High Resolution Ensemble Atlantic Basin Seasonal Hurricane Simulations

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Abstract

A very high resolution ensemble of seasonal Atlantic hurricane simulations are conducted using the FSU/COAPS global spectral model at a resolution T126L27 (a Gaussian grid spacing of 0.94˚). Four integrations comprising the ensembles were generated using the European Centre for Medium Range Weather Forecasts (ECMWF) time lagged initial atmospheric conditions centered on 1 June for the 20-years, 1986 to 2005. The sea surface temperatures (SSTs) were updated weekly using the Reynolds and Smith (1994) observed data. An objective tracking algorithm obtained from the ECMWF and modified for our model's resolution was used to detect and track the storms. It was found that the model's storm structure and tracks lengths are realistic. In addition, the 20-year interannual variability was simulated well by the ensembles with a 0.78 ensemble mean correlation. The ensembles tend to overestimate/underestimate the numbers of storms during July/September and produced only one CAT4 level storm on the Saffir-Simpson scale. Similar problems are noted in other global model simulations. All ensembles did well in simulating the record number of storms forming in the Atlantic basin during 1995 and 2005 and showed an increase in number of storms during La Niña and a decrease during El Niño events. The results are found to be sensitive to the choices of convection schemes and diffusion coefficients. The overall conclusion is that high resolution models such as the one used here are needed to better hindcast the interannual variability, however, going to even higher resolution does not guarantee better interannual variability, tracks or intensity. Improved physical parameterizations, such as using a non-hydrostatic convection schemes are likely to more accurately represent hurricane intensity.

1. Introduction

Manabe et al. (1970) were the first to show that a very low resolution General Circulation Model (GCM) could simulate hurricane-like vortices. Due to the resolution of the GCM, the storm structure tended to be much larger and weaker than observed with characteristic scales on the order of 2000-4000km. As computing power and our knowledge of tropical systems has increased, so has our ability to simulate hurricane-like vortices in current CGMS. Bengtsson et al. (1982, 1995, 2006); Broccoli and Manabe (1990); Haarsma et al. (1993) have all shown that one can perform seasonal hindcasting of tropical storm activity (i.e., simulations with known observed sea surface temperatures) a season or more in advance using models of various horizontal resolutions and that the hurricane-like vortices have a climatology and physical structure similar to the observed.

The basic idea of seasonal hindcasting of tropical storms is related to the idea that tropical storms activity is closely tied to characteristics of the large-scale circulation, sea surface temperatures (SSTs), horizontal vertical shear and low level vorticity (e.g. Gray 1979). Most of the time changes in the large-scale features can have a pronounced impact on the variability of Atlantic tropical storm activity. For example, during an El Niño, the number of tropical storms in the Atlantic tends to be reduced (Gray 1984, Shapiro 1987). It is these large-scale features that the GCM is able to reproduce reasonably well and thereby allowing GCMs to be used to forecast/hindcast tropical activity. The exact reason for the genesis of warm-core features in the GCMs' tropical system has however been called into question (Evans 1992, Lighthill et al. 1994) because of these features' sensitivity to the vertical wind shear. However, the interannual variability of modeled tropical storms has been found to be consistent with observations (Vitart and Stockdale 2001).

This study is using of an ensemble of seasonal integrations (June-November) using the FSU/COAPS global spectral model at a horizontal resolution of T126L27 (a Gaussian grid spacing of

0.94˚) in hindcasting the western Atlantic basin tropical storm activity for the 20-year period, 1986-2005. This paper examines whether the use of a high horizontal resolution improves the seasonal Atlantic hurricane hindcasts in terms of tracks, intensities, frequencies and interannual variability. The storm structure when compared to lower and higher resolution modeling studies show that the model is able to capture very well the observed interannual hurricane variability. While there has been studies that use higher horizontal resolution (e.g., Bengtsson et al. 2006; Oouchi et al. 2006), this work shows that one cannot discard the significance of the choices made for the dissipation coefficients and for other physical parameterizations.

This paper is divided up into the following six sections. Section 2 discusses the model and the experimental setup. The detection and tracking algorithm is discussed in Section 3. Section 4 discusses the results. Some sensitivity to the choice of convection scheme and diffusion coefficients are briefly discussed in Section 5. Summary and conclusions are presented in Section 6.

2. Model and Experiments

The Florida State University/Center for Ocean Atmospheric Prediction Studies (FSU/COAPS) model (Cocke and LaRow 2000) was used in the study. The resolution of the model was T126 with 27 vertical levels (T126L27). A relaxed Arakawa-Schubert deep convection scheme recently used at the Naval Research Laboratory (Hogan and Rosmond 1991) was the convection scheme employed in the experiments. A total of 80 experiments were conducted, four ensemble members for each of the 20 years (1986-2005). The time lagged initial conditions for the atmospheric model were obtained from the ECMWF reanalysis and were centered on 1 June of the respective year. The integrations were conducted for the six month period (June-November) to coincide with the Atlantic basin hurricane season. The observed SSTs were obtained from the Reynolds and Smith ((1994) dataset and were updated once per week using daily linear interpolation between the weeks.

3. Detection and Tracking Algorithm

Identifying interannual tropical storm variability can be divided into three methods. The first method uses statistical techniques (Gray et al. 1992, 1993, 1994; Hess et al. 1995, etc). The second method uses seasonal genesis parameters which are known to affect tropical cyclone activity (Ryan et al. 1992; Watterson et al. 1995; Thorncroft and Pytharoulis 2001). The third approach, and the one used in this paper, is to detect and track the simulated tropical cyclones activity in the FSU/COAPS GCM.

The detection algorithm is the same as that used in Vitart et al. (2003) and modified slightly for our model resolution. The detection algorithm is based on four criteria. First, a local vorticity maximum greater than $3.5 \times 10^{-5} s^{-1}$ is located at 850hPa. Next, the closet local minimum in sea level pressure is detected and defines the center of the storm. Third, the closest local maximum in temperature is detected between 500hPa and 200hPa and defines the warm core. The distance between the center of the storm and the center of the warm core must not exceed 2° latitude. From the center of the storm the temperature must decrease by at least 7°C within all directions within a distance of 4°. For our study, this was the criteria changed for our model resolution. Finally, the closest local maximum thickness between 1000hPa and 200hPa is identified and must not exceed 2° from the storm center. Detection of the tropical system must last for a minimum of two consecutive days for it to be considered a tropical system. In contrast to the Camargo and Zebiak (2002) detection algorithm which is both dependent upon model resolution and basin, the Vitart algorithm is based only on model resolution. In this paper, the observed tropical storms are identified by the National Hurricane Center Best Track data set, HURDAT (available at http://www.nhc.noaa.gov/pastall.shtml).

4. Results

4.1 Model Structure

Before examining the model's ability to simulate interannual variations in the west Atlantic Basin hurricane activity, we will first discuss the model's ability to simulate the hurricane-like structures. Several previous studies (e.g., Wu and Lau 1992, Bengtsson et al 1995 and Vitart et al. 1997) have all shown with various horizontal resolutions hurricane like features – convergence at low levels, divergence at upper levels, large amounts of precipitation and high relative humidities. These hurricane like features are dependent upon model resolution with more coarse the resolution the larger the hurricane features tends to be (Bengtsson et al. 1995).

Figure (1a) shows a randomly selected FSU/COAPS model hurricane's sea level pressure from ensemble one on day 134 of the integration. The storm is located just north of Puerto Rico. The central pressure is near 950hPa and the model exhibits closed pressure contours starting at 1005hPa indicating an intense storm; a category 3 on the Saffir-Simpson scale. The 850hPa wind magnitude (Figure 1b) shows a wind maximum of 50m s^{-1} on the eastern side of the storm and relatively calm winds near the center of the storm.

A east-west cross section through the storm center (at 24°N) of the temperature anomaly, meridional wind component and the total wind are shown in Figures (1c-e). The temperature anomaly (Figure 1c) shows the classic warm core structure of a mature hurricane with anomalies of 9K located near the center of the storm and extending upwards from about 500hPa to 200hPa. Cold anomalies can be found above 150hPa. The meridional wind cross section (Figure 1d) shows the cyclonic circulation through the depth of the troposphere with a slight hint of anticyclonic circulation above 150hPa. The strongest winds are located near 850hPa and reach speeds of 50m s^{-1}; as shown in Figure (1b). The strongest winds are; however, found near 800hPa and decrease upward. Weaker winds in the center of the storm are clearly identified with 5-10m s^{-1} winds extending downward into the center of the storm. Similar wind structure is found in the total 850hPa wind magnitude (Figure 1e) with the strongest winds located on the eastern side of the storm. The model storm is compact in size, something that is not seen in lower horizontal resolution studies.

4.2 Interannual Variability

The number of storms for each year from each ensemble is calculated from the detection algorithm and the ensemble mean is plotted along with the observed as a function of time in Figure (2). No rescaling of the figure was done. The observed number of storms is shown with the solid black line while the ensemble mean is the dotted line. The spread of the ensembles is shown by the two squares. Overall the ensemble mean does well in simulating the interannual variations in the storm numbers except during the cold ENSO event years of 1998 and 1999 when the ensemble mean was much higher than the observed. The spread of the ensembles was largest during the warm ENSO event of 1997 (a spread of 11 storms) although the ensemble mean was only two storms off the observed. As stated by Wu and Lau (1992) El Niño tends to reduce the number of tropical storms in the Atlantic while during La Niña the opposite occurs. This pattern of reduced number of storms during a warm event and increased numbers during a cold event is clearly seen in the ensemble mean. Although with such a large spread during the 1997 warm event shows that the model could be sensitive to the ENSO state, but with such a small record and ensemble size it is difficult to be certain. The model did well in simulating the record number of storms during 1995 and 2005.

The 20-year temporal correlation of the ensemble mean with the observed was 0.78. The observed variance was 25.25 for the 20-years of the study while the variance of the ensemble mean was slightly lower at 12.55, although ensembles one and four show variances much closer to the observed with values of 20.2 and 18.01 (see Table 1). The high correlation and variances noted are most likely related to the use of weekly observed SSTs and the choice of the convection scheme (as will be discussed briefly later). Table 1 shows the individual ensemble correlations, variance and the total number of storms for the entire 20-year period is shown below. Studies by (Gray 1984, Shapiro 1987 and Saunders and Harris 1997) all show that the SSTs can have a significant impact on the tropical storm statistics, especially in the Atlantic.

4.3 Frequency/Histogram

The observed and ensemble frequencies are shown in Figure (3). The observed monthly frequency (solid line) is calculated from the 20-years of the study. The observed shows a small increase from June to July and then a large increase in August with a peek in September followed by a sharp decline towards November. Although all four model ensembles (dashed lines) overestimate the number of storms in July and underestimate the storms during September. The magnitude is in good agreement with the observed, something that is not found in previous studies (e.g. Camargo and Zebiak 2002 (Fig 7a) or Camargo et al. (2005) (Fig. 6d)). Although these studies underestimated the number of tropical systems, they did; however, predict the maximum during September. Similar findings by Vitart et al. (1997) show a maximum number of storms occurring during September with an overestimate during July and a slight underestimate during September. All of these studies were with low resolution models, (T42), indicating that higher resolution (as shown in this study) does not guarantee the correct frequency distribution but might help with the magnitude of the distribution. The individual members of the ensemble all show the observed decline in storm activity going from October to November.

For each of the four ensembles the storm's lowest surface pressure was identified, accumulated and plotted as a histogram in Figure (4). Out of the four ensembles, the lowest surface pressure found was 936hPa, and occurred during 2001, indicating that even at this horizontal resolution the model was able to generate only one category 4 storm on the Saffir-Simpson scale and no category 5 storms. Intensity is still a problem despite the increased horizontal resolution. Similar difficulties in producing intense storms using a even higher resolution model than used in this study were noted by Bengtsson et al. (2006) and Oouchi et al. (2006). Indicating that model resolution (and perhaps model physics) are still insufficient. Switching the physical parameterization schemes and/or using a non-hydrostatic convection scheme maybe would yield more intense storms.

The ensembles produced the largest number of storms (around 600) with surface pressures between 980-1000hPa, mostly category 1 on the Saffir-Simpson scale. The majority of the rest of the storms range from 950hPa to 980hPa, category 2-3 level storms. There was a sharp decline (to around 70) storms with pressures greater than 1000hPa indicating that it is very difficult for storms with high surface pressures to satisfy the detection algorithm for more than two days. The underestimation of the surface pressure is still a problem with operational real-time forecasters (DeMaria et al. 2005). This problem also appears to be related to the insufficient horizontal resolution (Bender and Ginis 2000).

4.4 Storm Tracks

All storm tracks for the entire 20-years for June-November from ensemble 1 and the observed HURDAT data are shown in Figure (5a,b). The observed total number of storms for that period was 245 and the ensemble identified 242 storms (see Table 1). This close similarity of the ensemble members to the observed number is in contrast to other modeling studies which underestimate the number of tropical storms in the Atlantic (e.g., Camargo and Zebiak 2002, Bengtsson et al. 2006 and Vitart et al. 2006).

The model forms most of the storms near (10˚N,45˚W) with a west to northwest tracking

(Figure 5a). Most of the model storms re-curve towards to northeast before coming close to the North American eastern coastline with only a few storms making landfall along the east coast of the United States. The model tracks are in slight contrast to the observed tracks (Figure 5b) which show a more westward movement towards the U.S. before re-curving and consequently many more storms strike the eastern U.S. in the observations. In addition, observations show more storms tend to form closer to Africa. The model produced more land falling storms along the Gulf of Mexico coastline than along the eastern seaboard, especially along the northern Florida and the Alabama coasts but again too few compared to the observations. Similar tracks are also noted in the other ensemble members and therefore not shown.

The 1986-2002 850hPa streamlines were used to examine the discrepancy in ensemble one's model tracks as compared to the ECMWF reanalysis. It will be assumed that the 850hPa winds are a reasonable indicator of the steering currents for the storms. The streamlines from ensemble one are shown in Figures (6a,b). For examination purposes, because the model's hurricanes peak in August, the hurricane season was divided into two parts, June-August (Figure 6a) and September-November (Figure 6b). Similar streamline plots from the ECMWF reanalysis are shown in Figures (7a,b). During the first half of the season (Figs 6a, 7a), the model's 850hPa streamlines were similar to the ECMWF reanalysis except off the eastern U.S. coast where the flow is a little weaker in the model which tended to steer the majority of storms away from the U.S. The flow into the Gulf of Mexico was well simulated by the ensemble. Although not shown, the first half of the hurricane season is when most of the Gulf storms occurred with the favorable steering currents.

During the second half of the hurricane season (Figs 6b,7b), the 850hPa streamlines are no longer simulated well by the ensemble into the Gulf of Mexico and therefore not many storms occurred in the Gulf. The flow over the Atlantic is, however, simulated well by the ensemble with westward flow approaching the southeastern U.S. before eventually re-curving northeast.

The longest duration of a model storm, from all ensemble members, was 19.5 days while the average model storm duration was close to five days. Observations show that the average duration of an Atlantic tropical system is six days. Vitart et al. (1997) found that their average storm duration was four days.

5. A note on convection schemes and diffusion coefficients

Although not shown in this paper, two other convection schemes were tried. Both convection schemes were developed and are presently used at major U.S. centers. Only one experiment each for the 20-year period for both convection schemes were conducted. The results varied considerably with one of the convection schemes (a simplified Arakawa-Schubert scheme) failing to produce any storms during the 20-year period. This could perhaps be related to the stringent requirements for the detection of a tropical storm used in this paper. It is possible that by using a weaker detection criteria (the 7° warm core criteria could be too high for this convection scheme) that this convection scheme would have developed some tropical systems. The other convection scheme (a relative humidity and CAPE threshold scheme) did as well as reported in this paper except during the last 10-years of the experiment when only half the numbers of observed storms were produced. So the choice of convection scheme in our model is important. Similar findings were found by Vitart et al. (2001) where changes in the thermodynamics of the mean tropical background generated by different convection schemes were found to be the main cause for the changes in the tropical storm statistics.

Additionally, a brief test was done on the sensitivity of the value of the highly tunable diffusion coefficients (temperature, moisture, momentum and vorticity). The results show that the number of storms in our model was very sensitive to changes in the coefficients. During one experiment, the number of storms went from eight to 23 when smaller diffusion coefficients were used; the observed number of storms was six. We plan to study these sensitivities further in a future paper.

6. Conclusions/Summary

In this paper we have examined the use of the FSU/COAPS high resolution global model (T126L27) to study the seasonal hindcasting and variability of the western Atlantic hurricane seasons from 1986 to 2005. Weekly observed SSTs were used as lower boundary conditions and time lagged ECMWF initial conditions for the atmosphere were also used. This study used the Vitart et al. (2003) tropical storm detection/tracking algorithm but slightly modified for our higher resolution.

The ensemble members did a remarkable job in reproducing the total number of storms for the 20-year period: 242, 234, 234 and 249 storms compared to the observed value of 245 storms. The variability of the ensemble mean was also captured well with a temporal correlation of 0.78. The ensemble members also tended to cluster around the ensemble mean during much of the 20-years. Most notable exception was the El Niño year of 1997 when the ensemble spread was 11 storms, although the ensemble mean was only two storms away from the observed. During the cold events of 1998 and 1999 the model overestimated the number of storms with a similar increase in the spread. The model appears sensitive to the ENSO state, although with only 20-years it is difficult to be quantitatively definite. The model did produce fewer storms during warm events and more storms during cold events, something that is known to occur in the Atlantic. The observed variance during the 20 years was 25.25 and the ensemble mean was 12.75 with higher variances (greater than 18) noted in two of the ensemble members.

The tracks from the ensembles showed that the model tends to move the storms away from the United States too quickly, when observations show that storms come much closer to the eastern seaboard before re-curving. There were also too few storms which made it into the Gulf of Mexico compared to observations. Both of these results are a result of our atmospheric model's Atlantic steering flow (approximated by the 850hPa streamlines). The streamlines showed that during the first half of the hurricane season the westward flow over the Atlantic tends to turn northeast before it approaches the east coast of the United States while the model simulates well the westward flow into the Gulf of Mexico. The opposite occurs during the second half of the hurricane season. The westward flow into the Gulf of Mexico is prevented while the westward flow over the Atlantic is much better simulated with respect to the ECMWF reanalysis.

As far as intensity, the model produced more category 1 storms than any other category. Category 2-3 were next most frequent. The ensembles only generated one category 4 storm during the entire 20 years, indicating that it is still difficult even at this high resolutions to produce intense storms. Similar problems in simulating intense storms were noted by other even higher resolution models, suggesting resolution and perhaps even model physics are still insufficient. It remains a question as to whether a different convection scheme could produce more intense storms while still capturing the interannual variability. The ensembles overestimate/underestimate the number of storms forming during July/September although the magnitude of the frequency was well simulated.

One final thought, the results of this paper are encouraging that if given observed weekly updated SSTs the model can produced the observed interannual variability and total storm numbers with good fidelity. Tracks and intensities still remain problematic even at high resolutions; however, so at this stage using models at these resolutions (and physics) to study greenhouse gas emissions or global warming storm statistics (eg., intensity) seems premature.

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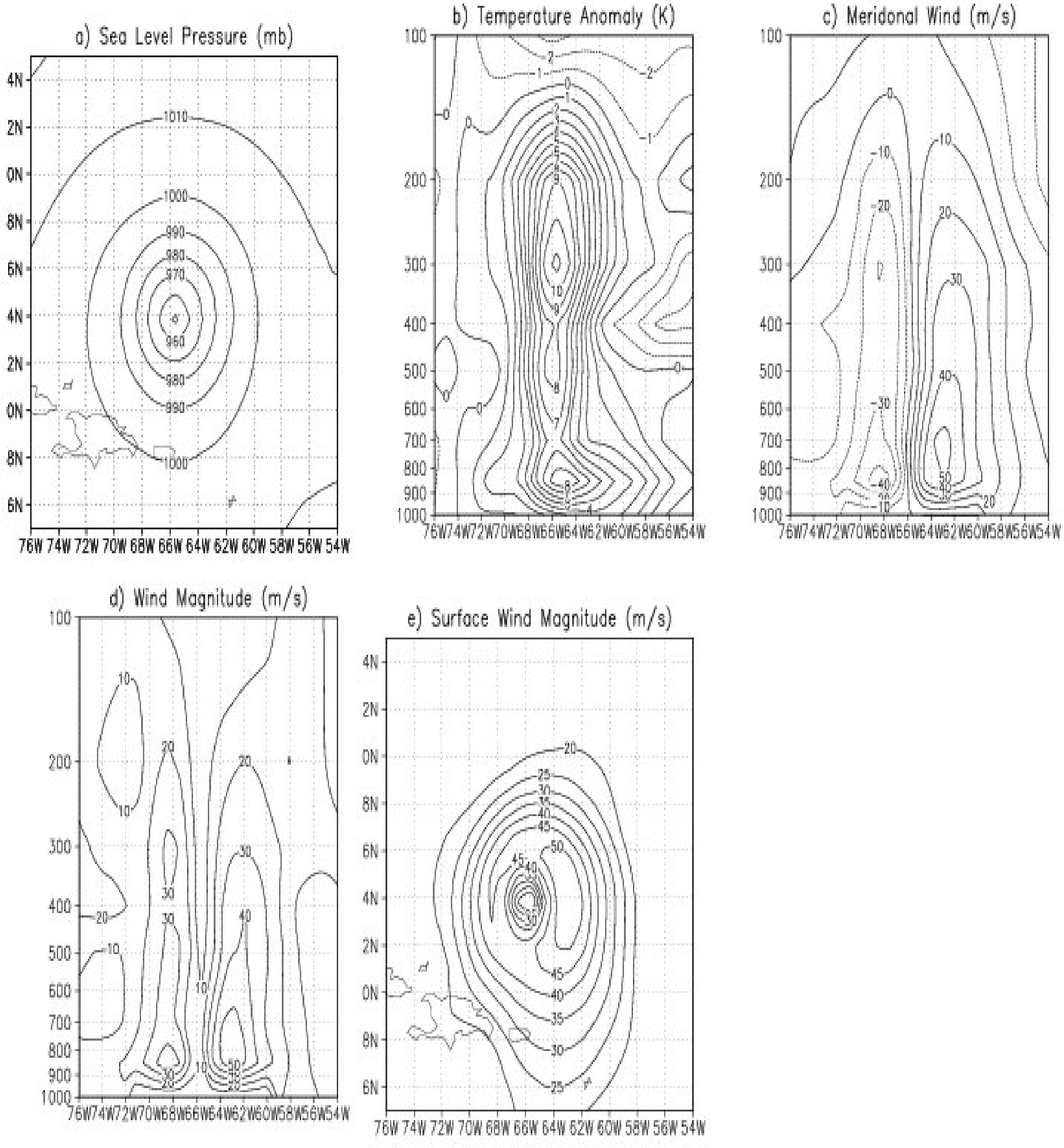

a) Sea Level Pressure (mb)

b) Temperature Anomaly (K)

c) Meridonal Wind (m/s)

d) Wind Magnitude (m/s)

e) Surface Wind Magnitude (m/s)

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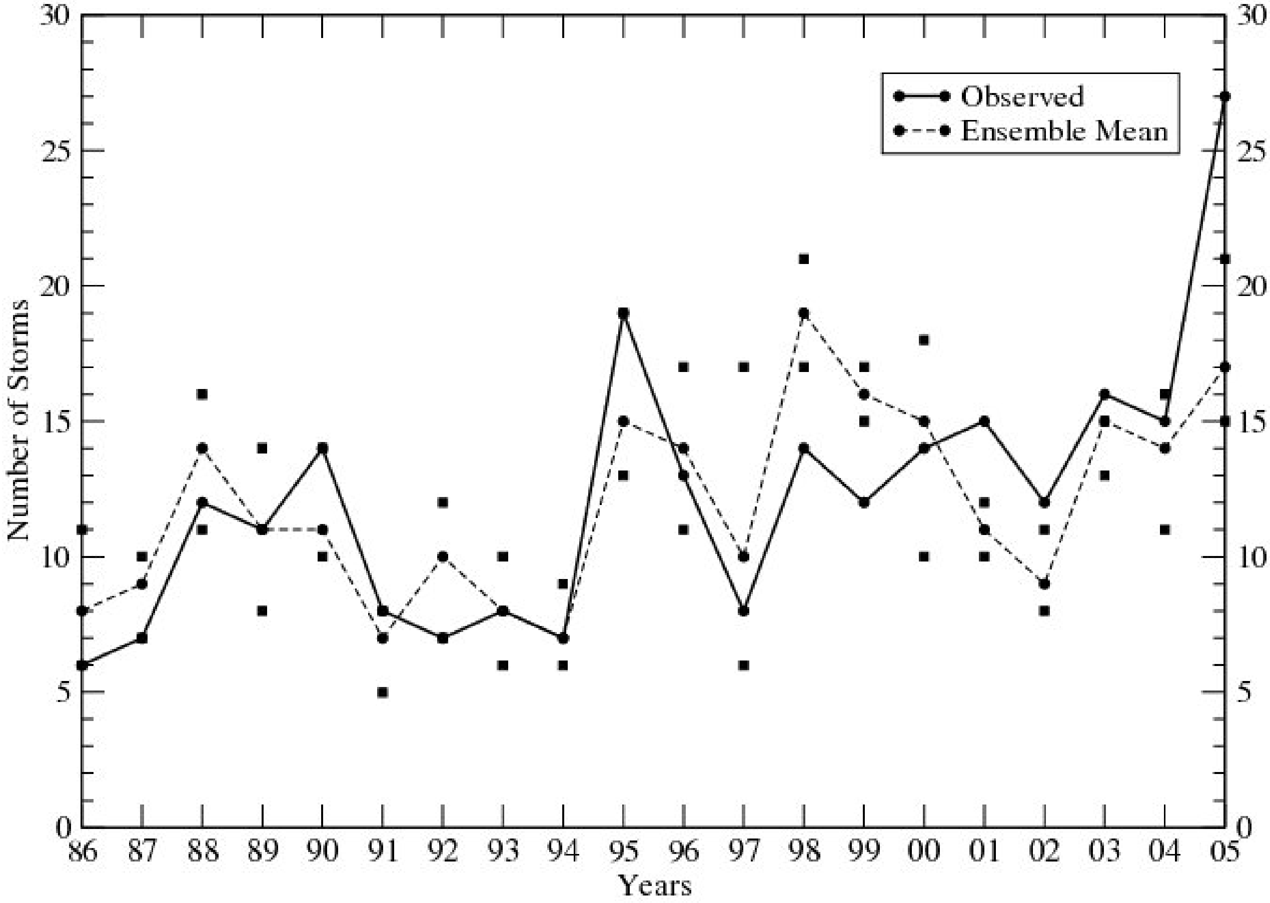

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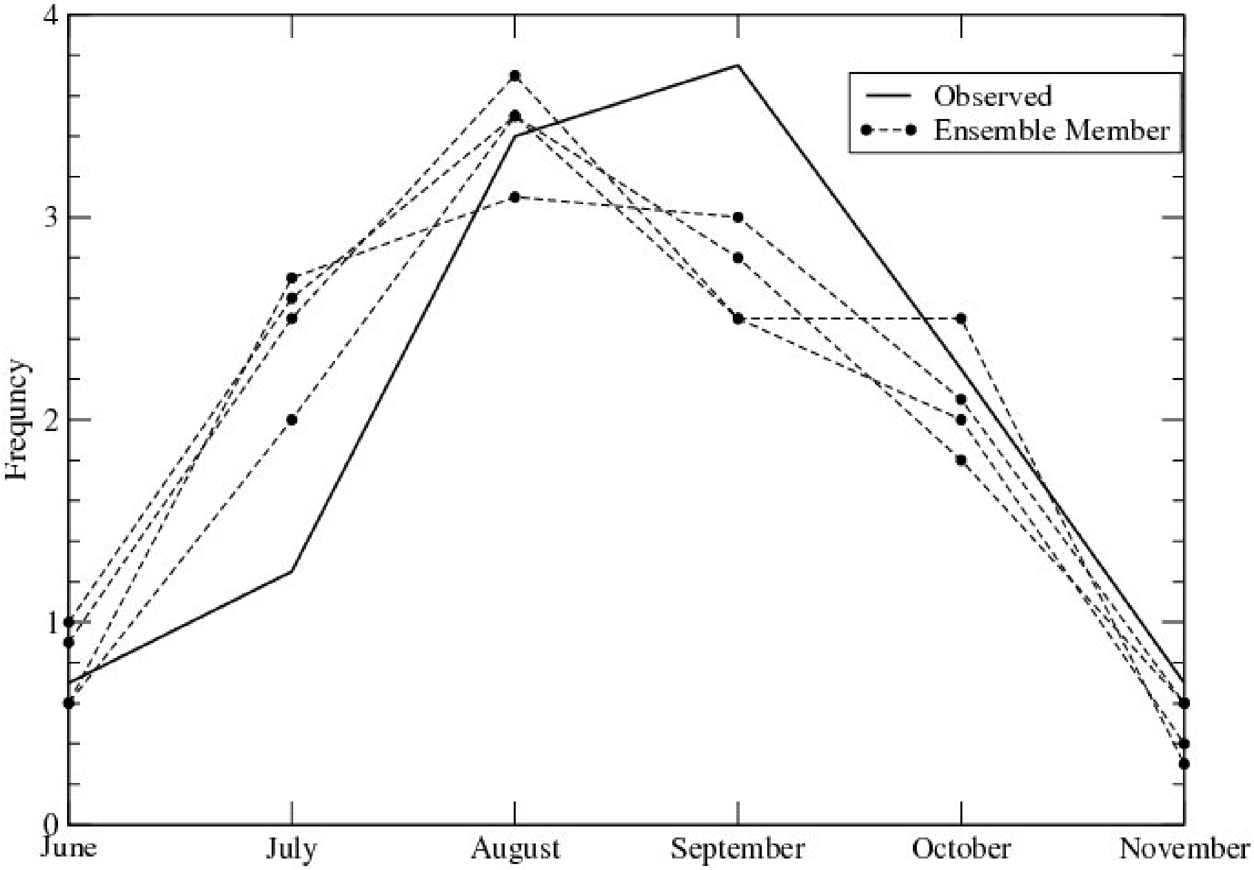

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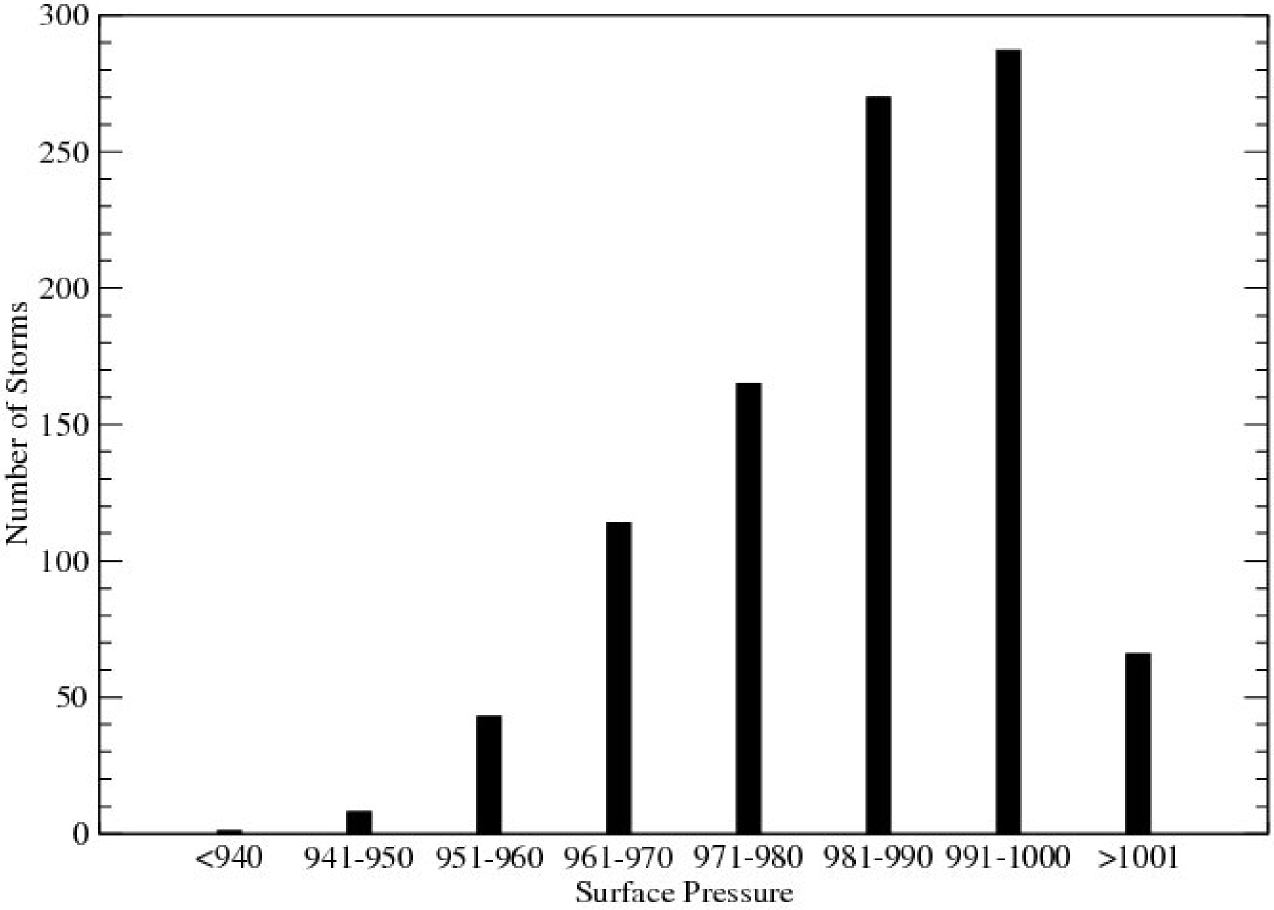

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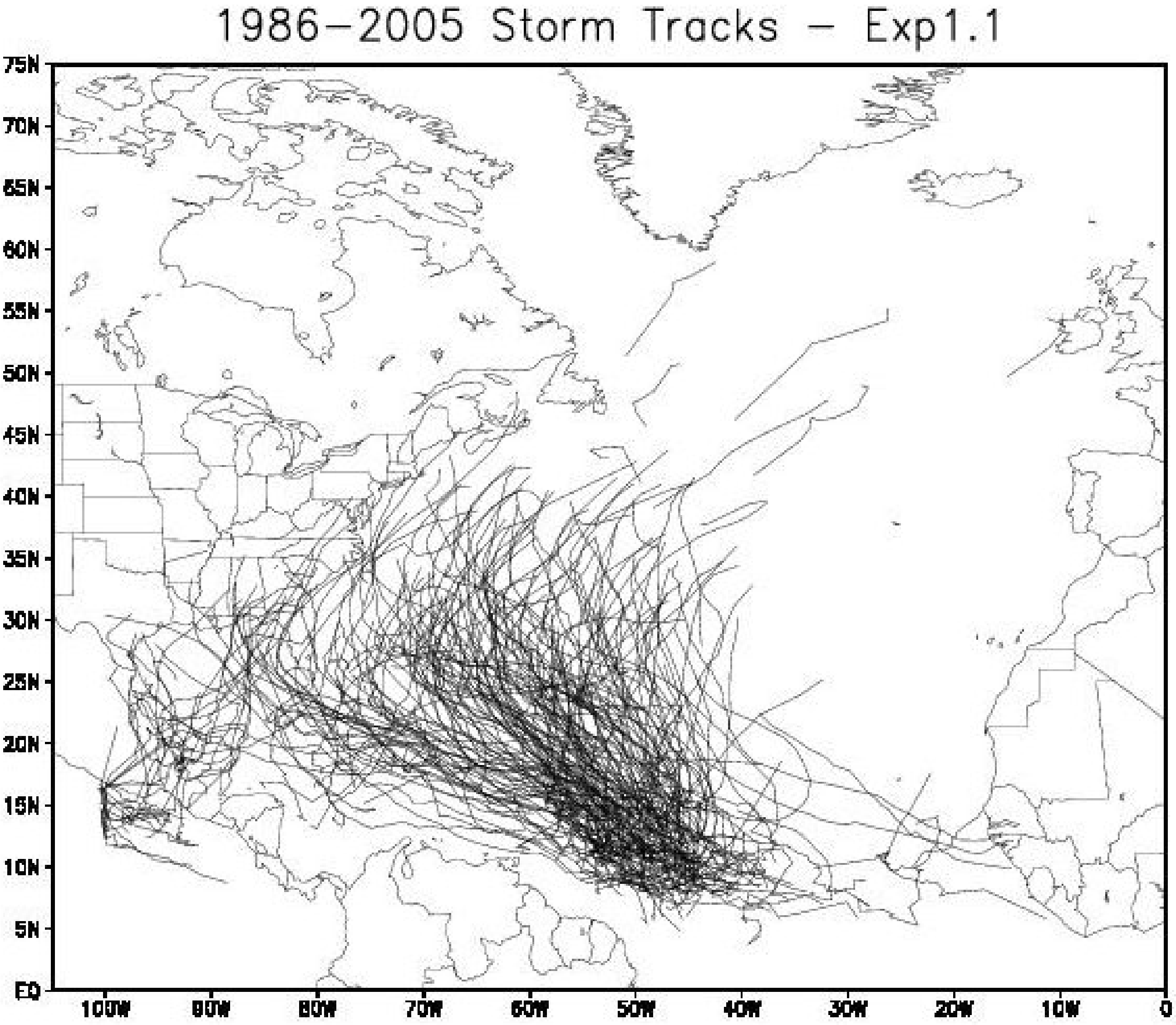

Figure 5a. Model storm tracks for the entire hurricane season (June-November) 1986-2005 from ensemble member 1.

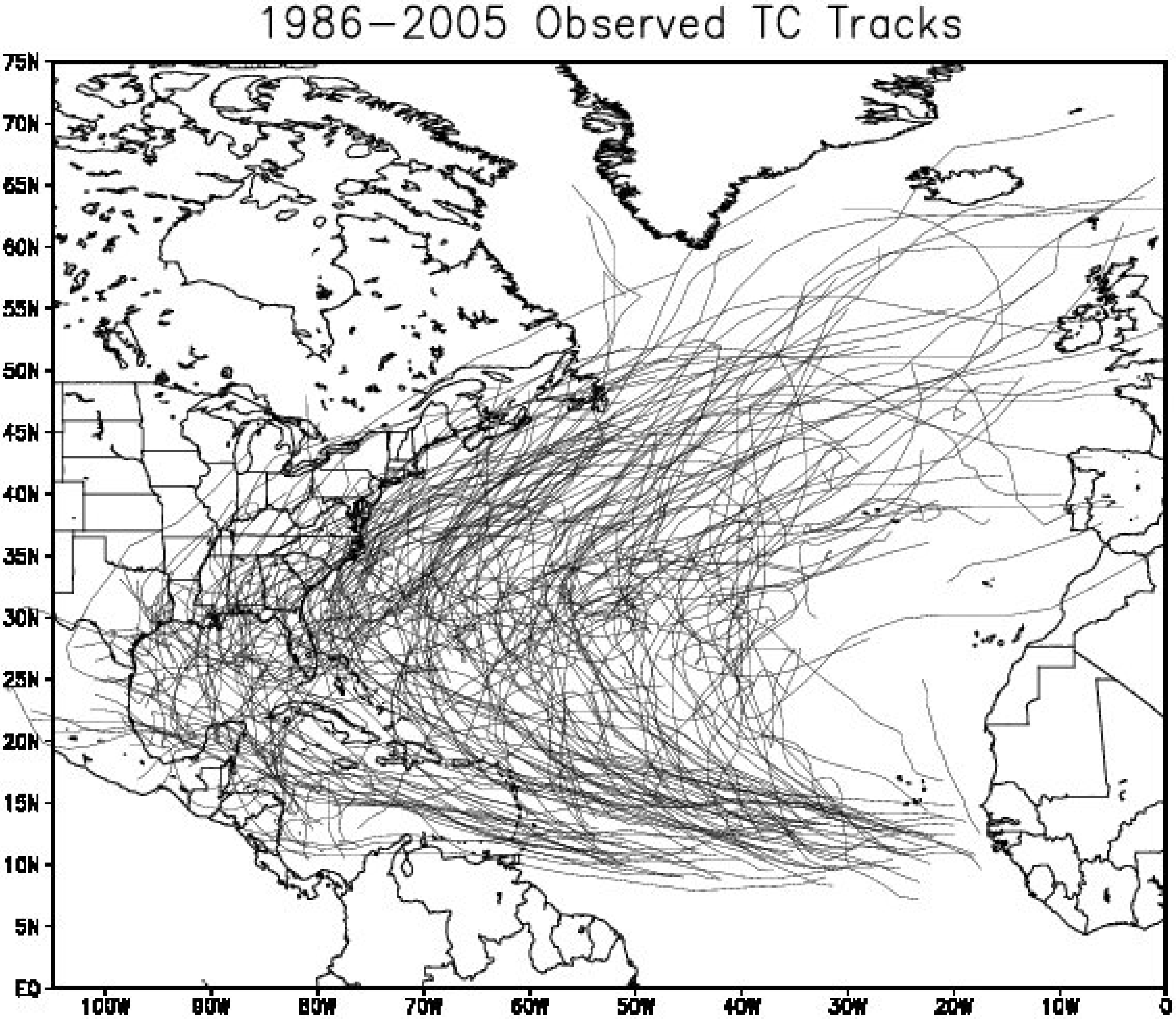

Figure 5b. Observed storm tracks from the HURDAT dataset for the entire hurricane season (June-November) 1986-2005.

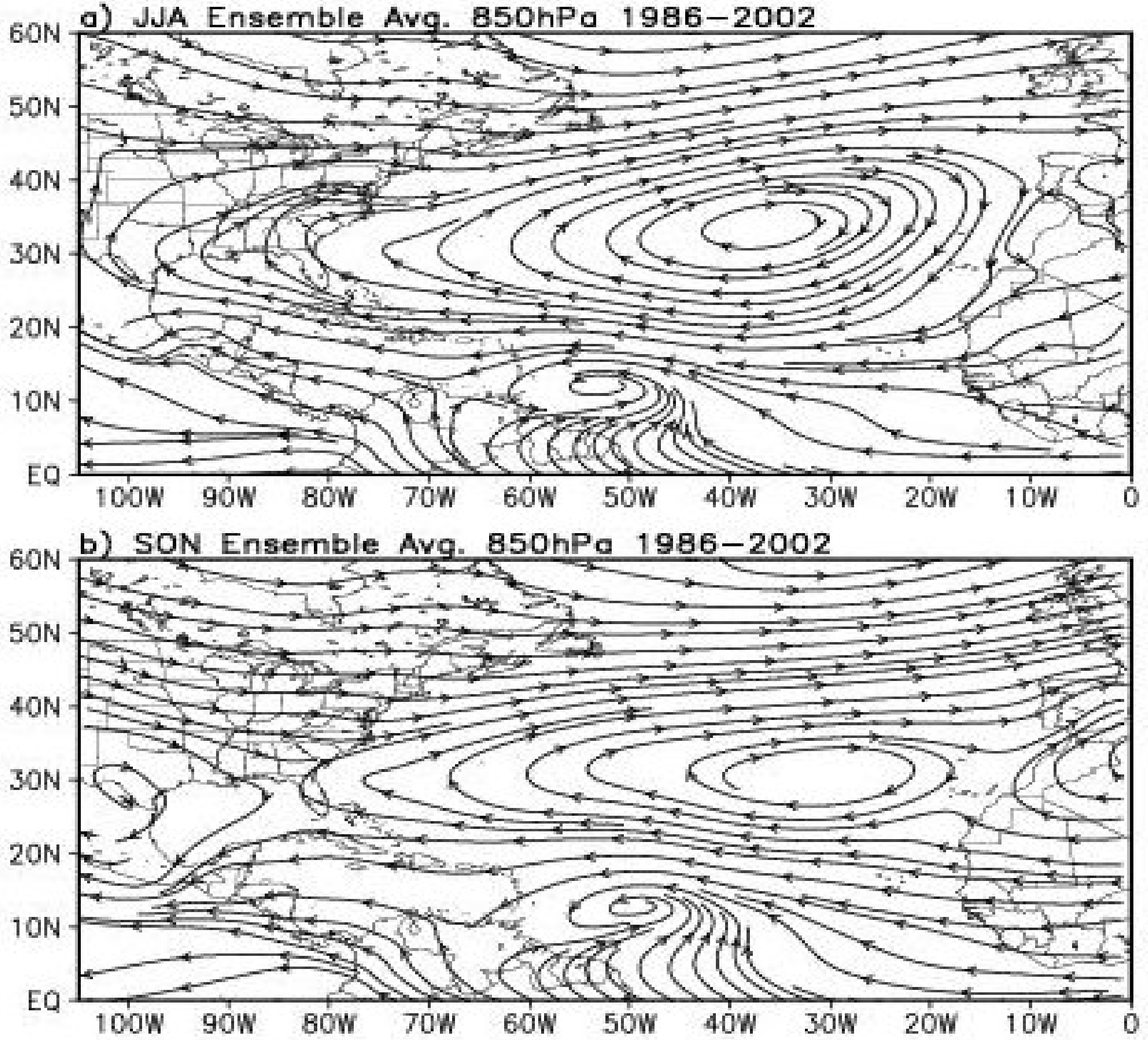

Figure 6. Average 850hPa streamlines for 1986-2002. (a) Ensemble 1, June-August (b) Ensemble 1, September-November.

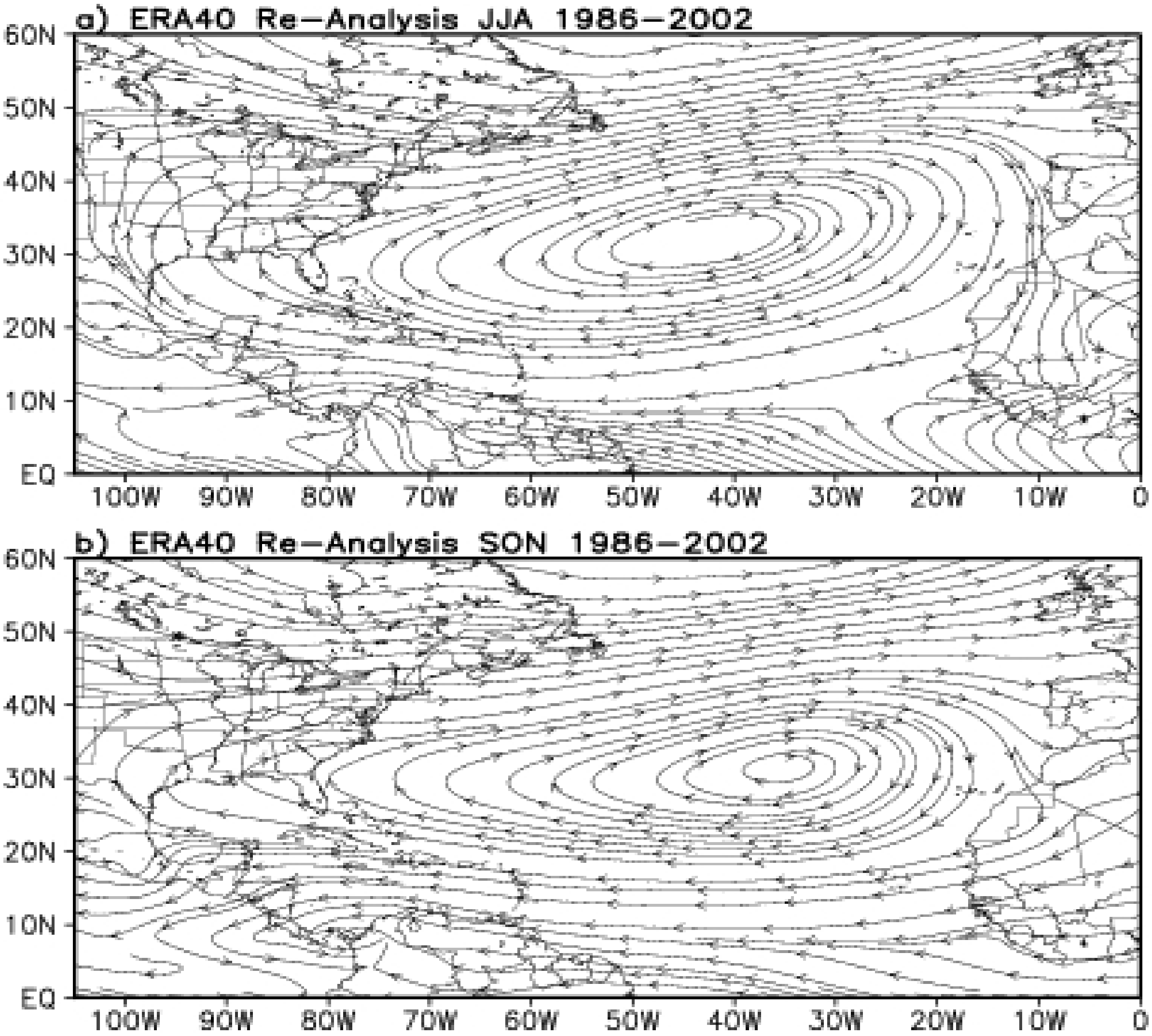

Figure 7. Average ECMWF Reanalysis 850hPa streamlines for 1986-2002. (a) June-August (b) September-November.

Table 1. Shows the total number of storms during the 20-year period from each ensemble and the observed. The 20-year temporal correlations between the ensembles and the observed are also shown along with the observed and ensembles variance.

	Observations	***Ensemble 1***	***Ensemble 2***	***Ensemble 3***	***Ensemble 4***
Total Storms	245	242	234	234	249
Correlation		0.76	0.51	0.71	0.62
Variance	25.25	20.2	12.96	18.01	14.89