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Julián Villamayor

Influence of the Sea Surface Temperature Decadal Variability on Tropical Precipitation: West African and South American Monsoon

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Influence of the Sea Surface Temperature Decadal Variability on Tropical Precipitation: West African and South American Monsoon

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To my parents and Jessi, for their unconditional support.

Supervisor's Foreword

The Earth's climate is a fascinating system made of multiple and complex interactions among its constituents the atmosphere, hydrosphere, cryosphere, lithosphere, and the biosphere. The awareness of climate change has put forward to society that the climate system is far from static and that it rather presents variability at very different timescales. In particular, climate can vary from one decade to the next, which can have important societal implications. Being able to foresee these changes would undoubtedly be of great value, as it would have applications in long-term planning. A necessary first step in this direction is enhancing our understanding of climate variability at decadal-to-multidecadal timescales, which is the general objective of this Ph.D. Thesis.

The continental regions in the Tropical Atlantic are among the most affected by changes in their rainfall regime. Water availability in the semiarid region of Northeast Brazil in South America affects the economy and shapes the population in the region. Also in South Africa, the Amazon's economic and ecological resources highly depend on rainfall. These regions are affected by the seasonal occurrence of the South American Monsoon and by its climate variability. In turn, to the east, the West African Monsoon modulates rainfall over the Sahel. This region is prone to drought occurrence, which has devastating humanitarian and economic impacts. The long-lasting Sahel drought in the 1980s stirred a great scientific effort to better understand its causes. Through its impact on the economy, rainfall variability at decadal timescales in these regions can also lead to stress in local population and migrations, affecting indirectly populations in other regions.

One of the main sources of tropical rainfall variability at decadal-to-multidecadal timescales is the change in the sea surface temperatures (SST). Previous research suggested links among changes in the rainfall regimes of the Sahel, Northeast Brazil, and Amazon regions and patterns of decadal-to-multidecadal variability in SSTs. However, the mechanism underlying such links and their simulation by state-of-the-art general circulation models had not been addressed in a systematic way, which constitutes the specific objective of this Ph.D. Thesis.

In this Thesis, Julián analyses the decadal-to-multidecadal patterns of SST variability simulated by 17 state-of-the-art general circulation models and evaluates their impact on rainfall associated with the South American and the West African Monsoons and the mechanisms underlying such impact. The analysis allows Julián to delve into issues like the effect of the external forcing in shaping this impact, the changes of the impacts under a climate change scenario with a strong increase of these forcings, and the relative contribution of the different SST variability patterns to the decadal variability of rainfall. Finally, as a case study, Julián analyses the late nineteenth century anomalously humid period in the Sahel, which has been little documented due to the scarcity of observations. By performing simulations with an atmospheric general circulation model driven by observed sea surface temperatures as boundary conditions, Julián is able to pinpoint the oceanic basin responsible for this humid period and explain the mechanism causing it.

Throughout his Thesis, Julián has been supported and advised by different internationally renowned researchers. For the analysis of the South American Monsoon, he enjoyed a 3-month visit at the University of São Paulo (Brazil) under the supervision of Tércio Ambrizzi, expert on climate variability in the region. For the West African case study, Julián collaborated with Myriam Khodri, Juliette Mignot, and Serge Janicot, experts in climate modeling, decadal variability, and the West African Monsoon, at the Institute Pierre Simon Laplace (IPSL) in Paris (France).

This Ph.D. Thesis constitutes a step forward in our understanding of changes in rainfall regimes in the regions studied and is also of great use to improve decadal prediction systems and to foresee the societal impacts of such changes. I, therefore, invite you to immerse yourself in this fascinating reading.

Madrid, Spain
March 2019

Elsa Mohino

Abstract

Introduction

The Sahel is the semiarid West African region between the Sahara desert and the wet tropical savanna. The Sahel rainfall depends on the West African Monsoon (WAM) system and peaks between July and September. The rainfall regimes of the Amazonia and Northeast regions, located in northern Brazil, depend on the South American Monsoon system. The Amazonia is the region covered by the Amazon River basin, where heavy rains occur throughout the year but with a rainier season extending from December to May. The Northeast is a semiarid region with a short rainy season between March and May.

Precipitation regimes in these three regions have undergone changes over time with important humanitarian, environmental and economic consequences and have been a major topic of study (e.g., Rodríguez-Fonseca et al. 2015; Zhou and Lau 2001; Marengo et al. 2016). At decadal-to-multidecadal timescales, these changes have been mainly associated with the global sea surface temperature (SST) variability. Particularly, the Sahel precipitation has been associated with the global warming (GW), the Atlantic Multidecadal Variability (AMV), and the Interdecadal Pacific Oscillation (IPO) modes of decadal-to-multidecadal SST variability (e.g., Mohino et al. 2011a). The Amazonia and Northeast rainfall changes have been related to the Pacific and the Atlantic SST variability at decadal timescales (e.g., Grimm and Saboia 2015), which is led by the AMV and IPO.

Climate study through Global Circulation Models (GCMs) is crucial to understand climate changes and assessing its effects. So, in the first part of this Thesis, a multi-model analysis is done addressing the influence of the main decadal-to-multidecadal modes of SST variability on precipitation in the Sahel, Amazonia, and Northeast using different GCMs simulations from the 5th phase of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012).

Particularly, in the Sahel, the decadal-to-multidecadal precipitation variability along the recent past and even for the future has been extensively studied, but barely prior to the twentieth century. Only a few studies suggest that the Sahel experienced a long wet period throughout the late nineteenth century. This motivates the second part of this Thesis, which seeks to reproduce this period with an atmospheric GCM (AGCM) forced with observed SST since 1854.

Objectives

The objective of this Thesis is to achieve a better understanding of the SST decadal-to-multidecadal variability on rainfall in the Sahel, Amazon, and Northeast regions. For that purpose, a multi-model analysis is done aiming to characterize the main modes of SST variability (GW, AMV, and IPO) in observations and CMIP5 simulations, assess their impacts on precipitation in the three regions and the causes of such links. Other goals are to seek whether these links are expected to change in the future, discuss an eventual role of the radiative forcing on the AMV and IPO, and assess the contribution of the SST modes to the total decadal-to-multidecadal rainfall variance in the regions of interest. A final objective is to find out whether the long rainy period of the late nineteenth century can be reproduced with an AGCM forced with observed SST and the factors that caused it.

Data and Methodology

Monthly data from different simulations of 17 CMIP5 models are used. The simulations analyzed are historical (simulates the recent past with imposed observed external radiative forcing), piControl (radiative forcing is fixed to pre-industrial values), RCP8.5 (future projections with a representative concentration pathway of high concentrations of greenhouse gases), and historicalGHG (similar to the historical simulation but with greenhouse gas forcing only) (Taylor et al. 2012). For the sake of robustness in the observational results, different SST and precipitation databases and reanalyses are analyzed.

A set of simulations is performed using the fifth version of the *Laboratoire de Météorologie Dynamique* (LMDZ) AGCM (Hourdin et al. 2013). In the first set of simulations, the LMDZ is run with imposed observed boundary conditions over 1854–2000. Second, a set of sensitivity experiments has been done for 1854–1910 imposing full variability of the SST only in the Atlantic or in the Indo-Pacific while the rest is fixed to the climatological seasonal cycle.

The methodology used is based on mathematical tools commonly used in climate studies, such as EOF, linear regression, and correlation analysis and filtering of time series, among others.

Results and Conclusions

The results are presented in two parts:

1. The first part shows the results of the multi-model analysis. CMIP5 models, on average, can reproduce the main observed features of the GW, AMV, and IPO and their impacts. The main results and conclusions obtained are:
   - The GW has been prone to aerosol changes in the recent past. This induces inter-model differences but does not affect the way CMIP5 models, on average, reproduce the rainfall response: a drying in the Sahel and more precipitation in Amazonia and Northeast of Brazil. The GW reduces the WAM low-level circulation in response to a tropical SST warming. It also enhances convection over northern Brazil through anomalous Walker circulation related with the tropical Pacific SST anomalies (SSTA) in observations. But CMIP5 models fail in reproducing the tropical Pacific SSTA in the GW pattern, affecting the reliability of the simulated precipitation response in northern South America.
   - During positive AMV phases, the Sahel and Amazonia precipitation are enhanced and reduced in the Northeast (the opposite during negative phases). Positive (negative) AMV induces interhemispheric pressure gradient promoting anomalous northward (southward) shifts of the Intertropical Convergence Zone.
   - The IPO has negative impact on rainfall in the three regions. Positive (negative) IPO produces Walker circulation anomalies from the tropical Pacific with anomalous subsidence (rise) over West Africa and northern South America.

The results also show that the aerosol radiative forcing effects induce inter-model uncertainties as to the simulated AMV, which shows slight differences between historical and piControl. The IPO signal, instead, shows no noticeable differences. This suggests that the AMV may have a component of external forcing, while the IPO is dominated by internal variability.

The RCP8.5 future projections reveal a different GW pattern and impacts on rainfall to the historical simulations. However, they show similar AMV and IPO behaviors. This suggests that changes in the precipitation response to the GW in the three regions studied are expected under the future scenario described by the RCP8.5 projections, but not in the case of the AMV and the IPO.

A multi-linear regression analysis between the GW, AMV, and IPO indices and the precipitation index of each region show that CMIP5 models, in general, do not reproduce the observed contribution of each mode of SST to the total decadal-to-multidecadal rainfall variability.

The proper simulation of the decadal-to-multidecadal rainfall variability in the regions studied is related to the correct SSTA distribution in the simulated patterns and with the monsoon atmospheric circulation sensitivity to the SST changes.

2. The second part of results shows that the LMDZ model reproduces a long Sahel rainy period in the late nineteenth century in response to observed SST forcing since 1854. The sensitivity experiments show that the Atlantic SST plays a dominant role inducing such a precipitation enhancement through enhanced convection over the Sahel and more moisture supply from the tropical Atlantic.

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- López-Parages, J., **Villamayor, J.**, Gómara, I., Losada, T., Martín-Rey, M., Mohino, E., … & Suárez, R. (2013): Nonstationary interannual teleconnections modulated by multidecadal variability. *Física de la Tierra*, **25**, 11–39. http://dx.doi.org/10.5209/rev_FITE.2013.v25.43433
- **Villamayor, J.** & Mohino, E. (2015): Robust Sahel drought due to the Interdecadal Pacific Oscillation in CMIP5 simulations. *Geophys. Res. Lett.*, **42**, 1214–1222. http://dx.doi.org/10.1002/2014GL062473
- Rodríguez-Fonseca, B., Suárez-Moreno, R., Ayarzagüena, B., López-Parages, J., Gómara, I., **Villamayor, J.**, … & Castaño-Tierno, A. (2016): A Review of ENSO Influence on the North Atlantic. A Non-Stationary Signal. *Atmosphere*, **7**, 87. https://doi.org/10.3390/atmos7070087
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It's funny to remember the day that Belén invited Rober and I to her office to offer to join the Tropa group, where I met Elsa and heard the concept of *decadal variability* for the first time. Rober and I left there jumping for joy because we were going to be paid for keep studying and asking "dude, what is *cadal*?". That's how it all started.

That's why I want to heartily thank Belén, for giving us such a great opportunity, and Elsa, for being keen to guide my work and for teaching me everything I know about research. I have always thought that teaching is one of the most beautiful and worthwhile things that can be done in life. That's why I want to especially recognize in these acknowledgements the enormous work of Elsa that is behind this Thesis.

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Contents

Acronyms

20CRV2c	NOAA-CIRES 20th Century Reanalysis version 2c
AEJ	African Easterly Jet
AGCM	Atmospheric Global Circulation Model
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMV	Atlantic Multidecadal Variability
ANOVA	Analysis of variance
AOGCM	Atmosphere-Ocean Global Circulation Model
ASWI	African Southwesterly Index
ATLVAR	Refers to the sensitivity experiment performed with the LMDZ model in which the Atlantic SST variability imposed
CMIP5	Coupled Model Intercomparison Project phase 5
CRU TS3.24.01	Climatic Research Unit time series version 3.24.01
DJFMAM	Refers to the season from December to May
ENSO	El Niño/Southern Oscillation
EOF	Empirical Orthogonal Function
ERA-20C	European Center for Medium-Range Weather Forecasts reanalysis of the 20th Century
ERSST.v4	Extended Reconstructed Sea Surface Temperature version 4
GCM	Global Circulation Model
GHGs	Greenhouse gases
GPCC v7	Global Precipitation Climatology Centre Version-7
GW	Global Warming
HadISST1	Hadley Center sea ice and sea surface temperature version 1
HLVP	High-level velocity potential
ICOADS	International Comprehensive Ocean-Atmosphere Dataset
INPVAR	Refers to the sensitivity experiment performed with the LMDZ model in which the Indo-Pacific SST variability is imposed
IPCC	Intergovernmental Panel on Climate Change
IPO	Interdecadal Pacific Oscillation

IPSL	*Institut Pierre Simon Laplace*
ITCZ	Intertropical Convergence Zone
JAS	Refers to the season from July to September
LMDZ	*Laboratoire de Météorologie Dynamique* "Zoom"
LLW	Low-level westerlies
NAO	North Atlantic Oscillation
OGCM	Ocean Global Circulation Model
PC	Principal Component
PDO	Pacific Decadal Oscillation
RCP8.5	Representative Concentration Pathway 8.5
REF	Refers to the simulations of reference performed with the LMDZ model in which all the SST variability is imposed
SACZ	South Atlantic Convergence Zone
SAH	Sahel precipitation
SALLJ	South American Low Level Jet
SAM	South American Monsoon
SPG	Surface pressure gradient
SST	Sea surface temperature
SSTA	Sea surface temperature anomalies
TEJ	Tropical Easterly Jet
THC	Thermohaline circulation
UDEL v4.01	University of Delaware Air Temperature and Precipitation version 4.01
WAM	West African Monsoon
WAWJ	West African Westerly Jet

Part I
Introduction to the Thesis

Chapter 1
Introduction

Abstract This Ph.D. Thesis addresses the influence that the sea surface temperature (SST) has on the tropical precipitation changes at time scales from one to several decades, which is typically referred to as decadal-to-multidecadal variability. Specifically, the focus of this work is on the effect on rainfall variability of the Sahel in West Africa and the Amazon and the Northeast of Brazil in South America. This Chapter begins with a brief explanation of the motivation of this study. Thereafter, some basic concepts are introduced to enter upon the subject, such as the global climate system, the main mechanisms that govern it and its variability. Then, the main modes of low-frequency SST variability and the mechanisms leading the tropical rainfall in the regions of interest are explained in detail. The last section of this Chapter is dedicated to review the research done on the relationship between the SST and the Sahel, the Amazon and the Northeast of Brazil precipitation low-frequency variability.

1.1 Motivation

The tropical precipitation is tightly related to the Intertropical Convergence Zone (ITCZ), which is the near-equatorial band of maximum surface wind convergence that is associated with strong convective activity. The ITCZ seasonally migrates meridionaly from south to north and back along the year determining the rainy seasons in tropical regions (Fig. 1.1). Over the Atlantic sector, the ITCZ latitudinal shifts vary year to year resulting in precipitation variability in the surrounding continental regions, especially in West Africa and northern South America (Nobre and Shukla 1996). The precipitation variability is particularly relevant for the West African region of the Sahel and the Amazonia and the Northeast of Brazil in South America, which are very sensitive to changes in their rainfall regimes.

The Sahel is the part of West Africa extending zonally between the Sahara desert to the north and the tropical rainy savanna to the south (roughly between 10°and 18°N) (Fig. 1.2). Climatologically, it is a dry region with a mean annual rainfall rate of 200 mm to the north and 600 mm to the south (Nicholson 2013). This region is

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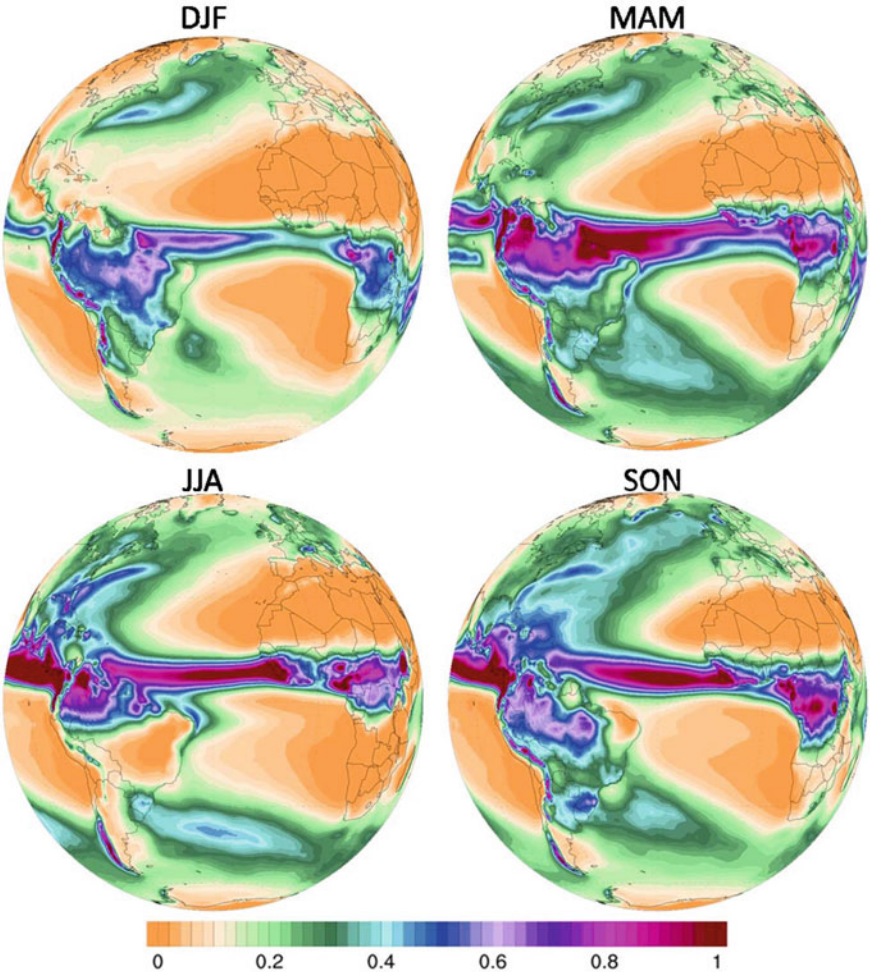

Fig. 1.1 Total seasonal precipitation (mm day^{-1}) from December to February (DJF), March to May (MAM), Jun to August (JJA) and September to November (SON) averaged over 1979–2012 using ERA-Interim reanalysis data. Image from Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA

extremely sensitive to rainfall changes during its rainy season, going from July to September (JAS), when the ITCZ reaches its northernmost position over West Africa. Indeed, the precipitation amounts in the Sahel have undergone important changes over time, with strong variability at different time scales (Fig. 1.3). In particular, the Sahel is one of the world's regions with the most marked rainfall variability at decadal time scales, which refers to changes in climate from some decades to others. Considering the precariousness of the countries in the Sahel and the climatic characteristics of the region itself, it is not surprising that such a change in the rainfall

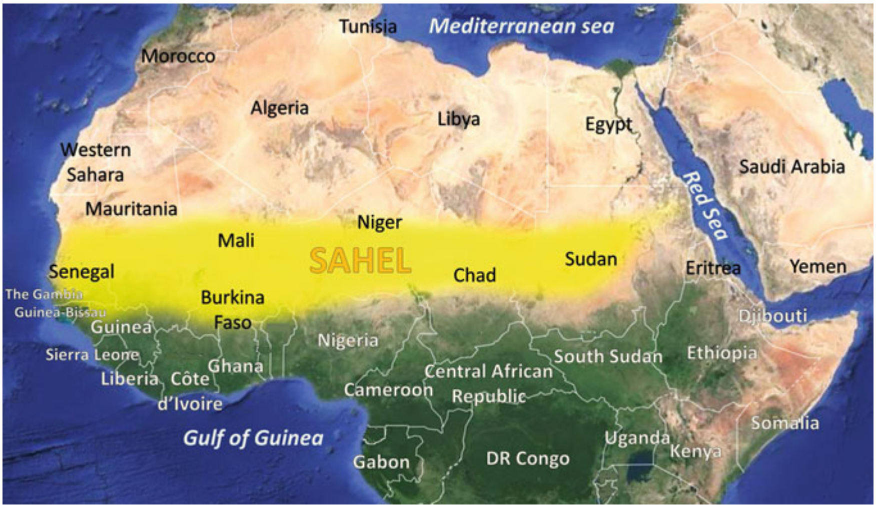

Fig. 1.2 The Sahel region in West Africa. Modified picture from Google Earth; data provided by SIO, NOAA, U.S. Navy, NGA, GEBCO Landsat/Copernicus Mapa GISrael ORION-ME

regime and the long persistence of drought conditions had dramatic economic and humanitarian consequences (Cook and Vizy 2006; Giannini et al. 2013). The decadal variability of the Sahel rainfall along the 20th century has therefore been the focus of numerous research works (e.g. Folland et al. 1986; Giannini et al. 2003; Caminade and Terray 2010; Mohino et al. 2011a; Rodríguez-Fonseca et al. 2015).

The Northeast[1] of Brazil is the northeastern tropical region of the country (Fig. 1.4). It is mostly a plateau area with a semiarid precipitation regime, in which typically no more than 400 mm of precipitation per year are recorded (Kousky 1979; da Silva 2004). This region has a short rainy season between Mach and May, when the ITCZ shifts to the south spanning this region. The Northeast is particularly prone and sensitive to changes on precipitation, especially to droughts. The local economy

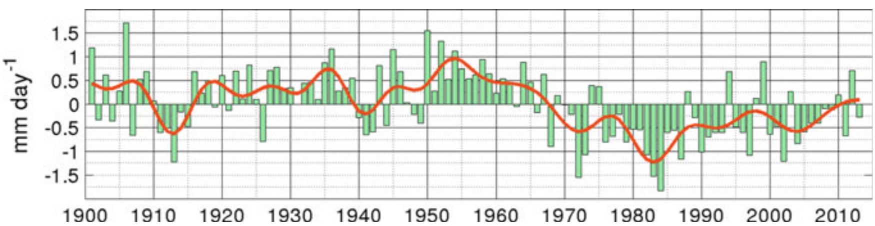

Fig. 1.3 JAS seasonal precipitation anomalies with respect to the 1901–2013 mean averaged over the Sahel region (between 17.5°W–10°E and 10°–17.5°N). Bars represent the inter-annual values and the curve is the 8-year low-pass filtered index. Data from GPCC.v7

[1]Also referred to as *Nordeste* in the literature.