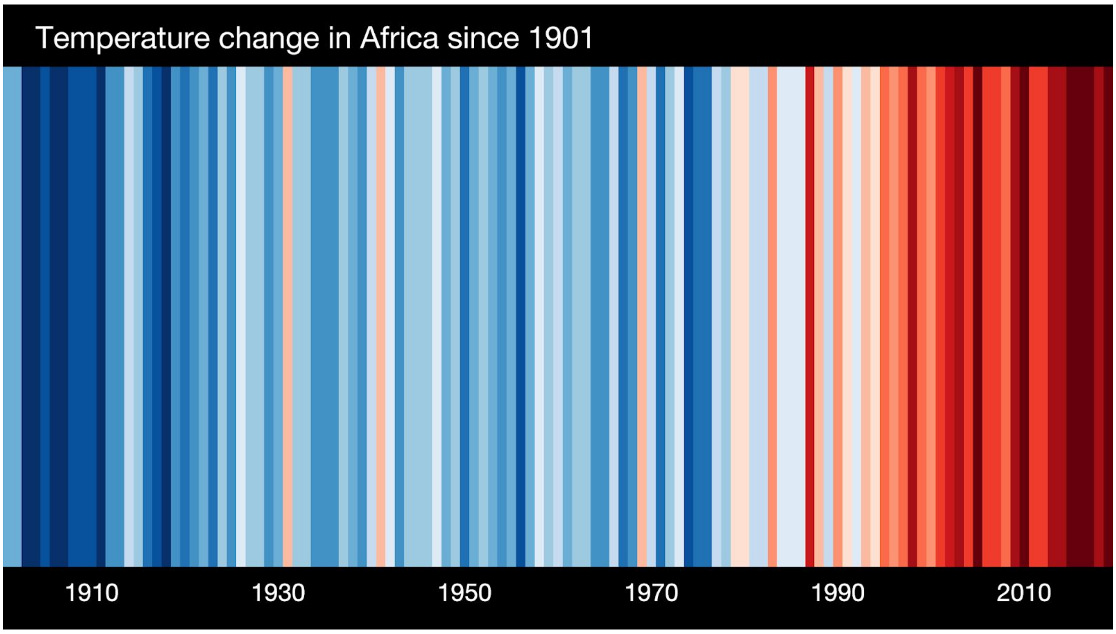
Weathering the Storm

Extreme weather events and climate change in Africa



Africa's climate is visualised as stripes that show how the continent's average temperature has changed over the decades from 1850–2019. Each coloured stripe represents one year; warmer years are red and cooler years are blue. The graphic was developed by Professor Ed Hawkins from the National Centre for Atmospheric Science at the University of Reading's Department of Meteorology in the United Kingdom. Billions of pieces of data were used to create hundreds of images that cover every country in the world and which are available to download free of charge. To create a climate stripes graphic for other countries, regions and states, or for the global overview, visit: https://showyourstripes.info (The graphic is licensed for reproduction as part the Creative Commons Attribution 4.0 International, CC BY 4.0).

Weathering the Storm:
Extreme weather events and climate change in Africa

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Take-home messages

- The projection in the Greenpeace report *Facing the Weather Gods*, published in 2013, was that the African continent would experience higher temperature rises than the global average, and increasing variance in rainfall over the tropics will lead to more extreme precipitation events, which could impact around 25% of the continent. These broad conclusions still stand.

- Climate change is one of the biggest challenges that African societies are facing and will continue to face this century and beyond.

- Many African communities are vulnerable to the impacts of extreme weather events because of their limited ability to cope and adapt to those events. Limited resources in terms of access to technology, skills development and economic capacity contribute to low levels of possible adaptation (see **section 5.0**).

- In the 100 years from 1900 and 2000, the continent warmed on average by 0.5 ℃ (see **section 2.0**).

- The mean annual temperature increase for much of the continent of Africa is projected to exceed 2 ℃ or to fall within the range of 3 ℃ to 6 ℃ by the end of the twenty-first century if high emissions continue (see **section 2.1**).

- Studies using numerical climate models at regional and global scales project that during the twenty-first century, heatwaves will occur more often, at higher intensities, and last for longer as greenhouse gas concentrations increase (see **section 2.1**). Africa's ten hottest years have all been recorded since 2005 (see **section 2.0**). Temperature across Africa is projected to be hotter than previously experienced in the recorded past, and to rise faster than the global average across most of the continent (see **section 4.1**).

- Observational data from the second half of the twentieth century suggest that heatwave duration and intensity have increased over parts of Africa, most notably parts of Southern Africa, East Africa and the north of the continent. South Africa is projected to become drier in the west and southwest, and wetter in the east (see **section 4.2**). Observed temperatures indicate that much of Africa experienced an increasing trend in 'cumulative heat' by 50% per decade between 1950 and 2017 (see **section 2.1**). ‘Cumulative heat’ is a conceptual metric described by the authors to assess the amount of ‘extra heat’ generated by extreme heat events. For example, if a heatwave is defined as air temperature above 30 ℃, and the temperature recorded is 33 ℃, the ‘extra heat’ produced is 3 ℃ (see **section 2.1**).

- Future projections for Africa through the twenty-first century follow the global trend in that the frequency, intensity and duration of extreme heat events are all expected to increase (see **section 2.1**).

- Climate scientists have found that anthropogenic climate change contributed substantially to the 2015–2016 extreme drought over Eastern and Southern Africa by accentuating the natural El Niño impacts (see **section 2.2**).

- If high greenhouse gas emissions continue, the expectation is for decreased mean annual rainfall in Southern and Northern African regions by the mid- to late twenty-first century and an increase in mean annual rainfall in Central and East African regions. Future rainfall patterns for West Africa are uncertain (see **section 2.3**).

- Whether or not tropical storms and cyclones will increase or decrease in frequency during the twenty-first century is not certain. Expectations are broadly for a small increase in the frequency of tropical cyclones that make landfall and impact East Africa from the Arabian sea, and fewer but more intense tropical cyclones in the Southern African region (see **section 2.4**).

- Attributing extreme weather events to one specific cause is not straightforward. It is important to note that extreme weather events can be caused by natural variability within the climate system, human activity or a complex interplay between the two (see **section 4.0**).

- Extinction of many endemic African species is possible even at the lower end of the range of possible projected temperature changes above pre-industrial levels due to climate change (see **section 5.6**).

- A lack of data, or the existence of unreliable data, for most areas of the African continent over the past century mean that it is difficult to reach conclusions about trends, most notably for rainfall patterns (see **Box 5**).

1.0 Introduction

Climate change is one of the biggest challenges that the African continent and its inhabitants are facing this century. Regions will be affected differently; the continent is vast, spans several distinct climate zones. Complex meteorological drivers are at play, including the Inter-Tropical Convergence Zone, the El Niño

Southern Oscillation, the West African Monsoon and the Indian Ocean Dipole, all of which may be impacted to some degree by climate change.

This report, *Weathering the Storm,* builds upon the 2013 Greenpeace *Facing the Weather Gods* report, which broadly concluded that climate change impacts for the African continent could be severe by the end of the twenty-first century and that the need to make deep cuts to global greenhouse gas emissions is urgent. *Facing the Weather Gods* concluded that although the general trend would be for a warmer and drier continent, some countries and regions would be affected more profoundly than others. The expectation in 2013 was that the continent would experience higher temperature rises than the global average, and increasing variance in rainfall over the tropics would lead to more extreme precipitation events, which could impact around 25% of the continent. These broad conclusions still stand, but during the intervening years the science has become more sophisticated and this report addresses those areas that most urgently point to the need for action.

Among the key climate projections in relation to the African continent from the most recent (Fifth) Assessment Report from the International Panel on Climate Change (Stocker et al. 2013, Table TS.2) are:

- increased summer monsoon rainfall in West Africa;
- increased rainfall during the short rains in East Africa (linked to increased sea surface temperature in the Indian Ocean); and
- increased rainfall extremes from landfall cyclones on the east coast, including Madagascar.

The 'State of the Climate in Africa 2019' report by the World Meteorological Organisation (WMO, 2020) points to temperature and precipitation as being the two key indicators that characterise the current climate in Africa and which continuously affect living conditions on the continent. Confirming the broad warming trends that have been observed over most of Africa, the WMO report also points out that in 2019, Northern and Southern Africa were much drier than normal while much of the Sahel and western central Africa were much wetter. Added to this was the fact that rains were more erratic than normal. Near-term predictions for 2020–2024 suggest:

- Continued warming, especially over Northern and Southern Africa;
- Decreased rainfall over both Northern and Southern African sub-regions;
- Increased rainfall over the Sahel.

The 'State of the Climate in Africa 2019' report also highlights the impacts of extreme weather on agriculture and points out that:

> "After decades of decline, food insecurity and undernourishment are on the rise in almost all sub-regions of sub-Saharan Africa."

As we enter the third decade of the twenty-first century, it is appropriate to revisit and update the findings and observations made in *Facing the Weather Gods*.

The intervening years have seen improvements in science and climate modelling, and a wealth of published literature (for example, Scholes et al., 2015; Sylla et al., 2016; Girvetz et al., 2019) on global and regional climate change, as well as vast datasets detailing demographics, climate and land-use change.

In many parts of Africa, the impacts of climate change – heatwaves with greater intensity, duration and frequency, together with droughts, more intense storms, more extreme rainfall events and crop failures – will be exacerbated by a combination of growing population, urbanisation and lack of access to information and resources (including money) to protect homes from extreme heat and from floods. Temperatures over the central interior regions of Southern Africa have been rising at about twice the average global rate of temperature increase over the past five decades (Engelbrecht et al., 2015).

As the climate continues to warm due to continuing greenhouse gas emissions from the burning of fossil fuels and other human activities, the world's traditional weather patterns are predicted to change. At the same time, it must be acknowledged that the global and regional dynamics that influence weather patterns remain uncertain, particularly so in a climate changing world. As a consequence, the models that make climate projections carry a high degree of uncertainty (Cook et al., 2014). What is clear, however, is that all weather, and the systems that drive it, are taking place in a world that has already experienced climate change.

Greenpeace's updated report, *Weathering the Storm,* aims to assess the current state of scientific knowledge regarding the trends and drivers of extreme weather events in Africa, by *inter alia*:

i. reviewing the available data on the intensity and frequency of extreme weather events;
ii. providing updated projections for the future that are based on the latest climate models; and
iii. discussing the implications of extreme weather events on human health, food security, resilience to extreme events, biodiversity and human conflicts.

Efforts have been made to limit the use of complex technical terms in this report. However, explanations of commonly used terms and concepts are included in **section 7.0**.

1.1 Africa in context

Africa is the world's second largest continent and covers a total land area of approximately 30,365,000 square kilometres (11,724,000 square miles). This is around 20% of the total global land mass. The continent is bisected by the Equator, which means that much of the land mass is in the tropics.

Noteworthy physical characteristics are the Sahara desert in the northwest, the world's second largest rainforest in the Congo Basin of Central Africa and the

6,400 km (4,000-mile)-long East African Rift System. Africa has many mineral resources but the economies of most countries are dominated, in terms of employment-share, by subsistence agriculture, the productivity of which is expected to be severely negatively impacted by climate change and overexploited soil. In spite of its large landmass, Africa's population was an estimated 1.35 billion in 2020, or 16% of the global population. The most populated regions of the continent are near lakes and along river basins, in coastal West Africa, Northern Africa and some highland areas. The population density is lowest in the desert and savanna regions (ourworldindata.org; britannica.com; Niang et al., 2014).

Sub-Saharan Africa is home to more than half of the world's extreme poor, amounting to approximately 400 million people. Most of those people live in rural areas and work in agriculture (Porciello et al., 2020). The significance of an increase in population figures is that climate extremes such as heat and rainfall are likely to disproportionately affect those who are least equipped to cope with the impacts of such events. As the twenty-first century progresses, the population of sub-Saharan Africa is expected to increase from 1.06 billion in 2019 to 3.7 billion in 2100 (UN, 2019a). The population increase is projected to be driven by a decrease in mortality of children under 5 years old and an increase in life expectancy (males and females combined) from around 63 years in 2020 to around 75 years in the 2090s. In addition, the continent of Africa (together with Asia) is predicted to experience the fastest rate of global urbanisation during the twenty-first century. Currently, 43% of Africa's population (424,000,000 people) is urban; by 2050 this figure is predicted to increase to almost 60% (1,258,000,000 people). However, urbanisation is not expected to be uniform across all African countries (UN, 2019b).

Africa crosses the equator and extends to the northern and southern latitudes and as a result its mix of climatic conditions is extremely varied. Climatic zones include humid tropical rainforest in the equatorial regions, seasonally arid tropical regions, desert and also subtropical Mediterranean regions (Hulme et al., 2001). The continent encompasses equatorial tropical forest ecosystems, tropical and subtropical woodlands and savannas, tropical grasslands, arid shrublands and desert vegetation (Midgley & Bond, 2015). The different climates make projecting future climate changes a challenge for climate scientists. Challenges in making future climate projections are also because future greenhouse gas emissions are difficult to predict, and different climate systems may also react in unpredictable ways to climate forcing.

Box 1: What is extreme weather?

No universally accepted definition of 'extreme weather' exists, even though an extreme weather event might be described as such by those who experience unusual weather. The nature of 'extreme' is relative to the normal or prevailing conditions. For example, a heatwave in Lesotho would have different temperature readings to a heatwave in Mali even though the magnitude of change from the usual temperature might be similar.

Extreme weather events are also described as rare events (and humans are not well adapted to cope with them) or severe events (that create loss or damage to infrastructure and/or ecosystems). Extreme weather events generally involve a number of variables that include a combination of climate variables and drivers and the location of such an event will determine its overall impact **(Fig. 1)** (Stephenson, 2008).

Extreme weather events can reflect changes in one or more underlying drivers, and the frequency and severity of events can change as a result (Scholes et al., 2015).

For the purposes of this report, the term 'extreme weather' is used to indicate weather conditions regarded as unusual or exceptional for the time of year or season and that may have negative social and/or environmental consequences. The extreme weather events covered in this report are consistent with the meteorological perspective: high temperatures, droughts, floods and cyclones. Extreme weather may cause death, starvation, damage to ecosystems, housing, infrastructure and agriculture, and may lead to evacuation or migration of inhabitants or crop failure. Events and issues associated with or caused by periods of extreme weather that are covered in this report include those to human health, food and water security, biodiversity, fire and locust swarms.

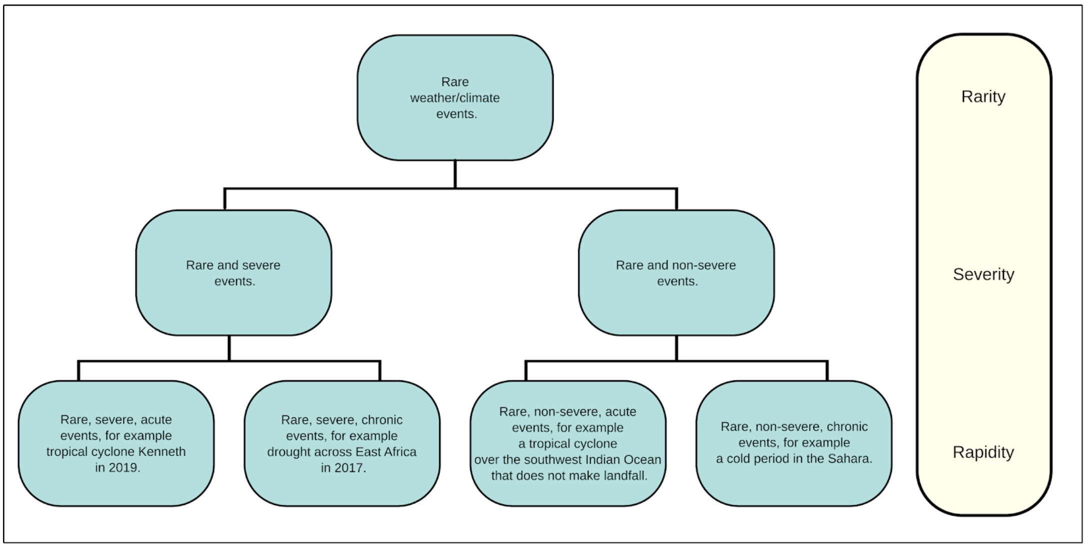

Figure 1*. A schematic describing rare, or extreme, weather events. Adapted from: Stephenson, 2008.*

Box 2: An overview of Africa's weather systems

The weather systems and phenomena that most affect climate variability in Africa are the West African Monsoon (Lafore et al., 2011), El Niño Southern Oscillation, sea surface temperature in the Indian and Atlantic oceans, and tropical cyclones (that affect East Africa, Southern Africa and the Madagascan coastal regions) (Christensen et al., 2013, section 14.8.7). Climate scientists are concerned because global warming-induced changes to major climate systems – including to drivers of African weather such as the West African Monsoon and the El Niño Southern Oscillation – could pass a tipping point this century that could induce rapid, irreversible climate changes (Lenton, 2011). A brief description of these climate systems is in **Box 4**.

The Intergovernmental Panel on Climate Change (IPCC) AR5 climate scenarios project that mean annual temperatures across Africa will increase during the twenty-first century and that changes in temperature will be greater over Northern and Southern Africa than Central Africa. Modelled projections of rainfall patterns through the twenty-first century to 2100 are less certain than those relating to temperature, but generally agree that Northern and Southern Africa will become significantly drier from around the middle of this century, whereas Central and Eastern Africa regions are likely to experience increases in mean annual rainfall. In the eastern regions the projection is for an overall wetter climate with more intense wet seasons. Future rainfall patterns for West Africa have varied projected outcomes (Niang et al., 2014). The projections broadly agree with those made in AR4. The IPCC AR5 report (as with AR4) approaches the continent of Africa on a continental or regional basis when it discusses observational and projected climate trends.

Box 3: An overview of climate modelling

Future climate projections are made using computer models. There are two broad categories of climate models:

(i) dynamical models, that are based on the physical climate processes; and

(ii) statistical models that are based on observational data.

Dynamical models are computer programs that simulate the chemical, physical and biological processes that control climate. These models can be 'atmosphere-only', 'ocean–atmosphere' or 'Earth System' models, depending on which parts of the climate system are included (atmosphere, oceans, land, biosphere and cryosphere). Each model type has advantages and disadvantages for researchers. For example, atmosphere-only models are not able to simulate how the ocean and atmosphere interact. This means that the model runs quickly and that uncertainty from the ocean model does not influence the result. However, atmosphere-only models are limited by the assumption that the climate change process being investigated does not influence the state of the ocean (Stone et al., 2019) and therefore cannot capture feedback effects.

By contrast, statistical models do not replicate chemical, physical and biological processes. Instead, statistical models are derived from the analysis of past weather patterns. The models are generated by deriving relationships between different climate parameters in meteorological archives. They can then be projected forward in time to indicate how these parameters might evolve. Statistical models reduce the complexity of the model needed to make a forecast. They are especially useful for predicting local weather patterns that have complexities not included in dynamic models. A key limitation of statistical climate modelling is that the model may not correctly represent climates that are significantly different to the meteorological archives used to design them.

<u>Model accuracy</u>
Climate scientists usually measure the accuracy of a model by comparing their simulation with observational data. For example, scientists test the climate models that are used to project future climates by simulating the present climate or past climate – the assumption being that if the model accurately simulates present and historical climates then the likelihood is that it will be reliable in projecting a future climate scenario (Xulu et al., 2020).

Studies are now also beginning to evaluate climate model predictions made decades ago to subsequent observations of what then actually occurred. One study concluded that, in general, projections published over the past five decades have been accurate in predicting the changes to global mean surface temperature which have since been observed (see **Box 5**) (Hausfather et al., 2020).

<u>Uncertainties</u>
The uncertainties in climate model results stem from three principal areas: scenario uncertainty (for example, uncertainty in the future atmospheric carbon dioxide concentration); natural variability (the day-to-day or decade-to-decade variation in weather and climate); and model uncertainty (models are never perfect representations of the climate system). In comparison to other global regions, Africa has a lack of observational weather

data from which to assess climate trends (Han et al., 2019). The incomplete knowledge of the climate system, especially in Africa, contributes to model uncertainty. Some climate models have known deficiencies in simulating the mean rainfall patterns and variability in Africa's weather patterns (James & Washington, 2013). In South Africa, for example, the models currently in use for operational purposes were developed in countries outside of Africa. Accordingly, the models may not be adequately 'tuned' to simulate local conditions (Bopape et al., 2019).

Researchers can estimate uncertainty by comparing the results of many different models, each run multiple times. Models are run many times to introduce small changes to the initial conditions in each model run. This produces different outcomes for each run of the same model. When the same result is produced by multiple climate models they can be more confident in the prediction. This is because each climate model is different and is likely to have different inherent errors or biases. Therefore, if different models produce the same result, that result is less likely to be a consequence of a deficiency in the model and more likely to represent a real climate effect. Model Intercomparison Projects (MIPS) are also used extensively in climate research, for example CMIP3 and CMIP5.

<u>Developing climate models</u>
Work to improve climate modelling aims to understand the discrepancies between the climate projections generated by model simulations and observational data collected from the field. This provides new understanding of the climate system allowing models to be improved. For example, CMIP3 and CMIP5 model projections overestimated the rain in East Africa's short rains season, which led researchers to doubt the projections made by models for later in the century (Yang et al., 2014). Subsequently, analysis of recent and current weather observations led researchers to conclude that the sea surface temperature of the western Indian Ocean is closely related to the rains over East Africa (Yang et al., 2015).

<u>Choose your model</u>
Different models have known strengths and weaknesses, and the best model will depend upon the region in question and the type of projection being made. Global climate models focus on the overall picture but may not accurately represent regional areas because the resolution is too coarse, which is why regional models are favoured for smaller areas of a country or continent. Dynamic models used to project the East African climate have been good at predicting the short rains and the Indian Ocean Dipole but not good at predicting extreme weather events. As computer climate modelling becomes more sophisticated there will probably be fewer uncertainties in projections of future climate changes (Nicholson, 2017).

<u>A future climate with no human intervention</u>
Climate scientists can create computer models to simulate the most likely scenario in a world that has not experienced anthropogenic greenhouse gas

emissions. Such simulations include data from the pre-industrial period (circa 1850) and natural forcings such as volcanic aerosols and solar irradiance (Christidis & Stott, 2014). This allows scientists to estimate how our future climate might have looked without human intervention.

An increasing body of attribution studies are evaluating the extent to which human activity is influencing the climate. These studies seek to distinguish between events that are the result of human-driven climate change and events that may result from natural climate variability and without human intervention.

2.0 An overview of the intensity and frequency of extreme weather events

The scientific consensus is that, at a global level, extreme weather events will increase in frequency and intensity as the twenty-first century progresses (for an overview of extreme weather, see **Box 1**). Land and ocean temperatures have increased on a global scale since pre-industrial times (Hoegh-Guldberg et al. 2018). Last year, 2019, was one of the world's three warmest years since records began; data show that 2014–2019 were the six warmest years since records began in the late 1800s (Blunden & Arndt, 2020; NOAA, 2020). The rate of temperature increase is not expected to be uniform across the globe and some regions have already exceeded an annual average rise of 1.5 ℃; the changes are particularly noticeable in the Arctic in the cold season and in mid-latitude regions in the warm season. Globally, the trend for rainfall is for increased occurrence of once-rare events (Chen et al., 2020).

Hulme et al. (2001) estimated that the African continent warmed on average by 0.5 ℃ between 1900 and 2000, although others have documented a global average temperature change of 0.89 ℃ over the same period; the warming is primarily attributed to human activity (Perkins, 2015). More recently, however, the United States National Oceanic and Atmospheric Administration (NOAA, 2020) suggested a considerably greater average increase of 0.12 ℃ per decade for the African continent. Analysing the data on such a decadal basis also indicates that, at both a global and continental level, the rate of temperature increase has been greater in the past few decades. For example, from 1880 and for much of the twentieth century until 1970, the global average rate of increase has been estimated to have been around 0.07 ℃ per decade, increasing to an average rate of 0.18-0.19 ℃ per decade from 1971 to the present day (Blunden & Arndt, 2020). In terms of Africa, the most recent estimates from NOAA (2020) suggest an increase from the 0.12 ℃ per decade before 1981 to a much faster rate of 0.31 ℃ per decade since then. The latest 'State of the Climate in Africa 2019' report (WMO, 2020) notes that in 2019, temperatures were averaged across mainland Africa at between 0.56 ℃ and 0.63 ℃ above the 1981–2010 long-term mean. The report says that 2019 was probably the third warmest year on record after 2010 and 2016. Temperatures in excess of 2 ℃ above the 1981–2010 average were recorded in South Africa, Namibia and in parts of Angola.

The upward trend in average annual temperature over Africa is evident from data observations and the continent's ten hottest years have all been since 2005 (Blunden & Arndt, 2020). At least three regions of Africa experienced temperature anomalies last year, in 2019, according to data analysed from two different datasets (HadCRUT 4.6 and NASA GISS). East, West and Southern Africa recorded land surface temperature increases of between 1–2 ℃ in comparison to the 1981–2010 base period. The increases are greater than the 2019 global land and ocean surface temperature, which fell between 0.44 ℃–0.56 ℃ above the 1981–2010 average (Blunden & Arndt, 2020). Future projections for this century for the African continent are increases in mean surface temperature that exceed the global mean, and an increase in the frequency of exceptionally hot days (see **section 4.1**).

Multi-model projections (using the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project phase 3) for Africa under 1 ℃, 2 ℃, 3 ℃ and 4 ℃ warming scenarios project that average temperatures across the continent will rise more than the global average. The magnitude of changes will increase in line with increased warming scenarios, with the greatest impacts being predicted for 3 ℃ and 4 ℃ scenarios. There are greater uncertainties regarding future rainfall patterns. Models predict that there will be changes to rainfall across the continent, but the nature of those changes (more rain, less rain, more intense rain or changes to the seasonality of rains, for example) is uncertain, especially in tropical regions. The precipitation trends from a number of models, however, project a wetter East Africa and changing rainfall patterns over the Sahel with some models projecting an increase in rainfall over the central Sahel and a decrease over the western Sahel (see **Box 2)**.

Observational data appear to support the projections. The World Meteorological Organisation (WMO, 2020) notes that in 2019, rainfall deficit in Southern Africa during the 2018–2019 season exacerbated an existing drought, but that heavy rainfall in 2019 led to flooding, and the footprints of rainfall from cyclones Idai and Kenneth were clearly visible in the annual precipitation anomalies despite the preceding drought conditions. Erratic rainfall in East Africa meant that an incipient drought was superseded by flooding. In addition to East Africa, much of the Sahel recorded above normal rainfall.

The accumulation of anthropogenic greenhouse gases in the atmosphere, largely from fossil fuel production and use, is of such magnitude that even if all emissions of climate-harmful gases were stopped immediately, there would not be immediate stabilization of atmospheric gases. The reason is firstly because of the complexity of the climate system and carbon cycle, and secondly because the persistence of greenhouse gases and aerosols in the atmosphere varies from just days to thousands of years. To remove all anthropogenic methane would take around 50 years, but to remove all anthropogenic carbon dioxide (CO_2) could take several hundred years (Collins et al. 2013, p1106). Clearly, the scenario is hypothetical because it is implausible that all greenhouse gas emissions will cease immediately, but the exercise is useful as an example of a 'best case' scenario to highlight the urgent need to slow and stop emissions.

Box 4: African weather drivers 101

El Niño–Southern Oscillation (ENSO) The ENSO influences extreme weather events globally, causing floods in some regions and droughts in others. It is a naturally occurring oscillating interaction between the tropical Pacific Ocean and the atmosphere that is composed of two alternate, opposing phases: El Niño and La Niña. El Niño occurs irregularly about every three to seven years and brings warm, dry air to Southern Africa and cool air and rain to eastern equatorial Africa. The opposite happens in La Niña years – cool air and rain to Southern Africa and warm, dry air to equatorial East Africa.

Indian Ocean Dipole (IOD) The IOD refers to an irregularly alternating sea-surface temperature difference in the waters of the west and east Indian Ocean. A positive Indian Ocean Dipole means that sea temperatures are warmer in the western Indian Ocean region and cooler in the east, bringing heavy rainfall to East Africa. A negative dipole is the opposite and causes drier conditions in East Africa. The effects of the IOD are exacerbated if the dipole is strongly positive or negative, which can bring flash floods or prolonged drought, respectively. The IOD also affects weather systems in Australia and Southeast Asia.

Inter-Tropical Convergence Zone (ITCZ) The ITCZ is a band of clouds that forms across the tropics. In Africa, the ITCZ brings seasonal daily intense rainfall between latitudes of approximately 23.5° N and S. The ITCZ shifts seasonally towards the hemisphere that is warmer in relation to the other but the precise mechanisms that control its position, and rainfall intensity, are unclear.

2.1 Heatwaves in Africa

Heatwaves are periods of time in which the ambient or outdoor air temperature is higher than usual. Many people will have experienced what they perceive to be a heatwave, but the definition is subjective. In the scientific literature, the definition of a heatwave is inconsistent – it is not possible to provide a universal definition or metric of a heatwave to cover all global regions. Heatwaves develop when high-pressure synoptic weather systems (an anticyclone) remain in the same location for a longer period than expected, which could be days or even months. Other factors are involved in the formation of heatwaves include low soil moisture and teleconnections with other climate systems (Perkins, 2015).

Observed data using figures from the second half of the twentieth century suggest that heatwave duration and intensity has increased over parts of Africa, most notably parts of Southern, East and Northern Africa. The observational temperature data indicate that much of Africa experienced an increasing trend in 'cumulative heat' by 50% per decade between 1950 and 2017 (Perkins-Kirkpatrick & Lewis, 2020). This study used 'cumulative heat', a new conceptual metric to assess the duration and intensity of heat waves during a season. For example, if a heatwave is defined as air temperature above 30 ℃, and the temperature recorded is 33 ℃, a temperature anomaly of 3 ℃ is produced. If the period of the heatwave lasted for 5 days, the 'cumulative heat' produced will be 15 ℃. On this basis, the authors estimated that the extra (cumulative) heat produced by heatwaves over parts of Africa is increasing by 10 ℃ per decade (Perkins-Kirkpatrick & Lewis, 2020).

Studies using numerical models at regional and global scales project that during the twenty-first century, heatwaves will occur more often, at higher intensities, and last for longer under enhanced greenhouse gas concentrations (Perkins, 2015). Modelling studies project that the continent of Africa will experience an increased number of hot and humid days as the century progresses, with a median increase of 2.5 heatwave events per season over Central and Southern Africa (Perkins-Kirkpatrick & Gibson, 2017). Parts of Africa (together with Central America and the Middle East) are projected to experience the greatest impact of heating and might experience an increase in heatwave duration by 10–12 days per season for every one degree of global heating (Perkins-Kirkpatrick & Gibson, 2017). Another projection (Rohat et al., 2019) suggests that by the 2090s, the number of people living on the continent of Africa who will be exposed to dangerous heat conditions may reach 86–217 billion person-days per year. The variance in the figures is because the computer model used different scenarios using 12 Shared Socioeconomic Pathway (SSP) – Representative Concentration Pathway (RCP) combinations.

But it is not only the infrequent but extreme heat events that are becoming more common; less extreme but also higher-than-usual temperatures are being experienced and can create long-term heat stress. Observational data show that Africa has experienced an increase in mean annual temperature over the past 50–100 years and projections suggest that the trend is set to continue. In comparison to the mean annual temperature in the late twentieth century, the mean annual temperature increase for much of the continent of Africa is expected to exceed 2 ℃, and possibly fall in the range 3 ℃ to 6 ℃, by the end of the twenty-first century if high emissions continue (Niang et al., 2014).

A warming climate over the next 50 years is projected to lead to the displacement of an estimated 1-2 billion people globally (figures specific to African countries are not available), particularly those who live in the desert regions along the equator, as the mean annual temperature in some regions exceeds 29 ℃. According to Xu et al. (2020), introducing strict climate mitigation measures and stopping greenhouse gas emissions, as in the RCP2.6 scenario, will reduce the impact of global heating on the human population in the most vulnerable regions.

Although much research into the nature of heatwaves has been carried out globally over the past 10-15 years, there are still data-poor regions, of which Africa is one (along with Central and South America, and India). Further research is needed to understand the extent to which human activity is causing changes to the systems that cause heatwaves and to investigate how climate variability will affect heatwave formation (Perkins, 2015).

In summary, global observed data have shown an increasing trend in the overall number and frequency of heatwave days from the twentieth and into the twenty-first century. Future projections for Africa through the twenty-first century follow the global trend in that the frequency, intensity and duration of extreme heat events are expected to increase. The data trends that show the long-term increase in ambient temperature will be important to policy makers to develop strategies to cope with extended periods of heatwaves and also periods of intense heatwaves. Recommendations from climate scientists are to monitor heatwave events on a global level for three to four decades to enable the broad trends to be more accurately assessed and better understood. Determining heatwave trends using data from fewer than several decades can be difficult because heatwaves are susceptible to internal climate variability, which means that short-term trends may not indicate long-term changes (Russo et al., 2016; Perkins-Kirkpatrick & Lewis, 2020). Failing to take measures, however, to reduce emissions while such studies are carried out to develop the evidence base would result in the time window for effective action being seriously compressed.

2.2 Drought in Africa

Drought can cause economic loss, bring crop failures, put food security at risk, and can lead to a shortage of safe, clean drinking water. Drought is an extended period of time in which a region receives less precipitation than expected. But attributing a drought – as with other extreme weather events – to just one cause is not straightforward because extreme events are usually caused by several different (albeit interacting) factors (see **section 4.0**).

Attribution research is a growing field of study that can help to evaluate the extent to which an extreme event has been driven by climate change. Research investigating the 2011 drought in East Africa found that anthropogenic climate change increased the risk of failure of the long rains in 2011, which had preceded the drought and led to dry conditions. But the same piece of research found that human influence was not significant in the failure of the 2010 short rains, which also created dry conditions but were greatly affected by La Niña (Lott et al., 2013).

Between 2015 and 2017 the Western Cape province in the southwest of South Africa was affected by three consecutive years of below-average precipitation. This, in turn, led to a serious water shortage in Cape Town with the possibility of a complete failure of the water supply at a point designated as 'Day Zero'. When the Day Zero event was analysed using a risk-based approach as a way of teasing out the part played by climate change it was estimated that climate change had made this otherwise very rare event more likely by a factor of three (Otto et al, 2018b).

In another example, the 2015–2016 extreme drought event in East Africa severely impacted the food and water security of more than 15 million people in Ethiopia, Kenya, Somalia and Southern Africa (Funk et al., 2018). The extreme drought caused severe food shortages and a nine-million tonne cereal crop deficit in the region, which meant that 28 million people had to rely on humanitarian food aid (Collins et al., 2019). In 2016, a very strong negative Indian Ocean Dipole (see **section 3.3**), affected the climate over East Africa, which experienced a failure in the seasonal short rains in October–December. During that time, some regions received less than 50% of their normal rainfall (Lu et al., 2018). Climate scientists found that anthropogenic climate change contributed substantially to the 2015–2016 extreme drought over East and Southern Africa by accentuating the natural El Niño impacts. Attributing the 2015–2016 drought entirely to anthropogenic climate change would not be accurate because of the strong natural variability in the ENSO and associated sea surface temperatures. However, research suggests that anthropogenic climate change significantly contributed to the exceptionally warm sea surface temperature during the El Niño and to an approximate 16% and 24% reduction in rainfall over East and Southern Africa (Funk et al., 2016; Funk et al., 2018). Other research also concluded that the drought that so severely affected East and Southern Africa was caused by a lack of rainfall exacerbated by a strong El Niño event that decayed into a weak La Niña (Lu et al., 2018).

The following year, in 2017, an extensive drought across East Africa affected Tanzania, Ethiopia, Kenya and Somalia when the March–June rains failed. Research indicates that exceptionally warm sea surface temperatures in the western Pacific and failure of the rains that caused the drought conditions in East Africa are associated with ENSO variations. Attribution research using climate model simulations indicates that the extreme sea surface temperature difference would be extremely unlikely without climate change driven by human activities (Funk et al., 2019). The humanitarian consequence was that the people living in the worst affected regions experienced near-famine conditions (Collins et al., 2019).

Models used to project drought over Southern Africa suggest that, with increased global heating, the intensity and frequency of drought conditions will increase but not all regions will be affected equally. A study focused on four major Southern African river basins (Orange, Limpopo, Zambezi, and Okavango river basins that were chosen for their economic importance in agriculture, mining, power generation and industry) projected that at 2 ℃ above the pre-industrial baseline (1861–1890) there would be a statistically significant increase in drought intensity over the southwestern coast, and an increase in drought frequency by two events per decade. If the average annual temperature increases further, by 3 ℃ in comparison to the pre-industrial baseline, more than half of South Africa and Namibia may be severe drought 'hotspots' (Abiodun et al., 2019).

Modelling studies and observational data suggest that the tropics (the meteorological term for the moist tropics and dry subtropics at roughly 30° S and 30° N) are increasing in size and are expanding in a polewards direction. Data suggest that the tropics have widened by around 0.5° of latitude per decade since 1979 (when routine satellite observations became possible). A change in the size of the tropics could lead to changes in the rain belt and expansion of subtropical desert, as well as affecting frequency of drought and wildfires. The reasons for the expansion of the tropics is a subject of current scientific research. One early theory was that the cause was predominantly human-driven, although more recent analysis has suggested that several additional factors might be involved; as well as anthropogenic greenhouse gas emissions and other pollutants, natural variability may also contribute. The expectation is that if greenhouse gas emissions continue then global heating will become the dominant cause driving the expansion of the tropics (Staten et al., 2018). The expansion of subtropical deserts could impact billions of people globally who live in semi-arid regions by affecting livelihoods through impacts on agricultural yields and the availability of freshwater.

2.3 Rainfall in Africa

Projections for future rainfall patterns over the African continent are more uncertain than those for future temperature changes. In other words, climate scientists are more confident in the accuracy of climate models to project future temperature changes than future precipitation changes (see **Box 2)**.

Neither the new-generation climate modelling using Climate Model Intercomparison Project 6 (CMIP6) (11 outputs analysed), nor the previous generation CMIP5 (29 outputs analysed), reached firm conclusions on the amount of change expected to rainfall over the Sahel during the twenty-first century. Greater confidence in precipitation projections over the Sahel (and other regions) will probably only be achieved with greater understanding of global circulation (Monerie et al., 2020).

That said, the general consensus is that under RCP8.5, Southern and Northern African regions are projected to experience decreases in mean annual rainfall by the mid- to late twenty-first century. In contrast, Central and East Africa are likely to experience increases in mean annual rainfall under RCP8.5 from around 2050 onwards. Projections for future rainfall patterns over the Sahel and West Africa are more uncertain because different models have produced different outcomes. However, some regional-scale models project an increase in the number of extreme rainfall days over West Africa and parts of the Sahel during the twenty-first century (Niang et al., 2014; Dosio et al., 2020).

Another climate modelling study, investigating changes to extreme weather events in Africa expected from the middle of the century, projects an increase in the frequency and intensity of rainfall over the Sahel during the summer rainy season, and an increase in the frequency, duration and intensity of rainfall over East Africa (Han et al., 2019). The modelling also projected reduced rainfall and increased duration of dry periods in southeastern Africa. The study has limitations because it used only one regional climate model; if such findings are subsequently confirmed by other models and studies then confidence in them would be increased.

To mitigate the impact of unpredictable and/or extreme rainfall events in future decades, the scientific consensus is to try and restrict the average global temperature rise to 1.5 ℃ (rather than >2 ℃) above pre-industrial temperatures. Doing so is likely to reduce the number of extreme precipitation days in many regions around the world, including Africa (Chen et al., 2020).

2.3.1 Surface water and runoff

Regions subject to extreme rainfall events may experience flooding and accelerated soil runoff. Although the primary driver of extreme rainfall events and altered rainfall patterns is climate change, human activity such as land clearance exacerbates the problems that result by, for example, enabling greater soil erosion, which leads to soil runoff blocking drainage channels.

Land-use change such as deforestation for agriculture, pasture and timber can make a significant impact on landscapes and can impact livelihoods. For example, in a study focused on the Olifants Basin in northeast South Africa, urbanisation and agriculture were identified as causing the greatest changes in surface water runoff, water yield and evapotranspiration. Land use and land cover change analysed using Landsat data from 2000 to 2013 found significant changes in the study area (that drains an area of approximately 50,000 km^2) in the balance between urban areas, agricultural lands and rangelands. Rangeland is an area of open land that is not used for growing crops or for agricultural practices, that may be used for hunting or grazing animals and typically is covered with natural grasses and shrubs. Urban areas increased from 13% in 2000 to 23% in 2013 and agricultural land increased from 15% in 2000 to 35% in 2013. By contrast, rangeland decreased from 69% in 2000 to 37% in 2013. The study used a model called the Soil and Water Assessment Tool to simulate the hydrological impact of the land-use and land cover change on surface runoff, water yield, lateral flow and groundwater. The most significant impact of the modelled changes in land use that took place between 2000 and 2013 was water runoff, which increased by 46.9% over the period. In figures, that is an increase of 14.52mm surface runoff water on average, annually, across the Olifants basin in 2013 compared to 2000. A decrease in the average annual groundwater recharge from 34mm in 2000 to 22mm in 2013 was attributed to increased surface runoff, less soil infiltration and higher evapotranspiration. The authors noted that other studies found similar effects of urbanisation (Gyamfi et al., 2016).

Urban environments tend to lack trees and vegetation and can be adversely affected by extreme weather events that can cause runoff (following heavy rainfall), dust storms (in periods of drought) and high heat. Coastal areas and settlements on rivers are vulnerable to sea level rise and flooding from sudden high volumes of water such as intense periods of rainfall during tropical cyclones. Measures proposed to make cities more resilient include reforestation of coastal areas to protect against storm surges and to help absorb excess rainfall, encouraging urban farming and forestry to absorb water and heat and to provide cooling shade (Kareem et al., 2020).

2.3.2 Storms

Storms that form over land are potentially devastating if they coincide with areas of habitation or agriculture because of flooding and run-off. Extreme rainfall events are predicted to increase in frequency globally with climate change.

Equatorial Africa, over the Congo Basin and the Sahel regions, are known to experience intense storms; Sahelian storms, for example, occur seasonally (June to September) in a narrow band between 10°–18°N across West Africa during the West African Monsoon. Although defining an 'intense storm' is not straightforward, it is generally accepted that the greater the convective vertical velocity, the more intense the storm (Zipser et al., 2006).

Rainfall over the Sahel varied during the twentieth century, with a wet period in the 1950s and 1960s, followed by drought in the 1970s and 1980s, whereas rainfall patterns since the 1990s have varied between years. Research has found that the frequency of the most intense storms – called 'mesoscale convective systems' – has increased over the Sahel in the past four decades, according to analysis of satellite data from 1982–2016 (Taylor et al., 2017). Mesoscale convective systems are a collection of intense storms that can last for at least 12 hours. In the Sahel, mesoscale convective systems can be vast, exceeding 25,000km^2, and have been shown on satellite data to coincide with extreme rainfall. The drivers of these intense Sahelian storms are unclear and are likely to be a combination of factors that include wind shear and drying air, coupled with warming temperatures over the Sahara.

Projections suggest a rise in extreme daily rainfall over the Sahel if the connection with the warming Sahara continues, but more research is needed to fully explore this scenario (Taylor et al., 2017). The relevance of these findings is that, with increased frequency and intensity of storms and rainfall, the risk of damaging flash floods also increases. In contrast, current data suggest that the frequency of intense storms is not expected to increase over the Congo Basin.

2.4 Tropical storms and cyclones in Africa

Tropical cyclones are storms that originate over the ocean when the surface water reaches or exceeds around 26 ℃. Tropical storms are associated with extreme rainfall and destructive high winds that can cause damaging coastal storm surges. The tropical cyclones that most frequently affect the African continent are generated in the southwest Indian Ocean basin and make landfall in Mozambique or Madagascar. Tropical storms that affect Africa also form on the Arabian Sea, making landfall in Somalia.

Tropical cyclones are graded from 1 (which have a diameter of 50-100km and sustained wind speeds of 119-153km/h) to category 5 (up to 500km in diameter with wind speeds exceeding 249km/h).

Some of the latest high-resolution computer models have projected that fewer tropical cyclones will form in the Southern Africa region as the climate warms but those that do form will be more intense. This is in line with projections suggesting that, although the global average number of tropical storms will decrease by 6–34% by 2100 (Knutson et al., 2010) as the troposphere is expected to hold more water vapour and latent heat than at present, the globally averaged intensity of tropical cyclones will increase by 2–11% over the same period. Increased intensity of tropical cyclones could enhance the risk to coastal communities of damage from storm surges, which may, in turn, be exacerbated by future sea level rise (Walsh et al., 2016).

As a consequence of fewer tropical cyclones, however, the Limpopo River Basin and southern, central and northern Mozambique are expected to receive less rainfall (Muthige et al., 2018).

The total number of tropical cyclones forming annually in the southern Indian Ocean is projected to decrease by 26% in the late twenty-first century in comparison to the present day (1982–2005), but the number of intense category 4 and 5 storms is projected to increase by 64% according to a computer modelling study. The study used the results of a multimodel ensemble of CMIP5 models for the RCP4.5 scenario to force a high resolution atmosphere model and subsequently a hurricane model to estimate changes in hurricane activity (Knutson et al., 2015), though the study did not project how many tropical storms would make landfall. For comparison, the global number of category 4 and 5 tropical cyclones forming annually in the late twenty-first century is projected to increase by 28% from the present-day baseline. The same study projected an average increase of 8.5% in rain rate, or the quantity of rainfall, by the late twenty-first century for all tropical cyclones forming over the southern Indian Ocean in comparison to the present day baseline (compared to a global projected increase of 14%). The authors suggest that their findings are in agreement with other studies (Knutson et al., 2015).

Tropical cyclones are also affected by wider weather systems. The Mascarene High, for instance, is part of the weather system that determines the path taken by tropical cyclones over the Mozambique Channel and Southern Africa, which can cause widespread destruction when they make landfall (Xulu et al., 2020). See also **section 3.2.1**.

Tropical cyclones that form in the North Indian Ocean and make landfall may affect East Africa. Future projections (2070–2100) using modelling scenarios with RCP8.5 predict an increase in the genesis of tropical cyclones in the Arabian Sea, but only a small increase of 0.5 tropical cyclones per decade that will make landfall and impact East Africa in the future scenario (Bell et al., 2020).

Nevertheless, cyclones that do make landfall and bring extreme heavy rainfall frequently cause severe damage to homes and infrastructure and may lead to outbreak of disease. Last year, 2019, was exceptionally active for southwestern Indian Ocean cyclones including two of the strongest known cyclone landfalls on the east coast of Africa. In March 2019, one of the most severe tropical cyclones ever recorded in the southern hemisphere made landfall in southeast Africa (WMO 2020). Cyclone Idai caused extensive flooding in Mozambique, Malawi and Zimbabwe, damaging more than 100,000 homes and killing more than 1,200 people – although millions of people are thought to have been affected (Blunden & Arndt, 2020). The human health consequences were serious: cases of diarrhoeal disease were reported at the end of March, and at the beginning of April in excess of 1,400 suspected cholera cases were reported (Chen & Azman, 2019). The estimated cost of damage to local infrastructure was approximately US$2.2 billion (Blunden & Arndt, 2020). The following month, in April 2019, Cyclone Kenneth landed on Cabo Delgado province in northern Mozambique, killing at least 45 people, left around 40,000 homeless and led to a cholera epidemic because the entire sewerage system was destroyed (Cambaza et al., 2019).

2.5 Wildfires in Africa

Fires are integral to some ecosystems and are a natural phenomenon on all continents except Antarctica. Geological records show that fire in tropical savannahs, including in Africa, spread across those regions approximately 7 to 8 million years ago. Fire has therefore been a phenomenon across the African continent for millions of years, and some plants have evolved to require natural fires to trigger germination (Brown et al., 1994).

Routine domestic use of fire by humans began around 50,000 to 100,000 years ago, and the use of fire specifically to manage plants and wildlife is believed to have begun tens of thousands of years ago. In more recent history, in line with the rise in industrialised economies, fire has been used to clear forests for agricultural land. But fires can become uncontrolled, especially during extreme drought events, and that raises the question of whether humans or the climate are more influential in determining fire patterns (Bowman et al., 2009).

Landscape fires can be defined as wild and prescribed forest fires, tropical deforestation fires, peat fires, agricultural burning and grass fires. The interactions between fires, land use and climate are therefore complex.

It is worth noting that, whatever the underlying causes of landscape fires, burning biomass produces harmful toxins including fine particulate matter (or $PM_{2.5}$, which are particles with a diameter of less than 2.5 micrometers), which contains black carbon components, harmful organic compounds and some inorganic species. One study (Johnston et al., 2012) used satellite-derived observational data of fire activity, to estimate average annual human exposure to landscape fire smoke for the period 1997–2006. The study estimated average annual mortality associated with exposure to landscape fire smoke to be approximately 339,000 worldwide, and disproportionately affected low-income countries. In sub-Saharan Africa, an average of 157,000 annual deaths were due to exposure to landscape fire smoke, making it the world's most severely affected region in relation to premature deaths from landscape fire smoke (ahead of estimations for Asia at 110,000 annual deaths and South America's 10,000 annual deaths).

2.5.1 Savannah

Scientists have used data from satellite observations beginning in the 1980s to analyse the extent of fire in global ecosystems and measure the impact of human activity on the occurrence of fires. Savannah ecosystems have the highest frequency of naturally occurring fire because of the alternate wet (which is the growing period) and dry seasons (van der Werf et al., 2008). In Africa, more than 80% of the burned area is in the savannah. However, there has been a decrease in savannah fires in Africa this century. A study that analysed 15 years of satellite data between 2002 and 2016 attributed the decrease in the area burned to increased moisture (rainfall), which reduced the flammability and spread of fire, particularly in the savannah regions (Zubkova et al., 2019).

In its Fifth Assessment Report, the IPCC noted that there were still significant uncertainties about the changes to vegetation cover across the African continent because of complex interactions of the weather systems and the impact of fire and grazing. As computer modelling continues to become more sophisticated and additional data become available, there should be fewer uncertainties in how vegetation responds to climate change (Niang et al., 2014).

2.5.2 Wetlands

Very little research has been undertaken to date on fires in Africa's wetlands. However, the use of fire by humans as an approach to management and conservation has been investigated in the KwaMbonambi wetlands in South Africa (Luvuno et al., 2016). Evidence from that study suggests that, as Africa's wetlands have been shaped in the past by the use of fire, any change in the fire regime as a result of climate change would be likely to induce further changes in wetland ecosystems. However, there are currently too few data available to draw any generalised conclusions about the likelihood of natural fires in African wetlands, or of the trends in and impacts of the use of fire as a management tool.

3.0 What are the drivers of extreme weather events in Africa?

Extreme weather events such as rainfall and drought are governed by complex weather systems and interactions between the ocean, atmosphere and land. Understanding the drivers behind extreme weather events is important to help prepare for and, as far as possible, mitigate or respond to the impacts of those events.

Predicting future climate scenarios carries a degree of uncertainty because the ways in which weather systems may change in response to climate change will depend upon complex interactions on different timeframes. A key factor that climate modellers must consider is the quantity of anthropogenic greenhouse gases that will be released into the atmosphere in future decades. That quantity is dependent upon future human behaviour – and that in itself is unpredictable.

Facing the Weather Gods highlighted that understanding of the drivers of African climate identified below is poor, but what has happened in the intervening years? Overall, the weather systems are becoming better understood but more research is still required; additional observational data will help to reduce uncertainties in modelling predictions. Climate forecasts are improving because of new observational systems, particularly those that are satellite based, and advances in computing can incorporate detailed physical, chemical and biological processes (IPCC, 2013).

Three main weather drivers were addressed in *Facing the Weather Gods*: the Inter-Tropical Convergence Zone (ITCZ); the West African Monsoon (WAM); and the El-Niño Southern Oscillation (ENSO) (already summarised in **Box 4**). These three major systems are revisited here, as well as other major global systems that influence Africa's weather. Possible future impacts of climate change on the main weather systems are discussed in the sections below.

3.1 The main drivers discussed in *Facing the Weather Gods*

As mentioned in *Facing the Weather Gods*, the Atlantic, Pacific and Indian oceans are instrumental in the formation of weather patterns and driving climate variability, although the relationships between the oceans and weather patterns need more research to be fully understood. In the tropical regions of the continent, the monsoon system dominates the climate. The dominant driver of East African rainfall is the sea surface temperature of the Indian Ocean, although the semi-annual rainfall over East Africa is driven by the ITCZ, and the ENSO also influences periods of drought and precipitation. Southern Africa is highly influenced by the oceans and ENSO (Christensen et al., 2013, section 14.8.7).

3.1.1 Inter-Tropical Convergence Zone (ITCZ)

As summarized in the *Facing the Weather Gods* report:

> "The Intertropical Convergence Zone (ITCZ) appears on satellite images as a band of clouds, often thunderstorms which encircle the globe near the equator. These clouds are formed by air convection driven by solar heating together with the converging trade winds. As this air rises it cools and leads to intense rainfall on an almost daily basis. The ITCZ moves seasonally over land as a result of the tilt of the Earth's axis and the changing solar zenith. It moves north in the northern summer and south in the northern winter (for an animation of the seasonal migration of the ITCZ, see ITCZ, 2020). This drives the seasonality of rainfall in Africa and the ITCZ is largely responsible for rainfall occurring between latitudes of approximately 23.5° N and S. The distance that the ITCZ moves seasonally is governed in part by differences in land and sea temperatures, and it moves a greater distance southwards in the central to eastern areas of the continent. As the ITCZ crosses areas twice, it gives rise to two wet periods. The degree of latitudinal movement

> also varies from year to year explaining some of the inter-annual variation in rainfall."

<u>East Africa</u>

East Africa, as defined in Nicholson (2017), includes Kenya, Uganda, Tanzania, Ethiopia, Eritrea, Djibouti, Somalia, South Sudan, Rwanda and Burundi (though historically, many researchers have regarded East Africa as Uganda, Kenya and Tanzania alone). Although climatology is highly variable across East Africa, the wider region described here includes the areas of East Africa which have two rainy seasons each year.

At present, the mean annual rainfall over East Africa is between 800 and 1,200 mm, with more arid and humid extremes in northern and highland regions respectively. Precipitation patterns over the region are complex and vary depending on the topography, season and also from year-to-year. Of the two rainy seasons, the long rains over East Africa fall in the period March–April–May, and produce more rainfall than the short rains (which fall during October–November), which are also less reliable. The main climate trends are that the long rains appear to have declined over much of East Africa and the short rains have increased, periods of drought have become longer and more intense and sometimes continue through rainy seasons, and severe floods have affected the region (Nicholson, 2017).

Rainfall patterns and variability over East Africa can broadly be explained by the seasonal migration of the ITCZ but research suggests that zonal winds over the central equatorial Indian Ocean are a complicating factor. On an inter-annual time scale, the El-Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are also important (Nicholson, 2017).

The ITCZ is a band of deep convective clouds – that is, clouds that can be up to 10km thick – that form across the tropics. The ITCZ shifts seasonally towards the hemisphere that is warmer in relation to the other but the precise mechanisms that control its position, and rainfall intensity, are unclear. Small changes in the atmospheric energy balance between the tropics and extratropics can lead to substantial ITCZ migrations. Consequently, climate modelling projections of future ITCZ movements are very uncertain. Future research to understand the processes that affect the position of the ITCZ will help climate modelling to project the movement of the ITCZ in the future (Schneider et al., 2014).

On the basis that the ITCZ influences rainfall patterns, understanding the mechanisms that influence the position of the ITCZ could be important in projecting East Africa's future climate scenario.

A number of climate systems (in addition to the ITCZ) influence rainfall over Africa, and the relationship between East Africa's rainfall patterns and global weather systems is complex. Although the influence of ocean surface water cooling/ warming on rainfall patterns is not yet fully understood, there does seem to be a relationship between sea surface temperatures in the Indian Ocean and precipitation. In addition, the variation in East Africa's short rains seem to be related to the Indian Ocean Dipole. The Indian Ocean Dipole (more so than the ENSO) seems to be more influential over variability of East Africa's short rains than over the region's long rains (Nicholson, 2017).

The atmosphere above East Africa is generally stable but the rainy seasons (March–April–May and October–November) coincide with increased sea surface temperature in the western Indian Ocean, which transports less-stable air to east Africa, bringing rains as the ITCZ passes over (Tierney et al., 2013; Ummenhofer et al., 2018). As the ITCZ continues its seasonal migration, the rains in Central Africa and the western highlands of East Africa arrive in June–September.

As the Indian Ocean has warmed, there has been a noticeable decrease in rainfall over West and Central Africa. The mechanism for this could be the presence of a strong Rossby wave that leads to a moisture deficit in the region, but also because of the ITCZ. The suggestion is that the decline in rainfall over West and Central Africa is because of a weakened Atlantic ITCZ, and the increase in rainfall over East Africa is a result of a strengthened Indian Ocean ITCZ. As warming intensifies in the Indian Ocean, the expectation is that the trends in rainfall response over Central and East Africa will also intensify – that is, the Central African region will continue to become drier, and the trend over East Africa will be for increased rainfall during the short rains (Dhame et al., 2020).

In summary, observed precipitation trends show drying over Central Africa and the Sahel (Dhame et al., 2020), and wetter short rains (October–November) and drier long rains (March–April–May) over the Horn of Africa (Liebmann et al., 2014).

Declining rains are of great consequence for agriculture, and therefore research to predict more accurately how rainfall patterns might change could help in the development of contingency plans for potential periods of drought. However, because rainfall patterns vary naturally on decadal timescales, it is important to note that a drought in one particular year could be caused by factors other than anthropogenic climate change. One theory for the precipitation changes, based on modelling predictions from a 40-member ensemble of ECHAM5 sea surface temperature-forced atmospheric simulations, suggests that the drier long rains (March–April–May) are because of increased sea surface temperatures in the ocean between Indonesia and the central Pacific, and the wetter autumn rains (October–November) are mostly attributed to increased sea surface temperature in the western Indian Ocean (even though the long rains are strongly correlated with ENSO and IOD) (Liebmann et al., 2014).

The ITCZ seems to be just one of a number of weather systems that influence rainfall patterns over East Africa. The reasoning is partly explained by the observation that the ITCZ is much further north during the equatorial rainy season (Nicholson, 2018). So although the ITCZ is an important driver of the seasonal rainfall over East Africa, research suggests that the ITCZ alone does not account for all the rainfall conditions in that region. The sea surface temperature in the western Indian Ocean influences the two rainy seasons, as does the ENSO (Yang et al., 2015; Nicholson, 2017; Nicholson, 2018). More research is needed to determine the extent of the relationship between East Africa's seasonal rains and the ITCZ.

3.1.1.1. IPCC AR5 and the ITCZ

Modelling (based on a CMIP5 multi-model ensemble of 18 models) under RCP8.5 suggests an increase by around 1.6mm per day rainfall associated with the ITCZ by the 2080s (Christensen et al., 2013, section 14.3.1.1).

3.1.2 West African Monsoon

The West African Monsoon is typically associated with wet summers (July–September) and drought in the winters. Unlike some other weather systems, the West African Monsoon is associated with variable rainfall. It is useful to consider the mechanisms of the West African Monsoon. The land warms faster than the ocean during the summer months, causing the ITCZ to migrate northwards, bringing cool air and rain. The ITCZ pushes back the warm northeasterly trade winds, also called the Harmattan. The ITCZ migrates southwards, towards equatorial Africa, by October, and the trade winds return (Cornforth, 2012).

Facing the Weather Gods included the following description of the West African Monsoon:

> "The West African Monsoon (WAM) is another important climate driver in Africa. The heating of the land causes air above the Sahara to rise, drawing warm moist air in from the sea 1000km to the south. This south westerly airflow then generates rainfall over parts of West Africa from April to June. In mid-July, the rainfall maximum moves suddenly northwards following the movement of the ITCZ. This movement is related to easterly atmospheric waves, which in turn are associated with the ITCZ. The precise relationships are not well characterised."

The West African Monsoon brings varying quantities of rainfall on timescales ranging from annual to multidecadal. Global sea surface temperature rise and the increase in atmospheric CO_2 are key drivers for change and variability in the West African Monsoon, according to analysis involving 12 atmospheric-ocean coupled models in the CMIP5 archive. Quantifying the impacts of CO_2 forcing (global heating) on the West African Monsoon still needs further research (Gaetani et al., 2017).

The West African Monsoon is an important water source for the Sahelian countries, bringing 80% of the rain from late June to late September. Fluctuations in the rainfall can arise because of changes in the wind and relative humidity. As the climate warms, the associated changes to weather systems may introduce greater uncertainties in projecting future weather using climate modelling. Multi-model analysis of CMIP5 and CMIP6 (an analysis of many climate model simulations) found that models are not consistent in their projections of how rainfall patterns over the Sahel may change in future decades and this is likely to be because, as the climate warms, the atmospheric circulation will change in ways that are currently difficult to model consistently. To date, different models have produced appreciably different end scenarios (Monerie et al., 2020).

The possible impact of climate-driven changes to the West African (and Indian) Monsoon on rainfall in East Africa, upon both summer rainfall and to the early and late months of the long and short rains, has so far been little studied (Nicholson, 2017).

3.1.2.1 IPCC AR5 and the West African Monsoon

The IPCC AR5, published since *Facing the Weather Gods*, provided valuable additional information, but much more has been published in the scientific literature since then. The next major IPCC review, AR6, is scheduled to be published in 2021 and 2022. AR5 draws on Coupled Model Intercomparison Projects (CMIP3 and CMIP5) but a more up-to-date modelling project, CMIP6, exists. Briefly: AR5 (Flato et al., 2013, section 9.5.2.4) found that while CMIP5 models better simulate monsoon climatology in comparison to CMIP3, the regional scale quality needed improving. As noted above, in relation to the West African Monsoon, different models project different outcomes, which highlights, for example, the difficulty in simulating the response of the African rain belt to anomalies in sea surface temperatures in the Atlantic (Flato et al., 2013, section 9.5.3.5.2). There is only low confidence in the accuracy of models predicting rainfall over West Africa (Christensen et al., 2013, sections 14.2.4, 14.8.7). Regarding temperature, ten regional climate models run for Africa overestimated the daily minimum temperature (Flato et al., 2013, section 9.6.3), again highlighting the overall uncertain nature of projecting changes to the climate (Flato et al., 2013).

In summary, future projections for the West African Monsoon outlined in the IPCC AR5 section on monsoons suggest that as global temperatures rise, monsoons will become more intense and affect a wider area as higher temperatures increase the moisture content of the air. That said, future regional trends in the intensity and timing of monsoons are uncertain in many parts of the world. Also, no long-term trends have been observed in the West African Monsoon and future projections of monsoon rainfall are unclear not least because of uncertainties in the model projections (Christensen et al., 2013, section 14.2.4).

3.1.3 El-Niño Southern Oscillation (ENSO)

Facing the Weather Gods acknowledged that understanding of the mechanisms and likely future behaviour of the El-Niño Southern Oscillation (ENSO) was poor, as was knowledge of its interactions with other climate drivers. How has research over the past seven years helped to advance understanding of the influence that ENSO has on African weather?

The ENSO influences extreme weather events globally, causing floods in some regions and droughts in others (Cai et al., 2018). Most of the severe droughts in Southern Africa have been associated with ENSO, and since the 1970s the influence of ENSO on the Southern African climate has become stronger (Rouault & Richard, 2005). The ENSO is a naturally occurring oscillating interaction between the tropical Pacific Ocean and the atmosphere and comprises so-called El Niño and La Niña phases. In summary, El Niño occurs every three to seven years and brings warm, dry air to Southern Africa and cool air and rain to eastern equatorial Africa. The opposite happens in La Niña years – cool air and rain are brought to Southern Africa and warm, dry air to equatorial East Africa.

The ENSO is a driver of year-on-year rainfall differences over East Africa with El Niño/La Niña years resulting in wet/dry conditions during the short rains (October-November). The impact of El Niño or La Niña on rainfall seems to depend on the temperature of the Indian and Atlantic Oceans at the time (Nicholson, 2017). The climatic impact of ENSO is slightly different in southeast Africa – the general scientific consensus is that El Niño years are drier and during La Niña years the conditions are wetter. However, the relationship between ENSO and rainfall over Southern Africa is complex and anomalies exist, possibly because of the variation in sea surface temperature in the Atlantic, Pacific and Indian Oceans during ENSO events (Hoell et al., 2015; Gore et al., 2020).

Work to understand the role of the ENSO has identified eight ENSO sea surface temperature patterns that influence rainfall over Southern Africa. During El Niño events, warmer than average sea surface temperature in the Atlantic and Indian oceans is associated with decreased rainfall over Southern Africa; El Niño with cooler than average sea surface temperature over the Indian Ocean is associated with increased rainfall over Southern Africa. La Niña is generally associated with a negative Indian Ocean Dipole (Lim & Hendon, 2017) – with increased precipitation over Southern Africa and decreased precipitation over East Africa. Understanding the behaviour of ENSO and associated systems will help to predict future periods of extreme weather over African regions (Hoell et al., 2015).

The ENSO has also been associated with elevated temperature over Southern Africa. Temperature affects evapotranspiration which can, in turn, impact on drought. One study that used ten regional climate models concluded that the connection between ENSO and drought conditions is because ENSO influences both rainfall and temperature (Meque & Abiodun, 2015).

Fast-forward to future decades, and the concern is that East African countries may experience an overall decline in rainfall as a result of climate change. In comparison to the twentieth century (reference period 1976–2005), projections for the end of the century (2070–2100) suggest a decrease in the mean rainfall over the region during the June–September and March–May seasons, and an increase in rainfall over equatorial and southern part of the region during October–December. The largest changes are projected in the equatorial region (Endris et al., 2019). Unresolved issues with climate models have led to conflicting findings in some areas. For example, while modelling consistently projects increased rainfall over East Africa from the long rains, observational data show a decline from the late 1980s through to the late 2000s. This is known as the East African Climate Paradox and appears to be due to a shortening of the rainy season (with later onset and earlier cessation) rather than by a decrease in the peak daily rainfall. In turn, this may be due to interactions between a variety of factors. Such issues need to be resolved before predictions are sound enough to inform decisions about adaptive strategies (Wainwright et al., 2019).

3.1.3.1 IPCC AR5 and the ENSO

The ENSO varies on an inter-decadal timeline. Models do not seem to agree on whether the observed changes in ENSO are because of anthropogenic changes or natural variability. The IPCC AR5 reports high confidence that the ENSO will remain the dominant mode of interannual variability with global influences through the twenty-first century, and that rainfall associated with the ENSO will become more intense (Christensen et al., 2013, section 14.4.4).

Since the IPCC's AR5 was published, a re-analysis of climate models that assess the impact of global heating on ENSO conclude that there will be an increase in sea surface temperature variance in the equatorial Pacific. The increased sea-surface temperature variance in the eastern Pacific during El Niño is attributed to climate change. The increased sea temperature will further drive strong equatorial Pacific El Niño events and, in turn, is expected to lead to an increase in extreme weather events in other ocean areas that can cause floods and droughts including in Latin America and the Caribbean (Cai et al., 2018).

3.2 Other meteorological systems relevant to extreme weather in Africa

3.2.1 The Mascarene High

The Mascarene High is a semi-permanent anticyclone (a weather system associated with calm weather) located above the Southern Indian Ocean, which undergoes strong inter-annual variations and influences weather patterns over Southern Africa and Australia (Vidya et al., 2020). Changes in the atmospheric circulation system due to climate change, such as the poleward migration of the Mascarene High, is highly likely to change the weather systems over Southern Africa, which may lead to shifts in the subtropical dry zones and significant changes in mid-latitude rainfall. Severe weather events such as floods and extreme cold can arise from atmospheric 'blocking' caused by the Mascarene High. A simplified explanation of this complex system is that the 'blocking' action of the Mascarene High is an anomaly that slows down the west–east ocean–atmosphere circulations over Southern Africa, which can mean, in turn, that unstable weather remains over a region for an extended period. An example was the weather system that affected eastern South Africa (Durban) in April 2019 when flooding killed at least 85 people and displaced thousands of others.

The Mascarene High also helps determine the path taken by tropical cyclones over the Mozambique Channel and Southern Africa, storms which can cause widespread destruction when they make landfall. According to Xulu et al. (2020), understanding weather systems such as the Mascarene High will help local societies to predict and plan adaptations for future weather events and reduce the loss of human life from tropical cyclone landfalls. The part played by the Mascarene High in future climate scenarios does not seem to have been extensively researched and, therefore, warrants further investigation.

3.2.2 Turkana low-level jet

The Turkana low-level jet blows through the Turkana Channel, a 700-km long stretch of low lying land between the Ethiopian and East African highlands in northern Kenya. The jet is a wind that regularly achieves 30 m s^{-1}, but occasionally reaches 60 m s^{-1}, and which is generally stronger at night time. The Turkana low-level jet was discovered in the 1980s but has still not been well studied, though it is thought to be involved in aridity in northeast Kenya, southern Somalia and southeastern Ethiopia, and rainfall variability in the East Africa region. The Turkana low-level jet may inhibit summer rains in northwest Kenya. Low-level jets in other regions of the world (such as the Great Plains of the central United States and the La Plata basin in South America) are associated with extreme rainfall. Changes to the Turkana low-level jet that occur as a result of global heating could affect rainfall patterns and, in turn, local agriculture and the economy. However, more studies are needed to assess the extent of influence of the Turkana jet on aridity and rainfall (Hartman, 2018; Nicholson, 2016).

3.2.3 Madden–Julian oscillation

This phenomenon is an area of tropical rain that is thought to partly influence the intensity of El Niño and La Niña events. The weather system is associated with increased rainfall in equatorial regions that operates on a 40–50 day cycle. Research indicates that the rainfall associated with the Madden–Julian oscillation will likely increase in intensity with anthropogenic climate change, but more research is needed to project the likely extent of the changes to rainfall, and to understand the influence on the oscillation from sea surface temperature fluctuations (Maloney et al., 2019).

3.2.4 Walker circulation

The Walker circulation is an atmospheric circulation pattern over the equatorial Indian and Pacific oceans. The Walker circulation is associated with ENSO and the two weather systems seem to be influential in rainfall patterns over East Africa (King et al., 2019).

3.3 Indian Ocean Dipole

The Indian Ocean Dipole refers to the sea-surface temperature difference on the two sides of the Indian Ocean. A positive Indian Ocean Dipole means that sea temperatures are warmer in the western Indian Ocean region and cooler in the east, bringing heavy rainfall to East Africa. A negative dipole is the opposite and brings drier conditions to East Africa. The most extreme recent strong negative Indian Ocean Dipole in 2016 was a key driver of the weak La Niña and the conditions contributed to the prolonged drought over East Africa that severely affected the livelihoods of more than 15 million people at the end of 2016 (Lu et al., 2018). The Indian Ocean Dipole also impacts weather systems further afield: in Australia, a positive dipole means less rain in the south and far north of the country, and a negative dipole means the opposite with more rainfall in the far north and over the southern region.

Hence, warm temperatures in the western Indian Ocean and cooler temperatures in the east Indian Ocean lead to high rainfall and flooding events in East Africa and droughts and fires in west Australia and southeast Asia because the rain 'follows' the warmer sea water. The extreme weather events associated with the Indian Ocean Dipole on two different continents have been widely reported in the mainstream global media (for example: Uchoa, 2019). The phenomenon is exacerbated if the dipole is strongly positive or higher than average, as happened in 1961, 1994, 1997 and 2019. Floods this year that affected an estimated six million people across East Africa, in Somalia, Ethiopia, Burundi, Djibouti, Kenya, Rwanda, Somalia, Tanzania and Uganda (BBC, 2020), have been attributed to extreme rainfall linked to the positive Indian Ocean Dipole.

The Indian Ocean comprises around 12% of the global ocean area, and yet has absorbed 28% of global ocean heat gain, which means that the Indian Ocean seems to absorb heat disproportionately to elsewhere. Measurements taken from 1960–2015 show that the upper 2,000m (but especially the uppermost 300m) of the Indian Ocean have undergone consistent warming and have warmed by 1.04 °C over the measurement period. More than 90% of the surface warming is attributed to anthropogenic greenhouse gas emissions (Collins et al., 2019, section 6.5.1.2). Projected changes to the Indian Ocean Dipole differ between the different models, but modelling under RCP8.5 indicates (with low confidence) an increase by a factor of three in the frequency of extreme positive IOD events. That translates to one event every 6.3 years over the twenty-first century, which would have serious implications for East African rainfall patterns (Cai et al., 2014).

Box 5: Humans as climate drivers

The connection between atmospheric carbon dioxide levels and the Earth's climate has been known about for more than 120 years. In 1896, the Swedish physicist/chemist Svante Arrhenius (who was awarded Nobel prize in chemistry in 1903) was the first person to quantify the warming effect of carbon dioxide on the Earth's atmosphere. Arrhenius undertook what he refers to in his paper as 'tedious calculations' and concluded that an increase in atmospheric CO_2 would have a warming effect on the Earth's atmosphere – for example, he noted that the temperature would rise in the Arctic regions by 8 ℃ or 9 ℃ if the CO_2 rose 2.5 or 3 times that of the (then) present level (Arrhenius, 1896). Modern observations show that the Arctic has warmed substantially since 1950 and warming is predicted to continue in the future, far exceeding the average global warming rate (Xu et al., 2013). Predictions are that by the end of the century, in comparison to the present day the Arctic will be 7 ℃–13 ℃ warmer in the autumn and 3 ℃–5 ℃ warmer in the spring (Overland et al., 2013). Although he received criticism at the time, Arrhenius's thinking was ahead of his time.

In the 1970s, scientists predicted that if atmospheric carbon dioxide levels doubled in comparison to pre-industrial levels, largely as a result of the burning of fossil fuels, then the global temperature increase would be in the range 1.5 ℃–4.5 ℃ – a range known as 'climate sensitivity'. In other words, climate sensitivity is the potential increase in temperature if anthropogenic carbon dioxide emissions continue until they are double that of the pre-industrial period. An analysis of many studies that were published during the past 20 years have predicted the same range in climate sensitivity that scientists predicted in the 1970s (IPCC, 2014a).

Analysis of 17 climate model projections published between 1970 and 2007 found that climate models over the past five decades have been "generally quite accurate" in predicting changes to global mean surface temperature (Hausfather et al., 2020).

The IPCC claimed in 1990 that if atmospheric CO_2 levels doubled that of pre-industrial times, the likely annual global temperature increase is 1.5 ℃–4.5 ℃, which is the same predicted temperature range in the most recent report, AR5.

The IPCC was set up in 1988 and published its first report in 1990 (IPCC, 1990). That report said that to stabilize long-lived gases (CO_2, N_2O, CFCs) at the then-present-day levels would mean reducing anthropogenic emissions of those gases by more than 60%. In 1990, average carbon dioxide concentration at Earth's surface was 353 parts per million (ppm). It also says that "episodes of high temperatures will most likely become more frequent in the future, and cold episodes less frequent". The report states an accepted climate sensitivity range from models of 1.5 ℃–4.5 ℃ (IPCC, 1990; Policymakers Summary, p. *xxv*).

When is it likely that atmospheric carbon dioxide levels will reach double that of the pre-industrial era? In the mid-1700s, the pre-industrial period, the level of atmospheric CO_2 was around 280 ppm. In 2019, the atmospheric CO_2 was 409.8 ± 0.1 ppm, an increase of almost 50%. The present atmospheric CO_2 concentration is at its highest for the past 800,000 years (Blunden & Arndt, 2020) (**Fig. 2**). Using data from ice cores, it is possible to analyse ancient atmospheric CO_2 levels. For example, 30,000 years ago the estimated CO_2 concentration in the atmosphere was 190ppm (Our World in data; https://ourworldindata.org/atmospheric-concentrations; NOAA https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide)

Fig. 2a shows a reconstruction of Antarctic temperature over the past 800,000, and **Fig. 2b** shows reconstructed CO2 concentrations over the same time period. The striking similarity between the two curves shows how closely atmospheric CO_2 concentrations have correlated with temperature, and hence with climate (using Antarctica as a proxy for global climate).

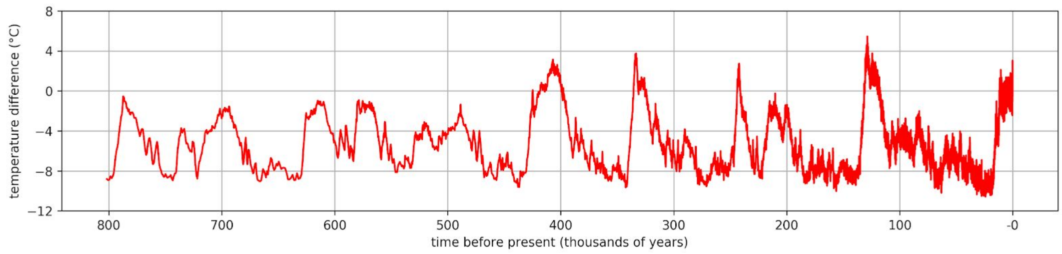

***Figure 2a**. Temperature reconstruction for Antarctica for the past 800,000 years. Data source: Jouzel et al. (2007).*

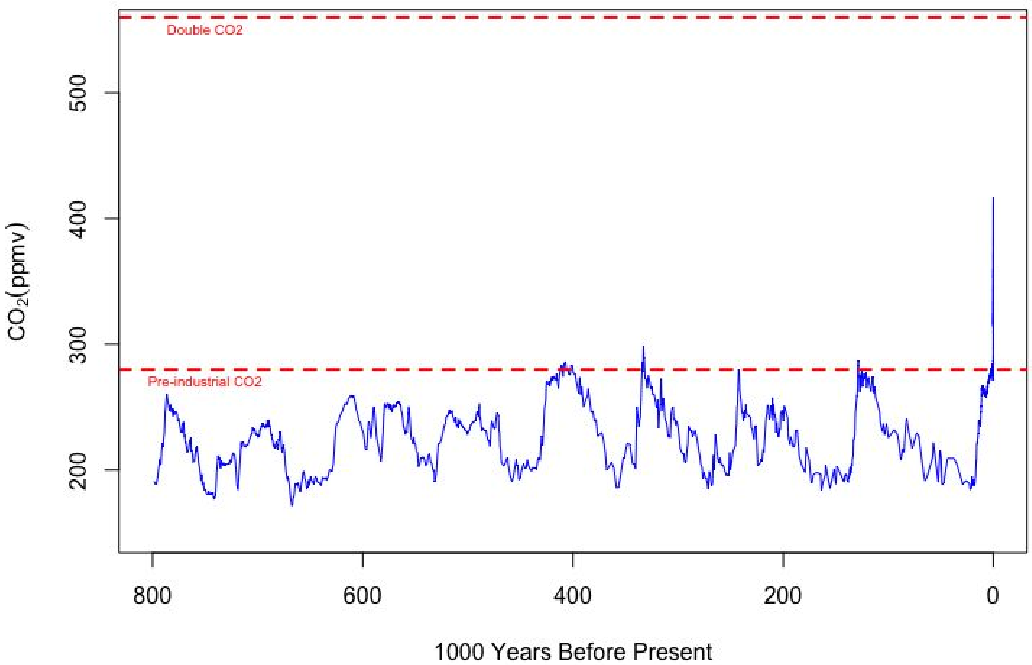

***Figure 2b**. A graph showing the past 800,000 years of atmospheric carbon dioxide concentration. CO_2 data after 1958 are from the Scripps CO_2 program (Keeling et al. 2001), CO_2 data from 1958 to 2000 years before present are from MacFarling Meure et al. (2006) and older CO_2 data back 800,000 years are from Lüthi et al. (2008).*

4.0 How might Africa's weather be affected in the future by global climate change

Attributing extreme or unusual weather events to a specific cause is not straightforward because extreme events can be caused by natural variability in climate systems, anthropogenic activity or, in most cases, a complex interplay between the two.

A first step towards understanding how the world's future climate might change is to look to the past to evaluate the extent to which human actions have influenced climate systems. The science of attributing significant weather events primarily to climate change or to natural fluctuations is a growing field of academic study (Otto et al., 2018a), though it presents a mixed picture and remains subject to substantial uncertainties and data limitations. For example, although climate change is recognised as having significantly increased the risk of prolonged drought in the Western Cape, South Africa (Otto et al., 2018b), analysis of the part played by climate change in the two failed rainy seasons that contributed to the 2010–2011 drought in Somalia was inconclusive (Otto et al., 2018a), and scientific evidence has so far not attributed increased rainfall in the Congo Basin to anthropogenic activity (Otto et al., 2013). Although there is also no clear evidence that the low rainfall during the 2016 drought in Kenya was caused by human activity, the high temperatures experienced at the time, and which are thought to have been related to climate change, may well have contributed to the severity of the drought (Uhe et al., 2018).

4.1 Future temperature projections

Climate projections are just that, projections. Challenges in making generalisations in relation to Africa's future climate include the continent's varied weather patterns (which, as noted in **section 1.1**, spans humid, arid, desert and subtropical Mediterranean climates), the difficulty in accurately projecting anthropogenic greenhouse gas emissions, and the extent to which different climate systems may react to climate forcing (Hulme et al., 2001). Climate modellers use observational data and the latest computers but there will always be some degree of uncertainty in making projections (Aloysius et al., 2016). For an explanation of climate modelling, see **Box 3**.

The African continent was warmer at the beginning of the twenty-first century than it was at the beginning of the twentieth century. The temperature trend is projected to increase across the continent in the twenty-first century (**Fig. 3**). Temperature is projected to rise faster than the global average across most of the continent to 2100 in comparison to a late twentieth-century baseline (data were averaged from 1985–1999) (James & Washington, 2013). Early estimates suggested that the African continent warmed on average by 0.5 ℃ in the twentieth century (Hulme et al., 2001), though more recent estimates suggest a much more substantive and now accelerating increase (for example, NOAA, 2020). The accuracy of such estimates for the African continent as a whole are inevitably limited by poor availability of observational data for many regions. From a global perspective, from 1880 until 1970, the global average rate of increase was 0.07 ℃ per decade. Then, during the final decades of the twentieth century, warming increased to a global average rate of 0.18-0.19 ℃ per decade from 1971 to the present day (Blunden & Arndt, 2020). In comparison, the most recent estimates from NOAA (2020) suggest an average for the African continent of 0.12 °C per decade til 1981, rising to 0.31 °C per decade in more recent years. Projections from Blunden & Arndt (2020) suggest that the range of warming in Africa through the twenty-first century will likely fall within the boundaries of less than 0.2 °C per decade to more than 0.5 °C per decade, which is consistent with the estimates above.

In terms of temperature records, the African continent has followed the global trend, with the continent's ten hottest years having all been recorded since 2005 (Blunden & Arndt, 2020) (see **section 2.0**). The extent of average annual warming will depend upon future greenhouse gas emissions; the average annual temperature for Africa could be 2 °C to 6 °C warmer in 2100 in relation to the 1961–1990 temperature average (Hulme et al., 2001). Although these estimates were made some years ago, more recent projections are broadly in agreement (Niang et al., 2014). The most recent IPCC report, AR5, discusses CMIP5 modelling projections which suggest that changes in mean annual temperature may exceed 2 °C above the late twentieth-century baseline over most land areas of Africa in the mid-twenty-first century under the RCP8.5 scenario, and exceed 4 °C over most land areas under the same scenario by the late twenty-first century. In addition, despite a relatively slower average increase compared to global average in past decades, temperatures across most of the African continent are projected to rise faster than the global average over the twenty-first century (James & Washington, 2013; Niang et al., 2014).

A number of papers published within the past five years discuss the importance of relative humidity in combination with temperature. Although increasing temperatures and periods of extreme heat are in themselves detrimental to health (see **section 5.1**), the combination of high temperatures with high relative humidity presents additional health challenges (see **section 5.1.1**). Metrics that incorporate both humidity and air temperature can be translated into a 'feels like' temperature that can be used to communicate periods of extreme heat. Researchers suggest that communicating warming extremes such as 1.5 °C or 2 °C, as discussed in the Paris agreement targets, does not relay a sufficient sense of urgency among non-scientists/experts for action to be taken to stop greenhouse gas emissions (Matthews et al., 2017).

Heat stress occurs when a person's core temperature increases as a result of external factors and homeostasis cannot be maintained. A study of global megacities found that, of those in Africa, Khartoum in Sudan is already experiencing periodic heat stress according to data analysis from the reference period 1979–2005. Under a global warming scenario of 1.5 °C, the city of Lagos, Nigeria, would experience heat stress for the first time, as would Abidjan on the Ivory Coast. Under a warming scenario of 2.7 °C Luanda in Angola would be added to the list of African cities experiencing heat stress; and under 4 °C global warming Kinshasa in the Democratic Republic of Congo would also become heat stressed (Matthews et al., 2017).

4.2 Future rainfall projections

Projections for future rainfall patterns over the African continent are more uncertain than the projections for future temperature changes (see **Box 2**). That said, the general consensus is that under RCP8.5, Southern and Northern African regions are predicted to experience decreases in mean annual rainfall by the mid and late twenty-first century. Others project that South Africa is likely to become drier in the west and southwest, and wetter in the east (Scholes et al., 2015). In contrast to the Northern and parts of Southern Africa, the Central and East African regions are likely to experience increases in mean annual rainfall under RCP8.5 from around 2050 (**Fig. 3**). Predictions of future rainfall patterns for West Africa are more uncertain because models have different outcomes. However, some regional-scale models predict an increase in the number of extreme rainfall days over West Africa and areas of the Sahel during the twenty-first century (Niang et al., 2014).

One study that analysed the likelihood of extreme rainfall events in Africa under global heating scenarios and using regional climate model data projected an increase in the frequency and intensity of rainfall over the Sahel during the summer rainy season from the mid-twenty-first century; an increase in the frequency, duration and intensity of rainfall in East Africa from the mid-century; and reduced rainfall and increased duration of dry periods in southeastern Africa. The study has limitations because it used only one regional climate model (Han et al., 2019). Other studies project an increase in rainfall over the central Sahel and a decrease over the western Sahel. However, precipitation changes over the Sahel are uncertain for reasons that include long-term lack of observational data that can be used for modelling to project future scenarios, and uncertainties in projecting future changes in atmospheric circulation patterns (Monerie et al., 2020).

Accurate rainfall predictions are necessary to help manage extreme weather events. Variations in the predictions made by computer modelling seem to arise if the various weather systems are not accurately represented in the models; therefore further work to understand how weather systems have behaved over past decades and centuries is needed. Part of the work will involve more extensive data gathering; the region as a whole is data-sparse. Research is ongoing to understand extreme weather patterns, particularly of rainfall, in East Africa (and elsewhere) (Ummenhofer et al., 2018).

Models in the Coupled Model Intercomparison Project Phase 5 (CMIP5) are not always in agreement regarding projections of rainfall over East Africa. Modellers test the accuracy of a model by comparing the model outcome with historical observations. The models tend to underestimate rainfall in the long rains (March–April–May) and overestimate rainfall in the short rains (October–November–December) (Yang et al., 2014). Accurate modelling is essential to help countries to prepare for future periods of extreme weather (King et al., 2019).

To mitigate the impact of unpredictable and/or extreme rainfall events in future decades, the scientific consensus is that restriction of the average global temperature rise to no more than 1.5 ℃ above pre-industrial temperatures is necessary. Doing so would likely reduce the number of projected extreme precipitation days in many regions around the world, including Africa.

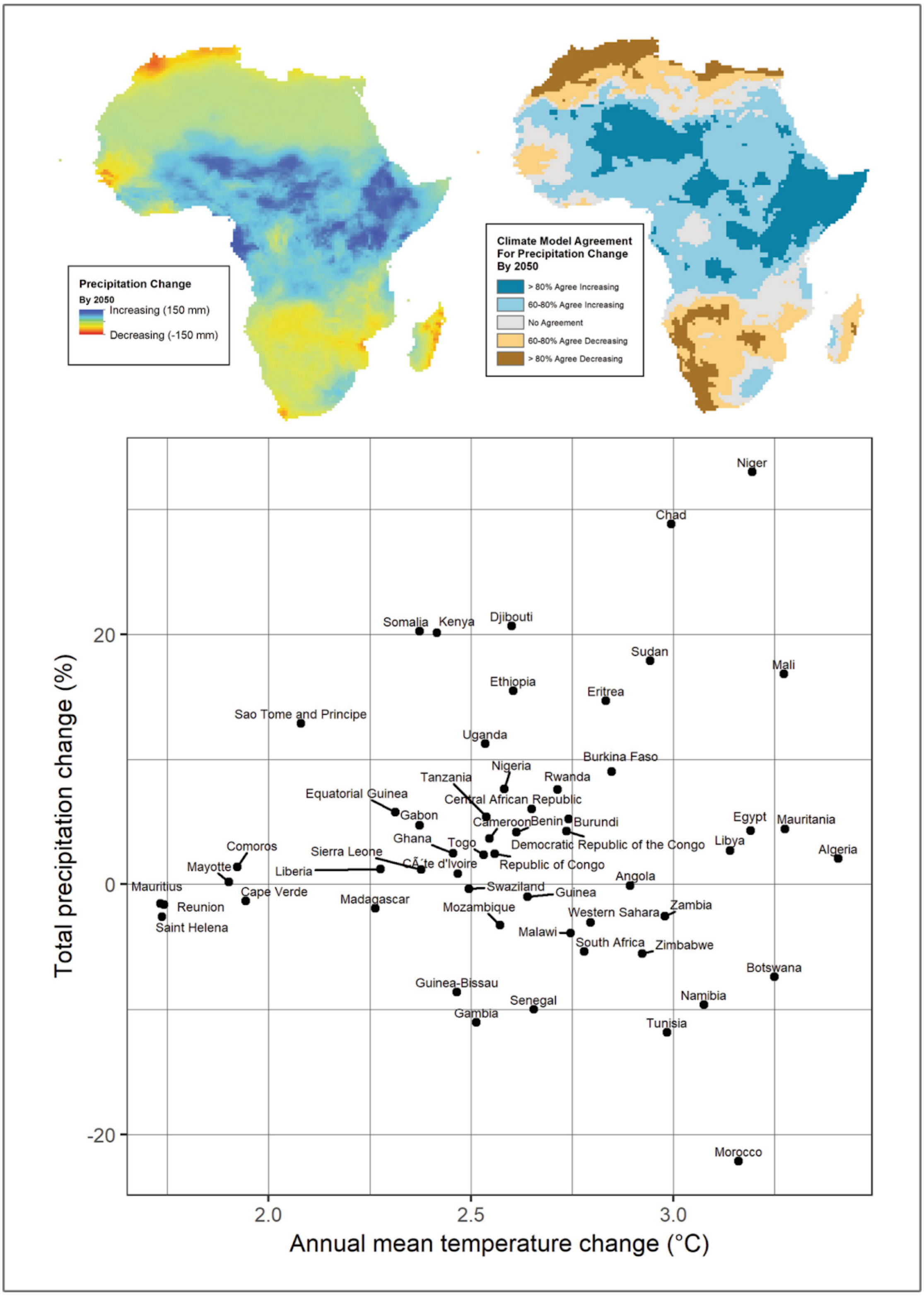

***Figure 3**. Climate model projections for Africa by 2050. **Top left**: Projected total annual precipitation changes, using data from the median Coupled Model*

Intercomparison Project Phase 5 (CMIP5) under RCP8.5. ***Top right****: CMIP5 model projections for future precipitation changes do not always agree; the regions for which model projections are in greatest agreement are shaded dark brown (decreased rainfall in Northern and Southern Africa) and dark blue (increased rainfall across Central and East Africa). There is no overall consensus between the models of the magnitude of precipitation change.* ***Bottom****: The average change in precipitation and temperature, by country, in 2050, based on projections by multiple CMIP5 models. Source: Girvetz et al., 2018. (This image is reproduced under the terms of the Creative Commons Attribution 4.0 International License, http://creativecommons.org/licenses/by/4.0/).*

4.3 Climate projections from the Intergovernmental Panel on Climate Change

At the time of publication of the report *Facing the Weather Gods*, the most up-to-date projections from the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4), were that the African continent would be likely to “experience higher temperature rises than the global average, becoming warmer and drier,” and that there were “some indications of increasing variance in rainfall across the global tropics as a whole, suggesting that extremes of wet and dry may be becoming more commonplace”.

One of the main findings in the IPCC’s Fifth Assessment Report (AR5) that built on the projections from AR4 was the increased evidence that anthropogenic activities have impacted the global climate system, which is seen in increased land surface and sea surface temperatures (SPM 1.2 in IPCC, 2014a). Specific to Africa, the IPCC AR5 found that most African governments have implemented some form of climate change adaptation strategies such as disaster risk management, making adjustments in technologies and infrastructure, and mitigating vulnerability through basic public health measures and livelihood diversification (section 4.4.2.1 in IPCC, 2014a). Key risks of a changing climate for Africa identified in AR5 (Fig. 2.4 in section 2.3, IPCC, 2014a) are those of water stress on river and lake systems for floods and drought; an increased risk of water-borne disease; and impacts on food security from reduced crop productivity. The IPCC also concluded that risks in all global regions (apart from the Polar regions and the ocean) can be reduced through a combination of mitigation and adaptation strategies, and more fundamentally by limiting the increase in global temperature.

West Africa, East Africa, Southern Africa and the Sahara are all projected by the IPCC (2014b) as ‘likely’ to experience an increase in the number of hot days and a decrease in the number of cold days per year in the latter three decades of this century (2071–2100). However, data for all four regions of the continent are inconsistent for some other factors, including drought and precipitation. The IPCC suggests that there is likely to be an increase in heavy precipitation and a decrease in dryness in East Africa. In Southern Africa the evidence points towards an increase in dryness (IPCC, 2014b, Table TS.6).

In summary: Global climate models have improved since AR4, but for Africa there is no clear evidence that improvements in resolution have led to significantly improved climate predictions so far. The projection from the CMIP5 models (the most up-to-date at the time of the AR5) for the twenty-first century was that further warming in all seasons across the continent is very likely and there will probably be seasonal changes in rainfall patterns Southern Africa is very dry and is very likely to remain very dry. There is no clear consensus among model projections regarding rainfall in West Africa. Rainfall over East Africa is likely to increase in the short rains season (Christensen et al., 2013, section 14.8.7).

These projections are also underpinned by the World Meteorological Organisation in its 'State of the Climate in Africa 2019' report (WMO, 2020).

4.4 Records of observational data

There is evidence that extreme heat events in sub-Saharan Africa are not routinely reported, which can mean that many people living in the region are unaware of the dangers posed by extreme heat until such episodes occur. In turn, this may lead to excess deaths. For instance, the emergency events database has recorded only two extreme heat events in sub-Saharan Africa between 1900 and 2019, yet has recorded 83 heatwaves in Europe between 1980 and 2019. The failure to implement heat-detection systems in less developed sub-Saharan African countries has been attributed to poor governance frameworks and lack of expertise (Harrington & Otto, 2020).

Box 6: Advances in climate science since *Facing the Weather Gods*

Facing the Weather Gods, published by Greenpeace in 2013, highlighted the lack of climate and weather data available for much of Africa, especially in central Africa, in comparison to other continents. Although there have been improvements in scientific modelling, some regions, the African continent included, are still data poor, which means that verifying the modelling projections using historical data is difficult. A lack of data, or the existence of unreliable data, for most areas of the African continent over the past century mean that it is difficult to reach conclusions about trends, most notably of rainfall (Niang et al., 2014). The situation will persist until a time when sufficient records are available to make judgments.

One response to the lack of health data for low- and middle-income countries (including Africa) was the establishment of The International Network for the Demographic Evaluation of Populations and their Health (INDEPTH), a health surveillance system (Sankoh & Byass, 2012). The network is now beginning to produce research and results (Coates et al., 2019). Any associations between health and climate change, and in particular with extremes such as heatwave days, will be difficult to determine, at least for some years, because of the many variables involved.

Since 2013, many climate modellers have endeavoured to understand the various discrepancies between model simulations and observational data. By understanding the processes involved, new understanding of the climate system is uncovered and models are improved (see **Box 2**).

The very first climate predictions that used computer modelling were in the 1970s. Scientific understanding and computing have both advanced significantly since then. The latest state-of-the-art supercomputers can now more accurately represent the Earth's climate at higher resolution by incorporating complex global weather systems, land-use changes, snow and ice cover, changing sea levels and temperature, and the interactions between these. Analysis of 17 climate models published between 1970 and 2007 to assess how well they projected global heating found that over the past five decades the models were "generally quite accurate" in predicting changes to global mean surface temperature (Hausfather et al., 2020).

The Coupled Model Intercomparison Project Phase 5 (CMIP5) that was used in the IPCC Fifth Assessment Report (AR5) – and since then the latest CMIP6 – can incorporate more information still and has greater capability than previous models, such as those used in AR4. CMIP5 includes Earth System Models with a more complete representation of forcings, new Representative Concentration Pathways (RCP) scenarios and more output for analysis (Collins et al., 2013).

Improvements in understanding the response of the climate system to increasing anthropogenic greenhouse gas emissions have led to new estimates of likely future scenarios. For example, in AR4, the climate sensitivity (see section 5.0) was given in the range 2 ℃-4.5 ℃, whereas in AR5, improvements in observational and model studies of temperature change meant that the estimated range broadened to between 1.5 ℃-4.5 ℃ (IPCC, 2013; p16).

5.0 The implications of extreme weather events on African communities

Climate observations and models broadly agree that – on a global level – extreme weather events are likely to occur more frequently and/or with greater intensity as the twenty-first century progresses (Niang et al., 2014). Extreme weather will clearly have an impact on the way we live our lives. This section considers some aspects of how people living across the African continent might be affected by extreme weather events.

5.1 Human health and heat exposure

Heat affects human health, mainly because exposure to extreme heat can exacerbate underlying health problems. Deaths can and do occur following periods of extreme heat, and while many people can cope with one single day of extreme temperatures, mortality rates increase during prolonged heatwave events that last for more than two days. The greatest health problems are during extended periods of extreme heat, when temperatures during the night and the day are high, because there is then no period for humans to recover or recuperate (Perkins, 2015).

The human body thermoregulates to maintain core temperature at typically 36.5 ℃–37.5 ℃. A wet-bulb temperature of 35 °C marks the upper physiological limit for human survival (Raymond et al., 2020). Overheating can lead to hyperthermia. Typically, overheating happens with fever but also if the external temperature is hot for a long period and the body is not able to cool down. A core body temperature of 38 ℃ is considered high and if it reaches 40 ℃ it becomes life threatening (NHS, 2020). If ambient temperature is more than 37 ℃ then the body will accumulate heat and is likely to become hyperthermic. Sweating to dissipate heat becomes ineffective at high relative humidity, which means that in high humidity even a lower ambient temperature can be deadly (Mora et al., 2017). Analysis of the combined effect of temperature and humidity on human health found that the high mortality rates in India and Pakistan during separate extreme heat events in 2015 were because of the combination of high temperatures and high humidity, a situation compounded because hospitals were over-capacity with patients suffering from heat-related illness (Wehner et al., 2016).

Heat-related health impacts can include increased morbidity through ischemic heart disease, ischemic stroke, cardiac dysrhythmia, dehydration, acute renal failure, heat illness, diarrhoea and heat stroke (Hopp et al., 2018). A loss of productivity is anticipated with sustained periods of heat particularly if combined with high humidity (Levy et al., 2016; Perkins-Kirkpatrick & Gibson, 2017).

Extreme heat events are known to cause heat-related deaths – the death toll from the European-wide heatwave in 2003 reached tens of thousands and peaked in France, Germany and Italy (Christidis et al., 2014; Mora et al., 2017).

Studies analysing exposure to extreme temperatures found that extreme heat events generally cause excess mortality within a few days. By contrast, extreme cold weather events cause excess mortality over a longer period of up to 25 days. Susceptibility to extreme weather events is influenced by factors including: the ability of a person to acclimatise, age, socioeconomic conditions, whether the setting is urban or rural and access to air conditioning (Anderson & Bell, 2009). High excess human morbidity and mortality rates are associated more with sustained periods of moderate temperatures rather than one-off very hot days (Gasparrini et al. 2015; Perkins-Kirkpatrick & Gibson, 2017).

5.1.1 Human survival in a hot and humid future

Humans have adapted to live within a broad temperature range of between 4 ℃ and 35 ℃. However, research has found that since the mid-Holocene (6,000 years before the present day) a majority of humans have chosen to live in regions with an average annual temperature of ~11 ℃ to 15 ℃ (Xu et al., 2020).

Global climate modelling projects that under a high-emissions, business-as-usual worst-case-scenario (the RCP8.5*SSP3 scenario), by 2070, the global mean human-experienced temperature increase will be 7.5 ℃ compared to the pre-industrial period (Xu et al., 2020). Not every continent will experience a surface temperature rise of such magnitude, but the modelling projection incorporates population growth under socioeconomic pathway 3 (SSP3), and population growth is projected to increase faster in hotter regions, which affects the projected mean temperature rise experienced by people. (For an explanation of the IPCC's Representative Concentration Pathways (RCP) and why this scenario has attracted controversy, see **section 7.0.**) The worst-case scenario projection, using the RCP8.5*SSP3 scenario and not allowing for migration, is that 3.5 billion people globally will be living in regions with a mean annual temperature of around or exceeding 29 ℃, which could be regarded as being or verging on being uninhabitable. So, a region with a mean annual temperature of 13 ℃ in 2020 might experience a mean annual temperature of 20 ℃ in 2070 – such as the climate presently found in Northern Africa. But even if greenhouse emissions are on a downward trajectory towards net zero in 2100 – the RCP2.6 scenario – the projections are that by 2070 around 2.6 billion people around the globe could be displaced due to inhospitable ambient temperatures.

The map in **Fig. 4** shows projected 'niche displacement' of people affected by land suitability for human habitation in 2070, modelled under RCP8.5 and with population changes under the SSP3 scenario. If the majority of humans continue to live in regions with mean annual temperatures of around 11 ℃–15 ℃, as has historically been the case, then the projection is that some regions of the world will become less suitable for humans and other regions will become more suitable. If the human population is distributed according to the mean annual temperature, then in 2070 the projection is that the trend in human migration will be from the regions on the map shaded red to those shaded green. If the RCP8.5*SSP3 projections are accurate (that is, that greenhouse gas emissions continue on a business-as-usual basis through the twenty-first century), regions of the Sahel, Southern Africa and East Africa could experience huge decreases in land suitable for human habitation by the last decades of the twenty-first century (Xu et al., 2020).

Anthropogenic climate change means that many regions of the world are predicted to experience average annual temperatures that are higher than those at present. Mean annual temperature is of relevance because as the global climate becomes hotter, some regions – including parts of the Sahel – may become too hot for human habitation. The number of people affected will depend upon the extent to which the global climate warms compared to preindustrial temperature observations – there is a big difference between the number of people impacted by a 2 ℃ average global temperature increase in comparison to a 1.5 ℃ increase. Even so, limiting the global average temperature rise to no more than 2 ℃ above pre-industrial levels is still not likely to prevent an increase in the frequency and intensity of extreme heat events (Diffenbaugh & Scherer, 2011). Some climate models predict mass migration of people away from regions that become too hot for human habitation, such as parts of Northern and Central Africa (Xu et al., 2020). Such widespread movement could lead to further cultural and political tensions within and beyond the regions worst affected. See also **section 5.6**.

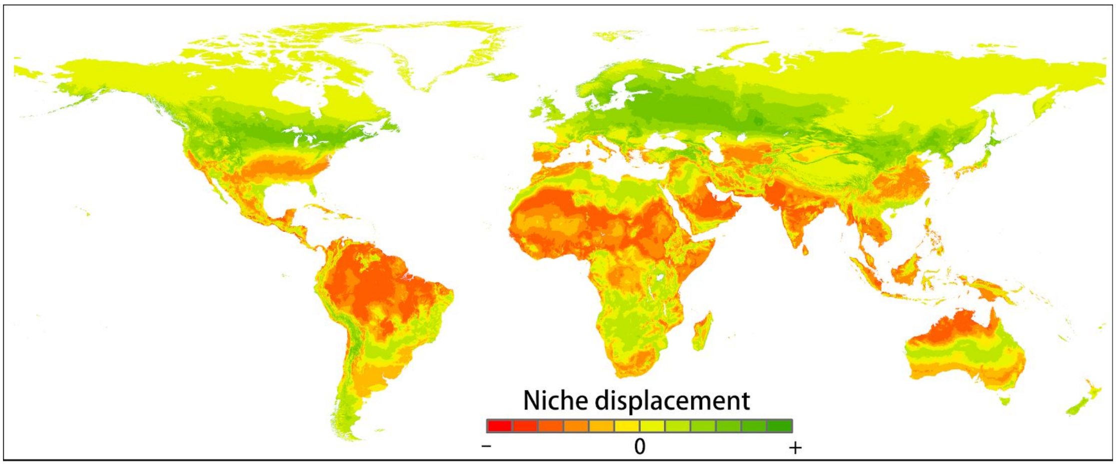

Figure 4. *By the late twenty-first century, human populations could be displaced from the red shaded regions, where the climate is projected to become inhospitable, to green shaded regions (Source: Xu et al., 2020; original material published under a CC BY-NC-ND license).*

5.2 Urbanisation

Research suggests that urbanisation can compound problems such as flood risk and heat exposure because cities commonly lack both green spaces to absorb rainfall and trees to provide shade. Urbanisation along coastlines may create particular problems for communities, which may then experience and have to cope with storm surges and coastal erosion, as well as more widespread structural problems such as poor sanitation (Lwasa et al., 2018; Okaka & Odhiambo, 2019; Rohat et al., 2019). Problems can often be disproportionately felt in the poorest communities whose residents tend to live in slums and shanties in the city margins. These may be particularly susceptible to flooding and also lack access to air conditioning or adequate shade. Rapid urbanisation coupled with land-use change and deforestation exacerbates the problems of a warming climate on local residents (Orimoloye et al., 2019), expanding the phenomenon of the 'urban heat island' into adjoining areas even less able to cope.

5.3 Food and water security

Agriculture is the largest single economic activity in Africa, accounting for around 60% of employment and, in some countries, more than 50% of gross domestic product (Collier et al., 2008). Agriculture in Africa is generally negatively impacted by extreme temperature events because many crops are already grown at the limits of their thermal tolerance and resistance to water stress. Moreover, a large proportion of agricultural production in Africa occurs in semi-arid regions, which are projected to become drier in the future (Scholes et al., 2015).

The World Meteorological Organisation notes in 'State of the Climate in Africa 2019' (WMO, 2020) that in facing a mix of increased temperatures, changing precipitation patterns, rising sea levels and more frequent extreme weather and climate events, there are also key risks to agriculture, which forms the backbone of national economies. Reduced crop productivity as a result of heat and drought stress, increased pest, disease and flood damage will result in serious adverse effects on food security and on livelihoods at regional, national and household levels. The World Meteorological Organisation (WMO, 2020) also states that under RCP8.5, reductions in mean yield of 13% are projected in West and Central Africa, 11% in Northern Africa and 8% in East and Southern Africa. Rice and wheat are predicted to be the most severely affected crops with millet and sorghum the least affected.

Climate changes are likely to impact food production. The IPCC reported in its Fifth Assessment Report (AR5) that measures to improve the resilience of food production have improved since AR4, but that the mitigation factors used currently will not be adequate in the long-term (Niang et al., 2014). Agroecological farming and agroforestry are being adopted in Africa and are helping to improve resilience to the changing climate, but the effectiveness of adaptation strategies depends upon factors including funding and technical support (Niang et al., 2014). For example, Guba is an organisation based in Eswatini, Southern Africa, that runs training courses in organic, sustainable and ecological farming (www.gubaswaziland.org).

Global climate change is likely to affect seasonal weather patterns. Concerns are that conversion of Africa's dry tropical forests and savannahs to croplands for food production will threaten the natural carbon stores in those biomes.

Extreme heat events – as well as droughts, floods and landslides – can impact livelihood activities such as farming and crop harvests (Orimoloye et al., 2019). A study that used 20,000 historical maize trials in Africa, combined with daily weather data, found that productivity of African maize decreased by 1% for every 1 ℃ warming above 30. In drought conditions the yield dropped by 1.7% under the same temperature conditions (Lobell et al., 2011). Food prices are expected to increase significantly, making the affordability of food a growing challenge for many African communities (Scholes et al., 2015).

Increased ambient temperature and changes to rainfall patterns may affect water availability. Water shortages may lead to food insecurity if water shortage and drought decrease crop yields and affect livestock. Limited access to safe drinking water, or damage to sanitation infrastructure, increases the risk of contracting diseases such as cholera or leishmaniasis (Niang et al., 2014; Cambaza et al., 2019). Extreme rainfall and flooding has been associated with outbreaks of diarrhoea (Levy et al., 2016).

5.4 Locust swarms

Throughout 2020, huge locust swarms, comprising millions of insects and covering many square miles, have been devastating crops across East Africa, as well as in countries further afield including Yemen, Iran, Pakistan and India. The Horn of Africa, notably Kenya, Ethiopia and Somalia, has been particularly badly affected this year. The swarms are the worst in Kenya for 70 years. The origin of the 2019–2020 upsurge can be traced back to specific climate conditions that favoured insect breeding. Tropical cyclones over the Arabian Peninsula in May 2018 and again in October the same year brought rains and favourable breeding conditions for locusts, which began swarming in January 2019 over Yemen and Saudi Arabia, reaching Somalia and Ethiopia from mid-2019 onwards. The swarms have continued to develop through 2020, affecting Somalia, Ethiopia, Kenya, Uganda, Sudan and Tanzania, bringing widespread devastation to areas already coping with a mix of floods and drought, and associated threats to food security (Salih et al., 2020; FAO, 2020).

Some reports in the scientific literature suggest that anthropogenic climate changes – such as increased temperature and rainfall over desert regions – contributed to the environmental conditions that lead to plagues of locusts (Meynard et al., 2020). However, attributing the current 2019–2020 locust swarm entirely to anthropogenic climate change is challenging because so many other factors are also involved. For example, Salih et al. (2020) suggest that pest control measures have been impacted by underfunding and financial constraints associated with the ongoing Covid-19 pandemic, thereby exacerbating the particularly devastating swarms seen this year.

5.5 Conflict

There is much debate in the scientific literature concerning the connection between violent conflict and weather extremes, with no overall consensus. For example, a study that analysed the records of violent conflicts in East Africa from 1991 to 2009 found no statistically significant relationship between precipitation anomalies and conflict in that region, but indicated that higher-than-normal temperatures increased the risk of violence (O'Loughlin et al., 2012). Another study, based on analysis of events in sub-Saharan Africa between 1980 and 2012, also suggested a link between temperature extremes and human conflict (O'Loughlin et al., 2014). The latter study found that colder temperatures have no effect on the risk of conflict, moderate temperatures reduce the risk of conflict (a reduction of 12%) and very hot temperatures increase the risk of violent events by 26.6% in comparison to the number of events during normal temperatures.

Overexploitation of natural resources coupled with climate change is expected to increase the risk of violent conflict (Niang et al., 2014). Tension and conflict could arise in the event of mass migration of people moving away from areas that begin to suffer the impact of extreme events such as heatwaves, flooding or drought (Matthews et al., 2017; Xu et al., 2020).

Others have discussed situations in which climate change may not be a direct cause of human–human conflict but the changing climate conditions can exacerbate volatile situations or can indirectly cause conflict, particularly in regions that do not have strong state support mechanisms. A recent report (ICRC, 2020) highlights tensions in the Central African Republic in which changing patterns of transhumance, the country's existing armed conflict, and access to resources such as water for livestock and for growing crops are being exacerbated by the changing climate such as increasing drought conditions. The situation is significant because 70% of the Central African Republic population rely on subsistence agriculture. Interruptions to the agricultural system could impact food security of those communities that rely on them, which extend beyond the borders of the Central African Republic.

5.6 Biodiversity

Before making projections of the extent to which biodiversity might be impacted by extreme weather events and by climate change, it is useful to first understand that Africa's ecosystems have been and continue to be shaped by water, fire and mega-herbivores (animals with a body mass greater than 1,000kg, such as elephants and rhinoceros) as well as climate (Midgley & Bond, 2015). Plants and animals have adapted in different regions to scarcity or abundance of water supply, fire hinders tree growth in the savannah and mega-herbivores consume vast quantities of plant matter and return nutrients to the soil.

Climate change-driven alterations in rainfall patterns and temperature, and the changing concentration of global atmospheric CO_2 are highly likely to drive changes in terrestrial ecosystems (Niang et al., 2014, section 22.3.2.1), and is a significant threat to endemic species across the African continent (Malcolm et al., 2006).

A modelling study assessing the possible impact of climate change on biodiversity suggested that South Africa's Cape Floral region (which has 5,682 endemic plant species and 53 endemic vertebrates) is particularly vulnerable to habitat loss under climate change. All climate modelling scenarios projected the extinction of more than 100 species and some modelling scenarios projected the extinction of more than 2,000 plant species from the Cape Floral region under doubled atmospheric CO_2 conditions in comparison to current baseline levels (Malcolm et al., 2006). Other regions of the continent are also projected to experience species extinction in a warming global climate. The estimated extinction of Afroalpine species endemic to the Bale Mountains of south-central Ethiopia under a scenario of 2 ℃ warming falls in the range 3.5–8.7% or 5–11 species; under both 3 ℃ and 4 ℃ of climate heating the estimated extinction range is 36-57% or 41–65 species (Kidane et al., 2019).

Some researchers suggest that future projections of vegetation structure and biodiversity in Africa are difficult to make without fully understanding how ecosystems will respond to disturbance and atmospheric CO_2. There is also the view that while some individual species will adapt to changing conditions, widespread changes to a habitat could lead to extinctions of endemic species (Malcolm et al., 2006).

Rainfall and temperature extremes are highly likely to impact biodiversity, but because of limited observational data, scientists are uncertain about the extent to which climate change could affect the availability and quality of freshwater in the future (Niang et al., 2014, section 22.3.3). The availability of water is a key driver in African ecosystems, perhaps more so than temperature. Lack of observational data means that it is difficult to determine trends in relation to species abundance or distribution of species in response to climate changes (Midgley & Thuiller, 2011).

5.7 Impacts on economic well-being

Climate change is not a problem of Africa's making, yet parts of Africa may be particularly negatively affected because of their geography, agricultural dependence and difficulties in adapting to changing weather patterns (Collier et al., 2008). Africa's economies are vulnerable to change, as illustrated by the work of Matyas & Silva (2013), which shows how rainfall patterns drive changes to the income of communities living in central and northern Mozambique. The study by Matyas & Silva (2013) also highlights the paradox of how damaging cyclones can also bring some positive effects on the economic position of households, either through beneficial rainfall or employment from reconstruction building work. A key point to note in relation to the aftermath of extreme weather events is that economic consequences will vary considerably depending upon the response made by individual countries.

Although households may have considerable experience of coping with temporary shocks, such defensive flexibility has not, to date, been combined with sustained ability to adapt to new circumstances or adopt new technologies (Collier et al., 2008). This suggests that there is great value in analysing weather and socio-economic data together to better understand patterns of vulnerability and potential responses to extreme weather events.

Future research that builds upon studies such as that by Matyas & Silva (2013), and others, will be important to help determine the relationship between extreme weather events and socio-economic well-being of African communities.

6.0 Concluding remarks

The picture of Africa that emerges from scientific studies and observational data is one in which climate patterns have already changed in many parts of the continent. As this report highlights, considerable uncertainties exist in relation to the extent to which regions and countries in Africa will be affected by climate change.

In recent years, several regions have experienced destructive extreme weather events. Examples include events such as the severe floods in South Africa in 2019; floods in 2020 across East Africa affected six million people in Somalia, Ethiopia, Burundi, Djibouti, Kenya, Rwanda, Somalia, Tanzania and Uganda by destroying livelihoods and homes; drought in 2015–2016 affected more than 15 million people in East Africa (Ethiopia, Kenya and Somalia) and Southern Africa. Tropical cyclone Idai, one of the most severe ever recorded, made landfall in southeast Africa and was followed the next month by tropical cyclone Kenneth, displacing thousands of people, ruining homes, causing a serious outbreak of cholera and an estimated US$2.2 billion damage to infrastructure.

Attributing extreme weather events entirely to anthropogenic climate change is difficult because of natural climate variability. However, the general scientific consensus is that global climate change will lead to more extreme climate events. In Africa, modelling projections indicate that by the end of the twenty-first century the mean annual temperature increase for much of the continent will exceed 2 ℃ – or fall within the range of 3 ℃ to 6 ℃ if high emissions continue. Heatwaves are projected to occur more often, at higher intensities, and last for longer under enhanced greenhouse gas concentrations. Rainfall projections for the continent are less certain because of the complexities involved in modelling multiple weather systems, but model projections are in general agreement that in comparison to the present, by 2050 there will be decreased rainfall in Northern and Southern Africa and increased rainfall across Central and East Africa). The likelihood is that the Southern African region will experience landfall from fewer but more intense tropical cyclones.

The broad conclusions drawn in the Greenpeace report *Facing the Weather Gods*, which was published in 2013, still stand. The expectations include those that the continent will experience more rapid temperature rises than the global average, and will experience increasing variance in rainfall. This report, *Weathering the Storm,* presents material that confirms and strengthens the predictions made in 2013.

Although there have been advances in scientific understanding of climate systems in the intervening years since *Facing the Weather Gods* was written, substantial gaps remain that require more research to fill (see **Box 6**). Climate modelling has become more sophisticated, but for Africa there is, as yet, no robust evidence that improvements in the resolution of the models have led to significantly improved climate change predictions. There is still a lack of reliable observational data for most regions across the continent and, therefore, projections – which are based on observational data – are questionable.

Provision must be made now to build resilience to extreme weather events to safeguard communities across the continent and to ensure food security in future decades. There is an urgent need to stop greenhouse gas emissions at source in a transition away from fossil fuels and to not address the growing climate crisis simply by relying on adaptation and mitigation alone.

7.0 Definitions and assumptions

African continent This report focuses on sub-Saharan Africa.

Ambient temperature In the context of weather, the ambient temperature is the air temperature. The temperature that a person feels may also be influenced by humidity or wind speed, but those will not affect the air temperature.

Climate forcing (also called radiative forcing) Earth receives light energy from the Sun. Some of that energy is reflected back into space, and some remains in the Earth system. The difference between the energy coming from the Sun and the energy remaining in the Earth's atmosphere is what causes global heating; this excess energy is called 'climate forcing' or 'radiative forcing'. The Earth's atmosphere retains the necessary warmth to support life because the mix of atmospheric gases – the so-called 'greenhouse gases' – keep some of the incoming energy in the atmosphere. To maintain steady atmospheric conditions, energy in must equal energy out. Higher amounts of greenhouse gases prevent more energy from returning to space and lead to positive climate forcing, and the Earth's atmosphere warms. Human activities including burning fossil fuels release greenhouse gases causing long-term warming of the atmosphere and the changes to the climate which result from this are referred to as 'anthropogenic climate change'.

Cumulative heat This is a new conceptual metric that aims to quantify the duration and intensity of heat waves during a season. It is the sum of each daily temperature anomaly above the threshold required to be classed as a heatwave for the duration of all heatwaves in a year. For example, if a heatwave is defined as ambient temperature above 30 ℃, and the temperature recorded is 33 ℃, the temperature anomaly produced is 3 ℃. If the period of the heatwave lasted for 5 days, the 'cumulative heat' produced is 15 ℃ (Perkins-Kirkpatrick & Lewis, 2020). The metric is useful for identifying regional heatwave trends – that is, heatwaves occurring across a region over a decades, although it may not necessarily be as effective when comparing different locations because the heat required to generate a heatwave in a hot, humid location is very different to the heat needed to generate a heatwave in a cold, dry place location.

Drought In agriculture, drought is generally defined as a decline in soil moisture caused by lack of rainfall, an increase in evapotranspiration caused by high temperature, or a combination of the two. Dry air and high wind speeds also contribute (Cook et al., 2014).

Dry bulb temperature Typically the measurement of ambient air temperature using a thermometer in a site away from rain and sunlight.

El Niño A climate phenomenon which causes above-average temperatures in the central and eastern tropical Pacific Ocean and nearby land areas. See **ENSO**, below.

El Niño–Southern Oscillation (ENSO) An alternating interaction between the surface water of the Pacific Ocean and the atmosphere above it which has big impacts on the weather patterns in the South Pacific and nearby land masses. It occurs irregularly on time scales of a few years between its two opposing phases El Niño and La Niña. During the El Niño phase, temperatures are above-average in the eastern part of the southern Pacific and nearby land masses (northern west coast of South America). During La Niña conditions, this area experiences relatively cold temperatures. Because the opposing phases of ENSO are large-scale differences in the atmospheric and oceanic circulation, it has effects on weather worldwide. Africa, South America and Australia are all impacted by ENSO (for more details see the Australian Government Bureau of Meteorology at http://www.bom.gov.au/climate).

Extreme weather events These are climate-related events, primarily floods, droughts, tropical storms or cyclones and wildfires (but not earthquakes).

Heatwave The World Meteorological Organisation defines a heatwave as: "A period of marked unusual hot weather (maximum, minimum and daily average temperature) over a region persisting at least three consecutive days during the warm period of the year based on local (station-based) climatological conditions, with thermal conditions recorded above given thresholds." This definition works on the understanding that different regions of the world and the local communities will be adapted to slightly different temperatures, therefore establishing a set heatwave threshold to cover all regions of the world would not be appropriate.

La Niña The opposite of El Niño, with sustained cooling of the Pacific Ocean and the atmosphere above it. See **ENSO**, above.

Representative Concentration Pathways The Representative Concentration Pathways were developed by the Intergovernmental Panel on Climate Change (IPCC) for the Fifth Assessment Report (AR5). RCP8.5 is a widely used pathway and is also the strongest of the four RCP scenarios. RCP8.5 is a very high-emissions global heating scenario and was developed as a 'worst-case' scenario, that imagines no climate mitigation policies are implemented, fossil fuel use is widespread and no measures are taken to reduce carbon emissions. RCP8.5 assumes 8.5 W/m^2 radiative forcing by 2100. Three other scenarios were developed to predict the outcome of future emissions: RCP2.6, RCP2.5 and RCP6. The RCP scenarios do not make consistent socioeconomic assumptions and RCP8.5 has attracted controversy in the literature for being unrealistic, but analysis has found that of the four RCP pathways, RCP8.5 is the best match for emissions between 2005–2020 (Schwalm et al., 2020). When used in conjunction with the Shared Socioeconomic Pathways (SSPs) a more comprehensive prediction is possible. A full explanation of climate modelling scenarios and their development is available from Carbon Brief at: https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario

Shared Socioeconomic Pathway (SSP) Five different scenarios or 'pathways' that consider how social, economic and demographics might change globally in the future. The SSPs imagine scenarios in which no climate mitigation policy exists. They range from SSP1, which predicts a rise of 3-3.5 ℃ by 2100 to SSP5, which predicts global heating of 4.7–5.1 ℃ above pre-industrial levels. The pathways were published in 2016 and are now beginning to be used in climate models alongside the Representative Concentration Pathways (RCPs) to help predict how greenhouse gas emissions may change. More detail on SSPs is available from Carbon Brief at: https://www.carbonbrief.org/explainer-how-shared-socioeconomic-pathways-explore-future-climate-change

Standardized Precipitation Index (SPI) Is used to characterize drought. On short timescales, it may include soil moisture. At longer timescales it may include groundwater and reservoir storage. It does not include changes in evapotranspiration.

Standardized Precipitation Evapotranspiration Index (SPEI) Is a multiscalar drought index developed by Vicente-Serrano et al. (2010) and uses precipitation and temperature data to determine the potential impact of climate change on drought severity. A multiscalar approach can incorporate different water sources and distinguish different types of drought. SPEI is used to indicate the maximum drought stress over a surface by comparing the highest evapotranspiration with the amount of precipitation.

Wet bulb temperature The temperature of the air taken using a thermometer with a wet sleeve over the bulb to enable the measurement of the moisture content of the air or the relative humidity. Wet bulb temperature is lower than dry bulb temperature unless the air is 100% humid.

Recommendations by Greenpeace Africa

Globally, all weather is now taking place in a climate changed world. The link between the burning of fossil fuels and the increased atmospheric carbon dioxide that drives the climate crisis is clear. The African continent is no exception and the scientific research used in writing this report predicts an Africa in which extreme weather events will become more commonplace as a result of temperature rises on land and at sea. In addition, where some extreme weather events have taken place, scientists have managed to identify a climate 'fingerprint' associated with them.

Globally, floods, heatwaves, droughts and cyclones appear to be becoming more frequent, more intense or both as well as less predictable, whereas associated events that are temperature related, such as wildfires, also appear to be becoming more common.

For the people living in Africa, extreme weather translates into death, food insecurity and water shortages, disease, displacement, poverty and conflict. The biodiversity on which many Africans depend is threatened with accelerated rates of extinction by global heating.

Apart from the major emitters which includes South Africa and Nigeria, African countries are responsible for an extremely small proportion of the greenhouse gases emitted that are driving global heating. It would be unjust to expect Africans simply to accept the predictions outlined in this report as a 'new normal' or expect them to rely on external aid to deal with the consequences. Accordingly, African countries must face the growing crisis by acknowledging and declaring a climate emergency and taking urgent action where they can build resilience and proactively choose socio-economic pathways that are not based on a reliance on fossil fuels.

Weather, climate data and information

There is a need to strengthen existing databases and to develop new ones that curate data on observed weather and climate trends in Africa. This is critical both to understanding the changes that have occurred already, and to be able to project future changes and to plan accordingly. In order to do this, Africa collectively needs to acquire the skills to become a developer of regionally relevant numerical weather and climate models.

In addition, African countries also need to be given a participative role in developing new databases and models rather than being dependent upon countries outside of Africa to produce relevant tools. Scientific understanding needs to be informed by indigenous knowledge, and research into the impacts of extreme weather need to be communicated widely in local and regional languages.

Oceans

This report makes clear the key role of the oceans in determining the weather that Africa experiences. The Indian Ocean Dipole, El Niño Southern Oscillation (ENSO), the Inter-Tropical Convergence Zone (ITCZ) all are important drivers of African weather. All depend upon ocean temperature differences and changes in ocean currents and upwelling. The intensity of cyclones and the speed at which they move is governed largely by sea surface temperature (SST). Warmer air over the oceans holds more moisture giving rise to more extreme rainfall as part of these events. As temperatures continue to rise, these physical drivers of weather will increasingly be affected.

Although not detailed in this report, increasing ocean temperatures threaten critical ecosystems such as coral reefs, and uptake of carbon dioxide from the atmosphere is progressively turning ocean waters more acidic. Add to this the additional pressures from pollution and overfishing and the case for an agreed and unified approach to ocean protection becomes clear.

Accordingly, Greenpeace Africa is calling for a shared vision and ambition for ocean protection and conservation by African countries. This should include the adoption of measures to fully protect 30% of the world's oceans by 2030.

Land use, food security and forests

Land use in Africa is critical to addressing the future impacts of extreme weather. Agriculture is a dominant component of economic activity across the continent, but is also extremely vulnerable to extreme weather events with many communities having limited capacities either to cope with specific events, or to adapt in the medium to long term. At the same time, land-use patterns outside of forested areas are increasingly shifting towards agriculture. The impacts of projected changes on rainfall and temperature upon agriculture and food security are likely to be profound both in established agricultural areas and in areas newly brought under cultivation.

At the same time, although not detailed in this report, forests play a key role in climate regulation, maintaining biodiversity and in protecting against some of the effects of extreme weather. Forests are increasingly vulnerable to extreme events. The Congo Basin rainforest, for example, is home to many indigenous peoples and local communities and hosts significant biodiversity. Like many global forests, the Congo Basin has been facing growing threats from resource extraction (timber and minerals), markedly increasing its vulnerability.

African countries need to develop an holistic approach to agriculture and forests, which can achieve both food security and forest protection. Embracing ecological farming and building on traditional farming methods will be essential for climate crisis adaptation. Local food production will help to increase food security over aid dependency among communities that are exposed to the impacts of extreme weather events.

For food security to be achieved in Africa, there needs to be an increase in capacity, skills and efficiency. Very significant yield losses of major crops are predicted as a result of climate change. Embracing ecological farming and building on traditional farming methods will be essential for climate adaptation. Skills can be enhanced through research and development based in part on indigenous skills. Improving networking and management systems and the creation of sustainable employment will help to reduce the high levels of inequality between rich and poor. Sustainable economic development in Africa is ultimately one key to assuring food security for African communities and protecting them to some degree from extreme weather events.

Energy

Nonetheless, while the majority of African countries are vulnerable to the impacts of extreme weather events, their contribution to greenhouse gas emissions has been minor in relation to the vast majority of historical emissions generated by developed countries. The energy pathways that are chosen now in Africa, however, will have significant implications for the prospects of limiting global heating to 1.5 ^{o}C. It is critical, therefore, for African countries to be aiming for 100% renewable energy.

African countries have some of the best renewable energy resources in the world. At the same time, energy poverty dominates across the continent. To address this situation, governments across Africa should be prioritising universal access to electricity through renewable energy investments, and should be avoiding the trap of dirty development based on fossil fuels. Renewable energy investments have a huge potential to save water, and to drive inclusive economic growth and job creation. If governments are serious about addressing the triple challenges of poverty, inequality and unemployment then barriers to renewable energy must be removed.

South Africa is a major emitter of greenhouse gases on the African continent and is the thirteenth biggest emitter in the world due to its almost complete reliance on coal. It is crucial that the South African government, in particular, prioritises raising ambitions to act on climate through a transition from fossil fuels to renewable energy. A phase-out of coal use should be achieved by 2040.

Greenpeace Africa's vision for the future

While the ability to accurately predict the specific impacts of global heating on African societies remains limited, it is very clear that global heating acts as a threat multiplier, exacerbating existing vulnerabilities such as poverty and inequality by driving extreme weather events. Social and environmental justice in Africa are deeply connected, and we must prioritise an integrated and intersectional approach to dealing with the climate crisis by prioritising resilience and economic development pathways built on green jobs and ending energy poverty.

The African continent is highly vulnerable to the impacts of global heating, but African governments have an opportunity to collectively and individually act in ways that will build resilience and avoid catastrophic climate change. Addressing the climate emergency involves transitioning to 100% renewable energy, avoiding energy pathways based on fossil fuel extraction and also protecting the oceans, forests and food security.

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