ENVIRONMENTAL RESEARCH
LETTERS

LETTER • OPEN ACCESS

The evolving roles of intensity and wet season timing in rainfall regimes surrounding the Red Sea

To cite this article: Kayden Haleakala *et al* 2022 *Environ. Res. Lett.* **17** 044039

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
21 October 2021

REVISED
16 January 2022

ACCEPTED FOR PUBLICATION
15 February 2022

PUBLISHED
21 March 2022

LETTER

The evolving roles of intensity and wet season timing in rainfall regimes surrounding the Red Sea

Kayden Haleakala[1,*], Haowen Yue[1], Sarfaraz Alam[2], Rouhin Mitra[1], Ageel I Bushara[3] and Mekonnen Gebremichael[1]

[1] Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, CA, United States of America
[2] Department of Geophysics, Stanford University, Stanford, CA, United States of America
[3] Zuhair Fayez Partnership Consultants, Ar Rabi, Riyadh, Saudi Arabia
[*] Author to whom any correspondence should be addressed.

E-mail: khaleakala@g.ucla.edu

Keywords: Red Sea, rainfall, intensity, East Africa, Arabian Peninsula, wet season

Supplementary material for this article is available online

Abstract

The Red Sea is surrounded by a diverse mixture of climates and is spanned by opposite hydrologic end-uses and geopolitical states. Unique water supply management challenges on both sides (related to agricultural and trans-boundary conflict in East Africa, and to groundwater depletion in the Arabian Peninsula) are made more severe by a rising demand, which underscores the importance of understanding shifts in rainfall supply to aid effective action. In this study, we characterize the relative importance of rainfall intensities to annual rainfall, the onset and duration of wet seasons, and the (statistically significant) trends in each of these over the region from 1981 through 2020 using daily gridded (0.05°) precipitation estimates. Results show that heavy rainfall (above 20 mm d^{-1}) does not necessarily benefit annual totals, as the wettest regions are shaped by moderate (between 5 and 20 mm d^{-1}) rainfall coupled with prolonged wet seasons. Observed trends in annual rainfall are underlain by interactions between shifting wet season lengths and rainfall intensities. Wet season length increases for 26% of the region, dampening the inherent drying resulting from shifts toward less-intense rainfall, and bolstering the inherent wetting from shifts toward more-intense rainfall. Regions shifting toward less- (more-)intense rainfall without an expanding wet season generally show negative (insignificant) rainfall trends. This reveals an important control that wet-day frequency has over wet-day intensity alone in shaping annual rainfall changes. We emphasize that the large-scale distribution of these shifts and their regional importance should punctuate cooperative efforts in sustainable resource management and transboundary governance.

1. Introduction

Geopolitical opposites span the Red Sea—a rich market of international food, water, and energy exchange (Wilson 2015, Narbone and Widdershoven 2021). The Arabian Peninsula (AP) lies to the east, with Saudi Arabia as the world's largest country with no permanent surface water bodies, and where potable water relies on groundwater pumping and desalination (Baig *et al* 2020). Despite scarce rainfall, it has the third-highest per-capita freshwater consumption, driven primarily by urban and agricultural use (Baig *et al* 2020). Oil exports drive its GDP (19th-highest at $700 M USD World Bank 2020). Conversely, west of the Red Sea exists several transboundary river basins draining from the Ethiopian Highlands (UNEP-DHI and UNEP 2016), where summer precipitation governs freshwater supply (Berhanu *et al* 2014, Nicholson 2017). While maintaining a wealth of fresh surface water, the Ethiopian GDP is relatively low ($107 M USD, World Bank 2020). Surface water reliance cascades down the Nile River to Sudan and Egypt (Conway 2005), where hydro-political stress has tended to invite either competitive conflict or cooperative effort as a result (Yoffe *et al* 2004, Wolf 2007).

Both sides (AP and Eastern Africa, hereafter EA) acknowledge the importance of sustainable water use and management in the face of rising population and climate and land cover changes despite such broad differences (Jones 2014, McNabb 2019, Baig *et al* 2020). For the AP, what little rainfall occurs presents the only natural opportunity to replenish an already-stressed groundwater supply (Almazroui *et al* 2017, Awadh *et al* 2021). For EA, rainfall variability (inter- and intra-annual) and its timing are principal to informing reservoir operations and agricultural strategies (Degefu 1987, Gissila *et al* 2004, McClain 2013) as well as transboundary water resource governance. These unique water supply challenges are exacerbated by demand-side (i.e., population and land cover) changes, which underscore the importance of understanding supply-side (i.e. precipitation) changes.

Numerous studies have leveraged *in situ* gauges, satellite remote sensing, and numerical weather prediction estimates of precipitation to advance understanding of rainfall behaviors and changes on both sides of the Red Sea. These prior efforts (summarized in sections 1.1 and 1.2) highlight complementary knowledge gaps concerning how rainfall behaves and changes, but none have presented a direct juxtaposition of both sides. Assessing the characteristic timing and intensities of rainfall and their importance to annual water supply region-wide is a collective research gap that can (a) provide a (hydrometeorological) basis for mutual understanding of incoming water supply differences with respect to trade and the food-water-energy nexus that nuances it, and (b) inform the unique and urgent hydrologic end-uses in EA and the AP in their respective sustainability efforts.

1.1. Rainfall East of the Red Sea: Arabian Peninsula

AP rainfall is generally irregular and infrequent. A climatological review of station and satellite-based observations in eastern Saudi Arabia reports most (over 50%) of its precipitation to occur between October and April (Awadh *et al* 2021), with the wetter southwestern region receiving 50–100 mm of rainfall annually from orographic convection (Hasanean and Almazroui 2015). These convective storms are brief (lasting a few hours) and localized (Patlakas *et al* 2021). The southwestern region of the AP is heavily influenced by Indian monsoons, where monsoonal rainfall (averaging 300 mm per occurrence) comprises about 60% of the annual rainfall. On the other hand, desert regions receive less than 60 mm annually, with some years receiving nothing (Almazroui *et al* 2012b, Hasanean and Almazroui 2015).

Trend analyses generally agree on decreasing annual rainfall (AlSarmi and Washington 2011, Hasanean and Almazroui 2015, Zittis 2018, Almazroui 2020, Wehbe and Temimi 2021), largely the result of recent declines from 1994 to 2009 (Almazroui *et al* 2012b). Rainfall extremes, which account for 40%–70% of annual rainfall (Almazroui and Saeed 2020), have been shown to occur more frequently in recent years, while weak rainfall occurrences diminish (Almazroui 2020). Although, extremes in the wetter regions of Saudi Arabia have demonstrated less-frequent but more-intense rainfall extremes (Luong *et al* 2020).

Few studies have characterized the seasonal distribution of rainfall (Almazroui *et al* 2012a, Mahmoud *et al* 2021), and none have investigated the extent to which the seasonal timing of rainfall has changed in the AP.

1.2. Rainfall West of the Red Sea: East Africa

In stark contrast, EA accumulates 300–1200 mm of rainfall annually (Fenta *et al* 2017) with much stronger spatial coherence in its interannual variability—a result of rainfall being driven by regional circulation, geography, and partially explained through teleconnections such as the El Niño-Southern and Madden-Julian Oscillations and Indian Ocean Dipole (Yang *et al* 2015, Nicholson 2017, Lüdecke *et al* 2021). This region carries two distinct rainfall regimes, the first consisting of summer (July–September) monsoonal rains over Northern Ethiopia and Sudan. These account for 50%–95% of the total rainfall (Conway 2005, Korecha and Barnston 2007). The 2nd regime is bimodal, consisting of 'long-rains' (March–May) and 'short-rains' (October–December) that generally preside over Southern Ethiopia and regions in Kenya and Uganda. While the long-rains are more persistent and carry more rainfall, short-rains drive interannual variability and extreme rainfall (Nicholson 1996, 2017, Camberlin and Wairoto 1997, Camberlin *et al* 2009, Wenhaji Ndomeni *et al* 2018). The timing (i.e. onset and cessation) of the wet season is generally early (late) in southwest (northeast) Ethiopia (Segele and Lamb 2005).

Rainfall trends are immensely heterogeneous and insignificant over large areas of EA (Fenta *et al* 2017, Gebrechorkos *et al* 2019). However, summer rains have been shown to decline steadily since the 1950s, owing to an abrupt reduction in the late 1990s (Nicholson 2017). Long-rains have undergone dramatic declines (Cattani *et al* 2018, Gebrechorkos *et al* 2019, Dabar *et al* 2021), while short-rains have shown upward trends (Kizza *et al* 2009, Onyutha 2018, Muthoni *et al* 2019). Drying has been tied to later wet season onset dates (Kniveton *et al* 2009) and earlier cessation (Seregina *et al* 2019). Trends in extreme rainfall have shown decreasing (increasing) frequency of high- (low-) intensity rainfall (Cattani *et al* 2018, Kalisa *et al* 2021), but are generaly weak and lack spatial coherence (Zhang *et al* 2005, Ongoma *et al* 2018).

For brevity, we have described a few salient features of EA rainfall despite a much larger body of

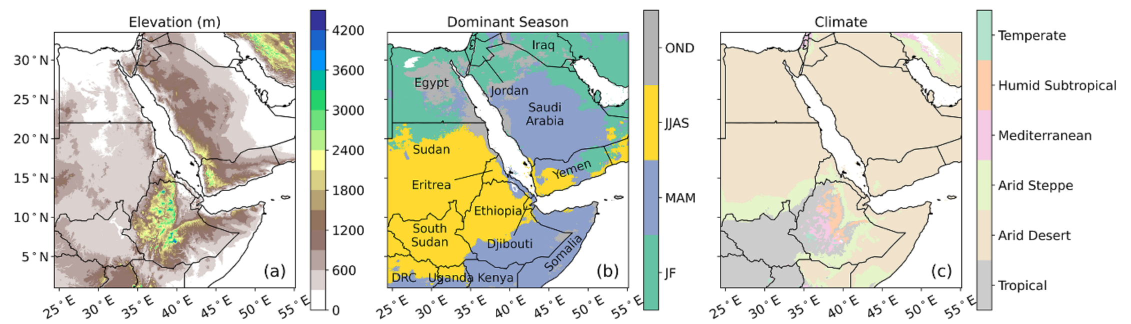

Figure 1. (a) Elevation, (b) climatologically-dominant wet season, and (c) Koppen–Geiger climate classification of the RSR with political boundaries. Elevations (1 km) were obtained from GTOPO30. The dominant wet season was obtained from the mode of the seasons (OND = October–December, JJAS = June–September, MAM = March–May, JF = January–February) carrying the greatest monthly average accumulated rainfall in 1981–2020 using CHIRPS v2.0. Climate classification data were obtained from the 1 km map developed by Beck *et al* (2018).

research. An excellent review of EA rainfall characteristics, drivers, and trends is provided by Nicholson (2017). No study, however, assesses the impact of shifting intensities to total rainfall.

1.3. Research objective

The goal of this study is to assess the behavior of varying rainfall intensities, their importance to annual totals, and their relationship to the seasonal timing of rainfall across the Red Sea as a whole. We employ a high-resolution daily gridded precipitation data set to address the following questions: (a) what are the relative contributions of light, moderate, and heavy rainfall to annual rainfall? (b) How does wet-season onset and duration vary across the region? (c) To what extent have relative intensity contributions and the timing and duration of wet seasons undergone considerable change?

2. Study region and data

2.1. The Red Sea region (RSR)

Most of the inland and upper latitudes of the RSR are low-lying desert (figures 1(a) and (c)). A strip of tropical landscape (south of 10° N) spans from South Sudan, the Congo, and northern Uganda into the high-relief Ethiopian Highlands. The dominant wet season in Ethiopia contains a mixture of monsoonal summer and springtime long-rains, which may switch from year to year (Segele and Lamb 2005, Bekele-Biratu *et al* 2018), resulting in a heterogeneous climate class (figure 1(c)). The AP is primarily dominated by spring rainfall and its topographic relief points toward the Red Sea. Sparse rainfall year-round makes for a spatially heterogeneous dominant wet-season north of 20° N on both sides of the RSR (figure 1(b)).

2.2. Climate hazards group infrared precipitation with stations

We obtained 40 years (1981 through 2020) of gridded (0.05°) daily precipitation from version 2 of the Climate group InfraRed Precipitation with Stations (CHIRPS) product (Funk *et al* 2015a). The data set is underpinned by a high-resolution precipitation climatology that incorporates a topographical grid and multiple streams of historic station- and satellite-based thermal infrared precipitation estimates (Funk *et al* 2015b). This climatology is adjusted by local regressions between Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis estimates and cold cloud top duration estimates, followed by a bias correction via daily gauge measurements (Funk *et al* 2015a).

The CHIRPS data set was chosen based on its regional (RSR) performance and collective suitability for describing the precipitation metrics used in this study (defined in section 3). These are namely the annual total precipitation, wet-day detection, and long-term persistence for trend analysis. Annual rainfall and storm detection from satellite-based products have been evaluated extensively in recent years, and CHIRPS has been shown to demonstrate superior skill to other products over the RSR along these lines (Bayissa *et al* 2017, Kimani *et al* 2017, Ayehu *et al* 2018, Dinku *et al* 2018, Gebrechorkos *et al* 2018, Diem *et al* 2019, Muthoni *et al* 2019, Zhao and Ma 2019, Nashwan *et al* 2019b, Al-Falahi *et al* 2020, Belete *et al* 2020, Nkunzimana *et al* 2020, Shen *et al* 2020, Geleta and Deressa 2021). As trend analysis requires long-term data stability, changes in precipitation gauge density (Nicholson *et al* 2019) or satellite platforms present a risk for gauge-corrected, satellite-based products to display spurious trends due to sensitivity to these changes (Maidment *et al* 2015). The CHIRPS algorithm at its core is a series of anomalies scaled by a high-resolution climatology, which has some *a priori* influence on the final, gauge-corrected product. Moreover, it leverages a 9 year overlap in two thermal infrared satellite records to offset one record and maintain consistency across the changing platforms (Funk *et al* 2015a). These features are resilient to these risks by design, and have shown long-term persistence over the RSR (Maidment *et al* 2015, Harrison et al 2019; figure S1 available online at stacks.iop.org/ERL/17/044039/mmedia). While this type of blended interpolation may not necessarily reproduce ground precipitation measurements (Funk et al 2015a), and while cold cloud top estimates can underestimate warm orographic rainfall (Dinku et al 2007), we deem CHIRPS to be the most suitable product over the RSR for the following precipitation metrics.

3. Methods

We consider three metrics to characterize rainfall behavior across the RSR, in addition to annual rainfall: (a) the relative contributions of differing rainfall intensities to the annual total, (b) the wet season onset timing and (c) duration. Measures of central tendency, dispersion, and trend were calculated for each metric, which we obtain in terms of the 'local water year (LWY)'.

3.1. The local water year (LWY)

Precipitation rhythms do not always obey the calendar year. Using the calendar year to assess annual rainfall in a winter-dominated climate, for instance, can create a misleading account that mixes two seasons together. Therefore, characterizations of timing and intensity contributions to annual rainfall must be made relative to a time frame that aims to centralize annual rainfall. Borrowing from stream discharge analysis (Wasko et al 2020), we define the LWY using a monthly rainfall climatology. For each pixel, we calculated the total monthly rainfall, averaged over the 1981–2020 record. The LWY for each pixel begins the first day of the month having the lowest average rainfall (figure 4(b)), ending 365 d later (366 if containing a leap year). The LWY is considered to be constant at each pixel. We use 39 years of data (LWY 1981–2019) based on this definition.

3.2. Rainfall intensity contributions to annual accumulations

We disentangle the role of varying storm types in characterizing annual rainfall by partitioning daily precipitation into light (below 5 mm d^{-1}), moderate (between 5 and 20 mm d^{-1}), and heavy (above 20 mm d^{-1}) rainfall days. For each LWY at each grid point, light, moderate, and heavy rainfall days were totaled and divided by the LWY total accumulation to yield the fractional contribution of each intensity category. We refer to these fractions as f_{Light}, f_{Moderate}, and f_{Heavy}.

3.3. Wet season timing and length

Regions having more than one rainfall regime challenge wet season onset/cessation definitions that aim to take multimodality into account (e.g. Segele and Lamb 2005, Dunning et al 2016, Seregina et al 2019). In this study, we use the LWY to define the wet season onset as the day 10% of the annual rainfall accumulates (t_a). LWYs accumulating less than 5 mm of rainfall were omitted. The day 90% of annual rainfall accumulates (t_b) marks the end of the wet season. This serves to 'center' when the bulk of precipitation occurs in both EA and the AP. The nominal wet season defined by the difference between t_b and t_a aims to account for a diverse range of climates, but can be inflated by multiple wet seasons or in regions that are characterized by a few scattered storms. We therefore define the effective wet season, D_e, as the number of dry days (having zero precipitation, N_{dry}) subtracted from the nominal duration (equation (1)).

$$D_e = (t_b - t_a) - N_{\text{dry}}. \tag{1}$$

In other words, D_e is the number of wet days that comprise the central 80% of LWY rainfall. This definition avoids common calendar year-related issues, such as falsely tracking the window of boreal winter seasons. However, it should be noted that our approach is tailored to understand the temporal distribution of regionally important rainfall, rather than to broadly predict the growing season(s). We therefore caution its use in an operational setting.

3.4. Statistical analysis

We characterize behavioral rainfall through measures of central tendency, dispersion, and linear trend in the annual precipitation, fractional contribution of different rainfall intensities, and the wet season onset and D_e. The arithmetic mean and interquartile range (IQR) for each metric were calculated per pixel as measures of central tendency and dispersion, respectively. Measures were sampled across LWYs to create maps of each metric. We tested for monotonic trends using the non-parametric Mann–Kendall test (Mann 1945). Theil-Sen slope estimates (Sen 1968) of linear trends are reported for statistically significant ($\alpha < 0.05$) cases; insignificant cases are omitted.

4. Results and discussion

4.1. A brief summary of annual rainfall

Average annual rainfall (figure 2(a)) has a stark contrast across 15° N, where the AP, Egypt and northern Sudan accumulate less than 250 mm. Majority accumulates south of 15° N in the Ethiopian Highlands and the Congo, reaching over 2000 mm. Orographic effects appear most prevalent in the Highlands, where the rainfall gradient broadly follows terrain (figure 1(a)). Similar behavior is present in the western AP, where a modest rainfall gradient reflects the Sarawat mountain range.

Interannual variability of rainfall (figure 2(b)) generally follows the magnitude of accumulation. The greatest variability (i.e. highest IQRs) occur at the

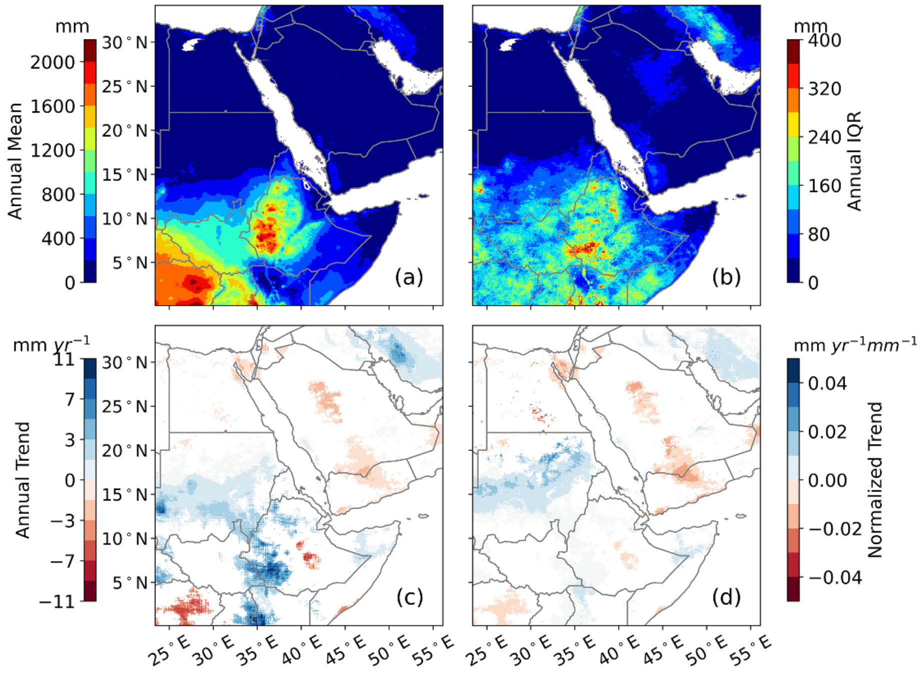

Figure 2. (a) Average and (b) IQR of annual rainfall for LWYs 1981–2019. (c) Slope of statistically significant trends in annual rainfall. (d) Normalized trends in rainfall expressed as the proportion of average annual rainfall.

boundary between southwestern Ethiopia and eastern South Sudan. IQRs are lower in the Congo relative to its higher annual rainfall, which points to a more persistent accumulation of rain. Conversely, the central and southwest AP have high IQRs relative to annual rainfall, highlighting its intermittent, irregular precipitation regime.

Annual precipitation is broadly stationary over most of the RSR, with 80% of the region having either no significant trend, or having trends weaker than ± 1 mm yr^{-1} (figure 2(c)). In EA, significant increases in rainfall occupy pockets of central Sudan (averaging 2.5 mm yr^{-1}), western Ethiopia (5.4 mm yr^{-1}), and the border of Uganda and Kenya (5.6 mm yr^{-1}), with the strongest increases occurring below 10° N. In contrast, the wet Congo shows the strongest decline in the RSR (averaging -4.6 mm yr^{-1}). A similar magnitude of drying exists in central Ethiopia (-4.6 mm yr^{-1}), located in the eastern Highland 'shadow' (figures 2(a) and (c)). These trend patterns agree with other trend analyses in Ethiopia (Gebrechorkos *et al* 2019, Beyene *et al* 2021), the southern RSR (Diem *et al* 2019, Muthoni *et al* 2019, Ngoma *et al* 2021), and Egypt (Nashwan *et al* 2019a).

In the AP, trends are largely negligible except for two regions of modestly decreasing rainfall (averaging -0.8 mm yr^{-1}), which is broadly consistent with other results in the AP (AlSarmi and Washington 2011, Alsaaran and Alghamdi 2022, Patlakas *et al* 2021). While these are weak with respect to the RSR as a whole, they are locally more important than those occurring in EA. Drying in the AP becomes more severe when expressed in terms of the proportion of average annual rainfall, i.e. normalizing the trend slope by annual rainfall (figure 2(d), darker shading). Similar locally-important wetting occurs across central Sudan.

4.2. Relative importance of rainfall intensity

While the fractional contributions of rainfall intensity generally follow total rainfall, this is not the case universally. Northern EA (largely the Sahara Desert) is exclusively shaped by light rainfall (below 5 mm d^{-1}, figure 3(a)), while majority of the remaining RSR gets most (56%–69%) of its annual rainfall at moderate intensities (5–20 mm d^{-1}, figure 3(b)). AP rainfall is shaped by light and moderate rainfall, which make up approximately 70% of average accumulation. The inland of Saudi Arabia and high-elevation southwest AP have some heavy rainfall contributions (above 20 mm d^{-1} contributing approximately 14% of annual rainfall (figure 3(c)). This result is a slightly different expression of rainfall intensity contributions in the AP than previously reported, where 40%–70% of annual rainfall comes from extremes (Almazroui and Saeed 2020). However, extremes in Almazroui and Saeed (2020) were defined as the 99th-percentile of daily rainfall, including dry days. This conceivably may deflate the value of 'extreme' rainfall to intensities that fall near or below our threshold for moderate versus heavy rainfall (figure S2). Heavy rainfall presides over a relatively small fraction of the RSR, and is most prevalent in the horn of Africa. Notably, an interplay between moderate and heavy rainfall contributions exist in the Ethiopian Highlands. Moderate rainfall dominates the southwestern region of

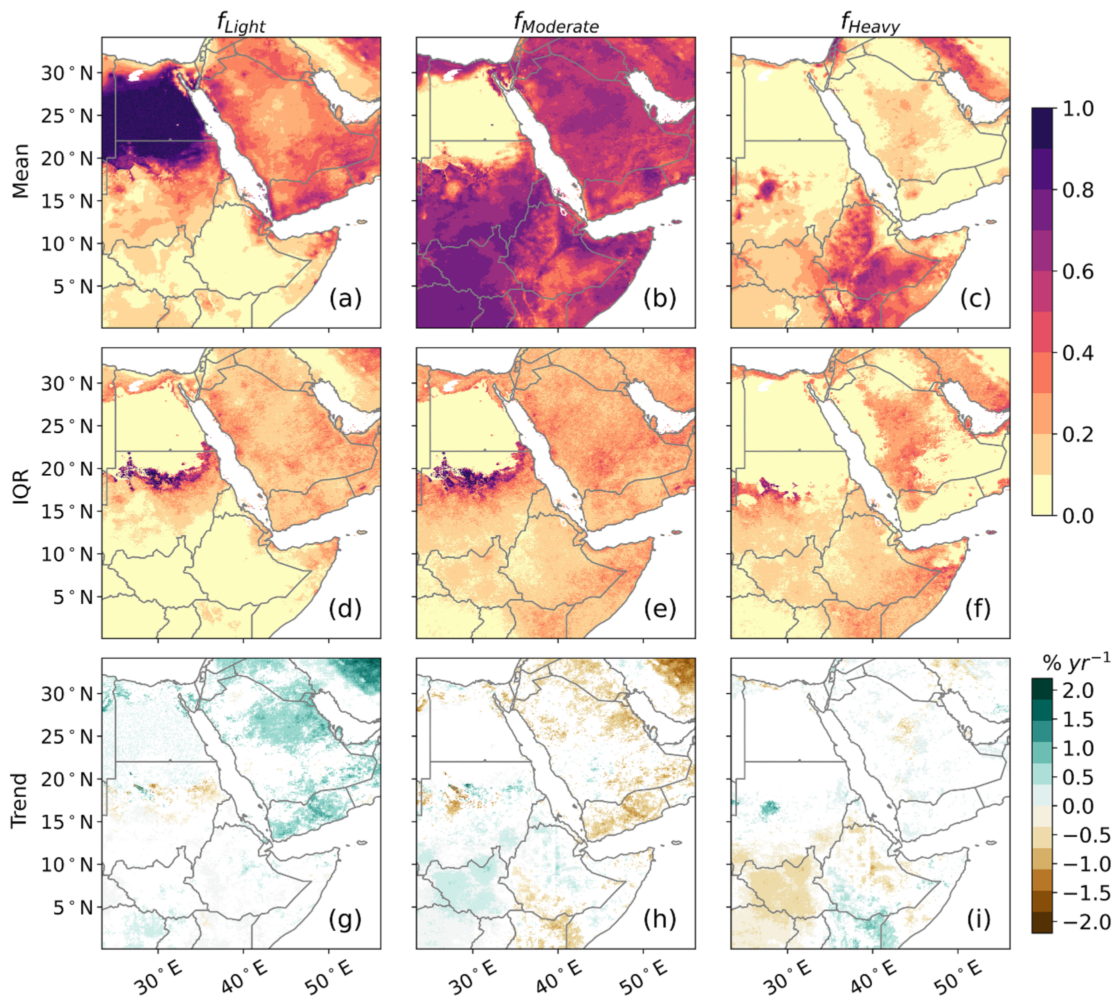

Figure 3. Annual (a)–(c) mean, (d)–(f) IQR, and (g)–(i) significant trend slopes of the fractional contributions of light, moderate, and heavy rainfall to annual rainfall.

the RSR (comprising 72% of rainfall in South Sudan and the Congo), where annual rainfall is greatest (figure 2(a)) and dominated by monsoonal summer rains (figure 1(b)). On the other hand, the heavy rains that have a strong contribution to rainfall in Kenya and southern Ethiopia (figure 2(c)) are associated with springtime long-rains (figure 1(b)) and overall lower rainfall (figure 2(a)). Accumulation therefore does not necessarily scale with intensity.

These intensity contributions can vary considerably from year to year. In the AP, IQRs average 0.19–0.23 for light (figure 3(d)) and moderate (figure 3(e)) rainfall. Similar variability is observed in the central and mountainous AP for heavy rainfall (figure 3(f)). Coupled with the heterogeneity of light and moderate contributions (figures 3(b) and (c)), this variability demonstrates the AP rainfall regime to be shaped by a mixture of light and moderate events, with some convective signatures influencing the inland. Over EA, particularly in the horn of Africa, similar variability exists for the moderate and heavy rainfall contributions (0.16 IQR) shaping the regime. There is a high-IQR band of light and moderate contributions around 19° N–20° N (figures 3(d) and (e)) that is consistent with neither terrain (figure 1(a)), climate (figure 1(c)), nor precipitation (figures 2(a) and (b)) features. This is likely an artifact of the threshold defining moderate rainfall, as this latitude band marks the transition between light- and moderate-dominated regions (figures 3(a) and (b)). While features spanning different intensity classes in EA and the AP may show a sensitivity to intensity category, they still draw the distinction that moderate-to-heavy rains predominate the Highlands while light-to-moderate rains predominate the AP and northern EA.

Trends in storm type contributions reveal three distinct shifts. First, primarily in Yemen and central and southern Saudi Arabia, increases in light contributions are coupled with decreases in moderate contributions (figures 3(g) and (h)). This can be interpreted as light rains 'replacing' moderate rains. Similarly, the second shift, present in central and South Sudan and in central and norhteast Ethiopia, increases in moderate rainfall replace decreases in heavy rainfall (figures 3(h) and (i)). Both of these

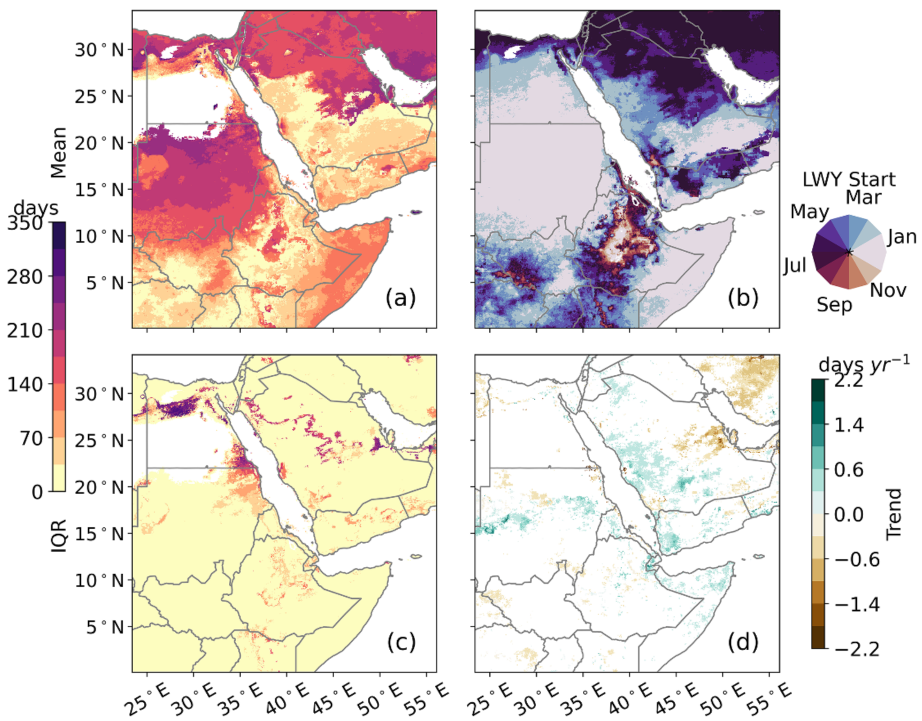

Figure 4. (a) Mean annual wet season onset day relative to (b) the LWY start. (c) IQR and (d) significant trend slopes of onset date. Positive (negative) values indicate later (earlier) onsets.

features demonstrate a shift toward more modest conditions, which appear compensatory for most of the area they occur in (i.e. they are coupled with negligible changes in annual rainfall (figure 2(c))). However, areas having locally important decreases in rainfall (figure 2(d)) are also accompanied by these shifts toward lighter rainfall. Conversely, the regions of southwestern Ethiopia and northern Kenya and Uganda that have increasing rainfall (figure 2(c)) are associated with a shift toward heavier rainfall contributions (figures 3(h) and (i)). However, the boundary between Somalia and Kenya share this shift toward heavier rainfall without any significant change in annual accumulation (figure 2(c)), which may be explained by differences in wet season length (discussed in section 4.4).

4.3. Wet season onset

The climatological onset date (t_a, figure 4(a)) shows a northward gradient toward later onsets, with considerable regional heterogeneity. This heterogeneity, particularly in the AP, largely matches the spatial pattern in LWY start date (figure 4(b)). It should be noted these onsets are with respect to the month of minimum rainfall. Taken together with the effective wet season length (D_e) being brief in the AP (averaging 46 d; figure 5(a)) and with t_a following LWY closely, this supports the notion that annual AP rainfall is shaped by few wet winter days (Hasanean and Almazroui 2015). In EA, t_a transitions from summer to spring in northern to South Sudan, while spring onsets occupy most of Somalia and eastern Ethiopia (figure 4(a)). The Ethiopian Highlands show strong heterogeneity in t_a, where peaks in terrain having relativley later onsets are surrounded by areas having earlier onsets. Coupled with regions of high IQR in t_a (figure 4(c)), this reflects the well-known variability in seasonal rainfall timing in Ethiopia (Segele and Lamb 2005).

Changes in t_a (figure 4(d)) are scattered and affect little area across the RSR, compared to changes in annual rainfall (figure 2(c)) and intensity classes (figures 3(g)–(i)). The most notbale shifts in t_a are in northern Sudan and the western AP, where positive trends indicate average onset recessions of 0.5 d yr^{-1}. Most onset advances toward earlier in the LWY occur further east in the AP (averaging 0.7 d yr^{-1}). A mixture of advanced/recessed t_a is peppered across the Ethiopian Highlands, but lack any spatial structure and are mostly insignificant. While some shifts may mark an astonishing redistribution of rainfall (e.g. a maximum of 4 d yr^{-1} over 39 years spans approximately 5 months), 90% of the RSR is (statistically) unaffected by onset changes (figure 4(d)) and are generally unassociated with shifts in annual rainfall (weak pattern correlation, figure 2(c)).

4.4. Wet season duration

Average D_e (figure 5(a)) closely resembles annual rainfall (figure 2(a)), with the longest and wettest seasons located in Ethiopia, South Sudan, and the Congo in EA (averaging 97 d), and in the southwestern mountainous regions of the AP (averaging

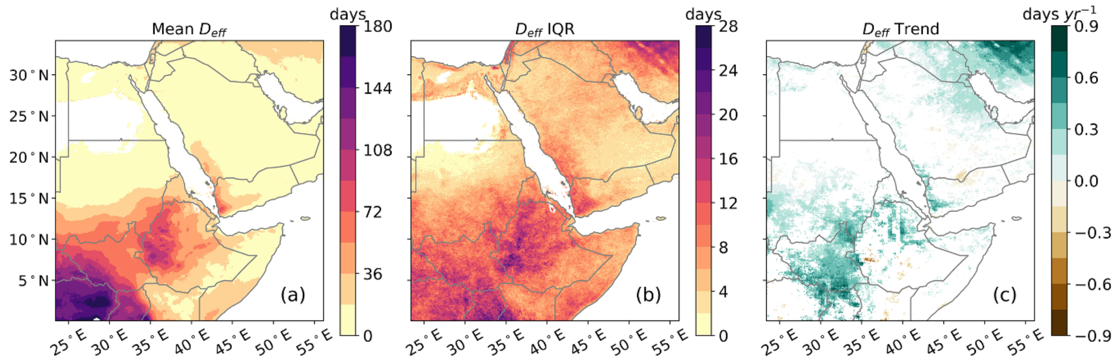

Figure 5. Annual (a) mean, (b) IQR, and (c) significant trend slopes of the effective wet season duration.

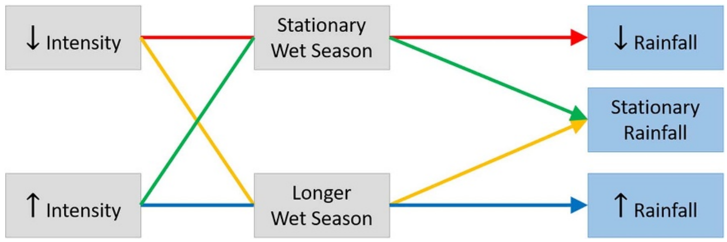

Figure 6. Conceptual summary of the observed rainfall changes in the RSR. Shifts in annual rainfall (right-side nodes) come from interactions between shifting wet season duration and shifting rainfall intensity (left- and center-nodes). Note that the wet season demonstrates a stronger control than intensity does on shifts in rainfall, ofsetting the expected increase from greater intensity (green line).

53 d). Interannual variabilty in D_e is also loosely tied to annual rainfall, where the wettest regions have the highest D_e IQRs (up to 3 and 4 weeks, figure 5(b)). This is to be expected, as the number of wet days is a common cause of both wet season length and magnitude.

Trends in D_e (figure 5(c)) have considerable water resource implications, and they reveal a principal interaction between observed shifts in rainfall (figure 2(c)) and their shifting intensities (figures 3(g)–(i)). Trends in D_e are generally positive or insignificant across the RSR, indicating an expanding (stationary) wet season for 26% (73%) of the region. These D_e trajectories (increasing or stationary) tend to modify the resulting trend in annual rainfall that a shift in rainfall intensity may impart (figure 6). For instance, the Congo and pockets of central AP show shifts toward lighter rainfall (figures 3(h) and (i)) that are associated with rainfall decreases (figure 2(c)), and generally absent shifts in D_e (figure 5(c)). On the other hand, South Sudan also shifts toward lighter rainfall, but a counteracting increase in D_e yields no significant change in annual rainfall. In northeast Ethiopia, shifts toward lighter rainfall and longer wet seasons even account for increases in annual rainfall in some areas. Similarly, areas becoming wetter that are shifting toward heavier rainfall (e.g. southwest Ethiopia and the border of Uganda and Kenya, figures 3(h) and (i)) have increasing D_e (figure 5(c)), while areas with no significant rainfall trends that shift toward heavier rainfall (e.g. the border of Kenya and Somalia) also have no significant changes in D_e. This again suggests that greater-intensity rainfall does not necessarily increase total rainfall. While it is possible that an underestimated variance in the CHIRPS data set (Funk *et al* 2015a, Muthoni *et al* 2019) can negatively bias the total rainfall from heavy wet days, the region this result applies to does not indicate such a bias (figure S2). So, wet season length is a crucial buffer that can dampen the inherent drying effect of lighter rains, or bolster the benefits (and potential flood hazard) of heavier rainfall.

This result agrees with the notion that a constriction of the wet season takes greater responsibility for reduced rainfall than a shift toward lighter rainfall does (Harrison *et al* 2019, Wainwright *et al* 2019). We demonstrate here, over a larger region of Africa and across the Red Sea, that this notion acts in both directions of increasing and decreasing rainfall. It is important to note that this expansion of D_e does not necessarily indicate an expanding growing season region-wide, because lighter rains compete against evaporative demand (Tomas-Burguera *et al* 2020). Rather, we interpret this as a bigger window for attentive, informed decision-making.

5. Summary and conclusions

The Red Sea hosts a variety of rainfall regimes, hydrologic end-uses and geopolitical states. It separates the AP to the east, where scarce rainfall provides crucial, intermittent recharge to a heavily stressed groundwater supply. West of the Red Sea is East Africa (EA), where multiple seasonal modes of rich rainfall support agriculture and transboundary resource governance. The wettest areas in the RSR contain the Ethiopian Highlands and the Congo in EA, and the coastal high elevations in the southwest AP. The driest regions are located in northern Sudan and Egypt in EA and the inland AP.

Understanding behavioral changes in rainfall is a common thread to both EA and the AP in their respective conservation and sustainability efforts. In this study, we (a) characterize the relative importance of different rainfall intensities to annual rainfall, (b) determine how the timing and duration of wet seasons vary across the region as a whole, and (c) assess the extent to which these have undergone considerable change in recent years (1981–2019).

Our key findings are as follows:

- Annual rainfall trends are stationary for 71% of EA and 84% of the AP. However, significant increases are observed in the EA in central Sudan, western Ethiopia, and at the border of Kenya and Uganda. Decreases are observed in EA in the Congo and in the inland AP in Yemen and central Saudi Arabia. Light- (under 5 mm d^{-1}) and moderate-intensity (5–20 mm d^{-1}) rainfall make up 81% of annual rainfall in EA and 92% in the AP. However, heavy rainfall (above 20 mm d^{-1}) comprises 46% of annual rainfall in the Ethiopian Highlands in EA. Trends in the relative importance of rainfall intensity to annual rainfall generally indicate annual rains are becoming increasingly shaped by less-intense rainfall in both EA (in the Congo, South Sudan and central/northeast Ethiopia) and the AP (in Yemen and inland Saudi Arabia). More-intense rainfall is shown to have a growing contribution to annual rainfall in southeast EA (in southern Ethiopia and at the border of Kenya and Somalia).
- The effective wet season length, D_e (defined here as the number of wet days within the central 80% of annual rainfall), is closely related to annual rainfall across the RSR, where the wettest regions (e.g. the Congo, South Sudan, and Ethiopian Highlands in EA, and the coastal mountains in the AP) have the longest wet seasons (averaging 97 d in EA and 53 d in the AP). Trends in D_e are stationary in 76% of EA and 74% of the AP, but increasing for 23% of EA and 24% of the AP. Increases in D_e are focused in northwest Ethiopia and central and South Sudan in EA, and in the coastal mountains, northeast Saudi Arabia and Iraq in the AP.
- Shifts in annual rainfall are controlled more by D_e than by rainfall intensity alone. Regions with expanding D_e can offset the inherent drying effect of lighter-intensity rainfall resulting in stationary rainfall (observed in South Sudan in EA), or accompany the increase in annual rainfall associated with higher-intensity rainfall (observed in southern Ethiopia and at the border of Kenya and Somalia in EA). Stationary D_e, on the other hand, can permit the drying effect of lighter rainfall to decrease annual rainfall (observed in the Congo in EA and inland Saudi Arabia in the AP).

Rainfall regime changes are regionalized and differ across the RSR. Successful closure of energy and water budgets at a large scale is necessary to place the shifts observed here into proper context. Moreover, while we have selected a precipitation data set based on performance measures and attributes most-suitable for the metrics and regions considered here, an ensemble of suitable products may bound uncertainties in estimated rainfall trajectories. Both of these efforts would provide a more confident illustration of the implications of behavioral rainfall changes, which must be done in a way that respects the boundary layer, surface and subsurface interactions that affect how rainfall is moved and stored on its way to urban and agricultural end-uses. Importantly, our observations highlight regions that are currently or may become hydrologically 'richer' or 'poorer'. We emphasize that the large-scale distribution of these shifts and their regional importance should punctuate cooperative efforts in sustainable resource management and transboundary governance.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://data.chc.ucsb.edu/products/CHIRPS-2.0/.

Acknowledgments

We sincerely thank three anonymous reviewers for helpful comments on previous versions of this manuscript. We acknowledge funding support from the NASA Precipitation Measurement Mission through Grant # 80NSSC19K0688.

ORCID iDs

Kayden Haleakala https://orcid.org/0000-0003-0551-4396
Haowen Yue https://orcid.org/0000-0002-4068-8810

References

Al-Falahi A H, Saddique N, Spank U, Gebrechorkos S H and Bernhofer C 2020 Evaluation the performance of several gridded precipitation products over the highland region of yemen for water resources management *Remote Sens.* **12** 2984

Almazroui M 2020 Rainfall trends and extremes in Saudi Arabia in recent decades *Atmosphere* **11** 964

Almazroui M, Islam M N, Balkhair K S, Şen Z and Masood A 2017 Rainwater harvesting possibility under climate change: a basin-scale case study over western province of Saudi Arabia *Atmos. Res.* **189** 11–23

Almazroui M, Islam M N, Jones P D, Athar H and Rahman M A 2012a Recent climate change in the Arabian Peninsula: seasonal rainfall and temperature climatology of Saudi Arabia for 1979–2009 *Atmos. Res.* **111** 29–45

Almazroui M, Nazrul Islam M, Athar H, Jones P D and Rahman M A 2012b Recent climate change in the Arabian Peninsula: annual rainfall and temperature analysis of Saudi Arabia for 1978–2009 *Int. J. Climatol.* **32** 953–66

Almazroui M and Saeed S 2020 Contribution of extreme daily precipitation to total rainfall over the Arabian Peninsula *Atmos. Res.* **231** 104672

Alsaaran N A and Alghamdi A S 2022 Precipitation climatology and spatiotemporal trends over the Arabian Peninsula *Theor. Appl. Climatol.* **147** 1133–49

AlSarmi S and Washington R 2011 Recent observed climate change over the Arabian Peninsula *J. Geophys. Res. Atmos.* **116** D11109

Awadh S M, Al-Mimar H and Yaseen Z M 2021 Groundwater availability and water demand sustainability over the upper mega aquifers of Arabian Peninsula and west region of Iraq *Environ. Dev. Sustain.* **23** 1–21

Ayehu G T, Tadesse T, Gessesse B and Dinku T 2018 Validation of new satellite rainfall products over the Upper Blue Nile Basin, Ethiopia *Atmos. Meas. Tech.* **11** 1921–36

Baig M B, Alotibi Y, Straquadine G S and Alataway A 2020 Water resources in the Kingdom of Saudi Arabia: challenges and strategies for improvement *Water Policies in MENA Countries* (Cham: Springer) pp 135–60

Bayissa Y, Tadesse T, Demisse G and Shiferaw A 2017 Evaluation of satellite-based rainfall estimates and application to monitor meteorological drought for the Upper Blue Nile Basin, Ethiopia *Remote Sens.* **9** 669

Beck H E, Zimmermann N E, Mcvicar T R, Vergopolan N, Berg A and Wood E F 2018 Present and future Köppen-Geiger climate classification maps at 1-km resolution *Nat. Sci. Data* **5** 180214

Bekele-Biratu E, Thiaw W M and Korecha D 2018 Sub-seasonal variability of the Belg rains in Ethiopia *Int. J. Climatol.* **38** 2940–53

Belete M, Deng J, Wang K, Zhou M, Zhu E, Shifaw E and Bayissa Y 2020 Evaluation of satellite rainfall products for modeling water yield over the source region of Blue Nile Basin *Sci. Total Environ.* **708** 134834

Berhanu B, Seleshi Y and Melesse A M 2014 Surface water and groundwater resources of Ethiopia: potentials and challenges of water resources development *Nile River Basin* (Cham: Springer) pp 97–117

Beyene T K, Jain M K, Yadav B K and Agarwal A 2021 Multiscale investigation of precipitation extremes over Ethiopia and teleconnections to large-scale climate anomalies *Stoch. Environ. Res. Risk Assess.* 1–17

Camberlin P and Wairoto J G 1997 Intraseasonal wind anomalies related to wet and dry spells during the "long" and "short" rainy seasons in Kenya *Theor. Appl. Climatol.* **58** 57–69

Camberlin P, Wairoto J G, Moron V, Okoola R, Philippon N and Gitau W 2009 Components of rainy seasons' variability in Equatorial East Africa: onset, cessation, rainfall frequency and intensity *Theor. Appl. Climatol.* **98** 237–49

Cattani E, Merino A, Guijarro J A and Levizzani V 2018 East Africa Rainfall trends and variability 1983–2015 using three long-term satellite products *Remote Sens.* **10** 931

Conway D 2005 From headwater tributaries to international river: observing and adapting to climate variability and change in the Nile basin *Glob. Environ. Change* **15** 99–114

Dabar O A, Camberlin P and Pohl B 2021 Spatial and temporal variability of rainfall over the Republic of Djibouti from 1946 to 2017 *Int. J. Climatol.* **41** 2729–48

Degefu W 1987 Some aspects of meteorological drought in Ethiopia *Drought and Hunger in Africa: Denying Famine a Future* (Cambridge: Cambridge University Press) pp 223–36

Diem J E, Konecky B L, Salerno J and Hartter J 2019 Is equatorial Africa getting wetter or drier? Insights from an evaluation of long-term, satellite-based rainfall estimates for western Uganda *Int. J. Climatol.* **39** 3334–47

Dinku T, Ceccato P, Grover-Kopec E, Lemma M, Connor S J and Ropelewski C F 2007 Validation of satellite rainfall products over East Africa's complex topography *Int. J. Remote Sens.* **28** 1503–26

Dinku T, Funk C, Peterson P, Maidment R, Tadesse T, Gadain H and Ceccato P 2018 Validation of the CHIRPS satellite rainfall estimates over eastern Africa *Q. J. R. Meteorol. Soc.* **144** 292–312

Dunning C M, Black E C L and Allan R P 2016 The onset and cessation of seasonal rainfall over Africa *J. Geophys. Res.* **121** 11405–24

Fenta A A, Yasuda H, Shimizu K, Haregeweyn N, Kawai T, Sultan D, Ebabu K and Belay A S 2017 Spatial distribution and temporal trends of rainfall and erosivity in the Eastern Africa region *Hydrol. Process.* **31** 4555–67

Funk C *et al* 2015a The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes *Sci. Data* **2** 150066

Funk C, Verdin A, Michaelsen J, Peterson P, Pedreros D and Husak G 2015b A global satellite-assisted precipitation climatology *Earth Syst. Sci. Data* **7** 275–87

Gebrechorkos S H, Hülsmann S and Bernhofer C 2018 Evaluation of multiple climate data sources for managing environmental resources in East Africa *Hydrol. Earth Syst. Sci.* **22** 4547–64

Gebrechorkos S H, Hülsmann S and Bernhofer C 2019 Long-term trends in rainfall and temperature using high-resolution climate datasets in East Africa *Sci. Rep.* **9** 11376

Geleta C D and Deressa T A 2021 Evaluation of climate hazards group infrared precipitation station (CHIRPS) satellite-based rainfall estimates over Finchaa and Neshe Watersheds, Ethiopia *Eng. Rep.* **3** e12338

Gissila T, Black E, Grimes D I F and Slingo J M 2004 Seasonal forecasting of the Ethiopian summer rains *Int. J. Climatol.* **24** 1345–58

Harrison L, Funk C and Peterson P 2019 Identifying changing precipitation extremes in Sub-Saharan Africa with gauge and satellite products *Environ. Res. Lett.* **14** 085007

Hasanean H and Almazroui M 2015 Rainfall: features and variations over Saudi Arabia, a review *Climate* **3** 578–626

Jones J A A 2014 *Water Sustainability: A Global Perspective* (London: Routledge)

Kalisa W, Igbawua T, Ujoh F, Aondoakaa I S, Namugize J N and Zhang J 2021 Spatio-temporal variability of dry and wet conditions over East Africa from 1982 to 2015 using quantile regression model *Nat. Hazards* **106** 2047–76

Kimani M W, Hoedjes J C B and Su Z 2017 An assessment of satellite-derived rainfall products relative to ground observations over East Africa *Remote Sens.* **9** 430

Kizza M, Rodhe A, Xu C Y, Ntale H K and Halldin S 2009 Temporal rainfall variability in the Lake Victoria Basin in East Africa during the twentieth century *Theor. Appl. Climatol.* **98** 119–35

Kniveton D R, Layberry R, Williams C J R and Peck M 2009 Trends in the start of the wet season over Africa *Int. J. Climatol.* **29** 1216–25

Korecha D and Barnston A G 2007 Predictability of June–September rainfall in Ethiopia *Mon. Weather Rev.* **135** 628–50
Lüdecke H, Müller-Plath G, Wallace M G and Lüning S 2021 Decadal and multidecadal natural variability of African rainfall *J. Hydrol. Reg. Stud.* **34** 100795
Luong T M, Dasari H P and Hoteit I 2020 Extreme precipitation events are becoming less frequent but more intense over Jeddah, Saudi Arabia. Are shifting weather regimes the cause? *Atmos. Sci. Lett.* **21** 1–8
Mahmoud M T, Mohammed S A, Hamouda M A and Mohamed M M 2021 Impact of topography and rainfall intensity on the accuracy of IMERG precipitation estimates in an Arid Region *Remote Sens.* **13** 13
Maidment R I, Allan R P and Black E 2015 Recent observed and simulated changes in precipitation over Africa *Geophys. Res. Lett.* **42** 8155–64
Mann H B 1945 Nonparametric tests against trend *Econometrica* **13** 245–59
McClain M E 2013 Balancing water resources development and environmental sustainability in Africa: a review of recent research findings and applications *AMBIO* **42** 549–65
McNabb D E 2019 *Global Pathways to Water Sustainability* (Cham: Springer)
Muthoni F K, Odongo V O, Ochieng J, Mugalavai E M, Mourice S K, Hoesche-Zeledon I, Mwila M and Bekunda M 2019 Long-term spatial-temporal trends and variability of rainfall over Eastern and Southern Africa *Theor. Appl. Climatol.* **137** 1869–82
Narbone L and Widdershoven C 2021 *The Red Sea Link. Geo-economic Projections, Shifting Alliances, and the Threats to Maritime Trade Flows* (Fiesole: European University Institute) (https://doi.org/10.2870/866338)
Nashwan M S, Shahid S and Abd Rahim N 2019a Unidirectional trends in annual and seasonal climate and extremes in Egypt *Theor. Appl. Climatol.* **136** 457–73
Nashwan M S, Shahid S, Abd Rahim N and Wang X 2019b Assessment of satellite-based precipitation measurement products over the hot desert climate of Egypt *Remote Sens.* **11** 555
Ngoma H, Wen W, Ojara M and Ayugi B 2021 Assessing current and future spatiotemporal precipitation variability and trends over Uganda, East Africa, based on CHIRPS and regional climate model datasets *Meteorol. Atmos. Phys.* **133** 823–43
Nicholson S E 2017 Climate and climatic variability of rainfall over eastern Africa *Rev. Geophys.* **55** 590–635
Nicholson S E, Klotter D, Zhou L and Hua W 2019 Validation of satellite precipitation estimates over the Congo Basin *J. Hydrometeorol.* **20** 631–56
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* ed T C Odada (London: Gordon and Breach) pp 25–56
Nkunzimana A, Bi S, Alriah M A A, Zhi T and Kur N A D 2020 Comparative analysis of the performance of satellite-based rainfall products over various topographical unities in Central East Africa: case of Burundi *Earth Space Sci.* **7** e2019EA000834
Ongoma V, Chen H and Omony G W 2018 Variability of extreme weather events over the equatorial East Africa, a case study of rainfall in Kenya and Uganda *Theor. Appl. Climatol.* **131** 295–308
Onyutha C 2018 Trends and variability in African long-term precipitation *Stoch. Environ. Res. Risk Assess.* **32** 2721–39
Patlakas P, Stathopoulos C, Flocas H, Bartsotas N S and Kallos G 2021 Precipitation climatology for the arid region of the Arabian peninsula—variability, trends and extremes *Climate* **9** 103
Segele Z T and Lamb P J 2005 Characterization and variability of Kiremt rainy season over Ethiopia *Meteorol. Atmos. Phys.* **89** 153–80
Sen P K 1968 Estimates of the regression coefficient based on Kendall's Tau *J. Am. Stat. Assoc.* **63** 1379–89
Seregina L S, Fink A H, van der Linden R, Elagib N A and Pinto J G 2019 A new and flexible rainy season definition: validation for the Greater Horn of Africa and application to rainfall trends *Int. J. Climatol.* **39** 989–1012
Shen Z, Yong B, Gourley J J, Qi W, Lu D, Liu J, Ren L, Hong Y and Zhang J 2020 Recent global performance of the climate hazards group infrared precipitation (CHIRP) with stations (CHIRPS) *J. Hydrol.* **591** 125284
Tomas-Burguera M, Vicente-Serrano S M, Peña-Angulo D, Domínguez-Castro F, Noguera I and El Kenawy A 2020 Global characterization of the varying responses of the standardized precipitation evapotranspiration index to atmospheric evaporative demand *J. Geophys. Res. Atmos.* **125** e2020JD033017
UNEP-DHI, and UNEP 2016 *Transboundary River Basins: Status and Trends, Summary for Policy Makers* (available at: www.geftwap.org/publications/river-basins-spm) (Accessed 29 July 2021)
Wainwright C M, Marsham J H, Keane R J, Rowell D P, Finney D L, Black E and Allan R P 2019 'Eastern African Paradox' rainfall decline due to shorter not less intense Long Rains *npj Clim. Atmos. Sci.* **2** 1–9
Wasko C, Nathan R and Peel M C 2020 Trends in global flood and streamflow timing based on local water year *Water Resour. Res.* **56** e2020WR027233
Wehbe Y and Temimi M 2021 A remote sensing-based assessment of water resources in the Arabian Peninsula *Remote Sens.* **13** 247
Wenhaji Ndomeni C, Cattani E, Merino A and Levizzani V 2018 An observational study of the variability of East African rainfall with respect to sea surface temperature and soil moisture *Q. J. R. Meteorol. Soc.* **144** 384–404
Wilson A 2015 1 Red Sea trade and the state *Across the Ocean: Nine Essays on Indo-Mediterranean Trade* (The Netherlands: Brill) pp 11–32
Wolf A T 2007 Shared waters: conflict and cooperation *Annu. Rev. Environ. Resour.* **32** 241–69
World Bank 2020 *World Development Indicators* (World Bank Group) (available at: https://databank.worldbank.org/reports.aspx?source=2%26series=NY.GDP.MKTP.CD%26country=#) (Accessed 28 July 2021)
Yang W, Seager R, Cane M A and Lyon B 2015 The annual cycle of East African Precipitation *J. Clim.* **28** 2385–404
Yoffe S, Fiske G, Giordano M, Giordano M, Larson K, Stahl K and Wolf A T 2004 Geography of international water conflict and cooperation: data sets and applications *Water Resour. Res.* **40** W05S04
Zhang X *et al* 2005 Trends in Middle East climate extreme indices from 1950 to 2003 *J. Geophys. Res. Atmos.* **110** 1–12
Zhao H and Ma Y 2019 Evaluating the drought-monitoring utility of four satellite-based quantitative precipitation estimation products at global scale *Remote Sens.* **11** 2010
Zittis G 2018 Observed rainfall trends and precipitation uncertainty in the vicinity of the Mediterranean, Middle East and North Africa *Theor. Appl. Climatol.* **134** 1207–30