Seasonal Atlantic tropical cyclone hindcasting/forecasting using two sea surface temperature datasets

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Seasonal Atlantic basin tropical cyclone hindcasts are conducted from 1986–2005 using the Florida State University/Center for Ocean Atmospheric Prediction Studies atmospheric global spectral model and two sea surface temperature products. The two sea surface temperature products are: the National Oceanic and Atmospheric Administrations Climate Forecast System Model’s 1 June forecast and the weekly observed sea surface temperatures. The hindcasts extend through the 180-day Atlantic hurricane season. A four member ensemble is generated for each year using time-lagged atmospheric initial conditions centered on 1 June of the respective year. The interannual variability of total number of Atlantic storms (tropical storms plus hurricanes) and accumulated cyclone energy using both sea surface temperature products yield high correlations which are statistically significant, although using the observed sea surface temperature product yields higher correlations. The results indicates that the Climate Forecast System Model’s sea surface temperatures are suitable for use in real-time seasonal tropical cyclone forecasting in the Atlantic basin in a two-tiered approach.


1. Introduction

Dynamical forecasting/hindcasting of tropical cyclone (TC) activity a season or more in advance is being conducted at a few research/government labs and academic institutions [e.g., Vitart et al., 2007; Camargo and Barnston, 2009; LaRow et al., 2008; Zhao et al., 2009]. Typically, these dynamical models are global atmospheric general circulation models (AGCMs) with horizontal grid spacing ranging from around 50 km to several hundred kilometers. These AGCMs exhibit hindcasting/hindcast skill of tropical cyclone activity that is in many cases superior to well known statistical models. For example, in the multi-model study of Vitart et al. [2007] a correlation coefficient of 0.81 was achieved between observed and predicted hurricane counts. Because of the relatively coarse horizontal resolution of the AGCMs these hurricane-type vortices are larger than their real world counterparts and as a result lack the mesoscale structures found in hurricanes such as an eye wall [Bengtsson et al., 1995; Vitart et al., 1997]. The idea that AGCMs can be used to forecast seasonal TC activity is largely due to the fact that tropical cyclones are modulated, especially in the North Atlantic, by the large-scale atmospheric conditions [e.g., Gray, 1979]. AGCMs are able to predict with a degree of skill the large-scale patterns arising from changes in the tropical sea surface temperatures.

2. Model and Experimental Setup

The Florida State University/Center for Ocean-Atmospheric Prediction Studies (FSU/COAPS) global AGCM [Cocke and LaRow, 2000] is used to study the predictive skill of TC activity in the North Atlantic. The AGCM was run for 20 hurricane seasons (June–November) from 1986–2005 using two sea surface temperature (SST) datasets. The first SST dataset is the Reynolds et al. [2002] weekly observed dataset (hereafter called OBS). Using observed SST data provides for an estimate of the possible upper bounds of skill in TC forecasting [Camargo et al., 2005]. The second SST dataset is produced by the Climate Forecast System model [Saha et al., 2006] used at the National Centers for Environmental Prediction (hereafter called CFS). A simple bias correction technique was applied to the CFS SSTs before using them in the FSU/COAPS model in order to remove the known CFS SST cold bias in the equatorial tropical Pacific and Atlantic [Saha et al., 2006] during the boreal summer. The bias correction is done in two steps. First, the predicted SST anomalies are determined from the forecast and model’s climatology and second, the anomaly is added onto the OBS climatology to the CFS SSTs before using them in the FSU/COAPS model’s climate drift. The FSU/COAPS model was run with a Gaussian grid spacing of 0.94° (T126) with 27 unevenly spaced vertical levels. For each year of the study, a four member atmospheric ensemble was generated using time-lagged initial conditions obtained from the European Centre for Medium Range Weather Forecasts (ECMWF) reanalysis and centered on 1 June of the respective year. The TCs are detected and tracked using an objective algorithm [Vitart et al., 2003] as modified in LaRow et al [2008].

3. SST Anomalies

Figure 1 shows the August, September, and October (ASO) average SST anomalies in the Niño-3.4 domain (top panel) and in the main development region (MDR) (bottom panel) from 1986–2005 from the CFS model and from the OBS datasets. The SST anomalies are examined since the number of Atlantic TCs in a given season has a large component that is predictable from SSTs [Vitart, 2006; LaRow et al., 2008; Zhao et al., 2009]. In this study, the MDR is defined as 10°N–20°N, 80°W–20°W. The
Niño-3.4 region (5°S–5°N, 170°W–120°W) is shown because the phase of the El Niño/Southern Oscillation (ENSO) cycle is known to help modulate TC activity in the northern Atlantic. Warm/cold ENSO events are generally associated with less/more TC activity in the Atlantic due in part to increased/decreased wind shear over the tropical Atlantic [Gray, 1984; Vitart and Anderson, 2001].

In Figure 1 (top) the OBS data shows that in ASO the Niño-3.4 region there were two large warm ENSO events (defined as SST anomalies greater than +1.5 K) during the 1986–2005 time period (1987 and 1997). The CFS model captured these positive anomalies although the CFS overestimated the magnitude by an average amount of almost 1.0 K. One large cold event occurred in 1988 with an observed average ASO anomaly of −1.5 K. The CFS SST anomaly for this time period was −1.0 K. Over the entire 20-year period, the ASO root mean square error of the CFS Niño-3.4 SST anomalies was 0.66 K. The temporal rank correlation between the CFS ASO SST anomalies and the OBS for the 20-year period was 0.78 (61% of the variance explained) which is statistically significant at the 99% confidence level. The CFS ASO SST anomalies exhibit a slight linear downward trend (−0.075 K yr⁻¹ which is significant at the 90% confidence level) while the OBS exhibits no discernible trend during the 1986–2005 time period. The rank correlation of the two time series is 0.86.

Figure 1. August, September, and October average SST anomalies from 1986–2005. Solid line is the observed from Reynolds et al. [2002] and the dashed line is the two month lead forecast from the CFS model. (top) Niño-3.4 domain (bottom) main development region. Units Kelvin.

Figure 2. Interannual variability of tropical cyclone numbers from 1986–2005. Solid line is the observed number from HURDAT and the dashed line is the ensemble mean from the FSU/COAPS model using the observed SSTs. Vertical bars represent the model’s ensemble spread. © American Meteorological Society. Reprinted with permission.
after removing the linear trend which could be explained by the downward drift of the CFS relative to the OBS.

The ASO average SST anomalies for the OBS and CFS in the main development region are shown in Figure 1 (bottom). Averaged over the 20-years, the ASO anomalies are much smaller than those observed in the Niño-3.4 domain with the OBS anomalies having a value of 0.14 K and −0.03 K in the CFS. The OBS data has a positive linear trend of 0.03 K yr⁻¹ which is significant at the 95% confidence level (p-value 0.457). The CFS generates a very small trend (+0.003 K yr⁻¹) that is not significant (p-value 0.81). The CFS model does reproduce the interannual variability well with the rank correlation of 0.71 between the two datasets (0.82 with the linear trend removed). Although it is not clear why, the largest difference between the two SST anomalies occurs during the last six years of the study (2000–2005). The CFS anomalies tend to remain negative in the MDR while the OBS anomalies are positive with a strong upward trend especially after 2001. This difference might arise if during the early years the CFS had more drift which would alter the CFS climatology. One would have to examine the non-bias corrected SST data to see if this was the case which is left for a future study.

4. Tropical Cyclone Numbers

Figures 2 and 3 show the ensemble mean total number of Atlantic TCs (hurricanes plus tropical storms) for each year from 1986 to 2005 from the FSU/COAPS AGCM using the OBS and the CFS datasets, respectively.

For each year the ensemble spread is shown by the vertical lines. Also shown is the observed number of tropical cyclones obtained from the National Hurricane Center Best Track dataset, HURDAT (available online at http://www.nhc.noaa.gov/pastall.shtml). No correction was applied to the TC numbers generated by the detection algorithm, unlike what is done by other modeling groups. The model is able to represent the TC interannual variability very well using both SST datasets. The standard deviation across the individual members of the ensemble, computed for each year and then averaged over all years, is 2.4 TCs/yr using the CFS SST anomalies and 2.2 TCs/yr using the OBS SSTs. The rank correlation between the observed TC numbers and the ensemble mean TC number using the OBS dataset is 0.78 (same as Figure 2 of LaRow et al. [2008]) and the rank correlation between observed and ensemble mean number of TCs using the CFS SSTs is 0.74. Both results are statistically significant at the 95% confidence level. Correlation after removing the linear trend is 0.60 using the CFS SSTs which compares to 0.37 from the Colorado State University’s statistical method [Klotzbach and Gray 2009]. The individual rank correlations for each ensemble is shown in Table 1 and the total number of TCs for each ensemble is shown in Table 2.

During the first five years of the study (1986–1990), the model performs better in terms of the ensemble mean using the CFS data compared to using the OBS data. The largest differences between the two simulations occurs during 1993, 1994 and 1999 with the CFS ensemble mean producing too many TCs and in 1998 when the OBS data produced too many storms. These large differences arise in spite of the fact that the ASO Niño-3.4 SST anomalies are

![Figure 3](image_url)  
Figure 3. Same as Figure 2 except using CFS SSTs.

### Table 1. Rank Correlations Between the Number of Tropical Cyclones From the Two SST Datasets With the Observed for the 20 Year Period

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Member 1</th>
<th>Member 2</th>
<th>Member 3</th>
<th>Member 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed SST</td>
<td>0.76</td>
<td>0.51</td>
<td>0.71</td>
<td>0.62</td>
</tr>
<tr>
<td>CFS SST</td>
<td>0.71</td>
<td>0.67</td>
<td>0.64</td>
<td>0.50</td>
</tr>
</tbody>
</table>

*All ensemble results are statistically significant at the 95% confidence level.

### Table 2. Total Number of Storms for the 20 Year Period From the Individual Ensemble Members Using the Two SST Datasets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Member 1</th>
<th>Member 2</th>
<th>Member 3</th>
<th>Member 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed SST</td>
<td>242</td>
<td>234</td>
<td>234</td>
<td>249</td>
</tr>
<tr>
<td>CFS SST</td>
<td>247</td>
<td>239</td>
<td>262</td>
<td>244</td>
</tr>
</tbody>
</table>

*The total number of observed TCs during 1986–2005 was 245 storms.
very similar between the OBS and CFS during these years as shown in Figure 1. In general, greater variability is noted in the ensembles using the CFS data compared to using the OBS data which could be due to the use of daily SSTs with the CFS data versus weekly OBS data. This is also seen in the total number of storms detected by each ensemble member as shown in Table 2. The TC variance averaged over the ensemble members for each year and then averaged all 20 years is 6.2 for the CFS and 5.71 using the OBS data.

Examination of the correlations between TC numbers and the SST anomalies in the Niño-3.4 domain reveals that the model tends to over emphasize this relationship by attributing too much of the TC number variation to ENSO. This is seen in the correlation between the observed number of storms from HURDAT with the OBS Niño-3.4 SST anomalies is \( r \approx 0.36 \) (statistically significant at the 95% level but only explains \( \sim 13\% \) of the variance). The model exhibits a stronger negative correlation of \( -0.64/-0.86 \) using the OBS/CFS SST which accounts for \( \sim 41%/74\% \) of the variance in TC number, respectively. Removal of the 2005 outlier does not significantly alter the correlations results.

### 5. Accumulated Cyclone Energy

Shown in Figure 4 is the ensemble seasonal mean Atlantic TC accumulated cyclone energy (ACE) [Bell et al., 2000] from the two SST experiments. Also shown is the observed ACE determined using HURDAT. ACE is defined as the sum of the square of the maximum surface winds in knots every six hours during the lifetime of the TC. The model’s ACE was calculated using the magnitude of the 850 hPa maximum winds determined by the detection/tracking algorithm and then multiplying the wind speed by 0.8 to reduce to the surface. The ACE correlation for the 20-year period using the OBS data with the observed ACE is 0.94 while the correlation is 0.73 using the CFS data. Both are statistically significant at the 95% confidence level. The only seasonal interval for which the OBS data failed to simulate the correct slope of the ACE was in 2004. After removing the linear trend the correlations fall slightly to 0.86 and 0.53 for the OBS and CFS data, respectively. As noted in Camargo et al. [2005] the ACE correlations tend to be higher than that for the number of TCs and is a result of the more continuous property of ACE.

### 6. The 2009 Real-Time Forecast

Based on the above results we conducted a real-time forecast using the bias corrected SSTs from the 29 May 2009 CFS forecast to dynamically forecast the 2009 Atlantic hurricane season. Using the same procedure as discussed above and by LaRow et al. [2008], time-lagged ECMWF atmospheric initial conditions were used to generate a four member ensemble using the FSU/COAPS model. The model predicted a mean of eight tropical systems and four hurricanes for the 2009 season. The standard deviation is 2.2 tropical storms and 0.8 for hurricanes. The mean ACE predicted for the season is 65 (scaled by 10000) with a standard deviation of only 3.5. The observed numbers for the 2009 Atlantic hurricane season were nine named storms, three hurricanes and an ACE of 52. A model hurricane is defined according to the 850 hPa wind speed magnitude determined by the detection/tracking algorithm. If this wind speed is greater than 41 ms\(^{-1}\) (33 ms\(^{-1}\) at the surface) the system is counted as a hurricane. The 2009 forecast is below the model’s 20-year mean of 13 tropical systems, eight hurricanes and an ACE of 52. A model hurricane is defined according to the 850 hPa wind speed magnitude determined by the detection/tracking algorithm. If this wind speed is greater than 41 ms\(^{-1}\) (33 ms\(^{-1}\) at the surface) the system is counted as a hurricane. The 2009 forecast is below the model’s 20-year mean of 13 tropical systems, eight hurricanes and an ACE of 113. At the time of the forecast, in early June, the contributing factors to the low activity were the possible re-emergence of anomalously warm SSTs in the tropical east Pacific (El Niño) and the cool SST anomalies in the tropical Atlantic as predicted by the CFS model. Since no coupled model will be able to produce perfect SSTs, it remains a question as to how much error is acceptable in the SSTs (or SST anomalies if bias corrected).
in the various ocean basins (relative or not) in order to produce a seasonal TC forecast that is considered skillful.

7. Conclusions

Twenty years (1986–2005) of seasonal Atlantic tropical cyclone (hurricanes plus tropical storms) frequency and accumulated cyclone energy was examined using two sea surface temperature datasets as lower boundary conditions in the FSU/COAPS AGCM. The first SST dataset was the observed Reynolds et al. [2002]. The second SST dataset was determined by the CFS model which was applied in a two-tiered approach to seasonal tropical cyclone forecasting. The SSTs from the CFS model were bias corrected before applying them in the AGCM. For each year, a four member atmospheric ensemble was generated using time-lagged initial conditions obtained from the ECMWF. The AGCM was able to reproduce the interannual variability of the TC activity with temporal correlations of 0.78 and 0.74 using the OBS and CFS SST data, respectively. Both correlations are statistically significant at the 95% confidence level. In terms of ACE, the correlation for the interannual variability was found to be higher than was noted for the TC numbers using the OBS SSTs. This agrees with other modeling studies. However, using the CFS dataset, the correlation of TC numbers was found to be slightly higher than was noted for ACE, although the difference was not significant. Overall, these results indicate the potential of the CFS model’s SSTs for use in seasonal hurricane forecasting. Based on these hindcast results, a real-time forecast was made for the 2009 hurricane season using the CFS May 29, 2009 forecast SSTs and a four member atmospheric ensemble. Our forecast called for eight named systems, four hurricanes and a mean ACE of 65. All values are below the ensemble. Our forecast called for eight named systems, four hurricanes and a mean ACE of 65. All values are below the

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References


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