10D.7 MULTI-DECADAL VARIABILITY OF WEST AFRICAN RAINFALL IN CMIP5 SIMULATIONS

Elinor R. Martin* and Chris Thorncroft
Department of Atmospheric and Environmental Sciences, SUNY Albany, Albany, New York

1. INTRODUCTION

Rainfall in the Sahel region of Africa shows a large multi-decadal signal, transitioning from wet conditions in the 1950s and 60s to dry conditions in the 70s and 80s and appearing to recover back to wet conditions during the 90s and 00s.

Multi-decadal variability in Sahelian rainfall has been attributed to variability in sea surface temperature (SST) in the Atlantic (Lamb 1978a,b; Folland et al. 1986; Hastenrath 1990; Rowell et al. 1995; Ward 1998; Zhang and Delworth 2006; Knight et al. 2006; Ting et al. 2009), Indian and Pacific ocean (Bader and Latif 2003; Giannini et al. 2003; Biasutti et al. 2008; Lu 2009; Caminade and Terray 2010; Mohino et al. 2011; Rodríguez-Fonesca et al. 2011). The global SST pattern associated with decadal and longer variability in Sahel rainfall is well known, with a distinct interhemispheric gradient, a warm north Atlantic and cold Indian ocean being conducive to a wet Sahel period (see Fig. 1). However, the dynamics behind the decadal forcing of Sahel rainfall by SST is less well understood, particularly in the case of the Indian Ocean.

Climate model experiments, along with observations, have been used to show the importance of the AMO in controlling multi-decadal fluctuation of Sahel and West African rainfall. The first low frequency mode of summer Sahel rainfall has been shown to be associated with the AMO SST pattern in the Atlantic. The first EOF of low frequency Sahel summer rainfall also matches closely with the regression of the low frequency rainfall on the AMO index (e.g. Zhang and Delworth 2006).

Model simulations (e.g. Bader and Latif 2003 and Giannini et al. 2003), attribute warming Indian Ocean SSTs to the increasingly dry Sahel conditions between the 1950/60s and 1980/90s via changes in the east-west overturning circulation increasing subsidence and stability over West Africa.

The connection between multi-decadal SST variability and West African rainfall needs to be understood in order to understand successes and failures in climate model simulations and to improve predictions in the region. This aim of this study is to investigate the ability of the Coupled Model Intercomparison Project 5 (CMIP5) coupled models to produce realistic multi-decadal variability in Sahelian rainfall in the 20th century.

**Corresponding author address*: Elinor R. Martin, Department of Atmospheric and Environmental Sciences, SUNY Albany, ES351, Albany, NY, 12222; email: emartin@atmos.albany.edu

2. DATA AND METHODOLOGY

This study uses 109 years (1901-2009) of monthly, land only, rainfall data from the Climate Research Unit (CRU) 3.1 precipitation dataset to provide observations of Sahel (10-20N 20W-10E) rainfall at 0.5 horizontal. The monthly HadISST data is used for global SST at 1 horizontal resolution for the same period.

Model output from the CMIP5 suite of experiments are used to assess the ability of global climate models to simulate multi-decadal variability of Sahel rainfall. This study uses "historical" simulations, initialized from pre-industrial control runs and forced with natural and anthropogenic atmospheric composition changes for the 20th century (1850-2005). All available model output was used, consisting of rainfall and SST from 21 models (15 modeling centers) with multiple ensembles, producing a total of 72 separate simulations.

In the analysis presented here, the annual cycle is removed from both rainfall and SST data and data is linearly detrended. Unless otherwise stated data is presented for summer (JAS). To isolate the multi-decadal signal data is low-pass filtered with a 10 year cut off frequency.

3. RESULTS

Before examining the multi-decadal variability in the CMIP5 simulations, it is necessary to assess the ability of the simulations to produce a realistic climate. The annual cycle of Sahel (as defined in Section 2) rainfall from the CRU dataset, along with the individual CMIP5 models (averaged over all ensembles) and a multi-model mean is shown in Fig. 1.

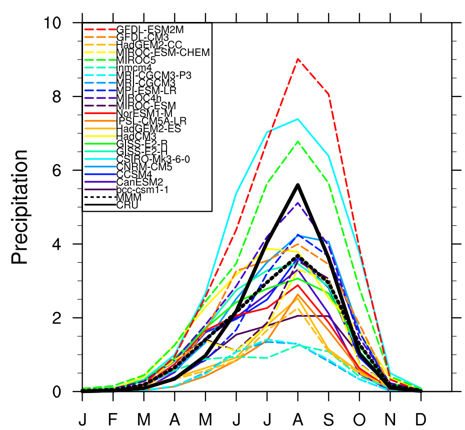

Figure 1: *Annual cycle of Sahel (10N-20N, 20W-10E) rainfall from observations (black solid) CMIP5 models (colored lines) and the multi-model mean (black dotted).*

Although the timing of the annual cycle is well represented by the CMIP5 models with a summer peak, the magnitude is not. The majority of models overestimate spring rains and underestimate summer rainfall (with the exception of 3 models that are too wet in summer). This can be partly explained by the overly warm SSTs to the south of the Sahel, in the Gulf of Guinea, as found in the CMIP3 models.

By examining the ratio of decadal to total variance in the Sahel rainfall index (SRI, JAS detrended rainfall anomalies) in the observations and models, a large underestimation of raw and relative decadal scale variance by the models is seen (not shown). Decadal variance accounts for up to 45 % of the total in observations, with the largest simulation less than 40 % and the average close to 15 %.

To examine the reduced decadal variability in the modeled Sahel rainfall, the Atlantic and Indian Oceans are assessed separately. Figure 2 shows the correlation between filtered SRI and global SST. As discussed in Section 1, Fig. 2 shows increased SST in the north Atlantic correlate with a wet Sahel, while increased SSTs in the Indian Ocean correlate with a dry Sahel. By averaging filtered JAS SST over the north Atlantic (0-70N, 75-10W) and Indian (30S-30N, 40E-100E) oceans, the relationships with each basin can be established in the observations and model simulations.

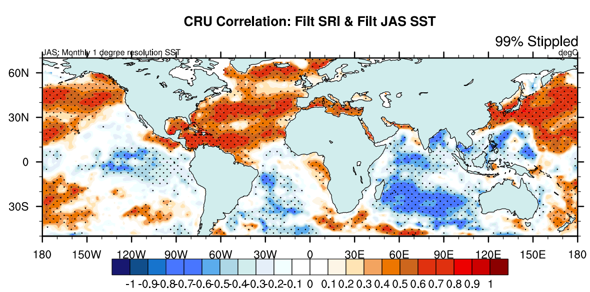

Figure 2: *Observed correlation coefficients between the filtered SRI and JAS SST. Correlations significant at 99 % are stippled.*

3.1 *Atlantic Ocean*

In observations, the correlation between decadally filtered Sahel rainfall and decadally filtered north Atlantic SST is 0.56 (significant at 99 % level) indicating warm SSTs correlate with a wet Sahel as expected. The same analysis is performed for each individual simulation from the CMIP5 ensemble with the model and observed correlations shown in Fig. 4 (left panel).

It is clear from Fig. 4 that the majority of model simulations have a positive correlation between multi-decadal Atlantic SST and Sahel rainfall. The correlations are generally weaker in the models than observed, but the majority are still significant at 95 %.

While this simple correlation gives tells us about temporal correlations, we gain not insight into spatial patterns or mechanisms involved. To further analyze the relationship between multi-decadal SST and Sahel rainfall the first EOF of filtered Atlantic SST was calculated and SST and precipitation regressed onto the associated principal component. These regressions are shown in Fig. 4 (top panels). The first EOF explains 57.7 % of the variance and the SST pattern strongly resembles that of the AMO, with warming confined to the north Atlantic and Mediterranean. The precipitation associated with this patterns shows a band of enhanced rainfall across the Sahel.

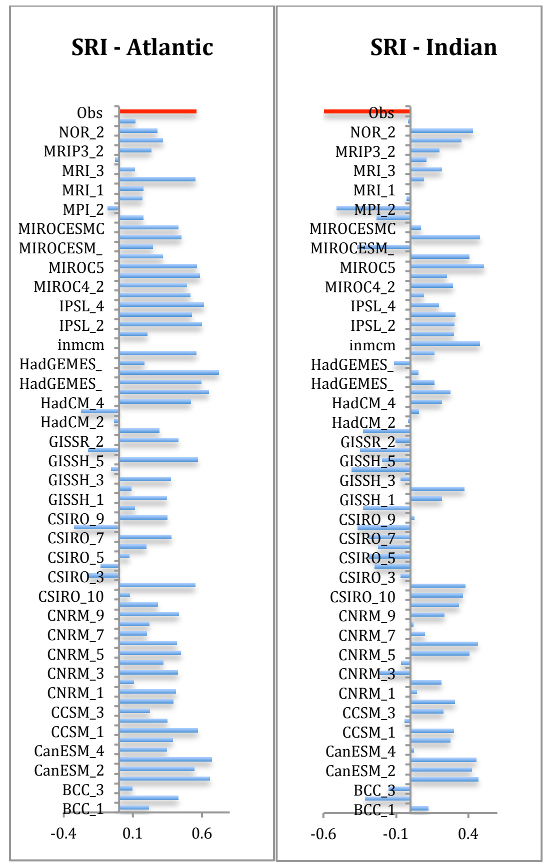

Figure 3: *Correlation coefficients between filtered SRI and Atlantic SST index (left) and Indian SST index (right). Observed values are shown in red (top bar) and model ensembles in blue. Not all model names are shown. The 95 % significance value is approximately 0.2.*

In the models, this EOF analysis produces similar, but not identical, results to the observations. The SST is often less well confined to the north Atlantic and Mediterranean and the precipitation response is weaker over land. One example of a good model result is also shown in Fig. 4 (bottom panels) with a strong precipitation signal across the Sahel.

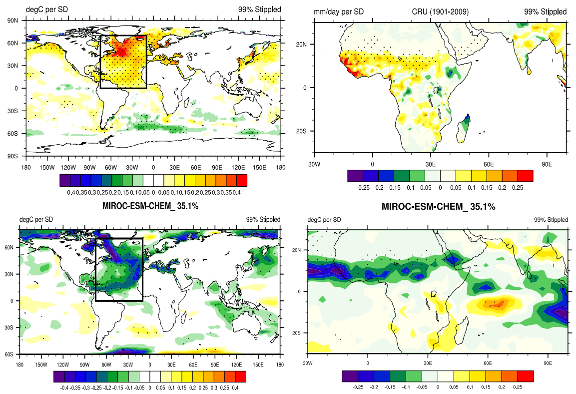

Figure 4: *Regression of JAS SST (left) and precipitation (right) onto the first EOF of filtered Atlantic (black box) JAS SST. Top panels show observations (EOF 1 explains 57.7 % of variance) and bottom panels show results from MIROC-ESM_CHEM model (EOF 1 explains 35.1 % of variance). Values significant at 99 % are stippled.*

3.2. *Indian Ocean*

The same analysis in Section 3.1 was performed for the Indian ocean SST with the results displayed in Figs. 3 (right) and 5. The observed correlation between the decadally filtered SRI and Indian ocean SST is -0.61, approximately the same magnitude as the correlation with the Atlantic SSTs but opposite in sign. The model runs however (Fig. 3 right panel), have more difficultly in simulating this negative correlation than the positive correlation with the Atlantic. Only two simulations have correlations less than -0.4, less than half of the simulations have negative correlations and almost a quarter of simulations are positive and significant at 95 %.

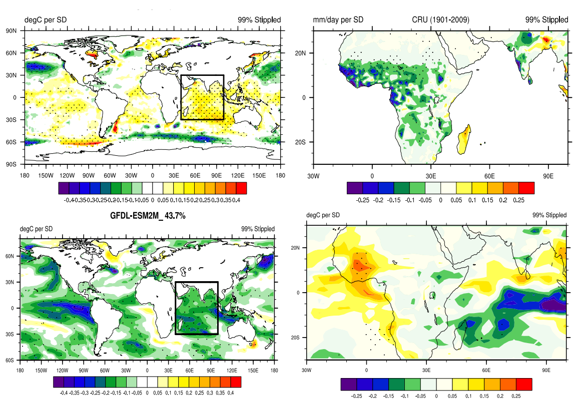

Figure 5: *As in Figure 4 but for the first EOF of filtered Indian Ocean (black box) JAS SST. Top panels show observations (EOF 1 explains 54.2 % of variance) and bottom panels show results from GFDL_ESM2M model (EOF 1 explains 43.7 % of variance). Values significant at 99 % are stippled.*

Determining whether the SSTs or mechanisms linking the SST and rainfall are incorrectly simulated is begun with the EOF analysis as described previously, but for the first EOF of filtered Indian Ocean SST. The results of observations and one simulation are shown in Fig. 5.

The first EOF (explains 54.2 % of variance) of observations shows large values in the Indian Ocean, as expected, but SSTs are less confined to this region than in the Atlantic case. Significant regression coefficients are also seen in the Pacific, both in the tropics and midlatitudes. The regression of precipitation onto the first EOF of Indian ocean SST shows negative values, as expected, as increased Indian Ocean temperature leads to drying in the Sahel. The precipitation pattern is more extensive than that of the Atlantic SST, with negative values across the Sahel and much of central Africa. Significant vales are also seen on the West coast of India and the maritime continent.

The models however, have difficulties in simulating both the mode of SST variability and connection with precipitation. Many models have a strong signal in the Indian Ocean but also have a much stronger signal than observed in the equatorial Pacific. This is illustrated by one model example shown in Fig. 5 (bottom panel), where the regression coefficients in the eastern equatorial Pacific are larger than those in the Indian Ocean.

The connection with precipitation is also erroneous in the models. Many models simulate little to no rainfall signal in the Sahel, even when the Indian Ocean signal is large. The rainfall is often located farther south than observed. The result shown in Fig. 5 is one of the few simulations with a signal of the correct sign over the Sahel despite it having a meridional orientation compared to the zonal nature of the observations.

4. SUMMARY

Based on 20th century precipitation and SST data from observations and CMIP5 historical simulations, the ability of the simulations to produce multi-decadal variability in Sahel rainfall has been investigated.

The CMIP5 simulations produce an annual cycle that matches the observed summer time peak, but with reduced magnitude on average. However, the multi-decadal variability of the model output is less than observed, as is the ratio between decadal and total variance with the multi-model average a third (15 %) of the observed value (45 %).

The multi-decadal Sahel rainfall has previously been shown (Fig. 2) to be linked to SSTs in both the Atlantic (positive correlation) and the Indian Ocean (negative correlation). The models are considerably more successful in reproducing the Atlantic-Sahel correlations and precipitation patterns than the Indian correlations. Not only are the magnitudes of the Indian Ocean correlations too small, they are often of the wrong sign. In addition to the large-scale correlations, the leading mode of filtered Indian ocean SST is often less confined to the Indian Ocean than observations, and West African rainfall projects weakly onto said mode. It is necessary to note however, that in observations filtered Atlantic and Indian Ocean SSTs are not correlated, but are often significantly correlated in the model simulations.

The mechanisms involved in the connection between both the Atlantic and Indian oceans have not yet been investigated. This mechanistic approach will regress variables such as temperature and circulation on the principal components of each basin's SST. This approach will help to identify deficiencies and successes in the multi-decadal connection between Atlantic and Indian SSTs and Sahel rainfall.

5. ACKNOWLEDGEMENTS

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