In the hot seat: Insolation, ENSO, and vegetation in the African tropics

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[1] African climate is changing at rates unprecedented in the Late Holocene with profound implications for tropical ecosystems and the global hydrologic cycle. Understanding the specific climate drivers behind tropical ecosystem change is critical for both future and paleomodeling efforts. However, linkages between climate and vegetation in the tropics have been extremely controversial. The Normalized Difference Vegetation Index (NDVI) is a satellite-derived index of vegetation productivity with a high spatial and temporal resolution. Here we use regression analysis to show that NDVI variability in Africa is primarily correlated with the interannual extent of the Intertropical Convergence Zone (ITCZ). Our results indicate that interannual variability of the ITCZ, rather than sea surface temperatures or teleconnections to middle/high latitudes, drives patterns in African vegetation resulting from the effects of insolation anomalies and El Niño–Southern Oscillation (ENSO) events on atmospheric circulation. Global controls on tropical atmospheric circulation allow for spatially coherent reconstruction of interannual vegetation variability throughout Africa on many time scales through regulation of dry season length and moisture convergence, rather than precipitation amount.


1. Introduction

[2] Ecosystems and rainfed agriculture provide essential resources to millions of Africans. Threats to tropical vegetation related to rapidly changing climate make this region extremely vulnerable [Intergovernmental Panel on Climate Change (IPCC), 2007] and have dangerous, costly implications for daily economy and subsistence [W.W. Forum, 2000; Few et al., 2004]. Despite these concerns, it remains uncertain how natural vegetation communities and cropland productivity will respond to altered atmospheric and oceanic circulation in the future and little infrastructure exists to mitigate these changes [Boko et al., 2007; Brown and deBeurs, 2008].

[3] Modern observational data and paleoclimate records are both powerful tools for understanding biosphere dynamics [Bradley, 1985]. Interpreting both types of records, however, is complicated by much uncertainty surrounding the question of what climatic mechanisms regulate African vegetation change today. Such changes have been attributed to insolation, low-latitude teleconnections to middle/high latitudes, drives patterns in African vegetation resulting from the effects of insolation anomalies and El Niño–Southern Oscillation (ENSO), upper level perturbations, sea surface temperature (SSTs), Hadley Cell intensity, and Intertropical Convergence Zone (ITCZ) excursions [Rossignol-Strick, 1983; DeMenocal and Rind, 1993; Nicholson and Selato, 2000; Hulme et al., 2001; Mercier et al., 2002; New et al., 2003; Nicholson and Grist, 2003; Anyah and Semazzi, 2004; Hoerling et al., 2006; Giannini et al., 2008, Chiang, 2009]. Therefore, studies of both past and future climate change create the need for quantitative constraints on the modern relationship between climate controls and vegetation.

[4] Rainfall seasonality in tropical Africa is determined by the annual migration of large-scale circulations like the ITCZ and Congo Air Boundary [Nicholson, 1996]. Summer rainfall occurs in southern and northern tropical Africa, and an equatorial bimodal regime lies in between. This simplistic model notwithstanding, the spatial heterogeneity of African vegetation indeed mostly results from regional controls on rainfall and dry season length, in addition to local factors such as topography, lake effects, continentality, and SSTs of adjacent oceans [Nicholson, 1996]. Rainfall varies over kilometers from <200 to >2000 mm/year and dry season length from 0 to >6 months. While biomes range from tropical rainforest to open desert, Africa is dominated by semi-arid or other seasonal vegetation that is very sensitive to hydrologic variability [White, 1983]. As a result of the mosaic of influences, it is unclear whether vegetation variability is influenced more by large-scale forcing or local/regional changes and how variability of rainfall amount and dry season length may independently affect vegetation [Hély et al., 2006].
Satellite data provide continuous, high-resolution data sets of vegetation productivity and can help identify the direct relationship between vegetation and climate on global to local scales [Russell and Wallace, 2004; Brown and deBeurs, 2008; Brown et al., 2010]. For this study, a 21 year 8 km resolution Normalized Difference Vegetation Index (NDVI) record (1980–2000) from NOAA’s Advanced Very High Resolution Radiometer (AVHRR) has been used to reconstruct patterns of interannual vegetation variability throughout tropical Africa [Tucker et al., 2005]. Whereas studies in the tropics have linked NDVI to SST and precipitation variability, the relative effects of atmospheric and oceanic variability at the continental scale has not been addressed [Anyamba and Eastman, 1996; Anyamba et al., 2002; Martiny et al., 2006; Brown et al., 2010]. In this study, we have regressed NDVI fields on climatic variables previously proposed as possible regulatory mechanisms for Afrotropical vegetation as well as assessing the relative importance of these variables in the tropical atmosphere-ocean system [Rossignol-Strick, 1983; DeMenocal and Rind, 1993; Nicholson and Selato, 2000; Hulme et al., 2001; Mercier et al., 2002; New et al., 2003; Nicholson and Grist, 2003; Anyah and Semazzi, 2004; Hoerling et al., 2006; Giannini et al., 2008, Chiang, 2009]. Our results provide a new perspective on tropical climate-vegetation interactions and modern vegetation variability within the African tropics.

2. Methods

Vegetation across the sub-Saharan African continent varies greatly in terms of its structure and composition [White, 1983]. Near the equator in West Central Africa, dense Guineo-Congolian rainforests and semi-deciduous forests are prevalent. In the rift valley of East Africa, even near the equator, vegetation is much more open with large areas of semi-arid vegetation consisting largely of Acacia dominated bushland, open woodland, and wooded grassland. To the north and south of the equator, respectively, Sudanian and Zambezian woodlands are located over extensive zones nearly from coast to coast. Further north and south, into the subtropics, scrublands and steppe of the Sahel and Karoo are replaced in some areas by absolute desert.

Although many studies have looked at controls on vegetation variability on local scales within a single vegetation type, few studies have looked at climatic influences on vegetation across broad spatial scales and across vegetation types to examine large-scale regional coherency of variability. This type of study is integral to understanding the relationship of vegetation to large-scale climate phenomena that control regional hydrology and identify areas particularly sensitive to change that are likely to be greatly altered in the future.

Normalized Difference Vegetation Index (NDVI), a satellite-derived index of absorbed red versus scattered near-infrared light, is highly correlated with vegetation net primary productivity [Tucker et al., 2005]. NDVI has been shown to be representative of African vegetation types, and thus is useful in quantitatively linking vegetation variability to climate factors that influence productivity on broad spatial scales [Davenport and Nicholson, 1993; Hély et al., 2006; Brown et al., 2010]. In order to better understand climatic controls across Africa, we used the 1980–2000 GIMMS AVHRR data set of Tucker et al. [2005] throughout sub-Saharan Africa. African biome NDVI values range from 0.1 (grassland, bushland) to 0.7 (evergreen rainforest) [Davenport and Nicholson, 1993; Hély et al., 2006]. At both extremes of vegetation density (very high and very low values of leaf area index), NDVI saturates. In order to account for this, values above 0.7 or below 0.1 are not considered. Following the methods of Russell and Wallace [2004], 3 month mean values of NDVI fields were used to represent the seasonal mean vegetation and were regressed on time series of climatic variables that represent variability in the tropical atmosphere-ocean system.

Regression coefficients between NDVI and each climate variable are displayed on the resultant regression maps. The patterns displayed in these maps represent regions of negative (brown) and positive (green) correlation to each climate variable, while grey represents regions of no relationship between NDVI and the climate variable used. Regression, instead of correlation, was conducted for this analysis, because regression coefficients produced and displayed in the maps in each grid cell have the added advantage of representing the quantitative relationship between climate and NDVI. These displayed values in each map represent the NDVI anomaly for one standard deviation of each climate time series. The purpose of the study is to evaluate the variability of NDVI over the study period rather than any possible trends in the data, so we chose a data set with a time range that has been used in similar studies linking vegetation to climate [Xu et al., 2010; Meng et al., 2011; Hountondji et al., 2009; Fabricante et al., 2009; Revadekar et al., 2012] and was also evaluated by Beck et al. [2011] and found to have the least error associated with temporal change.

The climate variables used for the analysis are important components within the tropical atmosphere-ocean system which are strongly correlated to rainfall both seasonally and from year to year [Nicholson, 1986; Camberlin et al., 2001; Hoerling et al., 2006; Seidel et al., 2008]. These are time series of SSTs and indicators of ITCZ position and intensity that have linkages to rainfall timing and amount and thus are likely to influence vegetation. We examine SST variability from within three regions of known importance for African rainfall: the Southern Atlantic, (0–20°S, 10°E–10°W), the North Indian Ocean, (15–25°N, 55–75°E), and the South Indian Ocean (16–30°S, 36–48°E) [Hoerling et al., 2006]. ITCZ indicators were chosen based on Seidel et al. [2008] and are outgoing long-wave radiation (OLR), 200 mb geopotential height (troposphere height), and incoming solar radiation at the top of the atmosphere (insolation). Within the region of the ITCZ, regions of low pressure at the surface and high pressure aloft follow the sun seasonally and result in the lofting of air masses deep into the troposphere causing clouds and rainfall. Thus, the extent of the ITCZ region can be tracked by evaluating changes in insolation as well as high troposphere heights and low OLR from extensive cloud cover.

To investigate the influence of climate variability on vegetation in the summer season of each hemisphere, December-January-February (austral summer) and June-July-August (boreal summer), time series were constructed for each variable for the 1980–2000 study period. SSTs are latitude-weighted mean values from the 1° x 1° HadISST1 data set [http://climexp.knmi.nl; Rayner et al., 2003]. ITCZ
indicator time series are the first empirical orthogonal function (EOF) of troposphere height, OLR, and insolation constructed using NCEP/NCAR Reanalysis data [http://www.esrl.noaa.gov/psd/, Kalnay et al., 1996] within tropical Africa (23°N–23°S, 0–40°E; Figure 1). EOFs are a statistical method allowing us to extract a single time series that represents the most important variability over a broad spatial scale. This technique was used for the ITCZ indicator time series as these variables were reconstructed over the whole of the tropics, including areas north and south of the equator. Unlike the SST time series, a simple average would not be representative of variability in both hemispheres at once. Plots of all time series used in this analysis are presented in Figure 2.

Figure 1. Leading EOFs used to produce time series for (a) December-January-February and June-July-August Insolation, (b) December-January-February and June-July-August OLR, and (c) December-January-February and June-July-August 200 mb geopotential height (troposphere height).
Significance of individual regression patterns was determined by a Monte Carlo test. First, the latitude-weighted mean covariance was calculated for each pattern. This was then compared with mean covariance produced by 10,000 regressions of random standardized time series and takes into account time series autocorrelation.

Finally, in order to evaluate the main components of variability in the tropical atmosphere-ocean system and the relationships between the climatic variables, we performed a separate principal components analysis (PCA) on all climatic variables discussed above. PCA is an analysis used commonly in climatological and ecological studies which allows for the reduction of dimensionality in large data sets and is used here in order to extract the main components of variability within a system [Jolliffe, 1990]. Loadings for the three significant axes are presented in the supporting information Table S1, and plots of all time series can be found in Figure 2.

3. Results

When each climate time series is regressed on NDVI, the ITCZ indicators consistently show consistently higher values than the SST time series (Table 1). Both the June-July-August and the December-January-February insolation time series show significant covariance with NDVI from the same season. Additionally, June-July-August OLR yields the highest covariance of all of the time series when regressed on NDVI within the same season. In contrast, covariance produced by SSTs is low and never reaches significant values (Table 1). This suggests that interannual vegetation variability is strongly controlled by atmospheric circulation.

The patterns produced by regressing NDVI on insolation within the same season are shown in Figures 3a and 3b. The December-January-February pattern shows a strong positive anomaly in southeast Africa with a negative anomaly in all other regions, especially marked in North and South Africa (Figure 3a). The June-July-August pattern is similar, but with signs reversed, showing a negative anomaly in East Africa and a strong positive anomaly persisting in North Africa (Figure 3b). Additionally, another positive anomaly stretches from the Indian to the Atlantic coast in southern Africa.

The pattern produced by regressing NDVI on June-July-August OLR within the same season is shown in Figure 4. Here we see a band of strong negative anomaly running zonally from 10°N to 15°N, a second weaker negative anomaly in South Africa, and a positive anomaly in the equatorial region.

3.1. Principal Components Analysis of Climatic Variables

In order to extract the main components of variability within the tropical climate system and interrelation of these climatic variables, a PCA was performed. The PCA resulted in three significant axes, explaining 60.0% of the variance (Table 1). A biplot with loadings of the first two axes shows that nearly half of the variance is explained by the first two PCs which load strongly on the ITCZ indicators (Figure 5; Table S1).
PC1 (23.8% variance) loads strongly on June-July-August insolation and contrasts with December-January-February insolation (Figure 5). In this 21 year record, insolation changes are the result of variations in solar irradiance, which show a strong negative correlation between seasons ($r = 0.812; p < 0.001$). This illustrates the antiphased nature of summer insolation anomalies and suggests the existence of an interhemispheric gradient such that, for a given year, high summer insolation in one hemisphere corresponds to lower summer insolation in the opposite hemisphere.

PC2 (20.4% variance) loads strongly on troposphere height in both seasons and contrasts with both seasons of OLR (Figure 5). The biplot supports the notion that both troposphere height and OLR are positively correlated between seasons (troposphere height: $r = 0.82, p < 0.001$; OLR: $r = 0.43, p = 0.05$) and negatively correlated with each other (December-January-February: $r = -0.631, p = 0.001$; June-July-August: $r = -0.262, p = 0.13$). OLR is a metric of atmospheric water vapor content, with high values indicating cloudless days. In contrast, high values of troposphere height indicate deep tropospheric convection producing tropical

Table 1. Climate Variable Regressions

<table>
<thead>
<tr>
<th>NDVI</th>
<th>DJF Troposphere Height</th>
<th>JJA Troposphere Height</th>
<th>DJF OLR</th>
<th>JJA OLR</th>
<th>DJF Insolation</th>
<th>JJA Insolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>December-January-February</td>
<td>0.0095</td>
<td>0.0128</td>
<td>0.0069</td>
<td>0.0101</td>
<td>0.0155$^{c,e}$</td>
<td>0.0106</td>
</tr>
<tr>
<td>January-February-March</td>
<td>0.0093</td>
<td>0.0130$^{d}$</td>
<td>0.0069</td>
<td>0.0085</td>
<td>0.0117</td>
<td>0.0079</td>
</tr>
<tr>
<td>February-March-April</td>
<td>0.0104</td>
<td>0.0131$^{d}$</td>
<td>0.0068</td>
<td>0.0094</td>
<td>0.0105</td>
<td>0.0083</td>
</tr>
<tr>
<td>March-April-May</td>
<td>0.0122</td>
<td>0.0121</td>
<td>0.0085</td>
<td>0.0097</td>
<td>0.0104</td>
<td>0.0091</td>
</tr>
<tr>
<td>April-May-June</td>
<td>0.0120</td>
<td>0.0120</td>
<td>0.0098</td>
<td>0.0082</td>
<td>0.0099</td>
<td>0.0098</td>
</tr>
<tr>
<td>May-June-July</td>
<td>0.0118</td>
<td>0.0116</td>
<td>0.0113</td>
<td>0.0080</td>
<td>0.0104</td>
<td>0.0110</td>
</tr>
<tr>
<td>June-July-August</td>
<td>0.0082</td>
<td>0.0111$^{d}$</td>
<td>0.0132$^{d}$</td>
<td>0.0076</td>
<td>0.0077</td>
<td>0.0091</td>
</tr>
<tr>
<td>July-August-September</td>
<td>0.0076</td>
<td>0.0108$^{d}$</td>
<td>0.0098</td>
<td>0.0071</td>
<td>0.0118</td>
<td>0.0111</td>
</tr>
<tr>
<td>August-September-October</td>
<td>0.0081</td>
<td>0.0128$^{d}$</td>
<td>0.0098</td>
<td>0.0134$^{d}$</td>
<td>0.0106</td>
<td>0.0084</td>
</tr>
<tr>
<td>September-October-November</td>
<td>0.0081</td>
<td>0.0129$^{d}$</td>
<td>0.0103</td>
<td>0.0135$^{d}$</td>
<td>0.0121</td>
<td>0.0089</td>
</tr>
<tr>
<td>October-November-December</td>
<td>0.0085</td>
<td>0.0133$^{d}$</td>
<td>0.0111</td>
<td>0.0135$^{d}$</td>
<td>0.0130$^{d}$</td>
<td>0.0091</td>
</tr>
<tr>
<td>November-December-January</td>
<td>0.0082</td>
<td>0.0132$^{d}$</td>
<td>0.0102</td>
<td>0.0116</td>
<td>0.0131$^{d}$</td>
<td>0.0123</td>
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</table>

<table>
<thead>
<tr>
<th>NDVI</th>
<th>DJF Atlantic</th>
<th>JJA Atlantic</th>
<th>DJF S. Indian</th>
<th>JJA S. Indian</th>
<th>DJF S. Indian</th>
<th>JJA S. Indian</th>
</tr>
</thead>
<tbody>
<tr>
<td>December-January-February</td>
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<td>0.0108</td>
<td>0.0083</td>
<td>0.0083</td>
<td>0.0107</td>
<td>0.0089</td>
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<tr>
<td>January-February-March</td>
<td>0.0083</td>
<td>0.0080</td>
<td>0.0082</td>
<td>0.0075</td>
<td>0.0094</td>
<td>0.0083</td>
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<tr>
<td>February-March-April</td>
<td>0.0083</td>
<td>0.0083</td>
<td>0.0082</td>
<td>0.0076</td>
<td>0.0084</td>
<td>0.0084</td>
</tr>
<tr>
<td>March-April-May</td>
<td>0.0091</td>
<td>0.0096</td>
<td>0.0086</td>
<td>0.0079</td>
<td>0.0091</td>
<td>0.0091</td>
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<tr>
<td>April-May-June</td>
<td>0.0094</td>
<td>0.0103</td>
<td>0.0084</td>
<td>0.0080</td>
<td>0.0088</td>
<td>0.0098</td>
</tr>
<tr>
<td>May-June-July</td>
<td>0.0108</td>
<td>0.0111</td>
<td>0.0090</td>
<td>0.0083</td>
<td>0.0088</td>
<td>0.0107</td>
</tr>
<tr>
<td>June-July-August</td>
<td>0.0121</td>
<td>0.0095$^{d}$</td>
<td>0.0092</td>
<td>0.0105</td>
<td>0.0106</td>
<td>0.0139$^{d}$</td>
</tr>
<tr>
<td>July-August-September</td>
<td>0.0126</td>
<td>0.0091</td>
<td>0.0085</td>
<td>0.0104</td>
<td>0.0098</td>
<td>0.0120</td>
</tr>
<tr>
<td>August-September-October</td>
<td>0.0130$^{d}$</td>
<td>0.0093</td>
<td>0.0086</td>
<td>0.0094</td>
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<td>0.0118</td>
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<td>0.0092</td>
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<tr>
<td>October-November-December</td>
<td>0.0107</td>
<td>0.0107</td>
<td>0.0113</td>
<td>0.0094</td>
<td>0.0101</td>
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<tr>
<td>November-December-January</td>
<td>0.0104</td>
<td>0.0110</td>
<td>0.0103</td>
<td>0.0108</td>
<td>0.0094</td>
<td>0.0114</td>
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</table>

$^a$Mean regression coefficients based on regression of 3 month means of African NDVI on all climatic variables.
$^b$Values are significant to 99%.
$^c$Values are significant to 95%.
$^d$Values are significant to 90%.
$^e$Bold values are regression patterns used in subsequent figures.

[18] PC1 (23.8% variance) loads strongly on June-July-August insolation and contrasts with December-January-February insolation (Figure 5). In this 21 year record, insolation changes are the result of variations in solar irradiance, which show a strong negative correlation between seasons ($r = -0.812; p < 0.001$). This illustrates the antiphased nature of summer insolation anomalies and suggests the existence of an interhemispheric gradient such that, for a given year, high summer insolation in one hemisphere corresponds to lower summer insolation in the opposite hemisphere.

[19] PC2 (20.4% variance) loads strongly on troposphere height in both seasons and contrasts with both seasons of OLR (Figure 5). The biplot supports the notion that both troposphere height and OLR are positively correlated between seasons (troposphere height: $r = 0.82, p < 0.001$; OLR: $r = 0.43, p = 0.05$) and negatively correlated with each other (December-January-February: $r = -0.631, p = 0.001$; June-July-August: $r = -0.262, p = 0.13$). OLR is a metric of atmospheric water vapor content, with high values indicating cloudless days. In contrast, high values of troposphere height indicate deep tropospheric convection producing tropical

Figure 3. NDVI regressions on insolation with mean covariance (COV), as displayed in Table 1, at the bottom right of each panel. (a) Regression map of December-January-February NDVI on December-January-February insolation, (b) regression map of June-July-August NDVI on June-July-August insolation. Double asterisks indicate 99% confidence and single asterisk represents 95% confidence.
storms, and low values indicate a more stable, stratified troposphere [Seidel et al., 2008]. Thus, PC2 suggests that higher troposphere height, or deep convection within the tropics, is coincident with lower OLR and increased cloudiness throughout the tropics.

All three significant PCs show an important contribution of variance from the SST time series (Table S1). In addition to insolation and OLR, PC1 loads on December-January-February and June-July-August North Indian Ocean SSTs and June-July-August South Indian Ocean SSTs, while PC2 shows a very high contribution from December-January-February South Indian Ocean SSTs. PC3 (15.8%) loads most strongly on Atlantic Ocean variability in December-January-February and June-July-August (Table S1).

SST variability in these regions is often considered important for rainfall patterns throughout Africa [Hoerling et al., 2006]. The PCA agrees with this, suggesting that SSTs play a strong role in driving the atmosphere-ocean system. However, despite the influence of SSTs on rainfall, no strong relationship exists between SST and NDVI (Table 1). It is possible that our study does not capture the relationship between SSTs and NDVI due to a problem of inappropriate temporal or spatial scale that does not capture SST variability. However, other studies using shorter time series or lower spatial resolution have used similar

Figure 4. NDVI regressions on OLR with mean covariance (COV), as displayed in Table 1, at the bottom right of each panel. Regression map of June-July-August NDVI on June-July-August OLR. Double asterisks indicate 99% confidence and single asterisk represents 95% confidence.

Figure 5. Axes 1 and 2 for PCA of all standardized climate time series with loadings of all variables. Red dots represent the loadings of individual years with years of warm ENSO events during (1988, 1999), marked in italics.
techniques to define significant relationships between SST and rainfall [Nicholson, 1986; Camberlin et al., 2001; Hoerling et al., 2006].

4. Discussion

4.1. Dry Season and Drought Stress

[22] The NDVI regression patterns produced by December-January-February and June-July-August insolation illustrate the response of vegetation across broad spatial scales and vegetation types to large-scale circulation within the tropical atmosphere (Figure 3). The patterns produced in both seasons are similar; however, the anomalies are of opposing sign due to the antiphased relationship between the insolation time series from each season. This means that when June-July-August insolation is high, December-January-February insolation is low that same year. Also, this suggests that a reversal of the insolation gradient produces a vegetation response of opposing sign.

[23] As the ITCZ tracks the sun north and south throughout the year, variable insolation within the tropics may affect vegetation through two mechanisms: enhanced rainfall or

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**Figure 6.** African mean vertical velocity fields and correlations on climate variables. (a) mean 1980–2000 December-January-February 500 mb vertical velocity field, (b) December-January-February 500 mb vertical velocity field correlated with December-January-February insolation, (c) mean 1980–2000 June-July-August 500 mb vertical velocity field, (d) June-July-August 500 mb vertical velocity field correlated with June-July-August insolation, (e) mean 1980–2000 June-July-August 500 mb vertical velocity field, (f) June-July-August 500 mb vertical velocity field correlated with June-July-August OLR. Bold contours on correlation plots are significant to 95%. 

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enhanced evapotranspiration. For both of the insolation regression patterns in Figures 3a and 3b, the positive anomalies occur in the summer hemisphere. Higher vegetation productivity during a rainy season when insolation is high suggests that it is unlikely that the insolation regression patterns are created by greater evaporation. These patterns instead seem linked to summer rains, whose position and intensity are determined by insolation [Nicholson, 1986].

One possible mechanism could be an intensification of Hadley circulation leading to greater summer rainfall. Although this may explain positive anomalies for both June-July-August and December-January-February in much of the summer hemisphere, a strong negative anomaly in southern July-August and December-January-February in much of the hemisphere rainy season [Nicholson, 1986] is observed beginning near 7°N, but extends much farther northward (Figure 6d). This suggests that rising air associated with rainfall is stronger and more northward with a southerly ITCZ which brings more rainfall and lengthens the growing season; however, a strong negative NDVI anomaly persists south of 20°S suggesting drier conditions (Figure 3a).

In East Africa, a meridional component of the ITCZ develops in December-January-February, the Congo Air Boundary, extending northeastward from Namibia. The Congo Air Boundary is a region of convergence of dry air originating from the northern Indian Ocean with moister air masses from the Congo basin and southern Atlantic Ocean. This eastward moisture penetration from the Atlantic is important for driving rainfall in East Africa during the southern hemisphere rainy season [McHugh, 2004]. The correlation of December-January-February insolation with 500 mb vertical velocity suggests that a southward shift of the ITCZ is mirrored by a southward shift of the semi-permanent South Atlantic anticyclone, an area of positive correlation west of southern Africa (Figure 6b). This southward retreat of the anti-cyclone results in reduced convection on the western side of the Congo Air Boundary leading to greater eastward Atlantic moisture penetration during austral summer and promoting a wetting in southeast and drying in southern Africa consistent with the pattern observed in the December-January-February NDVI regression pattern (Figure 3a). In contrast, when December-January-February insolation is low, a northward ITCZ and South Atlantic anti-cyclone block Atlantic moisture from penetrating further eastward.

In June-July-August, negative correlation between insolation and vertical velocity is observed beginning near the mean ITCZ position centered around 7°N, but extends much farther northward (Figure 6d). This suggests that rising air associated with rainfall is stronger and more northward when June-July-August insolation is high. Additionally, this band of negative correlation extends southward as well along the West African coast. This may be the result of a northward
extension of the South Atlantic anti-cyclone mirroring the northward ITCZ position as indicated by a strong area positive correlation in the Southern Atlantic.

[30] Tropical vegetation, particularly trees in areas with prolonged dry seasons, store starch during the growing season. Changes in ITCZ position alter the length of the dry season and growing season when deciduous trees hold their leaves and when vegetation is productive [Brown and deBeurs, 2008]. A time series of southern hemisphere (10–20°S; 0–40°E) and northern hemisphere (10–20°N; 0–40°E) dry days (days/year with < 0.5 mm rain) was created as a metric for the effect of length on vegetation. Figures 7a and 7b show the regression maps yielded by regressing December-January-February and June-July-August NDVI on southern and northern hemisphere dry days, respectively. Both patterns are significantly similar, but of opposing sign, to the December-January-February and June-July-August insolation regression patterns (Figures 3a and 3b). This suggests that higher insolation displaces the ITCZ toward the summer hemisphere and produces a shorter dry season and a longer growing season leading to increased vegetation productivity (Figure 8a).

[31] Studies of hydrology typically focus around mean annual precipitation (MAP); however, vegetation productivity is a function of effective moisture [Nicholson, 1986]. We propose that insolation controls vegetation productivity through two mechanisms when summer insolation is high: greater rainfall intensity and shorter dry season length due to a displacement of the ITCZ and subtropical anti-cyclones toward the summer hemisphere. Although enhanced convective precipitation associated with high summer insolation may help drive these vegetation anomalies, the relationship connecting rainy season productivity to the length of the preceding dry season should not be ignored. This is consistent with modeling results of Hély et al. [2006], demonstrating increased sensitivity of semi-deciduous and deciduous biome types to changes in dry season length.

4.2. Hadley Circulation and ENSO

[32] The OLR time series produces the highest value of covariance of all the time series when regressed on NDVI for June-July-August (Table 1). In addition, the EOF plot implies that anomalies of this variable are greater toward the sub-tropics (Figure 1). Thus, the June-July-August OLR pattern when regressed on NDVI results from changes in atmospheric circulation of the same sign throughout the tropics (Figures 1 and 4). Furthermore, although the troposphere height time series never yields covariance values with greater than 90% significance, the PCA biplot suggests an important antiphased relationship between these two variables (Figure 5). When troposphere height is high, OLR is low.

[33] The ITCZ can vary in intensity, mean position, and width [Nicholson, 1996]. The gradient of OLR from the equator to the sub-tropics, as observed by the EOF, suggests that the vegetation response in June-July-August is related to tropical belt width (Figure 1). Thus, the negative anomalies near the sub-tropics and positive anomalies near the equator are due to a narrower ITCZ during summers when OLR is high (Figure 4).

[34] This is supported by correlation of June-July-August OLR with June-July-August 500 mb vertical velocity. Figure 6f shows a positive correlation, indicating reduced convection, covering much of northern and central Africa. This circulation pattern would dry the sub-tropics and wet the equatorial region, as the ITCZ does not reach as far north.

[35] This is further supported by positive NDVI anomalies persisting even in the southern hemisphere during the June-July-August dry season, suggesting that enhanced precipitation near the equator influences vegetation into the dry season (Figure 4). This is perhaps the result of enhanced starch storage, common in southern African woody plants in years with a wetter, more productive rainy season [Rutherford, 1984]. Although the regression yields a 95% significant value only in northern hemisphere summer, numerous 90% significant values for regression of troposphere height and OLR...
suggest that this relationship may also exist for the short and long rainy seasons (March-April-May and October-November-December) as well as in December-January-February (Table 1).

[36] Such changes in atmospheric circulation throughout the tropics may suggest a link to climate modes on a global scale. Regression of the Southern Oscillation Index on June-July-August NDVI produces a pattern that is significantly similar to June-July-August OLR (Figure 8). This supports many studies linking ENSO to vegetation and rainfall anomalies throughout Africa [Anyamba and Eastman, 1996; Nicholson and Selato, 2000]. Higher troposphere heights throughout the tropics during ENSO events is consistent with results of our PCA, showing an antiphased relationship between OLR and troposphere height [Camberlin et al., 2001]. Furthermore, ENSO warm event years (1988, 1999) on the PCA biplot occur near the positive end of the second axis near both seasons of troposphere height (Figure 5). Cold events, associated with higher OLR and lower troposphere height, would produce a pattern similar to Figure 4. During warm events, the relationship is reversed when OLR is lower.

[37] Our study points to a strong, direct link between atmospheric circulation during ENSO events and African vegetation variability [Schreck and Semazzi, 2004]. Since the Southern Oscillation Index is calculated based on surface pressure, rather than SST anomalies, we observed that the immediate effect of ENSO on African vegetation is not related directly to SSTs but rather atmospheric height anomalies. The north-south symmetry of the OLR and Southern Oscillation Index patterns in NDVI is consistent with studies illustrating the effect of cold events on the ITCZ that promotes reduced convergence at the northern and southern extremes during rainy seasons [Janicot, 1997].

5. Conclusions

[38] Despite heterogeneous MAP and vegetation, global atmospheric controls on the ITCZ have a strong influence on interannual vegetation variability throughout Africa. Rainy season moisture convergence and dry season length have a profound effect on vegetation in both northern and southern tropical Africa. In contrast, commonly cited mechanisms, like SSTs, do not exhibit a strong connection.

[39] ITCZ variability and the African hydrologic budget are tightly connected to ENSO and insolation on short and long time scales (Figure 9). High summer insolation produces in ITCZ excursions resulting in a shorter dry season and positive vegetation anomalies in the summer hemisphere (Figure 9a). Higher atmospheric heights and a wider tropical belt during warm ENSO events result in a symmetrical vegetation pattern centered about the equator (Figure 9b).

[40] Although we support the suggestion that ENSO is the dominant mode of variability in the African tropics, our study points to a strong, direct link between atmospheric circulation, rather than SSTs, and vegetation productivity [Schreck and Semazzi, 2004]. One third of the African population lives in semiarid regions dependent on natural and rainfed agricultural resources especially sensitive to variability [IPCC, 2007]. It is yet unknown how ENSO frequency and amplitude will change with future warming [Collins et al., 2005; Yamaguchi and Noda, 2006]; however, it will almost certainly have a dramatic effect on African vegetation. Although the latest generation of climate models accurately simulate many aspects of atmospheric dynamics, inaccuracies of ENSO behavior and the ITCZ will hinder accurate predictions of future vegetation change, effects of tropical vegetation on the carbon and hydrologic cycles, and simulations of past vegetation dynamics.

[41] Despite the small amplitude changes over the time period studied (−0.25 W/m² or 0.018%) [Shindell et al., 2006], insolation has a marked effect on tropical atmospheric circulation and vegetation productivity. The effect of insolation on short time scales has been little investigated despite suggestions that very small solar irradiance changes may influence tropical rainfall patterns [Shindell et al., 2006]. On longer time scales, high-amplitude insolation variability is likely the primary mechanism of Afrotropical vegetation change.

Figure 9. Location of ITCZ (cloud position) and generalized patterns of vegetation anomalies (green = positive, brown = negative). These patterns are created by (a) insolation variability producing vegetation anomalies which are antiphased between the north and south hemispheres due to ITCZ excursions, and (b) OLR/troposphere height variability producing vegetation anomalies which are symmetrical about the equator due to ITCZ width changes.
This supports the many studies showing large-scale ecological and hydrologic changes in Africa that follow the beat of ENSO  

[42] Our analyses suggest that today ITZC width is mostly controlled by ENSO variability, but future warming may also affect ITZC width. A warmer atmosphere from anthropogenic forcing results in higher troposphere height and wider migrations, wetting the outskirt of the tropics and drying the equatorial region. Seidel et al. (2008) have already documented this widening of the tropics. This has particular implications, such as crop failure and desertification, for semi-arid vegetation that is extremely sensitive to changes in dry season length [Hély et al., 2006; McClean et al., 2005].

[43] In addition, southern Africa depends on the placement of mid-latitude westerlies and semi-permanent anti-cyclones determining the eastward penetration of moisture into sensitive semi-arid areas like East Africa [McHugh, 2004]. Recent studies suggesting a poleward westerlies displacement as the atmosphere warms imply that these regions could see a marked drying as moisture needed to drive convergence may no longer be available [McCabe et al., 2001].

[44] In much of Africa, nothing is more important to human lives and livelihoods than the seasonal rains following the sun each year and the plants sustained by this rainfall. Although the human relationship with plants has changed over time in Africa, the overarching climate mechanisms controlling landscape distribution and productivity have not. The quantitative constraints we provide here may give some insight concerning how climate change will and did affect the distribution of important ecosystems and the climate regimes under which crops thrive.

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