Decadal Variations of Intense Tropical Cyclones over the Western North Pacific during 1948-2010

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1. Introduction

The influence of global warming on tropical cyclone (TC) intensity has been extensively discussed over the past several decades (Emanuel 1987, 2005; Knutson et al. 1998, 2010; Knutson and Tuelya 2004; Bender et al. 2010). In the western North Pacific (WNP), studies suggested an increase in intense TCs (i.e. categories 4 and 5 in the Saffir-Simpson scale, hereafter Cat45) since the 1970s (Webster et al. 2005; Elsner et al. 2008), while longer TC records suggested that such an increasing trend in TC intensity is a part of interdecadal variations over the WNP basin (Chan 2006, 2008). Other studies indicated that the increasing Cat45 TCs since the 1970s was detected only in the Joint Warning Typhoon Center (JTWC) best track dataset (Wu et al. 2006; Kamahori et al. 2006; Song et al. 2010; Ren et al. 2011), suggesting substantial uncertainty in historical TC intensity records. It is clear that understanding of possible impacts of global warming on TC intensity is complicated by various natural variations and uncertainty in historical TC data.

Some studies have been conducted on the decadal and interdecadal variations in TC frequency and tracks over the WNP basin (Yumoto and Matsuura 2001; Matsuura et al. 2003; Yumoto et al. 2003; Ho et al. 2004; Liu and Chan 2008; Kim et al. 2010). Based on the Regional Specialized Meteorological Center of Tokyo (RSMC) TC dataset since 1951, Yumoto and Matsuura (2001), Yumoto et al. (2003) and Matsuura et al. (2003) found significant variations in TC frequency with a period of about 20 years and suggested that the interdecadal variability was associated with increased (decreased) sea surface temperature (SST) in the central and eastern equatorial Pacific, which strengthens the tropical westerlies (easterlies), leads to the eastward (westward) extension (retreat) of the monsoon trough and an anomalous cyclonic (anticyclonic) circulation east of the Philippines and thus increasing (decreasing) annual TC frequency. Ho et al. (2004) contrasted the track change between the two periods of 1951-1979 and 1980-2001 with the JTWC best track data and linked the interdecadal change to the westward expansion of the North Pacific subtropical high. Liu and Chan (2008) also suggested a significant interdecadal variability of the TC tracks in the WNP basin during the period 1960-2005. Based on a TC trajectory model, Wu et al. (2005) showed that two prevailing TC tracks in the

WNP basin have shifted westward significantly over the past four decades due mainly to changes in large-scale steering flows while TC activity in the South China Sea decreased.

However, relatively few studies have examined TC intensity changes in the WNP basin on the decadal and interdecadal time scales. Using the JTWC best track data during the period of 1960-2005, Chan (2006, 2008) showed prominent interdecadal variations in the frequency of Cat45 TCs with a period of about 18-32 years and argued that the variability was due to changes in the thermodynamcial and dynamical factors (e.g., SST, low-level vorticity, moist static energy and vertical wind shear), while Wu and Wang (2008) argued that changes in the proportion of the Cat45 TCs over the past three decades were associated with changes in TC formation locations and prevailing tracks. Furthermore, some studies suggested that TC maximum wind speeds in the JTWC dataset before 1973 were overestimated (Emanuel 2005, 2007). Currently, the uncertainty involved in these datasets has become an important issue in understanding of the possible influence of global climate change on TC activity in the WNP basin. Given considerable uncertainty in historical TC records, one question arises as to whether there are significant decadal and interdecadal variations of Cat45 TCs in the WNP basin, which is the main objective of this study. The knowledge gained from such an analysis may help to improve our understanding of the decadal variation of Cat45 TC frequency and provide important background and useful predictors for improving its potential of decadal prediction.

The rest of the paper is organized as follows. The datasets and processing used in this study are described in Section 2. The methodology and dynamically-derived climate changes in the basin-wide Cat45 TC frequency are presented in Section 3. The controlling factors for decadal variability of Cat45 TC frequency are identified in Section 4 and the associated large-scale pattern is investigated in Section 5. A brief summary is given in Section 6.

2. Datasets and Processing

The monthly SST is from the National Oceanic and Atmosphere Administration (NOAA) reconstructed SST (version 3) with horizontal resolution of $2^{\circ}\times 2^{\circ}$ (Smith and Reynolds 2004). The wind data is obtained from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset with horizontal resolution of $2.5^{\circ}\times 2.5^{\circ}$ (Kalnay et al. 1996). The TC information from the JTWC best track dataset includes TC center positions and intensity at six-hour intervals in the WNP basin. Wu and Zhao (2011) indicated that JTWC dataset is more reliable compared to other TC best track datasets available in the basin. Chan (2008) also argued that the intensity records from the JTWC dataset are relative reliable. For this reason, we use the JTWC dataset as the observation in this study. In the JTWC best track dataset, TC intensity was mainly estimated from aircraft reconnaissance in the pre-satellite era, which started around 1945, but was discontinued in 1987 (Landsea et al. 2006). Since then, the Dvorak technique that was developed during the 1970s has been used to estimate TC intensity from satellite imagery and other satellite-based measurements (Dvorak 1975; Landsea 2007). The evolution of the technique of TC intensity estimating can lead to inhomogeneity in the TC intensity records and thus caution should be taken to address long-term variations in TC intensity.

Emanuel (2005) extensively discussed that the evolution in measurement and estimation techniques introduces in historical records of TC wind speeds. Subsequently, Emanuel (2007) provided additional evidence supporting the need for a downward adjustment of intensities in the early part of record using the refined combined wind-pressure relationship in Emanuel (2005), and in agreement with Landsea's (1993) earlier analysis. In the present study, following Emanuel (2005, online supplement), we first adjust the maximum wind speeds in the JTWC dataset prior to 1973. As shown in Fig.1, the annual TC number is reduced prior to the 1970s after the adjustment. The annual Cat45 TC frequency is also substantially reduced prior to the 1970s (Fig.2a). As a result, the heightened Cat45 TC activity around 1960 in the historical (hereafter unadjusted) TC intensity records, which was argued as a peak of the interdecadal variations (Chan 2006, 2008), vanishes in the adjusted TC intensity time series. Instead pronounced decadal variations of the annual Cat45 TC frequency can be found, with most prominent peaks occurring around 1969, 1991 and 2004 (Fig. 2a).

Variations in the adjusted and unadjusted Cat45 TC frequencies during the period 1948-2010 are examined with a spectral analysis. As shown in Figs. 3a and 3b, all the unadjusted, adjusted and simulated Cat45 TC frequencies show interannual cycles although their significant spectral peaks are not exactly the same. On the decadal scale, a significant spectral peak is about 25 years in the unadjusted Cat45 TC frequency, while 12-18 years cycle can be found in the adjusted and simulated Cat45 TC frequency. Although the edge effects in spectral analysis, it is found that the results are robust because the significant periods are essentially the same when we use the wavelet analysis (Figures not shown). Zhao et al. (2011) suggested that interannual variations in TC intensity are dominated by the interannual variability of the monsoon trough associated with SST changes, but the associated physical mechanisms of the decadal variations of Cat45 TC frequency are not well understood in the literature, due mainly to short TC records and uncertainty in historical intensity records.

3. Methodology and Numerical simulations

Recently, an approach was used to assess historical TC intensity records (Wu and Zhao 2012). In the approach, the intensity of each storm is numerically simulated with a TC intensity model (Emanuel et al. 2006; Emanuel et al. 2008). Using this approach, Wu and Zhao (2012) found that the evolution of the basin-wide TC intensity in the JTWC best track dataset can be reasonably well simulated over the period of 1975-2007. In addition, they suggested that the Cat45 TC frequency is sensitive to changes in the vertical wind shear (VWS) and SST. For this reason, here we focus on the annual Cat45 TC frequency and conduct numerical simulations similar to those in Wu and Zhao (2012) by extending the study period back to 1948.

The TC intensity model is an axisymmetric numerical atmospheric model, coupled with a simple one dimensional ocean model (Emanuel 2006; Emanuel et al.

2008). Using the intensity model, Emanuel et al. (2008) explored the influence of various environmental factors on TC intensity. In this study, the observed TC tracks during the period of 1948-2010, and the corresponding VWS and SST along the TC tracks are supplied. The VWS is calculated as the magnitude of the monthly vector difference between 850 hPa and 200 hPa. and its effect is parameterized in the TC intensity model. Note that the influence of SST changes associated with TC-ocean interaction is not included in this study. All of the observed TCs in the JTWC dataset are allowed to move along the observed TC tracks and their intensity evolution is simulated in the intensity model. The intensity model is initialized with a warm-core cyclonic vortex. The maximum wind speed of the initial vortex is set to be 21 m s^{-1} after a series of numerical experiments because the model vortex weakens at the beginning of the simulation，which was also adopted in Wu and Zhao (2012) and Zhao et al. (2011). Note that the intensity of the initial vortex has a little influence on our simulations, very similar patterns and temporal variations except for the magnitude of TC intensity when we conducted a few sensitivity experiments. The other parameters of the initial vortex are the same as those in Emanuel et al. (2008). The same model setup is used for all the simulation in this study and the Student's t-test method is used to test the statistical significance at the 95% confidence level (Wilks 1995).

In the control experiment (CTRL) (Table 1), all of the TCs move with their observed tracks, experiencing the corresponding observed monthly VWS and SST along the TC tracks during the period 1948-2010. As shown in Fig.2a, the simulated Cat45 TC frequency is in good agreement with the adjusted Cat45 frequency. The correlation coefficient is 0.86 during the period 1948-2010, statistically significant with an effective sample size of 51, which is referred to Dawdy and Matalas (1964). As shown in Fig.3c, the significant spectral peaks in the simulated Cat45 TC frequency are about 2.5, 4, 5, 9 and 15 years. In agreement with the adjusted Cat45 frequency, the 18-32 year variability is not statistically significant in the simulated Cat45 TC frequency, suggesting that the 18-32 year variability is due mainly to the different wind-pressure relationships used in the JTWC records during the period 1948-2010.

Given the observed TC tracks used in the simulation, uncertainty in the simulation may result from missed or incomplete TC track records in the JTWC dataset, especially during the pre-satellite era (Landsea 2007). To demonstrate it, the JTWC best track data are divided into three periods: 1948-1964, 1965-1972 and 1973 -2010, which are based primarily on the development in the observational techniques. In 1965 satellite data started to be used to monitor TCs (Landsea 2007; Emanuel 2008) and a new wind-pressure relationship was used for estimating TC intensity since 1973 (Emanuel 2005). Here the average TC lifetime and the average time for a TC to achieve Cat45 intensity are examined. For the three periods, the average lifetime of the Cat45 TCs is 6.68, 8.25 and 8.84 days while the mean time to taking to achieve Cat45 intensity is 2.61, 3.13, 3.30 days, respectively. Further calculations suggested that the mean lifetime during the pre-satellite period is indeed significantly shorter than the two post-satellite periods, indicating incomplete track records in the JTWC dataset during the pre-satellite period. Moreover, the Cat45 TCs had relatively short lifetime in the pre-satellite era.

However, the adjusted Cat45 TC frequency prior to the satellite era may be reasonable. First, in the presence of aircraft reconnaissance during 1948-1972 and relatively long duration, Cat45 TCs should have less chance to be missed in the JTWC dataset than weak TCs. Second, the locations of reaching Cat45 intensity occurred mostly in the western part of the WNP basin, and could be covered by the aircraft reconnaissance stationed in Guam (Fig. 4).

In addition, the simulated Cat45 TC frequency is well consistent with the one in the adjusted dataset. Despite the relatively short duration in the pre-satellite era, both of the simulated and adjusted Cat45 TCs show a similar rapid intensification process. It is note that the simulated TC intensification is smaller than the observation (Wang and Zhou 2008). On average, the observed (simulated) Cat45 TCs take 48 hours to increase about 32 m s^{-1} (23 m s^{-1}) in the maximum wind before reaching Cat45 intensity during the period 1973-2010. The average time for a TC to achieve Cat45 intensity in the model is about 3.3 days, which also compares well with the observation. Associated with the lifetime of 6.68 days in the pre-satellite, it has enough time to allow TCs to reach the Cat45 intensity in the model.

4. Identification of the controlling factors for decadal variability

As shown in Fig. 2a, the adjusted records and simulation clearly show that the frequency of Cat45 TCs persistently increased with a nearly linear trend over the past 60 years although the simulated trend is smaller than the adjusted. While further study is needed to verify the increasing trend, here we focus on the decadal variability of the

Cat45 TC frequency. For this purpose, all variables in the following discussion have been detrended to reduce the influence of the long-term trend and a 5-year running average is also used to reduce the interannual influences. The influences of SST and VWS on the climate change of TC intensity were extensively discussed in previous studies (Goldenberg et al. 2001; Emanuel 2005, 2008; Webster et al. 2005; Wu et al. 2008; Zhao et al. 2011; Wu and Zhao 2012). Wu and Wang (2008) suggested that changes in the basin-wide TC intensity can be associated with shifts of the prevailing TC tracks. Here we examine the individual contributions of changes in TC tracks, SST and VWS to the decadal variability of Cat45 TC frequency by conducting three sensitivity experiments.

As shown in Table 1, Experiment T-Clim (V-Clim) is the same as the CTRL, but with the SST (VWS) along the TC tracks using the climatological mean during the period of 1948-2010, while experiment VT-Clim is run with both of the SST and VWS that are fixed in the climatological mean environment. Examination indicates that the simulated annual Cat45 TC frequency in the three sensitivity experiments are well correlated with that in the CTRL experiment (correlation coefficients all exceed 0.8) (Fig.5a), suggesting that neither SST nor VWS is the primary controlling factor for the decadal variations (Fig.5a). The influence of SST (VWS) changes on the decadal variability of the basin-wide Cat45 TC frequency can be obtained by contrasting V-Clim (T-Clim) and VT-Clim, respectively. As shown in Fig.5b, it is found that the simulated difference of Cat45 TC frequency between them is weakly correlated with the CTRL (both the correlation coefficients are about 0.09), also suggesting that SST (VWS) change has little direct influence on the decadal variability of Cat45 TC frequency. However, the combined effect of SST and VWS changes, which is examined by contrasting CNTL and the difference between CNTL and VT-Clim, is much larger than the sum of their individual contributions (Fig.6a). Its correlation with the simulated Cat45 frequency is 0.35, significant at a 95% confidence level. This indicates that the combination of SST and VWS changes contributes to the decadal variability in the basin-wide Cat45 TC frequency.

Wu and Wang (2008) suggested that the shifts in the TC prevailing tracks may have allowed more TCs to follow a longer journey that favors the development of intense TCs. In this study, the effect of the TC track change can be derived by contrasting the Cat45 TC frequencies between CTRL and VT-Clim. As shown in Fig.6b, both of them are well correlated with a correlation coefficient of 0.82, suggesting that the track change can nearly account for the decadal evolution of the basin-wide Cat45 TC frequency, in part because of the combined effect of SST and VWS change.

5. The associated large-scale pattern

As indicated above, numerical results suggest the change in TC tracks exhibit the dominant influence on the decadal variability of Cat45 TC frequency over the WNP basin. In order to understand how track changes can affect the decadal variations of Cat45 TC frequency, as shown Fig. 2b, we contrast the large-scale patterns between positive phases (1952-1957,1965-1973,1988-1996 and 2001-2006) and negative phases (1950-1951,1958-1964,1974-1987, 1997-2000 and 2007-2008).

In this section, we mainly focus on the associated large-scale patterns between positive and negative phases since 1965. It is mainly because satellite data started to be used in locating TC centers in 1965 so that TC track information in the best track data during the period is relatively reliable.

Figure 7 shows the differences in the TC formation frequency between the positive and negative phases. Compared to the negative phases, the TC formation is enhanced in the southeast part of the WNP basin (10°-20°N, 135°-170°E) in a positive phase with a moderate decrease over the northwest part (10°-25°N, 120°-135°E). Note that although some TCs over the WNP basin might be missed in the JTWC best track data before the satellite era, we find that the composite difference of TC genesis frequency between the positive and negative phases is similar when we use the data since 1948. This suggests that TC formation locations shift eastward during the positive phases, which is also indicated in the mean TC duration. For each individual year, the mean duration is defined by the averaged duration of all TCs that occurred in the peak TC season (July-September). The mean duration is 5.9 days for the positive phases, which is significantly longer than 4.5 days for the negative phases.

We further calculate the correlations between SST and the adjusted Cat45 TC frequency. A similar correlation pattern over the tropical central and eastern Pacific can be found for the periods 1965-2010 and 1948-2010, respectively (Fig. 8). It is clearly suggested that the increased Cat45 TC activity in the positive phases is closely associated with SST changes over the tropical central and eastern Pacific. Figure 9 shows the differences of the 850 hPa winds and SST between the positive and negative phases during the peak TC activity season since 1965. Similarly, we also found similar large-scale pattern between the positive and negative phases when we use the data from 1948 to 2010 (Figure not shown). To the west of the positive SST differences, westerly wind differences extend from the Philippines Sea to 170°E. Yumoto and Matsuura (2001), Yumoto et al. (2003) and Matsuura et al. (2003) suggested that increased (decreased) SST in the central and eastern equatorial Pacific strengthens the tropical westerlies (easterlies), leads to the eastward (westward) extension (retreat) of the monsoon trough. The eastward extension of the monsoon trough can be considered the response to the heating associated with the warming SST anomalies (Gill 1980; Holland 1995).

Ritchie and Holland (1999) found that more than 75% of TCs in the WNP basin are associated with the monsoon trough. Previous studies have found that TCs tend to form near the eastern end of the monsoon trough (Holland 1995; Briegel and Frank 1997; Ritchie and Holland 1999). Therefore we can conclude that the atmospheric response to the warming SST over the tropical central and eastern Pacific leads to the eastward extension of the monsoon trough, providing a favorable large-scale environment for TC formation and resulting in the eastward shift in TC formation locations. As suggested by Wu and Wang (2008), the eastward shift in the TC formation locations allows more TCs to follow a longer journey that favors the development of Cat45 TCs, compared to the negative phases.

6. Summary

Using the JTWC best track data during the period 1948-2010, this study examines the decadal and interdecadal variations of Cat45 TCs in the WNP basin and the associated mechanisms. The basin-wide annual Cat45 TC frequency is numerically simulated in a TC intensity model by allowing all of the observed TCs to move along the observed TC tracks. The simulated annual Cat45 TC frequency is in good agreement with the observation when the TC intensity prior to 1973 is adjusted with the combined wind-pressure relationship as in Emanuel (2005). The simulated and adjusted time series show decadal variations with three peaks around 1969, 1991 and 2004. Although the interdecadal variability with an 18-32 year period is found in the unadjusted Cat45 TC frequency during the period 1948-2010, it is insignificant in the simulated and adjusted Cat45 TC frequency. We argue that that the interdecadal variability in Chan (2006, 2008) is due mainly to the different wind-pressure relationships used in the JTWC records prior to 1973.

Numerical results show that changes in TC tracks is the most important factor for the decadal variations in the Cat45 TC frequency although the combined effect of changes in SST and VWS also contributes to the decadal variability. Further analysis suggests that the decadal fluctuations in TC tracks are closely associated with eastward shift in the TC formation locations. The warming SST over the tropical central and eastern Pacific leads to the eastward extension of the monsoon trough and then the eastward shift in TC formation locations. As suggested by Wu and Wang (2008), the eastward shift in the TC formation locations favors more TCs having a longer journey and having more chance for the development of Cat45 TCs.

It should be noted that the adjusted records and simulation clearly show that the frequency of Cat45 TCs persistently increased with a nearly linear trend over the past 63 years although the simulated trend is smaller than the adjusted. As suggested in Wu and Wang (2004) and Wu et al. (2005), long-term changes in prevailing TC tracks in the WNP basin have been identified, which may have contributed to the increase of the Cat45 TC frequency. Previous studies also argued that local SST change had contributed to the increasing trend of TC intensity in WNP (Emanuel 1987; Knutson et al. 1998; Knutson and Tuleya 2004; Bender et al. 2010). Furthermore, a recent statistical analysis indicates that the observed TC track changes in WNP are linked to global SST warming (Wang et al. 2011). However, the long-term increasing trend may subject to uncertainty in TC historical data and further study is needed.

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Table Captions

Table 1 Summary of numerical experiments conducted with the tropical cyclone intensity model

Figure Captions

Figure 1 The annual unadjusted (solid) and adjusted (dashed) number of tropical cyclones (TCs) reaching tropical storm strength in the Joint Typhoon Warning Center (JTWC) best track dataset over the western North Pacific (WNP) during the period 1948-2010. Where TC maximum wind speeds in the JTWC dataset prior to 1973 is adjusted with the recently-used pressure-wind relationship as described in Emanuel (2005).

Figure 2 (a) Unadjusted (green) adjusted (black) and simulated (red) annual number of

Cat45 TCs in the JTWC dataset over the WNP basin. A 5-year running average is applied to the time series. (b) Normalizations of adjusted (dashed) and simulated (solid) annual number of Cat45 TCs over the WNP basin. The time series have been detrended and a 5-year running average is also applied.

Figure 3 Spectral analysis of the annual number of the unadjusted (a), adjusted (b) and simulated (c) Cat45 TCs during the period 1948-2010 in the WNP basin. The 95% confidence levels with respect to the red noise spectrum are shown by the black dashed line.

Figure 4 The climatological mean SST (dashed contours) and mean vertical wind shear (solid contours) during the period 1948-2010 over the WNP basin. Dots represent locations of the first occurrence of Cat45 TC intensity reported in the adjusted JTWC dataset. The green box highlights location of the territory of Guam, where JTWC provides tropical cyclone watches and warning prior to 1999.

Figure 5 (a) Time series of the normalized annual simulated Cat45 TC number in experiments CTRL (solid line), V-Clim (dashed line with closed dots), VT-Clim (dashed line with plus sign) and T-Clim (dashed line with open dots) during the period 1948-2010, respectively; (b) the SST effect (dashed line with closed dots) and vertical wind shear effect (dashed line with open dots) on the decadal variability of Cat45 TC frequency, which can be examined by contrasting the experiments VT-Clim and V-Clim (T-Clim), respectively. The solid line as shown in (b) also represents the simulated Cat45 TC frequency from the CTRL experiment.

Figure 6 Time series of the normalized annual simulated Cat45 TC frequency for CTRL (solid line) and the difference between the CTRL and VT-Clim experiments (dashed line) (a), in which the environmental vertical wind shear and SST changed while the TC tracks remain unchanged, indicating the combined effect of SST and vertical wind shear on the decadal variability of Cat45 TC frequency. Similarly, (b) shows the time series of the normalized annual simulated Cat45 TC frequency for two experiments CTRL (solid line) and VT-Clim (dashed line), which indicates the effect of track changes on the decadal variability of Cat45 TC frequency. See the details in text.

Figure 7 Composite difference of TC genesis frequency (*100) over the peak TC season

(July-September) between the positive and negative phases. The difference with shading is statistically significant at the 95% level.

Figure 8 The correlation between the adjusted Cat45 TC frequency over the WNP basin and SST over the peak TC season (July-September) for (a) the period 1965-2010 and (b) and 1948-2010. The shaded areas indicate significant at the 95% confidence level.

Figure 9 Difference of the wind fields (vectors; unit: m s-1) at 850 hPa and SST (contours; interval for solid contours: 0.1℃) over the peak TC season (July-September). Only differences of wind field and SST above the 95% significance level are depicted by vectors and color shading, respectively.

Table 1 Summary of numerical experiments conducted with the tropical cyclone intensity model

Experiments	***Simulation Description***
CTRL	Both of SST and vertical wind shear are observed from 1948 to 2010.
T-Clim	SST is observed in the climatological mean during 1948-2010, but vertical wind shear changes with the observation from 1965 to 2010.
V-Clim	Shear is observed in the climatological mean during 1948-2010, but SST changes with the observation from 1965 to 2010.
VT-Clim	Both of SST and vertical wind shear are set to be those observed in the climatological mean during 1948-2010.

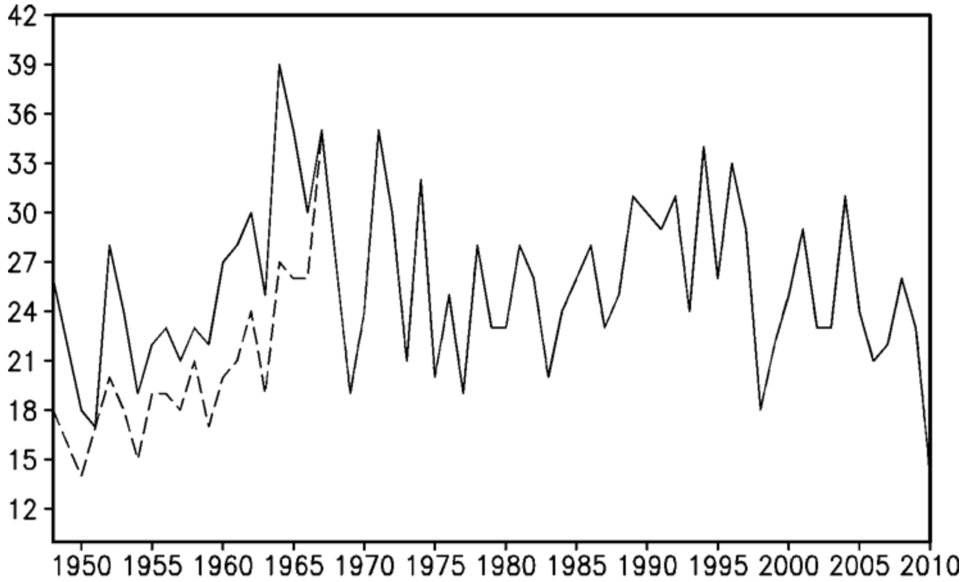


Figure 1 The annual unadjusted (solid) and adjusted (dashed) number of tropical cyclones (TCs) reaching tropical storm strength in the Joint Typhoon Warning Center (JTWC) best track dataset over the western North Pacific (WNP) during the period 1948-2010. Where TC maximum wind speeds in the JTWC dataset prior to 1973 is adjusted with the recently-used pressure-wind relationship as described in Emanuel (2005).

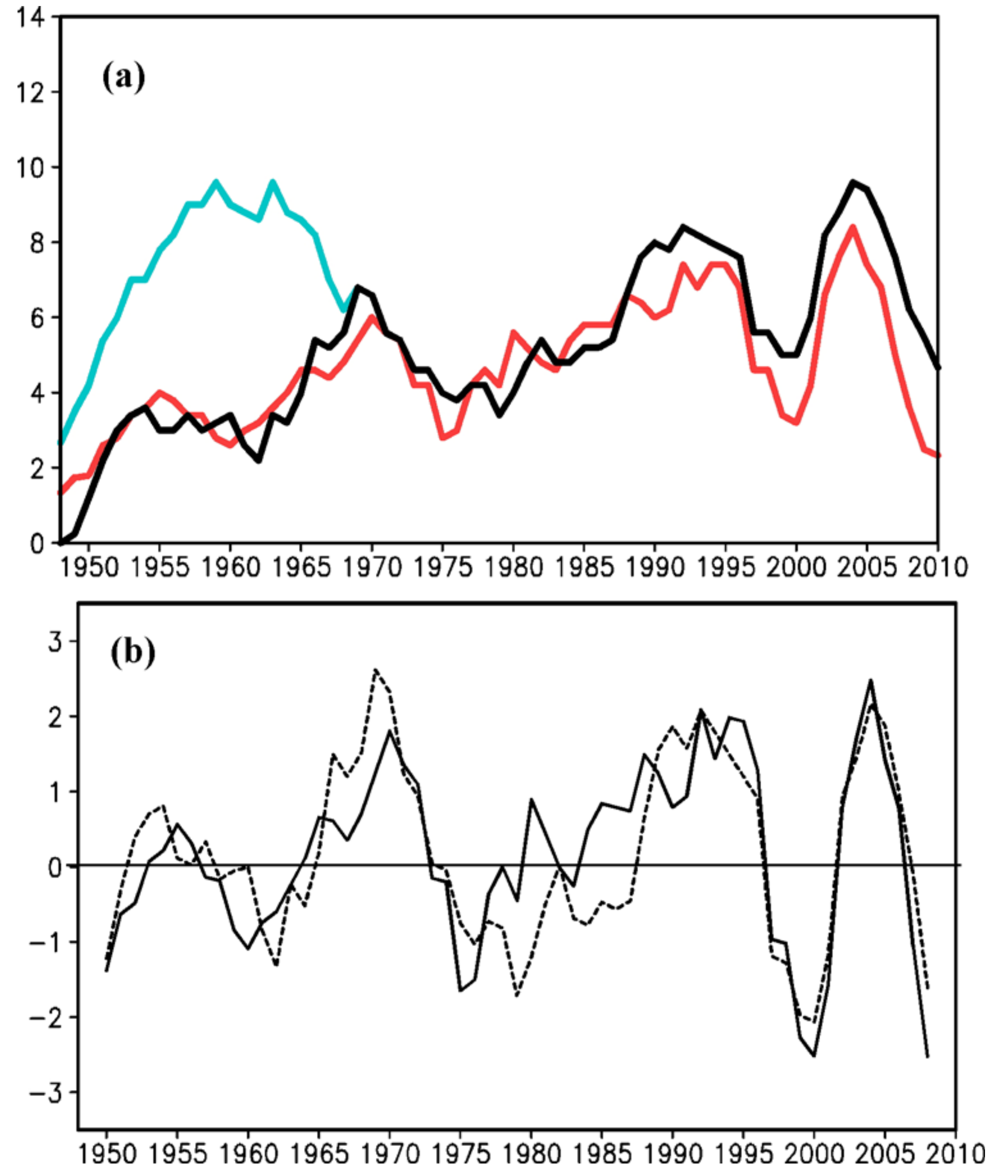


Figure 2 (a) Unadjusted (green) adjusted (black) and simulated (red) annual number of Cat45 TCs in the JTWC dataset over the WNP basin. A 5-year running average is applied to the time series. (b) Normalizations of adjusted (dashed) and simulated (solid) annual number of Cat45 TCs over the WNP basin. The time series have been detrended and a 5-year running average is also applied.

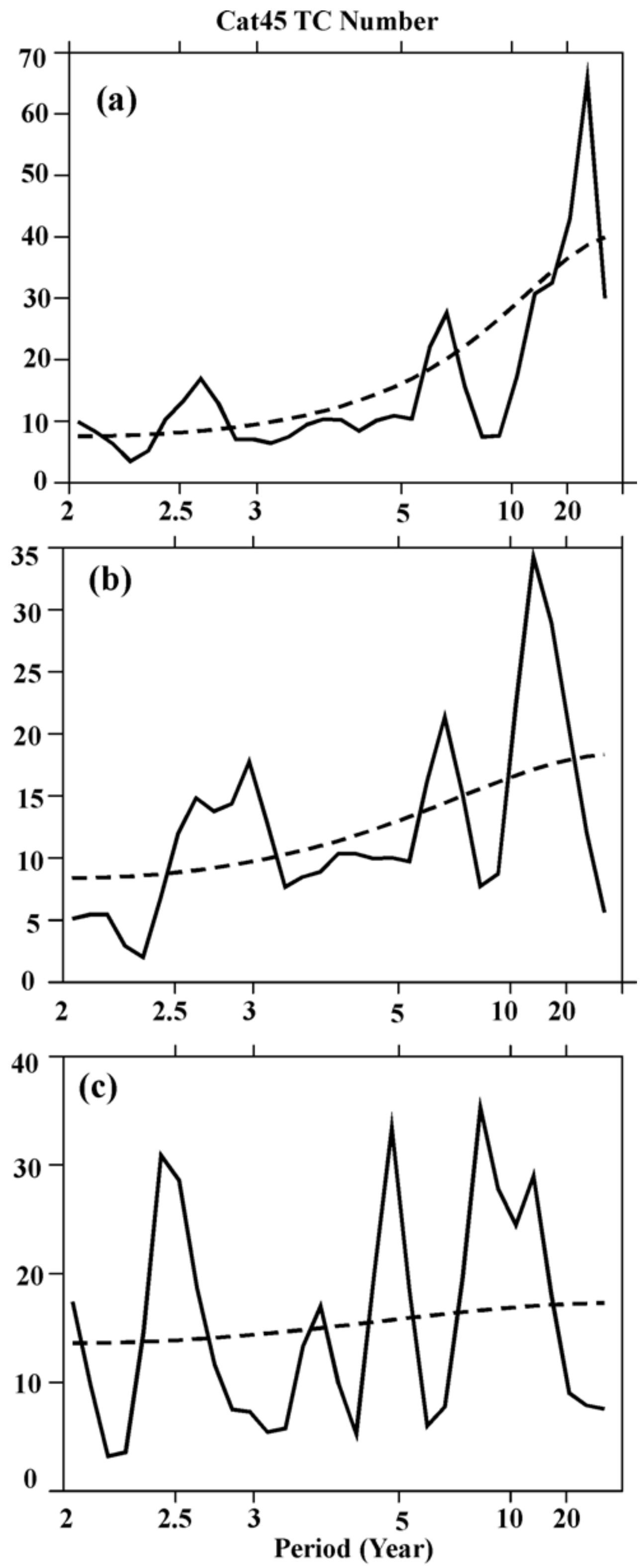


Figure 3 Spectral analysis of the detrended annual number of the unadjusted (a), adjusted (b) and simulated (c) Cat45 TCs during the period 1948-2010 in the WNP basin. The 95% confidence levels with respect to the red noise spectrum are shown by the black dashed line.

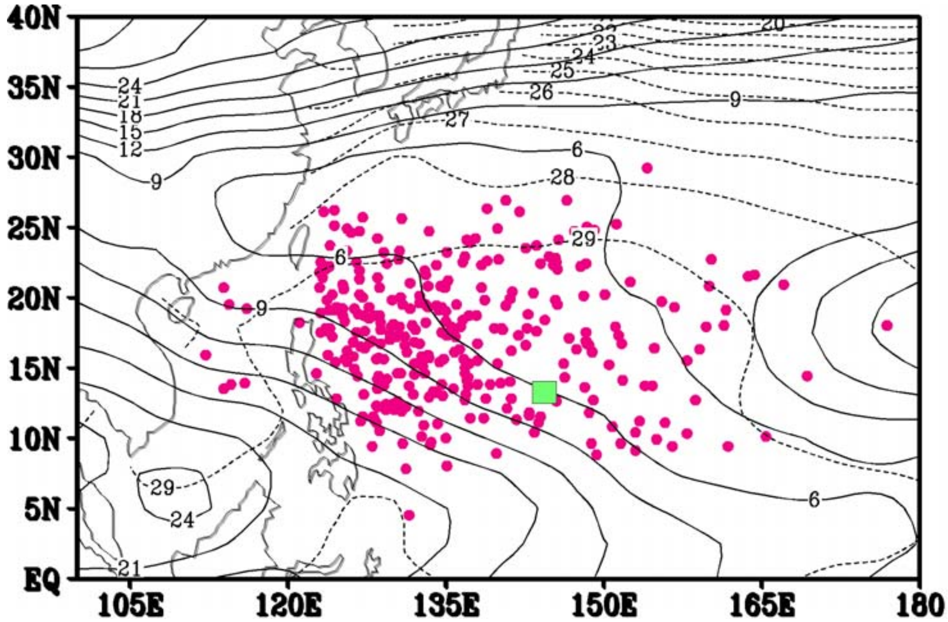


Figure 4 The climatological mean SST (dashed contours) and mean vertical wind shear (solid contours) during the period 1948-2010 over the WNP basin. Dots represent locations of the first occurrence of Cat45 TC intensity reported in the adjusted JTWC dataset. The green box highlights location of the territory of Guam, where JTWC provides tropical cyclone watches and warning prior to 1999.

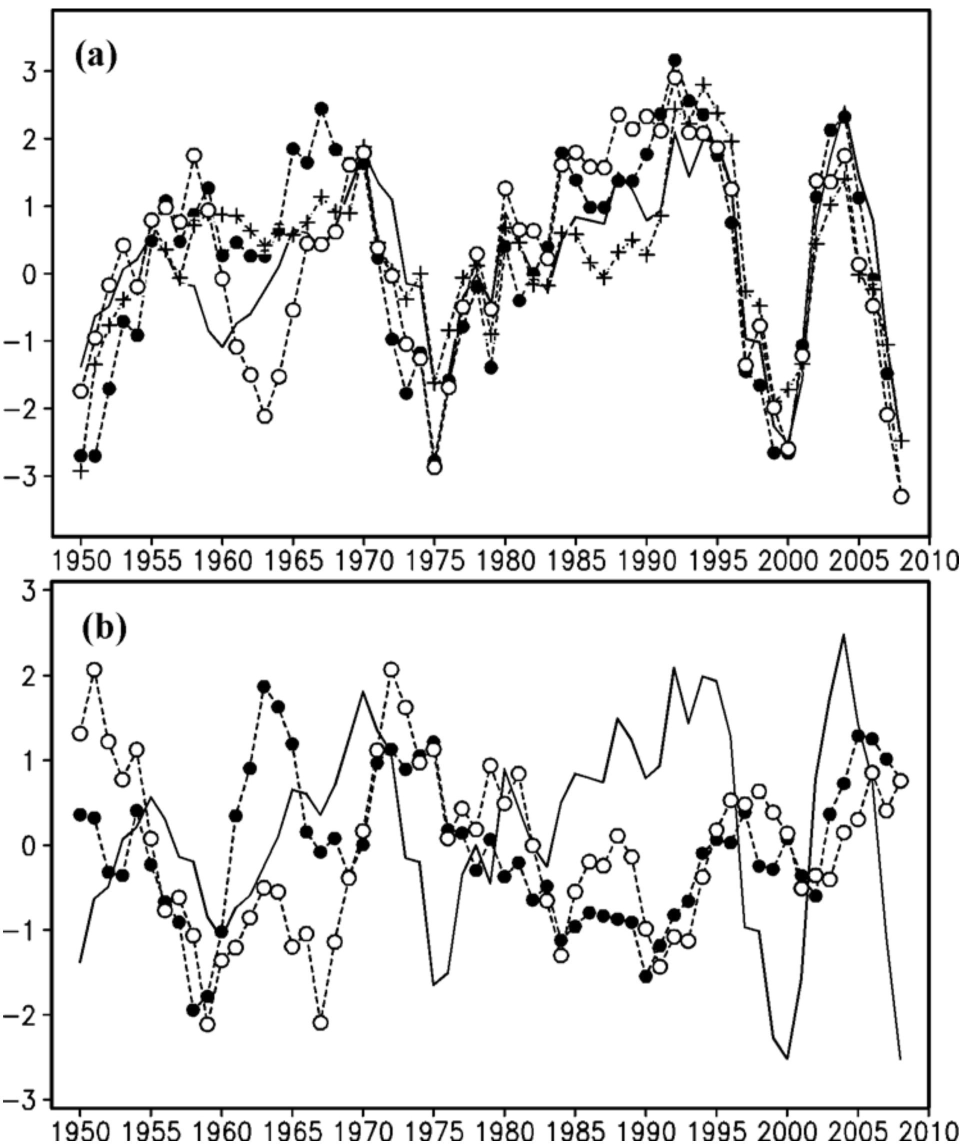
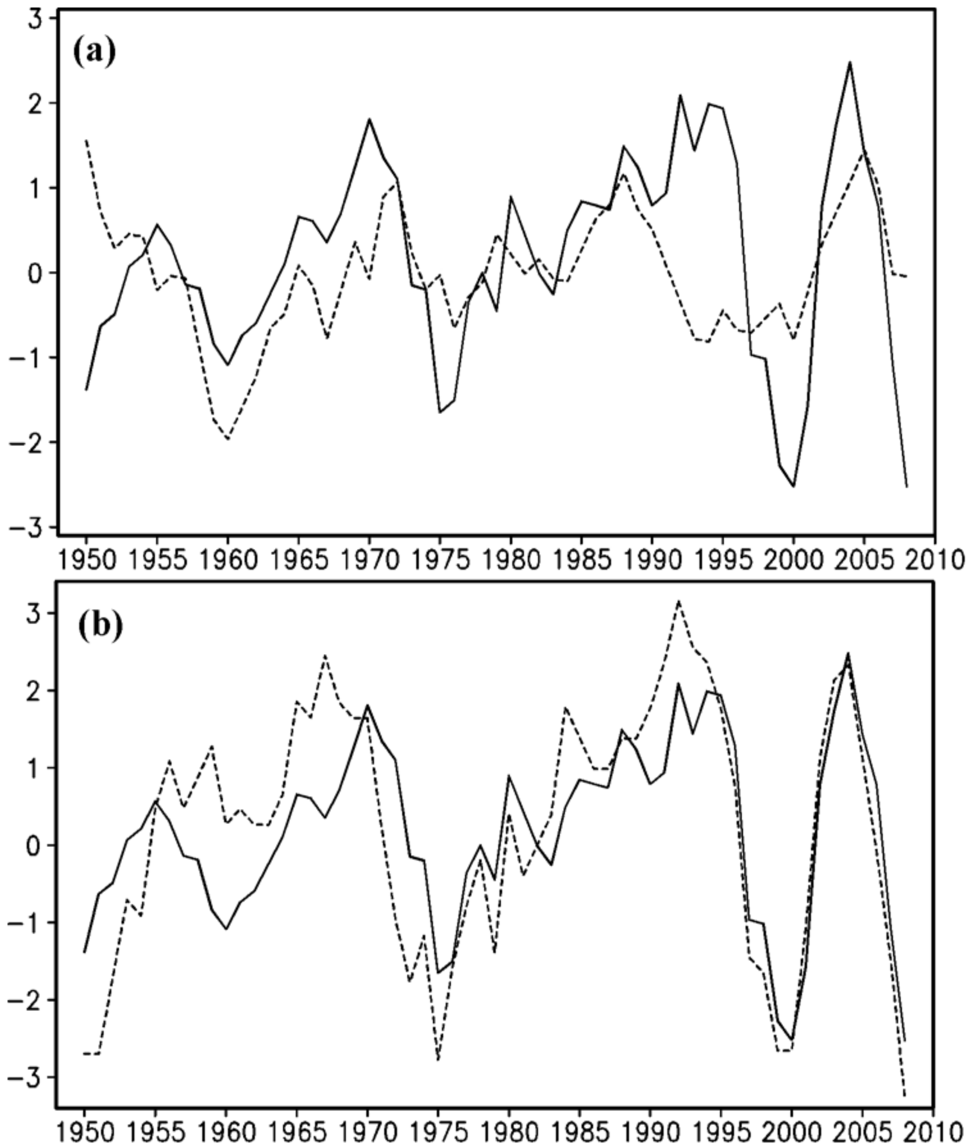


Figure 5 (a) Time series of the normalized annual simulated Cat45 TC number in experiments CTRL (solid line), V_Clim (dashed line with closed dots), VT-Clim (dashed line with plus sign) and T-Clim (dashed line with open dots) during the period 1948-2010, respectively; (b) the SST effect (dashed line with closed dots) and vertical wind shear effect (dashed line with open dots) on the decadal variability of Cat45 TC frequency, which can be examined by contrasting the experiments VT-Climand V-Clim (T-Clim), respectively. The solid line as shown in (b) also represents the simulated Cat45 TC frequency from the CTRL experiment.



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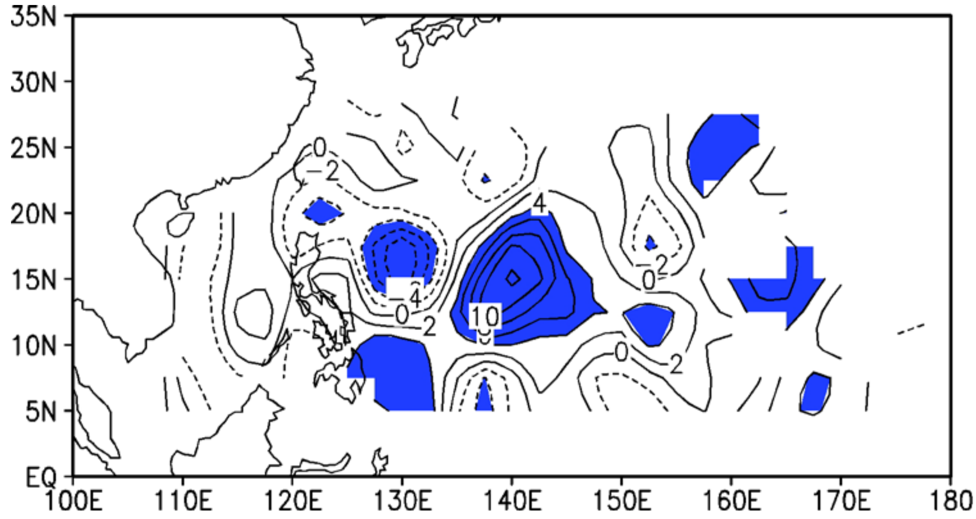

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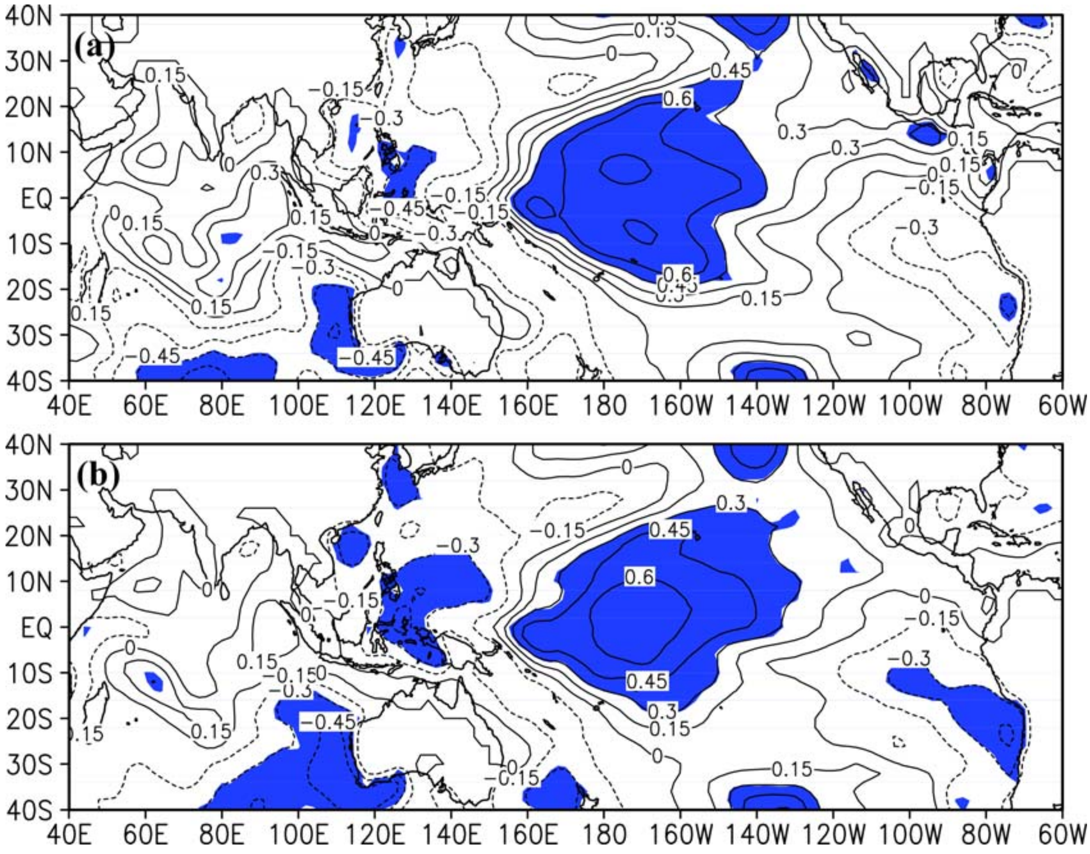

Figure 8 The correlation between the adjusted Cat45 TC frequency over the WNP basin and SST over the peak TC season (July-September) for (a) the period 1965-2010 and (b) and 1948-2010. The shaded areas indicate significant at the 95% confidence level.

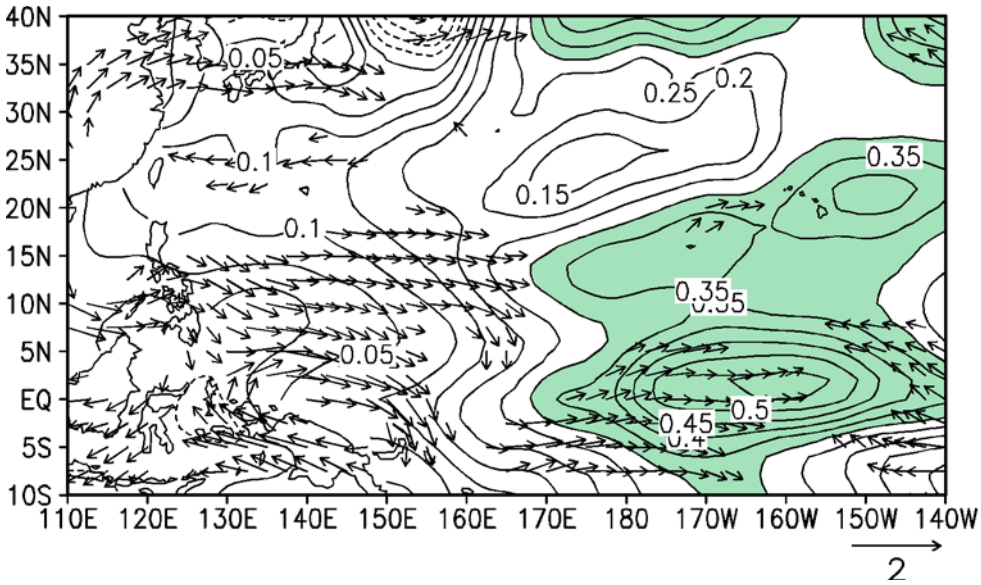

Figure 9 Difference of the wind fields (vectors; unit: m s^{-1}) at 850 hPa and SST (contours; interval for solid contours: 0.1℃) over the peak TC season (July-September). Only differences of wind field and SST above the 95% significance level are depicted by vectors and color shading, respectively.