15A.7 ATLANTIC HURRICANES AND CLIMATE CHANGE: PROJECTION OF A PEAK MONTH IN A FUTURE RECORD HURRICANE SEASON

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1. INTRODUCTION

To address the question of how tropical cyclones (TCs) might change in a future climate affected by global warming, recent work has focused on the addition of atmospheric anomalies predicted by general circulation models (GCMs) into simulations by finer-resolution mesoscale numerical or statistical models, a process known as “downscaling” (Knutson and Tuleya 2004; Knutson et al. 2007; Emanuel et al. 2008). In the current study, GCM-predicted temperature and moisture anomalies are used to provide altered initial conditions in simulations of the peak of hurricane season at the end of the 21st century in the Weather, Research and Forecasting (WRF) model. By adding the GCM-derived changes to analyzed data from a recent season, without modifying the wind field, the thermodynamic impact of climate change on tropical cyclone characteristics is isolated.

2. METHODS

The Advanced Research WRF model (WRF-ARW), version 3.0.1.1 (Skamarock et al. 2008), is used to simulate the entire month of September 2005, first with analyzed atmospheric conditions and then with the addition of temperature and moisture changes consistent with a GCM-simulated future tropical atmosphere. In all model runs, the Kain-Fritsch (KF; Kain and Fritsch 1993) convective parameterization is used on all domains, as well as the Community Atmospheric Model (CAM; Collins et al. 2004) scheme for both longwave and shortwave radiation.

A 4-member physics ensemble is run for both the current and future experiments, with the Morrison et al. (2008) double-moment microphysics (MP) scheme and the WSM 6-class (WSM6; Hong and Lim 2006) parameterizations (Table 1). Both the Yonsei University (YSU; Hong et al. 2006) and the Mellor-Yamada-Janjic (MYJ; Janjic 1994, 2002) planetary boundary layer (PBL) parameterizations are employed. The YSU scheme is used in conjunction with the alternative formula for exchange coefficients more appropriate for hurricane-force wind speeds (Skamarock et al. 2008, p. 72).

Ensemble Member	**Physics (PBL – MP)**
E1	YSU – Morrison
E2	MYJ – Morrison
E3	YSU – WSM6
E4	MYJ – WSM6

Table 1. The boundary layer and microphysical paramterizations used for each ensemble member.

A one-dimensional ocean mixed layer (OML; Pollard et al. 1973; Davis et al. 2008) model, available in recent WRF versions, is used to partially account for the cold wake generated by TCs. In order to use the OML in concert with time-varying SST analyses, some modification of the WRF source code was required. Source code was altered such that the SST anomalies computed by the OML in the previous 24 h are added to the new SST field at the time of the 24-hourly update. Therefore, observed SSTs are used, but with a component of the cold wakes generated by the model-simulated TCs included.

For initial and lateral boundary conditions on the outer domain, the control simulation utilizes 1° National Centers for Environmental Prediction (NCEP) Final Analyses from the Global Forecast System (GFS - FNL) and 0.5° Real-Time Global (RTG) SST analysis from 00 UTC 1 September to 30 September (Thiebaux et al. 2003). Lateral boundary conditions and SSTs are updated every 24 hours and output is produced every 12 hours.

Future temperature and moisture changes are computed using a 20-member ensemble of GCM simulations from the Intergovernmental Panel

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on Climate Change (IPCC) Fourth Assessment Report (AR4) for the A1B emission scenario (Fig. 1). Anomalies are computed using 10-year spatial averages over the Atlantic main development region, taken at the beginning and end of the 21st century. The averaging domain covers the region 8.5 – 15º N and 60 – 40º W, similar to the methods of the idealized study Hill et al. (2008). Temperature changes are added to the GFS and RTG analyses uniformly at every horizontal grid point, but are a function of pressure. Thus, no change is introduced in the horizontal temperature gradient, and there is little or no modification of the environmental shear. Moisture changes are introduced by keeping the relative humidity constant and then re-computing the mixing ratio with a higher temperature. The ensemble is run with a 54-mother domain and an 18-km 1-way nested domain (Fig. 1). Results presented here are from the 18-km nest.

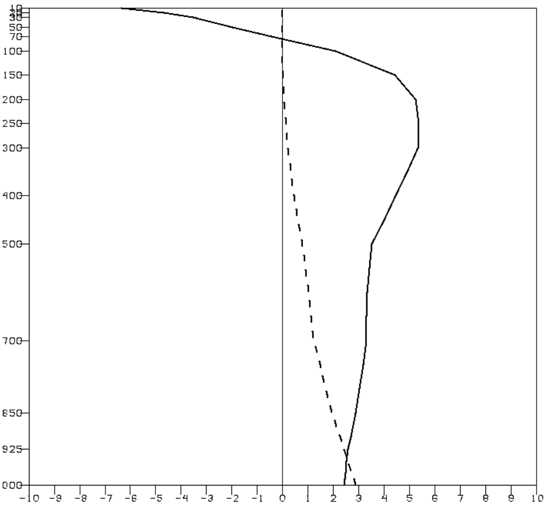

Fig. 1. Temperature (solid line) and mixing ratio (dashed line) anomalies calculated for the A1B IPCC emission scenario. The computed sea-surface temperature anomaly for this scenario is 2.21 K.

To objectively locate and track TCs in the model output, a detection algorithm is developed after the methodology of Knutson et al (2007), with an additional criterion that the TC center must be within 200 km of a grid cell 10-m wind of at least 17 ms^{-1}. In order to be classified as a hurricane, the TC must have 10-m winds in excess of 33 ms^{-1}. Once a TC qualifies as a hurricane, it is placed into a Saffir-Simpson category based on the minimum central pressure, using the central pressure thresholds found in Landsea (1993). Also, the TC must persist for at least 24 hours, or two output times, in order to be included in the storm statistics.

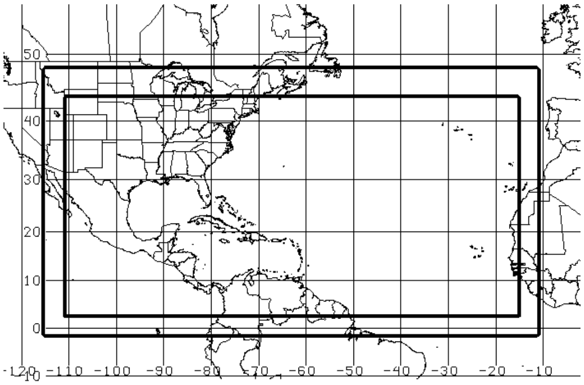

Fig. 2. WRF model domains with grid spacing of 54 and 18 km.

3. MODEL RESULTS

The ensemble performed with the original, unmodified September 2005 boundary conditions (hereby referred to as the current ensemble) generates more named storms, hurricanes, and major hurricanes than were observed (Table 2). In September 2005 observations, there were 6 named storms, 5 hurricanes and 2 major hurricanes (Beven et al. 2008). The average number of storms in the current ensemble overshoots the verification by 2.5 hurricanes and 1.5 major hurricanes. However, storm counts are somewhat sensitivity to the thresholds set in the detection algorithm, and is also difficult to compare the number of storms identified by an objective algorithm to those identified by the National Hurricane Center.

Simulations conducted with the YSU PBL scheme are much more active than those using the MYJ scheme, with YSU members simulating approximately 3 more named storms, hurricanes, and majors, compared to the ensemble average for the MYJ members (Table 2). The microphysical parameterization chosen makes less of a difference in the storm counts relative to the PBL scheme choice, with the ensemble averages of Morrison and WSM6 members exhibiting a difference of less than 1 storm all 3 categories.

In the future ensemble, there is a reduction in storm activity, with ensemble-totaled monthly accumulated cyclone energy (ACE in 10^4 kt^2; Bell et al. 2000) decreasing by approximately 15% (Table 2). Figure 2 shows ACE, accumulated over the entire simulation, both for each ensemble member and summed over all ensemble members. Each ensemble member does show a reduction in ACE with future, warmer conditions. However, the size of this decrease varies. There is no systematic trend for one particular PBL or MP physics choice to simulate a greater or smaller decrease in the future ACE. Overall, the sign of the change in future TC activity is not dependent on the choice of model physics, but the magnitude of such a change is sensitive.

Ensemble Member	**Named**	**Hurr**	**Major**	**ACE**
Current E1	12	9	5	157
Current E2	9	7	3	85
Current E3	13	9	5	153
Current E4	9	5	1	74
Ensemble Mean	*10.75*	*7.5*	*3.5*	*117*
Warming E1	10	7	4	116
Warming E2	7	5	3	77
Warming E3	7	5	4	147
Warming E4	7	3	0	58
Ensemble Mean	*7.75*	*5*	*2.75*	*99*
Warming+CO_2 E1	11	8	5	97
Warming+CO_2 E2	6	4	3	73
Warming+CO_2 E3	12	6	5	125
Warming+CO_2 E4	8	5	0	64
Ensemble Mean	*9.25*	*5.75*	*3.25*	*90*

Table 2. Number of named storms, hurricanes, major hurricanes, and accumulated cyclone energy (ACE) for each 18-km ensemble member, along with ensemble mean values.

The number of named storms, hurricanes, and major TCs are all reduced for future conditions, either for comparison of individual ensemble members with the same physics setup, or the ensemble average. The ensemble average of named storms decreases by 28% in the future, hurricanes decrease by 33%, and major storms by 21% in the future compared with the current ensemble. Future TCs do exhibit a slight increase in intensity. The average minimum central pressure for TCs in the future ensemble exhibits a modest decrease of 3.4 hPa relative to current conditions when taken over all members.

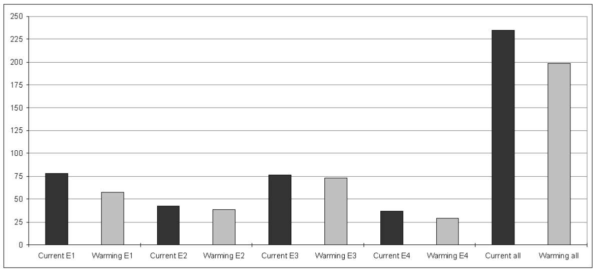

Fig. 2. ACE in 10^4 kt^2 shown summed over the entire month for each ensemble member, and for both ensembles summed over all members, with the physics options chosen for each member according to Table 2.

As in Bister and Emanuel (1998) and Zeng et al. (2007), the thermodynamic efficiency of a hurricane can be expressed

$$\varepsilon = \sqrt{\frac{SST - Tout}{Tout}}$$

(1)

Accordingly, an increase in SST suggests that TCs in the future atmosphere should be able to become more intense with great efficiency (Emanuel 1987). In evaluating (1), the SST within a 100-km radius of the storm center is used; this value is a proxy for the temperature of inflow air. The outflow temperature is taken near[1] the tropopause and spatially averaged in the same way.

Consistent with the warmer SST in the future simulations, the SST value is 1.9 K greater for those simulations. This is expected from the positive temperature anomaly added to the SST in the warming runs (Fig. 1). Although warmer SST is present in the future conditions, the average thermodynamic efficiency of TCs in the warmed atmosphere does not increase, due to the SST warming being largely offset by the increase in upper tropospheric temperature (Table 3). Since an increase in tropical mean SST corresponds with warming in upper tropospheric temperatures (e.g., Sobel et al.

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[1] The pressure level of the tropopause is determined by an objective algorithm that searches for an upper-level temperature inversion in a 100-km area around the storm. Outflow temperatures are taken at the level below.

2002), this offsets the expected increase in thermodynamic efficiency according to (1). Only areas with SST that warm more than the tropical mean experience an increase in TC intensity (Vecchi and Soden 2007; Swanson 2008, Vecchi et al. 2008). Shen et al. (2000) and Hill et al. (2008) also demonstrate that the stabilization of the upper troposphere in a future, warmer environment decreases the amount of intensification that would be expected from the SST change alone.

Quantity	**Current**	**Future**
Inflow temperature	*301.0*	*302.9*
Outflow temperature	*199.5*	*201.1*
Efficiency	0.713	0.712

Table 3. The efficiency characteristics of hurricanes in the current and warming ensembles, taken for all ensemble members at every instance of a hurricane. Italics are used to indicate whether comparison between the two mean values is statistically significant when applying a two-tailed Student's t-Test using a p-value threshold of 0.05.

12-h Precipitation	**Mean**	
	Current	Warming
Average for TCs	*50.8*	*57.7*
Maximum for TCs	*162.2*	*215.0*
Average for hurricanes	*68.6*	*82.8*
Maximum for hurricanes	*219.8*	*271.8*

Table 4. Mean 12-h precipitation total (mm), average or point maximum within 100 km of the storm center, taken for all ensemble members at every instance of a TC or hurricane.

Previous studies have found an increase in precipitation in TCs under warming conditions (Knutson and Tuleya 1999; Knutson and Tuleya 2004; Yoshimura et al. 2006; Hill et al. 2008; Knutson et al. 2008; Knutson et al. 2010). When considering either all TCs or just hurricanes, there is approximately a 15% increase in the area-average 12-hour precipitation in the future ensemble, averaged within 100 km of the storm center (Table 4). The *maximum* amount of precipitation in any grid cell within 100-km of the storm center exhibits a still more dramatic increase in the warming runs, a 33% increase when considering all TCs. The increase in the standard deviation of both the maximum and area-averaged precipitation also indicates that a larger range of rainfall totals is possible in the future atmosphere (not shown). Overall, there is evidence of increased precipitation associated with TCs in a warmer climate, as well as a larger span of possible precipitation totals for TCs for the future atmosphere.

An additional ensemble of model runs (hereafter referred to as the warming+CO_2 ensemble) is performed where CO_2 concentrations consistent with those determined for the A1B scenario at the end of the century are included by modifying the settings in the CAM radiation scheme in the WRF model. The default value used by the CAM scheme, 355 parts per million (ppm) by volume, is increased to 700 ppm, which is the concentration at the end of the 21st century within the A1B scenario according to the IPCC Working Group 1 Fourth Annual Assessment Report (Solomon et al. 2007, p. 822).

Compared to the original warming ensemble with the same physics options, this change in CO_2 concentration does result in some change to the storm statistics (Table 2). The monthly ensemble-averaged is slightly decreased by the explicit inclusion of greater CO_2. Overall, this variability is small relative to that between ensemble members, or current to future changes. It is notable that the number of major storms is approximately equal in the current ensemble and the warming runs when increased CO_2 is explicitly included, with only a small decrease that failed to be statistically significant[2].

4. CONCLUSIONS

A downscaling approach has been used to apply temperature and moisture changes, consistent with the atmosphere at the end of the 21st century derived from the IPCC A1B scenario, to an active month during the 2005 Atlantic hurricane season. The aim of this study is to isolate differences in future TC activity based on modification of the thermodynamic profiles, apart from changes in vertical wind shear. The active month of September of 2005 is replicated for a future, warmed atmosphere. A 4-member physics ensemble is run using the WRF model,

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[2] The criterion applied to storm counts for statistical significance is a paired Student's t-Test using a p-value threshold of 0.10.

and varying the microphysical and PBL parameterization schemes.

Comparison of the current and future 18-km grid spacing ensembles yielded the following results regarding the effect of future temperature and moisture changes on TC activity in an environment with no significant change in the vertical wind shear:
1.) The intensity of TCs is found to increase only slightly, by an average central pressure of ~3 hPa.
2.) TC frequency is reduced, with the ensemble average number of named storms decreased by 28%, hurricanes by 33%, and major storms by 21% (Table 2).
3.) An increase is found in the amount of precipitation associated with storms, both in maximum (33%) and spatially averaged (15%) values (Table 4).

The decrease in minimum central pressures of future TCs is small, with no statistically significant change in intensity when considering only hurricanes. Although the average intensity of TCs is not significantly changed, there is a decrease in the storm counts and ensemble-total ACE, by 15%, in the future runs. The sign of the change in TC activity is robust across all the ensemble members, with all members producing a decrease in TC storm counts and ACE, but varying in the magnitude of the reduction (Table 2).

5. FUTURE WORK

Early results from an ensemble with 6-km grid spacing and explicit convection only indicate some sensitivity of these results to grid spacing. A larger decrease in monthly ACE is found in the future; however, the magnitude of the decrease in future TC frequency is lessened with higher resolution (not shown). Therefore, future work will concentrate on further comparing these higher resolution results to those found by the 18-km ensemble.

The extension of this study into multiple months of the hurricane season would also provide further insight into the activity of TCs under global warming conditions, as would simulations of periods of weak TC activity, such as the 2007 Atlantic season.

6. ACKNOWLEDGEMENTS

This research was supported by DOE grant ER64448, awarded to North Carolina State University. The authors would also like to thank the Renaissance Computing Institute (RENCI) for making available their computing resources and technical support. The WRF model is made available by NCAR, funded by the National Science Foundation. We also thank the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the CMIP3 model output, and the WCRP's Working Group on Coupled Modeling (WGCM) for organizing the model data analysis activity. The WCRP CMIP3 multimodel dataset is supported by the Office of Science, U.S. Department of Energy.

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