Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL084872

Key Points:

- A 2D monsoon model produces similar changes to general circulation models in monsoon features when sea surface temperatures are increased
- Southward shift of the rainband is connected to regional forcing, while Sahel precipitation decrease is mainly driven by larger-scale change
- Precipitation change is strongly linked to large-scale drivers of temperature and moisture with additional spread from parameterizations

Supporting Information:

- Supporting Information S1

Correspondence to:

R. D. Dixon,
 rddixon@wisc.edu

Citation:

Dixon, R. D., Peyrillé, P., & Guichard, F. (2019). Sahelian precipitation change induced by SST increase: The contrasting roles of regional- and larger-scale drivers. *Geophysical Research Letters*, 46, 11,378–11,387. <https://doi.org/10.1029/2019GL084872>

Received 5 AUG 2019

Accepted 30 AUG 2019

Accepted article online 6 SEP 2019

Published online 23 OCT 2019

Sahelian Precipitation Change Induced by SST Increase: The Contrasting Roles of Regional and Larger-Scale Drivers

Ross D. Dixon¹ , Philippe Peyrillé¹, and Françoise Guichard¹

¹Centre National de Recherches Météorologiques, UMR 3589 CNRS and Météo-France, Toulouse, France

Abstract Representing the West African Monsoon is a major challenge in climate modeling because of complex mechanisms of interaction across scales. We study the monsoon precipitation response to a 4K increase in sea surface temperatures using an idealized meridional-vertical (2D) model, which allows separating regional- and larger-scale influences. The 2D simulations reproduce key features of Atmospheric Model Intercomparison Project simulations and indicate that, in response to sea surface temperature increase, large-scale changes induce a decrease of Sahel precipitation, while regional-scale mechanisms generate a southward shift of the rainband. Large-scale changes moisten and warm the free troposphere, while regional circulation changes increase low-level moisture. Precipitation in the control simulations accounts for much of the variance in precipitation change for both Atmospheric Model Intercomparison Project and 2D simulations. This response is strongly connected to the large-scale drivers of temperature and moisture, with an additional spread associated with the formulation of the convective parameterization.

Plain Language Summary The Sahel region of West Africa receives most of its annual rainfall during the monsoon season. Projections of monsoon precipitation are important to the region's growing population, yet climate models disagree on the magnitude and direction of precipitation change in future climates. This study uses a simplified model of the West African monsoon, which we show behaves similarly to complex global climate simulations. Our model allows us to disentangle monsoon changes due to directly changing sea surface temperatures from changes due to the larger-scale response to increased temperatures. We find that both play important roles in precipitation change, the direct forcing shifts the precipitation, while the large-scale forcing produces drying. Processes that occur on small spatial scales play an important role in producing precipitation. We investigate how a few of these are represented in our model and discover that the change in precipitation is mostly dependent on how the large-scale forcing produces precipitation in the current climate, with a spread that is connected to how these physical processes are represented. Our study shows the usefulness of a simplified monsoon model and increases understanding of how increasing sea surface temperatures alter the West African monsoon.

1. Introduction

The West African Monsoon (WAM) is the result of a complex interplay between the land, the ocean, and the atmosphere (Nicholson, 2013). Several studies have shown that WAM precipitation is strongly influenced by physical processes (e.g., atmospheric convection and surface fluxes) as well as regional- (Dixon et al., 2017; Nicholson & Webster, 2007) and larger-scale mechanisms, for example, the Madden-Julian Oscillation (Matthews, 2004) or the Indian Monsoon (Flaounas et al., 2012). Representing the climatic evolution of rainfall with global climate models (GCMs) is still a challenge due to lack of observations and incomplete understanding of subgrid-scale processes. GCMs have difficulties producing the rainfall distribution in the current climate (Roehrig et al., 2013; Martin et al., 2017), as well as in climate projections, where models disagree on both the magnitude (Seth et al., 2013; Vizi et al., 2013) and sign (Park et al., 2015; Biasutti & Sobel, 2009) of precipitation change.

The complexity of this regional response to global climate change has been explored in GCM simulations that separate changes in sea surface temperatures (SSTs) and CO₂ (Chadwick et al., 2017; Bony et al., 2013). Many studies have also focused on the role of SST distributions, as SSTs are important to Sahel precipitation on intraseasonal to interdecadal time scales (e.g., Folland et al., 1986; Giannini et al., 2003, 2013,

Rodríguez-Fonseca et al., 2015), and, in addition, explain a large portion of the climate projections of precipitation change (Held et al., 2005; Biasutti & Sobel, 2009; Park et al., 2015).

The Sahel is a region where precipitation change in climate scenarios is highly uncertain in sign and magnitude when using coupled models. Using idealized simulations with fixed SSTs, Gaetani et al. (2017) found that a global 4K increase of SSTs induced a decrease in WAM precipitation coupled with a southward shift of the rainband and attributed this response primarily to the global SST change. Their methodology shows a robust climate response when SSTs are fixed but does not directly separate the regional and global effects of SST changes. As presented below, our study addresses this issue by directly separating the large-scale response associated with global SST change from the regional meridional response to local SST increase.

Hill et al. (2017) showed that the response of Sahelian precipitation to SST increase changed from negative to positive in the Geophysical Fluid Dynamics Laboratory (GFDL) GCM when they introduced another convective parameterization. This was attributed to how the change in the moist static energy budget depended on the mean state of the current climate simulation. This mechanism was also seen in a larger ensemble of GFDL and Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations by Hill et al. (2018), who showed that models that produced more precipitation in their control simulations tended to produce more drying under increased SSTs. They hypothesized that the choice of parameterizations used in these models was the primary driver of different precipitation responses to global changes in SST. In this study, we explore a wide range of convective parameters to investigate the sensitivity of the monsoon response to choices in model parameterizations.

Limitations and complexities associated with GCMs have been addressed through a variety of approaches. These include innovative analyses that separate dynamical and thermodynamical components of the moisture budget (e.g., Seager et al., 2014) or simulations that isolate particular scales of interactions or physical processes of interest (Maher et al., 2019). For the WAM, these include dynamical downscaling (Akisanola & Zhou, 2018, 2019a), convection-permitting simulations (Stratton et al., 2018), and idealized models of the WAM (Peyrillé & Lafore, 2007; Peyrillé et al., 2007; Shekhar & Boos, 2017; Zheng et al., 1999). In order to gain a more basic understanding of the WAM response to increased SSTs, the present study uses a 2D meridional-vertical WAM model that is able to capture critical features of the WAM (Peyrillé & Lafore, 2007; Peyrillé et al., 2007) and to explore the sensitivity of the monsoon to several key aspects of the monsoon water cycle (Peyrillé et al., 2016). In particular, this framework allows the separation of 2D processes (regional meridional) from all other processes (global, large-scale, and regional zonal). We use it to separately analyze the large-scale response associated with global SST change, from the regional meridional response to local SST increase and to further explore the sensitivity of the monsoon response to a wide range of choices in model parameterizations.

As shown below, the model produces dynamic, thermodynamic, and precipitation changes, which are similar to those in GCMs. Both regional- and larger-scale forcings are shown to be important to capturing the full monsoon response. Analysis of intermodel variability and sensitivity experiments shows that the strength of the monsoon response is strongly influenced by choices of convective parameters, but the direction of change is more sensitive to the large-scale distribution of temperature and moisture that controls the current climate precipitation.

2. Data and Methods

We use the 2D model of Peyrillé et al. (2016; see also Peyrillé & Lafore, 2007; Peyrillé et al., 2007). This model represents a meridional-vertical transect centered along the prime meridian from 30°S to 40°N, with 22 vertical levels and a horizontal grid size of 150 km; this leads to a similar spatial resolution compared to the GCMs whose behavior we are investigating. Perpetual August simulations (incoming solar radiation, SST, and large-scale forcing fixed at August values) are run for 3 years, and we analyze the system once it has reached an equilibrium state. In practice, we consider the final year.

Following Peyrillé et al. (2016), the influence of larger-scale motions is taken into account in the simulations by prescribing a large-scale forcing, LS FRC, which represents the effects of regional and global dynamics missing in our 2D regional model (waves, zonal advection, and connections with the global scale). First, the model is run with a 3-day relaxation to zonally averaged 10°W to 10°E transects of potential

temperature and specific humidity taken from a reference state (e.g., reanalyses in Peyrillé et al., 2016). From this simulation, large-scale advective tendencies are derived from the temperature and specific humidity budgets. The simulations used in this paper apply these large-scale advective tendencies, along with a 10-day relaxation (to prevent potential model drift; in practice, this term is very small). See supporting information section S1 for further discussion of the 2D model formulation.

In Peyrillé et al. (2016), the authors investigated the dynamics of the annual cycle using large-scale forcing derived from reanalyses. In this study, the LS FRC is derived from reference states of 11 CMIP5 models (Taylor et al., 2012). We use CMIP5 output from simulations with fixed historical SSTs (Atmospheric Model Intercomparison Project [AMIP]) and simulations with SSTs increased by 4K everywhere (AMIP +4K SST). The models used here are listed in Table S1.

Three +4K SST simulations were run with the 2D model: REG, where SSTs are increased by 4K, while the large-scale forcing remains the same as in the control runs; LS, where the SSTs are the same as the control runs, but the large-scale forcing is derived from the AMIP +4K SST simulations; and REG+LS, which is forced by both increased SSTs and large-scale forcing from the AMIP +4K SST simulations. In this way, we can consider the 2D WAM response to only increasing SSTs (REG), the response to directly altering the meridional distribution of moisture and temperature (LS), and response to changes in both (REG+LS). We perform one set of 2D simulations for each AMIP simulation, and the results presented in sections 3.1 and 3.2 are for ensemble averages from these runs.

In the experiments in which the SST is altered (REG+LS and REG), the 2D model represents explicitly the response of the meridional-vertical circulation to a regional change in SST. In the experiments where the LS FRC is changed (REG+LS and LS), the 2D model simulates the response of the 2D circulation to the regional signature of remote influences (global SST change and connection with the tropics) and regional zonal dynamics.

3. Results

3.1. Precipitation Change in Response to SST Increase

Figure 1 shows the mean August precipitation profiles and anomalies from the AMIP and 2D ensembles. The AMIP profiles (averaged between 10°W and 10°E; Figure 1a) produce a decrease and southward shift in precipitation when SSTs are uniformly increased by 4K, consistent with Gaetani et al. (2017).

The 2D control ensemble (Figure 1b, black line) reproduces the general precipitation pattern seen in the AMIP simulations (Figure 1a, black solid line), although it underestimates precipitation in the Sahel and produces more precipitation north of 20°N (see Peyrillé et al., 2016, for more information on this issue).

In the REG+LS simulations (Figure 1b, orange line), the 2-D model produces the major features of the precipitation signal seen in the AMIP +4K SST simulations: Precipitation decreases north of 7°N, with a slight increase of precipitation along the coast, suggesting a southward shift of the rainband. The decomposition of the precipitation change using the large-scale and regional experiments is also shown in Figure 1b. The REG simulations (red line) produce a strong increase in precipitation south of 13°N (at the coast and in the southern Sahel). The LS simulations (blue line) produce a decrease in precipitation everywhere and shift the rainfall maximum slightly to the north. To the extent that the AMIP +4K SST and the REG+LS experiments share the same sensitivity, this implies that the AMIP +4K SST response is the result of both regional- and large-scale mechanisms. The southward shift in the 2D REG+LS is associated with regional circulation changes, while the decreased precipitation is driven by changes in the large-scale circulation.

The difference between the AMIP and 2D response is shown in Figure 1c. The magnitude of the precipitation response is similar in the AMIP +4K SST (black dashed line) and REG+LS (orange line). The 2D model ensemble produces a larger southward shift in precipitation than seen in the AMIP and a smaller decrease in Sahel precipitation. There is a large amount of variability between the simulations, which will be explored in section 3.3. Next we investigate the thermodynamic and dynamic response in the AMIP and 2D simulations to understand why the 2D model responds in the way it does and how decomposing the large-scale and regional signals contribute to the combined response.

Figure 1. Ensemble mean precipitation profiles (mm/day) for AMIP and 2D simulations. (a) AMIP simulations: AMIP (black solid) and AMIP +4K SST (black dashed). (b) 2D simulations: Control (black), REG+LS (orange), REG (red), and LS (blue). (c) Precipitation anomalies for REG+LS (orange), REG (red), LS (blue), and AMIP +4K SST (dashed black). AMIP = Atmospheric Model Intercomparison Project.

3.2. Thermodynamic and Dynamic Response

Changes in precipitation can be associated with local changes in static stability documented here with mean equivalent potential temperature (θ_e), potential temperature (θ), and $\theta_e - \theta$ anomalies averaged over the Sahel (10–20°N) for the 2D and AMIP simulations (Figure 2).

In the AMIP +4K SST simulations, there is a large increase in θ_e (between 10 and 15 K) throughout the entire column (black dashed line, Figure 2a). This is due to both warming (Figure 2b) and moistening (Figure 2c). The increase in specific humidity in the lower troposphere results in a slight decrease in stability below 6 km. The REG+LS simulations (orange line) closely reproduce the changes in moisture, temperature, and stability seen in the AMIP simulations.

The REG simulations (red line) produce a modest (2–4 K; Figure 2b) increase in low-level temperature, accompanied by moistening below 1 km and drying above (Figure 2c). These changes lead to a large (5 K) increase in moist static energy below 1 km, which destabilizes the lower levels. This destabilization, dominated by low-level moisture changes, is consistent with the increase in precipitation seen in this region (Figure 1c). The LS simulations (blue line) produce the large increase in θ_e seen in Figure 2a, explained by an increase in temperature (Figure 2b) and an increase in specific humidity in the free troposphere. This results in a slightly more stable θ_e profile, which is consistent with the decreased precipitation in these simulations. Extending the 2D results to the AMIP ensemble, it suggests that in AMIP +4K SST experiments, the large-scale changes moisten the free troposphere, while the regional meridional response is important for moistening the lower levels.

The moisture response across the full domain can be seen in latitudinal profiles of the change in precipitable water (PW), shown in Figure 2d. In the AMIP +4K SST simulations (black dashed line), there is a very large increase in PW, which approaches 20 mm between the coast and southern Sahel. The magnitude and location of this increase is well captured by the REG+LS simulations (orange line). Both the REG (red line) and LS (blue line) responses produce an increase in PW south of 10–15°N (by 5 to 10 mm); however, further north, this increase weakens, and Δ PW becomes negative across the northern edge of the Sahel. This recalls the vertical profiles shown in Figure 2c, which indicate that the regional- or large-scale forcing experiments are unable to produce the increase in water vapor throughout the entire column seen in the AMIP and REG+LS simulations.

Focusing now on the dynamics, vertical profiles of meridional and vertical wind in the 10–20°N region (Figure S1) show that the 2D control ensemble produces a vertical structure similar to the AMIP control ensemble, although the 2D simulations produce more top-heavy omega profiles. The 2D simulations also produce the same changes to the meridional circulation, with the LS and REG+LS ensembles intensifying the background meridional wind in the lowest levels and strengthening the return flow around 700 mb. This corresponds to a strengthening of the shallow meridional circulation and, in this region, slight anomalous accent in the lower levels with anomalous descent above.

Figure 2. Change in (a) ensemble mean equivalent potential temperature (θ_e), (b) potential temperature (θ), and (c) $\theta_e - \theta$ averaged over the Sahel region (10–20°N), along with (d) change in column precipitable water across the domain and (e) change in 0- to 500-m θ . In each plot, AMIP +4K SST (black dashed), REG+LS (orange), REG (red), and LS (blue).

Strengthening of the return flow is associated with a southward shift of the Saharan Heat Low (SHL; Shekhar & Boos, 2017). The meridional structure of low-level (averaged below 500 m) θ (Figure S2) also informs on the location of the SHL. The REG+LS (orange) simulations reproduce the large but nearly uniform increase in low-level θ seen in the AMIP +4K SST simulations (black dashed). There is slightly more warming above 10°N, which is associated with the slight southward shift in the SHL shown by Gaetani et al. (2017). When the forcings are separated, we find that the LS (blue) simulations produce a larger increase in low-level θ , whose maximum is located more southward. This southward shift in the SHL is connected with the strong decrease in precipitation across the Sahel (Dixon et al., 2017; Shekhar & Boos, 2017). The REG (red) simulations produce a smaller increase in low-level θ , which is complicated by a decreased warming along the coast associated with the increased precipitation there.

Changes in low-level zonal winds (Figure S3) also inform on changes in the dynamics of the SHL. In the REG+LS and LS simulations, there is a strengthening of the zonal wind below 850 mb between 15°N and 20°N, coupled with a weakening of the zonal wind north of 20°N, suggesting a southward shift in the zonal circulation associated with the SHL. In the REG simulations, the low-level zonal wind is weakened north of 10°N.

Changes to large-scale zonal features (i.e., the African Easterly Jet (AEJ), the Tropical Easterly Jet (TEJ), and SHL) strongly influence Sahel precipitation (Akinkanola & Zhou, 2019b; Nicholson, 2013). In the REG+LS, LS, and REG simulations, there is a strengthening and southward shift of the AEJ (Figure S1), which mirrors changes seen in AMIP (Gaetani et al., 2017). The TEJ is weakened in both AMIP and 2-D simulations. These zonal wind changes are associated with changes in the gradients of temperature, which in the 2-D simulations are forced by both the LS FRC and changes in meridional and vertical temperature advection. It is important to note that in our 2-D framework, the zonal wind does not advect heat, specific humidity, or momentum so that the LS FRC accounts for changes in temperature and moisture due to the zonal circulation.

The large increase in θ_e in REG+LS is associated with relatively weak changes in stability (Figure 2a), suggesting changes in meridional dynamics play an important role in the precipitation response. Analysis of the meridional circulation for both the LS and REG+LS simulations showed a weakening of the

circulation consistent with the AMIP ensemble (not shown). The advection term in the moisture budget was decomposed into dynamic (due to changes in circulation) and thermodynamic (due to changes in the water vapor gradients) components following the methodology used by Seager et al. (2014; Figure S4). Changes in precipitation minus evaporation ($P-E$) are strongly linked to changes in the dynamic component, while the thermodynamic component primarily balances changes in the LS FRC. The REG+LS experiment is not the sum of the two separate experiments, which shows nonlinearities are important. However, the REG+LS simulations produce the two dominant features of the REG and LS experiments, supporting the hypothesis that the increase of $P-E$ south of the peak precipitation is mainly driven by changes in SST, while the decrease of $P-E$ north of it seems related to changes in LS FRC.

3.3. Intermodel Variability

Although the ensemble mean produces a consistent response of the idealized monsoon to climate forcing, there is variability between the individual simulation responses. This is illustrated in Figure 3a, which shows the relationship between the change in Sahel precipitation and the control Sahel precipitation for both the REG+LS simulations (red) and the AMIP +4K SST simulations (blue).

While most of the 2D simulations produce a decrease in precipitation across the Sahel, a few simulations produce more precipitation. This increase in Sahel precipitation is not seen in the AMIP +4K SST ensemble, but Hill et al. (2017) showed that, with certain parameter choices, the GFDL model produces an increase in precipitation with +2K SST forcing. Both 2D and AMIP simulations that produce more precipitation in their control runs tend to have the largest decrease in precipitation when SST warming is applied. The 2D simulations produce a stronger relationship ($R=-0.87$) than the AMIP simulations ($R=-0.44$) and the 2D response is stronger than the AMIP response (both correlations significant at a 90% confidence interval).

In the separated REG and LS simulations, there is a strong, statistically significant relationship between anomalous and control precipitation in the REG simulations ($R=-0.78$), with a not statistically significant relationship in the LS simulations ($R=-0.38$). This indicates that the meridional circulation change associated with the increase in SSTs is primarily responsible for the explained variance between control and anomalous Sahel precipitation. Meridional mechanisms in the +4K SST AMIP simulations were explored by Hill et al. (2018), who found that Sahel precipitation is “reduced more in models with greater subsidence anomalies, greater enhancement of the meridional MSE gradient in the middle and upper troposphere, and more top-heavy climatological ascent.” We explore these dynamical relationships below and assess whether they are also present in the 2D simulations.

Figure 3b shows the correlation between the 10–20°N omega and precipitation anomalies at each model level for both the AMIP ensemble (blue) and 2D ensemble (red). Both ensembles have positive correlations below 800 mb, which are stronger toward the surface. Between 800 and 600 mb, both ensembles have negative correlations, which produces the strongest relationships around 600–700 mb, indicating that when SSTs are increased, models that produce more subsidence at these levels produce less precipitation.

This relationship between a decrease in Sahel precipitation and increased subsidence remains strong above 600 mb in the AMIP simulations but becomes statistically insignificant in 2D. Consistent with the arguments of Hill et al. (2018), the 2D simulations (in which precipitation decreases more in response to SST increase than in AMIP; Figure 3a) produce more top-heavy omega profiles (Figure 3c). Below 600 mb, where the 2D and AMIP simulations produce similar control omega profiles, there is good agreement in the relationship between the change in omega and the change in precipitation, suggesting similar dynamical mechanisms are responsible for the relationship between change in precipitation and control precipitation found in the AMIP and 2D ensembles.

We also analyzed the meridional gradient of θ_e and found that the gradient of θ_e becomes more enhanced in the lower and middle troposphere for all the REG+LS simulations at higher SSTs, in the same manner as in the simulations analyzed by Hill et al. (2018). This further supports the hypothesis that the same dynamical mechanisms produce this response in both 2D and 3D simulations.

3.4. Sensitivity to the Convection Parameterization

Numerous studies (e.g., Chadwick et al., 2017; Martin et al., 2017) have shown WAM precipitation is highly sensitive to physical parameterizations, most notably those for the convection scheme. Here we explore this

Figure 3. (a) Average 10–20°N change in precipitation versus the average 10–20°N control precipitation for REG+LS (red) and AMIP +4K SST (blue). (b) Correlation coefficients for each model level between the mean 10–20°N omega and precipitation anomalies for both AMIP (blue) and 2D (red). (c) Control simulation average 10–20°N omega for AMIP (blue) and 2-D (red) simulations. Ensemble average is given in the thick contour, with each ensemble member shown in the lighter, thinner contours. AMIP = Atmospheric Model Intercomparison Project.

sensitivity in the 2D model by altering the Kain-Fritsch/Bechtold convective parameterization (Bechtold et al., 2001). In this convection scheme, the precipitation efficiency (Peff), the fraction of condensate that reaches the surface as precipitation, is estimated as a function of the cloud base height and wind shear. Figure 4a shows the change in Sahel precipitation (10–20°N) when we fix Peff to values from 0 to 1.

Larger values of Peff lead to more precipitation, mirroring the sensitivity found by Peyrillé et al. (2016). When Peff is set to 0, there is so little precipitation in the Sahel that the +4 K SST forcing produces very little precipitation change. For values of Peff between 0.2 and 1, most simulations produce drying across the

Figure 4. The change in Sahel precipitation (10–20°N) for Peff sensitivity experiments. In (a), the response is grouped for each value of Peff, with each individual simulation shown in the colored points (representing the control Sahel precipitation) and mean for each ensemble in the large black points, while in (b), all Peff simulations with the same LS FRC are grouped together. Panels (c) and (d) have the same ensembles as (a) and (b), respectively; however, the response is plotted against each ensemble mean precipitation in the current climate (P_C), with each individual simulation shown in gray and the ensemble mean in black. The regression lines, correlation coefficients, and slopes show the relationship between the mean precipitation in the current climate and change in precipitation for the ensemble means. LS FRC = large-scale forcing; Peff = precipitation efficiency.

Sahel regardless of the value of P_{eff} . There is increased variability in precipitation change for simulations with larger values of P_{eff} associated with more precipitation.

For each set of P_{eff} simulations, the simulations that produce more control precipitation tend to produce more Sahel drying. This can be seen by organizing the simulations by LS FRC instead of P_{eff} value (Figure 4b), which shows that many simulations with the same LS FRC produce drying, while a smaller number produce moistening, regardless of the P_{eff} value. Plotting the P_{eff} and LS FRC ensembles as a function of ensemble mean current climate precipitation (P_C ; Figures 4c and 4d) shows that there is a strong relationship when simulations are grouped by LS FRC, where LS FRCs with less (more) current climate precipitation produce positive (negative) changes in Sahel precipitation. This is consistent with the relationship shown in Figure 3a and suggests that it is strongly driven by the meridional distribution of temperature and water vapor (which in our model are constrained by the LS FRC). In this perspective, the sensitivity to the convection scheme can be seen as a source of spread for this relationship (Figure 4b).

This hypothesis was further tested by altering the deep convective adjustment time scale (K_{ADJ}). K_{ADJ} determines the rate that subgrid-scale convection removes convective instability. Shorter time scales continually vent the lower levels, while longer time scales effectively turn off the convective scheme. In general circulations models, K_{ADJ} is on the order of 1 hr (Collins et al. 2006), while observational studies have suggested that K_{ADJ} ranges from 600 s to 3 hr (Bechtold et al., 2008; Kain & Fritsch, 1993). We perform sensitivity experiments where K_{ADJ} ranges between the extreme values of 5 min to 2 days.

The sensitivity of the monsoon response to changes in K_{ADJ} (Figure S3) is similar to the sensitivity to changes in P_{eff} . Simulations tend to produce a decrease in Sahel precipitation for all values of K_{ADJ} , and simulations that precipitate the most tend to dry the most. Organizing these simulations by LS FRC emphasizes the role of large-scale distributions of moisture in temperature in the monsoon response and reinforces our hypothesis.

4. Discussion and Conclusions

In this study we investigated the change in the WAM to an increase in SST with an idealized 2D model. When forced with both increased SSTs and the large-scale forcing associated with a global increase in SST, the 2D model produces a southward precipitation shift and a decrease in precipitation across the Sahel, similar to AMIP simulations. Increasing SSTs changes both the regional- and large-scale circulations, which we were able to separate and explore using the 2D model.

Both the large-scale and regional circulation changes play an important role in the increase in temperature and moisture seen in AMIP simulations under increased SST forcing. The large increase in θ_e is primarily due to the large-scale forcing, which agrees with Gaetani et al. (2017) who found that the +4K SST response was associated with a global “almost uniform” increase in moist static energy. They associated this with a global increase in water vapor. Our study shows that in the free troposphere, this increase of water vapor is indeed connected to changes in the large scale. However, regional circulation changes appear as the main driver of boundary layer moistening, which is critical for precipitation processes (Crook, 1996).

Analysis of the meridional circulation shows that the 2D model produces a weakened deep overturning circulation that is primarily associated with changes in the large-scale forcing, consistent with AMIP simulations (Gaetani et al., 2017). The decrease in Sahel precipitation cannot be explained by thermodynamics alone. The large increase in θ_e is associated with relatively weak changes in convective instability (Figure 2a) so that changes in dynamics appear to play a crucial role in precipitation changes.

There is a large range of Sahel precipitation responses among simulations (both AMIP and 2D), from strong drying to slight moistening. A large amount of variance in Sahel precipitation change is explained by the strength of precipitation in the control simulations and is dominated by the regional response. This variability is also seen in the AMIP simulations (Hill et al., 2018): Stronger drying in models with more convective activity is associated with increased subsidence and strengthened meridional gradient of θ_e in both the 2D and AMIP simulations.

We also found a strong sensitivity to the convective parameterization. By altering the P_{eff} and deep convective adjustment time in the convective parameterization scheme, we were able to produce control

precipitation that spans the range of AMIP values (almost no precipitation to 8 mm/day). Applying these parameterization changes to the LS+REG simulations shows they are more directly sensitive to the differences in large-scale advective forcing. This has implications for how altering convective parameterizations changes the WAM response to climate forcings. These simulations suggest that precipitation change in models are more sensitive to the ensemble of processes that control large-scale gradients in temperature and moisture (i.e., large-scale biases and parameterizations feedbacks onto regional and large scales), than directly and exclusively to changes in convection schemes.

In summary, in our simulations, the large-scale forcing produces the drying seen in the AMIP simulations, while the regional effect of increasing SSTs is critical for shifting precipitation southward, and the interactions between the two produce a large range of precipitation changes. These results highlight the difficulties in projecting precipitation in the Sahel region and stresses the importance of both large-scale and regional mechanisms in the Sahel precipitation response to an increase in regional and global SSTs and point to the value of models of intermediate complexity to advance our understanding of this question. Although specifically developed for the WAM in this study, our approach may be useful for investigating changes in other monsoon systems and tropical rainbands.

Acknowledgments

This research was supported by AMMA-2050. The model used in this study (MesoNH) can be obtained online (<http://mesonh.aero.obs-mip.fr/mesonh54>). We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP5, and we thank the climate modeling groups (listed in Supporting Information S1) for producing and making available their model output. The AMIP output can be found using the Earth System Grid Federation (ESGF; <https://esgf.llnl.gov/>). We thank the Editor and reviewers for their comments which helped improve and clarify this manuscript.

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