Final Scientific Report for
The Interhemispheric Pattern in 20th Century and Future Abrupt Change in Regional Tropical Rainfall

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Recipient Organization: The Regents of the University of California

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1. Executive Summary

The project investigates the role of the interhemispheric pattern in surface temperature – i.e. the contrast between the northern and southern temperature changes – in driving rapid changes to tropical rainfall changes over the 20th century and future climates. Previous observational and modeling studies have shown that the tropical rainband – the Intertropical Convergence Zone (ITCZ) over marine regions, and the summer monsoonal rainfall over land – are sensitive to the interhemispheric thermal contrast; but that the link between the two has not been applied to interpreting long-term tropical rainfall changes over the 20th century and future.

The specific goals of the project were to i) develop dynamical mechanisms to explain the link between the interhemispheric pattern to abrupt changes of West African and Asian monsoonal rainfall; ii) Undertake a formal detection and attribution study on the interhemispheric pattern in 20th century climate; and iii) assess the likelihood of changes to this pattern in the future.

In line with these goals, our project has produced the following significant results:

1. We have developed a case that suggests that the well-known abrupt weakening of the West African monsoon in the late 1960's was part of a wider co-ordinated weakening of the West African and Asian monsoons, and driven from an abrupt cooling in the high latitude North Atlantic sea surface temperature at the same time. Our modeling work suggests that the high-latitude North Atlantic cooling is effective in driving monsoonal weakening, through driving a cooling of the Northern hemisphere that is amplified by positive radiative feedbacks.
2. We have shown that anthropogenic sulfate aerosols may have partially contributed to driving a progressively southward displacement of the Atlantic Intertropical Convergence Zone (ITCZ) over the course of the 20th century prior to the 1980s. This is based on our detection and attribution analysis of 20th century simulations done by international modeling groups as part of the Coupled Model Intercomparison Project phase 3 (CMIP3). We repeated the same analysis with the current CMIP5 multimodel simulations, with essentially similar results.
3. Future projections of the global interhemispheric thermal gradient suggest a pronounced trend that well exceeds the 20th century range of behavior. The major cause of this trend is due to anthropogenic greenhouse gas emissions, acting in such a way as to warm the North more than the South. This result is based on our analysis of the CMIP3 and 5 simulations of future scenarios. The underlying suggestion is that tropical rainfall may concentrate more northwards in the future climate, though further research is required to more firmly establish that result.

Taken together, our results shows the important role of the interhemispheric thermal gradient in determining tropical rainfall changes in the 20th century and future. Our analysis specifically highlights high-latitude North Atlantic sea surface temperature, and anthropogenic sulfate aerosols, as important drivers of the interhemispheric gradient over the 20th century; and anthropogenic greenhouse gases in the 21st. The PI has written a review paper in order to promote the awareness of the interhemispheric gradient amongst the climate science community.

Our project was instrumental in developing the career of a postdoctoral scholar, as well as contributing to the research training of three Ph.D. candidates.

2. Research Accomplishments during the Period of the Grant

Below, we describe the main results of our research that addresses each of these goals. **NOTE**: in the description, I use the term 'interhemispheric pattern' and 'interhemispheric gradient' interchangeably. The term refers to changes in the thermal contrast between the hemispheres, either regionally (e.g. north and south tropical Atlantic) or globally (northern hemisphere and southern hemisphere).

i) Dynamical Mechanisms linking the interhemispheric pattern to West African and Asian monsoonal rainfall *(personnel involved: Yuwei Liu, Ivana Cvijanovic)*

In Liu and Chiang (2012), we examined the late 1960's abrupt weakening of the West African monsoon that previously studies suggested to be influenced by the interhemispheric gradient (e.g. Folland et al. 1986). Using observations and model simulations of the 20th century, we showed that the South and East Asian monsoons also exhibited an abrupt (but smaller) weakening during the 1960's; and that furthermore the monsoon weakening in the disparate regions were in fact co-ordinated, specifically tied to an abrupt cooling (and resulting higher surface pressure) over Eurasia and North Africa over this time. This cooling was part of a larger Northern hemispheric cooling as part of an interhemispheric pattern, which in turn was associated with an abrupt cooling of high-latitude North Atlantic sea surface temperature. The suggestion coming out of Liu and Chiang (2012) is that the late 1960's monsoon weakening was ultimately driven by high-latitude North Atlantic cooling, communicated to the tropics via cooling the entire Northern Hemisphere and resulting creation of an interhemispheric thermal gradient.

In order to further understand the influence of North Atlantic cooling on the interhemispheric pattern, Cvijanovic and Chiang (2012) undertook idealized model simulations of North Atlantic Cooling using an atmospheric model coupled to a thermodynamic slab ocean. The simulations showed that North Atlantic cooling readily generated a Northern hemispheric-wide cooling and weakening West African and Asian monsoon rainfall. By analyzing radiative feedbacks using a radiative kernel method (developed by Shell et al. 2008), we showed that high latitude North Atlantic cooling was effective at cooling the entire Northern Hemisphere in part because of positive radiative feedbacks from albedo and longwave effects of water vapor.

Taken together, our work suggests that the abrupt high-latitude North Atlantic cooling during the late 1960's may have been responsible for the abrupt late 1960's observed weakening of the monsoons, communicated via an interhemispheric pattern. Work on formally establishing the dynamical mechanism linking North Atlantic cooling to the monsoons is still ongoing (with graduate student Yuwei Liu).

ii) Formal Detection and Attribution study on the interhemispheric pattern in 20th century climate *(personnel involved: Ching-Yee Chang, Andrew Friedman. Collaborator: Michael Wehner)*

Here, we focused specifically on the tropical Atlantic interhemispheric gradient as our regional target, because of the relatively long observations over this region, and because the mechanisms of climate variations on interannual-to-decadal timescales are well-established. In Chang et al. (2011), we showed that there is in fact a long-term trend in the tropical Atlantic interhemispheric gradient, with the south warming faster than the north over the 20th century up to around 1980. We undertook a detection and attribution analysis of this trend using the CMIP3 multimodel simulations of the 20th century. These simulations collectively showed that at least a portion of the observed trend in the Atlantic interhemispheric gradient was a forced response (as opposed to resulting from internal variation in the climate system) – the ensemble mean showed a trend in the right sense, but with a significantly smaller magnitude than observed. Then, using the available single forcing simulations (i.e. simulations with only one of the 20th century forcings applied), we showed that only runs with anthropogenic sulfate aerosols could plausibly reproduce the trend. Thus, our results suggested that anthropogenic sulfate aerosol emissions may have progressively shifted the Atlantic ITCZ southwards over most of the 20th century.

Towards the end of the project, we repeated the same analysis as in Chang et al. (2011) with the new CMIP5 multimodel simulations as an essentially independent test of the conclusions of Chang et al. (2011). We found that the results in our earlier study were essentially the same in this new analysis (Chiang et al. 2012, submitted). However, two (of 18) models we examined systematically simulated the Atlantic interhemispheric gradient with a trend in the opposite direction to the observed, which suggests some uncertainty regarding the robustness of the conclusions of Chang et al. 2011. More surprisingly, the magnitude of the simulated trend did not increase, despite the fact that most CMIP5-class models include indirect effects (as opposed to only a fraction of the CMIP3-class models).

iii) The interhemispheric pattern in the future *(personnel involved: Andrew Friedman, Ching-Yee Chang. Collaborators: Yen-Ting Hwang and Dargan Frierson)*

In Friedman et al. (2012), we examined CMIP3 and 5 simulations of the global interhemispheric thermal gradient (i.e. Northern Hemisphere minus the Southern Hemisphere mean surface air temperature) over the 20th century and in future projections. The observed global interhemispheric gradient shows a very small range (+-0.4K) and relatively little trend for most of the 20th century, except for after 1980 when it exhibits an upward trend. Both the CMIP3 and CMIP5 multimodel ensemble means reproduce this relative lack of trend pre-1980, and the upward trend post-1980s. Interestingly, CMIP5 single-forcing runs demonstrate that the lack of trend is a result of a cancellation between aerosol forcing – which produce a downward trend – and greenhouse gases that produce an upward trend. After 1980, the aerosol influence levels off, leaving the greenhouse gas influence to manifest itself. The upward trend post-1980 extends into the 21st century projections, as a direct result of the increasing greenhouse gas influence. By 2100, both the RCP4.5 and RCP8.5 scenario change to the global interhemispheric gradients well exceed the 20th century range, with the North warming faster than the South. The suggestion from our study is that tropical rainfall will shift progressively towards the North over the 20th century, though this implication has yet to be fully assessed.

Finally (with postdoc Ching-Yee Chang), we undertook regional projections of the tropical Atlantic and tropical Pacific interhemispheric gradients over the 21st century using the CMIP3 future scenarios. As this work has yet to be documented, I briefly summarize the main results. We examined CMIP3 future simulations of two indices that measure the tropical Atlantic and tropical Pacific interhemispheric gradients, respectively (figure 1), and for 3 scenarios that straddle a range of climate changes: A1B ('middle of the road'), A2 (more emissions) and B1 (fewer emissions). We applied an EOF analysis on the individual timeseries for each region to extract the 'most common' signal; this was similar to what was done in Chang et al. (2011) for the 20th century simulations. The results show that while the Pacific interhemispheric gradient show a consistent downward trend (north warming more than south) across the multimodel simulations (figure 3), the Atlantic simulations show no such consistency across models (figure 2). This result is separately confirmed when the trend for each model simulation is computed, and the distribution of trends displayed (figure 4). Figures 2-4 show the result for the A1B scenario, but it also holds true for the A2 and B1 scenarios (not shown).

The reason why the Pacific shows consistent projections in the interhemispheric trend, but the Atlantic does not, remains to be explained. A strong possibility is that the Atlantic interhemispheric gradient is influenced by the strength of the Atlantic meridional overturning circulation, with is generally thought to weaken in the future but with a magnitude that varies significantly between models (e.g. Gregory et al. 2005). Given the nontrivial result, and also the fact that the CMIP5 simulations are now available, we are postponing writing up these results pending a similar analysis on the CMIP5 future scenarios, and analysis of causes.

iv) Other achievements

In order to promote the concept of the interhemispheric gradient and its usefulness in interpreting tropical climate changes, PI Chiang proposed a review paper on the subject to the *Annual Reviews of Earth and Planetary Sciences,* a highly-influential publication of scientific reviews. We were invited to contribute a review paper, which PI Chiang wrote in collaboration with his student Andrew Friedman. The review, titled "Extratropical Cooling, Interhemispheric Thermal Gradients, and Tropical Climate Change", was published in 2012.

PI Chiang also collaborated with Dr. Abigail Swann and Prof Inez Fung (UC Berkeley) on atmospheric circulation impacts resulting from a hypothetical afforestation of all of the available global land areas in the Northern Hemisphere. Afforestation on that scale produces a climate response essentially as described by an interhemispheric gradient with warming of the Northern Hemisphere and a northward shift of the tropical rainbands. The paper (Swann et al. 2012) was published in the *Proceedings of the National Academy of Sciences*.

3. Students and Postdocs trained on this grant

Dr. Ching-Yee Chang was the primary postdoctoral scholar hired to work on this project. She was hired in Nov 2008, and left this position in February 2012. Her doctoral studies were at the University of Maryland, and her thesis involved the coupled climate of the tropical Atlantic and specifically on causes of biases in coupled model simulations of that region. As such, her background was highly suited to the project. She did all of the analysis with the detection and attribution study of the tropical Atlantic interhemispheric gradient in the CMIP3 and 5 multimodel ensembles, and took the lead in writing up the CMIP3 study (Chang et al. 2010). She additionally analyzed future projections of the Atlantic and Pacific interhemispheric gradients in the CMIP3.

Three graduate students were trained on the project:

1) ***Mr. Yuwei Liu*** is a graduate student in PI Chiang's group. He did most of the analysis in the Liu and Chiang (2012) study, and took the lead in writing the manuscript. He is expected to complete his Ph.D. studies in the second half of 2013.
2) ***Mr. Andrew Friedman*** is a graduate student in PI Chiang's group. He did the bulk of the analysis in the Friedman et al. (2012) study, and took the lead in writing the manuscript. Friedman also contributed to the review paper on the interhemispheric gradient (Chiang and Friedman 2012), also did preliminary analysis that led to the Chang et al. (2011) paper. He is expected to complete his Ph.D. studies in the second half of 2013.
3) ***Dr. Ivana Cvijanovic*** was a Ph.D. candidate at the Centre of Ice and Climate at the University of Copenhagen. She visited PI Chiang's group for six months for her 'study abroad' requirement, where we started our project. She did all the model simulations and analysis for the project, and took the lead in writing the manuscript. She graduated earlier this year in 2012, and will be starting a postdoctoral position shortly at her former Ph.D. institute.

4. Publications Resulting from the Project

i) *Published*

1. Chang, C.-Y, J.C.H. Chiang, M.F. Wehner, A.R. Friedman, and R. Ruedy: "Sulfate aerosol control of Tropical Atlantic climate over the 20th century." *Journal of Climate*, **24**, 2540-2555 (2011).
2. Liu, Y., and J.C.H. Chiang: Co-ordinated abrupt weakening of the Eurasian and North African Monsoons in the 1960's and links to extratropical North Atlantic Cooling. *Journal of Climate*, **25**, 3532-3548 (2012).
3. Swann, A.L.S., I.Y. Fung, and J.C.H. Chiang: "Midlatitude Afforestation shifts General Circulation and Tropical Precipitation". *Proceedings of the National Academy of Sciences,* **109***,* 712-716 (2012).
4. Chiang, J.C.H., and A. R. Friedman: "Extratropical Cooling, Interhemispheric Thermal Gradients, and Tropical Climate Change". *Annual Reviews of Earth and Planetary Sciences,* **40**, 383-412 (2012).
5. Cvijanovic, I., and J.C.H. Chiang: "Global Energy Budget Changes to High Latitude North Atlantic Cooling and the Tropical ITCZ Response. *Climate Dynamics*, 10.1007/s00382-012-1482-1, published online 15 Aug 2012.

ii) Submitted

6. Friedman, A. R., Y.-T. Hwang, J. C. H. Chiang, and D. M. W. Frierson: "The Interhemispheric Thermal Gradient over the 20th Century and in Future Projections". In revision for *Journal of Climate*, July 2012
7. Chiang, J. C. H., C.-Y. Chang, and M. F. Wehner: "Long-Term Trends of the Atlantic Interhemispheric SST Gradient in the CMIP5 Historical Simulations. Submitted to *Journal of Climate,* July 2012

5. Projects involving computer modeling

Both Swann et al. (2012) and Cvijanovic and Chiang (2012) use the Community Atmosphere Model version 3 (CAM3) as part of their study. The CAM3 is an atmospheric general circulation model developed by the National Center for Atmospheric Research (NCAR), and is widely used in the climate modeling community. The CAM3 consists of a dynamical core containing the fluid dynamics equations for the atmosphere, and parameterizations for radiation, convection and clouds, and other sub-gridscale processes. The atmosphere model is coupled to a land surface model and a thermodynamic slab ocean. The CAM3 is well documented (Collins et al. 2004) and the performance has been reported in several publications (e.g. Collins et al. 2006). For Swann et al. (2012), the CAM3 was run on the NCAR Bluefire cluster, and for Liu and Chiang (2012) CAM3 was run in an in-house Linux cluster belonging to PI John Chiang's group.

6. References

Collins WD et al. (2004) Description of the NCAR Community Atmosphere Model (CAM3). Tech. Note NCAR/TN−464+STR, Natl. Cent. for Atmos. Res., Boulder, Colorado

Collins WD et al. (2006) The formulation and atmospheric simulation of the Community Atmosphere Model version 3 (CAM3). J. Clim. 19 (11), 2144-2161

Folland, C. K., T. N. Palmer, and D. E. Parker, 1986: Sahel rainfall and worldwide sea temperatures, 1901-85. Nature, 320, 602– 607.

Gregory, J. M. et al., 2005: A model intercomparison of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO2 concentration. *Geophys. Res. Lett.*, **32**, doi:200510.1029/2005GL023209.

Shell KM, Kiehl JT, Shields CA (2008) Using the Radiative Kernel Technique to Calculate Climate Feedbacks in NCAR's Community Atmospheric Model. J. Clim. 21, 2269-2282, doi:10.1175/2007JCLI2044.1

7. Figures

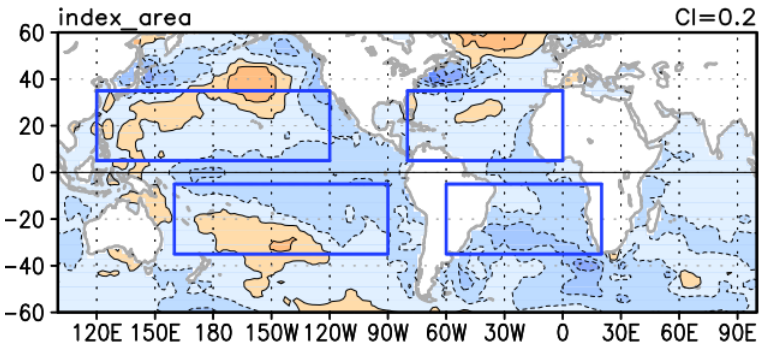

Figure 1. *Regions used to define the tropical Atlantic and tropical Pacific interhemispheric gradient indices. The Atlantic interhemipheric gradient index is the sea surface temperature averaged over the southern Atlantic box, minus that in the North tropical Atlantic (this index is used in Chang et al. 2011, and Chiang et al. 2012). The Pacific interhemispheric gradient index is the same, but for the Pacific boxes as shown.*

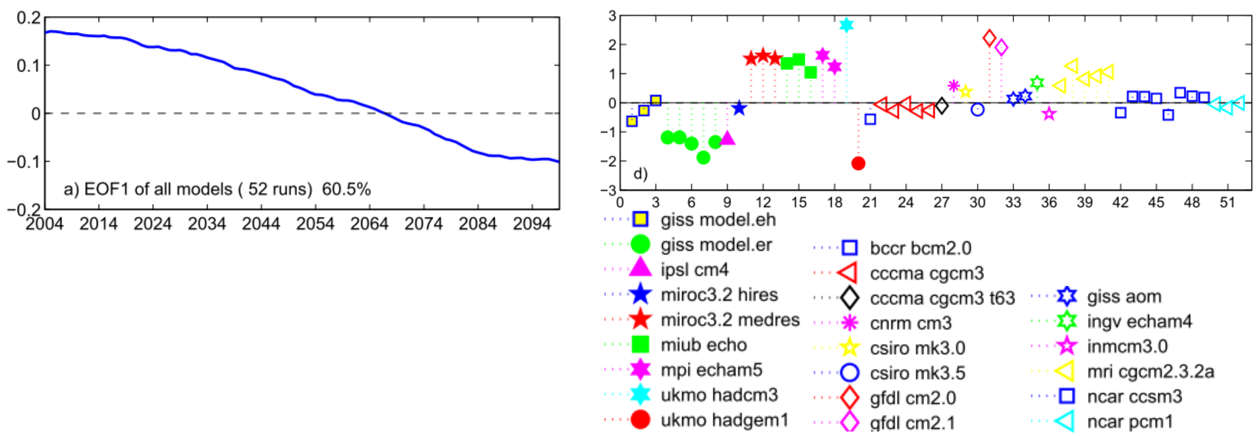

Figure 2. *EOF analysis of the Atlantic interhemispheric gradient index across individual CMIP3 ensemble members in the A1B scenario. Left panel: the leading principal component (PC1), showing a monotonic trend across the 21*st *century. Right panel: the individual loadings corresponding to PC1 (with the model type as indicated; so for example, entry 24 corresponds to the third ensemble member of the cccma cgcm3). The results show that there is relatively little consistency in the trend simulation across the various CMIP3 A1B simulations – some simulate an increasing trend (e.g. giss model er), others a decreasing trend (e.g. miroc3.2 medres), and yet others simulate essentially no trend (e.g. cccma cgcm3).*

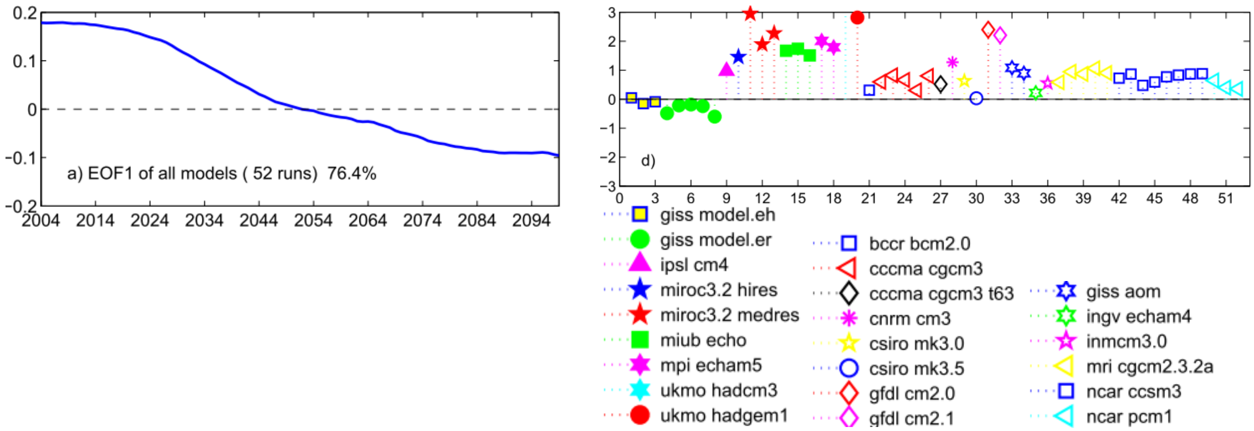

Figure 3. *As in figure 2, but for the Pacific interhemispheric gradient in the CMIP3 A1B scenario. The results show that most models possess a decreasing trend in the Pacific interhemispheric gradient over the 21st century (i.e. North warming faster than the South), implying that the Pacific ITCZ will increasingly shift northwards.*

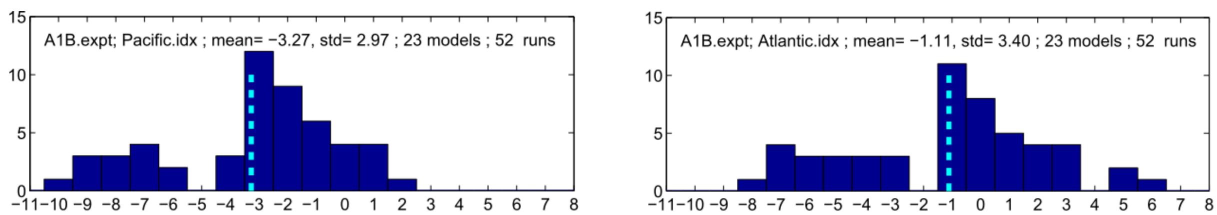

Figure 4. *Left panel: distribution of trend slopes for the Pacific interhemispheric gradient over the 21st century. Units are x 0.1K per 100 years. Almost all models show a negative trend, but there is a substantial spread in the magnitude across ensemble members. The dashed line is the multimodel ensemble mean trend. Right panel: as for the left panel, but for the Atlantic interhemispheric gradient. Unlike the Pacific, the Atlantic interhemispheric gradient shows a wide range in the trend and in both directions; the ensemble mean trend is close to zero slope.*