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Recent intensification of the seasonal rainfall cycle in equatorial Africa revealed by farmer perceptions, satellite-based estimates, and ground-based station measurements

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Abstract

Smallholder farmers and livestock keepers in sub-Saharan Africa are on the frontlines of climate variability and change. Yet, in many regions, a paucity of weather and climate data has prevented rigorous assessment of recent climate trends and their causes, thereby limiting the effectiveness of forecasts and other services for climate adaptation. In rainfed systems, farmer perceptions of changing rainfall and weather patterns are important precursors for annual cropping decisions. Here, we propose that combining such farmer perceptions of trends in seasonal rainfall with satellite-based rainfall estimates and climate station data can reduce uncertainties regarding regional climatic trends. In western Uganda, a rural and climatically complex transition zone between eastern and central equatorial Africa, data from 980 smallholder households suggest distinct changes in seasonal bimodal rainfall over recent decades, specifically wetter rainy seasons and drier dry seasons. Data from three satellite-based rainfall products beginning in 1983 largely corroborate respondent perceptions over the last 10–20 years, particularly in the southernmost sites near Queen Elizabeth National Park. In addition, combining all three information sources suggests an increasing trend in annual rainfall, most prominently in the north near Murchison Falls National Park over the past two decades; this runs counter to recent research asserting the presence of a drying trend in the region. Our study is unique in evaluating and cross-validating these multiple data sources to identify climatic change affecting people in a poorly understood region, while providing insights into regional-scale climate controls.

1 Introduction

More than 600 million rural people in sub-Saharan Africa rely on rainfed, staple crop agriculture, and so their livelihoods depend directly on the total amount and seasonality of rainfall (Rosegrant et al. 2002; Cooper et al. 2008; FAO 2015). Farm families face mounting

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limits to agricultural production due to a variable and changing climate in addition to inherently low-nutrient soils, barriers to use of mechanical and chemical inputs (including irrigation), and declining land availability (Sanchez 2002; Cobo et al. 2010; Tittonell et al. 2010; You et al. 2011). These conditions result in a farm system and population that are highly vulnerable to climatic impacts on food security (Schlenker and Lobell 2010), while the increasing pressure on arable land threatens biodiversity conservation efforts (Laurance et al. 2014; Lewis et al. 2015).

Scientific understanding of climate patterns and controls in the Albertine Rift region is highly uncertain, largely due to the poor quality of satellite- and gauge-based rainfall observations in central equatorial Africa. In broader equatorial Africa, most studies demonstrate increasing temperatures and decreasing annual rainfall totals over the past several decades (Malhi and Wright 2004; Funk et al. 2008; Farnsworth et al. 2011; Williams and Funk 2011; Lyon and DeWitt 2012; Hartmann et al. 2013; Jury and Funk 2013; Asefi-Najafabady and Saatchi 2013; Diem et al. 2014). However, trends are far less clear over central equatorial Africa due to unreliable rain gauge coverage (Washington et al. 2013) and disagreement among rainfall products (Maidment et al. 2015). As a result, climate-related services such as forecasts remain challenging to produce and disseminate to farmers (Lemos and Dilling 2007; Hansen et al. 2011).

While retroactively filling the gaps in rain gauge or satellite data coverage is impossible, a third source of information holds potentially transformative promise: perceptions of rainfall from smallholder farmers themselves. The fidelity of farmer perceptions regarding rainfall trends in sub-Saharan Africa has received increasing attention in recent years, and studies largely focus on climate-variable areas of sub-Saharan Africa (Maddison 2007; West et al. 2008; Osbahr et al. 2011; Kosmowski et al. 2016). Farmers maintain intimate knowledge of the spatiotemporal variability of precipitation patterns (Haile 2005), which they interpret relative to agroecological factors (e.g., growth, vigor, and senescence of specific crops) and environmental signs (flowering and fruiting of trees, wind and cloud movement, migratory birds; Ellen and Harris 2000; Roncoli et al. 2002). Farmer perceptions of rainfall trends are based on multiple patterns over time, informing both interpretation of previous conditions and expectation for coming seasons (Eakin 2000; Roncoli 2006). Households experiencing greater livelihood risk, or those living in areas of more marginal climate, may more accurately track rainfall trends (Kosmowski et al. 2016).

Indeed, farmer perceptions of rainfall trends are based on observation of multiple patterns over time, informing adaptive decisions and ultimately impacting food security (Marx et al. 2007; West et al. 2008; Adger et al. 2009; Orlove et al. 2010). The aggregation of environmental signs informs both farmer interpretation of previous conditions and expectation for coming seasons (Eakin 2000; Roncoli 2006). Along with the onset of seasonal rains, multiple factors, including total rainfall during growing seasons, are critical factor in determining yields (Thomas et al. 2007; Howe et al. 2014).

However, research directly comparing farmer perceptions of rainfall to satellite- or station-based estimates demonstrates varying alignment of the different information sources. Farmer perceptions of trends may be disproportionately influenced by past extreme events or by more recent seasons when considering a long-term period (Roncoli 2006), causing disagreement with satellite or gauge estimates. Farmers also may conflate rainfall with crop yield, and in some cases, agronomic characteristics such as soil fertility and soil moisture can decouple from seasonal precipitation (Slegers 2008; Diem et al. 2017). Even so, some studies demonstrate farmer perceptions of rainfall trends to align well with physical measurements, for both seasonal and total annual rainfall over a relatively recent period (Thomas et al. 2007; West et al. 2008; Kosmowski et al. 2016; see also Sánchez-Cortés and Chavero 2011; Howe et al. 2014). In general, while studies comparing different information sources cite varied reasons for inaccuracies of farmer perceptions, biases in scientific estimates receive less attention (e.g., station records from only single sites and potential inhomogeneities; changes to rain gauge networks over time; Dai et al. 1997; Maidment et al. 2015).

In this study, we combine farmer perceptions of trends in seasonal rainfall with satellite- and ground-based rainfall estimates in order to resolve uncertainties regarding regional climatic change. We focus on western Uganda, which is situated in topographically complex transition zone between eastern and central equatorial Africa, posing challenges for climate models that inform satellite-based products (Diem et al. 2017). We evaluate farmer perceptions of rainfall from 980 household surveys alongside three satellite-based rainfall products and three ground-based rainfall records. Unlike many previous studies, we address biases inherent in farmer perceptions and physical estimates alike, considering all information sources imperfect yet potentially useful.

2 Methods

2.1 Study area

The Ugandan Albertine Rift defines our study region (Fig. 1), including five sites surrounding national parks and adjacent communities: Murchison Falls, Kibale North, Kibale South, Rwenzori Mountains, and Queen Elizabeth. The Kibale National Park area was separated into two sites due the sharp elevational gradient, and corresponding social-biophysical differences, with Kibale North defined as northern communities at higher elevation (> 1200 m a.s.l.) on top of an escarpment and Kibale South defined as southern communities at lower elevation (< 1200 m a.s.l.).

The study region falls within a global biodiversity hotspot (Myers et al. 2000; Aukema et al. 2017), in which Ugandan parks protect approximately 23,000 km^2 for wildlife and habitat (IUCN and UNEP 2010). Human population density within the five study sites is exceptionally high; mean rural density in the study region is 166 people per square kilometer, with rural density greater than 400 people per square kilometer in the southernmost areas (Salerno et al. 2017a). Population growth is slightly higher than the national mean of 3.3%, fifth highest in the world (UBOS 2016). With intensifying land and resource constraints, farmers are increasingly shifting to maize dominated farming from agroforests of bananas, beans, potatoes, cassava, and other crops.

The Albertine Rift is a climatically complex transition zone between eastern and central equatorial Africa, spanning bimodal and unimodal rainfall zones, and experiencing rain shadow effects from variable topography. Much of the study region experiences two rainy seasons centered on the months of March and October; we refer to these as the first and second rains, respectively, separated by the first and second dry seasons (Diem et al. 2014). Dry seasons received appreciable rain, approximately 50% of annual totals in some areas (Fig. 1). This seasonality is most pronounced in the southern extent of the study region. However, rainfall at the northern extent of the Albertine Rift to the north of the Murchison Falls site approaches a unimodal regime, with a single rainy season from February to November.

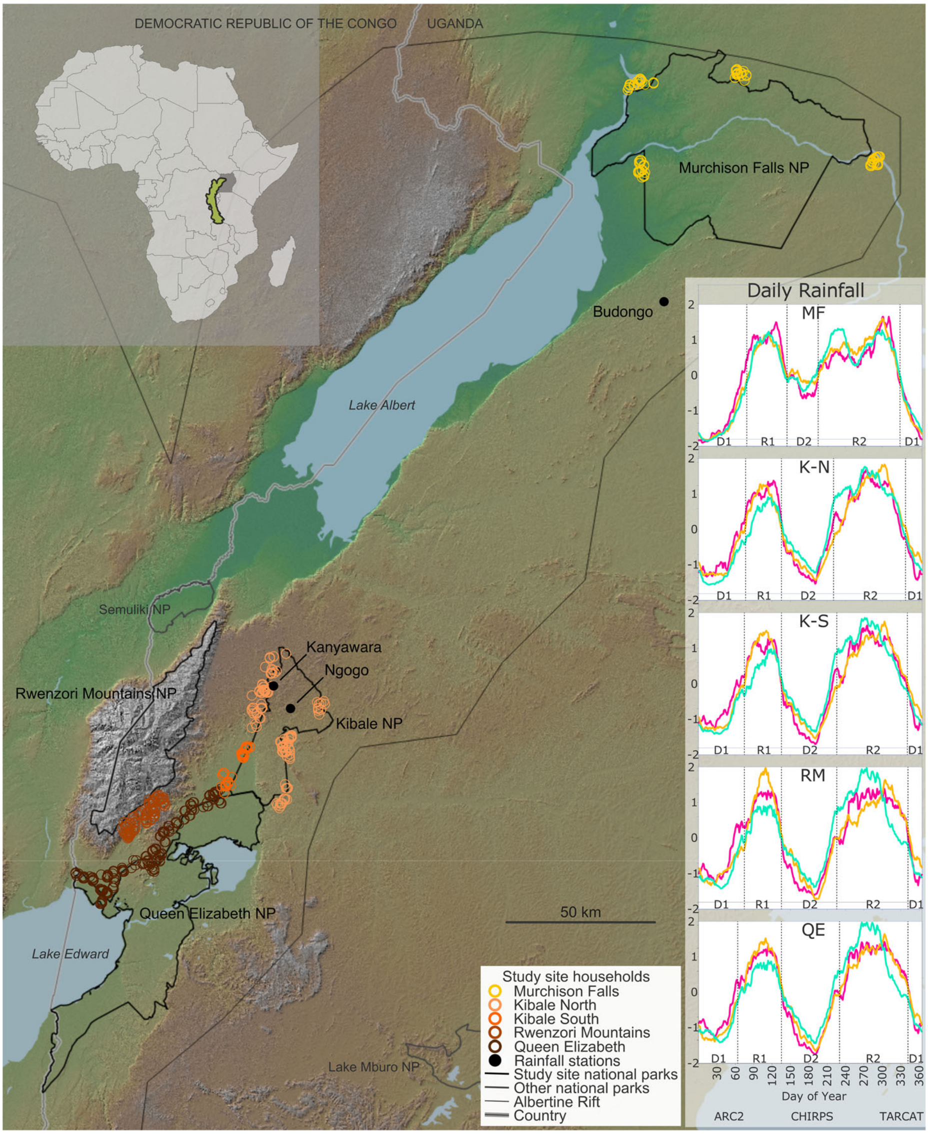

Fig. 1 Study region in the Ugandan Albertine Rift. Farmer perceptions of rainfall were recorded in 980 households (colored circles) adjacent to national parks (black polygons). Inset time series plots for each study site show standardized 15-day smoothed mean daily rainfall totals for 1983–2016. Within each plot, D1, R1, D2, and R2 refer to the first dry season (D1), first rainy season (R1), second dry season (D2), and the second rainy season (R2); dashed lines indicate boundaries between seasons

Rainfall to the east of the study region is largely determined by annual migrations of the Tropical Rain Belt, including influences from the Intertropical Convergence Zone and Congo Air Boundary (Nicholson 1996). These convergence zones have different moisture sources, and their relative positions control seasonal rainfall in East Africa. In contrast, 70% of rainfall in areas west of the study region is produced from mesoscale convective complexes, or large, intense storms bringing moisture from the Atlantic Ocean combined with evapotranspiration from the Congo Basin rainforest (Nesbitt et al. 2006; Jackson et al. 2009). We justify our selection of a study region with relatively small geographic extent due to the region's climatic complexity—a wider regionalization would mask interactions of the eastern and western controls—and our use of household data. We intensively sample households in five sites across the study region. Although small in extent, we argue that the high fidelity of multiple data sources within this complex region will produce valid findings with implications for African climate more broadly.

2.2 Farmer perceptions of rainfall trends

We conducted 987 household surveys in 2012 and 2013 across the five sites named above, spanning approximately 400 km along the Ugandan border with the Democratic Republic of the Congo. Households were selected for surveys following pilot work in the region and adhering to a geographic random sampling strategy (detailed in Salerno et al. 2017b). While smallholder agriculture is the dominant livelihood strategy, a small portion (< 5%) of the sample was exclusively livestock keepers of the Basongora tribe living in the Queen Elizabeth site. We make the assumption that all households comprising the sample have similar knowledge of rainfall patterns, and so we do not exclude or stratify the data based on livelihood. The majority of agriculture practiced in the study region is maize based, conducted on c. 2.5 ha per household, and includes additional food crops such as potatoes, cassava, millet, and beans (Salerno et al. 2017b). Due to the predominance of agriculture-based livelihoods, we refer to respondents as "farmers," although acknowledge multiple livelihood strategies.

Interviews were conducted with household heads or their spouses; mean respondent age was 41 years. A single set of questions was utilized in this study asking respondents to *compare current rainfall conditions during each of the seasons to conditions 10 or more years ago*. Answers were recorded as a five-category response: seasons are the same, drier, wetter, different every year, and do not know. We term seasons as first dry (~December–February), first rains (~March–May), second dry (~June–July), and second rains (~August–November). Seven surveys contained incomplete data and so were omitted from analyses; the effective total household sample was 980. We present basic descriptive summary plots of the rainfall change responses, organized by the five park-adjacent sites.

2.3 Satellite- and ground-based rainfall observations

Daily satellite-based rainfall estimates from 1983 through 2016 were extracted from three products: African Rainfall Climatology Version 2 (ARC2; Novella and Thiaw 2012), Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS; Funk et al. 2015), and TAMSAT African Rainfall Climatology And Timeseries (TARCAT; Maidment et al. 2015). ARC2 and TARCAT data begin in 1983, while CHIRPS data begin in 1981. ARC2, CHIRPS, and TARCAT have 0.10°, 0.05°, and 0.0375° spatial resolutions, respectively. ARC2 was missing 340 (i.e., 2.7%) daily rainfall values, and 80% of those missing values occurred between 1983 and 1990. The 1983–1990 period was missing 10% of the daily rainfall totals. TARCAT was only missing data for the first 10 days of 1983, and CHIRPS was serially complete.

High-quality, multi-decadal, ground-measured rainfall totals were available for only three locations (Fig. 1). The longest record, 1976–2016, existed at Kanyawara, which is located at the Makerere University Biological Field Station in Kibale National Park.[1] The 1993–2002 period was missing 23% of daily values; however, all months from 1983 through 2016 (with the exception of May of 2013) had complete rainfall. Serially complete daily rainfall data at Ngogo, which is located inside Kibale National Park and 10 km southeast of Kanyawara, were available for 1997–2016.[2] Ngogo data were used to estimate rainfall at Kanyawara in May 2013. Serially complete daily rainfall data at the Budongo Conservation Field Station (i.e., Budongo), which is located inside Budongo Forest Reserve, were available for 1993–2015.[3]

Rainy season durations and rainfall totals were calculated for each of the four seasons at the five sites using the daily ARC2, CHIRPS, and TARCAT rainfall values. At Murchison Falls, which is transitional between unimodal and bimodal rainfall regimes, duration and rainfall totals were also calculated for a single dry season and rainy season. A variation of the method in Dunning et al. (2016) was used for determining onset and cessation dates of rainy seasons in order to remove the impact of false onsets. Beginning and end of the climatological water seasons (1983–2016) were determined from cumulative differences over the course of a climatological year between the climatological mean rainfall for the day of a year minus the mean daily rainfall total derived from all days. The procedure was repeated for each year using only rainfall totals and the mean daily rainfall total for that year. All starting and ending dates were constrained to occur within 30 days of the climatological starting and ending days. Since ARC2 and TARCAT had missing daily rainfall totals, seasonal rainfall totals were upwardly adjusted using the ratio of total days per period by the number of days with a valid rainfall total.

Annual rainfall totals also were calculated at the five sites and at Kanyawara, Ngogo, and Budongo using the three satellite-based products. Mean calendar day rainfall totals were calculated with the 1983–2016 data, and missing ARC2 and TARCAT rainfall estimates for a specific calendar day were replaced with the mean value for that day.

Trends in seasonal rainfall totals and season duration were calculated for all periods of at least 10 years in length ending in 2013, which was the year the household surveys were completed. After a 2-year smoothing was applied, there were 11 periods retained, beginning with 1984–2013 and ending with 2004–2013. For each period, the Kendall–Theil robust line was used to estimate changes in rainfall total and season duration over each period; the robust line is the median of the slopes between all combinations of two points in the data as is affected minimally by outliers (Helsel and Hirsch 2002). One-tailed Kendall's correlation tests were used to assess the significance of measured trends ($\alpha = 0.05$).

Changes in annual rainfall and rainy season rainfall at the five sites were calculated within two periods, 1983–2016 and 1997–2016. As noted earlier, 1983 is the starting year of two of the three satellite products. The starting year of 1997 was chosen for the second period because it still yields a multi-decade period (i.e., 20 years), with nearly the entire period after the 1999 transition in boreal-spring rainfall in East Africa (Lyon and DeWitt 2012). The Kendall–Theil robust line and Kendall's tau correlation tests (one-tailed; $\alpha = 0.05$) were used within each period (i.e., 1983–2016 and 1997–2016). While El Niño events occurred in 1983 and 1997 and these events are known to cause elevated boreal-autumn rainfall in eastern equatorial Africa

[1] Data were provided by Thomas Struhsaker and Colin Chapman.

[2] Data were provided by Jeremiah Lwanga, David Watts, John Mitani, and Kevin Potts of the Ngogo Chimpanzee Project.

[3] Data were provided by Fred Babweteera of the Budongo Conservation Field Station.

(Nicholson and Kim 1997), the impact of El Niño on satellite-based rainfall estimates in western Uganda has been shown to be negligible (Diem et al. 2014). Therefore, the 1983–2016 and 1997–2016 trends shown in this paper should not be impacted significantly by El Niño.

Changes in annual rainfall derived from the satellite products were compared with rainfall changes at the rain gauges. The ARC2, CHIRPS, and TARCAT values were the estimates that corresponded to the cell in which the rain gauge was located. Data availability resulted in different periods used for the different gauges. The Kanyawara period was 1983–2016. Potential discontinuities in rainfall totals were reduced at Kibale National Park by using the mean of the Kanyawara and Ngogo totals. Therefore, a Kibale data set was created for 1997–2016. The Budongo period was 1993–2015. As with seasonal rainfall totals and duration, the Kendall–Theil robust line and Kendall's tau correlation tests (one-tailed; $\alpha = 0.05$) were used.

3 Results

3.1 Farmer perceptions of rainfall

Across most of the study region, farmers show marked uniformity in their perceptions of seasonal rainfall change. Compared to at least 10 years ago, farmers stated that the first and second rainy seasons were becoming wetter (72% and 86%, respectively; Fig. 2, blue bars), and the first and second dry seasons were becoming drier (80% and 93%, respectively; Fig. 2, red bars). The observation of drier dry seasons is possible due to the measurable rain events that occur, December to January and June to August, during periods of otherwise little rain.

Disagreement and uncertainty among households were evident at the Kibale sites, particularly Kibale North. A minority of Kibale North farmers observed the first rainy season becoming wetter (25%) and the first dry becoming drier (31%), in contrast to what was nearly consensus in other sites. The second rainy and dry seasons more closely resembled the other sites (with 51% and 83% reporting wetter second rains and drier second dry, respectively).

3.2 Trends in seasonal climate data corresponding to farmer perceptions

Data from two of the three satellite-based products indicate the two southernmost sites, Queen Elizabeth and Rwenzori Mountains, experienced decreasing dry season rainfall and increasing wet season rainfall (Fig. 3). CHIRPS and TARCAT data revealed significant wetting trends for the first rains, significant drying trends for second dry, and significant wetting trends for the second rains over the three decades. Trends tended to weaken the shortest periods (i.e., 2002–2013 and 2004–2013). Compared to the other two products, ARC2 rainfall showed opposite trends across longer periods but similar trends across shorter periods: significant wetting trends for the first dry during 1984–2014 and 1988–2013, a significant drying trend for the first rains during 1986–2013, and a significant drying trend for the second rains during 1984–2003. The three products were in agreement about trends in seasonal rainfall during periods with starting years in the 1990s (i.e., trends over the preceding 15 to 25 years): the rainy seasons became wetter and the dry seasons became drier.

Kibale South had less definitive trends in rainfall compared to the two southernmost sites, but trends are still evident; trends were further weakened at Kibale North. ARC2 and CHIRPS data showed a wetting trend for the first rains at Kibale South. But opposite to the trends at Queen Elizabeth and Rwenzori Mountains, CHIRPS data showed a significant wetting trend

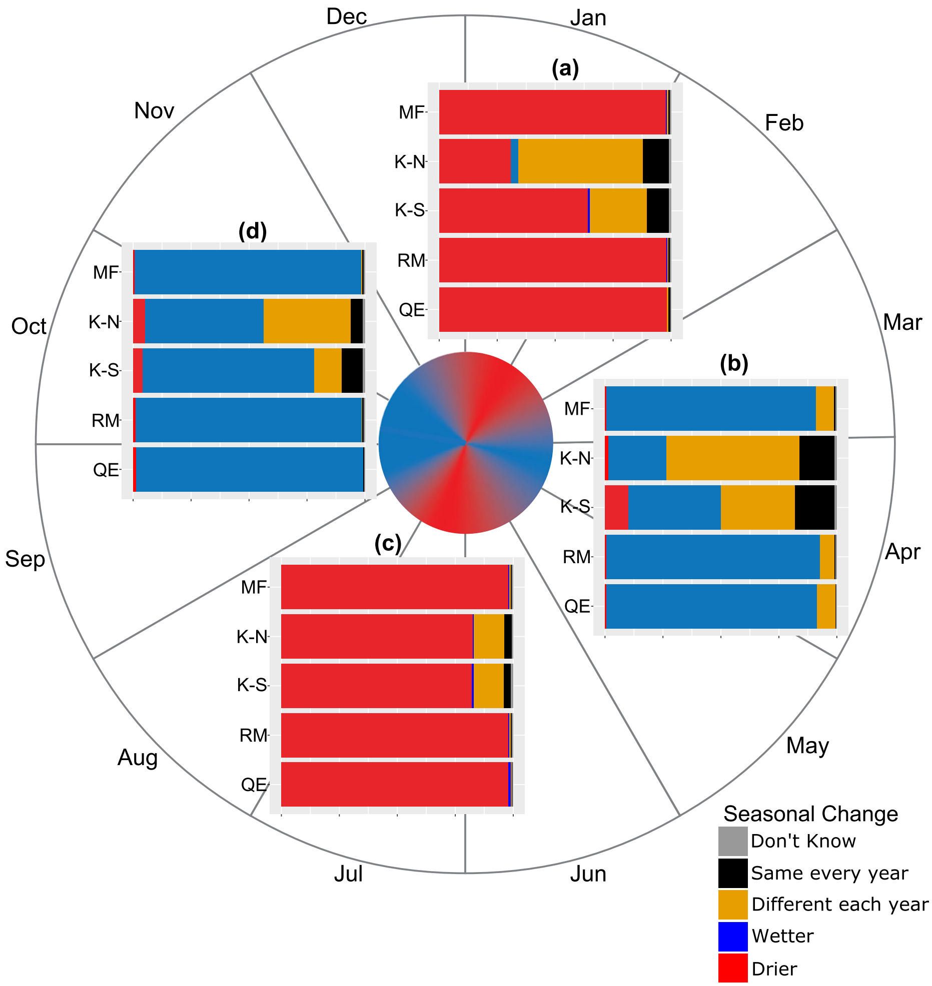

Fig. 2 Farmer perceptions of changes to wet and dry seasons over time. Farmers responded to questions pertaining to changes in the two wet and two dry seasons, comparing the present to greater than or equal to 10 years ago. Mean season timing and duration (represented as the circle at center, red (dry) and blue (wet)) are based on mean season duration and variance calculated from ARC2, CHIRPS, and TARCAT across all sites. Farmer perceptions of changes for each season (inset plots a–d) are displayed for each site, ordered north to south as top to bottom: Murchison Falls (MF, $n = 177$), Kibale North (K-N, $n = 208$), Kibale South (K-S, $n = 99$), Rwenzori Mountains (RM, $n = 187$), and Queen Elizabeth (QE, $n = 309$). Stacked bars correspond to proportion of responses for each site in each category

for the first dry at Kibale South. At Kibale North, ARC2 rainfall had a significant long-term (e.g., ~ 30 years) drying trend for the two rainy seasons and there were no significant trends for any of the seasons for the periods beginning between 1990 and 1998. CHIRPS rainfall had weak (and largely nonsignificant) trends at Kibale North for all seasons, but the drying trend for the first dry and the wetting trend for the first rains were consistent with the results at Queen Elizabeth and Rwenzori Mountains. For both ARC2 and CHIRPS data, there were no significant trends for the periods beginning between 1990 and 1996. In sharp contrast to ARC2 and CHIRPS data, TARCAT data showed rainy seasons getting wetter at Kibale South

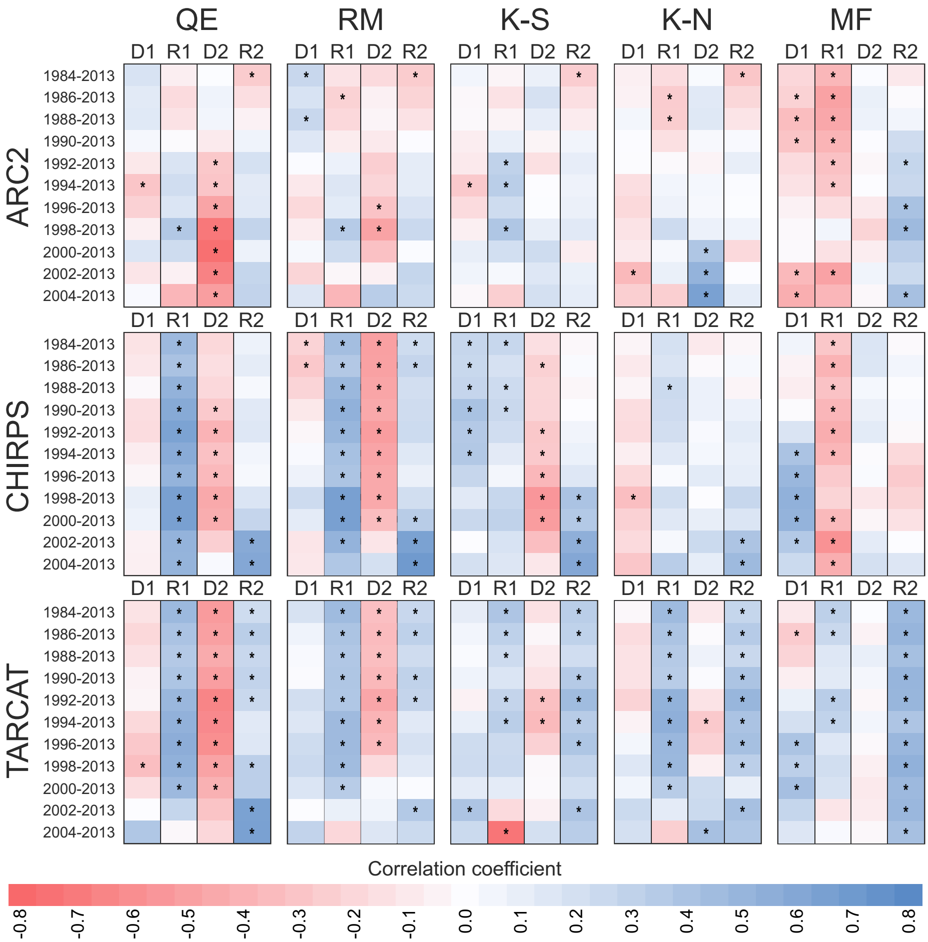

Fig. 3 Trends in seasonal rainfall. Heat maps are derived from the three satellite-based products (ARC2, CHIRPS, and TARCAT) for periods ending in 2013 at the five sites near national parks: Queen Elizabeth (QE), Rwenzori Mountains (RM), the southern part of Kibale (K-S), the northern part of Kibale (K-N), and Murchison Falls (MF). Seasonal trends are calculated for different periods, because start dates relative to anomalous years can significantly impact trends. Seasonal trends based on specific periods are calculated for the two dry seasons (D1, D2) and two rainy seasons (R1, R2). The time series were smoothed with a 2-year moving mean filter, and the degree of increasing and decreasing trends is noted in blue and red, respectively (significant ($\alpha = 0.05$; one-tailed) trends are denoted with asterisks)

and Kibale North. The rainy seasons had significant wetting trends over the preceding 15 to 30 years. The drying trends for the second dry season were substantially weaker than the trends at Queen Elizabeth and Rwenzori Mountains.

At the Murchison Falls site, there was considerable disagreement among the three products with respect to seasonal rainfall trends. ARC2 data showed significant drying trends, both long-term and short-term, for the first dry and first rains as well as significant wetting trends for the second rains over the preceding 10 to 20 years. CHIRPS rainfall was similar to ARC2 rainfall in that there were significant drying trends for the first rains and weak trends for the second dry. However, CHIRPS data showed a general wetting trend over approximately 20 years for the first dry. TARCAT rainfall had significant wetting trends for both rainy seasons, with the second rains having significant trends for all periods. Similar to CHIRPS data, TARCAT data revealed a significant decrease in first dry rainfall over the preceding 20 years. Similar to the two other products, TARCAT data also had weak trends for the long dry season.

3.3 Trends in annual and seasonal rainfall from 1983 to 2016

There were large differences among the data products concerning trends in annual and seasonal rainfall from 1983 to 2016, with ARC2 data showing decreasing rainfall, CHIRPS data showing mostly weak changes, and TARCAT data showing increasing rainfall (Fig. 4a). ARC2 rainfall had significant annual drying trends at all sites, with the percent decrease in rainfall from 1983 to 2016 ranging from − 13 to − 16%. There was a decrease in ARC2 rainfall for both seasons at the five sites; the significant decreases ranged from − 27 to − 37%. CHIRPS data generally showed first-rains rainfall increases when moving from south to north, and the only significant changes were increases (approximately 43%) in rainfall during the first rains at Queen Elizabeth and Rwenzori Mountains. TARCAT rainfall had significant annual and seasonal wetting trends at all sites. The annual increases ranged from 15 to 23%, the first-rains increases ranged from 21 to 98%, and the second-rains increases ranged from 19 to 29%.

3.4 Trends in annual rainfall from 1997 to 2016

In contrast to the findings of changes from 1983 to 2016, there was general agreement among the three products that rainfall increased at most sites from 1997 to 2016 (Fig. 4a). ARC2 data showed significant increases in annual rainfall (19%) and second-rains rainfall (39%) at Murchison Falls. CHIRPS had significant increases in first-rains rainfall at Rwenzori Mountains (35%). TARCAT data showed significant increases in annual rainfall at Kibale North (9%) and Murchison Falls (14%), and first- and second-rains rainfall at Queen Elizabeth (46%).

3.5 Comparison of satellite-based estimates with rain gauge measurements

Comparisons with ground-based measurements reveal possible bias in the rainfall products. The Kanyawara station measured a slight decrease in annual rainfall from 1983 to 2016, which was matched by CHIRPS data; however, ARC2 data showed a significant decrease of 19% and TARCAT data showed a significant increase of 17%. All three products were biased toward increased annual rainfall at Kibale (i.e., the mean of Kanyawara and Ngogo totals) from 1997 to 2016; there was no change in rainfall at the combined stations. None of the trends were significant, but TARCAT data did show a 10% increase in rainfall. Annual rainfall at the Budungo station increased 15% from 1993 to 2015, but the trend was not significant. ARC2 and TARCAT rainfall had significant increases of 12% and 23%, respectively, at Budongo. Similar to trends at Kibale North, the trend in CHIRPS rainfall at Budongo was small and not significant.

4 Discussion and conclusions

Overall, we report agreement between farmer rainfall perceptions and satellite-based estimates, suggesting that dry seasons are becoming drier and wet seasons are becoming wetter: an

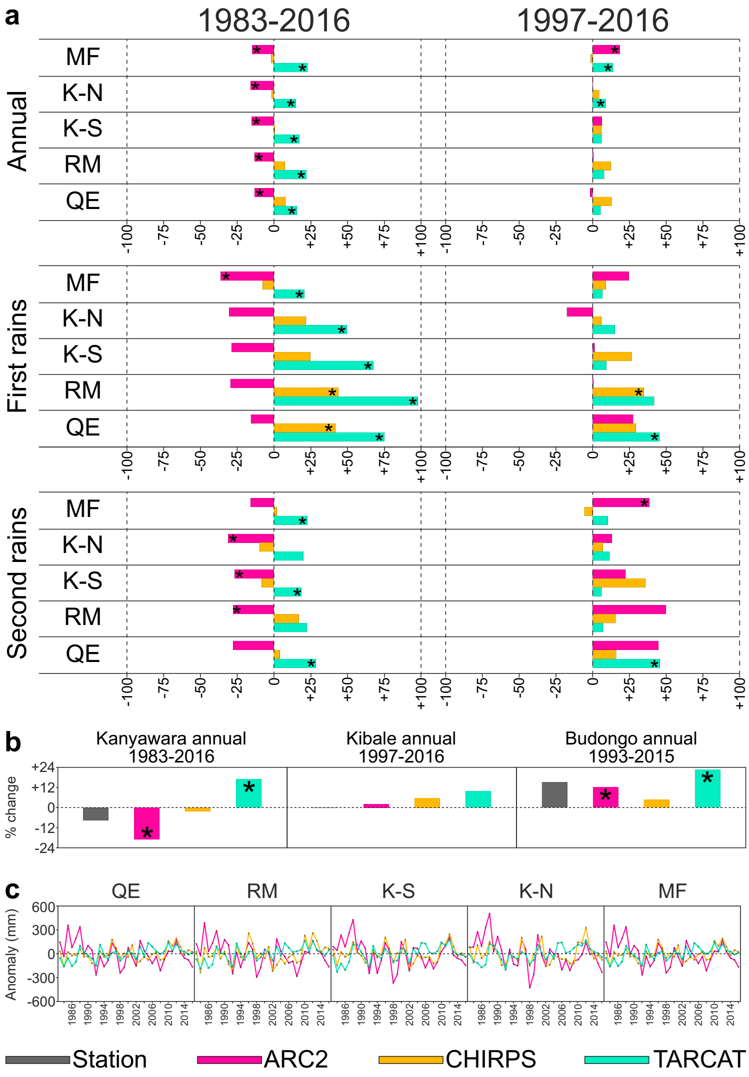

Fig. 4 Comparing changes in annual and seasonal rainfall across two time periods. **a** Percent change in annual and seasonal rainfall for the three products at the five sites from 1983 to 2016 and from 1997 to 2016. **b** Percent change in annual rainfall at the Kanyawara station, at Kibale (i.e., Kanyawara and Ngogo stations), and at the Budongo station. **c** Time series of annual rainfall anomalies at the five sites. Asterisks denote significant ($\alpha = 0.05$; one-tailed) trends

apparent intensification of the seasonal rainfall cycle in western Uganda. Satellite- and station-based data show an increase in total annual rainfall during the most recent 20-year period, but this trend is less clear extending back to the 1980s. Interestingly, rainfall in the center of the study region in the Kibale sites may be anomalous relative to other sites, with inconsistent perceptions among Kibale farmers and disagreement among the three satellite products; in support, ground-based measurements also show no consistent pattern.

4.1 Resolving multiple sources of information on seasonal rainfall trends

We interpret the general agreement across data sources as evidence of recent changes in rainfall seasonality. Findings indicate high confidence in trends toward drier dry seasons and wetter rainy seasons occurring in the three southern sites (Queen Elizabeth, Rwenzori Mountains, Kibale South), while seasonal patterns in Kibale North are variable, and trends are non-existent. Farmers were nearly uniform in their perceptions of drier dry seasons and wetter rainy seasons in the southernmost sites, and a majority were in agreement at Kibale South. All three satellite-based products show the drying and wetting patterns since the mid-1990s, and two of the products, CHIRPS and TARCAT, show seasonal trends extending back at least 30 years. The ground-based records beginning in 1983 from Kibale North do not provide precise information on seasonal rainfall totals because daily values are not serially present, though we are confident using these data to estimate total annual rainfall.

Taken together, all three information sources reveal more nuanced rainfall trends than previously reported (e.g., Williams and Funk 2011; Diem et al. 2014). In the southern sites where drier dry and wetter rainy seasons are evident, we suspect that changing season length was a major contributing factor (Fig. S1). Satellite-based products at Queen Elizabeth and Rwenzori Mountains, and to a lesser degree at both Kibale sites, show that one or both rainy seasons lengthened and dry seasons shortened. Therefore, in contrast to the general annual drying trend reported for the region (Ssentongo et al. 2018; Diem et al. 2014), we demonstrate the absence such of an annual trend and the presence of fewer yet more intense rainy season days.

Findings do not indicate why farmer and satellite-based observations were in disagreement at Murchison Falls, the northernmost site. If farmer perceptions are accurate, as we believe they are from other sites, then this would suggest inaccuracies in all three satellite products. These inaccuracies are likely, especially if potential biases in satellite products (e.g., the loss of gauges impacting ARC2, the potential wetting bias of TARCAT) differentially affect rainfall values at Murchison Falls (see Supporting Information). However, it is also possible that recorded farmer perceptions are inaccurate. Murchison Falls likely experiences notable rainfall during the second dry period (i.e., no distinct separation between the two wet seasons), and this may have caused confusion during surveys that required farmers to respond to questions regarding trends observed during four distinct seasons. Further investigation is needed to accurately discern changes in seasonal rainfall from this site.

4.2 Comparisons with previous research regarding regional rainfall

Findings contribute to recent evidence demonstrating that in some cases farmers observe and report rainfall changes in alignment with satellite- or ground-based rainfall estimates. Using a nationally representative sample from India, Howe et al. (2014) found the majority of farmers report changes in rainfall over the last decade that aligned with records from the nearest ground-based station. Using a similar national sample from Niger, Kosmowski et al. (2016) found farmer perceptions of worsening rainfall conditions to align with multiple measures from satellite-based estimates. Given the regional scope of these studies, as with our study as well, it is possible that a larger sample size or geographic scale or both may accurately average perceptions across local variability. Interestingly, in a regional investigation in Burkina Faso, West et al. (2008) observed that farmers recalled a decades-long drought and accurately attributed the trends to a decline in heavy rain events during the early period of the rainy season. These perceptions aligned with long-term station-based records, although respondent perceptions diverged from station records regarding a wetting trend in recent years. Similar to our findings, the Burkina Faso respondents demonstrated specificity in historical recall beyond coarse trends (i.e., decline in heavy rain events). In contrast, the majority of site-based studies comparing farmer perceptions and measured rainfall data sources report disagreement (e.g., Roncoli et al. 2002; Slegers 2008; Silvestri et al. 2012). Such disagreement is largely attributed to farmer observation being biased by recent seasons and extreme events, by crop yield and rainfall conditions becoming misaligned (e.g., yield declines resulting from soil fertility loss; Diem et al. 2017), and by local climatic variation.

Regarding persistent uncertainty over relative performance of satellite-based rainfall products in the region, our results support that TARCAT provides the most accurate estimates with which to assess rainfall trends. The relative accuracy of TARCAT is likely due in part to its independence from "real time" rain gauge data; as a result, inter-annual variations in rainfall are estimated only from changes in satellite data (Maidment et al. 2017). Both ARC2 and CHIRPS rely on gauge measurements, yet the number of ground-based stations in central Africa has decreased dramatically over the past several decades (Washington et al. 2013). Moreover, ARC2 is shown to produce particularly spurious estimates, due to its use of inconsistent station data over time (Dinku et al. 2018). TARCAT reproduced the rainy-season wetting and the dry-season drying trends observed in our Kibale gauge data, while also showing consistent, significant increases in rainfall during the single, long rainy season at Murchison Falls (Fig. S2).

Regarding links to wider climatic regions, increased primary productivity of the Sahel-Sudanian zone of Africa over the past several decades aligns with both the farmer perceptions and the TARCAT rainfall trends at Murchison Falls. A "greening" since the 1980s exists across the Sahel-Sudanian zone and extends south into northwestern Uganda (Vrieling et al. 2011; West et al. 2017). The increased productivity is most likely the result of increased seasonal rainfall (Fensholt and Rasmussen 2011). Taken together, our results highlight the climatic complexity of central equatorial Africa and the need to appropriately match available sources of climate information to research goals.

4.3 Changing rainfall in the Albertine Rift and implications for food security

This study contradicts the pre-existing view of decreasing equatorial Africa rainfall. Decreasing boreal-spring rainfall has been observed for all or parts of East Africa over the past several decades (Williams and Funk 2011; Lyon and DeWitt 2012; Yang et al. 2014) as well as for central equatorial Africa (Diem et al. 2014; Hua et al. 2016), based on satellite- and gauge-derived rainfall products. Assuming that ARC2 rainfall values are inflated in the 1980s and that farmers have accurate reliable of seasonal rainfall trends, rainfall during boreal spring (i.e., first rains) has not decreased in western Uganda. Conversely, ARC2 and TARCAT show a significant increase in rainfall over the past three decades, while ARC2 shows a significant increase over the past two decades. Our findings call into question claims of decreased rainfall in the region based on ARC2 data alone (Diem et al. 2014; Ssentongo et al. 2018).

Nevertheless, changes in seasonal rainfall do have implications for farmers in terms of food security and livelihood adaptation (Thomas et al. 2007). Wetter, longer growing seasons may potentially reduce the negative effects of increasing temperatures on soil moisture, as effects of temperature driven declines in food production are projected to be severe (Schlenker and Lobell 2010; Diem et al. 2017). However, in the southern, most densely-populated sites, observed recent, long, wet seasons caused substantial declines in potato and bean harvests due to fungal outbreaks and other diseases. In additon, changing intensity of rain events could variably impact production, though we were unable to examine rainfall intensity. Regardless of additional ongoing changes, farmers will need to adapt management practices such as planting and harvest schedules and seed selection due to changing seasonality (West et al. 2008). Farmers will likely continue to maintain higher fidelity perceptions of changing seasonality, which is critical, than of other rainfall patterns such as annual totals (Roncoli et al. 2002). Nonetheless, farmers' dependence on rainfall, and constraints in observing and adapting to changes, will ultimately contribute to increased vulnerability under future climate changes (Thomas et al. 2007; Cairns et al. 2013).

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