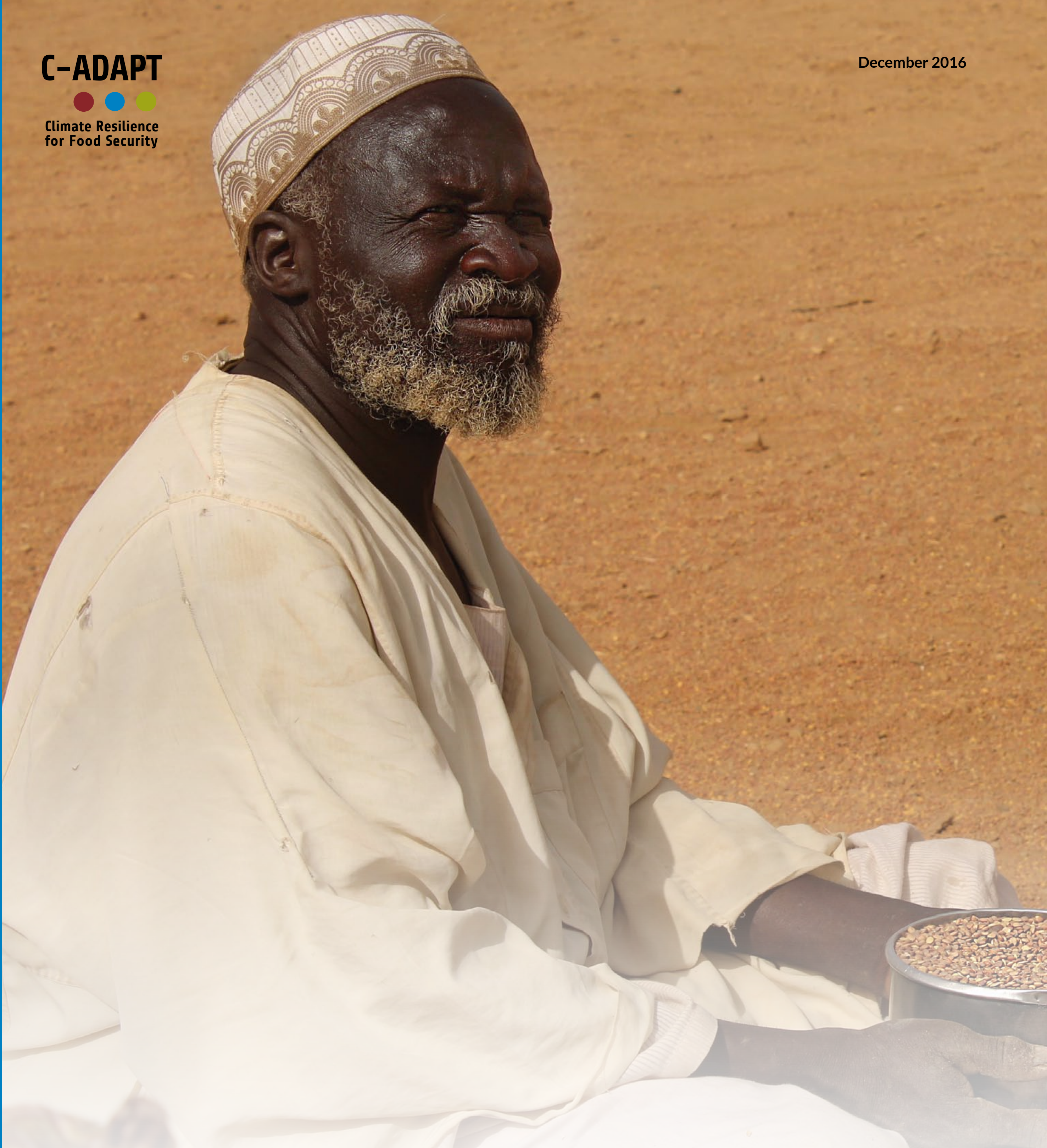
C-ADAPT

Climate Resilience
for Food Security

December 2016



Food Security and Climate Change Assessment: Sudan

WFP
World Food Programme
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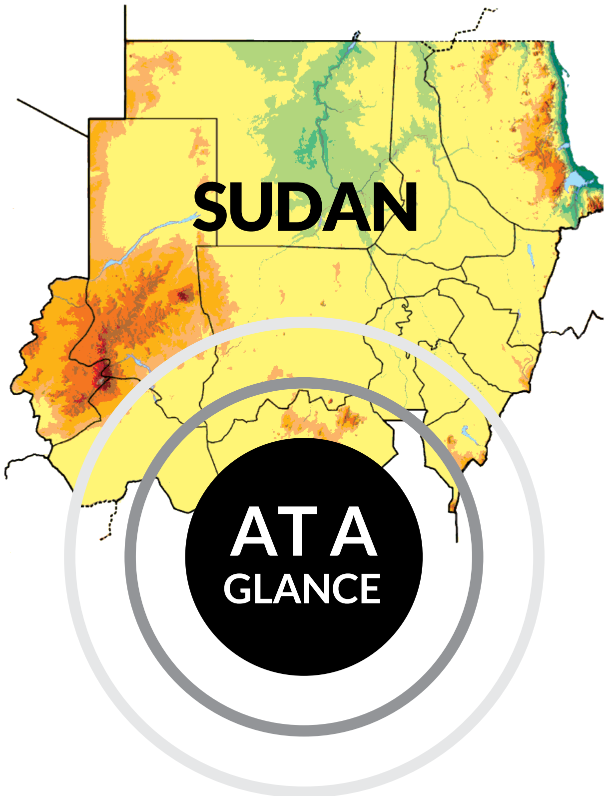
Table of Contents

Executive Summary



Food security and climate are closely linked in Sudan.

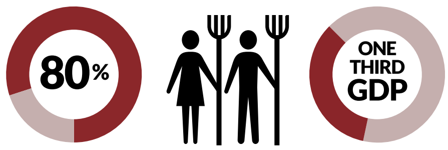
Agriculture accounts for around one third of Sudan's GDP and employs around 80% of the labour force. Agriculture is mostly rain-fed and is therefore sensitive to rainfall amounts and timings, making climate variability and change key factors in the future of Sudan's economy, livelihoods, and food security.

Sudan's climate is hot through the year, with seasonal rains. There is a north-south rainfall gradient and variability in annual rainfall amounts.

Sudan lies at the northern most extent of the Inter Tropical Convergence Zone (ITCZ) and therefore has a strong gradient of rainfall. Rainfall amounts also vary from year-to-year depending on the position and intensity of the ITCZ.

Livelihoods and agricultural production systems correspond to the climatological suitability of the region.

Pastoralism dominates in the north where rainfall totals are low and the onset of the rains is unreliable; cropping systems are more prevalent in the south where the rainy season is reliably longer and heavier.



Climate model projections for the 2040s show strong agreement for an increase in temperature, but no strong signal for changes in rainfall.

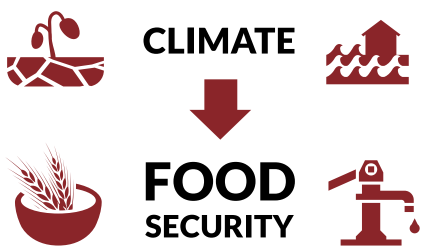
Climate change projections for Sudan indicate a substantial warming trend across the country. In contrast, rainfall projections are mixed, with most models projecting small increases in annual rainfall and some projecting small decreases. However, increased evaporation as a result of higher temperatures will have a negative impact on water availability.

All scenarios of projected climate change will result in increased heat stress, reductions in water availability, and continued variability, making food production more challenging.

Three scenarios that span the range of available plausible future climates for Sudan were studied. All scenarios showed varying extents of increased heat and water stress, and variability in timings and amounts of rainfall.

Adaptation measures should focus on reducing sensitivity, improving resilience to variability and extremes, and improving heat tolerance and water efficiency in agricultural production.

The climate projections can be thought of as a southward shift of the current climate to varying extents in each scenario. The concept that the future climate is analogous to a hotter version of the climate further north could be helpful to inform adaptation planning.



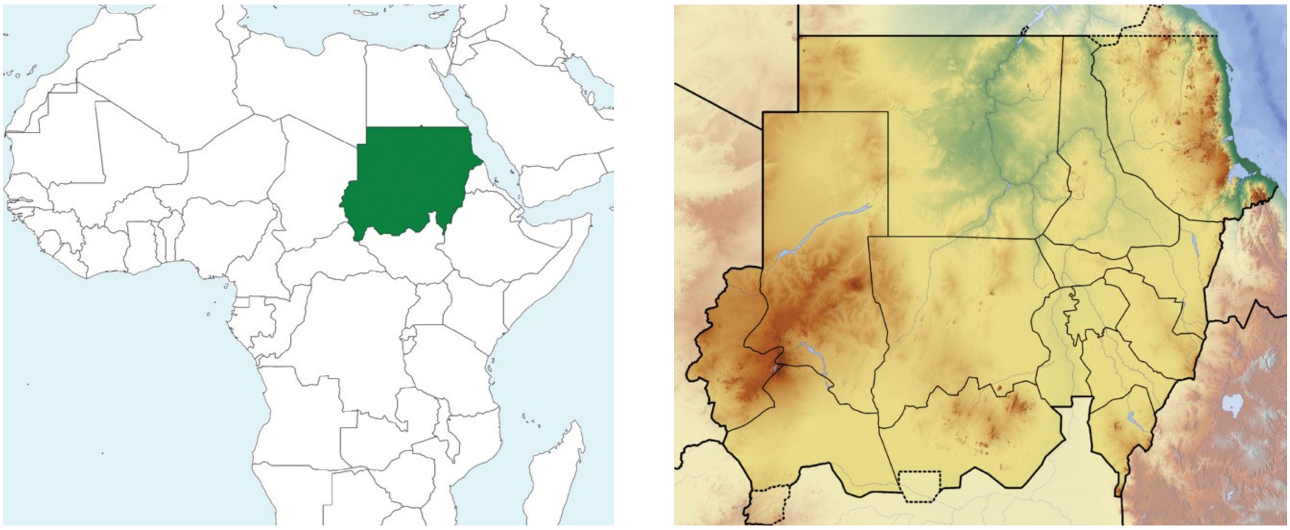
Storekeeper in Nyala, Darfur, accepting WFP vouchers which beneficiaries use to buy food for themselves.

1. Setting the scene: climate and food security in Sudan

Sudan is located in northeast Africa (Figure 1, left panel), and is bordered by Libya and Egypt to the north, South Sudan and Ethiopia to the south, Chad and the Central African Republic to the west, and Eritrea and the Red Sea to the east. The topography of Sudan is predominantly flat plains, with areas of higher elevation in three regions; the Marrah mountains to the west, the Nuba mountains to the south, and the Red Sea Hills to the east (Figure 1, right panel). The Blue and White Nile rivers meet in the country's capital, Khartoum, to form the Nile River which runs north through Egypt to the Mediterranean Sea.

FIGURE 1

Map showing location of Sudan in green (left panel) and topographical map of Sudan with areas of higher elevation shown in dark brown



Right panel source: https://commons.wikimedia.org/wiki/File:Sudan_location_map_Topographic.png

1.1. Sudan climate overview

Sudan lies within 8°N and 23°N, and has a climate that ranges from a hot desert climate in the north, hot semi-arid climate towards the south, and tropical wet and dry climate in the southeast and southwest (Peel et al. 2007). Annual average temperatures are around 30°C with little seasonal variation, and average maximum temperatures of around 35°C. The warmest months of the year occur in spring, with average monthly daytime temperatures reaching around 40°C. Spring coincides with the onset of the rainy season; typically from June to October. Rainfall in Sudan is driven by the Inter Tropical Convergence Zone (ITCZ); a band of convective rainfall that occurs where the surface heating of the Earth is strongest. Because of the tilt and orbit of the Earth, the ITCZ moves either side of the equator throughout the year, from the Tropic of Cancer in June to the Tropic of Capricorn in December. Sudan is located at the northernmost extent of the

ITCZ, meaning that Sudan experiences only one rainy season per year. In contrast, equatorial countries, such as Kenya, experience two rainy seasons each year: one as the ITCZ moves north in March to May, and the other when it moves south during October to December. The rainy season is longer and more intense in southern parts of Sudan and the length of the season and amount of rainfall reduces with increasing latitude as the ITCZ reaches its maximum northerly extent. The most northern areas of Sudan receive virtually no rainfall.

Wet season rainfall totals are highly variable from year-to-year due to large-scale dynamics in the climate system, such as the El Niño Southern Oscillation, that influence the position and intensity of the ITCZ. Years where the ITCZ has a more restricted latitudinal movement can result in delays to the onset of the rainy season across the country and reductions in annual rainfall. These years have particular implications for the northernmost regions of Sudan where little rain is received on average. In contrast to rainfall, there is little year-to-year variation in temperature.

1.1.1. Observed climate trends

Observed trends in climate are difficult to assess due to the lack of reliable and consistent meteorological data. There is evidence, however, of a continental warming trend over the 20th century, with increases of around 1°C in Sudan (Niang et al., 2014).

Assessing trends in rainfall is more complex due to the lack of available data, and the variability in both the total amount and timing of rainfall from year-to-year. However, there is evidence that rainfall amounts across the Sahel can vary naturally over decades, and it is not clear whether the cause of these trends is human-influenced long-term climate change or simply natural variability that may potentially reverse in the coming decades (Niang et al., 2014; Ackerly et al., 2011).

1.1.2. Projected climate trends

Projections from the latest Intergovernmental Panel on Climate Change Fifth Assessment report (IPCC AR5; IPCC, 2013; Niang et al., 2014) indicate a substantial warming trend across Sudan with projected temperature increases of between 1.5°C and 3°C in daily maximum temperature for Sudan by the middle of the 21st century. In contrast, there is no clear projected trend in mean annual rainfall for Sudan. The range of projections for the average change in rainfall across the models span both increases and decreases, although the absolute changes are relatively small (i.e. some model projections show relatively small increases and some relatively small decreases in total average annual rainfall). In contrast, there is large year-to-year variability in rainfall over Sudan, and by the mid-21st century this year-to-year variability exceeds any climate change signal (see Appendix B).

Up to the mid-21st century there is little difference in the pattern of climate change across different future greenhouse gas concentration scenarios (Stott et al . 2006). From the mid-21st century onwards, however, the climate change pathways under different greenhouse gas concentration scenarios do diverge. A scenario of on-going and substantial increases in future global emissions of greenhouse gases (this scenario is known as RCP8.5; van Vuuren et al., 2011) is consistent with projections where temperatures continue to increase to the end of the 21st century, from mid-century level. This scenario also indicates a small increase in annual rainfall in many model projections. In contrast, a scenario of rapid and sustained reduction in future global emissions of greenhouse gases (this scenario is known as RCP2.6; van Vuuren et al., 2011) is consistent with a stabilisation of climate conditions from the middle of the 21st century.

1.2. Food security and livelihoods in Sudan

Sudan has poverty rates at around 46% (World Bank, 2011) with approximately 18.5 million[1] people living in poverty. The majority of the population lives in rural settings (65% on average) and this proportion is higher in the western states (around 75%), with rural poverty at around 58% (World Bank, 2011). The World Bank estimates that up to 80% of the labour force is engaged in agriculture, accounting for around

1. Based on a population of 40,235 million people (UN Department of Economic and Social Affairs: Population Division, 2015).

one third of the GDP, a proportion that has increased in the last few years due to reduced revenue from oil. Agriculture, therefore, plays a critical role in both household and national economy.

Agriculture is also predominately rain-fed in Sudan, which means there is an inherent sensitivity to rainfall amounts and timings, making climate change a key factor in the future of Sudan's economy, livelihoods, and food security.

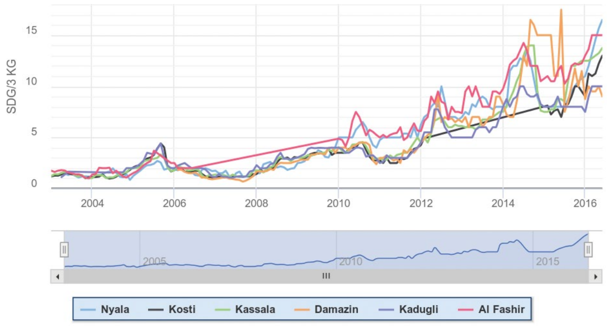
1.2.1. Food security factors in Sudan

Food security is tightly linked to agricultural production. However, as 60-75% of households (WFP, 2011; WFP, 2012; WFP, 2013) are reliant on food purchase, and fragmented markets being noted as a key issue in trade within Sudan (FEWS NET, 2015), physical and economic access to food and the trading of agricultural goods (market access) are also important factors. Agricultural labour is also an important source of income for poor households. As such changes in production will have a secondary impact on both labour opportunities and ability for employers to pay for the labour required (in the case of reduced yields), reducing income and thus access to food (lowered purchasing power). However, as some agricultural adaptations to climate change require more labour, it is difficult to accurately anticipate the changes within this income group without a solid understanding of the evolution of agricultural practices over the period projected within this report.

Sorghum is a key crop in Sudan and as such is the focus of price monitoring systems (WFP, 2016; FEWS NET, 2015). Market prices of sorghum have been steadily increasing over the last 9 years (with some lowering in 2011; Figure 2) with studies indicating that prices are likely to increase further if agricultural policies are not adjusted (Sassi, 2013). Market access is also important for the sale of agricultural products, with people living closer to Khartoum having better access to markets, whilst those further away face lower prices and difficulties of distance to main markets (FEWS NET, 2015).

In addition to food production for direct consumption, and sale at market, cash crops play an important part of food security at the household level, as well as nationally. Cotton, gum Arabic and sesame are important exports.

FIGURE 2
Monthly prices of sorghum in selected markets



Source: WFP
(http://vam.wfp.org/CountryPage_overview.aspx?iso3=SDN)

World Food Programme (WFP) assessments identify poverty as being a key contributor to food insecurity, with people that rely most on natural resources (charcoal, firewood, wild food) being the most vulnerable (WFP, 2011; WFP, 2012; WFP, 2013).

Sudan also has a long history of resource-based conflict as a result of competition for limited resources (water, pasture for livestock, etc.), particularly where the population is concentrated around such resources. These conflicts have led to displacement, and food insecurity as a result of reduced access to markets and loss of livelihoods. As such, western states have frequently experienced food insecurity at crisis or emergency levels (Integrated Food Security Phase Classifications (IPC) 3 and 4; IPC, 2016), as indicated by food security assessments and analysis. Resource conflict is also tied in with land tenure issues, a broader issue that affects households across Sudan, not including areas affected by conflict (UNEP, 2012).

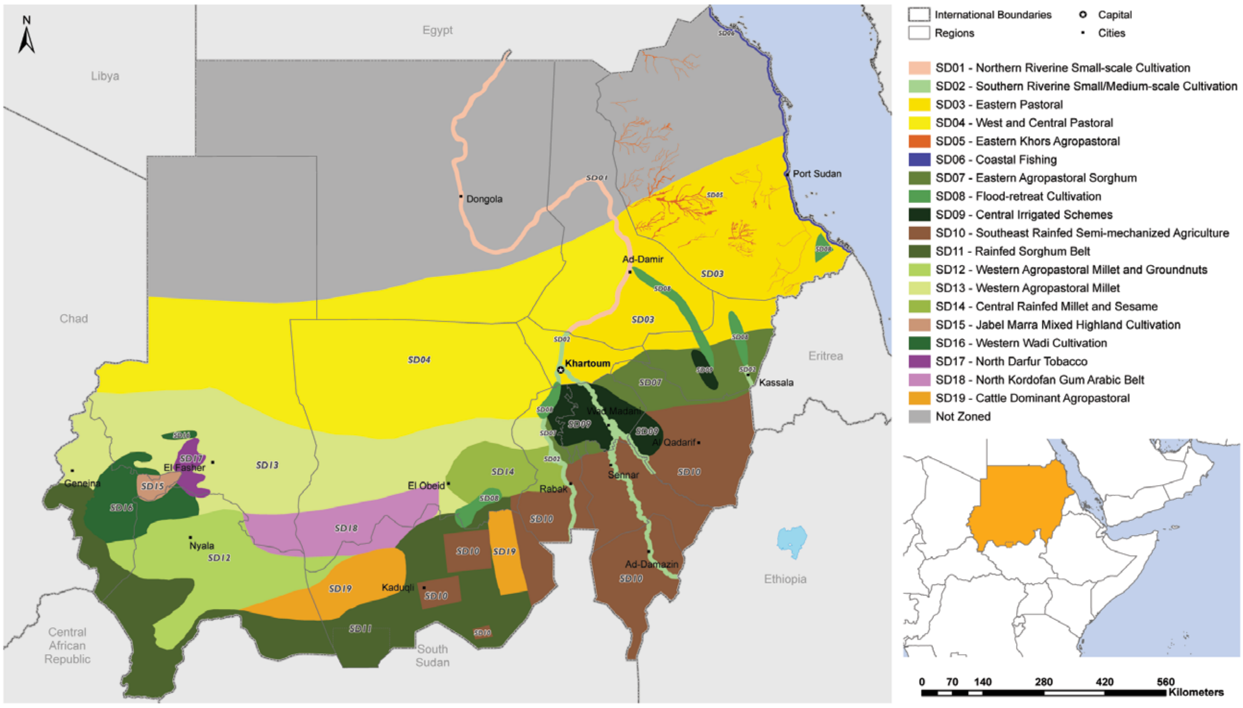
Further pressures on food security have been felt in years when reduced rainfall has led to insufficient availability of pasture, and reduced crop production and/or yield. The consequence of low water availability relative to demand, either as a result of a fluctuation and reduction in total rainfall, or simply delays in the onset of the rainy season, have seen decreased availability of cereals nationally, and potentially at the household level that may lead to reductions in dietary diversity for households producing vegetables for own consumption, and reductions in milk production from animals. The long droughts that occurred in 1983, 1997, 2000 and 2011 displaced large numbers of people and had devastating effects on the agricultural sector with severe consequences for food security (Elagib and Elhag, 2011; FAO, 2011).

1.2.2. Overview of livelihoods in Sudan

The livelihood activities in Sudan can be grouped into 19 categories, henceforth referred to as livelihood zones (LHZs; FEWS NET, 2011). These are a common way of categorising the predominant livelihood strategies and widely recognised by stakeholders in Sudan. A map is shown in Figure 3.

FIGURE 3

Livelihood zones of Sudan as defined by the Famine Early Warning System Network (FEWS NET)



Source: FEWS NET, 2011.

As noted above, up to 80% of the population (approximately 32 million people) are engaged in agriculture as a principle livelihood strategy. Agriculture in Sudan can be summarised into three main categories:

- Livestock
  - pastoralism (LHZs SD03 and SD04 from Figure 3)
  - agro-pastoralism (LHZs SD05, SD07, SD12, SD13 and SD19)
- Cropping
  - traditional rain-fed (LHZs SD11, SD14-SD17)
  - mechanised rain-fed (LHZ SD10)
  - irrigated (LHZ SD09)
  - riverine (LHZs SD01, SD02, SD08)
- Forestry (LHZ SD18)

These strategies exist according to the agro-climatic features of the country (as described within this report) and represent the key climate sensitive aspects of livelihoods in Sudan.

1.3. Methods

The analysis presented in this report, to assess the impact of projected climate change on livelihoods and food security in Sudan, has been a collaborative effort across climate science and food security disciplines. The approach taken here is based on an adaptation of the CLEAR methodology (WFP, 2014); a framework for assessing climate risk and food security, where a more narrative approach is taken to the food security analysis due to constraints of data availability.

The first step was to ensure a good understanding of the baseline climate and its relationship with current livelihoods and food security. Three climatologically similar zones were defined for the purpose of the climate analysis; climate zones A, B and C, (further detail on the selection of these zones is given in Box 1). The baseline climate was assessed using reanalysis [2] data for the 1981-2010 time period, and the baseline livelihoods and food security in each of the climate zones and their climate sensitivities was assessed through a review of the relevant literature and expert interpretation. Results of the baseline assessment of climate, livelihoods and food security are presented in Section 2.

Three plausible scenarios of projected climate change for the 2040s (2031-2060) that reflect the range of potential future changes in climate in Sudan were analysed, and the impact on livelihoods and food security was assessed in the context of the potential change from the present day (i.e. the baseline climate). Results of the future projections are presented in Section 3, and further detail about the methods and data used for both baseline and future assessments is given in Appendix A.

2. A blend of observed weather data and model data of past climate to provide gridded historical climate data.

BOX 1

Climate zones A, B and C

Due to the strong north-south gradient in annual rainfall amounts in Sudan, areas in the north and south of the country experince quite different climates, and as a result the livelihood activities are different. For example pastoralism occurs in the dry northern areas where rainfall is limited and the year-to-year variability means that the amount and timings of the rains are unreliable. Agriculture is predomiant in the southern regions where there is a reliably longer and heavier rainy season.

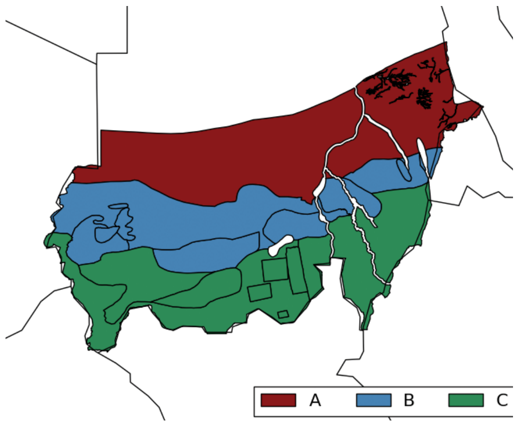
In order to determine a baseline climatology, three climatologically similar zones that reflect this gradient in rainfall were defined. This means that each climate zone represents an area where the climate is relatively uniform within a zone, but distinctly different from the other two zones. This is often done using aridity indices (Mohamed and Mohamed, 2010), however for the purpose of this report, where the climate information is interpreted from the perspective of livelihoods and food security in Sudan, the zones were selected by grouping the FEWS NET LHZs from Figure 3 into approximate latitudinal bands to reflect the rainfall gradient.

These are mapped in Figure 4, and the specific LHZs included in each climate zone are:

- Climate zone A (SD03, SD04 and SD05)
- Climate zone B (SD07, SD09 and SD13 – SD18)
- Climate zone C (SD10 – SD12 and SD19)

FIGURE 4

Climate zones A, B and C



Further detail about the specific LHZs included and excluded in climate zones A, B and C is given in Appendix A.

A lady in a WFP-supported IDP camp sifts the sorghum she has harvested.

2. Defining the baseline climate and food security in Sudan

In order to assess the impact of climate change on livelihoods and food security in Sudan, it was first necessary to understand the current relationship between climate, livelihoods and food security in order to provide context for the projections. In this section, a baseline is defined; assessments of the climate sensitivities of the main agricultural systems in Sudan are presented in Section 3.1, followed by descriptions of the recent climate and the climate sensitive activities of the current livelihoods in each of the climate zones A, B and C (see Box 1) in Section 3.2.

2.1. Climate sensitivities of main agricultural systems in Sudan

2.1.1. Livestock and pastoralism

Pastoralism is a key element of the Sudanese economy, contributing around 60% of the total agriculture revenue through livestock exports (camels and sheep are exported to Egypt, Saudi Arabia, and other Arab countries.) Despite this large contribution to GDP the majority of this revenue is from small holders or migratory producers (Behnke, 2012), and therefore there is a need for a strong network of livestock extension services. For households with small herds there are greater risks of important impacts to household food security, particularly in the case of losses.

Camels, goats, and sheep are most common livestock in climate zone A (pastoralism), the driest of the three zones (see section 2.2 for details). Pastoralists utilise rangeland grasses for feed and, due to the seasonal availability of such food, this livelihood system is transhumant and nomadic. In addition to the animals listed above, cattle are reared in the more southerly climate zones (B and C; agro-pastoralism) where fodder availability is of greater concern, with a variety of grasses and fodder crops being harvested for use (such as sorghum, alfalfa). Poultry is also a commonly kept livestock.

Households raise animals to subsidise income, and act as a source of food (milk and eggs), as well as act as a financial reserve. This is particularly the case for poorer households that have a small number of animals and could be considered small-holders.

The numbers of livestock held in Sudan are difficult to estimate as there has been no national livestock census since 1976, and subsequent projections may not be accurate (Behnke and Osman, 2012). However, estimates show that numbers are increasing, with reports identifying overgrazing (due to large numbers of livestock) as an important contributor to land degradation (UNEP, 2007; Egemi and Ganawa, 2014).

There is limited published literature discussing recent projections for land degradation, but one study classifies the main pastoralist regions (SD03 and SD04 from Figure 3) as very severe (Egemi and Ganawa, 2014).

Example of livestock rearing in climate zone C.

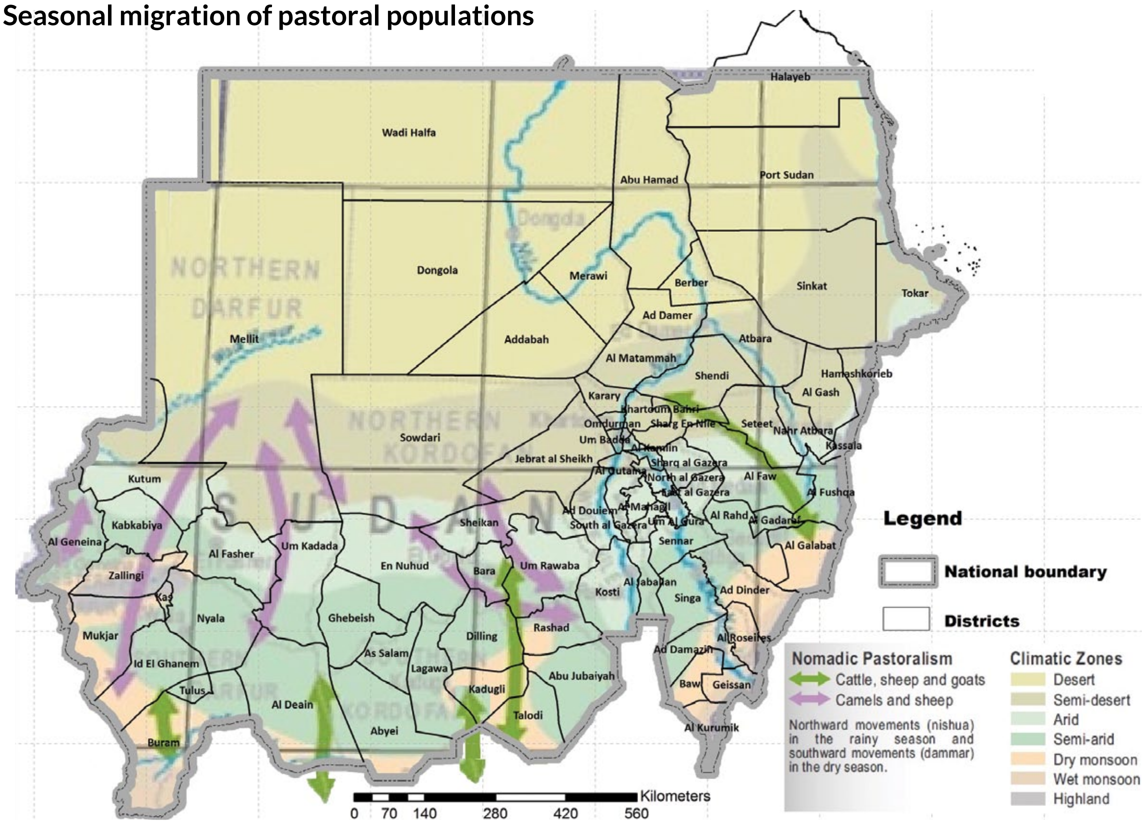
Temperature plays an important part for both grasslands and, therefore, food for livestock, and on animal health. As temperatures have increased across Sudan (see section 1.1.1 for details) evaporation has also increased, affecting water availability (Mahgoub, 2014). This has had an adverse impact on grasslands, which have become increasingly arid, as well as affecting water resource availability for animals (and humans). As such migration patterns have been becoming increasingly difficult, with shorter transit times being required (due to reduced water availability), increased susceptibility to diseases (Sulieman and Ahmed, 2013), and increased heat stress which leads to lower milk production, wool, and body condition, resulting in impacts on the sale value of animals. In addition, higher temperatures may also result in an increase in vector borne diseases, particularly in southern parts of Sudan (Kimaro and Chibinga, 2013).

Pastoralists are adept at making livelihood adjustments to variations in seasonal patterns (Sulieman et al., 2012), avoiding muddy soils and fly infested pastures. By following cyclic and migratory strategies and other opportunistic husbandry practices, the nomads were able to prevent the extinction of their livestock herds and flocks and maintain the bio-diversity of the local breeds (Sidamed, 1996).

However, changing rainfall patterns are an important factor for pasture production and rangeland rejuvenation, as well as other anthropogenic factors. Figure 5 indicates current migration patterns and shows migration from climate zone A to B in central areas, and climate zone A to C in eastern and western areas of Sudan. Changes in rainfall, combined with increased temperatures have already resulted in changes in how transhumance is practiced with more rapid transits required due to reduced availability of water (Sulieman and Ahmed, 2013). It is also competition for resources (water points, pasture, and traditional grazing areas with encroachment of agriculture) that has led to conflict, particularly in southern and western parts of Sudan (Yagoub and Egemi, 2012; UNEP, 2016).

FIGURE 5

Seasonal migration of pastoral populations



Source: IGAD Climate Atlas Sudan.

2.1.2. Cereal production

Sorghum and millet are by far the most widely grown crops in Sudan (see Table 1). These are primarily rain-fed and, therefore, highly sensitive to weather patterns. They are mainly planted between June and July, although earlier planting does occur in some LHZs. These two cereals represent about 90% of the national cereal production and are important crops for many households' food security. Of the two, sorghum is the most important, with millet production totals being only about 15% of those for sorghum.

TABLE 1

Average production of main cereals in Sudan

Cereal	Average production for 2010-2014 (thousand tonnes)
Sorghum	3,908
Millet	563
Wheat	310
Other	73
Total	**4,854**

Source: FAO/GIEWS Country Cereal Balance Sheets. (www.fao.org/giews/countrybrief/country.jsp?code=SDN)

Sorghum and millet both have a reasonably wide range of rainfall requirements (450-600mm/yr) for optimal production. The tolerance for adapting the growing period is narrower for sorghum (120-130 days), compared to millet where the growing period is shorter, but with more tolerance for variation (105-140 days; Critchley and Siegert, 1991) as well as rainfall requirements (as low as 125mm/year). In Sudan, sorghum is grown in all but three of the LHZs; these are SD03 and SD04, where average annual rainfall is low, and SD06, which is predominantly coastal fishing (Figure 3). Only in areas with seasonal rivers for irrigation can sorghum be grown with low average rainfall (SD05). The LHZs where sorghum grows have rainfall periods varying from 2-6 months and historically have experienced 10-25% variability in rainfall totals.[3] Millet is not as widely grown, with around half of the LHZs reportedly growing this cereal.

Wheat is cropped to a much lesser extent in Sudan, and is only grown in irrigated areas with mechanised farming techniques. It is, thus, less sensitive to weather and climate variability in Sudan. However, as wheat has become an increasingly important cereal for household consumption, any deficits must be filled by imports, meaning that increasing deficits in national production represent important increases in import costs.

More than 80% of sorghum and millet are grown in rain-fed conditions (Faki, Gumaa, & Ismail, 1995), meaning that a non-negligible fraction of sorghum is still grown under irrigation. This compares with wheat, which is predominantly irrigated. Sorghum is the major staple food crop consumed in the rural areas in most regions of the country. Wheat traditionally has been the staple food in the northern province and it recently became a staple in urban areas. Millet has been the major food staple in western Sudan (FAO, 1995).

During the 1980s, poor rainfall contributed to drops in national cereal production. Across Sudan a 10% decline in average rainfall levels induced a 5% drop in national cereal production (Teklu et al., 1991), with sorghum being more sensitive than millet (seeing 7% reduction compared to 3% respectively). Although production has recently been increasing, it is still based on rain-fed agriculture and remains sensitive to rainfall totals.

2.1.3. Cash crops

Cash crops in Sudan are grown using both irrigated farming and in rain-fed systems. Inevitably, rainfall is a more important factor for traditional rain-fed agriculture than irrigated schemes, while temperature is an important factor for both.

Market value of cash crops is also an important factor. The value of cash crops is a mixture of quality of the product brought to market (which is, in part, related to climate variables), but also related to market integration and international prices.

3. WFP HQ historic climate analysis, unpublished.

Smallholder women farmers in Darfur working their fields.

Cash crops of note in Sudan are:
- Cotton (SD09, SD10) – can be grown in rain-fed upland areas or irrigated areas;
- Sesame (SD10, SD11, SD13, SD14, SD19);
- Groundnuts (SD09, SD11, SD12, SD13, SD16, SD17, SD18, SD19);
- Horticultural products / Market Gardens (SD05, SD09, SD15, SD16) producing a variety for fruits and vegetables for both sale and own consumption;
- Tobacco (SD17) - for national consumption.

Cotton is an industry that has significantly declined since the 1980s when around 1 million bales a year were being produced to the current total of around 130,000 (just over one tenth of that 30 years ago). The limiting factors constraining cotton exports in Sudan is a function of low productivity that is related mainly to: the low use of agricultural inputs and uncertified seeds, high inflation rate and distorted exchange rate market, and low competitiveness because of high costs of production. Other factors, such as a shortage of finance, multiple taxes and fees, and non-conducive export policies are also considered constraints for cotton lint export (Yousif, 2015).

Efficient water management is required to avoid waterlogging of cotton (Babiker, 2008). Cotton has a critical requirement for water during October – November (can result in 40% losses if not met). This water requirement lasts until December for Upland Cotton and until the end of March for Egyptian Cotton. Drainage is very important to avoid waterlogging (which can lead to losses of 50-60%) particularly in mid-August (Babiker, 2008). Optimal temperatures are in the range 25-35°C, but even in the present day varieties in Sudan can be exposed to temperatures up to 42°C, making cotton particularly sensitive to any further temperature increases. Although there has been no upper limit determined, conditions higher than those maximum average temperatures experienced in Sudan are likely to have a negative effect on production (Ton, 2011).

Sesame is another cash crop in Sudan, and is more drought resistant than millet. As a result it has been used as a millet substitute in Northern Kordofan, as an adaptive approach to changing climate conditions (Bashier, 2015). Sesame is used for oil production and Sudan accounts for up to 50% of the output of African nations. It ranks about 3rd in the world as a producer (El Naim et al., 2012), despite productivity still being low (due to sub-optimal agricultural practices). Recent production has increased from 343,000 tonnes for the 5 year average (2008/09-2012/13) to 720,000 in 2014/15 and it is becoming a more important crop due to its drought tolerance (Zappacosta et al., 2015). Sesame varieties grown in Sudan mature within 75 to 150 days (depending on the cultivar), and are cultivated in areas that receive average annual rainfall amounts ranging from 350mm to 600mm. However the crop performs best in areas receiving 500mm per year. Optimal maximum temperatures are 30-35°C (depending on the variety); however, temperatures above 40°C during the flowering period (around July / August) will result in reduced seed production (El Naim et al., 2012). This suggests that, while sesame is drought tolerant, it performs best when there are relatively high levels of water availability, and that temperature is a critical limiting factor within Sudan.

Groundnuts are also an important crop for use within Sudan. Although there was a dip in production during the mid 2000s, current production is almost 100% higher than in the late 1990s (and up by 51% compared to the prior 5 year average (2008/09-2012/13) to around 1800 tonnes in 2014/15 (Zappacosta et al., 2015). Groundnut production may have less sensitivity to temperature fluctuations (although the optimal temperature range is 25-30°C), but is sensitive to total rainfall during the planting season (mainly June/July in Sudan). Crops can be grown in areas with as little as 300-400mm annual rainfall but requires 500-1000mm for commercial production. Rainfall is the most important factor for groundnut production (WMO, 2010).

Horticulture and market gardens support households' income as well as increased dietary diversity. Commonly grown vegetables/fruits are okra, onions, tomatoes, watermelon, green leafy vegetables, beans, spices, dates, and citrus fruits. These have a variety of sensitivities to climate change, but are found generally in cooler areas that receive higher amounts of rainfall. Many vegetables will germinate at relatively high temperatures, but will not survive well if these high temperatures persist beyond germination. Therefore, temperature tolerance is not long lived throughout the growing period and is likely to be exacerbated in the event of low rainfall. Crops such as watermelon are more heat tolerant than many other fruits, and require less rain as the season progresses.

2.1.4. Forestry - gum Arabic

Sudan is the leading exporter for gum Arabic in the world exporting around 100,000 metric tonnes in 2014 (this has been steadily increasing since its decline in 2010) and is seen as an important cash crop for national revenue. The gum comes from two species of acacia tree: Acacia senegal and Vachellia (Acacia) seyal (the latter being of lesser quality). The acacia trees play an important role in the agricultural system by providing shelter from soil erosion and are part of what is called the "bush-fallow system of shifting cultivation". In areas of Darfur and Kordofan where these acacias are found there have been substantial losses due to recurrent droughts, although restocking has allowed this industry to return to previous production levels. Trees can be tapped from 3-7 years (depending on planting method – seed or plant) until full maturity at 20-25 years. The most vulnerable time for these trees is in early development when they are at risk from damage by animals or neglect (and therefore risk from over grazing in unprotected areas). Decline in rainfall and increased temperatures have been shown to reduce yield (Ballal, 2011).

Production of gum Arabic has already shifted south since the droughts of the 1980s (El Fatih et al., 2007). Gum Arabic producers also prevent pastoralists from grazing on foliage in the area where the trees are grown. The survival of the gum Arabic industry is more strongly related to the complex issue of land degradation, to which climate change is a strong influencing factor. In the event of irrecoverable land degradation, there would likely be a livelihood and food security shock for households who use this as a significant source of income (Egemi and Ganawa, 2014).

2.1.5. Summary of climate sensitivities

Climate factors broadly affect multiple aspects of agriculture. For example, temperature increases result in increased evaporation and, in the case that this becomes a long-term average increase, a widening of the spatial range of many agricultural pests (Schmidhuber & Tubiello, 2007). Indeed, a temperature increase of just 1.5-2.5°C can make a difference to agricultural production (Sayed and Abdala, 2013). Any increases in rainfall will only result in increased water availability if temperature does not also increase. Soil moisture is also important for maintaining crops during the growing period (June-October, depending on the location in Sudan), although factors affecting soil moisture vary with rainfall, wind speed, temperature, and direct sunshine (Critchley and Siegert, 1991).

Climate imposes limitations on agricultural livelihoods across Sudan, with water availability being a critical factor. Reductions in water availability can be as a result of a delay in the onset of the rainy season, reduced total rainfall, or higher temperatures increasing evaporation. Coping mechanisms for managing risk to agricultural production associated with variability in rainfall include varying planting, switching crop types, and migration times, and installing pumps to extract groundwater to reduce dependence on in-year rainfall. These coping mechanisms are less effective in dealing with the direct impacts of heat-stress, and ultimately the absolute constraints of water availability cannot be directly overcome.

Where climate conditions reduce productivity and livelihood viability, households are also able to manage food security risk through prioritisation of essential spending, or temporary migration to copy with reduced income. However, ultimately the high levels of rain-fed agriculture and the dependence on that agriculture for food production and livelihoods mean that food security in Sudan is highly sensitive to the climate conditions in the region.

2.2. Baseline assessments of climate zones A, B and C

The description of the baseline climate used here follows the methodology presented in Appendix A, and focuses on annual rainfall amounts and maximum temperatures.

Maps of the annual average values for these two variables over the baseline period for each of the climate zones are shown in Figure 6, and the spatially averaged values are shown in Table 2.

There is a clear latitudinal gradient in rainfall, with climate zone A receiving the least rain and climate zone C receiving the most. Maximum temperature is fairly uniformly distributed across the three zones, with cooler temperatures experienced nearer the coast in climate zone A, and over higher ground to the west in climate zone B.

FIGURE 6

Average annual rainfall (top panels) and average value of daily maximum temperature (bottom panels) over the 1981-2010 baseline period for climate zones A (left panels), B (middle panels) and C (right panels)

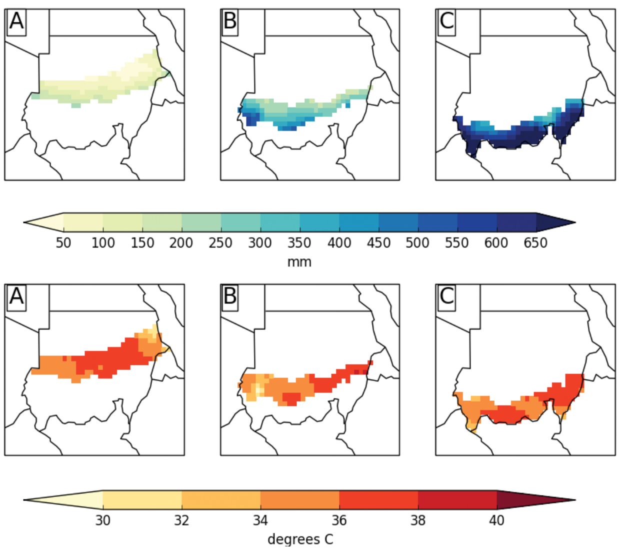


TABLE 2

Baseline climatology values (± standard error) for climate zones A, B and C.

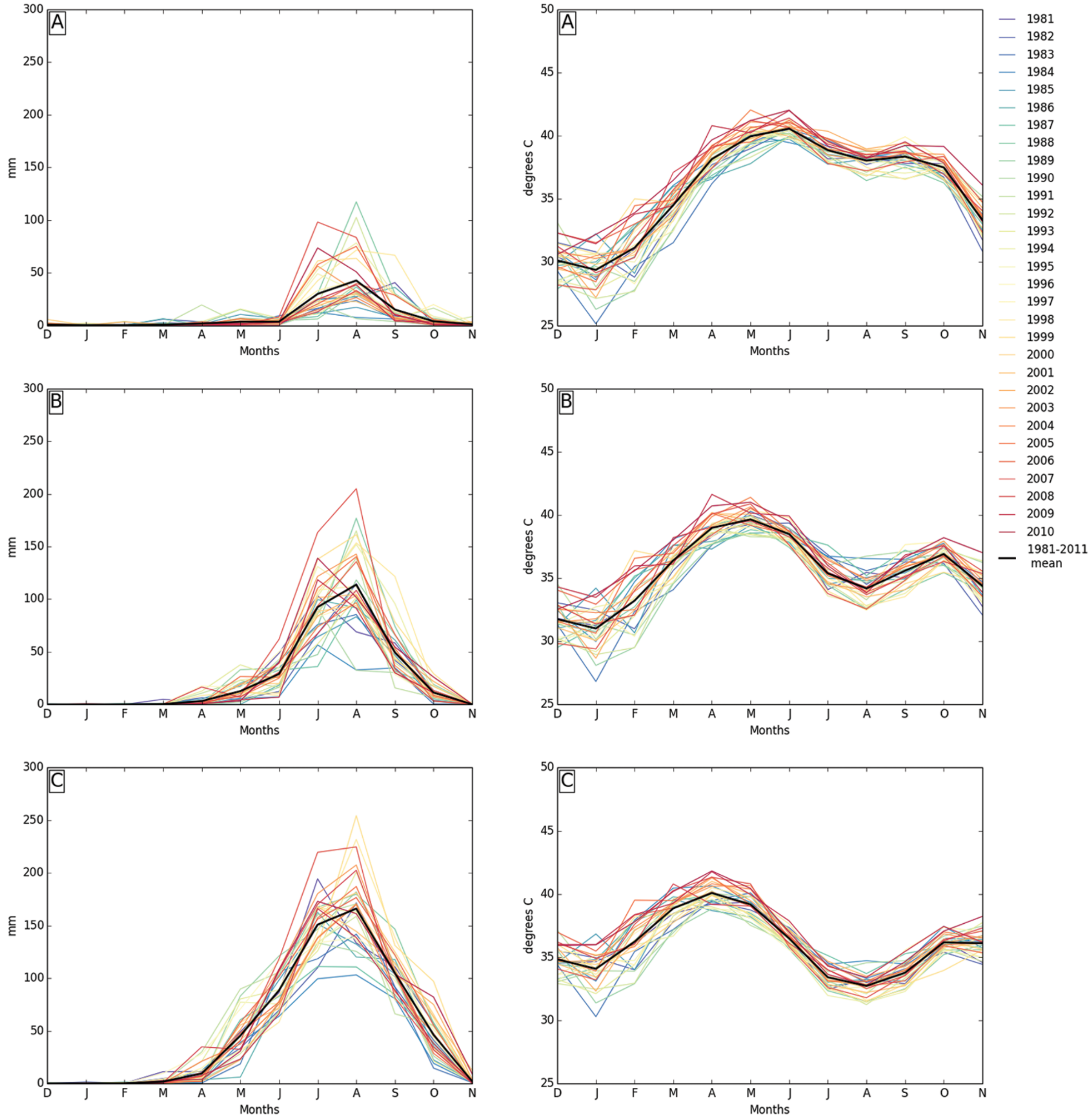
Baseline (1981-2010)	Average annual rainfall (mm)	Average value of daily maximum temperature (°C)	Average daily maximum temperature during hottest month of the year (°C)
Climate zone A	103.1 ±8.6	35.8 ±0.1	40.7 ±0.1
Climate zone B	312.4 ±13.3	35.5 ±0.1	39.8 ±0.1
Climate zone C	615.6 ±15.5	36.0 ±0.1	40.2 ±0.1

The annual patterns of rainfall and maximum temperature are plotted in Figure 7. It can be seen that there is large year-to-year variability in rainfall, particularly during the peak of the rainy season.

A warming trend is evident, with more recent years (oranges and reds) being warmer than earlier years (blues and greens), whereas there is no clear trend in rainfall amounts.

FIGURE 7

Annual profiles of rainfall (left panels) and maximum temperature (right panels) for the baseline period (1981-2010) for climate zones A (top panels), B (middle panels) and C (bottom panels). Individual years from 1981-2010 are shown with coloured lines and the 1981-2010 average is shown with a thick black line



2.2.1. Baseline assessment of climate zone A

Climate zone A is the driest of the three climate zones with annual rainfall totals ranging from around 100-150mm in the south and west of the zone to virtually no rainfall in the north and east (Figure 6, top left panel; the average across the zone is around 103.1mm; Table 2). This area is the northernmost extent of the passage of the annual rains, and the region is dependent on the rains travelling sufficiently far north each year, which does not happen every year. This region is, therefore, not only dry, but also highly variable from year-to-year. The rainy season starts in June and ends in September/ October, the shortest of the three zones, with peak rainfall amounts averaging around 30-40mm in August (Figure 7, top left panel). The average value of daily maximum temperature is around 35.8°C; Table 2) with central parts of the region experiencing slightly higher maximum temperatures than the east and west. The average value of the daily maximum temperature during the hottest month of the year, June, is around 40.7°C).

Livelihood activities are predominantly pastoral (LHZs SD03 and SD04; Figure 3), with the principle livestock being camels, goats, and sheep. Livestock mobility in Sudan is important for both seasonal transhumance and access to markets; animals move within the zone and to more southerly areas of the country (as seen in Figure 5). In addition to pastoralism, millet production occurs with poorer households in western parts.

A key aspect of the climate in this region that impacts on the pastoral livelihoods is the variability of rainfall amounts from year-to-year. This is particularly critical during the peak of the rainy season in years when large-scale climatic factors result in the rains failing to migrate as far north as usual. In such a dry region where the little water that falls is critical, delays in rainfall or a failure of the rains can have severe negative impacts on pasture and, therefore, on pastoralist livelihoods. In addition to highly variable and unevenly distributed rains, over-grazing has resulted in land degradation that is very severe in western and central areas and severe in eastern areas within this climate zone (Egemi and Ganawa, 2014; Abdi et al., 2013; section 3.1 on climate sensitivities of pastoralism).

View of rural villages in Mukjar, Darfur, where WFP implements resilience-building programs, like FFA.

Young boys in Kosti with their donkeys.

Pastoralism is not the only livelihood within climate zone A. The Eastern Khors Agropastoral (SD05) livelihood zone is a seasonal riverine system. This generally results in a more food secure area due to the contribution of river-irrigated cropping to household food security, resulting in relatively low recurrence of food insecurity. However, as agriculture occurs in seasonal rivers, this LHZ is sensitive to decreased annual rainfall and higher temperatures.

Outside of the Eastern Khors Agropastoral zone (SD05), food insecurity in this climate zone is moderately recurrent. Internally displaced persons (IDPs), created as a result of conflict in other parts of Sudan, migrate to the Eastern Pastoral LHZ. These IDPs are often food insecure, thereby contributing to the area being classified as food insecure. Food security is partly dependent on household's own production abilities and partly their ability to access markets for purchasing food (WFP, 2010a; WFP, 2012; WFP, 2013). As a result, food insecurity occurs due to a combination of vulnerability to limited production (livestock sales, milk) and subsequent ability to purchase food (market access, food prices etc.). The Eastern Pastoral LHZ (SD03) is generally more food insecure than the Western and Central Pastoral Zone (SD04) due to frequent and recurrent rain failures (FEWS NET, 2011) requiring food assistance yearly, compared to every 3 years.

Climate pressure on livelihoods comes from low rainfall and high temperatures (resulting in degeneration of rangelands, low water availability for agriculture, livestock and humans, and heat stress on animals). The threat of food insecurity due to climate change in this climate zone is high due to the current fragility of this ecosystem (Abdi et al., 2013).

2.2.2. Baseline assessment of climate zone B

Climate zone B receives much more rainfall than zone A, and annual rainfall amounts range from around 150mm in the north of the zone to around 400mm in the south (Figure 6, top middle panel; the average across the zone is around 312.4mm; Table 2). The rainy season typically starts in May, earlier than climate zone A, and ends in October. The wettest months are July-September, which receive around 100mm of rainfall per month on average (Figure 7, middle left panel). The average value of daily maximum temperature is around 35.5°C (Table 2) with higher values experienced in the east of the region and lower values in the west where the ground elevation is greater (Figure 6, bottom middle panel). There is a two peaked annual cycle in maximum temperature, with the larger peak of around 39.8°C on average occurring during May (the start of the rainy season), and the smaller peak of around 37°C occurring in October (the end of the rainy season; Figure 7, middle right panel; Table 2). The lowest maximum temperatures (around 31°C) occur in January.

Livelihood activities in climate zone B are predominantly agro-pastoral. The wetter conditions (compared to climate zone A) favour cereal crops (such as millet and sorghum), and in westerly LHZs horticulture and market gardens are common. Cash crops are also grown (sesame and cotton) although only in some LHZs (SD09, SD14). Gum Arabic is also cultivated within this climate zone. The rainfall amount, duration of rains, and temperatures permit the production of sesame (cotton is mainly grown using irrigation, except the Upland Cotton where rainfall is higher). Horticulture, that requires a higher average rainfall, is a feature of the western / southern areas. Cattle ownership is possible in this climate zone as a result of lower average temperatures. Livestock migration is also an important climate-sensitive feature in this zone; water needs (from surface water bodies) and grazing requirements along the routes are likely to be affected by climate change.

Rainfall amounts are variable from year-to-year, which is a key aspect of the climate for the livelihood activities in climate zone B, particularly rain-fed cropping systems that are dependent on sufficient rainfall at key stages in the cropping cycle. Planting, therefore, revolves around the annual seasonal rains. In some years, when the northerly migration of the rains is restricted, the onset of the rainy season and, therefore, rainy season totals can be negatively impacted. The same rainfall patterns affect livestock transhumance with reduced pasture and water availability.

Food insecurity in this climate zone is mainly present in the populations displaced by resource-based conflict (people are often displaced to eastern parts of Sudan). Food insecurity also occurs in years with low annual rains (and subsequently reduced crop yields), leading to reduced income and access to food. High levels of poverty are a key underlying issue in this climate zone. In addition, reduced access to markets affects income (crop sales), as well as contributing to fluctuating prices and reduced purchasing power. However, in general, this climate zone has lower risk of food insecurity, compared to climate zone A, with the Western Agropastoral Millet LHZ (SD13) being the most likely to be food insecure, where historically food assistance has been required every three years compared to 3-5 years or more elsewhere in the region.

2.2.3. Baseline assessment of climate zone C

Climate zone C is the wettest of the three climate zones with annual rainfall amounts ranging from around 400mm in the north to more than 700mm in the south (Figure 6, top right panel; the average across the zone is around 615.6mm; Table 2). The rainy season starts in April and ends in November - the longest rainy season of the three climate zones. The wettest months occur in July and August, each receiving around 150mm of rainfall on average (Figure 7, bottom left panel).

The average value of daily maximum temperature is around 36.0°C (Table 2), which is fairly uniformly distributed across the region (Figure 6, bottom right panel). Maximum temperatures peak at around 40.2°C on average during April (Figure 7, bottom right panel; Table 2). The impact of higher rainfall in this region means that maximum temperatures are reduced more significantly over the rainy season compared to the other climate zones, with the lowest maximum temperature occurring in August (the peak of the rainy season) at a value of around 32°C on average, i.e. less than the maximum temperatures experienced in January of around 34°C.

Livelihood activities in climate zone C are predominantly crop-based, with some livestock ownership. This is a zone that receives livestock during drier months as the pastoralists migrate (Figure 5) and can be prone to resource-based conflict and competition (UNEP, 2016; Yagoub and Egemi, 2012). Cotton, groundnut, sesame, wheat, sorghum, millet, cowpeas, and fruit and vegetables are all important crops in this zone. Livestock ownership provides milk to households and improves dietary intake.

Annual rainfall amounts in climate zone C also vary from year-to-year as a result of the variations in the timing and intensity of the ITCZ. However, although the rains may be delayed, or deliver less rainfall than average, rains do not fail to arrive, as can happen in some years in zone A (FEWS NET, 2011).

Food insecurity in LHZs within this climate zone is generally low and there is some surplus food production. Although Western Agropastoral Millet & Groundnut (SD12) is a food production deficient zone, it has good access to markets for cash crop sales and more stable food prices. Households are still predominantly reliant on purchasing food, but their own production contributes more significantly in this area. The western extent of this climate zone is prone to conflict as a result of competition of resources around traditional migration routes, and results in recurrence of food insecurity. Food assistance is, for the most part, not required for the general population in this climate zone. However, internally displaced populations do require food assistance regularly.

Although this climate zone is less likely to be food insecure, it is vulnerable to changes in climate as reduced rains and increased temperatures are likely to result in reduced productivity and lower production potential, in the absence of sufficient adaptive processes that improve climate resilience and adapt current practices to counter the impacts of climate change.

BOX 2

The importance of year-to-year variability

Within each climate zone of Sudan described in this report, livelihoods and food production systems are largely developed to match the most prevalent conditions. It is these 'average' conditions that we define as the climate. However, the weather naturally varies from year-to-year. This year-to-year variability can make it much more difficult to plan, and the resilience of food systems to that variability can be a critical factor in overall food security levels.

Climate change represents a trend in the long-term average climate conditions, but it also has the potential to alter the variability of that climate from year-to-year. There is little consensus on how year-to-year variability may change, but it is clear that both the overall climate suitability, and the variability of the climate from year-to-year, are critical to food production, livelihoods and food security.

Participants in WFP's Food Assistance for Assets Programme working in haffir construction.

Abu Musa hoeing his farm
in rural Kassala.

3. Scenarios of projected climate change and outcomes for livelihoods and food security for the 2040s

Three scenarios of projected climate change in Sudan, along with assessments of the associated pressure on livelihoods and indications for food security in each scenario, are presented in this section.

The scenarios are results from the analysis of three climate models for the 2031-2060 time period to represent change by the 2040s under the RCP8.5 greenhouse gas concentration scenario (van Vuuren et al., 2011). The three scenarios chosen reflect three different and plausible future changes in climate in Sudan, and span the range of climate model projections. More detail on the methods and choice of scenarios is given in Appendices A and B.

3.1. Summary of scenario outcomes

The projected climate change in Sudan for each of the three scenarios is summarised below:

- Scenario 1 is hotter and slightly wetter than the baseline. The higher temperatures increase evaporation meaning little change in overall water availability and higher levels of heat stress. This scenario shows little change in the variability of rainfall from year-to-year compared to the present day.
- Scenario 2 is hotter than scenario 1 and drier than the baseline. As a result, water availability will be lower than both the present day and scenario 1, and heat stress conditions will be larger. However, rainfall amounts and timings are typically less variable from year-to-year.
- Scenario 3 is the hottest of all three scenarios. This scenario is drier than the baseline on average, but with some regional variation. In addition to the impacts on water availability and heat stress this brings, this scenario shows the largest year-to-year variability of both rainfall amounts and timings across the three scenarios, and an increase in variability of the onset of the rainy season compared to the baseline climatology.

A summary table of the projected changes in the baseline climate zone characteristics from Table 2, for each scenario, is shown in Table 3. Summaries of the assessments of the outcomes for livelihoods and food security for each scenario of projected climate change are shown in Table 4. More detailed assessments are presented in Section 3.2.

Woman, smallholder farmer on her way to hoe her fields.

TABLE 3

Projected change in the baseline climatology values (± standard error) from Table 2 for the 2040s (2031-2060) relative to the baseline period (1981-2010) for climate zones A, B and C under the three future climate scenarios. The baseline values from Table 2 are also shown for reference

	Climate zone A			Climate zone B			Climate zone C		
	Average annual rainfall (mm) (and % for future scenarios)	Average value of daily maximum temperature (°C)	Average daily maximum temperature during hottest month of year (°C)	Average annual rainfall (mm) (and % for future scenarios)	Average value of daily maximum temperature (°C)	Average daily maximum temperature during hottest month of year (°C)	Average annual rainfall (mm) (and % for future scenarios)	Average value of daily maximum temperature (°C)	Average daily maximum temperature during hottest month of year (°C)
Baseline	103.1 ±8.6	35.8 ±0.1	40.7 ±0.1	312.4 ±13.3	35.5 ±0.1	39.8 ±0.1	615.6 ±15.5	36.0 ±0.1	40.2 ±0.1
Change in scenario 1	+10.1 ±4.9 (+9.8 ±4.8%)	+1.3 ±0.1	+ 2.3 ±0.2	+17.2 ±8.9 (+5.5 ±2.8%)	+1.3 ±0.1	+2.0 ±0.2	+24.4 ±9.8 (+4.0 ±1.6%)	+1.3 ±0.1	+2.2 ±0.1
Change in scenario 2	-10.6 ±4.3 (-10.3 ±4.2%)	+2.1 ±0.1	+2.8 ±0.2	-31.4 ±6.2 (-10.1 ±2.0%)	+2.3 ±0.1	+2.8 ±0.2	-58.4 ±8.0 (-9.5 ±1.3%)	+2.3 ±0.1	+2.6 ±0.2
Change in scenario 3	-15.3 ±6.3 (-14.8 ±6.1%)	+2.8 ±0.1	+2.9 ±0.1	-22.5 ±9.9 (-7.2 ±3.2%)	+2.8 ±0.1	+2.7 ±0.2	-5.8 ± 9.4 (-0.9 ±1.5%)	+2.8 ±0.1	+2.9 ±0.1

TABLE 4

Summary of climate, livelihoods and food security for the baseline and each of the three future scenarios

	Climate zone A	Climate zone B	Climate zone C
Baseline	**Climate:** driest climate zone; ~100mm rain per year, rainy season Jun-Sep. **Livelihoods:** mostly pastoralists and some agro-pastoralists in the east.	**Climate:** ~300mm rain per year, rainy season Mar-Oct. **Livelihoods:** mostly agro-pastoralists growing cereal and cash crops.	**Climate:** wettest climate zone; ~600mm rain per year, rainy season Apr-Nov. **Livelihoods:** mostly agricultural crops but pastoralists bring livestock in drier months.
Scenario 1	Scenario 1 represents a future with small increases in rainfall, particularly in the south and over higher elevation in the west. However, this scenario also exhibits increases in temperature resulting in greater evaporation, which potentially offsets much of the benefit for water availability. Year-to-year variability will remain a key challenge for livelihoods across Sudan in this scenario. Land degradation and animal health will both continue to be problems, exacerbated by increasing temperatures. This scenario will have negative impacts for cropping systems, particularly within areas where temperatures are already close to crop heat tolerance levels. Patterns of food insecurity are likely to remain similar to the present day, but with additional stress associated with higher temperatures, and possible on-going desertification in pastoral areas.		
Scenario 2	The increase in temperature in Scenario 2 is greater than for Scenario 1, and average rainfall is reduced compared to the present day. This combination means water availability will be a greater challenge in this scenario. As a result, all livelihood zones are likely to be exposed to significant challenges such as land degradation and reduced crop yields, with the possibility that some crops may no longer be possible to grow. Although the climate in this scenario is more hostile, there is some reduction in the amount of variability in rainfall from year-to-year, therefore, it may be more conducive to planning and adaptation measures. As such, food insecurity is likely to increase unless significant measures are taken to address production and land degradation.		
Scenario 3	Temperatures in Scenario 3 are much higher than both Scenarios 1 and 2. This scenario is also drier than the present day, on the whole, but with some increases in rainfall regionally, mainly in the current wettest areas. In addition, there is increased variability in year-to-year rainfall amounts and timings. This climate would result in reductions in water availability and increases in heat stress in most areas, combined with less reliable rains from year-to-year. As a result, there are likely to be large increases in food insecurity, particularly in already vulnerable and drought prone areas. Furthermore, crop production is likely to face important reductions in yield nationally, resulting in increased need for imports and higher market price vulnerability. Food insecurity is likely to be consistently higher with an increase in wide spread events. Livelihoods will face much stronger pressure in this scenario than the other scenarios, with local adaptations requiring modernised approaches.		

3.2. Detailed assessments of livelihoods and food security outcomes in each scenario

Detailed assessments of the projected climate change for the 2040s and the associated pressure on livelihoods and indications for food security for each of the three scenarios are presented in this section. Maps and annual profiles of the projected change in climate are presented for each scenario, see Box 3 for information about interesting these plots.

Participants in WFP's Food Assistance for Assets Programme working on haffir construction.

BOX 3

Interpreting the projected climate change plots

In sections 3.2.1 – 3.2.3, maps and annual profiles of the projected change in annual rainfall and maximum temperature for the 2040s (2031-2060) are presented. Note that these maps and annual profiles require different interpretation to the baseline maps and annual profiles shown in Section 2.2 (Figures 6 and 8). The maps (Figures 8, 10 and 12) show the projected change between the future and baseline time periods, and therefore recalling what the baseline climate is like in each of the climate zones gives context to these projections. For example, a projected change of 10mm is a change of around 10% of the annual rainfall received in climate zone A, the driest of the three zones, whereas the same projected change is only around 1.5% of the annual rainfall received in climate zone C, the wettest of the three zones. The baseline values and projected absolute and relative changes for each scenario per climate zone are given in Table 3 for comparison.

The annual profile plots for the three future climate scenarios (Figures 9, 11 and 13) show the individual years over the 2031-2060 time period in blue/red for rainfall/temperature respectively, and the mean is shown in black. For these plots, the range of values from the baseline period (1981-2010) is shaded in grey, with the baseline mean also shown in thicker, darker grey (note that this is not always visible), and therefore it is possible to compare the projected values and year-to-year variability for each month of the year with that experienced over the baseline period.

3.2.1. Projected climate change and outcomes for livelihoods and food security in Scenario 1

In scenario 1, the average annual rainfall and value of the average daily maximum temperature are both projected to increase in all climate zones by the 2040s. Maps and annual profiles of the projected change are shown in Figures 8 and 9 respectively. See Box 3 for tips on how to interpret these.

FIGURE 8

Projected change in average annual rainfall (top panels) and the average daily value of maximum temperature (bottom panels) under scenario 1 for climate zones A (left panels), B (middle panels) and C (right panels) for the 2040s (2031-2060) relative to the 1981-2010 baseline

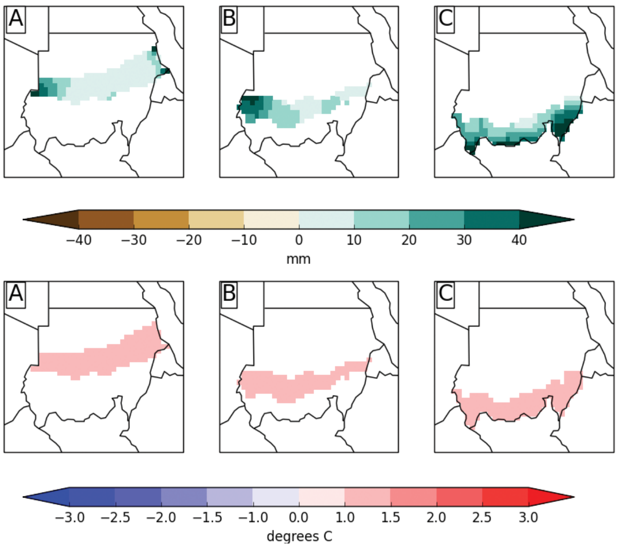
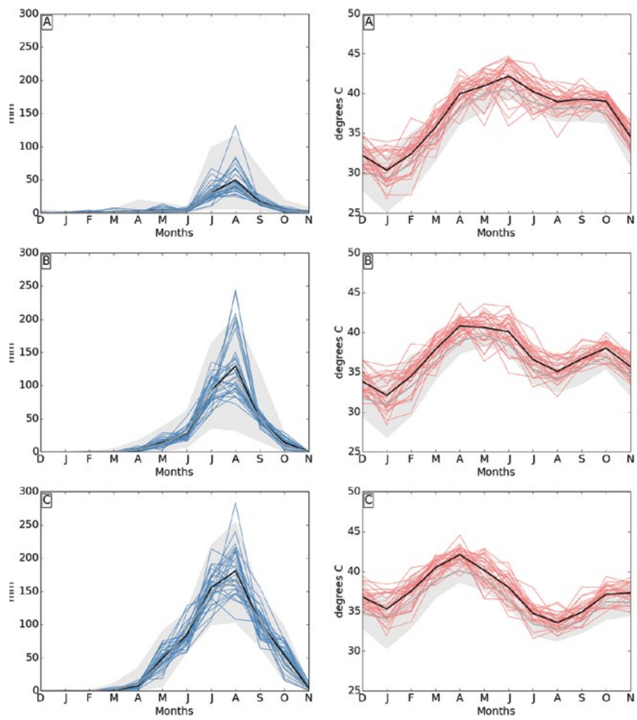


FIGURE 9

Annual profiles of rainfall (left panels) and maximum temperature (right panels) for the future time period (2031-2060) for climate zones A (top panels), B (middle panels) and C (bottom panels) under scenario 1



Scenario 1 outcomes for climate zone A

In climate zone A, there is a projected increase in the value of daily maximum temperature of around 1.3°C (Table 3; Figure 8, bottom left panel). Temperatures are projected to be higher throughout the year (Figure 9, top right panel). The current average value of the daily maximum temperature during the hottest month of the year is around 40.7°C (Table 3) and this is projected to increase by around 2.3°C (Table 3).

Climate zone A is the driest climate zone in the baseline (Figure 6), and so a projected increase of around 10% is small in absolute terms (around 10mm; Table 3), but relatively significant given the limited rainfall received on average in the zone (around 100mm per year). This could be beneficial in rangelands, particularly in the west where the largest increases are projected (Figure 8, top left panel), which may develop and recover better on average, however the projected increase in temperature will result in greater evaporation and could potentially offset any increases in rainfall. Therefore the main concern in this scenario is the increased temperatures and continued unreliability of the annual rains. The increased temperature is likely to increase heat stress in animals and potentially reduce milk production, and food access (with reduced income from milk sales and reduced value of animals). In addition, increased temperature will put pressure on crop production in the agro-pastoral zone (Eastern Khors Agro-Pastoral, SD05) as a result of temperature induced reduction in yield. As such, this LHZ may see some reduction in food access with increasing risk of food insecurity.

Year-to-year variability in rainfall is still a feature of this scenario; particularly in the lead up to the start of the rainy season where there is some indication of a 'false start' to the rains in March and May; however, the variability in rainfall amounts during the peak of the rainy season is somewhat reduced compared to the baseline (Figure 9, top left panel). As a result, despite a small increase in the average annual rainfall in this scenario, actual amounts from year-to-year will still vary, with some years receiving less rainfall than the average baseline amount. Such false starts could result in changes in migration patterns, with early migration occurring. Early returns could also result in premature grazing on rangelands and increased pressure on rejuvenation. It is possible that, without appropriate adaptive measures, food insecurity could increase if animals are exposed prematurely to lower amounts of food. Reduced milk availability and income from lower value of animals would also affect access to markets for the purchase of food. This would occur during years where rainfall is lower than expected.

The general trend in this climate zone is that food security is likely to remain in a similar long term pattern to that currently experienced, but with agro-pastoralists potentially seeing decline in food security due to decreased yields. Pastoral livelihoods will need to address issues of land degradation in order to maintain livelihoods, and ultimately food security. Adaptation to climate change in this zone could include improving resilience to year-to-year variability, increasing efficiency of water use and moving to more heat-tolerant agricultural practices.

Scenario 1 outcomes for climate zone B

The impact of increases in annual rainfall of around 5% (Table 3) in climate zone B is relatively small for livelihoods within this climate zone. However, any increases may assist with spread and increase of rain-fed areas using mechanised farming (a farming practice that has already led to increased loss of ranges and as a result there may be challenges to livestock production).

However, the higher temperatures projected across the zone (an increase of around 1.3°C relative to the baseline value of the average daily maximum temperature of around 35.5°C; Table 3) may well off-set any benefits of increased rainfall through increases in evaporation (Pimental, 1993; Turral et al., 2011), resulting in similar water availability to the baseline. In addition to this, however, the higher average temperatures are most likely to put general pressure on overall crop yields (although temperatures still remain within tolerance ranges of most crops). Such increases may also result in some heat stress on livestock (resulting in reduced milk production).

Given that this scenario has similar to baseline year-to-year variability in rainfall and water availability (Figure 9, middle panels), the current pattern of food insecurity is likely to remain. However, with the increase in average temperature, it is likely that crops (particularly sorghum and cotton) may see reduced yields without adequate adaptations, reducing income for households and creating increased strain on livelihoods.

Food security within this scenario could fluctuate more than is already experienced. Increased rain could result in some increase in production (particularly if mechanised farming expands). However, the temperature increase will put negative pressure on crop production and animal health (with some reduction in yield of sorghum) and require adaptive measures (such as improved cropping techniques and varietal choices). In the case that production is affected, a decrease in food security would follow with more frequent occurrence than baseline observations. Livelihoods are likely to need additional support to assist with adaptive measures. Due to the continuing year-to-year variability and pressure on production it is possible that more households will require livelihood support with increased food insecurity. However, this will not be as significant as for other scenarios.

Scenario 1 outcomes for climate zone C

The projected increases in rainfall in climate zone C are proportionally the smallest across all the climate zones (around 4%; Table 3), but the largest in absolute amounts as this region is the wettest in the baseline (Figure 8, top right panel). Average daily maximum temperatures are projected to increase by around 1.3°C relative to the baseline value of around 36°C, with the temperature of the hottest month projected to increase more (around 2.1°C relative to the baseline value of around 40.2°C; Table 3). The mean daily increase in temperature is most likely to put stress on crop yields (sorghum and millet, as well as groundnuts) as mean temperatures are already close to tolerance levels of many cereal crops. As this climate zone is important for national production even a small proportional change could be important for national food security, even if the impact on individual households, and their food security, is less pronounced.

Increased rainfall in this climate zone may also carry an increased risk of vector borne diseases for both humans and animals, as this is an area already prone to such issues. These increases could also lead to an increase in fodder availability and potential for crop production, if increases in temperature do not offset the rainfall increases. As such and on average, stability in this climate zone is quite likely to remain similar to that of the baseline.

Year-to-year variability is similar to the baseline (Figure 9, bottom panels) and, as such, variability in food security patterns should also remain similar to those currently observed. However, reduced yields as a result of increased temperatures may prove to reduce national production and put pressure on national food imports.

3.2.2. Projected climate change and outcomes for livelihoods and food security in Scenario 2

In scenario 2, the average annual rainfall is projected to decrease across Sudan compared to the baseline rainfall amounts. The value of the average daily maximum temperature is projected to increase compared to the baseline, with slightly larger increases projected compared to Scenario 1. Maps and annual profiles of the projected change are shown in Figures 10 and 11 respectively. See Box 3 for tips on how to interpret these. Note that in this scenario the rainfall in October in one particular year is larger than that seen over the baseline period, with associated reduction in temperature, as seen in Figure 11. This is a plausible feature in the climate model projection.

FIGURE 10

Projected change in average annual rainfall (top panels) and the average value of daily maximum temperature (bottom panels) under scenario 2 for climate zones A (left panels), B (middle panels) and C (right panels) for the 2040s (2031-2060) relative to the 1981-2010 baseline

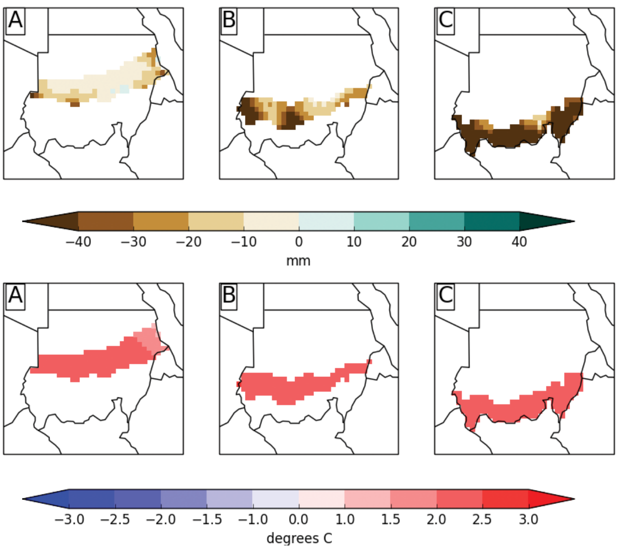
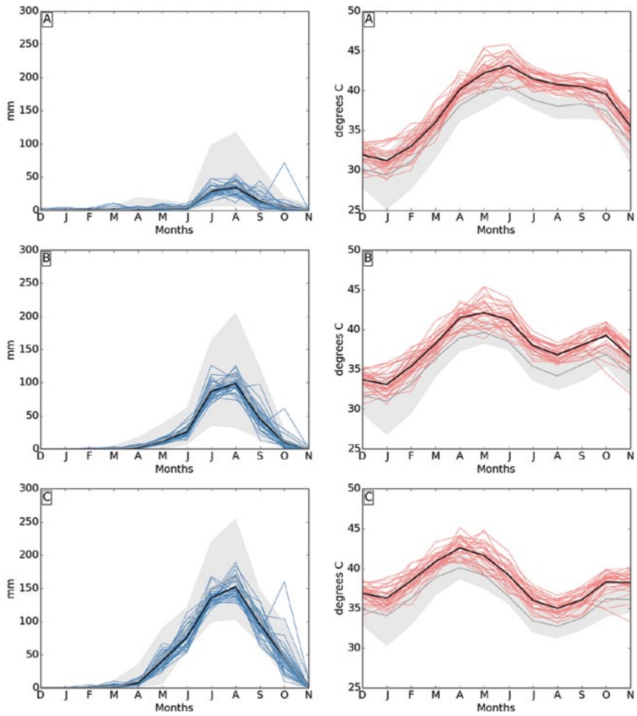


FIGURE 11

Annual profiles of rainfall (left panels) and maximum temperature (right panels) for the future time period (2031-2060) for climate zones A (top panels), B (middle panels) and C (bottom panels) under scenario 2



Scenario 2 outcomes for climate zone A

In climate zone A average annual rainfall is projected to decrease by around 10% compared to the baseline (Table 3). Although the decrease in this zone is the smallest absolute amount compared to the other climate zones in this scenario (Figure 10, top panels), this is a significant reduction in a region that only receives around 100mm of rainfall on average across the year. The decreases are projected to occur during the wettest months of the rainy season. Decreased rainfall is a significant risk for pastoralism due to the impact on available pasture and rangeland for the livestock, particularly if livestock numbers do increase. With unchecked grazing, it is possible that desertification becomes an increasing threat. As such, livestock may have to spend longer in areas of higher rainfall (and adequate grazing areas). This disruption in migration patterns could result in an increase in resource-based conflict.

This scenario exhibits higher projected temperature increases compared to scenario 1 (an increase of around 2.1°C relative to the baseline value of the average daily maximum temperature of around 35.8°C; Table 3). This could mean a greater risk to livestock via heat stress and reduction in water availability as a result of increased evaporation and reduced rainfall, compared to Scenario 1. Animal body condition and production is likely to be significantly affected, reducing income for households and contribution to national GDP (due to reduced quality animals available to the international market).

Agriculture in the Eastern Khors Agropastoral LHZ (SD05) is likely to see significant reductions in production due to the increased monthly temperatures, with reduced rainfall affecting even more crops that are drought resistant. Although the reduced year-to-year variability in rainfall amounts and timings in this scenario (Figure 11, top left panel) may help with planning, the ability to sustain agriculture in the long term in this LHZ will become increasingly difficult.

Scenario 2 outcomes for climate zone B

The projected decrease in annual rainfall (around 10%; Table 3) in this scenario is not uniformly distributed across climate zone B; relatively larger decreases are projected in western and central zones (Figure 10, top middle panel). This is a similar decline in average rainfall observed in the 1980s that was associated with a national decrease in sorghum (7%) and millet (3%) (see section 2.1.2; Teklu et al., 1991) and considered an important impact on national food security, as well as having implications for livelihoods and household food security.

The projected increase in temperature (an average increase of around 2.3°C relative to the baseline value of the average daily maximum temperature of around 35.5°C; Table 3), in addition to the reduced rainfall, is likely to affect evaporation, potentially causing worse impacts than those observed in the 1980s.

Gum Arabic production may also be negatively affected as a result of the reduced water availability. Other cash crops are likely to experience decreased yields, and consequent reductions in household income. Cereal production is also likely to be negatively impacted in this scenario, with lowered yields and overall production reduced.

In this zone livelihood production is faced with pressures that lead to declines in production (increased temperatures and reduced rainfall), and some livelihood elements may require significant adaptations (such as cash crop production, cattle rearing, or shifting to more drought resistant crops). Reduced year-to-year variability (Figure 11, middle left panel) is likely to assist with long term strategic planning, possibly not undermining accumulated efforts. However, food insecurity is likely to increase due to the pressures faced from reduced production and therefore access to food.

Scenario 2 outcomes for climate zone C

The largest projected decreases of rainfall for climate zone C occur in this scenario (Figure 10, top right panel). Annual rainfall amounts are projected to decrease by around 10% (Table 3). This region receives the largest amounts of rainfall and so is the least water stressed. Nevertheless a 10% reduction is a larger absolute change than for the other zones (Table 3). This decrease in rainfall could lead to important reductions in national production of cereal crops as well as livestock production, particularly in the western rain-fed mechanised areas (SD10). In addition to projected decreases in rainfall, temperatures are also projected to increase (an increase of around 2.3°C relative to the baseline value of the average daily maximum temperature of around 36.0°C;

Table 3), increasing evaporation and causing further heat stress on crops. As noted in the baseline section on climate sensitivities, crops in Sudan are sensitive, in terms of total production, to proportionally small reductions in rainfall. It is likely that this will have a greater effect on national food production than individual households. However, even small reductions in climate zone C, where a larger percentage of households are engaged in agriculture, are likely to result in a decline in food security. Although local adaptation strategies may mitigate some of the reductions the studies noted in section 2.1 suggest they are not adequate to deal with this level of climate change. In this scenario, livelihoods within this climate zone will decline and risk of food insecurity will increase, with more frequent occurrence.

3.2.3. Projected climate change and outcomes for livelihoods and food security in Scenario 3

In scenario 3, the average annual rainfall is projected to increase in some areas and decrease in others, with an overall average decrease projected across Sudan. The projected increase in the value of the average daily maximum temperature is the largest across the three scenarios, and there are also projected changes to the annual patterns of rainfall and maximum temperature. Maps and annual profiles of the projected change are shown in Figures 12 and 13 respectively. See Box 3 for tips on how to interpret these.

FIGURE 12

Projected change in average annual rainfall (top panels) and the average value of daily maximum temperature (bottom panels) under scenario 3 for climate zones A (left panels), B (middle panels) and C (right panels) for the 2040s (2031-2060) relative to the 1981-2010 baseline

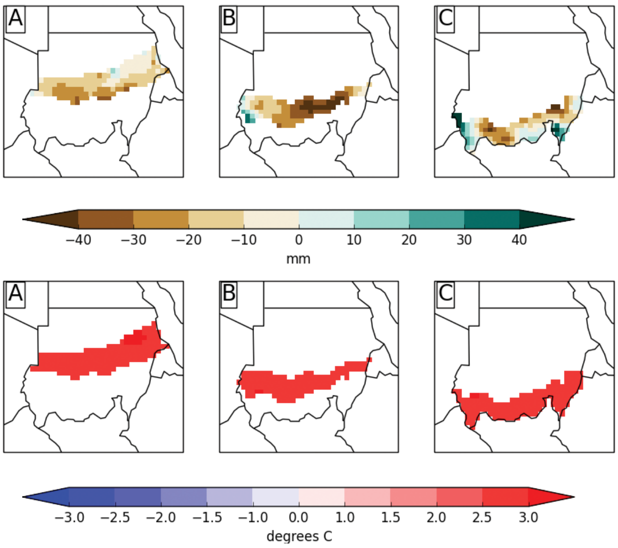
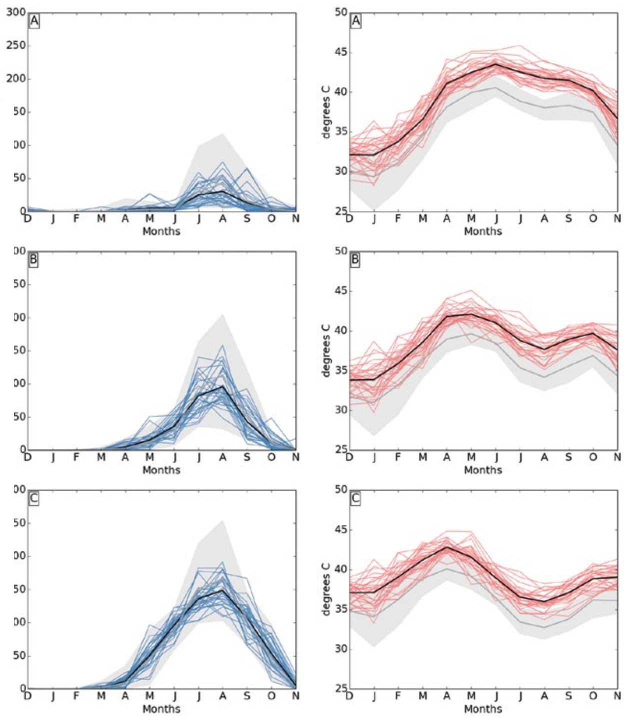


FIGURE 13

Annual profiles of rainfall (left panels) and maximum temperature (right panels) for the future time period (2031-2060) for climate zones A (top panels), B (middle panels) and C (bottom panels) under scenario 3



Scenario 3 outcomes for climate zone A

Out of all the scenarios, the largest projected decreases in rainfall occur in this scenario for climate zone A (Figure 12, top left panel). The total annual rainfall is projected to decrease by around 15% (Table 3) in a region which only receives around 100mm of rainfall on average per year. Rainfall amounts are slightly higher than the baseline average in the lead up to the rainy season (April – June) and then lower than the baseline average in every month of the rainy season (Figure 13, top left panel). In addition, year-to-year variability is higher in this scenario than the others described in this report, and often results in virtually no rainfall received across the zone in some years. In addition to these projected changes in rainfall, the largest increases in average daily maximum temperature are also projected in this scenario (an increase of around 2.8°C relative to the baseline value of the average daily maximum temperature of around 35.8°C; Table 3), and as a result of the reduced rains during the peak of the rainy season, the projected maximum temperatures over the summer months are higher than the highest values experienced over the baseline period.

The large decrease in rainfall compared to other scenarios presents a more significant risk of pasture degradation while the higher year-to-year variability (Figure 13, top left panel) will further exacerbate rangeland recovery issues. The larger increase in maximum temperature in this scenario presents a significant challenge to animal health, particularly if shade availability is reduced (due to increased land degradation).

Water availability will be increasingly challenged due to the reduction in rainfall and higher temperatures leading to increased evaporation. Such a climate is likely to result in important changes in carrying capacity of this zone for livestock, and lead to migration of these livelihoods further south and increased likelihood of resource-based conflict. A number of present day agricultural activities (such as millet which is currently grown by poorer households in the west) may well not be viable in the future within this scenario as evaporation of water in the Eastern Khors may be too great, rainfall inadequate, and more recurrent poor rainfall performances may result in an untenable environment for agriculture.

Scenario 3 outcomes for climate zone B

The larger projected increases in maximum temperature in this scenario (an average increase of around 2.8°C relative to the baseline value of the average daily maximum temperature of around 35.5°C; Table 3) which during key periods (the beginning and peak of agricultural seasons – June to September) are likely to represent a significant challenge for cropping success and yields in this climate zone due to increased evaporation during planting and crop development. This is particularly true for the eastern part of SD13 and for SD14 (both rain-fed areas) where the largest decreases in rainfall are projected (Figure 12, top middle panel). Although western areas are projected to see increases in rainfall on average, variability between years will continue to feature (similar to the baseline and largest of the three scenarios; Figure 13, bottom middle panel) and this will increase the risk of harvest failures. In addition, these westerly areas are also subject to the same large average temperature increases which may off-set the impact of the projected increases in rainfall on water availability to some extent.

For livestock, pressures on pasture rejuvenation will increase due to poor rainfall performance between years and overall decrease in rainfall. With pasture already overgrazed in central areas (by cattle) and increasing heads of livestock, rangeland will continue to be significantly challenged with no mitigation. This scenario represents a significant pressure on livelihoods, both agriculture (including forestry) and livestock, in this climate zone. Riverine and irrigated agriculture is less likely to see reductions in production but increased temperatures could result in reduced yield, particularly cotton. However, other important cash crops are located in this zone and as such this scenario represents a significant challenge to both food security and national exports of cash crops.

Overall, livelihoods within this zone will experience increased difficulty in building resilience as the year-to-year variability is likely to result in households more recurrently using detrimental coping strategies to adapt to climate changes. Increased food insecurity is likely to follow, with more households becoming food insecure within this scenario than the other two.

Scenario 3 outcomes for climate zone C

In climate zone C, the total annual rainfall across the zone is projected to decrease slightly, with mixed projections locally; the western and south-eastern areas projected to see increases and the central and eastern areas projected to see decreases (Table 3; Figure 12, top right panel). Average rainfall is likely to be quite variable leading to reduced yields and potentially failed crops if information around optimal planting time is not available. In addition, the projected large increases in maximum temperature (an average increase of around 2.8°C relative to the baseline value of the average daily maximum temperature of around 36.0°C; see Table 3) will put significant pressure on water availability for animals where rainfall is lower than the present day. Livestock migration could be interrupted due to variability of rainfall (and reduced rainfall) resulting in increased degradation of rangelands, along with surface decreased water availability, resulting in the need for faster transit times and increased risk of animal deaths.

Temperature increases are higher than average at key parts of the production cycle (at the beginning when germination and initial growth is occurring) as well as the peak periods of the rainy season (potentially offsetting any useful increases in rainfall via increased evaporation). These changes are likely to have important effects on yield and overall production of both cash and cereal crops, as both start to indicate important reductions in yields for mean monthly temperatures above 40°C.

Increased temperatures will put significant pressure on water availability for animals especially where rainfall is lower than the present day. This climate zone receives livestock from other parts of Sudan (Figure 5), and the projected rainfall pattern favours the areas of traditional migration. However, the increased temperature may also increase disease transmission in these areas, which may have a wider impact on livestock than just those households within this climate zone.

The change in risk to food insecurity is likely to increase within LHZs of this climate zone without adaptation measures. Reduced yield and livestock production will reduce overall income and access to food (own production). This area is most likely to face the largest crop reductions in Sudan, with livestock owners facing challenges in keeping animals fed and watered during the low points of rainfall variability (when surface water is least, and when heat stress is highest. In addition, some cereal cropping may no longer be viable in this area (see discussion in section 2.1). As a result of the changes in average climate conditions, compounded by increased rainfall variability (Figure 13, bottom left panel), food insecurity will likely rise. It is likely that this climate zone will see the largest increase (measured by number of households) becoming more food insecure, and requiring livelihood support to adapt to climate change.

Woman in Geneina, Darfur,
clearing the pathway.

4. Conclusions

Sudan lies on the northern most extent of the ITCZ, which means it has a strong gradient of rainfall, with almost none in the north, to relatively high amounts in the south. The rainfall in the country is seasonal, and varies from year-to-year depending on the position and intensity of the ITCZ.

Livelihoods and agricultural production systems correspond to the climatological suitability of the region. In the north, where rainfall totals are low and the onset of the rains are unreliable, pastoralism dominates; in the south where there is significantly more rainfall, and although variable, consistently arrives, cropping systems are more prevalent.

Agriculture is an important part of the economy of Sudan, employing up to 80% of the labour force and, accounting for around one third of the GDP. Those employed in agriculture are the poorest and most often food insecure. Agriculture is also predominantly rain-fed in Sudan, which means there is an inherent sensitivity to rainfall amounts and timings, making climate change key factors in the future of Sudan's economy, livelihoods, and food security.

Climate change projections for Sudan all agree on the signal for a substantial warming trend of between 1.5°C and 3°C across the country. In contrast, there is no clear projected trend in mean annual rainfall for Sudan. Projections for the average change in rainfall across the models are small and span both increases and decreases, with most models indicating an increase, and the year-to-year variability in rainfall exceeds any climate change signal.

Three scenarios of climate change were explored, based on the projections from three different climate models that span the spread of the wider model range. The three scenarios indicate that climate change will mean higher temperatures, reductions in water availability and continued year-to-year variability in a country highly sensitive to such changes. In all scenarios, there is the potential for increases in food insecurity across Sudan, with the scale of increase dependent on the scenario.

Adaptation measures should focus on reducing sensitivity, improving resilience to variability and extremes, and improving heat tolerance and water efficiency in agricultural production. The climate projections can be thought of as a southward shift of the current climate to varying extents in each scenario. The concept that the future climate is analogous to a hotter version of the climate further north could be helpful to inform adaptation planning. In addition, a more detailed study on water availability is recommended.

Young boys in Kosti
with their donkeys.

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Couple sifting and storing grains following harvest.

Appendix A. Methods and data

The analysis presented in this report, to assess the impact of projected climate change on livelihoods and food security in Sudan, has been a collaborative effort across climate science and food security disciplines. The approach taken here is based on an adaptation of the CLEAR methodology (WFP, 2014); a framework for assessing climate risk and food security, where a more narrative approach is taken to the food security analysis due to constraints of data availability.

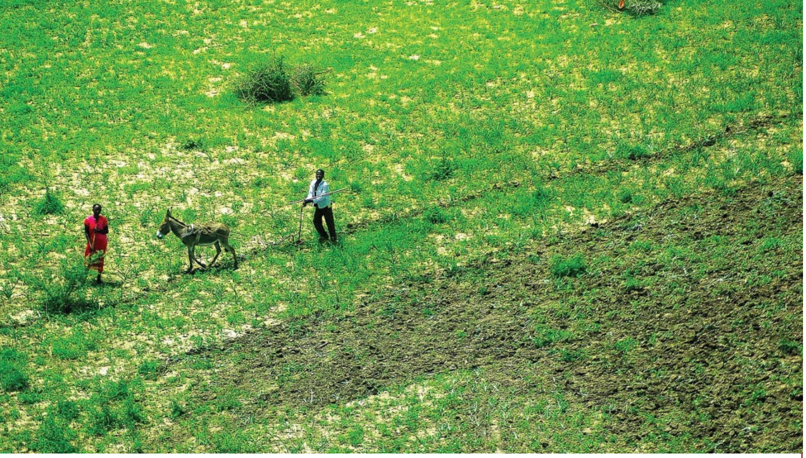
The first step was to ensure a good understanding of the baseline climate and its relationship with current livelihoods and food security. Three plausible scenarios of projected climate change were then analysed, and the impact on livelihoods and food security were assessed in the context of the potential change from the present day. This section describes the methods and data used for this analysis.

A.1. Climate analysis methods

The climate analysis undertaken in this report considers two time periods. The first is an assessment of the baseline climate, covering the period 1981-2010 to represent the present day. Due to the sparsity of reliable direct observations of climate across the region, this assessment is based on reanalysis data (a blend of observed weather data and model data of past climate to provide gridded historical climate data). The analysis then goes on to consider projected changes in climate from climate model outputs for the period 2031-2060, as representative of the climate in the 2040s.

To define the baseline climate of Sudan, monthly temperature and rainfall data from the WATCH forcing dataset (a gridded 0.5°x0.5° resolution meteorological dataset of present-day climate; Weedon et al., 2011) were analysed over the baseline period. For the future projections, change in these variables from three climate models were analysed for the future time period. The three climate models selected were from the fifth phase of the Coupled Model Intercomparison Project multi-model ensemble of models (CMIP5; Taylor et al., 2012); a collection of the latest generation of global climate models developed at different institutions around the world, and used to inform the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). These models represent equally plausible scenarios of future rainfall and temperature, and were chosen based on resolution and model performance criteria, and also to reflect the range of potential future changes in climate in Sudan most relevant to livelihoods and food security. Only one future greenhouse gas concentration pathway was considered (Representative Concentration Pathway 8.5 (RCP8.5); van Vuuren et al., 2011) as there is minimal difference in projected climate change between the future greenhouse gas concentration scenarios up to the 2040s. (This is because climate change during this period is largely a result of past greenhouse gas emissions and inertia in the climate system; Stott et al, 2006). Further detail about climate model projections and the use of individual models as scenarios of future climate change is given in Appendix B.

Due to the spatial resolution of the baseline and future climate data (i.e., the size of the data grid boxes relative to the area of the individual LHZs), it was not statistically meaningful to provide climatology data for individual LHZs. Instead, climatology data were grouped into three climate zones (A, B and C) that represent latitudinal bands to reflect the strong north-south gradient in annual rainfall across Sudan. Each of the three climate zones represents areas where the climate is relatively uniform within a zone, but distinctly different from the other two zones. The climate zones relate to groupings of the FEWS NET LHZs in Figure 3, and are mapped in Figure 4 and listed in Table A1. The climate zones are also defined in Box 1.



Couple in Darfur working their land .

Pastoralists with their livestock make their way across the country on a seasonal bases.

TABLE A1

Definition of climate zones A, B and C based on the FEWS NET livelihood zones (LHZs) in Figure 3[4].

Climate zone	FEWS NET LHZ code	FEWS NET LHZ name
A	SD03	Eastern Pastoral
	SD04	West and Central Pastoral
	SD05[5]	Eastern Khors Agropastoral
B	SD07	Eastern Agropastoral Sorghum
	SD09	Central Irrigated Schemes
	SD13	Western Agropastoral Millet
	SD14	Central Rainfed Millet and Sesame
	SD15	Jabel Marra Mixed Highland Cultivation
	SD16	Western Wadi Cultivation
	SD17	North Darfur Tobacco
	SD18	North Kordofan Gum Arabic Belt
C	SD10	Southeast Rainfed Semi-mechanized Agriculture
	SD11	Rainfed Sorghum Belt
	SD12	Western Agropastoral Millet and Groundnuts
	SD19	Cattle Dominant Agropastoral

4. Note that LHZs based on riverine systems (SD01 and SD02), flood retreat systems (SD06) and coastal fishing (SD08) are excluded from this analysis as the impacts of climate on these systems are complex due to their dependence on rivers and seas.

5. The Eastern Khors Agropastoral livelihood zone (SD05) is almost entirely included in climate zone A. However, this zone has been excluded from the climate data analysis as a small proportion of the zone exists in the northern desert regions which have been excluded from the analysis due to their lack of rainfall and inhabitants. Interpretations of the climate impact on the livelihood zone are included in the report based on the baseline climate and projected climate change in climate zone A.

A.2. Livelihoods and food security analysis methods

The assessment of the impact of climate change on food security in Sudan in this report was based on a review of the relevant literature, and expert interpretation. The analysis focuses on the agriculture-dependent livelihood zones (LHZs) (Figure 3; FEWS NET, 2011), and their relationship with the baseline climate conditions, thus their sensitivity to climate change. This provides a starting point to assess future climate impacts on food security under the three scenarios of projected climate change.

The baseline assessment of LHZ vulnerabilities follows the aggregation of the LHZs into the climate zones. The zones are aggregated according to their predominant livelihood strategies (i.e. pastoralism, agro-pastoralism, cropping).

For each climate zone, the baseline climate vulnerability and consequential food insecurity conditions are described, based on the FEWS NET LHZ Plus data (FEWS NET, 2011) and WFP food security assessments (WFP, 2010a; WFP, 2010b; WFP, 2011, WFP, 2012, WFP, 2013). These baselines are supplemented with more in-depth descriptions of their various building blocks, based upon a review of the secondary literature.

This identification of the sensitivity to climate of the various livelihood activities within each climate zone, together with the description of the current climate, is then used to indicate the climate-related pressure on each of these LHZ activities, and the consequent risk to food insecurity in the present day. This then sets the context for evaluating the effect of climate change on food insecurity risk.

Finally, the climate change projections provide scenarios of possible future climates that could be experienced by the 2040s. These scenarios of future climate change are interpreted to understand what different levels of projected climate change could mean for livelihoods and food insecurity in the future. This analysis considers how climate could exert pressures on specific systems as a result of their sensitivity to climate change, and the potential risk to food security in the future, relative to the experience of climate impacts in the present day.

A.3. Constraints and Limitations

There are three predominant livelihood strategies identified within Sudan: Pastoral; Agro-Pastoral; and Agriculture. The climate zones that were used for the climate analysis each represent distinctly different climates and, as such, naturally align with different livelihood strategies. As a result, the climate zones are the aggregation of similar LHZs (defined by FEWS NET), based on predominant livelihood strategies.

Within each of the climate zones (and thus, LHZs) the climate sensitive aspects are linked to potential pressures that have a bearing on the performance of specific crops and livestock. Thus, climate change will have a direct link to livelihood success and, consequently, food security.

This analysis has been carried out using LHZs as a scale over which impacts of climate change on food insecurity are assessed. However, there are a limited number of sources that have data aggregated in this way. In addition, food security in Sudan is greatly affected by conflict, with many areas classified as food insecure due to the presence of large numbers of internally displaced persons due to civil/resource-based conflict. As such, there are less data available to estimate the scale of food insecurity due to climate shocks for some populations.

A further limitation in our understanding of the specific meteorological characteristics of the region is the ability of the reanalysis and climate model data to accurately represent the climatology of the region. However, the limited observational record means that reanalysis offers the best source of information on the present day climate, by making use of the available observations. An added advantage is that it is compatible with the climate model data against which it is compared. Climate data is low resolution, both temporally and spatially and, while trends are well represented, specific weather events in individual locations and years are not. The climate data is a useful way of identifying the scale and direction of change; viewed in the context of the relationship between climate and food security in the present day, this information can help guide understanding of the scale of the challenge that climate change presents.

This report makes use of scenarios for future climate. These are not predictions, but are a sample of what is plausible across the range of modelled changes, that provide a useful basis for exploring what different levels of climate change might mean for future food security in Sudan.

Girl in one of the agro-pastoral livelihood zones of Sudan looks after her donkey.

Appendix B. Use of climate model projections

Climate models are a mathematical representation of the physical processes that govern the Earth's climate and are used to provide projections of climate change under different pathways of future greenhouse gas concentrations, known as Representative Concentration Pathways (RCPs; van Vuuren et al., 2011). However, there is no unique way of representing the key processes or solving the mathematical equations, meaning that there is inevitably some uncertainty in climate projections. It is, therefore, extremely important to quantify that uncertainty in order to provide context for climate projections. Indeed, many climate modelling groups around the world have developed their own climate models. Each model has strengths and weaknesses with some performing better than others in certain geographical regions (McSweeney et al. 2015). Notably, there is a phenomenon known as the 'East African Paradox' where climate models project increased rainfall in the near future for East Africa, but do not replicate the observed drying trend over the March-May season in their historical simulations (Rowell et al. 2015). Research is ongoing to determine whether this is related to model configuration (in which case there may be less confidence in the projected increased rainfall) or to the existence of a physically-plausible mechanism for a shift from a historical drying trend to a future wetting trend.

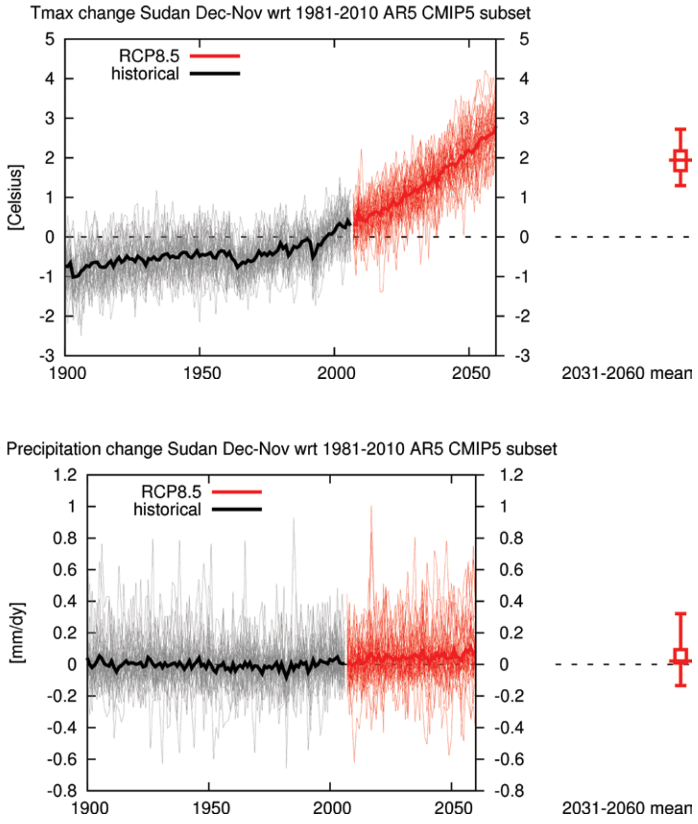
To be able to robustly compare outputs from different models, the models have to be run with the same experimental set up. This is achieved through the Coupled Model Intercomparison Project, now in its fifth phase (CMIP5; Taylor et al., 2012), which promotes a standard set of model simulations so that models can be compared and evaluated. Climate projections from around 40 CMIP5 models were used in the Inter-governmental Panel on Climate Change Fifth Assessment Report (IPCC AR5; IPCC, 2013; Niang et al., 2014), where the mean of the multi-model ensemble and spread across the models is used to communicate the projected change. One benefit of using many different models is that the spread of projections obtained provides a range of uncertainty for each variable of interest. For some variables, such as surface temperature, the projections from different models indicate a similar direction and magnitude of change. However, some other variables, such as rainfall for example, are more complex to model and the magnitude and direction of projected change may differ among different climate models.

For Sudan, there is high confidence that temperatures are projected to increase as all models in the CMIP5 ensemble show a projected increase in temperature, but there is uncertainty across the models as to the exact value of the increase. For example, by the 2040s (2031-2060), the multi-model mean of the projected increase in the average value of daily maximum temperature is around 2°C above the baseline period (1981-2010) under the RCP8.5 greenhouse gas concentration scenario, with a 5%-95% range of around 1.3°C – 2.7°C (Figure B1, top panel). In contrast, the projected changes in rainfall across the models span both small increases and small decreases. In this case, focusing only on the multi-model ensemble mean results in the differences in the projected direction of change cancelling each other out. This means that the multi-model mean shows almost no change compared to the baseline, but the spread across the model projections ranges from a decrease of 0.1mm/day to an increase of 0.3mm/day increase, (5%-95% range; Figure B1, bottom panel).

In addition to the multi-model mean acting to cancel out differences in projected changes, the multi-model mean also gives equal weight to all models, even those that are known to perform less well for certain geographic regions, such as Africa (McSweeney et al. 2015). A different way of presenting model projections is to take a scenario-based approach, where the outputs of individual models (selected based on criteria relevant to the task in hand) are considered as plausible scenarios of future change.

FIGURE B1

Time series of change in maximum temperature (top panel) and annual rainfall (measured in mm per day; bottom panel) relative to baseline period of 1981–2010 averaged over Sudan grid points. One line per CMIP5 model (thin lines; n=40) is shown plus the CMIP5 multi-model mean (thick line). The box-and-whisker plot on the right shows the percentiles with the box extending from 25% to 75%, the whiskers from 5% to 95%, and the 50% (median) denoted by the horizontal line



Source: KNMI Climate Change Atlas.

For this analysis, projections from three CMIP5 models were presented as three different scenarios of future climate change. These models represented equally plausible scenarios of future rainfall and temperature, and were chosen to reflect the range of potential future changes in climate in Sudan that are most relevant to livelihoods and food security. The models were selected based on:

- Resolution; high enough resolution was required so that a reasonable number of grid boxes were included in each of the climate zones defined in Section 2.1
- Performance in the region; performance in the Central and East Sahel region from Rowell et al., 2016 was considered,
- Spread of rainfall projections; the CMIP5 ensemble projects little change and the model spread spans zero (McSweeney et al., 2015). Models for this analysis were selected to represent the range of plausible projections of changes in rainfall; The first scenario represents a future where the total annual rainfall is increasing, whereas the other two scenarios both represent a future where the total annual rainfall is decreasing; one with no change to the annual pattern of rainfall, and the other with changes to the patterns of rainfall and temperature.

The models selected and used for this analysis were:

- Scenario 1 - CNRM-CM5
- Scenario 2 - HadGEM2-ES
- Scenario 3 - CSIRO-Mk3-6-0

As there is minimal difference in the climate projections between the future greenhouse gas concentration pathways by the 2040s, only one pathway is presented here (RCP8.5; van Vuuren et al., 2011).

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Woman crossing
a busy camp in Kosti.

December 2016

Food Security and Climate Change Assessment: Sudan

C-ADAPT Climate Resilience for Food Security: ANALYSES, INNOVATIONS & STANDARDS

The Climate Adaptation Management and Innovation Initiative (C-ADAPT) is an initiative funded by the Government of Sweden's fast-track climate finance that allows WFP and partners to explore innovative climate-induced food insecurity analyses, programmes and best practices, with the goal to help individuals, communities and governments meet their food and nutrition needs under a changing climate.

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