Final Report: **Modulation of extremes in the Atlantic region by modes of climate variability/change: A mechanistic coupled regional model study**

Award No. DE-SC0004966
Funding Period: 9/1/2010 - 8/31/2013 + one year no-cost extension
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Abstract

During the course of this project, we have accomplished the following:

1) Explored the parameter space of component models to minimize regional model bias
2) Assessed the impact of air-sea interaction on hurricanes, focusing in particular on the role of the oceanic barrier layer
3) Contributed to the activities of the U.S. CLIVAR Hurricane Working Group
4) Assessed the impact of lateral and lower boundary conditions on extreme flooding events in the U.S. Midwest in regional model simulations
5) Analyzed the concurrent impact of El Niño-Southern Oscillation and Atlantic Meridional Mode on Atlantic Hurricane activity using observations and regional model simulations

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I. Completed Research and Development Activities

i) Exploring the parameter space of component models to minimize regional model bias

Unlike global atmospheric models like CAM4, which are available for download with an optimal combination of "tuned" parameterization settings for good climate simulations, regional models, like the WRF model used in the Coupled Regional Climate Model (CRCM), must typically be tuned to produce the best simulations in the region of interest. We explored the parameter space of the WRF model, by using different choices for convection, radiation, and boundary layer parameterizations, with the goal of producing the best possible simulations over the U.S. region as well as the tropical Atlantic regions. Having a reasonable simulation of the mean state is essential to be able to proceed further with our research and analyze the statistics of extreme climate events. During this tuning exercise, we were able to identify two combinations of model parameters that gave rise to a "wet" and "dry" Amazon simulation. We carried both coupled and uncoupled RCM integrations using the "wet" and "dry" parameters to test a proposed hypothesis that weakened Amazon convection and the associated westerly surface wind biases in the western equatorial Atlantic were a major cause of tropical Atlantic SST biases in coupled models. We found that surface wind biases in the eastern equatorial Atlantic, *not* in the western equatorial Atlantic, were likely a major cause of biases in the coupled simulation. The results from this study are summarized in Patricola et al. (2011, 2012). We also carried out a companion study addressing the biases in the oceanic component, ROMS.

We have identified excessively diffuse thermocline simulations in the equatorial Atlantic as another possible cause of model biases in the tropical Atlantic (Xu et al., 2012).

ii) Impact of air-sea interaction on hurricanes
One class of extreme events that we have been focusing on is Atlantic hurricanes. In particular, we have been studying how the oceanic lower boundary condition affects the evolution of a hurricane. When a hurricane passes over the ocean, the enhanced oceanic vertical mixing associated with the strong winds leads to surface cooling that can act as a negative feedback on hurricane development. We have been studying two aspects of this air-sea interaction, (a) the role of the "barrier layer" and (b) the role of surface cooling.

Barrier layers (BL) are regions when the depth of the isothermal layer exceeds the depth of the mixed layer in the ocean. They occur in certain regions of the tropical Atlantic, especially the Caribbean. The presence of a barrier layer inhibits vertical mixing and can reduce the negative oceanic feedback on hurricane development. As the CRCM can simulate both hurricanes and barrier layers, it can serve as a useful tool to understand the interaction between the two.

a) The barrier layer of the Atlantic warm pool: Many Coupled General Circulation Models (CGCMs) tend to overestimate the salinity in the Atlantic warm pool or the Northwestern Tropical Atlantic (NWTA) and underestimate the surface salinity in the subtropical salinity maxima region. Most of these models also suffer from a sea-surface temperature (SST) bias in the NWTA region, leading to suggestions that the upper ocean salinity stratification may need to be improved in order to improve the BL simulations and thus the SST through BL-SST-Intertropical Convergence Zone (ITCZ) feedbacks. We used a CGCM to perform a set of idealized numerical experiments to understand the sensitivity of the BL and consequently SST in the NWTA region to freshwater flux and hence the upper ocean salinity stratification. We found that the BL of the western tropical Atlantic is quite sensitive to upper ocean salinity changes in the Amazon River discharge region and the subtropical salinity maxima region. The BL phenomenon is further manifested by the formation of winter temperature inversions in our model simulations. However, in the region of improved BL simulation, the SST response to it is not statistically significant. This study appeared in *Tellus* (Balaguru et al., 2011).

b) Ocean barrier layer's effect on tropical cyclone intensification: Improving tropical cyclone forecasts and mitigating its destructive potential require the knowledge of various environmental factors that influence the cyclone's path and intensity. Here, using a variety of observations and model simulations, we systematically demonstrate that tropical cyclone intensification is significantly affected by salinity-induced Barrier Layers, which are 'quasi-permanent' features in the upper tropical oceans. When tropical cyclones pass over regions with Barrier Layers, the increased stratification and stability within the layer reduce the storm induced vertical mixing and sea surface temperature cooling. This causes an increase in enthalpy flux from the ocean to the atmosphere and consequently an intensification of tropical cyclones. On average, tropical cyclone intensification rate is nearly 50% higher over regions with Barrier Layers, as compared to regions without. Our finding underscores the importance of observing not only the upper ocean thermal but also the salinity structure in the regions of deep tropical Barrier Layers, in order to improve ocean state estimates and modeling of Barrier Layer processes, which may prove to be important keys to more skillful prediction of tropical cyclone intensities. As the hydrological cycle may change under global warming, associated Barrier Layer changes need to be considered in projecting future tropical cyclone activity. This study appeared in *PNAS* (Balaguru et al., 2012).

ii) Impact of lateral and lower boundary conditions on extreme precipitation events
After determining the "optimal" combination of model parameter settings, we completed a 20-year integration using the 27-km uncoupled WRF model, using observed atmospheric state as lateral boundary condition and observed SST as the lower boundary condition (similar to the global AMIP-style integrations). Additionally, we carried out a companion 20-year integration using climatological atmospheric state and SST as boundary conditions, as well as another 20-year integration with uniform SST warming. We also carried out a few shorter integrations using different combinations of lateral and lower boundary conditions, e.g., climatological SST with observed lateral boundary conditions and observed SST with climatological lateral boundary conditions. By analyzing these integrations, we are able to distinguish between lateral boundary condition effects (like El Niño) and lower boundary condition effects (like Atlantic SST variability) in the Atlantic region.

As we were in the process of setting up our regional model integrations, we were approached by the U.S. CLIVAR Hurricane Working Group (HWG), which was interested in adding a regional model to their mix of global models, for intercomparison of hurricane simulations. Our regional model covers a fairly large domain, encompassing the entire Atlantic basin as well as the United States, and runs at a resolution finer than many of the global models, thus being able to simulate hurricanes. Since our planned integrations to assess the sensitivity of extreme events to boundary conditions were very similar to what was required by the protocol for the HWG Model Intercomparison, we decided to join the HWG and coordinate our experiments with them. We have submitted data from the 20-year AMIP, climatological and climate change integrations to the HWG data archive. We contributed to a paper providing an overview of the HWG activities (Walsh et al., 2014).

Analysis of the hurricane activity in the 20-year AMIP-style integration shows that the model exhibits considerable skill in capturing the observed interannual variations of hurricane activity (as measured by the Accumulated Cyclone Energy). We have analyzed the additional sensitivity experiments to identify the source of this predictive skill, i.e., whether it is the lateral boundary conditions or the lower boundary conditions? We have also analyzed the 20-year AMIP-style integration to study the statistics of hurricanes as well as extreme precipitation events over the U.S.

a) Simulation of flooding events: The role of sea surface temperature anomalies (SSTAs) in the Atlantic and eastern Pacific and high- and low-frequency atmospheric variability from the Pacific in the 1993 and 2008 Midwest floods is investigated with a regional climate model (RCM). The SSTAs insignificantly modulate the magnitude of the positive Midwest rainfall anomalies during the 1993 flood, but play significant secondary role in enhancing precipitation during the peak period of the 2008 flood by strengthening the southern portion of the Great Plains low-level jet and enhancing moisture transport from the Gulf of Mexico into the central U.S. RCM experiments that apply a 10-day low-pass filter to the western lateral boundary condition indicate that interactions between the eddy and time-mean flow played a significant, but counterintuitive role, during the 1993 flood. Results show that the above normal Pacific cyclone activity that was observed to trigger heavy Midwest precipitation interacted with the large-scale North American circulation in such a way as to dampen the positive rainfall anomalies, specifically by weakening vertically-integrated moisture transport and positive upper level divergence anomalies over the Midwest. This study appeared in *Climate Change* (Patricola et al., 2013).

b) Impact of El Niño-Southern Oscillation (ENSO) and Atlantic Meridional Mode (AMM) on Atlantic Hurricanes: Atlantic tropical cyclone (TC) activity is influenced by interannual tropical Pacific sea surface temperature (SST) variability characterized by the ENSO, as well as interannual-to-decadal variability in the interhemispheric gradient in tropical Atlantic SST characterized by the AMM. We participated in the US CLIVAR Hurricane Working Group and completed three 20-year Atlantic hurricane simulations using 27 km WRF in the Atlantic sector. Our analysis of observations and the HWG runs shows that 1) WRF is capable of simulating interannual Atlantic hurricane variability provided that accurate SST and atmospheric flow conditions are prescribed, 2) both AMM and ENSO play an important role in modulating Atlantic hurricane activity. Individually, the negative AMM phase (cool northern and warm southern tropical Atlantic SST anomalies) and El Niño each inhibit Atlantic TCs, and vice versa. The impact of concurrent strong phases of the ENSO and AMM on Atlantic TC activity was investigated. The response of the atmospheric environment relevant for TCs was evaluated using a genesis potential index. Composites of observed accumulated cyclone energy (ACE) suggest that ENSO and AMM can amplify or dampen the influence of one another on Atlantic TCs. Simultaneous strong El Niño and strongly positive AMM, as well as strong concurrent La Niña and negative AMM, produce near-average Atlantic ACE suggesting compensation between the two influences, consistent with the observational analysis. Strong La Niña and strongly positive AMM together produce extremely intense Atlantic TC activity, supported largely by above average mid-tropospheric humidity, while strong El Niño and negative AMM together are not necessary conditions for significantly reduced Atlantic tropical cyclone activity. A paper describing these results has been published in a special issue of *Journal of Climate* for hurricane working group (Patricola et al., 2014).

II. Project participants (supported in whole or in part)

Faculty: R. Saravanan and Ping Chang
Postdoctoral Researchers: Christina Patricola and Jen-Shan Hsieh

Software Engineer: Raffaele Montuoro
Graduate students: T. Verma, V. Ravikumar, Zhao Xu, and Xiaojie Zhu

III. Presentations and publications/manuscripts wholly or partially supported by this project

a) Peer-reviewed Publications

Balaguru, K., Chang, P., Saravanan, R., and Jang, C. J. 2011: The Barrier Layer of the Atlantic Warm pool: Formation Mechanism and Influence on the Mean Climate, *Tellus* A, **64** , 18162, doi: http://dx.doi.org/10.3402/tellusa.v64i0.18162.

Patricola, C. M., M. Li, Z. Xu, P. Chang, R. Saravanan, J.-S. Hsieh, 2012: An Investigation of Tropical Atlantic Bias in a High-Resolution Coupled Regional Climate Model, *Clim. Dyn*., **39**, 2443-2463, DOI10.1007/s00382-012-1320-5.

Balaguru, K., Chang, P., Saravanan, R., L. R. Leung, Z. Xu, M. Li & J.-S. Hsieh, 2012: Ocean Barrier Layers' Effect on Tropical Cyclone Intensification, *PNAS*, **109**, 14343-14347, doi:10.1073/pnas.1201364109/-/DC Supplemental.

Xu, Z., M. Li, C. M. Patricola, and P. Chang, 2013: Oceanic Origin of Southeast Tropical Atlantic Biases, *Clim. Dyn.*, DOI 10.1007/s00382-013-1901-y.

Patricola, C.M., P. Chang and R. Saravanan, 2013: Impact of Atlantic SST and High Frequency Atmospheric Variability on the 1993 and 2008 Midwest Floods: Regional Climate Model Simulations of Extreme Climate Events, *Clim. Change*, DOI 10.1007/s10584-013-0886-1.

Patricola, C.M., R. Saravanan and P. Chang, 2014: The Impact of the El Nino-Southern Oscillation and Atlantic Meridional Mode on Seasonal Atlantic Tropical Cyclone Activity, *Journal of Climate*, **14**, 5311-5328

Walsh, Kevin J. E., Suzana Camargo, G. Vecchi, A. S. Daloz, J. Elsner, K. Emanuel, M. Horn, Y.-K. Lim, M. Roberts, C. Patricola, E. Scoccimarro, A. Sobel, S. Strazzo, G. Villarini, M. Wehner, M. Zhao, J. Kossin, T. LaRow, K. Oouchi, S. Schubert, H. Wang, J. Bacmeister, P. Chang, F. Chauvin, C. Jablonowski, A. Kumar, H. Murakami, T. Ose, K. Reed, R Saravanan, Y. Yamada, C. Zarzycki, P.-L. Vidale, J. Jonas, N. Henderson, 2014: Hurricanes and climate: the U.S. CLIVAR working group on hurricanes, *Bulletin of the Amer. Meteorol. Soc.* Accepted. doi: http://dx.doi.org/10.1175/BAMS-D-13-00242.1.

b) Other publications

Patricola, C.M., P. Chang, R. Saravanan, M. Li, and J.-S. Hsieh, 2011: An investigation of the Tropical Atlantic bias problem using a high-resolution coupled regional climate model. US *CLIVAR Variations*, Vol. 9, No. 2, 8-12pp.

c) Presentations

Balaguru, K., P. Chang, R. Saravanan, J.-S. Hsieh, M. Li: Effect of Barrier Layers on the Sea Surface Temperature response to Tropical Cyclone Induced Mixing. American Geophysical Union, Fall Meeting, San Francisco, Dec. 2010.

Chang, P., R. Saravanan, M. Li, J.-S. Hsieh, C. M. Patricola, and K. Balaguru: A Study of Meso and Frontal Scale Air-Sea Interactions Using a High-Resolution Atlantic Regional Coupled Model. European Geosciences Union, General Assembly, Vienna, April 2011

Saravanan, R., P. Chang, J.-S. Hsieh, C. Patricola: High-Resolution Coupled Regional Climate Modeling: Applications to the Atlantic Sector. Guanajuato Water Conference, Mexico, May 2011

Saravanan, R., J.-S. Hsieh, C.M. Patricola, P. Chang, M. Li: High-resolution Coupled Regional Climate Modeling in the Atlantic Sector: Simulating the mean state and hurricane activity. DOE PI Meeting, Washington, DC, Sep. 2011.

Saravanan, R., J.-S. Hsieh, C.M. Patricola, P. Chang, M. Li: High-resolution Coupled Regional Climate Modeling in the Atlantic Sector. AGU Fall Meeting, San Francisco, CA, Dec. 2011

Patricola, C.M., M. Li, Z. Xu, P. Chang, R. Saravanan, J.-S. Hsieh: An Investigation of Tropical Atlantic Bias in a High-Resolution Coupled Regional Climate Model. AGU Fall Meeting, San Francisco, CA, Dec. 2011

Saravanan, R.: Simulating and understanding the role of Tropical Atlantic variability in the climate system. Ocean Sciences Meeting, Salt Lake City, UT, Feb, 2012.

Patricola, C., R. Saravanan, P. Chang, 2012: Simulation of Tropical Cyclones in the WRF Regional Climate Model. U.S. CLIVAR Hurricane Working Group Meeting, New Orleans, January 2012

Saravanan, R., J.-S. Hsieh, K. Balaguru, C. Patricola, M. Li, P. Chang, and R. Montuoro, 2012: Hurricanes and air-sea interaction: High-resolution regional climate modeling. U.S. CLIVAR Hurricane Working Group Meeting, New Orleans, January 2012

Hsieh, J.-S., M. Li, R. Saravanan, and Ping Chang: Impact of the Gulf Stream SST front on North Atlantic climate variability: a high-resolution regional model study. Ocean Sciences Meeting, Salt Lake City, UT, Feb, 2012.

Patricola, C.M., P. Chang, R. Saravanan, and R. Montuoro: The Effect of Atmosphere-Ocean-Wave Interactions and Model Resolution on Hurricane Katrina in a Coupled Regional Climate Model. European Geosciences Union, General Assembly, Vienna, April 2012

Patricola, C., R. Saravanan, and P. Chang: The Impact of the El Niño-Southern Oscillation and Atlantic Meridional Mode on Seasonal Atlantic Tropical Cyclone Activity. 25th AMS Conference on Climate Variability and Change, Austin, TX, January 2013

Varma, T., J, Hsieh, C., Patricola, R. Saravanan, P. Chang, 2013: Climate extremes in uncoupled and coupled regional climate models. 25th AMS Conference on Climate Variability and Change, Austin, TX, January 2013

Saravanan, R., C. Patricola, P. Chang: Hurricane simulations in a regional climate model. U.S. CLIVAR Hurricane Workshop, June 5–7, 2013, GFDL, Princeton, NJ

Patricola, C., R. Saravanan, and P. Chang: The impact of the El Niño-Southern oscillation and Atlantic Meridional mode on Atlantic Tropical cyclone activity. CLIVAR Tropical Atlantic Variability (TAV) Prediction and Research Moored Array in the Tropical Atlantic (PIRATA) Meeting, Venice, Italy, October 2013