EVALUATING THE IMPACTS OF CLIMATE CHANGE ON THE WEST AFRICAN MONSOON

An Undergraduate Research Scholars Thesis

by

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RESEARCH COMPLIANCE CERTIFICATION

Research activities involving the use of human subjects, vertebrate animals, and/or biohazards must be reviewed and approved by the appropriate Texas A&M University regulatory research committee (i.e., IRB, IACUC, IBC) before the activity can commence. This requirement applies to activities conducted at Texas A&M and to activities conducted at non-Texas A&M facilities or institutions. In both cases, students are responsible for working with the relevant Texas A&M research compliance program to ensure and document that all Texas A&M compliance obligations are met before the study begins.

I, Kerry Abernethy-Cannella, certify that all research compliance requirements related to this Undergraduate Research Scholars thesis have been addressed with my Research Faculty Advisor prior to the collection of any data used in this final thesis submission.

This project did not require approval from the Texas A&M University Research Compliance & Biosafety office.

TABLE OF CONTENTS

Page

SECTIONS

ABSTRACT

Evaluating the Impacts of Climate Change on the West African Monsoon

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This project covers the impacts of climate change on the West African Monsoon system using observations and simulations from a set of climate models. We focus on three variables that characterize the wet season: date of rainy season onset, date of rainy season demise, and total precipitation during the rainy season. These variables are calculated using gridded precipitation data only. We apply spatial and temporal analysis to identify model biases and patterns and use the existing literature to document and explain those patterns. Present (Historical) climate simulations (1981-2014) are validated against observations for the same period of time. Projections for the late twentieth century (2064-2100) are compared to present simulations.

Our findings indicate strong biases in demise and total precipitation, with a weaker bias relative to the projected change in monsoon behavior for onset. However, in the context of the delay in the onset and demise, as well as an increase in precipitation, these findings are largely consistent with the literature.

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NOMENCLATURE

IPCC	Intergovernmental Panel on Climate Change
SSP	Shared Socioeconomic Pathway
SSP 5.85/SSP585	IPCC’s fifth SSP wherein there is 8.5 Wm^{-2} of warming
Onset	Start of the Monsoon/Rainy/Wet Season (Days after January 1)
Demise	End of the Monsoon/Rainy/Wet Season (Days after January 1)
Total Precipitation	Sum of Precipitation during the Monsoon/Rainy/Wet Season
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station Data
hPa	hectoPascals of Air Pressure

1. INTRODUCTION

This study investigates the impact that climate change will have on the West African Monsoon by the end of the twenty-first century. The monsoon system is a critical consideration for water use projections, and investigation of the topic is important for future planning of both resource management and hydropower potential in the region (Ojo, Oni, and Ogunkunle 2003; Stanzel, Kling, and Bauer 2018).

The existing literature in this field provides a robust analysis of the strengths and deficiencies of climate models' abilities to project precipitation patterns in various monsoon regions (e.g., Monerie, Fontaine, and Roucou (2012), Biasutti (2013), Roehrig et al. (2013), Bombardi and Boos (2021)).

Biasutti (2013) and Monerie, Fontaine, and Roucou (2012) found that surface warming in West Africa will lead to an increase in rainfall during the monsoon season, which can be attributed to a northward migration of the West African Monsoon. Roehrig et al. (2013) found that the increased temperature, especially during the summer months, may be part of a negative feedback system, wherein a strengthening of the monsoon moderates a high temperature increase during the rainy season. Bombardi and Boos (2021) showed that there is a strong agreement between models on the effects of climate change on the timing of the monsoon, with most models predicting a delay in the median onset, especially on the coast, and a delay in the median demise, especially inland.

Figures 1.1.A and 1.1.B introduce the West African Monsoon system. Depicted is the seasonal reversal of low-level (850 hPa) wind anomalies (wind velocity minus the average for the day of the year) as well as the level of precipitation that fell each pentad, which is the way that CHIRPS groups precipitation and wind vector data.

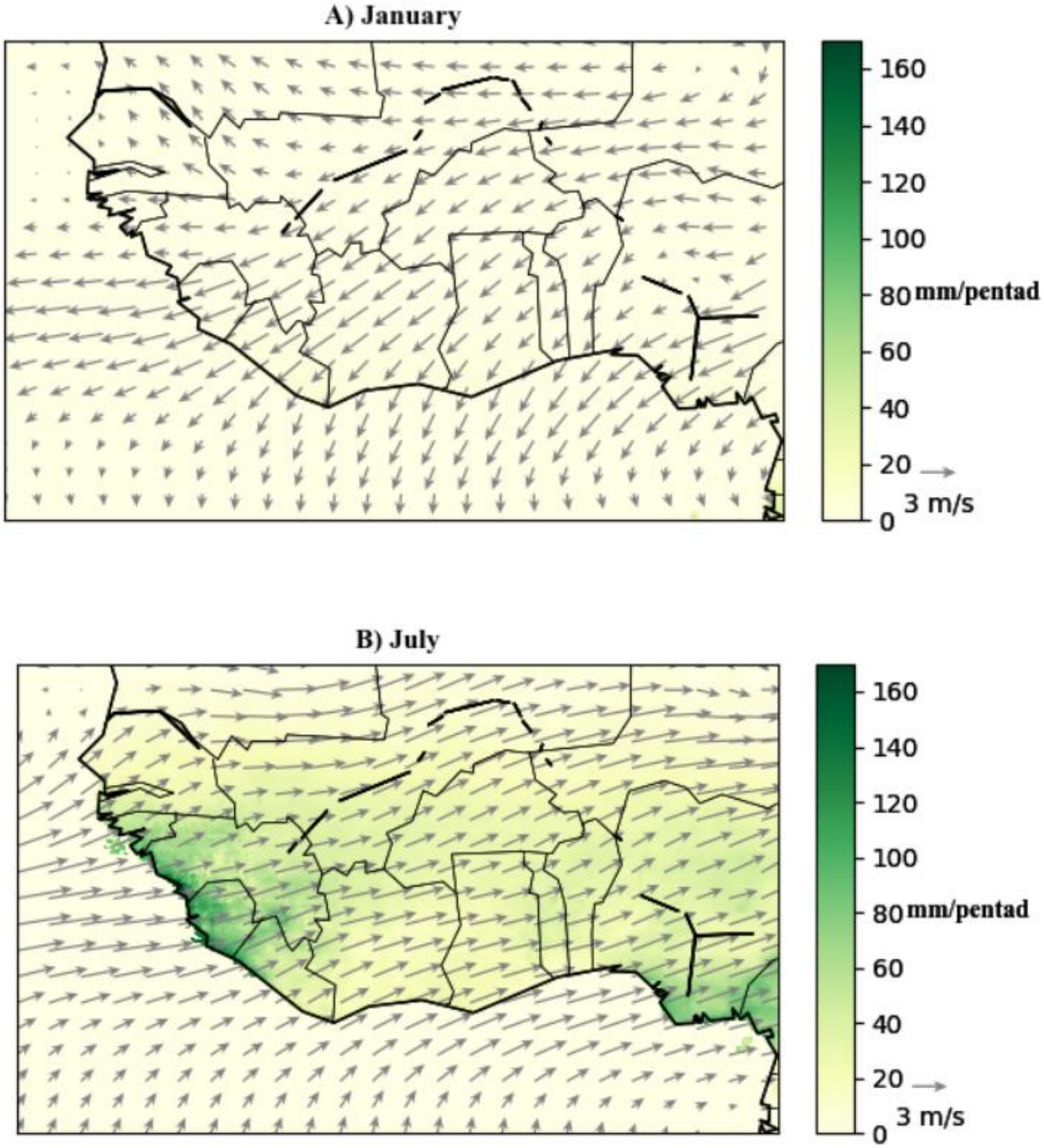

Figure 1.1: Precipitation and Wind Anomaly at 850 hPa over the West African Monsoon Region; The units of time are determined by grouping each month into five-day periods (pentads); For months of length 31 days, the final pentad will be six days long; For months of length 28 or 29 days, the final pentad will be shortened to 3 or 4 days, respectively.

The West African Monsoon, unlike the Asian Monsoon, is associated with a yearly cycle of shifting wind anomalies, not wind directions. Whereas the Asian Monsoon is characterized by an outright reversal of zonal and meridional wind (Li and Zhang 2008), West Africa is dominated by the persistence of low-level northeasterly wind, and thus the region's monsoon is only accompanied by a change in the anomaly of the wind, not a complete reversal (Gallego et al. 2015). The implications of this subtlety are that one characteristic of the monsoon system is a yearly variation in the strength of the northeasterly wind, called the *Harmattan* (He, Breuning-Madsen, and Awadzi 2007). This wind is weakest in the summer, when differential heating over land draws warm, moist air toward the continent during the wet season. The dry season occurs with a strengthening of the dominant northeasterly wind, which brings dry air from the Sahara into the monsoon region.

Most studies of climate change impacts on the West African monsoon focus on seasonal means, which are arbitrarily defined. We, in contrast, investigate the impacts of climate change on the timing of the West African monsoon using a more precise definition of the timing of the wet season. This study is intended to refine the work done by Bombardi and Boos (2021) and perform a more detailed evaluation of the impacts of climate change over West Africa.

We will examine the impacts of climate change on the West African Monsoon by comparing climate simulations from a sample of years during the present climate, for which observational data is available, and evaluating projections of future climate change. This will be done for simulations of several models following the methodology in Bombardi and Boos (2021).

This thesis seeks to investigate how the West African Monsoon may be affected by climate change, specifically, the most severe projection commonly used by climate scientists. The Intergovernmental Panel on Climate Change (IPCC) proposes five projections, called Shared Socio-economic Pathways (SSPs) to quantify possible futures of climate change. Each of these is numbered, and SSP5 is the pathway with the largest increase in greenhouse gas emissions, as well as the largest atmospheric concentration of greenhouse gases by 2100. Under this scenario, the IPCC expects a change in incoming solar radiation of 8.5 Watts per square meter. Thus, this projection is called SSP585 (or alternatively, SSP5.85). To analyze the effects of climate change, this thesis compares the climate during the last thirty years of the twenty-first century under the SSP585 projection to the climate as determined by the same models used for SSP585 applied to the last thirty years before now. We will also compare these to the observational data from the last thirty years to see what biases are introduced by the models. These will allow us to analyze three variables surrounding the monsoon: wet season onset, wet season demise, and total precipitation during the wet season.

2. METHODS

The process of analyzing the climate data is done in several steps. The first is to gather the observational data from the remote sensing datasets called CHIRPS. The climate model data comes from the models shown in Table 2.1. The next part is to analyze each dataset with the same gridpoints. This produces an ensemble of three variables (rainy season onset, rainy season demise, and total precipitation during the rainy season), over three datasets (observational data, model historical data, and model projection data). This is then analyzed over space (comparing observational data to model historical data and comparing model historical data to model projection data) and plotted to illustrate the changes in the distribution of the data. The observational data can also be plotted to provide an overview of the climate behavior of the region with precipitation means and low level (850 hPa) wind anomalies, as was shown in the introduction.

2.1 Data Collection

While the observation data is from CHIRPS, the historical climate data to which it is compared is gathered from several models, shown in Table 2.1, which is adapted from Bombardi and Boos (2021).

Table 2.1: Models and Members used for Data Collection

Center/Model	Resolution (lat × lon)	No. of Ensemble Members		Key References
		Historical	SSP585	
Beijing Climate Center (BCC)/BCC-CSM2-MR	1.125 × 1.125	3	1	Wu et al. (2019)
Canadian Centre for Climate Modelling and Analysis (CCCma) / CanESM5	2.8125 × 2.8125	31	34	Swart et al. (2019)
Centre National de Recherches Météorologiques (CNRM) - Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS) / CNRM-CM6-1	1.40625 × 1.40625	13	1	Aurore Voldoire (2018); A. Voldoire et al. (2019)
CNRM - CERFACS / CNRM-ESM2-1	1.5 × 2.0	5	1	Séférian et al. (2016)
Institute for Numerical Mathematics (INM) / INM-CM5-0	1.25 × 2.5	1	-	Volodin et al. (2019)
Institut Pierre-Simon Laplace (IPSL) / IPSL-CM6A-LR	1.25 × 1.25	32	-	Boucher et al. (2018)
Meteorological Research Institute (MRI) / MRI-ESM2-0	1.125 × 1.125	5	-	Yukimoto et al. (2019)
National Center for Atmospheric Research (NCAR) / CESM2	0.9375 × 1.25	10	2	Danabasoglu (2019b)
NCAR / CESM2-WACCM	0.9375 × 1.25	3	-	Danabasoglu (2019a)
Geophysical Fluid Dynamics Laboratory (GFDL) / GFDL-CM4	1.0 × 1.25	1	1	Guo et al. (2018)
GFDL / GFDL-ESM4	1.0 × 1.25	1	1	Krasting et al. (2018)
Nanjing University Information Science and Technology (NUIST) Earth System Model version 3 (NESM3) / NUIST-NESM3	1.875 × 1.875	1	1	Cao and Wang (2019)

2.2 Interpolation of Data into a Common Grid

Due to the discrepancy in resolution of the climate models, to compare model bias and accuracy, they were interpolated to a common grid using simple grid interpolation. They were re-gridded to match the spatial resolution of the model with the coarsest grid dimensions such that each matches the resolution of the Canadian Model: 2.8125° × 2.8125°. Unlike some methods, which seek to increase the fine detail of the grid, there was no data created to fill the gaps between pixels.

2.3 Collapsing Model Members into Statistics

To analyze the data spatially, we calculate the temporal average of historical data for each member for each model; the same is done for the SSP 5.85 data. To prevent the volume of data from each model from biasing the mean toward the data from those models, we begin by finding the average for each model, before calculating an ensemble average from all the models. This way, every model average, regardless of the number of members, will have the same weight for all statistical calculations. For spatial analysis, the ensemble mean for each grid point is calculated for the historical and SSP585 data, as well as for the CHIRPS observational data. For temporal analysis, the distribution of the three variables of interest (onset, demise, and precipitation) is calculated for historical, SSP585, and observational data.

2.4 Calculating Model Bias

Model Bias refers to a quantification of the inaccuracies of each model. Bias can be calculated for each variable of interest; in this study, these are onset, demise, and precipitation. To find the bias of the ensemble mean of the models, the observational variable is subtracted from the variable predicted by the ensemble. In this case, we use the historical data to quantify the variable, then subtract the mean of the observational data.

Another way to visualize model bias is through the comparison of the distribution of statistical summaries of each variable. This display can be seen in the figures 3.1 through 3.3.

3. RESULTS

Certain models overestimate or underestimate the onset, demise, and seasonal precipitation during the wet season. The biases in estimation allow us to consider the direction that the models predict. For example, a thorough analysis of precipitation data in the SSP585 scenario is predicated on consideration of the model bias; when the ensemble overestimates inland precipitation, and SSP585 projections that show the same can be considered with more scrutiny than if they were more accurate. When the models consistently place monsoon demise early compared to observations, as can be seen in figure 3.5, a model estimate that shows the demise occurring later in the future than they do now should be considered as biased in the opposite direction.

The distributions of each of the variables shows how onset, demise, and total precipitation vary across the respective datasets that generated them. The following figures give us insight into how these distributions vary.

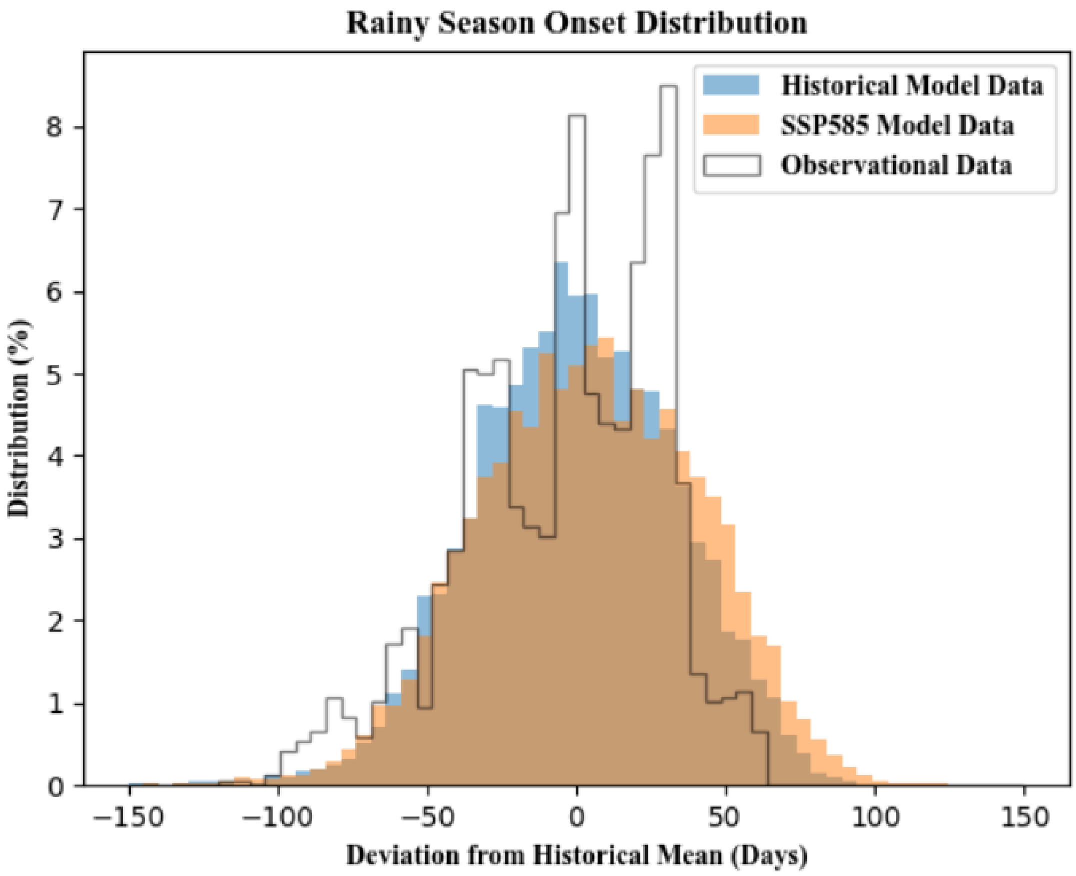

Figure 3.1: Rainy Season Onset Distribution; The distribution is centered at 0=μ, the mean of the historical model data; Model data is shown in solid colors, with historical data in blue and SSP585 data in orange; CHIRPS data is superimposed as a black outline

Here we see a change in the distribution of the onset of the rainy season. Clearly, the SSP585 model predicts a delay in rainy season onset (Fig. 3.1). This delay is most pronounced at the extremes of the distribution. The median for the historical onset is expected to shift five days, while the 99th percentile onset (that is, years during which the onset already occurs months later than average) is expected to be further delayed nearly two weeks.

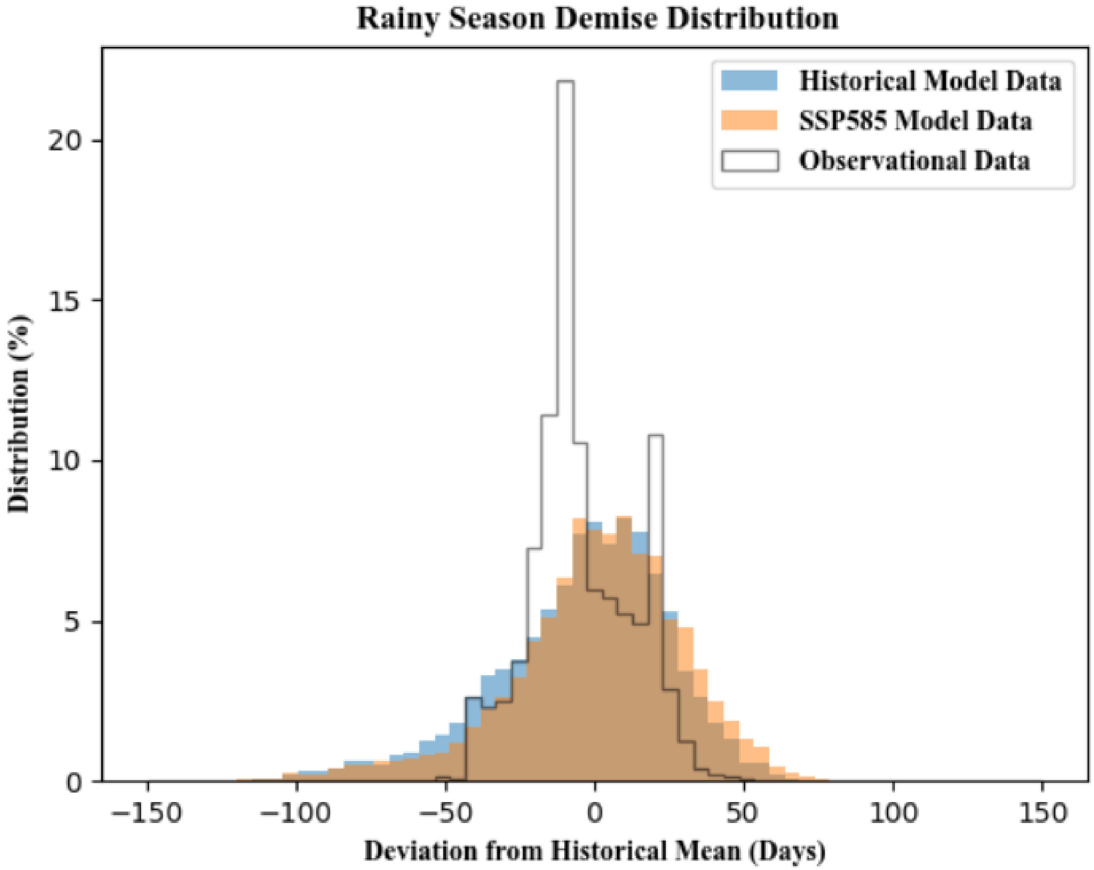

Figure 3.2: Rainy Season Demise Distribution; The distribution is centered at 0=μ, the mean of the historical model data; Model data is shown in solid colors, with historical data in blue and SSP585 data in orange; CHIRPS data is superimposed as a black outline

There is a similar situation with rainy season demise (Fig. 3.2). We can see the distribution shift to the right, indicating a delayed end to the rainy season. Taken together, the shift in onset and demise indicates a delay in the entire rainy season for West Africa. The bimodality of the observational distribution likely arises as a result of low data compared to the model distributions. Future studies may consider bootstrapping to address this.

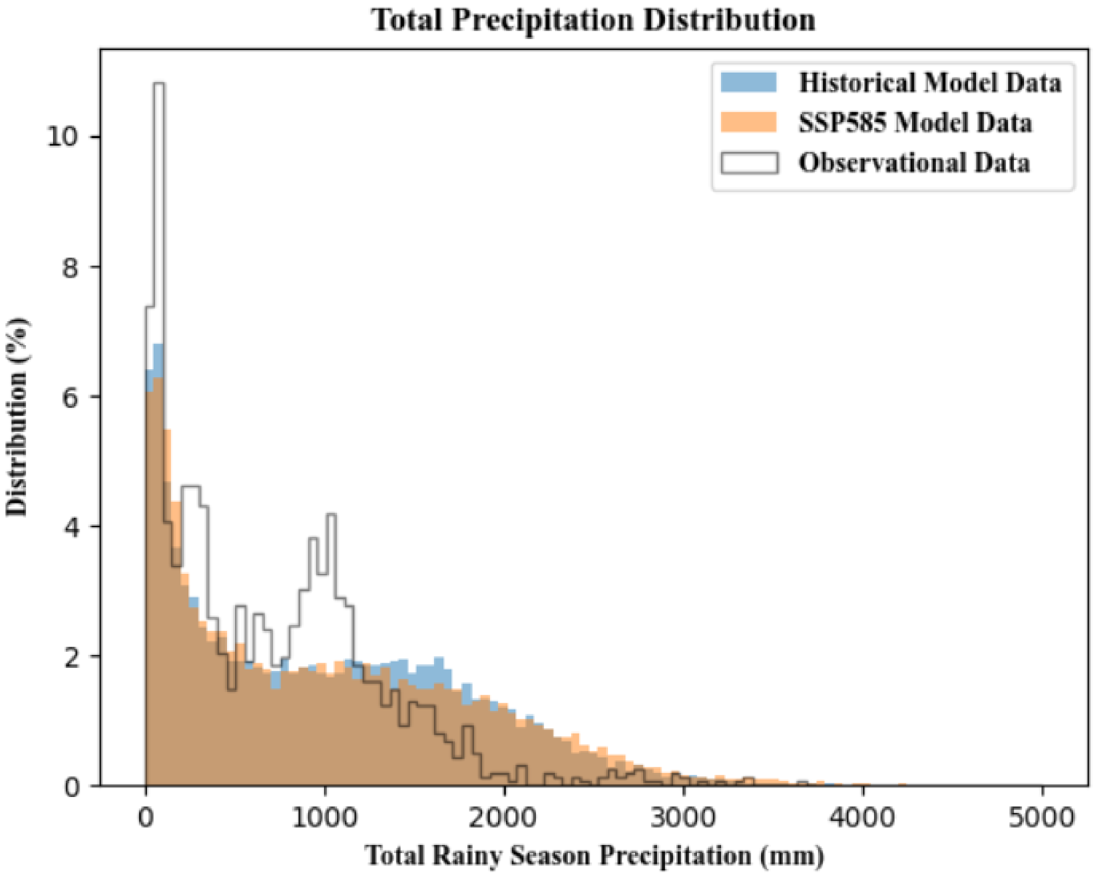

Figure 3.3: Total Rainy Season Precipitation Distribution; Model data is shown in solid colors, with historical data in blue and SSP585 data in orange; CHIRPS data is superimposed as a black outline

The last variable of interest is total precipitation during the rainy season. In most places along the distribution, historical and projected model data adhere closely compared to observational data, but there are a few notable places of deviation (Fig. 3.3). In general, we expect more precipitation along the entire distribution. The models predict fewer extremely dry years; those with under 100 millimeters of precipitation are expected to be less common, and the models predict more extremely wet years. This extreme is particularly pronounced: the 99th percentile shifts from under 3000 to over 3300 millimeters, meaning that the 1% of already extremely high precipitation years are expected to dramatically increase by 2100, much more so than the rest of the distribution.

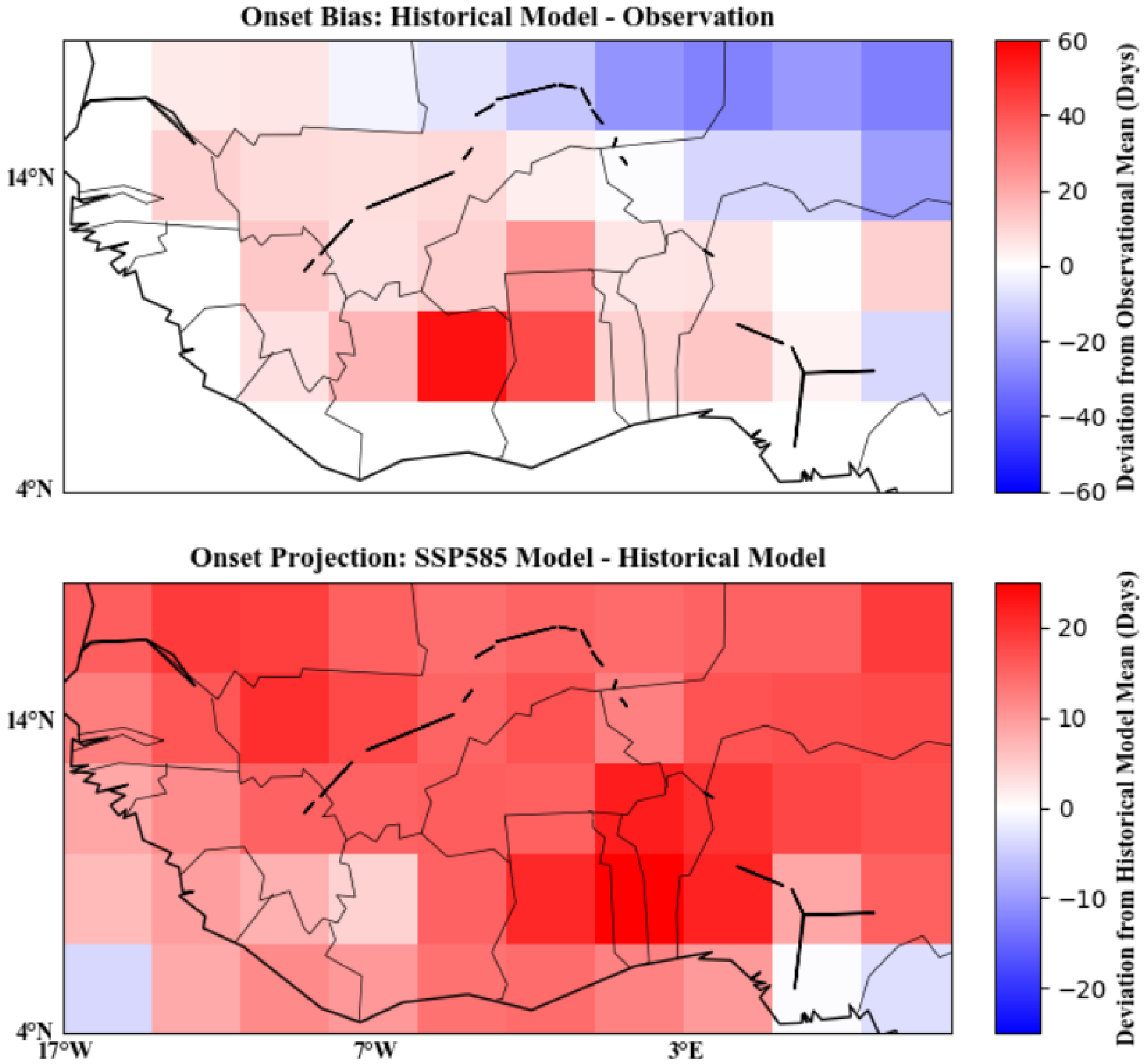

Figure 3.4: Model Bias and Projections for the West African Monsoon Onset under the SSP585 Scenario in the Same Region; White pixels are areas where the two datasets (either the observations and the historical model or the two model ensembles) agree; red pixels are where the historical model shows a later onset than what was observed/where there is a delay in the onset under SSP585; blue pixels are where the historical model places onset earlier than the observations/where there is an early onset under SSP585

The ensemble mean underestimates rainy season onset near the African inlands, while overestimating near the coast (Fig. 3.4). While most model bias is within a range of a few weeks of the observational data, in the northeast of the Ivory Coast, as well as in central Ghana, model bias is most extreme; the ensemble predicts a delay in the onset of nearly two months.

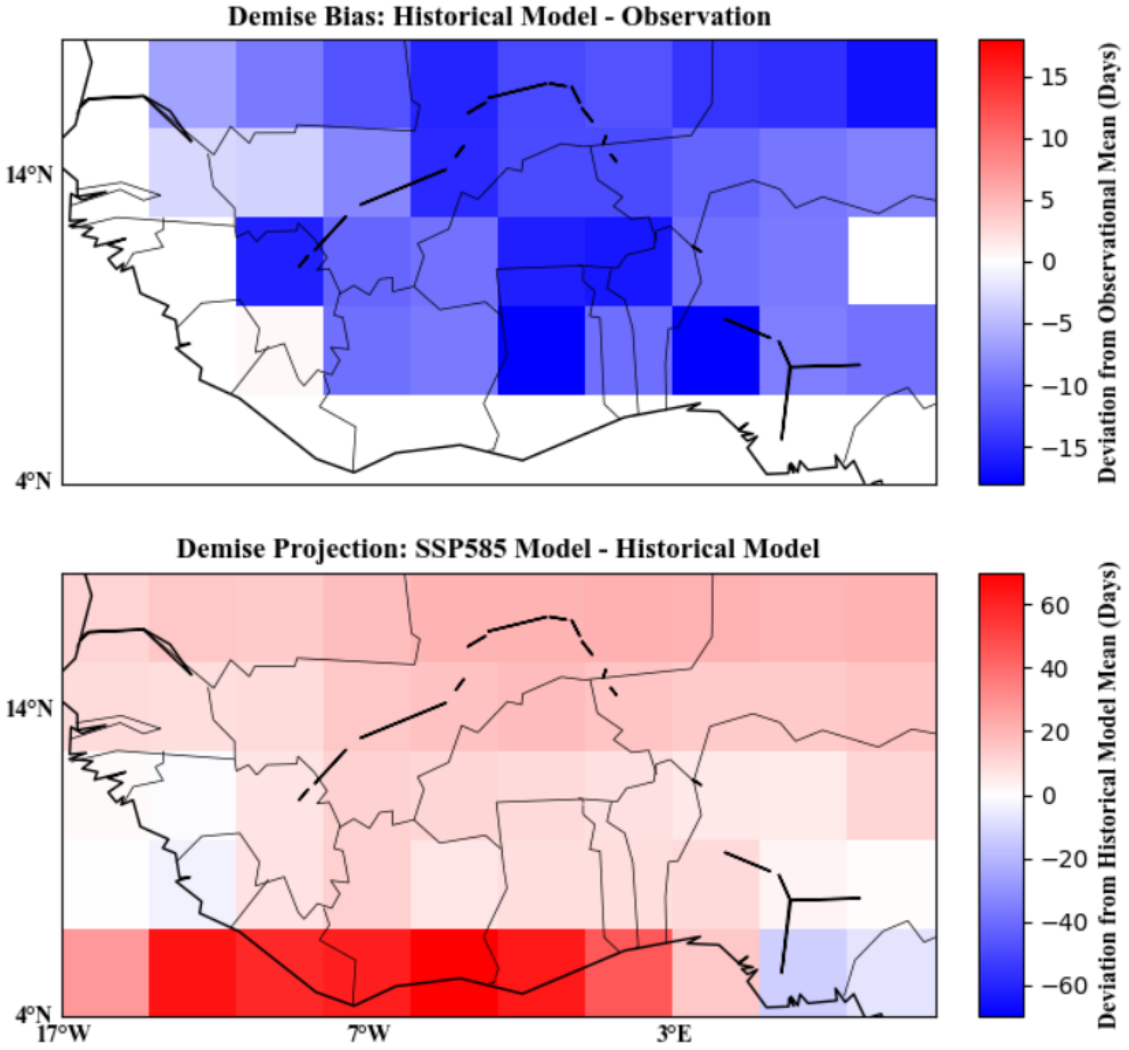

Figure 3.5: Model Bias and Projections for the West African Monsoon Demise under the SSP585 Scenario in the Same Region; White pixels are areas where the two datasets (either the observations and the historical model or the two model ensembles) agree; red pixels are where the historical model shows a later demise than what was observed/where there is a delay in the demise under SSP585; blue pixels are where the historical model places demise earlier than the observations/where there is an early demise under SSP585

In contrast, model bias for the demise is nearly uniformly early, but to a much smaller degree than the onset extremes, with the most severe underestimations at only two weeks (Fig. 3.5). This is remarkable clarity in the context of the model bias. The models project a delay of monsoon demise of a similar magnitude to that of the onset delay (Fig. 3.4), with the notable exception of the coast, where demise is expected to be delayed up to two months.

Unlike the CHIRPS observational data, the ensemble mean offers insight into off-shore climate conditions. The delay in monsoon onset is apparent from the figure, as is the uniformity and limitation of the scope (Fig. 3.4). A warming climate can shift the entire monsoon season later, as the demise is also expected to be delayed. This is expected to be of a similar magnitude to the onset delay, nearing a few weeks for most areas, and limited to two months in the majority of the most extreme cases (Fig. 3.5).

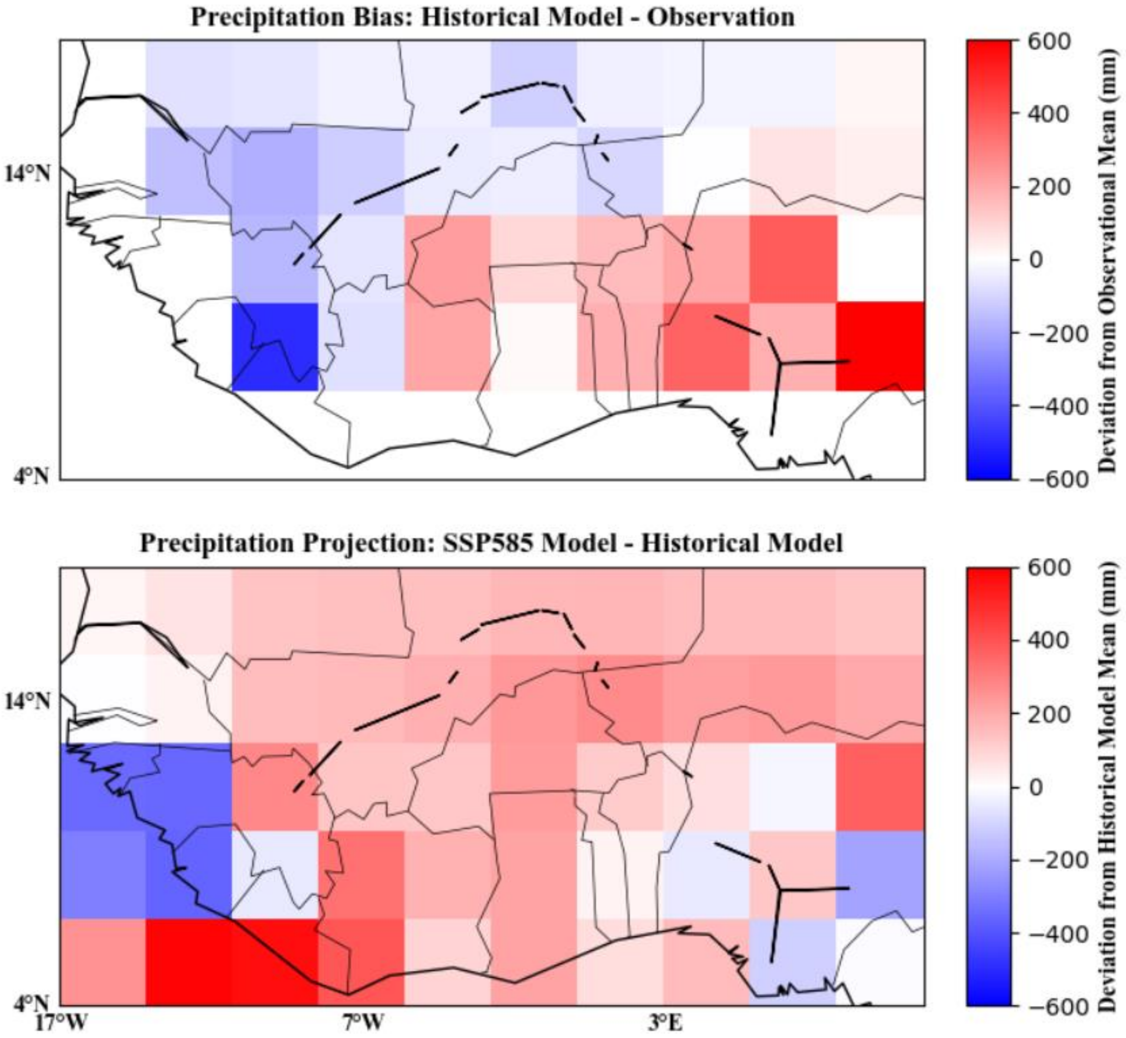

Figure 3.6: Model Bias and Projections for the West African Rainy Season Precipitation under the SSP585 Scenario in the Same Region; White pixels are areas where the two datasets (either the observations and the historical model or the two model ensembles) agree; red pixels are where the historical model shows more precipitation than what was observed/where there is an increase in precipitation under SSP585; blue pixels are where the historical model places precipitation higher than the observations/where there is an increase in precipitation under SSP585

The model bias for the ensemble's estimation of precipitation is far more disparate in uniformity (Fig. 3.6). There is little spatial cohesion in the estimate of bias, as the amount of precipitation varies wildly from year to year. This can be more accurately confirmed through an analysis of the Gaussian distribution; although that perspective collapses spatial distribution to one point, we are able to see the temporal variance, giving some insight into the regularity of the monsoon system, at least for the years during which we have historical observations available.

The projection of precipitation is an interesting case, as the expectation is just as disparate as the model bias, but also includes regional grouping of phenomena. For example, along the coasts of Sierra Leone, Guinea, and Guinea-Bissau, we can expect radical drying during the monsoon season, whereas further inland, we may expect a less extreme but more widespread increase in precipitation (Fig. 3.6).

Interestingly, in the edge cases in Central Nigeria with a significant bias, we can expect the SSP585 scenario to decrease precipitation. This is demonstrable regardless of inconsistency between pixels (Fig. 3.6).

4. CONCLUSION

This paper investigated the projected changes of the timing of and precipitation totals during the wet season over the West African Monsoon under a climate change scenario. We found that the current state-of-the-art climate models project a delay in both onset and demise of the wet season. The model also projects an increase in wet season rainfall.

The projected delay in monsoon demise is commensurate with the model bias, which underestimates demise for the twentieth century, potentially implying the models project an exaggerated delay for the demise, but this is not the case for onset. On the contrary, the onset biases are of similar magnitude to its projections, but in the same direction; thus, the onset delay we measure may exceed that which is projected by the models. The model ensembles show that the bias for demise is uniform, while the bias for onset differs according to proximity to the coast.

The distributions summarize how these models compare to the observed data. The rightward shifts that are characteristic of the extremes of the distributions are in agreement with the delays apparent by the maps, while the deviation in model projection for the precipitation distribution is uniquely consistent with the precipitation map's spatial deviations.

We can expect the monsoon to shift later in the year around the scale of one to two weeks. This has implications for water use policy, as planners should expect a delayed precipitation regime. Moreover, the shift in the precipitation data implies that West Africans should consider the increased probability of extreme rainfall during the wet season and plan accordingly.

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