Influence of Sea Surface Warming on Environmental Factors Affecting Long-Term Changes of Atlantic Tropical Cyclone Formation

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ABSTRACT

Despite the observed high correlation between the Atlantic sea surface temperature (SST) and the Atlantic tropical cyclone (TC) activity, interpretation of this relationship remains uncertain. This study suggests that the tropical Atlantic sea surface warming induces a pair of anomalous low-level cyclones on each side of the equator, providing favorable conditions for enhancing TC formation east of 45°W, while the effect of SST warming in the tropical Indian Ocean and Pacific Ocean tends to suppress the TC formation.

Over the past 30 years (1978–2007), the TC activity in the Atlantic basin is characterized with significant enhancement of TC formation east of 45°W, where the total TC number increased significantly compared to the period 1948–77. Despite the possible undercount of TCs, this study shows that the recently enhanced TC formation may not be totally accounted for by the poor TC observing network prior to the satellite era. The Atlantic sea surface warming that occurred in recent decades might have allowed more TCs to form, to form earlier, and to take a longer track, while the effect is partially offset by the SST warming in Indian and Pacific Oceans. This study suggests that the close relationship between the Atlantic SST and TC activity over the past 30 years, including basinwide increases in the average lifetime, annual frequency, proportion of intense hurricanes, and annual accumulated power dissipation index (PDI), as reported in previous studies, is mainly a result of the SST warming in the tropical Atlantic exceeding that in the tropical Indian and Pacific Oceans. The results agree with recent argument that the relative Atlantic SST change or the SST difference between the tropical Atlantic and other oceans play an important role in controlling long-term TC activity in the Atlantic basin.

1. Introduction

Recently a close relationship between the climate trends in tropical cyclone (TC) activity and sea surface temperature has been reported, leading to an intense debate regarding whether global warming is enhancing TC activity (Emanuel 2005; Webster et al. 2005; Landsea 2005, 2007; Hoyos et al. 2006; Chan 2006; Holland and Webster 2007; Vecchi et al. 2008). While many studies related the recently heightened TC activity to Atlantic sea surface warming (e.g., Goldenberg et al. 2001; Mann and Emanuel 2006; Santer et al. 2006; Elsner 2006; Elsner et al. 2006; Kossin and Vimont 2007; Latif et al. 2007; Emanuel 2008), how the sea surface warming affects the trends in Atlantic TC activity is not convincingly interpreted. Given the fact that TCs account for a significant fraction of damage and loss of life from natural hazards (Pielke and Landsea 1998; Pielke et al. 2008; Zhang et al. 2009), future changes in TC activity is one of the important issues in the report of the Intergovernmental Panel on Climate Change (IPCC; Solomon et al. 2007).

By linking to the theory of maximum potential intensity (MPI; Emanuel 1987), Emanuel (2005) and Webster et al. (2005) suggested that TC intensity has trended upward in the Atlantic basin over the past several decades. Webster et al. (2005) demonstrated basinwide increasing trends in

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the number and proportion of intense hurricanes (category 4 and 5 hurricanes with a maximum wind speed larger than 59 m s^{-1}) for all TC basins during the period 1970–2004. Using a methodology based on information theory, Hoyos et al. (2006) argued that these trends are linked directly to the SST trend in those basins. Emanuel (2005) showed a close relationship between the annual accumulated power dissipation index (PDI) for TCs in the North Atlantic and the underlying SST during the period 1949–2004 by defining the annual PDI as a collective effect of the TC intensity, lifetime, and annual frequency. Although the TC intensity estimates back to 1870 were dubious, a correlation was found to exist (Emanuel 2008). Emanuel (2007) pointed out that the MPI in the North Atlantic has increased by 10% since the 1970s by including decreasing surface wind speed and decreasing lower-stratospheric temperature in the thermodynamic calculations. These studies contended that the trends in TC activity were generally consistent with the prediction of the MPI theory, as well as numerical simulations using large-scale thermodynamic conditions derived from the IPCC global warming experiments (Knutson et al. 1998; Knutson and Tuleya 2004).

However, in agreement with Maue and Hart (2007), Wu et al. (2008) recently showed that with little change in the basinwide average intensity the significant increase in the annual accumulated PDI reported by Emanuel (2005) resulted mainly from the changes in the TC lifetime and annual frequency in the Atlantic basin, which are found to increase significantly over the period 1975–2004. Emanuel (2005) also noticed the elongated TC lifetime over the period 1975–2004, but argued that the increase may result from the longer survival time for more intense storms and changes in TC reporting practices. Holland and Webster (2007) documented the increase in the annual frequency in the three climate regimes since 1905 and related it to the significant warming SST in the tropical Atlantic. Wu and Wang (2008) provided a new interpretation about the trends in Atlantic TC activity after they found that the TC activity over the area of 10°–20°N, 30°–60°W was significantly enhanced, which agrees with Holland (2007) since DeMaria et al. (2001) and Goldenberg et al. (2001) found that TCs that form over this area have greater chance of reaching major hurricane strength. In contrast with previous studies, Wu and Wang (2008) proposed that more TCs might have been forming earlier, and taking a longer track that favors TC intensification, thus leading to the increase in the proportion of intense hurricanes as reported by Webster et al. (2005). Note that this increase is not large enough to change the basinwide average intensity (Wu et al. 2008).

Since some evidence shows that numerous TCs were missed in the database before basinwide monitoring via satellite (Landsea 2007; Vecchi and Knutson 2008), the key to understanding of TC climate change in the Atlantic basin is whether there is a physical mechanism responsible for the local enhancement of TC activity, which may also shed light on assessing the response of Atlantic TCs to global warming. The main objective with this paper is to address this issue. Compared to the MPI theory, this framework requires neither an increase in the maximum intensity of individual TCs, as shown by Webster et al. (2005), nor a significant increase in basinwide average intensity, as evident in Maue and Hart (2007) and Wu et al. (2008).

The framework may be associated with the atmospheric response to the tropicswide SST warming since studies found that effect of remote SST change plays an important role in controlling Atlantic TC activity (Vecchi and Soden 2007; Latif et al. 2007; Knutson et al. 2008). The remote SST effect has been also implied in previous studies through the association of precipitation in the Sahel region with the African easterly wave activity (Gray 1990; Landsea and Gray 1992) and the Saharan air layer activity (Wu 2007) because the variability of the Sahel rainfall is associated with the global tropical SST change (Giannini et al. 2003; Bader and Latif 2003; Lu and Delworth 2005; Hagos and Cook 2008). Thus investigation of the enhanced TC formation in the Atlantic basin should include the response of the atmospheric circulation in the Atlantic TC basin to SST changes in tropical Atlantic as well as in other oceans.

In this study the influence of the ongoing tropicswide SST change on Atlantic TC activity is explored. In particular, through numerical modeling, we show that sea surface warming that occurs in individual oceans can provide conditions for either enhancing or suppressing tropical formation over the east tropical Atlantic. Instead of simulating individual TCs, we focus mainly on changes in large-scale conditions for TC formation. First, we examine the variability of TC formation in the Atlantic basin.

2. Enhanced TC formation over the eastern North Atlantic

Holland (2007) and Wu and Wang (2008) suggested that the increasing trends of TC activity found in previous studies was associated with the enhanced TC formation in the eastern tropical Atlantic. For this reason, the TC data from 1948 to 2007 are examined to show the temporal and spatial features of the Atlantic TC formation. As we know, the reliability of TC data depends on how TCs are detected and measured. We consider that TC counts and formation locations are relatively reliable from 1945 onward because of the implementation of aircraft reconnaissance and the relatively dense ship traffic

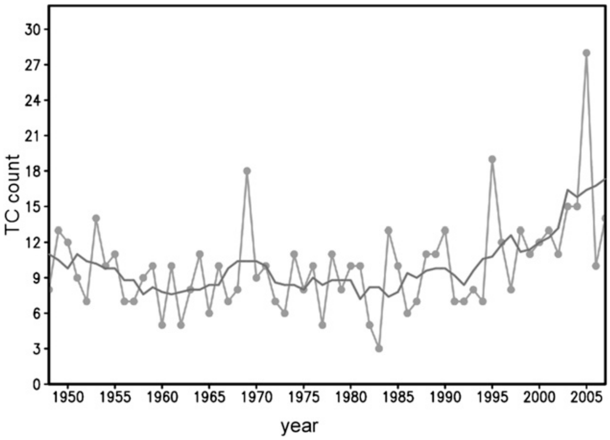

FIG. 1. Annual frequency of tropical cyclones formed in the Atlantic basin (the Gulf of Mexico, the Caribbean Sea, and the North Atlantic) during the period 1948–2007 with the annual value and 5-yr running mean shown with thin and thick lines, respectively.

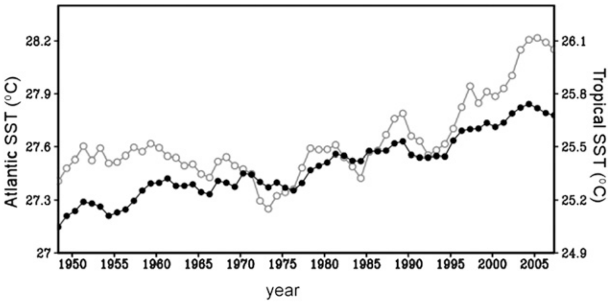

FIG. 2. Time series of the 5-yr running mean SST averaged over the area of 10°–20°N, 30°–60°W (open dots) and the global tropics between 30°S and 30°N (closed dots) from 1948 to 2007.

(Vecchi and Knutson 2008), but are still of unknown reliability in the eastern Atlantic until satellite reconnaissance in the 1960s, when earth-orbiting satellites started to track TCs. It is believed that few TCs were missed since the 1960s (Holland and Webster 2007; Emanuel 2008) after the satellite era. The best-track data from the reanalysis project of the Hurricane Research Division are used and are available online at: http://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html (Landsea et al. 2008).

Figure 1 shows the annual frequency of TCs (maximum sustained winds exceed 17 m s^{-1}) formed in the Atlantic basin (the Gulf of Mexico, the Caribbean Sea, and the North Atlantic) during the period 1948–2007. Superimposed with interannual variability, the 5-yr running mean of annual frequency clearly shows an unprecedented upswing over the past decade. The increasing trend can be recognized since the early 1980s. Goldenberg et al. (2001) first identified the upward trend and attributed it to the Atlantic multidecadal oscillation. Holland and Webster (2007) examined the Atlantic tropical cyclone numbers since 1855 and interpreted the upward trend as a transition to a new climatic regime in which annual TC frequency could stabilize at a significantly high level.

The monthly National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST (ERSST version 3) data from http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html is used in this study. Figure 2 shows the time series of the 5-yr running mean SST averaged over the area of 10°–20°N, 30°–60°W and over the global tropics between 30°S and 30°N. The former represents the SST change in the tropical Atlantic, especially in the area with the enhanced TC formation. The unprecedented TC annual counts observed since 1995 concurred with the record high SST in the tropical North Atlantic. The increasing trend in TC activity since the early 1980s was generally accompanied with the increasing SST. By comparing Fig. 2 with Fig. 1, we find that the coolest SST appeared in the mid-1970s while the annual TC count was the lowest in the early 1980s. This figure also shows that the Atlantic tropical SST has been increasing faster than the global tropical average since the mid-1970s.

The time difference between the SST change and TC activity arises from the TC interannual variability associated with the El Niño event in 1982–83 (Gray 1984). The 1983 hurricane season, with a total of only four named TCs, became the least active season since 1930 (Case and Gerrish 1984). Also, the 2-yr period (1982–83) became the first two consecutive years since 1871 in which no TCs occurred in the Caribbean Sea. This may have delayed the turning point of TC activity until the early 1980s rather than the middle 1970s.

Unlike the SST in the tropical Atlantic, the tropicswide SST has trended upward over the past 60 years without an obvious abrupt change in the mid-1970s (Fig. 2). The abrupt change shown in Fig. 2 also occurred in the Pacific warm pool (Kumar et al. 2004), but not in the Indian Ocean although the warming trend in several TC basins since the 1970s has been attributed at least partially to increasing greenhouse gas concentration (Solomon et al. 2007; Santer et al. 2006; Knutson et al. 2008). To examine changes in TC formation, based on the above analysis, it is reasonable that we divide equally the 60 years into two 30-yr periods: 1948–77 and 1978–2007.

Table 1 and Fig. 3 show the statistics and spatial distribution of TC formation for the two periods. The total number increased by 19.0% from 294 TCs during the first 30 years to 350 TCs during the second 30 years. As shown in Fig. 3, the increase in the annual frequency was not spatially homogeneous. For convenience, the Atlantic basin is divided into three subregions: west of 70°W, 45°–70°W and east of 45°W. There were as many TCs formed west of 70°W during the first periods as during

TABLE 1. The numbers and changes of tropical cyclone formation in different regions for two 30-yr periods.

	1948–77	1978–2007	Change (%)
10°–45°W	43	83	93.0%
45°–70°W	111	127	14.4%
70°–100°W	140	140	0.0%
Total	294	350	19.0%

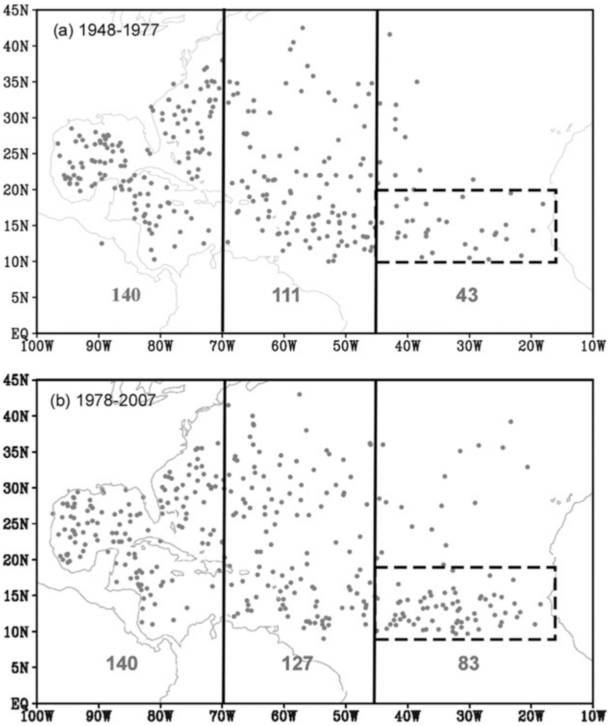

FIG. 3. Spatial distribution of tropical cyclone formation locations over two 30-yr periods: (a) 1948–77 and (b) 1978–2007. The Atlantic basin is divided into three subregions: west of 70°W, 45°–70°W, and east of 45°W. Dots and numbers indicate formation locations and total counts of tropical cyclones formed in the subregions.

the second period. In the middle Atlantic region (45°–70°W), the total number increased by 14.4% from 111 TCs during the first period to 127 TCs during the second period, but comparison of the formation locations in Figs. 3a and 3b indicates that significantly more TCs formed between 25° and 35°N during the period 1978–2007 than during the period 1948–77. This increase is likely due to a change in analysis practice by the National Hurricane Center (NHC) from 1970 to include more midlatitude systems (Holland and Webster 2007). The most significant increase in the TC formation occurred east of 45°W. The total number increased by 93.0% from 43 TCs during the first period to 83 TCs during the second period and this increase mostly occurred south of 20°N. The increase in TC formation is consistent with the finding by Wu and Wang (2008). Because of use of the frequency of TC occurrence that also counts the subsequent tracks of these increased TCs, the enhanced area shifts westward in their study.

The increased TC formation east of 45°W accounts for the significant increasing trend in PDI reported in the literature (Emanuel 2005; Wu et al. 2008). After the TC wind speeds prior to 1970 are adjusted based on Emanuel's (2005) formula, the annual accumulated PDI is calculated for the period 1948–2007 (Fig. 4a). In agreement with Emanuel (2005), the large upswing since 1995 is unprecedented despite multidecadal oscillations. However, the time series basically become a multidecadal oscillation with the least PDI in the 1980s if the TCs that formed east of 45°W are removed from the calculation. Figure 4b further shows the comparison of the annual accumulated PDI for TCs that formed east of 45°W with the SST averaged over the area of 10°–20°N and 30°–60°W. The excellent agreement between the two series in the overall trend over the past 60 years suggests that the TCs that formed east of 45°W played a dominant role in accounting for the unprecedented PDI trend as documented by Emanuel (2005).

Although aircraft reconnaissance was implemented in the Atlantic basin since mid-1945, it was very likely that TCs were missed in the existing TC database during the presatellite era, especially for the eastern Atlantic. Vecchi and Knutson (2008) estimated that the undercount in the TC database was ¼ TC yr^{-1} in the 1950s and 1960s. In this case, the enhanced TC formation east of 45°W is still obvious. Inferring a storm undercount based on the landfalling TCs, however, Landsea (2007) argued that numerous TCs were missed in the existing Atlantic TC count database. Assuming that a similar long-term average of TCs struck land, he suggested that 2.2 TCs yr^{-1} were missed for the period 1900–65, while one additional TC has been identified since 2002 because of improvements in monitoring tools and techniques.

It is also possible that satellite-based estimates of intensity commenced in the 1970s caused some TCs to be detected early, which otherwise may be found after moving west of 45°W. Considering the close relationship with SST shown in Fig. 4b and the results of numerical simulations in the following sections, we believe that the enhanced TC formation east of 45°W is not totally artificial although the enhancement may be overestimated due to missed TCs.

3. Numerical experiments

The atmospheric general circulation model ECHAM4.8 is used in this study. Based on the weather forecast model of the European Centre for Medium-Range Weather

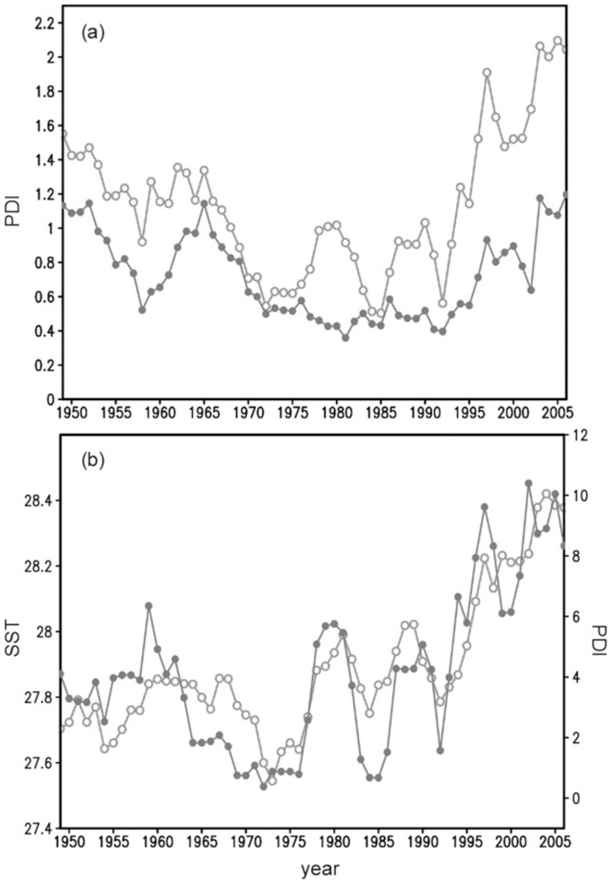

FIG. 4. (a) Time series of the annual accumulated PDI (unit: 1.0×10^7 m^3 s^{-3}) for all tropical cyclones in the Atlantic basin (open dots) and tropical cyclones that did not form in the box shown in Fig. 3 (closed dots), and (b) time series of the SST averaged over the area of 10°–20°N, 30°–60°W (open dots) and the annual accumulated PDI (unit: 1.0×10^6 m^3 s^{-3}) for tropical cyclones that formed in that box (closed dots). A 5-yr running average is applied to all of the time series.

Forecasts (ECMWF), the model has been modified at the Max Planck Institute for Meteorology and the German Climate Computing Centre (DKRZ) to make it suitable for climate simulation (Roeckner et al. 1996). The model uses a 19-level hybrid sigma-pressure coordinate system with the T42 horizontal resolution. The model physics include the turbulent surface fluxes calculated from Monin–Obukhov similarity theory, horizontal diffusion in the form of a hyper-Laplacian, the ECMWF radiation scheme, and the parameterization of cumulus convection (shallow, midlevel, and deep) that is based on the bulk mass flux concept of Tiedtke (1989).

A total of five simulations are performed (Table 2). In the control run (CTL), the annual SST cycle is obtained by averaging observed monthly SSTs from 1948 to 1977. To evaluate the influence of tropical SST warming, the second experiment, called the global tropics run (GOT), differs from the control run in the SST between 40°S and 40°N, which is the annual cycle obtained by averaging observed monthly SSTs from 1978 to 2007. Figure 5 shows the July–September SST change from the first 30-yr period (1948–77) to the second 30-yr period (1978–2007). The SST warming occurred throughout the Indian Ocean and Atlantic Ocean between 40°S and 40°N, with maxima of above 0.6°C in the Southern Hemisphere. To retain the warming pattern the SST forcing is extended from 40°S to 40°N. In the Pacific, significant warming occurred mostly east of the date line with a maximum of about 0.8°C near the coast of South America. The isolated negative SST anomalies, which appear mostly in the middle latitudes of the Pacific with magnitude of less than 0.2°C, are set to zero in these idealized experiments because we focus on the SST warming. In this study, the influence of SST warming on the interdecadal time scale is represented with the SST difference between the two 30-yr periods, while the interannual variability is filtered out because the SST forcing only includes the mean annual cycle.

TABLE 2. Description of the numerical experiments, in which negative SST anomalies are zeroed out.

Experiment name	Prescription of SST annual cycle
CTL	Global 1948–77 mean
GOT	1978–2007 mean between 40°S–40°N and 1948–77 mean elsewhere
TIP	1978–2007 mean in the Indian Ocean and Pacific Ocean (40°S–40°N, 20°E–70°W) and 1948–77 mean elsewhere
TIO	1978–2007 mean in the Indian Ocean (40°S–40°N, 24°–114°E) and 1948–77 mean elsewhere
TAO	1978–2007 mean in the Atlantic Ocean (40°S–40°N, 70°W–20°E) and 1948–77 mean elsewhere

To examine the role of the different ocean basins, we conduct three additional experiments, which differ from GOT in the tropical SST forcing between 40°S and 40°N (Table 2). In the tropical Indian Ocean and Pacific run (TIP), the mean SST annual cycle averaged over the second period (1978–2007) are used in the area of 40°S–40°N and 20°E–70°W. The other two experiments focus on tropical Indian Ocean (TIO) and tropical Atlantic Ocean (TAO), respectively, in which the mean SST annual cycle averaged over the second period (1978–2007) is applied only to the individual ocean basins.

A 30-yr simulation is performed for all of the five numerical experiments. About 84% of the Atlantic TCs formed east of 45°W in the wet season, with 95% of them in August and September. For this reason, our analysis is based on the outputs of the wet season [July–September

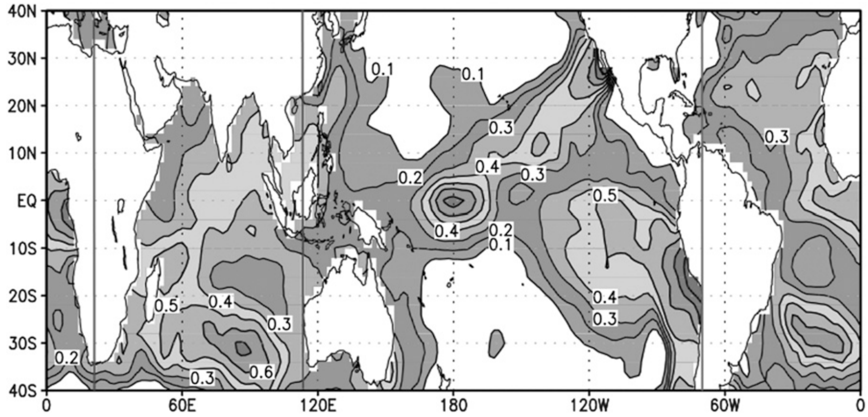

FIG. 5. JAS SST changes (°C) from the period 1948–77 to the period 1978–2007 with intervals of 0.1°C. Negative anomalies, which appear mostly in the middle latitudes of the Pacific, with a magnitude of less than 0.2°C, are set to zero. The vertical solid lines denote the borders of SST forcing in the TIP, TIO, and TAO experiments.

(JAS)] of the African summer monsoon from the last 20-yr simulation.

4. Model evaluation

The model performance in simulating African summer monsoon was already evaluated by several studies. For example, Latif et al. (2000) simulated the observed low-frequency North Atlantic Oscillation (NAO) index variations reasonably well; Schnitzler et al. (2001) forced the model with the observed SSTs from 1951 to 1994 and reproduced the Sahelian rainfall. Bader and Latif (2003) examined the impact of decadal-scale Indian Ocean SST anomalies on Sahelian rainfall and the NAO. In this study, we mainly focus on the simulated low-level wind and precipitation fields because of the observational data availability.

We first compared the JAS mean wind field from CTL with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Fig. 6). It is clear that the model realistically simulates the main observed features of low-level winds over the African continent during the period 1948–77, including the anticyclonic circulation centered at about 30°N, 5°E and the confluence zone between 5° and 10°N. Over the Atlantic, the model captures the easterly winds in the tropical Atlantic and the subtropical anticyclone centered at about 35°N, although the easterly winds tend to be too weak in the tropical North Atlantic. Note that, as an important factor for TC development, the model can also reasonably simulate the vertical wind shear over the Atlantic TC basin (Camargo et al. 2007; Latif et al. 2007).

To evaluate the model performance, three observational precipitation datasets are used in this study. The JAS mean precipitation from CTL is first compared with precipitation during the period 1948–77 from Global Precipitation Climatology Center (GPCC V4; more information available online at ftp://ftp-anon.dwd.de/pub/data/). As shown in Fig. 7a, the observed JAS mean precipitation contains three maxima over the western coast (10°N, 15°W), the Ethiopian highlands (10°N, 35°E), and the Cameroon highlands (5°N, 10°E). The model simulates a very similar precipitation pattern with similar magnitudes except a northeastward shift of the maximum precipitation over the Cameroon highlands (Fig. 7b).

Figure 7b shows that the model also simulates a strong precipitation belt between 3° and 15°N over the tropical Atlantic. Since there were no rain-gauge data over the ocean in the GPCC dataset, the JAS 1998–2007 mean precipitation from the Tropical Rainfall Measuring Mission (TRMM) 3B42 version 5 and the 1979–2007 JAS mean precipitation climatology from the Global Precipitation Climatology Project (GPCP) are used for a qualitative comparison (Fig. 8). The TRMM data is a blend of microwave and infrared precipitation estimates scaled to monthly rain-gauge measurements over land and the GPCP data is derived from rain-gauge data that were merged with the precipitation estimates of various satellites (Huffman et al. 2001). Despite the differences in time periods and data sources, the general features of the JAS mean precipitation from TRMM and GPCP are very similar. In addition to the three precipitation maxima over the continent, both of the datasets indicate a strong rainfall belt between 3° and 15°N over tropical Atlantic. The location of the observed rainfall belt is well simulated in CTL and GOT (figure not shown), but the model simulates a more complex precipitation pattern over the ocean than the satellite-derived data. In addition to the precipitation maximum over the western coast, CTL and

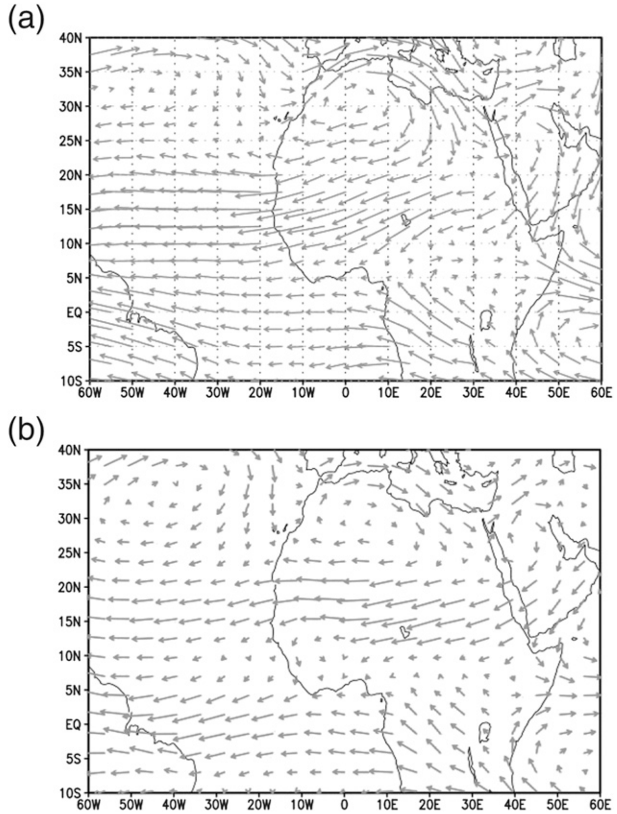

FIG. 6. The 700-hPa July–September mean wind field (a) from the NCEP–NCAR reanalysis averaged over the period 1948–77 and (b) from CTL.

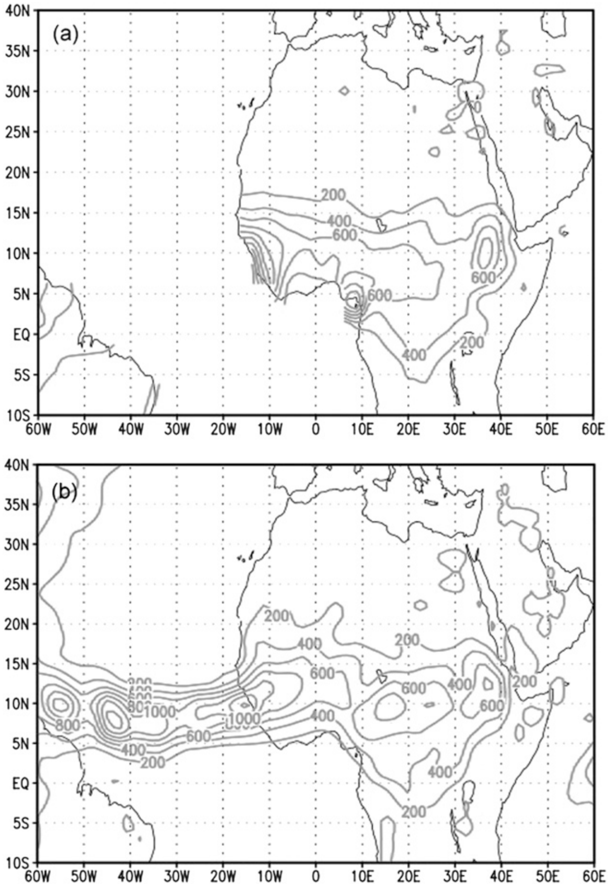

FIG. 7. JAS mean precipitation (mm) field (a) from the GPCC V4 averaged over the period 1948–77 and (b) from CTL.

GOT also produce strong rainfall maxima west of 35°W, which are missing in the TRMM and GPCP data.

In summary, the model captures many important features of the circulation and precipitation over the eastern tropical Atlantic and African continent. The model performance gives us confidence that the basic large-scale atmospheric features relevant to TC formation over the eastern tropical Atlantic can be simulated well when it uses the observed SSTs as a lower boundary condition.

5. Influence of ocean warming on TC formation

The influence on TC formation can be investigated by examining the deviations of simulated July–September mean fields associated with TC formation in GOT, TAO, and TIP from CTL. Gray (1975) found that the climatologic aspects of TC formation frequency are closely related to a few large-scale environmental conditions including warm ocean surface, strong low-level vorticity, weak vertical wind shear, and high relative humidity in the middle troposphere. Emanuel and Nolan (2004) defined a TC genesis potential index (GPI) to relate the spatial and temporal variability of TC genesis to a few environmental parameters including 850-hPa absolute vorticity, 700-hPa relative humidity, vertical wind shear between 850 and 200 hPa, and the potential intensity, which is associated with SST and atmospheric profiles of temperature and mixing ratio (Emanuel 1986). Murakami and Wang (2010) found that the GPI is more consistent with the observed TC formation over the eastern Atlantic by explicitly incorporating a vertical motion term. The low-frequency fluctuations on the interannual and interdecadal scales in Atlantic hurricane activity were related to a set of atmospheric and ocean conditions in the main development region (e.g., Shapiro and Goldenberg 1998; Goldenberg et al. 2001; Bell and Chelliah 2006). Since the increasing SST as the lower boundary forcing is already shown in Fig. 2, the changes in low-level vorticity, midlevel relative humidity, and vertical wind shear in these numerical experiments are examined here.

Figure 9 shows deviations of simulated July–September wind fields at 700 hPa in GOT, TAO, and TIP from CTL, representing changes in the lower-troposphere circulation due to ocean forcing. Note that GOT includes the SST

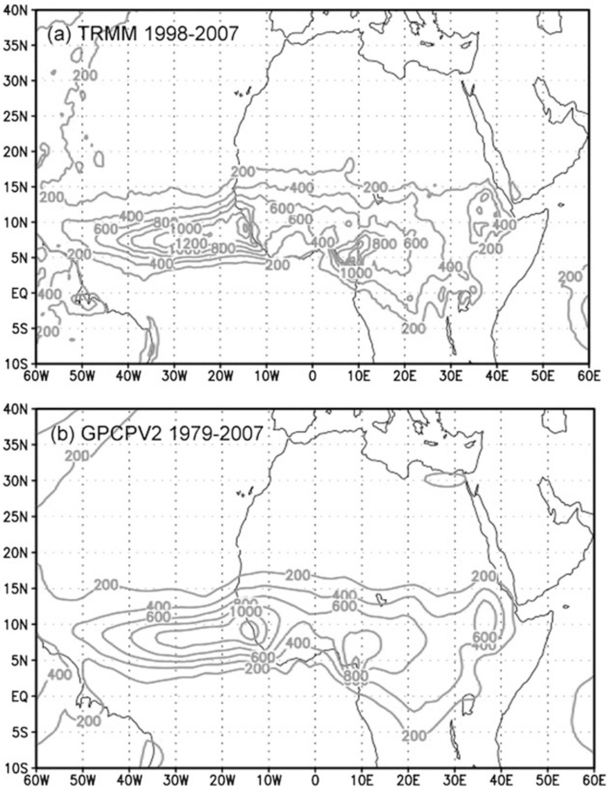

FIG. 8. JAS mean precipitation (mm) field (a) from TRMM over the period 1998–2007 and (b) from the GPCP V2 averaged over the period 1979–2007.

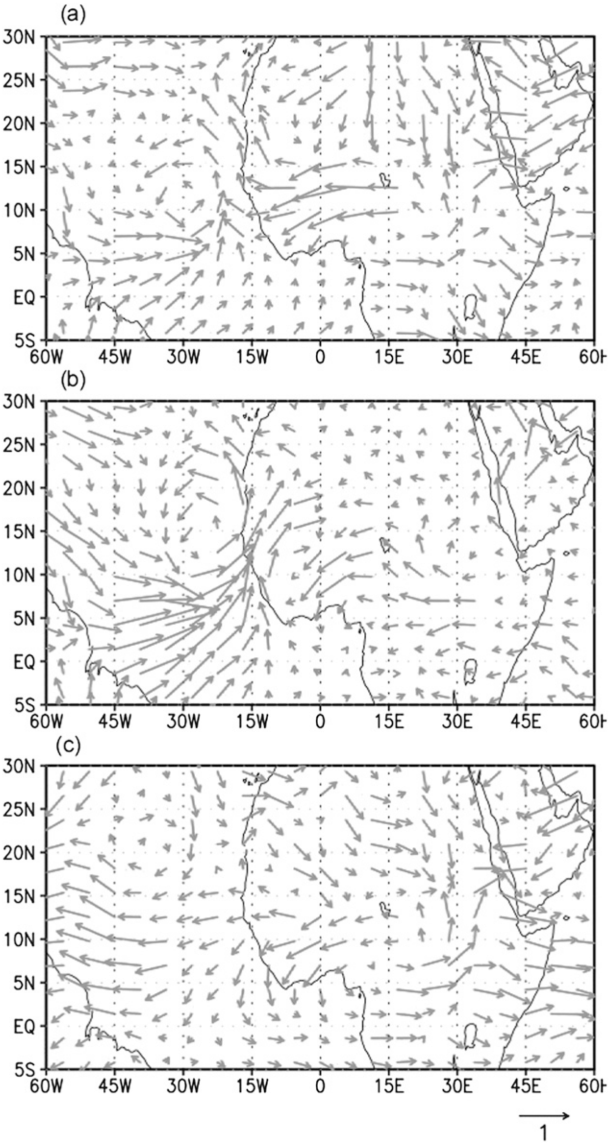

FIG. 9. Simulated differences of JAS mean 700-hPa wind vectors (m s^{-1}) in the (a) GOT, (b) TAO, and (c) TIP experiments from the CTL.

forcing over the whole global tropics while TAO and TIP are only forced by tropical Atlantic SSTs and a combination of tropical Indian Ocean and Pacific SSTs, respectively (Table 2). As shown in Fig. 9, an anomalous cyclone off the western African coast is induced in GOT and TAO, but not in TIP, suggesting that it mainly results from the Atlantic SST warming. The anomalous cyclone that is induced in the region with enhanced TC formation (10°–20°N and 45°–15°W) indicates an increase in the low-level vorticity that is favorable for TC formation (Gray 1975; Vitart et al. 1999).

Moreover, the induced anomalous cyclone also leads to increasing midlevel relative humidity and vertical motion, mainly in its south part, which are conducive to TC formation. Figure 10 displays deviations of the July–September mean relative humidity at 500 hPa in GOT, TAO, and TIP from CTL, representing changes in midlevel relative humidity. In association with the anomalous cyclone in GOT and TAO, there is positive anomalous relative humidity at 500 hPa but a negative one in TIP over the region with enhanced TC formation (10°–20°N, 45°–15°W). Further examination indicates that the increased (decreased) relative humidity is associated with the increased (decreased) upward vertical motion in the area (Fig. 11), which may be responsible for the increased relative humidity in the middle troposphere by enhancing the vertical transport of moisture flux. As shown in Fig. 11, the most significant upward motion (negative values) appears in GOT and TAO, but subsidence is observed in TIP, again suggesting the dominant role of the Atlantic SST warming in producing a favorable environment for TC development. Consistent with the enhanced vertical motion, the precipitation increases significantly in GOT and TAO off the west coast of North Africa (Fig. 12).

Forcing a higher resolution of the ECHAM model with observed monthly SSTs in individual oceans, Latif

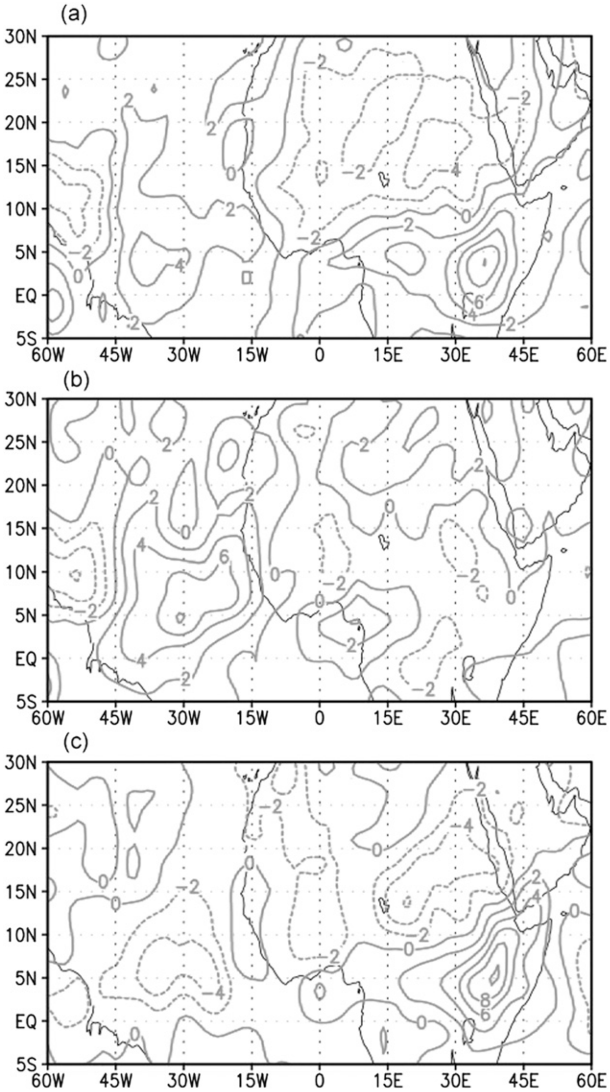

FIG. 10. Simulated deviations of JAS mean 500-hPa relative humidity (interval: 2%) in the (a) GOT, (b) TAO, and (c) TIP from the CTL.

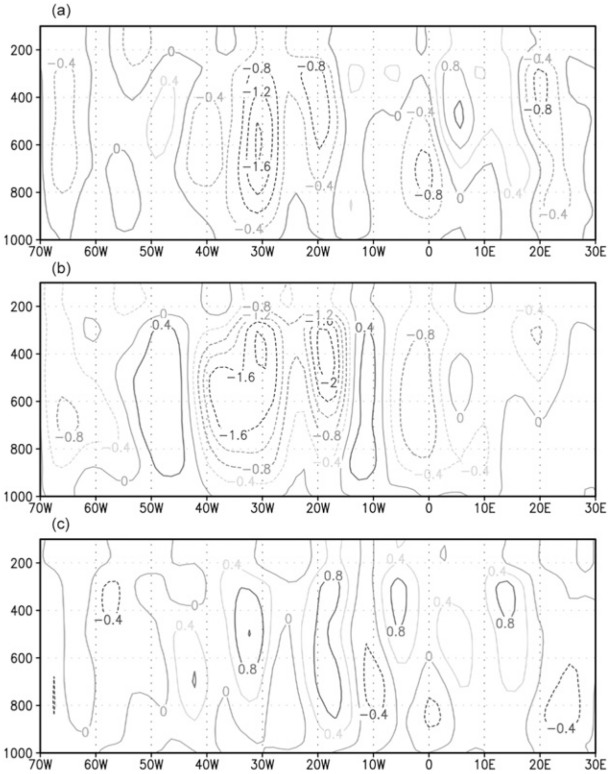

FIG. 11. Simulated differences of JAS mean vertical motion (interval: 0.4×10^{-2} pa s^{-1}) along 15°N in the (a) GOT, (b) TAO, and (c) TIP experiments from the CTL with zero contour suppressed.

et al. (2007) investigated how the SST warming occurred during the period 1870–2003 affects vertical wind shear, which is closely associated with TC activity (DeMaria et al. 2001; Frank and Ritchie 2001). They found that warming of the tropical North Atlantic reduces the vertical wind shear averaged over 10°–14°N, 20°–70°W while the warming of both the Indian and Pacific Oceans increases the vertical wind shear. Moreover, Vecchi and Soden (2007) examined the changes of the vertical wind shear in the experiments of the Intergovernmental Panel on Climate Change Fourth Assessment Report under the emission scenario A1B and found a prominent increase in the vertical shear over the tropical Atlantic. Since the increase in vertical wind shear in their study mainly occurs west of 40°W over the tropical North Atlantic, we suggest that may not be an important parameter for the enhanced TC formation east of 45°W.

Figure 13 shows the simulated differences of July–September vertical wind shear in the GOT, TAO, and TIP experiments from the CTL. The vertical wind shear between the upper troposphere (200 hPa) and lower troposphere (850 hPa) is calculated as $[(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2]^{1/2}$, where v_{200}, v_{850}, v_{200}, and v_{850} are the zonal and meridional wind components at 200 and 850 hPa, respectively. In the region (10°–20°N, 15°–45°W) with increased TC activity over the past 30 yr, the vertical shear change shows a similar pattern in the three experiments with an increase (decrease) of 1–2 m s^{-1} in the west (east) part. On average there is little change in the vertical wind shear. In general agreement with Latif et al. (2007), the vertical wind shear west of 35°W increases in the TIP experiment, but decreases in the TAO experiment. Note that Latif et al. (2007) only examined the change of vertical wind shear in their experiments.

In summary, the SST warming in the tropical Atlantic induces an anomalous low-level cyclone off the African coast, leading to increases in low-level vorticity and middle-level relative humidity, which are favorable for

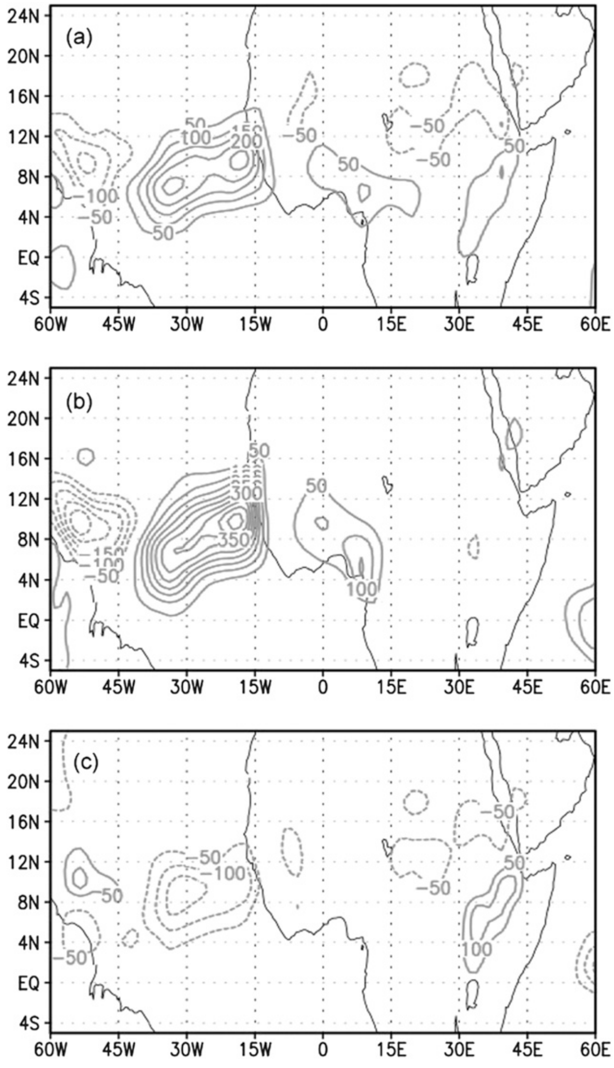

FIG. 12. Simulated differences of JAS mean precipitation (interval: 50 mm) in the (a) GOT, (b) TAO, and (c) TIP experiments from the CTL with zero contour suppressed.

TC formation (Gray 1975). However, the combined effect of SST warming in the tropical Indian Ocean and Pacific Ocean is opposite through the induced downward motion and reduced middle-level relative humidity. Therefore the results suggest that at least part of the increased TC formation in the region (10°–20°N, 15°–45°W) results mainly from the Atlantic warming, and its effect is partly offset by the SST warming in the tropical Indian Ocean and Pacific Ocean. The results agree with recent argument that the relative Atlantic SST warming or the SST difference between the tropical Atlantic and other oceans play an important role in controlling long-term TC activity in the Atlantic basin (Vecchi and Soden 2007; Latif et al. 2007; Knutson et al. 2008; Vecchi et al. 2008).

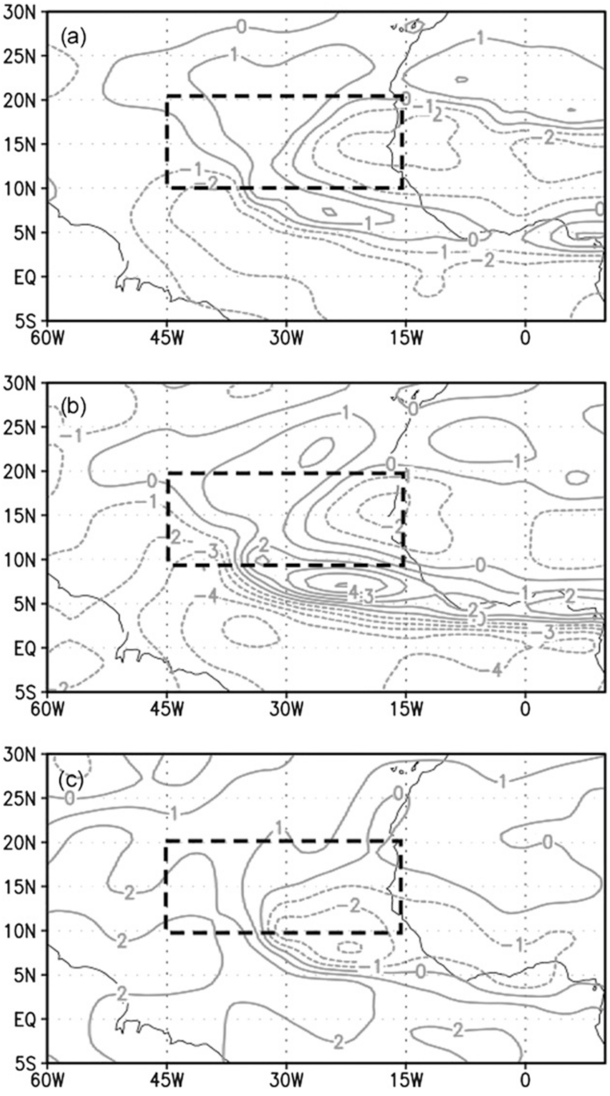

FIG. 13. Simulated differences of JAS vertical shear of horizontal winds (unit: m s^{-1}) in the (a) GOT, (b) TAO, and (c) TIP experiments from the CTL with zero contour suppressed.

6. Summary

While the total number of Atlantic TCs increased by 19.0% from 294 during the period 1948–77 to 350 during the period 1978–2007, the change in TC formation was not spatially homogeneous. With little change in the area west of 70°W and moderate subtropical increase in the middle Atlantic region (45°–70°W), TC formation was enhanced significantly in the Atlantic east of 45°W over the past 30 years. The total number increased by 93.0% from 43 TCs during the first period to 83 TCs during the second period. The significantly enhanced TC formation in this area is the key to understanding of the total changes in TC activity over the entire basin during the past 30 years.

Although the enhanced TC formation east of 45°W may be due to the poor TC observing network prior to the satellite era, it is consistent with the atmospheric response to the SST warming simulated with ECHAM4.8. Numerical experiments forced with the observed SSTs suggest that at least part of the observed increase in TC formation over the tropical eastern Atlantic results mainly from the Atlantic warming, but its effect is partly canceled by the SST warming in the tropical Indian Ocean and Pacific Ocean. The SST warming in the tropical Atlantic induces a pair of anomalous low-level cyclones on each side of the equator. The one off the African coast increases the low-level vorticity, middle-level relative humidity, and upward motion in the area (10°–20°N, 15°–45°W) with little change in vertical wind shear, which on balance are more favorable for TC formation. On the other hand, the combined effect of SST warming in the tropical Indian Ocean and Pacific Ocean reduces upward motion and middle-level relative humidity in the region, which are conditions less favorable for TC formation. This study supports previous findings that the relative Atlantic SST warming or the SST difference between the tropical Atlantic and other oceans is a key to understanding long-term TC activity in the Atlantic basin (Vecchi and Soden 2007; Latif et al. 2007; Knutson et al. 2008; Vecchi et al. 2008).

Maue and Hart (2007) and Wu et al. (2008) showed that since the middle 1970s upward trends in the basinwide average lifetime and annual frequency contribute to the unprecedented increase in the annual accumulated PDI as reported by Emanuel (2005). If we take the enhanced TC formation in the area of 10°–20°N, 15°–45°W into account, we can conclude that the upward trends in the basinwide average lifetime and annual frequency are associated with the enhancement of TC formation. Although its effect was partly offset by the SST warming in the tropical Indian Ocean and Pacific, the relative Atlantic SST warming occurring over the past 30 years allowed for more TC formation and earlier formation, leading to increases in the basinwide average lifetime and annual frequency. In addition, as suggested by Wu and Wang (2008), more TCs were capable to form east of 45°W that had greater chance of reaching major hurricane strength (DeMaria et al. 2001; Goldenberg et al. 2001). As a result, the proportion of intense hurricanes increased as reported by Webster et al. (2005). The observed high correlation between the Atlantic SST and the Atlantic TC activity is primarily due to the enhanced TC formation east of 45°W, caused by the competing influences of the SST warming in the Atlantic, Indian, and Pacific Oceans over the past 30 years.

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