Searching for Atlantic Thermohaline Circulation Strength Threshold Leading to Abrupt Change of the African Monsoon
(Project DE-FG02-08ER64620)

A Final Technical Report to
DOE-Abrupt Climate Change Modeling

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1. Research Objectives

- To further advance the hypothesis that changes in the Atlantic Meridional Overturning Circulation (AMOC) are among the most critical factors determining abrupt African Monsoon changes in response to future global warming.

- To quantify various uncertain environmental factors that may work individually or in concert to trigger these abrupt transitions, so that we can have a better understanding of the uncertainties in the model projection.

2. Research Accomplishment

During the four years of the project (the last year 2011-2012 is a no-cost extension), we made major advancements in several research areas closely related to the goals of the proposal. The following is a brief progress summary in each of these areas:

1) **CCSM3 fresh water forcing simulations:** We completed two ensembles of fresh water forcing simulations with the CCSM3 where we systematically increase the fresh water forcing strength in the subpolar region of the North Atlantic as described in the proposal. The purpose of these numerical experiments is to examine the sensitivity of the climate system to changes in the AMOC and to establish any threshold behavior in the AMOC that will lead to abrupt climate change. Each ensemble consists of two sets of runs that differ in their initial conditions. The two ensembles of runs differ in climate forcing configuration as follows:
    i. *Present Climate Fresh Water Forcing Experiments:* This ensemble contains two sets of simulations. Each set consists of 7 100-year runs under the present climate condition, each of which starts from an identical initial condition from a long control CCSM3 integration, but is subject to different fresh water forcing with strength of 0.1, 0.2, 0.3, 0.35, 0.4, 0.6, 1.0 Sv. The two sets differ in that the initial condition used in each set is different and they are separated by 50 years from the long CCSM3 control simulation.
    ii. *Future Climate Fresh Water forcing Experiments:* This ensenble of simulations is identical to the present climate fresh water forcing runs except that an A2 Scenario GHG forcing is also included.

    These simulations led to the following important findings:
    a. We discovered for the first time a dual-state behavior of CCSM3 tropical atmosphere under the present climate condition in response to changes in the AMOC. The appearance of dual-state behavior is sensitive not only to the fresh water forcing, but also to the initial condition. It requires the fresh water forcing to reach a certain threshold. In our case, the required fresh water forcing strength is about 0.4 Sv that roughly corresponds to a 10 Sv reduction in the AMOC.

Above this threshold, the two sets of fresh water forcing runs exhibit distinctively different behavior. In one set, the effect of AMOC reduction on climate is manifested mainly in a strengthened NH winter Hadley circulation and a southward shift of the ITCZ in response to a cooling of the mid- to high-latitudes, and a warming of the tropical and subtropical Atlantic, which is consistent with many previous studies. However, this response is not what occurs in the other set of runs. In this case, the precipitation response is significantly large, with a pattern that has larger east-west anomalies, and emerges through an abrupt transition with a very short time scale (~ one month). The transition includes 30%-70% reductions in precipitation over large swaths of Africa, Eurasia, and South America. Other regions, such as the typical dry Sahara and Australia see significant increases in precipitation. Furthermore, large changes in the vertical distribution of tropical clouds are found at the onset of the transition, which results in a 5.5 watt increase in global mean cloud radiative forcing through reductions in low-level clouds and increases in mid to upper level relative humidity and high-level clouds. Many continental paleoclimate proxy records during the last ice age appear to be in better agreement with this dual-state transition in the second set CCSM3 runs than the well documented response associated with a southern shift in the ITCZ.

b. The exact mechanism responsible for the dual-state behavior has not been identified. However, the fact that the dual-state behavior depends on ocean's initial conditions and fresh water forcing strength suggests that the ocean is important. A plausible mechanism responsible for the AMOC threshold behavior is the oceanic gateway mechanism proposed by Chang et al. (2008). We found that as the AMOC weakens beyond its threshold, the North Brazil Current (NBC) system reverses its direction from northward to southward. This change in the ocean circulation allows the warm salinity maximum water (SMW) in the north tropical Atlantic Ocean to intrude into the equatorial Atlantic and south Atlantic, causing warming in the thermocline and subsequently warming at the surface. However, the rapidity and scale of the transition implicate the atmosphere as the component that plays a major role in this dual-state behavior. We speculate that different styles of tropical convection, i.e., "shallow" and "deep" convection, may give rise to a different atmospheric state when sea surface temperatures are sufficiently high (Held et al., 2007; Sobel et al., 2007; Sessions et al., 2010).

c. The GHG influence appears to suppress the dual-state behavior. Although the cause for this difference in atmospheric responses is still under investigation, we speculate that the enhanced upper ocean stratification due to the GHG forcing may reduce upwelling in the tropical ocean, acting to weaken the effectiveness of the oceanic gateway mechanism.

Some of the results of the CCSM3 study were presented at the Science Team Meeting. A paper to be submitted to Nature has been written.

2) **NCAR CCSM3 and GFDL CM2.1 intercomparison study**: In addition to the suites of the water hosing experiments described above, we also carried out ensembles of water

hosing runs using NCAR CCSM3 and GFDL CM2.1 under identical fresh water forcing and conducted an inter-model comparison study of the models' response to AMOC changes. This study is motivated by the fact that in many current-generation of climate models, the bias problem in the tropical Atlantic sector is so severe that one of the most basic features of the equatorial Atlantic ocean – the eastward shoaling thermocline – cannot be reproduced (e.g., Richter and Xie 2008). This deficiency may seriously degrade the credibility of the models in their simulation and projection of future climate change in the Atlantic sector. In this study, we show that the bias in the eastern equatorial Atlantic has a major effect on sea-surface temperature (SST) response to a rapid change in the Atlantic Meridional Overturning Circulation (AMOC). By comparing identical water hosing experiments conducted with the two different coupled general circulation models, we dissect oceanic mechanisms underlying the difference in models' SST response. One of the most important and significant differences between the responses of the two models to the identical fresh water forcing in the Northern North Atlantic is manifested in equatorial SST changes. CM2.1 shows a considerable equatorial warming in excess of 1°C, whereas CCM3.0 has an insignificant warming of the order of 0.2°C. This result is perplexing given that the two models experience comparable warming in the equatorial thermocline. Our analysis suggests that the difference is attributed to the different degree of model bias in simulating equatorial upwelling. Although both models underestimate equatorial upwelling and thus show warm SST bias in the equatorial Atlantic cold tongue region, the extent of the bias problem is much more severe in CCSM3 than in CM2.1. The warm SST bias in CCSM3 approaches 9°C off the coast of southern Africa and there is virtually no upwelling in the eastern equatorial Atlantic. These biases inhibit the communication between the equatorial thermocline and surface mixed layer in the model and prevent the equatorial thermocline warming from affecting the SST. In view of the commonality of the tropical Atlantic bias problem to virtually all coupled climate models, we postulate that the effectiveness of the oceanic pathway change mechanism is underrated in many abrupt climate simulations, particularly paleoclimate simulations where the AMOC plays a vital role. A journal paper (Wan et al. 2010) based on this research has been published in the special volume of the *Deep Sea Research* dedicated to the first US AMOC Science Meeting, May 4-6, 2009, Annapolis MD.

3) **Paleo-salinity response to AMOC changes**: In a related study, we investigated the salinity response to an abrupt change in the AMOC. During periods of reduced Atlantic meridional overturning circulation (AMOC) associated with a freshening of northern North Atlantic surface water, paleo proxy records indicate a corresponding surface salinity increase over the entire tropical Atlantic. Although latitudinal-shifts in the mean position of the Atlantic Intertropical Convergence Zone (ITCZ) can explain certain features of the paleo salinity reconstructions, this mechanism does not offer an explanation for the reconstructed basin-wide paleo-salinity response to AMOC change. We present new results from general circulation model simulations that suggest the sea surface salinity (SSS) increase in the tropical north Atlantic during periods of weakened AMOC is mainly controlled by the atmospheric response to the North Atlantic cooling, while the oceanic teleconnection contributes to increased SSS over the equatorial and south tropical Atlantic Ocean. An important finding of this study is that a careful model-data comparison of paleo SSS response in the tropical Atlantic may provide insight into the realism of freshwater forcing during periods of reduced AMOC. Therefore, future paleo modeling studies should not only focus on the SST response, but also pay attention

to the SSS response to gain a full understanding of ocean and atmosphere processes in past abrupt climate changes. Since the surface process and the oceanic gateway mechanism are opposing each other in controlling SSS changes in the South Tropical Atlantic, the importance of ocean circulation changes is particularly noteworthy when SSS constraint is considered in past abrupt climate change studies. This study is published in *Geophysical Research Letter* (Wan et al. 2010).

4) **A study on nonlinear SST response to AMOC changes:** In another related study, we gained insight into nonlinear nature of the SST response to AMOC changes by using a simpler ocean circulation model. Previous coupled climate model simulations reveal that a dipole like SST pattern with cooler (warmer) temperature over the north (south) tropical Atlantic emerges in response to a slow-down of the Atlantic Meridional Overturning Circulation (AMOC). Using a 2-1/2 layer reduced gravity ocean model, we conducted a systematic investigation into oceanic processes controlling tropical Atlantic sea-surface temperature (SST) response to AMOC changes by varying the strength of the imposed AMOC return flow. It is found that the North Brazil Undercurrent (NBUC) reverses its direction in response to a shut-down of AMOC. Such circulation change causes a decrease in upper equatorial ocean stratification and warming in the Gulf of Guinea and off the coast of Africa. These findings point to the importance of oceanic dynamics in equatorial SST response to AMOC changes. Sensitivity experiments further show that the SST response behaves nonlinearly to AMOC changes. The rate of SST changes increases dramatically when the AMOC strength is below a threshold value. This nonlinear threshold behavior depends on the position of subsurface temperature gradient forming along the boundary between the northern subtropical gyre and tropical gyre that interacts with the western boundary current. Our analysis suggests that in order for the oceanic dynamics to have a dominant influence on tropical Atlantic SST in response to AMOC changes, two conditions must be satisfied: (1) the AMOC must weaken substantially so that the NBUC flows equatorward, permitting water mass exchange between the northern subtropical and tropical gyres; (2) the subsurface temperature front must be located in an optimal location where subsurface temperature anomalies induced by AMOC change are able to enter the equatorial zone. This work appeared in *Journal of Climate* (Wen et al. 2010, 2011).

3. Education and Human Resource Development

This project supported two graduate students' dissertation research at the Department of Oceanography, Texas A&M University. Dr. Ciahong Wen graduated in the summer of 2009 and is now a research scientist at NOAA/NWS/NCEP/Climate Prediction Center, Camp Springs, MD. Dr. Xiuquan Wan graduated in the fall of 2009 and is now an associate professor at the Ocean University of China, Qingdao, China.

4. Publications supported by this grant

Wen, C., P. Chang, R. Saravanan 2010, Effect of Atlantic Meridional Overturning Circulation Changes on Tropical Atlantic Sea-Surface Temperature Variability: A 2-1/2 layer Reduced Gravity Ocean Model Study, *J. Climate*, **23**, 312-332, doi: 10.1175/2009JCLI3042.1.

Wan, X., P. Chang, and M.W. Schmidt 2010: Causes of tropical Atlantic paleo-salinity variation during periods of reduced AMOC, *Geophys. Res. Lett.*, **37**, L04603, doi:10.1029/2009GL042013.

Wen, C., Chang, P. Saravanan, R. 2011: Effect of Atlantic Meridional Overturning Circulation on Tropical Atlantic Variability: A Regional Coupled Model Study, *J. Climate*, **24**, doi:10.1175/2011JCLI3845.1.

Wan, X., Chang, P. C. S. Jackson, L. Ji and M. Li., 2011: Effect of Climate Model Bias on Abrupt Cli- mate Change Simulations in Atlantic Sector, *Deep Sea Res. II*, **58**, 1904-1913,doi:10.1016/j.dsr2.2010.10.068.

Jackson, C. S., P. Chang, L. Ji and V. Parolkar, 2013: Dual-state behavior observed within the Community Climate System Model. *Nature*, submitted.