Multidecadal Trends and Interannual Variability of Rainfall as Observed from Five Lowland Stations at Mt. Kilimanjaro, Tanzania

INSA OTTE AND FLORIAN DETSCH

Environmental Informatics, Faculty of Geography, Philipps University of Marburg, Marburg, Germany

EPHRAIM MWANGOMO

Environmental Informatics, Faculty of Geography, Philipps University of Marburg, Marburg, Germany, and Tanzania National Parks, Arusha, Tanzania

ANDREAS HEMP

Department of Plant Systematics, University of Bayreuth, Bayreuth, Germany

TIM APPELHANS AND THOMAS NAUSS

Environmental Informatics, Faculty of Geography, Philipps University of Marburg, Marburg, Germany

(Manuscript received 16 March 2016, in final form 25 October 2016)

ABSTRACT

Future rainfall dynamics in the Kilimanjaro region will mainly be influenced by both global climate and local land-cover change. An increase in rainfall is expected, but rising temperatures are also predicted for the ecosystem. In situ rainfall of five stations is analyzed to determine seasonal variability and multidecadal trends in the lowlands and lower elevations of the Kilimanjaro region. Monthly rainfall totals are obtained from the Tanzanian Meteorological Agency, from two mission stations, and from a sugar cane plantation. The datasets of the two mission stations cover time spans of 64 and 62 years, starting in 1940 and 1942, while rainfall data obtained from the Tanzanian Meteorological Agency and from the sugar cane plantation start in 1973 and 1974 and thus cover 40–41 years. In one out of five stations, a significant weak negative linear long-term trend in rainfall is observable, which is also evident in the other locations but is not significant. However, humid and dry decades are evident and seasonality has changed, especially during the long rains between March and May. El Niño–Southern Oscillation (ENSO) in combination with positive Indian Ocean dipole (IOD) leads to enhanced rainfall during the year of ENSO onset and the following year. During La Niña years, rainfall increases in the following year, while during the onset year rainfall patterns are more diverse. Positive IOD leads to enhanced rainfall amounts.

1. Introduction

Future rainfall dynamics in the Kilimanjaro region will mainly be influenced by both global climate and local land-cover change. As the dense forest belt in low and

mid-elevations at Mt. Kilimanjaro acts as a water tower feeding major river systems, a resource for agriculture along the densely populated southern slopes (Hemp 2005), and a home for a vast variety of endemic species (Myers et al. 2000; Hemp 2006), variation of rainfall dynamics in this region is of particular interest. Of special importance are water-balance-related fluxes since significant changes in the local hydrological cycle will likely have the most serious or beneficial consequences for the regional ecosystem (Mölg et al. 2012). Even though an increase in precipitation is expected for the East African region (Shongwe et al. 2011), the actual characteristics of this trend might be overcompensated by increasing evaporation losses due to rising temperatures (Lobell

Denotes Open Access content.

Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JHM-D-16-0062.s1>.

Corresponding author e-mail: Insa Otte, ottein@staff.uni-marburg.de

DOI: 10.1175/JHM-D-16-0062.1

et al. 2011). In addition, the seasonal rainfall distribution is of similar importance for the vegetation system as the annual sum (Røhr and Killingtveit 2003).

Temporal rainfall variability in East Africa is a result of complex interactions of forced and free atmospheric variations (Chan et al. 2008), including sea surface temperature (SST) forcing (e.g., Appelhans and Nauss 2016) and large-scale teleconnections (Mutai and Ward 2000). The bimodal rainfall distribution that is shaped by a “short” (October–December) and “long” (March–May) rainy season, is caused by the seasonal migration of the intertropical convergence zone (ITCZ; Mutai and Ward 2000; Camberlin and Philippon 2002). Precipitation in low and midelevations is disconnected from the summit region at Mt. Kilimanjaro; nevertheless, the glaciated summits are extremely sensitive to variations in precipitation (Mölg et al. 2008, 2009a,b) [for further findings related to the glaciated summits, see, e.g. Hastenrath (2010), Mölg and Kaser (2011), and Mölg et al. (2012)].

Previous studies focusing on long-term rainfall trends in the larger East African sector have revealed no uniform trend. They depend highly on the actual considered measurement stations and time spans and conclude that either no or only small long-term trends exist. One of the first comprehensive rainfall analyses in East Africa that encompassed a considerable amount of station data was performed by Rodhe and Virji (1976) and showed no long-term trends between 1922 and 1974, apart from a station close to the northern Kenyan border, where rainfall slightly increased toward the 1970s. A slight increase in rainfall in East Africa is also found by Hulme (1992) between the periods of 1931 and 1960 as well as between 1961 and 1990. The analysis of Schreck and Semazzi (2004) using the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) for the October–December season shows an increasing rainfall trend during 1961–2001 in regions northward of a line connecting the Democratic Republic of Congo and Zanzibar. A decreasing trend is observed to the south of this region for the same time period. For Mt. Kilimanjaro, Hemp (2005) found negative rainfall trends during the last century.

Large-scale ocean–atmosphere interactions have been identified as a main driver for interannual rainfall variability in the East African region (e.g., Ogallo 1989). Previous studies of rainfall variability have mainly focused on El Niño–Southern Oscillation (ENSO) or on the Indian Ocean dipole (IOD), although some studies additionally highlight the role of the Atlantic Ocean (Nicholson and Kim 1997; Hastenrath et al. 1993). Regarding ENSO phases, increased rainfall amounts and floods are generally linked to El Niño, while decreased rainfall amounts and drought events occur during La

Niña years in East Africa (Wolff et al. 2011). With respect to El Niño, Nicholson and Kim (1997) showed that positive rainfall anomalies over many African sectors could be linked to the first half of the ENSO cycle while negative anomalies prevail in the second half. Similar results were found by Hastenrath et al. (1993), although they postulate ENSO-induced anomalies only for the short rains (October–December). In contrast, La Niña shows temporally reversed patterns with negative rainfall anomalies during the first half and above-average rainfall in the second half of the phase (Nicholson and Selato 2000). While the most consistent influence is given in southwestern Africa, the situation for Tanzania seems to be much more complicated, with both positive and negative rainfall deviations during the second half [see figures in Nicholson and Selato (2000)].

Recent studies highlight a greater influence of Indian Ocean SST on East African rainfall anomalies compared to ENSO SST anomalies (Appelhans and Nauss 2016; Black 2005; Mutai et al. 1998; Saji et al. 1999). For example, Saji et al. (1999) showed that the IOD was an ENSO-independent driver for severe rainfall in eastern Africa between 1958 and 1998, where warm events in the western Indian Ocean (i.e., positive IOD) are related to above-average rainfall over the region. Webster et al. (1999) also provided arguments for the independency of IOD from ENSO, even during the strong 1997/98 phase, although the relationship between ENSO and IOD is a matter of discussion (e.g., Fischer et al. 2005; Bracco et al. 2005; Annamalai et al. 2005).

These earlier publications provide various insights into the rainfall dynamics of the wider region; however, prior studies generally consider larger spatial domains and do not explicitly focus on the rather sensitive ecosystem of the southern slopes of Mt. Kilimanjaro that are in the center of this study. While there is clear evidence of the influence of ENSO and IOD on rainfall in East Africa, it is not clear how they altered rainfall variability during the last half century at the southern lower slopes of Mt. Kilimanjaro. The present study will primarily focus on intraseasonal variations of rainfall due to large-scale ocean–atmosphere interactions (ENSO and IOD), regarding all seasons (both wet seasons and dry seasons) based on a multidecadal rainfall time series collected at five lowland and low-elevation stations in the vicinity of Mt. Kilimanjaro.

2. Data and methods

a. Site description

Mt. Kilimanjaro (5895 m MSL) is known as the highest freestanding mountain in the world, located 340 km south of the equator on the northern border between

Tanzania and Kenya. The temporal rainfall distribution is governed by the north–south and south–north oscillation of the ITCZ, shaping a bimodal regime with two distinct rainy seasons, the more pronounced long rains from March to May and the short rains from October to December, which are generally centered around November but are more variable than the long rainy season. One distinct dry season ranges from June to September and a second short dry season ranges from January to February (e.g., Hemp 2005; Mölg et al. 2006; Appelhans and Nauss 2016). In general, rainfall at Mt. Kilimanjaro is highly dependent on moisture supply from the Indian Ocean (Mölg et al. 2009a) and hence is subject to variations in this supply induced by ENSO and IOD (Ropelewski and Halpert 1987; Latif et al. 1999; Goddard and Graham 1999). The vertical rainfall gradient at the southern slopes exhibits maximum amounts around 2200 m MSL (Hemp 2001; Appelhans et al. 2016). The northern slopes receive less rainfall than the southern slopes (Hemp 2005).

b. Rainfall station records

Available daily rainfall data from NOAA's Global Surface Summary of the Day (GSOD) station record (NCDC 2014) is discarded because of too many gaps. Instead, the time series analysis is based on monthly rainfall totals obtained from (i) the Tanzanian Meteorological Agency, (ii) two mission stations, and (iii) one sugar cane plantation. While gap-free monthly rainfall time series from January 1973 to December 2013 are available from the stations of the Tanzanian Meteorological Agency at Kilimanjaro International Airport (KIA; 890 m MSL) and Moshi Airport (Moshi; 830 m MSL), as well as from January 1974 to December 2013 at the sugar cane plantation of Tanganyika Planting Company Ltd. (TPC; 750 m MSL), the rainfall records from the mission stations Kilema (1430 m MSL; from January 1940 to December 2014) and Kibosho (1430 m MSL; from January 1942 to December 2014) contain a few data gaps, but they provide an excellent long-term dataset of rainfall totals starting in the 1940s.

The monthly rainfall data are measured with manual standard rainfall gauges. The rainfall quantity is determined on a regular basis, that is, on a (mostly) daily basis in recent years, but in longer time intervals (e.g., in a biweekly cycle) in earlier years (F. Nderukama 2014, personal communication). For the location of the stations, see Fig. 1.

1) PREPARATION OF MONTHLY RAINFALL TOTALS

For further analyses, gap filling is applied to the rainfall time series of Kibosho and Kilema. The time series of monthly rainfall totals at the mission station

FIG. 1. Overview of the study area including two stations of the Tanzanian Meteorological Agency at KIA and Moshi, two mission stations (Kilema and Kibosho), and one sugar cane plantation (TPC), which are used for long-term time series analysis of rainfall.

Kibosho covering from January 1940 to December 2014 exhibits 15.67% missing data (longest gap: 30 months), while at Kilema (from January 1942 to December 2014), 16.10% of the data are lacking (longest gap: 60 months). The data gaps in the rainfall time series are filled using a linear model. The predictor station for the gap filling is chosen based on the best cross-correlation results. The time series of Kibosho is filled by cross correlation with data from the station Moshi (coefficient of determination $R^2 = 0.52$, RMSE = 122 mm). As the time series of Moshi starts in January 1973, few data gaps, which occurred before 1973, remain after this step (3.56%, longest gap: 29 months). These data gaps are subsequently filled using the monthly rainfall data from Kilema ($R^2 = 0.36$, RMSE = 151 mm). The data gaps within the time series of Kilema are filled likewise with data derived from the Moshi record ($R^2 = 0.47$, RMSE = 96 mm). For the remaining gaps at Kilema (5.48% missing values, longest gap: 37 months) that occurred before 1973, Kibosho is used as independent variable ($R^2 = 0.34$, RMSE = 164 mm).

Outlier detection within the raw dataset is conducted by using Grubbs' test (Grubbs 1969). Highly significant ($p < 0.001$) outliers in the raw data are removed and replaced by respective monthly mean values of the preceding and consecutive five years. Within the context of quality control of the monthly rainfall datasets, a breakpoint analysis is conducted to detect possible structural changes (e.g., caused by changing measurement devices during the last century), which do not reveal any significant breaks in the datasets.

To retain a more robust and regional signal of rainfall climatology dynamics at the study sites, monthly rainfall

totals of Kilema and Kibosho as well as of KIA, Moshi, and TPC are averaged. Nevertheless, the resulting averaged time series are certainly not representative for the entire mountain area. This is indicated by the station-based findings by Duane et al. (2008) or the model studies by Fairman et al. (2011) and Mölg et al. (2009a), who show that the highest elevation zones are decoupled from the lower areas, as a consequence of the predominant flow-around regime at Mt. Kilimanjaro. Hence, the general patterns recorded at Kilema and Kibosho and at KIA, Moshi, and TPC (i.e., increasing/decreasing rainfall and intraseasonal changes) are likewise only valid for the low to probably midelevation areas of Mt. Kilimanjaro.

2) ANALYSIS OF THE INFLUENCE OF OCEAN–ATMOSPHERE INTERACTIONS ON RAINFALL

Regarding the dependence on lowland and low-elevation rainfall from ocean–atmosphere interactions, the influence of ENSO and IOD on the distribution of monthly rainfall amounts is investigated.

To characterize ENSO, we use the Oceanic Niño Index (ONI) that is based on SST anomalies in the Niño-3.4 region (5°S–5°N, 120°–170°W) since January 1950. The ONI is derived from the 3-month running mean of NOAA's Extended Reconstructed SST, version 3b (ERSST.v3b; Smith et al. 2008), and provided by CPC (2014). In addition, the classification scheme based on Null (2014) is utilized to classify individual years into weak, medium, or strong La Niña/El Niño or normal years.

For the IOD phenomenon, the dipole mode index (DMI) is used. The DMI represents the intensity of the IOD by an anomalous east–west SST gradient between the equatorial Indian Ocean (10°S–10°N, 50°–70°E) and the southeastern equatorial Indian Ocean (10°S–0°, 90°–110°E) and is provided by JAMSTEC (2014). The IOD events are classified as years with positive IOD or negative IOD or as normal years as stated by the Australian Bureau of Meteorology (2014).

For testing the statistical significance between ENSO and/or IOD status and changes in the monthly rainfall distribution, a factor analysis (El Niño/La Niña, El Niño/La Niña with/without positive/negative IOD, etc.; see categories in Figs. 4 and 5, described in greater detail below) using a generalized linear model and bootstrapping with 2000 samples is calculated. The original rainfall data have been square-root transformed and the model is fitted using one sine and one cosine term. Additional significance testing is conducted by using a one-way analysis of variance (ANOVA), which compares the means between different groups (e.g., ENSO and IOD) and determines whether any of those means are significantly different from each other.

3. Results and discussion

a. Trends in rainfall between 1940 and 2014

Long-term trend analysis of rainfall shows negative trends at all five stations (Figs. 2a,b,d–f). The strongest decline is recorded at Kibosho (-6.58 mm yr^{-1} , $p < 0.05$; without gap filling: -7.26 mm yr^{-1} , $p < 0.05$), while at Kilema (-1.87 mm yr^{-1} , $p = 0.37$; without gap filling: 0.53 mm yr^{-1} , $p < 0.86$), KIA (-1.35 mm yr^{-1} , $p = 0.55$), Moshi (-5.14 mm yr^{-1} , $p = 0.13$), and TPC (-3.11 mm yr^{-1} , $p = 0.29$) no significant trends are shown. Averaged annual rainfall sums for Kilema and Kibosho (1942–2014) and for KIA, Moshi, and TPC (1974–2013) are shown in Figs. 2c and 2g. The annual sums show an alternating pattern of slightly wetter and drier decades for both averaged stations. At Kilema and Kibosho the decade 1960–70 is rather wet, with only three years that are drier than average in each decade, while the last two decades (1990–2000 and 2000–10) are quite dry, with six (1990–2000) and eight (2000–10) years that are drier than average in each decade. The long-term trend between 1942 and 2014 is significantly ($p < 0.05$) negative with $-45 \text{ mm decade}^{-1}$ (cf. Fig. 2c). Considering the average rainfall values of KIA, Moshi, and TPC, the alternating patterns of wetter and drier decades are also noticeable. The long-term trend between 1974 and 2013 is negative with $-37 \text{ mm decade}^{-1}$ but not significant ($p = 0.16$, cf. Fig. 2g).

If years with positive or negative IOD and/or ENSO events of the KIA, Moshi, and TPC time series are considered as additional explanatory factors in this linear trend model, strong La Niña events show a weakly significant ($p < 0.10$) positive deviation, while medium La Niña denotes a weakly significant ($p < 0.10$) negative deviation over time. Furthermore, a weakly significant ($p < 0.10$) increase occurs during weak El Niño. This signal can also be detected if the monthly deviations from the long-term monthly mean, rather than the annual sums, are used as a basis for the linear regression and ANOVA (cf. Fig. S1). In addition, a significant trend over time ($p < 0.05$) can be found during the long rains, with a positive deviation in March but a negative deviation in April. This trend is also recorded by ANOVA with significantly ($p < 0.05$) deviating long rains, while no significant trend is observed for the short rainy season.

If the time series of Kilema and Kibosho is considered in the same linear trend model, weak El Niño events show a significant increase ($p < 0.05$) over time. Contrasting to KIA, Moshi, and TPC, a highly significant ($p < 0.001$) negative trend can only be found in March (not in April), indicating the onset of the main rainy season as well as a highly significant ($p < 0.001$) decrease of the long rainy season.

FIG. 2. Annual rainfall amounts based on monthly rainfall sums obtained from two mission stations [(a) Kilema and (b) Kibosho], from the Tanzanian Meteorological Agency [(d) KIA and (e) Moshi], and a sugar cane plantation [(f) TPC], as well as the mean of the respective stations [(c) Kilema and Kibosho mean and (g) KIA, Moshi, and TPC mean]. Blue bars denote annual sums based on monthly gap-free raw values. Dark blue bars display years with data gaps of one or more months. (For details of gap filling, see section 2b.) Light red and blue background coloring indicates positive and negative deviations from the long-term annual mean values. The black dashed line shows the overall linear trend and dark gray shading shows the corresponding 95% confidence intervals; asterisk indicates $p < 0.05$.

It has to be noted that the residuals of this linear model are not normally distributed but given a sample size ranging from 474 for the shortest to 876 for the longest time series, such significance levels are generally reliable (see, e.g., Lumley et al. 2002).

One noticeable feature of the distribution of dry years between 1998 and 2005 are enhanced rainfall amounts in 1998/99 and 2002 at Kilema and Kibosho and at KIA, Moshi, and TPC, although this time frame is generally considered as drought (e.g., Kijazi and Reason 2009a,b). While Kijazi and Reason (2009a,b) averaged across four stations, we averaged two (Kilema and Kibosho) and three (KIA, Moshi, and TPC) stations that are located at approximately the same elevation. Additionally, we only used stations in close vicinity to Mt. Kilimanjaro, but this still seems like quite a contrasting result. Nevertheless, the findings of Kijazi and Reason (2009a) can be conciliated with our study results since they only considered the short rains from October to December and the long rains from March to May. Hence, if rainfall shifted toward the dry seasons, the respective years could be classified as dry, although the annual amount might indicate a normal or even wet year. As a matter of fact, if the mean October–December anomalies (Fig. S1) for the years between 1998 and 2005 are averaged, all but the seasons of 2002 and 2004 show less-than-average

rainfall for Kilema and Kibosho and for KIA, Moshi, and TPC. While the small anomaly of the year 2004 is not evident in the results of Kijazi and Reason (2009a), El Niño in 2002 marks a clear positive deviation. For the long rains from March to May, a similar conclusion can be drawn, with three (1998/99 and 2002) out of eight years showing a positive deviation at KIA, Moshi, and TPC, while at Kilema and Kibosho only one year (1999) denotes above-average rainfall amounts. On the other hand, seven of the eight years experienced wetter-than-normal conditions during both dry seasons, which was also noted by Kijazi and Reason (2009a) as an out-of-season rainfall peak. This indicates the necessity to explicitly consider intra-annual rainfall variability, which is generally linked to weak zonal circulations that induce decreased subsidence of the descending branch of the Walker circulation (e.g., Hastenrath 2000; Hastenrath et al. 2007, 2010).

For long-term trends, our findings are partly in agreement with the general conclusion for the larger East African area as presented in the introduction. Whereas Rodhe and Virji (1976) and Hulme (1992), for example, detected no long-term trends or a slight increase in rainfall in East Africa, Hemp (2005) found strong negative trends for the last century at Mt. Kilimanjaro. Hemp (2005) used extended time series from Moshi (1902–2004) and two missions (1911 and 1922–2004),

FIG. 3. Long-term monthly mean rainfall averaged over the stations (top) Kilema and Kibosho (1950–2009) and (bottom) KIA, Moshi, and TPC (1974–2009) for each decade. The overall mean for the entire time span is displayed in the gray boxplot (solid horizontal line is median and circles are outliers).

which were analyzed in our study as well, in order to briefly characterize the environmental parameters at Mt. Kilimanjaro in a study focusing on vegetation dynamics. However, as already stated by [Hemp \(2005\)](#), the findings are mainly a result of distinctive features of the time series; for example, the Moshi time series shows considerable differences in rainfall by a factor of about 1.4 prior to and after a large data gap during and after World War I, which mainly caused the 34% decrease. Regarding the two higher locations, the trends of -27% and -39% are primarily a result of a few (outlier) years (which have been detected by Grubbs' test for the time interval used in this study) located before the 1970s with nearly twice the amount of rainfall than in all other years in combination with data gaps toward the end of the time series. Comparing these results highlights the particular importance of data preprocessing (e.g., quality control and gap filling).

b. Seasonal rainfall analysis

To get more detailed insights into seasonal rainfall patterns ([Fig. 3](#)), we investigated their relation to ENSO and IOD ([Figs. 4, 5](#)).

The long-term mean seasonal rainfall cycle between 1950 and 2009 (KIA, Moshi, and TPC: 1974–2009) is depicted by the gray boxplots in [Fig. 3](#). It shows the well-documented bimodal distribution. The long rains, with core rainfall amounts between March and May, are more abundant, while the short rains with their peak between October and December are more variable [see

also [Hastenrath \(2001\)](#)]. Regarding the monthly rainfall values within the other decades, distinguishable features related to the amount are also visible, although they are only weakly significant in the nonaveraged time series of Kilema (1960–69, $p < 0.10$), Kibosho (1960–69, $p > 0.90$; 2000–09, $p < 0.05$), and TPC (1980–89, $p > 0.90$; cf. [Fig. S2](#) and [Table S1](#)). The identified dry decades are reflected to a lesser extent during the short rains.

In summary, the intra-annual rainfall distribution cannot be simplified to a generally decreasing trend over time but should rather be conceived as seasonal fluctuations of rainfall with a quite large intraseasonal variability. While the long rains recently declined significantly over time ($p < 0.05$) from (decadal monthly median) peak values in April of 254 to 122 mm at KIA, Moshi, and TPC (from 540 to 348 mm at Kilema and Kibosho), the short rains became more abundant and potentially more prolonged (not significant). These findings are in accordance with [Camberlin et al. \(2009\)](#), who indicated a modulation of intra-annual rainfall occurrence with an unchanged annual amount for northeastern Tanzania and Kenya between 1958 and 2001. They also emphasize a tendency for rainfall decline during the main growing season [see also [Funk et al. \(2008\)](#)], which is not necessarily related to a change in the overall amount but may feel equivalent to decreasing rainfall from the perspective of many local farmers ([A. Hemp 2013](#), personal communication). The decreasing rainfall amounts during the long rains are well in line with findings from [Lyon and DeWitt \(2012\)](#), who associated the rainfall decline during

FIG. 4. Mean (top) Kilema and Kibosho and (bottom) KIA, Moshi, and TPC monthly rainfall sums grouped in boxplots (solid horizontal line is median and circles are outliers) according to El Niño and IOD phases. The frequency of their occurrence is given in parentheses for mean Kilema and Kibosho (1950–2014) phases and in square brackets for mean KIA, Moshi, and TPC (1974–2013) phases. Note that the y axes are not uniform for the sake of a better visualization of the phases.

the long rainy season in East Africa with large-scale SST changes in the tropical Pacific.

Regarding large-scale teleconnections, ENSO certainly explains large portions of the general East African

rainfall variance (see studies in the introduction), and fluctuations of the short rains are also strongly related to anomalies in the Indian and Pacific Oceans (e.g., Hastenrath et al. 1993). To obtain the influence of the

FIG. 5. Mean (top) Kilema and Kibosho and (bottom) KIA, Moshi, and TPC monthly rainfall sums grouped in boxplots (solid horizontal line is median and circles are outliers) according to La Niña and IOD phases. The frequency of their occurrence is given in parentheses for mean Kilema and Kibosho (1950–2014) phases and in square brackets for mean KIA, Moshi, and TPC (1974–2013) phases. Note that the y axes are not uniform for the sake of a better visualization of the phases.

TABLE 1. Mean rainfall amounts during El Niño and IOD phases (mm) based on monthly rainfall sums obtained from the Tanzanian Meteorological Agency (KIA and Moshi), a sugar cane plantation (TPC), and two mission stations (Kilema and Kibosho). Note that analysis at Kibosho and Kilema ranges from 1950 to 2014, at KIA and Moshi from 1973 to 2013, and at TPC from 1974 to 2013. Boldface values indicate increased annual rainfall sums, one asterisk indicates weakly significant increased (decreased) rainfall amounts with $p > 0.90$ ($p < 0.10$), two asterisks indicate significantly increased (decreased) rainfall amounts with $p > 0.95$ ($p < 0.05$), and three asterisks indicate highly significant increased (decreased) rainfall amounts with $p > 0.99$ ($p < 0.01$). For details, see Table S1.

	Mean rainfall	<i>All El Niños</i>	<i>El Niños only</i>	<i>El Niños w IOD+</i>	<i>Merely IOD+</i>	<i>Merely IOD−</i>
Kilema	1340	1488	1442	1591	1464	1382
Kilma without gap filling	1368	1501	1514	1478	1466	1489
Kibosho	1782	1879	1760**	2004*	2020***	2149
Kibosho without gap filling	1800	1815	1826	1740	1871*	2333
Kilema and Kibosho	1561	1669	1602	1798	1742	1766
Kilema and Kibosho without gap filling	1507	1557	1618	1457	—	2208
KIA	524	582	512	664	583	373*
Moshi	845	877	906	977	886*	819
TPC	518	541	498	601	532	542*
KIA, Moshi, and TPC	631	666	605	752*	668	578

most dominant atmosphere–ocean interactions on rainfall patterns in the Kilimanjaro region, the years have been grouped into ENSO- and IOD-related classes. As the teleconnection effects are time lagged, the considered classes start with the second half of the year in July. We defined this as the onset of the ENSO and IOD year, which ends 20 months later in February. Likewise, Pohl and Camberlin (2011) stated that ENSO anomalies peak between October and December in East Africa. Our designated time span of 20 months for analyzing the effect of ENSO and IOD on rainfall amounts in the onset year, main year, and postevent year consequently comprises one onset short rainy season, followed by one long rainy as well as another short rainy season.

Figures 4 and 5 show the resulting monthly mean rainfall cycle for ENSO phases, further differentiated in El Niño (Fig. 4) and La Niña (Fig. 5) for averaged

rainfall at Kilema and Kibosho as well as at KIA, Moshi, and TPC. An additional distinction into five groups was made between all El Niños, which can include IOD (*all El Niños*); El Niños without IOD (*El Niños only*); El Niños with simultaneously occurring IOD (*El Niños w IOD±*); and merely positive/negative IOD, which can also include weak El Niño/La Niña (*merely IOD±*). The same determination was applied to La Niña phases. Summarized mean annual rainfall amounts are shown in Table 1 for all occurring El Niño and IOD phases and in Table 2 for all occurring La Niña and IOD phases (note that Tables 1 and 2 also include values with no gap filling).

Significantly lower rainfall amounts ($p < 0.05$) are denoted during *El Niños only* and weakly significant increased rainfall ($p > 0.90$) during *El Niños w IOD+* at Kibosho and in the averaged values of KIA, Moshi, and TPC (cf. Table 1). Please note that no *El Niños w*

TABLE 2. As in Table 1, but for La Niña and IOD phases. For details, see Table S3.

	Mean rainfall	<i>All La Niñas</i>	<i>La Niñas only</i>	<i>La Niñas w IOD+</i>	<i>La Niñas w IOD−</i>	<i>Merely IOD+</i>	<i>Merely IOD−</i>
Kilema	1340	1199	1186	946	1377	1464	1382
Kilma without gap filling	1368	1236	1237	839	1366	1466	1489
Kibosho	1782	1726	1641	2218*	1416	2020***	2149
Kibosho without gap filling	1800	1667	1455	—	2232	1871*	2333
Kilema and Kibosho	1561	1462	1414	1181	1798	1742	1766
Kilema and Kibosho without gap filling	1507	1438	1251	—	1811	—	2208
KIA	524	463	514	355	284	583	373*
Moshi	845	803	823*	656	834*	886*	819
TPC	518	461	470*	359	517	532	542*
KIA, Moshi, and TPC	631	581	612	457	545	668	578

IOD− is recorded during 1942–2014. Highly significant enhanced rainfall amounts ($p > 0.99$) occur during *merely IOD*+ at Kibosho and weakly significant increased rainfall ($p > 0.90$) at Moshi and at TPC during *merely IOD*−, while weakly lower rainfall amounts ($p < 0.10$) occur during *merely IOD*− at KIA (cf. Tables 1 and 2). Weakly significant higher rainfall amounts ($p > 0.90$) are present during *La Niñas w IOD*+ at Kibosho, while weakly significant lower rainfall ($p < 0.10$) occurs during *La Niñas only* and *La Niñas w IOD*− at Moshi as well as during *La Niñas only* at TPC (cf. Table 2).

In general, all El Niños and *IOD*+ phases lead to above-average rainfall amounts in both the short rains of the onset year and the subsequent long rains (cf. Fig. 4). Since the long-term means are heavily influenced by the frequency of El Niños, no significant intraseasonal variations are observable. If the general El Niño signal is decomposed, basically, two distinct patterns emerge at the averaged values of KIA, Moshi, and TPC.

The first pattern is associated with *El Niños w IOD*+ (cyan). They show above-average rainfall in both the short and subsequent long rainy season, with amounts exceeding the long-term mean values by about a factor of 2 during the short rains of the onset year. While no intraseasonal changes are apparent for the long rains, the short rains in the onset year clearly show a negative change in the intraseasonal rainfall distribution (i.e., maximum rainfall toward earlier in the rainy season), which might even indicate an actual shift of the entire rainy season. Furthermore, *El Niños w IOD*+ prevent the dry season during January and February with constant above-average rainfall amounts.

The second pattern is a result of the *merely IOD*− (yellow). They show considerably lower rainfall amounts during the short rains of the onset year but exhibit a precipitation maximum during February prior to the onset of the long rains. Nevertheless, one should keep in mind that since 1974 (i.e., the start of the averaged time series KIA, Moshi, and TPC) only three *merely IOD*− phases have been recorded, so this result should be interpreted with caution.

The rainfall pattern of *merely IOD*+ (green) is similar to the one for *El Niños only* (blue) during the short rains, showing a positive intraseasonal change. The subsequent long rains, on the other hand, show likewise above-average rainfall amounts as already identified for *El Niños w IOD*+ (cyan).

Regarding the rainfall patterns of the short rainy season following the onset year, *El Niños only* and *merely IOD*− phases lead to slightly below-average rainfall amounts but to distinctly enhanced rainfall values during the following dry season (January–February). For all phases associated

with positive *IOD*s, the rainfall amounts during the short rains are enhanced.

In general, for El Niño and *IOD*+ phases at averaged values of Kilema and Kibosho, the features described above still hold true for the short rains in the onset year, except that the *merely IOD*+ (green) shows nearly the same pattern as *El Niños w IOD*+ (cyan). During the long rains, *merely IOD*+ and *El Niños w IOD*+ show distinctly below-average values, while *merely IOD*− (yellow) shows enhanced rainfall amounts. In contrast to KIA, Moshi, and TPC, rainfall amounts during *merely IOD*+ phases show distinctly enhanced values at Kilema and Kibosho after the long rains.

While rainfall amounts at Kilema and Kibosho are in a similar range, the different rainfall amounts between Moshi and KIA as well as between Moshi and TPC are especially obvious during the long rains (cf. Fig. S2), although KIA (TPC) is located only 30 km (20 km) to the southwest (south) of Moshi. The notable difference in rainfall can presumably be associated with a greater impact of large-scale teleconnections to the southeastern part (and Moshi) of the greater Kilimanjaro region. Yet, distinct enhanced rainfall amounts may likewise be an impact of the proximity to the mountain and hence reflect orographical modifications of the mesoscale signal. Probably the most striking feature of Fig. 4 is the diverging influence of *merely IOD*−, leading to the most distinctly enhanced rainfall amount during the long rains at Kilema and Kibosho, but to decreased rainfall values at KIA, Moshi, and TPC, while *El Niños w IOD*+ increases rainfall during the long rains at KIA, Moshi, and TPC and decreases it at Kilema and Kibosho. This quite diverse influence of *merely IOD*− as well as *El Niños w IOD*+ at the elevated stations Kilema, Kibosho, and TPC and at the lowland stations KIA, Moshi, and TPC support the findings of Plisnier et al. (2000), who stated that the ENSO impact is highly differentiated in space.

In summary, El Niños lead to above-average rainfall in both the short rains of the onset year with considerably higher rainfall amounts for combined El Niño and positive *IOD* phases. Changes in the rainfall distribution in the short rainy season toward later in the onset year can generally be related to El Niño, but this behavior is overcompensated by positive *IOD* phases.

Compared to the quite differentiated rainfall patterns associated with different groups of El Niño phases, the picture of various *La Niña* phases (Fig. 5) is much more homogeneous regarding both the various phases and the stations. Rainfall amounts are generally below average, except for *La Niñas w IOD*+ (cyan) during December in the onset year at Kilema and Kibosho and at KIA, Moshi, and TPC. During the long rains,

La Niñas w IOD+ (cyan) or *La Niñas w IOD−* (dark green) show above-average rainfall during the rainy season in the long rains as well as a maximum in the following short rains at Kilema and Kibosho. At KIA, Moshi, and TPC *La Niñas w IOD+* increases rainfall values during the long rains, while *La Niñas w IOD−* leads to rainfall amounts below average. Please note that from 1950 to 2013 only two *La Niñas w IOD+* phases and only four *La Niñas w IOD−* phases (only two from 1973 to 2013) occurred, so these findings should be interpreted with caution. During the short rains in the following year, *La Niñas only* (blue) tend to have above-average rainfall amounts, positively shifted in time at Kilema and Kibosho and at KIA, Moshi, and TPC, while *La Niñas w IOD−* lead to decreased rainfall amounts at KIA, Moshi, and TPC but increased rainfall at Kilema and Kibosho.

Previous studies generally conclude that El Niño years are associated with higher-than-average rainfall amounts and La Niña years with lower rainfall in the East African region (e.g., [Indeje et al. 2000](#); [McHugh 2006](#)). In our analysis, the latter case is valid except for *La Niñas w IOD+* at both averaged time series and at Kilema and Kibosho for *La Niñas w IOD−*, especially during the long rainy season. La Niñas also exhibit slightly above-average rainfall amounts during the short rains in the onset year. Regarding El Niños, increased rainfall amounts can be observed during *all El Niños* and *El Niños w IOD+* if the annual mean amounts are compared. If the intraseasonal rainfall distribution is regarded, it becomes obvious that the rainfall distribution of the short rains in the onset year at KIA, Moshi, and TPC is delayed toward December, with one or two rather dry months before and a considerable intensified dry period afterward. Prolonged and more variable short rains during combined El Niño and IOD+ phases are in accordance with theory relating this phenomenon to large-scale Walker circulation anomalies along the equatorial Indian Ocean ([Hastenrath et al. 1993, 2007](#)). Reduced rainfall amounts notable during *El Niños w IOD+* in the second short rainy season at Kilema and Kibosho and at KIA, Moshi, and TPC are in accordance with the findings of [Nicholson \(1996\)](#).

Although both short and long rains at Mt. Kilimanjaro are altered by the individual ENSO and IOD phases, the relative variability of the short rains is larger, which indicates a more direct coupling to macroscale mechanisms. Such a finding is consistent with the results of [Hastenrath \(2000\)](#) or [Chan et al. \(2008\)](#), who showed that the short rains exhibit a stronger interannual and intraseasonal variability, mirroring the large-scale phenomena like ENSO and the varying intensity of the zonal circulation cell along the equatorial Indian Ocean. In contrast to previous findings from [Lyon and DeWitt](#)

FIG. 6. Correlation matrix of (a) Kilema and Kibosho and (b) KIA, Moshi, and TPC monthly mean rainfall (x axis) against monthly values derived from the median of ENSO (based on DMI) and IOD (based on ONI) (y axis). Displayed are resulting tau values of Mann–Kendall correlation. Significant values ($p < 0.05$) are marked in frames.

(2012), who associated decreasing rainfall amounts during the long rains with large-scale changes in the tropical Pacific, the long rains at the lowlands and low elevations of the southern slopes of Mt. Kilimanjaro are more likely associated with local factors and—as stated by [Camberlin et al. \(2009\)](#)—large-scale influences might primarily be responsible for the onset of the rainy season and not for the intensity.

Correlations between rainfall and combined ENSO–IOD indices are depicted in Fig. 6 for averaged values at Kilema and Kibosho and for averaged values at KIA, Moshi, and TPC. ONI is used as a proxy for ENSO while DMI is utilized for IOD events. Both indices are averaged for the monthly correlation analysis, hereafter referred to as a combined ENSO–IOD index, and significant ($p < 0.05$) values are framed. Because of

changing positive/negative slopes (and partly absolute values) of the ONI and DMI within the season, the interpretation of the correlations is not straightforward in the sense that positive correlations always lead to positive rainfall anomalies.

The correlations between the combined ENSO–IOD index and the average rainfall values at KIA, Moshi, and TPC (cf. Fig. 6b) show that the intensified rainfall of the short rainy season in the onset year is already significantly (and positively) correlated with the respective ocean patterns since July–August, which is equivalent with a time lag of up to 6 months. Similar time lags are found for the generally lower-than-average rainfall amounts in the short rainy season of the following year. Shorter correlation time lags are evident for the transition between the increased (IOD related) or decreased (ENSO-only related) rainfall amounts of February–March between the short and long rainy season. A very similar pattern emerges for the correlation between combined ENSO–IOD index and the average rainfall values at Kilema and Kibosho (cf. Fig. 6a) during the short rains of the onset and the following year. In contrast to mean values at KIA, Moshi, and TPC, a longer time lag is observable during the dry season in July between the long and short rains of the following year.

Regarding the absolute values, similar correlations are found by Plisnier et al. (2000), who correlated multimonth aggregations of the Moshi rainfall station between 1981 and 1994 against values of SST for the Niño-4 region. However, they identified only time lags of up to 2 months and just for the short rainy seasons in the onset year.

4. Summary and conclusions

We aimed to provide an updated version of rainfall analysis focusing on the lowlands and low elevations of the Kilimanjaro region and thus supplement former studies with a larger spatial domain. A special emphasis was given to the interannual variability of rainfall and its relation to ENSO and IOD phases.

The time series of Kilema and Kibosho as well as of KIA, Moshi, and TPC were averaged to obtain a more regional signal, representative for the foothills and lower elevations, probably even for the midelevations, of the Kilimanjaro region. Regression analysis of long-term rainfall records shows a negative trend at all of the five considered stations over the last 74 (Kilema and Kibosho) and 40 (KIA, Moshi, and TPC) years, respectively, although this trend is only significant at Kibosho and the averaged values of Kilema and Kibosho. This finding might be a link to other studies that partly show significant trends with opposite directions farther north and

farther south of Mt. Kilimanjaro. Aside from that, the indicated negative trend is primarily caused by significantly reduced rainfall amounts during March (Kilema and Kibosho) and April (KIA, Moshi, and TPC). In contrast to the missing significance at Kilema, KIA, Moshi, and TPC for the overall long-term annual rainfall trends, seasonal rainfall analysis showed distinct variations in the distribution of rainfall at all five stations that are of major relevance from an agro-ecological perspective. The main rainy season declined significantly, while the short rains recorded an observable yet not significant increase. Additionally, the dry season tends toward above-average rainfall amounts, if the rainy seasons are drier than average.

As rainfall was also analyzed with respect to the status of ENSO and IOD, some seasonal patterns of rainfall could be related to these large-scale drivers. Generally, El Niño and/or positive IOD phases caused increasing rainfall in the short rains of the onset year and the following long rains at KIA, Moshi, and TPC, while El Niños combined with positive IOD caused decreasing rainfall during the long rains at Kilema and Kibosho. La Niña phases generally cause below-average rainfall amounts in the short rains of the onset year as well as in the subsequent long rains. A distinct increase occurs during the short rains in the post-onset year, with peak rainfall amounts in November for all three La Niña phases. If La Niñas occur in combination with positive IOD, rainfall amounts will increase during all rainy seasons at Kilema and Kibosho as well as at KIA, Moshi, and TPC.

These findings highlight the importance of IOD in modifying ENSO-related rainfall patterns in the Kilimanjaro area, although the influence is spatially differentiated. The latter is evident from the diverse (temporal) rainfall patterns induced during El Niño combined with positive IOD within a radius of 80 km between the Moshi and KIA and the Kilema and Kibosho rainfall records. Although both rainy seasons are altered by ENSO and IOD, the short rains exhibit a larger relative variability. This indicates a more direct coupling to macroscale mechanisms of the short rains. Regarding the long rains, large-scale influences are mainly responsible for the onset of the rainy season, but local factors gain dominance in the advancement of the long rains.

Acknowledgments. This study was carried out in the framework of the research unit “Kilimanjaro ecosystems under global change: Linking biodiversity, biotic interactions and biogeochemical ecosystem processes” (KiLi). It was funded by the German Research Foundation [Deutsche Forschungsgemeinschaft (DFG); funding ID Ap 243/1-2 and Na 783/5-2] and supported by the Tanzania Commission for Science and Technology (COSTECH), the Tanzania Wildlife Research Institute (TAWIRI), and the Mount Kilimanjaro National Park (KINAPA). We thank the administrations of Kibosho and Kilema Missions,

Mr. Pierre Noel from the Tanganyika Planting Company (TPC), as well as the Tanzania Meteorological Agency (TMA) for providing their rainfall data.

REFERENCES

- Annamalai, H., S. P. Xie, J. P. McCreary, and R. Murtugudde, 2005: Impact of Indian Ocean sea surface temperature on developing El Niño. *J. Climate*, **18**, 302–319, doi:10.1175/JCLI-3268.1.
- Appelhans, T., and T. Nauss, 2016: Spatial patterns of sea surface temperature influences on East African precipitation as revealed by empirical orthogonal teleconnections. *Front. Earth Sci.*, **4**, 3, doi:10.3389/feart.2016.00003.
- , E. Mwangomo, I. Otte, F. Detsch, T. Nauss, and A. Hemp, 2016: Eco-meteorological characteristics of the southern slopes of Kilimanjaro, Tanzania. *Int. J. Climatol.*, **36**, 3245–3258, doi:10.1002/joc.4552.
- Australian Bureau of Meteorology, 2014: Australian rainfall pattern during Indian Ocean dipole years. Accessed 22 July 2014. [Available online at <http://www.bom.gov.au/climate/iod/>.]
- Black, E., 2005: The relationship between Indian Ocean sea-surface temperature and East African rainfall. *Philos. Trans. Roy. Soc. London*, **A363**, 43–47, doi:10.1098/rsta.2004.1474.
- Bracco, A., F. Kucharski, and F. Molteni, 2005: Internal and forced modes of variability in the Indian Ocean. *Geophys. Res. Lett.*, **32**, L12707, doi:10.1029/2005GL023154.
- Camberlin, P., and N. Philippon, 2002: The East African March–May rainy season: Associated atmospheric dynamics and predictability over the 1968–97 period. *J. Climate*, **15**, 1002–1019, doi:10.1175/1520-0442(2002)015<1002:TEAMMR>2.0.CO;2.
- , V. Moron, R. Okoola, N. Philippon, and W. Gitau, 2009: Components of rainy seasons variability in equatorial East Africa: Onset, cessation, rainfall frequency and intensity. *Theor. Appl. Climatol.*, **98**, 237–249, doi:10.1007/s00704-009-0113-1.
- Chan, R. Y., M. Vuille, D. R. Hardy, and R. S. Bradley, 2008: Intraseasonal precipitation variability on Kilimanjaro and the East African region and its relationship to the large-scale circulation. *Theor. Appl. Climatol.*, **93**, 149–165, doi:10.1007/s00704-007-0338-9.
- CPC, 2014: Cold and warm episodes by season: Historical El Niño/La Niña episodes (1950–present). NOAA/NWS, accessed 22 July 2014. [Available online at http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml.]
- Duane, W. J., N. C. Pepin, M. L. Losleben, and D. R. Hardy, 2008: General characteristics of temperature and humidity variability on Kilimanjaro, Tanzania. *Arct. Antarct. Alp. Res.*, **40**, 323–334, doi:10.1657/1523-0430(06-127)[DUANE]2.0.CO;2.
- Fairman, J. G., Jr., S. N. Udaysankar, S. A. Christopher, and T. Mölg, 2011: Land use change impacts on regional climate over Kilimanjaro. *J. Geophys. Res.*, **116**, D03110, doi:10.1029/2010JD014712.
- Fischer, A. S., P. Terray, E. Guilyardi, S. Gualdi, and P. Delecluse, 2005: Two independent triggers for the Indian Ocean dipole/zonal mode in a coupled GCM. *J. Climate*, **18**, 3428–3449, doi:10.1175/JCLI3478.1.
- Funk, C., M. D. Dettinger, J. C. Michaelsen, J. P. Verdin, M. E. Brown, M. Barlow, and A. Hoell, 2008: Warming of the Indian Ocean threatens eastern and southern African food security but could be mitigated by agricultural development. *Proc. Natl. Acad. Sci. USA*, **105**, 11 081–11 086, doi:10.1073/pnas.0708196105.
- Goddard, L., and N. E. Graham, 1999: Importance of the Indian Ocean for simulating anomalies over eastern and southern Africa. *J. Geophys. Res.*, **104**, 19 099–19 116, doi:10.1029/1999JD900326.
- Grubbs, F., 1969: Procedures for detecting outlying observations in samples. *Technometrics*, **11**, 1–21, doi:10.1080/00401706.1969.10490657.
- Hastenrath, S., 2000: Zonal circulations over the equatorial Indian Ocean. *J. Climate*, **13**, 2746–2756, doi:10.1175/1520-0442(2000)013<2746:ZCOTEI>2.0.CO;2.
- , 2001: Variations of East African climate during the past two centuries. *Climatic Change*, **50**, 209–217, doi:10.1023/A:1010678111442.
- , 2010: Climate forcing of glacier thinning on the mountains of equatorial East Africa. *Int. J. Climatol.*, **30**, 146–152, doi:10.1002/joc.1866.
- , A. Nicklis, and L. Greischar, 1993: Atmospheric–hydrospheric mechanisms of climate anomalies in the western Indian Ocean. *J. Geophys. Res.*, **98**, 20 219–20 235, doi:10.1029/93JC02330.
- , D. Polzin, and C. Mutai, 2007: Diagnosing the droughts in equatorial East Africa. *J. Climate*, **20**, 4628–4637, doi:10.1175/JCLI4238.1.
- , —, and —, 2010: Diagnosing the droughts and floods in equatorial East Africa during boreal autumn. *J. Climate*, **23**, 813–817, doi:10.1175/2009JCLI3094.1.
- Hemp, A., 2001: Ecology of the pteridophytes on the southern slopes of Mt. Kilimanjaro. Part II: Habitat selection. *Plant Biol.*, **3**, 493–523, doi:10.1055/s-2001-17729.
- , 2005: Climate change–driven forest fires marginalize the impact of ice cap wasting on Kilimanjaro. *Global Change Biol.*, **11**, 1013–1023, doi:10.1111/j.1365-2486.2005.00968.x.
- , 2006: Vegetation of Kilimanjaro: Hidden endemics and missing bamboo. *Afr. J. Ecol.*, **44**, 305–328, doi:10.1111/j.1365-2028.2006.00679.x.
- Hulme, M., 1992: Rainfall changes in Africa: 1931–1960 to 1961–1990. *Int. J. Climatol.*, **12**, 685–699, doi:10.1002/joc.3370120703.
- Indeje, M., F. H. M. Semazzi, and L. J. Ogallo, 2000: ENSO signals in East African rainfall seasons. *Int. J. Climate*, **20**, 19–46, doi:10.1002/(SICI)1097-0088(200001)20:1<19::AID-JOC449>3.0.CO;2-0.
- JAMSTEC, 2014: Dipole mode index (DMI): SST DMI dataset (monthly from 1958 to 2010) derived from HadISST dataset. Accessed 22 July 2014. [Available online at http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi_HadISST.txt.]
- Kijazi, A. L., and C. J. C. Reason, 2009a: Analysis of the 1998 to 2005 drought over the northeastern highlands of Tanzania. *Climate Res.*, **38**, 209–223, doi:10.3354/cr00784.
- , and —, 2009b: Analysis of the 2006 floods over northern Tanzania. *Int. J. Climatol.*, **29**, 955–970, doi:10.1002/joc.1846.
- Latif, M., D. Dommenges, M. Dima, and A. Grötzner, 1999: The role of Indian Ocean sea surface temperature in forcing East African rainfall anomalies during December–January 1997/98. *J. Climate*, **12**, 3497–3504, doi:10.1175/1520-0442(1999)012<3497:TROIOS>2.0.CO;2.
- Lobell, D. B., M. Bänzinger, C. Magorokosho, and B. Vivek, 2011: Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat. Climate Change*, **1**, 42–45, doi:10.1038/nclimate1043.
- Lumley, T., P. Diehr, S. Emerson, and L. Chen, 2002: The importance of the normality assumption in large public health data sets. *Annu. Rev. Public Health*, **23**, 151–169, doi:10.1146/annurev.publhealth.23.100901.140546.
- Lyon, B., and D. G. DeWitt, 2012: A recent and abrupt decline in the East African long rains. *Geophys. Res. Lett.*, **39**, L02702, doi:10.1029/2011GL050337.

- McHugh, M. J., 2006: Impact of South Pacific circulation variability on East African rainfall. *Int. J. Climatol.*, **26**, 505–521, doi:10.1002/joc.1257.
- Mölg, T., and G. Kaser, 2011: A new approach to resolving climate–cryosphere relations: Downscaling climate dynamics to glacier-scale mass and energy balance without statistical scale linking. *J. Geophys. Res.*, **116**, D16101, doi:10.1029/2011JD015669.
- , M. Renold, M. Vuille, N. J. Cullen, T. F. Stocker, and G. Kaser, 2006: Indian Ocean zonal mode activity in a multi-century integration of a coupled AOGCM consistent with climate proxy data. *Geophys. Res. Lett.*, **33**, L18710, doi:10.1029/2006GL026384.
- , D. R. Hardy, N. J. Cullen, and G. Kaser, 2008: Tropical glaciers, climate change, and society: Focus on Kilimanjaro (East Africa). *Darkening Peaks: Glacier Retreat, Science, and Society*, B. Orlove, E. Wiegandt, and B. Luckman, Eds., University of California Press, 168–182.
- , J. C. H. Chiang, and N. J. Cullen, 2009a: Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modelling. *Quart. J. Roy. Meteor. Soc.*, **135**, 1439–1455, doi:10.1002/qj.461.
- , N. J. Cullen, D. R. Hardy, M. Winkler, and G. Kaser, 2009b: Quantifying climate change in the tropical midtroposphere over East Africa from glacier shrinkage on Kilimanjaro. *J. Climate*, **22**, 4162–4181, doi:10.1175/2009JCLI2954.1.
- , M. Großhauser, A. Hemp, M. Hofer, and B. Marzeion, 2012: Limited forcing of glacier loss through land-cover change on Kilimanjaro. *Nat. Climate Change*, **2**, 254–258, doi:10.1038/nclimate1390.
- Mutai, C. C., and M. N. Ward, 2000: East African rainfall and the tropical circulation/convection on intraseasonal to interannual timescales. *J. Climate*, **13**, 3915–3939, doi:10.1175/1520-0442(2000)013<3915:EARATT>2.0.CO;2.
- , —, and W. Colman, 1998: Towards the prediction of the East Africa short rains based on sea surface temperature atmosphere coupling. *Int. J. Climatol.*, **18**, 975–997, doi:10.1002/(SICI)1097-0088(199807)18:9<975::AID-JOC259>3.0.CO;2-U.
- Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent, 2000: Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853–858, doi:10.1038/35002501.
- NCDC, 2014: Global Summary of the Day (GSOD). NOAA/NCDC, accessed 22 July 2014. [Available online at <http://gis.ncdc.noaa.gov/all-records/catalog/search/resource/details.page?id=gov.noaa.ncdc:C00516>.]
- Nicholson, S. E., 1996: A review of climate dynamics and climate variability in Eastern Africa. *The Limnology, Climatology and Paleoclimatology of the East African Lakes*, T. C. Johnson and E. Odada, Eds., Gordon and Breach, 25–56.
- , and J. Kim, 1997: The relationship of the El Niño–Southern Oscillation to African rainfall. *Int. J. Climatol.*, **17**, 117–135, doi:10.1002/(SICI)1097-0088(199702)17:2<117::AID-JOC84>3.0.CO;2-O.
- , and J. C. Selato, 2000: The influence of La Niña on African rainfall. *Int. J. Climatol.*, **20**, 1761–1776, doi:10.1002/1097-0088(20001130)20:14<1761::AID-JOC580>3.0.CO;2-W.
- Null, J., 2014: El Niño and La Niña years and intensities: Based on Oceanic Niño Index (ONI). Accessed 22 July 2014. [Available online at <http://ggweather.com/enso/oni.htm>.]
- Ogallal, L. J., 1989: The spatial and temporal patterns of the East African seasonal rainfall derived from principal component analysis. *Int. J. Climatol.*, **9**, 145–167, doi:10.1002/joc.3370090204.
- Plisnier, P. D., S. Serneels, and E. F. Lambin, 2000: Impact of ENSO on East African ecosystems: A multivariate analysis based on climate and remote sensing data. *Global Ecol. Biogeogr.*, **9**, 481–497, doi:10.1046/j.1365-2699.2000.00208.x.
- Pohl, B., and P. Camberlin, 2011: Intraseasonal and interannual zonal circulations over the equatorial Indian Ocean. *Theor. Appl. Climatol.*, **104**, 175–191, doi:10.1007/s00704-010-0336-1.
- Rodhe, H., and H. Virji, 1976: Trends and periodicities in East African rainfall data. *Mon. Wea. Rev.*, **104**, 307–315, doi:10.1175/1520-0493(1976)104<0307:TAPIEA>2.0.CO;2.
- Rørh, P. C., and Å. Killingtveit, 2003: Rainfall distribution on the slopes of Mt. Kilimanjaro. *Hydrol. Sci. J.*, **48**, 65–77, doi:10.1623/hysj.48.1.65.43483.
- Ropelewski, C. F., and M. S. Halpert, 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.*, **115**, 1606–1626, doi:10.1175/1520-0493(1987)115<1606:GARSPP>2.0.CO;2.
- Saji, N. H., B. N. Goswami, P. N. Vinayachandran, and T. Yamagata, 1999: A dipole mode in the tropical Indian Ocean. *Nature*, **401**, 360–363.
- Schreck, C. J., and H. M. Semazzi, 2004: Variability of the recent climate of eastern Africa. *Int. J. Climatol.*, **24**, 681–701, doi:10.1002/joc.1019.
- Shongwe, M. E., G. J. van Oldenborgh, B. van den Hurk, and M. van Aalst, 2011: Projected changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa. *J. Climate*, **24**, 3718–3733, doi:10.1175/2010JCLI2883.1.
- Smith, T. M., R. W. Reynolds, T. C. Peterson, and J. Lawrimore, 2008: Improvements to NOAA’s historical merged land–ocean surface temperature analysis (1880–2006). *J. Climate*, **21**, 2283–2296, doi:10.1175/2007JCLI2100.1.
- Webster, P. J., A. M. Moore, J. P. Loschnigg, and R. R. Leben, 1999: Coupled ocean–atmosphere dynamics in the Indian Ocean during 1997–98. *Nature*, **401**, 356–360, doi:10.1038/43848.
- Wolff, C., G. H. Haug, A. Timmermann, J. S. Sinninghe Damasté, A. Brauer, D. M. Sigman, M. A. Cane, and D. Verschuren, 2011: Reduced interannual rainfall variability in East Africa during the last ice age. *Science*, **33**, 743–747, doi:10.1126/science.1203724.