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Predictability of Atlantic Hurricane Activity by the NMME Coupled Models

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1. Purpose

The overall purpose of the project is to assess the ability of the coupled climate models in the North American Multi-model Ensemble (NMME), and in particular NOAA's CFSv2 model, to predict within-season variations of Atlantic tropical cyclone (TC) activity. For example, the Madden Julian Oscillation (MJO) is known to modulate within-season variations of hurricane activity. If the NOAA CFSv2 model, and/or other models in the ensemble of NMME models, are found to be able to predict the locations and intensity of within-season variations of cyclone activity with sufficient accuracy, an operational system utilizing these model predictions is to be developed and implemented. The operational aspect of the project is to set up an improved model-based TC prediction system to provide timely predictions during the Atlantic hurricane season.

1. Results and Accomplishments

During the first year (FY13), hindcast data from the very high-resolution (T-382) NCEP Climate Forecast System (CFS) model was sent from Climate Prediction Center (CPC) to IRI and set up in IRI's Data Library. Regarding the model itself, this CFS was somewhat of a hybrid version between CFSv1 and CFSv2; no high-resolution version of the CFSv2 version was yet available, but would become available (unknown to us at the time) for the final year of the project. These model runs covered the Atlantic hurricane seasons of 1982-2010 and were initialized in April and allowed to run freely for 7 months each year, allowing for diagnosis of its MJO vs. TC behavior. MJO diagnosis software was created at IRI, and its diagnostics were confirmed correct against previous benchmark MJO diagnostics using Reanalysis data (Wheeler and Hendon 2004). MJO diagnosis was then carried out on the high-resolution CFS hindcast data at IRI. Meanwhile, the CPC people worked on 45-day runs of the standard resolution (T126) version of CFSv2, initialized 4 times daily for 11 years of hurricane season. Among other things, we aimed to determine if the additional resolution in the T-382 version of the CFS model could result in more skillful forecasts of tropical cyclone activity than those of the standard resolution model. A more operationally oriented aim at CPC was to set the CFSv2 model up for routine TC predictions for the North Atlantic and other ocean basins during their respective TC seasons.

During FY14, IRI work included extensive analyses of MJO versus TC behavior for the high-resolution (T-382) CFS hindcasts covering 1982-2010. As an example, Figure 1 shows accumulated cyclone energy (ACE) in the model during the TC-enhancing MJO phase 1 and TC-suppressing MJO phase 6, along with the corresponding observed ACE. Favorable reproduction of the observations by the model is indicated. Comparisons between observed and modeled TC activity of four different types (TC number, ACE, TC genesis and TC rapid intensification) also indicated that the high resolution CFS model reproduces reality fairly well in terms of the amount of activity as a function of the MJO phase (Fig. 2). Also during this year, CPC sent to the IRI the massive data sets from the standard resolution (T-126) CFSv2, initialized 4 times daily and run out to 45 days during the 1999-2012 period. IRI folks verified these against observations (something unable to be done with the high-resolution CFS runs, which are free-running, initialized only early in the season). Accuracy is shown to be on par with results of previous work, as for example in predicting the MJO phase going out to about two weeks in advance (Fig. 3). At CPC, verification analyses for the standard resolution CFSv2 were conducted and it was found to reproduce the anomalous number of TCs over the North Atlantic basin quite well, as shown in Fig. 4.

In FY15, TC analyses on the 45-day hindcast runs of the operational CFSv2 T-126 model during the 1999-2010 period were extended to glean further details, and comparisons between its skill and that of the T-382 (high resolution CFS) were conducted. At IRI, TC activity was analyzed over seven subsectors of the North Atlantic (shown in Fig. 5) as a function of the MJO phase, and the centroid of TC activity was also computed for each MJO phase (Fig. 6). The result for number of tropical cyclones (not shown) is similar. Figure 6 shows, first, that the model TCs tend to occur about 6˚ farther south, and nearly 10˚ farther east, than those in nature. This southeast displacement has been partly attributable to biases of the CFS model in large-scale environmental fields, such as vertical wind shear and anomalous outgoing longwave radiation (see Figs. 4, 5 and 6 in Barnston et al. 2015b). But more to the point of this analysis, the centroid is seen to migrate eastward during MJO phases 1 through 4, and migrate back westward during phases 6 through 8, both in observations and in the high-resolution CFS hindcasts. This provides an opportunity, albeit slight, to differentiate the location of maximum activity within the Atlantic in medium-range forecasts of TC activity in accordance with the predicted MJO phase. Other ways of showing the influence of MJO phase on TC activity were investigated (not shown here). During early 2015 a paper detailing the analyses described above and discussing implications for better forecasts of Atlantic TC activity, was submitted to *Monthly Weather Review* and published late in the calendar year (Barnston et al. 2015b). Additionally, a summary of the main findings in that paper were presented at NOAA's 40th Climate Diagnostics and Prediction Workshop (Barnston et al. 2015a).

At CPC, skill analyses were conducted for predictions of TC track positions over five ocean basins worldwide, using the CFSv2 operational (T-126) model, for varying lead times up to the sixth week. Figure 7 shows Heidke skills for each basin for each of the first four weekly lead times. The Heidke skill score is defined as:

$$Heidke\ Skill\ Score = 100\ x\ \frac{(Hits - Expected)}{(Total - Expected)}$$

where Hits is the number of correct forecasts, Expected is the number of correct forecasts expected by chance, and Total is the total number of forecasts. When the number of hits is the same as the total, all forecasts are successful and the Heidke skill score is 100. When the number of hits is the same as the number of hits expected by chance (e.g., one-third of the total for tercile-based category forecasts), the Heidke skill score is 0. Negative skill scores are possible.

Heidke Skill for the Atlantic basin is seen to be quite high for forecasts of the first week, and at lower levels for the longer lead times. Extensive skill analyses were done for TC genesis, and useful Heidke skill scores were found for most of the seven ocean basins, especially for shorter lead times. Some years showed much better skill than others, as seen by the contrast in performance between 2000 and 2003 in the North Atlantic basin (Fig. 4), and this large variation occurs in the other basins also.

The CPC effort also focused on the real-time experimental predictions that commenced January 1, 2014. These predictions were based on the same operational CFSv2 45-day forecasts, produced as four-member ensembles initialized 6-hourly, producing 16 ensemble forecast members analyzed daily to make TC activity forecasts for the weeks 1 through 4. Detection and tracking of TCs were performed for all seven global ocean basins. The number of TCs and their tracks during the weekly forecast intervals were generated, corrected for model bias. False alarms were removed using the model's climatological false alarm track density determined for each interval based on the 1999-2012 CFSv2 hindcasts. This process involved converting the storm tracks into 1^ox1^o grids and subtracting both the weekly storm track climatology and also the weekly false alarm climatology, which describes the frequency of occurrence of TS activity in locations where it does not occur in the observations. The resulting weekly TC activity predictions were displayed for the CPC forecasters producing the Global Hazards and Benefits Outlooks at http://cpcintradev.ncep.noaa.gov/~wd52lw/cfs_tc/amin.html .

During the final year of the project (FY16), CPC obtained data for the CFSv2 model, but at the high (T-382) resolution, combining this higher resolution with the more advanced CFSv2 model. (The CFS T-382 model discussed above used the older MOM3 ocean model, rather than the better MOM4, and also lacked some better model features of CFSv2.) This high-resolution CFSv2 could then be compared, on a more level playing field, against the operational CFSv2 (with only T-126 resolution) for TC forecasting skill. IRI analyzed the comparative model behavior characteristics and skills. For example, the fraction of time spent in each MJO phase is compared in Fig. 8 between the observations, the CFS high-resolution, and the CFSv2 high resolution. Although the CFSv2 shows a slightly different result from the CFS, it is no closer to the observations than the CFS. Similarly, the spatial migration pattern of the centroid of TC activity as a function of MJO phase did not resemble that of the observations more in the high resolution CFSv2 than in the high resolution CFS (Fig. 9). All told, it was found that the higher resolution CFSv2 did not show evidence of higher skill than the operational CFSv2. This either means that the resolution is not a very important factor allowing CFS models to better reproduce observed TC behavior, or that the resolution does matter but the sample sizes (number of cases) available in the analyses are insufficient to discern the skill differences. Another complicating factor is the somewhat differing periods of record between the two model versions, with a short overlap period of 1999 to 2010 between them.

At CPC, using the 45-day hindcasts, further progress was made in evaluating the level of predictive skill of the NCEP CFSv2 model for tropical cyclone activity on intraseasonal timescales. Because the CFSv2 is a fully-coupled climate prediction system, it is well equipped to handle forecasts out to Weeks 1 to 4, and would be expected to incorporate the effects of the MJO phase on TC activity. The ultimate objective here is to provide an objective tool for CPC forecasters, with accompanying skill diagnostics.

Using the detection and tracking algorithm documented by Camargo and Zebiak (2002), prediction of TC activity was evaluated with the 14-year (1999-2012) CFSv2 hindcast dataset. The hindcast suite includes 45-day forecast runs initialized every 6 hours, four times a day. With four members per day, members for the most recent five days were grouped to form a daily 20-member hindcast ensemble. These ensembles were used to create daily storm count and storm track forecasts by ocean basin for Weeks 1 through 4. Figure 10 shows the anomaly correlation (AC) scores for storm count with the period average score represented by straight, solid lines. The basins with the highest Week 1 score have average values between 0.49 and 0.51. The average AC for the Atlantic (ATL) basin (0.33) is brought down by two bad years (2002 and 2003). As expected, skill drops with lead time, but there is still skill evident in most basins for Weeks 2-4 with scores for Week 4 remaining above 0.2.

A journal paper describing all aspects of the model skill evaluation is in preparation at CPC (Long et al. 2016b), following their presentation at NOAA's 40th Climate Diagnostics and Prediction Workshop (Long et al. 2016a).

This project was initially expected to be expanded to other models in the NMME set, besides CFSv2, to form a multi-model ensemble of TC predictions. However, this part of the work was unable to be addressed because the required 6-hourly model hindcast and real-time forecast data for the non-CFSv2 models did not become available during the time frame of the project as initially expected. As a result, our work was devoted purely to various versions of the CFS model, and perhaps was able to delve more deeply into them that would have been possible if tending to an expanded set of models.

2. Summary of Accomplishments

In summary, the extensive analyses demonstrated the level of reality and skill in three versions of the CFS model: (1) a high-resolution (T382) version that is intermediate between CFSv1 and CFSv2, (2) the standard resolution (T126) operational version of CFSv2, and (3) a high-resolution (T382) version of CFSv2 that became available toward the end of the period of our study. Because four-times daily hindcast data from other (non-NOAA) models of the NMME did not become available during the study period, they could not be included in the study. The main conclusions follow:

1. All three version of CFS replicate Atlantic tropical cyclone (TC) behavior reasonably well generally, and particularly in response to the phase of the MJO.

2. The model versions tend to show TC activity centered slightly southeastward of where they are located in observations, possibly because of biases revealed in field variables such as outgoing longwave radiation and vertical wind shear.

3. As suggested in observations, TC activity tends to migrate slightly to the east as the MJO progresses from phase 1 to 4, and then back to the west as the MJO progresses from phase 5 to 8. This TC location response to MJO appears too minor to be noticeable to forecasters, but is taken into account in the model predictions.

4. The high resolution versions of CFS and of CFSv2 do not show clear signs of being able to reproduce TC behavior more accurately than the standard operational versions.

5. The standard operational version of CFSv2 is predicts TC activity and TC tracks quite well during the first future week, with slowly decreasing skill during weeks 2 to 4 for TC activity and rapidly decreasing skill during week 2 for TC tracks.

6. Operational real-time predictions of TC activity began at the beginning of 2014 using the standard operational version (at T126 resolution) of the CFSv2 model. Real-time monitoring of performance accompanies the forecasts, as shown in Fig. 11 for the 2016 North Atlantic hurricane season up through the beginning of July.

3. Publications and Reports

3.1 Publications by Principal Investigators

Barnston, A. G., N. Vigaud, L. N. Long, M. K. Tippett, and J.-K. E. Schemm, 2015a: The impact of the MJO on Atlantic tropical cyclone activity in NOAA's CFS model. NOAA 40th Climate Diagnostics and Prediction Workshop, Oct. 26-29, Denver, Colo. Link: http://www.cpc.ncep.noaa.gov/products/outreach/CDPW40/Barnston_MJO-TC_CDPW40.pdf

Barnston, A. G., N. Vigaud, L. N. Long, M. K. Tippett, and J.-K. E. Schemm, 2015b: Atlantic tropical cyclone activity in response to the MJO in NOAA's CFS model. *Mon. Wea. Rev.,* **143**, 4905-4927.

Long, L. N., J.-K. E. Schemm, and S. Baxter, 2016a: Intraseasonal Tropical Storm Prediction in the NCEP CFSv2 45-Day Forecasts. *Climate Prediction Science & Technology Digest* (associated with 40th Climate Diag. and Prediction Workshop); http://www.nws.noaa.gov/ost/climate/STIP/40CDPW/40CDPW_Digest.pdf

Long, L. N., J.-K. E. Schemm, and S. Baxter, 2016b: Intraseasonal prediction of global tropical storms during week 1 through week 4 using CFSv2. *Wea. Forecasting,* **31**, in preparation.

3.2 Other Relevant Publications

Camargo, S.J. and S. E. Zebiak, 2002: Improving the Detection and Tracking of Tropical Cyclones in Atmospheric General Circulation Models. *Wea. Forecasting*, **17**, 1152-1162.

Wheeler, M. C., and H. H. Hendon, 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Wea. Rev*., **132**, 1917–1932.

4. PI Contact Information

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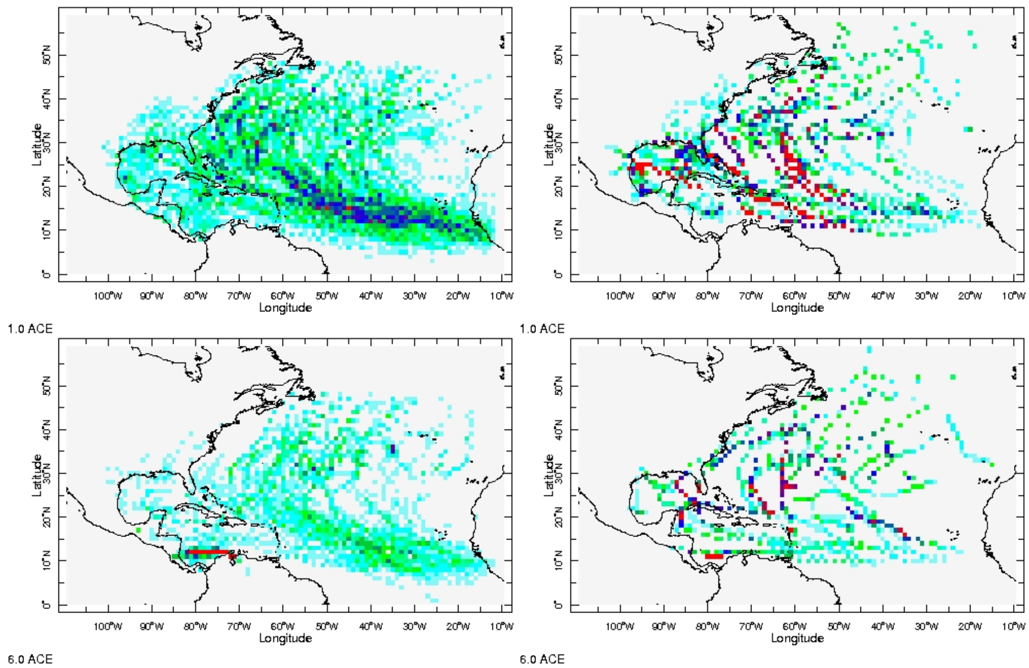

Figure 1. *Atlantic tropical cyclone activity, represented by storm accumulated cyclone energy (ACE) in CFS T382 model (left column) and in observations (right column). The first row shows ACE during the phase 1 of the MJO, second row during phase 6 of MJO. Five members of CFS model are initialized in late April of each year.*

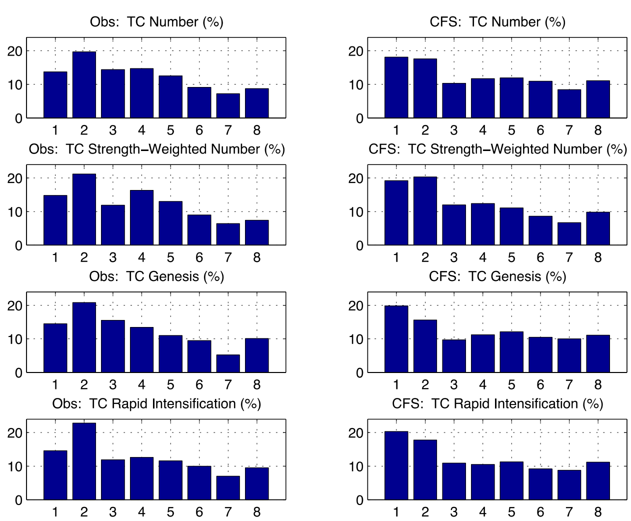

Figure 2. *Atlantic percentage distribution of Atlantic hurricane activity by MJO phase for observations (left column) and for CFS T382 model (right column), for number of storms (top row), accumulated cyclone energy (row 2), storm genesis (row 3) and*

instances of rapid intensification (bottom row). Correlation between the observed and model patterns are 0.71, 0.87, 0.52 and 0.76, respectively.

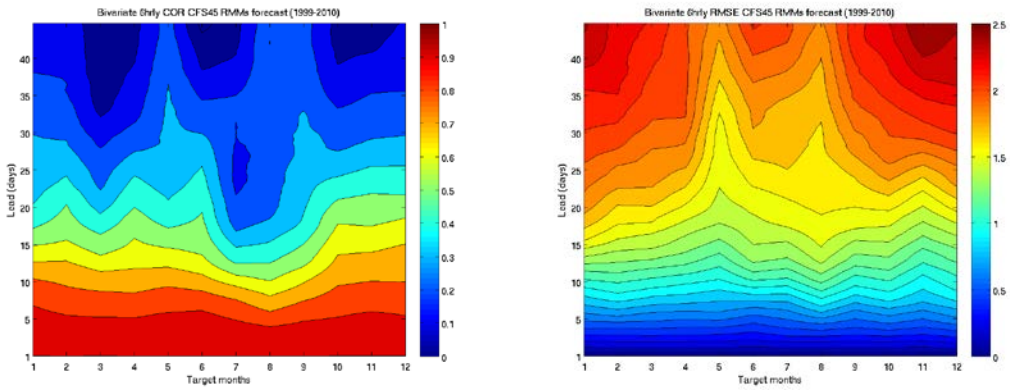

Figure 3. *Verification of MJO behavior (RMM1 and RMM2) in CFSv2 T126 model initialized 4 times daily and run to 45 days: Anomaly correlation (left) and RMSE (right) as a function of target season (x-axis) and lead time (y-axis).*

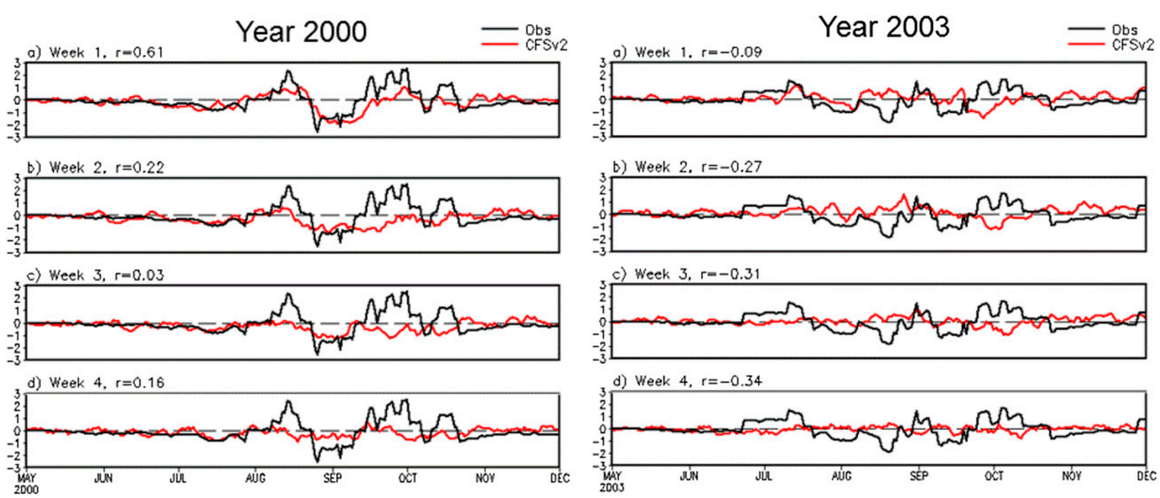

Figure 4. *Time series of anomalous TC number over the Atlantic basin for the 2000 and 2003 storm seasons. Anomalies are defined with respect to the 12 years of study for the date within the TC season. The forecasted anomalous TC number (red) for week 1–4 are compared to observed TC anomalous number (black) from the NHC Best Track HURDAT. Correlation scores between the forecasts and observations are indicated above each panel.*

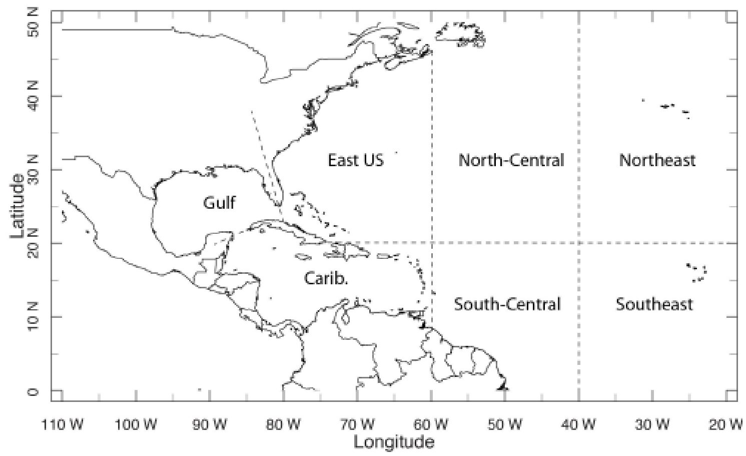

Figure 5. *Seven subregions of the North Atlantic basin used in the study.*

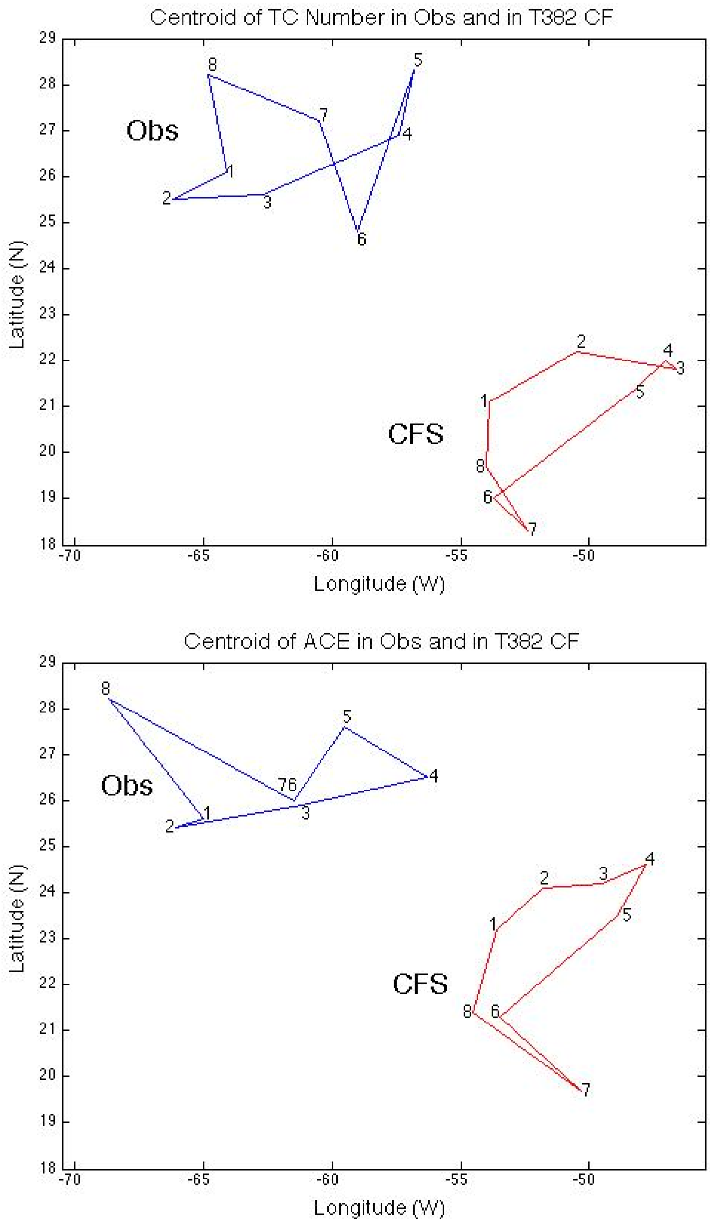

Figure 6. *Location of the centroid of TC activity for each of the 8 MJO phases, for (left) TC number and (right) ACE. Centroid locations are shown in blue for the observations, and in red for the high-resolution T382 CFS model. The MJO phase number is shown at the vertices of the line segments.*

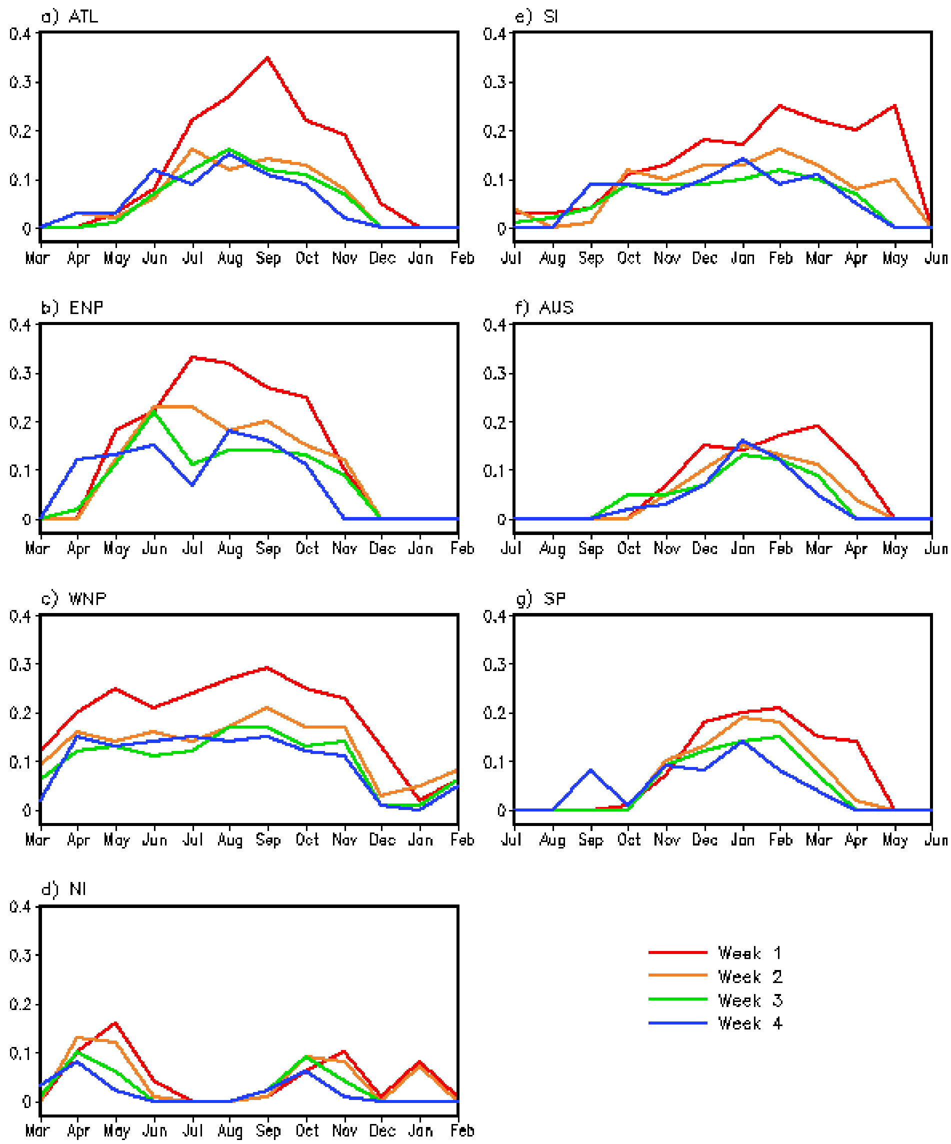

Figure 7*. Monthly mean Heidke scores for track position prediction over the Atlantic (ATL), Eastern North Pacific (ENP), Western North Pacific (WNP), Northern Indian (NI), Southern Indian (SI), Australian (AUS) and Southern Pacific (SP) basins averaged over the 1999-2012 period. The scores for weeks 1, 2, 3 and 4 forecasts are in red, orange, green blue, respectively.*

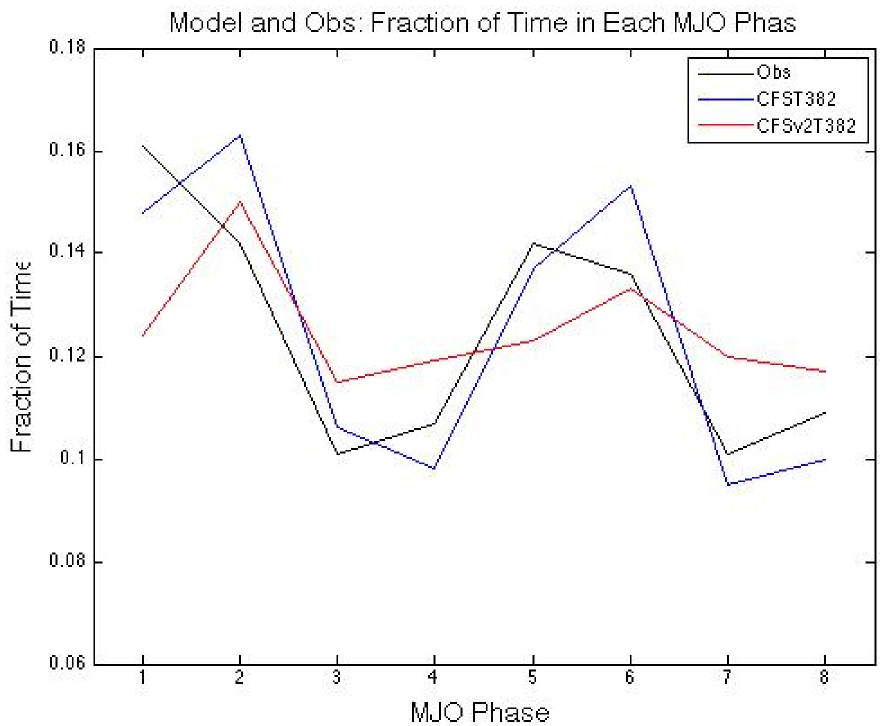

Figure 8*. Fraction of total time between May and November spent in each MJO phase in the observations (black line), the high resolution CFS that uses MOM3 ocean model (blue), and same but for CFSv2 using the MOM4 ocean model (red).*

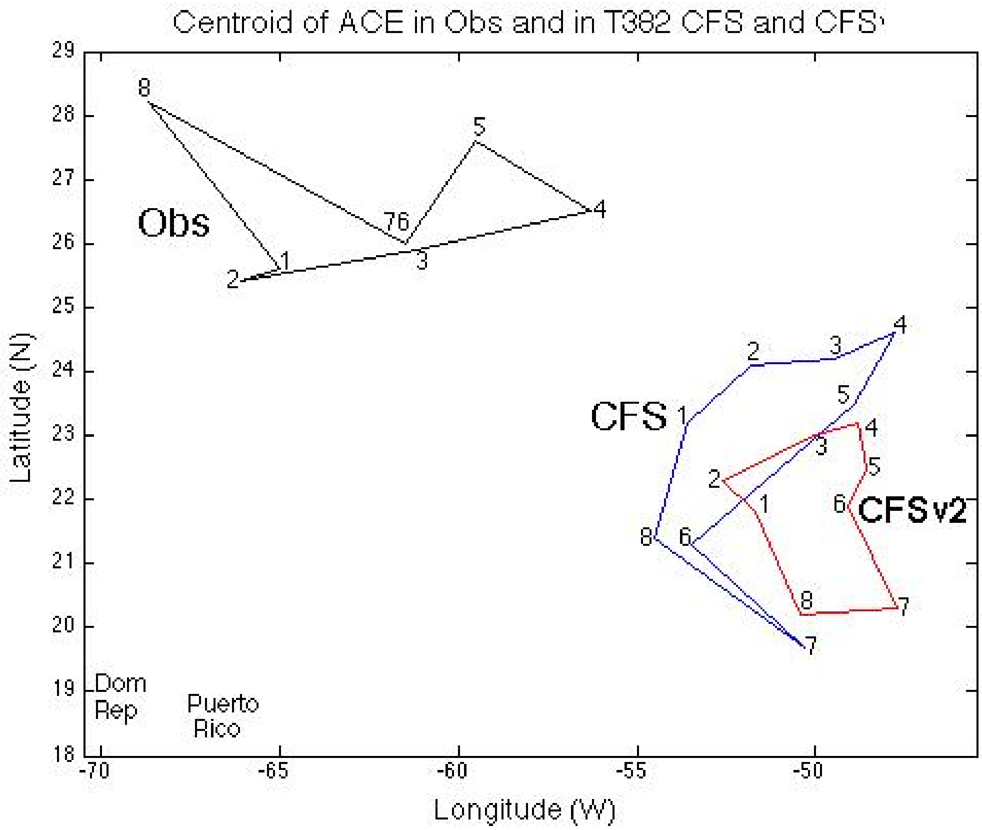

Figure 9. *Location of the centroid of TC activity for each of the eight MJO phases for ACE. Locations are shown in black of the observations, blue for the CFS high resolution model that uses MOM3 ocean model, and red for the CFSv2 high resolution model that uses MOM4 ocean model.*

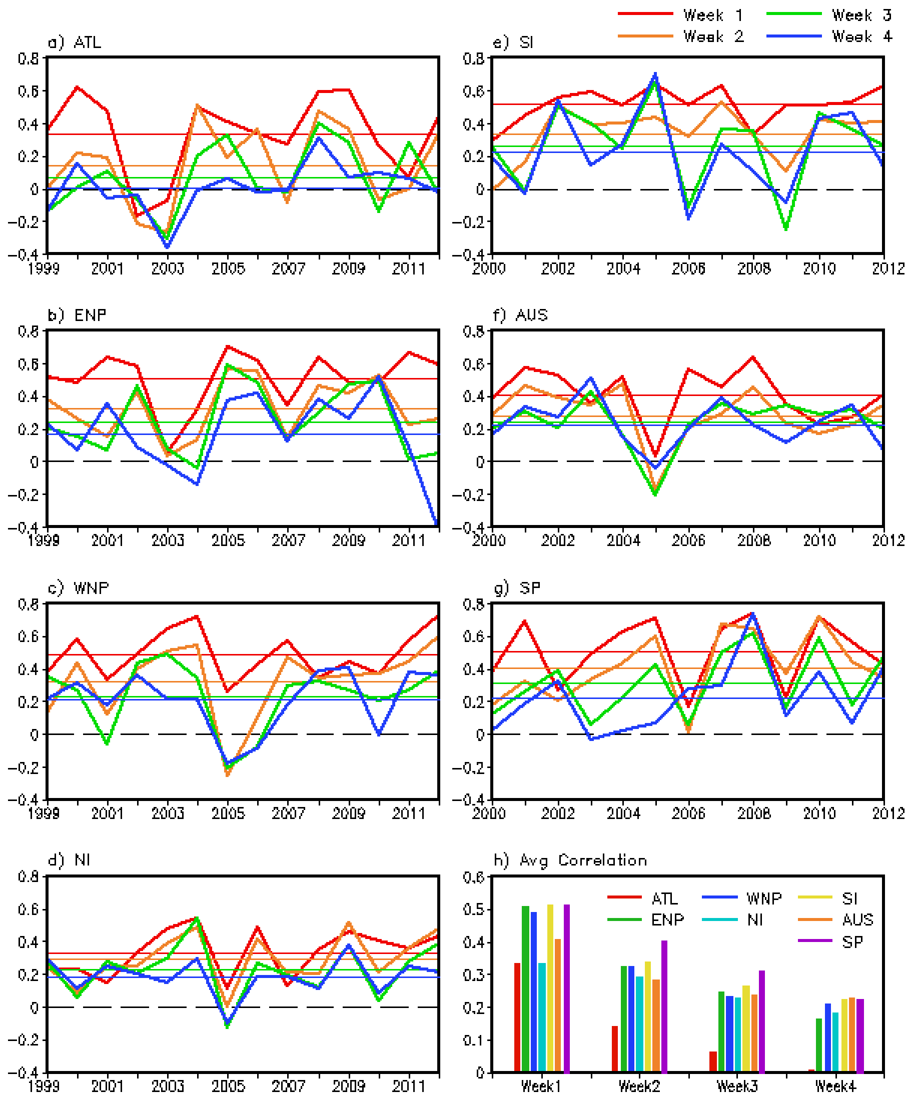

***Figure 10**. Tropical storm count anomaly correlations by lead time (week number) for the four Northern Hemisphere basins (a-d) for 1999-2012, and the three Southern Hemisphere basins (e-g) for 2000-2012. The average correlations are shown using a straight, solid line and also in bar graph form (h).*

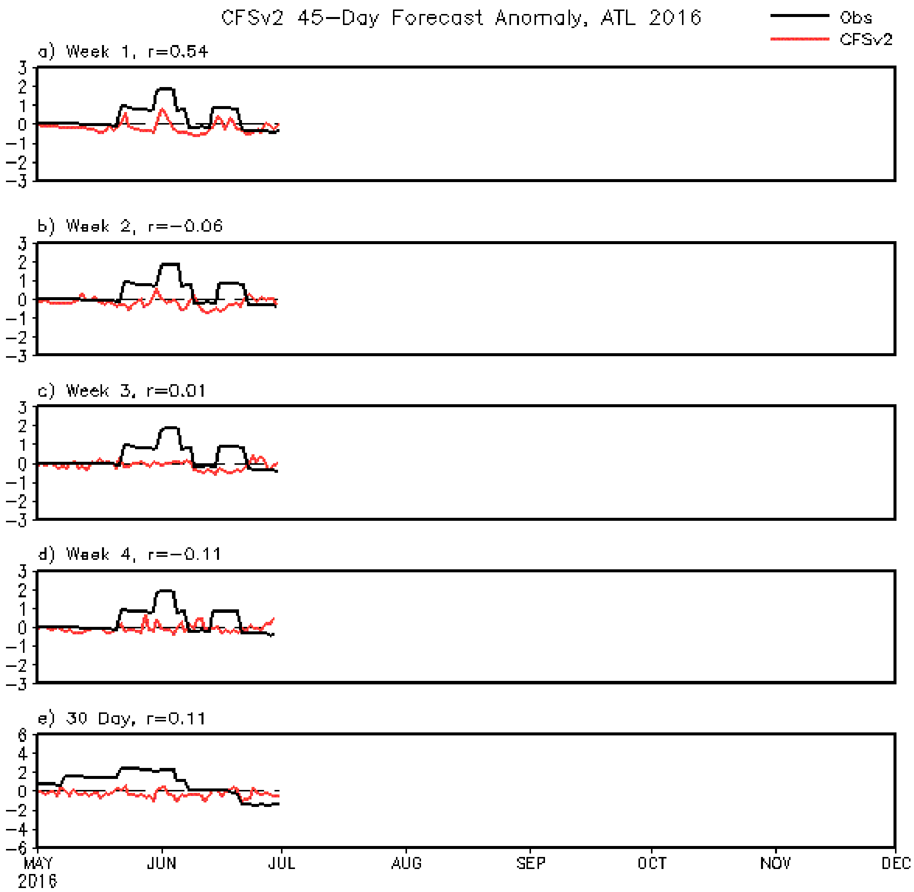

Figure 11. *Time series of accumulated tropical storm counts over the Atlantic Basin for the 2016 storm seasons up to early July. The accumulated TS count forecasts (in red) for week 1 through week 4, and 30-day are compared to observed TS counts (in black) from the NHC HURDAT Best Track dataset. Correlation scores between the forecasts and observations are indicated above each panel.*