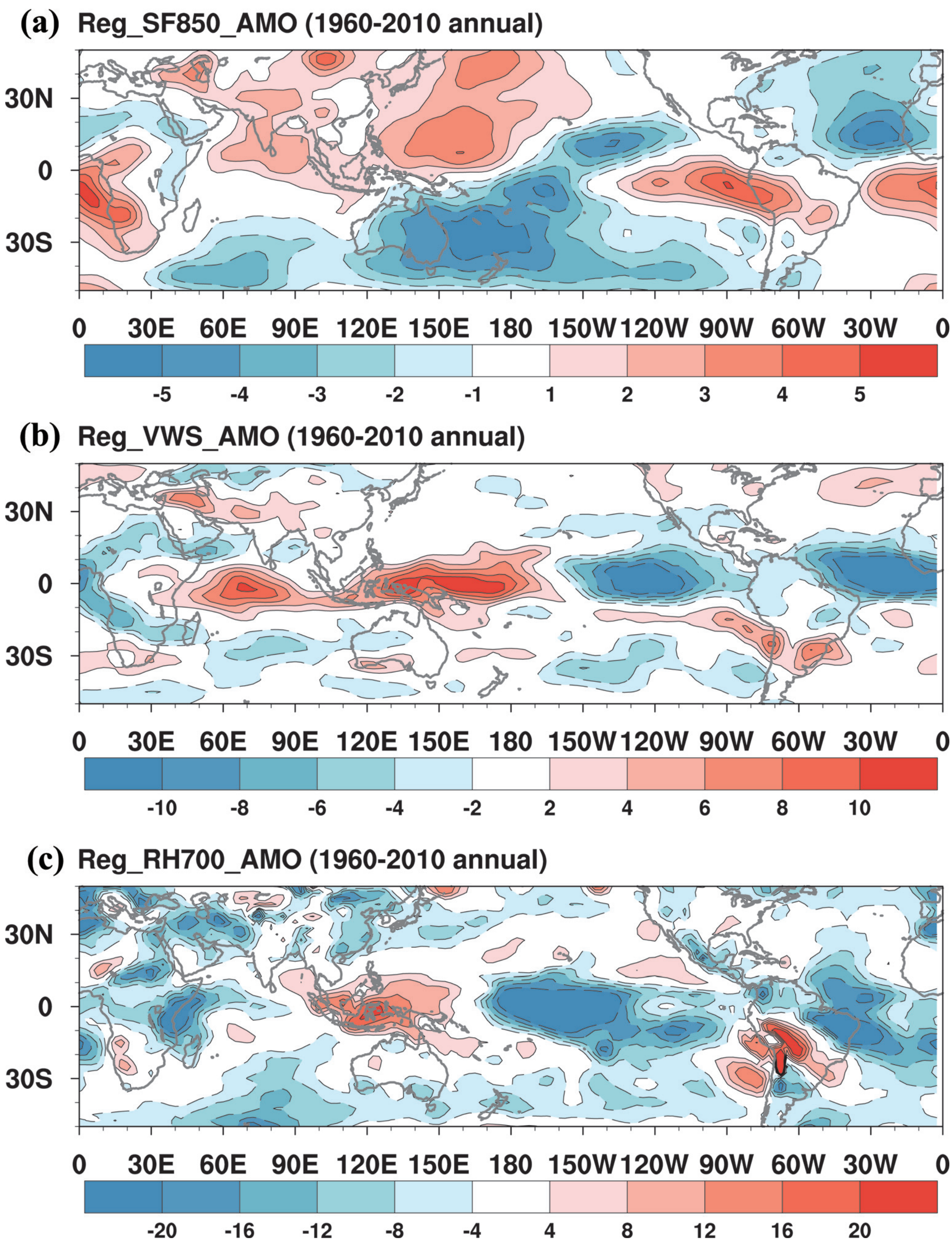

Figure 8. Same as in **Figure 7** except for the AMO index.

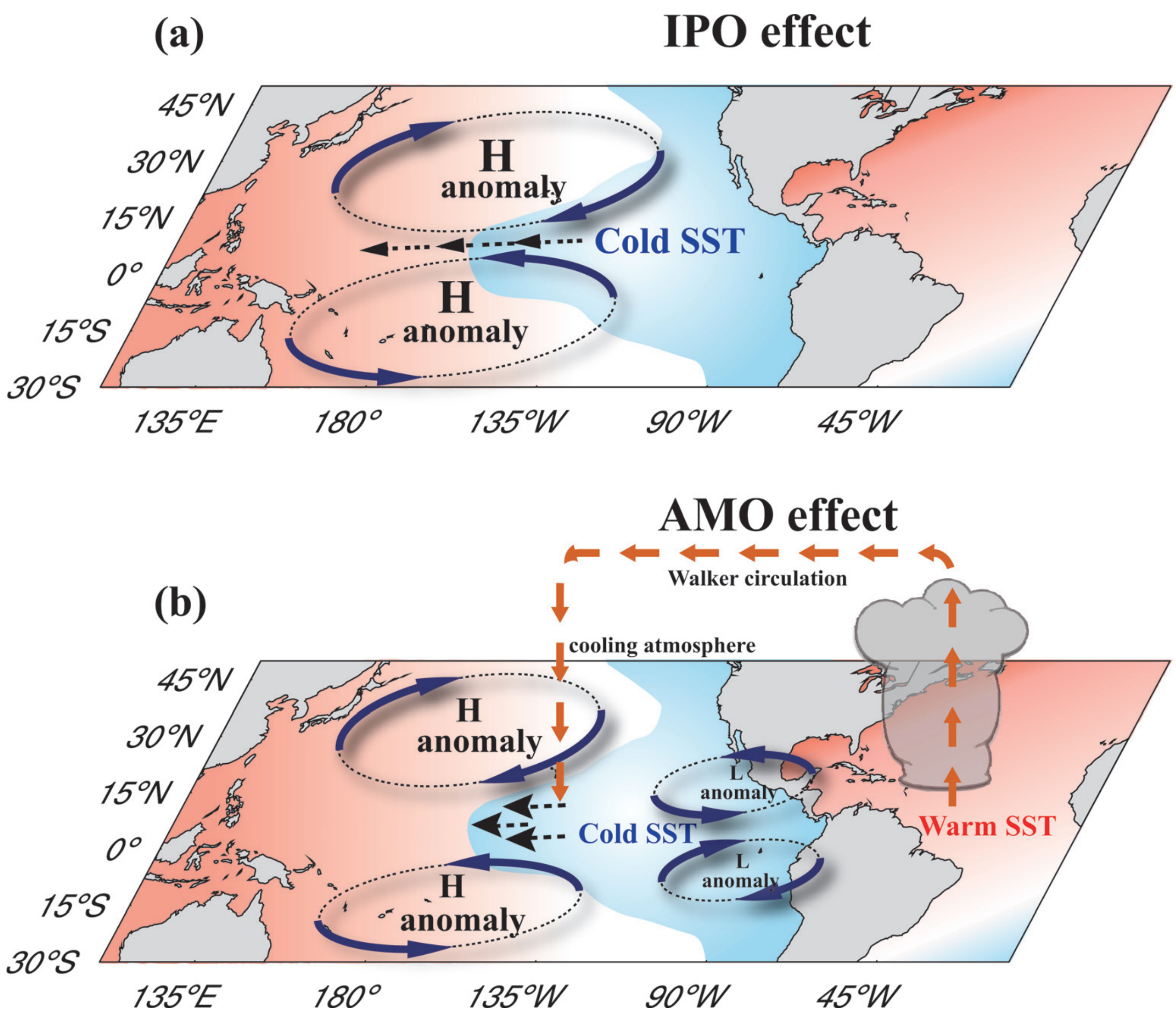

Figure 9. Schematic diagram illustrates how the IPO and AMO affects the abrupt change of TC activity in late 1990s.

synchronized with the CRS in 1996/1997 in the view of interdecadal timescale. The regression of 850 hPa stream function on the AMO reveals a pair of cyclone anomaly in the ENP and a pair of anticyclone anomaly in the western Pacific (**Figure 8a**). That indicates the effect of negative IPO phase on suppressing the TC activity in the western Pacific was fuehrer enhanced by the remote impact of a positive AMO associated positive SSTA in the tropical Atlantic (**Figure 8b–c**). The AMO not only exerts a remarkable remote impact on the TC activity in the Pacific, it associated local change in thermodynamic also directly contributes to the abrupt increase of TC number in the Atlantic in 1993/1994 [10, 14, 15].

The combined effect of IPO and AMO on the TC activity in the Pacific in the late 1990s is presented in the schematic diagram (**Figure 9**) and described as followings: the negative IPO associated Mega La Niña SST anomaly forces a pair of basin-scale anomaly in the Pacific, in which the anticyclone associated negative vorticity and positive vertical zonal wind shear anomalies may substantially suppress the TC activity in the WNP and WSP (**Figure 9a**). Meanwhile, the AMO associated positive SSTA in tropical Atlantic drives a pair cyclonic circulation anomaly in the ENP, as well as an east-west overturning circulation anomaly in the Atlantic-Pacific, with subsidence branch in the equatorial central Pacific (**Figure 9b**). The downward motion in the equatorial central Pacific produces a low-level easterly anomaly and a positive vertical zonal wind shear anomaly in the tropical western Pacific, which provides an unfavorable large-scale dynamic condition for TC activity in the WNP and WSP. Additionally, the downward motion induced diabetic cooling anomaly generates a Rossby wave-like response of an anticyclone anomaly in its northwest (southwest) in the WNP (WSP), which in term the associated negative vorticity anomaly tends to suppress the TC activity in the WNP (WSP).

5. Conclusion

The possible impact of basin-scale CRS on the abrupt change of TC activity in various genesis regions, including the Pacific, Indian Ocean and Atlantic Ocean was investigated in this report. Here, a RSI index is use to detect a climate regime shift and an abrupt change of annual mean TC number in various genesis regions. It reveals that the worldwide TC activity experienced four significant abrupt changes during 1960–2014, including (i) an abrupt increase/decrease in the ENP/WNP in the early 1970s, (ii) an abrupt increase in the ENP and WNP in the early 1980s, (iii) an abrupt increase in the NAT/ENP in the middle 1990s, and (iv) an abrupt decrease in the WNP/WSP in the late 1990s. The abrupt change in the early 1970s, early 1980s and late 1990s is closely related with the CRS in 1971/1972, 1976/1977 and 1996/1997 respectively. The other abrupt change identified in North Atlantic in 1993/1994, is related with the decadal variation of AMO. That is an abrupt change of TC activity in specific genesis region is generally accompanied by an abrupt TC activity change in the other region.

Observation reveals that the abrupt change of TC number in various genesis regions is closely related with a basin-scale CRS or low frequency variability of the coupled climate system. The SVD analysis reveals that the CRS in 1976/1977 and 1996/1997 is primarily determined by the leading mode (i.e., IPO-like SST), whereas, the CRS in 1971/1972 is primarily dominated by the second SVD (i.e., CP La Niña-like SST). Among the four abrupt changes of TC activity, the last abrupt change in the late 1990s is especially pronounced because that the IPO and AMO joint together to contribute to the interdecadal change of TC activity in the Pacific basin. We demonstrated that the CRS-induced large scale oceanic and atmospheric background changes may lead to an abrupt change in TC activity in various genesis regions. The effect of CRS on the abrupt change of TC activity is further supported by the regression analysis of the TC activity-related large-scale factors on the first two SVDs.

It has been identified that an abrupt change occurred in TC activity in the various genesis regions of the Pacific during the late 1990s. The interdecadal decrease in TC activity in the WNP during the late 1990s had been reported widely in recent studies [8, 12, 13, 33]. However, in this chapter, a new interpretation of this interdecadal change has been proposed. Here, we

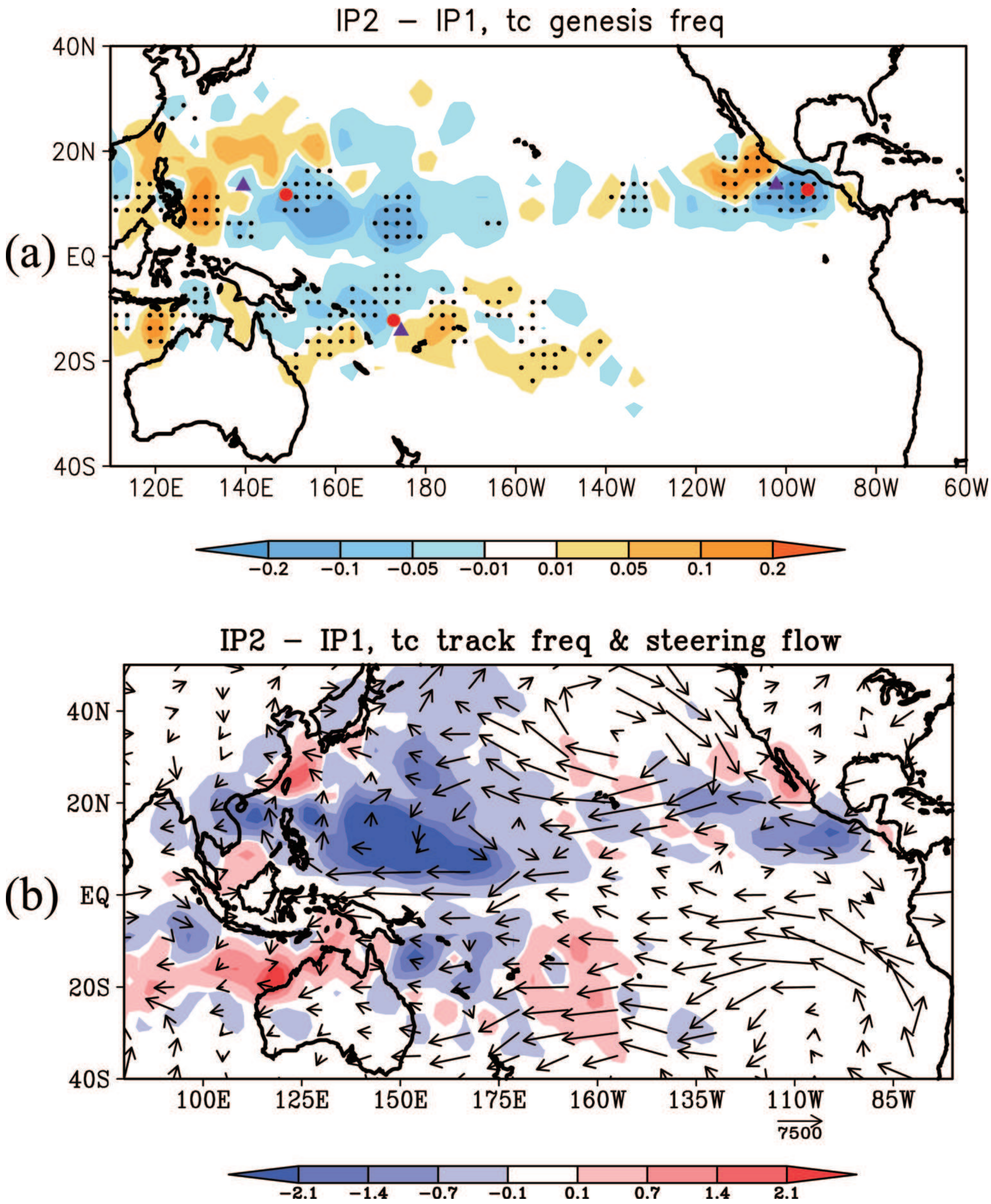

Figure 10. Difference of (a) TC genesis density and (b) TC track density relevant to the climate regime shift in 1996/1997 between the IP1 (1989–1997) and IP2 (1999–2008). The symbols "●" and "▲" denotes the mean TC genesis position during IP1 and IP2, respectively. The dots in (a) indicate that the change in TC genesis frequency was at 5% significance level. The vectors in (b) indicate the steering flows that are defined as the vertical integrated horizontal winds from 850 to 300 hPa.

assumed that the abrupt change in TC activity in the WNP during the late 1990s was part of the phenomenon of basin-scale change in TC activity in the Pacific basin. In addition the TC genesis number, the CRS in the late 1990s had also resulted in a significant change in the mean TC genesis location in the WNP and ENP. The mean TC genesis location in WNP shift westward significantly from 149°E to 140°E, and the mean location in ENP shifts from approximately from 95°W to 102°W (**Figure 10a**). This westward shift in the ENP leads to a change in TC genesis frequency that resembles the response to global warming [34]. Of particular note is that the westward shift of the mean location of TC genesis in the WNP was accompanied by an increase in TC activity in the western WNP and southeastern part of the South China Sea (e.g., [35]). Studies had shown that the increase in TC activity in the western WNP could lead to a significant increase in TC landfalls in Taiwan [13, 36]. Irrespective of the increase in TC genesis frequency, our study showed that the modulation of the CRS-induced circulation on the steering flow (i.e.., westward extension and northward curving near the Philippine Sea) also contributed substantially to the increase in TC landfalls in Taiwan after late 1990s (**Figure 10b**).

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