BACKGROUND REPORT ON

THE STATUS AND POSSIBLE EVOLUTION OF CLIMATE PROJECTIONS IN WEST AFRICA

OCTOBER 2013

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ARCC

African and Latin American
Resilience to Climate Change Project

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AFRICAN AND LATIN AMERICAN RESILIENCE TO CLIMATE CHANGE (ARCC)

OCTOBER 2013

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ACRONYMS AND ABBREVIATIONS

AEJ	African Easterly Jet
AMMA	African Monsoon Multidisciplinary Analysis
AMO	Atlantic Multidecadal Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
AR3	Third Assessment Report
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
AWJ	African Westerly Jet
CFSR	Climate Systems Forecast Reanalysis
CGCM	Coupled Global Climate Model
CIP	Climate Information Platform
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Downscaling Experiment
CSAG	Climate System Analysis Group
ECMWF	European Centre for Medium-Range Weather Forecasts
ESM	Earth System Models
ENSO	El Niño-Southern Oscillation
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploration of Meteorological Satellites
FEWS	Famine Early Warning System
GCM	General Circulation Model
GHCN	Global Historical Climatology Network
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
HRV	High-Resolution Visible
IPCC	Intergovernmental Panel for Climate Change
IR	Infrared

ITCZ	Intertropical Convergence Zone
MCS	Mesoscale Convective System
MSG	Meteosat Second Generation
MSLA	Mean Sea Level Anomaly
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
NOAA	National Oceanic and Atmospheric Administration
PIRATE	The Pilot Research Moored Array in the Tropical Atlantic
RCD	Regional Climate Downscaling
RCM	Regional Climate Model
RCP	Representative Concentrative Pathways
SLP	Sea Level Pressure
SRES	Special Report on Emission Scenarios
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
TEJ	Tropical Easterly Jet
TRMM	Tropical Rainfall Measuring Mission
VIS	Visible
WAIS	West Antarctica Ice Sheet
WAWJ	West African Westerly Jet
WGCM	Working Group on Coupled Modelling
WOA	World Ocean Atlas
WRCP	World Climate Research Program
XBTs	Expendable Bathy Thermographs

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EXECUTIVE SUMMARY

The U.S. Agency for International Development (USAID) commissioned The African and Latin American Resilience to Climate Change (ARCC) project to organize various desk studies focusing on the vulnerability of West Africa to climate, both current and future. These individual studies fall under the umbrella of the '*West African Vulnerability Assessment.*' This particular report presents the findings from an assessment of the status and possible evolution of climate projections for the region. It highlights both the strengths and limitations of such data for building a picture of climate change in West Africa. Furthermore, this report shows that climate modeling is a complicated task in West Africa, with many challenges linked to limitations within models, availability of observed data, and the unique and complex climate dynamics of the region.

The climate[1] of West Africa is complex, with a distinct north-south rainfall gradient evident between the wet coastal region and the drier Sahel located further to the north. The Sahel has possibly been the most documented region of West Africa, in terms of climate, due to the impact of a multi-decadal drought towards the end of the 20th century. As noted by Giannini et al. (2008), changes in rainfall patterns experienced in the Sahel are "unparalleled globally, in magnitude, spatial extent and duration." Although the Sahel is home to major cities such as Dakar (Senegal), Niamey (Niger), Bamako (Mali), and Khartoum (Sudan), a large portion of the populations of these countries live in rural areas and are highly dependent on agriculture as a source of food and income. It is for this reason that understanding regional rainfall patterns, both past and future, is of such importance.

One of the key drivers[2] of the spatial distribution of rainfall in West Africa is temperature contrasts between the land and ocean. These gradients set up the regional rain producing circulation pattern, commonly known as the West African Monsoon. The onset of the monsoon takes place along coastal West Africa in the spring months. This is the wettest phase of the monsoon. During July, there is a strong northward latitudinal shift in the monsoon, referred to as the "monsoon jump," during which peak rainfall intensities occur in the Sahel. By the end of August, the monsoon rains begin to return to the coast, and the Sahel begins to transition into the dry season.

Regions within West Africa display considerable rainfall variability at annual, decadal, and multi-decadal time scales. This variability was long thought to be due to desertification, but more recently has also been linked to anomalous circulation in the jet streams, and to anomalies in sea-surface temperatures both regional and global. Identifying the contribution of any one particular feature or climate driver to West African rainfall variability is difficult due to the complex nature of the interactions involved. It is likely that the influence of an individual driver may vary for different regions within West Africa, at different times of the year, and is also modified by interaction with the effects of other drivers.

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[1] Weather is generally defined as the conditions of the atmosphere at a particular place over a short period of time, while climate is generally defined as the average or mean atmospheric conditions over a longer period (usually over a 30-year period) at that location or across a region.

[2] The term "drivers" is used to describe any local or remote atmospheric, ocean, or land surface feature that influences the weather and climate in a particular area. Examples include sea-surface temperatures, topography, jet-streams, high pressures systems, and vegetation.

Full understanding of the African climate is hindered by the lack of availability of long period, continuous sequences of observed climate data. This is of concern as it limits understanding of regional climate change and variability which takes place over multiple decades. The primary source of historical climate information comes through *in-situ* data (e.g., rain-gauges). Although many regions contain station-based datasets housed by various local weather agencies, this data is fragmented and of questionable quality. Data that has not been through stringent quality control tests may produce misleading climate signals, and thus have negative consequences when used in decision making.

Remote sensing (satellite based) products have somewhat filled the void by providing observations at a relatively high spatial and temporal resolution. The data from satellites have increased understanding of climate processes on a global scale, and have been invaluable in advancing numerical weather prediction and early warning systems. However, such products also have their limitations; they still require a considerable amount of validation and contain biases in many areas.

Another source of climate information is computer modeling. The field of numerical modeling is based on mathematical equations that are used to represent the dynamics of the climate system. The most well-known example of modeling is the general circulation model (GCM) or climate model. While most models are based on the same physical principles and even use largely similar numerical methods, there are many choices available to model developers during model development. Different numerical methods can be used to solve the fundamental physical equations, while different approximations, known as parameterizations, can be used to represent processes such as convective rainfall, cloud properties, and radiation balances (i.e., processes that occur on scales smaller than the model resolution). The result is that each model, while following the same basic principles, can produce different simulations of the current climate and different projections of the future climate state.

Although models may produce different projections of future climate, there are a number of characteristics that are common through nearly all models. In particular, all models agree on global temperature increases with greatest increases in the northern hemisphere high latitudes. Many models agree on increases in extreme rainfall in tropical areas and on significant changes in circulation (intensification of high pressure belts and shifts in the mid-latitude cyclone tracks).Where models often disagree is around regional scale changes in rainfall patterns and details of shifts in seasonality (e.g., the start and end of the rainy season). Models disagree on these characteristics because regional scale rainfall processes are strongly governed by local scale topography, land-surface characteristics, sea-surface temperatures, and other complex regional processes. These are poorly represented by most models, and often are approximated by starkly different parameterizations within the models. Unfortunately, these disagreements between different models are often of critical importance for the purposes of this report— that is, with regards to resilience planning and decision-making — as it is at the regional scale that changes in rainfall are likely to have the most critical societal impacts.

Even though the scientific community attempts to use climate models to provide robust and useful information to assist decision makers, their projections inherently include uncertainties, which stem from a number of different sources. These sources can be categorized as follows:

- *Natural Variability*: This is also known as "climate noise," and refers to the internal variability of the climate system that occurs irrespective of changes in external forcing[3]
- *Emission-Scenario Uncertainty*: Also known as forcing uncertainty, this relates to the lack of knowledge of how future society will alter atmospheric emissions of greenhouse gases, which can be considered as an external factor influencing the climate system.
- *Model-Response Uncertainty*: This arises from the use of different models that produce diverse results despite being forced with the same external forcing. This can be broken down into imperfect understanding, where the small scale physical processes are not well understood (e.g., cloud radiative effects and precipitation processes) and also model inadequacies (e.g., representing fine scale processes through parameterizations).
- *Initial Condition Uncertainty*: This is due to sparse or incomplete observations in time and space, of the type which are needed to initialize the model. This uncertainty is more likely to present a challenge in the shorter time scales, like weather forecasting and decadal forecasting.

Some uncertainty can potentially be addressed through improved models (e.g., increased resolution and better parameterizations) and downscaling methodologies. Downscaling is the process used to produce information at a higher resolution than GCMs. There are two main approaches to downscaling, either through dynamical methods (e.g., using a regional climate model forced with GCM data) or through statistical methods (e.g., empirical relationships between large-scale[4] processes and the local climate).However, downscaling introduces a new set of uncertainties, and some uncertainty will always be present. By understanding the limitations of the range of models and methods, decision makers can be better equipped when dealing with climate information.

An assessment of the effectiveness of various GCMs and regional climate models (RCMs) in simulating current West African climate reveals that many challenges still exist. In particular, the models struggle to accurately represent the range of climate drivers that play a role in the region. It is this poor representation of the multiple climate drivers in the models that adds to the uncertainty in future projections. For example, GCMs have trouble simulating the tropical Atlantic sea surface temperature, which is critical to accurately simulating the West African Monsoon system. In addition, the sensitivity of models to the parameterizations used and the choice of boundary conditions can also lead to diverse results. Regional climate models are needed to provide the finer resolution data required for impacts or adaptation studies and the CORDEX-Africa project has the potential to provide this information. However, these models still show strong biases compared to observations, as well as differences between models. Overall, the scientific studies documented in this report have illustrated the enormity of the challenge faced when trying to produce future climate projections for West Africa.

Noting these caveats, the results presented in this report do suggest that the West African region will not respond to climate change in a uniform manner. The Sahel is projected to warm more than the Guinean Coast, while the western Sahel is more likely to dry (especially at the beginning of the season)

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[3] External climate forcing encompasses any phenomena that *influences* the climate system but is not *part* of the system. The most common and dominant example is variation in solar radiation, referred to within this document and elsewhere as radiative forcing.

[4] Sometimes described as 'synoptic-scale' and refers to processes or weather systems occurring on scales ranging from a few hundred kilometers to several thousand kilometers.

compared to the central and eastern Sahel, which is projected to become wetter (especially during the end of the rainy season). There is also some preliminary evidence that high-elevation areas may respond differently from lower-elevation regions, with an increase projected over the Guinean Highlands and Cameroon Mountains. With regards to the coastal regions, it is projected that these regions may become increasingly vulnerable to an increase in sea-level rise and coastal storm surges, although there is a high degree of uncertainty associated with these projections. This is particularly difficult to evaluate due to the lack of observations as well as the poor representation of sea-level rise (knowledge deficiency) and storm surges (model resolution deficiency) in models.

West African future climate projections, particularly the near-term (next five to ten years), are inherently uncertain. This is a result of both chaotic variability in regional atmosphere-ocean processes, and because models cannot fully simulate all aspects of the climate system due to resolution constraints and the need to parameterize complex processes. It needs to be recognized that climate science will continue to evolve and improve, and while the focus of a given study or instrument specifically be on West Africa, any progress in the field as a whole will still undoubtedly improve understanding of region's climate. With West Africa in mind, the following areas still need to be addressed:

- The development of a better weather observation network (or maintaining what is already in place through country meteorological services and other organizations). This must be considered a long term investment as the real value of observations is only realized after ten to fifteen years after installation of an observing station. Observation data forms the basic foundation of climate information that is used to better our understanding of regional climate variability. Planning for future climate change requires a deeper understanding of what drives regional climate variability.
- There are still many unknowns regarding West African climate dynamics. Significant research effort in this area has the potential to make important progress. Projects such as AMMA and others have already proved the value of focused research combined with intensive observations. This is one area of scientific research that could play a big role in improving our understanding of future climate projections and reducing uncertainties.
- Model development (e.g., improving resolution, parameterizations, etc.) will continue to take place. Improvements in parameterizations in particular (i.e., how rainfall processes or land surface feedbacks are simulated in the model) could be beneficial for West Africa. Most model development takes place in the Northern Hemisphere with a great deal of focus on the higher latitudes. While some model development is focused on improving the models in equatorial and tropical regions (e.g., CSAG-UCT CAM5 model improvement activities), more focus on these regions could reap valuable benefits both in understanding regional climate processes as well as reducing uncertainty in future projections.
- Other avenues for improvement in West Africa climate projections include the relatively new fields of bias correction and decadal prediction. These methodologies are currently under review in the scientific community. Bias correction attempts to correct systematic errors in model outputs in order to make the results more directly useful to decision making. Decadal predication attempts to extend concepts in weather forecasting to multi-year forecasts.
- CORDEX-Africa will produce large quantities of climate data for Africa. Primarily this will provide a large suite of downscaled climate simulations for Africa which will enable a comprehensive evaluation of downscaling methods, strengths, and limitations.

The continued development of observational systems, core science research, climate modeling, and downscaling is essential to improving the information available to climate adaptation, and it affects impacts practitioners. However, these developments are currently fairly slow with little real progress or change in large-scale messages between different generations — the CMIP3 (IPCC AR4) and CMIP5

(IPCC AR5) — of climate projections. If anything, model disagreement and uncertainty has increased in recent years as models have become more complex. Thus, the real challenge is in the area of planning or decision making given uncertain climate information.

Traditional top-down approaches involved first producing climate projections for a particular region for variables such as mean temperature and annual rainfall. The projections are then examined in order to infer potential climate change impacts. Finally, adaptation plans, policy changes, or other decisions are made in order to avoid or reduce the consequences of these impacts in a particular sector.

There are a number of problems with this approach. In order to gain a good insight into the potential impact of a changing climate it is necessary to have a good understanding of the socio-ecological-economic system involved. These systems are complex and incorporate non-linear feedbacks, non-climatic stressors, and cross-sector interactions. Moreover, first order projected changes in temperature or rainfall often fail to reveal the true vulnerabilities of such systems. Vulnerabilities can manifest through complex combinations of climatic stressors such as changing seasonality, rainfall intensity and temperature/rainfall relationships, multi-year droughts followed by heavy rainfall, and so on. Vulnerabilities also emerge through combination with non-climatic stressors such as urban migration, political instability, and economic crises.

There is growing evidence that approaching the decision making process through cross-sectoral co-exploration of the climate information, analysis of historically impactful events and their drivers, and exploration of multiple possible future climate "stories" will produce better decisions and policies to reduce societal vulnerability to a changing climate.

1.0 INTRODUCTION

At the request of United States Agency for International Development (USAID), the African and Latin American Resilience to Climate Change (ARCC) project was tasked with assessing climate change vulnerability in West Africa to help inform USAID activities addressing this vulnerability. As a sub-component of the larger project, this report focuses on current understanding of climate projections, their utility, and potential improvements in that utility. It addresses how future climate projections are made, from the need for observations on the ground to dealing with uncertainty. A better understanding of the limitations of current projections will also inform current decision making by providing donors and governments the ability to identify variables that won't be projected with reasonable certainty until the distant future, as well as decisions that might be better delayed until projections have improved.

"Climate change is the greatest global challenge facing humankind in the 21st century" was the declaration issued at the World Economic Forum in Davos, Switzerland in 2000. Since that statement was made, how far has the scientific community progressed in terms of understanding climate change and its potential consequences? This question is particularly relevant for West Africa, which has been heavily impacted by climate in the past through crises of water availability, food security, mass migration of people, and conflict. Population increase in West Africa has played its own role by putting significant pressure on ecosystems, with the removal of vegetation in the grassland region of the north and removal of forested regions in the south.

The progress of climate change science has been considerable over the past decade. To some extent this has been enabled by advances in computational power and thereby the complexity and detail captured by climate models. However, a possibly more important contribution has been satellite based observations and intensive collaborative field observation campaigns, such as African Monsoon Multi-disciplinary Analysis (AMMA). These observations have provided key data and evidence that has informed significant advances in the understanding of regional and global scale climate systems. This improved understanding has been incorporated into climate models, producing projections of future changes to the climate system.

Clearly, there are still aspects of regional and global climate system dynamics that are poorly understood and this introduces uncertainties into climate projections. Assumptions and simplifications have to be made in climate models, which can produce contradictions and disagreements between models. However, an equally important challenge lies in the interface between climate scientists and decision makers. At the most basic level, miscommunication between the climate science community and decision makers can often be attributed to the language or terminology used by the different groups (e.g., see Box 1). Beyond basic terminology and conceptual understanding, the following questions describe some key areas of importance related to the application of climate science to policymaking and other adaptation decision making:

- What is the utility of climate projections in decision making on particular time horizons and spatial scales?
- How best can climate projections, and their associated uncertainties, be communicated to decision makers?
- Can climate science and the production of climate projections respond in a more tailored way to the information needs of the decision making process?

Traditionally, climate projections have been provided through a top down approach where projections are fed into the decision making process as one of a range of stressors involved. However, more recently there has been a move to engage with climate science throughout the decision process. This is more of a bottom up approach, strongly guided by descriptions of existing vulnerabilities and risks at appropriate spatial and time scales. Climate projections are then explored in a search for evidence of particular future risks under a changing climate. Projections are also used to explore the viability and potential efficacy of proposed adaptation response measures. This report does not pre-suppose a particular approach to incorporating climate projections into decision making processes but does draw on an existing literature base that largely stands within the traditional top-down approach.

BOX 1. PREDICTION, PROJECTION, AND SCENARIO

A lot of confusion regarding climate change is often found in the language used by the scientific community. Three of the common terms used to describe a future climate state are: *prediction*, *projection* and *scenario*. According to the IPCC (2007) they are defined as follows:

Climate Prediction: "A prediction or climate forecast is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future (e.g., at seasonal, interannual, or long-term time-scales)."

Climate Projection: "A projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, often based upon simulations by climate models. Climate projections are distinguished from climate predictions in order to emphasize that climate projections depend upon the emission/concentration/radiative forcing scenario used, which are based on assumptions, concerning, for example, future socio-economic and technological developments that may or may not be realized, and are therefore subject to substantial uncertainty."

Climate Scenario: "A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change , often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require information about other matters such as the observed current climate. A 'climate change scenario' is the difference between a climate scenario and the current climate."

In some cases these terms are used interchangeably, which adds confusion to communities using the information.

The layout of the report is as follows: Section 2 provides an in-depth account of the sources of climate data, including how they are created or collected, and their individual strengths and limitations. The aim is to provide the reader with background on the science behind climate projections. Section 3 covers rainfall production in West Africa, from historical observations, current simulation and projected future changes. With a population that is heavily dependent on rain-fed subsistence agriculture, arguably the most important climatic variable in West African is rainfall. In addition, climate models are often evaluated by how well they simulate regional rainfall patterns, both spatially and temporally, as well as how they capture particular features that play a role in rainfall variability. Projections of rainfall also introduce the largest sources of uncertainty into the projections. Projections of temperature introduce significantly less uncertainty as the disagreement between models regarding projected temperature changes is relatively small. It is for these reasons that the report is heavily biased towards rainfall. It does not attempt to downplay other factors, such as the role of an increase in regional temperature, which may be just as important as rainfall changes in the agriculture sector, or sea-level rises, which may be

more of a concern for coastal residents. Chapter Four provides a synthesis summary of the report and presents some recommendations for where USAID efforts could be directed in West Africa.

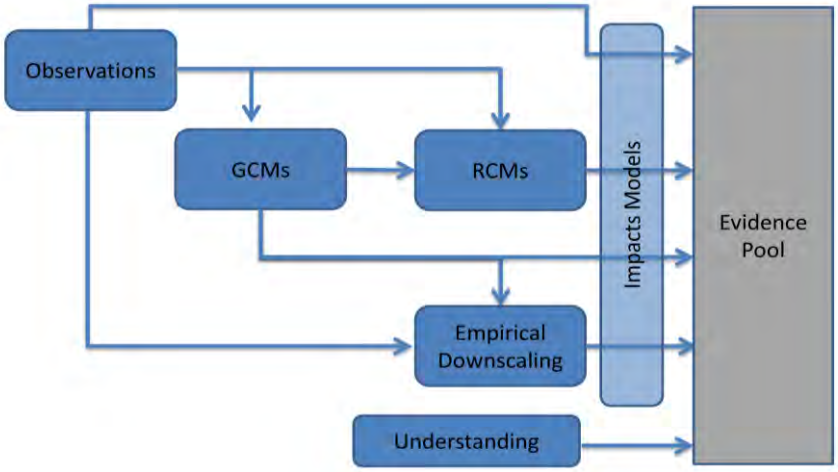
2.0 SOURCES OF CLIMATE INFORMATION

2.1 INTRODUCTION

A key foundation of responding to climate change is using climate information that is both relevant and useful. A single source of climate data is not enough to develop a valid storyline of regional climate change, which is why the climate science community relies on numerous sources of data. It also needs to be recognized that the various types of climate data are only of value if used at the appropriate space and time scales.

Observations form the building blocks of our understanding of the climate system (Figure 1). These observations, such as that from *in-situ* data (e.g., rain-gauges) and remote sensing products (i.e., satellites), provide current and historical climate information, which is used to assess past trends and variability. Although most users are only interested in weather and/or climate over land areas, the ocean environment, which covers around 70 percent of the Earth's surface, plays a vital role in the climate system. For this reason, an intensive effort has been devoted to developing a better understanding of ocean processes, through improved ocean observations.

FIGURE 1. A SCHEMATIC OF THE AVAILABLE SOURCES OF CLIMATE INFORMATION AND HOW THEY FEED INTO ONE ANOTHER. IT IS THE COMBINATION OF THESE SOURCES OF INFORMATION THAT INCREASES OUR UNDERSTANDING OF REGIONAL CLIMATE CHANGE



Source: Jack, 2013

Computer models (e.g., GCMs and RCMs in Figure 1) provide another source of climate information, with the most well-known output being future climate projections. Although the scientific community attempts to use climate models to provide robust and useful information to assist decision makers,

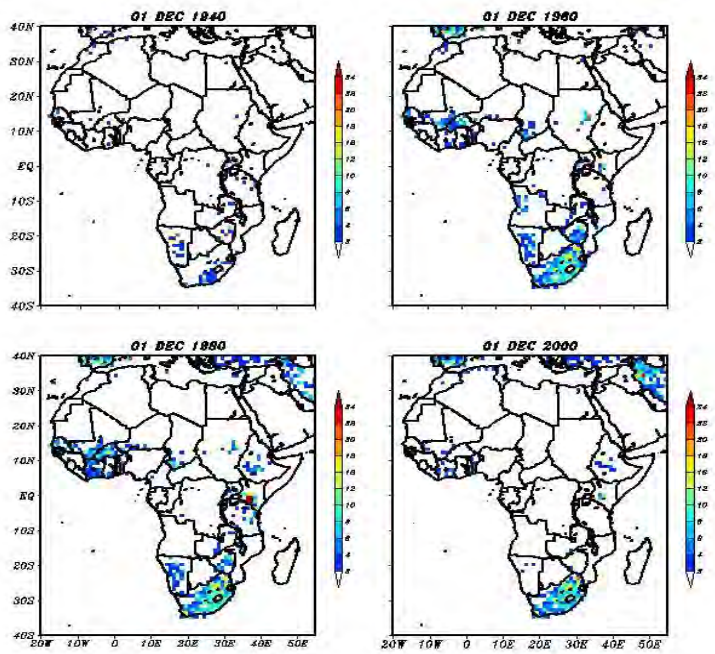
future climate projections inherently incorporate a range of uncertainty sources, which is discussed in this chapter.

2.2 OBSERVATIONS

2.2.1 In-situ Sources

In terms of surface-based weather observation platforms (e.g., rain-gauges, radiosondes, etc.), Africa is mainly a data sparse region, which generates a problem for monitoring local weather and climate. Not only are there challenges with spatial and temporal availability of data, but the data is further limited due to the lack of quality control. These issues are not confined to the region, but are problematic worldwide. An example of data scarcity over the African continent is illustrated in Figure 2. The data used to create Figure 2 comes from the Global Precipitation Climatology Centre (GPCC) and are used to create continuous global precipitation datasets at varying spatial resolutions. It is evident that only isolated parts of southern Africa, East Africa, and West Africa contain sufficient data for a relatively thorough historical climate analysis. It is possible that the figure may be misleading due to local weather agencies holding longer data records. Apart from these data being costly to retrieve, they also involve problems with quality control.

FIGURE 2. THE EVOLUTION OF AFRICAN RAIN



Source: GPCC. Gauge data incorporated into the Global Precipitation Climatology Project (GPCC) since 1940 through 2000 at 20 intervals. Values refer to the number of stations in each grid cell.

In-situ observations are needed to assess the climate of the region, as well as any local trends experienced. In addition, they are required to assess the skill[5] of computer models in simulating the climate, to validate remote sensing products, or to be used in data assimilation techniques to produce reanalysis products (see Box 2). Arguably the most utilized type of in-situ source used in West Africa is the rain-gauge. Daily rainfall data from rain-gauges, both automatic and manual, are extremely useful to not only determine long term trends in a region, but also assists with evaluating changes in rainfall characteristics, such as the onset, intensity, frequency, dry spells, etc. One of the most complete African rainfall datasets is the African archive of rainfall data used by Nicholson (1986, 1993, and 2008). It contains about 1300 station records, most of which begin before 1920 and extend to 1998[6]. The data have been incorporated into other global archives, such as the Global Historical Climatology Network (GHCN). The difficulty of obtaining rain-gauge data for West Africa has been noted in the scientific community. Nicholson (2013) suggests that it has become increasingly difficult to assess regional rainfall changes in parts of West Africa due to the lack of rain-gauge data post-1990s. It is because of this lack of ground-based observations that alternative data sources have become essential.

BOX 2. REANALYSIS PRODUCTS

Information from satellites and weather stations not only provides information on the current state of the African continent, but is also used to inform reconstructions of the recent past climate through various reanalysis projects. This process entails using the latest advances in climate models and the assimilation of observations to reconstruct the past climate in a 3-dimensional state. The latest version of reanalysis datasets, such as the Climate Systems Forecast Reanalysis (CFSR) (Saha et al., 2010), contain output at a relatively high spatial (~38 km) and temporal resolution (six hourly). The advantage of such products is the complete spatial coverage and relatively long time coverage (30+years). These products are therefore extremely useful for studies of climate, particularly in data sparse regions. A summary of reanalysis products available for research into West African climate is provided in Table A1in the Annex.

Although such data is used routinely in long-term climate studies, there are known limitations with such reanalysis, particularly the earlier versions. For example, the use of NCEP Reanalysis Data for historical analysis has been questioned by some researchers due to possible errors identified in tropical divergent circulations and rainfall (e.g., Poccard et al., 2000; Kinter et al., 2004) and some inconsistencies in Southern Hemisphere circulation (e.g., Tennant, 2004). Additionally, it has also been noted that different reanalysis products exhibit different characteristics in the West African region (Zhang et al., 2008; Meynadier et al., 2010). Thus, caution should be applied when using the details of a single reanalysis product. In order to gain more confidence in results using reanalysis data, new methods used to understand the climate regime of a region have often included multiple reanalysis datasets instead of just a single source (e.g., Nuygen et al., 2013).

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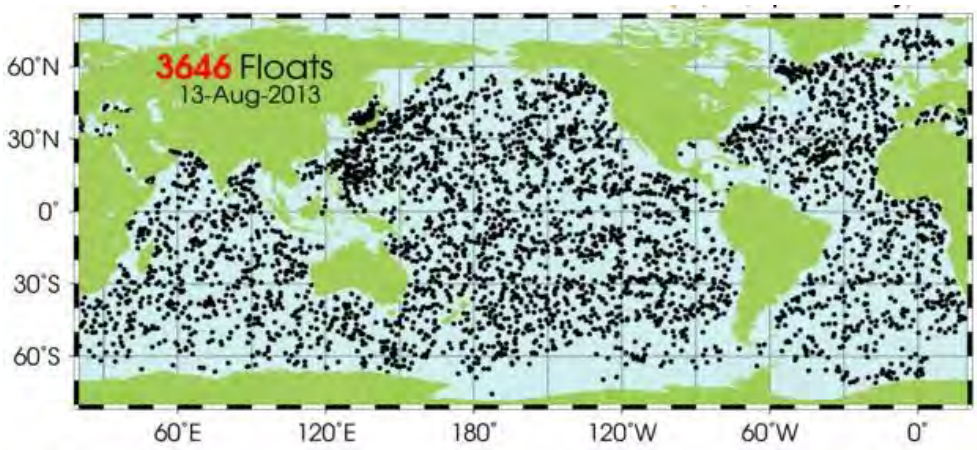
5 Skill is a general term used to describe the ability of a model to represent reality. In practice a number of different statistical methods are used to quantify model skill. Most methods have been developed within the weather forecasting and seasonal forecasting fields though many can also be applied to model evaluation on longer time periods.

6 There is no obvious reason why it ends at this particular date, but the author (Nicholson) has stated in a recent paper that they have had difficult retrieving data since the late 1990s.

Surface-based observations are not restricted to the land, with various observation platforms also deployed in the ocean. The oceans play a central role in the climate system, on both short and long timescales (e.g., circulation patterns and moisture transport affecting daily weather, while absorption of excess heat and carbon dioxide (CO_2) from the atmosphere playing a role in long term climate patterns). A few examples of such ocean-based in-situ observations are autonomous floats, which form part of the ARGO program (Figure 3), and, specific to West Africa, the PIRATA program (see Box 3). The passive ARGO floats, which oscillate between the surface and depths of 2000 m, record temperature, salinity, and pressure. These floats are deployed globally and return 100,000+ water column profiles per year. Float profiles are digitized, collated, and quality-controlled at centralized portals in near real-time, from where they are freely available. Additional gridded products[7] are available from multiple agencies at resolutions up to 0.5° and at monthly intervals from 2004 to present. ARGO data is used (1) to observe regional oceanographic processes, (2) to monitor global ocean variability on seasonal to decadal scales, (3) to constrain model evolution through assimilation schemes, and (4) in the initialization of global climate models (e.g., included in CMIP5, which is discussed later).

FIGURE 3. DISTRIBUTION OF ARGO FLOAT REPORTS FROM AUGUST 13TH, 2013



Source: University of California-San Diego ARGO, 2013

While *in-situ* oceanographic information is internationally coordinated and widely available, often freely and in real time, there is minimal information concerning locally deployed coastal instrumentation or mooring systems. While investigations appear to have been conducted (e.g., the COCES/COCES-II programs conducted by OGS, Trieste), data is sparse, not readily available, and lacks continuity. For example, around 50 percent of the tide gauge data (Permanent Service for Mean Seal Level, 2013) from West Africa is only available prior to 1993. Beginning in 1994, the World Ocean Atlas (WOA) program synthesizes all observed oceanographic data into a gridded climatology of the world oceans (Levitus and Boyer, 1994a, 1994b). The latest WOA product, was produced in 2009, and includes temperature (Locarnini et al., 2010) and salinity (Antonov et al., 2010) at 1° x 1° resolution on 33 standardized depth levels. The WOA products have been instrumental in uncovering the recent warming trend in the global oceans (Levitus et al., 2000).

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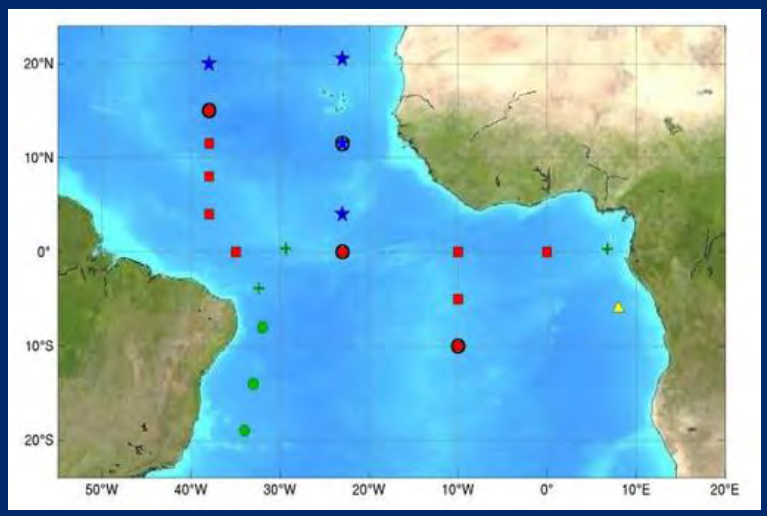
[7] A gridded product refers to data that is based on or projected onto a latitude x longitude grid. The size of a single grid determines the spatial resolution of the data and is usually given in degrees or kilometers.

BOX 3. PIRATA

The Pilot Research Moored Array in the Tropical Atlantic (PIRATA) program, designed to monitor tropical Atlantic processes, operates two permanent ATLAS buoy stations in the Gulf of Guinea, providing surface meteorological and sub-surface information on salinity, temperature, and ocean currents in the top to 500 m (Bourlès et al., 2008; Servain et al., 1998). Data is available daily, in near real-time, and data provision will continue until late-2013. The Sao-Tome island station, part of this array, transmits hourly sea level, sea-surface temperature (SST), sea-surface salinity (SSS), and sea-level pressure (SLP) measurements (Figure 4). An annual oceanographic research cruise to the western array, ongoing since 1997, deploys Expendable BathyThermographs[8](XBTs) and performs regular instrument casts to gather salinity temperature and current data in the sub-surface. All cruise data and reports are available online (PIRATA, 2013).

FIGURE 4.THE PIRATA BACKBONE OF ATLAS BUOYS (RED SQUARES), NORTHEAST EXTENSION (BLUE STARS), SOUTHWEST EXTENSION (GREEN CIRCLES), SOUTHEAST EXTENSION PILOT PROJECT (YELLOW TRIANGLE), AND ISLAND-BASED OBSERVATION SITES (GREEN CROSSES). BUOYS WITH BAROMETERS AND THE ABILITY TO ESTIMATE NET HEAT FLUX ARE INDICATED WITH BLACK CIRCLES.



Source: PIRATA, 2013

2.2.2 Remote Measurements

Climate observations have advanced quite significantly since the inception of the satellite era. This is predominantly due to satellites being able to cover an extensive range of space and timescales. A primary source of information for West Africa is the data provided by the constellation of Meteosat

[8] Obtains similar information to ARGO floats, but transmit only a single temperature/salinity profile while falling through the water column at a pre-defined rate.

Second Generation (MSG) satellites operated by the European Organisation for the Exploration of Meteorological Satellites (EUMETSAT). The MSG satellites (Meteosat-8, -9, and -10) are the new generation of European geostationary[9] meteorological satellites, providing continuous observation of the earth's full disk centered on the Greenwich meridian (see Schmetz et al., 2002). These satellites cover a large spectral range, from visible, known as either 'warm' or 'solar' channels, to infrared or 'cold' channels. Eleven of the channels have a sampling resolution of around three kilometers and are able to scan the full disk of the earth, while the HRV channel produces images with approximately one kilometer resolution. Due to the satellite being geostationary it can produce frequent images over the same area (±15 minutes intervals), which allows for rapid changes in the atmosphere to easily be detected.

BOX 4. REMOTE SENSING OF THE OCEAN

Remote sensing of sea-surface temperatures (SST) of the ocean is another key component in understanding West Africa climate. This is due to local SST patterns influencing regional atmospheric circulation and hence, rainfall over West Africa (the importance of ocean SST is highlighted later in the report). Prior to the satellite-era, observations of the sea surface were sparse, and no large-scale picture of the ocean state existed. Since ~1979, remote sensing platforms have produced near-continuous, globally-gridded data sets on the event (typically five to seven days) and climate scales. Typically, SST data products are a synthesis of multiple sources; remote and *in situ*, with some of the products highlighted in Table A2in the Annex.

Other ocean products derived from satellites include sea surface salinity (used to deduce river outflow specifics, constrain model fields and close the global hydrological budget [Lagerloef, 2002]), sea surface height (used extensively in quantifying sea-level rise [Church, 2004, 2006]), and upwelling dynamics (through primary productivity, the foundation for nearly all ocean food webs). These types of observations can play a critical role in providing information for local communities. For example, changes in upwelling dynamics of the Gulf of Guinea may have long term impacts on phytoplankton biomass and community structure, with consequences for regional fisheries. However, these products require regional validation, historically lacking in African coastal waters.

Satellites, such as the MSG, are not only useful for detecting changes or processes in the atmosphere, but also monitor surface conditions over the continents and ocean (see Box 4). One of the most useful land surface products for West Africa has been the Normalized Difference Vegetation Index (NDVI), which is used as a proxy for the state of vegetation. NDVI is calculated as the difference between near-infrared (NIR) and visible (VIS) reflectance values normalized over the sum of the two (Eidenshink, 1992). This product has been widely used by the scientific community to estimate green biomass and plant productivity. It can also be used to reflect local climate variability, such as changes in rainfall and temperature. The loss of vegetation or desertification was once seen as one of the key drivers of the Sahelian drought in the 1970s and 1980s (discussed in section 3). It is for this reason that many studies

[9] Geostationary Satellite – A satellite that orbits the equatorial plane (altitude around 22,000 miles) at the same speed as the Earth rotates and thus, always observes the same area of the Earth's surface.

have used NDVI to monitor the response of vegetation to climate changes in the West Africa (e.g., Malo and Nicholson, 1990; Anyamba and Tucker, 2005).

With regards to rainfall, due to the sparse location of global rain-gauges, satellites are used to fill the void in information. Thus, one of the main challenges of the weather satellite observation-era has been to improve satellite based rainfall estimates (i.e., using the satellite data to determine how much rainfall fell in a specific location). Early methods used to infer satellite-based rainfall estimates were based on the reflectivity of clouds and from cloud top temperature, which are provided by the visible and infrared (IR) data from geostationary satellites (e.g., Arkin and Meiser, 1987). Although this approach provided data at relatively greater spatial and temporal resolution than rain-gauge data, these approximations proved to be ineffective due to the weak link between these particular cloud properties and rainfall (Ebert et al., 2007). Essentially, it was the development of passive microwave sensors aboard polar orbiting satellites[10] that improved the accuracy, coverage, and resolution of rainfall estimates. One such example is that of the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched in November 1997 (Simpson et al., 1988; Kummerow et al., 1998).

Merged rainfall products were the next innovation of the satellite era. These products work by combining data from numerous satellites and their various onboard sensors, which are then adjusted with rain-gauge data to correct for biases in the satellite based estimates. Initial merged products, such as the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997; Adler et al., 2003), were relatively low in resolution on both temporal and spatial scales (monthly and 2.5°x2.5° latitude-longitude grid) and thus, were inadequate for monitoring finer-scale rainfall features. Since then, rainfall products, such as TRMM, have been produced at a higher spatial (e.g., 0.25° x 0.25°) and temporal resolution (e.g., 3-hourly rainfall totals). One limitation with using such products is that they are only available from the end of the 20th century / beginning of the 21st century. A summary of the available rainfall datasets that cover West Africa is provided in Table A3 in the Annex.

The full utilization of satellite-based rainfall datasets remains hindered by the uncertainty and unreliability associated with the rainfall estimates. Validation studies have shown that such products can work particularly well in some environments (e.g., locations where convective rainfall dominates), but can perform poorly in others (e.g., locations with high topography). However, given the limitations of rain-gauge datasets within many regions around the world, the use of satellite rainfall products appears to be a feasible solution to fill the void. It is for this reason that numerous satellite-derived precipitation validation studies (i.e., "ground truthing") have been conducted over the past few years (e.g., Adler et al., 2001; Wolff et al., 2005; Huffman et al., 2007; Ebert et al., 2007,and others) and are continuing to take place.

Overall, satellites play an integral part in collecting information that is used to advance the science community's knowledge of regional climate patterns. They provide a unique platform to continuously monitor the land, ocean, and atmosphere at various timescales, depending on the type of satellite and the instruments on board. Two of the key limitations of such a data source are that the information provided is only available for the last few decades of the 20th century (best case scenario) and that the products often require extensive validation.

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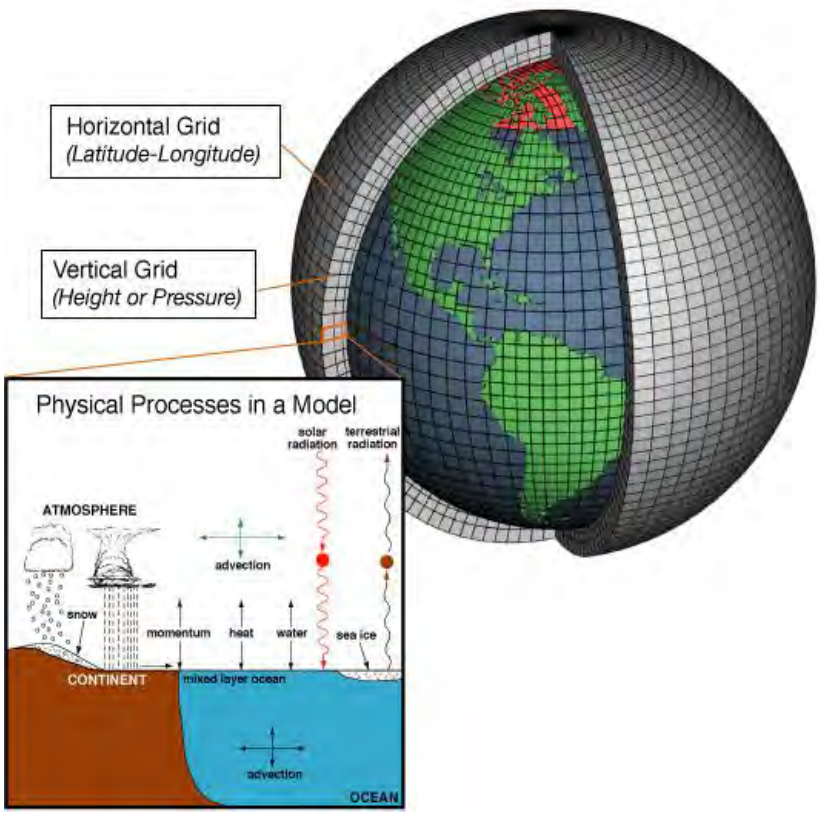
[10] Polar Orbiting Satellite – A satellite that orbits the Earth at low altitudes (~600 miles) crossing the equator every few hours. The low altitude allows for finer resolution but means that the satellite is always moving relative to the earth, requiring far more complex post-processing and analysis of the resultant image stream.

2.3 NUMERICAL MODEL OUTPUT

2.3.1 General Circulation Models (GCM)

A climate model is an executable computer code that solves a set of mathematical equations, which are designed to approximate the dynamics of the climate system. These equations (i.e., equations of motion, and conservation of energy, mass, and momentum) are discretized on a grid and solved numerically with the use of powerful computers. Values assigned to each grid box represent the average atmospheric state (temperature, humidity, wind speed, etc.) within the box (Figure 5). Numerical methods are used to represent transfers of mass, moisture, and energy between boxes according to dynamics equations.

FIGURE 5. SCHEMATIC SHOWING HOW THE EARTH IS BROKEN UP INTO A GRID OF "BOXES"



Source: National Oceanic and Atmosphere Administration (NOAA), 2013. The size of the box refers to the spatial resolution. Calculations are performed in each box and on the neighboring boxes at each time step in the model.

The process is not as straight forward as it appears, because an infinite number of boxes are required to accurately represent the atmospheric state at any moment in time. Processes that occur on scales smaller than the grid size of the model (e.g., convective processes that form rain clouds) have to be approximated, in a process known as parameterization. Climate modelers try to avoid parameterization problems by increasing the spatial resolution (size of the boxes). This increase in resolution results in the complex parameterized processes being resolved in the model. However, there are two limitations here; firstly, there are computational constraints (i.e., computers are not powerful enough to simulate very large numbers of boxes), and secondly, our understanding of some of the physical processes that

take place in the atmosphere is not complete. Nevertheless, climate models have progressed significantly since its first inception in the 1950s, developing from one-dimensional energy balance models to fully coupled atmosphere-ocean general circulation models (see Box 5) that represent the major climate system components (atmosphere, ocean, land surfaces, and cryosphere) and can capture complex large scale processes such as El Niño–Southern Oscillation (ENSO).[11]

BOX 5. COUPLING THE OCEAN AND ATMOSPHERE

The atmosphere and ocean are a strongly coupled system, with exchanges of heat, water, momentum, and biogeochemical processes. These ocean-atmosphere interactions play a key role in regional climate variability, where they not only influence daily weather patterns, but play a major role in long-term climate patterns. It is thought that while the atmosphere may dominate the day to day weather, the oceans, holding more energy and heat, play a larger role in controlling the climate.

Although coupling of ocean-atmosphere general circulation models (AOGCMs) began in the late 1960s and 1970s, real progress in their development took place in the 1980s and 1990s. The driving factors behind this progress was not only growth in attention to anthropogenic climate change (more commonly known as "global warming" due to greenhouse gases at the time), but the realization that one of the largest climate phenomenon,[12] the El Niño–Southern Oscillation (ENSO), evolves through complex ocean-atmosphere interactions (Neelin et al., 2004).

Replacing 'slab' ocean models by fully coupled ocean-atmosphere models is seen as one of the most significant steps forward in climate modeling over the past few decades. This process has resulted in a better understanding of simulated climate change, particularly in oceanic regions. Current AOGCM grid cell resolutions range between 100 km to 600 km and have between 10 to 20 vertical pressure levels in the atmosphere and as many as 30 ocean layers. Models now not only simulate the ocean and atmosphere, but also include a number of geophysical, chemical, and biological processes (see Figure 6). These models are commonly referred to as Earth System Models (ESMs).

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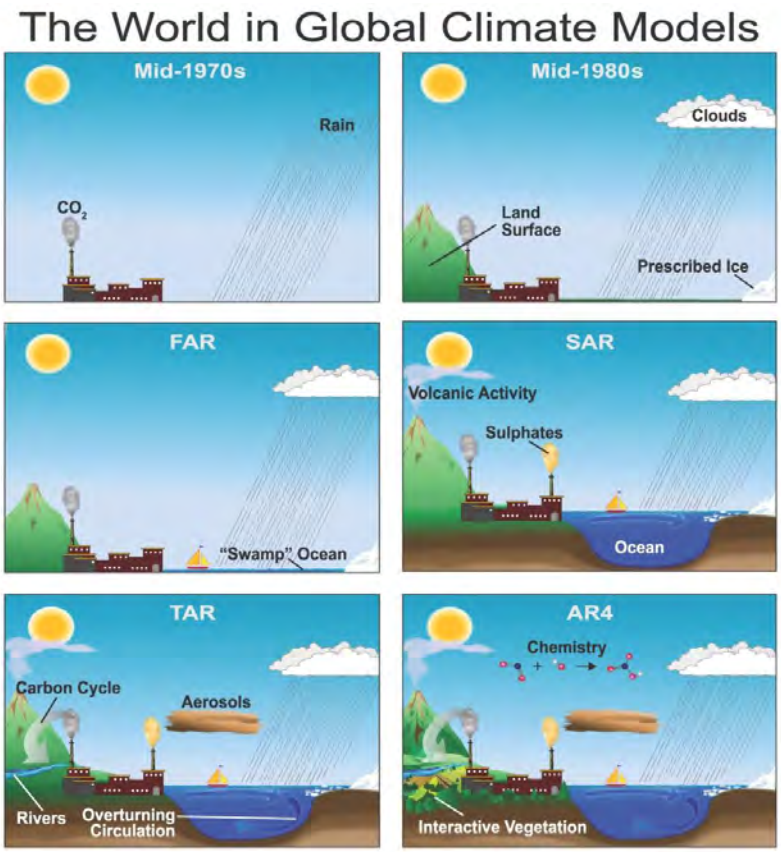
[11] ENSO – El Niño – Southern Oscillation refers to large-scale anomalous sea-surface temperatures in the Pacific Ocean.

[12] Although ENSO is a tropical Indo-Pacific phenomenon, it is known to influence climate patterns around the world (Trenberth, 1997).

FIGURE 6. THE PROGRESS OF MODELING IN TERMS OF CAPTURING THE DYNAMIC AND COUPLED CLIMATE SYSTEM



Source: IPCC AR4 Working Group I Report (2007)

2.3.2 Assumptions, Strengths, and Limitations

The use of climate models in projecting future climate change has come under close scrutiny recently due to evidence suggesting that the Earth has not warmed over the last decade as originally projected by models. Various mechanisms have been proposed to be the cause behind this hiatus in the warming trend. These mechanisms range from changes in stratospheric water vapor (Solomon et al., 2010), changes in the deep-ocean heat uptake (Meehl et al., 2011) to changes in surface temperature of the equatorial waters in the Pacific (Kosaka and Xie, 2013). To some degree, the lack of long-term global observations, particularly of the deep ocean, has hampered efforts to understand the different climate sensitivities. This situation has exposed the uncertainty (or lack of scientific knowledge) in the role that individual mechanisms play in the climate system.

Thus, while climate models have enabled significant advances in our understanding of the climate system, our ability to predict future weather and the impact of changing greenhouse gas emissions, there remain significant challenges and limitations. In the context of climate change, model disagreement stands out as one of the greatest challenges. There now exist upward of 30 different coupled climate models scenarios (see Box 6 for an example) that have been used to produce projections of future climate change given different emission scenarios (see Box 7). However, for the same emission scenario, these different models produce wide-ranging projections of the future climate, particularly regarding rainfall. This poses a serious challenge to the use of the climate projections derived from climate models.

Model disagreement is a result of a number of factors. While most models are based on the same physical principles and even use largely similar numerical methods, there are many choices available to model developers during model development. Different numerical methods can be used to solve the fundamental physical equations, while different approximations (i.e., parameterizations) can be used to represent processes such as convective rainfall, cloud, and radiation balances. The result is that each model, while following the same basic principles, can produce different simulations of the current climate and different projections of the future climate state.

BOX 6. WHAT IS CMIP5?

The Coupled Model Intercomparision Project (CMIP) was established under the World Climate Research Program (WRCP) by the Working Group on Coupled Modelling (WGCM). The goal was to provide a standard experimental protocol for studying the output of coupled Atmosphere-Ocean GCMs in order to facilitate model improvement through better model quality control and a better understanding of model behavior (Meehl et al., 2000). The output of phase three of CMIP was used extensively in the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report (AR4).[13] The fifth phase of the Coupled Model Intercomparison Project (CMIP5) is the latest set of coordinated climate model experiments (see Taylor et al., 2012).

The aims of CMIP5 are to evaluate how realistic the models are in simulating the recent past; to provide projections of future climate change on both the near term/decadal predictions (out to 2035) and long term (out to 2100 and beyond); and to better understand some of the key factors responsible for differences in model projections. The models used in CMIP5 offer more complexity than those used in earlier joint modeling projects. Both near- and long-term experiments are run with AOGCMs, which was also used for earlier CMIP projects. The CMIP5 models have a spatial range of 0.5° to 4° for the atmosphere and 0.2° to 2° for the ocean. Nearly half of the CMIP5 atmospheric models have an average latitudinal resolution finer than 1.3°, compared to one model in CMIP3 (Taylor et al., 2012). Similar resolution increases are found in the ocean component of the models. Additionally, the long-term experiments will also be coupled to biogeochemical components that account for the important carbon fluxes between the ocean, atmosphere, and land carbon reserves (i.e., the carbon cycle). These more advanced models (Earth System Models) have not been used before in CMIP (Taylor et al., 2012).

However, while differences exist in the projected future climate, a number of characteristics are common across almost all models. In particular, all models agree on global temperature increases with greatest increases in the northern hemisphere high latitudes. Many models agree on increases in extreme rainfall in tropical areas and on significant changes in circulation (intensification of high pressure belts and shifts in the mid-latitude cyclone tracks).

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[13] The IPCC produces an extensive review of the latest climate science, known as an *Assessment Report*, approximately every five to six years. To date, four have been published, with the fifth due late 2013 or early 2014.

Where models disagree is often around regional scale changes in rainfall patterns and details of shifts in seasonality (e.g., onset and cessation of rainfall seasons). Models disagree on these characteristics because regional scale rainfall processes are strongly governed by local scale topography, land surface characteristics, sea-surface temperatures, and other complex regional processes. These are poorly represented by most models, and approximated by often starkly different parameterizations within the models. Unfortunately, these disagreements are often of critical importance to society, as it is at the regional scale that changes in rainfall are likely to have the most critical societal impacts. A number of strategies have developed to deal with the resultant uncertainty in the climate projections. These strategies are discussed in the section on uncertainty below.

BOX 7. EMISSION SCENARIOS: SRES VERSUS RCPs

The IPCC AR4 modeling experiment (CMIP3) used SRES (Special Report on Emission Scenarios, [IPCC, 2000]) scenarios to dictate the concentrations of various greenhouse gases to be included within the simulated atmospheres of the models. Forty different emissions scenarios were developed to represent different possible scenarios of global and regional development, trade, technological development, mitigation, and policy. In practice only six scenarios were simulated and used extensively and many analyses focus on only two or three scenarios such as A1B1, B1, and A2.

For the IPCC AR5 experiment (CMIP5) the SRES scenarios were replaced by RCPs (Representative Concentration Pathways). These are documented in Moss et al., (2010). The motivation for using RCPs was to avoid the complexity of describing multiple global scale socio-economic scenarios and translating these into greenhouse gas concentrations, as RCPs concentrate directly on different scenarios of atmospheric radiative forcing.* Four RCPs have been defined – one "low" scenario (RCP 2.6), two intermediate (RCP 4.5 and RCP 6), and one high (RCP 8.5). The number indicates the equivalent top of tropopause change in radiative forcing in the year 2100. So RCP 8.5 represents a pessimistic scenario where the radiative forcing produced by continuously increasing greenhouse gases is equivalent to 8.5 $W.m^{-2}$by 2100. RCP 2.6 represents a scenario where emissions begin to drop well before 2100 and so represents a relatively optimistic scenario incorporating various mitigation actions.

* Radiative forcing (expressed in Watts per square meter, $W.m^{-2}$) is the difference in energy received by the Earth and that radiated back out to space. This difference is primarily caused by changes in greenhouse gases and aerosol concentrations in the atmosphere. A positive forcing (i.e., more energy received) means that the atmosphere is getting warmer. Within the IPCC, the term is used to describe how human activities or another factor may perturb the atmosphere, changing the balance of incoming and outgoing energy.

2.3.3 Downscaling: Dynamical and Statistical Approaches

Because the grid resolution of a GCM is very coarse (often greater than 200 km), it is necessary to apply a procedure whereby finer-scaled information can be generated. This is particularly relevant for the vulnerability, adaptation, and impacts community. Downscaling is one such method used to represent

the relationship between the large scale drivers and local climates. Most downscaling methods can be considered as a form of either *dynamical downscaling* or *empirical/statistical downscaling*.

As the name implies, dynamical downscaling techniques produces a simulation of the regional climate using the physics and dynamics equations that describe the climate system. The most common approach is to force a Regional Climate Model[14] (RCM) with the output of the GCM (Giorgi and Mearns, 1999; Castro et al., 2005). This means that the boundary of the RCM is driven by the large scale pressure, moisture and momentum fields from the GCM.[15] Using the same physics equations as in the GCM, the RCM is run at a much higher spatial resolution (25 to 50 km), and thus can capture finer scale processes (see Box 8 for an example). Land surface features, such as topography, regional water bodies, and vegetation cover, are also better represented in the RCM due to the higher resolution. This suggests that local climate features will be better resolved in the RCM.

It needs to be remembered that although the RCM is run at a higher spatial resolution than a GCM, there are atmosphere processes that are still required to be parameterized (e.g., convection). It is also assumed that the boundary conditions provided by the GCM are accurate enough to force the local climate. If there are any errors in the GCM, these could potentially be retained and amplified through the RCM. Questions have been raised whether GCMs can skillfully simulate regional forcing by major atmospheric circulation features such as ENSO and monsoons (Paeth et al., 2008). There is also no two-way interaction between the GCM and RCM, meaning that any alterations made by the higher resolution RCM are not fed back into the GCM. Another limiting factor with this method is computational constraints. Running an RCM is a computationally expensive process, which limits the number of simulations that can be performed. Ideally one would like a large ensemble of simulations to encompass the range of future projections (discussed in the next section).

Empirical/Statistical downscaling methods on the other hand use historical climate data to build empirical relationships between large-scale processes and the local climate (Hewitson and Crane, 1996; Wilby and Fowler, 2010). These relationships are then applied to the output from a GCM to construct a local climate. Within Empirical/Statistical downscaling there are roughly three categories of approaches, which are broadly defined as *transfer functions*, *weather generators*, and *weather analogues*. For brevity, a detailed description of these approaches is not provided here, but the reader is directed to Maraun et al., 2010, for a review. It should be noted that the spatial and temporal detail captured by each approach depends heavily on how the statistical relationship between the local variable of interest (e.g., rainfall) and large-scale circulation (e.g., pressure, humidity) is derived.

The main advantage of this method is that it can provide projections at a range of space and time scales, whereas the RCM is limited by its resolution. So information can be provided down to the "station scale" at a daily resolution using this method. This appears to make the task of comparing historical observations at a station with future projections slightly easier. Additionally, it does not require the intense computation like dynamical downscaling, which results in the production of more downscaled

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[14] A Regional Climate Model, such as Weather Research and Forecasting model (WRF; www.wrf-model.org), is a numerical model that is run at a much higher spatial (10 to 50 km) and temporal resolution over a limited geographical area.

[15] Note that the input for the downscaling procedure varies depending on the time scale of interest (i.e., short-term forecast, seasonal prediction, climate change). See Castro et al. (2005) and Wilby and Fowler (2010) for an overview. For the purpose of this report we are referring to downscaling methods for medium to long-term climate change.

datasets. This could be viewed as a disadvantage because due to the volume of data, it may not be thoroughly checked.

There are a few assumptions included in this methodology, with the first being that the main drivers for the local climate are large-scale circulation. Although this method does capture the dominant forcing of the local climate, there may still be some processes that may be unresolved, as there are other factors that are important for local weather patterns besides large-scale circulation. The second assumption is that the GCM can accurately simulate the large-scale circulation. If the GCM fails to do so, the errors will propagate through the downscaling process. Similarly, if the quality of the observation data[16] used to derive the statistical relationship is poor, then this will negatively affect the projections. Possibly the biggest assumption with this method is that the relationship between the large-scale drivers and local climate will be the same in the future as in the past. This is likely of greater concern for long-term projections, whereas near-term projections often assume climate stationarity (wherein the near future climate dynamics will be the same as the past).

2.3.3 Applying Downscaling Approaches to West Africa

The choice of downscaling method used for West Africa will very much depend on the question that is being asked. Of course, each method also has its strengths and limitations.

Statistical downscaling is a popular method because of its relative simplicity and low computational demands. The two key criticisms of statistical downscaling are related to stationarity and local feedbacks. Most statistical downscaling methods are dependent on capturing a relationship between large scale climate and local scale climate using historical observations. There is therefore a stationarity assumption, in that scale relationship may not remain the same under a future climate. This is most likely in areas of strong climate gradients and is therefore relevant for the Sahel.

Statistical downscaling also does not explicitly capture local scale feedbacks through processes such as land use change and soil moisture feedbacks. This means that if there are positive or negative feedbacks at play in the local climate they will not be reflected in the statistically downscaled responses.

Both of these caveats are relevant in the West African context though, to what degree they influence the projected changes remains unknown. Critics would argue that regional climate models are not subject to such caveats and therefore provide more realistic projections. Comprehensive comparisons between statistically downscaled projections and dynamically downscaled projections will begin to emerge out of the ongoing CORDEX project as the CORDEX-SD component of the project ramps up.

The challenges with dynamical downscaling are twofold. First, most RCMs exhibit very strong systematic biases (bias in the means) relative to observations. This raises questions around their representation of precipitation processes that, like GCMs, are parameterized rather than explicitly simulated. Their only real advantage over GCMs is the relatively higher resolution (CORDEX simulations are at 50km or 25km for some models). It is unclear (though starting to emerge from CORDEX) what the impact of these systematic biases or errors are on the projected changes they simulate. Initial evidence to be presented at the CORDEX2013 conference suggests that the systematic bias does have a strong

[16] Of course the lack of observational data can be a limiting factor because without the data no statistical relationships can be derived. This data is also needed to validate downscaling output.

influence on the projected changes, and therefore needs to somehow be accounted for when using the output of RCMs.

The other significant challenge with RCMs is the computational expense and the technical knowledge required. This strongly limits the number of RCM based projections available. As a result, explorations of multi-model ranges of projections are limited three or four. Statistical downscaling, in contrast, allows for the much faster downscaling of multiple GCMs and therefore the exploration of a much wider and arguably more representative envelope of projections.

So, in short, statistical downscaling currently seems to offer more advantages for decision making. If anything, statistical downscaling methods tend to carry through the projected changes of the GCMs but with local scale detail. Many RCM projections produce projected changes of the opposite sign to the driving GCM, which still requires a lot of work to unpack and explain.

BOX 8. AN INTRODUCTION TO CORDEX

Coordinated Regional Downscaling Experiment (CORDEX) is a program initiated by the WCRP task force on Regional Climate Downscaling, with a main goal of developing regional climate change projections for the world's continents and their component regions at 50 km for input into impact and adaptation studies. Both dynamical and statistical methods are included in the CORDEX project, though only dynamical results are available at this time.[17]

The boundary forcing conditions for the CORDEX RCMs are based on the CMIP5 projections, both the historical simulations (1950 to 2005) and the future projections (2006 to 2100). The priority was placed on the RCP 4.5 and 8.5 projection runs, while RCP 2.6 was considered optional depending on the user group's computational facilities (storage and processing). Simulations forced at their boundary by ERA-Interim reanalysis are also performed to evaluate the ability of the RCMs to simulate the historical climate.

Africa was identified as one of the key domains for CORDEX activities, which is due to the region's perceived high vulnerability to climate change and the sparse availability of regional data on climate change (the preliminary results are provided later in the report). Currently only the CORDEX-Africa simulations forced by ERA-Interim and a multi-physics ensemble for Africa (2001-2006) have been completed. The full set of CORDEX-Africa historical and future projections is not yet available, although a few modeling groups have finished some or all of their simulations.

2.3.4 Dealing with Uncertainty

Perhaps the biggest challenge to the application and interpretation of climate projections, whether GCM output or downscaled, is the issue of uncertainty. It is imperative to understand that the fundamental physics and large-scale dynamics of the climate system are well understood and have been thoroughly investigated over the past century. The uncertainty primarily exists when translating that understanding into projections of climate at sub-global scales using computer models that are imperfect representations of the climate system. Model projections are inherently uncertain, both because of

[17] See the WCRP overview of CORDEX design at http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html.

chaotic variability in atmosphere-ocean processes, but also because a model cannot fully resolve the climate system. These issues are even more relevant at smaller regional and local scales where multiple factors modulate the global response of the climate system to increased greenhouse gas forcings.

Uncertainty in climate projections is perceived to arise due to three[18] main factors (Tebaldi and Knutti, 2007; Hawkins and Sutton, 2009):

- *Natural Variability*: Also known as "climate noise," this refers to the internal variability of the climate system that occurs irrespective of changes in external forcing (unforced variability). Natural variability is often linked to processes that are considered internal to the coupled ocean-atmosphere system. For example, processes such as ENSO or the Atlantic Multidecadal Oscillation (AMO) are dominant modes of internal variability that manifest in altered circulation patterns affecting weather and climate. See Box 9 on how this influences near-term model output.
- *Emission-Scenario Uncertainty:* Also known as forcing (see Box 7for details on emission scenarios) uncertainty, this factor relates to the lack of knowledge of how future society will alter atmospheric emissions of greenhouse gases, which can be considered as an external factor influencing the climate system (e.g., what will emissions of greenhouse gases be in a few decades time?).
- *Model-Response Uncertainty*: Arising from different models which produce diverse results despite being forced with the same external forcing. This can be broken down into imperfect understanding, where the physical processes are not well understood (e.g., cloud radiative effects and precipitation processes) and also model inadequacies which relate both to coarse resolutions and systematic errors that are introduced by using equations to represent a coupled nonlinear complex system.

Globally, uncertainty in near-term projections is largely insensitive to the greenhouse gas forcing, and is dominated instead by the internal variability of the climate system (natural variability), the initial state of the ocean, and inter-model responses (Hawkins and Sutton, 2009, 2011). The importance of natural variability in uncertainty increases as the region of interest is reduced to a smaller spatial scale (e.g., note the difference in orange shading between the two panels in Figure 7). On longer time scales, the uncertainty in greenhouse gas forcing becomes more important (e.g., note how the green shading expands as the lead time increases in Figure 7). Deser et al. (2012) argue that uncertainty due to natural variability is unlikely to be reduced even as climate models improve or as projections in greenhouse gases become more accurate. This is because of the "inherently unpredictable nature of unforced climate fluctuations." It does not apply to all regions equally, with some being more sensitive to natural variability than others.

Thus, it is important to recognize that climate model output contains systematic biases (see Box 10for more information on this) and inherent, irreducible uncertainties. Characterizing and quantifying this uncertainty in future projections still remains an arduous task. Yet it is a crucial step for adaptation and mitigation planning. One way to quantify uncertainty is by running multi-model ensembles (as used in producing Figure 8), which can be used to inform probabilistic climate projections. It needs to be remembered that the climate system is chaotic in nature; thus there may be a single history, but any one of multiple divergent futures is possible. Therefore it is useful to take an ensemble approach when studying future climate change. The ensemble approach is also used to pull together results from

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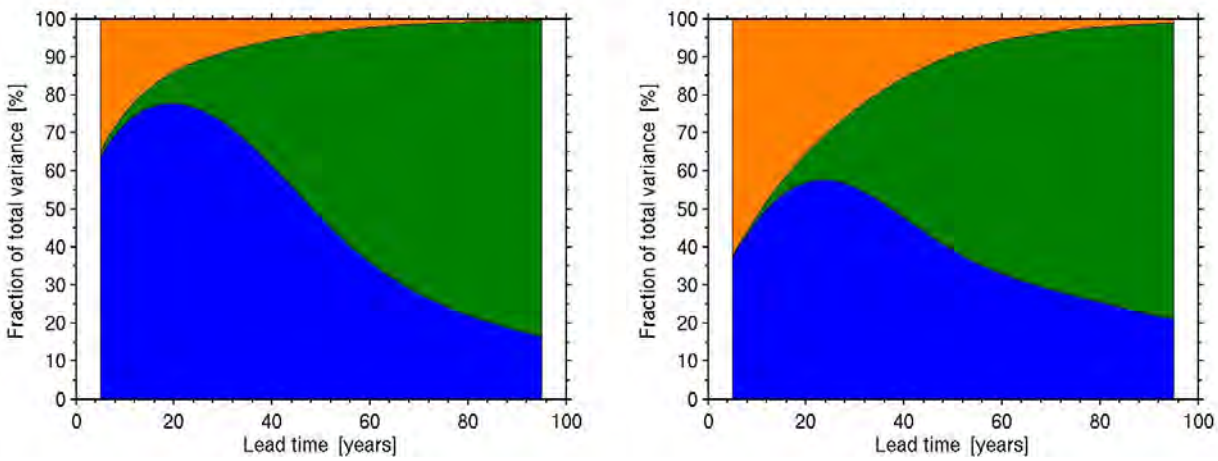
[18] Initial Conditions Uncertainty could be included, but it is more relevant for the shorter time scales like weather forecasting and even decadal forecasting.

multiple models.[19] Agreement among different models increases the confidence because it suggests that the results are not sensitive to the details of parameterization or model physics. Over short-term forecasts (e.g., daily, seasonal, etc.) it has also been shown that combining models generally increases the skill compared to single-model forecasts (e.g., Palmer et al., 2005). Probabilistic projections attempt to capture the uncertainty associated with the biases and model imperfections discussed above, but there are theoretical constraints limiting the ability to produce reliable probabilistic projections (Stainforth et al., 2007).

FIGURE 7. THE FRACTION OF TOTAL VARIANCE IN DECADAL MEAN SURFACE AIR TEMPERATURE PREDICTIONS EXPLAINED BY THE THREE COMPONENTS OF TOTAL UNCERTAINTY IS SHOWN FOR A GLOBAL MEAN (LEFT) AND THE SAHEL REGION MEAN (RIGHT).



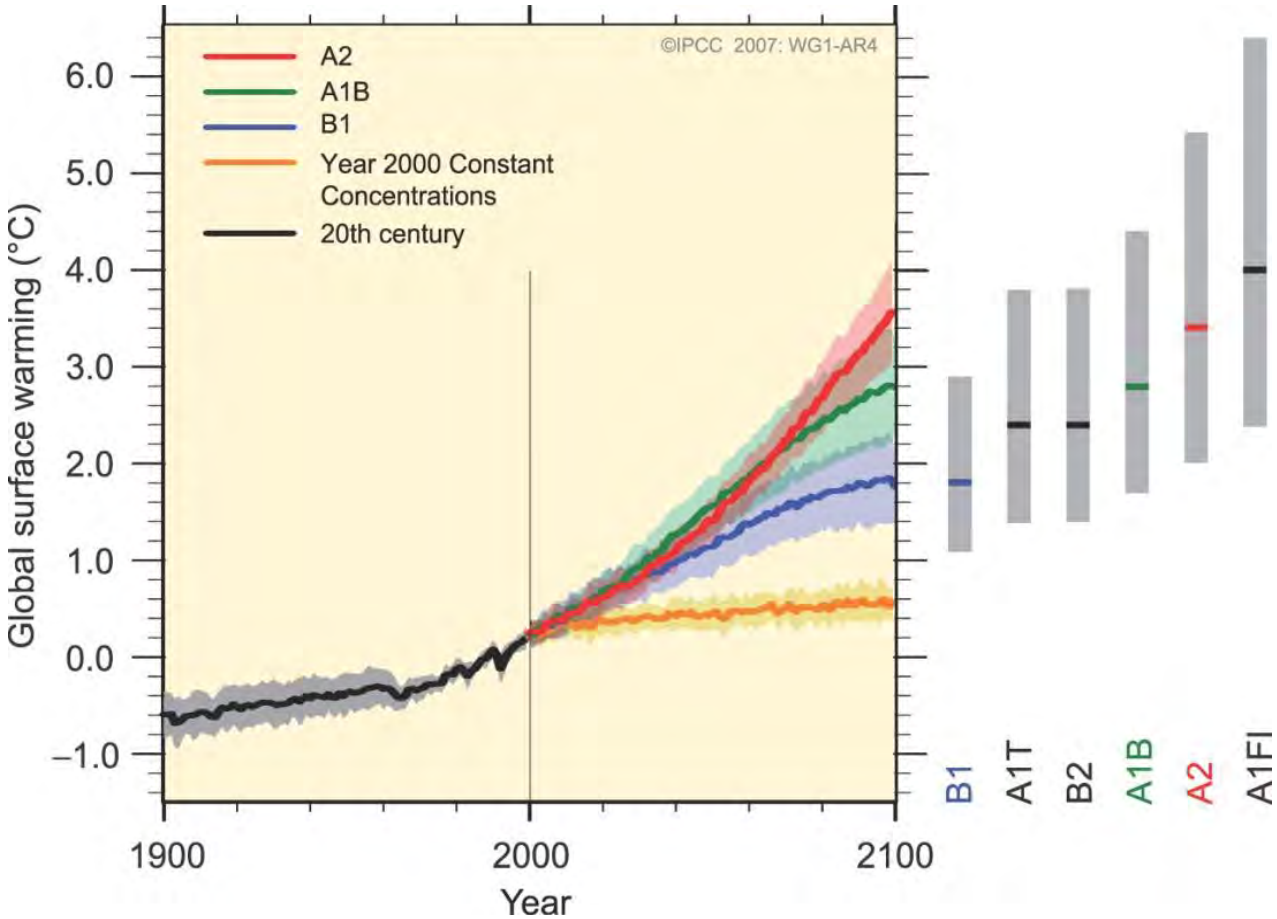
Source: Hawkins and Sutton, 2009. Green regions represent scenario uncertainty, blue regions represent model uncertainty, and orange regions represent the internal variability component. As the size of the region is reduced, the relative importance of internal variability increases.

A major discussion point is how to combine the different models from an ensemble, particularly when using Bayesian methods or weighted averages (Tebaldi and Knutti, 2007). Weighted averaging, where "better" models are given more weight, appears to be a logical choice. The difficulty is in quantifying the model reliability or skill in the absence of a verification period, and then in determining how best to apply the weights to the models. One method to weight a model is to determine how well the model replicates the recent past climate, climate variability, or well understood climate processes. While simulating past climate well does not necessarily mean a model is reliable for simulating the future climate, it does add a good degree of credibility to model results. There is real value to be gained in examining how models that can capture past variability in a particular region represent changes to the climate in that region under different future emissions scenarios. Such analyses are quite complex, however, and require good understanding of regional climate dynamics, access to good observation data,

[19] Multi-model ensembles are usually defined as a set of model simulations from structurally different models, while multi-member ensemble is many simulations from an individual model.

and understanding of climate modeling. Still, any such analysis can add important weight to the evidence base supporting particular future impacts scenarios.

FIGURE 8. AN EXAMPLE OF UNCERTAINTY FROM THE IPCC AR4 WORKING GROUP I REPORT



Source: IPCC AR4 Working Group I report. The figure shows the spread of surface warming projected for the future (up to 2100) from the different CO2 emission scenarios. Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B, and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios.

BOX 9. WHY DO MODELS STRUGGLE WITH NEAR-TERM CLIMATE?

A recent focus in climate modeling is exploring whether there is any skill in predicting the climate on a number of time scales using the same model, known as seamless forecasting[20] (Palmer et al., 2008). A lot of attention has been placed on near-term timescales,[21] through a process referred to as "decadal prediction" (Meehl et al., 2009). The demand for such near-term climate predictions is primarily due to the large social and economic implications associated with these time frames. Many decision makers require climate information on the near-term, but this is a time frame where the models lack skill and contain a lot of uncertainty (see black line in Figure9). What is the cause behind this? The two main underlying problems are natural variability in the climate system and uncertainty in the initial conditions used in the model.

The foundation of decadal prediction is based on a concept similar to that which meteorologists use to forecast the daily weather. In contrast to long term climate change projections, which are started from randomly selected preindustrial climate states, decadal prediction, like weather forecasts, are initiated with accurate present climate and ocean conditions. The understanding is that on decadal time scales, the initial conditions used, particular the ocean temperature structure, contributes significantly to prediction skill. The decadal prediction is produced using multiple simulations from either one model or a multi-model ensemble, often initiated using slightly different initial conditions, and is based on the statistics of the model output (Meehl et al., 2013). One advantage of decadal predictions compared to long-term climate projections is that the outcome can be tested though a process known as hind-casting. This typically entails running the decadal predictions models initialized at various points in the past using the available observational datasets. The model "predictions" or hind-casts can then be validated against the actual climate observed and evaluations of skill performed.

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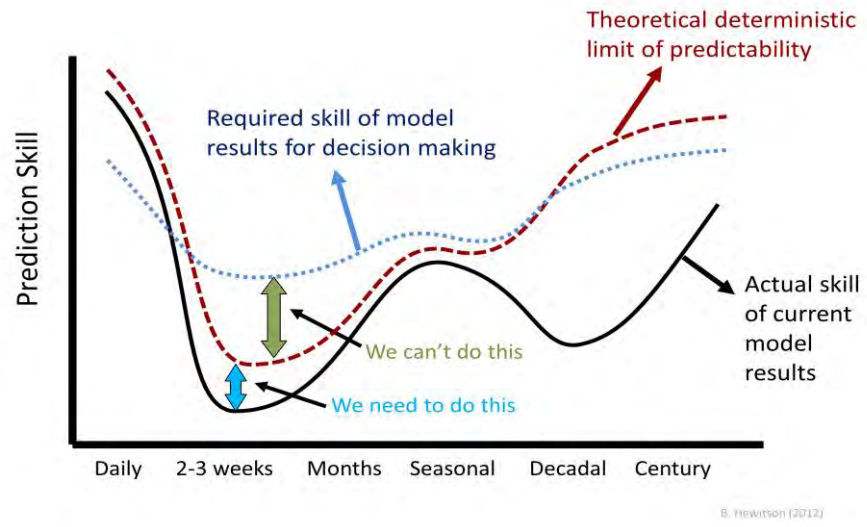
20 For this box the words 'forecast' and 'prediction' are used interchangeably.

21 Near-term here is defined as the next five to 10 years, while decadal prediction often covers the next 10-30 years.

FIGURE 9. SCHEMATIC OF HOW MODEL SKILL VARIES WITH TIME



Source: Hewitson, 2012. In this schematic, time is represented on the black line. The theoretical limit (red line) is based on model improvements, better initial conditions and better understanding of the climate. The blue line represents the limit to which model skill needs to improve in order for the output to be of any value for decision makers.

A challenge in decadal prediction is the initialization of the simulations, where the accurate representation of the state of the oceans and atmosphere is crucial. Lorenz (1963) demonstrated that even with a hypothetically perfect numerical model, including the perfect representation of physical processes, unavoidable uncertainty in the initial conditions will grow and ruin the run. Such an issue occurs with weather forecasts, where the forecast remains fairly accurate the first few days but deteriorates considerably a week or so later (depending on the region; see black line in Figure 9). As discussed previously, a problematic issue with climate models is that they cannot perfectly simulate the observed climate. When initialized with observations, they tend to drift towards their own equilibrium of an imperfect climate (Meehl et al., 2009). The success in the first few years of a decadal prediction could be linked to the fact that the simulations are run from a snapshot of the current climate (i.e., the skill comes from the initial state). Thus, the near-term conditions are simulated rather well, but longer into the run the climate evolves and any deviation is amplified through the run. There are various methods to deal with the model drift, which include full field initialization and anomaly initialization (see Meehl et al. (2013) for a review).

Overall, Figure 9 shows that the both the skill and theoretical limit in predicting climate is not constant, but differs across various timescales. There are a number of clear patterns or cycles, most notably the daily and annual cycles, where the predictability is high. However, there are also periods where the predictability of the climate is much lower, such as a weather forecast two-three weeks ahead or near-term climate. The skill of the model is dependent not only on the timescale, but also on what climate variable or characteristic is being investigated (e.g., a seasonal forecast may be skillful for predicting a 'wetter than average summer,' but farmers may need to know how the rainfall will be distributed through the season, since this impacts the crop variety or management practice selected).

Uncertainty in downscaled climate projections is a complicated subject and is the focus of much ongoing work worldwide. Progress is being made on understanding the underlying sources of uncertainty, and how best to manage these. Most of the sources of uncertainty in downscaling have been mentioned already as they apply to GCMs. New sources of uncertainty in downscaling methods arise from imperfect downscaling tools and methods used, including inappropriate application of these tools. It should be noted that downscaling cannot reduce the uncertainty of the driving GCM and may actually introduce further uncertainty that limits our confidence in the magnitude of projected changes.

Some uncertainty issues can be addressed through improved downscaling methodologies. However, some proportion of uncertainty will always remain. It is therefore best to understand the possible range of projected change, using, where possible, estimates of probabilities. To do this, as many models as is practical are run under the various emission scenarios. The result is a range and a central estimate of the likely change. This allows the user to have a more defensible projection of the direction of change, even though the absolute magnitude of projected change will remain uncertain. Despite recent advances in downscaling methods, it needs to be recognized that the characterization of the uncertainty in such products is currently limited by the availability of downscaled data.

BOX 10. SHOULD BIAS CORRECTION BE APPLIED?

The climate system simulated by both GCMs and RCMs are often characterized by biases, which are generally defined as systematic differences between the model output and that of observations. These biases then propagate to impact models, and thus affect the quality of climate change assessments. The source of bias in the models can be linked to a few factors, some of already discussed, including imperfect representation of atmospheric physics, errors in process parameterizations, lack of energy balance closure, and inadequate representation of local feedbacks at the land-atmosphere interface (Maraun, 2012; WCRP, 2009).

A current topic in the climate science community is whether bias correction (the correction of model output towards observations in a post-processing stage) should be applied to the model output. Due to the demand for data required to drive climate change impact studies, a few bias correction methods taking the form of post-processing of the GCM output have been developed. However, the validity of such an approach is increasingly criticized in the community of climate and impact researchers and practitioners (e.g., Ehret et al., 2012). This criticism is based on the grounds that bias correction is essentially a necessity-driven empirical manipulation of data with little or no physical justification. It should be remembered that climate models are based on a set of mathematical equations that describe the physics of the climate system. These equations do the "bookkeeping" and ensure that nothing is gained or lost within the model physics. By applying a bias-correction it ends up creating model output that is not internally compatible with the mass and energy conservation laws. It can also introduce additional error, while at the same time artificially reducing output uncertainty or hiding uncertainty. This could negatively affect results of impact models, both numerically and in terms of end-user confidence.

So why do bias correction? Overall climate model biases can have a magnitude often comparable to, or even exceeding the magnitude of the climate change signal (e.g., Hagemann et al., 2012). Importantly, these GCM biases propagate down the model chain and are altered (either magnified or dampened) with each subsequent step. Due to non-linearities and thresholds involved in impact models (e.g., runoff generation in response to rainfall) this often prevents interpretation or a realistic application of raw climate model output in such models (Wilby, 2010; Rojas et al., 2011). Some form of bias correction is currently needed to deal with this problem. However, the process of improvement of GCMs (and RCMs) to be bias-free is not straightforward and requires more attention and a better understanding of the causes and effects. This topic will likely continue to receive considerable attention in the near future.

2.4 CHAPTER SUMMARY

In terms of understanding regional climate, both past and future, there are four principal sources of climate information that can be used, which include:

- *In-situ* observations, which provide perspective on trends and variability;
- Remote sensing products, which give more spatial and temporal detail;
- GCMs, which highlight large-scale changes that respond to climate forcing; and
- Downscaling methods, which produce finer detailed information on future climate.

Observations are the building blocks of our understanding of the climate system. Observations are also used to validate the output from climate models and used in empirical/statistical downscaling methods. A major limitation in improving the scientific understanding of the climate in Africa is the lack of available quality controlled observations. This lack of data is due to numerous issues, ranging from financial constraints to the theft/damage of *in-situ* instruments. Remote sensing products have somewhat filled the void by providing observations at a relatively high spatial and temporal resolution. However, such products also have their limitations, with the main one being that they still require considerable amount of validation, particularly rainfall derived products. Both *in-situ* observations and remote sensing products are used for data assimilation techniques to create historical 3D reanalysis data, which at the moment are extensively used in the research of regional climate dynamics (see next chapter).

The section has also described how numerical models are used to represent the physical processes of the atmosphere, oceans, cryosphere (snow and ice), and land surfaces. They are extensively used in the field of climate science, where they complement observations (e.g., reanalysis products), are used for experiments (e.g., what will happen to West African climate if deforestation continues to take place?), and help with the understanding of climate theory. They are valuable tools used to improve our understanding and predictability of the climate on seasonal, annual, decadal, and centennial time scales. Possibly the most well-known use of climate models is how they provide information on future climate projects based on anthropogenic climate change. They represent the most advanced tools currently available for simulating the response of the global climate system to increasing greenhouse gas concentrations.

Numerical models have their limitations, particularly when it comes to uncertainty in projections, limiting their use for decision makers. This uncertainty is based on numerous factors that range from imperfect models through to not knowing how society will change or react in the future to climate related challenges. The main source of uncertainty also varies on the time frame of the projection. An example provided here was based on near term climate projections. Given that climate is a chaotic system, it remains extremely difficult to project what will likely take place in the next five to 10 years. To reduce such uncertainty would require better global observations (i.e., initial conditions in the model) as well as a better understanding of natural climate variability. The former remains a challenging task and is unlikely to improve in the near future, while the latter may improve through continued research.

3.0 CLIMATE PROJECTIONS FOR WEST AFRICA

3.1 BACKGROUND TO THE PROJECTIONS

Several studies have investigated the regional expression of global climate change over West Africa. Nearly all these studies rely on Atmospheric-Ocean Global Climate Model (broadly referred to as GCMs in this report) simulations forced by a range of greenhouse gas emission scenarios (SRES and RCPs; see Box7). Most scientific literature is based on the output from models in CMIP3, with a few recent journal articles showing results from the latest CMIP5 archive. Given the coarse resolution of GCMs, higher-resolution data is produced via downscaling methods. In this case, the primary methods documented over West Africa are Regional Climate Models (RCMs) and multi-model GCM-RCM ensembles.The first part of this chapter provides a summary on the current understanding of rainfall over West Africa, as climate models are often evaluated (or provide confidence) by how well they simulate current climate (see Box11). A lot of the scientific terminology used later in the chapter is based on this section, in particular the section comparing how models simulate current climate. This is rounded off with a discussion of the results from the literature on future climate change in West Africa.

BOX 11. HOW ARE MODELS EVALUATED?

The usefulness of climate projections depends on the confidence of their simulations, and there are ways to evaluate the accuracy of future projections (Vizy et al., 2012). The first and most common method is to examine the skill of the model in simulating current climate. The evaluation should not just focus on comparing rainfall and temperature values against observations (see previous chapter); it should also include analysis of regional climate dynamics (e.g., circulation patterns) to see if the model is getting the right result for the right reason.

An analysis of how physical processes respond to global warming is another method of testing the confidence of model projections. The confidence in a model's simulation is improved if its response agrees with the current understanding of the region's climate dynamics. The model dynamics can be compared to known modes of variability on different scales. For example, if the model projects the greatest increase in temperatures in summer over the Sahara, and this results in a deepening of the monsoon low and enhanced moisture convergence, and therefore results in increasing rainfall over the Sahel, this agrees with our current understanding of how the regional climate operates and provides increased confidence in the projections.

The confidence in future projections is to some extent dependent on the future period selected. As mentioned before, the climate is a chaotic system and the climate change signal can be lost in the interannual or decadal variability (noise). Most users are interested in the change by the mid-21st century, however the climate change signal may not yet be discernable from natural variability or at least not statistically significant. One way to improve the confidence is to compare the near-term change to that of the far future; if they agree in the sign of change, then we can have more confidence in the near-term projections. It must be noted that this assumes that there are no non-linearities in the system; and this may not be valid for West Africa, which shows very strong inter-decadal variability.

3.2. HISTORICAL WEST AFRICAN RAINFALL

3.2.1 Dynamics of West African Rainfall

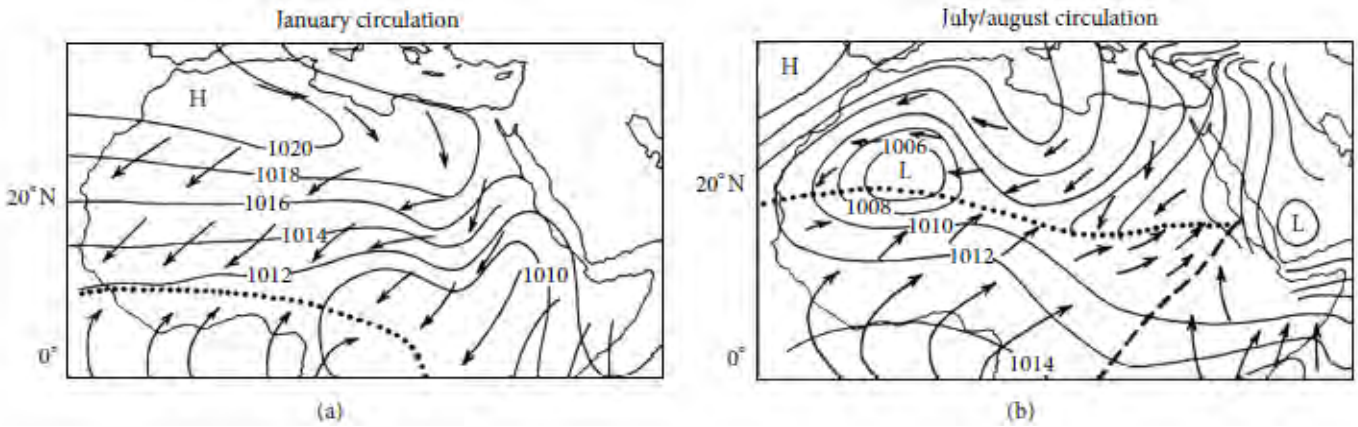
Rainfall in the tropics is largely produced through a process known as deep convection, which develops due to instability within the atmosphere. The process starts with the heating of the surface (either land or ocean) due to solar radiation. This warms the surface air and it begins to rise. However, the warming is not large enough to lift it through the full depth of the atmosphere. Moisture or water vapor is required so that when the parcel of air rises, condensation takes place, releasing latent heat, and thus making the air parcel able to continue ascending. This uplift can also be generated through small scale turbulence or large-scale weather patterns. With enough moisture, large deep convective clouds develop and the significant amounts of moisture are precipitated out (see Box 12). The two key components here are the initial warming and moisture content in the lower atmosphere.

BOX 12. MESOSCALE CONVECTIVE SYSTEMS

In terms of rainfall producing systems, most of the rainfall in West Africa is largely associated with organized, large-scale thunderstorms known as Mesoscale Convective Systems (MCSs). An MCS is distinct from other convective systems based on its spatial and temporal characteristics. A very broad definition is that they are a long-lived (≥3 hours) cumulonimbus cloud system that contains a nearby precipitation area of roughly 100 km or more in at least one direction (Houze 2004). Lebel et al. (2003) estimated that about 12 percent of the total number of MCSs produced 90 percent of the rainfall during the peak rainy season in the Sahel region. Similarly, Nesbitt and Zipser (2003) suggest that very intense MCSs, which may only consist of around 3 to 4 percent of all rain events, produce up to 80 percent of Sahelian rainfall. This suggests that the number of intense systems per season may play a crucial role in seasonal rainfall totals in the Sahel.

The dominant regional process behind the rainfall regime in West Africa is the West African Monsoon, which is driven by the seasonal cycle of radiative heating of the Earth's surface. The classical picture of the monsoon involves southwesterly monsoon flow from the Atlantic converging with the dry, northeasterly Harmattan winds that originate in the Sahara (Figure 10). The northeasterly winds are associated with the Saharan Heat Low. This convergence zone is known at the Intertropical Convergence Zone (ITCZ) and until recently was thought to be the zone where most of the rainfall occurred through local thermal instability in warm and humid air (facilitated by the convergence). It is a simple concept that is used to explain the latitudinal gradient of rainfall over West Africa (see Box 13).

FIGURE 10. SCHEMATIC OF SURFACE WIND (ARROWS) AND PRESSURE (MB) OVER WEST AFRICA DURING WINTER (LEFT) AND AT THE PEAK OF THE SUMMER MONSOON (RIGHT)



Source: Nicholson, 2013. The dotted line denotes the position of the ITCZ.

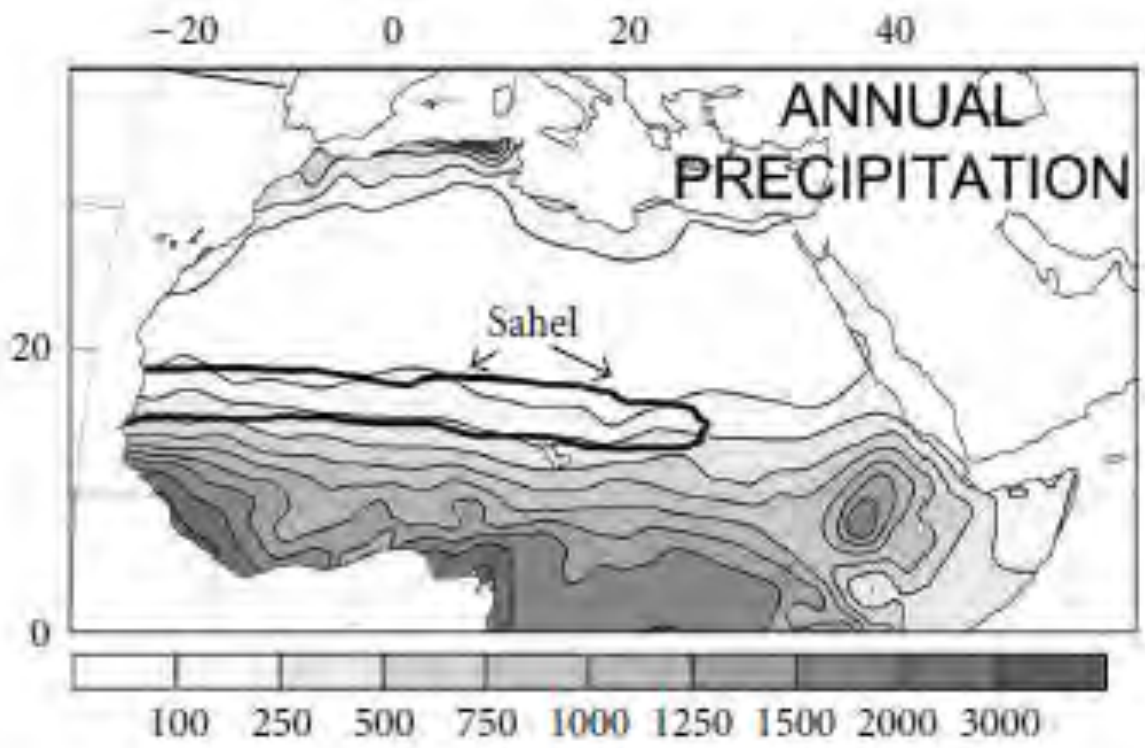
The monsoon can be described in four key phases (after Thorncroft et al., 2011). The first is the *oceanic phase* (November to mid-April), with the main rain belt positioned over the equator (i.e., over the warm ocean) and little rain falling over the West African continent. By mid-April to May, the *coastal phases* begins, with the warm waters in the equatorial region beginning to cool through surface wind stresses and the peak in rainfall moving to the coastal region (~ 4°N). This is the wettest phase in the cycle, with rainfall totals in excess of 1500 mm a season (Figure 11). The first half of July is dominated by the *transitional phase*, which coincides with rainfall decreasing in the coastal region and the onset of rain in the Sahel region. By mid-July the rainfall intensifies and becomes established in the Sahelian region (*Sahelian Phase*). The rainfall in the Sahel generally starts abruptly, with this process being termed the "monsoon jump" (Janicot and Sultan, 2001). Overall, there is a very strong meridional (i.e., north-south) rainfall gradient in the Sahel, with mean annual rainfall varying from 100 to 200 mm in the north to about 500 to 600 mm in the south (Figure 11). Most of this rainfall takes place during the boreal summer[22] and early autumn months (mid-July to September), with a maximum occurring during August (Figure 12). By the end of August the rains begin to weaken and the peak rainfall starts to return to the coast relatively smoothly when compared to the jump experienced at the beginning of the season.

[22] In the report the term "boreal summer" refers to the months of June, July, and August.

BOX 13. IS THE ITCZ THE MAIN RAINFALL MECHANISM?

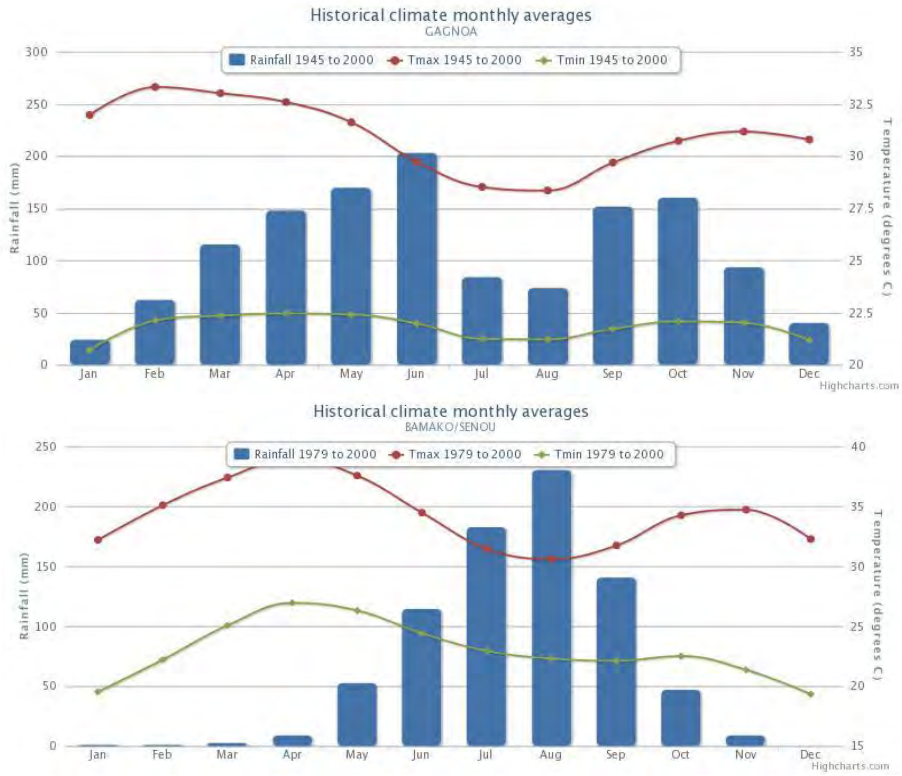
The ITCZ has often been used by the seasonal forecasting community to predict West African rainfall (e.g., Famine Early Warning System [FEWS] ITCZ monitoring [National Weather Service, 2013]). In recent years, questions have been raised about the validity of the conceptual view that rainfall in West Africa is predominantly linked to the ITCZ. Although convergence and uplift takes place along this zone, the maximum rainfall is usually found further equator-ward (up to 1000 km away), in a region where there is enough moisture to support strong convection. Thus, some researchers, (e.g., Nicholson, 2009), argue that this concept of the ITCZ as the main controller of West African rainfall is outdated and may be over-simplified. The recent literature describing West African rainfall highlights the diminished importance of surface features, such as the ITCZ, and the prominence of features in mid- to upper level circulation, the heat low, and large-scale, organized convective systems. For brevity, a detailed discussion is not included here; the reader is directed to Nicholson (2009, 2013) for a review of the ITCZ and West African rainfall.

FIGURE 11. MEAN ANNUAL PRECIPITATION OVER WEST AFRICA (IN MM).



Source: Nicholson, 2013. Location of the Sahel is indicated.

FIGURE 12.FIGURES SHOWINGTHE MEAN MONTHLY RAINFALL (BLUE BARS), MEAN MONTHLY MINIMUM AND MAXIMUM TEMPERATURE (GREEN AND RED LINE, RESPECTIVELY) FROM THE STATION IN GAGNOA IN THE IVORY COAST (TOP) AND BAMAKO IN MALI (BOTTOM)



Source: Created using the Climate Information Platform (CIP) developed by CSAG

3.2.2 Trends and Variability

West Africa rainfall is characterized by a high degree of variability on a range of time scales, from interannual to multi-decadal time scales (i.e., from year to year and from decade to decade). Arguably it is the persistent anomalous conditions (e.g., anomalous wet periods [1930s, 1950s, and 1960s] and dry periods [1970s and 1980s]) in the Sahel that have received the most attention in West Africa climate studies. The most recent dry period, which started abruptly in the late 1960s and persisted into the 1990s, was one of the worst observed. Rainfall remained below the long-term mean in every year during this period, while the 1980s was considered the most intense dry period, with rainfall falling to below 60 percent of the long term mean (Nicholson, 2005).

There is some debate in the scientific community over whether the rains in the Sahel have recovered after this intense drought. The dry conditions are thought to have continued during the 1990s, with one or two years during that period having received above average rainfall (Nicholson et al., 2002; L'Hôte et al., 2002). Some studies have shown that rainfall conditions have been generally improving since the late 1990s and in recent years (Nicholson, 2005; Lebel and Ali, 2009), which have agreed with observed vegetation greening in the region (Olsson et al., 2005). However, these results vary spatially, with some results showing that the recovery was confined to the eastern region, while in the western region the drought still persists (Lebel and Ali, 2009). Additionally, the peak in August rainfall has not recovered to the levels that preceded the drought (Nicholson, 2005; Lebel and Ali, 2009). Thus, the view on whether the drought ended in the 1990's depends on the region, the year, and the months that are being

assessed. It should be noted that conditions post-1990 have been difficult to evaluate, in part due to the difficulty in obtaining rain-gauge data[23] and having to rely on satellite data (Nicholson, 2013).

The decadal to multi-decadal variability was originally perceived to be due to local land-surface forcing in perpetuating the rainfall anomalies (Charney, 1975). It was proposed that the severe drought of the 1970s and 1980s in the Sahel was caused by overgrazing, resulting in increases in the surface albedo (i.e., reflectivity) of the region. Increases in the albedo results in less absorbed solar radiation at the surface. Later on, other mechanisms such as soil moisture and evapo-transipiration were also included. This all fell under the concept of "desertification," which can be roughly defined as humans transforming the land to such an extent that there is an irreversible decline in productivity. However, more recent analysis has suggested that the process of desertification in the Sahel has been dramatically exaggerated and it was generally reversible (e.g., Prince et al., 1998).

As for interannual variability (i.e., changes in rainfall from one year to the next), early studies often attributed it, particularly in the Sahel, to changes in the latitudinal position of the ITCZ (Bryson, 1973; Kraus, 1977). However, this relationship is not as robust as first thought, with later studies identifying only weak links between the ITCZ position and Sahel rainfall (e.g., Nicholson, 1980). These studies however did identify some relationship between the intensity of the ITCZ and rainfall of the region. Thus, the results indicated that other climate drivers likely play a stronger role in rainfall variability in the region. From more recent studies and advances in data products, it has now been established that interannual and decadal rainfall variability in the region is in fact strongly coupled to mid- to upper-level circulation features (see Box 14). In addition, sea surface conditions in the surrounding Atlantic Ocean, as well as the more remote Indian and Pacific Ocean, are thought to have a considerable impact on climate variability in West Africa (see Box 14).

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[23] The reason/s behind this are not given, but as alluded to in section 2, station data can be particularly difficult to retrieve due to numerous factors. These range from local agencies withholding the data for financial reasons (i.e., why hand it out for free when it can be paid for) to poor maintenance/data recording due to lack of funding.

BOX 14. REGIONAL DRIVERS OF WEST AFRICAN RAINFALL

West African rainfall is closely associated with the strength and location of a few prominent zonal (east-west) jet streams (regions of strong winds) that are positioned at various levels in the troposphere. There are two pronounced easterly jet streams over West Africa, the mid-level Africa Easterly Jet (AEJ; also known as the West African Jet) and the upper-level Tropical Easterly Jet (TEJ). The AEJ has possibly received more attention due to its association with the development of phenomenon known as African Easterly Waves, which are often linked to rainfall in the region. It is also plays a role in transporting moisture from Central Africa to the west.

At the lower levels of the atmosphere there are two important westerly jets that play a role in West African rainfall patterns. The first of the low level jets is the African Westerly Jet (AWJ), which was first described by Grist and Nicholson (2001). The AWJ does not feature every year in West African climate dynamics, but rather appears in wet years only during the late summer months (July–September). The second is the West African Westerly Jet (Pu and Cook, 2010). It is typically found over the eastern Atlantic Ocean and West Africa (around 10°N) during the months of May through to September. Due to the relatively recent discovery of this jet, there is limited detail about the role it plays in West Africa climate dynamics.

Sea-surface temperatures (SST) anomalies around the world are perceived to play a key role in regulating interannual and decadal rainfall variability (or high and low frequency variability) in West Africa through changes in the monsoon (Folland et al., 1986; Janicot et al., 2001; Giannini et al., 2003; Mohino et al., 2011). Overall, the oceans play a key role in moisture supply and in the generation of atmospheric circulation patterns. It was originally thought that monsoon variability, hence rainfall variability, was associated with SST anomalies in the South Atlantic and Gulf of Guinea (Lamb, 1978; Hastenrath, 1984) or inter-hemispheric SST gradients, particularly between the North and South Atlantic (Folland et al., 1986). Through observations and model-based studies, recent research has shown that it may be near global-scale SST anomalies that have played a prominent role in the drying of the Sahel during the second half of the 20th century. In particular, warming in the equatorial Indian Ocean (Bader and Latif, 2003) and tropical Pacific Ocean (Lu and Delworth, 2005) are perceived to have played a dominant role.

Although the climate of West Africa may be predominantly driven by large-scale circulation patterns, it is very sensitive to regional scale feedback processes linked to properties such as soil moisture and vegetation cover. However, it has been established that land-surface forcing likely plays a secondary role in driving the climate (Zeng et al., 1999). Essentially, land surface feedbacks amplify the climate conditions brought about through changes in ocean SST anomalies.

3.3 THE SIMULATION OF CURRENT CLIMATE

Climate models show significant systematic errors in simulating the West African climate, especially in CMIP3. The Intertropical Convergence Zone (ITCZ) over the Atlantic is displaced equator-wards in almost all simulations, and renderings of the ocean temperatures in the Gulf of Guinea are often too warm and lack the region of cold upwelling in the western Gulf of Guinea during boreal summer (Richter and Xie, 2008; Roehrig et al., 2013). This results in a southward displacement of the monsoon and a biased simulation of spatial rainfall patterns. Models also show a wide variety of behaviors in reproducing the amplitude and pattern of the African Easterly Wave, which as alluded to previously, is strongly linked to regional rainfall. Another poorly simulated feature is the Saharan heat low, which is a key driver of the monsoon at the seasonal and intra-seasonal time scale (Roehrig et al., 2013).

Monerie et al. (2012) explore the improvements of present climate over the African monsoon region simulated by the CMIP3 and CMIP5 models. They show that both CMIP3 and CMIP5 models provide realistic representations of the spatial pattern of surface temperature during the summer season, with highest temperatures found over the Sahara and decreasing temperatures towards the Gulf of Guinea. However, they still contain a warm bias over the West African region and over the ocean. Although SSTs in the Atlantic Ocean in CMIP5 are more realistic, in terms of spatial representation, than that found in CMIP3, they still contain a warm bias compared to observations. This could potentially increase the meridional temperature gradient driving the monsoon circulation.

In terms of rainfall, CMIP3 and CMIP5 models both produce similar spatial patterns to that of the observational dataset (GPCP) on the seasonal timeframe. A slight difference is that the rain belt is found to penetrate further north over the continent, especially over the central Sahel. The CMIP3 models simulate weaker precipitation over the regions that typically experience maximum precipitation (the Coast of Guinea and Cameroon Mountains), while overestimating precipitation amounts along the Gulf of Guinea and over the northern Sahel. This is consistent with a stronger meridional temperature gradient. Although CMIP5 models produce higher rainfall totals, they are found to produce more realistic values that CMIP3, particularly over the regions of maximum precipitation (Monerie et al., 2012). The CMIP5 models are able to simulate some inter-annual and decadal variability, but it is of smaller magnitude than that found in observations (Biasutti, 2013).

Given the limitations of GCMs, several international projects have produced higher resolution downscaled data (from single RCMs through to multi-model ensembles). These include the African Monsoon Multidisciplinary Analysis Model Inter-comparison Project (AMMA-MIP; see Box 15), the West African Monsoon Modelling and Evaluation (WAMME) initiative, the Ensembles-based Perditions of Climate Change and Their Impacts (ENSEMBLES) and most recently the Coordinated Regional Downscaling Experiment in Africa (CORDEX-Africa) project (see Box 16for a full discussion on CORDEX-Africa). Some of the key messages coming out of these studies are that many RCMs can now improve the simulation of rainfall compared to that from their boundary condition dataset (either a reanalysis dataset or GCM model) since their higher spatial resolution allows smaller scale processes to be explicitly resolved (Sylla et al., 2010; Nikulin et al., 2012).

RCMs driven by the same GCM often show very different results, both between RCMs and between the RCM and GCM. This implies that systematic errors in the RCM appear to be driven only to a small extent by errors in the driving GCM, which means that these errors are primarily due to the representation of local/regional processes within each RCM (Sylla et al., 2010). Druyan et al. (2008) noted that an increased resolution does not necessarily increase the quality of simulations since some of the physical processes occur at an even finer resolution than that provided by the RCMs. For example, rainfall over West Africa is primarily from large-scale convective systems called Mesoscale Convective Systems (see Box 12). Models are not yet able to accurately simulate the dynamics of these systems and therefore they rely on convection approximations or parameterizations to capture the precipitation response. The choice of convection approximation used in the model (i.e., the parameterization) clearly influences their behavior and strong biases relative to observations were found in the surface fluxes and other physical parameterizations for many models (Paethe et al., 2011; Ruti et al., 2011). This may be one of the reasons why models have difficulty simulating the climate, especially the rainfall, over the West African region, even in RCMs.

BOX 15. AFRICAN MONSOON MULTIDISCIPLINARY ANALYSIS

The African Monsoon Multidisciplinary Analysis (AMMA), launched in 2002, is an international and interdisciplinary project developed to better the knowledge and understanding of the West African Monsoon and its variability (Redelsperger et al., 2006). The first phase of AMMA (2002-2010) was broken into three observation periods: Long-term Observing Period (2001-2010), the Enhanced Observing Period (2005-2007) and the special Observing Period (2005). The second phase (2010-2020) is currently underway.

Apart from improving the understanding of regional climate, AMMA also focuses on developing and upgrading some of the local land based observation systems. Although the aims of the project have been primarily scientific based, there is considerable effort placed on educating and empowering local African agencies in various aspects of climate science. The observation component of AMMA is also complimented by various modeling aspects, with the three main inter-comparison exercises being (Ruti et al., 2011):

- AMMA Land Surface Model Inter-comparison (ALMIP)
- AMMA Model Inter-comparison Project (AMMA-MIP)
- Chemistry Model Inter-comparison Project (CHEMIP)

The main aims of these joint modeling projects is to validate and test the models on how well they represent West African processes, as well as to identify where the modeling can be improved. The observation networks developed or maintained for these projects—and the modeling exercises themselves—may be extremely regionally focused, but they still play a large role in the scientific community's understanding of the climate on a global scale.

Apart from seasonal rainfall totals and spatial distribution, other rainfall characteristics, such as onset, rainfall intensity, dry spells, rain days, etc., are also vital indicators on how well models simulate current climate. These rainfall characteristics are often what concerns local farmers the most because they can have a considerable impact on the crops. However, there is very little literature on this subject. The ability of four CMIP5 GCMs and a single RCM to simulate daily intense rainfall events over Africa is explored by Crétat et al. (2013). In their study, daily intense rainfall is defined as those values that exceed the 95th percentile threshold (i.e., extremes) and model output is validated against two satellite-derived rainfall datasets. The CMIP5 models were found to generally show similar skill to that in the earlier CMIP3 models, with most drastically overestimating the frequency of intense daily rainfall events, especially in the tropics. The models were not able to simulate the correct intensity and generally overestimated the spatial coverage of these intense rainfall events. In contrast, the single RCM was seen to accurately capture the spatial and temporal characteristics of intense daily rainfall events. However, it was found to overestimate the frequency and underestimate the intensity of such events.

In other results, RCMs are found to show distinct systematic errors in simulating West African rainfall, where they generally produce too frequent low rainfall events, which result in dry spell durations (the number of days with no rain between rain events) that are too short (Ibrahim et al., 2012). It should be noted that RCMs do not only differ from the observations, in terms of rainfall amplitude and spatial pattern, but also vary considerably with one another (Paeth et al., 2011).

Ultimately, the realistic simulation of West African rainfall patterns, both spatially and temporally, remains very challenging. As discussed earlier in this chapter, oceanic process, circulation patterns and land surface feedbacks all play an integral role in the West African climate. Thus, any small error in the models' representation of these rainfall drivers can result in unrealistic representation of rainfall variability and future change. It is important, however, to note that climate change projections are

exploring the response of a climate model to changes in greenhouse gas concentrations. A model's response to the changing concentrations in the future may be "correct" even if its simulation of observed climate produces biases. For example, if a model places the monsoon rainfall distribution too far south, this does not negate the message produced when the same model shifts the rainfall pattern northwards in a future climate projection. For this very reason, filtering or weighing models based on performance in simulating current climate is a highly debated issue within the climate modeling community. Current developments in evaluation and filtering of models are based more on how well models capture processes that drive variability, such as ENSO, rather than how well they represent the mean observed climate patterns.

BOX 16. CORDEX-AFRICA RESULTS

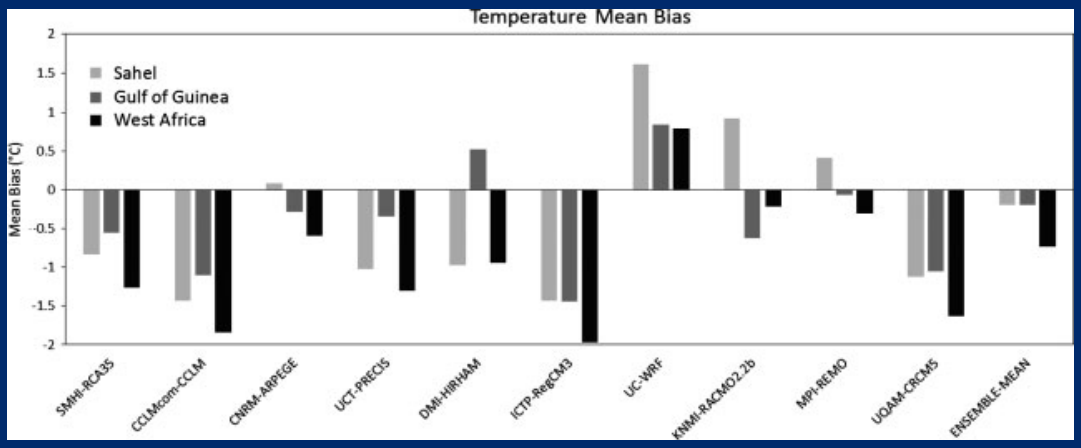
CORDEX-Africa project represents the most recent and largest multi-RCM ensemble project for Africa, and therefore it is important to discuss its results in greater depth here. Ten RCMs, each using the same domain and 50 km resolution, are forced at their boundaries by a reanalysis dataset, known as ECMWF-Interim Reanalysis, over a historical period. The results from the simulations are then compared to a selection of various observed datasets.

The RCM seasonal temperature simulations are in good agreement with observations and are able to depict the temperature gradient from the cold upwelling in the Gulf of Guinea and the warm temperatures in the Sahara (strong meridional temperature gradient). However, most models exhibit a cold bias over the region, with a few models showing a warm bias especially over the Sahel (Figure 13) (Gbobaniyi et al., 2013). All RCMs are found to simulate the spatial pattern of West African summer precipitation quite accurately. It is evident that rainfall biases vary significantly from model to model in terms of sign, magnitude, and spatial extent. Some models overestimate or underestimate the rainfall over the full region, while others exhibit strong but opposite biases within the region, often organized in a dipole-type pattern (Figure 14) (Nikulin et al., 2012; Gbobaniyi et al., 2013).

The CORDEX-Africa RCMs are also able to reproduce the pattern, timing, and amplitude of West African Monsoon rainfall with a varying degree of accuracy. Most captured the two rainfall maxima (over the Gulf of Guinea and over the Sahel), but struggled to capture the positioning, intensity, and duration of the monsoon rainfall. The majority of the models are able to simulate the northward jump in precipitation from the Gulf of Guinea to the Sahel at roughly the correct time of year, but few are able to accurately simulate the gradual retreat south in November (Nikulin et al., 2012; Gbobaniyi et al., 2013).

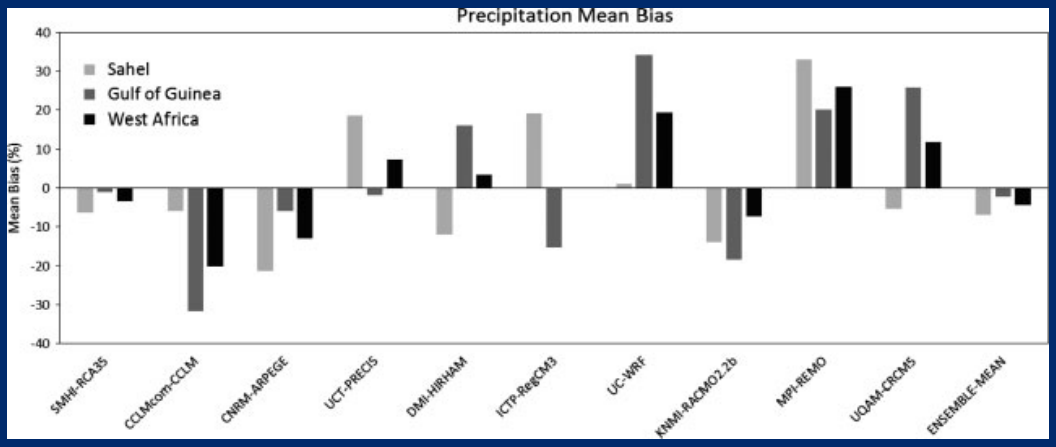
The annual cycle of precipitation over West Africa, and more specifically within the Sahel and Gulf of Guinea sub-regions, is captured by the RCMs, but a wide spread around the observed cycle is still found within both sub-regions, with some models significantly overestimating or underestimating the magnitude of rainfall (Figure 15). The model bias is far lower during the end of the rainy season within the Sahel sub-region. An early onset (i.e., start) of the rainy season is a common bias in the models which can to some extent explain the biases in the development stage of the season (Nikulin et al., 2012; Gbobaniyi et al., 2013).

FIGURE 13. MEAN BIAS IN MEAN TEMPERATURE CLIMATOLOGY FOR THE PERIOD JUNE-SEPTEMBER 1990-2008 FOR EACH OF THE RCMS AND TIER MULTI-MODEL ENSEMBLE WITH RESPECT TO UDEL OBSERVATIONS



Source: Gbobaniyi et al., 2013

FIGURE 14. MEAN BIAS IN MEAN RAINFALL CLIMATOLOGY FOR THE PERIOD JUNE-SEPTEMBER 1990-2008 FOR EACH FOR THE RCMS AND TIER MULTI-MODEL ENSEMBLE WITH RESPECT TO GPCP OBSERVATIONS

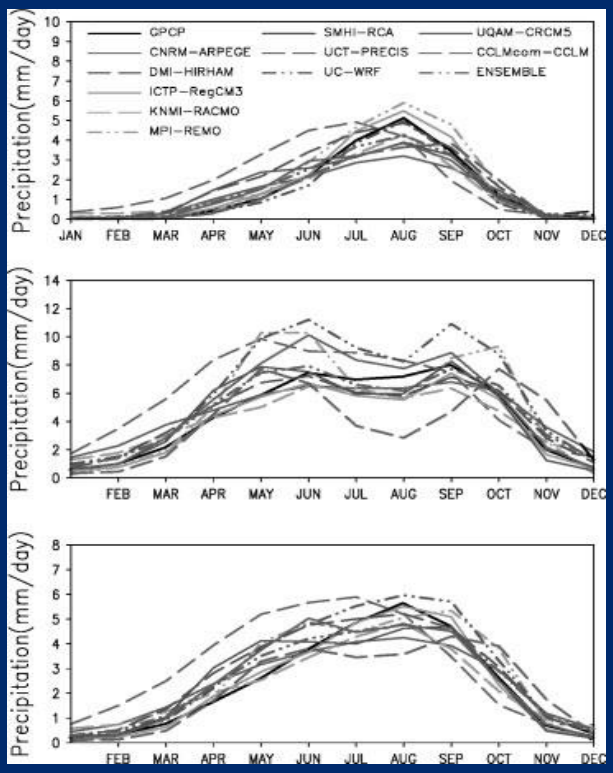


Source: Gbobaniyi et al., 2013

Precipitation over West Africa exhibits a very clear diurnal cycle. Unfortunately RCMs in CORDEX-Africa generally have a poor representation of this cycle; they suffer biases in the frequency of occurrence, intensity, and timing of rainfall during the day, and these biases are strongly linked to the way convective processes are parameterized in the models. The majority of RCMs precipitate too early with a maximum intensity around local noon instead of in the late afternoon/evening (Nikulin et al., 2012).

The CORDEX-Africa multi-model mean generally outperforms the individual models when looking at seasonal mean or annual cycle. This is because it smoothes the diverse biases found in the individual model simulations. The ensemble mean can only partly correct the amplitude of the diurnal cycle of precipitation, but it cannot improve the phase of maximum precipitation intensity (Nikulin et al., 2012).

FIGURE 15. ANNUAL CYCLE OF MONTHLY PRECIPITATION (MM DAY-1) AVERAGED OVER THE SAHEL (TOP), THE GULF OF GUINEA (MIDDLE), AND ALL WEST AFRICA (BOTTOM) FOR THE PERIOD 1990-2008 FOR GPCP OBSERVARTIONS, EACH OF THE RCMS AND THEIR MULTI-MODEL ENSEMBLE



Source: Gbobanayi et al., 2013

3.4 THE SIMULATION OF FUTURE CLIMATE

3.4.1 Rainfall

GCM simulations included in the IPCC Third Assessment Report (AR3) did not indicate any consensus regarding the sign and magnitude of Sahel rainfall change for the 21st century (Hulme et al., 2001). The next generation of models that were included in the IPCC AR4 were still unable to reach a consensus regarding how water availability in West Africa will change towards the end of the 21st century (Bernstein et al, 2007). The AR4 highlighted the lack of regional climate studies as being a key limitation that needed to be addressed. The last few years have seen a large increase in studies focusing on climate change in Africa, and in West Africa in particular. It is for this reason that the science community is in a much better position to model and understand both the current and the projected future climate of West Africa.

Druyan (2011) reviews a number of recent research studies which looked at how climate change may influence rainfall and hydrology over West Africa (between 10°-20°N). Seven of these studies focused on the mid-21st century while eight also looked at the end of the century. Some of the studies projected wetter conditions into the future, while others projected drier conditions (however, the latter were

mostly for the distant future); these results are included in Table 1. As indicated throughout the report, the correct simulation of the West African climate is challenging since multiple physical mechanisms compete to drive the change either upwards or downwards. The review stated that the models' climate change projections were tainted due to the variety of model deficiencies in simulating of one or more physical processes, and that no consensus could be established from these studies regarding the impact of climate change on precipitation over West Africa in the second half of the 21st century.

There may be large uncertainty in the projected change of seasonal mean rainfall totals but this is mainly due to large disagreements during the core of the rainy season. A more robust message is found in the beginning and end of the Sahel (10°-20°N) rainfall season. Strong agreement in a negative anomaly during the beginning of the season (May and June) and positive anomaly at the end of the season (October) is evident in the CMIP3 models by the end of the 21st century (Biasutti and Sobel, 2009). This implies that a potential shift in the rainfall season (i.e., later onset and cessation) could take place. More recent work by Biasutti (2013), comparing twenty CMIP5 GCMs, has similar results to the CMIP3 study, but also shows that the negative change in the early season is restricted to the western Sahel, while the positive change at the end of the season extends across most of the Sahel (Figure 16).

TABLE 1. SUMMARY OF CLIMATE CHANGE IMPACTS ON PROJECTED SAHEL RAINFALL FOR SELECTED STUDIES. IMPACTS ARE RELATIVE TO LATE 20TH-CENTURY SAHEL RAINFALL. SOME STUDIES PROVIDED RESULTS ONLY FOR THE FIRST OR SECOND HALF OF THE 21ST CENTURY, WHILE OTHERS PROVIDED RESULTS FOR BOTH. THE DASH SIGNIFIES THAT THE PERIOD WAS NOT COVERED IN THE PROJECT.

Study	First half of 21st century	Second half of 21st century
Hulme et al. (2001)	Small impacts	Ensemble drying; No consensus among GCMs
Maynard et al. (2002)	N/A	Enhanced rainfall
Held et al. (2005) (CM2)	Slightly rainier	Progressively drier
Haarsma et al. (2005)	N/A	Drier - North West and East Sahel; Rainier - Southern Sahel
Kamga et al. (2005)	Progressively rainier	Progressively rainier
Hoerling et al. (2006)	Progressively rainier	N/A
Cook and Vizy (2006)	No impact	Drier, only last 20 years
Biasutti et al. (2008)	Uncertain	Uncertain
Biasutti and Sobel (2009)	N/A	Delay in onset and therefore shortening of rainy season in Sahel
Patricola and Cook (2010)	N/A	Drier in June–July; Rainier in August

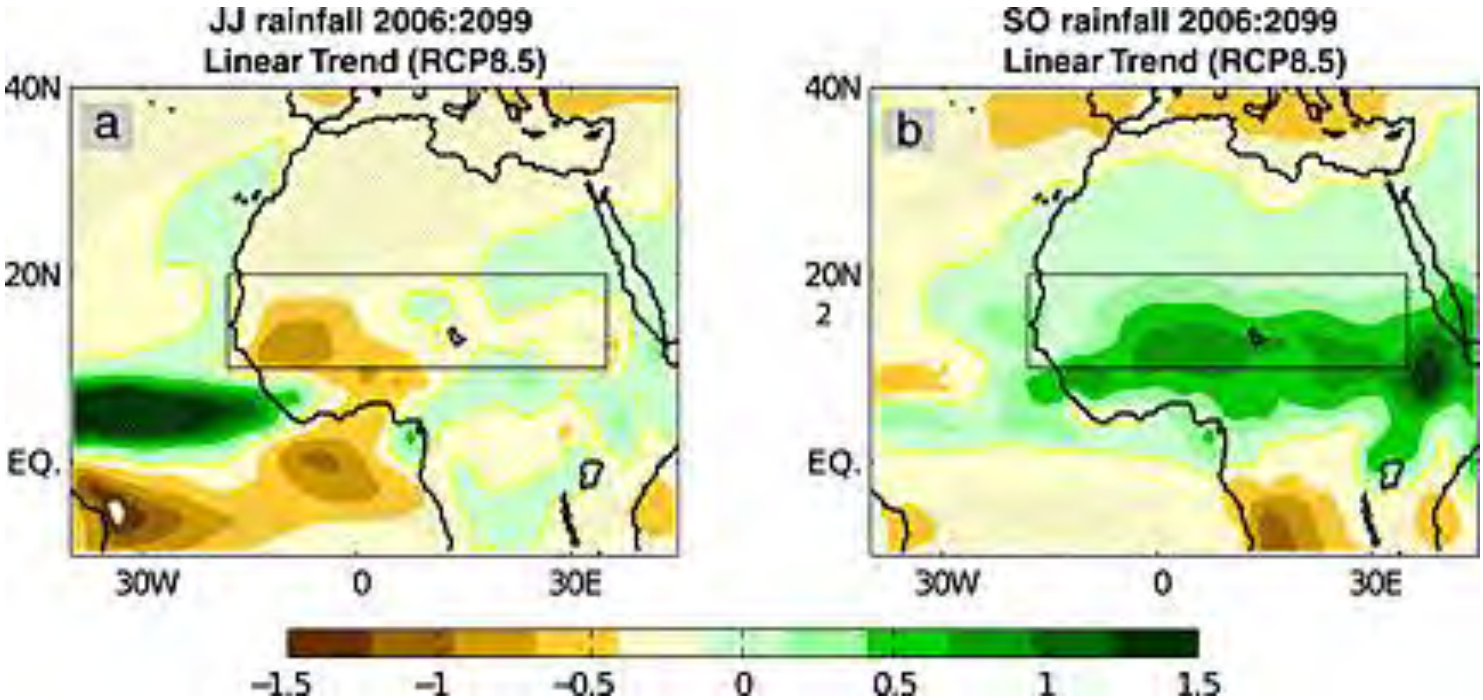
Study	First half of 21st century	Second half of 21st century
Paeth et al. (2011)	Uncertain	N/A
Monerie et al. (2012)	Rainier over eastern Sahel, drier over western Sahel.	N/A
Sylla et al. (2012)	Slight wetting (drying) over high-elevation (low-elevation)	Stronger wetting (drying) over high-elevation (low-elevation)
Vizy and Cook (2012)	Increase in extreme rainfall days, but extreme rainfall intensity is uncertain, decrease in dry days over eastern Sahel	N/A
Biasutti (2013)	N/A	Delay in onset (over western Sahel) and intensification of rainfall during the peak and decay periods over most of Sahel region.
Laprise et al. (2013)	Uncertain	Uncertain
Roehrig et al. (2013)	N/A	Rainier over eastern Sahel, drier over western Sahel.
Vizy et al. (2013)	Increase rainfall, especially intensity	Increase rainfall, especially intensity

Source: Based on Druyan, 2011

The future changes in the West African Monsoon (one of the main rainfall drivers) represented by both CMIP3 and CMIP5 GCMs have recently been explored by the scientific community (e.g., Monerie et al., 2012; Roehrig et al., 2013). Although there is a clear warming projected by the CMIP5 models into the future, especially over land (Figure 17), there is still a large inter-model spread in both the amplitude and spatial pattern of warming. However, this differential warming impacts the monsoon dynamics through the cold upwelling of Guinean cold tongue[24] no longer being evident, while the warmer Sahara strengthens the temperature gradient. It is these thermal changes that create the conditions for a reinforced monsoon in the future. Monsoon rainfall is projected to increase in the eastern half of the Sahel, but to decrease in Western Sahel (Figure 17). The agreement between models on the sign of change varies across the region, with some regions in West Africa showing strong agreement and other areas showing no agreement (Figure 17).

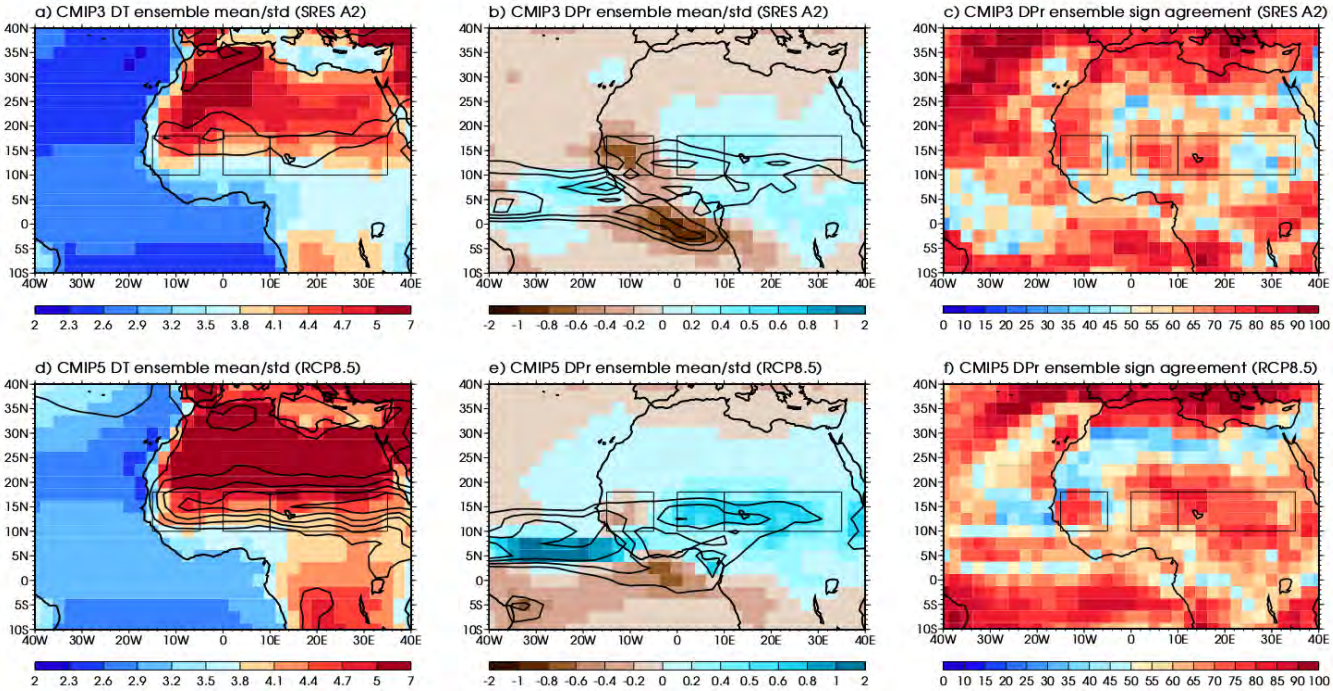
[24] Cold water that is brought to the surface through equatorial upwelling is referred to as the cold tongue.

FIGURE 16. RAINFALL PROJECTIONS FOR THE ONSET AND DEMISE SEASONS



Source: Biasutti, 2013. RCP 8.5 trends in Sahel rainfall in the multi-model mean for the onset season (June and July, left) and the demise season (September and October, right). Maps are in mm/day and are the difference between the end points of the linear trend over 2006:2099. The mean available ensemble runs is used for each model (using 20 models). Stippling indicates grid boxes where 15 or more of the models produce either a positive or negative trend.

FIGURE 17. CLIMATE PROJECTIONS OF 2-METER TEMPERATURE (COLORS IN °K) PLOTTED AS THE DIFFERENCE BETWEEN THE PERIODS 2071–2100 AND 1971–2000 FOR THE JAS SEASON, FOR THE CMIP3 SRES A2 ENSEMBLE MEAN



Source: Roehrig et al., 2013. The CMIP3 inter-model standard deviation is indicated in contours, with one contour every 0.2 °K, beginning at 1.0 °K. b) Same as a) but for precipitation (in mm/day). The standard deviation is indicated in contours, with one contour every 0.3 mm/day, beginning at 1.0 mm/day. c) Percentage of models of the CMIP3 ensemble that agree on the sign of the CMIP3 ensemble mean precipitation changes. d), e), and f) same as a), b), and c) respectively, but for the CMIP5 RCP8.5 model ensemble.

The use of GCMs does not appear to provide any obvious or consistent messages in West Africa rainfall. A number of studies have dynamically downscaled GCM future projections over the West African region. Future projections from the ENSEMBLES and AMMA projects are compared in the paper by Paeth et al. (2011). In their study, nine RCMs, each driven by one of two CMIP3 GCMs, are run over the period 1990-2050. No agreement between models is found in future precipitation change over West Africa and all models exhibited substantial spatial variations in magnitude and sign of change, though the multi-model mean change shows a slight negative anomaly by the mid-21st century. The study notes that no systematic relationship is found between the RCMs which share the same driving GCM. This may imply that the boundary conditions play a less dominant effect than the internal RCM dynamics.

The influence of fine-scale topography on projected rainfall over West Africa has also been explored using a single RCM (ICTP-RgCM3) driven by a single GCM (ECHAM5) (Sylla et al., 2012). Focusing on the end of 21st century, the GCM projects a wetter climate along the Gulf of Guinea and drier conditions in the Sahel. The RCM generally replicates this pattern, but extends the drying further south. The projections show clear differences between the low-elevation (negative change) and high-elevation (positive change) terrain of the Guinean Highlands and Cameroon Mountains. The positive changes are associated with an intensification of the hydrological cycle driven by an increased low-level moisture convergence resulting in increased uplift, instability, and moisture over the mountainous areas. This results in more frequent and intense daily rainfall.

3.4.2 Temperature

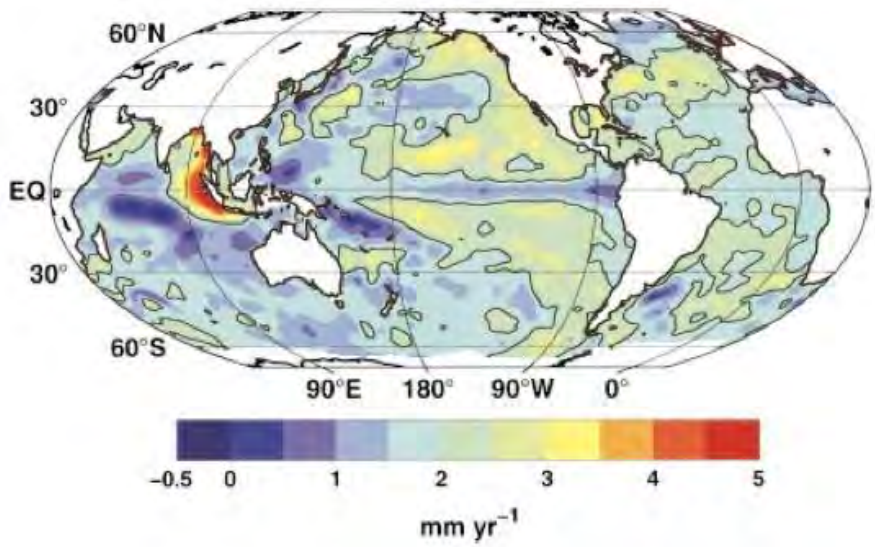
A consistent message of future warming over the West African region has been seem in both the CMIP3 and CMIP5 results (Monerie et al., 2012; Vizy et al., 2013). With the smallest warming found over the Guinean coast (~3.5 by late 21st century) and the magnitude of warming increasing rapidly into the interior, reaching ~5 degrees along the Sahel/Sahara boundary by the late 21st century under the RCP 8.5 scenario (Figure 17) (Roehrig et al., 2013). Large uncertainty still remains in the absolute magnitude and rate of change, and the spatial pattern across the region.

Temperature statistics such as annual extreme temperature range, daily temperature range, and heat wave days are all important statistics for a range of sectors including local agriculture, human health, and infrastructure. Vizy and Cook (2012) explored the projected change in these statistics by the mid-21st century using a single RCM, and therefore these results should not be taken as definitive. A summary of their key findings, however, is presented here: annual extreme temperature range is projected to decrease over the full West African region, primarily due to minimum temperatures warming more than maximum temperatures. The daily temperature range is projected to decrease over the Guinean coastal region during spring and autumn and over the Sahel during the full rainy season. The number of heat wave days is projected to increase over much of the Sahel, but not over the coastal region.

3.4.3 The Coastal Environment

The effects of climate change are not limited to climate variables, such as changes in rainfall and temperature, but also extend to changes in the ocean. Two of the more pressing issues for the coastal regions of West Africa are sea-level rise and coastal storm surges. Sea-level rise (SLR) is attributable to two major sources: the thermal expansion of the oceans and the loss of ice from the land into the oceans. Historically, tide gauge data shows a globally averaged SLR of between 150 mm and 250 mm since 1870, with a recent acceleration observed between 1993 and 2003 (Church and White, 2006; Pachauri and Reisinger, 2007). It is unclear if this acceleration is due to natural decadal variability, but the general linear rise is unmistakable. This rise is variously attributable to the thermal expansion of the oceans (57 percent), decreases in glaciers and ice-caps (28 percent) and losses from polar ice sheets (15 percent) (IPCC, 2007). Globally, SLR is not evenly distributed. Observed trends in the southeast Atlantic between 1950 and 2000 suggest that West Africa has experienced a regional increase of 1.5 - 2 mm per year (Church et al., 2004), increasing to around 3 mm per year between 1992-2009 (Grinsted et al., 2009) (Figure 18). Typically, SLR is projected as a global average, and most risk assessments for West Africa use this as a starting value. Based on the magnitude of observed SLR in West Africa, which appears near the global average, this assumption seems reasonable, but suggests that a more regional investigation is required.

FIGURE 18. REGIONAL DISTRIBUTION OF SEA-LEVEL RISE BETWEEN JAN 1950 AND DEC 2000



Source: Church et al., 2004. Reconstructed sea level fields using tide gauge data. The solid line is 2.0 mm yr-1and the contour interval.

So what is projected to take place in the future? Under the various IPCC AR4 emissions scenarios,[25] global SLR is projected to increase at a further 0.18-0.38 m (SRES, B1) to 0.26-0.59 m (SRES, A1F1) by the end of the 21st century (IPCC, 2007). However, these estimates are inherently uncertain as they are based on uncertainties in the simulation of the carbon-climate cycle and they do not include the full effects of changes in ice-sheet dynamics and loss. For example, if the effects of thermal expansion of the oceans, which assume SLR as a linear function of temperature, is considered, a global rise in sea level is estimated at 0.54-0.75 m (SRES, B1) to 0.68-0.89 m (SRES, A2), approximately twice the previous values (Horton et al., 2008). In addition, contributions to global SLR from melting glaciers and ice caps are also uncertain. Ice flow fluxes in the AR4 GCMs are static, where they are set at observed 1993-2003 values. However, ice loss from Greenland and the West Antarctic Ice Sheet (WAIS) has been observed to be accelerating (Krabill et al., 2004; Rignot and Kanagaratnam, 2006; Velicogna and Wahr, 2006; Shepherd and Wingham, 2007). Although, AR4 includes sensitivity experiments in which fluxes increase linearly in time, producing an additional 0.2 m SLR (Pachauri and Reisinger, 2007 (AR4)), recent polar observations suggest that these will still substantially underestimate ice-melt based SLR contributions (Holland et al., 2006). In the case of a low-probability, high-impact event, such as the total loss of the WAIS, it would raise global mean sea level by 5-6 m (Tol et al., 2006). Following global estimates, regional SLR in West Africa is assumed to be between 0.5-2 m above 1990 levels by 2100. An extreme rise of 5 m, although highly dependent on the future of the WAIS, is unlikely, but has been considered in previous vulnerability reports (Tol et al., 2006; Dasgupta et al., 2007).

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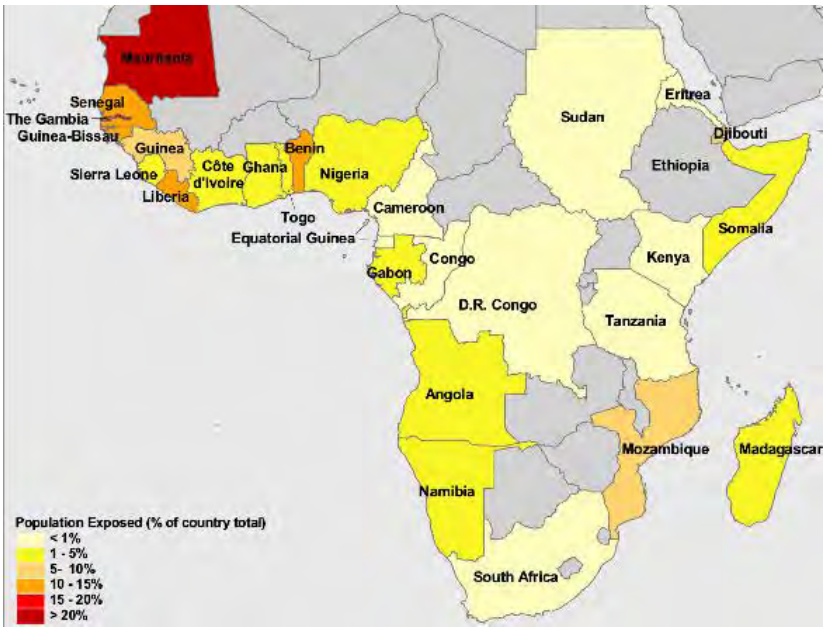
[25] Note that the emission scenarios for AR4 are based on SRES and not the RCPs used in CMIP5. The six families of SRES used in AR4 include: A1F1, A1B, A1T, A2, B1, and B2. The examples used in this paragraph are for a low and high greenhouse gas emission scenario.

Why is this important for West Africa? Much of coastal West Africa is low-lying, characterized by mangroves, lagoons, and delta systems. These regions are typically inundated at high tide, making the coastal zone vulnerable to SLR. Approximately 50 percent of the population of West Africa lives within 100 km of the coast (UNIDO/GCLME, 2010). Prior to 1990, 0.4 million people were affected by coastal flooding annually (Nicholls et al., 1999). With a ~0.4 m increase in SLR, this number would rise to as high as 36 million by 2080, due to high population concentrations on coastal mega-deltas (Nicholls et al., 1999). A 2007 World Bank Policy Report (Dasgupta et al., 2007) considered the regional effects of incremental 1 m SLR up to an extreme value of 5 m (Figure 19). The report finds that there are substantial differences in the intra-regional sensitivity to SLR driven flooding. For example, while the populations of Cameroon and the nations to the south may be largely unaffected by even a 1 m rise, The Gambia, Mauritania, Guinea-Bissau, Liberia, Benin and Senegal face substantial risk, with over 5 percent of the nation's inhabitants impacted by a regional SLR of 3 m or more. A rise of 5 m would cost Mauritania 25 percent of its GDP, with 35 percent or its urban coastal area affected. The loss of 12 percent of its coastal agriculture and impacts on 20 percent of its coastal urban area would cost Gambia upward of 15 percent of its GDP. Benin also faces substantial impacts. AR4 estimates that up to 10 percent of regional GDP would be required in adaptation costs, but analyses have highlighted the inability of these areas to implement adaptation strategies, denoting the area as very high-risk (Nicholls and Tol, 2006).

FIGURE 19. POPULATION OF WEST AFRICA AFFECTED BY 5 M SEA-LEVEL RISE



Source: Dasgupta, 2007

Nearly 15 percent of the world's mangroves are also found in West Africa (UNIDO/GCLME, 2010). Mangroves, which provide coastal protection from storm surges and act as fish nurseries, are at risk from changes in sedimentation rate driven by SLR and local human-induced processes (e.g., dam building, construction, clearing for agriculture, and changes in sedimentation and siltation). Spatial analysis of mangrove and wetland loss in Cameroon (Fonteh et al., 2009; Ellison and Zouh, 2012) highlights the threats that these systems face, as they are already experiencing substantial die back at the seaward edge. SLR is likely to exacerbate this habitat loss, with attendant consequences for regional fisheries and ecosystems (see Box 17). Estimates suggest the extensive loss of coastal wetlands in Gabon, Cameroon, Guinea, Guinea Bissau, and Nigeria is associated with a SLR of ~1 meter (UNIDO/GCLME, 2010; Dasgupta et al., 2007).

BOX 17. WEST AFRICAN FISHERIES AND CLIMATE CHANGE

Fisheries in the Gulf of Guinea region are predominantly artisanal. Available stock information, suggests a 10 percent decrease in catch since 2000 (UNIDO/GCLME, 2010). However, this drop can be attributed to regional over-exploitation, pollution, habitat destruction and mismanagement. A 16-member state program has been established to co-ordinate fisheries regional management with the goal of attaining sustainability and addressing some of these concerns (Ukwe et al., 2006). However, as yet, minimal research has been conducted into the capacity of these fisheries under climate change and there is no information concerning how fisheries may respond to changes in their physical ecosystem.

In recent decades, zooplankton biomass in the Gulf of Guinea has shown a downward trend, attributed to a warming of surface waters and reducing the productivity of the local upwelling system (Wiafe et al., 2008). As SSTs are set to continue to rise under all emission scenarios in the IPCC AR4, zooplankton communities, part of the food-web which supports regional fisheries, may continue to decline in biomass, with consequences for the local economy, biodiversity and food provision. In addition, coral bleaching, a stress response associated with warmer temperatures, is projected to increase, and the effects of increased acidification may serve to exacerbate the stress on local reef systems.

It is not only SLR that local coastal communities have to contend with. Strong winds associated with off-shore low-pressure weather systems, such as tropical cyclones or other large convective systems, can produce regional SLR that is higher than would be expected through tidal processes alone. This may cause extensive coastal flooding through what is known as a storm surge. Consequently, storm surge intensity, extent, and frequency depend on local sea level and the prevalence of suitable wind conditions, and are typically most destructive when they occur at high tide. Regional reports confirm annual storm surge events that raise local sea level by up to 6 m along the coast of Ghana (Boateng, 2012).

Our current understanding is that ocean warming results in increased SLR due to thermal expansion, and enhanced tropical storm generation due to increases in available heat potential or energy in the system (Emanuel, 2005; Webster et al., 2005; Bengtsson et al., 2006). As a result, the risk of increased flooding and storm surge damage is projected to increase. In low-lying coastal regions, such as West Africa's mega-deltas, the consequences for regional populations are likely to be severe and compounded by a lack of available resources for adaptation and mitigation (UNIDO/GCLME, 2010).

Dasgupta (2009) considered the vulnerability of West African nations that are likely to experience both more intense storms and a 1m sea-level rise. Percentage increases in surge zone extent are greatest in Cote d'Ivoire, Benin, the Republic of the Congo and Liberia (all suggesting a +50 percent increase), while Nigeria shows the greatest concentration of surge zones in the region and a ~35 percent increase in zone extent under the imposed conditions. High coastal populations in Cote d'Ivoire, Benin, and Nigeria result in the greatest human vulnerability in these nations, while Ghana, Togo, and Nigeria would lose ~50 percent of their GDP (UNIDO/GCLME, 2010). All of Nigeria's coastal agriculture would be affected, along with over 50 percent of the coastal crops of Ghana, Togo, and Equatorial Guinea (Dasgupta, 2009).

The resolution of GCMs (150-300 km) is not sufficient to resolve tropical storms (IPCC, 2007). To obtain more realistic estimates of storm surge extent, intensity and frequency, two approaches are used. In the dynamical downscaling approach, the large-scale climate state from the GCM is used to force a regional climate model that produces high-resolution winds that are subsequently applied to locally specific storm surge models (Lowe et al., 2001; Debenard et al., 2003). Alternatively, storm surge projections can be made from the statistical relationships between present day storm occurrence and the large-scale state, then extrapolated into the future (von Storch and Reichardt, 1997). Low

confidence in the circulation patterns of GCMs, and the limited availability of downscaled products, contribute to a high degree of uncertainty in projected storm surge changes (IPCC, 2007).

3.5 CHAPTER SUMMARY

The scientific studies highlighted in this chapter have illustrated the enormity of the challenge faced when trying to make future projections over West Africa. The climate of West Africa is complex and characterized by multiple drivers, which play a role in variability on interannual to decadal time scales. It is the poor representation of these climate drivers in models that add to the uncertainty in future projections. For example, GCMs have trouble simulating the tropical Atlantic SSTs which are critical to accurately simulating the West African Monsoon system.

In addition, the sensitivity of models to the parameterizations used and the choice of boundary conditions can also lead to diverse results. Regional climate models are needed to provide the finer resolution required for impacts or adaptation studies and the CORDEX-Africa project has the potential to provide this information. However, these models still show strong biases compared to observations, as well as between models and even within each individual model.

Noting these caveats, the results presented above do suggest that the West African region will not respond to climate change in a uniform manner. The Sahel is projected to warm more than the Guinean Coast, while the western Sahel is more likely to dry (especially at the beginning of the season) compared to the central and eastern Sahel which is projected to become wetter (especially during the end of the rainy season). There is also some preliminary evidence that the high-elevation areas may respond differently to the lower-elevation regions, with an increase projected over the Guinean Highlands and Cameroon Mountains.

With regards to the coastal regions, although there is a high degree of uncertainty, it is projected that these regions may become increasingly vulnerable to an increase in sea-level rise and coastal storm surges. This is particularly difficult to evaluate due to the lack of observations as well as the poor representation of sea-level rise (knowledge deficiency) and storm surges (model resolution deficiency) in numerical models.

4.0 REPORT SUMMARY

4.1 WEST AFRICAN CLIMATE AND PROJECTIONS

The climate of West Africa is considerably complex, with a distinct north-south rainfall gradient evident between the wet coastal region and the drier Sahel located further north. One of the key drivers for the diverse climate is thermodynamic contrasts between the land and ocean, which sets up the regional rain-producing circulation patterns, commonly known as the West African Monsoon. The onset of the monsoon takes place along the coast of West Africa in the spring, which is thought to be the wettest phase of the monsoon. During July, there is a large northward latitudinal shift in the monsoon, referred to as the "monsoon jump," with peak rainfall intensities now occurring in the Sahel. By the end of August, the monsoon rains begin to return to the coast, following the source of surface heating (the sun) as it migrates towards the Southern Hemisphere.

West Africa, in particular the Sahel, has received considerable scientific attention since the 1970s due to the prolonged wet and dry periods this region has experienced. This variability was first thought to be due to desertification, but has since also been linked to anomalous circulation in the jet streams and sea-surface temperatures anomalies, both regional and global. Although local land-surface feedbacks are perceived to play a secondary role, they are still seen as vital components in rainfall variability. Identifying the contribution of any particular feature in West African rainfall variability is difficult to evaluate due to the complex nature of the interactions. It is likely that the influence of an individual mechanism may vary depending on the region within West Africa and the time of the year.

Why is this important to understand? Climate models need to be able to simulate such features to accurately capture West African rainfall patterns, both spatially and temporally. The usefulness of climate projections depends on the confidence of their simulations and there are a number of ways to test the accuracy of these projections, which include:

- Evaluating the models' ability to accurately simulate the recent past climate;
- Using an ensemble approach, both within a model and between models, which provides information on not just the mean response, but also the range or envelope of projected changes; and
- Exploring the projected changes in physical processes, which improves the confidence that the models are projecting the temperature and rainfall response for the right reason,

In this report, an evaluation of how models simulate the current climate reveals that the models struggle with accurately simulating the rainfall patterns. The sensitivity of models to the parameterizations used and the choice of boundary conditions is one of the main reasons for the diverse results (both within a model and between different models). GCMs have trouble simulating features such as the tropical Atlantic sea-surface temperatures which, is critical to accurately simulating the West African Monsoon system. Regional climate models are needed to provide the finer resolution required for impacts or adaptation studies. The CORDEX-Africa project has the potential to provide such information. However, these models still show strong biases compared to observations, as well as between models and within each individual model.

Future projections suggest that the Sahel will warm more than the Guinean Coast, but there still remains large uncertainty in the absolute magnitude and rate of temperature change. To date, very little work has focused on changes in temperature statistics over West Africa, such as days exceeding a specified temperature threshold or the number of consecutive days of extremely hot conditions (i.e.,

heat wave). Such statistics will possibly give a better idea of how key sectors, like agriculture, health, and transport, should respond or adapt to future climate.

Projected changes in rainfall patterns reveal that the western Sahel is more likely to dry (especially at the beginning of the season) compared to the central and eastern Sahel, which are projected to become wetter (especially during the end of the rainy season). There is also some preliminary evidence that suggests the high-elevation areas may respond differently to the lower-elevation regions, with an increase projected over the Guinean Highlands and Cameroon Mountains. Of course these projections vary depending on the time frame under consideration (e.g., first half of the 21st century versus the second half).

The uncertainty in future projections is not limited to climate variables, such as rainfall, but also extends to oceanic processes. This is of concern because much of coastal West Africa is low-lying, characterized by mangroves, lagoons, and delta systems, and, more importantly, is heavily populated. Historical data reveals that sea-level rise has already been taking place over a long period of time, with a recent acceleration towards the end of the 20th century. The exact range of future predicted sea-level rise is strongly compromised by the input into climate models as well as the methods used to determine the rise. There is even less robust information about how climate change may influence storm surges in the region. The current understanding is that ocean warming results in increased sea-level rise due to thermal expansion, and enhanced tropical storm generation (i.e., storm surge) due to increases in available energy in the atmosphere. As a result, the risk of increased flooding and storm surge damage is projected to increase in the future.

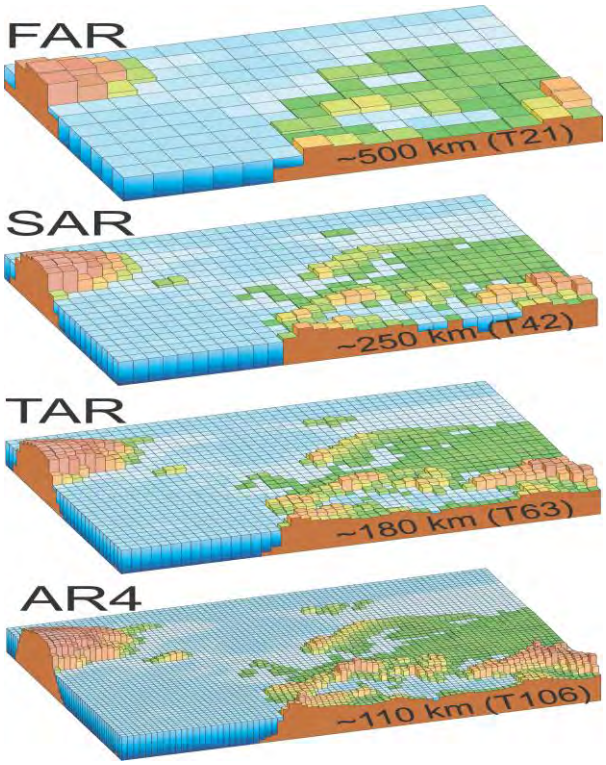
4.2 AVENUES FOR IMPROVEMENT IN CLIMATE SCIENCE

4.2.1 Climate Models

Climate models have become considerably complex and are now incorporating many of the interacting components of the climate system (e.g., the inclusion of aerosols, carbon cycle, land surface feedbacks, etc.). The new generation of complex models (i.e., CMIP5) was widely expected to provide more detail and more certain climate projections. Some preliminary results have indicated that the projected changes from the new models are not that different from those used in the IPCC AR4 (e.g., Knutti and Sedláček, 2012). Despite considerable model development, the change in model spread (a measure of uncertainty) from CMIP3 to CMIP5 has not shown significant change. This may not install confidence with decision makers and the public, as it may appear that the understanding of climate change is becoming less clear. However, it needs to be considered that the processes within the new set of models are of much greater detail, which implies the models have improved in that sense. On a regional scale, an increase in model complexity does have its benefits. An example of this would be the inclusion of an interactive land scheme within the model. There is already evidence that interactive land surface schemes, which represent the land-surface feedbacks, improve the performance of climate models in West Africa through a better representation of circulation patterns and hydrological processes (Steiner et al., 2009; van den Hurk and van Meijgaard, 2010).

Increased model resolution has long been thought to be a primary avenue for increased skill in GCMs (see Figure 20for an example). Increasing resolution allows for finer scale processes to be explicitly captured rather than approximated through parameterizations. These higher resolution simulations have been enabled through increases in computer power. However, currently the level of spatial detail required still exceeds what is practical computationally and even the highest resolution climate models still require parameterizations. It is debatable whether the resolution increases that have been implemented have substantially improved model performance.

FIGURE 20. THE PROGRESS OF MODEL SPATIAL RESOLUTION FROM THE IPCC FIRST ASSESSMENT REPORT (TOP) TO THE FOURTH REPORT, AR4 (BOTTOM)



Source: IPCC, 2007

Due to computational constraints, regional models have been pursued as a more efficient means of capturing local scale processes at finer resolutions for a limited spatial area. There remains much debate as to whether such approaches actually provide more information than GCMs or whether they just produce high resolution "noise." In many cases, it is necessary to forgo high-resolution for the sake of longer integration times and increased experimentation (i.e., sensitivity experiments). As a result, much work has also gone into further improving parameterizations. This ties in strongly with observations of weather and climate processes at fine scales. Development of parameterizations of processes such as convection is highly dependent on being able to observe convective processes in detail. Modern observation platforms such as Doppler radar and satellite products have enhanced the observation of such processes greatly. Much room likely still exists to improve parameterizations. Particularly interesting developments involve the use of statistical/stochastic parameterization sub-models, using very high resolution model output to capture fine scale processes and developing empirical approximations based on this output.

4.2.2 New Methodologies

'New Methodologies' is broadly defined here as methods that have recently been developed or currently under development by the climate science community to obtain more information from climate models. This report has already covered some of the foremost methodologies that will be discussed in the latest IPCC report. These include concepts such as decadal prediction, various methods of downscaling, and bias correction.

Model weighting is another area currently under research with regards to reducing uncertainty in future projections. As the name suggests this involves weighting a model's output based on a set of criteria (i.e.,

removing or reducing the role of poor performing models in the ensemble). The contentious issue is what set of metrics are used to weight a model? Different applications required skill in different aspects of the climate system. So while some metrics may focus on mean annual rainfall and temperature, others may focus on seasonal onset. As a result, model weighting becomes sector and application specific. It is also not a given that a model that performs well over the historical climate period will perform poorly or well in simulating the future climate. The majority of applications of multi-model projections, including the IPPC AR5 report, use a "one model one vote" approach where each model is given equal weighting regardless of its performance. More effort could be placed on developing a more robust methodology for the weighting of models, with particular focus being on whether it captures the main modes of climate variability and regional dynamics in a particular region of interest, such as West Africa.

4.2.3 Bridging the Communication Gap

Continued development of observational systems, core science research, climate modeling, and downscaling, are essential to improve the information available to climate adaptation and impacts practitioners. However, these developments are currently fairly slow with little real progress or change in large-scale messages between the CMIP3 (IPCC AR4) and CMIP5 (IPCC AR5) climate projections. Model disagreement has, if anything, increased in recent years as models become more and more complex. Downscaling methods have diversified both through the development of RCMs as well as a diversity of empirical downscaling approaches, bias correction, and pattern scaling. The result is actually an increase in the range of future projected climates presented to decision makers and policy developers. The real challenge, and most urgent research avenue, is therefore in the area of planning and decision making within the context of uncertainty.

Traditionally, a top down approach has been used to integrate climate projections into decision making and planning. Climate projections of changing rainfall and temperature patterns are provided to decision makers in the form of reports including large numbers of maps and plots. The burden is laid on the decision maker to engage with the climate projections and to determine how these intersect the contexts within which they are operating. The decision maker is required to evaluate the relative importance of the climate information in relation to other stressors and driving forces (economics, development policy, socio-economic drivers, etc.).

Bottom up approaches acknowledge that the decision-making context requires specific climate information and metrics. For example, agricultural planning requires information relevant to crop growth cycles such as onset dates, or rainfall intensity in critical months. This specified information is then provided to the climate scientists who attempt to provide information that best addresses these information needs. In many sectors it is difficult to identify climate metrics that are relevant, particularly if no prior understanding of climate impacts exists. Decision makers are often left floundering and resort to requesting very basic climate information which is inappropriate to their context.

Surrounding both approaches is the key issue of uncertainty which often looms as an impenetrable barrier to decision making, and results in falling back on a "no regrets" approach. The key area of research therefore lies in the intersection of uncertain climate projections with the decision making process through a co-exploration (neither top down nor bottom up). Some initial explorations of this have been undertaken, though little formal documentation exists. Key elements are likely to be:

- Selection of appropriate (for given context and time/space scales) climate information;
- An exploration of the decision making processes and identification of cross-sectoral and cross-scale "critical points," some of which may be climate related; and
- A description of the intersection of the range of possible future climates with these climate critical points.

Initial investigation suggests that useful progress can be made through such co-explorations. Aspects of uncertainty can often be sidestepped by recognizing that some climate scenarios pose little risk and so only those scenarios that trigger critical points need be considered. This often reduces the range of scenarios involved.

There is also a wealth of online data portals available that contain climate change information; however they are very scientifically orientated, placing limitations on their usefulness. Thus, another aspect of climate science under investigation is the use of climate visualizations. Simply put, this refers to the representation of climate information in the form of graphs and figures that are easy to interpret by the average user whilst containing sufficient detail so that they are not misleading. There is a fine balance in communicating such complex information in a simple but not over-simplified manner, which is why this avenue of research is still being investigated.

4.3 RECOMMENDATIONS FOR WEST AFRICA

The scope for improvements in climate projections in West Africa is broad, with numerous possible avenues that can be taken. The previous section highlighted generic possibilities in which future projections will likely improve as well as communicating those changes. In terms of reducing the uncertainty of future projections specific to West Africa the following areas need attention (the section below is divided into two groups, an atmosphere component and an ocean component, along with three sub-groups; observations, GCMs, and regional modeling).

4.3.1. Future Avenues for Research (Atmosphere)

Observations:

1. Emphasis should be placed on developing an improved observation network (i.e., rain-gauge network) in the region, with data that is quality controlled and open to the research community. Alternatively, a collection of the existing data and maintenance of the current network structure is suggested (e.g., build on programs like AMMA). However, both options must be a long term project. This can potentially serve two main purposes. Firstly, from a historical climate perspective, such data can be used to identify past climate trends (spatially and temporally), improve understanding between regional climate variability and large-scale modes of variability (e.g., ENSO), and be assimilated into reanalysis products, leading to their improvement. Secondly, from a future climate projections perspective, a complete set of observations for the region will improve initial conditions that are fed into models running decadal predictions. Additionally, they can be used to build empirical relationships between large-scale processes and the local climate for statistical downscaling purposes. It will also help establish an early warning system network.

GCMs:

1. A common thread among nearly all avenues for improvement in future climate projections is the need for better models. There is a desire to add more complexity to climate models by adding in more components. However, this should not be to the detriment of understanding how well the current processes and feedback are represented in models. It does add the risk of adding more "known unknowns" when it comes to increasing complexity.

2. Improvements in parameterizations may help to further reduce currently existing biases in rainfall patterns found in West Africa. In particular, these should capture the small-scale features that play a crucial role, such as land-surface feedbacks, which are known to play a key role in the regional climate.

3. The methods to combine GCM, RCM, and statistical downscaled products (i.e., multiple data sources) are still not clear due to the highly complicated nature of such data. An additional issue is transferring climate change information from GCMs into impact models.

Regional:

1. Possibly the biggest avenue for improvement are through the CORDEX-Africa experiments that will become available shortly. This will not only provide more insight into why regional climate models struggle to capture West African climate dynamics, but will also be valuable in seeing how the dynamics might change in the future. CORDEX-Africa experiments will also provide assistance in dealing with multi-GCM-RCM model uncertainty.
2. Numerous statistical downscaling methods are available, but very few have been employed over West Africa. Statistical downscaling is computationally inexpensive, allowing for large ensembles of data to be created using multiple observation and GCM dataset. This assists in dealing with the problem of uncertainty. However, these methods are limited by observation data availability, as discussed above. These methods will complement the dynamical downscaling from CORDEX.
3. As evident in this report, there is still little research been conducted on secondary variables, such as rainfall intensity, dry spell duration, onset and cessation of the rainy season, and extremes. This is potentially a huge gap in the scientific community, and work in this area is urgently needed in West Africa, particularly for the agriculture industry.
4. There is large scope for attribution studies (i.e., identifying the source of detected climate change) to be conducted in West Africa. However, such methods require large ensembles to perform such probabilistic analysis.

4.3.2. Future Avenues for Research (Ocean)

Observations:

1. The Gulf of Guinea is poorly observed, and there is little to no coastal observation data available. While *in situ* methods may be expensive, existing remote sensing platforms are able to provide substantial information on regional primary productivity. Efforts to develop tools that can be used to quantify phytoplankton biomass and community structure in coastal waters should be encouraged. Considering that this region is thought to play an important role in regional atmosphere circulation patterns (and hence rainfall), observations will help understand the mechanisms behind this.

GCMs:

1. Models have a tendency to be designed to capture one climate state well. This perhaps calls into question their ability to capture threshold events, tipping points, and bi-stability in ocean states. The ability of current ocean models to capture alternative climate paradigms and the factors that govern these states requires much investigation.
2. Improvements in parameterizations may help to further reduce currently existing biases in SST (a known problem in the tropical Atlantic), which often results in the poor simulation of the West African Climate (particularly rainfall).

Regional:

1. Minimal work has been done to catalogue the oceanographic and coastal processes at work in the Gulf of Guinea. Regional models, applied to this area, would be able to give some idea of the effects of tides, storm surges, etc., in ways that GCMs cannot due to restrictions on resolution. Effects of

sea-level rise are largely drawn from geographical information system (GIS) assessments, with little research conducted into the actual dynamics of the processes concerned.

2. Biogeochemical modeling of the region could determine how local physical processes affect the distribution of nutrients and low-trophic level biology in the Guinea Current Large Marine Ecosystem (GCLME). Downscaling of GCMs to force regional NPZD (nutrient, phytoplankton, zooplankton, detritus) models could shed light on the potential fragility of fisheries.

4.3.3. Outside the Science

With the arrival of the CMIP5 model experiments in 2012/2013, the related production of CORDEX downscaled projections in 2013/2014 and the ever widening array of satellite and hybrid observed datasets, the quantity of data available to climate science, decision makers, policy developers, and practitioners is unprecedented. However, the challenge of translating this data into actionable information and from there, into robust decisions, policy, or interventions, has become greater and greater.

Two significant risks are at play. Firstly, many practitioners, overwhelmed by the wide range of data available, resort to overly simple or indefensible methods of analysis. More depressingly, an ever growing suite of commercialized climate services have emerged, offering simple solutions and answers, but using indefensible methods. There is a serious risk that important decisions and policy developments are being made based on indefensible information.

The second significant risk is that faced with the ever widening array of data, practitioners lose "faith" in the climate science and in the value of climate projections and resort to purely "no regrets" solutions that ignore valuable and robust messages of change.

To address these two risks, two main areas of focus can be identified. The first is improving the interaction and communication between climate scientists and decision makers. It is important that both fields better understand the other's methods, approaches, needs, and limitations. The decision makers become better able to understand the information presented to them while the climate scientists become better able to understand the needs of decision makers. In some cases, this facilitation can best be done through "intermediaries." Such a role would involve understanding both fields and acting as a bridge between the two communities.

The second area of focus should be capacity development, with a large focus on practitioners and decision makers, but also including climate scientists. It is only through a growing awareness and understanding of the relative merits and limitations of different sources of climate information and methods of using such information that we can ensure that robust, well-informed decisions will be made, both in the developing world, and also in the developed world.

5.0 SOURCES

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ANNEX I: PRODUCTS, VARIABLES, AND DATASETS

TABLE A1. THE VARIOUS REANALYSIS PRODUCTS AVAILABLE FOR STUDYING WEST AFRICAN CLIMATE DYNAMICS.

Reanalysis Products						
Product	**Name**	**Organization**	**Period**	**Reference**	**Temporal Resolution**	**Spatial Resolution****
NCEP-I	National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR)	NCEP-NCAR	1958 – present	Kalnay et al., 1996	6h	2.5° x 2.5° x 17
NCEP-DOE II	NCEP/Department of Energy Global Reanalysis 2	NCEP-DOE	1979 – present	Kanamitsu et al., 2002	6h	2.5° x 2.5° x 17
CFSR	Climate Forecast System Reanalysis	NCEP	1979 – present	Saha et al., 2010	6h*	0.5° x 0.5° x 36
ERA-40	European Centre for Medium-Range Weather Forecasts (ECMWF)	ECMWF	1957 – 2002	Uppala et al., 2005	6h	2.5° x 2.5° x 23
ERA-Interim	ECMWF Interim Re-Analysis	ECMWF	1979 – present	Dee et al., 2011	6h	0.75° x 0.75° x 37
MERRA	Modern Era Retrospective-Analysis for Research and Applications	NASA	1979 – 2009	Rienecker et al., 2011	3h	2/3° x 1/2° x 42
JRA-25	Japanese 25-yr Reanalysis	JMA	1979 – 2009	Onogi et al., 2007	6h	1.25° x 1.25° x 23
20CR	National Oceanic and Atmospheric Administration (NOAA)–Cooperative Institute for Research in Environmental Sciences (CIRES) Twentieth-Century Reanalysis version 2	NOAA–CIRES	1871 – 2008	Compo et al., 2011	6h	2.0° x 2.0° x 24

* Some products are available at 1h resolution

** Longitude, Latitude and Pressure levels

TABLE A2. A LIST OF OCEAN VARIABLES DERIVED FROM *IN-SITU* OBSERVATIONS AND REMOTE SENSING PRODUCTS.

Gridded Oceanographic Product		Organization	Period	Reference	Temporal Resolution	Spatial Resolution
Variable	**Data set**					**lon x lat (x depth)**
Mean Sea Level Anomaly (MSLA)	AVISO	CNES	1992 - present	www.aviso.oceanobs.com	7-Daily	0.33° x 0.33°
Sea-surface salinity (SSS)	Aquarius	NASA	2011 - present	Lagerloef et al., (2008)	7-Daily	150 km x 150 km
Sea-surface temperature	HadISST	UKMO	1871 - present	Rayner et al., (2003)	Monthly	1° x 1°
	GHRSST	NOAA/ESA/UKMO/NASA	2005 - present	www.ghrsst.org	6-Hourly	< 10 km x 10 km
	OISST (Reynolds)	NOAA	1981 - present	Reynolds et al., (2002)	7-Daily	1° x 1°
Ocean color	GLOB-COLOUR	ESA	1997 - present	www.globcolour.info	Daily, 8-Daily, Monthly	4 km x 4 km
Wind vectors (scatterometry)	QuikSCAT†/ASCAT	NASA/NOAA/ESA	1999 - present	http://manati.star.nesdis.noaa.gov	Daily	25 km x 25 km
Temp. / Sal. / Velocity reanalysis	SODA v2.1.6	UoM, A&M	1958 – 2008	Carton and Giese, (2008)	monthly	0.25° x 0.4° x 40*
Temp. / Sal. / Oxygen	WOA09	NODC-NOAA	climatological	Locarnini et al, (2009) **	Monthly, Annual	1° x 1° x 33*

†platform failed 2009

** temperature field

TABLE A3. THE TABLE COVERS MOST OF THE RAINFALL PRODUCTS THAT COVER AFRICA (INCLUDES OBSERVATIONS FROM IN-SITU MEASUREMENTS AS WELL AS DERIVED REMOTE SENSING PRODUCTS)

Rainfall Products Covering Africa							
Product	**Name**	**Organization**	**Source**	**Period**	**Reference**	**Temporal Resolution**	**Spatial Resolution**
CMAP	CPC Merged Analysis of Precipitation	CPC	Merged	1979-2011	Xie and Arkin, 1997	Monthly	2.5° x 2.5°
CRU TS 2.0	Climate Research Unit	CRU (UAE)	Gauge-based	1901-2000	Mitchell et al. 2003	Monthly	0.5° x 0.5°
FEWS-ARC2	Climate Predition Center - Famine and Early Warning System - African Rainfall Climatology version 2	CPC/FEWS	Merged	1983-present	Novella and Thiaw, 2013	Daily	0.1° x 0.1°
GHCN	Global Historical Climatology Network	NOAA/NCDC	Gauge-based	(Station Dependant)	Peterson and Vose, 1997	Daily	Station
GPCCv6	Global Precipitation Climatology Center (GPCC) Full Data Reanalysis version 6	GPCC	Gauge-based	1901-2010	Schneider et al. 2011	Monthly	1° x 1°
GPCPv1	Global Precipitation Climatology Project version 1	WMO/WRCP/GEWEX	Merged	1996-2012*	Huffman et al. 2001	Daily	1° x 1°
GPCPv2	Global Precipitation Climatology Project version 2	WMO/WRCP/GEWEX	Merged	1979-2012*	Adler et al. 2003	Monthly	2.5° x 2.5°
RFE2.0	Rainfall Estimate Product	CPC	Merged	2000 - present	Xie and Arkin, 1997	Daily	0.1° x 0.1°
TRMM 3B42 v7	Tropical Rainfall Measuring Mission 3B42 verison 7	NASA	Merged	1998 - present	Huffman et al. 2007, 2010	3 hourly	0.25° x 0.25°

* Available for a few months in 2013

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