NOTES AND CORRESPONDENCE

What Has Changed the Proportion of Intense Hurricanes in the Last 30 Years?

LIGUANG WU

Laboratory for Atmospheres, NASA Goddard Space Flight Center, Greenbelt, and Goddard Earth and Technology Center, University of Maryland, Baltimore County, Baltimore, Maryland

BIN WANG

Department of Meteorology, and IPRC, University of Hawaii at Manoa, Honolulu, Hawaii, and College of Physical and Environmental Oceanography, Ocean University of China, Qingdao, China

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ABSTRACT

The recently reported increase in the proportion of intense hurricanes is considerably larger than those projected by the maximum potential intensity (MPI) theory and the results of numerical simulation. To reconcile this discrepancy, the authors examined the best-track datasets for the North Atlantic (NA), western North Pacific (WNP), and eastern North Pacific (ENP) basins. It was found that the changes in the tropical cyclone formation locations and prevailing tracks may have contributed to the changes in the proportion of the intense hurricanes over the past 30 yr. The authors suggest that the changes in the formation locations and prevailing tracks have a profound impact on the basinwide tropical cyclone intensity. Thus, how the atmospheric circulation in the tropical cyclone basins responds to the global warming may be a critical factor in understanding the impacts of global warming on tropical cyclone intensity.

1. Introduction

Current theories suggest that the maximum potential intensity (MPI) of tropical cyclones (TCs) would increase as the underlying sea surface temperature (SST) rises (Emanuel 1987; Holland 1997). Further studies indicate that both the averaged and maximum intensities of TCs will increase in response to the warming of the underlying ocean (e.g., Knutson et al. 1998; Knutson and Tuleya 2004). These results imply that in a warmer climate, more TCs will reach the strengths of hurricane (maximum wind speed larger than 32 m s^{-1}), major hurricane (maximum wind speed larger than 49 m s^{-1}), and intense hurricane[1] (category 4 and 5 hurricanes with a maximum wind speed larger than 59 m s^{-1}).

For this reason, changes in TC intensity have been examined in terms of the number of major hurricanes (Goldenberg et al. 2001) and the percentage of typhoons or intense tropical cyclones (Chan and Liu 2004; Webster et al. 2005). Webster et al. (2005) found that the number and proportion of TCs reaching intense hurricanes have increased over the past 35 yr in all TC basins. Emanuel (2005) demonstrated that the annual accumulated power dissipation index (PDI) of tropical cyclones, which is a combination of the observed intensity, duration, and frequency of tropical cyclones, has increased significantly in the western North Pacific (WNP) and North Atlantic (NA) basins since the mid-1970s. Emanuel (2005) suggested that a 10% increase in potential intensity could lead to a 65% increase in PDI. These studies have fueled a debate regarding the relationship between global warming and hurricane intensity (for a recent summary see Curry et al. 2006).

Although the observed intensity changes have been generally believed to be consistent with the MPI theories and numerical simulations (Webster et al. 2005; Curry et al. 2006), an issue is how much the change in

[1] This terminology is used for all tropical cyclone basins in this note.

Corresponding author address: Dr. Liguang Wu, NASA GSFC, Code 613.1, Greenbelt, MD 20071.
E-mail: liguang@agnes.gsfc.nasa.gov

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TC intensity resulted from the given SST increase. Webster et al. (2005) found that when SST increased by 0.5°C, the increase in the maximum wind speed is about 5%. This ratio is a factor of 2–4 times larger than that estimated from the MPI theories and numerical simulations (Emanuel 2005; Curry et al. 2006). Emanuel (1987) projected a 5% increase in the peak wind speed of tropical cyclones for every 1°C increase in SST; Knutson and Tuleya (2004) found an averaged increase of 6% in the maximum wind speeds for the projected SST increase ranging from 0.8° to 2.4°C. These discrepancies suggest that the observed rate of change in TC intensity may not be solely attributed to the local thermodynamic effect of the underlying warming SST, as suggested by the MPI theories.

In addition to the thermodynamic processes that control the maximum intensity of individual TCs, other factors may affect the basinwide-averaged TC intensity. DeMaria et al. (2001) and Goldenberg et al. (2001) noticed that TCs that form over the tropical Atlantic (from the African coast to 60°W and south of 20°N) have a greater chance of reaching major hurricane strength. We speculate that the basinwide TC intensity will increase as relatively more TCs form in this region. Using the best-track data from 1965 to 2003, Wu et al. (2005) showed that over the past four decades, two prevailing typhoon tracks in the WNP have shifted significantly westward. If TCs move along a prevailing track that favors the development of intense hurricanes, the proportion of intense TCs and the basinwide TC intensity would increase. Rapid intensification (RI) is an essential characteristic of category 4 and 5 hurricanes and supertyphoons. All category 4 and 5 hurricanes in the Atlantic basin (Kaplan and DeMaria 2003) and 90% of the supertyphoons in the western North Pacific (Wang and Zhou 2008) experience at least one RI process in their life cycle. Wang and Zhou (2008) found that over the past 40 yr, when the mean formation latitude shifts southward (either seasonally or from year to year) in the WNP, the RI process and proportion of supertyphoon also increase. This shift in the formation regions is determined by large-scale circulation change rather than local SST effects.

Motivated by such thinking, this note will present the possible association of intense hurricanes with changes in the TC major formation locations and prevailing tracks by examining the best-track data from 1975 to 2004 in the NA, eastern North Pacific (ENP), and WNP TC basins.

2. Data and methodology

The TC best-track data for the NA and ENP basins from the National Hurricane Center (NHC) and for the WNP basins from the Joint Typhoon Warning Center (JTWC) were used in this study. The TC information in the datasets includes the center location (latitude and longitude) and maximum sustained wind speed in knots for each 6-h interval. The TC activity in the selected three basins accounts for 90% and 62% of the annual TC numbers in the Northern Hemisphere and globally, respectively. The wind and SST data were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset.

The TC major formation locations and prevailing tracks are determined based on the frequency of occurrence of TCs, which is defined on each grid box of 2.5° latitude by 2.5° longitude (Wu and Wang 2004). The frequency indicates how often TCs affect a specific grid box. In this study, the prevailing tracks are detected as the grids with high frequency relative to the adjacent grids. Moreover, to the lowest order, the trend in the frequency of occurrence is estimated on each grid box by a linear regression equation: $f_i = a_i + b_i t$, where t is time and f_i is the frequency on the ith grid. The first term (a_i) represents the base state at $t = 0$ 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). In this note, we focus only on how the changes in the tropical cyclone formation locations and prevailing tracks can contribute to the reported changes in the proportion of intense hurricanes over the past 30 yr, although these changes may also affect the variability in tropical cyclone intensity on the decadal and interannual time scales.

3. Major formation locations and prevailing tracks of intense hurricanes

As mentioned in section 1, an intense hurricane may form in a particular region and move along a track with a favorable large-scale environment for its intensification. Figure 1 shows the frequency of occurrence for intense hurricanes (solid contours) and the SST (dashed contours) averaged over the peak hurricane season (August–October for the NA basin and July–September for the WNP and ENP basins). For comparison, the prevailing tracks of all TCs are also plotted in Fig. 1 for the NA and WNP basins. In the NA basin (Fig. 1a), the TC prevailing tracks are generally similar to those found with an objective clustering approach (Elsner 2003).

In the NA basin, TCs that affect the coastal regions of the United States take the first prevailing track from

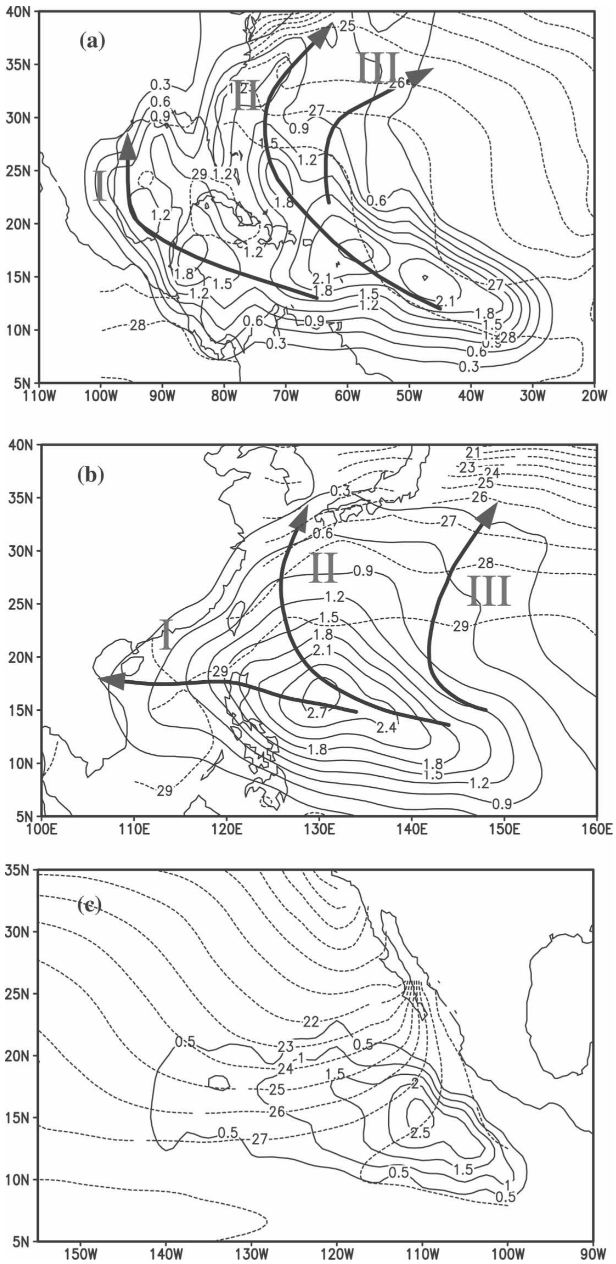

FIG. 1. Frequency of occurrence of intense hurricanes (solid contours), mean SST (dashed contours), and TC prevailing tracks (arrows) for (a) NA, (b) WNP, and (c) ENP. The intervals of frequency of occurrence are 0.3 h yr^{-1} for the NA and WNP basins and 0.5 h yr^{-1} for the ENP basin, and the SST intervals are 1.0°C.

the Caribbean Sea to the Gulf of Mexico (track I) and the second prevailing track from the tropical Atlantic to the East Coast (track II), while TCs taking the third prevailing track (track III) remain far away from the east coast of North America and recurve northeastward (Fig. 1a). The high frequencies of intense hurricanes generally coincide with the warm waters of the tropical Atlantic, western Atlantic, Caribbean Sea, and Gulf of Mexico. Intense hurricanes mainly follow prevailing tracks I and II, where the SST exceeds 28°C. In particular, the origins of intense hurricanes are in the central tropical Atlantic over 10°–20°N and 30°–70°W with very high frequencies of occurrence. This region is roughly consistent with the formation region favorable for major hurricanes (DeMaria et al. 2001; Goldenberg et al. 2001).

In the WNP basin, three prevailing tracks are identified for all TCs (Fig. 1b). First, a westward-moving track extends from the tropical Pacific to the Philippine Sea and South China Sea (track I). Second, TCs move from the tropical Pacific to Korea and Japan, influencing the coastal region of East Asia and the surrounding waters (track II). Third, TCs take the prevailing track recurving northeastward east of 140°E (track III). With their origins in the central tropical North Pacific, the intense hurricanes primarily take the first two prevailing tracks extending westward of 140°E.

Figure 1c shows the spatial distribution of the frequency of occurrence for intense hurricanes in the ENP basin. The intense hurricanes, which form over the tropical ocean, generally maintain a certain distance from the continent by taking a northwestward track. A common climatological feature for the three basins is that intense hurricanes form in the deep tropics and tend to remain over relatively warmer tropical waters before landfalling or recurving toward midlatitudes, thus allowing longer lifetimes (figure not shown).

4. Association of changes in the major formation locations and prevailing tracks with intense hurricanes

The changes in the frequency of occurrence of all TCs are fitted linearly on each grid point to demonstrate how the major formation locations and prevailing tracks changed over the last 30 yr. The linear trends in the NA basin for the period 1975–2004 are shown in Fig. 2a. The TC activity shows a basinwide increase since the annual frequency of TCs has generally increased over the past 30 yr. However, Fig. 2a shows a relatively large increase in the frequency of occurrence over the central tropical Atlantic (10°–20°N, 30°–60°W). A comparison of Figs. 1a and 2a reveals that the significant enhancement of TC activity and the highest frequency of occurrence for intense hurricanes take place in the same region (the central tropical Atlantic). This coincidence suggests that the increase in the proportion of intense hurricanes is associated with the increased number of tropical cyclone formations in this region.

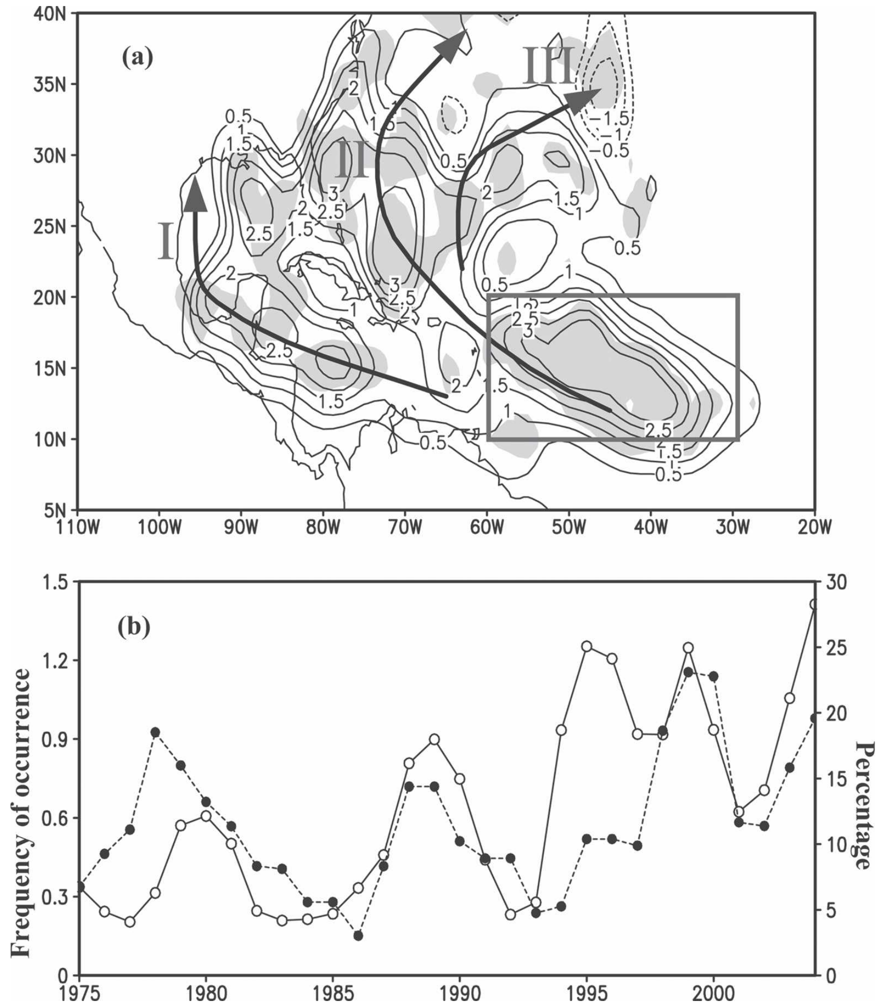

FIG. 2. (a) The 30-yr (1975–2004) linear trend of the frequency of occurrence of TCs in the North Atlantic basin [contour; unit: h (10 yr)$^{-1}$] with the contours of less than 0.5 suppressed. The areas with confidence levels exceeding 95% are shaded. Shown are also the TC prevailing tracks (arrows). (b) Time series of the frequency of occurrence of all TCs averaged over 10°–20°N and 30°–60°W (open dots; yr^{-1}) and the proportion of intense tropical cyclones for the NA basin (closed dots). The selected region is shown by the rectangle in (a).

To confirm this, the time series of the frequency of occurrence averaged (open dots) over 30°–60°W and 10°–20°N (the rectangle in Fig. 2a) are compared with the proportion of the intense hurricanes (closed dots) in Fig. 2b. To reduce the effect of interannual variability, a three-point smoother was applied twice to smooth time series. Note that the proportion of the intense hurricanes is measured by the ratio of the intense hurricanes to the total number of all the TCs. Figure 2b shows that the long-term changes in the proportion of intense hurricanes generally follow the frequency of occurrence of TCs in the central tropical Atlantic. The upward trend in the proportion of intense hurricanes agrees with the enhanced TC activity in the region. Although other factors such as SST and vertical wind shear may be responsible for changes in TC intensity, the agreement between the two time series shown in Fig. 2b suggests the contribution of the increased TC formation in the central tropical Atlantic to the generally increasing trend in the proportion of intense hurricanes over the past 30 yr.

In the WNP basin, although the overall proportion has trended upward over the past 30 yr, a significant decrease appeared in the 1990s. Figure 3a shows that negative tendencies occurred over the central South China Sea, while positive tendencies occurred in the region from Taiwan to the waters south of the Korean Peninsula and Japan. The frequency of occurrence de-

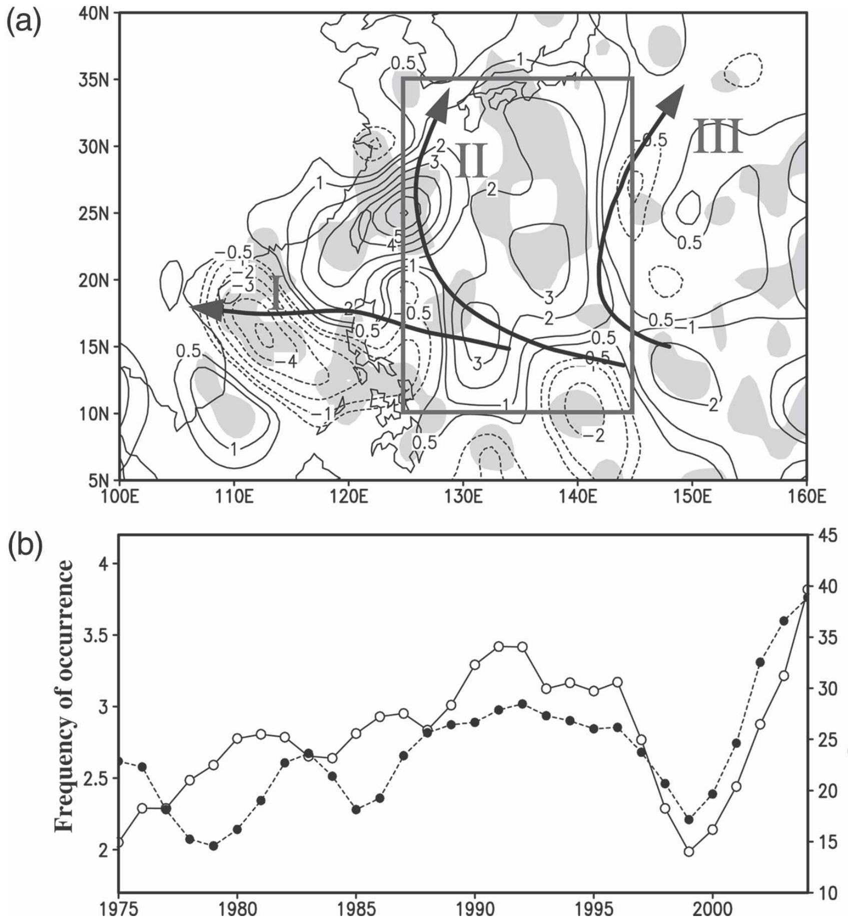

FIG. 3. (a) Same as in Fig. 2a, but for the NWP basin. (b) Same as in Fig. 2b, but over 10°–35°N and 125°–145°E for the WNP basin.

creased in the South China Sea, but increased along the second prevailing track, suggesting a shift in the prevailing tracks over the past 30 yr. Using a trajectory model, Wu et al. (2005) suggested that the track shift resulted from changes in large-scale steering flows, which were characterized by an anomalous cyclonic circulation centered over eastern China. That is, over the past 40 yr, eastern and northward steering flows were enhanced over the South China Sea and West Pacific, respectively. This shift should have little influence on the proportion of intense hurricanes in the whole basin because the shifted track is also favorable for the development of intense hurricanes. However, the positive trends between 125° and 145°E and negative trends to the east indicate a westward shift of prevailing track III. Compared with Fig. 1b, the TCs that originally take the third prevailing track now might have an increased chance of becoming intense hurricanes. The track shift increases the time period that the storms remain over the warmer waters and their opportunities to reach greater intensity, thus contributing to the increased proportion of intense hurricanes. The relationship between the long-term changes in the proportion of the intense hurricanes and the frequency of occurrence of all tropical cyclones averaged over 10°–35°N, 125°–145°E (rectangle in Fig. 3a) can be clearly seen from Fig. 3b.

As mentioned above, the intense hurricanes in the ENP basin take a northwestward track, maintaining a certain distance from the west coast of Central America. The linear trends of the frequency of occurrence show that the TC activity between 120° and 140°W has been significantly enhanced during the period 1975–92 but reduced during the period 1993–2004 (Figs. 4a,b). These interdecadal variations coincided with the change in the proportion of intense hurricanes, which increased and reached a peak in the early 1990s, followed by a substantial decrease (Fig. 5). Dividing the period 1975–2004 into two equal periods, Webster et al. (2005) found that more hurricanes in the ENP reached category 4 and 5 strengths during the period 1990–2004 than during the period 1975–89, leading to a 10% in-

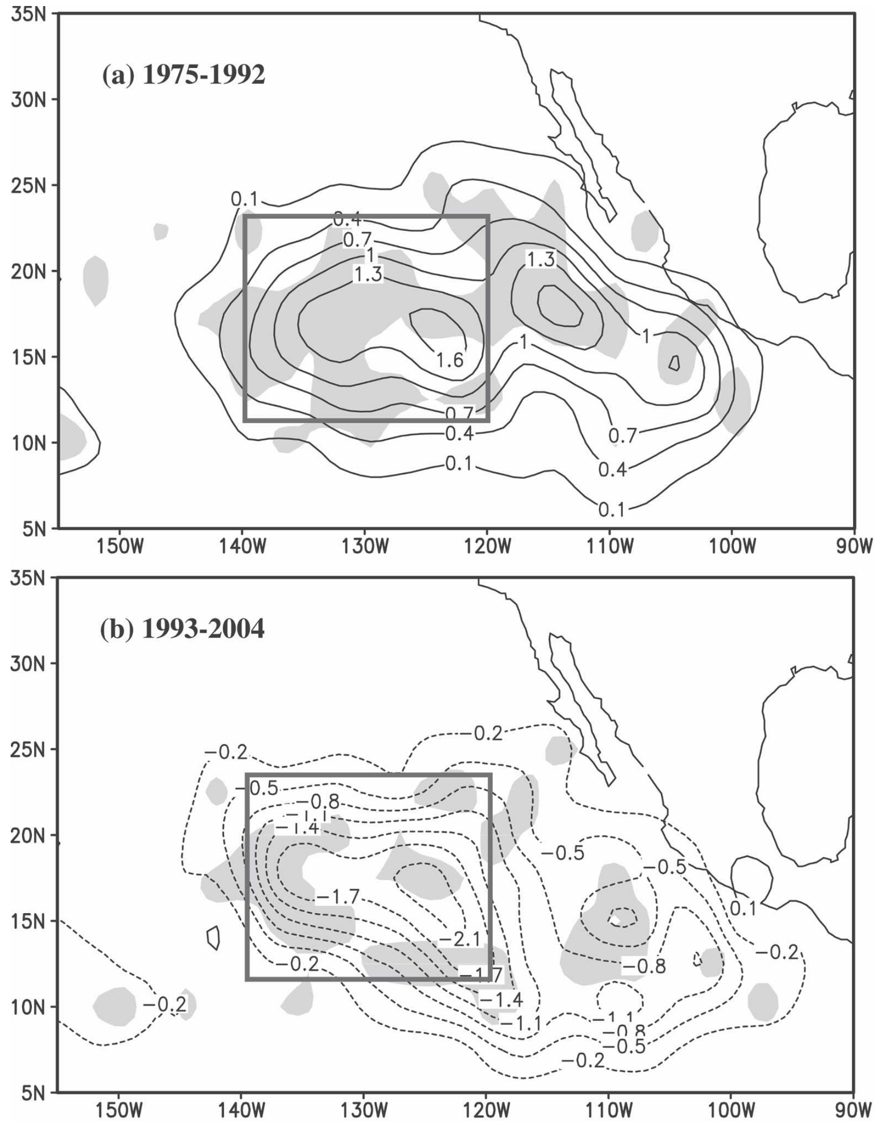

Fig. 4. The linear trend of the frequency of occurrence of TCs [contour; unit: h $(10\ \mathrm{yr})^{-1}$] for the periods (a) 1975–92 and (b) 1993–2004. The areas with confidence levels exceeding 95% are shaded. The rectangle shows the region for averaging the frequency of the occurrence in Fig. 5.

crease in the proportion of intense hurricanes in this basin. However, careful analysis indicates that 74% of the intense hurricanes during the second period formed between 1990 and 1997. Thus, the increases in the number and proportion of intense hurricanes in the ENP basin vary with the choice of periods. For example, 37 and 25 intense hurricanes formed during the periods of 1985–94 and 1995–2004, respectively. The ratios of intense hurricanes to all hurricanes were 33% and 34% for these two periods, respectively.

To reduce the effect of the changes in the annual frequency, Fig. 5 also shows the change of the frequency of occurrence averaged over 12°–24°N, 120°–140°W (rectangles in Fig. 4) relative to that averaged over 10°–20°N, 100°–120°W. In this selected region, most significant changes in TC frequency occurred (Fig. 4). The increase (decrease) trend in the proportion of intense hurricanes is associated with the enhanced (reduced) TC occurrence over the region (12°–24°N, 120°–140°W).

5. Influence of vertical wind shear

In addition to SST, the effect of vertical wind shear on TC development has long been recognized (Riehl

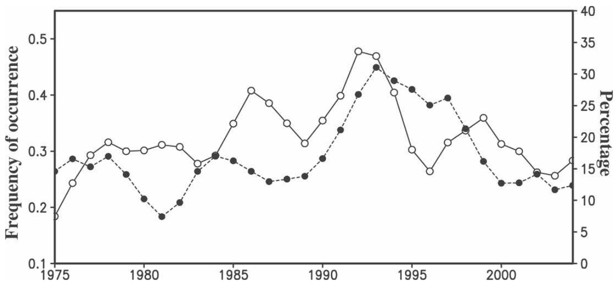

FIG. 5. Time series of the ratio of the frequency of occurrence of all tropical cyclones averaged over 12°–24°N and 120°–140°W to that averaged over 10°–20°N and 100°–120°W (open dots; yr^{-1}) and the proportion of intense tropical cyclones for the ENP basin (closed dots).

and Shafer 1944; McBride and Zehr 1981; Merrill 1988) and has been confirmed in recent numerical simulations (Frank and Ritchie 2001; Wu and Braun 2004; Wong and Chan 2004; Wu et al. 2006). In this study, the vertical shear is defined as the difference in monthly wind speeds between 200 and 850 hPa averaged over the peak periods of TC activity and over the primary regions of TC 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 6 shows that in the NA basin the vertical wind shear has been reduced by 1.7 m s^{-1} over the past 30 yr, according to a linear fit. The decreasing shear in the NA basin, together with increasing SST, may have allowed more storms to form and to form earlier, leading to the enhanced TC activity in the tropical Atlantic (Fig. 2a). Although the vertical shear is calculated with the monthly wind fields, this is consistent with the fact that both the TC annual frequency and lifetime increased over the past 30 yr (Wu et al. 2008). In the WNP and ENP basins, however, no trend is evident in the vertical shear, suggesting that it may have little influence on the changes in the proportion of intense hurricanes in the WNP and ENP basins.

6. Summary

Defining the frequency of occurrence on each grid box, we have examined the changes in the TC major formation locations and prevailing tracks using the historical best-track datasets in the NA, WNP, and ENP basins. We found that the changes in the TC major formation locations and prevailing tracks may have contributed to the changes in the proportion of intense hurricanes over the past 30 yr. We suggest an additional mechanism that may be responsible for the reported increases in the proportion of intense hurricanes in the NA and WNP basins over the past 30 yr.

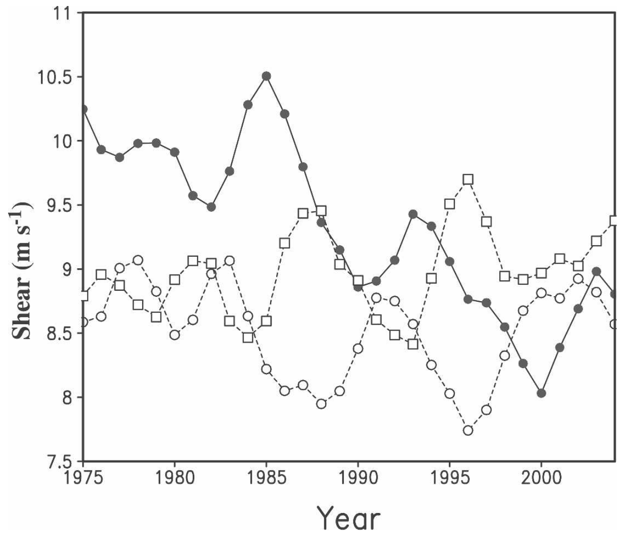

FIG. 6. Time series of vertical shear for the NA basin (closed dots), the WNP basin (open dots), and the ENP basin (open squares). See text for details.

In the NA basin, the TC formation has been enhanced in the central Atlantic, leading to more storms with a higher chance of reaching greater intensity. In the WNP basin, the TC prevailing tracks have shifted westward, allowing more storms to follow a longer journey that favors the development of intense hurricanes. As a result, the proportion of intense hurricanes generally increased in these two basins over the past 30 yr. In the ENP basin, however, the change in the proportion of intense hurricanes peaked in the early 1990s.

We mentioned that the shift in the formation location in the NA basin might be a result of the warming SST and decreasing vertical shear. What exactly caused the warming SST and decreasing vertical shear is not clear, although some studies related the warming SST to the ongoing climate change (Mann and Emanuel 2006; Curry et al. 2006). In the WNP basin, Wu and Wang (2004) assessed the possible impacts of the global climate change on TC tracks using the large-scale steering flows taken from the outputs from two Geophysical Fluid Dynamics Laboratory (GFDL) global warming experiments. The GFDL experiments suggested the enhanced northward steering flow in the WNP basin during the period 2030–59. Using a simple trajectory model, Wu and Wang (2004) predicted that more tropical cyclones would take a recurving track during the period 2030–59. Recently, Wu et al. (2005) found a similar track shift in the last 40 yr. It seems that the projected track shift in the GFDL global warming experiments has already been seen in the last 40 yr.

The present study suggests that the assessment of the impacts of global warming on TC intensity should consider the possible future changes in TC formation locations and tracks. The latter is closely associated with the response of the atmospheric circulation to the tropics-wide SST warming in the tropical cyclone basins.

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