IOP Publishing *Environ. Res. Lett.* **15** (2020) 1040b5 https://doi.org/10.1088/1748-9326/abb90b

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
15 July 2020

REVISED
10 September 2020

ACCEPTED FOR PUBLICATION
16 September 2020

PUBLISHED
13 October 2020

LETTER

Observed changes in flood hazard in Africa

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Keywords: Floods, Africa, trends, extreme precipitation

Supplementary material for this article is available online

Abstract

Floods represent a major natural hazard in Africa, causing over 27 000 fatalities during the period 1950–2019. Despite its relevance, little is known about changes in flood hazard across this continent due to the lack of long-term high-quality streamflow records. Here we use a newly assembled discharge dataset of African rivers, and provide a long-term comprehensive view of flood hazard across this continent. We show that the annual maximum peak discharge does not exhibit a monotonic pattern, but overall decreasing trends prior to 1980 and increasing trends afterwards, especially in western and southern Africa. Our results indicate that these differing trends can be ascribed to changes in extreme precipitation around 1980. Moreover, these changes in intense precipitation pre/post 1980 are due to increased thunderstorm activity associated with enhanced convective available potential energy and zonal vertical shear driven by cooling temperature trends over western Africa. The changes in flood hazard in southern Africa can be tied to changes in Namibia low-level jet. Therefore, the observed increase in flooding since 1980 suggests that it would be beneficial to improve the monitoring, modeling and communication of flood hazard to reduce the socio-economic impacts of these events.

1. Introduction

Several studies have shown a possible increase in flood hazard for different regions of the globe based on both observations and future climate-driven scenarios (e.g. Alfieri *et al* 2017, Do *et al* 2017, 2020, Hodgkins *et al* 2017), however, there is also significant regional variability and the attribution of these changes is often contradictory (Najibi and Devineni 2018, Yin *et al* 2018). Even though there are continental-scale analyses to document long-term trends in floods and their potential driving mechanisms (e.g. Villarini *et al* 2009, Ivancic and Shaw 2015, Blöschl *et al* 2015, 2019, Winsemius *et al* 2016, Wasko and Sharma 2017, Wasko and Nathan 2020), very little is known at the African scale, and most of the published work deals with sub-regions with a limited number of stations (e.g. Di Baldassarre *et al* 2010, Nka *et al* 2015, Wilcox *et al* 2018). For instance, Di Baldassarre *et al* (2010) examined 79 series mostly located in central and north Africa spanning from 1900 to 2000; they found no significant monotonic trends in annual maximum discharge at 65 stations, with increasing trends at only 4 hydrometric stations. Despite the lack of clearly increasing trends, they commented on the increase in flood fatalities in several African countries, especially during 1990–2009. Do *et al* (2017) provided a global assessment of flood trends using the Global Runoff Data Centre (GRDC) database, including 58 stations across Africa. Over the period 1955–2014, they reported a global decrease in flood magnitude, in particular in West Africa, but increasing trends for stations located in South Africa. Nka *et al* (2015) and Wilcox *et al* (2018) analyzed long term trends in 11 catchments located in West Africa; they reported an increase in flood magnitude after the 1980s at some sites, even though the flood magnitudes were smaller than what was measured in the early 1950s. Only a few studies have previously analyzed flood trends in North Africa (Abida and Ellouze 2008, Khomsi *et al* 2016), without detecting statistically significant trends. Africa is usually under-represented in global analyses due to the limited number of stations with observed discharge available in databases such as the GRDC (Wasko and Sharma 2017, Yin *et al* 2018).

It is therefore clear that we have limited observational evidence to provide a comprehensive and continent-wide assessment of the changes in flooding across Africa. Here we leverage a newly compiled discharge dataset to provide the first continental assessment of trends in Africa, and to relate these findings to changes in the large-scale environmental conditions from 1950 to 2010.

2. Data and methods

The database used in the present work is based on the collection of stations from the GRDC and the SIEREM (Dieulin *et al* 2019) databases with a minimum of 10 full years of daily discharge data between 1950 and 2018. Years with more than 5% missing days were discarded. In cases when different time series existed for the same station in the different databases, only the longest series was kept to avoid issues related to the use of different rating curves. This work results in the largest ever built database of daily discharge data in Africa, with a total of 1529 stations. These stations belong to different climate zones, according to the Köppen-Geiger climate classification. The main climate zone is Savannah (class Aw) (687 stations located in the west and central Africa basins). The second most represented climate zone is Steppe-hot (Bsh), with 207 stations located in the Sahel region and south Africa (Botswana, Namibia). The temperate with dry winter classes (Cwa and Cwb) includes 187 and 125 stations respectively, located in South Africa (Zambia, Angola, Rwanda, Mozambique, Zimbabwe). The 98 stations belonging to the Desert-hot class (Bwh) are mostly located in the northern and southern boundaries of the Sahara desert. Eighty-seven stations under a temperate climate with dry hot summer, corresponding to Mediterranean climate (Csa), are found in North Africa and southwestern part of South Africa.

Station catchments have been delineated with the Hydroshed DEM (Lehner *et al* 2008) (http://hydrosheds.cr.usgs.gov) at 15 sec resolution. Dams and reservoirs have been extracted from the Global Reservoir and Dam Database (GRanD) v1.3 (Lehner *et al* 2011) to identify regulated basins. The number of dams included in each river basin has been extracted. The rivers are considered regulated if at least one dam exists in the catchment area, otherwise the river is considered natural. It should be noted that other structures like small dams that may not be included in the GRanD database could be present in the catchments classified as natural. In addition, land cover maps from the European Space Agency (ESA) CCI Land Cover time-series v2.0.7 (ESA 2017) at a 300 m spatial resolution were also considered; the number of pixels for each land cover class in the basins has been extracted for 1992 and 2015 to provide estimates of land cover changes. In addition to the catchment data, the number of deaths, the population affected and the total damage costs related to flood events since 1950 are extracted from the Emergency Events Database (EM-DAT, CRED/UCLouvain, Brussels, Belgium—www.emdat.be).

Annual maximum discharge values are extracted from the daily series with at least 15 complete hydrological years (September of year n to August of year n + 1) between 1950 and 2010 resulting in 884 viable stations (it should be noted that the definition of the hydrological year could influence the detection of flood trends; Wasko *et al* 2020). For trend detection, we use the Mann-Kendall test (Mann 1945) adapted to account for autocorrelation (Hamed and Ramachandra Rao 1998). To get a quantitative estimate of the slope of the trend, we use the Sen slope estimator (recognizing that it implies a linear trend, rather than a monotonic pattern). Since the Mann-Kendall test only detects monotonic changes, we also use the Pettitt test (Pettitt 1979) on the annual maximum discharge values to detect change points. The Kruskal-Wallis test (Kruskal and Wallis 1952) is implemented to evaluate the difference in catchment properties (i.e. catchment size, elevation, land cover classes) for stations with significant trends. It is a non-parametric method for testing whether different samples originate from the same distribution and it is equivalent to a one-way analysis of variance but relaxing the Gaussian hypothesis for the response variables.

The atmospheric variables are obtained from National Centers for Atmospheric Prediction and the National Center for Atmospheric Research reanalysis (Kalnay *et al* 1996) at 2.5° × 2.5° spatial resolution. These variables include surface temperature, and three-dimension winds, temperature and specific humidity. Daily precipitation is obtained from the Rainfall Estimates on a Gridded Network (REGEN) data set (Contractor *et al* 2020), which is a global land-based data set starting from 1950 based on an interpolated network of *in situ* data. The REGEN data set combines different *in-situ* data including the Global Historical Climatology Network—Daily (GHCN-Daily) hosted by National Centres of Environmental Information, USA, and the Global Precipitation Climatology Centre made by Deutscher Wetterdienst, leading to a high station density compared to other datasets. Tropical cyclone information is obtained from the International Best Track Archive for Climate Stewardship, including six-hourly longitude, latitude, maximum sustained wind and time at each tropical cyclone center (Knapp *et al* 2010). Tropical cyclone locations are binned into 5° × 5° grids.

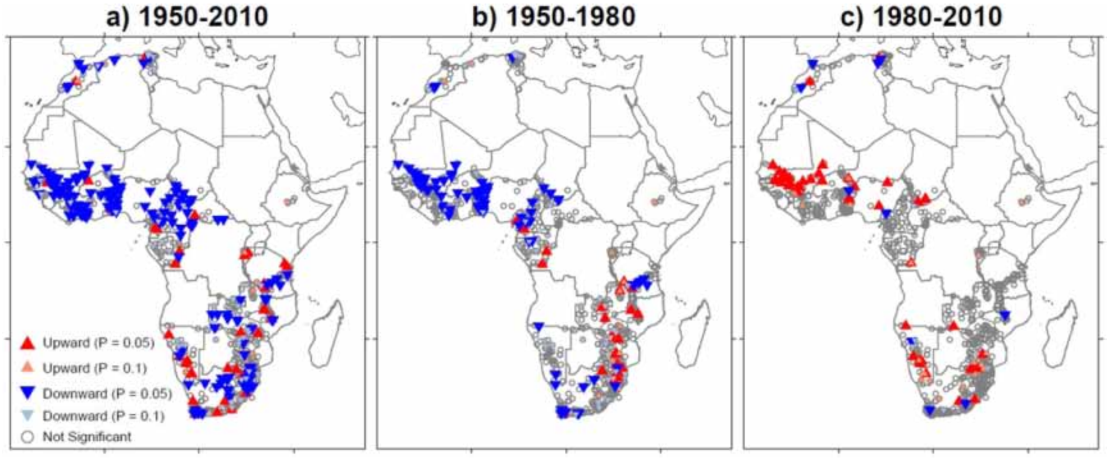

Figure 1. Trends in annual maximum discharge across Africa. The results are based on the Mann-Kendall test applied to the time periods: (a) 1950–2010, (b) 1950–1980, and (c) 1980–2010.

3. Results

Figure 1(a) shows that there are statistically significant decreasing trends in annual maximum discharge at 214 out of 884 stations during 1950–2010, with increasing trends at only 60 stations. Overall, the largest changes are clustered in western and southern Africa. Based on these results, we would conclude that flooding in Africa has been decreasing since the 1950s, consistent with the results obtained by previous studies (Do *et al* 2017, Wasko and Sharma 2017). However, a closer observation of the time series highlights the presence of abrupt changes in these records, similar to what previously detected in some rivers in West Africa, including the Senegal and Niger basins (Wilcox hbox*et al* 2018, Descroix *et al* 2018). Statistically significant change points are detected at 168 stations, with most of the changes occurring in the 1970s and 1980s (figure S1 (https://stacks.iop.org/ERL/15/1040b5/mmedia)). Therefore, if we split the time series before and after 1980 and perform the trend analysis on each of the two sub-series separately (Villarini *et al* 2009), we end up with a different story (figures 1(b)–(c)). The decreasing trends identified over the entire period were largely representative of the tendencies prior to 1980 (figures 1(a)–(b)). However, the picture is much different after 1980: most of the detected trends are now increasing, especially in western and southern Africa. For the time period 1950–1980, 100 negative trends and 42 positive trends are reported. However, 68 upward trends are detected after 1980 and only 19 decreasing (at the 5% significance level; figures 1(b) and (c)). When considering the number of deaths, the population affected and the total economic costs of floods, these quantities show increasing trends since 1950 (figure 2). The number of deaths has remained elevated but stable since 1990 with more than 6000 deaths/decade due to floods. Over the whole period 1950–2019, floods caused the deaths of 27 702 people, affecting over 82 million people, and the total costs of floods show a marked increase after the year 2000. While these impacts include changes in population, exposure and reporting, they better align with the idea that flooding in Africa has been increasing, rather than decreasing as we would have concluded based on the analyses of the entire record.

Why do we see these differences before and after 1980? We started by examining the differences in catchment properties to distinguish stations with positive or negative trends using the Kruskal-Wallis test. Stations with decreasing trends in annual maximum discharge during the period 1950–1980 have, on average, a larger catchment size and lower elevation than catchments with positive trends. For the time period 1981–2010, robust comparisons cannot be made since there are only 19 catchments with decreasing trends. The presence of dams and reservoirs does not strongly influence flood trends, since only one third of the basins with decreasing floods during the two sub-periods are regulated by at least one dam or reservoir. However, the presence of dams is respectively higher (smaller) in the sample of stations with decreasing (increasing) trends by comparison with the stations without trends. These findings are consistent with previous studies in other regions, which described larger catchments being more prone to decreasing floods (Ivancic and Shaw 2015, Do *et al* 2017, Sharma *et al* 2018) due to a greater influence of soil moisture storage (Nathan and Wasko, 2019), and similar trends in regulated or natural catchments (Ficklin *et al* 2018). No relationships could be found between flood trends and the land cover of the basins, highlighting the complex interplays between catchment morphology, land use and land cover with climatic variability.

While it is hard to identify physical drivers associated with these basins as responsible for the observed

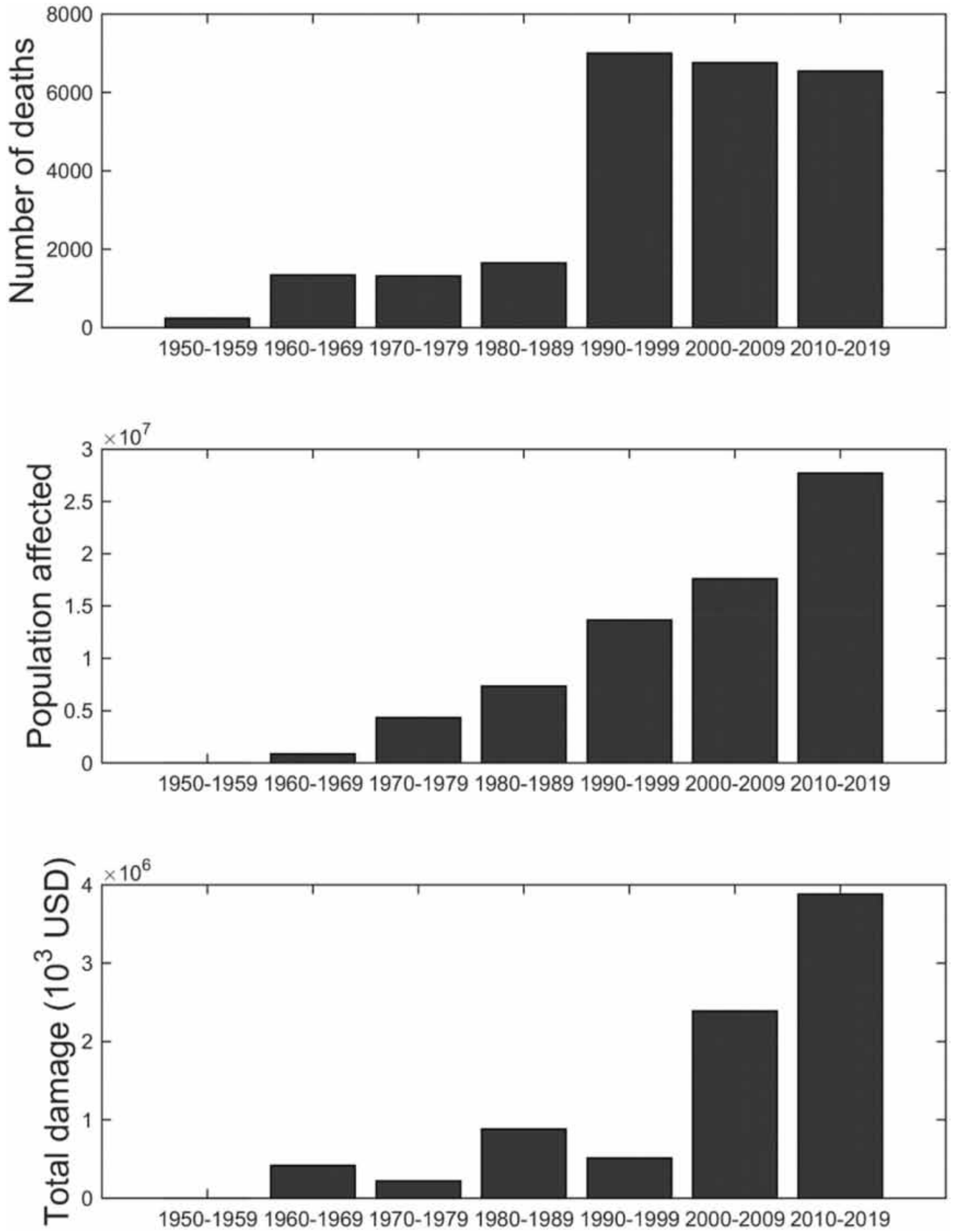

Figure 2. Number of deaths, population affected and total damage costs (valid for the dates in which the events happened) by decades since 1950 related to floods in Africa (Source: EM-DAT database).

trends, changes in the weather and climate of this continent provide a framework to interpret these results. Total precipitation at the annual or seasonal scales decreased between 1950–1980 and 1981–2010 (figure S2). Analyses of extreme precipitation, on the other hand, tell a different story (figure 3). There are decreasing trends in the 99th percentile of the seasonal precipitation distribution during 1950–1980, while the opposite is true for the 1981–2010 period (see also Harrison *et al* 2019). These results are consistent during both June-July-August (JJA) and December-January-February (DJF), and the strongest signal is in West Africa, consistent with what was found by Panthou *et al* (2018) and Taylor *et al* (2017) and during JJA. Therefore, the precipitation analyses indicate that the observed reversal of the trends in flood extremes pre- and post-1980 is not consistent with changes in the total amount of precipitation, but rather with changes in extreme precipitation, especially in West Africa.

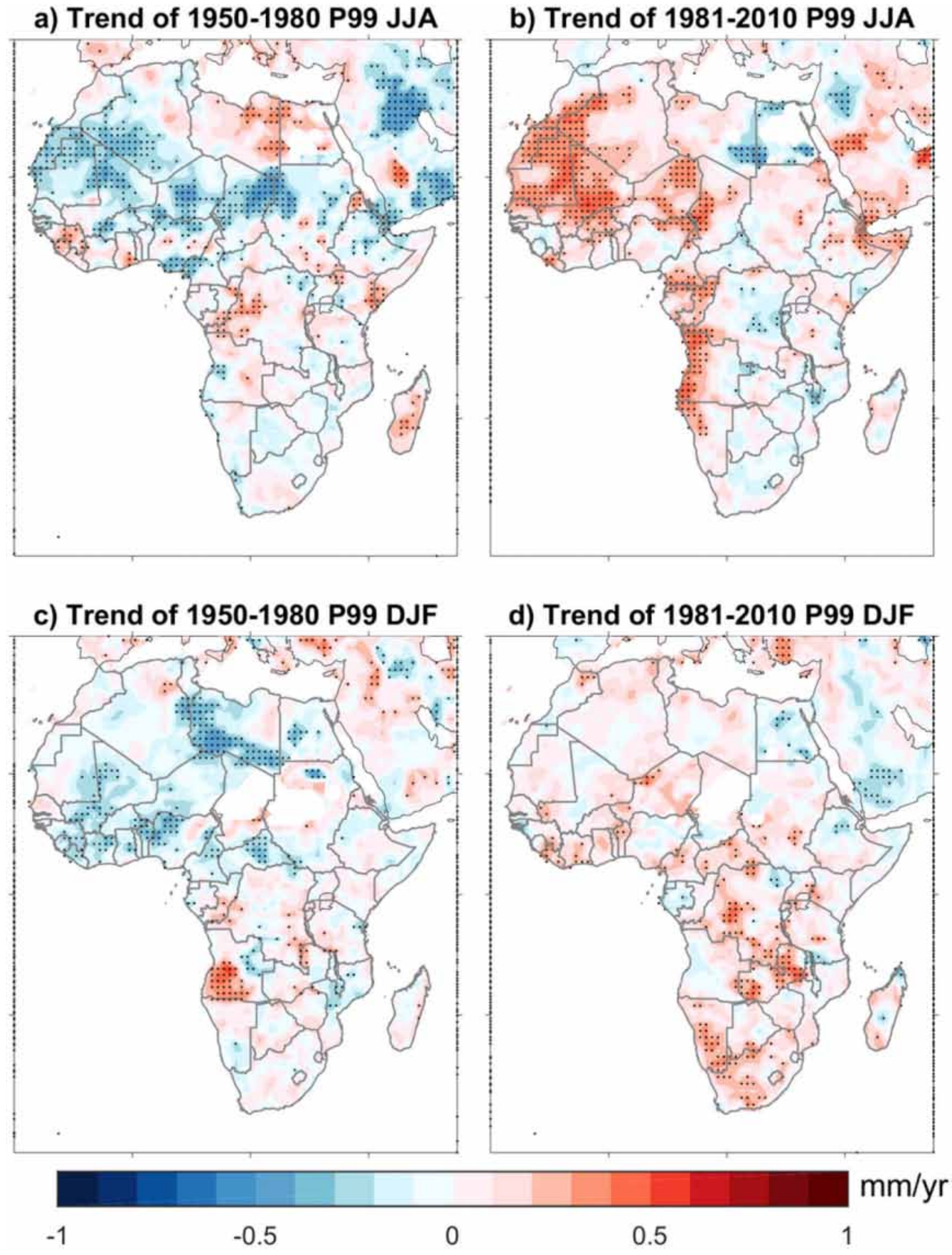

Figure 3. Trends in extreme precipitation. The top panels show the trends in the 99th percentile of the daily precipitation distribution (shading, mm/yr) during June-August, while the bottom panels the results for December-February. The left (right) columns represent the trends computed over the 1950–1981 (1981–2010) period. The hatching represents regions where the trends are statistically significant at the 0.05 level.

The next question we ask is related to the drivers responsible for the observed changes in extreme precipitation. Figure 4 shows that these results can be explained in terms of changes in the environmental conditions conducive to summertime thunderstorms and mesoscale convective systems. In JJA during 1950–1980, convective available potential energy (CAPE) shows increasing trends in southern West Africa, and decreasing trends north of it (figure 4(a)). The situation is very different, however, during 1981–2010: the decreasing trends are much more muted, and have been replaced by increasing trends, matching well the region exhibiting increasing trends in flooding and extreme precipitation post-1980 (figure 1(c)). These findings are further supported by the analyses of the zonal vertical shear, leading to

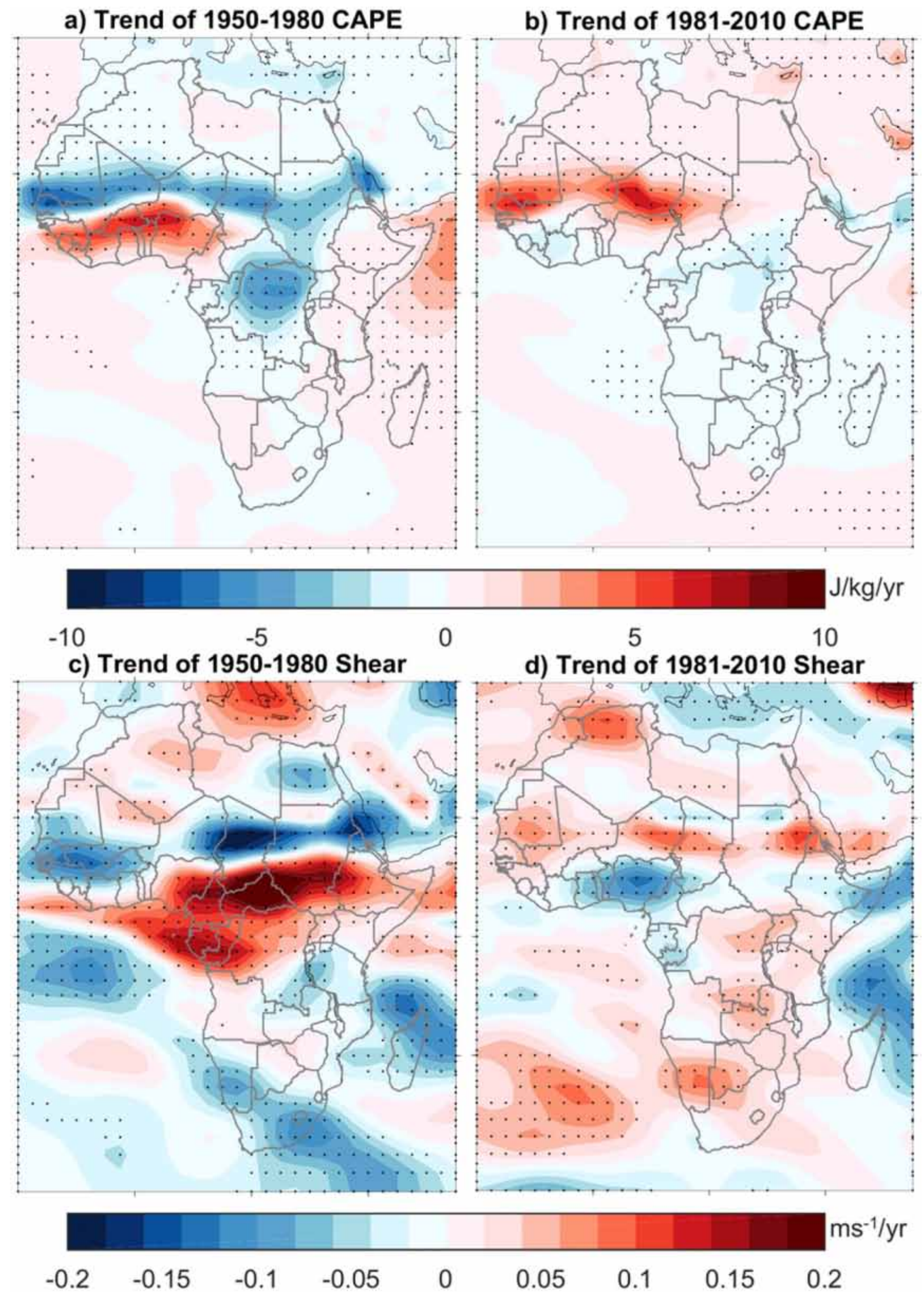

Figure 4. Results showing the climate drivers for the observed changes in extreme precipitation. The top panels show the trend of JJA CAPE (shading; units: J kg yr^{-1}), while the bottom panels the trends in vertical wind shear (computed as the wind difference between 925 hPa and 600 hPa levels; units: ms^{-1} yr^{-1}). The left (right) panels show the results for the 1950–1980 (1981–2010) period. The hatching represents regions where the trends are statistically significant at the 0.05 level.

more favorable conditions for the enhancement of mesoscale convective activity during 1981–2010 compared to 1950–1980 (figure 4, bottom panels). From a climate dynamics perspective, these results can be tied to a cooling trend in western Africa in JJA during 1981–2010. Climatologically, the mean temperature in the Saharan region is higher than the Sahelian region during JJA (Cook and Vizy 2015), causing a meridional temperature gradient (north high and south low) (figure S3). Moreover, we find negative temperature trends in the Sahelian region and positive trends in the Saharan regions during JJA of 1981–2010 (figure S3). The Saharan/Sahelian warming/-cooling trends may lead to an increase in the meridional temperature gradient, which may be responsible for the increasing vertical shear based on the thermal wind relationship (figure S3).

If we switch our attention to southern Africa, we detect a reversal in trends pre/post 1980, even though of a smaller magnitude compared to West Africa. The trends in extreme precipitation are different between the two sub-period in DJF (figure 3, bottom panels). The trends in southern Africa can be explained in the context of the Namibia low-level jet, which transports moisture in south-west Africa (figure S4). Comparing the intensity of the jet before and after 1980, we observe that there is an enhancement of moisture transported on land in the most recent decades, leading to an enhancement in extreme precipitation over that part of the continent. Analyses of tropical cyclone activity in south-eastern Africa do not point to a significant difference between the two periods (figure S5).

4. Conclusions

This study provided a comprehensive view of the changes in flood hazard across Africa, and showed that flood extremes have not been changing monotonically. We were able to attribute these changes to extreme precipitation associated with thunderstorms and mesoscale convective systems in West Africa, and to changes in the Namibia low-level jet in southern Africa. Based on these results, flood hazard in Africa can alternate between quiet and active periods in response to the large-scale environmental conditions. A careful assessment of future climate conditions will be necessary to get a better indication of the flood hazard for this continent during the 21st century. In particular, we showed that total and extreme precipitation can have opposite trends, with the latter playing an important role in explaining the trends in flooding. This has important implications as we consider what the future flood hazard for Africa may shape up to be. For instance, recent climate scenarios (Kendon *et al* 2019) indicate that most of tropical Africa is projected to experience more intense precipitation, while at the same time a reduction in wet-season rainfall. Therefore, according to our findings, it is also likely that flooding would be projected to increase.

Here we were able to attribute the observed changes in flood extremes largely to the climate system; when we tried to frame them in the context of changes that happened within the watersheds, we did not find that they could explain the differences in trends among different basins. With that said, future work should evaluate in more details the role played by changes in the landscape, land use/land cover, and damming, as we expect that they modulate the hydrologic response to the observed changes in extreme precipitation (Laraque *et al* 2001, Descroix *et al* 2009, 2012, 2018, Mahe *et al* 2013, Sidibe *et al* 2018). Given the high vulnerably of African countries to flooding, the results highlight the benefits of improving monitoring, modeling and communication of the flood risk across this continent to mitigate the adverse impacts of future floods.

Acknowledgments

This material is based upon research supported by the Thomas Jefferson Fund of the Embassy of France in the United States and the FACE Foundation. The authors would like to thank Nathalie Rouche and Claudine Dieulin for the SIEREM data extraction and processing. The data provided by the Global Runoff Data Centre, 56068 Koblenz, Germany is also acknowledged. Villarini also acknowledges the support of the U.S. Army Corps of Engineers' Institute for Water Resources.This work is dedicated to the memory of Claudine Dieulin who passed away in January 2020 during the course of this project.

Author contributions

YT and GV designed the experiments; YT and WZ performed the analyses. All authors interpreted the results and wrote the paper.

Competing interests

Nothing to declare.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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