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Empirical Relationships of Sea Surface Temperature and Vegetation Activity with Summer Rainfall Variability over the Sahel*

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Received 13 May 2015; in final form 15 October 2015

ABSTRACT: Regional land surface and remote ocean variables have been considered as primary forcings altering the variability of summer rainfall over the Sahel. However, previous studies usually examined the two components separately. In this study, the authors apply statistical methods including correlation, multivariate linear regression, and Granger causality analyses to investigate the relative roles of spring–summer sea surface temperature (SST) and vegetation activity in explaining the Sahel summer rainfall variability from 1982 to 2006. The remotely sensed normalized difference vegetation index (NDVI) is used as an indicator of land surface forcing. This study shows that

* Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/EI-D-15-0028.s1>.

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DOI: 10.1175/EI-D-15-0028.1

spring and summer SSTs over the subtropical North Atlantic have significant positive correlations with summer rainfall. The spring and summer NDVIs over the Sahel have significant negative and positive correlations, respectively, with summer rainfall. Based on the multivariate linear regression analysis, the adjusted R^2 for the integrated model with both the land and ocean variables is 0.70. It is around 2 times larger than the model with SST alone (adjusted $R^2 = 0.36$). To further investigate the causal relationships of summer rainfall with the SST and NDVI variables selected in the integrated multivariate model, the authors perform a Granger causality test. This study finds that summer NDVI over the Sahel does Granger cause summer rainfall over the Sahel, while the summer SST over the subtropical North Atlantic does not Granger cause the summer rainfall. The results indicate that the regional land surface forcing has a relatively strong contribution to Sahel summer rainfall, compared to the remote ocean forcing, during the recent decades.

KEYWORDS: Normalized difference vegetation index; Sea surface temperature; Sahel; Summer rainfall; Granger causality

1. Introduction

The Sahel is located in the narrow band of semiarid land between the Sahara Desert to the north and the Sudanian Savanna to the south (Xue and Shukla 1993; Figure 1; lying between 13°–20°N latitude and 15°W–20°E longitude). It is known for the highly variable rainfall climate. Wetter conditions in the Sahel occurred in the 1920s, 1930s, and 1950s (Fink et al. 2006). During the period of 1970–90, however, the Sahel underwent prolonged drought, and it has been asserted as an irreversible desertification region (Dai et al. 2004; Lamprey 1988). After this period, there was some partial recovery in rainfall over the Sahel since mid-1980s (Eklundh and Olsson 2003; Olsson and Hall-Beyer 2008; Sanogo et al. 2015; Tucker and Nicholson 1999). The majority of people over the Sahel rely on the rain-fed agriculture and nomadic animal husbandry (FAO 2011). The large variation in the rainfall has caused famine for more than 10 million people (Perez et al. 2012). A better understanding of the influencing factors for the rainfall variability over the Sahel could improve the predictive skill in rainfall forecasting, which will benefit the local people.

Sahel rainfall is known to be strongly influenced by sea surface temperature (SST), both globally and in oceans adjacent to the African continent (Martin and Thorncroft 2014; Mohino et al. 2011; Rowell 2003; Zhang and Delworth 2006). Bah (1987) found that reduced summer rainfall in the Sahel was associated with warm SST in the Gulf of Guinea. Giannini et al. (2003) stated that the drying trend in the Sahel was attributed to warmer-than-average SSTs in the equatorial Indian and eastern equatorial Atlantic oceans, which weakened the continental convergence associated with the monsoon. Zheng et al. (1999) described a mechanistic study on the role of the tropical Atlantic SST variability in the dynamics of the West African monsoon and found that a warm spring SST resulted in a wet monsoon. Hagos and Cook (2008) investigated the influences of the decadal Indian and Atlantic Ocean SST anomalies on the late-twentieth-century Sahel precipitation variability and stated that the modeled partial recovery of the precipitation in the 1990s was mainly related to the warming of the northern tropical Atlantic

Figure 1. The land-use and land-cover types of Africa from the MODIS land-cover dataset in 2001. The Sahel region is outlined in red.

Ocean. A number of different atmospheric general circulation models (GCMs), forced with SSTs over the past century, have been able to simulate the major characteristics of the Sahel rainfall variability (Folland et al. 1986; Giannini et al. 2003; Hoerling et al. 2006; Lu and Delworth 2005; Tippett and Giannini 2006).

Land surface processes have also been investigated as one of the major factors influencing the West African climate system (e.g., [Lee et al. 2016](#); [Xue et al. 2012](#)). Land surface processes related to land-use and land-cover change (LULCC) can affect biophysical properties over the land through modifying the surface albedo, partitioning the surface energy between sensible and latent heat fluxes, and altering the roughness of the land surface, which subsequently can influence the climate ([Foley et al. 2003b](#); [Mahmood et al. 2014](#); [McPherson 2007](#); [Dirmeyer et al. 2010](#); [Pielke 2005](#); [Wang et al. 2006](#)). [Van Noorden \(2006\)](#) stated that more vegetation can transfer more moisture into the atmosphere by evapotranspiration, and the darker surface of vegetation with lower albedo compared with sand absorbed more solar radiation, which might create more rainfall over Africa. [Los et al. \(2006\)](#) concluded that vegetation effects accounted for about 30% of annual rainfall variation in the Sahel. It appears that both regional land surface and remote ocean forcings may be responsible for the variability of the Sahel rainfall.

While the previous studies are concerned with the land and ocean factors separately, the relative contribution of the two different components is not yet quantified. Moreover, the correlations of Sahel summer rainfall with the SSTs in the Atlantic and Indian Oceans during the recent decades for 1982–2006 ([Figure 2](#)) become weaker, compared to those during the previous decades for 1957–81 (see [Figure 1](#) in the supplemental information). In addition, the recent Sahel rainfall was not successfully predicted for most models by the same linear link to SST that explained rainfall variations during the twentieth century ([Biasutti et al. 2008](#)). It may be that the SST-forced variation in Sahel rainfall is controlled by different mechanisms, and other forcing besides SST (e.g., land surface processes) could play a role in controlling the rainfall variability ([Biasutti et al. 2008](#)).

To explore the relative contributions of regional land surface and remote ocean forcings to rainfall variability in the Sahel, we examine the empirical relationships of summer rainfall over the Sahel with vegetation activity and SST during spring [March–May (MAM)] and summer [June–September (JJAS)] seasons from 1982 to 2006. In doing so, we address the following questions: 1) What are the relative associations of vegetation activity and SST in explaining the summer rainfall variability in the Sahel, and 2) what are the causal relationships of Sahel summer rainfall with vegetation and SST?

2. Data and methods

2.1. Data

The Climate Research Unit (CRU) precipitation data are used as the rainfall data in this study. CRU datasets are based on more than 4000 weather stations distributed around the world, including temperature, precipitation, cloud cover, frost day frequency, and so on. The CRU version 3.21 is used in this study, which spans the period of 1901 to 2012, with monthly temporal resolution and 0.5° by 0.5° spatial resolution ([Mitchell et al. 2004](#)).

The monthly SST data from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST), version 1.1, at 1° spatial resolution is used in this study as the indicator of ocean heat sources. HadISST temperatures from

Figure 2. The correlation coefficients of detrended SST at each grid point in the Atlantic and Indian Oceans during (a) spring and (b) summer with detrended time series of summer rainfall area averaged over the Sahel from 1982 to 2006. The contour is the 10% significant level. The area-averaged SSTs are calculated over the regions shown in boxes.

1870 to present are reconstructed using a two-stage, reduced space, optimal interpolation procedure, followed by the superposition of quality-improved gridded observations onto the reconstructions to restore detail (Rayner et al. 2003).

The normalized difference vegetation index (NDVI) related to photosynthetically active radiation, leaf area, vegetation fraction, and net primary productivity can be used to evaluate the dynamic changes of vegetation cover (Carlson and Ripley 1997; Gamon et al. 1995; Rouse et al. 1974; Tucker et al. 2005). This study applies NDVI as the indicator of vegetation activity over the Sahel. The NDVI first generation (NDVIG) dataset derived from the Advanced Very High Resolution Radiometer (AVHRR) Global Inventory Modeling and Mapping Studies (GIMMS) is used. AVHRR GIMMS NDVIG dataset, with 8 km of spatial resolution and 15 days of temporal sampling, is widely used in climate and vegetation studies (Jiang et al. 2013; Myneni et al. 1997) because of its long time sequence, which covered from July 1981 to December 2006. To be consistent with the temporal resolution (monthly) of CRU precipitation and the HadISST data, the NDVIG data are integrated to monthly. The study period is from 1982 to 2006, which is the overlapped period of the three datasets.

2.2. Statistical methods

2.2.1. Correlation analysis

Spatial correlation analysis is applied to determine the associations of gridded spring–summer SST and NDVI with mean summer rainfall area averaged over the Sahel region. To obtain the association based on interannual variability, we remove the long-term trend of each variable by subtracting n^* slope from the original SST, NDVI, and precipitation values (n is 1, 2, 3, . . . , 25). The slopes are estimated from simple linear regression. Significance tests for the correlation coefficients are performed and statistically significant regions at the 10% level are contoured on the map. The time series of seasonal-mean SSTs area averaged over the regions significantly correlated with Sahel summer rainfall, and the NDVI time series over the Sahel region are calculated for the multivariate linear regression analysis.

2.2.2. Multivariate linear regression analysis

To examine the roles of SST and land surface (i.e., NDVI) variables in summer rainfall variability over the Sahel, we implement the multivariate linear regression analysis. We first apply the multivariate linear regression model with SST alone and then integrate the NDVI information. In the multivariate regression model, the area-averaged mean summer precipitation over the Sahel is used as the dependent variable. The area-averaged mean spring–summer SSTs over the significant ocean regions and NDVIs over the Sahel are used as independent variables. The dependent variable is expressed as the sum of the independent variables $x_1, x_2, \dots, x_m$ multiplied by their coefficients $\beta_0, \beta_1, \dots, \beta_m$ and residuals ε (Mueller et al. 2010) in the following equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_m x_m + \varepsilon. \quad (1)$$

The independent variables are correlated among themselves (i.e., multicollinearity), so the best subset has to be identified. This is done via F statistic and Mallows' C_p methods (e.g., [Helsel and Hirsch 1992](#); [Lee et al. 2008](#); [Neumann et al. 2003](#)). The best subset is then used to establish the multivariate linear regression model. To obtain a reliable multivariate linear regression model, we test the key assumptions of linear regression [i.e., the residuals are white noise with zero mean and constant variance ([Von Storch and Zwiers 2001](#))] through scatter-plots, histogram, quantile–quantile (Q–Q) plot, and autocorrelation function (ACF) plot of the residuals. We also confirm the normality of the residuals using a one-sample Kolmogorov–Smirnov (KS) test ([Von Storch and Zwiers 2001](#)). The overall performance of the models and the individual independent variables are further assessed by the F test and Student's t test, respectively. Finally, the adjusted R^2 for both models are calculated to investigate whether integrating the NDVI information could improve the performance of the model of SST alone, and the partial correlation coefficients in the integrated model are calculated to examine the relative contributions of SST and NDVI on Sahel summer rainfall. The subset of the independent variables in the integrated multivariate model is considered in the Granger causality test.

2.2.3. Granger causality test

Because the aforementioned analysis does not necessarily imply a causal relationship of summer rainfall with spring–summer SST and NDVI, we further assess the causality of summer rainfall with the selected SST and NDVI variables using the Granger causality test. The Granger causality defined by [Granger \(1969\)](#) is as follows: A variable X is causal for another variable Y if knowledge of the past history of X is useful for explaining the future state of Y over and above knowledge of the past history of Y itself. So if the prediction of Y is significantly improved by including X as a predictor, then X is said to be a Granger cause for Y .

In this study, the interactions between precipitation with spring–summer SST and NDVI are

$$\text{Precip}_t = \sum_{i=1}^p \alpha_i \text{Precip}_{t-i} + \sum_{i=1}^p \beta_i \text{NDVI}_{t-i} + \varepsilon_t, \quad (2)$$

$$\text{Precip}_t = \sum_{i=1}^p \gamma_i \text{Precip}_{t-i} + \sum_{i=1}^p \delta_i \text{SST}_{t-i} + \eta_t, \quad (3)$$

where α , β , γ , and δ are regression coefficients; ε and η are white noise error; and p is the lag length ($=1$ in this study). In Equations (2) and (3), the current precipitation is a function of past values (the previous year in this study) of NDVI and SST, respectively, and past values (the previous year in this study) of precipitation itself. To test whether NDVI causes precipitation, we estimate a restricted form of Equation (2) where we eliminate the NDVI. This is done statistically by restricting β in Equation (2) to zero as follows:

$$\text{Precip}_t = \sum_{i=1}^p \alpha'_i \text{Precip}_{t-i} + \varepsilon'_t, \quad (4)$$

$$\text{Precip}_t = \sum_{i=1}^p \gamma'_i \text{Precip}_{t-i} + \eta'_t. \quad (5)$$

In the same line, we test whether SST causes precipitation by estimating a restricted form of Equation (3) in which we restrict δ to zero [Equation (5)]. Next, to test whether the restricted estimates are statistically significantly different from the unrestricted estimates [i.e., Equations (2) or (3)], the following F ratio is calculated:

$$F_{\text{ndvi(or SST)} \sim \text{precip}} = \frac{(\text{SSE}_R - \text{SSE}_U)/H}{\text{SSE}_U/(n - K)} \sim F_{H, n-K}, \quad (6)$$

where SSE_R and SSE_U is sum of squared errors of restricted and unrestricted versions of Equations (2) or (3), respectively. The term H is the number of coefficients set to zero in the restricted version, K is the number of the predictors in the unrestricted version, and n is the number of observations. If $F_{\text{ndvi (or SST)} \sim \text{precip}}$ is less than $F_{H, n-K}$, we accept the null hypothesis that the variable eliminated from Equations (2) or (3) (e.g., NDVI or SST) does not Granger cause the dependent variable (e.g., precipitation). Otherwise, we reject the null hypothesis. The two regression models in the Granger causality test are used for quantifying the statistical difference between the models with and without the interesting variable (NDVI or SST in this study). Therefore, it does not necessarily imply whether the previous condition of NDVI (or SST) is significant in predicting the precipitation of the next year.

3. Results

3.1. Correlations of Sahel rainfall with SST and NDVI

Figure 2 shows the spatial patterns of correlation coefficients between detrended SST at each grid point in the Atlantic and Indian Oceans during spring and summer and detrended time series of summer rainfall area averaged over the Sahel. The Atlantic SST is the focus of this study because it has been identified as one of the primary forcings, altering the monsoon rainfall in West Africa in the previous observational and climate modeling studies (e.g., [Martin and Thorncroft 2014](#); [Shanahan et al. 2009](#)). In spring season, the tropical North Atlantic SST anomalies are significantly negatively correlated with Sahel summer rainfall, and the subtropical North Atlantic SST has a significant positive correlation with the summer rainfall (Figure 2a). The significant positive correlation between subtropical North Atlantic SST and Sahel summer rainfall is also observed in the summer season (Figure 2b), which indicates the subtropical North Atlantic SSTs in both the pre-monsoon and monsoon seasons could be one of the important oceanic forcings for Sahel rainfall. The significant negative correlation in the tropical North Atlantic is getting weaker, while there is a significant negative correlation in the midlatitude North Atlantic region in summer.

(a) Spring

(b) Summer

Figure 3. The correlation coefficients of detrended NDVIs at each grid point in the Sahel and its surrounding lands during (a) spring and (b) summer with detrended time series of Sahel summer rainfall from 1982 to 2006. The contour is the 10% significant level. The area-averaged NDVIs are calculated over the regions shown in boxes (the Sahel region is the same as in [Figure 1](#)).

The correlation coefficients of detrended NDVI at each grid point in the Sahel and its surrounding lands during spring and summer with detrended time series of Sahel summer rainfall are shown in [Figure 3](#). In the spring season, the NDVIs in most of the Sahel regions present negative correlations with Sahel summer rainfall,

especially significant in eastern Mali and western Niger (Figure 3a). In the summer season, there is a strong positive relationship between vegetation and rainfall over the Sahel, characterized by the distinct zonal band of positive correlation around 15°N latitude (Figure 3b).

3.2. Multivariate associations of Sahel rainfall with SST and NDVI

In the correlation analysis, spring SSTs over the tropical and subtropical North Atlantic and summer SSTs over the subtropical and midlatitude North Atlantic have significant correlations with Sahel summer rainfall. The detrended time series of area-averaged SSTs during spring and summer are extracted over the significantly correlated regions (shown as in the boxes of Figure 2). The detrended time series of area-averaged NDVIs over the Sahel region (shown as in the boxes of Figure 3) during spring and summer are also extracted. We use the time series variables as potential predictors to establish the multivariate linear regression models for Sahel summer rainfall.

The scatterplots of Sahel summer rainfall with SST and NDVI time series are shown in Figure 4. The absolute r values range from 0.35 to 0.71, with the highest r value between summer rainfall and summer NDVI in the Sahel, and the lowest r value between summer rainfall and spring SST in the tropical North Atlantic. All of the time series of SSTs and NDVIs have significant correlations with summer rainfall at the 10% significant level.

Based on the subset selection criteria (F statistic and Mallows's C_p), summer SST over the subtropical North Atlantic is selected for the model based on SSTs alone. Spring and summer NDVIs over the Sahel and summer SST over the subtropical North Atlantic are selected for the integrated model, considering both SSTs and NDVIs. The models of SST alone and integrating NDVI are

$$\begin{aligned} &\text{SST alone: Sahel summer precipitation} \\ &= 25.88 \times \text{summer subtropical North Atlantic SST} - 618.46, \end{aligned} \quad (7)$$

$$\begin{aligned} &\text{Integrated: Sahel summer precipitation} \\ &= -660.29 \times \text{spring Sahel NDVI} + 526.66 \times \text{summer Sahel NDVI} \\ &\quad + 16.72 \times \text{summer subtropical North Atlantic SST} - 382.63. \end{aligned} \quad (8)$$

The F statistics for the two models are 14.29 and 20.1, respectively. The corresponding p values are less than 0.05 (Tables 1 and 2), which indicate that both models have significant linear relationships at the 5% significant level. The Student's t tests (Tables 1 and 2) show that each independent variable in the two models has significant roles in the respective model as the p values are less than 0.05.

The scatterplots, histograms, Q-Q plots, and ACF plots for the two models are shown in Figure 5. For the integrated model (Figure 5b), the residuals distribute evenly around the zero line, indicating that the mean of the residuals is

Figure 4. Scatterplots of Sahel summer rainfall with spring-summer (a) SSTs area averaged over the North Atlantic and (b) NDVIs area averaged over the Sahel.

approximately zero. The histogram of the residuals suggests that the residuals are nearly normal with a zero mean. The quantiles of the residuals show good fit with the quantiles of standard normal in the Q–Q plot. The assumption of normal distribution for the residuals is also confirmed by KS test. The p value of the KS test for the integrated model is 0.80, which accepts the null hypothesis that residuals are normal distribution. For the SST alone model (Figure 5a), the scatterplot and Q–Q plot of the residuals are normally distributed in general. While the histogram of the residuals is positively skewed (tail on the right side),

Table 1. Multivariate linear regression of Sahel summer rainfall with SSTs alone. The adjusted R^2 is 0.36. The F statistic is 14.29, and the p value is 0.001.

	Estimate	Std Error	t statistic	p value
Intercept	−618.46	175.17	−3.53	0.0018
Summer subtropical North Atlantic SST	25.88	6.85	3.78	0.0010

Table 2. Multivariate linear regression of Sahel summer rainfall with both SSTs and NDVIs. The adjusted R^2 is 0.70. The F statistic is 20.1, and the p value is 2.222×10^{-6} .

	Estimate	Std Error	t statistic	p value
Intercept	-382.63	127.60	-3.00	0.0068
Spring Sahel NDVI	-660.29	196.93	-3.35	0.0030
Summer Sahel NDVI	526.66	129.31	4.07	0.0005
Summer subtropical North Atlantic SST	16.72	5.28	3.17	0.0046

the KS test supports the normality of residuals by accepting the null hypothesis that residuals are normally distributed (p value = 0.59). In the ACF plots, there are no estimates falling outside the 95% confidence limit (the dotted line in the ACF plots of Figures 5a and 5b), denoting that there is no autocorrelation of residuals for the two models. Thus, the statistical inspections support the normality and independence of the residuals of the SST alone and integrated models.

The model based on SST alone can explain 36% variance in Sahel summer rainfall, since the adjusted R^2 is 0.36, while the integrated model can explain 70% variance of Sahel summer rainfall, as the adjusted R^2 is 0.70. The performance of the integrated model is around 2 times better than the model based on SST alone, indicating the important role of NDVIs in the Sahel summer rainfall variability. To further investigate the relative contributions of the selected SST and NDVI variables on Sahel summer rainfall in the integrated model, we calculate the partial correlation coefficients of SST and NDVIs with summer rainfall. The partial

(a) For the model with SST alone **(b) For the integrated model with both SST and NDVI** **Figure 5. Normality and autocorrelation tests of the residuals for the (a) model based on SST alone and (b) integrated model based on both SST and NDVI.**

Table 3. Granger causality tests between Sahel summer rainfall with the selected SST and NDVI variables.

Model	Degree of freedom (Df) of residual	Df	F statistic	p value
Test 1: Sahel summer rainfall $\sim$ Sahel summer rainfall + spring Sahel NDVI				
Unrestricted	21			
Restricted	22	1	2.71	0.1145
Test 2: Sahel summer rainfall $\sim$ Sahel summer rainfall + summer Sahel NDVI				
Unrestricted	21			
Restricted	22	1	9.48	0.0057
Test 3: Sahel summer rainfall $\sim$ Sahel summer rainfall + summer subtropical North Atlantic SST				
Unrestricted	21			
Restricted	22	1	0.05	0.8174

correlation coefficients of Sahel rainfall with spring and summer Sahel NDVIs are -0.59 and 0.66 , respectively, and that with summer subtropical North Atlantic SST is 0.57 . All of the corresponding p values are less than 0.05 , indicating the significant roles of the selected NDVI and SST variables in explaining the variation of Sahel summer rainfall. Compared to SST, the association of NDVIs with Sahel rainfall is stronger.

3.3. Causal relationships of Sahel rainfall with SST and NDVI

In [section 3.2](#), the integrated multivariate model, including both SST and NDVI variables, explained 70% variance of Sahel summer rainfall. The selected independent variables (i.e., spring and summer NDVIs over the Sahel and summer SST over the subtropical North Atlantic) have significant correlations with Sahel summer rainfall. However, whether the variables do cause the variability of Sahel summer rainfall is unknown. To further reveal the causal relationships of Sahel summer rainfall with the SST and NDVI variables, we perform the Granger causality test between Sahel summer rainfall and the three independent variables, respectively.

The Granger causality test requires the stationarity of the time series variables ([Granger 1969](#)). We apply a Student's t test to assess the trend of slopes in the four detrended time series (one dependent and three independent variables). The all p values of the t statistics are larger than 0.80 , implying that the null hypothesis that slopes equal 0 is safely accepted, which subsequently confirms the stationarity of the four variables used in the Granger causality test.

[Table 3](#) shows the results of the Granger causality test. Test 1 in [Table 3](#) represents the Granger causality between Sahel spring NDVI and summer rainfall. The null hypothesis that spring NDVI over the Sahel does not Granger cause Sahel summer rainfall is accepted, which indicates that spring Sahel NDVI does not Granger cause Sahel summer rainfall. The significant Granger causal relationship is found for summer Sahel NDVI, since the p value is less than 0.05 (test 2 in [Table 3](#)). While test 3 in [Table 3](#) shows that summer subtropical North Atlantic SST does not Granger cause Sahel summer rainfall, as the p value is larger than 0.05 . Thus, in the integrated multivariate model, NDVI in summer does Granger cause Sahel summer rainfall, but spring NDVI and summer SST do not Granger cause the rainfall variability. Additionally, we conduct the Granger causality tests for NDVI

to Sahel summer rainfall with the regression model including both NDVI and SST. The results of additional analysis, considering the SST in the regression models of the Granger causality test, confirm the Granger cause of summer NDVI to Sahel summer rainfall (see Table 1 in the supplemental information). The results from Granger causality tests support the important role of summer NDVI in controlling Sahel summer rainfall.

4. Discussion and conclusions

We examine the empirical relationships of Sahel summer rainfall with SST and NDVI in boreal spring and summer from 1982 to 2006. The significant negative correlation of Sahel rainfall with spring tropical North Atlantic SST in the surrounding ocean of the Sahel (i.e., eastern tropical North Atlantic) is found. It might be due to the weakening of monsoon development induced by the decreased heat contrast between the land and ocean because of the warmer SST in the surrounding ocean of the Sahel. The physical processes are consistent with the findings of [Giannini et al. \(2003\)](#) that the warmer-than-average eastern equatorial Atlantic SST, which weaken the continental convergence associated with the West Africa monsoon, could be associated with the drying trend in the Sahel. The significant positive correlations of Sahel summer rainfall with spring and summer SSTs are observed at the subtropical North Atlantic Ocean, which may attribute to more moisture transport from the warmer SST to the Sahel regions through the northwesterly winds from the high pressure cell (Azores high) in the subtropical Atlantic ([Hameed and Riemer 2012](#)). It is consistent with previous studies that stated warming of the North Atlantic coincides with wet periods in the Sahel (e.g., [Martin and Thorncroft 2014](#)).

The significant negative correlation between spring Sahel NDVI and summer rainfall might be related to the weakening of the West Africa monsoon during the monsoon developing period. For instance, increased vegetation greenness in the spring season may increase evapotranspiration over the land, which could decrease land surface temperature and results in the weakening of monsoon development by reducing heat contrast between the land and ocean. [Lee et al. \(2009, 2011\)](#) revealed that in India and East Asia, the spring vegetation activities result in more evapotranspiration, which decreases the land surface temperature and subsequently decreases the land–ocean heat contrast. The decreased land–ocean heat contrast could weaken the monsoon development and thereby decrease early monsoon rainfall. During the summer season, the strong positive correlation between NDVI and precipitation over the Sahel could be associated with a positive feedback in vegetation and rainfall interactions ([Foley et al. 2003a](#); [Ford et al. 2015](#); [Lee et al. 2016](#); [Los et al. 2006](#); [Meng et al. 2014](#)). The positive feedback could be explained by the plausible physical processes that more vegetation activity in summer can provide more moisture static energy ([Eltahir 1998](#); [Lo and Famiglietti 2013](#)) for precipitation processes through increasing evapotranspiration. The recent changes in vegetation activity over the Sahel may be largely attributable to the human-induced LULCC related to a significant increase in the percentage of land used for crops and pastures ([Lee et al. 2016](#)).

The multivariate linear regression models established by using both SST and NDVI variables indicate that the adjusted R^2 value ($=0.70$) of the integrated model

improves around 2 times more than that of the model based on SST alone ($=0.36$). The results reveal that in recent years the land surface processes could significantly contribute to explaining the variability of Sahel summer rainfall. The partial correlation coefficients of spring and summer Sahel NDVIs in the integrated multivariate model are larger than that of summer subtropical North Atlantic SST, which supports that the biogeophysical processes of vegetation play an important role in controlling Sahel summer rainfall.

The Granger causality test reveals that there is an improvement in explaining Sahel summer rainfall by including Sahel summer NDVI. However, the ability to explain Sahel summer rainfall by including summer subtropical North Atlantic SST is not significantly improved. The results from the Granger causality test further confirm our findings that in the recent decades the land surface processes related to vegetation change exert important roles in explaining the Sahel summer rainfall variability.

In summary, the findings from the empirical analyses support that both regional land surface (NDVI) and remote ocean (SST) forcings contribute to Sahel rainfall from 1982 to 2006. Compared to SST, the NDVI could better capture the Sahel rainfall variability during the recent 25 years. The significant Granger cause of Sahel NDVI to Sahel rainfall during summer implies that greening the Sahel during the recent decades (e.g., [Olsson and Hall-Beyer 2008](#)) accounts for the recent moistening of the Sahel. However, the AVHRR NDVIg dataset used in this study only spans from 1982 to 2006, which limits the long-term time series analysis. An NDVI dataset extending up to date is needed to obtain more robust statistical results. While our study focused on identifying the empirical relationships of Sahel rainfall with SST and NDVI, caution should be taken when physically interpreting the statistical relationships generated by correlation, linear regression, and a Granger casualty test. The potential physical processes suggested in this study need further examination.

Acknowledgments. The study was supported in parts by the West Virginia University Senate Grant for research and scholarship. We are grateful to Jingjing Liang and Zhou Mo in the Division of Forestry and Natural Resources of West Virginia University and Lei Meng in the Department of Geography of Western Michigan University for providing detailed comments on statistical analysis. We also thank Jothiganesh Shanmugasundaram at the Department of Geology and Geography of West Virginia University for helpful comments for improving an early version of the manuscript. We thank the two anonymous reviewers for their constructive comments.

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