Sensitivity of Atlantic Tropical Storm Frequency to ENSO and Interdecadal Variability of SSTs in an Ensemble of AGCM Integrations

F. VITART

Program in Atmospheric and Oceanic Science, Princeton University, Princeton, New Jersey

J. L. ANDERSON

NOAA/Geophysical Fluid Dynamics Laboratory, Princeton University, Princeton, New Jersey

(Manuscript received 13 September 1999, in final form 3 April 2000)

ABSTRACT

A significant reduction (increase) of tropical storm activity over the Atlantic basin is observed during El Niño (La Niña) events. Furthermore, the number of Atlantic tropical storms displays an interdecadal variability with more storms in the 1950s and 1960s than in the 1970s and 1980s. Ensembles of simulations with an atmospheric general circulation model (AGCM) are used to explore the mechanisms responsible for this observed variability.

The interannual variability is investigated using a 10-member ensemble of AGCM simulations forced by climatological SSTs of the 1980s everywhere except over the tropical Pacific and Indian Oceans. Significantly fewer tropical storms are simulated with El Niño SSTs imposed over the tropical Pacific and Indian Oceans than with La Niña conditions. Increased simulated vertical wind shear over the Atlantic is the most likely explanation for the reduction of simulated tropical storms during El Niño years. SST forcing from different El Niño events has distinct impacts on Atlantic tropical storms in the simulation: simulated tropical storms are significantly less numerous with 1982 SSTs imposed over the tropical Pacific and Indian Oceans than with 1986 SSTs.

The interdecadal variability of tropical storm activity seems to coincide with an interdecadal variability of the North Atlantic SSTs with colder SSTs in the 1970s than in the 1950s. Ensembles of AGCM simulations produce significantly more tropical storms when forced by observed SSTs of the 1950s than when forced by SSTs of the 1970s. This supports the theory that the interdecadal variability of SSTs has a significant impact on the expected number of Atlantic tropical storms and suggests that Atlantic tropical storms may be more numerous in coming years if North Atlantic SSTs are getting warmer. A significant increase of vertical wind shear and a significant decrease in the convective available potential energy over the tropical Atlantic in the 1970s may explain the simulated interdecadal variability of Atlantic tropical storms.

1. Introduction

Manabe et al. (1970) noticed for the first time that low-resolution atmospheric general circulation models (AGCMs) are able to create tropical depressions reminiscent of observed tropical storms. Several studies (Bengtsson et al. 1982, 1995; Haarsma et al. 1993) have demonstrated that the simulated tropical storms have a climatology and physical characteristics close to those of observed tropical storms. Vitart et al. (1997, 1999) reported on simulated tropical storms with an intraseasonal and interannual variability consistent with observations over the western North Atlantic, eastern North Pacific, and western North Pacific. The frequency of simulated tropical storms is strongly correlated to the interannual variability of the simulated large-scale circulation as in observations (Vitart et al. 1999). Therefore over basins where the AGCM simulates a realistic large-scale circulation (like the western North Atlantic), it is able to simulate a realistic interannual variability of tropical storm frequency. In particular, the interannual variability of simulated tropical storms over the western North Atlantic is significantly correlated to ENSO (Vitart et al. 1999) as in observations. This suggests that an AGCM can be a valuable tool to study the variability of tropical storm frequency and to explain the mechanisms of such variability.

The frequency of Atlantic tropical storms is observed to have significant variability on a number of different timescales. This paper focuses on the interannual variability, which is primarily due to the impact of ENSO, and interdecadal variability. Since it is generally believed that interannual and interdecadal tropical storm variability are caused by distinct physical mechanisms, attempting to simulate both gives a better measure of the capabilities of the model to reproduce important

---

Corresponding author address: Dr. Frederic Vitart, ECMWF, Shinfield Park, Reading, RG2 9AX, United Kingdom.
E-mail: nec@ecmwf.int

aspects of the observed physical constraints on tropical storms.

Gray (1984) and Shapiro (1987) conclude that ENSO is responsible for a significant part of the strong interannual variability of Atlantic tropical storms. During El Niño events, Atlantic tropical storms are significantly less numerous. For example, there were only 4 Atlantic tropical storms observed in 1983, well below the observed 1980s average of nearly 10 storms per year. Gray (1984), Shapiro (1987), and Goldenberg and Shapiro (1996) attribute this reduction of tropical storm activity to stronger upper-tropospheric westerlies and lower-level easterlies during El Niño years. The hypothesized impact of El Niño on observed tropical storms can be summarized as follows. During an El Niño event, warm SST anomalies in the tropical eastern Pacific increase deep-cumulus convection and create locally enhanced divergence in the upper troposphere and enhanced convergence in the lower troposphere. Because the lower-tropospheric circulation over the tropical Atlantic is dominated by easterlies, the vertical wind shear is increased. In addition, Gray (1984) and Shapiro (1987) noticed that El Niño was associated with reduced cyclonic vorticity in the lower troposphere and anticyclonic vorticity in the upper troposphere above the Caribbean Basin. This also contributes to creating a more hostile environment for Atlantic tropical storm genesis and development.

There is little doubt about the impact of El Niño on observed Atlantic tropical storms. However, other mechanisms than suggested in Gray (1984), Goldenberg and Shapiro (1996), and Shapiro and Goldenberg (1998) may be possible. One major difficulty with observations is that Atlantic SSTs are varying too; therefore, it is difficult to isolate the impact of El Niño. With a sufficiently realistic AGCM, an ensemble of model simulations can be used to clarify the mechanism of the impact of El Niño by isolating the impact of Pacific SSTs on the simulated tropical storms from the impact of Atlantic SSTs. To do this, two ensembles of AGCM integrations have been performed forced with the *same SSTs* over the Atlantic basin, but with *different SSTs* over the equatorial Pacific and Indian Oceans. In this framework, it is possible to determine with confidence if El Niño has a significant impact on simulated tropical storms independent of the local Atlantic SSTs. In addition, one can compare the impacts of two different El Niño events on the tropical storm activity over the western North Atlantic.

In addition to interannual variability, observed Atlantic tropical storms seem to display an interdecadal variability with an average of 10.4 storms per year detected during the 1950s and only 8.2 storms per year during the 1970s (Neumann et al. 1993). The interdecadal variability is particularly strong for *intense* (or major) Atlantic hurricanes (sustained winds of at least 50 m s^{-1}); (Landsea and Gray 1992). Atlantic SSTs also display an interdecadal variability (Kushnir 1994) characterized by an apparent dipole between the Northern and Southern Hemispheres (Mehta 1998). During the 1950s, the SSTs over the North (South) Atlantic were warmer (colder) than in the 1970s. Several studies (Saunders and Harris 1997; Goldenberg and Landsea 1997; Landsea et al. 1999) have suggested a link between the interdecadal variability of SSTs over the Atlantic basin and the interdecadal variability of Atlantic tropical storm frequency. An indirect link (Gray 1990) has been hypothesized where colder North Atlantic SSTs as in the 1970s lead to reduced precipitation over the Sahel region and dryer conditions over the Sahel are implicated in reducing tropical storm frequency over the Atlantic basin (Goldenberg and Shapiro 1996). Since the length of reliable records for Atlantic tropical storms are very limited, an ensemble of AGCM simulations may be able to clarify the nature and strength of any link between SST variability and tropical storm frequency.

A description of the ensemble experiments is presented in section 2. Section 3 presents a comparison of the impacts of an El Niño and a La Niña event on the simulated tropical storms over the western North Atlantic, and section 4 evaluates the impact of interdecadal changes of SSTs on the simulated Atlantic tropical storms.

2. Description of the experiments

The AGCM used in the ensemble (Stern and Miyakoda 1995) is a T42 atmospheric model with 18 vertical levels forced by observed SSTs. Atmospheric model parameterizations include relaxed Arakawa–Schubert convection (Moorthi and Suarez 1992); shallow convection (based on Tiedtke 1988); Matthews' surface albedo and snow albedo (Gordon 1992); three-level soil moisture; orographic gravity wave drag (Stern and Pierrehumbert 1988); cloud prediction and marine stratocumulus linear regression scheme (Gordon 1992); Gibbs' filtered orography (Navarra et al. 1994); radiative transfer (12-h averaged) that varies seasonally; stability-dependent vertical eddy fluxes of heat, momentum, and moisture throughout the surface layer, the planetary boundary layer and the free atmosphere (Sirutis and Miyakoda 1990); and $k\nabla^4$ horizontal diffusion. The surface temperatures over land and sea ice are determined by solving surface heat balance equations (Gordon and Stern 1982).

The basic design of the experiments is the same in section 3 (impact of El Niño) and section 4 (interdecadal variability); only the SST forcing differs. All the SSTs used in the present study are based on observed monthly means from the National Centers for Environmental Prediction (Reynolds and Marsico 1993) interpolated to individual days. The tropical storm season begins in June and ends in November. Since it takes at least a few weeks for the AGCM to adjust to its boundary conditions, the AGCM simulations begin several months be-

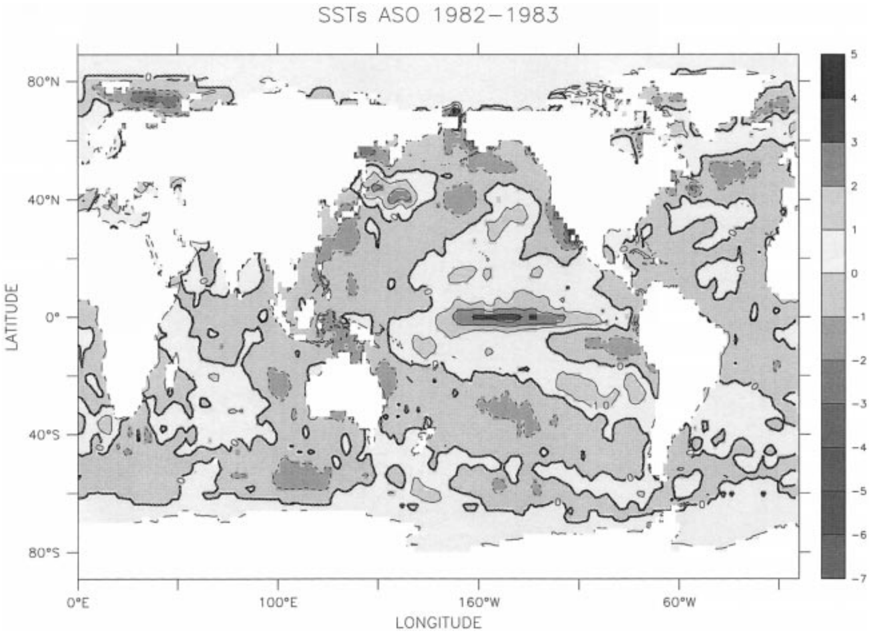

FIG. 1. Difference in Aug–Oct average SSTs (in °C) between 1982 and 1983.

fore the start of the tropical storm season, on 1 April and end on 30 November.

Bengtsson et al. (1995) and Tsutsui and Kasahara (1996) have demonstrated that the tropical storm frequency simulated by an AGCM can vary significantly depending on the details of the initial conditions. In other words, the AGCM produces noise that is of same order of magnitude as the tropical storm variability due to changes in SSTs. To filter this noise, an ensemble of 10 AGCM simulations is created for each experiment in this study with 10 different atmospheric initial conditions. The initial conditions have been extracted from an experiment where the AGCM was integrated for 17 yr (from 1 January 1979 to 31 December 1996) forced by observed SSTs. The initial conditions were taken from 1 April 1986 to 1 April 1995 sampled every year; each of these ‘‘analyses’’ was then used as an initial condition as if it were the analysis for 1 April for each set of experiments.

An objective procedure tracks simulated tropical storms by locating low pressure systems with a warm temperature anomaly between 500 and 200 mb (warm core) during at least two consecutive days (Vitart et al. 1997). The AGCM has a tendency to simulate Atlantic tropical storms farther west than observed (Vitart et al. 1997), which makes their geographical distribution more consistent with the distribution of observed intense tropical storms (hurricanes).

3. Impact of El Niño and La Niña on Atlantic tropical storms

In this section the statistics of the tropical storms over the western North Atlantic simulated during an El Niño event, 1982, are compared to the statistics during a La Niña event, 1988. These years were selected since the 1982–83 El Niño was the strongest of the 1980s, and the eastern equatorial Pacific SST anomalies were stronger in 1982 than in 1983 from August to October (peak of the Atlantic tropical storm season) according to Fig. 1. The strongest La Niña of the 1980s occurred in 1988.

Vitart et al. (1997) have shown that an AGCM forced by observed SSTs simulates significantly fewer Atlantic tropical storms when forced by globally specified SSTs of 1982 then when forced by globally specified SSTs of 1988. To investigate the mechanism of the impact of El Niño on simulated tropical storms, an experiment similar to a Tropical Ocean and Global Atmosphere experiment (Lau 1985) has been realized: an AGCM is forced by *climatological* SSTs everywhere except over the tropical Indian and Pacific Oceans between 20°S and 20°N where *observed* SSTs are used. Over the transition zone between observed and climatological SSTs, a linear interpolation is used to avoid strong discontinuities. The climatological SSTs are the observed monthly SSTs interpolated to individual days and averaged from 1980 to 1989.

In the first experiment (EXP82) the tropical Indian and Pacific Oceans SSTs are those observed in 1982 while in the second experiment (EXP88) these SSTs are those observed in 1988. The tropical Indian and Pacific Oceans temperature anomalies averaged over the Atlantic tropical storm season (June–October) are presented in Fig. 2. The EXP82 SSTs have a positive temperature anomaly over most of the east Pacific (El Niño year), with a maximum warming along the equatorial eastern Pacific of about 1.8°C while the western part of

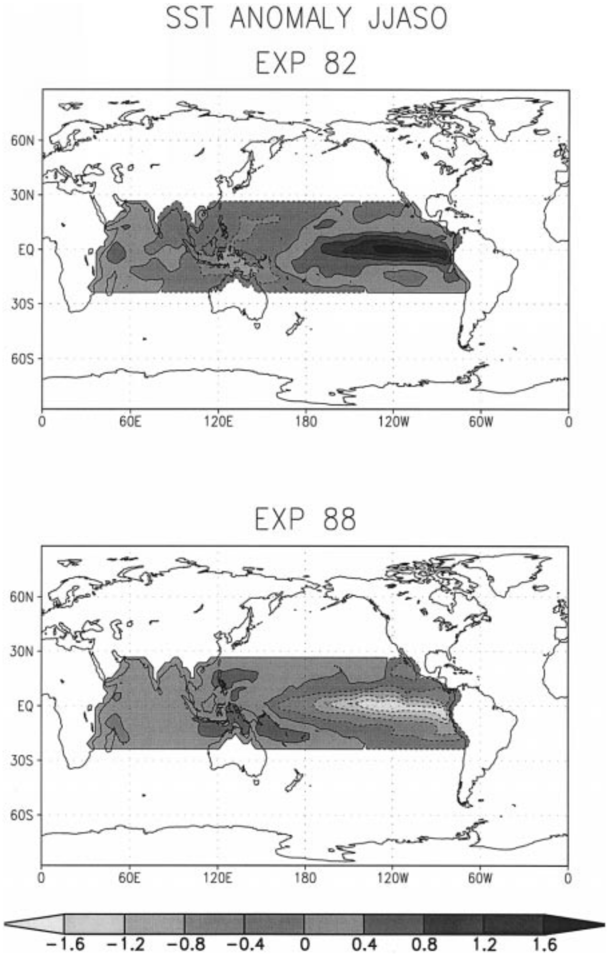

FIG. 2. Difference between Jun–Oct average SSTs (in °C) for (a) EXP82 and (b) EXP88 and climatological SSTs for the 1980s. Tropical Pacific and Indian Oceans SSTs correspond to 1982 SSTs for EXP82 and 1988 SSTs for EXP88.

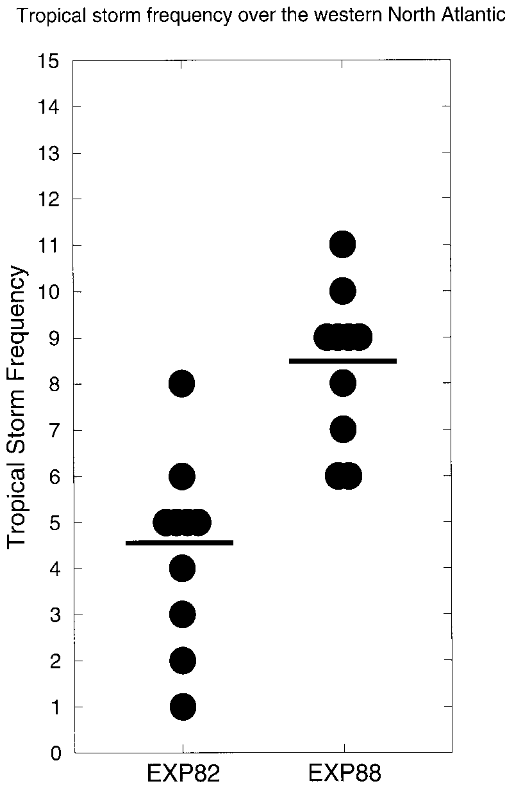

FIG. 3. Ensemble distribution of tropical storm frequency over the western North Atlantic for EXP82 and EXP88. Each circle represents one member of the ensemble. The horizontal line represents the mean of the ensemble.

the Pacific basin is colder than normal. EXP88 has negative temperature anomalies over the eastern part of the equatorial Pacific (La Niña year), with a maximum cooling of about 1.8°C along the equator. Outside of the shaded regions in Fig. 2, EXP82 and EXP88 have identical SSTs.

a. *Tropical storm statistics*

As described in the previous section, the AGCM was integrated for 8 months starting on 1 April with 10 different initial conditions forced with the prescribed SSTs for EXP82 and EXP88. The first month of integration has been discarded to allow the AGCM to adjust to the SSTs. The number of simulated tropical storms has been counted over the western North Atlantic for each ensemble member using the procedure for detecting simulated tropical storms.

In EXP82 (El Niño), the mean number of simulated Atlantic tropical storms is 4.4 while in EXP88 (La Niña), the mean number of Atlantic tropical storms is 8.4. A Wilcoxon–Mann–Whitney test (W test; DeGroot 1989) applied to the ensemble distributions of tropical storm frequency with EXP82 and EXP88 (Fig. 3) indicates that the distributions are statistically different with a significance of 99.3%.

Simulated tropical storms tend to be less *intense* with EXP82 than with EXP88 (Fig. 4) but the difference is not significant. The ensemble distributions of tropical storm *longitude* (Fig. 4) are not significantly different between EXP82 and EXP88. Simulated tropical storms tend to be located at higher latitude in EXP82 (El Niño condition) than in EXP88 (la Niña condition; Fig. 4), which is consistent with observations by Gray (1984) and Goldenberg and Shapiro (1996). The difference between the two ensemble distributions of tropical storm *latitude* is however not significant. Finally, the mean *duration* of the storms (number of days a tropical storm lasts; not shown) does not vary significantly from one experiment to the other.

The significant difference between the tropical storm frequency distributions for EXP82 and EXP88 demonstrates that the Pacific and Indian Oceans SSTs have a significant impact on the simulated Atlantic tropical storms. This impact is independent of Atlantic SSTs as suggested in Gray (1984), Shapiro (1987), and Golden-

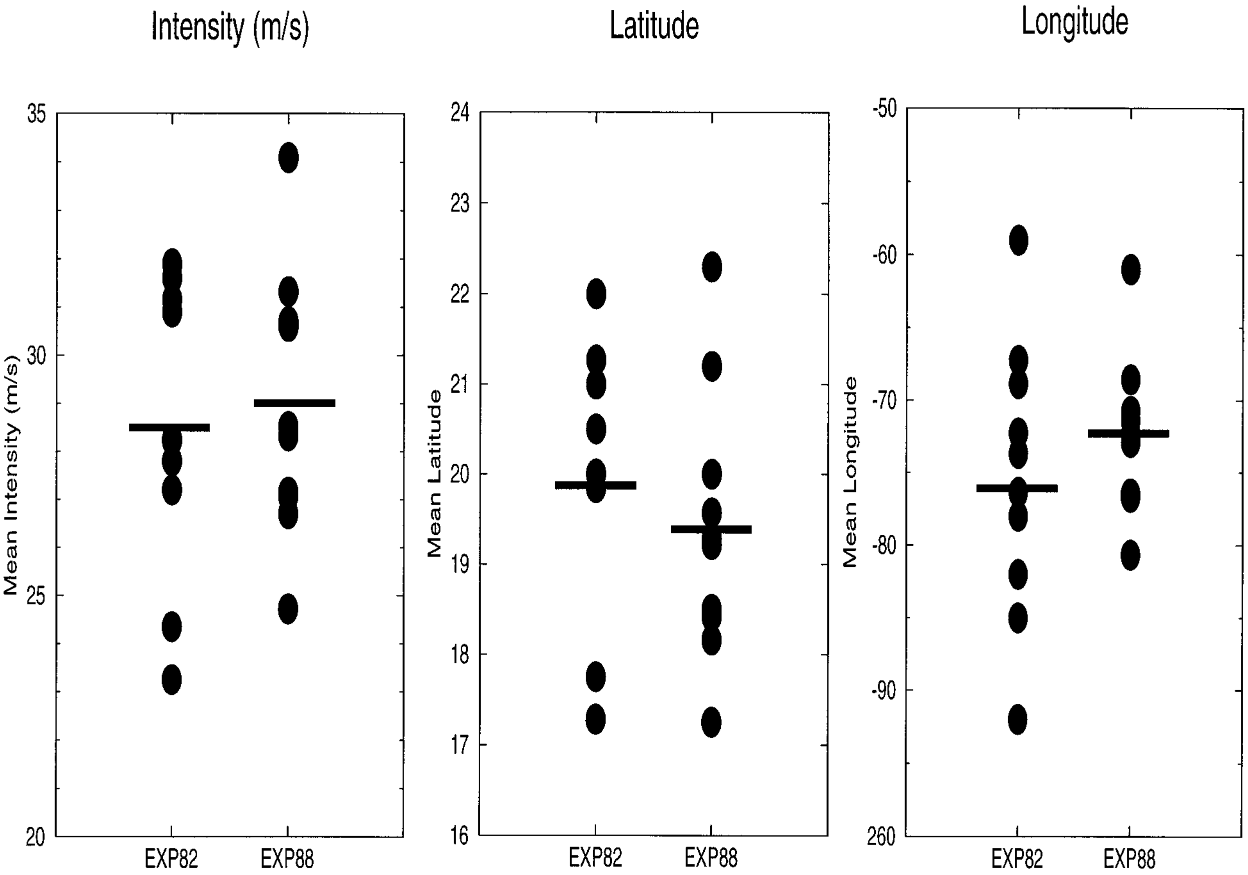

FIG. 4. Ensemble distribution of tropical storm intensity, latitude, and longitude over the western North Atlantic for EXP82 and EXP88. Each circle represents one member of the ensemble. The horizontal line represents the mean of the ensemble.

berg and Shapiro (1996). The rest of this section explores how the SSTs have a remote impact on the simulated tropical storms over the North Atlantic. Gray (1979) isolated six large-scale parameters related to increased frequency of tropical storm genesis. Three of them are dynamic parameters: above-average low-level vorticity; weak vertical shear of the horizontal wind; and significant value of the planetary vorticity (observed tropical storms are always located at least a few degrees of latitude poleward of the equator). The three others are thermodynamic parameters: midlevel moisture; conditional instability through a deep layer; warm and deep oceanic mixed layer. It is likely that the remote impact of El Niño on Atlantic tropical storms occurs through one of these dynamic or thermodynamic parameters.

b. Large-scale circulation

The three dynamic large-scale parameters described by Gray (1979) are examined first. The planetary vorticity is identical in EXP82 and EXP88, so this parameter has been discarded. The low-level vorticity is believed to have an impact on observed tropical storm cyclogenesis through Ekman pumping. The vertical wind shear also plays a fundamental role in tropical storm genesis (Shapiro 1987; Goldenberg and Shapiro 1996). With strong vertical wind shear, cloud cluster ventilation is strong and enthalpy and moisture cannot be accumulated above the center of the developing storm, preventing pressure falls. An additional parameter, the upper-tropospheric vorticity may also play an important role in tropical storm genesis (McBride 1981a,b; McBride and Zehr 1981). Vitart et al. (1999) have shown that the interannual variability of vertical wind shear, 850-mb vorticity, and 200-mb vorticity combined can explain more than 80% of the interannual variability of simulated tropical storm frequency from 1980 to 1988 over all the basins where the ensemble displays potential predictability of tropical storm frequency. Here, the lower- and upper-level vorticity are defined at 850 and 200 mb, respectively, and the vertical wind shear of the horizontal wind is defined as the magnitude of the difference of wind at 850 and 200 mb.

The ensemble distributions of vertical wind shear and 200- and 850-mb vorticity simulated with EXP82 and EXP88 have been averaged over the period from June to October. The vertical wind shear is significantly stronger in EXP82 than in EXP88 over the western part of

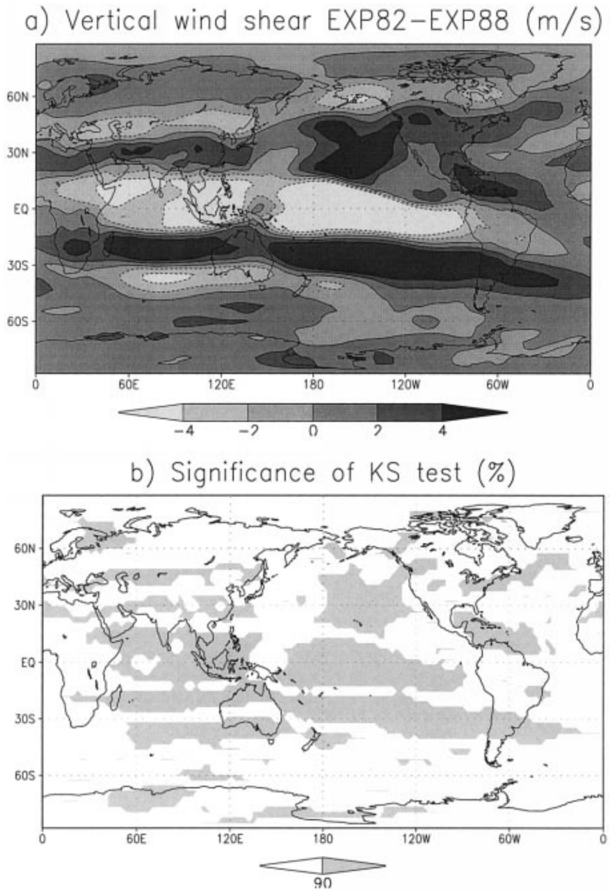

FIG. 5. (a) Difference of vertical wind shear simulated by EXP82 and EXP88. The vertical wind shear has been averaged over the 10 members of the ensemble and from Jun to Oct. (b) A KS test has been applied to detect a difference between the two 10-member ensembles of vertical wind shear. Shaded areas represent regions where the significance exceeds 90%.

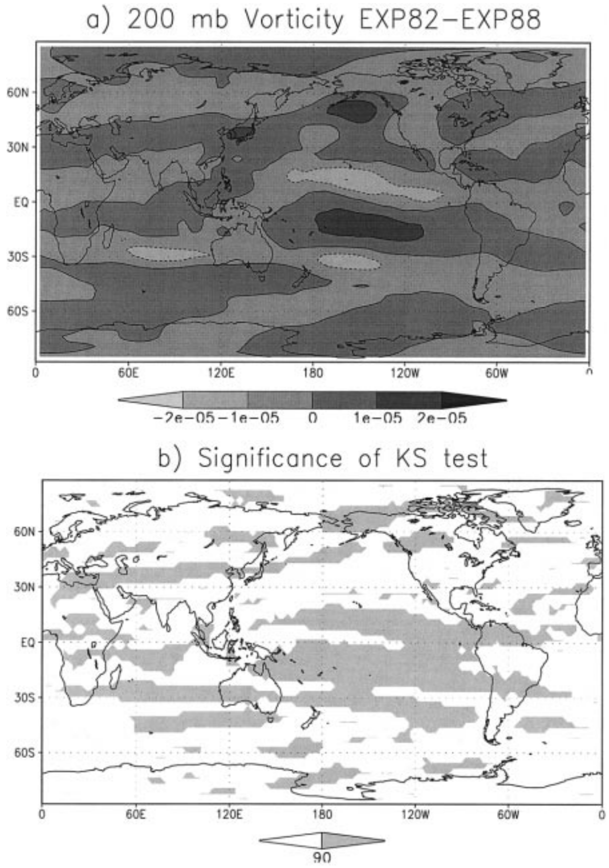

FIG. 6. As in Fig. 5 but for the 200-mb vorticity (s^{-1}).

the Atlantic basin with an increase of wind shear of approximately of 4 m s^{-1} (Fig. 5). This increased vertical wind shear is mostly due to an increase in upper-tropospheric westerlies in EXP82 over most of the Atlantic basin.

The 850-mb vorticity is more anticyclonic in EXP82 than in EXP88 over most of the tropical North Atlantic, particularly over the Gulf of Mexico and the eastern part of the basin (not shown). However the difference is not significant according to the Kolmogorov–Smirnov test (KS test; Press 1986; Knuth 1981), although observations (Shapiro 1987) indicate a significant decrease (increase) of low-level cyclonic vorticity over the Caribbean, Gulf of Mexico, and tropical Atlantic west of Africa during El Niño (La Niña) years. The KS test indicates a significant increase of cyclonic vorticity at 200 mb between EXP82 and EXP88 over a portion of the central North Atlantic (Fig. 6), in agreement with observations (Goldenberg and Shapiro 1996).

Averaging the dynamic fields from August to October (the peak of the tropical storm season) gives similar differences (not shown). This is consistent with the uniform difference in tropical storm frequency between EXP82 and EXP88 during the entire tropical storm season.

c. Thermodynamic parameters

The three thermodynamic parameters cited by Gray (1979) are discussed next. Atlantic SSTs are identical in EXP82 and EXP88, so they cannot be responsible for differences in the tropical storm frequency. The vertical profiles of temperature and mixing ratio give some information on how midlevel moisture and convective instability are different between the experiments. To evaluate the instability through a deep layer, the convective available potential energy (CAPE; e.g., Williams and Renno 1993) has been computed. For the CAPE calculation, pseudoadiabatic ascent was assumed for an air parcel lifted from the lowest level. Water condensate loading, ice physics, and the convective inhibition energy contribution were not included.

Temperature and mixing ratio have been averaged over the region where most Atlantic tropical storms develop (10°–25°N, 90°–30°W) and over the period from

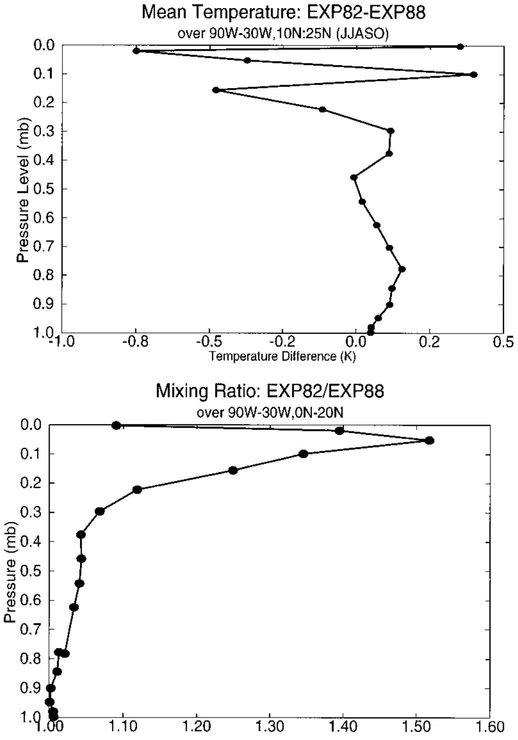

FIG. 7. Vertical profiles of temperature differences and the ratio of mixing ratio between EXP82 and EXP88. Temperature and mixing ratio have been averaged over the 10 members of the ensemble, over the tropical storm main development region (10°–25°N, 90°–30°W) 25N) and over the period from Jun to Oct.

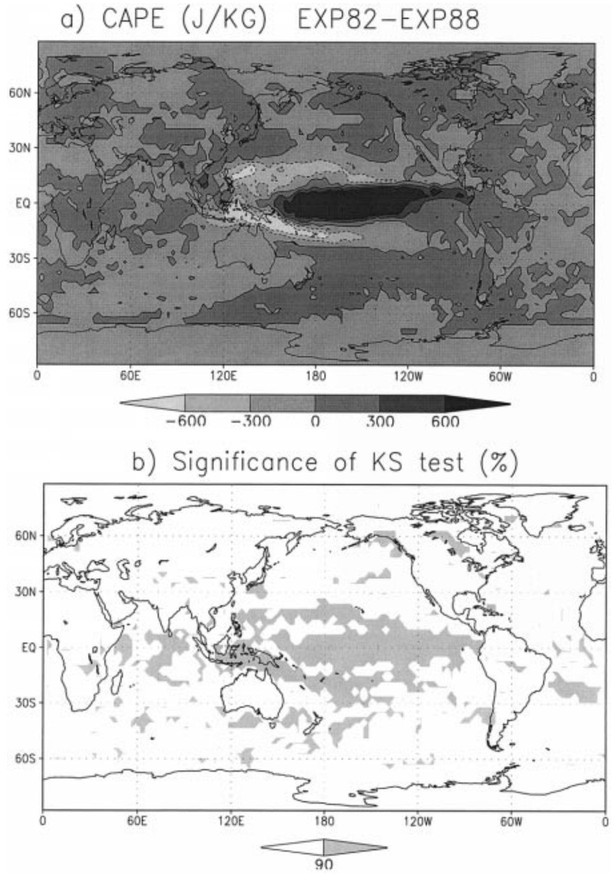

FIG. 8. As in Fig. 5 but for CAPE instead of vertical wind shear.

June to October. The vertical profiles averaged over the 10 members of the ensembles are presented in Fig. 7. The differences in temperature and mixing ratio between EXP82 and EXP88 increase with height. This may be related to the mean circulation that intensifies over the Atlantic in the upper troposphere during El Niño events. The main difference between EXP82 and EXP88 appears to be located mostly in the stratosphere with a difference of temperature of 0.8°C and 50% more humidity in EXP82 than in EXP88 at 100 mb (Fig. 7). The impact of the strong and significant (not shown) differences in the stratospheric temperature and mixing ratio profiles between EXP82 and EXP88 probably have little impact on simulated tropical storms that do not extend higher than 200 mb. In the troposphere, the temperature difference between EXP82 and EXP88 is in general not significant (not shown) except between 700 and 850 mb where a slight warming of about 0.1°C appears in EXP82. It seems unlikely that the difference in temperature profiles explains the difference in tropical storm frequency between EXP82 and EXP88. The troposphere seems to be slightly more humid in EXP82 than in EXP88 by about 5% (Fig. 7) between 850 and 300 mb, and by about 15% between 300 and 200 mb. The difference in mixing ratio is significant over most of the vertical levels (not shown).

CAPE has been calculated for all members of the ensemble. The difference in CAPE between EXP82 and EXP88 is displayed in Fig. 8a and the significance of the KS test applied to detect a difference between the ensemble distributions is displayed in Fig. 8b. Over the tropical North Atlantic, the ensemble distributions of CAPE with EXP82 and and EXP88 are not significantly different except over a small area, which is probably just noise. Therefore the thermodynamic conditions over the tropical North Atlantic are not different enough to explain the significant difference of tropical storm activity between EXP82 and EXP88. This suggests that the link between ENSO and the simulated tropical storm frequency is almost strictly from circulation changes that do not affect significantly the CAPE over the tropical Atlantic.

In summary, changes of SSTs over the tropical Pacific and Indian Oceans affect significantly the activity of simulated tropical storms over the Atlantic through changes in the simulated large-scale circulation, primarily in the upper troposphere. The increase of upper-tropospheric wind over the tropical Atlantic during an El Niño year increases the vertical wind shear by about 4 m s^{-1} in EXP82 (the average vertical wind shear over the tropical North Atlantic is 14 m s^{-1} in EXP82), which

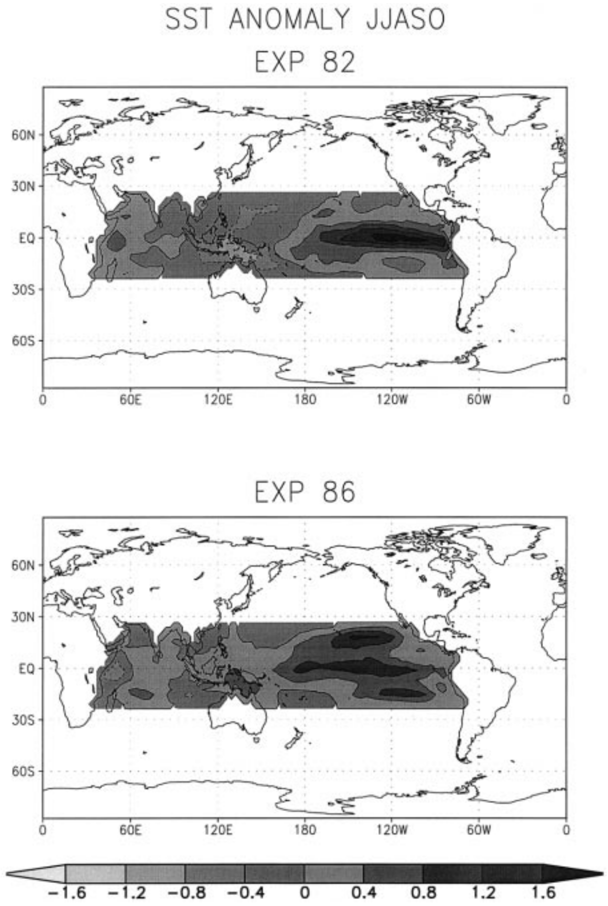

FIG. 9. As in Fig. 2 but for EXP82 and EXP86.

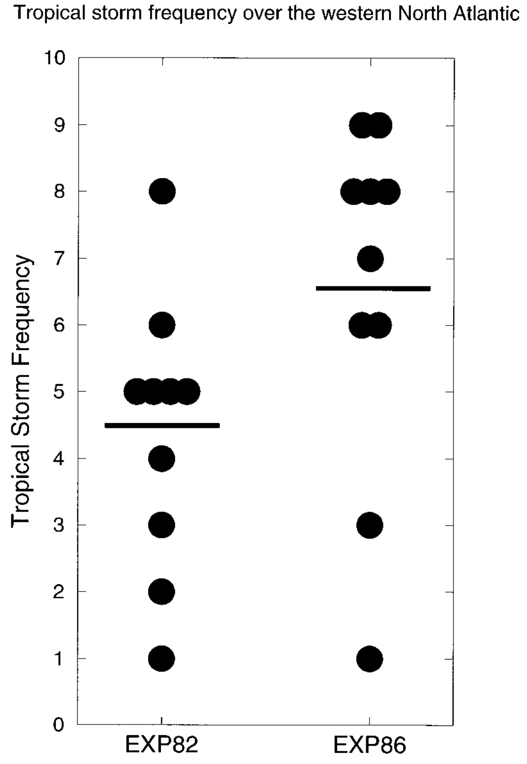

FIG. 10. Ensemble distribution of tropical storm frequency over the western North Atlantic for EXP82 and EXP86. Each circle represents one member of the ensemble. The horizontal line represents the mean of the ensemble.

is probably enough to inhibit the formation of the simulated tropical storms.

d. Comparison between the impacts of two El Niño events on Atlantic tropical storms

Trenberth (1991) states that the impact of El Niño events may have two or more different ''flavors.'' For instance, California can experience very wet conditions (such as 1940–41, 1982–83, and 1991–92) or drought (1986–87 and 1987–88), depending on how far east the ENSO-related rainfall extends in the tropical Pacific. This section evaluates if two different El Niño events impact differently the frequency of Atlantic tropical storms. For that purpose, a third ensemble of AGCM integrations (hereafter referred to as EXP86) has been realized using the same methodology as for EXP82 and EXP88 with SSTs over the tropical Pacific and Indian Oceans from 1986 (Fig. 9). The year 1986 is usually not considered as an El Niño year, however, during the Atlantic tropical storm season, a warm anomaly was developing over the eastern Pacific. The warm anomaly was less intense in 1986 than in 1982 but its shape extended into higher latitudes between 20°N and 20°S (Fig. 9). The present section explores whether the differences in shape and intensity between the temperature anomaly over the eastern Pacific in 1982 and 1986 have an impact on the simulated Atlantic tropical storms.

A 10-member ensemble has been created for EXP86 with the same initial conditions and period of integration as for EXP82 and EXP88. The ensemble distribution of tropical storm *frequency* (Fig. 10) is significantly higher with EXP86 than for EXP82 (96% significance according to the W test.). The average number of tropical storms simulated with EXP86 is 6.5 compared to 4.4 with EXP82. The distribution of tropical storm frequency with EXP86 is closer to the distribution for EXP82 than for EXP88. In other words, the 1986 SSTs over the tropical Pacific reduce the number of Atlantic tropical storms, but not as much as the 1982 SSTs. There is no significant difference between the ensemble distributions of tropical storm *intensity, longitude,* or *latitude* (not shown), since the KS test indicates a significance of only 20%, 30%, and 31%, respectively.

The difference in wind shear between EXP86 and EXP88 over the western North Atlantic (not shown) is consistent with the difference of vertical wind shear between EXP82 and EXP88 (Fig. 5). The impact of the 1986 tropical Pacific and Indian Oceans SSTs seems to be an increase of the vertical wind shear over most of the tropical North Atlantic. However the amplitude of

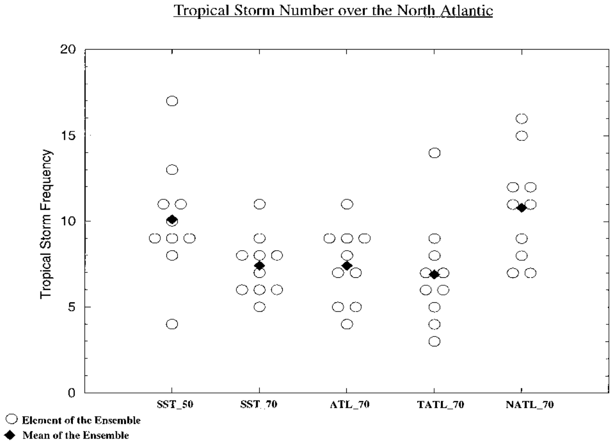

FIG. 11. Number of tropical storms simulated over the western North Atlantic by the 10-member ensembles for experiments SST_50, SST_70, ATL_70, TATL_70, and NATL_70. Each circle represents one member of the ensemble while the diamonds represent the mean of the ensemble.

the vertical wind shear over the tropical North Atlantic basin is lower with EXP86 than with EXP82 particularly over the Gulf of Mexico. This may explain why the number of simulated tropical storms is higher with EXP86 than with EXP82.

4. Interdecadal variability of Atlantic tropical storm frequency

Observed tropical storms, particularly intense hurricanes (Landsea and Gray 1992) were more numerous in the 1950s than in the 1970s and 1980s. To evaluate if an AGCM is able to simulate such interdecadal variability, a set of 10-member ensembles of the AGCM forced by observed climatological SSTs (Reynolds and Marsico 1993) of the 1950s and the 1970s has been realized. The monthly SSTs have been interpolated to individual days and averaged from 1950 to 1959 (1970–79). They are referred to as the SSTs of the 1950s (1970s). Simulations forced by the SSTs from the 1950s (1970s) are referred to as SST_50 (SST_70) hereafter. The procedure for tracking simulated tropical storms has been applied to the 10-member ensembles of SST_50 and SST_70. The number of tropical storms simulated over the North Atlantic has been counted for each member of the ensembles.

Figure 11 displays the number of tropical storms for each member of the SST_50 ensemble; it varies from 4 to 17 with a mean of 10.1 simulated Atlantic tropical storms per season (close to the 10.4 tropical storms per season observed in the 1950s). The scatter in the number of tropical storms obtained with SST50 is important (Fig. 11) and emphasizes the necessity of using an ensemble of AGCM simulations to evaluate the impact of SSTs on simulated tropical storms.

The number of simulated tropical storms obtained with SST forcing from the 1970s (SST_70) ranges from 4 to 11 (Fig. 11), with a mean of 7.4 tropical storms per season, close to the observed tropical storm frequency of 8.2 per season. The ensemble distribution of tropical storm frequency with SST_70 is significantly different with 97.6% significance according to the W-test from the tropical storm ensemble distribution in SST_50. In other words, the AGCM simulates significantly fewer tropical storms when forced by SSTs of the 1970s than when forced by SSTs of the 1950s. This is consistent with the observed interdecadal variability of tropical storms over the North Atlantic and suggests that the interdecadal variability of SSTs may be partly responsible for this observed change in Atlantic tropical storm activity. No significant difference in Atlantic tropical storm intensity and location has been detected between SST_50 and SST_70, in contradiction with observations (Landsea and Gray 1992).

The *interannual* variability of Atlantic tropical storms is strongly constrained by the tropical Pacific SSTs both in simulations and in observations. During El Niño years, the warm SST anomaly over the eastern tropical Pacific seems to be responsible for increased vertical wind shear over the western part of the tropical Atlantic basin, which leads to a significant reduction in the number of both simulated and observed tropical storms (section 3). It is possible that the reduction of simulated North Atlantic tropical storms in SST_70 is due to SST anomalies over the Pacific, even though SST differences between the 1950s and 1970s are relatively small there (Fig. 12a). To check this hypothesis, an experiment (ATL_70) similar to SST_50 but with climatological SSTs of the 1970s over the Atlantic basin and SSTs of the 1950s everywhere else (Fig. 12b) has been performed. The number of Atlantic tropical storms obtained in ATL_70 varies from 4 to 11 with an average number of 7.4 per season (Fig. 11). The ensemble distribution of simulated tropical storms in ATL_70 is not significantly different from that obtained with SST_70 (W test significance less than 90%) but is significantly different from the ensemble distribution obtained with SST_50 (W-test significance of 96%). This indicates that the AGCM simulates fewer tropical storms when forced by observed Atlantic SSTs of the 1970s than when forced by observed SSTs of the 1950s implying that Atlantic SSTs are primarily responsible for the reduction of simulated tropical storms over the Atlantic basin. A 5-member AGCM ensemble with Pacific SSTs of the 1970s and SSTs of the 1950s everywhere else was also created. The ensemble distribution of Atlantic tropical storm frequency did not display significant differences from SST_50 according to the W test. This suggests that Atlantic SSTs are primarily responsible for the reduction of simulated tropical storm activity over the Atlantic basin.

It is possible that cooler SSTs over the tropical North Atlantic where tropical storms develop are responsible for the interdecadal variability of simulated tropical storm frequency. To test this hypothesis, an ensemble (TATL_70) with the same set of 10 initial conditions as

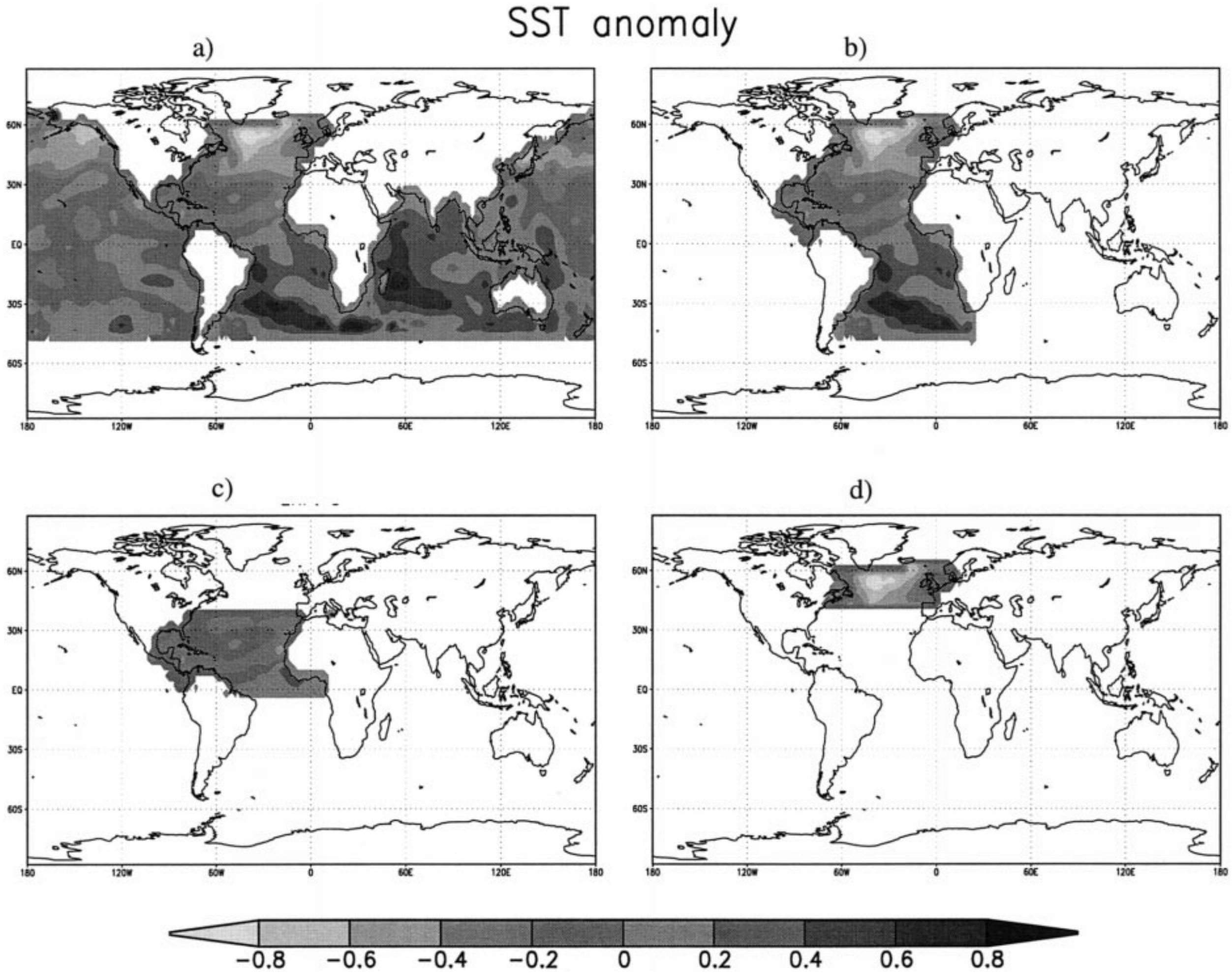

FIG. 12. (a) Differences between SSTs for the 1970s and 1950s; this is also the difference in SST forcing between AGCM simulation experiments SST_70 and SST_50. Differences in SST forcing between experiments (b) ATL_70, (c) TATL_70, and (d) NATL_70 and the SST forcing for experiment SST_50. The shaded regions indicate those areas where SSTs (in ° Celsius) from the 1970s are applied.

in SST_50 but forced by the SSTs of the 1950s everywhere except over the tropical North Atlantic (Fig. 12c) has been integrated. The W test does not detect a significant difference between the ensemble distribution obtained with TATL_70 (Fig. 11) and the distributions obtained with SST_70 and ATL_70. On the other hand the ensemble distribution of tropical storm frequency obtained with TATL_70 is significantly different (98% significance with the W test) from the ensemble distribution for SST_50. This suggests that the colder tropical North Atlantic SSTs of the 1970s create a significant reduction in simulated tropical storm frequency that is roughly the same as the reduction obtained when SSTs of the 1970s are used everywhere.

The strongest interdecadal SST differences over the Atlantic basin are located between 50° and 60°N. This SST variability might have an indirect impact on the large-scale circulation over the tropical North Atlantic and on the Atlantic tropical storm activity analogous to the impact of warm SST anomalies over the tropical eastern Pacific during an El Niño year. The possibility of a remote impact from extratropical SST anomalies located near Greenland has been tested by an ensemble of simulations (NATL_70) forced with SSTs of the 1950s everywhere except over the extratropical North Atlantic where SSTs from the 1970s are used (Fig. 12d). The ensemble distribution of simulated tropical storm frequency obtained in NATL_70 is not statistically different from SST_50 but is statistically different from the ensemble distribution of simulated tropical storm frequency obtained in SST_70 and TATL_70 according to the W test. This indicates that the extratropical SST anomaly has no significant impact on simulated tropical storm activity through the large-scale circulation. However, it is possible that the cooler SSTs over the tropical Atlantic in the 1970s are a consequence of the stronger extratropical cooling between 50° and 60°N over the North Atlantic (Delworth et al. 1997); the experiments described here are unable to explore such mechanisms since SSTs are fixed.

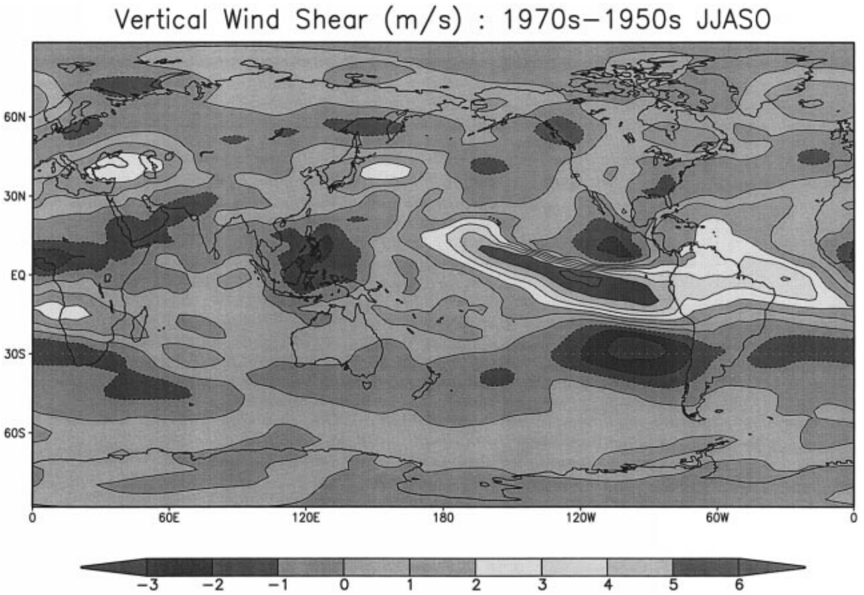

FIG. 13. Difference of Jun to Oct mean vertical wind shear simulated by experiments forced by SSTs from the 1970s (SST_70) and 1950s (SST_50). The vertical wind shear is defined as the magnitude of the difference of the wind at 200 mb and the wind at 850 mb.

SSTs can impact the simulated tropical storm frequency in at least two ways: a change in SSTs may lead to a change in the thermodynamic structure of the atmosphere or to a change in the large-scale circulation. The tropical Atlantic SSTs in the 1970s are colder than in the 1950s leading to a tropical Atlantic troposphere that is more stable in the 1970s than in the 1950s. A calculation of CAPE indicates a significant difference of approximately 200 J Kg^{-1} (about 15%) between the 1970s and the 1950s over the region where most Atlantic tropical storms develop. This significant difference in CAPE may be an explanation for the reduced simulated tropical storm frequency in the 1970s.

No significant change in the 850-mb vorticity has been detected between SST_50 and SST_70, however, a significant increase in simulated vertical wind shear appears in SST_70 (Fig. 13). This increase of vertical wind shear would be expected to lead to fewer tropical storms. The AGCM simulates both thermodynamic (CAPE) and also dynamic (vertical wind shear) conditions that may explain the reduction of Atlantic simulated tropical storms in the 1970s. Both the decrease of CAPE and the increase of the vertical wind shear are found with the same amplitude in ATL_70 and TATL_70, but disappear in NATL_70. This confirms that the SSTs of the 1970s over the tropical Atlantic are responsible for the decrease of CAPE and increase of vertical wind shear.

The possible impact of the North–South Atlantic dipole (Fig. 12b) on the frequency of the simulated Atlantic tropical storms has not been directly addressed in present study. It is possible that the combination of a strong negative extratropical SST anomaly in the North Atlantic with a positive anomaly in the South Atlantic could produce some relevant circulation change. However, the small difference in tropical storm frequency between TATL_70 and ATL_70 (Fig. 11) suggests that the effect of the dipole on the simulated tropical storms would probably be modest.

5. Conclusions

When forced by SSTs of 1982 instead of 1988 over the tropical Pacific and Indian Oceans, the ensemble of AGCM integrations simulates significantly fewer tropical storms over the North Atlantic. When forced by climatological SSTs of the the 1970s instead of the 1950s, the model simulates significantly fewer Atlantic tropical storms. The results of these simulations are in agreement with observations: observed tropical storms are leas numerous during an El Niño year than during a La Niña year and observed tropical storms were more numerous in the 1950s than in the 1970s. Therefore, the present study demonstrates that an ensemble of AGCM integrations is successful in simulating two examples of Atlantic tropical storm variability: the impact of El Niño and the impact of the interdecadal variability of Atlantic SSTs.

In both sets of experiments (ENSO variability and interdecadal variability), the ensemble experiments differ only in SSTs. Therefore the changes in SSTs are responsible for the variability of the simulated tropical storms over the western North Atlantic. In the case of the first set of experiments (El Niño experiment), it is the SSTs over the tropical Pacific and Indian Oceans that are responsible for the reduction of simulated tropical storm activity over the western North Atlantic. In the case of interdecadal variability it is the tropical Atlantic SSTs that are responsible for the interdecadal variability of Atlantic tropical storms. Therefore, the model is successful in simulating a local impact as well as a remote impact of SSTs on the simulated tropical storms.

The variation of SSTs over the tropical Pacific and Indian Oceans has a significant impact on the simulated upper-tropospheric circulation over the western North Atlantic. On the other hand no significant changes in lower-tropospheric circulation and thermodynamic parameters except mixing ratio have been simulated by the ensemble of AGCM integrations. The increase of vertical wind shear over the western North Atlantic during El Niño conditions is the most likely explanation for the significant reduction of simulated Atlantic tropical storms. This is in agreement with observations by Gray (1984) and Goldenberg and Shapiro (1996). The physical mechanism for the interdecadal variability of simulated Atlantic tropical storms is not that clear. When forced by tropical Atlantic SSTs of the 1970s instead of the 1950s, the ensemble of AGCM integrations simulates a significant increase of vertical wind shear and a significant reduction of CAPE. Both of these tendencies are conducive to a reduction of tropical storm activity. It is likely that the combination of the reduction of vertical wind shear and decrease of CAPE explains the significant reduction of the simulated tropical storms during the 1970s compared to the 1950s.

The comparison of the impacts of two eastern Pacific warm events seems to indicate that the intensity and spatial organization of the SST anomalies have an impact on the simulated tropical storm frequency. On the other hand, the difference between two El Niño events does not have a significant impact on the simulated tropical storm location or on the location of the increased vertical wind shear over the tropical North Atlantic.

An ensemble of AGCM integrations has produced a simulation of the impact of SSTs on tropical storm frequency over the North Atlantic basin. The simulated effects of both interdecadal SST variability (predominantly a direct impact of local SST forcing) and interannual SST variability (predominantly a remote impact of El Niño–related SST anomalies) appear to be consistent with observations. This suggests that AGCMs may be useful tools for making seasonal predictions of anomalous tropical storm frequency (Vitart et al. 1997; Graham and Tyree 1999). In addition, it gives increased confidence that AGCMs can provide useful information about the impacts of global warming on tropical storm frequency. However, it is possible that the AGCM would be less proficient in simulating the frequency of Atlantic tropical storms in the presence of both interannual ENSO variability and large (global warming induced) local SST forcing if the impact of these two factors on storm frequency was opposite. Further AGCM research and an augmented observational record would shed further light on this important question.

The AGCM used in the present study has a very coarse resolution and physical parameterizations that may not be able to capture the details of real-world tropical storms and the large-scale circulation that may affect Atlantic tropical storms; for instance, the simulation of the interannual variability of the African easterly jet displays a number of shortcomings. Therefore, these results must be viewed with caution. Experiments with increasingly realistic AGCMs should help to clarify further the interannual and interdecadal variability of Atlantic tropical storms. Future plans include evaluating the impact of the interdecadal variability and trends of *Pacific* SSTs (Knutson and Manabe 1998) on Atlantic tropical storms using the same framework of experiments as in the present study and focusing on decades where the Pacific SSTs are significantly different.

Acknowledgments. The authors would like to thank Dr. Tom Delworth, Tom Knutson, and Dr. Kirk Bryan for their stimulating discussions and help, and two anonymous reviewers whose comments proved invaluable in improving the presentation of the material.

REFERENCES

Bengtsson, L., H. Böttger, and M. Kanamitsu, 1982: Simulation of hurricane-type vortices in a general circulation model. *Tellus,* **34,** 440–457.

——, M. Botzet, and M. Esh, 1995: Hurricane-type vortices in a general circulation model. *Tellus,* **47A,** 175–196.

DeGroot, M. H., 1989: *Probability and Statistics.* Addison-Wesley, 723 pp.

Delworth, T. L., S. Manabe, and R. J. Stouffer, 1997: Multidecadal climate variability in the Greenland Sea and surrounding regions: A coupled model simulation. *Geophys. Res. Lett.,* **24,** 257–260.

Goldenberg, S. G., and L. J. Shapiro, 1996: Physical mechanism for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate,* **9,** 1169–1187.

——, and C. W. Landsea, 1997: Are we seeing a long-term upturn in Atlantic basin major hurricane activity related to decadal-scale SST fluctuations? Preprints, *Seventh Conf. on Climate Variations,* Long Beach, CA, Amer. Meteor. Soc., 305–310.

Gordon, C. T., 1992: Comparison of 30-day integrations with and without cloud–radiation interaction. *Mon. Wea. Rev.,* **120,** 1244–1277.

——, and W. F. Stern, 1982: A description of the GFDL global spectral model. *Mon. Wea. Rev.,* **110,** 625–644.

Graham, N. E., and M. Tyree, 1999: Simulation of Atlantic hurricane frequencies in an ensemble of GCM simulations: 1979–96. Preprints, *23d Conf. on Hurricanes and Tropical Meteorology,* Dallas, TX, Amer. Meteor. Soc., 262–265.

Gray, W. M., 1979: Hurricanes: Their formation, structure and likely role in the tropical circulation. *Meteorology over the Tropical Oceans,* D. B. Shaw, Ed., Royal Meteorological Society, 155–218.

——, 1984: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

——, 1990: Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science,* **249,** 1251–1256.

Haarsma, R. J., J. F. B. Mitchell, and C. A. Senior, 1993: Tropical disturbances in a GCM. *Climate Dyn.,* **8,** 247–257.

Knuth, D. E., 1981: *Seminumerical Algorithms.* Vol. 2, *The Art of Computer Programming,* Addison-Wesley, 688 pp.

Knutson, T. R., and S. Manabe, 1998: Model assessment of decadal variability and trends in the tropical Pacific Ocean. *J. Climate,* **11,** 2273–2296.

Kushnir, Y. J., 1994: Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions. *J. Climate,* **7,** 141–157.

Landsea, C. W., and W. W. Gray, 1992: The strong association between western Sahelian monsoon rainfall and intense Atlantic hurricanes. *J. Climate,* **5,** 435–453.

——, R. A. Pielke Jr., A. M. Mestas-Nuñez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change,* **42,** 89–129.

Lau, N. C., 1985: Modeling the seasonal dependence of the atmospheric response to observed El Niños 1962–1976. *Mon. Wea. Rev.,* **113,** 1970–1996.

Manabe, S., J. L. Holloway, and H. M. Stone, 1970: Tropical circulation in a time-integration of a global model of the atmosphere. *J. Atmos. Sci.,* **27,** 580–613.

McBride, J. L., 1981a: Observational analysis of tropical cyclone formation. Part I: Basic definition of data sets. *J. Atmos. Sci.,* **38,** 1117–1131.

——, 1981b: Observational analysis of tropical cyclone formation. Part III: Budget analysis. *J. Atmos. Sci.,* **38,** 1152–1156.

——, and R. Zehr, 1981: Observational study of tropical cyclone formation. Part II: Comparison of nondeveloping versus developing systems. *J. Atmos. Sci.,* **38,** 1132–1151.

Mehta, V. M., 1998: Variability of the tropical ocean surface temperatures at decadal–multidecadal timescales. Part I: The Atlantic Ocean. *J. Climate,* **11,** 2351–2375.

Moorthi, S., and J. Suarez, 1992: Relaxed Arakawa–Schubert: A Parameterization of moist convection for general circulation models. *Mon. Wea. Rev.,* **120,** 978–1002.

Navarra, A., W. F. Stern, and K. Miyakoda, 1994: Reduction of the Gibbs oscillation in spectral model simulations. *J. Climate,* **7,** 1169–1183.

Neumann, C. J., B. R. Jarvinen, C. J. McAdie, and J. D. Elms, 1993: Tropical cyclones of the North Atlantic Ocean, 1871–1992. Historical Climatology Series 6-2, NOAA, Ashville, NC, 193 pp.

Press, W. R., 1986: *Numerical Recipes: The Art of Scientific Computing.* Cambridge University Press, 102 pp.

Reynolds, R. W., and D. C. Marsico, 1993: An improved real-time global sea surface temperature analysis. *J. Climate,* **6,** 114–119.

Saunders, M. A., and A. R. Harris, 1997: Sea warming as a dominant factor behind near-record number of Atlantic hurricanes. *Geophys. Res. Lett.,* **24,** 1255–1258.

Shapiro, L. J., 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Wea. Rev.,* **115,** 2598–2614.

——, and S. L. Goldenberg, 1998: Atlantic sea surface temperature and tropical cyclone formation. *J. Climate,* **11,** 578–590.

Sirutis, J., and K. Miyakoda, 1990: Subgrid-scale physics in 1-month forecasts. Part I: Experiment with four parameterization packages. *Mon. Wea. Rev.,* **118,** 1043–1064.

Stern, W., and R. Pierrehumbert, 1988: The impact of orographic gravity wave drag parameterization on extended range predictions with a GCM. Preprints, *Eighth Conf. on Numerical Weather Prediction,* Baltimore, MD, Amer. Meteor. Soc., 745–750.

——, and K. Miyakoda, 1995: Feasibility of seasonal forecasts inferred from multiple GCM simulations. *J. Climate,* **8,** 1071–1085.

Tiedtke, M., 1988: Parameterization of cumulus convection in large-scale models. *Physically-Based Modeling and Simulation of Climate and Climate Change,* M. Schlesinger, Ed., D. Reidel, 375–431.

Trenberth, K. E., 1991: General characteristics of El Niño Southern Oscillation. *Teleconnections Linking Worldwide Climate Anomalies,* M. Glantz, R. Katz, and N. Nicholls, Eds., Cambridge University Press, 113–142.

Tsutsui, J.-I., and A. Kasahara, 1996: Simulated tropical cyclones using the National Center for Atmospheric Research community climate model. *J. Geophys. Res.,* **101,** 15 013–15 032.

Vitart, F., J. L. Anderson, and W. F. Stern, 1997: Simulation of interannual variability of tropical storm frequency in an ensemble of GCM integrations. *J. Climate,* **10,** 745–760.

——, ——, and ——, 1999: Impact of large-scale circulation on tropical storm frequency, intensity, and location simulated by an ensemble of GCM integrations. *J. Climate,* **12,** 3237–3254.

Williams, E., and N. Renno, 1993: An analysis of the conditional instability of the tropical atmosphere. *Mon. Wea. Rev.,* **121,** 21–36.