Tropical drivers of interannual vegetation variability in eastern Africa

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Abstract

Here, we use idealized climate model simulations to elucidate the governing processes for eastern African interannual hydroclimate and vegetation changes and their relationship to the El Niño-Southern Oscillation (ENSO). Our analysis focuses on Tanzania. In the absence of ENSO-induced sea surface temperature anomalies in the Tropical Indian Ocean, El Niño causes during its peak phase negative precipitation anomalies over Tanzania due to a weakening of the tropical-wide Walker circulation. Resulting drought conditions increase wildfires and decrease vegetation cover. Subsequent wetter La Niña conditions reverse the trend, causing a gradual 1-year-long recovery phase. The 2-year-long vegetation response in Tanzania can be explained as a double-integration of local rainfall, which originates from the seasonally-modulated ENSO Pacific-SST forcing (ENSO Combination mode). In the presence of interannual TIO SST forcing, the southeast African ENSO precipitation and vegetation responses are muted due to Indian Ocean warming and the resulting anomalous upward motion in the atmosphere.

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Key Points:

- El Niño warming in tropical Pacific triggers two-year long vegetation decrease in eastern Africa.
- Indian Ocean SST anomalies mute ENSO’s direct impact on eastern African vegetation.
- Vegetation changes in eastern Africa can be understood as a double-integration of seasonally-modulated rainfall response.

ABSTRACT

Here, we use idealized climate model simulations to elucidate the governing processes for eastern African interannual hydroclimate and vegetation changes and their relationship to the El Niño-Southern Oscillation (ENSO). Our analysis focuses on Tanzania. In the absence of ENSO-induced sea surface temperature anomalies in the Tropical Indian Ocean, El Niño causes during its peak phase negative precipitation anomalies over Tanzania due to a weakening of the tropical-wide Walker circulation. Resulting drought conditions increase wildfires and decrease vegetation cover. Subsequent wetter La Niña conditions reverse the trend, causing a gradual 1-year-long recovery phase. The 2-year-long vegetation response in Tanzania can be explained as a double-integration of local rainfall, which originates from the seasonally-modulated ENSO Pacific-SST forcing (ENSO Combination mode). In the presence of interannual TIO SST forcing, the southeast African ENSO precipitation and vegetation responses are muted due to Indian Ocean warming and the resulting anomalous upward motion in the atmosphere.

Plain Language Summary

In this study, we demonstrate how sub-Saharan African vegetation responds to the El Niño–Southern Oscillation (ENSO) through a series of idealized perturbation experiments. In the absence of TIO (Tropical Indian Ocean) warming, El Niño generates less precipitation, while La Niña produces more rainfall over Tanzania during austral summer. The local climate response is mainly controlled by the interaction between interannual ENSO variability and the seasonal cycle (ENSO combination mode). El Niño-induced Tanzanian rainfall deficit leads to prolonged negative vegetation anomalies for 2 years via an accumulated effect of increased wildfire occurrences. However, in the presence of TIO warming, the rainfall response to ENSO over Tanzania is muted by the impact of TIO warming, which in turn results in only small net changes of vegetation, consistent with observations.

1. Introduction

Natural fluctuations in Africa's vegetation are affected by rainfall and wildfire variability (Camberlin et al., 2007; Hawinkel et al., 2016; Musau et al., 2016; Archibald et al., 2010; Andela et al., 2014; Papagiannopoulou et al., 2017; Zubkova et al., 2019). Especially the Sahel, eastern Africa, and southern Africa show large interannual variations in terrestrial productivity, which can be attributed to year-to-year changes in water stress (Williams et al., 2008).

The El Niño-Southern Oscillation (ENSO) has been considered a primary climate driver for rainfall variability in parts of Africa. Evidence from observations shows that El Niño events can cause drought in southern Africa, and enhanced precipitation and corresponding floods in eastern Africa (Nicholson and Kim, 1997). Earlier studies documented a strong relationship between ENSO and the Normalized Difference Vegetation Index (NDVI) over eastern and southern Africa. (Camberlin et al., 2001; Anyamba et al., 2002; Philippon et al., 2014; Anyamba et al., 2018). In contrast, over the Sahel, the relationship between ENSO and NDVI is weak (Philippon et al., 2009).

Observations and model experiments show an asymmetric atmospheric response over Africa between El Niño and La Niña (Frauen et al., 2014). In addition, nonlinear ENSO teleconnections over Africa might be also affected by ENSO-induced asymmetric sea surface temperature (SST) responses over the Atlantic and Indian Oceans. SST variability over the south Atlantic Ocean influences rainfall over the Sahel in the opposite sense of ENSO (Camberlin et al., 2001). Indian Ocean Dipole (IOD) events, typically accompanied by ENSO, positively correlate with eastern African rainfall during the short rainy season (Wenhaji et al., 2018; Wolff et al., 2011). Apart from ENSO, the vegetation response to climate factors is also modulated by nonlinear land processes. Globally, a nonlinear relationship between net primary production and rainfall is observed for grasslands (Yang et al., 2008). Interannual vegetation changes over eastern Africa show a nonlinear relationship with rainfall variability and a strong dependency on land cover type is observed (Hawinkel et al., 2016).

Although the aforementioned studies have demonstrated the impacts of ENSO on African vegetation based on observations, we still lack a deeper understanding of how interannual SST changes in the Indian and Pacific Ocean influence vegetation anomalies and which role wildfires play. In this study, we investigate the vegetation response over sub-Saharan Africa to ENSO through a series of model experiments and compare them to the observations.

2. Data and Experiments

2.1 Observations

We used precipitation data from Global Precipitation Analysis Products of the Global Precipitation Climatology Centre (GPCC) (Schneider et al., 2014), 200 hPa wind from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis generation 5 (ERA5) (Malardel et al., 2016), and SST from the Hadley Centre Sea Ice and Sea Surface Temperature data set version 1 (HadISST1) (Rayner et al., 2003). To characterize observed vegetation changes, we utilized leaf area index (LAI) data derived from the Global Inventory Modeling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI3g) for the period 1982 to 2011 (Zhu et al., 2013). The monthly Global Fire Emissions Database version 4 (GFEDv4) (Randerson et al., 2015) was used to characterize the 1994-2014 wildfire activity.

2.2 Model and Experiments

We conducted a suite of atmospheric general circulation model (AGCM) experiments with the Community Earth System Model (CESM 1.2.2) using the Community Atmosphere Model version 4.0 (CAM4) (Neale et al., 2013) and Community Land Model version 4.0 (CLM4) (Oleson et al., 2010; Lawrence et al., 2011) with active Carbon-Nitrogen (CN) biogeochemistry. The model, which uses a horizontal of approximately 1-degree, was spun up until the carbon and nitrogen pools were equilibrated to a 1957-2016 SST climatology boundary forcing and present-day greenhouse gas concentrations. We then performed four different types of AGCM experiment ensembles to investigate the vegetation response over sub-Saharan Africa to interannual tropical SST variability starting from these equilibrated initial conditions.

First, a control experiment (CTRL) was carried out with a repeating global climatological SST forcing for the period 1957-2016 using a 3-member ensemble. The CTRL largely reproduces the observed precipitation (PRCP), LAI, and burned area climatological patterns. Climatological mean precipitation over central Africa and southeastern Africa and burned area over some parts of Ethiopia, Tanzania, Angola, and South Africa are somewhat overestimated in the model (Figure S1).

To illustrate the impact of observed ENSO variability, a "Pacific" experiment was conducted by adding the observed SST anomalies over the tropical eastern Pacific (15°S-15°N, 180°-90°W) for the period 1957-2016 to the climatology with a 10-member ensemble. A "Tropics" experiment was forced with SST anomalies over the whole tropics (15°S-15°N) for the period 1957-2016 to investigate the response to other modes of pantropical SST variability in addition to ENSO with a 3-member ensemble. An idealized

"Periodic" experiment was designed to investigate the response to symmetric ENSO variability (see for instance Stuecker et al., 2015). The regressed ENSO SST anomaly pattern over the tropical eastern Pacific with an idealized sinusoidal 2.5 years periodicity was added to the observed SST climatology (1957-2016) and the experiment was run for 100 years with a 3-member ensemble. The climate response in all perturbation experiments is defined relative to the control experiment climate. Outside the tropical SST perturbation regions, SST forcing is similar to the CTRL simulation.

3. Results

3.1 The Walker circulation response to ENSO

To investigate the drivers of the vegetation response over Africa, we first focus on the tropical large-scale atmospheric circulation and its interannual variations. The position and strength of the Walker circulation are closely coupled to SST anomalies in the tropical Pacific. Both the Periodic and the Pacific experiments (SST anomalies are only prescribed in the tropical Pacific) show pronounced Walker circulation changes between El Niño and La Niña events with anomalous ascending motion over the eastern Pacific region (and corresponding upper-level divergence) and anomalous descending motion (and corresponding upper-level convergence) during the peak ENSO phase of December-January-February [D(0)JF(1)] (Fig. 1a, b). Importantly, the edge of the descending motion extends to the African continent in the two experiments. In contrast, the Tropics experiment shows that the center of the descending motion shifts toward the Maritime Continent, inducing weaker subsidence around the Indian and Atlantic Ocean, accompanying tropical Indian Ocean (TIO) warming (Fig. 1c). This large-scale circulation response is similar to what is seen for the observations (Fig. 1d). The TIO warming pattern seen in Figure 1c, d is largely forced by El Niño and then is prolonged for several months after the El Niño event due to the so-called capacitor effect (Xie et al., 2009; Cai et al., 2019). The pattern of large-scale atmospheric anomalies in the Tropics experiment (Fig. 1c) is more consistent with the observations (Fig. 1d) than the Periodic and Pacific experiments (Fig. 1a, b). This suggests that TIO warming affects the change of the large-scale atmospheric circulation around the African continent related to ENSO, as suggested by Liu et al., (2020).

3.2 The response of rainfall, vegetation, and wildfire over Africa to ENSO

Here, to focus on the symmetric (i.e., linear) response to El Niño and La Niña events, we show El Niño minus La Niña composites. Observed composite differences between El Niño and La Niña events display pronounced positive precipitation anomalies over the Horn of Africa and negative anomalies over Southern Africa in D(0)JF(1) (Fig. 2j). The three experiments (Periodic, Pacific, and Tropics) reproduce these anomalies reasonably well (Fig. 2a, d, g). However, a small positive precipitation anomaly simulated by the Tropics experiment in the northeastern part of South Africa is not captured in the observations.

Interestingly, the Periodic and the Pacific experiments exhibit a 50 % D(0)JF(1) rainfall reduction over Tanzania for the El Niño minus La Niña composite (Fig. 2a, d) and an accompanying negative Net Primary Production (NPP) anomaly during January-February-March of the decaying ENSO year [JFM(1)] (Fig. 2b, e). In contrast, the observations and the more realistic Tropics experiment show only very weak rainfall anomalies over Tanzania, in agreement with Latif et al., (1999). This suggests that tropical Indian or Atlantic Ocean SST anomalies might play an important role in muting the direct Pacific response over this region. We hypothesize specifically that the negligible observed rainfall response over Tanzania in the observations can be attributed to a compensation between the direct Pacific effect and the El Niño-related Indian Ocean warming effect on the Walker circulation (Fig. 1b, c).

This hypothesis is further supported by the lead-lag relationship between ENSO and LAI anomalies in the Periodic and the Pacific experiments (Fig. 2k). According to this analysis ENSO is leading LAI anomalies in Tanzania by about one year in these two experiments, whereas no statistically significant correlation can be found in the Tropics experiment. ENSO negatively correlates with LAI over Tanzania at a maximum lag of 16-months (R = 0.49, $p < 0.00001$) in the Pacific and 18-months (R = 0.58, $p < 0.00001$) in the Periodic experiments (Fig. 2k). In contrast, for the Tropics experiment, the correlation is not significant (R = 0.06, p=0.11) (Fig. 2k). Regarding the LAI response to ENSO at this 16-18 months lag (that is, in May-June-July in year 2 after the ENSO event peak time: MJJ(2)), we find larger negative anomalies over Tanzania in the Pacific and the Periodic experiments (Fig. 2c, f), while they are much weaker anomalies in the Tropics experiment and the observations (Fig. 2i, l). Moreover, the delayed response over Tanzania to ENSO is also found in wildfire activity (Fig. 3). The periodic experiment shows negative anomalies in burned area over Tanzania in D(0)JF(1) and statistically insignificant differences in the Pacific and Tropics experiments, as well as in the observations. However, the Periodic and the Pacific experiments show a 10-20 % increase in burned area over Tanzania in September-October-November in year 1 after ENSO event peak time [SON(1)]

(Fig. 3a-d), whereas the observations and the Tropics experiment show statistically insignificant differences (Fig. 3e-h).

3.3 Combination mode-driven rainfall response over Tanzania

The temporal evolution of the rainfall response over Tanzania to ENSO shows a rapid transition during the peak phase of both El Niño and La Niña in both the Periodic and the Pacific experiments, but not in the Tropics experiment (Fig. 4). The rainfall response is particularly pronounced in the former during the peak phase of ENSO in D(0)JF(1), which is also the climatological wet season (Fig. 4, Fig. S2). This illustrates the tight coupling between climatological conditions and the imposed ENSO signal. To further understand the distinct atmospheric response to ENSO in the absence of TIO SST anomalies, we hypothesize that the precipitation response over Tanzania to ENSO is driven by the seasonally modulated interannual ENSO variability, which is referred to as a Combination mode (C-mode) (Stuecker et al., 2013). According to this simple model the precipitation anomalies can be written as

$$P^{¿}(t)=\alpha\, ENSO(t)+\beta\, ENSO(t)\cdot\cos(\omega_a t)(1),$$

where $\alpha \wedge \beta$ are the regression coefficients on the ENSO and theoretical C-mode predictors, and ω_a the frequency of the annual cycle. One can also include a white noise precipitation forcing, but since we consider ensemble mean properties in a linear model, the noise forcing is not necessary to understand the temporal evolution. The time-series in the Periodic and Pacific experiments show that the reconstructions of precipitation anomalies over Tanzania via the C-mode equation reproduce the seasonally varying simulated rainfall response to ENSO well (Periodic: $R=0.64$, $p < 0.00001$, Pacific: $R= 0.65$, $p < 0.00001$) (Fig. 4). The simulated La Niña response is somewhat reduced as compared to the El Niño rainfall anomaly. This is reminiscent of an atmospheric nonlinearity to otherwise symmetric SST forcing.

3.4 Role of wildfires in the vegetation response to ENSO

Wildfires can play a potential role in vegetation change through climate-fire-vegetation interactions (Ryan et al., 1991; Chikamoto et al., 2015). In the absence of TIO warming in the Periodic and Pacific experiments, El Niño induced drying increases the occurrence of fires, which is manifest in the prolonged positive anomalies in burned area lasting for about one year after the peak of El Niño (Fig. 4 a, b). For wet savannas in Africa, an increase in fuel moisture can lead to a decrease in the burned area (Zubkova et al., 2019), while for dry savannas, an increase in moisture facilitates more fires (Archibald et al., 2009). To investigate the causal linkages between precipitation and wildfire responses to ENSO, we hypothesize that changes in burned area *B*, are driven by precipitation variability P^*. Here we choose P^* as the ENSO-reconstructed precipitation anomaly from equation (1). We assume in its simplest linearized form that the burned area does not depend on the available vegetation which allows us to introduce a fixed mean recovery timescale (μ^{-1}), in which the burned area can regrow. The simplified linearized model then reads:

$$\frac{dB(t)}{dt} = -\mu_1 B - \theta_1 P^{*}(t) \quad (2).$$

Appropriate parameters values are given in Table S1. The reconstruction of burned area response over Tanzania captures the simulated temporal evolution reasonably well (R=0.82, $p < 0.00001$), suggesting that the burned area response can be determined essentially by the time integral of the direct ENSO effect and the C-mode term. Previous studies support the notion that the lagged response of wildfire activity in some areas can be linked to the integrated effect of antecedent precipitation anomalies (Westerling et al., 2003; Zubkova et al., 2019). In the Periodic experiment, less rainfall over Tanzania during the wet season [D(0)JF(1)] and successive dry season promote a lagged response in burned area in SON(1) (Fig. S2). Subsequently, LAI anomalies over Tanzania slowly develop after the peak of El Niño and are prolonged until the following La Niña event. Especially, the peak of negative anomalies in LAI occurs during the mature La Niña phase in December-January-February in year 2 [DJF(2)], in spite of the maximum rainfall anomalies during this time (Fig. 4, Fig. S2). The vegetation response to climate factors also depends on vegetation resistance and resilience (De Keersmaecker et al., 2015). Accordingly, we hypothesize that the LAI response can be largely explained by the integrated effect of burned area (equation 2), where L represents temporal variation of LAI, and λ is 8 month^{-1} as an inverse damping time scale (characterizing vegetation resilience):

$$\frac{dL(t)}{dt} = -\mu_2 L - \theta_2 B(t) \quad (3).$$

According to this simplified double-integration model (equations 1-3) the LAI response over Tanzania correlates highly with simulated LAI anomalies (R=0.72, $p < 0.00001$), indicating that the lagged and prolonged vegetation response to ENSO is explained by vegetation resilience and the integrated effect of wildfire activity. Similar double-integration models have been introduced to explain also the emergence of low-frequency marine biogeochemical variability (Di Lorenzo et al., 2013).

4. Discussion and Conclusions

In this study, we explored how vegetation in the southeastern part of Africa changes in response to interannual ENSO variability through a series of model experiments. Focusing on Tanzania, we found that, in the absence of TIO variability, the rapid transition of precipitation anomalies during ENSO events are determined by the interaction between ENSO and the annual cycle (the so-called C-mode). After the occurrence of El Niño, the pronounced decrease in rainfall over Tanzania leads to enhancement in burned area with a time delay, thereby prolonging a marked vegetation decrease for 2 years. This response can be explained by the integrated effect of wildfire (double integrated effect of precipitation) and vegetation resilience through an idealized dynamical model, which explains the AGCM results reasonably well.

However, in the real world, there is no evidence for robust changes in precipitation, wildfire, and vegetation over Tanzania, in relationship to ENSO. This is because TIO warming during El Niño events compensates the rainfall response to ENSO over Tanzania (Fig. 4c) by weakening the anomalous atmospheric subsidence (Fig. 1 b,c). This offset response is consistent with the opposite impact between Indian Ocean Basin-wide mode (IOBM) and ENSO on seasonal rainfall variability over Africa discussed in Preethi et al., (2015). The IOD is another primary climate factor which can affect rainfall and vegetation variability over East Africa (Williams and Hanan, 2011; Preethi et al., 2015; Hawinkel et al., 2016), but the IOD impact to eastern Africa peaks in September-November [SON(0)] (Fig. S3). This is too early to cause major precipitation and vegetation anomalies in Tanzania (Fig. 4, Fig. S3).

Furthermore, we emphasize the necessity to understand African vegetation variations driven by the interaction between ENSO and TIO warming under a warmer climate through further studies. Future projections show that TIO warming related to ENSO will likely be intensified (Zheng et al., 2011; Chu et al., 2014; Tao et al., 2015). Thus, our results provide a framework to assess future coupled changes in rainfall, wildfires, and vegetation induced by the relationship between ENSO and TIO warming in response to global warming.

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Figure. 1 Composite differences of SST anomalies (shading; unit: K), and 200 hPa velocity potential anomalies in D(0)JF(1) (contours; unit: $m^2 s^{-1}$, scaled by 10^6) between El Niño and La Niña events for the Periodic experiment (a), the Pacific experiment (b), the Tropics experiment (c), HadISST1 and ERA5 reanalysis (d): El Niño events: 1982, 1987, 1991, 1997, 2002, 2009; La Niña events: 1984, 1988, 1999, 2000, 2007, 2010 for the Pacific experiment, the Tropics experiment, and the observations. Negative values (dashed lines) indicate anomalous upward motion and positive values (solid lines) indicate anomalous downward motion. Stippling indicates a statistically significant difference at the 95% significance level for the 200 hPa velocity potential.

Figure. 2 Composite differences (unit: %) between El Niño and La Niña events for precipitation (PRCP) anomalies in D(0)JF(1), net primary production (NPP) anomalies in JFM(1), and Leaf Area Index (LAI) anomalies in MJJ(2) for the Periodic experiment (a-c), the Pacific experiment (d-f), the Tropics experiment (g-i), as well as PRCP and LAI for the observations (j, l). Stippling indicates a statistically significant difference at the 95% significance level. Black box shows the surrounding Tanzania region (2-13°S, 28-42°E), The lead-lag cross-correlation between the Niño3.4 index and LAI anomalies over Tanzania for the Periodic experiment (yellow), the Pacific experiment (blue), and the Tropics experiment (red) (k).

Figure. 3 Composite differences of burned area (unit: %) between El Niño and La Niña events for the Periodic experiment, the Pacific experiment, the Tropics experiment, and the observations for D(0)JF(1) (a-d) and SON(1) (e-h): El Niño events: 1997, 2002, 2009; La Niña events: 1999, 2000, 2007, 2010 for observations. Stippling indicates a statistically significant difference at the 95% significance level.

Figure. 4 Time evolution over Tanzania (2-13°S, 28-42°E) for the Periodic experiment (a), the Pacific experiment (b) and the Tropics experiment (c): Niño3.4 index (solid yellow/blue/red line; unit: K), C-mode index (dashed gray line; unit: K), Tropical Indian Ocean (TIO) SST anomalies (solid gray line; unit: K), precipitation anomalies (solid yellow/blue/red line; unit: mm/day), reconstructed precipitation anomalies (dashed gray line), burned area (solid yellow/blue/red line; unit: fraction), reconstructed burned area anomalies (dashed gray line), LAI anomalies (solid yellow/blue/red line; unit: m^2/m^2), and reconstructed LAI anomalies (dashed gray line). Transparent shading indicates ± 1 standard deviation.