



Research papers

Debilitating floods in the Sahel are becoming frequent

Nadir Ahmed Elagib^{a,*}, Islam Sabry Al Zayed^b, Suhair A. Gayoum Saad^c,
Mohamad Ibrahim Mahmood^d, Mohammed Basheer^e, Andreas H. Fink^f

^a Böckingstr. 55, Köln Mülheim 51063, Cologne, Germany

^b Technical Office, National Water Research Center (NWRC), Cairo, Egypt

^c Al Rawabi Dairy Company, P.O. Box 50368, Dubai, United Arab Emirates

^d Higher Council for Environment and Urban and Rural Promotion, Khartoum State, Sudan

^e Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester, United Kingdom

^f Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany



ARTICLE INFO

This manuscript was handled by Emmanouil Anagnostou, Editor-in-Chief.

Keywords:

Flash flood
Riverine flood
Flood impact
Flood forecasting
Adaptation
Extremes
Sahel

ABSTRACT

Despite the long-lasting and widespread drought in the Sahel, flood events did punctuate in the past. The concern about floods remains dwarf on the international research and policy agenda compared to droughts. In this paper, we elucidate that floods in the Sahel are now becoming more frequent, widespread, and more devastating. We analyzed gridded daily rainfall data over the period 1981–2020, used photographs and satellite images to depict flood areas and threats, compiled and studied flood-related statistics over the past two decades, and supported the results with peer-reviewed literature. Our analysis revealed that the timing of the maximum daily rainfall occurs from the last week of July to mid-August in the Eastern Sahel, but from the last week of July to the end of August in the Western Sahel. In 2019 and 2020, flash and riverine floods took their toll in Sudan and elsewhere in the region in terms of the number of affected people, direct deaths, destroyed and damaged houses and croplands, contaminated water resources, and disease outbreaks and deaths. Changes in rainfall intensity, human interventions in the physical environment, and poor urban planning play a major role in driving catastrophic floods. Emphasis should be put on understanding flood causes and impacts on vulnerable societies, controlling water-borne diseases, and recognizing the importance of compiling relevant and reliable flood information. Extreme rainfall in this dry region could be an asset for attenuating the regional water scarcity status if well harvested and managed. We hope this paper will induce the hydroclimate scholars to carry out more flood studies for the Sahel. It is only then encumbered meaningful opportunities for flood risk management can start to unveil.

1. Introduction

The climate of the Sahel Region, which expands from west to east Africa (Fig. 1), is renowned for variability and related phenomenal stressors (Epule et al., 2018). Coping with climate variability and change in the Sahel, as in other parts of Africa, is beset by challenges such as limited expertise, preparedness, and resources needed to handle climate issues (Walsh et al., 1994; Washington et al., 2006).

Although droughts and floods are two phenomena of the same water cycle, research customarily focuses on either of the two extremes due to their complexity and differences in temporal and spatial scales (Ward et al., 2020). The Sahel drought has attracted increasing interest amongst scholars and policymakers worldwide since its onset

in the early 1970s (Tanaka et al., 1975; Kerr, 1985; Hulme, 2001; Nicholson et al., 2018). While scientists from Africa are urging the United Nations to support preparations for imminent droughts in view of exacerbating climate change (Nature Editorial (NE), 2019; Padma, 2019), floods in the Sahel went far unacknowledged. In Africa, disasters connected with floods are the most frequent and the costliest while those related to droughts account for the largest number of fatalities (WMO, 2020). Until 2018, research on the flood phenomena in the Sahel was 44% less than that of drought stressors (Epule et al., 2018). This attitude has, consequently, compounded the human and environmental vulnerability to floods. Tarhule (2005) stated that “historical flood records lack comprehensiveness, standardization, quality control, and scientific rigor.”

* Corresponding author at: Current address: Institute of Geography, Faculty of Mathematics and Natural Sciences, University of Cologne, Cologne, Germany.
E-mail address: nelagib@uni-koeln.de (N.A. Elagib).

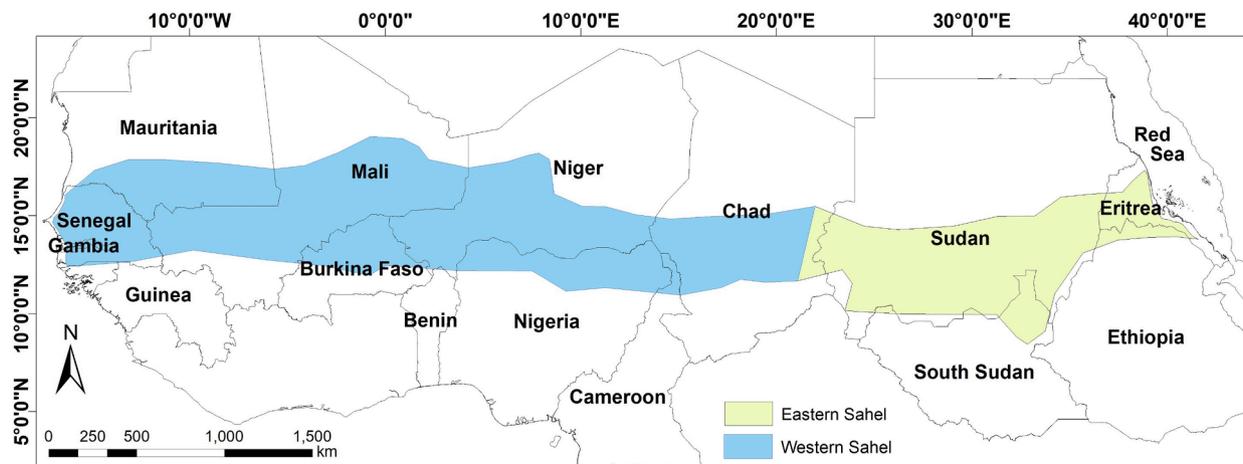


Fig. 1. Map of the countries encompassing the Sahel region.

A plethora of studies has investigated the changing and variable rainfall observed over the Sahel. Rainfall characteristics are changing in the Sahel at large from east to west. Daily rainfall data from both ground observations and satellites indicate an increase in the frequency of extreme events, the intensity of rain, and the inter-annual variability (Suliman and Elagib, 2012; Ly et al., 2013; Zhang et al., 2017). These results reveal an increasing intensity and occurrence probability of extreme rainfall rather than a rainfall recovery, roughly since the beginning of the 21st century, with the intensification being stronger in the Eastern Sahel than the Western Sahel (Panthou et al., 2018).

Rivers in the Sahel have demonstrated changes in their flows. Analyses of discharge data of the Senegal and Niger Rivers indicate an intensification of the hydrological signal in the Western Sahel. Modification of the hydrological regimes in these rivers is demonstrated by an increase in the annual maxima (Wilcox et al., 2018) and a twin-peak hydrograph (Descroix et al., 2012). In 2010, 2012, and 2013, the Niger River recorded the highest discharge peaks ever since the 1920s (Casse and Gosset, 2015). The flows of the Nile River in the Eastern Sahel show successive above-average anomalies during the 21st century (Taye and Willems, 2012; Basheer and Elagib, 2019; Basheer et al., 2021; Elagib et al., 2021a).

Investigations into the occurrence of heavy rainfall and rain-induced floods and their causes in the Sahel Region are necessary because of the devastation these events bring to people and properties (e.g., loss of lives and destruction of houses and infrastructures), as well as to the environment and socioeconomic systems (Tarhule, 2005). Floods also cause interruption to primary health care facilities and services (Abbas and Routray, 2013).

Therefore, we investigate the flood risk in the African Sahel Region in light of recent rainfall and river flow tendencies. Outlooks for skillful flood forecasts and adaptation are remarked. A viewpoint is established in a hope for guiding individual, societal, and regional activities.

2. Study area

The Sahel is around 3.1 million km² body of land, spanning 5,900 km across an arid and semi-arid belt of Africa from east to west between the Saharan desert, the rainforests of Central Africa, and the Guinean Coast (Fig. 1). The region stretches from Senegal and Gambia on the Atlantic coast through Mali, Mauritania, Burkina Faso, Nigeria, Niger, Chad, and Sudan to the northwestern part of Ethiopia and Eritrea on the Red Sea coast. A total of 407.4 million people were estimated to live in the 11 Sahel countries as of 2014 (Table 1). This population is projected to reach 597.9 million by 2030. Grassland, shrubs, and small thorny trees are the main land covers in the region. The importance of the region originates from its abundant human, cultural and natural resources.

However, risks of climate change, poor soil, growing population, and increasing pressure on the natural resources challenge the sustainable development, poverty reduction, and environmental restoration of the Sahel Region (Mohamed, 2011; Sissoko et al., 2011; Elagib et al., 2021b). Despite its concomitant vulnerability to the impacts of climatic variability and land degradation, subsistence agricultural activities constitute the dominant contributor to the Sahel economy, food security, and livelihoods.

3. Materials and methods

3.1. Flood-related statistics

This study used secondary data on the number of affected people, direct deaths, and destroyed and damaged houses, and disease outbreaks and deaths related to flood events. Unless otherwise indicated, these data were compiled from reports of the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), ReliefWeb, and Flood-List. Depending on the availability of country-level data, these sources provide annual situation reports, including statistics on the above-stated attributes. For this study, a follow-up of the reporting updates was ensured to obtain the latest statistics. For Sudan, these data were extracted from OCHA situation reports for the period 1998–2020. Examining these data enables diagnosing the flood phenomena in terms of the exposure to danger, harm, or loss, i.e., risk.

3.2. Spatio-temporal maximum daily rainfall

In this research, the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) version 2.0 rainfall product was selected for assessing extreme events over Sudan and the Sahel. The CHIRPS dataset is developed and maintained by the U.S. Geological Survey (USGS) and the Climate Hazards Group of the University of California (Funk et al., 2015) and was selected for two reasons. First, it has a long daily time series (1981 to date) with a spatial resolution of around 5 km. Second, validation results ranked the performance of CHIRPS highest using multiple rainfall indices across East and Sub-Saharan Africa (Dinku et al., 2018; Harrison et al., 2019). The maximum rainfall value for each pixel was calculated and visualized for the Sahel countries and for the Eastern and Western Sahel over the period from 1981 to 2019.

3.3. Flood inundation photographs and mapping

Photographs, were requested by the authors through personal communications with freelance press photographers, photography hobbyists, and colleagues in order to document flood incidents and threats.

Table 1
Population of the Sahel countries.

Country	Population mid-2014 [§] (millions)	Percentage from totalAdaptation	Population Density [§] (persons/km ²)	Projected population Mid-2030 [§] (millions)	Percentage from total
Senegal	13.9	3.4	71	21.8	3.6
Gambia	1.9	0.5	169	3.1	0.5
Mali	15.9	3.9	13	26.3	4.4
Mauritania	4.0	1.0	4	5.6	0.9
Burkina Faso	17.9	4.4	65	28.4	4.7
Nigeria	177.5	43.6	192	261.7	43.8
Niger	18.2	4.5	14	33.8	5.7
Chad	13.3	3.3	10	21.8	3.6
Sudan	38.8	9.5	21	55.1	9.2
Ethiopia	99.5	24.4	87	130.5	21.8
Eritrea	6.5	1.6	56	9.8	1.6
Total	407.4			597.9	

[§] Source: Haub and Kaneda (2014).

Additionally, Landsat 8 satellite images were retrieved from the United States Geological Survey (USGS) data center to detect flood areas as explained below. Cloud cover was a limiting factor in processing the images and identifying flood areas.

A floodwater detection method (Al Zayed and Elagib, 2017) was used to identify flood areas in 2019 and 2020. The method utilizes the Normalized Difference Vegetation Index (NDVI) and the Evaporative Fraction (EF) to detect water pixels. It is known that water pixels have negative NDVI values (Pettorelli et al., 2005; Ma et al., 2007) and have high EF values of ≈ 0.75 – 1.0 (Al Zayed et al., 2016). Both the NDVI and EF were calculated using Landsat 8 satellite images with a 30-m spatial resolution. The NDVI was derived from the reflectivity-corrected red (band 4) and near-infrared (band 5) bands, using the equation (band 5–band 4)/(band 5 + band 4) as described by Vermote et al. (2016). EF was derived by retrieving the Land Surface Temperature (LST) from the thermal band (band 10) after radiance conversion based on the methodology of USGS (2019) as follows: $EF = (LST_h - LST_x) / (LST_h - LST_c)$, where LST_h is the average of three hot pixels taken from the land, LST_c is the average of three cold (water) pixels, and LST_x is the LST pixel value for the satellite image.

For the 2019 flood event, a total of 146 satellite images covering Sudan (paths: 171–179; rows: 45–52) were processed for the periods before and after the rainy event of 9–10 August 2019 that caused widespread flooding. Nine images were selected and analyzed to capture flash floodwater considering the cloud-cover and spatial representation of the Sudanese states. For the 2020 flood event, fifteen satellite images with minimal cloud cover were selected and processed to capture the flood along some reaches of the Nile River.

3.4. River water levels

Daily river water level data were obtained for the Khartoum river gage, located on the Nile in Khartoum City (Sudan’s capital). These data cover the 1954–2020 period. Each year in this period was classified into normal, alert, critical, or flooding based on the maximum daily river water level and the riverine flood alarm thresholds used for Khartoum gage by the Ministry of Irrigation and Water Resources of Sudan. This analysis enabled understanding the change in the severity, occurrence, and frequency of Nile riverine floods.

3.5. Probability and return period of maximum rainfall

Time series of the maximum daily rainfall occurring in a year, as obtained from CHIRPS, were employed to construct a mathematical relationship that estimates the rainfall with a given probability of exceedance and a return period. Two approaches, as described by Mansell (2003), were compared. The first approach involves ranking the

data in descending order and using Weibull’s Formula given by Eqs. (1) and (2) below.

$$P = \frac{m}{n + 1} \tag{1}$$

$$T = \frac{1}{P} \tag{2}$$

where P is the probability of exceedance, m is the rank, n is the data size, and T is the return period in years. The maximum rainfall-return period relationship was plotted in a normal-log form.

In the second approach, the Gumbel distribution form was used as follows. Gumbel distribution relies on two parameters, namely the mean (μ) and the standard deviation (σ) of the data under analysis. The maximum rainfall for a given return period can be obtained based on the cumulative distribution.

$$R = \mu + \frac{\sqrt{6}}{\pi} \sigma y - 0.5772 \frac{\sqrt{6}}{\pi} \sigma \tag{3}$$

where y is the reduced variate and is given as

$$y = -\ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \tag{4}$$

The probability of a rainfall (r) exceeding a given rainfall (R) is calculated based on the following equation:

$$P(r \geq R) = 1 - \exp[-\exp(-y)] \tag{5}$$

where y can be obtained by rearranging Eq.(3) to give

$$y = \frac{R + 0.5772 \frac{\sqrt{6}}{\pi} \sigma - \mu}{\frac{\sqrt{6}}{\pi} \sigma} \tag{6}$$

Then, the return period of a magnitude of rainfall is obtained using Eq. (2).

3.6. Meteorological causes of the most recent disastrous floods

To enrich the discussion on the major meteorological factors influencing the flood events, the causes of the 2019 and 2020 floods in Sudan were linked to the atmospheric moisture budget. The monthly total columnar water vapor (tcwv), the tropospheric moisture flux, and the flux divergence were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) product ERA5 (Hersbach et al., 2020) with a spatial resolution of $0.25^\circ \times 0.25^\circ$. The anomalies for the 2019 and 2020 wet seasons of the above-mentioned variables were calculated with respect to the 1981–2010 mean.

3.7. Literature review

Secondary data in the form of published scientific literature were used to identify the documented flood events during the recent past, support the present analysis of flood frequency, ascribe the flood incidents and impacts, and explore the existing and potential attempts to flood forecasting in the region. This literature is cited in the relevant sections and appropriately detailed in the reference list.

4. Results

4.1. Flood occurrence, distribution, and magnitude

During the period 1981–2019, the CHIRPS data show a highest rainfall recorded in one day across the Sahel region of 216.9 mm (Fig. 2a). Out of the 39-year data record, 21 maxima occurred in the Eastern Sahel while 18 maxima were recorded in the Western Sahel (Fig. 2b). The CHIRPS data plotted in Fig. 2b show that the maximum rainfall in the Eastern Sahel, excluding Eritrea, often occurs during the

last week of July to mid-August. In Eritrea, the maximum occurs during mid-March to mid-April. The Western Sahel experiences the maximum rainfall in the period from the last week of July to the end of August.

Following the peak Sahel drought in the 1980s, the literature has reported flood occurrences across the region in 1995, 1998, 1999, 2002, 2003, 2005, 2006, 2007, 2008, 2012, 2013, 2014, and 2017 (Williams and Nottage, 2006; Tschakert et al., 2010; Paeth et al., 2011; Samimi et al., 2012; Boyd et al., 2013; Mahmood et al., 2017; Adegoke et al., 2019). The spatial distribution of the maximum daily rainfall recorded for these years is depicted in Fig. 2c. Sahel-wide, this maximum occurs mostly in the far west, the south-central part, eastern Sudan, or the far east. The highest daily rainfall recorded during 1981–2019 is displayed in Fig. 2d.

During the first fortnight of August 2019, a heavy rainstorm developed over a large part of Sudan (top-left corner in Fig. 3). Unlike the locally unprecedented 200 mm storm of 1988 in Khartoum (Hulme and Trilsbach, 1989), the extent of wet conditions leading to flooding on the 9th and 10th of August 2019 across Sudan was exceptionally vast (Fig. 3). Many parts of the country received a high proportion of their August rain in this storm.

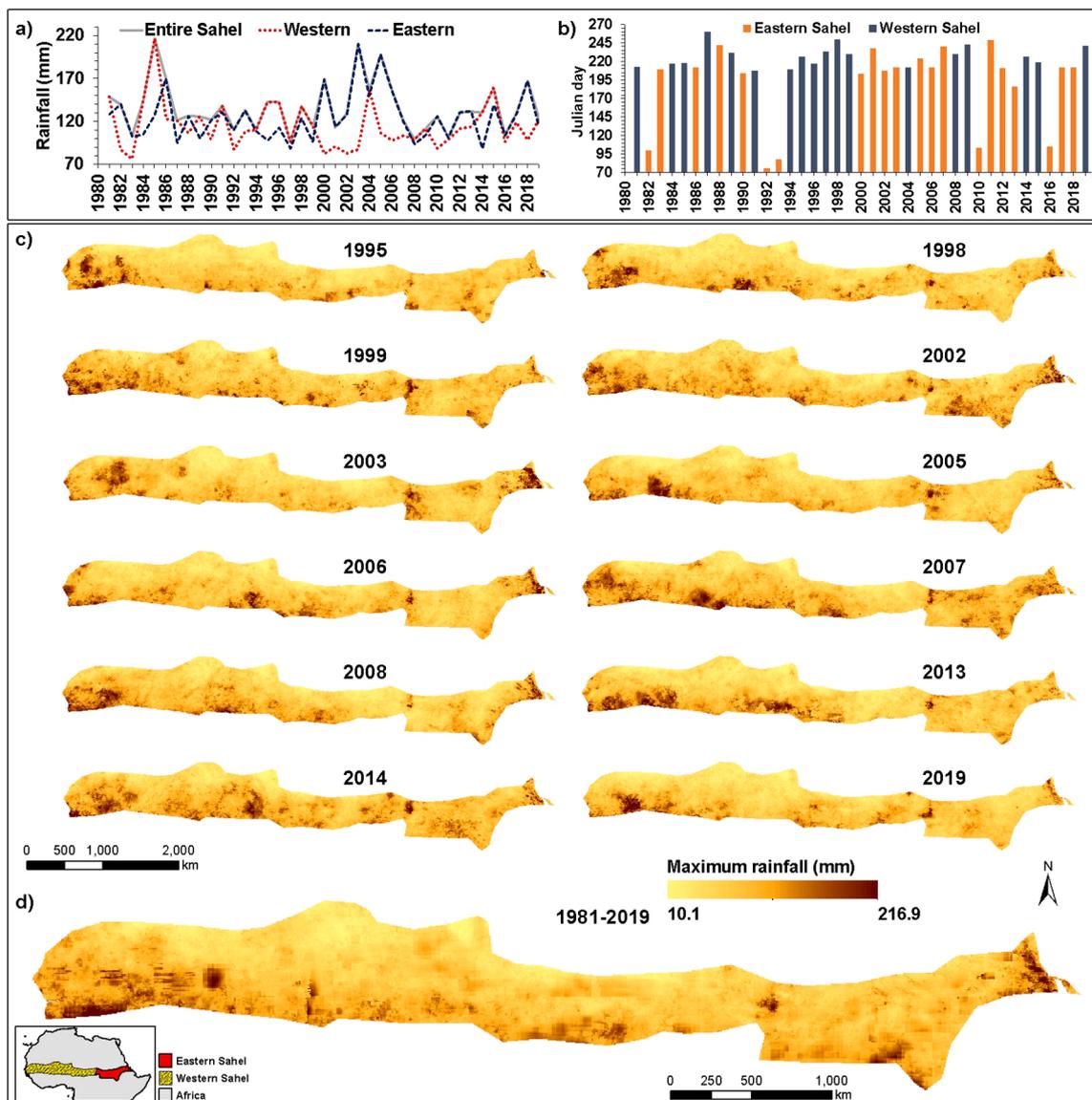


Fig. 2. CHIRPS-based estimates of maximum rainfall across the Sahel region. a) Temporal evolution, b) day of occurrence, c) spatial distribution for well-known flood years, and d) highest during 1981–2019. Data for the Eastern Sahel shown in (c) exclude Eritrea, which has different timing of occurrence of maximum rainfall (see text for detail).

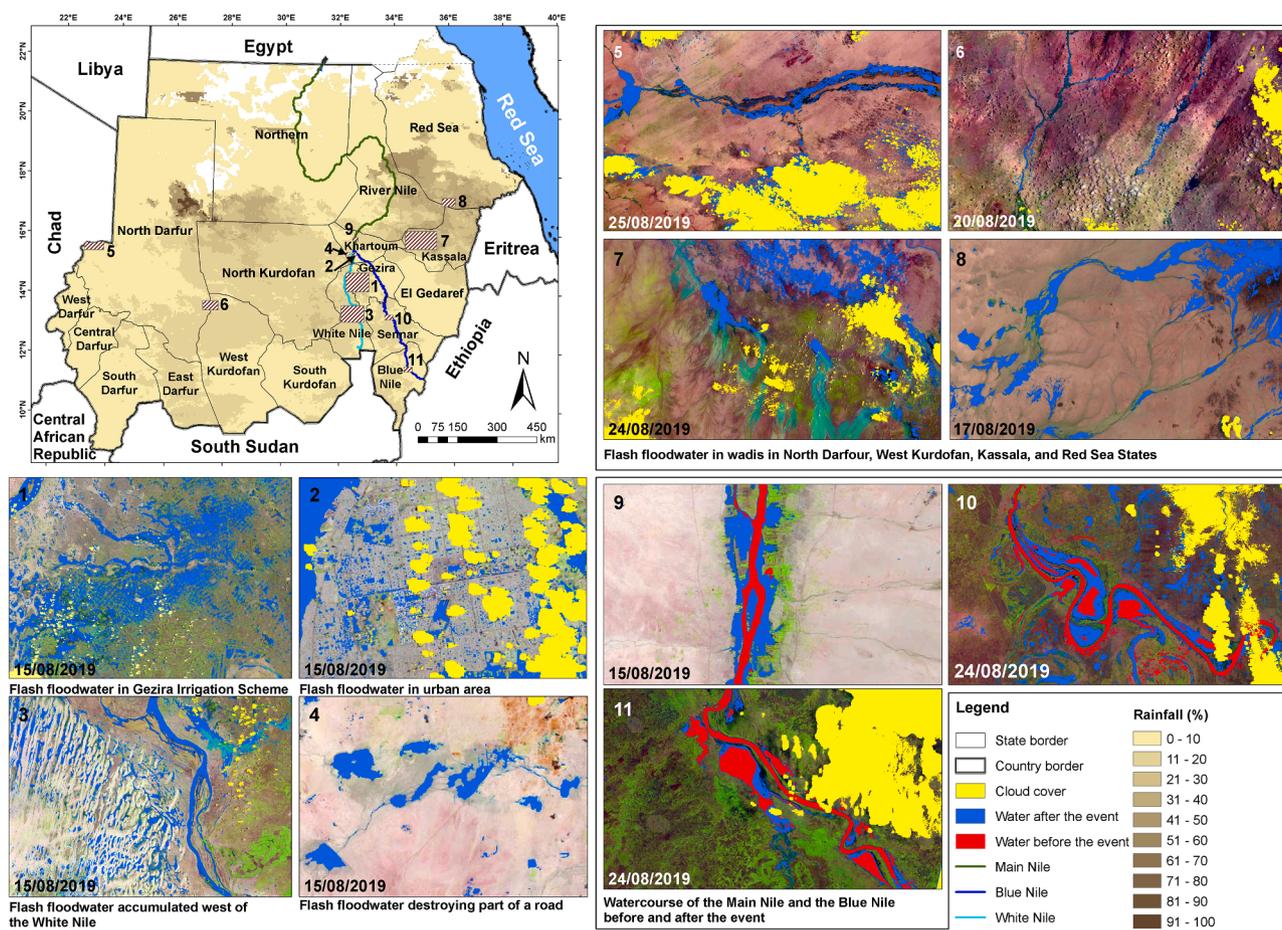


Fig. 3. Flash flood event of August 2019 across Sudan presented by spatial distribution of CHIRPS rainfall (top-left corner map) and selected inundated areas (scenes 1 to 11). Rainfall on map is the total received during the 9th and 10th of August 2019 expressed as a percentage from the total August 2019 rainfall.

Based on the Weibull probability formula, the frequency curves of maximum daily rainfall are shown in Fig. 4. The results are given for the Eastern, Western, and Entire Sahel region in addition to four selected Sahelian countries, which have been frequently reported to encounter flood events. The results in Fig. 4 are compared with those obtained using the Gumbel distribution function (see Table 2). The table shows approximately similar results concerning the maximum rainfall at short return periods. At long return periods, the difference in rainfall estimates between the two approaches diverges.

As for riverine flood events, the Nile River in the eastern part of the Sahel is a striking case to perceive. For instance, the 67-year long time series of the maximum water levels of the Blue Nile recorded at the capital of Sudan (Fig. 5) manifests 27 (40.3%) occurrences of flood alarms, 18 (26.9%) critical cases, and 19 (28.4%) alert events against only 3 (4.5%) normal years. The 21st century has so far been unequivocal in its increasing Nile flows. During the last decade alone, Khartoum witnessed 8 flood alarms with increasing severity. Comparing Fig. 5 with Fig. 2c, the synchronous occurrence of extreme rainfall in the Eastern Sahel and Nile water levels, representing alert, critical, and flooding events, is evident. In 2020, the Nile water level at Khartoum reached an unprecedented level (380.65 m asl), which exceeded the peak levels reached in 1946 (380.1 m asl) and in 1988 (379.94 m asl), as reported by Davies and Walsh (1997). Subsequent to rainfall in the source region of the Nile, particularly the Ethiopian Highlands, an exceptionally widespread fluvial flooding developed in Sudan during August and September. The water levels of all dam reservoirs in Sudan increased, and some of the Nile River tributaries overflowed (Fig. 6).

4.2. Flood impacts

In the Eastern Sahel, particularly Sudan, not only were the years 2019 and 2020 characteristic of flood impacts, but they were also part of a state of more than two decades of spatio-temporal losses of property and lives (Fig. 7). For instance, unusually early rainy season with heavy and persistent rain in 1999 caused severe and widespread floods in central Sudan (Williams and Nottage, 2006), affecting 1,841,180 people, destroying 30,707 houses, and damaging 64,350 houses (Fig. 7). Compared to the 1988 flood (Hulme and Trilsbach, 1989; Sutcliffe et al., 1989), the severity of the 2019 flood event in Sudan did not prompt immediate and substantial world attention to catalyze relief actions. A few television networks broadcasted scenes of mass havoc. In the aftermath, the government of Sudan was challenged by an economic recession and environmental and health disasters. To place the 2019 flooding in Sudan in the Sahelian context, we compare its impacts with the well-documented 2007 flood event of the Sahel. In 2007, the west Sahelian floods affected 429,376 people, displaced 84059, and killed 153 (Boyd et al., 2013). As of 21 November 2019, the 2019 flood affected 426,300 people, led to the death of 78 people, damaged 35,725 houses, and destroyed 49,535 houses in Sudan alone. The year 2019's flooding in Sudan disconnected 123 villages in the White Nile State from access by relief campaigns (Assayha, 2019). In Niger in the Western Sahel, heavy rains and flooding of the Niger River in 2019 affected 211,366 people, killed 57 people, and damaged 16,375 houses. In 2020, the Sahel flooding resulted in 2,006,000 affected people, 181,500 destroyed houses, and 417 deaths, with 56.4, 54.5, and 62.3% of these numbers, respectively, reported across Sudan alone (Fig. 8) from both fluvial or pluvial floods. Heavy rains and river flooding across Chad,

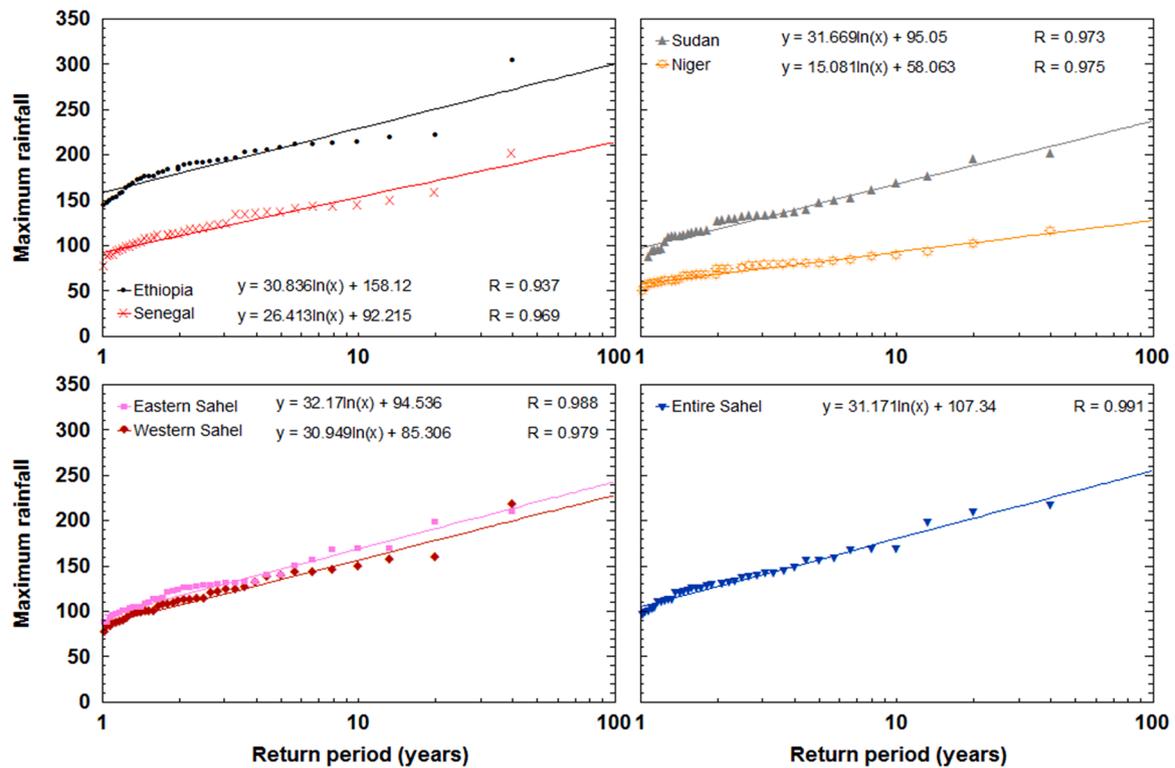


Fig. 4. Regional and country-specific frequency curves of the maximum daily rainfall based on the Weibull probability formula. The regression equations represent the normal-log relationship between the maximum rainfall and the return period. All regressions are at least significant at $p = 0.001$.

Table 2

Comparison between the estimates of the frequency analysis between Weibull form and Gumbel distribution.

Form/Distribution	Parameter	Region/Country						
		Entire Sahel	Eastern Sahel	WesternSahel	Senegal	Niger	Sudan	Ethiopia
Weibull form	R (mm) with T = 2 years	128.9	116.8	106.8	110.5	68.5	117.0	179.5
	R (mm) with T = 10 years	179.1	168.6	156.6	153.0	92.8	168.0	229.1
	R (mm) with T = 40 years	222.3	213.2	199.5	189.6	113.7	211.9	229.1
Gumbel distribution	μ (mm)	136.0	125.2	114.9	117.5	72.5	125.3	187.6
	σ (mm)	28.7	28.4	27.6	23.7	13.5	28.4	28.7
	R (mm) with T = 2 years	131.2	120.6	110.3	113.6	70.3	120.7	182.9
	R (mm) with T = 10 years	173.4	162.3	150.8	148.4	90.1	162.3	225.0
	R (mm) with T = 40 years	205.4	193.8	181.4	174.8	105.0	193.9	256.9
	P_r of $r \geq 150$ mm	0.259	0.168	0.104	0.092	0.000	0.168	1.0
	T (years) of $r \geq 150$ mm	3.9	6.0	9.7	10.8	–	6.0	1.1
	P_r of $r \geq 200$ mm	0.032	0.019	0.011	0.006	0.000	0.019	0.3
	T (years) of $r \geq 200$ mm	31.5	52.8	94.3	154.5	–	52.6	3.6

including the capital N'Djamena, in 2020 caused ravages, thus affecting 64,670 households (or 388,000 people), displacing hundreds of thousands of people, destroying hundreds of thousands of hectares of cultivated land, washing away thousands of cattle and inundating storekeepers' stocks in markets.

Based on Figs. 3 and 7, one can infer that the most disrupted areas in terms of the number of affected people in Sudan are occasionally located adjacent to river streams (e.g., Northern, Gezira, White Nile, Khartoum, Kassala, and Sennar states), densely populated urban centers (the capital: Khartoum State), and engulfed by huge wadis (e.g., North Kurdofan State). In 2020, pluvial floods affected North Darfur State the most, whereas the most affected states as a result of rivers that overflowed their banks were Khartoum, Blue Nile, Sennar, and Gezira states (Figs. 6 and 8a).

Flash and riverine flood damages pose major threats in the Sahel Region. Exemplary of these threats are best depicted in Figs. 9 and 10 for the 2019 and 2020 flood disasters in Sudan, respectively. The Nile floodwater inundated a large number of farmlands (Fig. 10a-c). The

2020 flash and riverine floods damaged approximately 2.2 million hectares of croplands in Sudan and, consequently, put vulnerable households at risk of food insecurity.

An additional salient feature is the health impacts. Due to the widespread presence of stagnant floodwaters during the flood seasons of 2019 and 2020, mosquitos found breeding grounds. In 2019, a cholera outbreak in Sudan started in September following the August flash floods. The first cases were reported in the states adjacent to South Sudan, likely related to a large number of refugees without access to clean drinking water or sanitation who mostly rely on open defecation. The cholera outbreak rapidly spread to more than eight states in Sudan due to the movement of people. Due to the quick response of the Sudanese Government in announcing the cholera outbreak, calling for local and international organizations to provide health and food assistance, the cholera cases were limited. Malaria in Sudan breached the epidemic threshold in 2019 as over 1.8 million cases were reported. The collapse of pit-latrines (Fig. 9a), totaling more than 5000 in 2019 and 16,000 in 2020, and the mixture of their contents with floodwater

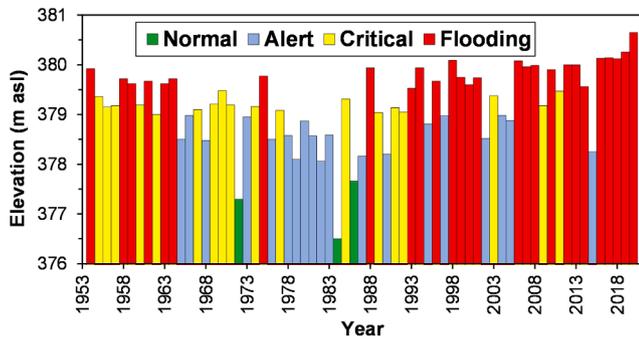


Fig. 5. Maximum daily water level of the Blue Nile at Khatoum gaging station, Sudan. Alert: $378 \leq \text{Water level} < 379$; Critical: $379 \leq \text{Water level} < 379.5$; Flooding: $379.5 \leq \text{Water level}$, where the water levels are in m above sea level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represented breeding grounds for several water-borne diseases, such as cholera. Water resources were extensively damaged in 13 states due to contamination. Floodwater mixed with solid waste in residential areas was noticed during the flood of September 2020. Many collection points

of solid waste inside flood zones were inundated, and waste of different types mixed with floodwater and represented a source of water pollution (Fig. 10f). Reported disease outbreaks and casualties across Sudan during the period from 9 August 2019 to 8 January 2020 were 97 cases of diphtheria (including 13 deaths), 4225 dengue fever cases (including 13 deaths), 572 rift valley fever cases (11 deaths), 296 chikungunya cases (including 5 deaths), and 346 cholera cases (11 deaths). In September 2020, 120 cases of fever attributed to floods (including 8 deaths) were reported in the Northern State in Sudan by the Federal Ministry of Health (2020a). As a result of lessons learned from the 2019 flood disaster, the Sudanese Government fought to avoid another cholera outbreak in 2020 by preparing emergency response plans for the whole country (Federal Ministry of Health (2020b)). In 2020, a special focus was devoted to the most affected states in the country (Khartoum, Sennar, and Northern states).

5. Discussion

Albeit in varying magnitude and place of occurrence, the above findings and data are striking in the sense that floods in the Sahel have become recurrent, and their impacts have become more devastating. In the Eastern Sahel, particularly Sudan, pluvial and fluvial flood occurrences are not unique in the history of record of the last two centuries

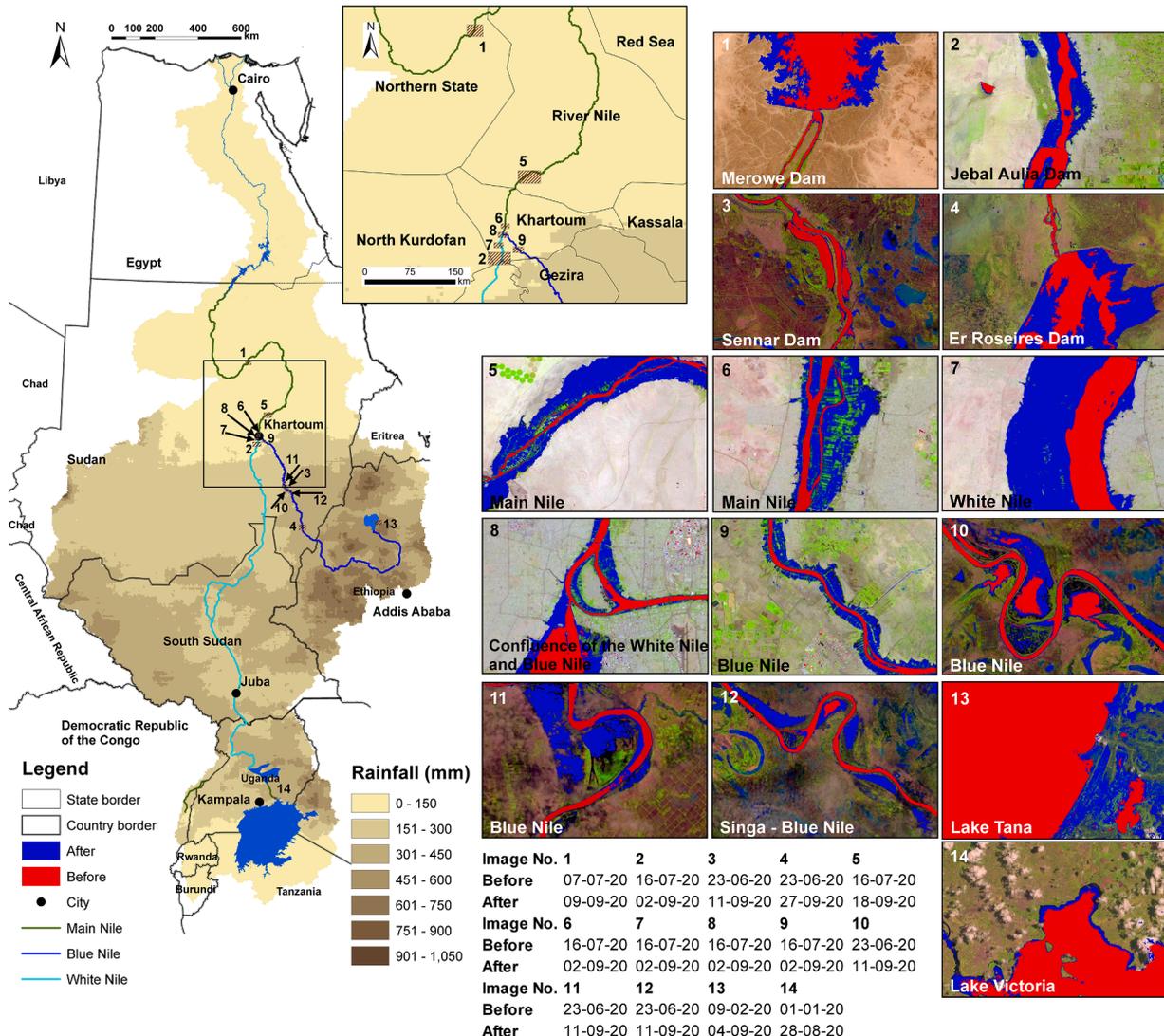


Fig. 6. Nile Basin flood event of 2020 presented by spatial distribution of CHIRPS total August-September rainfall (left map) and selected inundated areas (scenes 1 to 14 before and after the flood event).

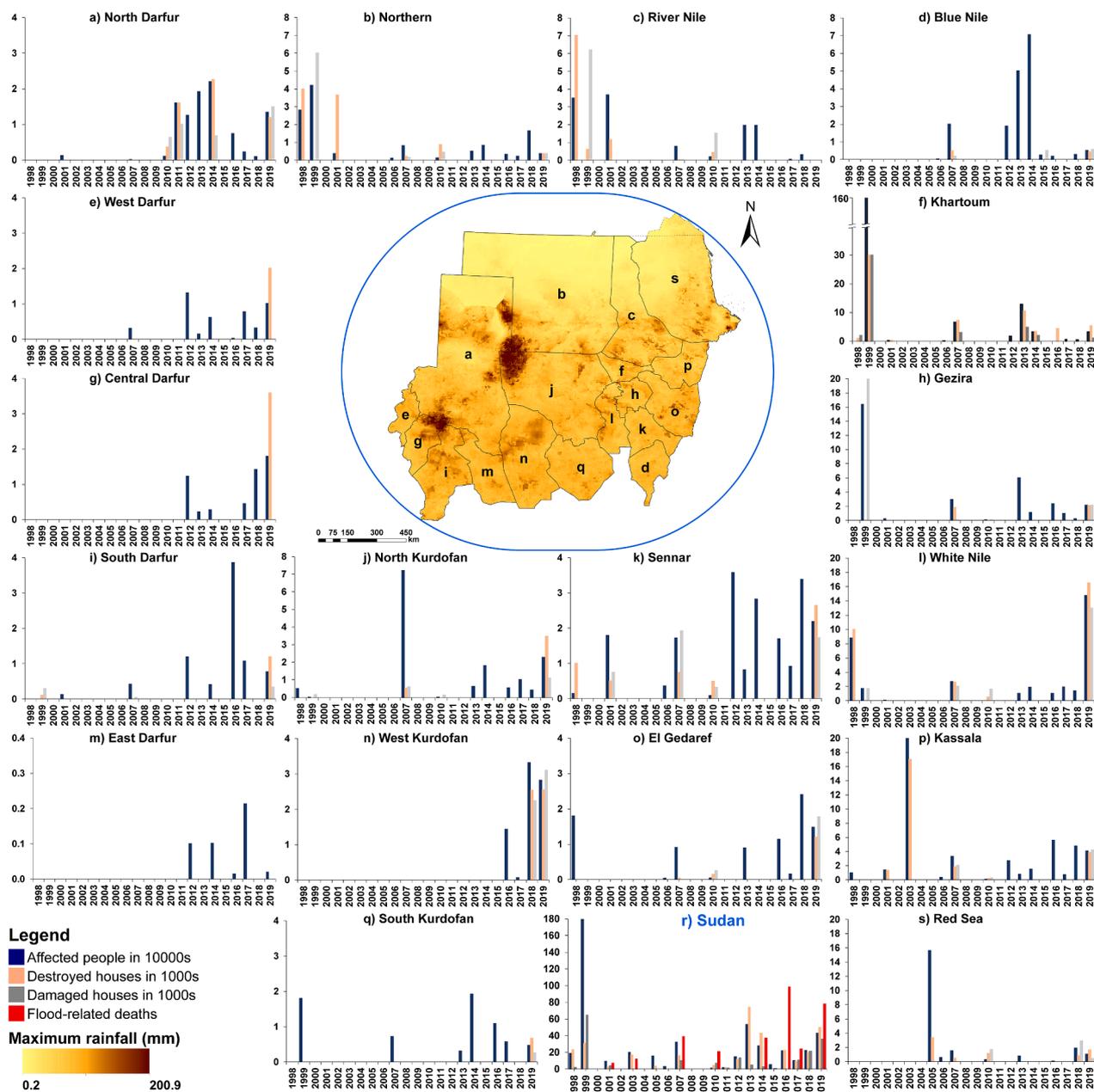


Fig. 7. Maximum daily rainfall based on CHIRPS estimates (map) and temporal impacts of flood events (bar graphs) during the period 1998–2019 across Sudan. Data for the Darfur Region were not available, especially during the civil war that broke out in 2003.

(Hulme and Trilsbach, 1989; Sutcliffe et al., 1989; Walsh et al., 1994). This section traces the possible causal factors associated with the past flood events in the region, the opportunities for, and the challenges to, skillful seasonal rainfall or flood forecasts. A hopeful discussion on how to move forward toward flood risk management is also provided.

5.1. Causes of floods

The rainfall results reported above identify extreme rainfall, consecutive daily rainfall events, and high river water levels as hydroclimatic causes of floods. It is to be noted that the rise in the streamflow of the Nile, i.e., from the Blue Nile and White Nile, subsequent to cumulative rainfall amounts in these regions was the main hydroclimatic reason for the riverine flood in Sudan in 2020 (Fig. 6). Such concurrent Nile and flash floods are not unusual in the history of records. A similar case was reported in the 1988 flood year (Sutcliffe et al., 1989; Walsh et al., 1994; Davies and Walsh, 1997). One could back the impact

statistics in Fig. 7 with the recurrence analysis of maximum daily rainfall given in Table 2. The table indicates a maximum daily rainfall of 117.0 mm (based on the Weibull formula) or 120.7 mm (based on Gumbel distribution) can occur in Sudan at least once in 2 years. Such an amount of daily rain is extreme for a region with arid and semi-arid climate conditions that receives a median annual rainfall of 87.2 to 658.4 mm (Elagib, 2009). A cautionary note should be made here that the absolutes of return values might have been underestimated due to the use of CHIRPS. Kpanou et al. (2021) presented proof that CHIRPS has lower 95th percentiles than rain-gauge values due to its algorithm.

The influence of sea surface temperatures on the Sahel interannual rainfall variability, i.e., the observed characteristics of wet and dry years in the Sahel, are explained by previous studies (Nicholson and Webster, 2007; Hagos and Cook, 2008). There remains, however, a question of whether the observed increase in rainfall intensity is influenced by “large-scale changes in the atmospheric circulation or more local factors enhancing the convection intensity or both” (Panthou et al., 2014). Cook

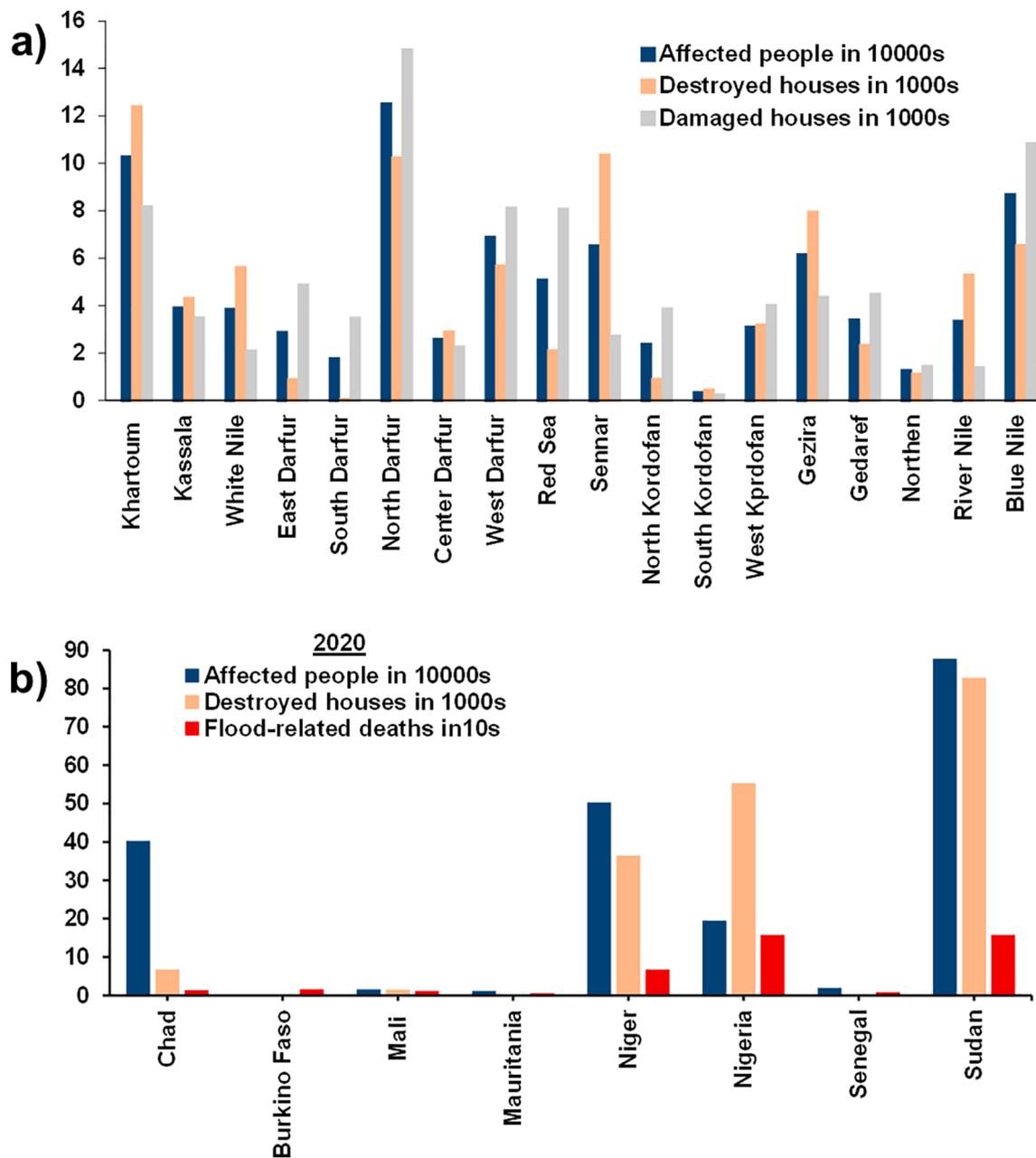


Fig. 8. Flood impacts on people and houses in 2020: a) State-specific statistics for Sudan as of 6 October 2020 and b) Country-specific statistics for the Sahel.

(2008) argues that the future may hold additional important influences. Multi-decadal satellite observations from the Western Sahel reveal rapid intensification of mesoscale convective systems, which are suggested to be strongly related to the global land temperature but weakly related to the recovery of annual rainfall (Taylor et al., 2017). The influence of anthropogenic greenhouse-gas and aerosol forcing is also suggested to have played a role in the recent, as well as the sustenance of, recovery in the Sahel rainfall (Haarsma et al., 2005; Dong and Sutton, 2015). Ficchi and Stephens (2019) found an influence of the patterns of variability of the Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO) on the timing of the start of the rainy season that translates into changes in river flood timing in sub-Saharan Africa, particularly East Africa. The wetter-than-normal rainy season in 2017 over West Africa, including the Western Sahel, was linked to the propagation of more intense, larger, and colder mesoscale convective systems across the region (Adegoke et al., 2019).

Mekonen (2020) attributed the above-average rainfall in the Sahel in 2019, with its largest positive anomalies in Chad and Sudan and drier conditions along the Guinea and western coastal regions, to persistently below-average sea surface temperatures off the coast of West Africa. Later in the year 2019, a record-breaking IOD led to extreme wet conditions in the headwaters of the White Nile (Wainwright et al., 2020). The extreme rains in the Blue Nile catchment in June–September 2020 could be partly attributed to a developing weak La Niña conditions; La Niña is known to enhance the rains during the Ethiopian Kiremt rainy season (June–September). Fig. 11a–d show the mean and anomalous atmospheric water vapor flux vectors for August 2020 for Sudan and its surroundings. Fig. 11b reveals anomalous and convergent westerly moisture flux in the belt 10–14°N, where the climatological moisture flux is easterly (Fig. 11a). A cyclonic flow in central-west Sudan, which can be interpreted as a vertically deeper and northward displacement of westerly monsoon flow, is evident. Fig. 11d exhibits anomalously high

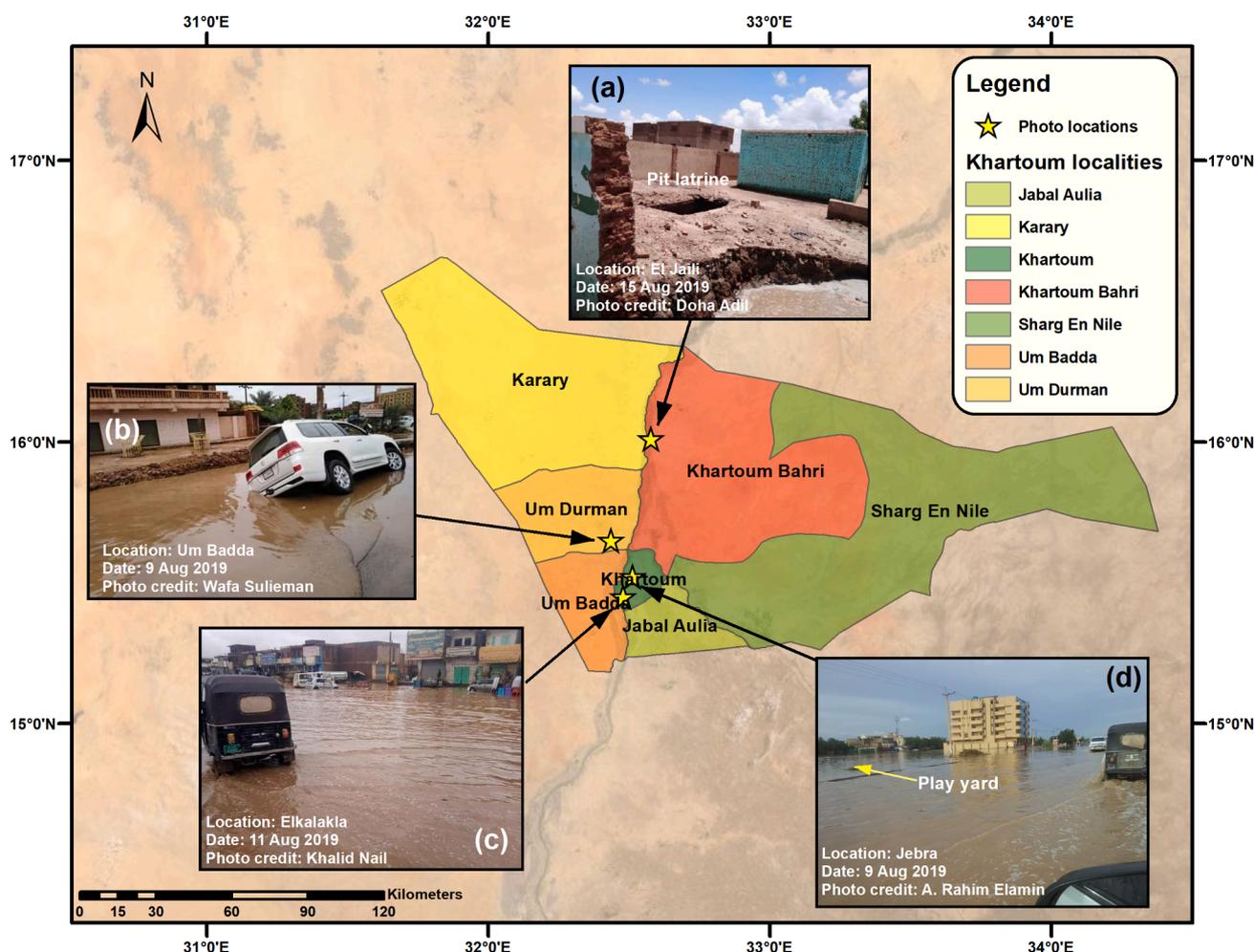


Fig. 9. Flash flood threats to Khartoum State in 2019. (a) Collapsed pit latrine, (b to d) vehicles trapped in flooded roads, and floodwater surrounded houses and markets, and (d) inundated residential complexes and play yards.

total columnar water vapor content (tcwv) values that prevailed in the entire region in August 2020, with strong anomalies in the order of 15–20% in the area of the strongest climatological zonal moisture gradient between 14° and 18°N (Fig. 11c). It is worth mentioning that the entire Sahel experienced positive rainfall anomalies during the 2020 West African monsoon season, of which August was the peak month. Unlike in the first half of the 20th century, wetter Kiremt rains over the Ethiopian highlands in the more recent period (1969–1999) were related to anomalous westerly flow across the Sahel (Bahaga et al., 2019 – their Fig. S3). Moreover, a significant positive correlation with the Atlantic Meridional Oscillation (AMO) emerged. The 2020 Sahel and Kiremt rains align with this recent multidecadal trend since the AMO was positive with the largest amplitude in August 2020 (<https://psl.noaa.gov/data/correlation/amon.us.data>). While anomalies of moisture flux weakened in September (not shown in Fig. 11), the troposphere remained anomalously moist over the region, likely facilitating the development of convective rainstorms.

The observations reported above with respect to the most recurrently flood-disrupted areas in Sudan (Figs. 3, 6, 9, and 10) concur with reports in the literature of the Sahel at large. An increase in the number of flood events per year has been recently reported, with urban areas suffering catastrophic consequences (Mahmood et al., 2017; De Risi et al., 2018; Adegoke et al., 2019; Tazen et al., 2019). Many flood events and impacts are traced back to proximity to, or settlement in, flood-prone areas (e.g., rivers flood plains, wadis, and low-lying areas), clay-silt soil that is compacted or of low infiltration capacity, inadequate drainage systems, lack of adaptation experience, poor quality of housing, changes in land

use, bad governance, weak institutional capacity, and/or poor urban planning (Hulme and Trilsbach, 1989; Walsh et al., 1994; Tarhule, 2005; Mahmoud et al., 2014; 2017; De Risi et al., 2018; Horn and Elagib, 2018; Adegoke et al., 2019; Tazen et al., 2019). In the Eastern Nile, the changes in land use/cover and degradation of the Upper Blue Nile Basin in Ethiopia increased high flows and decreased low flows (Bewket and Sterk, 2005; Woldesenbet et al., 2017).

5.2. Potential for climate and flood projection, forecasting and modeling

Climate projections of the mean changes in Sahel rainfall for the 21st century remain uncertain even under the latest Coupled Model Inter-comparison Project Phase 6 (CMIP6) model experiments, although the ensemble mean rainfall shows a robust increase in the central and eastern parts (Monerie et al. 2020). Projections indicate a likelihood of an increase in rainfall intensity over most of the Sahel rather than lengthening of the wet season (Vizy et al., 2013). Under climate change, climate model simulations further suggest an increase in the total annual and the year-to-year variability of the Nile flow in the 21st century (Siam and Eltahir, 2017). According to recent modeling scenarios, extreme precipitation events (e.g., extremely and consecutive wet days) are expected to increase in the future in the Central and Eastern Sahel in contrast to West Africa (Diedhiou et al., 2018; Aziz et al., 2019; Tegegne et al., 2020). The likely intensification of extreme and heavy precipitation events in Ethiopia (Tegegne et al., 2020) implies amplification of the probability of intense runoff and flood risks in the Eastern Sahel. However, almost all studies are thus far based on global or regional



Fig. 10. Flash and riverine floods threats to Sudan in 2020. a) Greenhouses, b) banana farmlands and c) other farmlands, where cattle egrets foraged for food, inundated when the Main Nile overran its banks. d) Floodwater of the Blue Nile in southeastern Sudan spilled into the streets and reached residential and built-up areas. e) and f) White Nile floodwater reached residential area and garbage collection point, respectively. g) and h) Heavy rains flooded electricity transmission lines and large open areas crossed by interstate highways, which usually lack culverts and block natural runoff. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

climate models that do not explicitly resolve the rain-bearing convective systems over Africa (e.g., [Salih et al., 2018](#)). Here, simulating future storms at convection-permitting resolution holds large promises in providing more confidence in predicting future extreme rainfall events, as shown recently by [Kendon et al. \(2019\)](#) and [Finney et al. \(2020\)](#).

Cumulative rainfall during consecutive rainy days appears to drive flooding in parts of the Sahel Region, for example, in Niger ([Taylor et al., 2017](#)). In East Africa, the influence of positive and negative phases of both IOD and ENSO can cause a difference in timing of the river flood of more than three months ([Ficchi and Stephens, 2019](#)); thus, skillful IOD and ENSO

seasonal predictions have a high potential for useful flood predictions. We notice from the literature for the eastern part of the Sahel (e.g., Khartoum) that floods took place repeatedly during the first fortnight of August, i.e., the peak of the rainy season ([Hulme and Trilsbach, 1989](#); [Williams and Nottage, 2006](#); [Mahmood et al., 2017](#)). Following the drought era, the Western Sahel zone appears to be confronting severe flood events almost throughout the first three weeks of August ([Tarthule, 2005](#); [Paeth et al., 2011](#); [Samimi et al., 2012](#)). This information could guide forecasters/prediction experts to improve the skillfulness of models during these periods of the season to improve the preparedness for flood management.

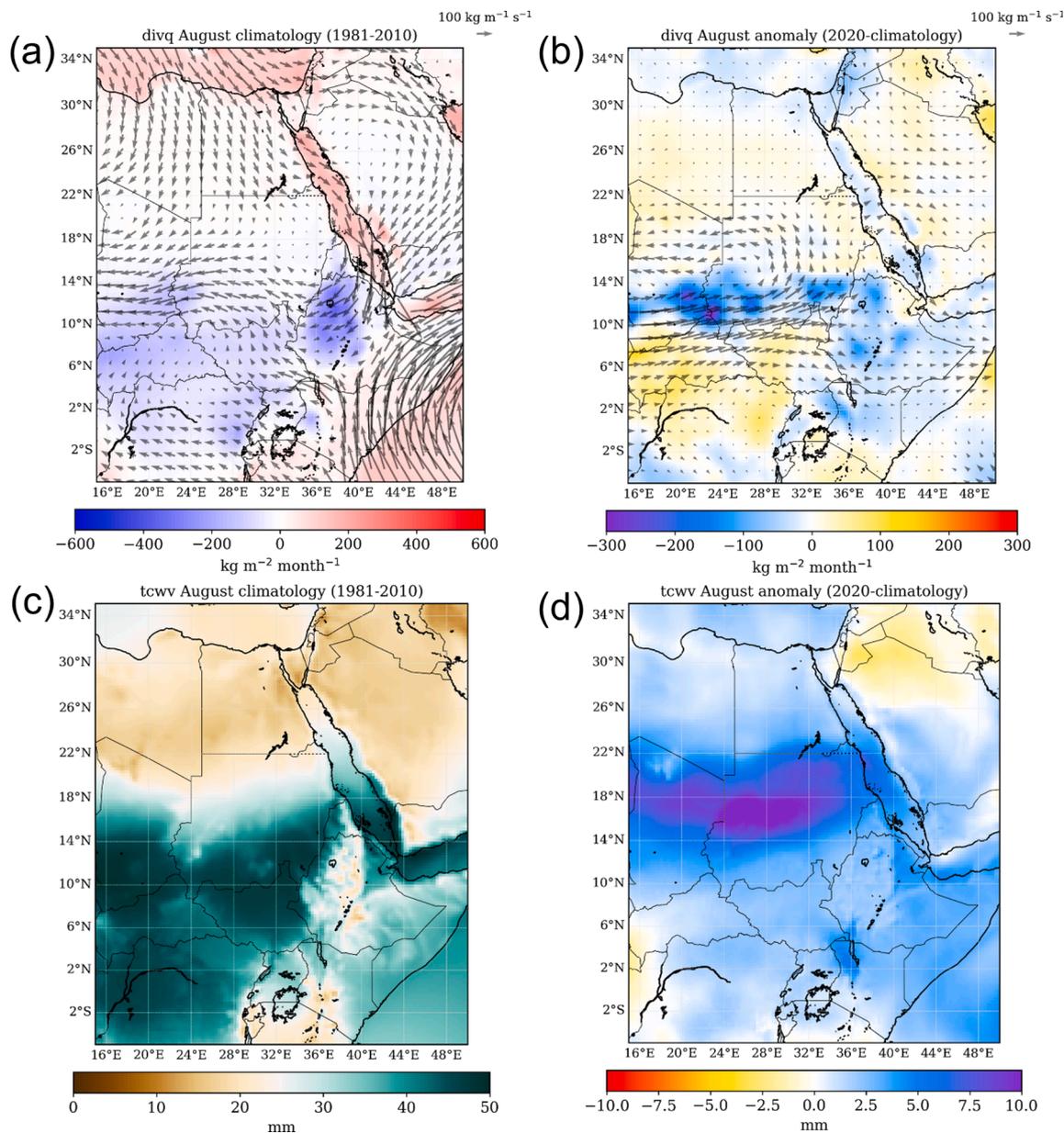


Fig. 11. Components of the atmospheric moisture budget in August 2020 in comparison to the climatology of 1981–2010. Moisture flux (vectors) and flux divergence presented as (a) mean and (b) anomalies. Negative (positive) values denote moisture flux convergence (divergence). (c) and (d) as in (a) and (b) but for total columnar water vapour content (tcwv). divq is the generic term referring to divergence and convergence of total atmospheric moisture flux.

Patt et al. (2007) concluded that “developing user-specific forecasts and interactive communication” is key to the success of the programs intended to utilize climate forecasting in Africa in climate adaptation and disaster risk reduction. The following part of this section offers an overview of attempts made to date to provide seasonal rainfall or flood forecast and modeling for the Sahel region.

The use of data on sea surface temperature anomalies and ENSO to issue seasonal rainfall predictions has been in practice by the West African Climate Outlook Forums since 1998 (Tschakert et al., 2010). Similarly, these predictors have been in use by the IGAD Climate Prediction and Application Centre (ICPAC) of the Intergovernmental Authority on Development (IGAD) in delivering climate services to Eastern Africa, including the East African Sahel countries.

For Sahelian catchments in the West African Sahel, Nka et al. (2015) found significant coherence between flood trends and trends in the maximum 5-day consecutive rainfall. However, they recommended using hydrological models to overcome the limitations inherent in the statistical rainfall-runoff relationship analysis, which overlooks the

spatial and temporal variability in specific hydrological processes.

Amarnath et al. (2016) used the Hydrologic Modeling System (HEC-HMS) to simulate the rainfall-runoff processes to improve flood forecasting in the Gash River Basin in Ethiopia and Sudan. The HEC-HMS model was supplemented with a land-use map, Digital Elevation Model (DEM) inputs, and the Soil Conservation Service (SCS) curve number (CN) and SCS unit hydrograph (UH) techniques to transform rainfall into runoff. The simulation performed well for river discharge values of lower than 200 m³/s. Compared to conventional forecasting methods, the flood forecast model improved the near real-time application by 12 h. However, Amarnath et al. (2016) emphasized the imperativeness of augmenting the data inputs to the model, such as catchment characteristics (e.g., evapotranspiration and land-use change impacts) on the water balance in addition to water abstraction in the upstream areas.

Recently, Fiorillo and Tarchiani (2017) proposed a Flooding Risk Evaluation Method (FREM) for small-medium basins based on a simplified version of the Soil Water Assessment Tool (SWAT), integrated

with remote sensing, Geographic Information Systems (GIS), and field surveys. Adopted at sub-basin level in Niger, they argued that the physically-based method is computationally efficient. A similar hydrological method was also used to develop catchment response to climate and land use changes in the Upper Blue Nile sub-basins in Ethiopia (Woldesenbet et al., 2018).

The Sudan Ministry of Water Resources and Irrigation developed a flood forecasting system for the flows of the Gash River (a transboundary basin shared between Ethiopia, Eritrea, and Sudan) using integrated satellite-based rainfall estimates and evapotranspiration, GIS, SCS-CN and SCS-UH, and HEC-HMS to share information on arriving floods with farmers through smart Information and Communication Technology (ICT) in the Gash Delta of Eastern Sudan (Amarnath et al., 2018). The work demonstrated a high potential for enabling the farmers to apply this information and manage their decisions for optimizing farm profits.

Due to scant data, Babker et al. (2020) demonstrated the applicability of the SCS-CN method coupled with GIS, land use/cover maps, DEM, soil data, and freely accessible gridded rainfall estimates for estimating the floodwater in the transboundary Baraka River Basin in Eritrea and Sudan. The approach proved successful for floodwater harvesting.

Current model-based seasonal forecasting of rainfall does not explicitly resolve convection, as the spatial resolution is usually too coarse. Lead-time-dependent bias corrections are thus mandatory (e.g., Lorenz et al. 2020). As a reference, the latter authors provide bias-corrected and spatially disaggregated daily precipitation ensemble forecasts for the Blue Nile. This attempt holds the promise to develop an improved ensemble flood forecast for that catchment.

5.3. Way forward

The ability to attribute causes of changing magnitude and frequency of floods is compounded by several factors, including precipitation extremes and characteristics, causative mechanisms of storms, changes in antecedent hydrologic conditions (water storage) and management, land-use changes, variations and trends in seasonal sea temperatures, etc. Quantifying these changes provides a crucial information base for optimizing our response and adaptation (Hirsch and Archfield, 2015; Sharma et al., 2018).

Climate variability over the last three decades should guide the management of rainfall-dependent activities and sectors (Conway, 2011). The present analysis should prompt more attention to floods, side-by-side with the prolonged focus on drought events, in order to capture the best interventions to manage both climate stressors on the region. There exist attempts to offer seasonal rainfall or flood forecast for the Sahel region; however, they remain humble in view of recurring catastrophic floods. The results of the present investigation on the timing of occurrence of extreme rainfall in the eastern and western parts of the Sahel represent possible forward-looking information for flood prediction. Understanding climate-related impacts and opportunities helps make societies resilient to future climate variability and change (Pielke Jr, 2005). However, to make effective adaptation decisions in the face of uncertain climate predictions, the vulnerability of climate-dependent decisions and the various means of reducing this vulnerability need to be well understood by the vulnerable societies (Dessai et al., 2009). Knowledge about future Sahel floods needs to guide relevant adaptation plans. By adapting to the inevitable climate change and variability, we could substantially reduce the number of those at increased risk of storm flooding (Parry et al., 1998). However, the lack of attention to flood risks in the Sahel hinders the development of effective flood adaptation plans. It is high time now that the effect of mere on-lookers within the communities of hydrology and climate sciences and policymaking come into play. Flood in the Sahel is currently viewed as an abnormality. This unviable attitude results in perceiving rainfall as a liability rather than a potential asset, exactly similar to the attitude used

to justify failing to “integrate drought characteristics into the planning process” (Hulme, 1987). Amid the ever synchrony of dry and wet conditions in the region, concerns about opportunities for floodwater harvesting should be stimulated to attenuate water scarcity in the region.

Health-wise, the control measures for cholera are vaccination for short-term mitigation and securing clean water supply for the affected regions for long-term prevention. Comprehensive vaccination would reduce future outbreaks because it treats the asymptomatic carriers, who would otherwise become a disease source. Control of mosquito-transmitted diseases is more complicated than cholera. Studies within the Sahel proved that this vector could migrate with the wind for distances as far as 300 km to affect other areas (Huestis et al., 2019). Hence, these diseases could be described as “transboundary” and must be controlled by inter-regional plans. In the year 2017, the World Health Organization (WHO) approved the Global Vector Control Response (GVCR), which should guide actions to prevent diseases and responses to outbreaks (WHO, 2017). The Ministry of Health of Khartoum State in Sudan launched an insecticide spraying campaign in cooperation with localities to combat flies and mosquitoes across the state (Sudan News Agency, 2020).

All plans and actions toward flood-risk reduction necessitate reliable information on projected hydroclimate changes (Taylor et al., 2017). Demand for information to make decisions is high in the region, likewise in many parts of Africa (Conway, 2011). Updated return periods of river discharges are imperative to ensure protection against floods and better river basin management (Wilcox et al., 2018). Relevant and reliable climate information is needed in managing all climate-sensitive diseases (Thomson et al., 2011). Unfortunately, the lack of recognition of the high flood risk and the paucity of data constrain relevant research and mitigation efforts (Tarhule, 2005).

6. Conclusions

The authors herein adopted a primary and secondary data integration method to study the recent Sahel pluvial and fluvial flood hazards, causes, status-quo, and forward-looking plans and actions for reducing the flood risks in the region. In light of the present investigation, it seems that the region is as liable to suffer from frequent floods as it is prone to multi-decadal droughts. The consequent massive flood of 2019 and 2020 in the Sahel, together with a sequence of yearly occurrence of heavy rainfall events during the past two decades, provide compelling evidence of an increasing risk of floods in the region. Addressing both extremes through a holistic risk management approach allows for better identification of relevant tradeoffs and synergies (Ward et al., 2020). Changes in natural patterns of climate variability and rainfall intensity, human interference in the physical environment, soil characteristics, and poor urban planning and governance are key influential factors in the increase of flood risk. Attempts made to date to communicate timely seasonal rainfall or flood forecasts remain humble, given that widespread havoc and devastation are becoming commonplace. Unlike droughts, the looming disaster brought about by the recent frequent floods in the Sahel is largely omitted worldwide among researchers and policymakers. Similar to the long-lasting Sahel drought of the 1970s and 1980s, a persistence of the flood risks would not surprise anyone if the recent history is any guide and given the expected climate change scenarios. Against the backdrop of alternating flood and drought risks to resources (e.g., water, land, and energy) and the environment in the Sahel zone, overlooking the characteristic flood situation in the hydroclimate of the Sahel is no longer viable.

7. Data availability statement

The [Flood-related statistics] data that support the findings of this study are available in/from [UN Office for the Coordination of Humanitarian Affairs], <https://reports.unocha.org/en/>, ReliefWeb [<http://reliefweb.int/>] and FloodList [<http://floodlist.com>]. The [Climate

Hazards Group InfraRed Precipitation with Stations (CHIRPS)] data that support the findings of this study are available in/from [U.S. Geological Survey (USGS) and the Climate Hazards Group of the University of California], [<https://data.chc.ucsb.edu/products/CHIRPS-2.0/>]. The [Landsat satellite images] data that support the findings of this study are available from [United States Geological Survey (USGS) data center at <https://earthexplorer.usgs.gov/>] with the identifier(s) [Landsat 8 OLI/TIRS Digital Object Identifier (DOI) number: <https://dx.doi.org/10.5066/F71835S6>]. The [ERA5 data (Copernicus Climate Change Service, 2017)] are available via <https://cds.climate.copernicus.eu>.

Author contributions

N.A.E. conceived the study, conducted the rainfall frequency analysis, and wrote the original manuscript. I.S.A. contributed by downloading, processing, mapping the satellite datasets, describing the corresponding data and methods, and creating the map of the study area. S.A.G.S contributed to the literature review and drafting of the health impacts. M.I.M. contributed to the compilation, analysis, and plotting of OCHA data graphs and drafting of the manuscript. M.B. contributed by analyzing the Nile water level, designing Figs. 5 and 9 and the graphical abstract, and substantively revising the manuscript. A. H.F. contributed to the meteorological explanation of the 2019 and 2020 wet conditions and literature review on climate projections and seasonal forecasts. All authors discussed the results and commented on the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank all of those who provided photos to support the depiction of flood impacts. They are all credited on the photographs. We thank Marlon Maranan for creating Fig. 11.

References

- Abbas, H.B., Routray, J.K., 2013. A semi-quantitative risk assessment model of primary health care service interruption during flood: Case study of Aroma locality, Kassala State of Sudan. *Int. J. Disaster Risk Reduct.* 6, 118–128.
- Adegoke, J., Sylla, M.B., Taylor, C., Klein, C., Bossa, A., Ogunjobi, K., Adounkpe, J., 2019. On the 2017 rainy season intensity and subsequent flood events over West Africa. In: Adegoke, J., Sylla, M.B., Bossa, A.Y., Ogunjobi, K., Adounkpe, J. (Eds.), *Regional Climate Change Series: Floods*. WASCAL Publishing, Ghana, Accra, pp. 10–14.
- Al Zayed, I.S., Elagib, N.A., 2017. Implications of non-sustainable agricultural water policies for the water-food nexus in large-scale irrigation systems: A remote sensing approach. *Adv. Water Resour.* 110, 408–422.
- Al Zayed, I.S., Elagib, N.A., Ribbe, L., Heinrich, J., 2016. Satellite-based evapotranspiration over Gezira Irrigation Scheme, Sudan: A comparative study. *Agric. Water Manage.* 177, 66–76.
- Amarnath, G., Alahacoon, N., Gismalla, Y., Mohammed, Y., Sharma, B.R., Smakhtin, V., 2016. Increasing early warning lead time through improved transboundary flood forecasting in the gash river Basin, Horn of Africa. In: Thomas E. Adams, III & Thomas C. Pagano (eds.), *Flood Forecasting: A Global Perspective*, Chapter 8, Academic Press, pp. 183–200.
- Amarnath, G., Simons, G.W.H., Alahacoon, N., Smakhtin, V., Sharma, B., Gismalla, Y., Mohammed, Y., Andriessen, M.C.M., 2018. Using smart ICT to provide weather and water information to smallholders in Africa: The case of the Gash River Basin, Sudan. *Clim. Risk Manage.* 22, 52–66.
- Assayha, 2019. <https://www.assayha.net/>.
- Aziz, F., Obuobie, E., Sylla, M.B., Jeong, J., Daggupati, P., 2019. Trends and projections of climate extremes in the Black Volta River Basin in West Africa. *Theor. Appl. Climatol.* 137 (1–2), 513–532.
- Babker, Z., Elagib, N.A., Al Zayed, I.S., Sulieman, R., 2020. Floodwater harvesting to manage irrigation water and mesquite encroachment in a data-sparse river basin: an eco-hydrological approach. *River Res. Appl.* 36 (9), 1852–1867.
- Bahaga, T.K., Fink, A.H., Knippertz, P., 2019. Revisiting interannual to decadal teleconnections influencing seasonal rainfall in the greater horn of africa during the 20th century. *Int. J. Climatol.* 39, 2765–2785.
- Basheer, M., Elagib, N.A., 2019. Temporal analysis of water-energy nexus indicators for hydropower generation and water pumping in the Lower Blue Nile Basin. *J. Hydrol.* 578, 124085.
- Basheer, M., Sulieman, R., Ribbe, L., 2021. Exploring management approaches for water and energy in the data-scarce Tekeze-Atbara Basin under hydrologic uncertainty. *Int. J. Water Resour. Dev.* 37 (2), 182–207.
- Bewket, Sterk, W.G., 2005. Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia. *Hydrol. Process.* 19, 445–458.
- Boyd, E., Cornforth, R.J., Lamb, P.J., Tarhule, A., Lélé, M.I., Brouder, A., 2013. Building resilience to face recurring environmental crisis in African Sahel. *Nat. Clim. Chang.* 3, 631–637.
- Casse, C., Gosset, M., 2015. Analysis of hydrological changes and flood increase in Niamey based on the PERSIANN-CDR satellite rainfall estimate and hydrological simulations over the 1983–2013 period. *Proc. Int. Assoc. Hydrol. Sci.* 370, 117–123.
- Cook, K.H., 2008. The mysteries of Sahel droughts. *Nat. Geosci.* 1, 647.
- Conway, D., 2011. Adapting climate research for development in Africa. *WIREs Clim. Change* 2, 428–450.
- Davies, H.R.J., Walsh, R.P.D., 1997. Historical changes in the flood hazard at Khartoum, Sudan: lessons and warnings for the future. *Singapore J. Trop. Geogr.* 18 (2), 123–140.
- Descroix, L., Genthon, P., Amogu, O., Rajot, J.L., Sighomnou, D., Vauclin, M., 2012. Change in Sahelian Rivers hydrograph: The case of recent red floods of the Niger River in the Niamey region. *Global Planet. Chang.* 98, 18–30.
- Dessai, S., Hulme, M., Lempert, R., Pielke Jr, R.A., 2009. Do we need better predictions to adapt to a changing climate? *Eos. Trans. Am. Geophys. Union* 90, 111–112.
- De Risi, R., Jalayer, F., De Paola, F., Lindley, S., 2018. Delineation of flooding risk hotspots based on digital elevation model, calculated and historical flooding extents: the case of Ouagadougou. *Stoch. Environ. Res. Risk Assess* 32, 1545–1559.
- Diedhiou, A., Bichet, A., Wartenburger, R., Seneviratne, S.I., Rowell, D.P., Sylla, M.B., Diallo, I., Todzo, S., N'datchoh, E.T., Camara, M., Ngatchah, B.N., 2018. Changes in climate extremes over West and Central Africa at 1.5 °C and 2 °C global warming. *Environ. Res. Lett.* 13 (6), 065020.
- Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., Ceccato, P., 2018. Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Q. J. R. Meteorol. Soc.* 144, 292–312.
- Dong, B., Sutton, R., 2015. Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nat. Clim. Change* 5, 757.
- Elagib, N.A., 2009. Assessment of drought across central Sudan using UNEP dryness ratio. *Hydrol. Res.* 40 (5), 481–494.
- Elagib, N.A., Gayoum Saad, S.A., Basheer, M., Rahma, A.E., Gore, E.D.L., 2021a. Exploring the urban water-energy-food nexus under environmental hazards within the Nile. *Stoch. Environ. Res. Risk Assess* 35, 21–41.
- Elagib, N.A., Khalifa, M., Babker, Z., Musa, A.A., Fink, A.H., 2021b. Demarcating the rainfed unproductive zones in the African Sahel and Great Green Wall regions. *Land Degrad. Dev.* 32 (3), 1400–1411.
- Epule, T.E., Ford, J.D., Lwasa, S., 2018. Climate change stressors in the Sahel. *GeoJ.* 83, 1411–1424.
- Federal Ministry of Health, 2020a, Preliminary Report on Reported Fever Cases in Northern State in Sudan Available at: <http://fmoh.gov.sd/index.php/posts/post/1937>. Accessed on 4 October 2020.
- Federal Ministry of Health, 2020b. Emergency Response to Flood Season. Available@ <http://fmoh.gov.sd/assets/uploads/files/2861d-ix9ov-it57d.pdf>, Accessed on 4 October 2020.
- Ficchi, A., Stephens, L., 2019. Climate variability alters flood timing across Africa. *Geophys. Res. Lett.* 46 (15), 8809–8819.
- Finney, D.L., Marsham, J.H., Rowell, D.P., Kendon, E.J., Tucher, S.O., Stratton, R.A., Jackson, L.S., 2020. Effects of explicit convection on future projections of mesoscale circulations, rainfall and rainfall extremes over Eastern Africa. *J. Clim.* 33, 2701–2718.
- Fiorillo, E., Tarchiani, V., 2017. A simplified hydrological method for flood risk assessment at sub-basin level in Niger. In: Tiepolo, M., Pezzoli, A., Tarchiani, V. (Eds.), *Renewing Local Planning to Face Climate Change in the Tropics*. Green Energy and Technology. Springer, Cham.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci. Data* 2, 1–21.
- Haarsma, R.J., Selten, F.M., Weber, S.L., Kliphuis, M., 2005. Sahel rainfall variability and response to greenhouse warming. *Geophys. Res. Lett.* 32.
- Hagos, S.M., Cook, K.H., 2008. Ocean warming and late-twentieth-century Sahel drought and recovery. *J. Clim.* 21, 3797–3814.
- Harrison, L., Funk, C., Peterson, P., 2019. Identifying changing precipitation extremes in Sub-Saharan Africa with gauge and satellite products. *Environ. Res. Lett.* 14, 085007.
- Haub, C., Kaneda, T. 2014. World population data sheet. Population Reference Bureau. Washington, DC.
- Hersbach, H., Bell, B., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, Janisková, E.M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I.,

- Vamborg, F., Villaume, S., Thépaut, J.-N., 2020. The ERA5 global reanalysis. *Q. J. R. Meteorol. Soc.* 146, 1999–2049.
- Hirsch, R.M., Archfield, S.A., 2015. Flood trends: Not higher but more often. *Nat. Clim. Change* 5 (3), 198–199.
- Horn, F., Elagib, N.A., 2018. Building socio-hydrological resilient cities against flash floods: Key challenges and a practical plan for arid regions. *J. Hydrol.* 564, 125–132.
- Huestis, D.L., Dao, A., Diallo, M., 2019. Windborne long-distance migration of malaria mosquitoes in the Sahel. *Nature* 574, 404–408.
- Hulme, M., 1987. Rainfall in central Sudan: An asset or a liability? *Geoforum* 18, 321–331.
- Hulme, M., 2001. Climatic perspectives on Sahelian desiccation: 1973–1998. *Global Environ. Change* 11, 19–29.
- Hulme, M., Trilsbach, A., 1989. The August 1988 storm over Khartoum: its climatology and impact. *Weather* 44, 82–90.
- Kendon, E.J., Stratton, R.A., Tucker, S., Marsham, J.H., Berthou, S., Rowell, D.P., Senior, C.A., 2019. Enhanced future changes in wet and dry extremes over Africa at convection permitting scale. *Nat. Commun.* 10 (1), 1–14.
- Kerr, R.A., 1985. Fifteen years of African drought. *Science* 227, 1453–1455.
- Kpanou, M., Laux, P., Brou, T., Vissin, E., Camberlin, P., Roucou, P., 2021. Spatial patterns and trends of extreme rainfall over the southern coastal belt of West Africa. *Theor. Appl. Climatol.* 143, 473–487.
- Lorenz, C., Portele, T.C., Laux, P., Kunstmann, H., 2020. Bias-corrected and spatially disaggregated seasonal forecasts: a long-term reference forecast product for the water sector in semi-arid regions. *Earth Syst. Sci. Data Discuss.* [preprint]. <https://doi.org/10.5194/essd-2020-177> in review.
- Ly, M., Traore, S.B., Alhassane, A., Sarr, B., 2013. Evolution of some observed climate extremes in the West African Sahel. *Weather Clim. Extremes* 1, 19–25.
- Ma, M., Wang, X., Veroustraete, F., Dong, L., 2007. Change in area of Ebinur Lake during the 1998–2005 period. *Int. J. Rem. Sens.* 28, 5523–5533.
- Mahmoud, W.H., Elagib, N.A., Gaese, H., Heinrich, J., 2014. Rainfall conditions and rainwater harvesting potential in the urban area of Khartoum. *Resour. Conserv. Recycl.* 91, 89–99.
- Mahmoud, M.I., Elagib, N.A., Horn, F., Saad, S.A., 2017. Lessons learned from Khartoum flash flood impacts: An integrated assessment. *Sci. Total Environ.* 601, 1031–1045.
- Mansell, G.M., 2003. *Rural and urban hydrology*. Thomas Telford, UK. ISBN: 727732307, 405 978-0727732309.
- Mekonen, A., 2020. Africa [in “State of the Climate in 2019”]. *Bull. Amer. Meteorol. Soc.* 101 (8), S350–S362. https://doi.org/10.1175/2020BAMSStateoftheClimate_Chapter7.e.
- Mohamed, A.B., 2011. Climate change risks in Sahelian Africa. *Reg. Environ. Change* 11 (1), S109–S117.
- Monerie, P.A., Wainwright, C.M., Sidibe, M., Akinsanola, A.A., 2020. Model uncertainties in climate change impacts on Sahel precipitation in ensembles of CMIP5 and CMIP6 simulations. *Clim. Dyn.* 55 (5), 1385–1401.
- Nature Editorial (NE), 2019. Ending drought. *Nature* 573, 310.
- Nicholson, S.E., Fink, A.H., Funk, C., 2018. Assessing recovery and change in West Africa’s rainfall regime from a 161-year record. *Int. J. Climatol.* 38, 3770–3786.
- Nicholson, S.E., Webster, P.J., 2007. A physical basis for the interannual variability of rainfall in the Sahel. *Q. J. R. Meteorol. Soc.* 133, 2065–2084.
- Nka, B.N., Oudin, L., Karambiri, H., Paturel, J.E., Ribstein, P., 2015. Trends in floods in West Africa: Analysis based on 11 catchments in the region. *Hydrol. Earth Syst. Sci.* 19 (11), 4707–4719.
- Padma, T.V., 2019. African nations take UN to task. *Nature* 573, 319.
- Paeth, H., Fink, A.H., Pohle, S., Keis, F., Mächel, H., Samimi, C., 2011. Meteorological characteristics and potential causes of the 2007 flood in sub-Saharan Africa. *Int. J. Climatol.* 31, 1908–1926.
- Panthou, G., Lebel, T., Vischel, T., Quantin, G., Sane, Y., Ba, A., Ndiaye, O., Diongue-Niang, A., Diopkane, M., 2018. Rainfall intensification in tropical semi-arid regions: The Sahelian case. *Environ. Res. Lett.* 13, 064013.
- Panthou, G., Vischel, T., Lebel, T., 2014. Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol.* 34, 3998–4006.
- Parry, M., Arnell, N., Hulme, M., Nicholls, R., Livermore, M., 1998. Adapting to the inevitable. *Nature* 395, 741.
- Patt, A.G., Ogallo, L., Hellmuth, M., 2007. Learning from 10 years of climate outlook forums in Africa. *Science* 318 (5847), 49–50.
- Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends Ecol. Evol.* 20, 503–510.
- Pielke Jr, R.A., 2005. Mis defining “climate change”: consequences for science and action. *Environ. Sci. Policy* 8, 548–561.
- Salih, A.A., Elagib, N.A., Tjernström, M., Zhang, Q., 2018. Characterization of the Sahelian-Sudan rainfall based on observations and regional climate models. *Atmos. Res.* 202, 205–218.
- Samimi, C., Fink, A.H., Paeth, H., 2012. The 2007 flood in the Sahel: causes, characteristics and its presentation in the media and FEWS NET. *Nat. Hazards Earth Syst. Sci.* 12, 313–325.
- Sharma, A., Wasko, C., Lettenmaier, D.P., 2018. If precipitation extremes are increasing, why aren’t floods? *Water Resour. Res.* 54 (11), 8545–8551.
- Siam, M.S., Eltahir, E.A., 2017. Climate change enhances interannual variability of the Nile river flow. *Nat. Clim. Change* 7, 350.
- Sissoko, K., van Keulen, H., Verhagen, J., Tekken, V., Battaglini, A., 2011. Agriculture, livelihoods and climate change in the West African Sahel. *Reg. Environ. Change* 11 (1), S119–S125.
- Sudan News Agency Khartoum State launches a spraying campaign to control flies and mosquitoes Available at: <https://www.sun-sd.net/read?id=700180> 2020. Accessed on 3 January 2021.
- Suleiman, H.M., Elagib, N.A., 2012. Implications of climate, land-use and land-cover changes for pastoralism in eastern Sudan. *J. Arid Environ.* 85, 132–141.
- Sutcliffe, J.V., Dugdale, G., Milford, J.R., 1989. The Sudan floods of 1988. *Hydrolog. Sci. J.* 34, 355–364.
- Tanaka, M., Weare, B.C., Navato, A.R., Newell, R.E., 1975. Recent African rainfall patterns. *Nature* 255, 201–203.
- Tarhule, A., 2005. Damaging rainfall and flooding: The other Sahel hazards. *Clim. Change* 72, 355–377.
- Taye, M.T., Willems, P., 2012. Temporal variability of hydroclimatic extremes in the Blue Nile basin. *Water Resour. Res.* 48.
- Taylor, C.M., Belušić, D., Guichard, F., Parker, D.J., Vischel, T., Bock, O., Harris, P.P., Janicot, S., Klein, C., Panthou, G., 2017. Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature* 544, 475.
- Tazen, F., Diarra, A., Kabore, R.F., Ibrahim, B., Bologo/Traoré, M., Traoré, K., Karambiri, H., 2019. Trends in flood events and their relationship to extreme rainfall in an urban area of Sahelian West Africa: The case study of Ouagadougou, Burkina Faso. *J. Flood Risk Manage.* 12, e12507.
- Tegegne, G., Melesse, A.M., Alamirew, T., 2020. Projected changes in extreme precipitation indices from CORDEX simulations over Ethiopia. *East Africa. Atmos. Res.* 247, 105156.
- Thomson, M.C., Connor, S.J., Zebiak, S.E., Jancloes, M., Mihretie, A., 2011. Africa needs climate data to fight disease. *Nature* 471, 440.
- Tschakert, P., Sagoe, R., Ofori-Darko, G., Codjoe, S.N., 2010. Floods in the Sahel: an analysis of anomalies, memory, and anticipatory learning. *Clim. Change* 103, 471–502.
- USGS, 2019. *Landsat Missions*. United States Geological Survey. <https://www.usgs.gov/1-and-resources/nli/landsat/using-usgs-landsat-level-1-data-product>.
- Vermorel, E., Justice, C., Claverie, M., Franch, B., 2016. Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sens. Environ.* 185, 46–56.
- Vizy, E.K., Cook, K.H., Crétat, J., Neupane, N., 2013. Projections of a wetter Sahel in the twenty-first century from global and regional models. *J. Clim.* 26, 4664–4687.
- Wainwright, C.M., Finney, D.L., Kilavi, M., Black, E., Marsham, J.H., 2020. Extreme rainfall in East Africa, October 2019–January 2020 and context under future climate change. *Weather* 75 (1), 26–31.
- Walsh, R.P.D., Davies, H.R.J., Musa, S.B., 1994. Flood frequency and impacts at Khartoum since the early nineteenth century. *Geogr. J.* 160, 266–279.
- Ward, P.J., de Ruiter, M.C., Mård, J., et al., 2020. The need to integrate flood and drought disaster risk reduction strategies. *Water Secur.* 11, 100070.
- Washington, R., Harrison, M., Conway, D., Black, E., Challinor, A., Grimes, D., Jones, R., Morse, A., Kay, G., Todd, M., 2006. African climate change: taking the shorter route. *Bull. Am. Meteorol. Soc.* 87, 1355–1366.
- WHO, 2017. *Global Vector Control Response 2017–2030*. World Health Organization. <https://www.who.int/vector-control/publications/global-control-response/en/>.
- WMO, 2020. In: 2020 State of Climate Services: Risk information and early warning systems, WMO-No. 1252. World Meteorological Organization, Switzerland, p. 48.
- Wilcox, C., Vischel, T., Panthou, G., Bodian, A., Blanchet, J., Descroix, L., Quantin, G., Cassé, C., Tanimoun, B., Kone, S., 2018. Trends in hydrological extremes in the Senegal and Niger Rivers. *J. Hydrol.* 566, 531–545.
- Williams, M., Nottage, J., 2006. Impact of extreme rainfall in the central Sudan during 1999 as a partial analogue for reconstructing early Holocene prehistoric environments. *Quatern. Int.* 150, 82–94.
- Woldesenbet, T.A., Elagib, N.A., Ribbe, L., Heinrich, J., 2017. Hydrological responses to land use/cover changes in the source region of the Upper Blue Nile Basin. *Ethiopia. Sci. Total Environ.* 575, 724–741.
- Woldesenbet, T.A., Elagib, N.A., Ribbe, L., Heinrich, J., 2018. Catchment response to climate and land use changes in the Upper Blue Nile sub-basins, Ethiopia. *Sci. total Environ.* 644, 193–206.
- Zhang, W., Brandt, M., Guichard, F., Tian, Q., Fensholt, R., 2017. Using long-term daily satellite based rainfall data (1983–2015) to analyze spatio-temporal changes in the Sahelian rainfall regime. *J. Hydrol.* 550, 427–440.