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Journal
Journal of Geophysical Research: Atmospheres, 124(3)

ISSN
2169-897X

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Publication Date
2019-02-16

DOI
10.1029/2018jd029160

Peer reviewed

Using Information Theory to Evaluate Directional Precipitation Interactions Over the West Sahel Region in Observations and Models

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Abstract

Water availability has historically been one of the most significant threats to African regional social and economic well-being. Over the Sahel region, a megadrought during the 1960s and 1970s induced by an abrupt and substantial rainfall reduction caused widespread famine and death. The postdrought recovery, which is still ongoing, has been characterized by gradual increases in rainfall, but with dramatic fluctuations. The large negative human impacts, slow recovery, and variability raise important questions of why and how rainfall dynamics evolve and interact with other components of the regional climate system. Here we provide an observational assessment of rainfall interactions mechanisms (informed by directional transfer of information entropy) that regulate Sahel rainfall. We quantitatively demonstrate that (1) sea surface temperature over the Gulf of Guinea controls moisture advection and transport to the West Sahel region and (2) strong bidirectional interactions exist between local vegetation dynamics and rainfall patterns. Then we assess the directional interaction patterns from nine state-of-the-art Earth System Models (ESMs). We find that most ESMs are able to represent either the unidirectional control of sea surface temperature on precipitation or the bidirectional interaction between vegetation and precipitation. However, none of the ESMs represents both interactive patterns. The GFDL and IPSL-CM5A-LR models successfully reproduced observed patterns over ~50% of the West Sahel region but were not accurate in reproducing observed precipitation regional trends or interannual variation. We propose that the directional information transfer is a powerful mechanistic benchmark to assess model fidelity at the process level.

1 Introduction

Precipitation change over the African Sahel is one of the most dramatic worldwide examples of climate variability (Chappell & Agnew, 2004). The semiarid Sahel region (defined as 10–20°N, 20°W to 40°E) receives mean annual precipitation (MAP) between 100 and 200 mm/year in the north and around 500 to 600 mm/year in the south (Nicholson, 2013). Between the late 1960s and late 1980s, an abrupt 30% decrease in precipitation occurred over most of this region. The impacts of this dramatic precipitation decline were intensified by the region's vulnerable ecological and geomorphological features, resulting in over 100,000 deaths from starvation after the drought (Druyan, 2011). Subsequent recovery of precipitation in Southern Sahel region has been quite limited, and furthermore, Northern Sahel's precipitation decrease even intensified over this duration (Nicholson, 2005).

Recent studies, primarily based on Earth System Model (ESM) outputs, have proposed different hypotheses for factors controlling the variation of Sahel precipitation, including the influence from Atlantic and global sea surface temperature (SST; Folland et al., 1986; Giannini et al., 2003; Rowell et al., 1995); land-atmosphere interactions including from vegetation, albedo, dust, and aerosols (Charney et al., 1977; Huang et al., 2009; Hui et al., 2008; Zeng et al., 1999); the migration of the Intertropical Convergence Zone (Nicholson & Grist, 2003; Sultan & Janicot, 2000); and West African Monsoon (Taylor, 2008; Zheng & Eltahir, 1998). Currently, two interacting mechanisms are widely supported: (1) Warming SSTs weaken the land-ocean temperature contrast and force deep convection toward the ocean (Giannini et al., 2003), leading to reduction in continental moisture convergence, with its impacts intensified by (2) variation in moisture-driven vegetation interactions induced by the interrupted recycling of moisture through precipitation and evapotranspiration (Zeng et al., 1999). Charney et al. (1977) and Zeng et al. (1999) also proposed that barren soil with larger albedo leads to increased atmospheric subsidence and thereby decreased moisture convection and precipitation. Aerosols such as dust have relatively small effects on precipitation through increased midtroposphere radiative heating, surface cooling, and ice and cloud condensation nuclei in comparison to SST and vegetation's impact (Huang et al., 2009; Hui et al., 2008). Some studies also conclude that the West African Monsoon influences the amount of moisture transported from the Atlantic to the Sahel region (Taylor, 2008).

Variations in ESM model configurations have resulted in different conclusions regarding the relative significance of different climate factors on Sahel precipitation. For example, Taylor et al. (2002) concluded that observed vegetation changes are not large enough to trigger dramatic precipitation variation over the Sahel region in their model; while Zeng et al. (1999) showed that considering vegetation feedbacks in a climate model led to better reproduction of observed interdecadal variation. There is a general consensus that SST dynamics are correlated with Sahel precipitation (Giannini et al., 2003; Hagos & Cook, 2008). Folland et al. (1986) asserted that interhemispheric SST gradients enhance moisture convection and strongly influence precipitation, and Lamb (1978) argued that subtropical and equatorial Atlantic regions play a more significant role. The conclusions and implications coming from each study appear dependent on the model used, which makes it difficult to generalize conclusions to other models.

Importantly, observational benchmarks for Sahel precipitation interactions and mechanisms do not yet exist, making evaluation of simulated interactive patterns from individual models difficult.

To address the lack of direct observational evidence and disagreement among modeling studies on West Sahel precipitation interactions, our first objective here is to develop an observationally based interaction-pattern benchmark against which models can be compared (hereafter referred to as a “mechanistic benchmark”) using transfer entropy analysis. The mechanistic benchmark will quantify the direction and strength of information passed between various components of the system, thereby identifying and quantifying mechanistic interconnections. We develop this mechanistic benchmark using observed SST, vegetation properties, and precipitation. Our second objective is to combine a traditional benchmark approach (e.g., emergent precipitation long-term trends and interannual variability, Kumar et al., 2013) and the mechanistic benchmark to evaluate state-of-the-art fully coupled ESMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5).

2 Methodology

We focused on two prevailing hypotheses potentially responsible for West Sahel precipitation variation (Figure 1). First, warm SSTs weaken land-ocean temperature contrast and migrate deep convection to the ocean, which leads to precipitation decreases over land (Giannini et al., 2003). Second, terrestrial vegetation dynamics control water (evapotranspiration) and energy (surface albedo) fluxes into the atmosphere and thus impact local precipitation (Zeng et al., 1999). Each hypothesized interactive pattern was upheld or falsified by quantifying directional information entropy transfer (section 2.2) between West Sahel precipitation and (1) SST and (2) leaf area index (LAI).

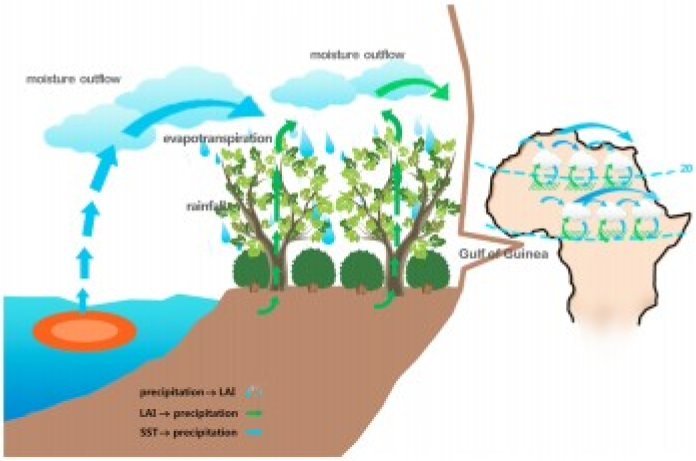

Figure 1. Conceptual model of hypothesized mechanisms that control variability in Sahelian precipitation: (1) The African West Sahel region receives moisture through low-level southwesterly flow from the Gulf of Guinea. Therefore, West Sahel precipitation is strongly controlled by SST variation over the Gulf of Guinea. (2) Vegetation growth in the West Sahel region is influenced by water availability and land surface vegetation dynamics that control water and energy fluxes into the atmosphere and therefore affect local precipitation. SST = sea surface temperature; LAI = leaf area index.

2.1 Data

SST in the Gulf of Guinea was provided by NOAA Optimum Interpolation (OI) SST V2 (Reynolds et al., 2002). This data set combines daily in situ, bias-corrected satellite retrieval (Smith & Reynolds, 1998), as well as modeled SST starting from 1981 and interpolates to a monthly time scale at a 1° × 1° resolution. Since advective moisture from the Gulf of Guinea strongly controls West Sahel precipitation (Sultan & Janicot, 2003), we extracted and averaged the SST over the Gulf of Guinea (1°W to 8°E, 0–5°N) for our analysis.

For vegetation dynamics, we used GLASS LAI as a proxy, which was derived from Advanced Very High Resolution Radiometer (AVHRR) LAI, Moderate Resolution Imaging Spectroradiometer (MODIS) LAI, and CYCLOPES LAI using a neural network approach (Liang & Xiao, 2012). We defined the West Sahel region to be between 10°N and 20°N and between 20°W and 10°E. The LAI product over this region, available since 1982, was extracted for each individual grid cell at a 0.5° × 0.5° resolution.

Precipitation data came from Climate Research Unit (CRU ts3.2) from 1901 to 2014 (Harris et al., 2014). This product gridded over 2,000 precipitation stations onto 0.5° × 0.5° resolution regular grids and provided a monthly climatology mean and anomaly over the West Sahel region.

Similar to the observations, we analyzed the monthly precipitation, LAI over the West Sahel region, and SST over the Gulf of Guinea from nine ESMs that participated in the CMIP5. We used historical emission-driven fully coupled simulations (esmhistorical) from bcc-csm1–1-m, CanESM2 (Chylek et al., 2011), CESM1-BGC (Lindsay et al., 2014), GFDL-ESM 2G (Dunne et al., 2012), HadGEM2-ES (Collins et al., 2011), inmcm4 (Volodin et al., 2010), IPSL-CM5A-LR (Cattiaux et al., 2013), MPI-ESM-LR (Brovkin et al., 2013), and NorESM1-ME (Tjiputra et al., 2013).

Since we focused on precipitation variation and its underlying controls and interactions, we detrended all data sets by first removing the long-term trend with a 10-year moving average and then the seasonal cycle by subtracting the mean seasonal cycle averaged across the whole time series. Next we investigated the information entropy transfer between the residual (anomaly) time series.

2.2 Causation Pattern Analysis

Based on information theory, directional interactions (or causation) can be quantitatively measured by how much information entropy is transferred between variables (Schreiber, 2000; Shannon, 2001). First, we calculate Shannon Information Entropy (*H*, a measure of uncertainty, quantified in bits) of a variable (*X*) (i.e., SST over the Gulf of Guinea, LAI, or precipitation):

$$H = -\sum_{x_i} p(x_i) \log_2 p(x_i) \quad (1)$$

where x_i is a possible value of variable X and $p(x_i)$ is the probability of x_i within the whole time series X. Given two time series X [x_i: i = 1:n] and Y [y_j: j = 1:n] (e.g., precipitation and SST), the directional information entropy transfer from X to Y ($T_{X->Y}$) is a measure of the extent to which knowledge of X independently reduces uncertainty in Y's future behavior, once the reduction of uncertainty derived from knowledge of Y's own past behavior is accounted for. It is calculated as

$$T_{X->Y} = \sum_{y_i, y_{i-k\Delta t}, x_{i-l\Delta t}} p(y_i, y_{i-k\Delta t}, x_{i-l\Delta t}) \log_2 \frac{p(y_i | y_{i-k\Delta t}, x_{i-l\Delta t})}{p(y_i | y_{i-k\Delta t})} \quad (2)$$

where k and l refer to the block length history of y and x on which estimates of uncertainty reduction of y_i are conditioned. Here we use k and l = one time step as a conservative choice (Ruddell & Kumar, 2009) and drop the superscript in future reference to these variables. The τ is the time lag over which X transfers information to Y. If the transferred entropy (in bits) is larger than a significance threshold, the directional impact was interpreted as statistically robust. The significance threshold is calculated by randomly shuffling the time series X and Y to destroy temporal relationships between the variables and computing the transfer entropy. The significance threshold is then selected as the α = 0.05 value from the Monte Carlo distribution of transfer entropies.

For this study, we define “interactions” under the climate change context to be significant bidirectional information exchange between two climate relevant variables; while “control” is unidirectional information flow from source process to sink process. For example, if patterns in the precipitation time series ($x_{i-\tau}$) significantly reduce uncertainty in future values of the LAI time series (y_i) beyond the reduction uncertainty due to knowledge of LAI's history (y_{i-1}), then unidirectional control of precipitation on LAI is identified. If directional control of LAI on local precipitation is similarly identified, a bidirectional "interaction" is identified. We evaluated information transfer between all pairs of variables at all possible lags τ to test for the existence of hypothesized hydroclimatological interactions at the scale of the West Sahel. Here we report the maximum amount of information transferred over all lags examined and its associated time scale.

3 Results and Discussion

Our goals were to (1) introduce the transfer entropy technique to analysis of coupled land, ocean, and atmosphere analyses at high temporal and spatial scales; (2) demonstrate that transfer entropy quantitatively measures the strength and direction of controls; and (3) highlight the fact that CMIP5 models failed to capture the observed directional controls, even though some of them successfully capture the emergent pattern of Sahel precipitation.

3.1 Observed Control of West Sahel Precipitation

We analyzed two hypothesized controls on West Sahel precipitation variation: (1) local vegetation-precipitation interaction and (2) remote SST-precipitation interaction. Due to data availability, we limited our analysis to between 1982 and 2014. We hypothesized (1) a unidirectional control from the Gulf of Guinea SST on West Sahel precipitation and (2) bidirectional interactions between vegetation dynamics and West Sahel precipitation. The hypotheses were supported (rejected) if the relevant information transfer was statistically significant (insignificant).

3.1.1 SST Control on West Sahel Precipitation

The African Sahel region receives moisture through low-level southwesterly flow from the South Atlantic Gulf of Guinea across the Southwestern coast of West Africa (Lamb, 1978; Sultan & Janicot, 2000). Strong advection of moisture over the West Sahel region and Guinea Coast often leads to corresponding precipitation changes (Nicholson & Webster, 2007). Therefore, to assess the influence of convection-driven moisture controls on precipitation, and vice versa, we take a spatial range for the Gulf of Guinea to be [1°W to 8°E and 0–5°N].

Information transfer from SST over the Gulf of Guinea to West Sahel precipitation was significant over 93% of analyzed West Sahel grid cells (Figures 2 and A1). In contrast, information transfer from West Sahel precipitation to SST over the Gulf of Guinea was much smaller; less than 1% of the grid cells transferred significant information, which is well below the experiment-wide false positive rate of α = 0.05 (Figure 3). Therefore, our information transfer-based analysis supports the hypothesis that SST variation over the Gulf of Guinea unidirectionally controls precipitation variation over the West Sahel region. This observed directional control from SST to West Sahel precipitation was consistent with modeling studies (Biasutti et al., 2008; Folland et al., 1986; Giannini et al., 2003; Lamb, 1978; Vizy & Cook, 2001). For example, Giannini et al. (2003) suggested that the oceanic warming around Africa might have reduced the difference in temperature between land and ocean, making deep convection migrate to the ocean while reducing precipitation on land. In addition to analyzing the maximal transfer entropy and its associated time scale, we also analyzed the probability density distribution of response time scales (time lags; Figure A1).

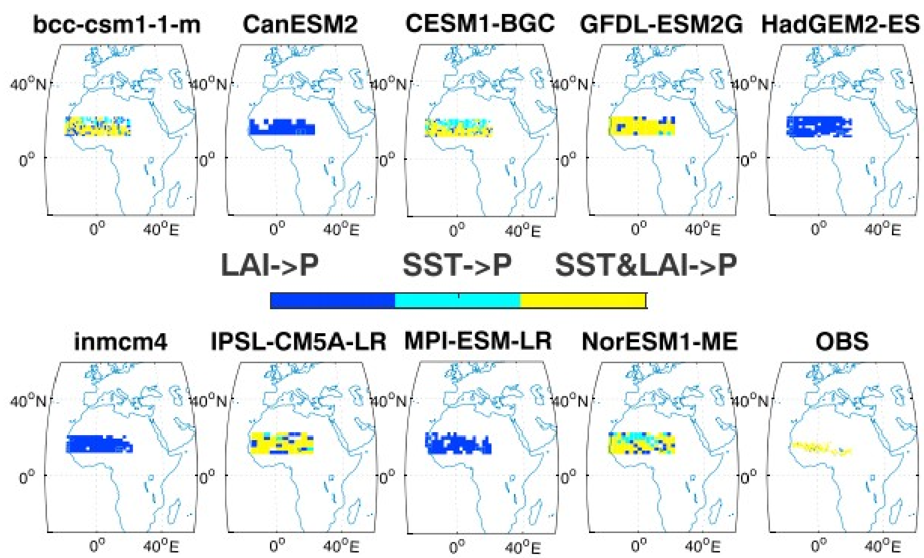

Figure 2. Directional interaction (1) only from leaf area index (LAI; blue), (2) only from Gulf of Guinea sea surface temperature (SST; cyan), or (3) from both LAI and SST (yellow) to West Sahel precipitation. Only statistically significant grid cells are shown in color.

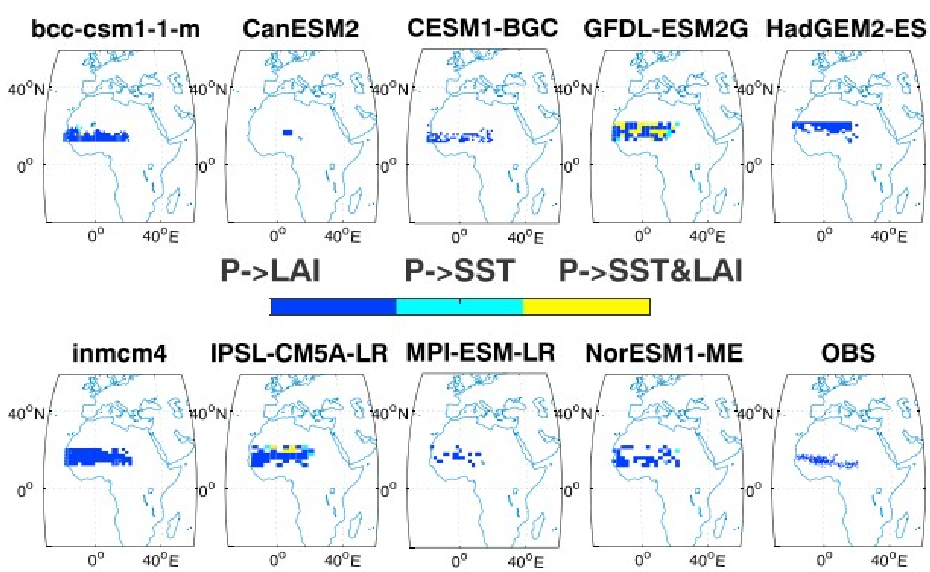

Figure 3. Directional interaction from West Sahel precipitation to (1) only leaf area index (LAI; blue), (2) only Gulf of Guinea sea surface temperature (SST; cyan), or (3) both SST and LAI (yellow). Only statistically significant grid cells are shown in color.

3.1.2 Vegetation Control Over West Sahel Precipitation

Another widely acknowledged hypothesis is that local vegetation-precipitation interactions control West Sahel precipitation (Wang & Eltahir, 2000; Zeng et al., 1999; Zheng & Eltahir, 1998). For example, using an ecosystem model, Hickler et al. (2005) showed that vegetation growth in the West Sahel region was mostly influenced by water availability but not by temperature variability. Another modeling study showed that variation in precipitation was closely related to variation in vegetation cover (Zeng et al., 1999). However, there is a general lack of observational demonstration of vegetation-precipitation interactions.

Here we used observed LAI as an indicator for local vegetation coverage and variation, reducing uncertainties caused by solely relying on simulation data as in previous studies. Over 99% of the study's grid cells showed significant information transfer from precipitation to LAI, suggesting the importance of precipitation to LAI interannual variability in the West Sahel region (Figures 3 and A1). Further, over 99% of the study's grid cells showed significant amount of information transfer from LAI to precipitation (Figure 2), suggesting that local variation in evapotranspiration and its impact on the surface energy balance contributes to changes in atmospheric moisture and energy for convection, and therefore to changes in regional precipitation.

Charney et al. (1977) first proposed that overgrazing in the West Sahel region may be the cause of persistent drying by enhancing a positive biogeophysical interaction. In particular, the reduced amount of vegetation leads to an increase in albedo and a cooler land surface over which air descends and dries, consequently suppressing precipitation. This dynamic was seen in many subsequent studies that used coupled biosphere-atmosphere models, suggesting that reduction in vegetation intensifies West Sahel drying, although the triggering mechanism of West Sahel drought may include changes in a combination of controls, including land cover and SST (Wang & Eltahir, 2000). However, the coupled climate models used in previous studies applied a wide variety of underlying assumptions and process representations. Observational demonstration of Charney's hypothesis is challenging due to the fact that regression-based (R^2) or lead/lag correlations assume linear relationships between variables, although the system is inherently nonlinear. As a formal nonlinear causal inference framework, transfer entropy can address such challenges. Here the data demonstrate a causal relationship among observed precipitation, SST, and LAI. Our approach provides a first observational evaluation of directional interaction patterns affecting West Sahel precipitation. These resolved interactions can serve as useful model evaluation benchmarks, as discussed below.

3.2 ESM Benchmarking

We next combined observed MAP amount as well as precipitation, SST, and vegetation interaction patterns identified by transfer entropy analysis to benchmark nine state-of-the-art ESMs from CMIP5.

3.2.1 MAP Benchmark

MAP over the West Sahel region ranged from 400 to 600 mm/year (Figure 4a). Among the nine CMIP5 ESMs, CESM1-BGC performed the best in reproducing the precipitation trend between 1982 and 2004, although interannual variation was poorly simulated. A majority of the models underestimated average precipitation. Inmcm4, bcc-csm1-1-m, and IPSL-CM5A-LR underestimated average precipitation by up to ~70%, while GFDL-ESM 2G's precipitation was ~60% overestimated compared to observations.

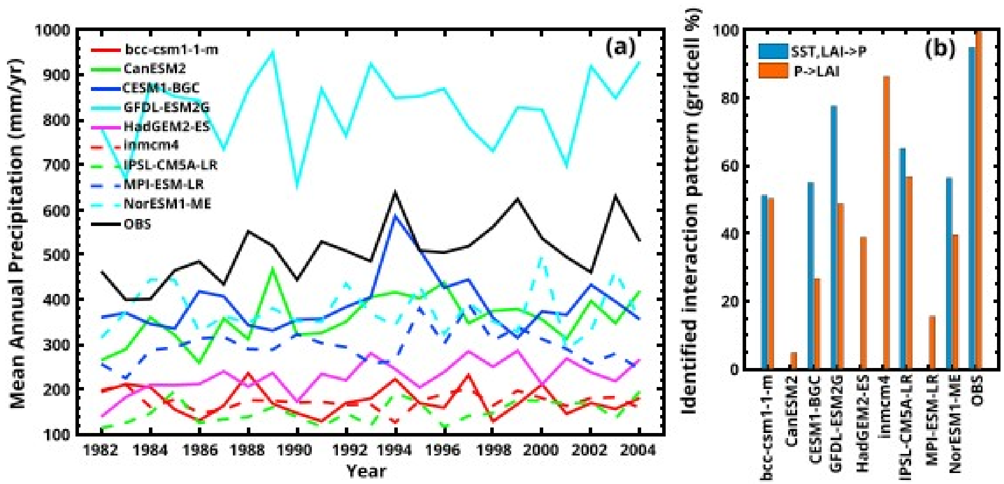

Figure 4. (a) Emergent benchmarks (here mean annual precipitation) for West Sahel precipitation from observations and CMIP5 ESMs. (b) Percentage of model grid cells exhibiting interactions consistent with the observed mechanistic benchmark for West Sahelian precipitation. SST, LAI, and *P* are sea surface temperature, leaf area index, and precipitation, respectively.

3.2.2 Mechanistic Benchmark

We argue that metrics to quantify directional causation responsible for precipitation variation are needed. Following our analysis above, we used the observed information transfer between modeled (1) SST and precipitation and (2) LAI and precipitation as quantitative benchmarks for the underlying mechanisms affecting West Sahel precipitation. Although the observational data showed that 93% of grid cells transfer significant information from both LAI and SST to precipitation (Figures 2 and 4b), GFDL-ESM 2G, IPSL-CM5A-LR, CESM1-BGC, bcc-csm1-1-m, and NorESM1-ME predict that 77%, 65%, 55%, 51%, and 56% of the grid cells transfer significant information from both factors, respectively, while other models generally failed (significant entropy transfer appeared over less than 1% of grid cells) to capture either LAI or SST's observed impact on precipitation. We also found that only one third of the ESMs captured the precipitation control on LAI over at least half of their grid cells (Figures 3 and 4b). The models that most closely reproduce the observation relationship were inmcm4, IPSL-CM5A-LR, bcc-csm1-1-m, and GFDL-ESM 2G with 86%, 56%, 50%, and 49% of the studied grid cells being statistically significant, respectively.

In summary, GFDL-ESM 2G and IPSL-CM5A-LR most accurately reproduced observed interactions in more than 50% of the study's grid cells. All tested CMIP5 models generally captured the precipitation control on vegetation but largely failed to reproduce both LAI and SST's influence on precipitation. Although GFDL-ESM 2G and IPSL-CM5A-LR relatively well reproduced the observed mechanistic interactions, they either dramatically overestimated (GFDL-ESM 2G) or underestimated (IPSL-CM5A-LR) precipitation amount for the West Sahel region, suggesting that capturing both the interaction patterns and the emergent precipitation amount is challenging and important. Our results suggest that a full evaluation of climate models requires a combination of mechanistic and traditional emergent pattern benchmarks.

Global warming has the potential to alter SST-precipitation-LAI coupling and generate insights into changes of controlling factors for West Sahel regional climate (Hill et al., 2018). We therefore split our analysis time window into two 20-year time periods: 1982–2001 and 1994–2014. The mean SST over the Gulf of Guinea warmed by 0.2 °C for the 1994–2014 time period relative to the 1982–2001 time period (Figure A3). However, this warming signal was not strong enough to trigger significant changes in the coupling that dominated West Sahel precipitation. SST and LAI still jointly dominated West Sahel precipitation dynamics, and local precipitation exerted strong interactions with LAI but not with remote SST (Figure A4).

Besides the two major coupling hypotheses, we also investigated the relationship between land surface energy fluxes and local precipitation, as a result of land surface vegetation cover variability (i.e., LAI). Surface energy propagates into the atmosphere, via either latent or sensible heat fluxes. The former supplies water and facilitates local precipitation, while the latter warms the surface air and increases the saturation point of the air. Both of these processes could affect local precipitation. We found a strong control of either solely sensible heat or both sensible and latent heat fluxes on the local precipitation (Figure A2) based on observations (Jung et al., 2011). Using the observed directional control as a benchmark, we further found that that bcc-csm1-1-m is not able to capture most of the directional control. Other models (CanESM2, CESM1-BGC, GFDL-ESM 2G, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, MPI-ESM-LR, and NorESM1-ME) generally captured the directional control; however, the spatial distribution of the controls are highly diverse.

3.3 Limitations and Future Work

Our study focuses on the effects of SST and vegetation as two widely studied mechanisms potentially contributing to variability in West Sahel precipitation. Other possible interactions, including the West African Monsoon (Cook & Vizy, 2006), dust (Yoshioka et al., 2007), aerosol loading and greenhouse gases (Held et al., 2005), and Intertropical Convergence Zone migration (Sultan et al., 2003) were not considered in this study but are potentially important for future work. For example, Folland et al. (1986) suggested a testable hypothesis that smaller (larger) Northern-Southern Hemisphere SST contrasts are associated with drier (wetter) conditions over the West Sahel. In addition, atmospheric jets that transport moisture into and out of the Sahel region (Grodsky & Carton, 2003; Patricola & Cook, 2010; Pu & Cook, 2012) could be critically important in controlling moisture availability and precipitation events over the Sahel region. In particular, strong correlation has been identified in which a wet Sahel corresponded to a strong West African westerly jet, and vice versa. More importantly, such correlation was much stronger than the correlation between the southerly moisture fluxes induced by West African monsoon and precipitation (Pu & Cook, 2012). Our future work will focus on testing more relevant hypotheses over a larger scale (e.g., remote oceanic forcing rather than just Gulf of Guinea SST) that can potentially lead to the change of precipitation over West Sahel.

Another limitation comes from the observational data for SST and LAI, which do not extend to the driest period (in the 1960s), thus limiting the temporal range of our observational data-driven findings. This analysis is also limited to monthly temporal and ~100-km^2 spatial scales that are most relevant to climate modeling. However, some interactions could happen quickly and over smaller spatial domains. For example, evapotranspiration interactions with precipitation could happen diurnally (Schär et al., 1999). Although we focused on interaction patterns at monthly time scales to develop benchmarks for climate models, future work should extend these benchmarks to finer temporal and spatial scales.

4 Conclusions

In this study, we applied information theory to evaluate two widely acknowledged hypotheses regarding controls on West Sahel region precipitation variability: (1) unidirectional control of SSTs over the Gulf of Guinea on West Sahel precipitation and (2) bidirectional interactions between West Sahel precipitation and local vegetation dynamics. Based on information transfer between observed variables, we developed mechanistic benchmarking metrics for CMIP5 ESM predicted precipitation over the West Sahel region. In combination with traditional emergent pattern benchmarks (e.g., mean and trends in annual precipitation), we found that most ESMs were able to capture either the directional control of SST on precipitation or bidirectional interactions between vegetation and precipitation. However, none of the models captured both interactive patterns and the emergent mean and trends of regional precipitation. We recommend that a combination of mechanistic and traditional emergent pattern benchmarks should be used to better assess and inform processes that require improved representation in climate models.

Acknowledgments

This research is supported by the Director, Office of Science, Office of Biological and Environmental Research of the U.S. Department of Energy under contract DE-AC02-05CH11231 as part of the Regional and Global Climate Modeling (RGCM), RUBISCO SFA. All used data are available from public repository: SST (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.highres.html), LAI (http://glcf.umd.edu/data/lai/), precipitation (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_3.26/cruts.1804231117.v3.26/pre/), and CMIP5 model outputs (https://cera-www.dkrz.de/WDCC/ui/cerasearch/).

Appendix A

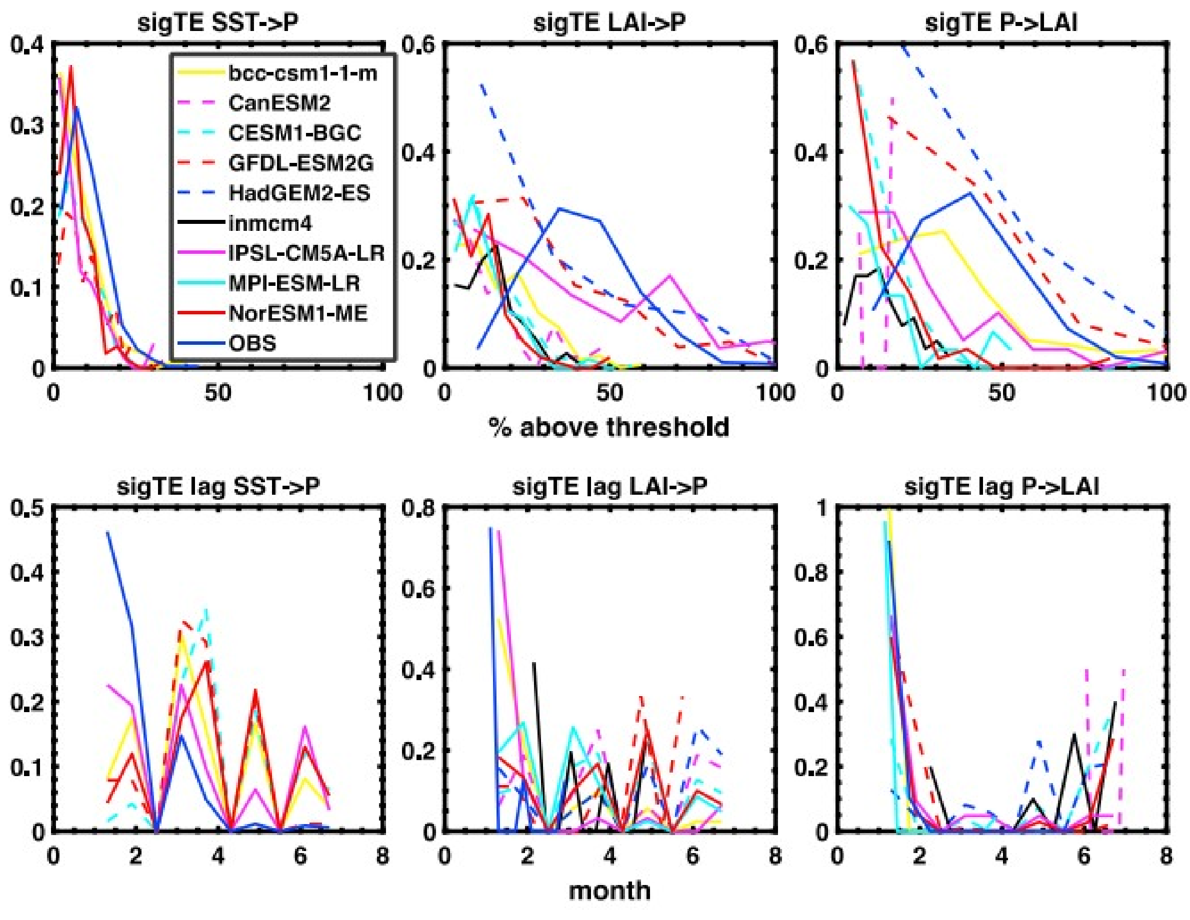

Figure A1. Probability distribution function of percentage of maximum transfer entropy above significant threshold (upper three panels: $(TE_{\mathrm{max}} - TE_{\mathrm{threshold}})/TE_{\mathrm{threshold}} \times 100$) and associated time lags (lower three panels) for directional impact (1) from Gulf of Guinea sea surface temperature (SST) to West Sahel precipitation; (2) from leaf area index (LAI) to West Sahel precipitation; and (3) from West Sahel precipitation to leaf area index (LAI).

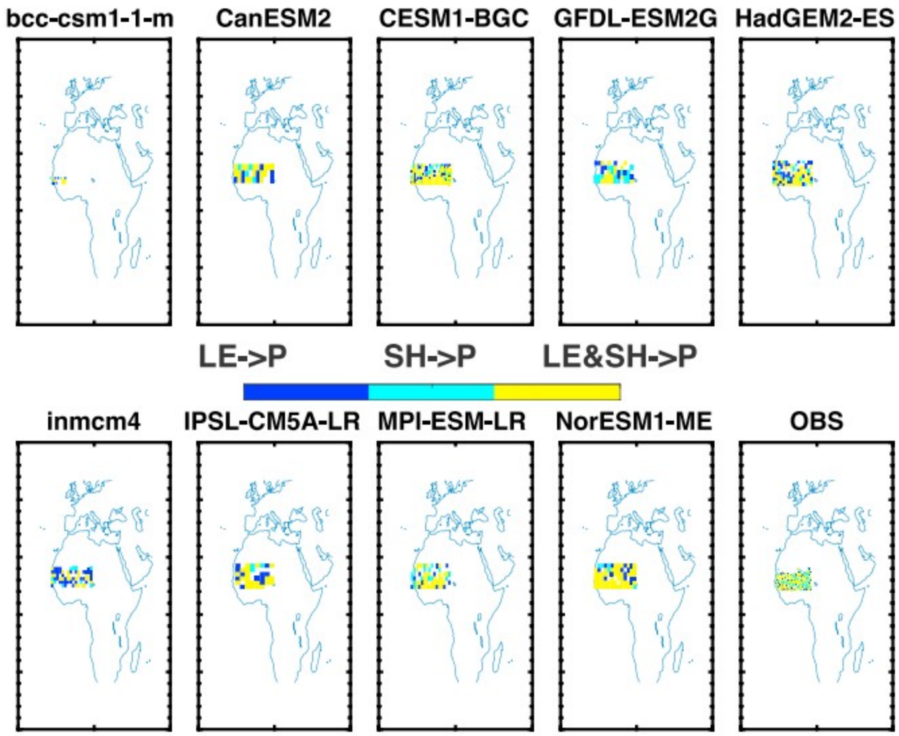

Figure A2. The directional impacts of surface energy fluxes (LE: latent heat versus SH: sensible heat) to precipitation. Colors indicate regions with information transfer above the significance threshold.

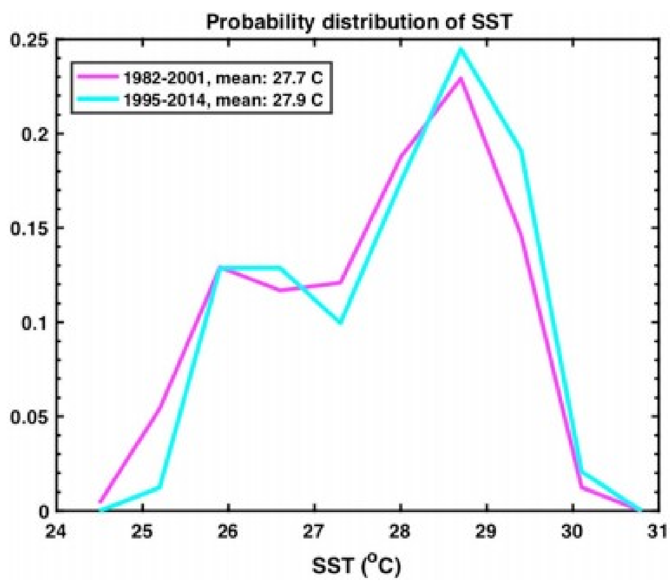

Figure A3. Sea surface temperature (SST) over the Gulf of Guinea from 1982 to 2014. Magenta and cyan lines represent the first 20-year and the last 20-year SST probability distribution. The means of distributions shift by 0.2°, from 27.7 to 27.9 °C.

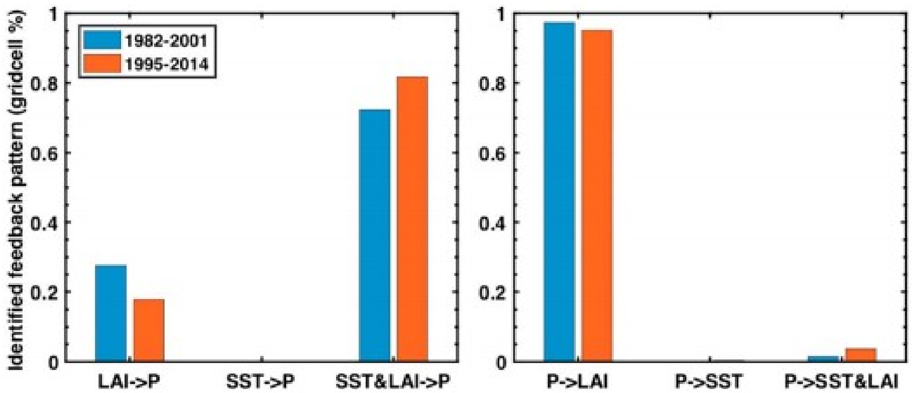

Figure A4. Interaction paradigms among (1) sea surface temperature (SST) over the Gulf of Guinea, (2) precipitation, and (3) leaf area index over the West Sahel.

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