7B.2 MODEL SIMULATED CHANGES IN TC INTENSITY DUE TO GLOBAL WARMING

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1. Introduction

The impact of global warming on tropical cyclone (TC) maximum intensity has recently become a topic of frequent investigation. In the absence of external factors detrimental to TC intensification (e.g. vertical wind shear, dry air entrainment, upwelling, land interactions) the maximum intensity of a TC increases as the sea surface temperature (SST) increases. This relationship has been shown to exist utilizing observational data (e.g. DeMaria and Kaplan 1994) and also theory (e.g. Emanuel 1986; Emanuel 1988; Emanuel 1995). Therefore, it is logical that if SSTs over the climatologically favored regions where TCs exist were to increase due to global warming, TCs could become stronger.

Projections of future climate change are often made with the aid of coupled atmosphere-ocean general circulation models (AOGCMs). AOGCMs do produce TC-like disturbances, and could therefore be used to study future TC intensity. However, computing limitations require that these models be run at fairly coarse resolution, precluding resolution of important physical processes that can impact TC intensity (e.g. storm-scale variations in turbulent fluxes, eye-eyewall mixing, TC secondary circulations). If the AOGCMs are unable to accurately represent current TC intensity, it is unrealistic to expect future TC intensity to be any better represented. Therefore, assessing changes in future TC intensity using AOGCMs is not the most accurate approach.

In order to better simulate TC intensity, previous studies have used higher resolution regional models nested within AOGCMs (e.g. Knutson and Tuleya 1998, 1999). In this approach, the AOGCM provides the large-scale environmental conditions to the nested model, which can better simulate TC intensity due to its higher resolution. A more idealized approach was later introduced (e.g. Knutson and Tuleya 2001, 2004) whereby large scale boundary conditions (e.g. SST, atmospheric temperature and water vapor) for the high resolution model are provided by an AOGCM (this approach is often referred to as downscaling). These boundary conditions, often averaged over time and space, are used to represent typical conditions that support strong TCs. By utilizing AOGCM forecasts with different projections of CO_2 concentrations, the impact of global warming on TC intensity can be studied, since the large-scale conditions passed to the higher resolution model would be different under different climate scenarios.

In this study, we utilize a downscaling approach, with lateral boundary conditions for a high-resolution model derived from an ensemble of recent AOGCM forecasts. The goal of this study is to assess how the maximum TC intensity would change between the present day and the end of the 21st century, if AOGCM projected changes in SST and atmospheric temperature and moisture were to occur. In addition, we seek to specifically address how changes in atmospheric stability may offset increases in TC intensity that would occur due to SST increase alone.

TCs are simulated using a high-resolution, convection resolving model configuration, in contrast to some previous studies which were forced to employ cumulus parameterization (CP) due to coarser grid spacing. The omission of a CP scheme allows for the TC secondary circulation to be better resolved, leading to a more realistic structure and a better projection of possible intensity change.

In following sections, a more detailed description of the methodology is provided, along with an overview of initial results.

2. Methodology

In our approach, first simulations of an idealized TC inserted within a large-scale environment consistent with current conditions in part of the Atlantic main development region (MDR, Fig. 1) were performed. Current climate values were computed using monthly-mean 2.5 degree NCEP/NCAR reanalysis data from September 2005. Monthly mean data were used in order to smooth diurnal variations and transient weather

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disturbances. 0.5° Real-time global (RTG) SST data were used, and the average SST for the region was found to be 29.25° C.

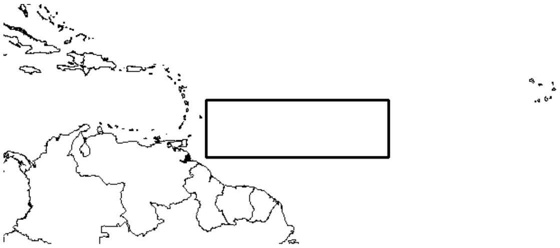


Figure 1. Outline of averaging region. The region encompasses 8.5 – 15° North, and 60 – 40° West.

Next, changes in the maximum potential TC intensity[1] (MPI) in this region during the 21st century were analyzed utilizing an ensemble (20 members) of AOGCMs from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), A1B[2] scenario. The area-averaged MPI (Fig. 2) increases throughout the 21st century, with a peak value in 2089. The ensemble-mean AOGCM projected *changes* in the average SST, surface pressure, and atmospheric temperature and moisture in the aforementioned region between September 2005 and September 2089 were computed (shown in Fig. 3), and these changes were then added to the current analysis averages to produce large-scale environmental conditions consistent with the future climate.

The ensemble-average AOGCM SST change was found to be ~2.1°C, yielding a future SST value of 31.35°C. Projected increases in atmospheric moisture were largest in the lower troposphere, with mixing ratio increases of up to 2.5 g kg^{-1} at the 1000-hPa level. Temperatures are projected to warm throughout the troposphere, with the maximum warming (up to ~4. 7°C) near the 250-hPa level. These changes are fairly similar to previous studies. Although a limited region of the Atlantic Ocean was used for the averaging, both the current climate values and the AOGCM anomalies were not highly sensitive to the exact region (not shown).

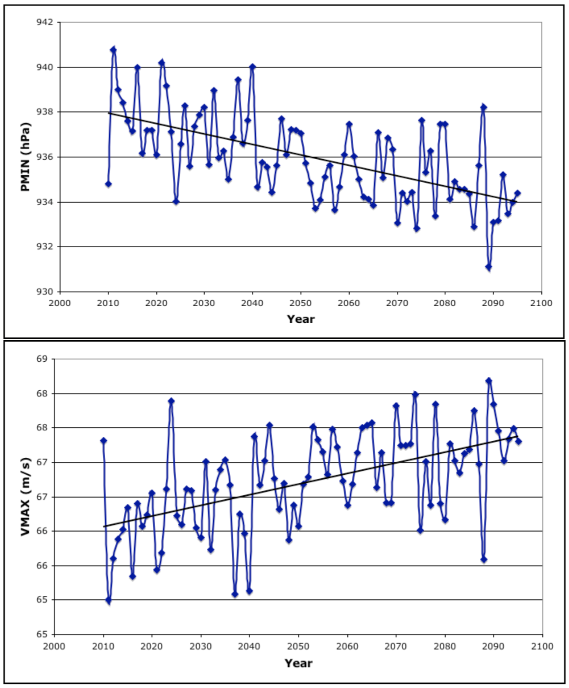
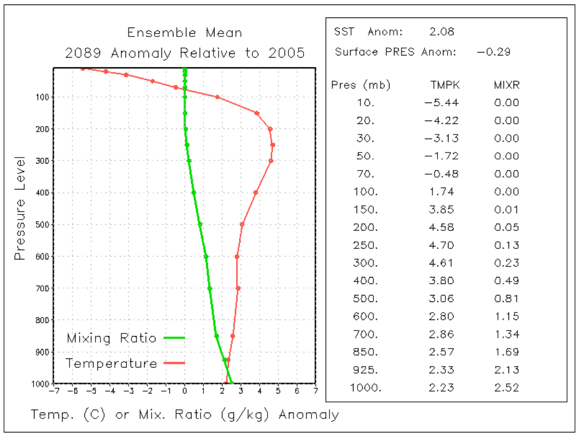


Figure 2. AOGCM ensemble mean MPI values for the region shown in Fig. 1. Top panel displays minimum central pressure, and bottom panel displays maximum 10-m wind speed.



SST Anom: 2.08

Surface PRES Anom: −0.29

Pres (mb)	TMPK	MIXR
10.	−5.44	0.00
20.	−4.22	0.00
30.	−3.13	0.00
50.	−1.72	0.00
70.	−0.48	0.00
100.	1.74	0.00
150.	3.85	0.01
200.	4.58	0.05
250.	4.70	0.13
300.	4.61	0.23
400.	3.80	0.49
500.	3.06	0.81
600.	2.80	1.15
700.	2.86	1.34
850.	2.57	1.69
925.	2.33	2.13
1000.	2.23	2.52

Figure 3. AOGCM forecasted temperature change between 2005 and 2089 for the month of September, in the region shown in Fig. 1.

The impact of vertical wind shear is not included in this study. Although changes in shear will likely impact the *number* of TCs in a given season, it may not reduce the intensity of the strongest TCs, which typically develop during time periods and in locations where shear is low. Future changes in the thermal structure of the upper ocean could impact the amount of SST cooling due to upwelling and therefore TC intensity, but this change is not addressed in this study. Previous work indicates that the inclusion of a coupled ocean model did not change the

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[1] MPI computed using a subroutine written by Prof. Kerry Emanuel, available at: ftp://texmex.mit.edu/pub/emanuel/TCMAX

[2] Under this emissions scenario, CO_2 emissions peak in 2050, and the utilization of new renewable energies is assumed.

primary qualitative conclusions relative to a static SST, uncoupled model configuration (Knutson and Tuleya 2001).

Version 2.2 of the Weather Research and Forecasting (WRF-ARW) model (Skamarock et al. 2007) was initialized with an idealized TC centered at 10ºN. This initial vortex, inserted within the horizontally uniform aforementioned current and future environments, possessed maximum winds of 30 m s^{-1}, and a minimum sea level pressure of ~981 hPa. The horizontal wind field was specified according to Chan and William's (1987) horizontal wind profile, and a vertical structure was introduced by multiplying the wind speeds by a function that decreases monotonically with pressure above 850 hPa (as done in Kwok and Chan 2005). Temperatures are calculated using thermal wind balance, pressure perturbations are computed from the hypsometric equation, and hydrostatic geopotential heights are determined. Outside of the vortex, the environment is calm, yielding a no-shear environment favorable for TC intensification. The maximum intensity after a sufficiently long integration period was found not sensitive to the strength of the initial vortex (not shown).

Model TCs generally move west northwestward due to beta-drift, necessitating the use of a moving nest configuration. Simulations utilized a high-resolution inner domain (2-km grid spacing) nested within an outer domain with 6-km grid spacing. The inner nest utilized an automatic vortex-tracking algorithm to keep the storm nearly centered in this domain. Simulations on both domains utilized 47 vertical layers, with a higher concentration in the boundary layer and a model top of 10-hPa. Model simulations were integrated for 10 days, allowing sufficient time for the TCs to reach a maximum intensity. Model output was produced every 3 hours, with the assumption that this interval is sufficiently frequent to capture the maximum intensity.

Model simulations of TCs are sensitive to model configuration, including grid spacing, and the parameterization of microphysical processes and turbulent mixing (e.g. Davis and Bosart 2002). In order to obtain the best estimate of the average change in maximum TC intensity, a small ensemble of model simulations utilizing different combinations of model physics was performed. Model simulations were performed using one of the following microphysics schemes (Kessler, Purdue-Lin, WSM6) along with either the YSU or MJY surface layer/PBL parameterization schemes, yielding a total of 6 model simulations each for the current and future climate scenarios. The rapid radiative transfer model (RRTM) longwave radiation scheme and the Goddard shortwave radiation scheme are used in all model simulations.

As was shown in Fig. 3, AOGCMs predict tropospheric warming that is maximized near the 250-hPa level. More specifically, the ensemble mean increase in temperature at the 250 hPa level (4.7 K) is more than double the increase at the 1000 hPa level (2.2 K). The physical cause for this warming profile is related to latent heating, which is fully realized in the upper troposphere with moist adiabatic ascent. The resulting atmospheric stabilization has been shown in previous studies (e.g. Shen et al. 2000) to partially offset the increase in TC intensity that rising SSTs would alone produce, although the impact of the stabilization largely depended upon the TC intensity. In order to study the impact of tropospheric stabilization on future TC intensity, simulations are performed where the entire troposphere is warmed by the same amount (~2°C). Following the assumption that the tropical atmosphere is approximately moist adiabatic, this profile of warming could occur if surface air temperatures warm by the same amount as the sea surface, but relative humidity values decrease.

3. Current and Future TC Intensity

Maximum TC intensity is assessed by examining the minimum sea level pressure (MSLP) and maximum model 10-m wind speeds at each 3-hourly output time. With each model physics configuration the future environment produced a stronger TC than the current environment, although the difference in maximum intensity varies. Figure 4 displays the ensemble average MSLP values for the current and future climate simulations. The simulated TCs follow a similar evolution in intensity, with rapid strengthening during the first 2 days of integration, slow intensification through day 7, and then gradual weakening between days 7 and 10. The average MSLP values are ~14 hPa lower in the future simulations averaged between days 3 and 10.

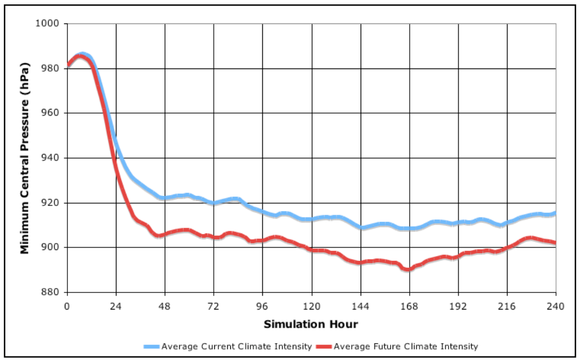

Figure 4. Ensemble average time-series of average minimum central pressure for the current climate (blue) and future climate (red) model simulations.

The ensemble average maximum model 10-m wind speeds (Fig. 5) are larger in the future simulations, but the average increase of ~4 m s^{-1} (averaged between days 3 and 10) is not extremely large. The relatively small increase in maximum wind speed (relative to the MSLP reduction) may be due to the model surface exchange coefficients. In the MYJ and YSU surface layer parameterization schemes, the exchange coefficient for momentum increases with wind speed (e.g. Hill and Lackmann 2008), in contrast with recent observations which suggest that the drag coefficient may levels off at wind speeds above ~ 30 m s^{-1} (e.g. Black et al. 2007). The large amount of drag at high wind speeds may lead to model 10-m winds that are too slow, given the pressure gradients present.

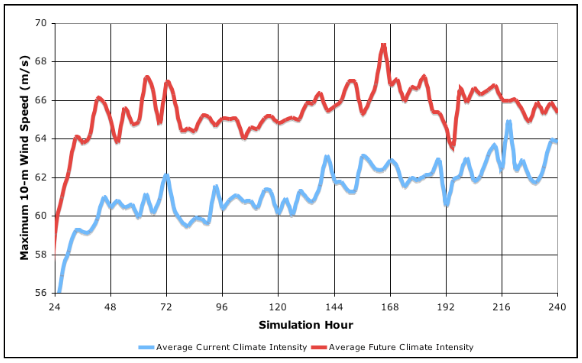

Figure 5. Ensemble average time-series of maximum 10-m wind speed (m s^{-1}) for the current climate (blue) and future climate (red) model simulations. Note that simulation results from after 1 day of model integration are shown, in order to highlight the differences.

4. Precipitation Amounts

In addition to the hazard that wind poses to those in the path of a strong hurricane, flooding rainfall is also a major source of casualties and damage. KT04 found an 18% increase in the average precipitation rate within 100-km of TC center in simulations of future TCs. The WRF model outputs the instantaneous precipitation rate, allowing for a comparison to be made between the current and future climate simulations. Our results are consistent with KT04, and indicate an average increase in precipitation within 100-km of TC center of ~18% in the future TC simulations. Averaged over 250 or 500-km areas, the increase in average precipitation in the future TC simulations is ~ 8% and 6%, respectively.

5. The impact of tropospheric stabilization

Figure 6 is similar to Fig. 4, although it includes the average MSLP values for the future climate simulations with constant tropospheric warming with height (in black). It is evident that the tropospheric stabilization offsets some of the intensification that would otherwise occur in the future climate. Averaged over simulation days 3 – 10, the future simulations with no stabilization are ~14 hPa deeper than those including stabilization, and ~30 hPa deeper than the current climate simulations. Based upon these results, tropospheric stabilization offsets the potential TC intensification by ~50%.

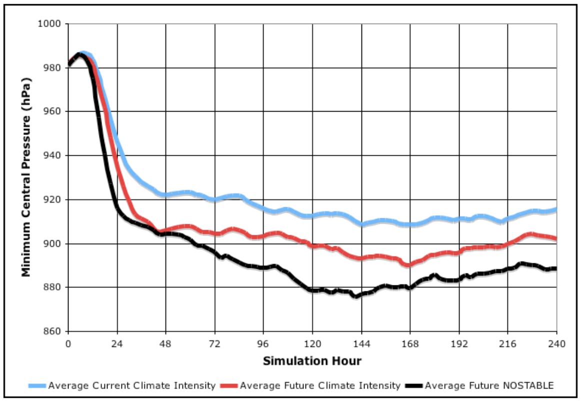

Figure 6. Time-series of average minimum central pressure for the current climate (blue), future climate (red), and future climate without tropospheric stabilization (black).

6. Discussion and Conclusions

In this study, the impact of climate change on the maximum intensity of TCs was investigated. The approach used herein combined observational data, AOGCM output, and high-resolution TC modeling. Previous work was extended in this study by utilizing a larger number of AOGCMs for the initial and lateral boundary conditions, along with a convection resolving model configuration. In addition, the impact of tropospheric stabilization on the intensity change was investigated by performing simulations with a constant warming throughout the troposphere.

Initial results indicate an increase in the maximum intensity of future TCs. The largest change is seen in the minimum central pressure, with future TCs exhibiting central pressures ~14 hPa deeper. The average increase in maximum wind speed in the future TC simulations is modest (~4 m s^{-1}), and may be due to the model's momentum exchange coefficient. The average TC rainfall was found to increase in the future climate simulations by ~18% within 100-km of the TC center.

The change in TC intensity found in the future simulations is linked to both projected changes in the atmosphere and ocean. Tropospheric stabilization, present in all the AOGCM forecasts, plays a role in offsetting the large increase in intensity that would occur solely based on the projected SST change. Model simulations performed without the projected change in stabilization but including the projected SST change indicate that the stabilization reduces the increase in TC intensity by ~50%. Uncertainty exists in the AOGCM projections of both the atmosphere and the ocean, and the amount of atmospheric stabilization, relative to the increase in SST will play a crucial role in shaping the intensity of future TCs.

7. Future Investigation

The results of this study should be extended in a number of ways. Further model simulations with different initial vortices and/or different model physics would be desirable in order to test the robustness of the intensity changes. Averaging the current conditions and the future anomalies over a different region or in a different ocean basin may provide additional insight into how the maximum intensity may change under slightly different conditions. Also, the A1B emission scenario used to drive the AOGCMs used herein likely produces less warming than would some other emissions scenarios. Model results would likely be different if another scenario were used to derive the lateral boundary conditions for the nested model.

Model simulations shown here were performed using WRF version 2.2, which has now been updated to version 3.0. In addition to providing a larger number of physics options, the new model version also includes the option to use modified surface exchange coefficients that are designed to more accurately represent fluxes at high wind speeds over water. This improved representation of surface fluxes may lead to a different estimate of the increase in maximum wind speed in future TCs.

Acknowledgements

This research was funded by NSF grant ATM-0334427, awarded to North Carolina State University, and DOE grant ER64448, awarded to North Carolina State University.

The WRF model was made available through NCAR, sponsored by the NSF.

Model simulations were performed at the Renaissance Computing Institute (RENCI), which is supported by UNC Chapel Hill, NCSU, Duke University, and the state of North Carolina.

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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