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Key Points:
- CESM low warming simulations are used to analyze mean and extreme high-temperature events over Africa under 1.5 and 2 °C warming worlds
- Currently, once-in-20-year heat events across Africa may become approximately twice as common under 2 °C world than under 1.5 °C world
- Limiting warming to 0.5 °C lower than 2 °C may lead to between 29% and 42% reductions in intensity and frequency of heat events across Africa

Supporting Information:
- Supporting Information S1

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High-Temperature Extreme Events Over Africa Under 1.5 and 2 °C of Global Warming

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Abstract With anthropogenic global warming, heat-related extreme events are projected to increase in severity and frequency. Already vulnerable regions like Africa will be hard-hit. Therefore, such regions could benefit from low global warming levels. Using the Community Earth System Model low warming simulations, we investigate changes in temperature extremes across Africa as a function of global mean temperature in the context of the implications of the Paris Agreement's targets. A significant warming across Africa is projected at the 1.5 °C warming world and is amplified at the 2 °C world, exceeding the mean global warming rate. Specifically, North Africa and East Africa regions are projected to have the highest and lowest temperature changes of 0.63 °C (0.60–0.67 °C) and 0.50 °C (0.47–0.54 °C), respectively, between the 1.5 and 2 °C warmer worlds. Consequently, hot events are also estimated to increase with global warming. We showed that limiting warming to 1.5 °C instead of 2 °C may lead to 29% (27–31%) to 35% (33–37%) reduction in severity of hot events and to 31% (30–33%) to 42% (39–48%) reduction in the frequency of the threshold-based high-temperature events across Africa. The highest reductions are projected over North Africa. Furthermore, restricting warming to 0.5 °C lower than 2 °C might also result in 28% (34–40%) to 37% (25–34%) reduction in severity of once-in-10/20-year heat events across Africa with North Africa having the highest benefits than tropical regions. Thus, restricting warming to low levels may indeed translate to substantial benefits of reduced intensity and frequency of extreme heat events across Africa.

Plain Language Summary As global warming continue to increase extreme daily temperatures, efforts to limit this warming to low levels could be of much benefit to Africa, an already vulnerable populous region. Therefore, the agreed 1.5 and 2 °C global warming targets under the Paris Agreement might have substantial paybacks. Here, we used a suite of unique climate simulations to investigate differences in high-temperature extremes under the 1.5 and 2 °C warming worlds across Africa. We found that limiting warming to 0.5 °C lower than 2 °C may lead to benefits of between 29% and 42% reductions in intensity and frequency of heat events across Africa, with the largest benefit estimated over North Africa. Currently, relatively rare once-in-20-year heat events across Africa may become approximately twice as common under 2 °C world as compared to under 1.5 °C world. Therefore, limiting global warming to 1.5 °C instead of the previously suggested 2 °C could translate into substantial benefits across Africa.

1. Introduction

The projected surface temperature increase in the 21st century over Africa is estimated to be faster than the global average increase, specifically in more arid regions (Engelbrecht et al., 2015; Niang et al., 2014). The continent is not only warming more rapidly than most regions elsewhere, but the smaller interannual temperature variability which African regions experience, especially in the tropics, lead to higher signal-to-noise ratios, hence resulting in such areas becoming even more vulnerable to climate change (Harrington et al., 2016; King & Harrington, 2018). A 3–5 °C temperature increase is projected over the tropical regions of Africa by the end of the 21st century relative to current climate (Engelbrecht et al., 2015) under the low mitigation scenario (A2: Intergovernmental Panel on Climate Change, IPCC, 2000). Specifically, West Africa on average is projected to experience a 3 to 6 °C summer temperature increase between 1981–2000 and 2031–2050 (Diallo et al., 2012) under the A1B emission scenario (IPCC, 2000). Consequently, heat-related extreme events are also estimated to increase more rapidly in most parts of Africa, which also suffer from low adaptive capacities (IPCC, 2012; King & Harrington, 2018; Niang et al., 2014).

Of late, increased occurrences of extreme high-temperature events linked to global warming have been reported over most parts of the world (Dosio et al., 2018; IPCC, 2012; Seneviratne et al., 2012). In large parts of Africa, increases in warm days and warm nights have been observed, specifically in the Sahel region and West Africa for the period between 1961 and 2000 (New et al., 2006). With temperatures in an upward trend in Africa, several regions have also recently observed record-breaking high daily temperatures. For example, Vredendal in South Africa and Luxor in Egypt reported extreme high record-breaking temperatures of 48.4 and 47.6 °C, respectively, in 2015 (World Meteorological Organization, 2016). Places in North Africa, that is, Bilma, Faya-Largeau, and Dongola also observed record heat of magnitudes 48.2, 47.6, and 49.6 °C, respectively, in 2010 (Masters, 2010). A high number of heatwave days annually ranging between 40 and 50 days were also observed in northern parts of Africa over the period 1989–2009 (Cook & Vizy, 2012). In August 2015, more than 90 people died in Egypt due to a heatwave that affected Northeast Africa (Mitchell, 2016). These temperature extremes also substantially decrease labor productivity and aggravate heat-related health problems in both livestock and humans (Seneviratne et al., 2012). For example, an increased heat stress on humans over West Africa caused by global mean temperature increase is projected (Sylla et al., 2018).

Without global warming mitigation efforts, increases in temperature-related extremes could get much higher. Thus, efforts to pursue low global warming levels might be of considerable benefit. Although the 2 °C limit above preindustrial levels (PILs) has been under discussion for years as a benchmark for dangerous impacts (James et al., 2017; Knutti et al., 2016), many African and small-island countries highly susceptible to the dangers of climate change raised concern that a 2 °C target might not be enough to shield them from risk associated with a 2 °C warming (Rogelj et al., 2015). Therefore, they welcomed the 2015 Paris Agreement with great expectations. An agreement centered on further limiting global warming to 1.5 °C above PIL. Considering the significance of these temperature thresholds in the context of Africa, there is considerable importance in exploring the impacts that could be avoided by limiting warming to 1.5 °C instead of 2 °C.

In other regions elsewhere, such as East Asia, North America, Europe, and Australia, there have been extensive studies on climate change impacts at 1.5 and/or 2 °C of global warming (e.g., H. Chen & Sun, 2018; King & Karoly, 2017; King et al., 2017; Li, Zhou, et al., 2018; Li, Zou, & Zhou, 2018; Yohe, 2017). Limiting global warming to 1.5 °C instead of 2 °C may have benefits of avoiding 35–46% of the increases in extreme temperature events in terms of intensity, duration, and frequency across East Asia (Li, Zhou, et al., 2018). In the United States, a 0.5 °C global warming lower than a 2.0 °C global warming could avoid aggregated economic damages, which include economic damages associated with extreme weather events, by roughly 0.35% (0.2–0.65%) of the gross domestic product by 2100 (Yohe, 2017). On the other hand, events similar to the European (Australian) record hot summer of 2003 (record hot summer of 2012–2013) would be substantially less likely by approximately 24% (25%) in a world at 1.5 °C global warming compared to 2 °C global warming (see King and Karoly (2017) and King et al. (2017) respectively). Overall, these studies highlight the potential benefits of limiting warming to half a degree lower than 2 °C across different parts of the world.

Although Africa is one of the regions projected to be hard-hit by the brunt of climate change (Niang et al., 2014), similar studies on the impacts of 1.5 and 2 °C of global warming have been relatively limited in comparison to other parts of the world. However, in the recent past, there have been studies that employed regional climate models driven by global models from phase five of the Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012) in investigating climate risks at 1.5 °C and/or 2 °C warming levels over Africa (Klutse et al., 2018; Maure et al., 2018; Nikulin et al., 2018; Osima et al., 2018; Pokam Mba et al., 2018). The collective finding from these studies is that the 0.5 °C upsurge in global warming from 1.5 °C leads to insignificant increases in precipitation in most parts, especially in the subtropics. These studies investigated several extreme precipitation events; however, they did not analyze temperature-based extreme events. Their studies also lack quantification and comparison of potential benefits of limiting warming to 0.5 °C lower than 2 °C. Nevertheless, a general increase in the frequency and severity of hot extremes was projected using CMIP5 models by Schleussner et al., 2016 over tropical Africa and a significant increase in heat wave magnitudes was projected across Africa (Dosio et al., 2018) due to a half a degree increase in global warming from 1.5 °C. More unprecedented heat discomfort was also projected for West Africa under 2 °C than under 1.5 °C. While these studies provided information on the impacts of 1.5 and 2 °C of global warming, which was missing, one limitation is that they were based on transient projections of CMIP5 models. The time-slice approach used on the CMIP5 global climate models in deriving the 1.5 and 2 °C global warming level projections can be intricate when a time period of transient change that still has a strong trend is used (Herger et al., 2015).

The need for analyzing the difference in climate impacts at the two Paris Agreement temperature targets has prompted new model experiments. Notable examples are the atmosphere-only model experiments from the Half a Degree Additional Warming, Prognosis and Projected Impacts project (Mitchell et al., 2017; Wehner et al., 2018), and the Community Earth System Model (CESM) low warming simulations (Sanderson et al., 2017). Apart from the widely used CMIP-style data sets, which use the time-slice method, the CESM low warming experiment provides a different approach in analyzing climate impacts at 1.5 and 2 °C warming levels. It is based on a suite of fully coupled simulations which have near-equilibrium climate (Long et al., 2014; Olivie et al., 2012) at warming levels of interest, that is, 1.5 and 2 °C global warming levels (see section 2 and supporting information). In the recent past, these CESM low warming simulations were used to analyze climate extremes over different African regions under 1.5 and 2 °C warming levels—focusing on record-breaking annual and seasonal extremes (Nangombe et al., 2018). Different from that, in this study, we use the same dataset to analyze *daily high-temperature* events at 1.5 and 2 °C global warming scenarios over African subregions. Specifically, the following scientific questions are addressed: (1) How does surface air temperature in African regions respond to enhanced global warming of 1.5 and 2 °C above PIL? (2) To what extent will the severity and frequency of extreme temperature events change between the current and future conditions (at 1.5 and 2 °C global warming levels) across Africa? (3) What are the magnitudes of benefits to Africa from limiting global warming to 1.5 °C instead of 2 °C in the context of high-temperature extreme events?

The remainder of the paper is structured as follows: Section 2 describes data and methods. Results are outlined in section 3, and the final section (Section 4) provides a summary and conclusions.

2. Data and Methods

2.1. Observations

This study utilizes three observational gridded data sets to evaluate the CESM simulations used here. These are (1) Climate Prediction Centre (CPC; Chen & Xie, 2010), (2) Climate Research Unit (Harris et al., 2014), and (3) Global Historical Climatology Network (Peterson et al., 1998). CPC and Climate Research Unit observational data sets are at 0.5° spatial resolutions, while Global Historical Climatology Network data set is available at a coarse resolution of 5°. The time range 1979 to 2005 in months was used here for the validation process. We established that all three datasets are consistent in representing spatial variation in temperature over Africa (Figure S1). The CPC observational data were regridded onto a 1° resolution and used in bias correcting the model simulations used in the study. CPC was chosen for the bias correction process as it is available in the daily form, that is, a requirement for computation of daily extreme indices desired in this study.

2.2. CESM Low Warming Experiment

Simulations from the CESM low warming experiment provided by the National Center for Atmospheric Research (Sanderson et al., 2017) were designed specifically for climate impacts analysis at the 1.5 and 2 °C global warming levels above PIL consistent with the Paris Agreement targets. The procedure for generating these simulations involved usage of a Minimal Complexity Earth Simulator to simulate the coupled climate of the CESM model and structuring it in such a way that it is computationally controllable to deduce greenhouse gas (GHG) emission trajectories that result in the CESM model simulations having the required global mean temperature levels (Sanderson et al., 2017). Using these GHG pathways, 11 long range (2006–2100) climate simulations were generated, which achieve desired temperature goals of 1.5 and 2 °C above the 1850–1920 PIL. Only well-mixed GHGs concentrations are changed between the two scenario simulations; that is, other radiative forcing concentrations were prescribed based on the Representative Concentration Pathway 8.5 protocol throughout the 21st century (Sanderson et al., 2017). These two suites of simulations generated were named 1.5degNE and 2.0degNE, herein discussed as simulations for the 1.5 and 2 °C warmer worlds respectively. They were formulated such that the global mean temperature rise "Never exceed" 1.5 °C and 2 °C above the 1850–1920 PIL respectively by the end of the 21st century. These 1.5 and 2 °C simulations stabilize around the year 2050 and 2090 at 1.5 and 2 °C temperature levels above PIL respectively then maintain these levels until 2100. Here, we use 2071 to 2100 to represent the 1.5 °C and 2 °C warming world period consistent with previous studies (Li, Zhou, et al., 2018; Nangombe et al., 2018; Sanderson et al., 2017). Of late, different periods have been used to represent PIL. For example, Hawkins et al. (2017), Sanderson et al. (2017), Schurer et al. (2017), and Zhang et al. (2018) used 1720–1800, 1850–1920, 1850–1900, and 1861–1890 as preindustrial periods respectively. Other studies pointed out that any preindustrial period after 1850 might not be ideal as some human-induced global warming had possibly occurred already by 1850 (Abram et al., 2016; Herger et al., 2015; Schurer et al., 2013), rendering the 1850–1920 PIL used in the CESM simulations possibly inadequate. In the meantime, Knutti and Rogelj (2015) highlighted that choosing a preindustrial period prior to 1850 might not be ideal as there are no available global instrumental data record of temperature and trustworthy emission data to estimate carbon dioxide emissions between about 1750 and 1850, specifically records for land use and land use changes are hardly known (see supporting information). Attention should be paid on the impact of proxy for a preindustrial climate in future studies.

These ocean-atmosphere coupled global simulations extend a previous large ensemble of CESM historical climate simulations ranging from 1920 to 2005 (Kay et al., 2015). Eleven historical realizations are used here and a period 1976–2005 is selected to represent the current world. The model is available at 1° spatial resolution. Further in-depth details of the experimental design of these simulations are provided in Sanderson et al. (2017).

2.3. Bias Correction and Extreme Indices

Model biases in the historical daily maximum and minimum temperature simulations were corrected using a bias correction method, which has a way of preserving long-term absolute trend and variability of simulated data at all time scales (Hempel et al., 2013). The daily temperature variability correction is done with calendar month and grid-specific transfer functions that are factored into the simulated daily data for correction. Each time point of time series is added with a constant offset C that is derived from an average difference between the observations and simulations during the 27-year 1979–2005 (m) reference period (using January as an example month). That is,

$$C = \left(\frac{1}{27}\sum_{i=1}^{m=27} T_i^{\mathrm{OBS}} - \frac{1}{27}\sum_{i=1}^{m=27} T_i^{\mathrm{GCM}}\right) \tag{1}$$

where T_i^{OBS} and T_i^{GCM} describe the observed and simulated January monthly mean temperatures respectively for year i at each grid point.

The corrected daily temperature for January is then computed from

$$TT_{i,j}^{\mathrm{GCM}} = C + T_{i,j}^{\mathrm{GCM}} \tag{2}$$

where the corrected and uncorrected temperatures for year i and day j in January at every grid point are represented by $TT_{i,j}^{\mathrm{GCM}}$ and $T_{i,j}^{\mathrm{GCM}}$ respectively. The same approach is applied in correcting model simulations for daily maximum and minimum temperature for all the other months and grid points of the study area. The corrected daily simulations were then used to compute the high-temperature indices.

2.4. Extreme High-Temperature Indices

Six high-temperature indices from the Expert Team on Climate Change Detection Indices (Zhang et al., 2011) are employed in this study as pointers of a changing climate (Table 1). The indices were calculated using the bias-corrected daily maximum and minimum temperatures. Those based on intensity (hereafter, referred to as heat intensity extremes), are the warm day events (TXx), warm night events (TXn), 3-day warm days events (TXx3day), and the 3-day warm nights events (TNx3day), while those based on frequency (hereafter, referred to as heat frequency extremes) are the frequency of warm days (TX90p) and the frequency of warm nights (TN90p). The 1-day intensity indices (TXx and TNx) were chosen here as they are mainly relevant for analyzing changes in the physical climate system, while the 3-day intensity indices were chosen for their more direct relevance in impact analysis. For example, past studies have used TXx3day as an acceptable definition of a heat wave (Meehl et al., 2004; Tebaldi & Wehner, 2018). We investigate the intensity and frequency of heat events at different low warming levels across four African subregions. The subregions are

Table 1
Definitions of the Extreme Temperature Indices Used in This Study

Extreme indices	Indicator name	Definition	Unit
TXx	Max Tmax	Annual maximum daily maximum temperature	°C
TNx	Max Tmin	Annual maximum daily minimum temperature	°C
TXx3day	3-day warm day event	Maximum 3-day mean daily maximum temperature	°C
TNx3day	3-day warm night event	Maximum 3-day mean daily minimum temperature	°C
TX90p	Hot days frequency	Days when TXx > 90th percentile	days
TN90p	Hot nights frequency	Days when TNx > 90th percentile	days

North Africa (NA: 15–30°N, 20°W to 40°E), East Africa (EA: 11.4–15°N, 25°E−51°E), West Africa (WA: 11.4°S to 15°N, 20°W to 25°E), and Southern Africa (SA: 35–11.4°S, 10°W to 52°E). Previous studies have provided a comprehensive evaluation of CMIP5 models, including CESM, for their ability to reproduce trends and variability in these indices (e.g., Sillmann et al., 2013).

2.5. Calculation of Return Value

Ten- and 20-year return values of the six daily extreme indices under study were also calculated using the Generalized Extreme Value (GEV) distributions method (Coles, 2001). The parameters of the GEV distributions for the six extreme indices in both 1.5 and 2 °C warming worlds were computed first. We then estimated the 10- and 20-year return values by fitting stationary GEV distributions. A GEV distribution is a flexible three-parameter distribution model that combines the Gumbel, the Fréchet and the Weibull extreme value family of distributions (Coles, 2001). The GEV cumulative distribution function (CDF) for an example random variable x is given as

$$F(x,\mu,\delta,\xi) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\delta}\right)\right]^{-1/\xi}\right\}, \quad \text{for } 1+\xi\left(\frac{x-\mu}{\delta}\right)>0 \tag{3}$$

where μ, σ, and ξ are the location parameter, the scale parameter, and the shape parameter, respectively. The shape parameter (ξ) directs the tail behavior of the distribution. The subcomponents defined by $\xi = 0$, $\xi > 0$, and $\xi < 0$ relate to the Gumbel (type I), Fréchet (type II), and Weibull (type III) families, respectively (Tebaldi & Wehner, 2018).

2.6. Avoided Impacts

Impacts of heat events that are avoided (Avoided Impacts, AI) at 1.5 °C warmer climates compared with impacts at 2 °C warmer climates were explored using the computation below:

$$\text{AI} = \frac{\left(\Delta 2^{\circ}\text{C} - \Delta 1.5^{\circ}\text{C}\right)}{\Delta 2^{\circ}\text{C}} \times 100\% \tag{4}$$

where AI is the avoided impacts and $\Delta 1.5^{\circ}$C and $\Delta 2^{\circ}$C are the respective changes in the 1.5 and 2 °C global warming levels with respect to current levels (Frame et al., 2017; Li, Zhou, et al., 2018; Zhang et al., 2018).

2.7. Uncertainty Ranges and Statistical Test Method

We derive the 10th to 90th percentile uncertainty ranges of the extreme event changes between the present-day and the warmer scenarios (1.5 and 2 °C) by utilizing the bootstrapping sampling method. The uncertainty ranges of the differences in magnitude between the two warmer scenarios and the associated avoided impact uncertainty ranges are also estimated. Here, to calculate uncertainty ranges of the changes in the magnitude and frequency of extreme events between the current scenario and the two warmer scenarios, 5,000 bootstrapped subsamples from each extreme event of interest are used. In the first step, we resampled 75% of the simulations from each scenario randomly with replacement during bootstrapping (i.e., 8 of the 11 members for the current scenario, 1.5 and 2 °C scenarios). In the second step, the changes in magnitude between the current levels and the 1.5 and 2 °C warmer scenarios are estimated 5,000 times using the randomly sampled simulations from step 1. In the third and final step, the 10th and 90th percentile

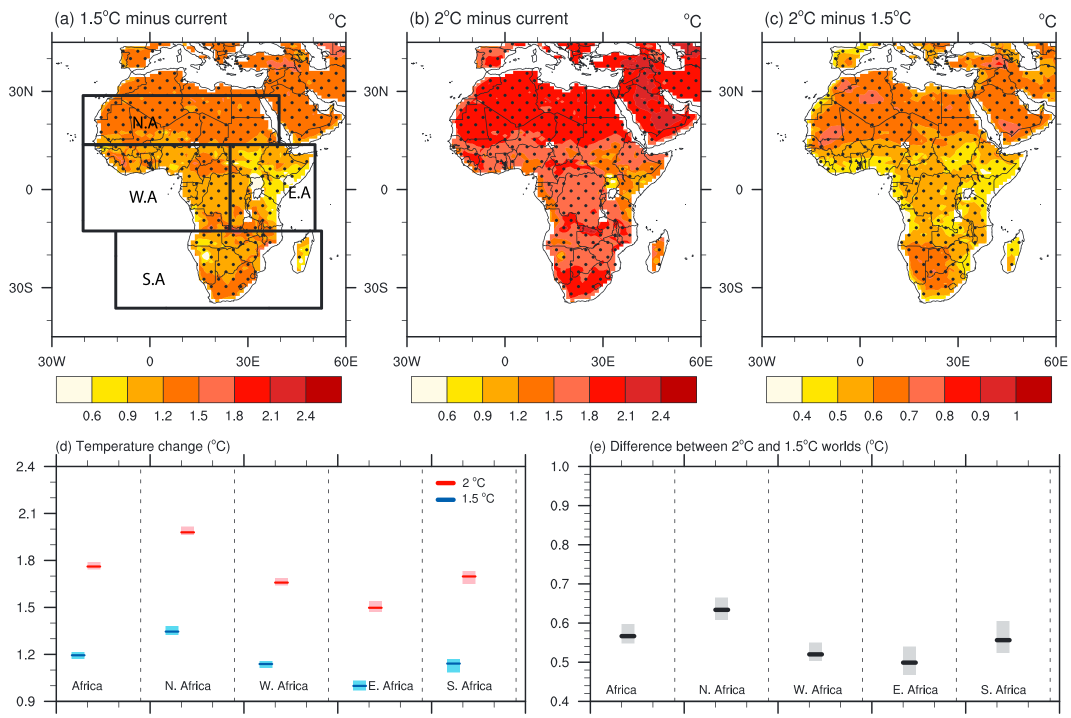

Figure 1. Changes in surface air temperature between 1.5 and 2 °C warming levels. Changes under 1.5 and 2 °C relative to the current levels are shown in (a) and (b), respectively, while the estimated differences between the two warming levels are shown in (c). Regional surface temperature changes under 1.5 and 2C relative to current levels are shown in (d), while differences between the warmer worlds are shown in (e). Areas with above 95% confidence level using Student's *t* test in (a)–(c) are indicated by hatching. Bars depict 10% to 90% confidence range from bootstrapping. Black boxes in (a) show regions analyzed in (d) and (e).

confidence intervals, which are the 500th and 4,500th values of the 5,000 sorted bootstrapped samples, are derived, respectively. The same approach is then also used to calculate uncertainty ranges of the changes in the magnitude of the once-in-10-year and once-in-20-year extreme events between the current scenario and the two warmer scenarios. Uncertainty ranges for the estimated avoided impacts from limiting warming to 1.5 °C instead of 2 °C is also calculated by applying the 75% resampled simulations from the 1.5 and 2 °C scenarios to equation (4). Then this is also repeated 5,000 times to deduce the 10–90% confidence intervals for the avoided impacts, which will also be the 500th and 4,500th values of the 5,000 sorted bootstrapped samples, respectively. The Student's *t* test is employed to test the significance of the mean spatial changes of the surface temperature and high-temperature extreme events of interest between two scenarios.

3. Results

Prior to the use of the CESM model in the calculation of the extreme indices under study, bias correction was done to reduce model bias. After bias correction, the model simulations realistically captured the general features of the observed heat events over Africa (Figure S2). The largest bias correction effect was observed on the heat intensity extremes and slight to no effect was observed on the heat frequency extremes (Figure S2), as was also noted over East Asia (Li, Zhou, et al., 2018). Disparities in the details of the results exist depending on the definition of extreme temperatures and changes used, whether being considered is 1 versus 3-day event based extremes, minimum versus maximum temperature and whether the changes are expressed in terms of intensity or frequency.

3.1. Changes in Surface Air Temperature Over Africa

African subtropics are projected to have the largest magnitude of warming under 1.5 and 2 °C global warming worlds, while the tropical west and east coastal regions have the least (Figures 1a, 1b, and 1d). Madagascar and many coastal regions have the weakest warming signal due to the influence of a slow warming rate of oceans (Déqué et al., 2016). The projected temperature increase in northern Africa is higher than in other regions largely due to the strengthening of the North Africa Thermal Low in the 21st century

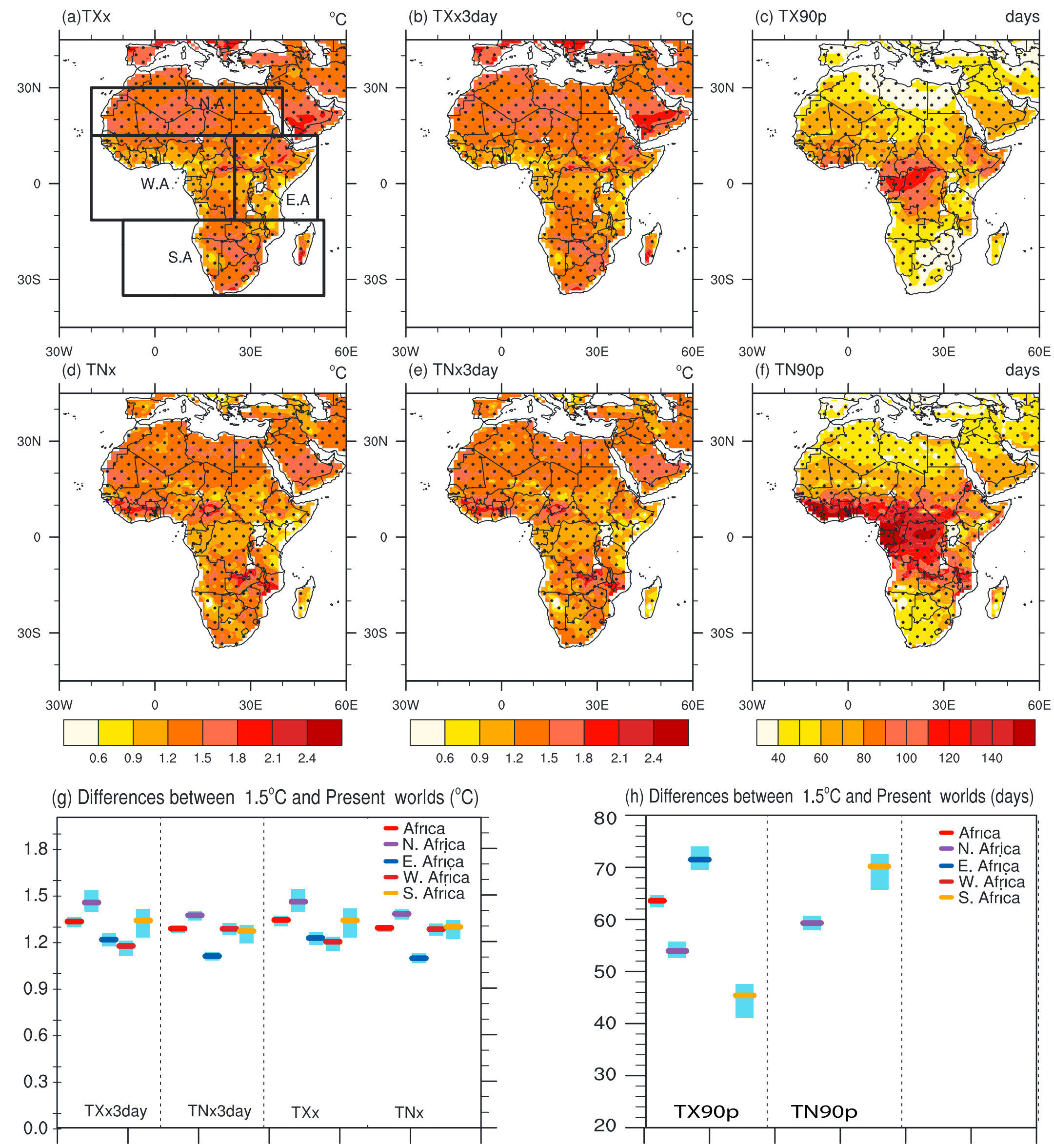

Figure 2. African extreme temperature changes from the current world to the 1.5 °C warmer world. Panels (a), (b), (d), and (e)) and (c) and (f) show high-temperature extreme events based on intensity (TXx, TXx3day, TNx, and TNx3day) and threshold (TX90p and TN90p), respectively. Areas with above 95% confidence level using Student's t test in (a)–(f) are indicated by hatching. Panels (g) and (h) show estimated differences in the magnitude of high-temperature indices based on intensity and threshold, respectively. Bars depict 10% to 90% confidence range from bootstrapping. Estimates for Africa, North Africa, East Africa, West Africa, and Southern Africa are represented by red, purple, blue, brown, and orange colored polylines, respectively. The spatial extent of each region is shown by black boxes in (a).

being projected (Cook & Vizy, 2012; Niang et al., 2014). Here, the model suggests highest (lowest) warming magnitudes in NA (EA) of 1.98 ± 0.03 °C (1.50 ± 0.04 °C) and 1.34 ± 0.03 °C (1.00 ± 0.03 °C) under 2 °C world and 1.5 °C world respectively with respect to current levels (Figures 1a, 1b, and 1d). An additional 0.5 °C warming above 1.5 °C is projected to result in Africa being 0.57 °C (0.54–0.6 °C) warmer (Figures 1c and 1e). Specifically, NA and EA with the highest and lowest change, are estimated to be 0.63 °C (0.60–0.67 °C) and 0.50 °C (0.47–0.54 °C) warmer respectively under 2 °C than under 1.5 °C world (Figures 1c and 1e).

3.2. Changes in Extreme High-Temperature Events Over Africa

Changes in heat events in Africa under 1.5 °C world with respect to current levels is shown in Figure 2. The significant increase in heat extremes over most parts in Africa is more prominent than mean temperature

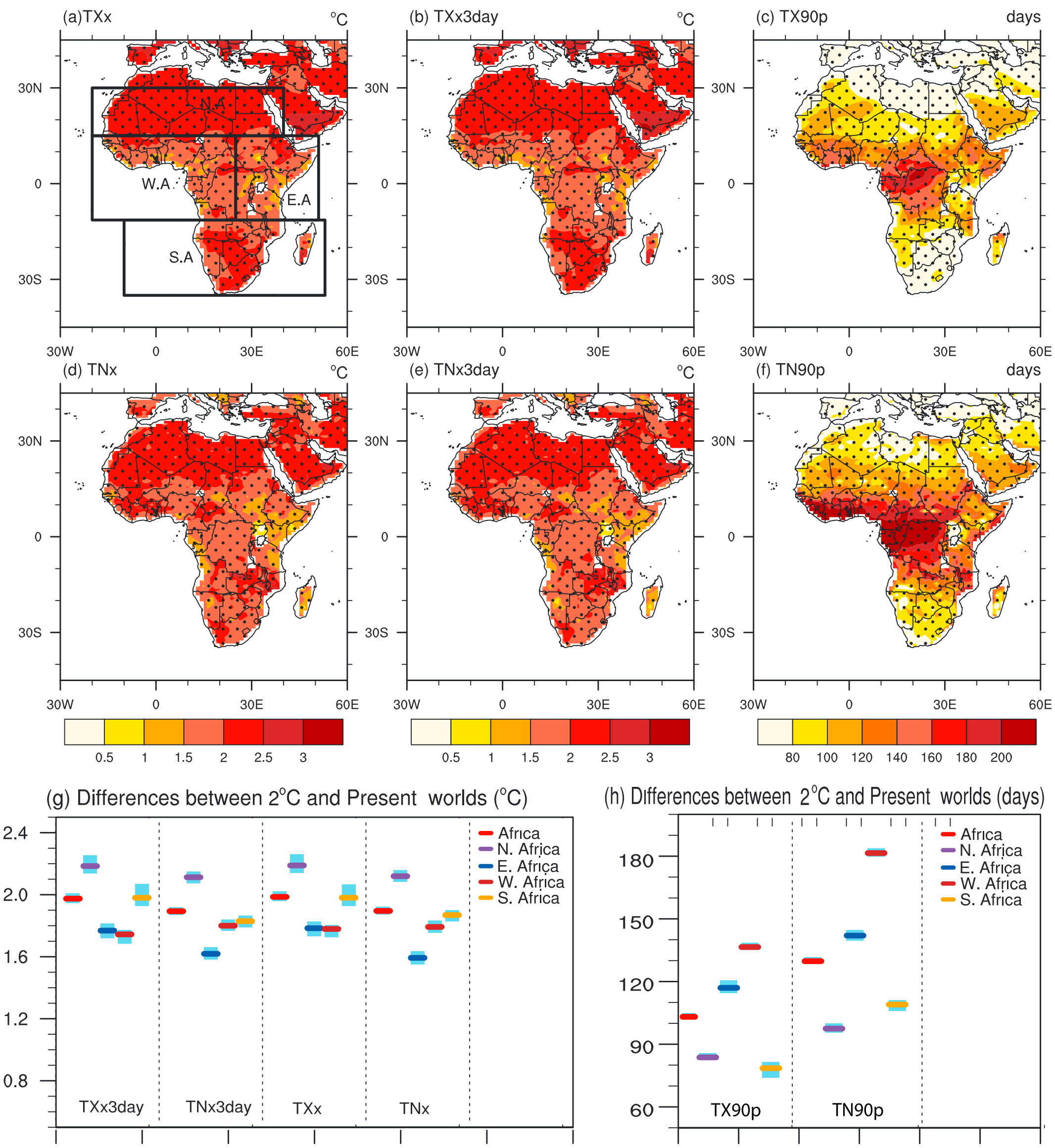

Figure 3. Same as Figure 2 but for changes from the current world to the 2 °C warmer world. Note that the color scales in this figure are different from those in Figure 2.

increase (cf. Figures 1 and 2). All the heat intensity extremes follow similar spatial patterns (Figures 2a, 2b, 2d, and 2e). Nonetheless, considerable regional variations exist (Figures 2h and 2g). NA has the highest average differences ranging from 1.37 °C (1.33–1.40 °C) for TNx3days to 1.46 °C (1.39–1.54 °C) for TXx under 1.5 °C with respect to current levels, which can be attributed to North Africa having the fastest increase in surface air temperature than other regions in Africa (cf. Figure 1). The differences are smallest in the tropical coastal areas following also the weakest warming signal in these areas. Areas in the tropics are projected to have higher differences in the occurrence of TX90p and TN90p between 1.5 °C and current levels compared to subtropical regions. Specifically, in WA, the differences is 84 days ± 2 days for TX90p and is 126 days ± 3 days for TN90p, while for NA, the difference is 54 days ±2 days for TX90p and about 2 months ±1 day for TN90p.

On the other hand, under a 2 °C world, Africa might be exposed to more severe and more frequent heat events than those under a 1.5 °C world. Figure 3 shows the changes in intensity and frequency of heat events from current world to a 2 °C warming world. Both types of heat events follow the same geographical patterns as those for the changes between 1.5 °C and current level albeit with substantially higher magnitudes. For

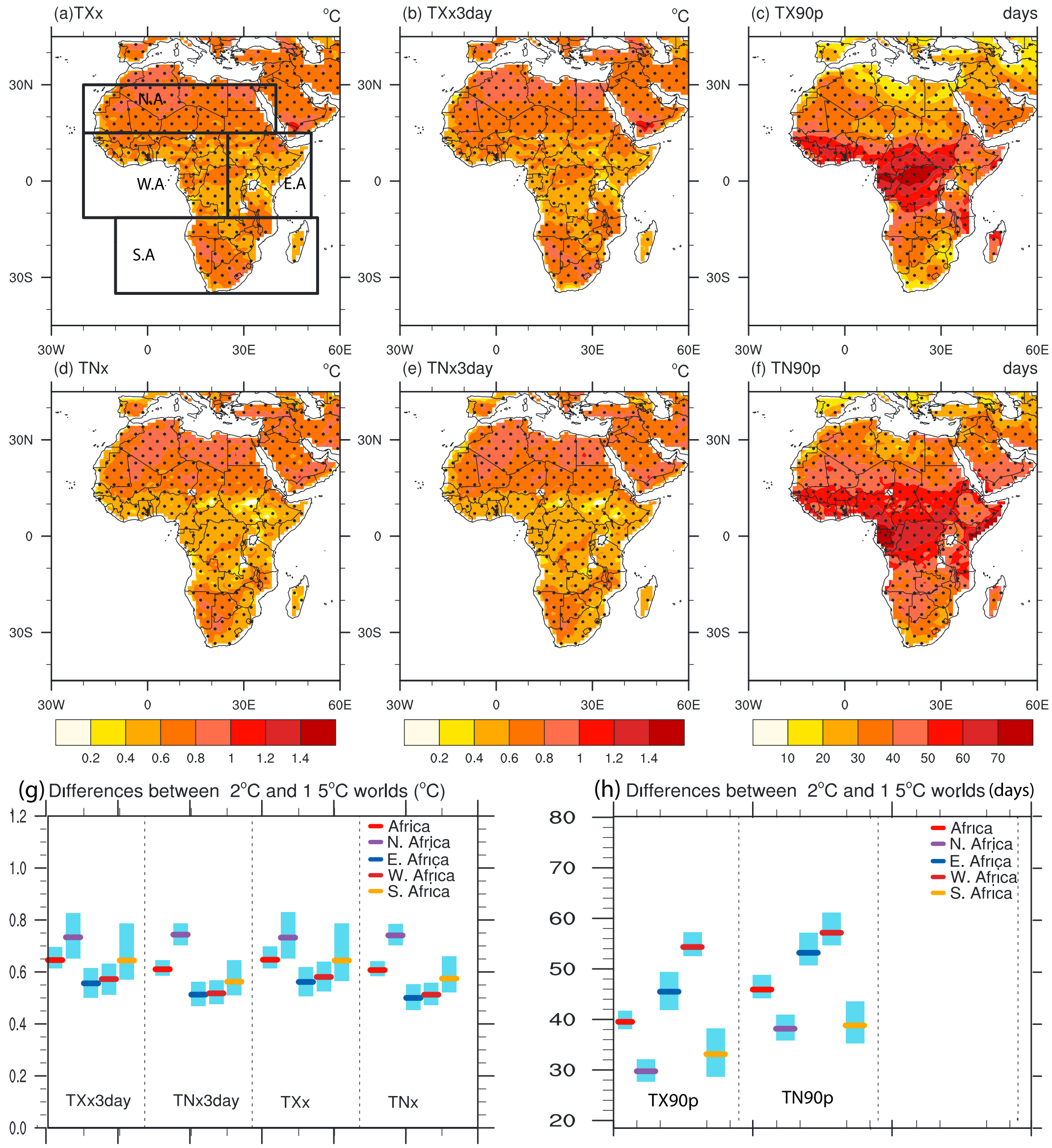

Figure 4. Differences in extreme events between 1.5 and 2 °C global warming scenarios. Panels (a), (b), (d), and (e) and (c) and (f) show high-temperature indices based on intensity (TXx, TXx3day, TNx, and TNx3day) and threshold (TX90p and TN90p), respectively. Areas with above 95% confidence level using Student's *t* test in (a)–(f) are indicated by hatching. Panels (g) and (h) show estimated differences in the magnitude of high-temperature indices based on intensity and threshold respectively. Bars depict 10% to 90% confidence range from bootstrapping. Estimates for Africa, North Africa, East Africa, West Africa, and Southern Africa are represented by red, purple, blue, brown, and orange colored polylines respectively. The spatial extent of each region is shown by black boxes in (a).

example, WA is projected to have 184 days more of TX90p under 2 °C scenario with respect to current levels while under 1.5 °C, the change is almost 2 months less (126 days).

There are distinct subcontinental differences in the magnitude of hot extremes responding to global warming. In terms of the frequency of hot extremes (i.e., TX90p and TN90p), the West African region and parts of Central Africa depict the highest increase as the climate warms (Figures 2c, 2f, 3c, and 3f). This is possibly because of the relatively small interannual present-day variability in the tropics, implying that climate change signals here are likely to emerge earlier than in other African regions (Mahlstein et al., 2011). Meanwhile, the intensity of heat extremes (i.e., TXx, TNx, TXx3day, and TNx3day) displays particularly large increases in NA (Figures 2a, 2b, 2d, 2e, 3a, 3b, 3d, and 3e), mostly following the relatively higher increases in annual mean temperature over NA (Figure 1). This is associated with the projected strengthening of the

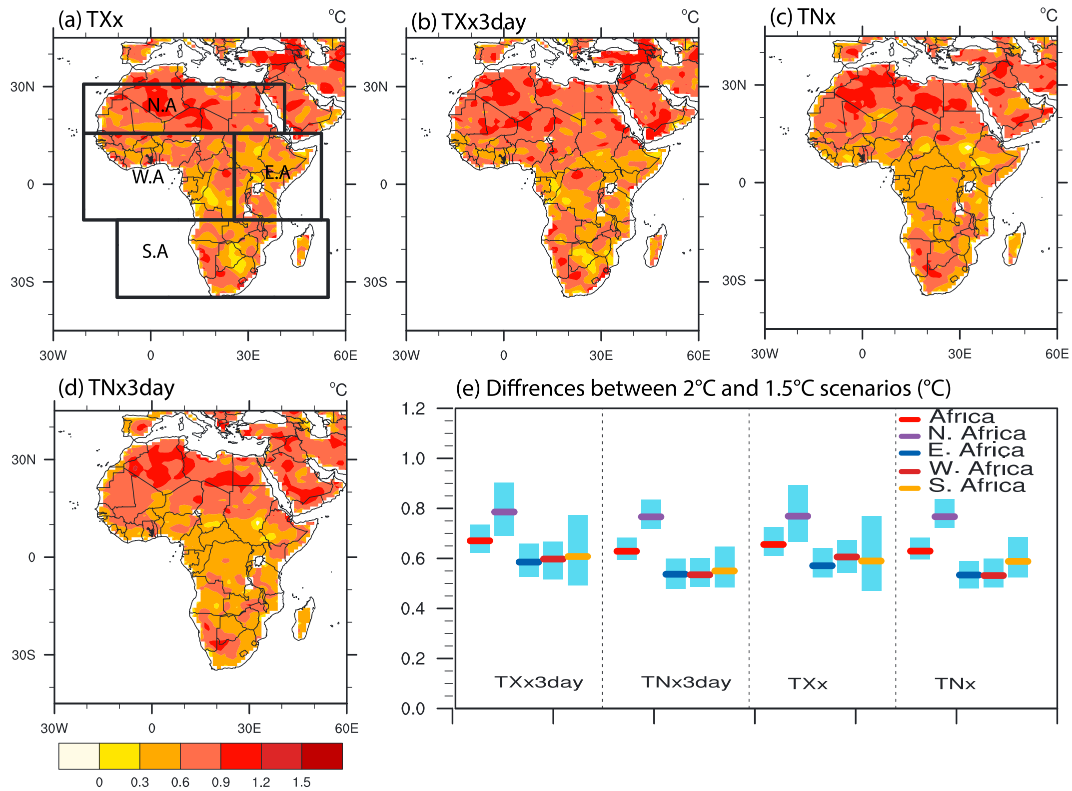

Figure 5. Differences in once-in-20-year heat events between the 1.5 and 2 °C thresholds. (a) TXx, (b) TXx3day, (c) TNx, and (d) TNx3day. The estimated differences in the magnitude of extreme temperature events across different African regions between the 1.5 and 2 °C worlds is shown in (e). Polylines in different colors represent estimates over different regions. Bars represent the 10–90% confidence intervals derived from bootstrapping. Estimates for Africa, North Africa, East Africa, West Africa, and Southern Africa are represented by red, purple, blue, brown, and orange color polylines, respectively. The spatial coverage of each region is shown by black boxes in (a). The differences are in degrees Celsius.

North African Thermal Low in the 21st century, and a large increase in the longwave back radiation induced by GHG forcing in the dry atmosphere (Cook & Vizy, 2012; Niang et al., 2014).

Respective changes in heat events from 1.5 °C world to 2 °C are shown in Figure 4. All the heat intensity extremes follow similar spatial patterns (Figures 4a, 4b, 4d, and 4e). Nonetheless, considerable regional variations exist. NA has the highest average differences, for example, 0.75 °C (0.72–0.79 °C) for TXx3day, and EA has mostly the least differences, for example, 0.5 °C (0.45–0.55 °C) for TNx (Figure 2g and Table S1). Heat frequency extremes depict largest differences in the tropical areas (Figures 2c and 2f). TN90p in WA is projected to have the largest differences of approximately 2 months (55–61 days) between the two warming levels, while TX90p in NA has the smallest difference of approximately 1 month (28–32 days; Figure 2h).

Frequent extreme events in the current world (e.g., once-in-10- and once-in-20-year events) usually result in substantial social and economic losses. Figure 5 shows changes in once-in-20-year heat events between the 1.5 and 2 °C warming scenarios. For all the once-in-20-year heat intensity events, northern areas have the highest differences compared to other regions. Particularly, TXx3day in NA has the highest difference of 0.81 °C (0.70–0.94 °C), while TNx in WA has the smallest difference of 0.54 °C (0.49–0.78 °C) between the 1.5 and 2 °C worlds (Figure 5 and Table S2). Spatial patterns and intensity differences between the once-in-20-year heat events and the once-in-10-year events are small (cf. Figures 5 and S3).

How heat events with 10-year return periods in the current period would change to under 1.5 and 2 °C worlds is explored in Figure 6. These once-in-10-year events are projected to become more common in the 2 °C world. They change from occurring once every 10 years to occurring approximately between once a year and once in 5 years across Africa (Figures 5b, 5d, 5f, and 5h). Specifically, parts of the Sahel region and West Africa are projected to have extreme events with the shortest return periods of less than 3 years for most heat extremes. However, the same heat events are projected to become between once-in-5-year and once-in-10-

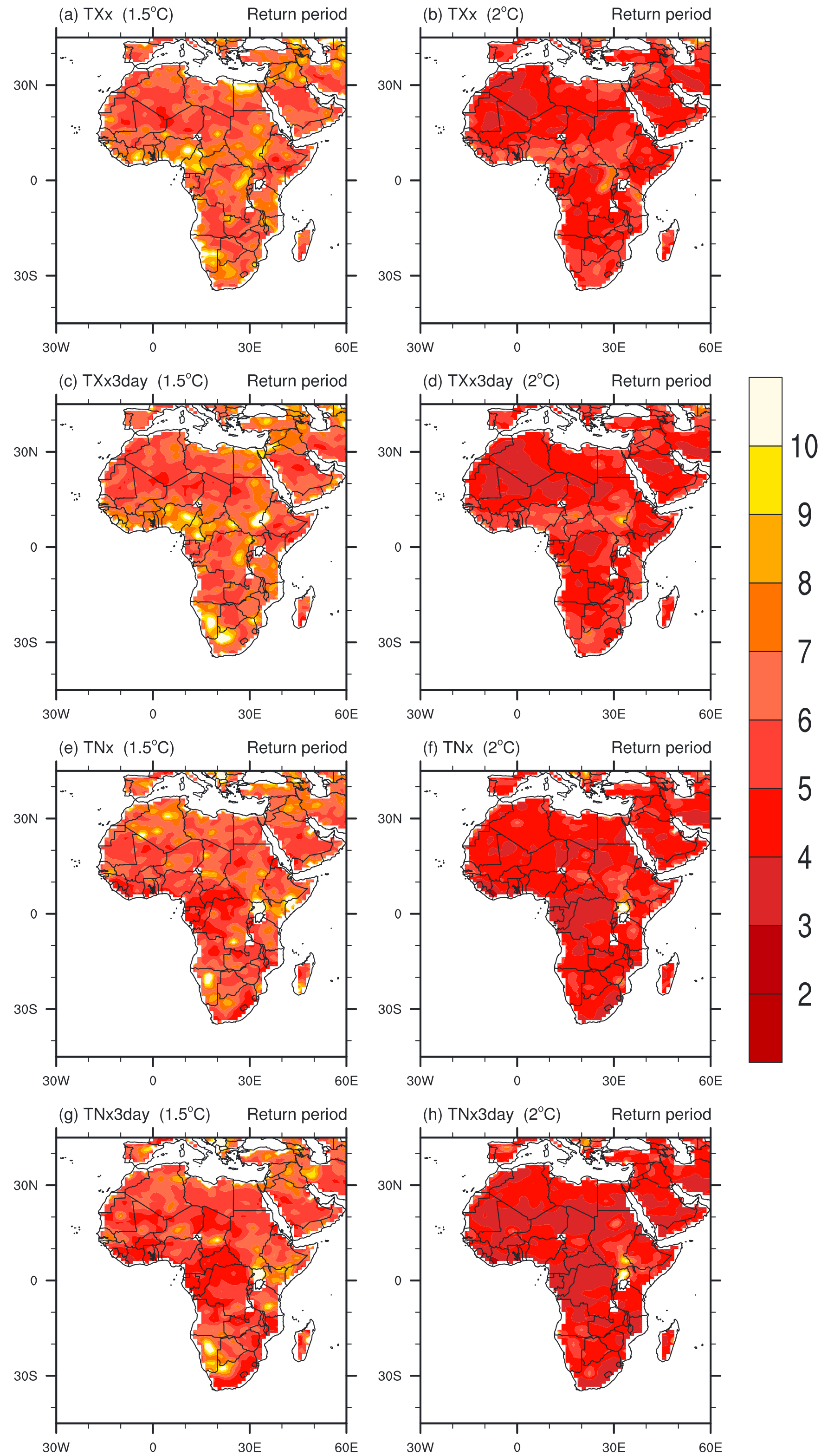

Figure 6. Projected return periods under 1.5 and 2 °C scenarios of heat events that had a 10-year return period in the current world. Panels (a), (c), (e), and (g) show return periods in years for TXx, TXx3day, TNx, and TNx3day respectively under the 1.5 °C scenario that had an estimated 10-year return period in the current scenario, while (b), (d), (f), and (h) show return periods in years for TXx, TXx3day, TNx, and TNx3day respectively under the 2 °C scenario that had an estimated 10-year return period in the current scenario.

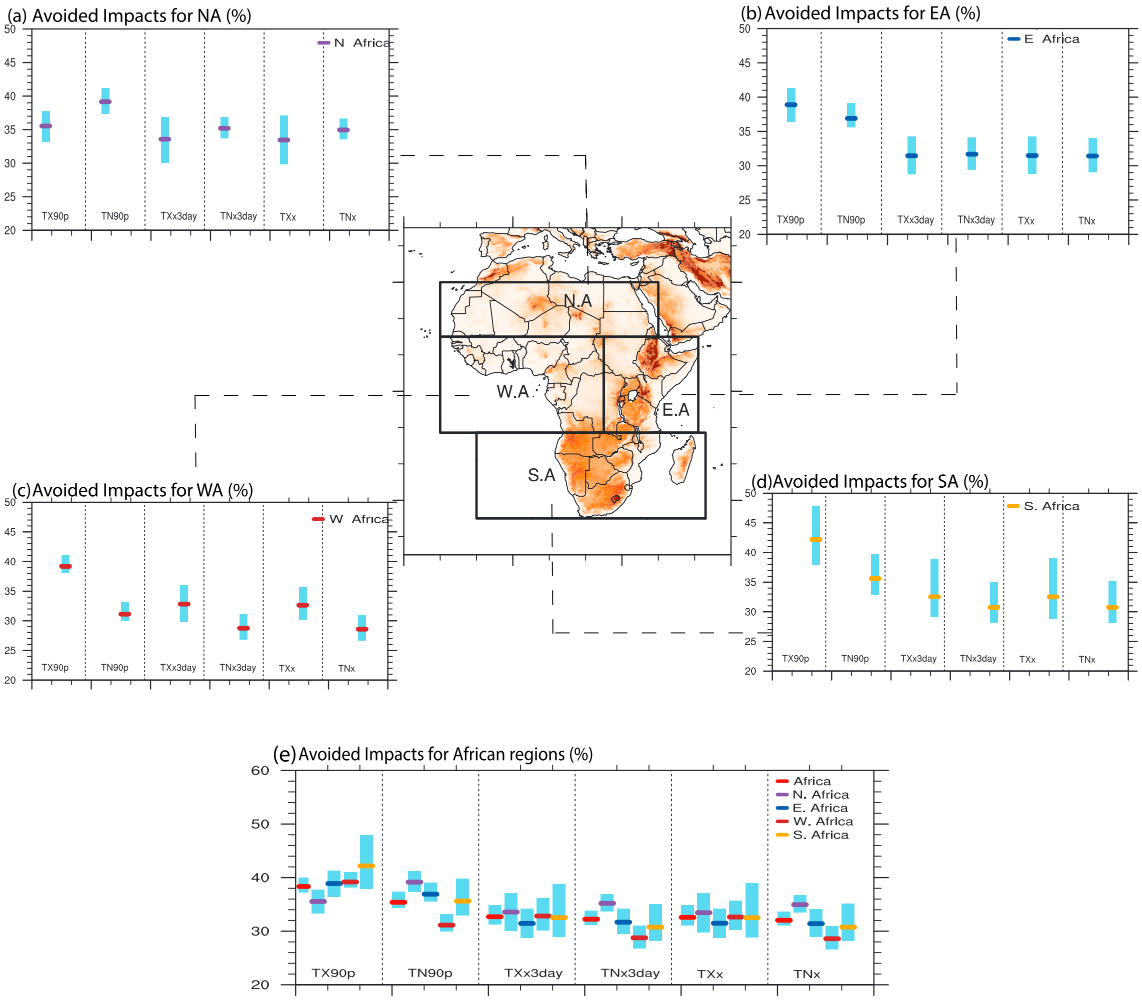

Figure 7. Projected avoided impacts across Africa from limiting warming to 1.5 °C instead of 2 °C. Reduced impacts of TX90p, TN90p, TXx3day, TNx3day, TXx, and TNx from limiting global warming to 1.5 °C compared to 2 °C over the (a) North Africa, (b) East Africa, (c) West Africa and (d) Southern Africa region. (e) shows the avoided impacts for all the regions put together. Estimated reduced impacts (polylines) and 10–90% confidence intervals derived from bootstrapping (bars) are shown. Estimates for Africa, North Africa, East Africa, West Africa, and Southern Africa are represented by red, purple, blue,brown, and orange colored polylines, respectively. Center plot shows Africa's topography and the spatial extent of each region used to calculate average regional magnitudes.

year events under the 1.5 °C world (Figures 6a, 6c, 6e, and 6g). In general, comparing how the currently once-in-10-year heat events change to under 2 °C and under 1.5 °C, show a difference in frequency of approximately double with the former having a higher frequency of occurrences. Hence, this signifies a potential advantage of limiting warming to 1.5 °C instead of 2 °C. Similarly, rare once-in-20-year events in the current period, are projected to become more common (occurring between once-in-4- and once-in-10-year) under the 2 °C warmer world across Africa (Figures S4, S4d, S4f, and S4h). However, the same heat events are projected to become between once-in-10-year and once-in-20-year events under the 1.5 °C world.

3.3. Reduced Impacts of Heat Events From Low Warming

Projected regional avoided impacts of extreme high-temperature events over Africa from limiting global warming to 1.5 °C instead of 2 °C are highlighted in Figure 7. Keeping warming to at most 1.5 °C instead of 2 °C is projected to make the highest difference over NA (Figure 7a) compared to other regions (Figures 7b-d) for all heat events except TX90p. Limiting warming to 0.5 °C lower than 2 °C is projected to translate to heat extremes being between 33.4% (29.8–37.1%) and 39.2% (37.3–41.3%) less severe across Africa (Figure 7). On the other hand, TNx events in WA are projected to have the lowest benefit of 29%

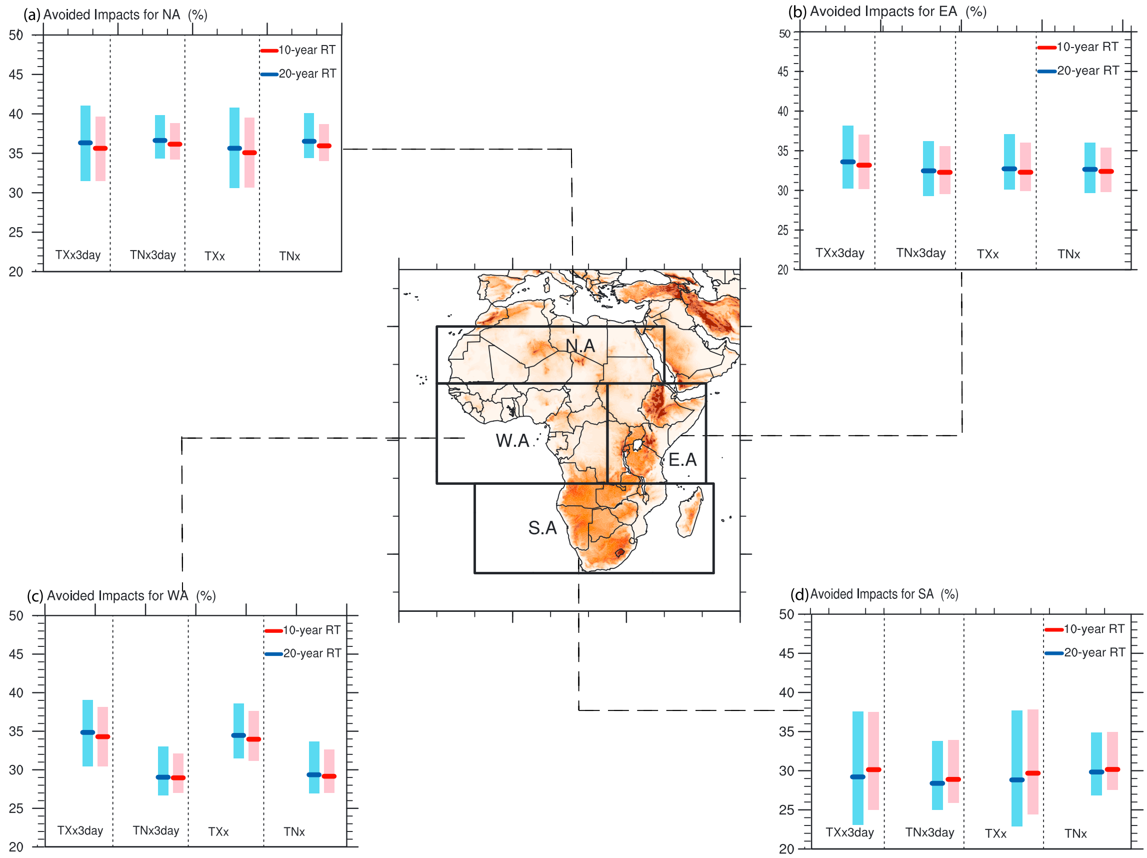

Figure 8. Projected avoided impacts of once-in-10/20-year extremes across Africa from limiting warming to 1.5 °C instead of 2 °C. Estimated reduced impacts of 10-year and 20-year return values of TXx3day, TNx3day, TXx, and TNx extreme events from limiting global warming to 1.5 °C compared to 2 °C over the (a) North Africa, (b) East Africa, (c) West Africa and (d) Southern Africa region. Estimates (polylines) and 10% to 90% confidence intervals derived from bootstrapping (bars) are shown. Estimates of the avoided impacts from temperature extremes with 10-year and 20-year return values are represented by red and blue colored polylines, respectively. Center plot shows Africa's topography and the spatial extent of each region used to calculate average regional magnitudes.

(27%–31%) reduction in severity (Figure 7c). We also note that in almost all the regions, the threshold based extreme events have higher benefits compared to the intensity extremes from constraining warming to 1.5 °C instead of 2 °C (Figure 7e).

Furthermore, we quantified potential avoided intensification of heat intensity events with 10 and 20-year return values across Africa from limiting warming to half a degree lower than 2 °C in Figure 8. The avoided impacts for the once-in-10-year heat events are closely similar to that of the once-in-20-year heat events, nonetheless with comparatively smaller magnitudes. This is associated with almost similar differences in the magnitude of extreme events between 1.5 and 2 °C shown in Figures 5 and S3 for the once-in-20-year and once-in-10-year heat events. The model suggests that a half a degree less warming would make the greatest difference across Africa to the once-in-20-year TXx3day events avoiding an additional 34% (31–38%) of intensification (Figure 8). At the regional scale, the 0.5 °C less warming would make the highest and lowest difference in the intensification of the once-in-20-year heat events in NA and SA, respectively. Specifically, it would result in the avoidance of 37% (34–40%) intensification of once-in-20-year TNx3day events in NA (Figure 8a) and 28% (25–34%) avoided intensification of once-in-20-year TNx3day events in SA (Figure 8d). Therefore, constraining global warming to 1.5 °C instead of 2 °C in future could reduce the frequency of extreme high-temperature events by between 28% (25–34%) to 37% (34–40%) across African regions (Figure 8).

4. Summary and Conclusions

The CESM low warming experiment was the first initiative that produced a suite of fully coupled model simulations at near-equilibrium 1.5 and 2 °C of global warming above preindustrial levels. These simulations are the only currently existing simulations of *short-term stabilization scenarios* at 1.5 and 2 °C of global warming. Using the CESM low warming experiment dataset, we analyzed the changing temperature magnitudes and related daily heat extreme events over Africa in both current and future conditions (1.5 and 2 °C warming levels). Simple bias correction method was applied on the simulated daily maximum and minimum temperatures used in calculating the high-temperature extreme indices used here. We summarize the main findings as follows:

1. A significant warming is projected across Africa at the 1.5 °C warming world and is amplified at the 2 °C warming world exceeding the mean global warming rates over most regions. The model suggests highest (lowest) warming magnitudes in NA (EA) of 1.98 ± 0.03 °C (1.50 ± 0.04 °C) and 1.34 ± 0.03 °C (1.00 ± 0.03 °C) under the 2 °C and 1.5 °C warmer worlds respectively with respect to current level. Consequently, subtropical (NA) and tropical areas (EA) are projected to have the highest and lowest changes from the 0.5 °C additional warming, respectively, of 0.63 °C (0.60–0.67 °C) and 0.50 °C (0.47–0.54 °C).
2. The magnitude of heat extreme events is projected to be significantly more across Africa under a 2 °C world than under 1.5 °C world. The differences range between about 0.5 °C ± 0.05 °C for TNx in EA and 0.74 °C ± 0.04 °C for TNx3day in NA. Currently once-in-10-year heat events are estimated to become between annually and once-in-5-year extreme events across Africa under the 2 °C world, compared to becoming between once-in-5-year and once-in-10-year events under 1.5 warming world. A difference in the occurrence of almost double.
3. Limiting warming to 1.5 °C instead of 2 °C may lead to benefits ranging from 29% (27–31%) to 35% (33–37%) reduction in severity of heat events across Africa and 31% (30–33%) to 42% (39–48%) reduction in the frequency of threshold-based heat events. Furthermore, it may lead to benefits of between 28% (34–40%) and 37% (25–34%) reduction in severity of once-in-10/20-year heat extremes across Africa—with North Africa having the highest percentage benefits than tropical regions.

Previous studies and our study generally agree on the direction of change of heat events with global warming (Dosio et al., 2018; Schleussner et al., 2016). However, our study according to our knowledge is novel in that it is the first that attempts to quantify and compare across Africa's sub-regions the potential climate benefits associated with restricting warming to the Paris Agreement temperature targets using the unique fully coupled CESM Low warming simulations. It may also be the first to quantify and compare the reduction in intensity of the once-in-10/20-year extreme heat events emanating from limiting warming to 0.5 °C lower than 2 °C across different regions in Africa.

Our overall message is that keeping the Paris Agreement goals in the context of Africa cannot be overemphasized. If the CESM simulations are representative of the true climate system, limiting global warming to 1.5 °C instead of the previously suggested 2 °C could indeed translate into substantial benefits of reducing the intensity and frequency of extreme heat events across Africa.

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