Hydrologic Extremes in a Changing Climate: a Review of Extremes in East Africa

Meron Teferi Taye[1] · Ellen Dyer[2]

Abstract

Purpose Eastern Africa has a complex hydroclimate and socio-economic context, making it vulnerable to climate change-induced hydrological extremes. This review presents recent research on drivers and typologies of extremes across different geographies and highlights challenges and improvements in forecasting hydrological extremes at various timescales.

Recent Findings Droughts and floods remain the major challenges of the region. Recently, frequent alterations between droughts and floods have been a common occurrence and concern. Research underlines the heterogeneity of extremes and the impact of climate change as increased intensity and duration of extremes. Moreover, the importance of local and antecedent conditions in changing the characteristics of extremes is emphasized.

Summary A better understanding of these drivers and how they interact is required. Observational and modeling tools must capture these relationships and extremes on short timescales. Although there are improvements in forecasting these extremes, providing relevant information beyond meteorological variables requires further research.

Keywords Climate change · Hydrological extremes · Floods · Droughts · Large-scale drivers · East Africa

Introduction

Hydrologic extremes such as floods and droughts are becoming more frequent and severe with increased negative impacts (e.g., [1, 2]). The Intergovernmental Panel on Climate Change (IPCC) reports that the changing climate has caused a 30% increase in the frequency of extreme precipitation events globally [3]. The intensification of extreme precipitation at a global scale was evident in two-thirds of high-quality precipitation stations analyzed by Sun et al. [4]. Worldwide, it is estimated that the number of people at risk of floods will increase from 1.2 to 1.6 billion from 2010 to 2050 [5]. Moreover, Naumann et al. [6] showed that two-thirds of the global population will experience a progressive increase in drought conditions with global warming.

The context for these changing hydrologic extremes is a variable and changing climate. Global average surface temperatures

have risen by 1.1 °C since the late nineteenth century [3, 7, 8], mainly due to anthropogenic climate change. According to the World Meteorological Organization (WMO), the warmest years on record have occurred since 2015, with the top three warmest years being 2016, 2019, and 2020 [9]. Changes in atmospheric circulation patterns have been observed, including changes in the strength and frequency of wind systems that, in turn, influence storm intensity and distribution [3, 10, 11]. The El Niño-Southern Oscillation (ENSO) has a significant influence on the global atmospheric circulation. An extreme El Niño event (warm phase) occurred in 2015–2016, while 2020–2022 experienced unusually consecutive La Nina years (cold phase). These events contributed to high global temperatures during 2013–2022 with a 1.14 °C increase in global temperature above the pre-industrial baseline [9]. Different parts of the globe experienced floods and droughts associated with these events. For instance, [12] showed the triple-dip La Nina's contribution to Pakistan's flooding and droughts in southern China, while the Horn of Africa experienced multi-season droughts during this period [13•].

Hydrologic extreme events have overwhelming impacts on vulnerable and low-income communities that are already at risk due to their weak socioeconomic status, low adaptive capacity, and current and future high population growth [14–16]. The East Africa region is one of these vulnerable

✉ Meron Teferi Taye
meron.taye@cgiar.org; meron.t.taye@gmail.com

1 International Water Management Institute, East Africa and the Nile Basin, Addis Ababa, Ethiopia

2 School of Geography and the Environment, University of Oxford, Oxford, UK

areas exposed to water-related disasters, both floods and droughts [13•, 17, 18]. Understanding the impacts of the changing climate on hydrologic extremes is useful for adaptation planning and protecting communities and the environment for current and future generations [15, 16].

This review paper presents progress and current themes in research of hydrologic extremes through the lens of East Africa and its complex climate, hydrological, and data context and attempts to answer the following questions:

- What kind of hazards, or multi-hazard events, are becoming common drivers of hydrologic extremes?
- Is there improvement in forecasting and projecting hydrological extremes in short and long timeframes?

This paper used a narrative review approach using publications within the last five years related to the research questions raised above. The next section describes the East African region, followed by an overview of the state of research on hydrologic extremes in the East African region. Sections four and five answer the two research questions, followed by conclusions.

East Africa

This study focuses on East Africa, including Burundi, Djibouti, Ethiopia, Eritrea, Kenya, Rwanda, Somalia, South Sudan, Sudan, Tanzania, and Uganda (Fig. 1). The region has a diverse climate, ranging from hot, dry regions to cooler, wetter highland regions, with considerable variability in seasonal rainfall [19] and a very complex topography. It is largely influenced by large-scale seasonal atmospheric patterns and the warm waters of the Indian Ocean [16] and Atlantic Ocean [20–22]. The rainfall is characterized by an unimodal cycle with a wet season from July to September (JAS) for the northern parts of the region within the Nile basin (Ethiopia, Sudan) [23] and a bimodal annual cycle in the rest of the region, featuring long rains from March to May (MAM) and the short rains from October to December (OND) [11]. The extreme rainfall magnitudes differ geographically as can be seen from Fig. 1 based on the last decade's (2013–2022) 95th percentile rainfall. This region's economy mainly depends on agriculture, with a large percentage of the population relying on subsistence rain-fed agriculture and pastoralism. The frequent occurrence of hydrological extremes, like droughts and floods, harms the already vulnerable population suffering from severe poverty and economic turmoil [14]. Food and water insecurity, conflict, and migration are some of the dire implications of climate change on the region's population, leading to massive humanitarian needs.

Geographical heterogeneity of climate change impacts

As climate change is a complex phenomenon, different geographic regions may experience varying patterns and magnitudes of change with effects that differ across
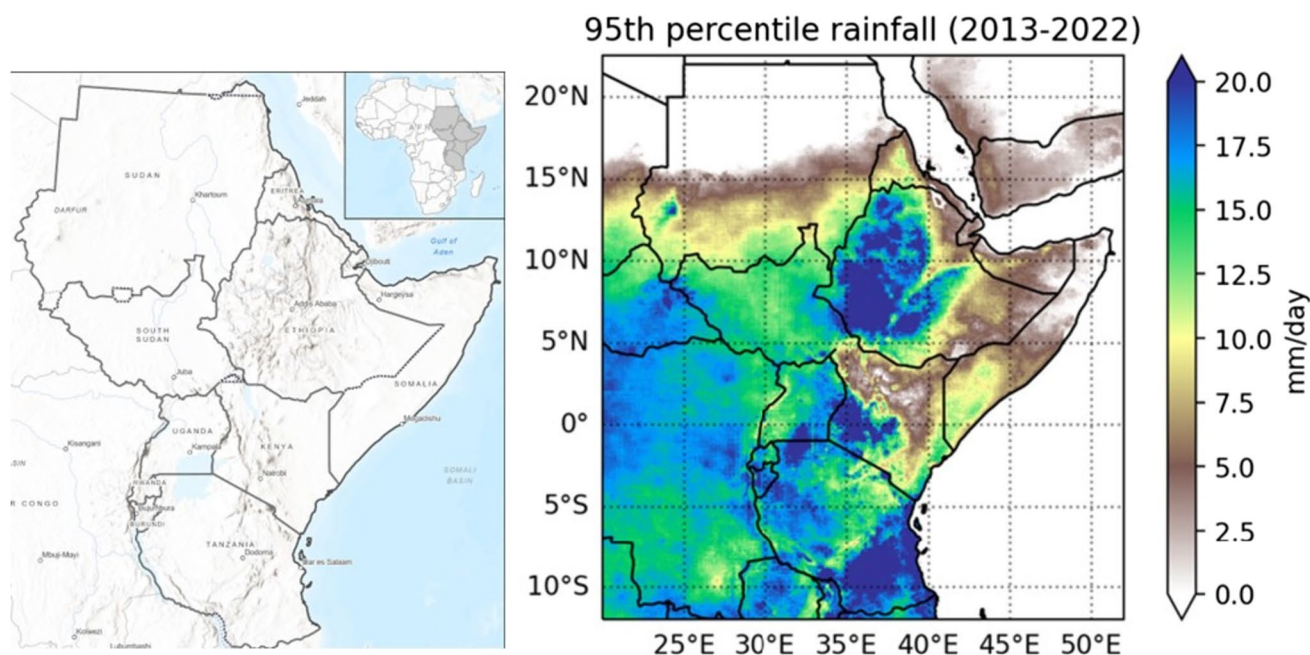

Fig. 1 Location map of the Eastern African countries and extreme rainfall defined as the 95th percentile of rainfall during the last decade, 2013–2022. Data source: CHIRPS v2.0 rainfall

regions [24]. Although global-scale drivers of change in rainfall and temperature might be similar, their local realizations are heterogeneous. The translation and modulation of large-scale change and variability to local hydrological extremes are critical in understanding disaster risk preparedness and adaptation strategies.

The Eastern African region experiences the impacts of climate change in different forms. For instance, below-average rainfall occurred for six consecutive rainy seasons in the Horn of Africa during the period 2020–2023 [25] leading to the third longest and most widespread drought on record [26] with dire implications for food security. Conversely, other parts experienced extreme floods, e.g., the 2020 floods in Ethiopia, Rwanda, Kenya, Burundi, and Uganda, and the 2022 floods in South Sudan [16, 18, 27, 28]. However, the impacts of the "triple-dip" La Nina [27] related event during 2020–2022 were felt differently across the region as La Nina is correlated with drought in the Horn of Africa [13•] and in the eastern bimodal areas of Ethiopia and higher rain rates in the unimodal western areas of Ethiopia [22, 29].

Rainfall

Looking at historical rainfall extreme trends, Gebrechorkos et al. [30] showed that the number of consecutive wet days decreased statistically significantly in western Ethiopia, eastern Kenya, and some parts of Tanzania based on data from 1981 to 2016. Moreover, consecutive dry days increased considerably by up to 150 days in some parts of Eastern Ethiopia, Kenya, and Tanzania for the same period. Due to very low rainfall in the most critical rainfall season of JAS, the drought in 2015 impacted millions of people in Ethiopia, reported to be the worst in five decades [31], corresponding to the exceptionally strong El Niño event. On the other hand, the 2019 OND rainy season across East Africa was one of the wettest seasons on record, with several locations receiving more than double the climatological rainfall, leading to floods [11, 32]. This occurred during an anomalously positive phase of the Indian Ocean Dipole (IOD) but neutral ENSO conditions [32]. In August 2019, Sudan experienced exceptional wet conditions where most parts of the country received a high proportion of their August rain in a two-day storm [33]. The Lake Victoria basin, which encompasses Burundi, Kenya, Rwanda, Tanzania, and Uganda, experienced extensive floods in 2019–2020 and anomalous drought conditions in early 2022 [34]. In 2023, Ethiopia experienced anomalously high rainfall in March and April, which is abnormal for a secondary rainy season in the country, and low rainfall in the primary rainfall season in July and August, showing shifts in rainfall occurrences. These recent events are a testament to the geographical heterogeneity of rainfall extreme occurrences.

Large-scale drivers

This heterogeneity in extremes is due to cascading complexity in the interactions of large-scale to localized drivers. Rainfall variability over Eastern Africa is attributed to variability in tropical Pacific Sea Surface Temperatures (SSTs) through the ENSO and the Pacific Decadal Oscillation (PDO) [11]. ENSO is associated with interannual variability in rainfall with heterogeneous correlations across the region. Slower modes of variability like the PDO can lead to the Pacific SST gradients that favor the La Nina phase of ENSO, which is associated with droughts in the bimodal zones of East Africa and flooding in the dominant JAS season in Ethiopia [35]. The IOD is an extremely important driver of rainfall variability in East Africa and can intensify the effect of ENSO conditions. For instance, positive IOD and El Nino conditions can cause high rainfall and flooding in the OND season due to their collective weakening impact on the Walker circulation. However, moisture flows and convergence (or divergence) have a substantial effect on rainfall variability [11]. The Congo Air Boundary [36] is an important feature that defines the convergence between westerlies of Atlantic origin and easterlies from the Indian Ocean. It is gaining more attention as a driver of rainfall variability from Ethiopia to South Africa, influenced by the Atlantic and Indian Ocean variability and moisture. Moreover, the Madden–Julian Oscillation (MJO) associated with eastward propagating low-level wind and convection anomalies [37] impacts coastal and inland areas differently at an intra-seasonal scale, which means that rainfall anomalies within Kenya, for example, can be out of phase [18, 38]. The combined impact of and feedback between these drivers of variability signify that the conditions for rainfall extremes can be compounded across timescales in ways that can be challenging but crucial to predict so that the impacts of hydrological extremes can be managed effectively.

Antecedent conditions

Another player in the heterogeneity of extremes and their impacts are antecedent conditions that are more frequently linked to impacts of extreme flood and drought. The nature and importance of these antecedent conditions also have different characteristics at different timescales [39], potentially adding important information that can be used to adapt to hydrological extremes. Woldemeskel and Sharma [40] have suggested an antecedent precipitation index to highlight the importance of moisture conditions before extreme rainfall in the modulation of floods and that this is an important part of the climate change story for flooding and droughts. The heterogeneity of

land surface conditions also suggests that examining the development of extremes like droughts must be done in both time and space [41]. Along with rainfall and temperature changes at the local and regional scale, the land-surface context has a role in the heterogeneity of hydrological extremes.

Typology of common extremes

The Eastern African region experiences diverse forms of hydrologic extremes. The list below includes some basic definitions used to describe event types.

- Riverine flood: An overflow of water that inundates a normally dry area caused by rising water from a river, stream, or drainage ditch. Flooding can be caused by anomalous and prolonged rainfall, and it may last days or weeks [42].
- Flash flood: A flood caused by heavy or excessive rainfall in a short period, also influenced by infiltration capacity. They can occur relatively quickly after rainfall events [43].
- Drought: An event characterized by below-average precipitation, which can last for months or years and develop slowly and is a complex natural hazard. There are different types of droughts, including meteorological, agricultural, and hydrological. Hydrological droughts result from a lack of water in the hydrological system, manifesting abnormally low streamflow in rivers and unusually low levels in lakes, reservoirs, and groundwater [44].
- Flash drought: Droughts that arise rapidly and change conditions from "normal" to problematically dry in weeks [45].
- Dry spell: A dry spell was first defined as a period of at least 15 consecutive days with no day receiving ≥ 1.0 mm of precipitation [46]. Paton [47] puts the plainest meaning of a dry spell in a physical sense as a string of consecutive days with zero rainfall. The minimum number of consecutive dry days required to define a dry spell depends on local context and application. This is also the case for prolonged dry spell days. However, prolonged dry spells are less severe than drought.

Viewing these extreme events as compound events provides a framework that can help to break down the different drivers of extremes and the relative severity of their impacts [48, 49]. Understanding the drivers of these extreme typologies is crucial to understanding how they might change in the future. As some research suggests, concurrent extremes (e.g., flooding and extreme heat or droughts and heatwaves) will become the norm rather than the exception in East Africa [50]. Examples from other regions and types of extremes include research on conditional concurrent extremes in variables like wind and precipitation [51] and humid heat waves [52]. Ward et al. [1] argue that most research on hydrological

risks tends to focus on either flood risk or drought risk. However, floods and droughts are extremes of the same hydrological cycle and must be considered together. Indeed, where successive extreme events occur, such as flooding followed by drought conditions, one extreme event might create the antecedent conditions for a subsequent event, which will have a much different impact than if they occurred in more neutral conditions. Prioritizing a compound framework that incorporates such antecedent conditions will be useful to better understand impacts along with drivers.

Droughts

In Eastern African countries, drought is a widespread and persistent problem in the region [53, 54]. Haile et al. [55] summarized that around 100 drought episodes have been recorded in East Africa since the 1970s. In contrast, drought has occurred every three years since 2005, with a drought event extending over two or more rainy seasons at times. The most common drought conditions in recent years have been reported due to very low MAM rainfall in most East African countries [55, 56]. It affects agricultural, pastoral, and agro-pastoral communities in southern Ethiopia, northeastern Kenya, and most lowland areas of Somalia. Some parts of East Africa are known for persistent drought conditions, e.g., the Horn of Africa [13•]. Other parts of East Africa experience shorter period droughts that range in 2–6-year cycles [57].

Most research activities in the region focus on meteorological drought, and there is limited understanding of how this meteorological drought translates to hydrological and agricultural droughts. In terms of forecasts, there are several regional institutions, such as the Intergovernmental Authority on Development (IGAD) Climate Prediction and Applications Centre (ICPAC) and Nile Basin Initiative (NBI), that provide drought forecasts and early warning information [58, 59]. However, translating these forecasts to the most critical impacts on local agriculture and hydrological variables requires further research. Studies that attempted to show the effect of drought on streamflow from a future projection perspective are limited (e.g., [60, 61]). At the same time, there are several climate change impact studies on meteorological variables and average flow conditions. A recent study by Odongo et al. [62] found that the wet western areas of the Horn of Africa have a precipitation accumulation period of about 1–4 months, while in the dryland regions, about 5–7 months of precipitation accumulation can guide forecasting and management of droughts. Such research helps translate meteorological drought to relevant sectors of hydrology and agriculture.

Floods

Floods in Eastern African countries are hydrological extremes that result in loss and damage of lives and

property [2]. Reported examples include flood damages in African cities [63], regional floods [29], and flood fatalities [64]. Most flood research is hindered by a lack of observation of long-term streamflow extremes [65], and this is more so in data-scarce regions such as the Eastern African countries. Using hydrological and hydrodynamic models, the Eastern Nile flood forecasting system uses satellite products to simulate streamflow forecasts at selected locations [59]. This is a common modeling approach implemented in such data-limited conditions. The other possibility is looking at the changes in the antecedent conditions before rainfall, as demonstrated by Woldemeskel and Sharma [40]. They noted that in some large catchments, increased wetness leads to higher floods when antecedent wetness is the main flood-causing factor, whereas, in small catchments, increased extreme daily rainfall will cause higher floods. For example, in Kenya's Nzoia River, both heavy and high antecedent rainfall were identified as critical drivers of flooding [29]. As described above, one key point is understanding the large-scale drivers that influence drought or flood-prone conditions and whether these are prolonged or whether there is a relatively immediate oscillation between these conditions. Omondi and Lin [57] have highlighted the importance of a 2–6-year interannual cycle in East Africa and related this to ENSO. Also, there have been long-term changes in the Standard Precipitation Evapotranspiration Index in the twentieth century that highlight how changes to these oscillations and oscillations on longer timescales can impact conditions in which extremes can occur. For instance, the prevalence of two-year La Nina events has been highlighted as a relatively predictable feature [13•]. Similarly, research suggests that multi-year La Nina events (longer than two years) tend to be preceded by a strong El Nino event in both observations and climate models [66]. Even though there is some encouraging predictability for forecasting such events, there are complex interactions that can contribute to characteristics of these large-scale conditions [67] and they are modulated by long-term changes in temperature and local conditions on shorter timescales. Some studies have shown an increase in ENSO SST variability, but the strength of the consensus on this increasing change among studies may be sensitive to the model generations used and to the length of periods used in the analysis [68]. For instance, observations in the last two decades have shown a decrease in variability; however, this period is sensitive to the phase of decadal-scale oscillations [68]. This change in variability is associated with an increase in extreme El Nino and La Nina events and an increase in fluctuation between extreme El Nino and La Nina events [69]. Unfortunately, future projections of ENSO characteristics are fraught with uncertainties, and changes to characteristic teleconnections are no different [70]. East Africa has been shown as a potential hotspot for increased low-intensity precipitation reversal under the high-emissions scenario using the Community Earth System Model large ensemble. However, some areas of East Africa are also at risk of becoming hotspots for precipitation whiplash or extreme reversals between drought and pluvial conditions [71].

Flash floods and flash droughts

Getting to grips with these reversals requires a good understanding of events that occur on short timescales and can include both river and flash flooding events as well as flash droughts. Flash droughts, explained as droughts that arise rapidly and change conditions from "normal" to problematically dry in a matter of weeks, are increasing in frequency due to global temperature increase [45]. Such sudden onset and rapid intensification of droughts are challenging for drought early warning [72] and may have dire implications for areas dependent on crop production. Christian et al. [73] showed increasing flash drought risk in croplands at the global scale. However, there is limited information on whether there is an increase in flash droughts in the Eastern African region. Nevertheless, the concept that faster-onset droughts in a warmer future will be common [74] might be an important aspect to be investigated in the region in relation to adaptation to climate change.

Flash flooding is increasing in different parts of Eastern African countries due to human-induced climate change and land use modifications in rural and urban settings. Two types of flash floods, riverine flash floods, and storm flash floods are common in the Eastern Nile region [58]. The classic example of frequent flash floods in Ethiopia occurs in Dire Dawa town [75, 76], while the Dodoma region in central Tanzania is susceptible to flash floods every year [77]. Urban cities such as Addis Ababa are experiencing increased flash flooding during rainy seasons that disrupt transportation, in addition to causing damage to infrastructure and loss of lives and properties [78]. Rural areas are also prone to flash flooding, including arid areas such as Turkana in Kenya, where drought is hard to measure as conditions are persistently dry but punctuated by extreme flash flooding [79]. Flash floods occur very quickly; thus, observing flash floods is a challenge in gauging sparse areas because of their short timescales relative to satellite overpasses if one wants to use remotely sensed products. Their prediction and management are similarly difficult. The Weather Research and Forecasting (WRF) model is commonly used to simulate heavy precipitation events and riverine floods in different parts of Eastern Africa [58, 79]. However, the use of this model is limited in forecasting flash floods. Research in the areas of better early warning systems, flood forecasts, flood protection measures, and improved catchment conservation approaches is needed to avoid the negative consequences of flash floods.

Challenges and advancements in forecasting hydroclimatic extremes

A key to reducing the impacts of hydroclimatic extremes is to be able to anticipate when, where, and how much precipitation will fall and generate streamflow or lack thereof [65, 80]. Producing such forecasts has only become possible in recent years due to the integration of meteorological and hydrological modeling capabilities, improvements in data, satellite observations, and increased computer power [81–83]. Satellite- and radar-based monitoring provides near-real-time climate data with high spatiotemporal resolutions [84, 85]. Several statistical and diagnostic tools are available to preprocess and assess estimates, significance tests, and the likelihood of hydroclimatic extreme events (e.g., [82, 86–88]. There are significant advancements on a global scale. However, the application of these approaches in the Eastern African region is challenged by different factors. For instance, hydroclimatic extremes prediction and assessment are challenged by limited data availability, process understanding, modeling and prediction methods, and definition of extreme events that can affect the outcome of extreme value analysis [65, 89, 90].

Seasonal forecasts and forecasts with lead time of days are usually used in flood early warning systems. Recently, a system that forecasts riverine flooding and provides early warning called Flood-PROOFS East Africa is operational for the Greater Horn of Africa with a forecast range of 5 days supporting the African Union Commission and the Intergovernmental Authority on Development (IGAD) Disaster Operation Center [91]. ICPAC provides region-wide climate forecasting and early warning at different timescales, from weekly to seasonal forecasts primarily focusing on precipitation and temperature. Recent advancement in predicting droughts is reported by Funk et al. [92•] who stated how climate change interaction with La Nina events are producing extreme but predictable Pacific SST gradients, leading to the possibility of drought prediction with a lead time of eight months. Improved sub-seasonal to seasonal forecasts are facilitated by a better mechanistic understanding of dynamical model skill of relevant drivers' variability and by co-producing these forecasts with users as demonstrated in the African Science for Weather Information and Forecasting Techniques (SWIFT) project [93, 94]. Advancements in the accessibility of forecasts through systems such as Next Generation (NextGen) and the Python Climate Predictability Tool (PyCPT) tool also support the expanded use of dynamical forecasts at relevant timescales in East Africa [95]. Such advancements are important in providing relevant information for decision-makers and communities to increase preparedness for hydrological extremes.

Forecasting beyond meteorological variables on hydrological and agricultural relevant variables is still in the early stages. One such development is being piloted in Africa by Tropical Applications of Meteorology using Satellite data and ground-based observations: Agricultural Early Warning System (TAMSAT-ALERT) provides reliable forecasts of soil moisture conditions at timescales from weeks to months to inform germination up to crop yield [96]. It is done by using meteorological variables to drive a land surface model. Forecasting drought conditions using machine learning for vegetation health with the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite information has also been trailed over Kenya, showing that forecast information might be diversified without developing complex mechanistic models [97]. Nakalembe [98] argues that urgent investment is needed in Sub-Saharan African countries in earth observation-based systems to support agricultural early warning and monitoring for this to materialize.

Scope of climate model projections

At the climate change time scale, limited publications for East Africa evaluate the projected future impacts of climate change on hydrological extremes. Most climate change impact research outputs focus on the mean hydrological conditions. There is consistency in the increasing trend of temperature rise in all scenarios, climate models, and time periods until the end of the twenty-first century. However, there are significant differences in the precipitation projections depending on the climate model, selected scenario, and future horizon [17, 30, 61]. A critical issue in East Africa is that models project a wide range of precipitation futures for the region and these coupled models have predicted increasing rainfall in the historical MAM season when observations showed decreasing rainfall [99, 100]. This highlights that the first step in projecting future hydrologic extremes in East Africa is fraught with uncertainty due to how models capture key atmospheric processes or coupling between SSTs, regional climate [101], and local conditions.

These differences also translate to unclear projections on hydrological extremes that are usually expressed as high flows and low flows or the 95th and 5th percentiles. Generally, climate change impact assessment on hydrological extremes involves a chain of steps. Typically, one has to choose climate models, future scenarios, downscaling methods, hydrological models, calibration parameters, and the selection of appropriate extreme indices. Each step has uncertainties related to the choices made [102, 103•, 104]. Making choices in these tools and methods based on processes and contextual applicability rather than convention or convenience is critical. Selecting climate models based on their performance on a range of metrics is not enough, ensuring that key physical processes are captured is critical

[101]. Downscaling methods for future projections range from dynamic to statistical, but in both cases, assumptions and methods should be addressed and evaluated before application, especially in the case of extremes [105]. Similarly, choosing hydrologic models should consider appropriate catchment characteristics to adequately capture the influence of temperature or land surface changes [106].

Conclusions

Research on hydrologic extremes in East Africa has heavily focused on quantifying the characteristics of historical events to understand future extremes in a changing climate. Hydrologic extremes in East Africa include a host of event typologies that challenge planning and disaster risk management: oscillation between droughts and floods, seesawing between chronically wet and dry periods, and fluctuations between short-term flash flooding and extreme drought.

Many studies report contradictory changes to hydrologic extremes over time for a given location or basin at historical timescales (e.g., [22, 102]). There is a general sentiment that those changes are linked to climate change. However, the impact of choices on data type (gauge observed data, satellite, reanalysis), the period used for the analysis, and the possibility of natural variations or changes due to human factors are not usually fully explored. Therefore, there is a lack of information on the attribution of obtained trends to historical climate change, natural variability, or other factors related to land use change and human interventions. These aspects are potential areas for further research.

A key feature highlighted by research on hydrologic extremes in the region is the heterogeneous distribution of extremes experienced in space and time. For instance, El Nino can cause droughts in one part of the region and floods in the other. This is also a common situation within a country, e.g., in Ethiopia. The recent years with consecutive droughts followed by floods are a testament to the need to better forecast these kinds of events and their impacts.

To better model, predict, and manage hydrologic extremes, a better understanding of their drivers is required. This necessitates that studies go beyond focusing on rainfall and temperature and include other variables and parameters, such as soil moisture, vegetation, and evaporation, in their assessments. This will also require research focusing on antecedent conditions and oscillations between drought and flood conditions at various timescales. Taking a multivariate, multi-driver, or compound event approach is necessary to understand the impacts of changing baseline conditions. Understanding these mechanisms is essential to improve projections of events. For instance, reducing the uncertainty in projections of future change of key large-scale drivers such as ENSO is important. This is in terms of a

better understanding of regionalized teleconnections and how climate models project these changes.

The tools required to quantify and measure hydrologic extremes and their drivers are undergoing continuous development, and forecasting such extremes will remain an important part of adapting to climate change. There has been a lot of progress on tools to measure and model hydrologic extremes. Still, some key areas require further effort, including measuring and forecasting intra-seasonal extremes like flash floods and droughts and combining dynamical and process-based modeling with new statistical and machine learning techniques.

In a changing climate, risk-based decision-making is becoming more relevant. At seasonal scales, providing information on hydrological and agricultural relevant variables beyond the standard meteorological variables is important for practical decisions. Currently, limited efforts are there to translate climate information into water availability and operational water management practices such as irrigation scheduling and dam operations. The challenge for policymakers and water managers is to make sound decisions in the face of uncertainty [100]. For strategic-level decisions that require climate change timescale projections, several improvements are required from climate models' representation of the region's climate to monitoring hydrological variables and improvements in the types of hydrological models used for such long-range projections. Studies that reduce the uncertainty in the chain of assessing climate change's impact on hydrological extremes are encouraged to boost policymakers' confidence in scientific data, tools, and information.

Managing changing extremes will require a multidisciplinary and, ideally, transdisciplinary approach to understanding the complex drivers of extremes. Hence, sustained co-production of information among meteorologists, hydrologists, decision-makers, and local stakeholders is required to develop more relevant and useful metrics and responses to hydrological extremes. This will also drive new and more locally relevant physical research programs. Physical research can drive better preparedness and responses to expected hydrological extremes due to climate change, although there are factors driving the impacts of extremes that are not only physical. These include the complex sociopolitical setting of the Eastern African countries, their institutional set-ups, relationships among different levels of government, and resource limitations. There is also a need to understand differences in rural and urban settings as well as the socio-economic differences of communities in terms of adapting to the expected changes.

Finally, although there are advancements in tools and data pertaining to climate variables, the impact on hydrological extremes is still unclear. Moreover, there is a disconnect between information generated from the research community and how that can be translated into practical changes

on the ground in terms of practices on better water management, disaster risk prevention, and improving livelihoods. This will be an important pathway for future research for the development sector in addition to improving our knowledge of which extremes are becoming more extreme and how their spatial and temporal distributions are changing.

Declarations

Competing Interests The authors declare no competing interests.

Disclaimer However, the views expressed, and information contained in it are not necessarily those of or endorsed by FCDO, which can accept no responsibility for such views or information or for any reliance placed on them.

References

Papers of particular interest, published recently, have been highlighted as:
● Of importance
●● Of major importance

1. Ward PJ, Ruiter MC, Mård J, Schröter K, Van Loon A, Veldkamp T. The need to integrate flood and drought disaster risk reduction strategies. Water Sec. 2020;11:100070. https://doi.org/10.1016/j.wasec.2020.100070.
2. Hagos YG, Andualem TG, Yibeltal M, Mengie MA. Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in upper Awash River basin, Ethiopia. Appl Water Sci. 2022;12:148. https://doi.org/10.1007/s13201-022-01674-8.
3. Intergovernmental Panel on Climate Change (IPCC). Climate change. The physical science basis. Contribution of Working Group I to the Sixth Assessment. Cambridge, UK: Cambridge University Press; 2021. p. 2021.
4. Sun Q, Zhang X, Zwiers F, Westra S, Alexander LV. A global, continental, and regional analysis of changes in extreme precipitation. J Clim. 2021;34:243–58. https://doi.org/10.1175/JCLI-D-19-0892.1.
5. World Meteorological Organization (WMO). United in Science 2020. A multi-organization high-level compilation of the latest climate science information. Geneva. 2020. public.wmo.int/en/resources/united_in_science (Accessed July 2023).
6. Naumann G, Alfieri L, Wyser K, Mentaschi L, Betts RA, et al. Global changes in drought conditions under different levels of warming. Geophys Res Lett. 2018;45:3285–96. https://doi.org/10.1002/2017GL076521.
7. Kuntla SK, Saharia M, Kirstetter P. Global-scale characterization of streamflow extremes. J Hydrol. 2022;615. https://doi.org/10.1016/j.jhydrol.2022.128668.
8. Tierney JE, Ummenhofer CC, PB DM. Past and future rainfall in the Horn of Africa. Sci Adv. 2015;1(9) https://doi.org/10.1126/sciadv.1500682.
9. World Meteorological Organization (WMO). Past eight years confirmed to be the eight warmest on record. Press Release Number: 12012023. 2023. https://public.wmo.int/en/media/press-release/past-eight-years-confirmed-be-eight-warmest-record (Accessed July 2023).
10. Ochieng PO, Nyandega I, Wambua B, Ongoma V. Linkages between Madden–Julian oscillation and drought events over Kenya. Meteorog Atmos Phys. 2023;135(9) https://doi.org/10.1007/s00703-022-00948-9.
11. Palmer PI, Wainwright CM, Dong B, Maidment RI, Wheeler KG, Gedney N, et al. Drivers and impacts of Eastern African rainfall variability. Nat Rev Earth Environ. 2023;4(4):254–70. https://doi.org/10.1038/s43017-023-00397-x.
12. Jeong H, Park H, Chowdary JS, Xie S. Triple-Dip La Niña contributes to Pakistan flooding and Southern China drought in Summer 2022. Bull Amer Meteor Soc. 2023;104:E1570–86. https://doi.org/10.1175/BAMS-D-23-0002.1.
13.● Anderson W, Cook BI, Slinski K, Schwarzwald K, McNally A, Funk C. Multiyear La Niña events and multiseason drought in the horn of Africa. J Hydrometeorol. 2023;24(1):119–31. https://doi.org/10.1175/JHM-D-22-0043.1. **This article offers insights into the controls of multiyear droughts in the Horn of Africa. The possibility and limitations of using long lead time forecasts of La Nina to predict prolonged periods of drought in the region is increasingly important given the recent multi-year La Nina and its impacts in the region.**
14. Ayugi B, Dike V, Ngoma H, Babaousmail H, Mumo R, Ongoma V. Future changes in precipitation extremes over East Africa based on CMIP6 Models. Water. 2021;13(17):2358. https://doi.org/10.3390/w13172358.
15. Chapmane S, Bacon J, Birch CE, Pope E, Marsham JH, Msemo H, et al. Climate change impacts on extreme rainfall in Eastern Africa in a convection-permitting climate model. J Clim. 2022;36:93–109. https://doi.org/10.1175/JCLI-D-21-0851.1.
16. Scanlon BR, Rateb A, Anyamba A, Kebede S, Macdonald AM, Shamsudduha M, et al. Linkages between GRACE water storage, hydrologic extremes, and climate teleconnections in major African aquifers. Environ Res Lett. 2022;17(1). https://doi.org/10.1088/1748-9326/ac3bfc.
17. Onyutha C. Analyses of rainfall extremes in East Africa based on observations from rain gauges and climate change simulations by CORDEX RCMs. Clim Dyn. 2020;54:4841–64. https://doi.org/10.1007/s00382-020-05264-9.
18. Kebacho LL, Sarfo I. Why Eastern Africa was not dry during the 2020 short rainy season despite La Niña and a negative Indian Ocean Dipole: interplay between the Madden-Julian Oscillation and La Niña in modulating short rain. Theor Appl Climatol. 2023;153:1191–201. https://doi.org/10.1007/s00704-023-04519-9.

19. Richardson K, Calow R, Pichon F, New S, Osborne R. Climate risk report for the East Africa region. Met Office, ODI. FCDO. UK. 2022. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/services/government/eastafrica_climateriskreport_31012022-1.pdf.

20. Dyer E, Hirons L, Taye MT. July–September rainfall in the Greater Horn of Africa: the combined influence of the Mascarene and South Atlantic highs. Clim Dyn. 2022;59(11–12):3621–41. https://doi.org/10.1007/s00382-022-06287-0.

21. Dyer E, Washington R. Kenyan long rains: a subseasonal approach to process-based diagnostics. J Clim. 2021;34(9):3311–26. https://doi.org/10.1175/JCLI-D-19-0914.1.

22. Taye MT, Dyer E, Charles KJ, Hirons LC. Potential predictability of the Ethiopian summer rains: understanding local variations and their implications for water management decisions. Sci Total Environ. 2021;755:142604. https://doi.org/10.1016/j.scitotenv.2020.142604.

23. Taye MT, Willems P, Block P. Implications of climate change on hydrological extremes in the Blue Nile basin: a review. J Hydrol Reg Stud. 2015;4:280–93. https://doi.org/10.1016/j.ejrh.2015.07.001.

24. Shongwe ME, van Oldenborgh GJ, van den Hurk B, van Aalst M. Projected changes in mean and extreme precipitation in Africa under global warming. Part II: East Africa J Climate. 2011;24(14):3718–33. https://www.jstor.org/stable/26191108

25. United Nations High Commissioner for Refugees (UNHCR). As the Horn of Africa drought enters a sixth failed rainy season, UNHCR calls for urgent assistance. 28 February 2023. https://www.unhcr.org/news/briefing/2023/2/63fdbcee4/horn-africa-drought-enters-sixth-failed-rainy-season-unhcr-calls-urgent.html. Accessed Nov 2023

26. Amha Y, Demissie T, Amdihun A., Otieno V, Afiesimama E, Murombedzi J, et al. Unrelenting catastrophic droughts and successive failed rainy seasons in the Greater Horn of Africa: what can we do better to protect millions of smallholder farmers and livestock keepers from extreme weather and climate crisis? 2023, Policy brief. United Nations. Economic Commission for Africa; United Nations. Economic Commission for Africa (2023-06). Addis Ababa, https://hdl.handle.net/10855/49838. Accessed Nov 2023

27. World Meteorological Organization (WMO). Triple-Dip La Niña persists, prolonging drought and flooding. 2022. https://public.wmo.int/en/media/press-release/triple-dip-la-ni%C3%B1a-persists-prolonging-drought-and-flooding# (Accessed July 2023).

28. LeComte D. International Weather Highlights 2020: Record Atlantic Tropical Season, Historic Flooding in Asia and Africa. Weatherwise. 2021;74(3):26–35. https://doi.org/10.1080/00431672.2021.1896936.

29. MacLeod D, Graham R, O'Reilly C, Otieno G, Todd M. Causal pathways linking different flavours of ENSO with the Greater Horn of Africa short rains. Atmos Sci Lett. 2021;22(2):e1015. https://doi.org/10.1002/ASL.1015.

30. Gebrechorkos SH, Hülsmann S, Bernhofer C. Changes in temperature and precipitation extremes in Ethiopia, Kenya, and Tanzania. Int J Climatol. 2019;39(1):18–30. https://doi.org/10.1002/joc.5777.

31. Sohnesen TP. Two sides to same drought: measurement and impact of Ethiopia's 2015 historical drought. EconDisCliCha. 2020;4:83–101. https://doi.org/10.1007/s41885-019-00048-w.

32. Wainwright CM, Finney DL, Kilavi M, Black E, Marsham JH. Extreme rainfall in East Africa, October 2019–January 2020 and context under future climate change. Weather. 2021;76(1):26–31. https://doi.org/10.1002/wea.3824.

33. Elagib NA, Al Zayed IS, AG SS, Mahmood MI, Basheer M, Fink AH. Debilitating floods in the Sahel are becoming frequent. J Hydrol. 2021;599:126362. https://doi.org/10.1016/j.jhydrol.2021.126362.

34. Pavur G, Lakshmi V. Observing the recent floods and drought in the Lake Victoria Basin using Earth observations and hydrological anomalies. J Hydrol Reg Stud. 2023;46:101347. https://doi.org/10.1016/j.ejrh.2023.101347.

35. Nicholson SE. An analysis of recent rainfall conditions in eastern Africa. Int J Climatol. 2016;36(1):526–32. https://doi.org/10.1002/joc.4358.

36. Howard E, Washington R. Drylines in southern Africa: rediscovering the Congo air boundary. J Clim. 2019;32(23):8223–42. https://doi.org/10.1175/JCLI-D-19-0437.1.

37. Pohl B, Camberlin P. Influence of the Madden-Julian Oscillation on East African rainfall. I: Intraseasonal variability and regional dependency. Q J R Meteorol Soc. 2006;132(621):2521–39. https://doi.org/10.1256/QJ.05.104.

38. Peng J, Dadson S, Leng G, Duan Z, Jagdhuber T, Guo W, Ludwig R. The impact of the Madden-Julian Oscillation on hydrological extremes. J Hydrol. 2019;571:142–9. https://doi.org/10.1016/j.jhydrol.2019.01.055.

39. Bischiniotis K, Van Den Hurk B, Jongman B, Coughlan De Perez E, Veldkamp T, De Moel H, Aerts J. The influence of antecedent conditions on flood risk in sub-Saharan Africa. Nat Hazards Earth Syst Sci. 2018;18(1):271–85. https://doi.org/10.5194/nhess-18-271-2018.

40. Woldemeskel F, Sharma A. Should flood regimes change in a warming climate? The role of antecedent moisture conditions. Geophys Res Lett. 2016;43(14):7556–63. https://doi.org/10.1002/2016GL069448.

41. Liu Y, Liu Y, Wang W, Fan X, Cui W. Soil moisture droughts in East Africa: Spatiotemporal patterns and climate drivers. J Hydrol Reg Stud. 2022;40:101013. https://doi.org/10.1016/j.ejrh.2022.101013.

42. Kundzewicz ZW, Kanae S, Seneviratne SI, Handmer J, Nicholls N, Peduzzi P, et al. Flood risk and climate change: global and regional perspectives. Hydrol Sci J. 2014;59(1):1–28. https://doi.org/10.1080/02626667.2013.857411.

43. Gosset M, Dibi-Anoh PA, Schumann G, Hostache R, Paris A, Zahiri EP, et al. Hydrometeorological extreme events in Africa: the role of satellite observations for monitoring pluvial and fluvial flood risk. Surv Geophys. 2023;44(1):197–223. https://doi.org/10.1007/S10712-022-09749-6/FIGURES/12.

44. Tallaksen LM, HAJ VL. Hydrological drought: processes and estimation methods for streamflow and groundwater. In: Developments in Water Science. Amsterdam, the Netherlands: Elsevier Science BV; 2004. p. 48.

45. Walker DW, Van Loon A. Droughts are coming on faster. Science. 2023;380:130–2. https://doi.org/10.1126/science.adh3097.

46. Douguedroit A. The variations of dry spells in Marseilles from 1865 to 1984. Int J Climatol. 1987;7(6):541–51.

47. Paton E. Intermittency analysis of dry spell magnitude and timing using different spell definitions. J Hydrol. 2022;608(127645) https://doi.org/10.1016/j.jhydrol.2022.127645.

48. Zscheischler J, Martius O, Westra S, Bevacqua E, Raymond C, Horton RM, et al. A typology of compound weather and climate events. Nat Rev Earth Environ. 2020;1:333–47. https://doi.org/10.1038/s43017-020-0060-z.

49. Zscheischler J, Westra S, SI VDHBJJS, Ward PJ, Pitman A, et al. Future climate risk from compound events. Nat Clim Change. 2018;8(6):469–77. https://doi.org/10.1038/s41558-018-0156-3.

50. Muheki D, Deijns AAJ, Bevacqua E, Messori G, Zscheischler J, Thiery W The perfect storm? Concurrent climate extremes in East Africa, EGUsphere [preprint], 2023. https://doi.org/10.5194/egusphere-2023-1712.

51. Huang WK, Monahan AH, Zwiers FW. Estimating concurrent climate extremes: a conditional approach. Weather Clim Extremes. 2021;33:100332. https://doi.org/10.1016/j.wace.2021.100332.

52. Birch CE, Jackson LS, Finney DL, Marsham JM, Stratton RA, Tucker S, et al. Future changes in African heatwaves and their drivers at the convective scale. J Clim. 2022;35(18):5981–6006. https://doi.org/10.1175/JCLI-D-21-0790.1.

53. Funk C, Harrison L, Shukla S, Pomposi C, Galu G, Korecha D, et al. Examining the role of unusually warm Indo-Pacific sea surface temperatures in recent African droughts. Q J R Meteorol. 2018;144(S1):360–83. https://doi.org/10.1002/qj.3266.

54. Zeleke TT, Giorgi F, Diro GT, Zaitchik BF. Trend and periodicity of drought over Ethiopia. Int J Climatol. 2017;37(13):4733–48. https://doi.org/10.1002/joc.5122.

55. Haile GG, Tang Q, Hosseini-Moghari SM, Liu X, Gebremicael TG, Leng G, et al. Projected impacts of climate change on drought patterns over East Africa. Earth's Future. 2020;8:e2020EF001502. https://doi.org/10.1029/2020EF001502.

56. Ayugi B, Eresanya EO, Onyango AO, Ogou FK, Okoro EC, Okoye CO, et al. Review of meteorological drought in Africa: historical trends, impacts, mitigation measures, and prospects. Pure Appl Geophys. 2022;179:1365–86. https://doi.org/10.1007/s00024-022-02988-z.

57. Omondi OA, Lin Z. Trend and spatial-temporal variation of drought characteristics over equatorial East Africa during the last 120 years. Front Earth Sci. 2023;10:1064940. https://doi.org/10.3389/FEART.2022.1064940/BIBTEX.

58. Eastern Nile Technical Regional Office (ENTRO). Eastern Nile flood forecast and early warning enhancement. Summary Report, Addis Ababa, Ethiopia. 2020. available at https://nilebasin.org/nileday/wp-content/uploads/2021/02/Eastern-Nile-Flood-Forecast-and-Early-Warning-Enhancement.pdf. Accessed July 2023

59. Intergovernmental Authority on Development (IGAD) Climate Prediction and Applications Center (ICPAC). Summary for decisioion makers seasonal forecast June to September 2023 https://www.icpac.net/documents/730/GHACOF_64_Summary_for_Decision_Makers.pdf 2023. Accessed July 2023

60. Hirpa FA, Alfieri L, Lees T, Peng J, Dyer E, Dadson SJ. Streamflow response to climate change in the Greater Horn of Africa. Clim Chang. 2019;156(3):341–63. https://doi.org/10.1007/s10584-019-02547-x.

61. Gebrechorkos SH, Taye MT, Birhanu B, Solomon D, Demissie T. Future changes in climate and hydroclimate extremes in East Africa. Earth's Future. 2023;11(2) https://doi.org/10.1029/2022EF003011.

62. Odongo RA, De Moel H, Van Loon AF. Propagation from meteorological to hydrological drought in the Horn of Africa using both standardized and threshold-based indices. Nat Hazards Earth Syst Sci. 2023;23:2365–86. https://doi.org/10.5194/nhess-23-2365-2023.

63. Douglas I. Flooding in African cities, scales of causes, teleconnections, risks, vulnerability and impacts. Int J Disaster Risk Reduct. 2017;26:34–42. https://doi.org/10.1016/j.ijdrr.2017.09.024.

64. Di Baldassarre G, Montanari A, Lins H, Koutsoyiannis D, Brandimarte L, Blöschl G. Flood fatalities in Africa: from diagnosis to mitigation. Geophys Res Lett. 2010;37:L22402. https://doi.org/10.1029/2010GL045467.

65. Brunner MI, Slater L, Tallaksen LM, Clark M. Challenges in modeling and predicting floods and droughts: a review. WIREs Water. 2021;8(3) https://doi.org/10.1002/wat2.1520.

66. Iwakiri T, Watanabe M. Mechanisms linking multi-year La Niña with preceding strong El Niño. Sci Rep. 2021;11(1):1–11. https://doi.org/10.1038/s41598-021-96056-6.

67. Hasan NA, Chikamoto Y, MJ MP. The influence of tropical basin interactions on the 2020–2022 double-dip La Niña. Front Clim. 2022:4. https://doi.org/10.3389/fclim.2022.1001174.

68. Cai W, Ng B, Wang G, Santoso A, Wu L, Yang K. Increased ENSO sea surface temperature variability under four IPCC emission scenarios. Nat Clim Chang. 2022;12(3):228–31. https://doi.org/10.1038/s41558-022-01282-z.

69. Cai W, Santoso A, Collins M, Dewitte B, Karamperidou C, Kug JS, et al. Changing El Niño–Southern Oscillation in a warming climate. Nat Rev Earth Environ. 2021;2(9):628–44. https://doi.org/10.1038/s43017-021-00199-z.

70. Fredriksen H, Berner J, Subramanian AC, Capotondi A. How does El Niño–southern oscillation change under global warming—a first look at CMIP6. Geophys Res Lett. 2020;47(22) https://doi.org/10.1029/2020GL090640.

71. Cheng L, Liu Z. Detectable increase in global land areas susceptible to precipitation reversals under the RCP8.5 scenario. Earth's Future. 2022;10(12):e2022EF002948. https://doi.org/10.1029/2022EF002948.

72. van Ginkel M, Biradar C. Drought early warning in agri-food systems. Climate. 2021;9(9):134. https://doi.org/10.3390/cli9090134.

73. Christian JI, Martin ER, Basara JB, Furtado JC, Otkin JA, LEL L, et al. Global projections of flash drought show increased risk in a warming climate. Commun Earth Environ. 2023;4:165. https://doi.org/10.1038/s43247-023-00826-1.

74. Yuan X, Wang Y, Ji P, Wu P, Sheffield J, Otkin JA. A global transition to flash droughts under climate change. Science. 2023;380:187–91. https://doi.org/10.1126/science.abn6301.

75. Adane GB, Kassa AK, Toni AT, Tekle SL. Spatial runoff estimation under different land uses and rainfall frequencies: case of flood-prone Dechatu River Catchment, Dire Dawa, Ethiopia. Arab J Geosci. 2022;15:1092. https://doi.org/10.1007/s12517-022-10360-7.

76. Billi P, Alemu YT, Ciampalini R. Increased frequency of flash floods in Dire Dawa, Ethiopia: change in rainfall intensity or human impact? Nat Hazards. 2015;76(1373-1394) https://doi.org/10.1007/s11069-014-1554-0.

77. Msabi MM, Makonyo M. Flood susceptibility mapping using GIS and multi-criteria decision analysis: a case of Dodoma region, central Tanzania. Remote Sens Appl: Soc Environ. 2021;21:100445. https://doi.org/10.1016/j.rsase.2020.100445.

78. Jemberie MA, Melesse AM. Urban flood management through urban land use optimization using LID techniques, City of Addis Ababa, Ethiopia. Water. 2021;13:1721. https://doi.org/10.3390/w13131721.

79. Haines DS, Imana CA, Opondo DM, Ouma DG, Rayner PS. Weather and climate knowledge for water security: institutional roles and relationships in Turkana. REACH Working Paper 2017: 5: 22-pp. https://reachwater.org.uk/wp-content/uploads/2017/09/2017_10_WorkingPaper_Haines-et-al-1.pdf. Accessed Nov 2023

80. Nooni IK, Tan G, Hongming Y, Saidou Chaibou AA, Habtemicheal BA, Gnitou GT, Lim Kam Sian KTC. Assessing the Performance of WRF Model in Simulating Heavy Precipitation Events over East Africa Using Satellite-Based Precipitation Product. Remote Sens. 2022;14(9):1964. https://doi.org/10.3390/rs14091964.

81. Emerton RE, Stephens EM, Cloke HL. What is the most useful approach for forecasting hydrological extremes during El Niño? Environ Res Commun. 2019;1(3) https://doi.org/10.1088/2515-7620/ab114e.

82. Li W, Chen J, Li L, Chen H, Liu B, Xu CY, Li X. Evaluation and bias correction of S2S precipitation for hydrological extremes. J Hydrometeorol. 2019;20:1887–906. https://doi.org/10.1175/JHM-D-19-0042.1.

83. Brown A, Milton S, Cullen M, Golding B, Mitchell J, Shelly A. Unified modeling and prediction of weather and climate: a 25-year journey. Bull Amer Meteor Soc. 2012;93(12):1865–77. https://doi.org/10.1175/BAMS-D-12-00018.1.

84. Koriche SA, THM R. Application of satellite products and hydrological modelling for flood early warning. Phys Chem Earth. 2016;93:12–23. https://doi.org/10.1016/j.pce.2016.03.007.

85. Hamada A, Murayama Y, Takayabu YN. Regional characteristics of extreme rainfall extracted from TRMM PR measurements. J Clim. 2014;27(21):8151–69. https://doi.org/10.1175/JCLI-D-14-00107.1.

86. Worako AW, Haile AT, Taye MT. Implication of bias correction on climate change impact projection of surface water resources in the Gidabo sub-basin, Southern Ethiopia. J Water Clim Chang. 2022;13(5):2070–88. https://doi.org/10.2166/wcc.2022.396.

87. Kalisa W, Igbawua T, Ujoh F, Aondoakaa IS, Namugize JN, Zhang J. Spatio-temporal variability of dry and wet conditions over East Africa from 1982 to 2015 using quantile regression model. Nat Hazards. 2021;106(3):2047–76. https://doi.org/10.1007/s11069-021-04530-1.

88. Hennemuth B, Bender S, Bülow K, Dreier N, Keup-Thiel E, Krüger O, et al. Statistical methods for the analysis of simulated and observed climate data, applied in projects and institutions dealing with climate change impact and adaptation. CSC Report 13, Climate Service Center, Germany. 2013.

89. Igobwa AM, Gachanja J, Muriithi B, Olukuru J, Wairegi A, Rutenberg I. A canary, a coal mine, and imperfect data: determining the efficacy of open-source climate change models in detecting and predicting extreme weather events in Northern and Western Kenya. Clim Chang. 2022:174. https://doi.org/10.1007/s10584-022-03444-6.

90. Cowls J, Tsamados A, Taddeo M, Floridi L. The AI gambit: leveraging artificial intelligence to combat climate change—opportunities, challenges, and recommendations. AI & Soc. 2021;38(1):283–307. https://doi.org/10.1007/s00146-021-01294-x.

91. Alfieri L, Libertino A, Campo L, Dottori F, Gabellani S, Ghizzoni T, et al. Impact-based flood forecasting in the Greater Horn of Africa, EGUsphere [preprint] 2023: https://doi.org/10.5194/egusphere-2023-804

92.● Funk C, Harrison L, Segele Z, Rosenstock T, Steward P, Anderson CL, et al. Tailored forecasts can predict extreme climate informing proactive interventions in East Africa. Earth's Future. 2023;11:e2023EF003524. https://doi.org/10.1029/2023EF003524. **This article provides the latest progress in terms of forecasting droughts in East Africa before 8 months. The possiblity of forecasting in such a long lead time is useful for communities and decision makers to proactively prepare for droughts.**

93. De Andrade FM, Young MP, Macleod D, Hirons LC, Woolnough SJ, Black E. Subseasonal precipitation prediction for Africa: forecast evaluation and sources of predictability. Weather Forecast. 2021;36(1):265–84. https://doi.org/10.1175/WAF-D-20-0054.1.

94. Hirons L, Thompson E, Dione C, Indasi VS, Kilavi M, Nkiaka E, et al. Using co-production to improve the appropriate use of sub-seasonal forecasts in Africa. Clim Serv. 2021;23:100246. https://doi.org/10.1016/j.cliser.2021.100246.

95. Acharya N, Ehsan MA, Admasu A, Teshome A, KJC H. On the next generation (NextGen) seasonal prediction system to enhance climate services over Ethiopia. Clim Serv. 2021;24:100272. https://doi.org/10.1016/j.cliser.2021.100272.

96. Boult VL, Asfaw DT, Young M, Maidment R, Mwangi E, Ambani M, et al. Evaluation and validation of TAMSAT-ALERT soil moisture and WRSI for use in drought anticipatory action. Meteorol Appl. 2020;27:e1959. https://doi.org/10.1002/met.1959.

97. Lees T, Tseng G, Atzberger C, Reece S, Dadson S. Deep learning for vegetation health forecasting: a case study in Kenya. Remote Sens. 2022;14(3):698. https://doi.org/10.3390/rs14030698.

98. Nakalembe C. Urgent and critical need for sub-Saharan African countries to invest in Earth observation-based agricultural early warning and monitoring systems. Environ Res Lett. 2020;15:121002. https://doi.org/10.1088/1748-9326/abc0bb.

99. Rowell DP, BBB B, Nicholson SE, Good P. Reconciling past and future rainfall trends over East Africa. J Clim. 2015;28(24):9768–88. https://doi.org/10.1175/JCLI-D-15-0140.1.

100. Wainwright CM, Marsham JH, Keane RJ, Rowell DP, Finney DL, Black E, Allan RP. 'Eastern African Paradox' rainfall decline due to shorter not less intense Long Rains. npj Clim Atmos Sci. 2019;2(1):34. https://doi.org/10.1038/s41612-019-0091-7.

101. Schwarzwald K, Goddard L, Seager R, Ting M, Marvel K. Understanding CMIP6 biases in the representation of the Greater Horn of Africa long and short rains. Clim Dyn. 2023;61(3–4):1229–55. https://doi.org/10.1007/s00382-022-06622-5.

102. Dadson SJ, Lopez HP, Peng J, Vora S. Hydroclimatic extremes and climate change, water science, policy, and management: a global challenge. Wiley; 2019. p. 11–28. https://doi.org/10.1002/9781119520627.ch2.

103.● Meresa H, Zhang Y, Tian J, Ma N, Zhang X, Heidari H, et al. An integrated modeling framework in projections of hydrological extremes. Surv Geophys. 2023;44:277–322. https://doi.org/10.1007/s10712-022-09737-w. **This article presents how to disentangle the uncertainty related to projecting climate change impact of hydrological extremes. The suggested methodology helps to identify the uncertainties, their contribution to the projected extreme flow. This will better inform the users and assist in robust decision making.**

104. Malede DA, Agumassie TA, Kosgei JR, Andualem TG, Diallo I. Recent approaches to climate change impacts on hydrological extremes in the Upper Blue Nile Basin, Ethiopia. Earth Syst Environ. 2022;6:669–79. https://doi.org/10.1007/s41748-021-00287-6.

105. Hewitson BC, Daron J, Crane RG, Zermoglio MF, Jack C. Interrogating empirical-statistical downscaling. Clim Chang. 2014;122(4):539–54. https://doi.org/10.1007/S10584-013-1021-Z/FIGURES/4.

106. Sharma A, Wasko C, Lettenmaier DP. If precipitation extremes are increasing, why aren't floods? Water Resour Res. 2018;54(11):8545–51. https://doi.org/10.1029/2018WR023749.