Changes in Tropical Cyclone Intensity Over the Past 30 Years: A Global and Dynamic Perspective

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ABSTRACT

The hurricane season of 2005 was the busiest on record and Hurricane Katrina (2005) is believed to be the costliest hurricane in U. S. history. There are growing concerns regarding whether this increased tropical cyclone activity is a result of global warming, as suggested by Emanuel (2005) and Webster et al. (2005), or just a natural oscillation (Goldenberg et al. 2001). This study examines the changes in tropical cyclone intensity to see what were really responsible for the changes in tropical cyclone activity over the past 30 years.

Since the tropical sea surface temperature (SST) warming also leads to the response of atmospheric circulation, which is not solely determined by the local SST warming, this study suggests that it is better to take the tropical cyclone activities in the North Atlantic (NA), western North Pacific (WNP) and eastern North Pacific (ENP) basins as a whole when searching for the influence of the global-scale SST warming on tropical cyclone intensity. Over the past 30 years, as the tropical SST increased by about 0.5 °C, the linear trends indicate 6%, 16% and 15% increases in the overall average intensity and lifetime and the annual frequency. Our analysis shows that the increased annual destructiveness of tropical cyclones reported by Emanuel (2005) resulted mainly from the increases in the average lifetime and annual frequency in the NA basin and from the increases in the average intensity and lifetime in the WNP basin, while the annual destructiveness in the ENP basin generally decreased over the past 30 years. The changes in the proportion of intense tropical cyclones reported by Webster et al (2005) were due mainly to the fact that increasing tropical cyclones took the tracks that favor for the development of intense tropical cyclones in the NA and WNP basins over the past 30 years. The dynamic influence associated with the tropical SST warming can lead to the impact of global warming on tropical cyclone intensity that may be very different from our current assessments, which were mainly based on the thermodynamic theory of tropical cyclone intensity.

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Submitted to Journal of Climate

Feb. 15, 2006

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ABSTRACT

The significant increase in the power dissipation index (PDI) in the North Atlantic (NA) and western North Pacific (WNP) basins and the increases in the number and proportion of intense tropical cyclones (categories 4 and 5) in all tropical cyclone basins have been reported in response to the warming tropical sea surface temperature (SST) over the past 30 years. This study examines the changes in tropical cyclone intensity from a global and dynamic perspective by focusing on what were really responsible for these identified changes in tropical cyclone activity.

Analysis of the trends in tropical cyclone activity indicates that the reported increase in the annual accumulated PDI resulted mainly from the increases in the lifetime and annual frequency in the NA basin and from the increases in the average intensity and lifetime in the WNP basin, while the annual accumulated PDI in the eastern North Pacific (ENP) basin generally decreased over the past 30 years. The reported changes in the proportion of intense tropical cyclones were due mainly to changes in prevailing tropical cyclone tracks. Increasing tropical cyclones took the prevailing tracks that favor for the development of intense tropical cyclones in the NA and WNP basins over the past 30 years, leading to an increase in the proportion of intense tropical cyclones. The shift in the prevailing track was associated with the decreases in average intensity, average lifetime, annual accumulated PDI, and proportion of intense tropical cyclones in the ENP basin since the early 1990s.

The changes in dynamic factors, which are also associated with the global-scale SST warming, should be emphasized in understanding of the climate change of tropical cyclone intensity. The atmospheric response to the SST warming may have opposite influences on tropical cyclone intensity in different basins. It is better to treat the tropical cyclone activities in the NA, WNP and ENP basins as an entity when searching for the influence of the global-scale SST warming on tropical cyclone intensity. Over the past 30 years, as the tropical SST increased by about 0.5 °C, the linear trends indicate 6%, 16% and 15% increases in the overall average intensity and lifetime and the annual frequency, followed by a 32% increase in the annual PDI. Since the decreasing vertical wind shear and changing prevailing tracks may be results of the global-scale tropical SST warming, the possible impact of global warming on tropical cyclone intensity may be significantly different from our current assessments, especially for a particular tropical cyclone basin.

1. Introduction

Several recent studies have explored the tropical cyclone intensity change over the past few decades. Trenberth (2005) noticed that the Atlantic hurricane activity has been significantly enhanced since 1995 in terms of the Accumulated Cyclone Energy (ACE) index, which is the collective effect of the intensity, lifetime and annual frequency of tropical cyclones. Defining the Power Dissipation Index (PDI) of tropical cyclones, Emanuel (2005) demonstrated that the annual accumulated PDI has increased markedly in the western North Pacific (WNP) and NA basins since the mid-1970s and contributed the upward trend to the both longer storm lifetimes and greater storm intensities. In addition, Webster et al. (2005) examined the tropical cyclone number, duration, and intensity over the past 35 years for all the tropical cyclone basins and found an increase in the number and proportion of tropical cyclones reaching category 4 and 5 strengths (maximum wind speed larger than 56 m s^{-1}). Chan and Liu (2004) also showed that in the WNP basin there was no significant relationship between the typhoon activity parameters (the annual frequency of typhoons, its ratio to the total number of tropical cyclones, and its destruction potential) and the local SST warming during the period 1960-2003.

The existing prevailing perspective is that the tropical cyclone intensity changes are related to underlying Sea Surface Temperature (SST) changes. Tropical SSTs have trended upward over the past 50 years (Kumar et al. 2004). The warming trend, which is generally believed to be associated with the ongoing global warming since 1970s (Houghton et al. 2001), is statistically significant in all of the tropical cyclone basins except the southwest Pacific (Webster et al. 2005). In a theoretical model, Emanuel (1987) proposed that the maximum potential intensity (MPI) of tropical cyclones in a greenhouse gas-warming climate would increase. Using a simple thermodynamic MPI model (Holland 1997), Henderson-Sellers et al.

(1998) also predicted more intense tropical cyclones as the tropical SST becomes warming. Knutson et al. (1998), Knutson and Tuleya (1999), Knutson et al. (2001) and Knutson et al. (2004) ran a hurricane model with large-scale thermodynamic conditions (atmospheric temperature and moisture profiles, and SSTs) derived from global warming experiments and found that hurricanes simulated in warming conditions are stronger and have higher precipitation rates than under present-day conditions. The Intergovernmental Panel on Climate Change (IPCC) suggested that it is likely that peak wind intensities of tropical cyclones will increase by 5 to 10% in the 21st century (Houghton et al. 2001).

However, the dependence of tropical cyclone intensity on SST turns out to be rather weak in the observation. Merrill (1988) examined the relationship between maximum wind speeds of individual tropical cyclones and the underlying SST for the Atlantic basin and Evans (1993) extended this analysis to include five tropical cyclone basins. Both of them found that SST is not a dominant factor in the tropical cyclone intensification process. Chan and Liu (2004) suggested that dynamic factors such as vertical wind shear and the juxtaposition of various flow patterns outweigh the thermodynamic control.

The reliability of these conclusions and especially the causes responsible for these documented changes remain controversial. An important issue is that the direct effect of the moderate increase in SST can explain only part of the observed increase in the annual accumulated PDI or tropical cyclone intensity (Emanuel 2005). Whether the recent researches really provided observational evidence for the tropical cyclone intensification over the past 30 years has been questioned (Herr 2005, Landsea 2005). We think that three issues should be addressed before answering this question. First, the annual accumulated ACE and PDI, which are calculated over an entire year for all tropical cyclones in a basin, reflect the combined effect of the intensity, lifetime, and annual frequency. The increases in the annual accumulated ACE and PDI do not necessarily result from the enhanced tropical cyclone intensity. Second, it has been found that tropical cyclones formed over the tropical Atlantic (from Africa to 60 °W and south of 20 °N) have more chance to reach the major hurricane strength (maximum wind speed larger than 50 m s^{-1}) (DeMaria et al. 2001, Goldenberg et al. 2001). This implies that, unlike individual tropical cyclones, the shifts in formation locations and prevailing tropical cyclone tracks may result in changes in the number and proportion of intense tropical cyclones (categories 4 and 5). Third, the basin-wide SST warming in a basin can lead to the simultaneous atmospheric response in another basin as demonstrated in the ENSO warm phase (Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996), which may obscure the relationship between SST and tropical cyclone intensity as demonstrated in previous idealized numerical experiments. Regardless of whether the documented changes in tropical cyclone activity are a result of anthropogenic activity or are due to a long-term natural variability (e.g., multi-decadal oscillation), it is important to clarify what are really responsible for these identified changes in tropical cyclone activity, which is the primary objective of this study.

In this study, tropical cyclone intensity will be examined using the historical tropical cyclone data for the NA, WNP and eastern North Pacific (ENP) basins. The three basins generally represent the tropical cyclone activity in the northern Hemisphere, accounting for the 90% and 62% of tropical cyclone activity in the northern Hemisphere and in the global, respectively. Following Emanuel (2005) and Webster et al. (2005), the annual tropical cyclone activity in a basin is characterized by an average intensity, lifetime, and annual frequency as an entity.

2. Data and indices for tropical cyclone activity

The tropical cyclone data used in this study are obtained from the National Hurricane Center (NHC) best-track datasets. The tropical cyclone information in these datasets includes the center location (latitude and longitude) and maximum sustained wind speed in knots for each 6-hour interval. Although the historical data are available since 1851, 1945 and 1949 for the NA, WNP and ENP basins, respectively, relatively reliable estimation of storm intensity and location depends on the availabilities of satellite coverage and aircraft measurements. Airborne reconnaissance missions were undertaken in the western North Pacific and North Atlantic regions beginning around 1945. The annual tropical cyclone frequency is believed to be reliable since the satellite era beginning in the mid-1960s. Techniques for estimating tropical cyclone intensity from satellite imagery and other satellite-based measurements were developed during the 1970s (Dvorak 1975).

Cautions should be taken to interpret the tropical cyclone intensity before 1970. For the North Atlantic, Landsea (1993) documented a change in the wind-pressure relationship in 1970, leading to lower wind speed estimates. For the western North Pacific, the wind-pressure relationship was revised in 1973. Following Emanuel's (2005) polynomial curves, we adjust the maximum sustained wind speeds in the WNP (before 1973) and NA basins (before 1970). We also mainly focus our analysis on the period 1975-2004. The wind and SST data are from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis dataset.

The storm activity index (SAI) such as the annual accumulated ACE and PDI (Trenberth 2005; Emanuel 2005) can be written in a general form:

$$SAI = \sum_0^N \sum_0^\tau V_{\max}^n, \qquad (1)$$

Where V_{max} is the maximum sustained wind speed of tropical cyclones and n is an integer. The two $\sum$ denote the summations for the lifetime (τ) of each tropical cyclone in a six-hour interval and then for all the tropical cyclones (N) in a specific basin. When $n=2$ and $n=3$, SAI becomes the annual accumulated ACE and PDI, respectively. As $n=0$ and 1, SAI can be called the annual accumulated tropical cyclone frequency and momentum (hereafter TCF and TCM, respectively). According to (1), except TCF, SAI is a function of the intensity, lifetime and annual frequency of tropical cyclones. TCF is independent of tropical cyclone intensity or maximum sustained wind speed (V_{max}).

In order to distinguish the individual contributions from the intensity, lifetime and annual frequency to PDI, we define an average intensity and lifetime of tropical cyclones for a specific basin in this study. The average intensity can be obtained by averaging the mean maximum wind speed first over the lifetime for each tropical cyclone and then for all the tropical cyclones in a basin. According to (1), in fact, it is the ratio of TCM to TCF. Similarly, the average lifetime is the ratio of TCF to the annual tropical cyclone frequency (N).

3. Why has the annual accumulated PDI changed?

As shown by Emanuel (2005), the annual PDI in the NA and WNP basins generally increased with the increasing SST over the past 30 years. Figure 1 shows the evolutions of the accumulated PDI and the mean SSTs averaged over the primary tropical cyclone activity regions (5-30°N, 40-90°W for the NA basin, 5-30°N, 120-180°E for the WNP basin, and 5-20°N, 100-140°W for the ENP basin) for the peak months (July to October). If the trend from 1975 to 2004 is fitted linearly, based on the fitted PDI values in 1975, the NA, WNP and ENP basins account for about 11%, 59% and 30% of the total annual accumulated PDI, respectively. The linear trends show that the annual PDI has been increased by 161% and 73% in the NA and WNP basins, respectively, as the SST increased persistently over the past 30 years (Fig. 1). For the WNP basin, the upward trend occurred mostly before 1990s. The upward trends generally agree with Emanuel's (2005) results. The annual PDI over the ENP generally trended upward by the 1990s. However, as the SST continued to increase, the annual accumulated PDI decreased significantly since then, leading to an overall downward trend of 13% over the past 30 years.

Emanuel (2005) argued that the increasing trend in the annual accumulated PDI resulted from the collective increases in intensity and lifetime. Because the annual accumulated PDI is a function of intensity, lifetime, and annual frequency of tropical cyclones in a basin, it is instructive to examine the trends of these parameters over the past 30 years. In comparison with the SSTs, Fig. 2 shows the time series of the tropical cyclone average intensity for the period 1975-2004 in the NA, WNP and ENP basins, respectively. Although theoretical studies (Emanuel 1987; Holland 1997) and numerical modeling (e.g., Knutson et al. 1998; Knutson and Tuleya 2004) predict that tropical cyclone intensity increases with increase in the underlying SST, an upward trend occurred only in the WNP basin with the average intensity increasing by 11% over the past 30 years (Fig. 2b). Except various oscillations, there is no statistically significant trend for the average intensity in the NA and ENP basins (Figs. 2a and 2c). In the ENP basin (Fig. 2c), a nearly linear upward trend can be found by the early 1990s, which was followed by a rapid decrease in the average intensity.

Figures 3 shows the evolution of the average lifetime of tropical cyclones in comparison with SST. In 1975 the average life was about 4.2, 5.5 and 4.3 days in the NA, NWP and ENP basins, respectively. According to the linear fitting, the average lifetime extended to 6.3 days in the NA basin in the past three decades, whereas there were no statistically significant trends for lifetime in the WNP and ENP basins. It is interesting to note that the NA basin replaced the

WNP basin and became the one with the longest lifetime since the mid-1990s. Emanuel (2005) argued that strong storms have a long lifespan because they take a long time to reach their peak intensity for fixed rates of intensification and dissipation. This argument is not true for the average lifetime. Comparing Figs. 3a and 3b with Figs. 2a and 2b indicates that the significant increase in the average lifetime in the NA basin occurred with little change in the average intensity, while the significant increase in the average intensity over the WNP basin was not accompanied by any increase in the average lifetime.

The most significant increase in the annual frequency or number of tropical cyclones occurred in the NA basin with a linear increase of 51% over the past three decades (Fig. 4a). In the WNP basin (Fig. 4b), in agreement with Chan and Shi (1996), the annual frequency generally increased until the mid-1990s. Although the SST was still on a generally upward trend, the annual frequency trended downward since the mid-1990s, leading to an overall 15% increase over the past 30 years. In the ENP basin (Fig. 4c), the overall linear decrease in the annual frequency was 11% over the past three decades. The decrease primarily occurred since the early 1990s. The long-term trends and timing of the changes in the WNP and ENP basins suggest that the annual frequencies are not directly related to the SST that has been persistently trended upward in the three tropical cyclone basins over the past 30 years. Rigorously speaking, the frequencies in the WNP and ENP basins show interdecadal variations rather than linear trends, and these interdacadal variations were not consistent with the SST variations.

As the tropical SSTs increased in all the three tropical cyclone basins over the past three decades, here our analyses do not generally support the argument by Emanuel (2005) that changes in the annual accumulated PDI were a result of the increases in lifetime and storm intensity. In the NA basin, the increase in the annual accumulated PDI resulted primarily from the increases in the annual frequency and average lifetime. In the WNP basin, on the other hand, the significant increase of the annual PDI was associated with the increases in the average intensity and annual frequency. In the ENP basin, the decrease in the annual frequency primarily contributed to the reduction in the annual PDI.

4. What caused the increases in the proportion of intense tropical cyclones?

Current hurricane MPI theories (Emanuel 1987; Holland 1997; Henderson-Sellers et al. 1998) and numerical simulations using mean environments from global warming experiments (Knutson et al. 1998; Knutson and Tuleya 2004) suggest that the peak wind speed of tropical cyclones increases as the underlying SST is warming. One implication is that more and more tropical cyclones can reach hurricane (maximum wind speed larger than 32 m s^{-1}), major hurricane (maximum wind speed larger than 50 m s^{-1}), and intense hurricane (maximum wind speed larger than 56 m s^{-1}) strengths in a warming climate. Thus, as an alternative, the change in tropical cyclone intensity was also examined in terms of the number of major hurricanes (Goldenberg et al. 2001), the percentage of intense hurricanes (Webster et al. 2005), the ratio of number of typhoons to the total number of tropical cyclones (Chan and Liu 2004). Following these previous studies, in this study we calculated the percentage of intense tropical cyclones to the total numbers of tropical cyclones (Fig. 5).

Despite the presence of various oscillations, an upward trend in the proportion of intense tropical cyclones can be easily seen in the NA and WNP basins for the past 30 years and in the ENP basin before the early 1990s (Fig. 5). In the ENP basin, the decrease starting in the early 1990s coincided with the decreases in the average intensity, average lifetime and annual frequency (Figs. 2c, 3c, and 4c). As indicated by the thick line in Fig.5, the overall proportion of intense tropical cyclones for the three basins has trended upward over the past 30 years. These results agree with Webster et al. (2005). The influence of the increase in the proportion of intense tropical cyclones on the average intensity can be roughly estimated. In the WNP basin, for example, if the average intensities for intense and non-intense tropical cyclones are 85 and 65 knots, an increase in the proportion from 20% to 30% can increase the average intensity by $65\times(70\%-80\%)+85\times(30\%-20\%)=2$ knots. This approximately contributes 30% to the increase (6.7 knots) in the average intensity observed in the WNP basin. For the NA basin, the influence is small (<1 knot) due to the relatively small proportion of intense tropical cyclones (Fig. 5).

Previous studies suggested that the average intensity increased as the underlying SST increases (Knutson et al. 1998, Wu et al. 2005). This should also be true for intense tropical cyclones. For this reason, we examine the evolution of the average intensity for the intense tropical cyclones (Fig. 6). Although the underlying SST increased, there were no long-term trends in all the three basins over the past 30 years. Moreover, unlike the prediction of the MPI theories (Emanuel 1987; Holland 1997), the maximum hurricane wind speed did not show any upward trend over the past 30 years (Webster et al. 2005). These results indicate that the increasing proportion of intense tropical cyclones was not accompanied with the increases in their maximum wind speeds and average intensity, suggesting that the increasing proportion of intense tropical cyclones may be not a thermodynamic result of the increase in the underlying SST as suggested in the previous studies.

On the other hand, intense tropical cyclones have a much longer average lifetime than the average tropical cyclones (Figs. 3 and 7). In the NA basin the average lifetime is ~5 days for all tropical cyclones, but ~9 days for intense tropical cyclones. This means that intense tropical cyclones have to take such tracks that they can survive much longer before dissipating or transferring into extra-cyclones. We can imagine that, if more and more tropical cyclones take these tracks due to changes in large-scale steering flow or formation locations, the proportion of intense tropical cyclones is expected to increase, but without the corresponding changes in the maximum wind speed and average intensity. The relationship between formation locations and tropical cyclone intensity was documented in previous studies. For example, ~85% of Atlantic major hurricanes develop from African waves and most major hurricanes begin development in the tropical Atlantic from Africa to 60 °W and south of 20 °N (Goldenberg et al. 2001; DeMaria et al. 2001).

To examine the influence of the shift in tropical cyclone prevailing tracks on the proportion of intense tropical cyclones, we identify the prevailing tracks by defining the occurrence frequency of tropical cyclones on each grid box of 2.5° latitudes by 2.5° longitudes (Wu and Wang 2004; Wu et al. 2005). The frequency is counted at a 6-hour interval using the best-track data and measures how frequently a specific grid box is affected by tropical cyclones. On the first order, the trend in the occurrence frequency over the past 30 years can be fitted on each grid box by linear regression: $f_i=a_i+b_i t$, where t is time and f_i is the occurrence frequency on the ith grid. The first term (a_i) represents the base state at $t=0$ (1975) and the second term ($b_i t$) represents the changes associated with linear trends. The significance of the linear trend on each grid box is tested with the Mann-Kendall method (Kundzewicz and Robson 2000).

Prevailing tracks can be detected as the pathways with relatively high occurrence frequency averaged over the period 1975-2004. For simplicity, the lines with arrowheads in Fig. 8 schematically indicate the prevailing tracks in the NA basin, which are generally similar to those found with an objective clustering approach (Elsner 2003). Tropical cyclones that affect the coastal region of the United States take the first prevailing track from the Caribbean Sea to the Gulf of Mexico and the second prevailing track from the tropical Atlantic to the east coast of the United States, while tropical cyclones taking the third prevailing track remain far away from the coastal region and recurve northeastward. Figure 8a also shows the occurrence frequency of intense tropical cyclones. The intense tropical cyclones mainly took the first two prevailing tracks since the tropical cyclones that take these tracks survive longer over relatively warm waters than those taking the third prevailing tracks (Shapiro and Goldenberg 1998; Elsner 2004).

As we discussed above, the annual frequency has been increased by 51% in the NA basin over the past 30 years. If the increased tropical cyclones favor the first two prevailing tracks, the number and proportion of intense tropical cyclones increases. The estimated linear trends of the occurrence frequency are shown in Fig. 8b. The tropical cyclone activities have been enhanced primarily along the first two prevailing tracks, suggesting the increasing potential of becoming intense hurricanes. This is consistent with the increase in the proportion of intense tropical cyclones in the NA basin (Fig. 5a). One important implication is that the coastal region of the United States south of 40°N has experienced increasing tropical cyclone influence over the past 30 years in terms of the occurrence frequency of tropical cyclones.

In the WNP basin, three prevailing tracks can be identified (Fig. 9a). The first is a westward-moving track extending from the tropical Pacific to the Philippine Sea to South China Sea. The second is from the tropical Pacific to Korea and Japan, which influences the coastal region of East Asia and the surrounding waters. Some tropical cyclones take the third prevailing track recurving northeastward east of 130°E. As shown in Fig. 9a, intense tropical cyclones in this basin primarily took the first two prevailing tracks.

Figure 9b shows the changes in the occurrence frequency in the WNP basin during the past 30 years. The negative tendencies over the central South China Sea and the positive tendencies from the Taiwan Island to the waters south of the Korean peninsula and Japan indicate a significant shift in the prevailing track. In concurrence with the SST warming, Fig. 9b suggests that the influence of tropical cyclones decreased in South China Sea, but increased along the second prevailing track, which is also favorable for intense tropical cyclones. More and more tropical cyclones moved northwestward along the second prevailing track, increasing the influence of tropical cyclones on East Asia. As a result, the shift of the first prevailing track should lead to little influence on the proportion of intense tropical cyclone activity in the whole basin. However, the positive tendencies to south of Japan indicate a westward shift of the third prevailing track, increasing the chance for those that take the third prevailing track to intensify into intense tropical cyclones. Therefore the shifts in the prevailing tracks contributed to the overall increase in the proportion of intense tropical cyclones in the WNP basin, which, as discussed above, moderately increased the average intensity. Wu et al. (2005) contributed the prevailing track shift to the change in the large-scale atmospheric circulation.

In the ENP basin, if the period 1975-2004 is equally divided, Webster et al. (2005) found that more hurricanes reached the category 4 and 5 strengths during the period 1990-2004 than during the period 1975-1989, leading to a 10% increase in the ratio to the total hurricanes. However, further analysis indicates that 74% of the intense hurricanes during the second period formed from 1990 to 1997. That is, among the 50 intense hurricanes, only 13 of them occurred from 1997 to 2004, when the average intensity decreased rapidly (Fig. 2c). Thus the increases in the number and proportion of intense hurricanes in the ENP basin depend on the selected periods. For example, 37 and 25 intense hurricanes formed during the periods of 1985-1994 and the period of 1995-2004. The ratios of intense hurricanes to all hurricanes were 33% and 34% for these two periods, respectively.

Figure 10a shows the spatial distribution of the occurrence frequency for intense tropical cyclones in the ENP basin. In order to have a longer lifetime for intensification, intense tropical cyclones generally maintained a certain distance from the continent and took a northwestward track. However, the tropical cyclone activity along the prevailing track has been significantly reduced in terms of the occurrence frequency (Fig. 10b). Further examination of the evolution of the occurrence frequency at 15°N, 115°W indicates that the downward trend primarily started from the early 1990s (Fig. 11). The timing is consistent with the decreases in the average intensity (Fig. 11), the proportion of intense hurricanes (Fig. 5), the annual frequency (Fig. 4c), and the average lifetime (Fig. 3c). It is suggested that the track shift toward the coastal region was associated with the reduced tropical cyclone activity that started in the early 1990s.

5. Dynamic factors that affect average tropical cyclone intensity

As mentioned in section 1, current assessments of the potential impacts of global warming on tropical cyclone intensity are almost solely based on thermodynamic control of tropical cyclone intensity. That is, a higher SST would lead to more energy being transferred from the ocean to the atmosphere, and thus stronger tropical cyclones. Emanuel (1987) predicted that the peak wind speed of tropical cyclones should increase by about 5% for every 1 °C increase in SST. Knutson and Tuleya (2004) found a 6% increase in maximum surface wind speed in response to the SST changes ranging from 0.8 to 2.4 °C. In the real atmosphere, on the other hand, many studies suggest that dynamic factors are also important. The destructive impact of the vertical wind shear on individual tropical cyclones has long been recognized (Merrill 1988) and confirmed in recent numerical simulations (Frank and Richie 2001; Wu and Braun 2004; Wu et al. 2006). Wu et al. (2005) showed that changes in large-scale steering flow led to changes in prevailing tracks in the WNP basin and thus, as discussed in the last section, changes in the average intensity and proportion of intense tropical cyclones. The interannual variations of tropical cyclone intensity over the WNP basin were associated with that low-level cyclonic and upper-level anticyclonic shears (Wang and Chan 2002, Yang et al. 2006).

Changes in dynamic factors may result from the response of the atmospheric circulation to SST anomalies, and the response in a particular basin is not solely determined by the local SST anomalies within a basin. For example, positive SST anomalies associated with warm-phase ENSO have been linked to increasing vertical wind shear in the NA basin (Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996). As a result, the SST warming associated with ENSO in the Pacific leads to less tropical cyclone activity in the NA basin. Sutton and Hodson (2005) examined the response of the sea-level pressure to the an idealized Atlantic Multidecadal Oscillation (AMO) SST anomaly pattern using an atmospheric general circulation model and found substantial low-pressure anomalies over the southern United States, the Gulf of Mexico and tropical Atlantic in the summer but moderate high-pressure anomalies over tropical and subtropical Pacific regions (Sutton and Hodson 2006, personal communication). Although how the atmospheric circulation responds to the ongoing tropical SST warming trend are not clear, the numerical results suggest that the influences of dynamic factors associated with SST anomalies may be opposite in different basins.

In this study, the vertical shear is defined as the difference of wind speeds between 200 and 850 hPa over the peak periods of tropical cyclone activity (July-September for the WNP and ENP basins and August-October for the NA basin) and in the primary regions of tropical cyclone activity (5-30°N, 40-90°W for the NA basin, 5-30°N, 120-180°E for the WNP basin, and 5-20°N, 100-140°W for the ENP basin). Figure 12 shows the comparisons of the average intensity (dashed) with the vertical wind shears (solid) averaged over each tropical cyclone basin since

1975. According to the linear fits (thick solid lines), the vertical wind shear has decreased by 1.7 and 0.3 m s^{-1} in the NA and WNP basins (Figs. 12a and 12b), respectively, but increased by 0.4 m s^{-1} in the ENP basin (Fig. 12c) over the past 30 years. Among the three tropical cyclone basins, only the decreasing vertical shear over the WNP was accompanied with the increase in the annual average intensity (Fig. 12b). Note that the decreasing vertical shears seems to have more effect on the non-intense tropical cyclones because there was no corresponding increase in the average intensity of intense tropical cyclone (Fig. 6). One possible reason is that intense tropical cyclones usually developed with weak influence of vertical wind shear. For the ENP basin, although the overall increase in vertical shear was consistent with the decrease in the average intensity, the timing of the intensity change in 1990s indicates that the increasing shear cannot account for the rapid decrease of the average intensity (Fig. 12c). As discussed in the last section, the prevailing track shift was mainly responsible for the decrease in average intensity (Fig. 11). Figure 13 shows the comparison of the evolutions of vertical wind shear between the WNP basin and the ENP basin. The evolutions were generally out of phase not only for decadal oscillations but also for the long-term trend, suggesting that the influences of the change in vertical shear were opposite in the two basins.

The exact physical mechanisms that control the average intensity for a tropical cyclone basin are not clear. It seems that the dynamic factors have opposite influence on tropical cyclone intensity in different tropical cyclone basins. It is likely that the changes in dynamic factors are associated with the tropical SST anomalies. As a result, the relationships of tropical cyclone intensity with SST and vertical wind that have been demonstrated in previous studies may be obscured and cannot be detected in a particular basin. To highlight the effect of vertical shear and SST, it may be better to combine the three basins as an entity.

For the vertical wind shear (Fig. 12d), there was a net decrease of 0.5 m s^{-1} in the mean shear averaged over the combination of the three basins. It is likely that the shear change was part of the atmospheric response to the global-scale SST warming. The negative effect is very clear for both the long-term trend and oscillations. Fig. 14 shows the collective tropical cyclone activity in terms of the changes in the average intensity and lifetime, annual frequency, and annual accumulated PDI. Following a decreasing trend from the mid-1960s, the mean SST started to trend upward in the mid-1970s. Over the past 30 years, it increased by about 0.5 °C. The linear trends for the data from 1975 to 2004 (thick solid lines) indicate the 6%, 16% and 15% increases in the average intensity (Fig.5a) and lifetime (Fig. 5b) and the annual frequency (Fig. 5c), followed by a 32% increase in the annual PDI (Fig. 1d). Considering the associated shifts in prevailing tracks and decrease in vertical wind shear, the 6% increase in the average intensity was reasonable. The change in the average intensity well followed the long-term trend in SST with a nearly linear upward trend over the past 30 years (Fig. 14a).

6. Summary

To understand how tropical cyclone intensity has changed in response to the tropical SST warming over the past 30 years, we examined the tropical cyclone activities in the NA, WNP and ENP basins using the historical best track datasets. The tropical cyclone activity for a specific basin is characterized by an average intensity, average lifetime, and annual frequency. Our emphasis was placed on identifying the physical mechanisms associated with the long-term trends in tropical cyclone intensity.

We found that the changes in the annual accumulated PDI resulted from the changes in different parameters for different basins. Over the past 30 years, the increases in the annual accumulated PDI were due to the increases in the lifetime and annual frequency in the NA basin, but due to the increases in the average intensity and lifetime in the WNP basin. The overall annual accumulated PDI in the ENP basin, which accounts for 30% in total, decreased although the underlying SST trended generally upward.

For a particular tropical cyclone basin, the relationships of the annual average intensity with SST and vertical wind shear were more complicated than those predicted by the MPI theories and high-resolution hurricane models. The complexity results from two aspects. First, the average intensity for a basin is different from the intensity of individual tropical cyclones since the shift in the prevailing tracks can change the average intensity. Over the past 30 years, increasing tropical cyclones took the prevailing tracks that favor for the development of intense tropical cyclones in the NA and WNP basins and the proportion of intense tropical cyclones increased. As a result, the tropical cyclone influences on East Asia and the coastal United States increased over the past 30 years. In the ENP basin, since the early 1990s, the decreases in the average intensity, the average lifetime, the annual frequency, and proportion of intense tropical cyclones were associated with the shift in prevailing track. Second, the global atmospheric circulation change should be emphasized in understanding of the climate change of tropical cyclone intensity. The change in atmospheric large-scale circulation in a particular basin is not solely determined by the local SST anomalies within the basin. Remote forcing from other basins might be as important as the local SST forcing. In this sense, the global-scale tropical SST warming can have more profound influence on tropical cyclone activity than the SST forcing specified in theoretical and numerical models which focus on local or regional SST effects.

The opposite influence of the atmospheric responses in different tropical cyclone basins can obscure the relationship between tropical cyclone intensity and SST that has been well established in theoretical and numerical models. We suggest that it is better to treat the tropical cyclone activities in the NA, WNP and ENP basins as an entity when searching for the influence of the global-scale SST warming on tropical cyclone intensity. The collective increases in the average intensity and lifetime, and annual frequency are about 6%, 16% and 15%, followed by the 32% increase in the annual accumulated PDI. By taking the effects of the decreasing vertical wind shear and shifts in the prevailing tropical cyclone tracks into account, the 6% increase in the average intensity is reasonable.

This study suggests that cautions should be taken to extend the results on tropical cyclone intensity obtained from an individual case study to a basin scale. A physical factor such as tropical cyclone track is not responsible for individual tropical cyclone intensification, but may be important to the average intensity for a tropical cyclone basin. How the atmosphere responds to the global-scale SST warming and what factors are responsible for the change in the average intensity for a particular basin are still not clear. In the NA basin, for example, as the changes in SST, vertical wind shear, and prevailing tracks are all favorable for tropical cyclone intensification, but little change occurred to the average intensity. Further study along this direction is still needed. Since it is likely that the decreasing vertical wind shear and changing prevailing tracks are also associated with the global-scale tropical SST warming, the possible impact of global warming on tropical cyclone intensity may be significantly different from our current assessments, especially for a particular tropical cyclone basin.

Acknowledgments. This research was supported by Dr. Ramesh Kakar (NASA HQ) through the NASA EOS project (EOS/03-0000-0144).

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Figure Captions

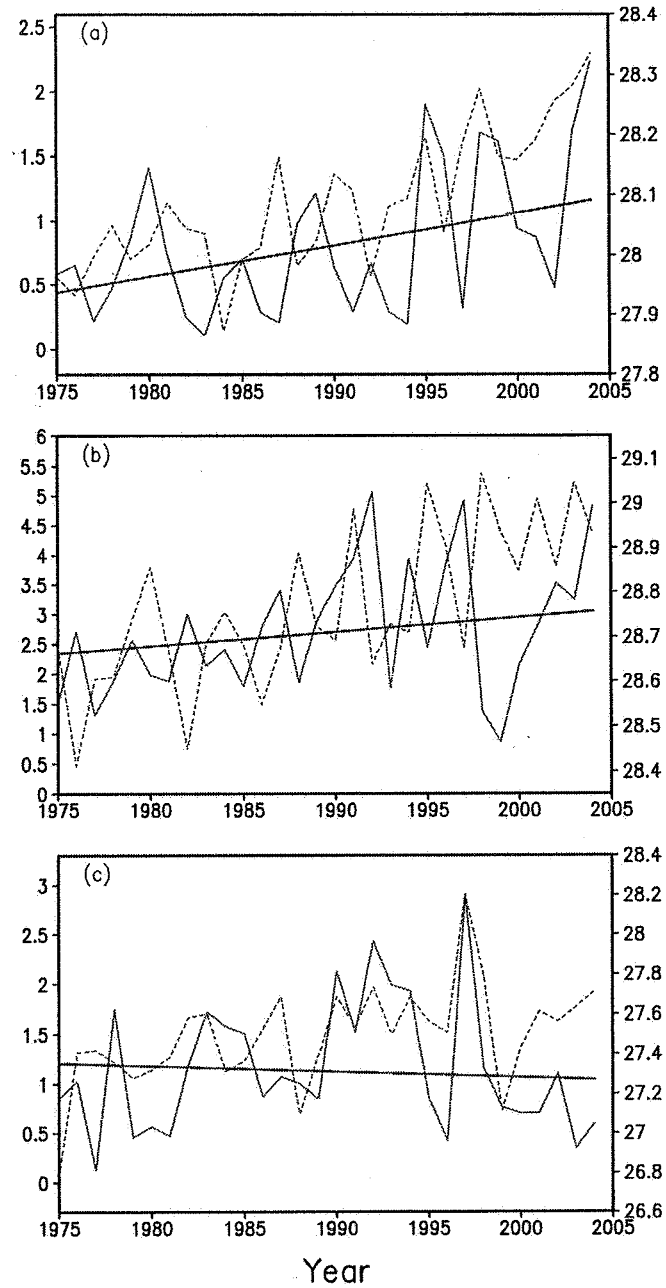

Figure 1 Time series of the annual accumulated PDI (solid, unit: 1.0×10^{8} kt^{3}) and mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are averaged over the areas of 5-30°N, 40-90°W in (a), 5-30°N, 120-180°E in (b), and 5-20°N, 100-140°W in (c) during July to October.

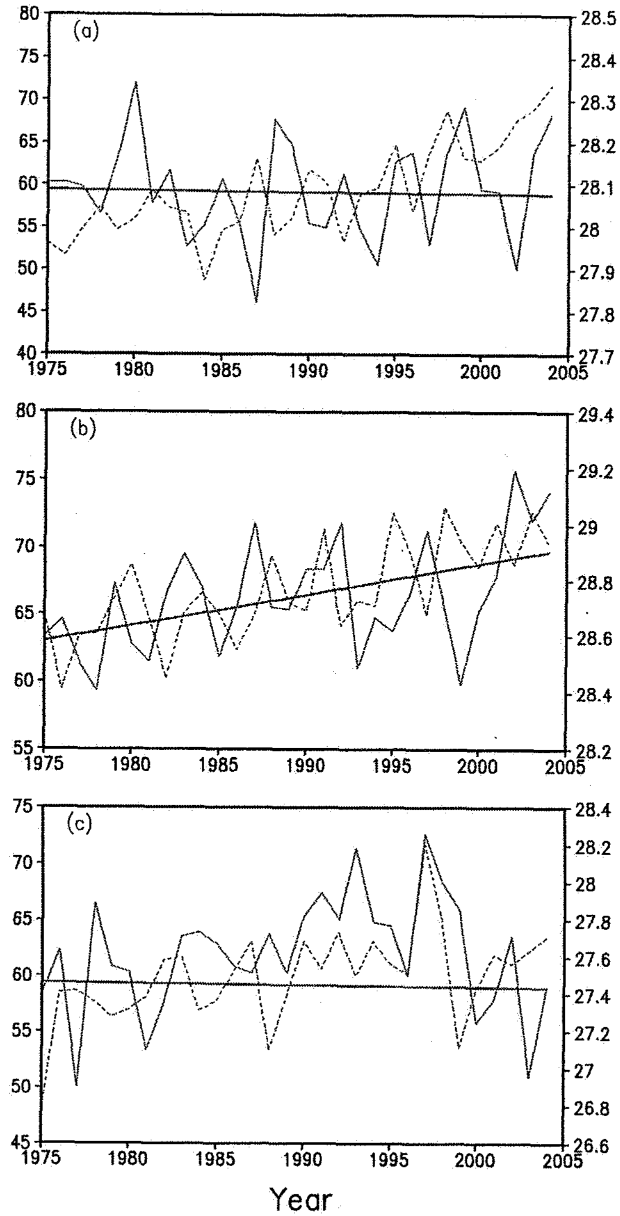

Figure 2 Time series of the average tropical cyclone intensity (solid, unit: kt) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Fig. 1.

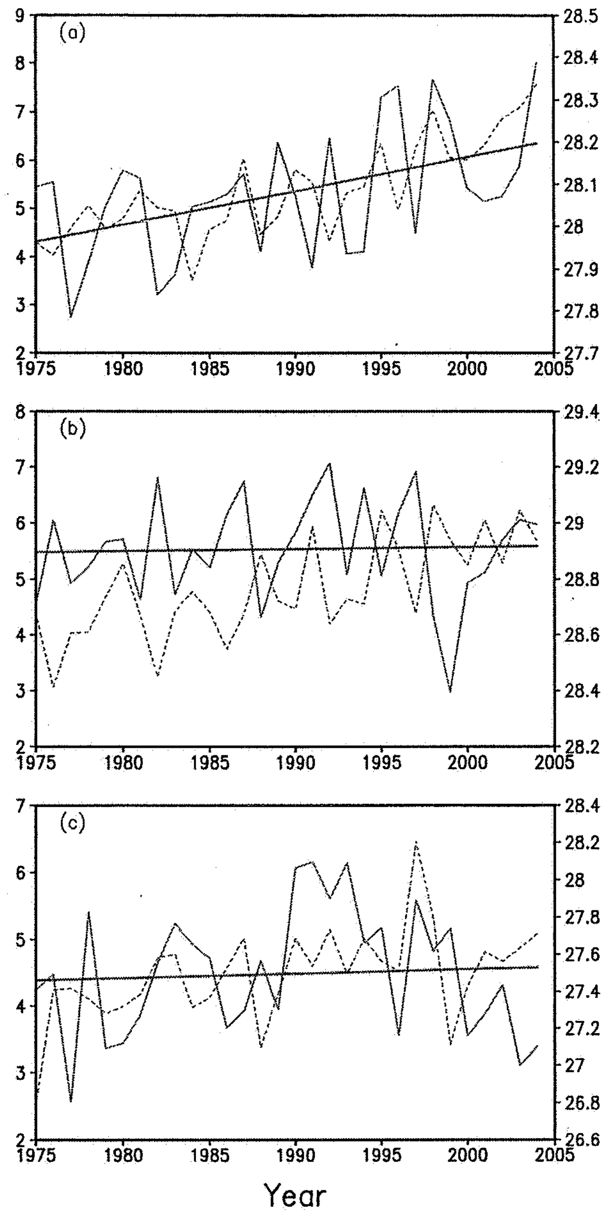

Figure 3 Time series of the average tropical cyclone lifetime (solid, unit: day) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Fig. 1.

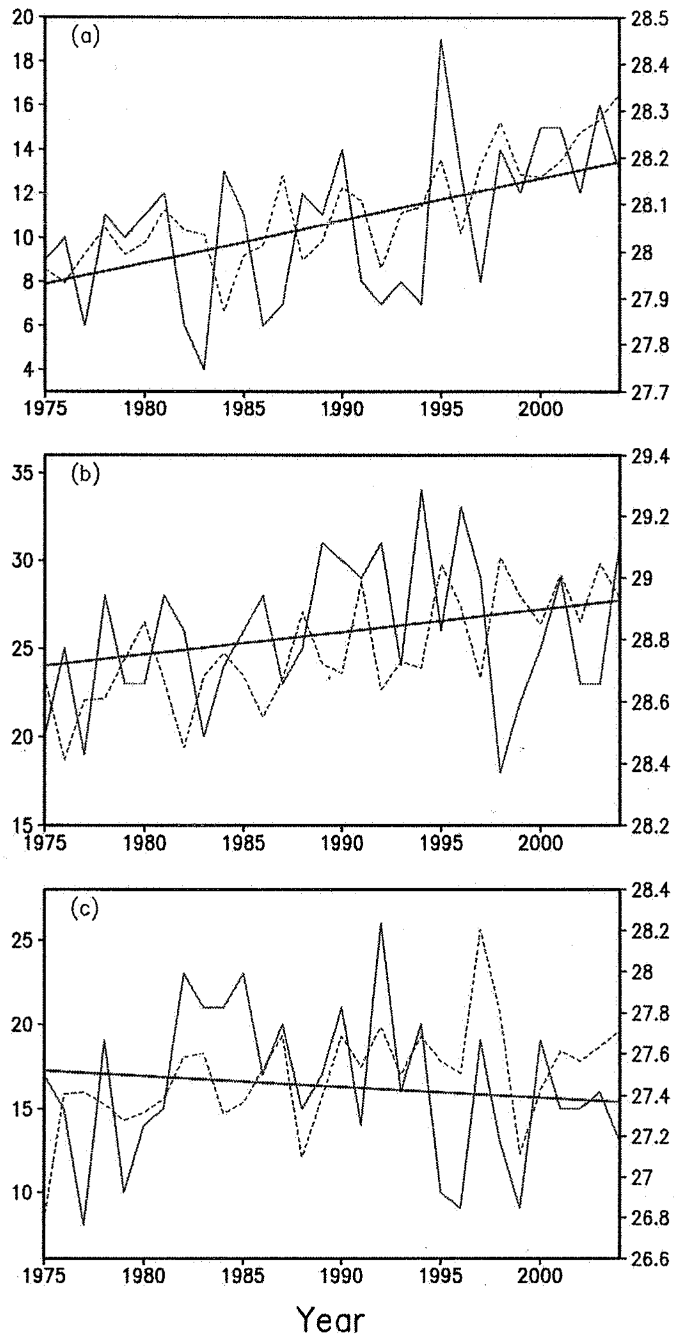

Figure 4 Time series of the annual tropical cyclone frequency (solid) and the mean SSTs (dashed, unit: °C) for (a) the NA basin, (b) the WNP basin, and (c) the ENP basin. The SSTs are the same as in Fig. 1.

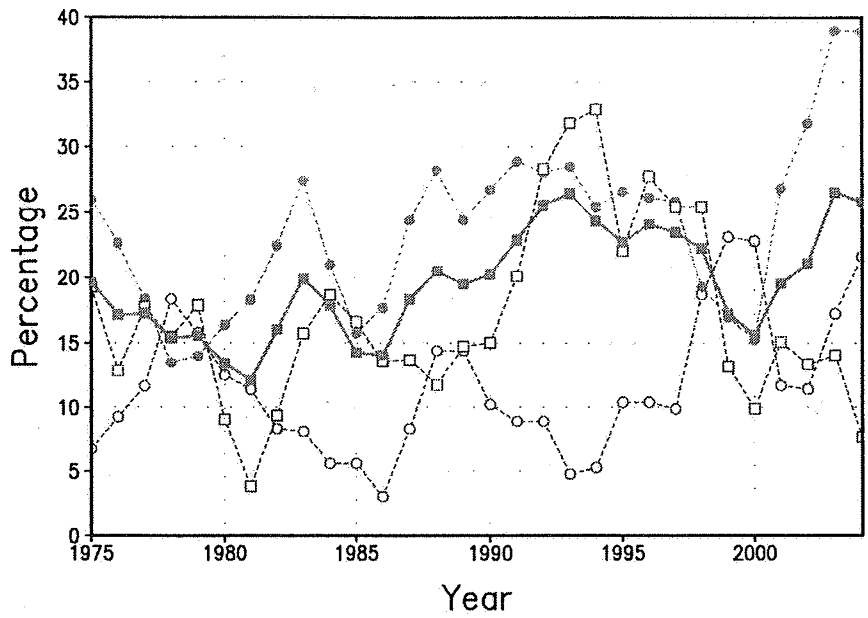

Figure 5 Time series of the percentages (%) of intense tropical cyclones reaching categories 4 and 5 for the NA basin (open dots), the WNP basin (closed dots), the ENP basin (open squares), and the combination of these basins (closed squares) after a three-year running meaning.

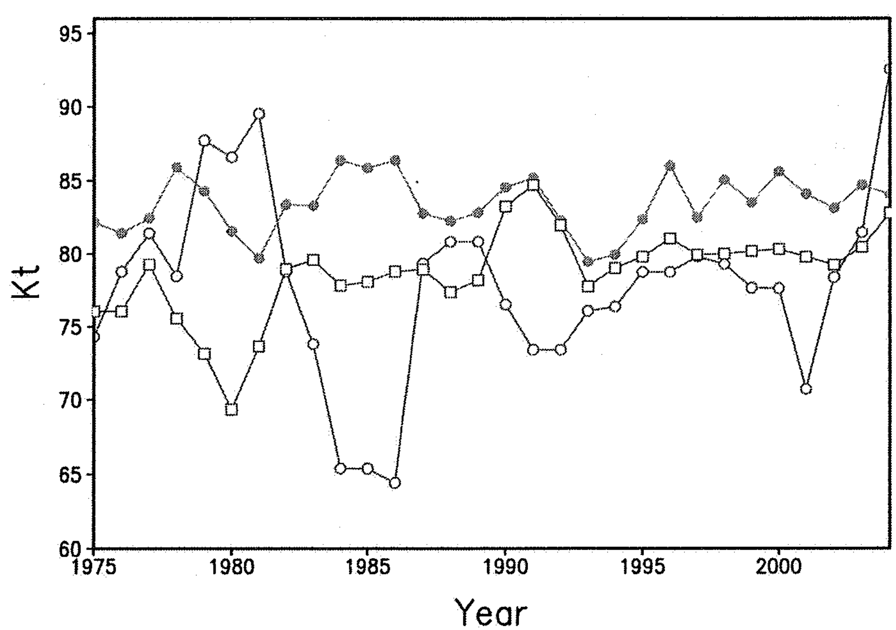

Figure 6 Time series of the three-year running means of the average intensity (kt) of intense tropical cyclones reaching categories 4 and 5 for the NA basin (open dots), the WNP basin (closed dots), and the ENP basin (open squares).

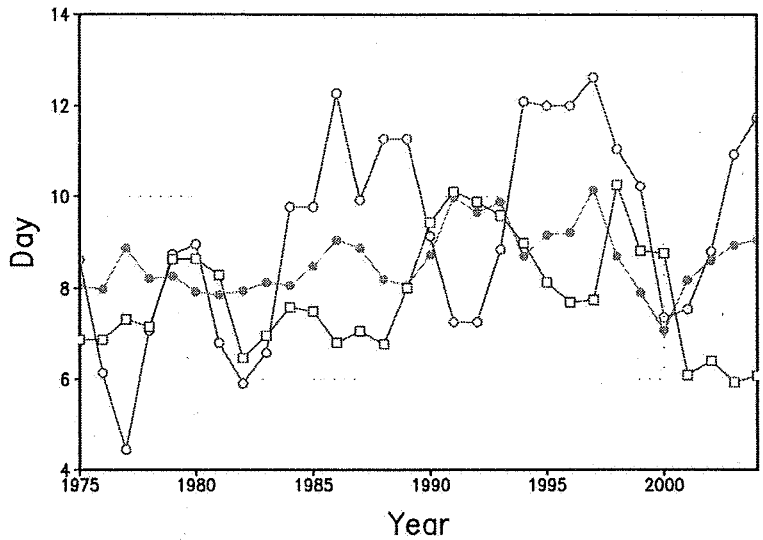

Figure 7 Time series of the average lifetime (day) of intense tropical cyclones reaching categories 4 and 5 for the NA basin (open dots), the WNP basin (closed dots), and the ENP basin (open squares) after a three-year running meaning.

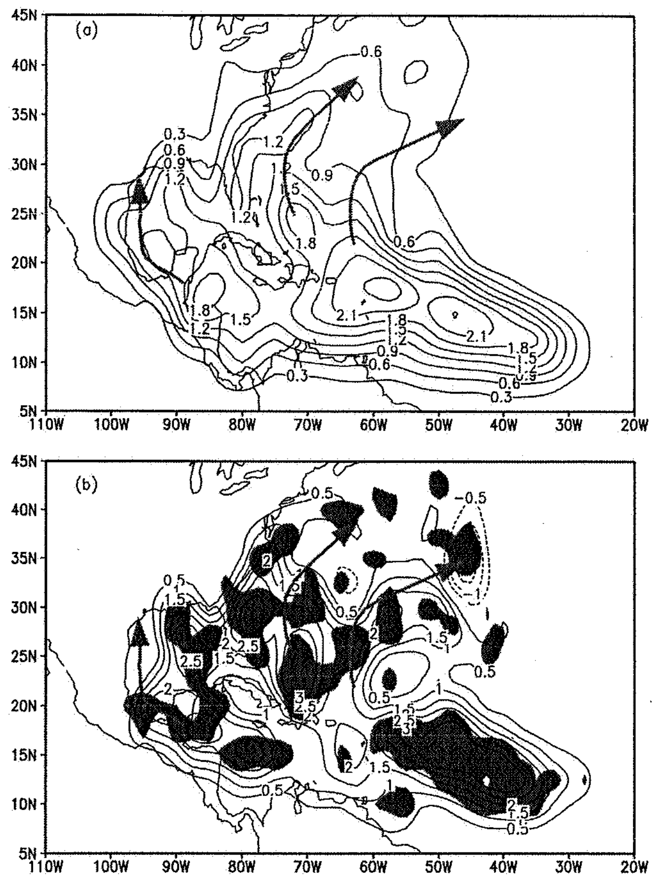

Figure 8 (a) Hurricane prevailing tracks (green lines with arrows) and contours of the intense tropical cyclone frequency of occurrence with intervals of 0.3 hour year^{-1}. (b) The linear trend of the tropical cyclone occurrence frequency [contour, unit: hour (10 year)$^{-1}$] with the contours of less than 0.5 suppressed. The areas with confidence level exceeding 95% are shaded. The red thick solid lines with arrows denote the prevailing tropical cyclone tracks.

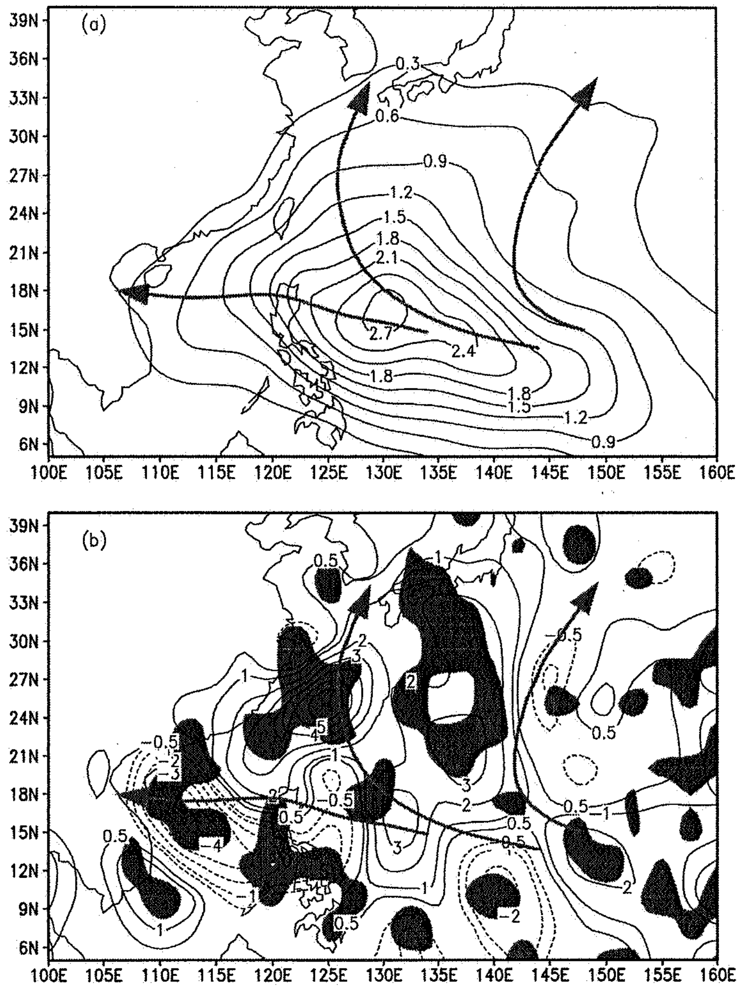

Figure 9 Same as Fig. 8, but for the WNP basin.

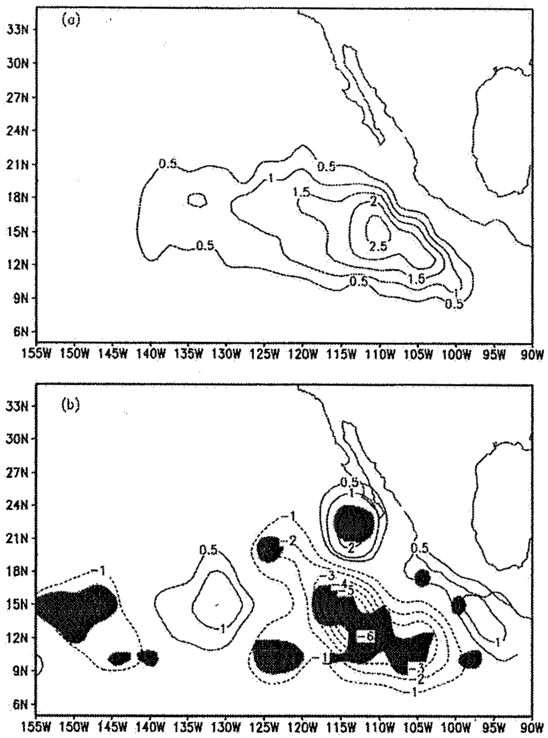

Figure 10 (a) Contours of the intense tropical cyclone frequency of occurrence with intervals of 0.5 hour year^{-1} in the ENP basin. (b) The linear trend of the tropical cyclone occurrence frequency [contour, unit: hour (10 year)$^{-1}$] with the contour of zero suppressed. The areas with confidence level exceeding 95% are shaded.

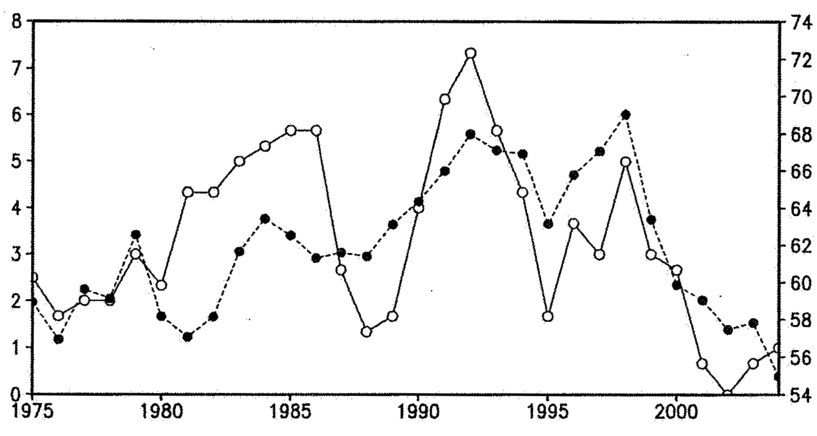

Figure 11 Time series of the three-year running means of the frequency of tropical cyclone occurrence (solid, year^{-1}) at 15°N, 115°W and the average intensity (dashed, kt).

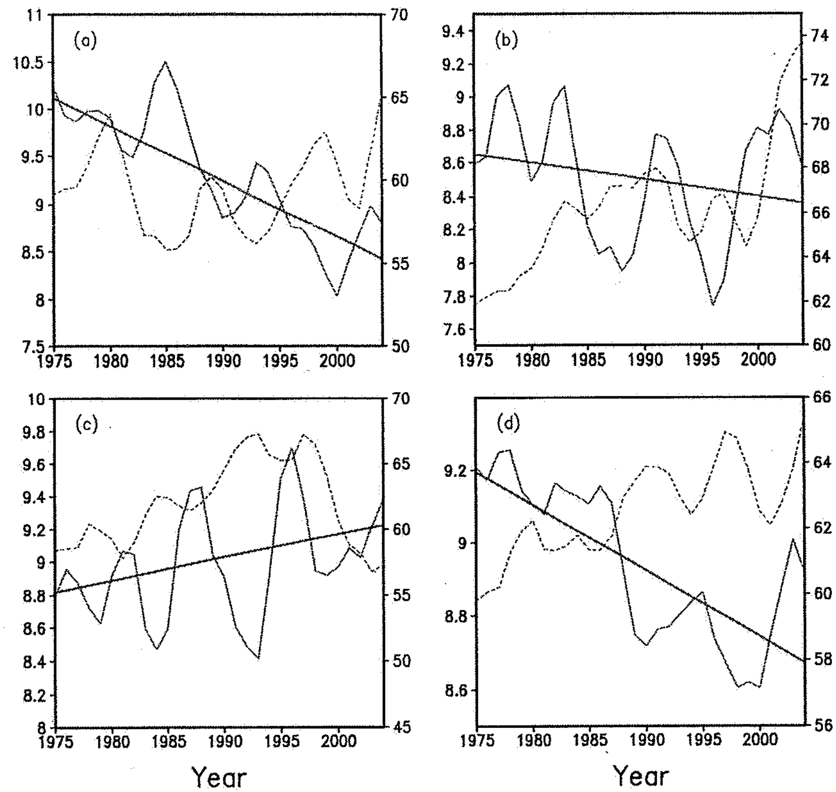

Figure 12 Comparisons of the time series between the vertical wind shears (solid, m s^{-1}) and the average intensity of tropical cyclones (dashed, kt) for (a) the NA basin, (b) the WNP basin, (c) the ENP basin, and (d) the combination of these three basins.

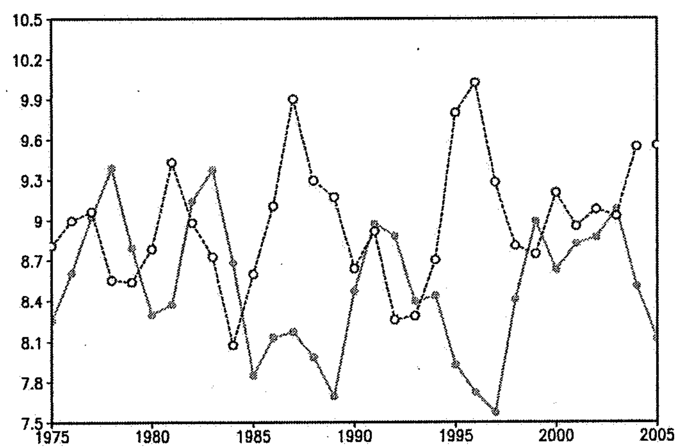

Figure 13 Time series of the vertical wind shears (m s^{-1}) for the WNP basin (closed dots) and the ENP basin (open dots).

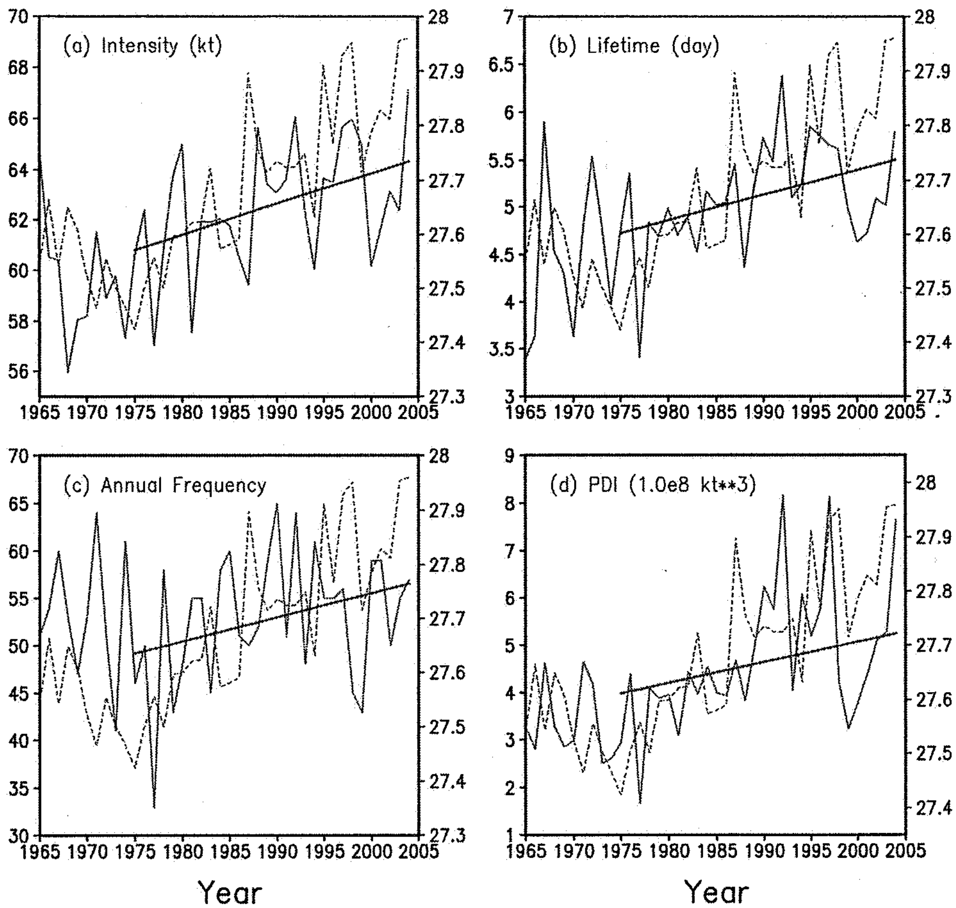

Figure 14 Comparisons of the time series between the mean tropical SST (dashed) averaged over 5-30 °N and (a) the annual mean intensity (kt), (b) the annual mean lifetime (day), (c) the annual frequency and (d) the annual PDI, respectively, for the combination of the NA, WNP, and ENP tropical cyclone basins during the period of 1965-2004. The thick solid lines are the linear fits.