Seasonal Forecasting of Tropical Storms Using Coupled GCM Integrations

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ABSTRACT

The ECMWF Seasonal Forecasting System, based on ensembles of 200-day coupled GCM integrations, contains tropical disturbances that are referred to as model tropical storms in the present paper. Model tropical storms display a genesis location and a seasonal cycle generally consistent with observations, though the frequency of model tropical storms is significantly lower than observed, particularly over the North Atlantic and the eastern North Pacific. Several possible causes for the low number of model tropical storms are discussed.

The ECMWF Seasonal Forecasting System produces realistic forecasts of the interannual variability of tropical storm frequency over the North Atlantic and the western North Pacific, with strong linear correlations and low rms error obtained when comparing the forecasts to observations. The skill of the seasonal forecasting system in predicting the frequency of tropical storms is likely to be related to its skill in predicting sea surface temperatures. In particular, the model seems successful in predicting the occurrence and development of El Niño and La Niña events, and their impact on the large-scale circulation over the Atlantic. For the period 1991–99, a comparison with the statistical forecasts issued by the Colorado State Hurricane Forecast Team suggests that the ECMWF seasonal forecasting system produces a better June forecast of the total number of tropical storms over the North Atlantic. These results establish the feasibility of real-time forecasting of tropical storm statistics by dynamical methods.

1. Introduction

The frequency, mean intensity, and mean location of observed tropical storms can display an important interannual variability. For instance, since the introduction of satellite observations, frequency over the North Atlantic has ranged from 4 to 21 tropical storms per season. The mean location of tropical storms over the western North Pacific can shift significantly from one year to another. These seasonal changes in tropical storm activity can have an important impact on the probability of landfall and damage created by these sometimes devastating meteorological events. Therefore, forecasting the statistical characteristics (tropical storm frequency, mean intensity, or mean location) for the next tropical storm season may be useful for evaluation of risks and water resource management.

Seasonal forecasting of tropical storms is based on the idea that tropical storm activity is largely dependent on characteristics of the large-scale circulation, such as sea surface temperatures (SSTs), vertical shear of the horizontal wind and low-level vorticity (Gray 1979). Changes in the large-scale circulation can have a profound impact on the probability of tropical storm genesis and can explain a large part of the interannual variability of the tropical storm frequency. For instance, the Atlantic tropical storm activity significantly decreases during El Niño years (Gray 1984; Shapiro 1987): the displacement toward the eastern Pacific of deep convection during El Niño years creates an increased intensity of the upper-tropospheric westerlies over the tropical North Atlantic. This subsequently causes a stronger vertical shear and therefore a more hostile environment for the development of Atlantic tropical storms. Anomalies in the large-scale circulation are strongly related to sea surface temperature anomalies in the Tropics, which have some predictability on seasonal timescales. Therefore, some aspects of the large-scale circulation over the Tropics can be predicted months in advance.

Currently several forecasts of tropical storm frequency based on statistical methods are issued every year for the Australian basin (Nicholls 1992), for the western North Pacific (Chan et al. 1998), and for the Atlantic by Colorado State University (Gray et al. 1992, 1993, 1994), the National Oceanic and Atmospheric Administration (http://www.cpc.ncep.noaa.gov/products/outlooks/hurricane.html), and University College of London (http://forecast.mssl.ucl.ac.uk/). These statistical forecasts can be issued up to one year in advance (Gray 1992). They are based on predictors such as El Niño, Sahel rainfall, or quasi-biennial oscillation (QBO) activity (Gray et al. 1992, 1993, 1994), which

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are believed to have an impact on the large-scale circulation over the ocean basin where the tropical storms are developing. Statistical methods use records from the past to identify the predictors and to establish the empirical equations of the forecasting system. They are based on the assumption that these equations will still be valid for the next tropical storm season. This assumption makes empirical methods very vulnerable to significant changes in the climate, due for example to interdecadal variability. In addition, the use of statistical methods is limited by the low number of previous years of record. An alternative to empirical methods is the use of a dynamical model that solves equations describing the atmospheric and oceanic circulation.

The present paper explores the use of an ensemble of coupled GCM integrations to predict tropical storm activity. This method is based on the ability of low-resolution GCMs to create tropical storm disturbances (Manabe et al. 1970). Numerous studies (Bengtsson et al. 1982; Haarsma et al. 1993; Wu and Lau 1992) have confirmed the conclusions of Manabe et al. (1970) that GCMs can create tropical cyclones that have strong similarities with real-world tropical storms: convergence, high moisture content, strong upward motion, and heavy precipitation at the lower levels of the tropical storm, and anticyclonic vorticity and divergence at 200 mb. Bengtsson et al. (1995) found that model tropical storms in the European Centre for Medium-Range Forecasts (ECMWF)–Hamburg, version 3 model (ECHAM3) develop only in areas where the sea surface temperature exceeded 26°C, in agreement with observations by Gray (1979). In addition, they presented a 2D cross section of a model tropical storm that agrees well with a Pacific composite observed typhoon (Frank 1977). On the other hand, tropical storms generated by a coarse-resolution GCM lack the presence of an eye, an eyewall, and rainbands, which often characterize observed tropical storms. In addition, model tropical storms have a larger horizontal extent than in observations (Bengtsson et al. 1995). These deficiencies in the physics of model tropical storms are likely to have a significant impact on their intensity and trajectories, but are unlikely to have a first-order impact on their seasonal variability. An upper air wind field that permits a warm core to develop above the center of a tropical storm is believed to be one of the key elements that explain the interannual variability of observed tropical storms (Gray 1984; Goldenberg and Shapiro 1996). Since model tropical storms display a realistic warm core (Bengtsson et al. 1982; Haarsma et al. 1993; Vitart et al. 1997), they are likely to be sensitive to vertical wind shear. This suggests that although the realism of their genesis has often been questioned (McBride 1984; Evans 1992; Lighthill et al. 1994), the interannual variability of model tropical storms may be consistent with observations, if the model correctly predicts the interannual variability of the vertical wind shear.

The tropical storm interannual variability in GCMs was first investigated by Wu and Lau (1992). They integrated an R15 model forced by observed SSTs for 15 yr and found a significant correlation between eastern equatorial Pacific anomalies and tropical storm frequency over the western North Pacific, the North Atlantic, and the South Pacific, in agreement with observational studies. Vitart et al. (1997) explored the ability of a GCM to simulate the interannual variability of tropical storm frequency using an ensemble of integrations for the period 1980–88. This study showed that the model, a T42 GCM developed at the Geophysical Fluid Dynamics Laboratory (GFDL), was able to simulate a realistic interannual variability of tropical storm frequency over the North Atlantic, the eastern North Pacific, the western North Pacific, and the Australian basin. Vitart et al. (1999) related the simulated interannual variability of tropical storm to the simulated interannual variability of vertical wind shear, 850-mb vorticity, and 200 mb vorticity. Very high correlations (larger than 0.8) were found between the interannual variability of simulated tropical storms and the first combined EOF of vertical wind shear, 850-mb vorticity, and 200-mb vorticity. This suggests that the simulated tropical storms are sensitive to the the interannual variability of the local troposphere, in agreement with observations and with the hypothesis of Gray (1979) on the impact of large-scale circulation on tropical storm genesis. Basins where the GFDL GCM fails to simulate a realistic interannual variability of tropical storms correspond to basins where the model fails to simulate a realistic interannual variability of the large-scale circulation.

All the above studies have been based on *atmospheric* GCMs forced by observed SSTs. In the present paper the ability of a *coupled* GCM to forecast realistic interannual variations of tropical storm frequency is explored, and the possibility of an operational dynamical forecast of tropical storm statistics is discussed. Although the main focus of the present paper is the frequency of tropical storms, one other statistic is also considered: the mean location of tropical storm genesis. In the present forecasting system, the genesis position of the tropical cyclone corresponds to the position where the tropical cyclone has been detected for the first time by the objective procedure.

All the statistics concerning observations have been obtained from the National Hurricane Center (in Miami, FL) and the Joint Typhoon Warning Center (in Guam). In the present paper, tropical storm statistics are evaluated over seven ocean basins: North Atlantic (NA), eastern North Pacific (ENP) (east of 180°), western North Pacific (WNP), north Indian Ocean (NI), south Indian Ocean (SI, west of 105°E), Australian basin (AUS) (from 105° to 165°E), and South Pacific (SP, east of 165°E).

The seasonal forecasting system at ECMWF is presented in section 2, followed by a brief evaluation of its skill in predicting the interannual variability of SSTs in section 3. The objective method used for tracking the model tropical storms generated in the seasonal forecasts is described in section 4. The climatology of the simulated tropical storms is discussed in section 5 and their seasonal variability in section 6. The skill of the coupled GCM at ECMWF in forecasting the interannual variability of Atlantic tropical storm frequency is evaluated and compared with the forecasts produced by the Colorado State Hurricane Forecast Team in section 7.

2. Seasonal forecasting system at ECMWF

The ECMWF Seasonal Forecasting System (Stockdale et al. 1998) is based on a coupled GCM that has been extensively integrated for 200-day forecasts. The atmospheric component has a T63 spectral resolution and a 1.875° grid for surface and physical processes; there are 31 vertical levels with a model-top level located at about 10 mb. The ocean resolution is equivalent to 2° in midlatitudes, but in the Tropics the resolution increases to 0.5° in the meridional direction, so as to resolve the equatorial waves that are important for El Niño. The atmospheric and land surface initial conditions are provided by an operational analysis produced by ECMWF. Ocean initial conditions are provided by an analysis of the ocean state made by assimilating surface temperature analyses and all available subsurface thermal ocean data (Reynolds and Smith 1994; Smith et al. 1991), and forcing the ocean with observed winds.

The atmosphere and ocean are coupled directly without flux corrections and the coupled system is integrated forward for 200 days from the initial conditions. One forecast is made each day, and once a month a forecast ensemble is created, by taking the set of approximately 30 forecasts with start dates centered on the first of the month. This ensemble will henceforth be referred to as the forecast ensemble, and is assigned a nominal start date of the first of the month. Errors in the component models lead to a drift in the climate of the coupled system. Therefore it is necessary to calibrate the forecasts with the climatology of the coupled GCM. To estimate the climatology of the coupled system, a set of 11 6-month forecasts has been made from the first of each month for 6 yr of an earlier period (1991–96). For each starting date (the first of a month), the 11 forecasts of all the 6 yr from 1991 to 1996 are combined to constitute a total ensemble of 66 members, which will henceforth be referred to as the climatology ensemble. The calibration of model forecasts against model climatology is an essential step in numerical forecasting. Note, however, that the best method of calibration (e.g., additive or multiplicative) may depend on the quantity being predicted and that the ability of calibration to produce viable forecasts of a particular quantity must be checked empirically.

The atmospheric component of the coupled system creates model tropical storms with a vertical structure similar to Fig. 1 in Vitart et al. (1997). The tangential velocity is maximum in the lower troposphere, and an anticyclonic circulation is visible in the upper troposphere. The ECMWF model tropical storms display a warm core generally located between 500 and 400 mb [lower than in Vitart et al. (1997)]. The relative humidity reaches 100% near the center of the storm.

3. Seasonal forecast of SSTs

The predictability of tropical storm statistics on the seasonal timescale is justified by two factors: tropical SSTs have a predictability that can exceed a few months and tropical SSTs have a significant impact on tropical storm statistics (Gray 1984; Shapiro 1987; Saunders and Harris 1997; Shapiro and Goldenberg 1998). Therefore, having skill in predicting the interannual variability of tropical SSTs is a necessary condition for a dynamical system to be successful in predicting the interannual variability of tropical storms. The present section evaluates the skill of the ECMWF Seasonal Forecasting System in predicting SST anomalies. A more comprehensive study will be presented in a forthcoming publication.

The model SSTs tend to be biased cold by more than 1°C after 6 months of integrations over most of the Tropics. Nonetheless, after calibration for mean errors, the coupled GCM produces better seasonal forecasts of sea surface temperature anomalies than persistence over the tropical Pacific and Indian Ocean (Fig. 1). Over the tropical Atlantic, the skill is about the same as persistence. The tropical SSTs predicted by the ECMWF Seasonal Forecasting System display an interannual variability that in most regions is positively correlated with observed SSTs (Reynolds and Smith 1994) (Fig. 1a). However significant differences with observations appear over certain areas, such as west of the Mexican coast, where eastern North Pacific tropical storms tend to form, or over the south Indian Ocean where the linear correlation rarely exceeds 0.6 (90% significance). These inconsistencies with observed SSTs variability may impact, at least locally, the predicted tropical storm variability.

The ECMWF Seasonal Forecasting System displays skill in forecasting SST anomalies over the Niño-3 region (5°N–5°S, 150°–90°W). Of particular relevance for this paper, the system was successful in forecasting the onset of the 1997 El Niño event and, from June onward, the amplitude during the Atlantic tropical storm season was well predicted (Fig. 2). Dur-

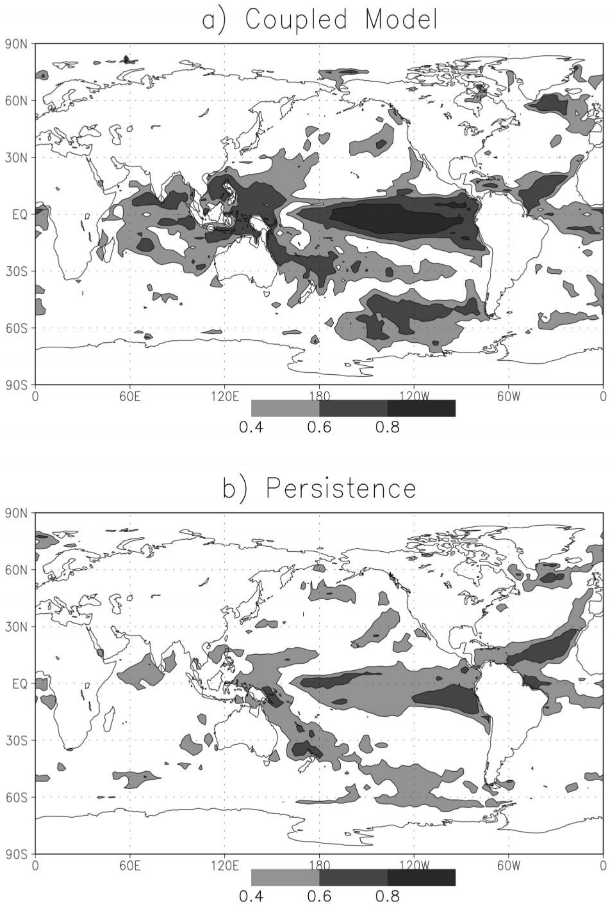

FIG. 1. Point correlation map of seasonal mean SST anomalies for the period 1991–99 between (a) the ECMWF Seasonal Forecasting System and observations and (b) persisted SST anomalies and observations. The seasonal mean SSTs have been averaged for months 3, 4, and 5 of each forecast. The contour interval is 0.2, with the first contour at 0.4.

ing the 1997–98 El Niño event, subsurface changes in the ocean and the shift in convective activity were realistically simulated by the model (Stockdale et al. 1998). As ENSO has an important impact on observed tropical storms (Gray 1984; Shapiro 1982; Goldenberg and Shapiro 1996; Landsea 2000), the ability of the coupled GCM to forecast the evolution of ENSO events is important for its skill in forecasting tropical storm variability.

4. Tropical storm detection

A major problem when tracking tropical storms from models and from analysis consists in detecting as many as possible without detecting extratropical storms or weak tropical depressions. Since weak tropical disturbances and extratropical storms have an interannual variability that is different from tropical storms, it is crucial to eliminate all these systems in our statistics. Therefore, the criteria for detecting a model tropical storm have been chosen to be harsh enough so that, when applied to ECMWF analyses projected on the same low-resolution grid as the GCM outputs, almost all systems detected correspond to observed tropical storms. This strategy has the important advantage of ensuring that the frequency of model tropical storms can be directly compared to the observed tropical storm frequency. The algorithm to detect the simulated tropical storms is the following:

1) A local maximum of vorticity larger than $3.5 \times 10^{-5}\ s^{-1}$ at 850 mb is located and the closest local minimum sea level pressure is defined as the center of the storm.
2) The closest local maximum of averaged temperature between 500 and 200 mb is located and is defined as the center of the warm core. The distance between the center of the warm core and the center of the storm must not exceed 2° latitude. From the center of the warm core the temperature must decrease by at least 0.5°C in all directions within a distance of 8° latitude.
3) The closest local maximum thickness between 1000 and 200 mb is located. The distance between this local maximum and the center of the storm must not exceed 2° latitude. From this local maximum, the thickness must decrease by at least 50 m in all directions within a distance of 8° latitude.

Although three criteria on maximum temperature anomaly and maximum thickness between 1000 and 200 mb seem to be redundant since both of these features characterize the presence of a warm core, utilizing these two features was a useful way to eliminate several extratropical storms that satisfied one of the criteria.

All of these criteria must be satisfied to define a storm. To locate the position of the center with a higher precision than the model resolution, an algorithm similar to the one described by Murray and Simmonds (1991) is used. Bicubic splines interpolate the fields listed below from the gridpoint values and then a conjugate gradient algorithm locates the position of a maximum or a minimum of the fields. After storms are located for each day, an objective procedure is applied to find storm trajectories as follows:

1) For a given storm, we examine whether there are storms that appear on the following day at a distance of less than 800 km (this represents a speed of about 18.5 kt). This distance is small enough to reduce the risk of connecting two different tropical storms. Some tropical storms do in fact move faster than this during at least part of their lives, and in such cases part of the track will not be detected. However, very few storms move faster than this speed for their entire life, making it unlikely for a storm to be missed altogether. Equally, the possibility of counting the same fast moving

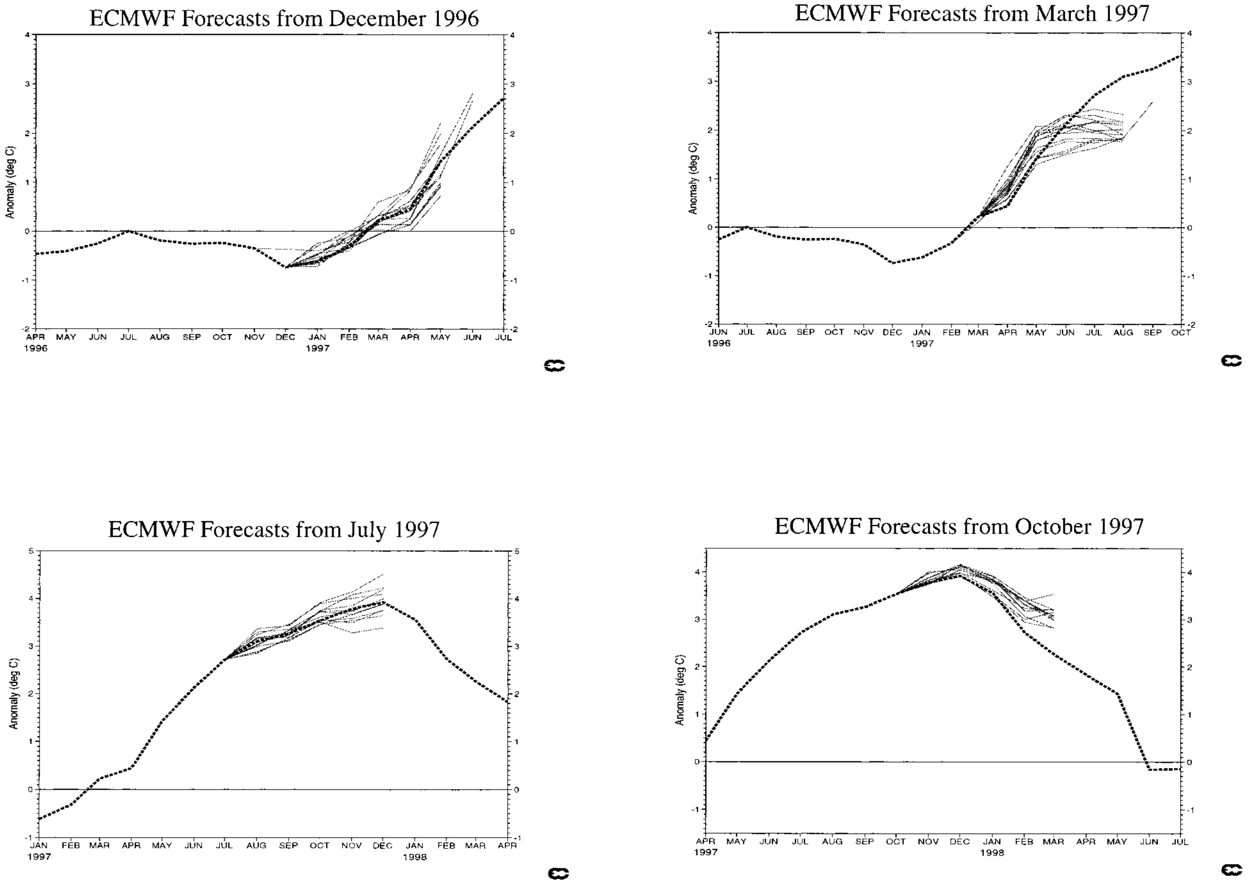

FIG. 2. Plume of monthly mean SST anomalies predicted for the Niño-3 region (5°S–5°N, 90°–150°W). Each light line represents one member of the ensemble. The heavy line shows the observed values. The initial date of the forecast is 1 Dec 1996 (top-left panel), 1 Mar 1997 (top-right panel), 1 Jul 1997 (bottom left panel), and 1 Oct 1997 (bottom-right panel).

storm several times is reduced by an additional criterion imposing a minimum duration of 2 days. In summary, the choice of 800 km as a maximum distance is likely to shorten the track of some detected tropical storms, but has small impact on the tropical storm frequency, which is the main focus of the present paper.

2) If there is no such storm, then the trajectory is considered to have stopped. If there is more than one storm in the following day (less than 10% of cases), a preference is given to a westward and poleward trajectory since the majority of model tropical storms move in that direction.
3) To be considered as a model tropical storm trajectory, a trajectory must last at least 2 days and have a maximum wind velocity within an 8° circle centered on the middle of the storm, which must be larger than 17 m s^{-1} at 850 mb (in the atmospheric model, this corresponds to a wind speed of about 12 m s^{-1} at 10 m above the surface) during at least 2 days (not necessary consecutive). The criteria on the minimum intensity of model tropical storms is less restrictive than the official criteria used to identify observed tropical storms (17 m s^{-1} at 10 m above the surface), because a coarse-resolution model cannot produce wind speeds as high as in the real world.

Cases satisfying all these criteria will henceforth be referred to as model tropical storms. These criteria have been adjusted to give the most realistic tropical storm detection from the ECMWF operational global analyses on the same horizontal grid as the atmospheric component of the coupled GCM. When applied to the 1998–99 ECMWF operational global analyses, the algorithm detects 75% of all the tropical storms observed during that period. Only six nonobserved tropical storms are detected, all of them located over the north Indian Ocean. Removing the warm core criteria increases the rate of detection of observed tropical storms in the analysis to about 85%, which is consistent with Serrano (1997), but it also increases dramatically the number of nonobserved tropical storms.

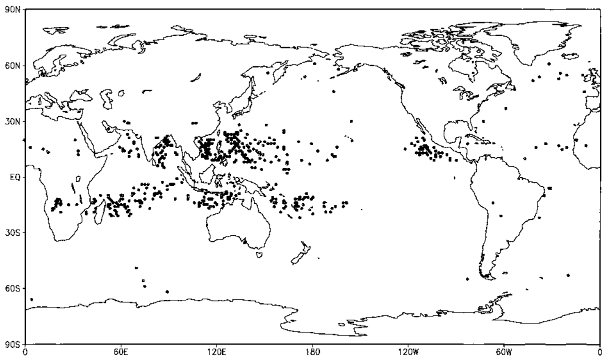

FIG. 3. First position of all the tropical storms generated by 6-month integrations of the coupled GCM starting on 1 Jan and 1 Jul 1991–99 (this represents a total of 9 yr of integrations). Each point represents the first appearance of at least one tropical storm.

5. Tropical storm climatology

a. Climatology description

The locations of the first positions of tropical storms generated by a set of single 6-month forecasts starting on 1 January and 1 July 1991–99 are presented in Fig. 3.

Over the Atlantic, the genesis of the model tropical storms is primarily located in the eastern part of the basin. Most of these model tropical storms originate from model easterly waves that propagate over and west of Africa. The scarcity of model tropical storms forming over the Caribbean and the Gulf of Mexico may significantly contribute to the deficit in the total frequency of tropical storms over the Atlantic basin (Fig. 4). The location of model tropical storms over all the other ocean basins is quite realistic and comparable to observations. However the model has a tendency to create tropical storms too close to the equator, particularly over the south Indian Ocean, whereas observed tropical storms do not occur within 3° latitude from the equator. Several storms are detected in the high latitudes during wintertime, which may correspond to high-latitude phenomena such as polar lows or hybrid tropical–extratropical cyclones, which exhibit some tropical storm characteristics as described in Emanuel and Rotunno (1989). The model simulates tropical storms in the South Atlantic, where such events are never observed. In addition, a substantial number of model tropical storms are detected over land. Although it is possible that these land storms are mesoscale convective systems that meet the detection criteria over the continental United States and other regions, the fact that no land tropical storms are present in the ECMWF analysis suggests a problem with the model physics. Tuleya (1994) pointed out insufficiently accurate surface tempera-

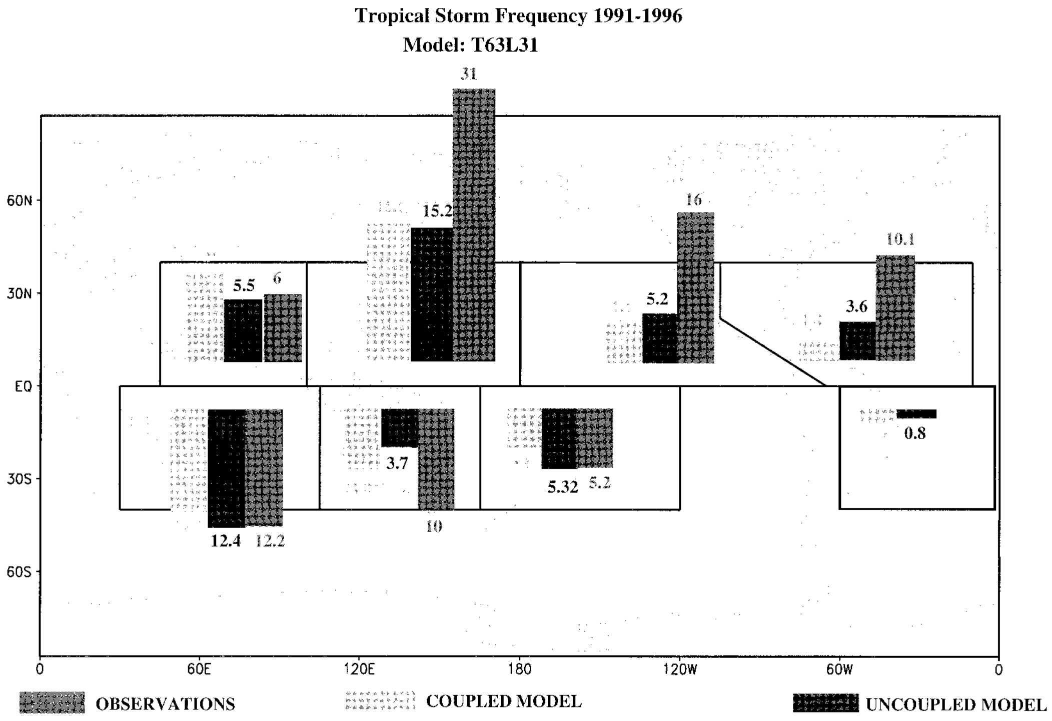

FIG. 4. Mean tropical storm frequency over the North Atlantic, eastern North Pacific, western North Pacific, south Indian Ocean, Australian basin, the South Pacific, and the South Atlantic from 1991 to 1996 in observations, and coupled and uncoupled (atmosphere forced by observed SSTs) integrations. The numbers represent the annual tropical storm frequency over each ocean basin. In the model integrations (coupled or uncoupled), the tropical storm frequency has been averaged over all the members of the ensemble.

TABLE 1. (a) Tropical storm frequency in a three-member ensemble over the Southern Hemisphere from Dec 1987 to Mar 1998 as a function of the model resolution and (b) total number of model tropical storms form Jun to Sep 1987 as a function of the CAPE threshold.

Resolution	T63	T159	T319
Expt 1	1	8	11
Expt 2	10	10	7
Expt 3	4	13	12
Mean	5	10.33	10

CAPE threshold	0	100	250	500
Expt 1	2	6	19	13
Expt 2	4	7	20	22
Expt 3	5	8	22	29
Mean	3.7	7	20.3	21.3

ture prediction as being a possible source of land tropical storm genesis in the GFDL Hurricane Model. Such unrealistic locations of tropical storm genesis have also been detected in other GCMs (Bengtsson et al. 1982; Vitart et al. 1997). From now on, a land mask has been applied to remove these land tropical storms from the tropical storm statistics.

Although the coupled GCM forecasts a moderately realistic location of tropical storm genesis, its climatological frequency over each ocean basin differs greatly from the observations (Fig. 4). The coupled GCM simulates fewer tropical storms than observed over all the basins except over the north Indian Ocean. The deficit is particularly important over the North Atlantic and the eastern North Pacific, where the model simulates about four times fewer storms than observed. Over the western North Pacific and the Australian basin, the model simulates half as many as observed. The difference is smaller over the South Pacific and the south Indian Ocean. The rest of the present section will attempt to explain this strong deficit in model tropical storm frequency.

b. Impact of GCM resolution

The low resolution of the GCM is a possible candidate to explain the low number of model tropical storms. To evaluate the impact of resolution, a three-member ensemble of 4-month integrations starting on 1 November 1987 has been realized with three different horizontal resolutions: T63, T159, and T319 of the same ECMWF atmospheric model forced by prescribed varying SSTs. The procedure for tracking the model tropical storms has been applied to all the members of the ensemble with the three different resolutions. The number of tropical storms increases with resolution (Table 1a) for the limited set of sensitivity experiments, but even with T319 resolution, the mean simulated tropical storm frequency is only half the number observed (21 observed tropical storms compared with 10 in the model).

The criteria for tracking model tropical storms may be too harsh when applied to T63 resolution. However, the number of tropical storms detected with the same procedure applied to the ECMWF analysis projected on the same T63 horizontal grid is higher than that with the seasonal forecasting system.

c. Impact of errors in the model large-scale circulation

One additional possible explanation of the low frequency of model tropical storms might be the drift in SSTs produced by the coupling between the ocean and the atmospheric components of the GCM. However, an analysis of tropical storms simulated with an *uncoupled* version of the GCM (atmosphere only, using observed SSTs) displays a tropical storm frequency generally more realistic than the one obtained with the coupled GCM (particularly over the Atlantic Basin and the South Pacific) but still well below observations (Fig. 4).

The seasonal forecasting system simulates a vertical wind shear (defined as the difference between the winds at 850 and 200 mb) significantly larger than observed over the northern part of the North Atlantic basin and over the eastern North Pacific, during the tropical storm season (Fig. 5). Over the western North Pacific, the predicted vertical wind shear is on average about the same as observed (Fig. 5), when it is underestimated over the north Indian Ocean (not shown) and all the basins located in the Southern Hemisphere during the period December to April (not shown). Although, the difference between model and observed vertical wind shear may contribute to the strong deficit of tropical storms over the North Atlantic and the eastern North Pacific, it is not strong and uniform enough to explain the deficit in the total number of tropical storms. The same conclusion can be applied after comparing the predicted and observed climatological 850-mb vorticity (not shown).

d. Sensitivity to convective parameterization

Another possible explanation could be the physics of the atmospheric model. The atmospheric GCM, through the cumulus convection scheme, may generate an atmosphere that is thermodynamically too stable and, therefore, less likely to produce tropical storms (Vitart et al. 2001). A series of experiments has been realized to evaluate the impact of the cumulus convection on the frequency of the simulated tropical storms. The cumulus parameterization is a mass-flux scheme from Tiedtke (1989), which is triggered when the background convective available potential energy (CAPE) (e.g., Williams and Renno 1993) is nonzero. The model forced by prescribed varying SSTs has been integrated for 4 months starting on 1 June 1987 with three different initial states;

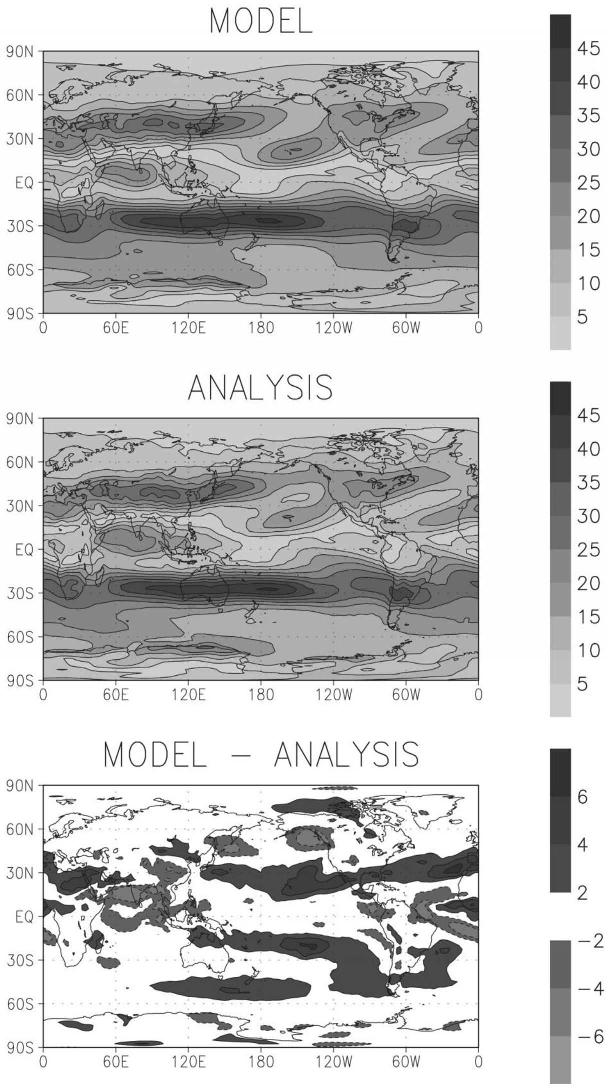

FIG. 5. Climatological vertical wind shear between 200 and 850 mb predicted (top) by the ECMWF Seasonal Forecasting System starting on (top) 1 Jun and (middle) in the ECMWF analysis. (bottom) The difference between the predicted and analyzed vertical wind shears. The vertical wind shear has been averaged over the period from Jul to Nov and from 1991 to 1996. In addition, the predicted vertical wind shear has been averaged over all the members of the forecast ensemble.

the objective procedure for tracking model tropical storms has been applied to the three members of the ensemble. In addition to the control run, the atmospheric model has been integrated with modifications to force the deep convection to occur only if the CAPE exceeds 100, 250, or 500 J Kg^{-1}. This set of experiments has been motivated by the fact that the deep convection scheme seems to stabilize excessively the simulated tropical atmosphere. Adding a CAPE threshold is a way to reduce the action of the parameterized deep convection. The simulated tropical storm frequency increases as the CAPE threshold increases (Table 1b). However, the increase does not appear to be linear. Instead, there seems to be a value of the CAPE threshold between 100 and 250 J Kg^{-1} above which the model produces a much larger number of tropical storms. Additional experiments are needed to confirm this conclusion. In the control run, the frequency of simulated tropical storms is well below the observed frequency, but it becomes closer to observation as the CAPE threshold increases. A similar experiment has been realized for the winter season (not shown): the strong increase in tropical storm frequency with increasing CAPE threshold is again verified. The effect of the CAPE threshold on tropical storm frequency is much stronger than the effect of increasing the resolution (Table 1a).

However, it may be possible that the increase of model tropical cyclone frequency when the CAPE threshold rises happens for an unrealistic physical reason. It is possible that high values of CAPE threshold are necessary in coarse-resolution GCMs to produce reasonable numbers of cyclones, as a compensation for deficient resolution, poor convection schemes, and potential intensities that are too small. In addition, increasing the CAPE threshold negatively impacts certain aspects of the mean climate simulated by the ECMWF atmospheric model, preventing such a method from being used operationally. For instance, the distribution of total precipitation gets unrealistic in the Tropics (not shown). More details on the impact of increasing the CAPE threshold on the mean climate of the model will be discussed in a forthcoming publication.

In summary, the simulated tropical storm frequency seems to be more sensitive to changes in the physics of the atmospheric GCM than to increases in the horizontal resolution. However, the resolution of the GCM has a strong impact on the *intensity* of the model tropical storms and on their *tracks*, although this will not be discussed here.

6. Tropical storm seasonal variability

The seasonal variability of the observed and simulated tropical storm frequency (Fig. 6) has been evaluated by averaging for each ocean basin and each month the number of tropical storms that have been observed during the period 1991–96. The number of simulated tropical storms has been averaged over all the members of the climatology ensemble.

Over the North Atlantic, the observed tropical storm frequency shows a maximum in August–September. This is well captured by the coupled GCM although the peak in September is not very sharp in the simulation. Over the eastern North Pacific, the maximum frequency appears in July both in the observations and in the coupled forecast system. Over the western North Pacific, tropical storms can be observed at all times of the year, which is also true in

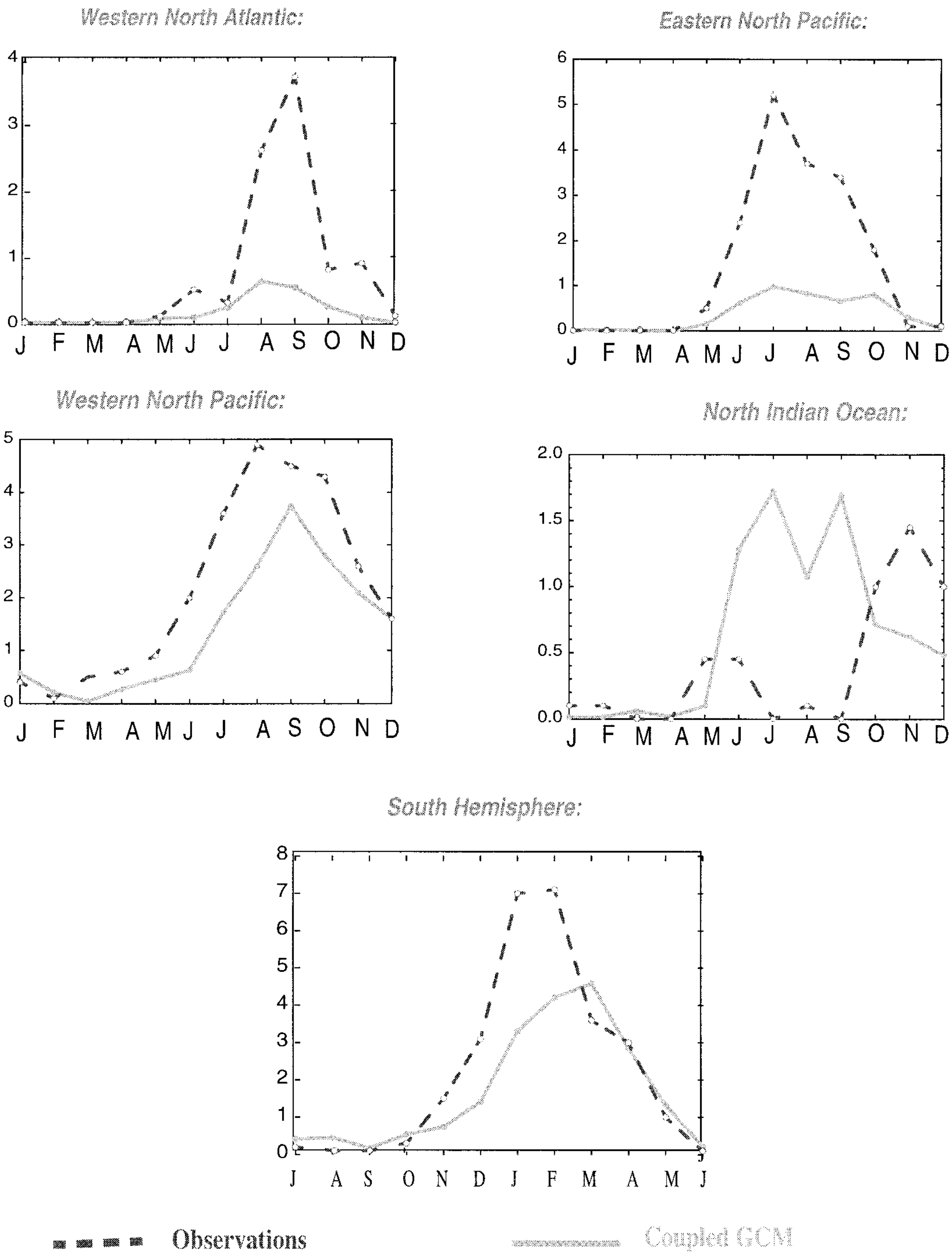

FIG. 6. Seasonal variability of tropical storm frequency over the North Atlantic, the eastern North Pacific, the western North Pacific, the north Indian Ocean, and the Southern Hemisphere.

the coupled GCM. The peak of the season occurs in August in observations, but later in the coupled forecasts. The north Indian Ocean displays two periods of tropical storm activity: the first one is the period May–June and the second one the period October–November (when most of the tropical storms develop). The coupled GCM does not capture that seasonality, but rather creates a maximum of tropical storm activity during the summer. Over the Southern Hemisphere most of the observed tropical storms occur in January–February. The coupled forecasts create a seasonality of tropical storms over the Southern Hemisphere that is 1 month later than observations, with a peak in March. In summary, the coupled GCM cre-

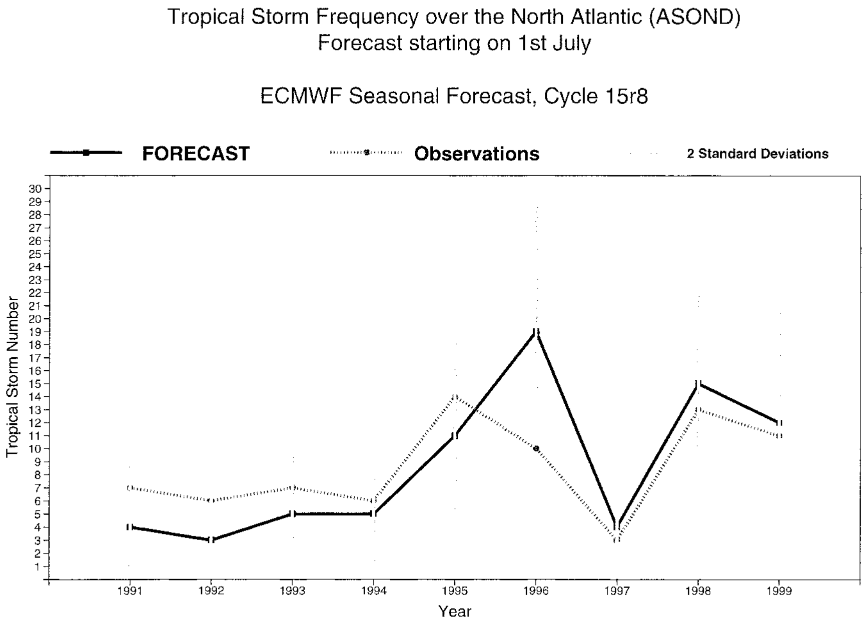

FIG. 7. Interannual variability of tropical storm frequency over the western North Atlantic for the period 1991–99. The dashed line represents observations, the black line the mean of the ensemble of scaled forecasts starting on 1 Jul and covering the period from Aug to Nov. The vertical lines represent two standard deviations in the ensemble of forecasts.

ates tropical storms with a seasonality close to observations, except over the north Indian Ocean. However, the peak of the season tends to be 1 month too late in the model. This is unlikely to be explained by errors in the predicted SSTs, since the atmospheric component of the coupled GCM forced by observed SSTs displays the same intraseasonal variability of tropical storm frequency.

7. Tropical storm seasonal forecasts

a. Forecasting system

As described in section 2, an ensemble forecast of 30 members is realized each month by integrating the ECMWF Seasonal Forecasting System for a period of 200 days. In the present study, only the 5-month period from the second month to the sixth month after the nominal starting date of the ensemble forecast is considered. This period is common to all the members of the 6-month forecast ensemble (they all start at a different date; see section 2). In addition, this period is at least 2 weeks away from the starting date of any member of the ensemble forecast, which ensures that the range of deterministic atmospheric prediction is exceeded. The procedure for tracking the model tropical storms has been applied to the 30 members of the ensemble forecast and to the 66 members of the climatology. The number of tropical storms over each basin has been counted for each member of the ensemble, and the probability distribution function of tropical storm frequency in the forecast is compared to the probability distribution function in the climatology. A Wilcoxon–Mann–Whitney test (WMW test; see, e.g., Wonnacott and Wonnacott 1977) evaluates if the predicted tropical storm frequency is significantly different from the climatology. Over each ocean basin, the tropical storm frequency in the forecast is then multiplied by a factor such that the seasonal number of model tropical storms averaged from 1991 to 1996 coincides with the observations. From now on, all the results presented in this paper are scaled using the above method (this applies to Fig. 7 onward) in order to remove the systematic bias in the model tropical storm frequency. No scaling procedure has been applied to adjust the genesis position climatology of the forecast to observations. The latitude and longitude of the genesis position of the tropical storms have been averaged for each member of the forecast and climatology ensembles over the last 5 months of the integration.

b. Verification

A verification of the tropical storm seasonal forecasting system has been undertaken by evaluating its skill during the 6 yr of climatology (1991–96) and the first 3 yr of forecasts (1997–99). The total period of validation (1991–99) is not enough to fully estimate the skill of the coupled GCM, but it is probably sufficient to give a general idea of the behavior of the seasonal forecasting system.

Over the North Atlantic, the model displays a trop-

TABLE 2. Linear correlation between observed and predicted tropical storm frequency over the North Atlantic, eastern North Pacific, and the western North Pacific during the period 1991–99. Significance levels are in parentheses. Bold numbers correspond to a significance larger than 90%.

Starting date / Period of forecast	1 Apr MJJAS	1 May JJASO	1 Jun JASON	1 Jul ASOND
North Atlantic	**0.67** (97)	**0.60** (92)	**0.74** (97)	**0.75** (98)
Eastern North Pacific	0.07 (1)	0.2 (39)	0.49 (82)	**0.76** (98)
Western North Pacific	**0.81** (99)	**0.78** (98)	**0.73** (97)	**0.77** (98)

TABLE 3. Rms error between observed and predicted tropical storm frequency during the period 1991–99. The rms errors between observed and climatological tropical storm frequency are in parentheses. Bold numbers indicate when the forecast has a lower rms error (i.e., more skill) than climatology.

Starting date / Period of forecast	1 Apr MJJAS	1 May JJASO	1 Jun JASON	1 Jul ASOND
North Atlantic	**2.3** (3.4)	**4** (4.2)	**2.7** (4.2)	**3.3** (3.8)
Eastern North Pacific	4.5 (4.2)	**4.7** (4.9)	**4.2** (4.7)	**1.9** (3.3)
Western North Pacific	**2.5** (5.2)	**3.3** (5.5)	**3** (4.2)	**1.9** (2.1)

ical storm interannual variability from 1991 to 1999 that is consistent with observations (Fig. 7) except in 1996, when the model tends to forecast an unrealistically large number of tropical storms. Despite this unrealistic forecast in 1996, the linear correlation between observed and predicted interannual variability is positive and larger than 0.6, which represents a significance greater than 90% (Table 2). The rms errors between observed and predicted tropical storm frequency (after scaling) (Table 3) are smaller than rms errors using the climatological frequency of tropical storms as a forecast, suggesting that the coupled GCM produces a useful forecast over the North Atlantic.

Over the WNP, the coupled GCM displays skill in forecasting the interannual variability of tropical storm frequency (Fig. 8): for the forecasts starting from April to July, the linear correlation with observed tropical storm frequency exceeds 0.7 (this represents a significance larger than 98%) (Table 2) and the rms error with observations (Table 3) is smaller than the rms error of climatology. In addition to tropical storm *frequency*, the model displays a large skill in forecasting the interannual variability of tropical storm *longitude* and *latitude*, with linear correlation with observation larger than 0.8 (98% significance) and 0.85 (99% significance), respectively, for all the forecasts starting from April to July. Over WNP, the model has more skill to predict the geographical location of tropical storms than it has to predict their frequency. This is likely due to the fact that the main impact of ENSO on WNP tropical storms is to shift their genesis position rather than affect their frequency.

Over the other ocean basins, the skill of the coupled GCM in forecasting a realistic interannual variability of tropical storm frequency is not as strong as over the North Atlantic and the western North Pacific. The coupled GCM displays some skill in forecasting the interannual variability of tropical storm frequency over the eastern North Pacific (Table 2) and the South Pacific (not shown), although the skill over these two basins is restricted to shorter-term forecasts, when the starting date of the forecast is just before or at the

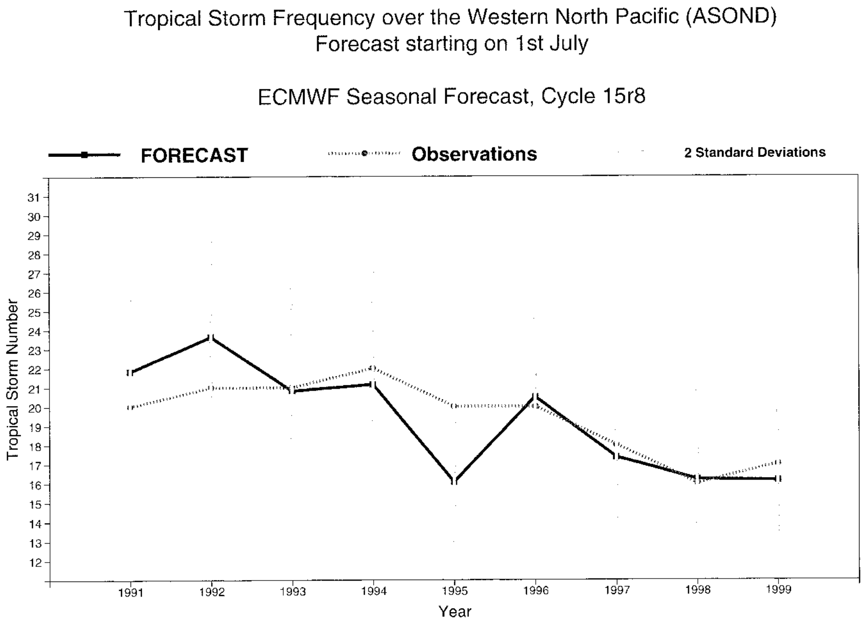

FIG. 8. Same as in Fig. 7 but for the western North Pacific.

TABLE 4. Linear correlation between the interannual variability of observed and predicted vertical wind shear, and 850- and 200-mb vorticity for the period 1991–99. The large-scale parameters have been averaged over each ocean basin. Over the Northern Hemisphere, the forecasts starts on 1 Jun and the large-scale parameters have been averaged over the period from Jul to Nov. Over the Southern Hemisphere, the forecasts start on 1 Dec and the large-scale parameters have been averaged from Jan to May. Significance levels are in parentheses. Bold numbers correspond to a significance larger than 90%.

	Basins						
	NA	ENP	WNP	NI	SI	AUS	SP
Vertical wind shear	**0.76** (98)	0.50 (83)	**0.78** (99)	**0.76** (98)	0.25 (48)	−0.02 (0)	0.48 (82)
850-mb vorticity	**0.60** (91)	**0.71** (97)	**0.78** (99)	**0.95** (99)	**0.70** (96)	**0.76** (98)	**0.84** (99)
200-mb vorticity	**0.87** (99.7)	0.01 (0)	**0.88** (99)	0.05 (11)	0.38 (68)	0.44 (77)	**0.66** (95)

beginning of the tropical storm season. Over the Indian Ocean regions and the Australian basin, the linear correlation between forecast and observations never exceeds 90% significance.

The Atmospheric Model Intercomparison Project run described in Vitart et al. (1997) using a GCM model developed at GFDL (Gordon and Stern 1982) displays considerable skill in simulating a realistic interannual variability of tropical storms over the western North Pacific and the North Atlantic, and particularly poor skill over the Indian Ocean basins, much as the present ECMWF seasonal forecasting system does. Vitart et al. (1999) related this discrepancy from one basin to another to the skill of the GFDL model in simulating interannual variations of the vertical wind shear, and 200- and 850-mb vorticity. To check if this statement is also valid for the ECMWF Seasonal Forecasting System, the three large-scale parameters predicted by the coupled GCM starting on 1 June for the Northern Hemisphere and 1 December for the Southern Hemisphere have been averaged over each ocean basin and over 5 months of integrations. Basins where the ECMWF model displays skill in predicting tropical storm frequency coincide with the basins where the interannual variations of all the predicted mean large-scale parameters are consistent with observations (Table 4).

Although the coupled GCM displays skill in predicting SSTs (Fig. 1), errors in the forecasting of SST anomalies can be an important source of error for the forecast of the interannual variability of tropical storm frequency. To evaluate this error, an 11-member ensemble of integrations has been created in exactly the same framework as the coupled integrations, but this time the atmospheric component is forced by observed sea surface temperatures. Over the North Atlantic, the atmospheric model displays a strong skill in simulating the interannual variability of tropical storms with a correlation of 0.94 when forced by observed SSTs (Table 5). This suggests that the 1996 bad forecast is either due to a bad forecast of SSTs or to the coupling. However, in uncoupled integrations forced by the predicted SSTs (after drift correction), the atmospheric model simulates an interannual variability of Atlantic tropical storms similar to that obtained with the full coupled GCM. Therefore, the cause of the 1996 bad forecast over the Atlantic is likely to be linked to errors in the sea surface temperature anomalies, whose forecasts over the tropical North Atlantic were worse in 1996 than for the rest of the period 1991–99 (not shown). Additional experiments would be needed to determine which patterns in the predicted SSTs are responsible for this overestimation. Over all the other ocean basins, the atmospheric GCM forced by observed SSTs does not display significantly stronger skill than the coupled GCM, except maybe over the Australian basin (Table 5). This suggests that the skill of the present system to predict a realistic interannual variability of tropical storms is more limited by errors in the atmospheric model than by errors in the predicted SSTs.

The rest of this section discusses two examples of tropical storm variability that the coupled GCM seems able to forecast successfully. The first example concerns the impact of ENSO on the tropical storm sta-

TABLE 5. Linear correlations between the interannual variability of observed and model tropical storm frequency for the period 1991–96. The forecast refers to coupled GCM integrations and simulation refers to integrations where the atmospheric component of the coupled GCM is forced by observed SSTs. The starting date of the model integrations is 1 Jul over the Northern Hemisphere and 1 Oct over the Southern Hemisphere. Significance levels are in parentheses.

	Basins						
	NA	ENP	WNP	NI	SI	AUS	SP
Starting date	1 Jul	1 Jul	1 Jul	1 Jul	1 Oct	1 Oct	1 Oct
Period of integration	ASOND	ASOND	ASOND	ASOND	NDJFM	NDJFM	NDJFM
Forecast	0.63 (84)	0.86 (97)	0.68 (86)	0.39 (56)	−0.46 (65)	0.57 (76)	0.60 (76)
Simulation	0.94 (99.9)	0.63 (84)	0.62 (81)	0.30 (50)	−0.60 (82)	0.50 (69)	0.50 (69)

tistics. The second example concerns the intense Atlantic tropical storm season of 1995.

1) Tropical storm variability due to ENSO

The impact of ENSO on observed tropical storm frequency variability is particularly significant over the North Atlantic: during El Niño years, the Atlantic tropical storm activity is significantly reduced; the increase of vertical wind shear over the western Atlantic due to an eastward shift in the deep convection over the tropical Pacific has been proposed as a mechanism to explain the impact of ENSO on the Atlantic tropical storm variability (Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996). Over the other ocean basins, the impact of ENSO on observed tropical storm frequency is generally not significant (McBride 1995), although it can have a significant impact on the tropical storm *genesis location.* For example, tropical storms in the western North Pacific tend to form farther east during an ENSO warm event (Chan 1985). In addition, Revell and Goulter (1986 a,b), Hastings (1990), and Evans and Allen (1992) have pointed out that the frequency of cyclone formation east of 170°E increases during an ENSO warm event. Although ENSO can explain less than 50% of the total variance of observed tropical storm interannual variability (McBride 1995) (other factors like the interdecadal variability of tropical Atlantic SSTs can affect significantly the frequency of Atlantic tropical storms), it remains the strongest and most significant factor that has been identified as affecting the interannual variability of observed tropical storms.

ENSO impacts the observed tropical storm statistics through its impacts on the large-scale circulation. Therefore, in order to be successful in predicting the interannual variability of tropical storms, it is crucial for the coupled GCM to display skill in predicting the occurrence and developments of El Niño and La Niña events and their impacts on the model large-scale circulation. A larger period of integrations would be needed in order to evaluate the skill of the ECMWF seasonal forecasting system to predict ENSO events. However, the coupled system was successful in forecasting the onset of the 1997 ENSO event and its development during the Atlantic tropical storm season (see section 3 and Fig. 2). The impact of the 1997–98 El Niño on the simulated vertical wind shear in the Tropics is generally consistent with analysis (Fig. 9). Over the tropical North Atlantic, the coupled GCM simulates an increase of vertical wind shear over most of the main region where tropical storms develop (Fig. 9), a decrease of cyclonic low-level vorticity, and an increase of subsidence (not shown) as in climatology.

During the period of verification (1991–99), two La Niña (1995–96, 1998–99) and four El Niño (1991–92, 1993, 1994–95, 1997–98) events occurred according to Trenberth (1997). The number of ENSO

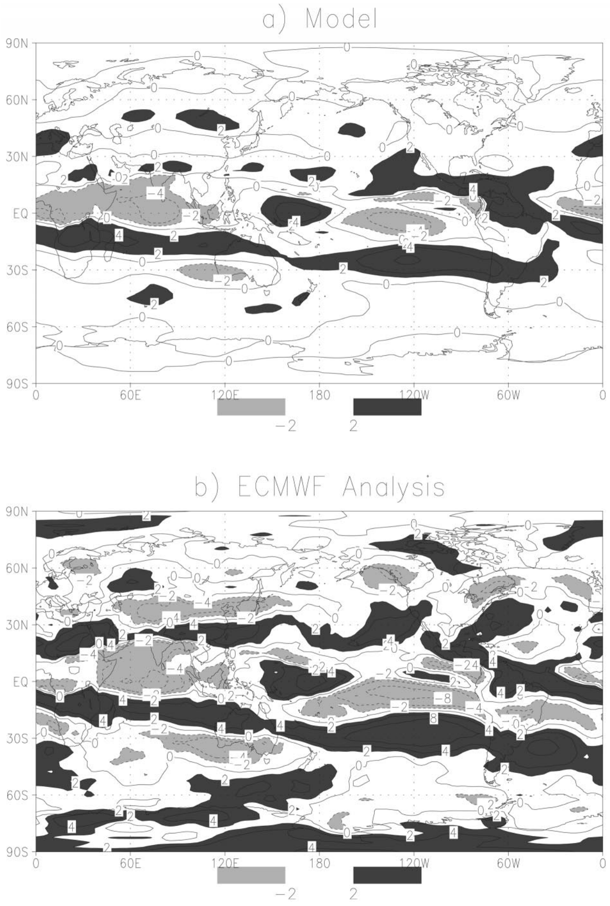

FIG. 9. Vertical wind shear anomaly between 200 and 850 mb (a) predicted by the ECMWF Seasonal Forecasting System starting on 1 Jun 1997 and (b) from ECMWF analysis for the period Jul–Nov 1997 and relative to the period 1991–96. The predicted vertical wind shear has been averaged over all the members of the forecast ensemble.

events is not large enough to definitively assess the skill of the coupled GCM to forecast the tropical storm variability linked to ENSO. However, over the North Atlantic, the seasonal forecasting system predicts significantly fewer tropical storms when El Niño is present during the Atlantic tropical storm season (1991, 1992, 1993, 1994, and 1997) and significantly more in the presence of La Niña (1998 and 1999) (Fig. 7), which is consistent with observations. In addition, the model forecasts a significant shift (significant according to the *t* test) in tropical storm genesis location over the western North Pacific (Fig. 10) and over the South Pacific (not shown). The predicted tropical storms over the western North Pacific have a genesis located more eastward (westward) than in the climatology during the 1997 El Niño (1998 La Niña) tropical storm season as in observations (Chan 1985). In summary, the seasonal forecasting system seems successful in forecasting tropical storm variability during El Niño and La Niña years and the strong skill

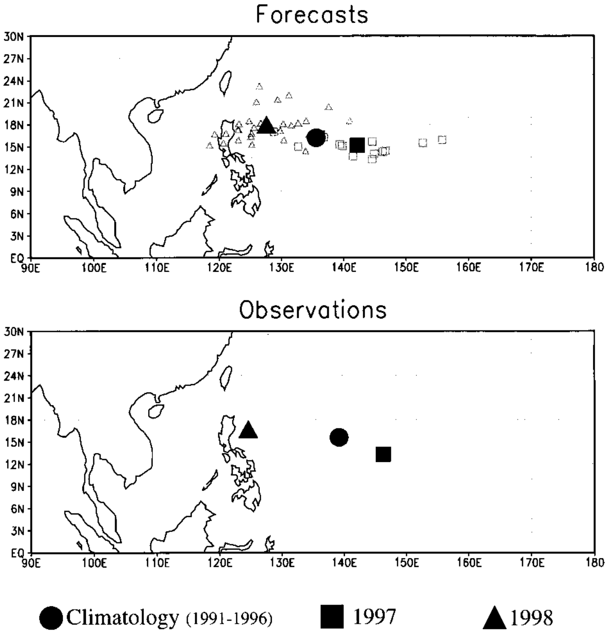

FIG. 10. Mean genesis position of all the tropical storms that occurred during 1 yr over the western North Pacific. (top) Each big symbol represents the mean of all the members of the ensemble, and each small symbol represents one member of the ensemble. (bottom) Each big symbol represents the mean genesis position during 1 yr of observation.

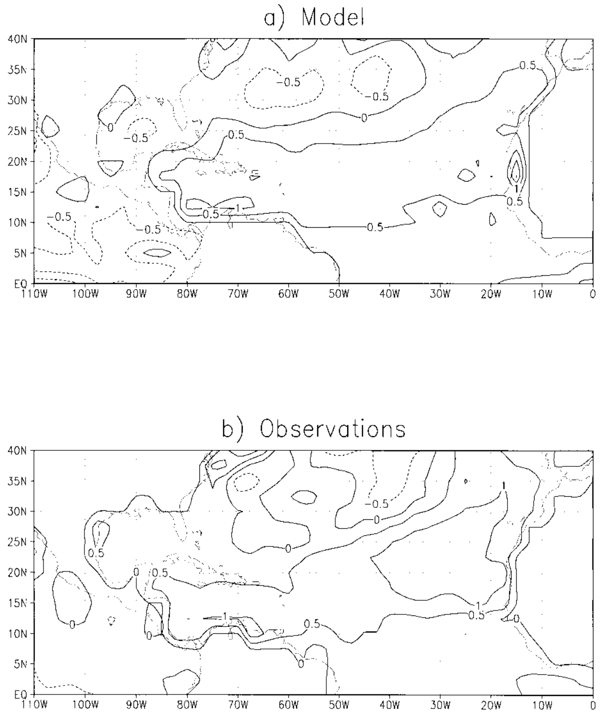

FIG. 11. Sea surface temperature anomalies for the period Jul–Oct 1996 (a) predicted by the ECMWF Seasonal Forecasting System starting on 1 Jul 1996 and (b) observed (Reynolds and Smith 1994). The predicted sea surface temperatures have been averaged over all the members of the forecast ensemble. The climatology is defined over the period from 1991 to 1995.

displayed by the coupled GCM in forecasting the tropical storm variability due to ENSO is an important step toward forecasting the complete interannual variability of tropical storms.

2) Atlantic tropical storm variability not related to ENSO

ENSO is not the only important signal present in the interannual variability of tropical storms over the North Atlantic. Atlantic SSTs can modulate the frequency of tropical storms over this basin, as is believed to be the case in 1995 (Saunders and Harris 1997; Shapiro and Goldenberg 1998). In 1995, 19 tropical storms were observed, which represents just less than twice the climatological number. During the 1995 Atlantic tropical storm season, the mean sea surface temperature anomaly averaged over the Niño-3 region was $-0.8°C$. This anomaly is not strong enough to explain the exceptional frequency of Atlantic tropical storms that year. On the other hand, Atlantic SSTs displayed particularly warm anomalies during that year particularly in the eastern part of the basin where the anomaly exceeded 1°C.

The ECMWF seasonal forecasts starting on 1 July 1995 predict a realistic temperature anomaly over the North Atlantic (Fig. 11) for the period August to September. The SST anomaly was already present in the initial conditions and the model maintains this anomaly for all the period of integration (not shown). In addition, the model correctly predicts the evolution in time of the anomaly with a cooling in the eastern part of the basin, and warming in the western part of the basin (not shown). The seasonal forecast system predicts more tropical storms in 1995 than in the climatology (defined in that case with the years 1991, 1992, 1993, 1994, and 1996) (Fig. 7) although the model underestimates the particularly large number of tropical storms in the beginning of the season. The model does not predict a La Niña event for that period, and the Atlantic sea surface temperature anomalies appear as a likely explanation for the increased number of model tropical storms.

Gray (1997) relates the strong 1995 Atlantic tropical storm season to an interdecadal signal of Atlantic SSTs. He argues that Atlantic SSTs since 1995 are closer to SSTs in the 1950s when Atlantic tropical storms were particularly strong and numerous, in contrast to the 1970s and 1980s. According to Gray (1997), the cycle of salinity in the Atlantic oceanic conveyor belt is responsible for the interdecadal change of Atlantic SSTs. The ECMWF Seasonal Forecasting System does not simulate this mechanism. However, the presence of an interdecadal variability in the oceanic initial conditions makes it possible for the coupled GCM to eventually simulate its impact on the frequency of tropical storms. The ECMWF Seasonal Forecasting System predicts significantly more tropical storms during the period 1995–99 than during the first 4 yr (1991–94) (Fig. 7), consistent with observations. Whether this difference in model tropical storm frequency is due to interannual variability or to an interdecadal trend of SSTs is not clear, and nine years is certainly not enough to reach a firm conclusion on an interdecadal variability of the tropical storms simulated by the coupled model.

3) Comparison with a statistical forecast

Forecasts of Atlantic tropical storm frequency are issued each year by the Colorado State Hurricane Forecast Team (CSHFT; Gray et al. 1992, 1993, 1994). These forecasts, available since 1984, are based on statistical methods and are produced as early as November of the year prior to the predicted Atlantic tropical storm season. They are updated in April, June, and August. Since the ECMWF Seasonal Forecasting System only makes forecasts 6 months in advance, the CSHFT forecasts issued in June and in August will be compared to the ECMWF forecasts for the period 1991–99.

The CSHFT forecast in June tends to predict a tropical storm frequency close to climatology, whereas the ECMWF dynamical system predicts a much stronger interannual variability (Fig. 12). The interannual variations of Atlantic tropical storm frequency seem more realistically predicted with the ECMWF Seasonal Forecasting System than with the CSHFT forecast. The linear correlation between predicted and observed interannual variability of Atlantic tropical storm frequency is larger with the ECMWF seasonal forecast (0.78) than with the CSHFT forecast (0.55). The rms error is lower with the scaled ECMWF seasonal forecast (2.8) than with the CSHFT forecast (3.5). This suggests that the seasonal forecasting system described in this paper displays more skill in forecasting the Atlantic tropical storm frequency 3 months before the peak of the season than the statistical method developed at Colorado State University. However, in August, the CSHFT forecasts displays more skill than the ECMWF Seasonal Forecasting System in predicting the tropical storm frequency except for the El Niño year 1997 and the La Niña year 1998 (Fig. 12), where the ECMWF forecasts were particularly accurate. The linear correlation with the observed interannual variability is about 0.8 with both the ECMWF and the CSHFT forecasts. In summary both CSHFT and ECMWF forecasting systems display skill in forecasting the Atlantic tropical storm frequency from August. However the ECMWF Seasonal Forecasting System seems to produce more realistic forecasts than CSHFT in June.

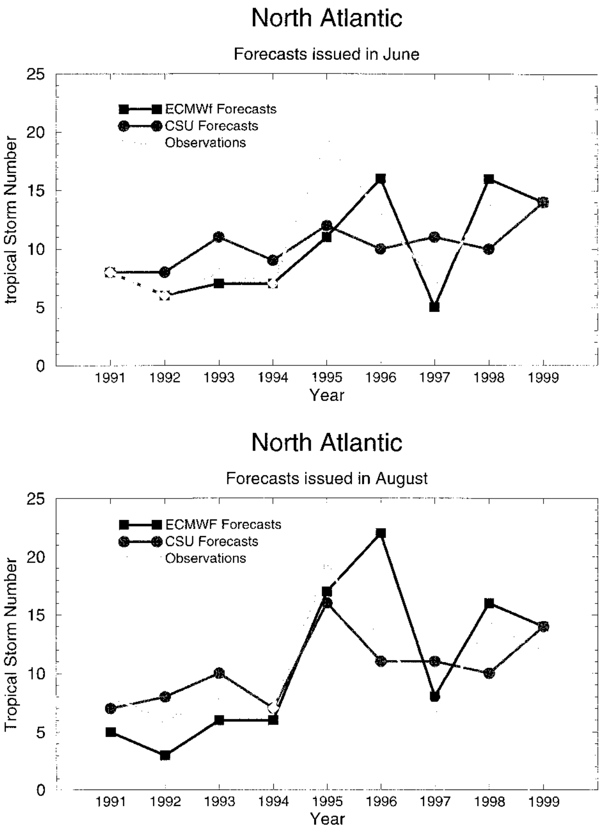

Fig. 12. Interannual variability of tropical storm frequency over the North Atlantic in observations (dashed line), predicted with the ECMWF Seasonal Forecasting System, then scaled (dark full line) and predicted with the CSHFT statistical model (light full line). Forecasts are issued in (top) Jun and (bottom) Aug.

8. Conclusions

The present paper explored the skill of seasonal forecasts of tropical storm frequency and location using a dynamical method instead of the statistical methods that are currently operational. This method is not purely dynamic since the frequency of model tropical cyclones has been adjusted based on a bias in the model. The tropical storms generated by an ensemble of coupled GCM integrations are tracked using an objective procedure. The probability distribution function of the ensemble forecast of tropical storm frequency or location is compared to the probability distribution function of the climatology. A forecast is then issued when both probability distribution functions are significantly different with a level of confidence larger than 90% according to the WMW test.

Although it generates fewer tropical storms than observed, particularly over the North Atlantic and the eastern North Pacific, the coupled GCM displays significant skill in forecasting the interannual variability of tropical storm frequency over the North Atlantic and the western North Pacific. It also forecasts realistic shifts in the tropical storm genesis location over the western North Pacific. This suggests that such a model could be used to produce skillful forecasts of geographic threats. The model is not as successful over the other basins however, particularly over the Indian Ocean, where the model appears to have little skill. The skill of the coupled GCM in ENSO forecasts contributes significantly to its skill in predicting a realistic interannual variability of tropical storm frequency over the North Atlantic and the western North Pacific.

The present seasonal forecasting system suffers several limitations. The physical structures of model tropical storms differ considerably from observations due to the too coarse horizontal resolution of the atmospheric GCM. The climatological frequency of tropical storms is generally significantly lower than observed and the automatic procedure for tracking model tropical storms is not perfect (the criteria are harsh in order to avoid selecting nontropical storm systems, and several tropical storms may be rejected). Improving the realism of model tropical storm structure and climatology and improving their tracking will probably improve the seasonal forecasts. The atmospheric component of the coupled model forced by observed SSTs performs somewhat better than the coupled model, particularly over the North Atlantic (Fig. 4 and Table 5) but most of the errors remain. This suggests that errors in the atmospheric model are the dominant factor reducing the skill of the present system.

The present study suggests that it is possible to realize seasonal forecasts of tropical storm statistics by using a dynamical system. However, a larger sample of years of background integrations of the coupled GCM would be needed to fully assess the skill of the dynamical forecast. Future plans for the longer term include the use of a finer-resolution GCM (T159). This would help to improve the detection of model tropical storms and make forecasts of other tropical storm statistics such as interannual interannual variability of mean tracks or probability of landfalls over large regions more feasible.

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