Climate risk report for the Sahel region

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Image location: Chad

Contents

Executive summary

This report highlights the headline risks to consider in any climate resilient development planning for the Sahel region. Key climate-related risks for the Sahel have been identified by considering climate change projections and climate hazards in the 2050s, and how these hazards may interact with dynamic underlying socio-economic vulnerabilities. The key interactions in this region were identified as being related to water resources, agriculture and pastoralism, aquaculture and fisheries, settlements and infrastructure, human health and mortality, and biodiversity and ecology.

The Sahel region examined in this report includes the Sahel G5: Mauritania, Mali, Burkina Faso, Niger and Chad. The region's climate is characterised by semi-arid tropical conditions. Conditions in the northern extents of the Sahel are similar to, but less extreme than, the Sahara Desert to the north. Conditions to the far south are tropical with similarities to the climate of inland West Africa.

Temperatures have increased at a rate of approximately 0.2 to 0.3 °C per decade between 1980 and 2015 in the Sahel, which is consistent with the global average. Rainfall over the Sahel is highly variable. After a protracted wet period in the middle of the twentieth century, rainfall declined dramatically in the 1970s and 1980s before recovering from the 1990s onwards, although it remains substantially lower than during the wet 1950s and 1960s.

For the Sahel region, where the climate is already harsh, climate change, even at relatively low levels, has the potential to exceed limits to adaptation in some regions during some periods of the year. Thermal stress is a considerable threat to the region, as combinations of heat and humidity exceeding the physiological limit for humans and livestock may be exceeded periodically, posing a threat to human survival, and at the very least causing considerable disruption to activities such as outdoor labour. There is high confidence in an increase in the number of days per year above 35°C, and high confidence in an increase in the number of days above 40°C, with the number of days above these thresholds exceeding 40 days per year by 2050, presenting a considerable risk to heat stress.

There is lower confidence around how rainfall in the region may change in the future and projections are quantitatively uncertain. However, summer precipitation associated with the West Africa Monsoon is projected to increase, especially over the central and eastern Sahel, while rainfall is projected to decrease in the far west of the Sahel, especially near the coast of Mauritania. Climate models also indicate an increase in rainfall variability from year to year as well as more erratic rainfall patterns throughout the year. Furthermore, the Sahel is projected to experience delayed rainfall onsets, influencing the timing and extent of the rainy season.

The Sahel is a dynamic region, experiencing large population growth, urbanisation and economic transformation. Climate projections and climate change impacts assessments can only ever provide a partial picture of the role climate change may play in shaping socio-economic and development outcomes.

Most of the risks identified in this report are not new in the Sahelian context (although extreme risks associated with the crossing of certain heat and humidity thresholds may be an exception). People, animals, agriculture, and the natural environment have already adapted over periods of decades to millennia to survive in the highly variable and uncertain Sahelian climate, and this process of adaptation continues today. Climate change is intensifying existing risks and will continue to do so for the foreseeable future. It may lead to the emergence of new risks, and to the limits of adaptation being reached or exceeded in some contexts. However, in most cases, the level of risk, and people's capacity to adapt to climate change and its impacts, will depend heavily on policy and related decisions that influence how individuals, communities and societies in the Sahel are able to respond, and who can access which resources.

Our analysis identifies the following key risks as the most critical across the Sahel. These risks are interdependent and will interact, with certain risks acting in concert to amplify or, in some instances, offset each other. This report is based on a regional level analysis, therefore, risks at the national level may vary and would require a more detailed country level analysis.

Risks to water resources

The G5 Sahel countries experience low overall levels of water stress, based on freshwater withdrawal as a proportion of available freshwater resources, but access to water varies widely across and within countries. Rapid urbanisation and displacement places significant stress on water resources and infrastructure in specific contexts and locations. Water availability also varies over time, both seasonally and on longer timescales, due to climatic variability and drought.

Climate change may combine with increased water demand due to population and economic growth to exacerbate existing water stress. Annual temperature increases and temperature extremes across the Sahel region could increase evaporative water losses and reduce surface runoff and groundwater recharge, presenting risks to water availability.

Higher temperatures will amplify increases in water demand through increased need for water for irrigation and the greater demand for water by crops in warmer conditions. Demand for water is also increasing as a result of agricultural expansion, mining, and increased household consumption driven by economic development, rapid urbanisation and a growing population. Even in areas where rainfall is projected to increase, higher temperatures may result in an overall decline in surface runoff and groundwater recharge, undermining water security. Projected increases in intense rainfall events and associated flooding pose risks to water infrastructure, supply systems and water quality, particularly in urban areas.

Sea level rise around the coast of Mauritania presents risks of saltwater intrusion into coastal aquifers, contaminating freshwater resources and increasing flood risks by inhibiting the infiltration of surface runoff.

Existing patterns of social marginalisation and inequality, for example related to gender, income, livelihood, and disability, will shape risks associated with changes in water availability and access, as well as other climate-related risks discussed below. Climate-related risks to water availability, demand, supply and quality in the Sahel region will also be mediated by transboundary water management dynamics, including forms of both conflict and cooperation.

Risks to agriculture and pastoralism

Agriculture and livestock are critical to livelihoods, food security and the economies of the Sahel G5 countries. Climate change may pose direct threats to agriculture via extreme temperatures, reduced water availability, increased rainfall, heavier rainfall that may damage crops and interrupt harvesting, and potential changes in the prevalence of pests and diseases.

More frequent and severe extreme temperatures will reduce soil moisture and groundwater recharge, increase the likelihood that tolerance thresholds will be exceeded for certain crops and livestock, and combine with increases in rainfall variability and the length of dry periods to increase drought severity and irrigation demand. A projected delayed onset to the wet season may result in shorter growing seasons. Projected increases in annual rainfall in the eastern and central Sahel may not translate into greater water availability due to greater evaporation and reduced surface runoff associated with higher temperatures, while small changes or declines in rainfall in the western Sahel will reduce soil moisture, increasing water stress and irrigation demand. Increased rainfall variability and extremes will increase risks of crop damage, soil erosion, and livestock mortality, particularly in more easterly regions. Rainfall deficits, amplified by higher temperatures, will increase periodic water stress and may result in reduced runoff, river flow and lake levels, adversely impacting rainfed and flood-recession agriculture.

Pastoralism is affected by declines in and changes in the availability, distribution and seasonal prevalence of pasture and water resources, and extreme heat that can affect animal health and productivity. The reduction of land available to pastoralists as a result of agricultural expansion is an on-going problem that may also be exacerbated by the changing climate. Changes in the timing of agricultural activities and seasonal resources have the potential to alter pastoralists' movements and increase the likelihood of competition and conflict between herders and farmers. While pastoralism represents a successful strategy for navigating high climatic and environmental variability and uncertainty, the vulnerability of pastoralists to climate variability and change has increased as a result of hostile policy environments, changes in land tenure, agricultural expansion, reduced access to water sources and pasture lands, and the disruption of transhumance routes by roads, urban development and industrial activity. These factors reduce their ability to deploy strategies based on mobility to manage increased climate variability and uncertainty.

Risks to aquaculture and fisheries

Fisheries represent an important socioeconomic activity and livelihood source across the Sahel region, centred on lakes, reservoirs and rivers, wetland and floodplain systems, and coastal fisheries in Mauritania. Inland fisheries have been affected by declines in lake levels, the general depletion of surface waters due to rising water demand, pollution from urban waste, agriculture and mining, and dam construction.

Freshwater fisheries are at risk from further reductions in water body extent that may be accelerated by climate change, reducing fish recruitment and survival. Increases in the intensity of rainfall extremes may pose threats in the form of pollution and increased sediment input from runoff extremes, affecting water quality and turbidity. Higher water temperatures reduce oxygen content and vertical mixing of the water column and can increase the susceptibility of fish to disease.

Increased evapotranspiration and temperatures of inland freshwater bodies, as well as increasing sea surface temperature, negatively affect fish health and stocks. Projected changes in rainfall patterns may increase flooding and runoff, with detrimental consequences downstream for lake and river fisheries. Anthropogenic factors, including agricultural and industrial water use, pollution, dam construction, and regulatory regimes, may interact with climate change to further increase risks to inland fisheries.

Marine fish stocks are vulnerable to a complex mixture of interacting climate change impacts, including higher ocean temperatures that tend to reduce both vertical mixing and oxygen content, ocean acidification that affects key species in marine food webs, and changes in ocean currents that result in shifts in ocean productivity. Projected sea level rise may present risks to coastal fisheries infrastructure, such as ports, harbours, launching and landing sites, and processing facilities. Changes to water sources and fish stocks may also constrain existing adaptive livelihood strategies, especially for poverty-affected individuals and households.

Risks to settlements and infrastructure

Countries in the Sahel have experienced a rapid growth in populations in recent decades, which has contributed to the rapid growth of urban centres, amplified by rural-urban migration. This increase in urban populations has resulted in pressure on infrastructure and services, with insufficient coverage of water and sanitation services and aging or insufficient water infrastructure, resulting in water pollution, contamination and the occurrence of waterborne diseases.

Continued population growth and rapid urbanisation will result in increasing pressure on services such as water, energy and health services, amplified by climate change. Higher temperatures will increase water demands for irrigation, livestock and domestic consumption in both rural and urban areas, and in some locations will be coupled with declines in rainfall. Climate change will mean increased demand for cooling and reduced electricity transmission capacity, as a result intensifying heat extremes that may increase the risk of power outages. Climate extremes will result in periodic disruption to a broad range of infrastructure services, particularly where infrastructure is already fragile and overstretched. This is most likely to be the case where urban populations are increasing rapidly.

Rainfall variability and potentially reduced river flow may pose risks to hydropower which is increasingly important in the Sahel. Increased flood risk and damage will combine with increasing demands on fragile and inadequate infrastructure to amplify risks associated with complex disasters in urban contexts.

Urban areas also experience sudden influxes of people displaced by drought, flooding, agricultural failure, while conflict and extreme heat also trigger population movements. Any additional rural-urban migration associated with the impacts of climate change on rural livelihoods would further increase the pressure on urban infrastructure. Shifts in the monsoon may result in the abandonment or growth of settlements, and in the further concentration of populations in urban areas, via displacement and migration to avoid risks or exploit new opportunities.

Risks to human health and mortality

Health and mortality outcomes have improved in the Sahel over the past two decades, as has access to water, while progress on sanitation has been slower. Climate change has the potential to slow or reverse health gains, via intensified risks associated with droughts, floods and heat extremes, and their impacts on water security, food security and heat-related mortality and morbidity. Health risks associated with climate change will be much greater for residents of informal settlements in the Sahel.

Extreme heat and humidity hazards could result in widespread mortality across the region alongside risks including dehydration, heat-stroke, reduced productivity, interaction with respiratory conditions, and impacts on health associated with reduced water quality. Extreme heat risks are greatest for the elderly, infants and individuals with health conditions. Heat extreme risks will be most acute for poverty-affected individuals and households with limited access to cooling technologies and most acute in populations in informal settlements. Outdoor labourers such as construction workers and farmers will be adversely impacted by heat risk. Outdoor labour during the hotter months may become impossible or at least limit the hours of outdoor work to early mornings, especially in the north.

Risks from extreme heat are compounded in urban centres by the Urban Heat Island (UHI) effect. This means rising temperatures will place particular pressure on urban infrastructure and expose urban populations to increased risk of heat stress. Temperature increases may be less pronounced in coastal areas, but higher humidity means heat stress will still be a risk here.

Another serious cause for concern is increased risks from dangerous combinations of heat and humidity. Wet-bulb temperatures approaching or above 35°C, considered the upper survivable limit for human beings, are projected to occur in parts of the eastern and western Sahel for a global warming of 1.5°C (2030s-2040s), and across much of the region for a warming of 2°C (2050s-2060s).

Flood events present risks to human health associated with death and injury, waterborne diseases (e.g. cholera), contamination of water supplies, and damage to medical infrastructure and disruption of medical services, as well as displacement, food insecurity and malnutrition, and psychological impacts. More intense rainfall may also contribute to increases in malaria prevalence in some locations.

Risks to biodiversity and ecology

Climate-related environmental changes and associated habitat changes may affect species behaviour, abundance and distribution, including migration, resulting in reduced biodiversity. Anthropogenic pressures including pollution, ecosystem fragmentation and destruction, and the disruption of migration routes will increase the vulnerability of species and ecosystems to climatic stresses.

Aquatic ecosystems (notably in the Inner Niger Delta and around Lake Chad), mountain ecosystems and protected areas are 'hotspots' of biodiversity in the Sahel region. These and other refugia (e.g. oases and temporary or permanent pools or *gueltas*) represent reservoirs of biodiversity from which plant and animal species recolonise the Sahel and Sahara during humid periods. Increases in extreme high temperatures, and seasonal temperatures outside the range of historical variations, may adversely affect plant and animal species through increases in heat stress and moisture deficits, reducing biodiversity and eroding the capacity for such recolonisation.

Coastal and marine ecosystems in Mauritania are at risk from a combination of sea-level rise, increased water temperatures, ocean acidification, and changes in water chemistry, circulation and oxygen content, combined with anthropogenic pressures associated with fishing, mineral extraction, urban development and coastal infrastructure.

Ecosystems are being made more vulnerable to these climate related stresses by local anthropogenic stresses related to land use, ecosystem fragmentation, and environmental pollution, as well as adaptation practices such as water infrastructure development and agricultural intensification alongside the potential expansion of other economic activities such as mining.

Headline climate statements for the Sahel	
Temperature	• The Sahel region is predominantly hot and dry throughout the year. • The current climate in the Sahel region is around 1˚C warmer than it was in pre-industrial times (1850-1900), with the rate of increase in recent decades consistent with the global average. • Climate change means that temperatures in the region are increasing, and by the 2050s the annual temperature will have increased by around 1.5-4 C, compared with the pre-industrial past. The exact amount of this warming depends on the level of global greenhouse gas emissions. (IPCC AR6 Atlas, 2021) • The intensity and frequency of hot extremes are projected to increase, with maximum temperatures increasing and exceeding key thresholds for longer periods in the year. Projections show high confidence in an increase in the number of days per year above 35°C and in the number of days above 40°C. The number of days above these thresholds could exceed 40 days per year by 2050. • Wet-bulb temperatures approaching or above 35°C, considered the upper survivable limit for human beings, are projected to occur in parts of the eastern and western Sahel for a global warming of 1.5°C (2030s-2040s), and across much of the region for a warming on 2°C (2050s-2060s).
Precipitation	• There is lower confidence around how rainfall in the region may change in the future and projections are quantitatively uncertain • Summer precipitation associated with the West Africa Monsoon is projected to increase, especially over the central and eastern Sahel • Rainfall is projected to decrease in the far west of the Sahel, especially near the coast of Mauritania. • Increase in rainfall variability from year to year as well as more erratic rainfall patterns throughout the year. • The onset of the rainy season is projected to be delayed, as the climate warms, which will affect both the timing and extent of the seasonal rains.
Oceans	• Sea level around the coast of Mauritania is projected to continue to rise by around 0.3 m between the 2000s and the 2050s. • Erosion and flooding of the coastal areas will be a major risk for coastal infrastructure. • Sea surface temperatures are projected to increase by 0.6-1.9˚C above pre-industrial levels by the 2050s. This warming will lead to increased deoxygenation and an increase in the frequency and intensity of marine heatwaves, with impacts for marine life and specifically fish stocks on which the coastal populations depend. • A warming ocean results in a projected decrease in the upwelling system of the Canary Current over the 21st century.

Headline risk statements for the Sahel	
Water resources	• Greater stress on water security will result from higher temperatures and temperature extremes both reducing water availability and increasing water demand. • Water infrastructure and water quality is at risk from flooding associated with heavy rainfall and sea level risk. Urban and coastal areas in Mauritania are of particular concern. • Large-scale climate adaptation responses and economic diversification (e.g., agricultural and mining expansion) may increase water demands and place additional pressure on water resources. • Existing patterns of social marginalisation and inequality, such as gender and income, will shape risks associated with changes in water availability and access. • Climate-related risks to water availability, demand, supply, and quality in the region will be mediated by transboundary water management dynamics, including both conflict and cooperation.
Agriculture and food security	• Increases in temperature extremes and in rainfall extremes (and associated flood risks) may increase risks of crop loss and damage, soil erosion, and livestock mortality. • Increases in rainfall variability and the length of dry periods will combine with increased evapotranspiration driven by higher temperatures to reduce soil moisture, surface waters (e.g., river flows, lake levels), and groundwater recharge, with adverse effects on growing seasons and crops (especially for widespread rainfed and flood-recession agriculture) and increasing water stress and irrigation demand. • The vulnerability of farmers and pastoralists to climate variability and change is intensified. • Adaptation strategies in response to climatic changes may have adverse environmental impacts.
Aquaculture and fisheries	• Temperature increases could reduce oxygen levels and increase evapotranspiration and temperatures of inland freshwater bodies as well as increasing sea surface temperature, negatively affecting fish stocks. • Increased rainfall variability and extremes may increase flooding and runoff in lake and river systems, with detrimental downstream consequences. • Projected sea level rise may present risks to coastal fisheries infrastructure, such as ports, harbours, launching and landing sites, and processing facilities. • Anthropogenic pressures such as agricultural and industrial water use, dam construction, and government regulations and restrictions may interact with climate change to further increase risks to fisheries and constrains existing adaptive livelihood strategies.

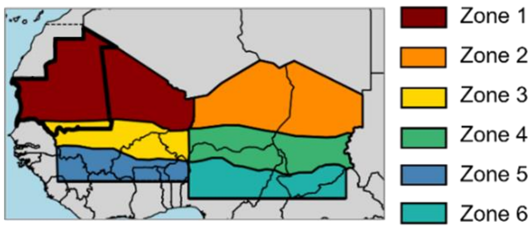
Settlements and infrastructure	• Higher temperatures, coupled in some locations with declines in rainfall, will likely combine with population growth and mobility and rapid urbanisation to create increasing demands for water, energy and health services. • Climate extremes may result in periodic disruption to infrastructure services, particularly where infrastructure is already fragile and overstretched, such as rapidly growing urban centres and informal settlements. • Increasing flooding presents risks including damage to housing, basic service, transport, power, communications, food, and water infrastructure, amplifying risks associated with complex disasters in urban contexts. • Changes in patterns of productivity, habitability and climate risks may drive longer-term changes in the regional distribution of populations and settlements.
Health and Mortality	• Increases in the intensity, frequency and duration of heat extremes, including wet-bulb temperatures, pose considerable threats to human health and life through dehydration, heat-stroke, interaction with respiratory conditions, and impacts on water quality. • Increases in precipitation and flood events present risks associated with death and injury, changing prevalence of communicable waterborne diseases, contamination of water supplies, and damage to medical services, as well as displacement, food insecurity, and psychological impacts. • The health and mortality impacts of climate-related changes will be especially great for already vulnerable populations, including the elderly, infants, people with existing health conditions, outdoor labourers, residents of informal urban settlements, and poverty-affected populations.
Biodiversity and ecology	• Changes in temperature and rainfall seasonality and extremes may adversely affect terrestrial, aquatic, and mountain biodiversity through changes in the health, survival, behaviour, abundance and distribution of plant and animal species, in combination with anthropogenic pressures (e.g., pollution, ecosystem fragmentation and destruction). • Increased water stress and reduced runoff associated with precipitation and temperature changes may have adverse impacts on wetland, lake, and delta ecosystems that act as regional ‘reservoirs’ of biodiversity. • Coastal and marine ecosystems in Mauritania face risks from a combination of increasing sea levels and changes in water temperatures, chemistry, circulation and oxygen content, combined with anthropogenic pressures associated with fishing, mineral extraction, urban development and coastal infrastructure. • Conservation and restoration programmes could have adverse effects on local livelihoods based on natural resources, in turn intensifying patterns of marginalisation and inequality.

Country summaries

Analysis is conducted at the regional level using six newly identified zones. These country summaries are intended to help direct reading towards the relevant sections within the report by country; they are not a complete assessment of the full range of risks at a country level.

Mauritania country profile

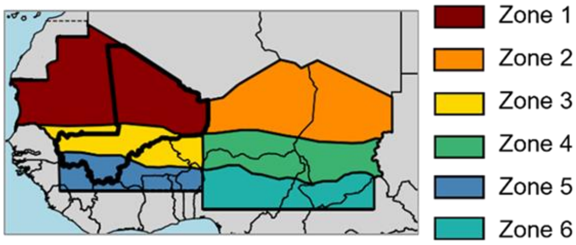
Mauritania is located in the northwest of the region and is included in zone 1, with the very southern extent in zone 3.



Summary of analysis relevant to Mauritania	Report section
Mauritania experiences an arid climate, with much of the country encompassing part of the Sahara Desert. Approximately 50% of the population live in and around urban centres. Livestock raising is the predominant livelihood, along with some agriculture. Southern Mauritania is characterised by mixed agropastoralism, and mobile pastoralism dominates in the north. In the Sahara region, an export ore and mining resource economy dominates. Coastal fisheries also represent an important industry, accounting for 35 – 50% of exports.	4.2, 4.3
The already high temperatures reaching daily averages of up to 35°C, are projected to continue to rise across Mali, increasing heat-related risks. Temperature increases and precipitation decline may have positive or negative impacts on different crops.	4.4, 4.5
Annual rainfall projections are uncertain but suggest an increase in annual rainfall. There is medium confidence in precipitation decrease the far west of the Sahel, especially on the coast of Mauritania, potentially exacerbating water stress for coastal settlements. Interannual rainfall variability and the timings of seasonal rains is projected to increase, which may exacerbate agricultural stresses. Projected increases in the frequency and intensity of heavy rainfall events raise flood risk and resulting agricultural losses and increase the spread of water-borne diseases. Projected decreases in soil moisture across the majority of Mauritania increase the potential for drought, with direct impacts on agricultural productivity, and higher temperatures and lower rainfall may increase irrigation demands, with agriculture accounting for ~90% of water withdrawals in Mauritania.	4.1, 4.2, 4.4, 4.5
There is high confidence in continued sea level rise around the Mauritania coast. This is likely to have detrimental impacts such as increased coastal flood risk and coastal erosion, which may cause damage to coastal infrastructure, and saltwater intrusion into coastal aquifers and contamination of freshwater resources.	4.4, 4.5, 4.6
Regional risks relevant to Mauritania	**Report section**
Expansion of water-intensive mining activities in response to global energy transitions and changes in agricultural livelihoods may increase water demands.	4.1
Heat stress is a key risk in urban environments such as including Nouakchott, Babade, Akjout, Atar, Chinquett and Oudane, with impacts greatest for outdoor workers.	4.5
Increased drought risk has direct impacts on agricultural productivity, and irrigation demands are likely to increase with higher temperatures and lower rainfall, with agriculture accounting for ~90% of water withdrawals in Mauritania.	4.2
Projected marine climate-related changes including increasing ocean temperature, acidification and deoxygenation, pose risks for coastal fisheries via impacts on marine species and for coastal and marine ecosystems and biodiversity.	4.3, 4.6

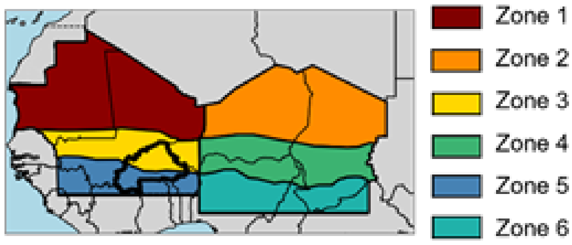
Mali country profile

Mali is landlocked and located mostly across the Saharan and Sahelian regions. It spans zones 1, 3 and 5.



Summary of analysis relevant to Mali	Report section
Mali experiences a hot and dry climate, with the country divided into the nomadic region of the Sahel and Sahara and the agricultural region of the Sudanic zone. The Niger River provides the main transport and trading route, and its periodic flooding supports fertile agricultural soil and livestock pastures. The population is centred largely along the Niger River and approximately three-fifths of the population is rural. Agriculture is the dominant economic sector in the country, accounting for nearly 40% of GDP and 60% of all employment. Central and eastern Mali is characterised by irrigated agriculture, and rainfed agriculture dominates in the south. South-central Mali is characterised by mixed agropastoralism, and mobile pastoralism dominates in arid northern regions. The Inland Niger Delta (IND) is an area of major importance to agricultural sectors. Inland fisheries in the IND system are an important livelihood source and the country is one of the largest producers of fish in western Africa.	2. 4.2, 4.3
Already high temperatures (reaching daily averages of up to 35°C) are projected to continue to rise across Mali, increasing the risk of heat-stress related health risks, particularly in urban environments in the south (including the capital city of Bamako), where the Urban Heat Island (UHI) effect may exacerbate these risks at night. In cities close to rivers and lakes, including Bamako, humidity is likely to be higher, increasing the likelihood of critical wet bulb temperatures during the hottest months.	4.4, 4.5
Annual rainfall projections suggest an increase in annual average rainfall across Mali. Seasonal rainfall change is more uncertain with little change in all seasons in the north of the country (zone 1); an increase or decrease across all seasons for central parts (zone 3); and a drying spring signal and wetting summer and winter signals for the south (zone 5). With increasing interannual variability in precipitation, inundation of floodplains of the IND may be less reliable. Intense rainfall events may exacerbate urban flooding, with settlements and infrastructure close to major rivers and lakes (such as Bamako) particularly vulnerable to flooding. Increases in the likelihood and extent of flooding will impact the runoff in river and lake catchments such as the IND. Projected decreases in soil moisture across the majority of Mali increase the potential for drought, with direct impacts on agricultural productivity and water demand, with agriculture accounting for 98% of water withdrawals in Mali.	4.1, 4.2, 4.4
Regional risks relevant to Mali	**Report section**
Risks to water resources include increased water withdrawals in the agricultural sector	4.1
Agricultural and pastoralist livelihoods are particularly vulnerable to water stress and decreases in soil moisture, especially for widespread rainfed agriculture in the south	4.2
Urban settlements and infrastructure, including in Bamako, are particularly vulnerable to intense rainfall events and flood risks	4.4
Heat-related health and mortality risks are particularly significant in urban environments and in cities close to water bodies where humidity is higher, such as Bamako	4.5

Burkina Faso country profile

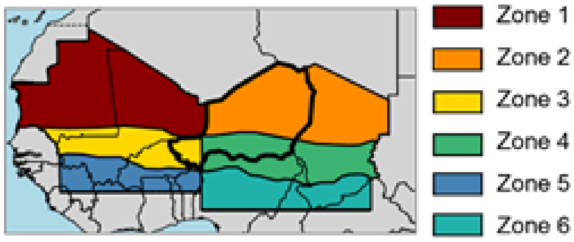


Burkina Faso is landlocked and spans two zones; zone 3 in the north and zone 5 in the south.

Summary of analysis relevant to Burkina Faso	**Report section**
Burkina Faso is characterised by savanna and the climate is generally sunny, hot and dry. Approximately 50% of the population are densely settled in the eastern and central regions. More than two-thirds of the population are rural and live within villages, which tend to be grouped towards the centre of the country. Rainfed agriculture dominates in most of Burkina Faso, though the highly variable nature of rainfall in the Sahel means that these livelihood regions are highly dynamic. The south of the country is characterised by mixed agriculture supported in places by small-scale irrigation. Livelihoods in the north are based primarily on agro-pastoralism.	4.2
The already high temperatures (reaching daily averages of up to 35°C) are projected to continue to rise in both the north and the south of Burkina Faso, increasing the risk of heat stress-related health risks, especially for the 60% of Burkina Faso's urban population living in informal settlements. Temperature increases have also already led to negative impacts on cereal production.	4.2, 4.5
Annual rainfall projections show an increase in average annual rainfall for both the north and south. Much of the projected increase in precipitation occurs in the wet season (June-September), although increases in the winter (October-February) season are indicated in southern Burkina Faso. Seasonal rainfall change projections are more uncertain, with individual model projections for northern Burkina Faso showing either an increase or decrease across all seasons. Projections for southern Burkina Faso are more consistent with a drying signal in spring, a small wetting signal in summer, and small wetting signal in winter. Projected precipitation changes suggest potential increases in groundwater recharge in the south of Burkina Faso, which could present new or expanded opportunities for agricultural production and livestock grazing, and in turn affect migration patterns. Projections indicate a decrease in soil moisture across the northern half of the country, increasing the potential for agricultural and ecological drought, with direct impacts on agricultural productivity and water demand, with agriculture accounting for about 50% of water withdrawals in Burkina Faso.	4.1, 4.2
Regional risks relevant to Burkina Faso	**Report section**
Expansion of water-intensive mining activities in response to global energy transitions and changes in agricultural livelihoods may increase water demands.	4.1
Climatic changes present risks to dominant rainfed agriculture	4.2
Heat stress is a particular concern for urban centres such as Ouagadougou, this combined with risks to water availability are most acute for the 60% of urban populations living in informal settlements.	4.4
Heat-related health and mortality risks are particularly significant in urban centres, especially informal settlements, and for vulnerable populations.	4.5

Niger country profile

Niger spans across zones 2, 3 and 4 in the north, southwest and southeast, respectively.

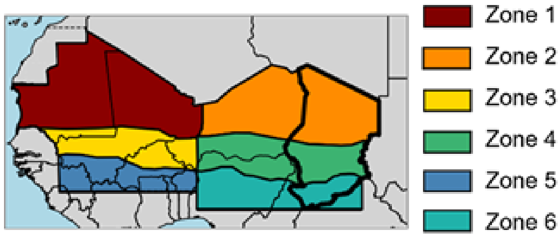


Summary of analysis relevant to Niger	**Report section**
The northern two-thirds of Niger lies in dry tropical desert, while the southern part of the country is characterised by Sahelian climate. About one-fifth of the population lives in towns. The rural population comprises nomadic and sedentary (largely agricultural) populations, as well as fishers around Lake Chad and the Niger River. Rainfed agriculture dominates in the southernmost regions of Niger and south-central Niger is characterised by mixed agropastoralism. Mobile pastoralism dominates in the north. Agriculture in the Niger Bend region is based on flood recession cultivation. Agriculture constitutes the largest sector of Niger's economy, accounting for nearly 40% of GDP and ~75% of all employment. The sector accounts for nearly 90% of water withdrawals in the country.	4.2
The already high temperatures (reaching daily averages of up to 33-35°C) are projected to continue to rise across Niger.	4.3, 4.4, 4.5
Projections of annual average precipitation change show little change in the north, an increase of up to 20% in the southwest and no clear consensus for the southeast. Projected change in seasonal precipitation is more uncertain. Projected rainfall change is significant in the southeast due to the impact on river flows and lake levels. Heavy rainfall events are projected to increase in frequency and intensity.	4.1, 4.2, 4.3, 4.4

Regional risks relevant to Niger	**Report section**
Expansion of water-intensive mining activities in response to global energy transitions and changes in agricultural livelihoods may increase water demands, with agriculture accounting for nearly 90% of water withdrawals.	4.2
Increases in the temperatures of freshwater bodies, particularly in shallow lakes such as Lake Chad, reduces oxygen levels and may increase evapotranspiration, in turn affecting fisheries.	4.3
Heat stress is particularly a risk in cities such as Niamey and Agadez, where the Urban Heat Island (UHI) effect could further exacerbate these at night.	4.5
Settlements and urban centers close to major rivers and lakes such as Niamey are particularly vulnerable to flooding and have been severely affected in recent years.	4.4
Projected rainfall change will affect water depth, quality, nutrients and extent and, in turn, agricultural and fishing livelihoods	4.3
An increase in extreme heavy rainfall events have implications for major river basins, such as Lake Chad, which may experience more frequent flooding and runoff, with detrimental impacts for downstream lake and river fisheries.	4.3

Chad country profile

Chad spans across zones 2, 4 and 6 in the north, centre and south, respectively.



Summary of analysis relevant to Chad	Report section
Chad's terrain is that of a shallow basin with a wide range of latitudes and climates that span from wet and dry tropical to hot arid. Although the fifth largest country in Africa, most of the northern part lies within the Sahara and population density is low (~ 8 persons per square km). Agriculture accounts for nearly 50% of Chad's GDP, and agricultural employment accounts for roughly 75% of all employment. Rainfed agriculture dominates in southern Chad, which is characterised by mixed agropastoralism. Mobile pastoralism dominates in northern arid regions. In the centre and south of the country, flood recession cultivation occurs around the Logone and Chari rivers. Lake Chad is highly significant due to the fisheries, agriculture, livestock production and other services it provides. Inland fisheries represent an important socioeconomic activity and livelihood source in the Lake Chad system.	4.2, 4.3
Already high temperatures experienced across Chad (reaching daily averages of up to 30 – 33 °C) are projected to increase. Rising temperatures will increase the risk of heat-stress related health risks, particularly at night. In cities close to rivers and lakes, such as N'Djamena, humidity is likely be higher, increasing the likelihood of critical wet bulb temperatures during the hottest months when evaporation is highest.	4.2, 4.3, 4.4, 4.5, 4.6
Chad receives very little rainfall in winter, with most falling between June and September. Projections of annual average precipitation change projections show little change for the north; no clear consensus for the centre and an increase of up to 20% in the south. Much of the projected increase occurs in the wet season (June-September), although increases in the winter (October-February) season are indicated in the south. Projected seasonal precipitation change is more uncertain. Heavy rainfall events are projected to increase in frequency and intensity, Extreme heavy rainfall events have implications for major river basins, such as Lake Chad, which may experience more frequent flooding and runoff, with detrimental impacts for downstream lake and river fisheries. Projected rainfall change in central Chad is significant due to the impact on river flows and lake levels, affecting water depth, quality, nutrients and extent and, in turn, agricultural and fishing livelihoods.	4.3, 4.4, 4.6
Regional risks relevant to Chad	**Report section**
Risks to water resources include impacts of rainfall changes on river flows and lake levels, and impacts of rising temperatures on groundwater	4.1
Higher temperatures and rainfall changes may affect the balance between groundwater influx and evapotranspiration presenting risks to widespread rainfed agriculture and oasis agriculture in Ounianga in the Ennedi region of Chad.	4.2
Rainfall changes present risks to river flows, lake levels and water conditions, and fishing livelihoods. Increasing temperatures of freshwater bodies, particularly in shallow lakes such as Lake Chad, also reduces oxygen levels and vertical mixing affecting fisheries as well as wider ecosystems and biodiversity.	4.3, 4.6
Urban centres, especially the nearly 90% of urban populations living in informal settlements, face risks from increased heat stress, changes in water availability and flooding	4.4
Settlements close to major rivers and lakes such as N'Djamena are particularly vulnerable to flooding	4.4
Heat stress risks are significant in N'Djamena and other urban areas where the Urban Heat Island (UHI) effect, and where humidity is higher close to rivers and lakes.	4.5
Major river systems such as the Lake Chad Basin, increasing variability and frequency of extreme events may cause biodiversity changes or loss and associated changes to ecosystem services.	4.6

Glossary

Acronyms

AR5	IPCC 5th Assessment Report
AR6	IPCC 6th Assessment Report
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CORDEX	CoOrdinated Regional climate modelling Downscaling EXperiment
ENSO	El Niño Southern Oscillation
FCDO	Foreign, Commonwealth & Development Office (UK Government)
GCM	Global Climate Model
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GMST	Global Mean Surface Temperature
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Inter-Tropical Convergence Zone
MHW	Marine Heat Waves
MJO	Madden-Julian Oscillation
NAO	North Atlantic Oscillation
ODI	Overseas Development Institute
pCO_2	Partial Pressure CO_2
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SLR	Sea Level Rise
SSA	Sub-Saharan Africa
SST	Sea Surface Temperature
SWI	Saltwater Intrusion
UHI	Urban Heat Island
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
WAM	West African Monsoon

Technical terms

These definitions have been taken from the IPCC reports from 2001, 2013, 2014, 2018, 2019, and 2021; the Met Office website (www.metoffice.gov.uk/weather/learn-about; https://www.metoffice.gov.uk/hadobs/monitoring/climate_modes.html); Wikipedia, the World Atlas (https://www.worldatlas.com); Dixon et al (2020)'s "Africa through the farming system lens: Context and Approach" (see Appendix C for more details); and the Cambridge dictionary (https://dictionary.cambridge.org/).

Term	Definition
Adaptation	In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.
Aerosols	A suspension of airborne solid or liquid particles, with a typical size between a few nanometres and 10 μm that reside in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in several ways: through both interactions that scatter and/or absorb radiation and through interactions with cloud microphysics and other cloud properties, or upon deposition on snow- or ice-covered surfaces thereby altering their albedo and contributing to climate feedback.
Agropastoral [livelihood]	Mixed crop-livestock farming found in semi-arid (medium rainfall) areas of Africa, typically with low access to services. It includes the dryland mixed farming system of North Africa, often depending on wheat, barley and sheep. In SSA the main food crops are sorghum and millet, and livestock are cattle, sheep and goats. In both cases, livelihoods include pulses, sesame, poultry and off-farm work.
Anomaly	The deviation of a variable from its value averaged over a reference period.
Anthropogenic	Resulting from or produced by human activities.
Arid pastoral and oasis [livelihood]	Extensive pastoralism and scattered oasis farming associated with sparsely settled arid zones across Africa, generally with very poor access to services. Livelihoods include date palms, cattle, small ruminants and off-farm work, irrigated crops and vegetables.
Atlantic Multidecadal Oscillation/Variation (AMO/AMV)	The Atlantic Multidecadal Oscillation/Variation (AMO/AMV) has two phases, a positive phase where sea-surface waters in the North Atlantic are warmer than average and a negative phase when they are colder than average. There are a number of ways of calculating an AMO "index" which depend on the way that the longer-term trend seen in the observed record is dealt with. It is not entirely clear what causes changes in the AMO. Long records of the AMO from non-instrumental sources suggest that it is a long-lived natural fluctuation generated spontaneously within the ocean-atmosphere system. However, there is also evidence that switches in phase can be driven by changes in the output of manmade pollution. The different

	phases of the AMO have been associated with a variety of impacts. The positive phase has been associated with reduced Arctic sea ice, melting of the Greenland ice sheet, increased hurricane activity in the North Atlantic and increased rainfall over the Sahel region of sub-Saharan Africa. The cold negative phase has the opposite impacts: cooling at high latitudes, reduced hurricane activity and a drier Sahel.
Atmosphere	The gaseous envelope surrounding the earth, divided into five layers – the *troposphere* which contains half of the Earth's atmosphere, the *stratosphere*, the mesosphere, the thermosphere, and the exosphere, which is the outer limit of the atmosphere.
Baseflow	The portion of the streamflow that is sustained between precipitation events, fed to streams by delayed pathways. Also called drought flow, groundwater recession flow, low flow, low-water flow, low-water discharge and sustained or fair-weather runoff.
Baseline	The state against which change is measured. It might be a 'current baseline,' in which case it represents observable, present-day conditions. It might also be a 'future baseline,' which is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.
Baseline Water Stress	The ratio of total water withdrawals to available renewable water supplies. Water withdrawals include domestic, industrial, irrigation and livestock consumptive and non-consumptive uses. Available renewable water supplies include surface and groundwater supplies and considers the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more competition among users.
Biodiversity	The part of the Earth System comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.
Carbon Dioxide (CO_2)	A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance.
Catchment	An area that collects and drains precipitation.
Climate	In a narrow sense, climate is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization.

Climate Change	A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.
Climate Feedback	An interaction in which a perturbation in one climate quantity causes a change in a second and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced.
Climate Impacts	Impacts describe the consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability.
Climate Indicator	Measures of the climate system including large-scale variables and climate proxies.
Climate Mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
Climate Model	A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for some of its known properties.
Climate Projection	The simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases (GHG) and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.
Climate Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence.
Climate System	The highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere and the interactions between them.
Climate Variability	Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate at all spatial and temporal scales beyond that of individual weather events.

Confidence	The robustness of a finding based on the type, amount, quality and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement across multiple lines of evidence.
Crop Water Deficit	A water deficit occurs whenever water loss exceeds absorption. The use of total water potential as the best single indicator of plant water status has its limitations while attempting to understand the effect of water deficits on the various physiological processes involved in plant growth. Water deficits reduce photosynthesis by closing stomata, decreasing the efficiency of the carbon fixation process, suppressing leaf formation and expansion, and inducing shedding of leaves.
Disaster	A 'serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts' (UNGA, 2016).
Downscaling	A method that derives local- to regional-scale (up to 100 km) information from larger-scale models or data analyses.
El Niño Southern Oscillation (ENSO)	The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere–ocean phenomenon, with preferred time scales of two to about seven years, is known as the El Niño-Southern Oscillation (ENSO). The cold phase of ENSO is called La Niña.
Emissions Scenario	A plausible representation of the future development of emissions of substances that are radiatively active (e.g., greenhouse gases (GHGs), aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change, energy and land use) and their key relationships.
Enhanced Greenhouse Effect	The process in which human activities have added additional greenhouse gases into the atmosphere, this has resulted in a 'stronger' greenhouse gas effect as there are more gases available to trap outgoing radiation.
Evaporation	The physical process by which a liquid (e.g., water) becomes a gas (e.g., water vapour).
Evapotranspiration	The process in which water moves from the earth to the air from evaporation (= water changing to a gas) and from transpiration (= water lost from plants).
Exposure	Exposure describes the presence of people; livelihoods; species or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Extreme/heavy precipitation event	An extreme/heavy precipitation event is an event that is of very high magnitude with a very rare occurrence at a particular place. Types of extreme precipitation may vary depending on its duration, hourly, daily or multi-days (e.g., 5 days), though all of them qualitatively represent high magnitude. The intensity of such events may be defined with block maxima approach such as annual maxima or with peak over threshold approach, such as rainfall above 95th or 99th percentile at a particular space.
Fifth Assessment Report (AR5)	The latest series of IPCC reports published in 2013-2014, reports are divided into publications by three working groups.
Fossil Fuels	Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.
Global Breadbasket	The term "breadbasket" is used to refer to an area with highly arable land. The breadbaskets of the world are the regions in the world that produce food, particularly grains to feed their people as well as for export to other places.
Global Warming	The estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centred on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.
Greenhouse Effect	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect.
Greenhouse Gas (GHG) Concentrations	Lead to an increased infrared opacity of the atmosphere and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing that leads to an enhancement of the greenhouse effect, the so-called enhanced greenhouse effect.
Greenhouse Gases (GHGs)	The gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). [IPCC, 2018]
Hazard	The potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.

Heat Stress	A range of conditions in, e.g., terrestrial or aquatic organisms when the body absorbs excess heat during overexposure to high air or water temperatures or thermal radiation. In aquatic water breathing animals, hypoxia and acidification can exacerbate vulnerability to heat. Heat stress in mammals (including humans) and birds, both in air, is exacerbated by a detrimental combination of ambient heat, high humidity and low wind-speeds, causing regulation of body temperature to fail.
Heatwave	A period of abnormally hot weather often defined with reference to a relative temperature threshold, lasting from two days to months. Heatwaves and warm spells have various and, in some cases, overlapping definitions.
Ice sheet	An ice body originating on land that covers an area of continental size, generally defined as covering >50,000km^2, and that has formed over thousands of years through accumulation and compaction of snow. [IPCC, 2019]
Impacts	Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system.
Intergovernmental Panel on Climate Change (IPCC)	The leading international body for the assessment of climate change. Scientists come together approximately every six years, to assess peer-reviewed research in working groups to generate three reports including the Physical Science Basis, impact adaptation and vulnerability, and Mitigation of Climate Change.
Intertropical Convergence Zone (ITCZ)	The Intertropical Convergence Zone (ITCZ) is a band of low pressure around the Earth which generally lies near to the equator. The trade winds of the northern and southern hemispheres come together here, which leads to the development of frequent thunderstorms and heavy rain.
Marine heatwave	A period during which water temperature is abnormally warm for the time of the year relative to historical temperatures with that extreme warmth persisting for days to months. The phenomenon can manifest in any place in the ocean and at scales of up to thousands of kilometres.
Mitigation	A human intervention to reduce the sources or enhance the sinks of greenhouse gases.
North Atlantic Oscillation (NAO)	The North Atlantic Oscillation (NAO) is a large-scale atmospheric process that governs local weather patterns as it influences the intensity and location of the North Atlantic jet stream. It is defined as the pressure difference between the Azores islands and Iceland: a positive (negative) NAO is associated with higher (lower) than average pressure difference.
Ocean acidification	A reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide (CO_2) from the atmosphere, but can also be 38 caused by other chemical additions

	or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity.
Overharvested	Refers to harvesting a renewable resource to the point of diminishing returns.
Paris Agreement	The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties (COP) to the UNFCCC. The agreement, adopted by 196 Parties to the UNFCCC, entered into force on 4 November 2016 and as of May 2018 had 195 Signatories and was ratified by 177 Parties. One of the goals of the Paris Agreement is 'Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels', recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the Agreement aims to strengthen the ability of countries to deal with the impacts of climate change.
Projection/projected	A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socio-economic and technological developments that may or may not be realised.
Radiative Forcing	The change in the net, downward minus upward, radiative flux (expressed in W m-2) at the tropopause or top of atmosphere due to a change in a driver of climate change, such as a change in the concentration of carbon dioxide (CO_2) or the output of the sun.
Reanalysis	Atmospheric and oceanic analyses of temperature, wind, current and other meteorological and oceanographic quantities, created by processing past meteorological and oceanographic data using fixed state-of-the-art weather forecasting models and data assimilation techniques.
Representative Concentration Pathways (RCPs)	Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover.
Resilience	The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.
Resolution	In climate models, this term refers to the physical distance (metres or degrees) between each point on the grid used to compute the equations. Temporal resolution refers to the time step or time elapsed between each model computation of the equations.

Risk	The potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazard.
Runoff	The flow of water over the surface or through the subsurface, which typically originates from the part of liquid precipitation and/or snow/ice melt that does not evaporate or refreeze and is not transpired.
Scenario	A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts but are used to provide a view of the implications of developments and actions.
Signal	Climate signals are long-term trends and projections that carry the fingerprint of climate change.
Sixth Assessment Report (AR6)	The latest series of IPCC reports published in 2021-2022, reports are divided into publications by three working groups. At the time of writing this report only the Working Group I contribution to the Sixth Assessment Report published in 2021 was available to use.
Soil moisture	Water stored in the soil in liquid or frozen form. Root-zone soil moisture is of most relevance for plant activity.
Special Report on Emissions Scenarios (SRES)	A report by the Intergovernmental Panel on Climate Change (IPCC) that was published in 2000. The SRES scenarios, as they are often called, were used in the IPCC Third Assessment Report (TAR), published in 2001, and in the IPCC Fourth Assessment Report (AR4), published in 2007.
Storm surge	The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place. [IPCC, 2019]
Stream Flow	Water flow within a river channel, for example, expressed in m^3s^{-1} 25 . A synonym for river discharge.
Teleconnection	Association between climate variables at widely separated, geographically fixed locations related to each other through physical processes and oceanic and/or atmospheric dynamical pathways. Teleconnections can be caused by several climate phenomena, such as Rossby wave-trains, mid-latitude jet and storm track displacements, fluctuations of the Atlantic Meridional Overturning Circulation, fluctuations of the Walker circulation, etc. They can be initiated by modes of climate variability thus providing the development of remote climate anomalies at various temporal lags.

Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. In climate change analysis, it may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour.
United Nations Framework Convention on Climate Change (UNFCCC)	The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in May 1992 and opened for signature at the 1992 Earth Summit in Rio de Janeiro. It entered into force in March 1994 and as of May 2018 had 197 Parties (196 States and the European Union). The Convention's ultimate objective is the 'stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.' The provisions of the Convention are pursued and implemented by two treaties: the *Kyoto Protocol* and the *Paris Agreement*. [IPCC, 2018]
Urban Heat Island	The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, effects on heat retention, and changes in surface albedo.
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm, and lack of capacity to cope and adapt.
Weather	The conditions in the air above the earth such as wind, rain, or temperature, especially at a particular time over a particular area.

Image location: Niamey, Niger

1 Introduction

1.1 Purpose of this report

This report provides an evidence base on the Sahel region's current climate and its variability and looks at how this is expected to change by the 2050s. It also identifies how these changes could impact socio-economic development within individual countries. The aim is to inform and support development programming and policy dialogue in each country. This report is part of a series of Climate Risk Reports for the UK Government's Foreign, Commonwealth & Development Office (FCDO).

This report takes a methodological approach for translating and communicating climate information, applying it to socio-economic contexts that development planners need to consider[1]. It combines the Met Office's climate science expertise with socio-economic analysis of the Sahel region provided by Overseas Development Institute (ODI). FCDO regional representatives have also provided input to ensure it is both usable and relevant. Collaborating in this way has allowed us to tailor and frame future climate projections so that they are easier to include in development planning. See appendix for more information about the key stages in this methodology.

Key aspects of the region also included in the analysis, such as geography, major river basins and population densities, are also shown in Figure 1 (b, c and d).

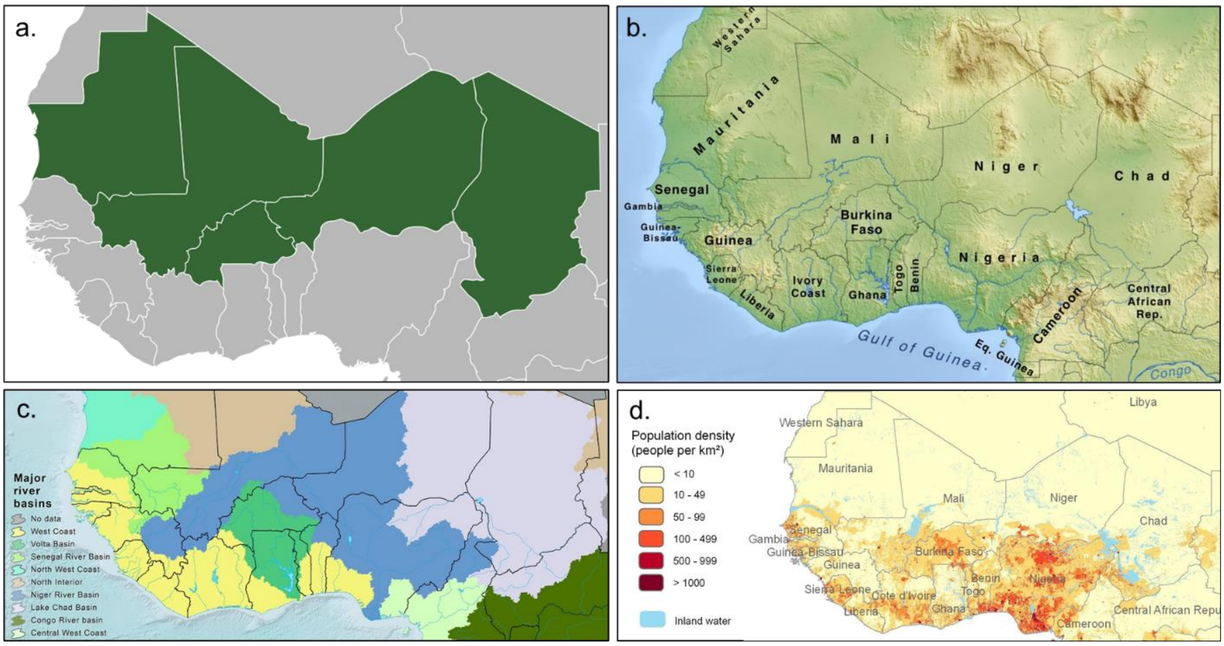


Figure 1: The Sahel region considered in this report. a. countries included in the analysis, b.: geography of the region (elevation and major rivers), c. major river basins d. population density.

[1] A report documenting the Met Office Climate in Context methodology is in preparation and due to be published in 2021.

1.2 Methodological approach

1.2.1 Methods and data

The socio-economic contributions to this report draw on a review of the relevant literature and key informant interviews with climate and agronomy experts within the Sahel region. Outputs from these analyses informed the identification of appropriate livelihood groupings and key socio-economic variables, as well as suitable climate indicators to support the climate data analysis.

This report draws on bespoke climate data analysis in the selected zones (see Section 3.2 and relevant scientific literature). This involved processing gridded reanalysis[2] data to characterise the current climate over the 1981-2010 baseline period, and climate model projections to assess the projected trends in average temperature and precipitation for the 2050s (using 2041-2070 future time period compared to the baseline period). The analysis focuses on quantifying projected changes in annual, seasonal and monthly means in the spatial analysis zones. We drew information on the projected changes in other climate variables and indicators – such as Sea Surface Temperature (SSTs), Sea Level Rise (SLR) and relevant climate extremes – from relevant scientific literature, noting where baseline and future time periods differ from the bespoke analysis.

To characterise the baseline climate, we processed temperature from WFDEI[3] (Weedon et al., 2014) and precipitation data from CHIRPS3 above[3] (Funk et al., 2015) over the 1981-2010 baseline period. Using this dataset and time period keeps this report consistent with FCDO climatology briefing notes provided to FCDO offices for the countries in the Sahel region.

We used global and regional climate model simulations to assess the projected change in temperature and precipitation for the 2050s under the RCP8.5 (van Vuuren et al., 2011) and SSP585 (O'Neill et al., 2016) scenarios[4]. This future time period and scenario combination represents an increase in global average temperature of around 2.5˚C compared to pre-

[2] A gridded dataset that blends climate observations and model data to present the current climate for use as a baseline in future climate assessments.

[3] All observational and reanalysis datasets have associated uncertainties and limitations. For example, reanalysis datasets may underestimate observed extremes, and cannot fully represent localised features such as intense precipitation caused by complex topography, partly due to their limited resolution in space and time. Additionally, ERA5 precipitation fields are derived from 'forecast' output and are therefore more affected by imperfections within the underlying model. The benefit, however, of using reanalyses is that they provide a systematic approach to producing gridded, dynamically consistent datasets for climate monitoring, particularly over data-scarce regions. However, the use of these data to characterise climatological means for the purpose of this analysis is largely uninfluenced by these biases, and the benefits of using a dataset that is globally consistent and consistent with other climate information products outweighs this.

[4] The RCP8.5 Representative Concentration Pathway (van Vuuren et al., 2011) represents a future pathway of on-going and substantial increases in future global emissions of greenhouse gases. Other pathways represent stabilisation or reduction of future emissions, however there is little difference in the projected climate change between these pathways in the 2050s time period. Analysis of the RCP4.5 scenario was also conducted, and results were broadly consistent with those presented here for RCP8.5. Note that RCP8.5 refers to CMIP5 model projections - the CMIP6 equivalent is SSP585 (O'Neill et al., 2016).

industrial levels. This is higher than the goal of limiting warming to well below 2˚C set by the United Nations Framework Convention on Climate Change Paris Agreement[5].

The baseline period considered in this report represents an observed increase of around 1 °C in global average temperature.

We used the following model simulations in this analysis:

- 30 Global Climate Model (GCM) simulations from the World Climate Research Project (WCRP) Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012), used to inform the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (IPCC AR5, 2014). The resolution of these models varies by model, ranging from 100-300km.
- 20 GCM simulations from the WCRP CMIP Phase 6 (CMIP6; Eyring et al., 2016) used to inform the most recent IPCC Assessment Report (AR6; IPCC, 2021). The resolution of these models is around 70km, though this varies between models.
- 20 Regional Climate Model (RCM) simulations from the WCRP CoOrdinated Regional climate modelling Downscaling EXperiment (CORDEX; Giorgi and Gutowski, 2015). These are downscaled CMIP5 simulations over the CORDEX Africa domain (AFR-44) at a resolution of 50km.

See appendices for more details on the specific model simulations included.

1.3 How to use this report

This report presents climate information in the context of the socio-economic challenges of the Sahel region, framed in terms of the key climate risks. The aim is to help development planners focus in on areas that may need attention and to identify the questions they need to ask when considering climate risks in their development plans. This report does not include every climate risk, rather it brings the Sahel's most prominent regional climate risks to the fore. Note that climate risks are not isolated threats: how they interact with, and compound other sources of risk can be hard to disentangle. The climate analysis and subsequent discussion outline the needs of a development pathway between the present day and the 2050s, so they have been designed to highlight the key risks to consider in future development plans. The country summaries provided in the executive summary outline prominent climate risks for each country within the regional context. However, these summaries do not provide a national level analysis; additional climate risks may apply at a national scale, and these should also be considered in a national or subnational development plan. This report offers a starting point for better understanding some of the key regional risks relevant to development programming within FCDO. For individual programmes where relevant risks are identified, or where national or sub-national scale risk information is required, additional climate and socio-economic analysis is recommended.

Section 2 sets the scene with an overview of the current vulnerability and climate resilience in the Sahel region. The current climate already includes large areas where some aspects of human and ecological systems area already at their limits, or are not well adapted to the harsh

[5] https://unfccc.int/

environment they are in. This section justifies the need for an intersectional approach when it comes to interpreting compound risks associated with, or exacerbated by, climate change.

Section 3 focuses on the current climate and future climate projections for the Sahel region and takes a geographical approach. It includes a summary of the region's climate and explains how the region is divided into six bespoke spatial analysis zones. The remainder of this section is organised by spatial analysis zone. In each zone the baseline climate is presented in context with the socio-economic situation of the zone, followed by the future projections and how they apply to zone-specific future climate risks. There is also a look-up table that relates countries to specific zones (see Table 1).

Section 4 presents the interpretation of the climate projections in terms of climate risk factors. It is structured by six key development themes: water resources, agriculture and pastoralism, aquaculture and fisheries, settlements and infrastructure, human health and mortality, and biodiversity and ecology. Each development theme features an overview of the relevant socio-economic trends and a summary of the relevant climate projections from Section 3. This is followed by a discussion on the implications and potential compound risks involved for each of the prominent climate risks we've identified.

Image location: Niamey, Niger

2 Vulnerability and climate resilience in the Sahel region: an intersectional approach

The five countries considered in this report –Mauritania, Mali, Burkina Faso, Niger and Chad – are collectively known as the 'G5 Sahel', following the establishment of the G5 regional cooperation framework in 2014 for the coordination of regional approaches to security, governance, economic development, and infrastructure.

There are multiple and closely interconnected socio-economic and political conditions in the Sahel region that are associated with risks and vulnerabilities in their own right, including political and security crises, demographic changes such as urbanisation, ecological and agricultural changes, food insecurity, and energy challenges. The risks, vulnerabilities, and outcomes associated with these factors may be exacerbated by climate variability and change. Countries in the region have been shaped by post-independence political crises, including multiple coups in all five countries. Over the past decade, violent conflict in the region has intensified and garnered increasing international attention, notably with the emergence and expansion of armed groups affiliated with Al-Qaeda and later the Islamic State, from northern Mali into Burkina Faso and Niger, and from northern Nigeria into Chad and Niger. Border regions, including the Liptako-Gourma region between Burkina Faso, Mali and Niger, and the Lake Chad region between Niger and Chad, have been centres of violent conflict (ICG, 2021; Nsaibia and Duhamel, 2021; OECD/SWAC, 2014, 2020b). Military responses, including national military operations, regional responses by the G5 Sahel Joint Force and the Multinational Joint Task Force in the Lake Chad Basin, and international operations including the UN Multidimensional Integrated Stabilization Mission in Mali and France's Opération Barkhane, have also contributed to socio-economic disruptions in the region (Adam and Moderan, 2021; ICG, 2021).

Focus Box 1: Exposure, vulnerability and development

A climate or disaster hazard does not in itself create risk. Risk is a function of both an individual's or community's exposure and vulnerability to a hazard (Figure 2, IPCC, 2014). Exposure and vulnerability are separate, yet both emerge from socio-economic contexts and are exacerbated by uneven development dynamics such as: rapid urbanisation and demographic change, environmental degradation, weak governance, and lack of economic opportunity (Figure 2, IPCC, 2014). Climate vulnerability and poverty are often mutually reinforcing; a growing body of evidence highlights the role of climate risk in persistent poverty and poverty traps (Hansen et al, 2019; Sachs et al., 2004). This is a challenge exacerbated by the political marginalisation of many poor and climate vulnerable people (Wisner et al., 2003).

Climate change is interwoven with development challenges and across the Sustainable Development Goals. As factors such as economic inequality, education, gender, nutrition, and health, shape the risk profile of individuals and communities, supporting sustainable development indirectly supports their capacity for managing climate risk (Wisner et al., 2003; Schipper and Pelling, 2006).

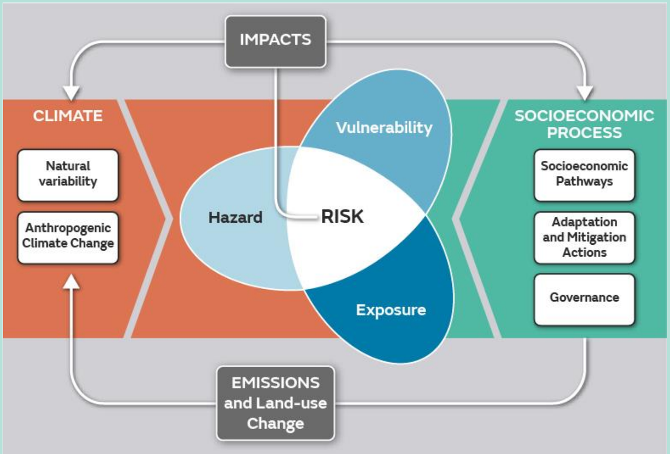


Figure 2: Climate risk is the product of the hazard, vulnerability to the hazard and exposure to the hazard. Image adapted from IPCC (2014).

Patterns of political marginalisation and exclusion, weakened governance systems, and economic inequality and instability, have contributed to conflict dynamics in the Sahel region (ICG, 2020; Kwasi et al., 2019). Nearly 2.5 million people have been internally displaced in the five countries (with over 50% located in Burkina Faso) and over 900,000 people are refugees within the region (with over 50% located in Chad) (UNHCR, 2021). An estimated 6.5 million people are experiencing food insecurity and 13.4 million people are in need of humanitarian assistance in Burkina Faso, Mali, and Niger alone (WFP, 2021). 33 million people in the region (over 40% of the population) live in extreme poverty (Kwasi et al., 2019).

Adaptation responses to environmental and climatic changes in the region have long existed and include changes in mobility by pastoralists, agricultural and livestock diversification, agroecological innovations, income diversification, and water harnessing (Epule et al., 2017; FEWS NET, 2017; Magrath, 2020). Although political and economic instability may hinder the large-scale adoption of adaptive responses to climatic variability and change, these existing and long-standing strategies point to the potential for future adaptations and resilience to climate-related changes among populations in the Sahel region.

Water resources

Levels of access to drinking water vary widely across countries in the region, with 51% of Chad's population having access to safe drinking water in 2018 compared to 82% in Burkina Faso. The agricultural sector accounts for the largest proportion of water withdrawals in most G5 countries: 98% in Mali, 91% in Mauritania, 88% in Niger, 76% in Chad, and 51% in Burkina Faso (FAO AQUASTAT, 2021).

The Sahel region has experienced large-scale environmental change since the severe droughts in the 1970s and 1980s, which had profound effects on agricultural and pastoral production systems (ICG, 2020). However, existing evidence on contemporary environmental change in the Sahel, including its 'greening' and patterns of drought and 'desertification' (see Focus Box 6 on desertification) is mixed (Rasmussen et al., 2016). Environmental changes in the region, such as changes in vegetation patterns or flood patterns, have been associated with both climatic variability *and* changes in land use (Aich et al., 2015; Leroux et al., 2017). In particular, land-use changes have had more localised impacts, while climate variability and change have had regional impacts, including the droughts of the 1970s-80s.

Water resources in the Sahel are shared across national boundaries. Transboundary water resources are associated with four main river basins (the Senegal River Basin, the Niger Basin, the Volta Basin, and the Lake Chad Basin) and five main transboundary aquifer systems (the Iullemeden Aquifer, Liptako-Gourma-Upper Volta, Senegalo-Mauritanian, Taoudeni Basin, and Lake Chad systems). Water resources within and between countries (including patterns of water abstraction and seasonal flooding) have been affected by the construction of dams along rivers in the region, including large dams along the Niger River for irrigation and hydroelectric power (Liersch et al., 2019; Morand et al., 2012).

Agriculture and pastoralism

In 2020, agriculture (including forestry and fishing) accounted for roughly 20% of Burkina Faso and Mauritania's GDP, nearly 40% of Mali and Niger's GDP, and nearly 50% of Chad's GDP (World Bank, 2021). Rates of agricultural employment as a proportion of total (paid or profit-making) employment in the region ranged from roughly 30% in Burkina Faso and Mauritania, to 60% in Mali and approximately 75% in Chad and Niger in 2019, with employment in the agricultural sector higher among men than women in most countries (World Bank, 2021). The livestock sector is an important component of the agricultural sector, accounting for an average of 40% of agricultural GDP in Sahelian countries (Leonhardt, 2019). In Burkina Faso, cattle production accounts for roughly 40% of total agricultural added value and 26% of agricultural export value (Zoma-Traoré et al., 2020), while in Mali, livestock herding accounts for about 10% of the country's GDP and 44% of agricultural GDP (Leonhardt, 2019; Marega and Mering, 2018). Livestock numbers in the region have increased substantially in recent decades due to the commercialisation and expansion of the livestock sector (Marega and Mering, 2018), with many farmers as well as urban residents investing revenues in livestock (Hiernaux et al., 2014). The livestock trade is oriented around cross-border trade, often between G5 countries and neighbouring West African countries (de Haan, 2016; Simonet and Carabine, 2021; Valerio, 2020).

Changing modes of production, including agricultural expansion and increasing commercialisation, have profoundly affected farming and herding livelihoods through changes in land use, access, and control, disruption of resource governance systems (FAO, 2018; ICG, 2020). Since the colonial era, economic development in the Sahel region has been heavily founded on the commercialisation of agriculture, and the expansion of agriculture into areas viewed as 'under-utilised' (van Keulen and Bremen, 1990; Benjaminsen et al., 2012; Doso, 2014). Large-scale cultivation expanded across the Sahel region following the droughts of the 1970s and 80s, linked to state-led agricultural and hydraulic development projects and involving the extension of cultivated areas into historically marginal areas, including areas housing key resources used by pastoralists (Wells and Burke 1990, Thébaud and Batterbury 2001). Decentralisation policies and administrative reforms implemented across G5 countries since the 1990s have affected farming and herding sectors through changes to land tenure and land and natural resource management systems (Bouaré-Trianneau, 2013; Ickowicz et al., 2012; Leonhardt, 2019; Marega and Mering, 2018). Agricultural development has also involved the widespread privatisation and commercialisation of land, and large-scale acquisitions of land by private (national and foreign) investors (Ickowicz et al., 2012; Leonhardt, 2019).

Conflict and insecurity as well as restrictions on movement and border closures in response to armed activity have disrupted internal and cross-border agricultural and livestock production, movement and trade, and in turn affected crop yields, food prices, livelihoods and food security (FAO, 2019; FEWS NET, 2017; Kwasi et al., 2019).

Aquaculture and fisheries

Inland fisheries represent an important socioeconomic activity and livelihood source across the Sahel region, centred on lakes, reservoirs and rivers as well as wetland and floodplain systems, notably the Lake Chad and Inner Niger Delta systems (Melcher et al., 2018; Morand et al., 2012; Okpara et al., 2016). Total fisheries production reached over 25,000 tonnes in Burkina Faso in 2019, over 40,000 tonnes in Niger, roughly 95,000 tonnes in Mali, and roughly 107,000 tonnes in Chad, with capture fisheries accounting for the vast majority and aquaculture accounting for a fraction of total production (FAO, 2021; World Bank, 2021).

Coastal fisheries are limited to Mauritania, where fisheries account for roughly 10% of the country's GDP and between 35 and 50% of exports (Trégarot et al., 2020). Mauritania's fisheries have undergone intense growth since the 1960s and catches have increased dramatically in recent decades, rising from roughly 16,000 tonnes in 1980 to over 950,000 tonnes in 2018 (Trégarot et al., 2020; World Bank, 2021). Industrial fleets account for the vast majority of domestic catches by volume, targeting demersal species (e.g., octopus, hake, shrimp), while small-scale fleets operate primarily in shallow waters closer to shore and have experienced declining catches in recent decades (Nagel and Gray, 2012). The rapid expansion of the fishmeal industry in Mauritania since 2010 (concentrated in northern port of Nouadhibou) has also placed pressures on fish stocks, with catches of small pelagic fish, such as sardinella, for fishmeal rising from 50,000 tonnes in 2011 to 240,000 tonnes in 2014 (Corten, 2014; Corten et al., 2017).

Settlements and infrastructure

Demographic factors will shape future patterns of socio-economic and climatic vulnerability and resilience in the Sahel region. The population of the G5 countries increased from about 33 million people in 1990 to 81 million in 2018 and is projected to rise to 152 million by 2040 (Kwasi et al., 2019). Between 1950 and 2012, population growth rates in the region ranged from 1.9% in Mali to 3.2% in Niger (OECD/SWAC, 2014). Although much of the population resides in rural areas, the urban population in the G5 countries increased from under five million people in 1990 to nine million in 2000, more than doubling to 20 million by 2015 and rising to nearly 26 million in 2020, while the number of settlements of more than 10,000 people rose from 118 in 1990 to 379 in 2015. Urbanisation levels are lower than in most African countries, ranging from 17% in Niger to 42% in Mauritania in 2015 (compared to 46% in the wider West African region and 50% across African countries) (OECD/SWAC, 2020a; UN Habitat, 2021; World Bank, 2021). This represents a dramatic increase in recent decades: in 2000, urban populations accounted for 24%, on average, of populations in the G5 countries (UN Habitat, 2021).

In 2020, the proportion of urban populations with access to at least basic sanitation services ranged from 40% in Burkina Faso and Chad, to just over 50% in Chad and Mali, to 75% in Mauritania (although levels of water and sanitation access are higher in urban areas than rural areas). In 2019, the proportion of urban populations with access to electricity ranged from 37% in Chad, 50% in Niger, 65% in Burkina Faso, and roughly 90% in Mauritania and Mali (World Bank, 2021). In 2018, an average of 66% of urban populations in the G5 countries resided in informal settlements or 'slums', a proportion higher than the regional average of 26% in Northern and Western Africa and the world average of 24% (UN Habitat, 2021). The proportion of the urban population living in informal settlements in 2018 was 46% in Mali, 57% in Burkina Faso, 61% in Niger, 80% in Mauritania, and 87% in Chad.

The expansion of urban centres in the Sahel has been linked to internal and regional migration from rural areas, associated with factors such as socioeconomic transformation (including changes in agricultural and pastoral systems discussed in Section 4.2), food crises, and environmental change (Issaka, 2015; McDougall, 2021; OECD/SWAC, 2014). Most migration in the Sahel takes place within the region and toward urban centres, with young people making up most migrants (OECD/SWAC, 2014). Recent evidence shows that climatic shock events, such as temperature and precipitation anomalies, alongside political, economic and social factors, including development policies and agricultural expansion, are associated with both increased *and* decreased mobility (Bertoli et al., 2020; Gray and Wise, 2016; Selby and Daoust, 2021). These changes in mobility most directly affect agricultural and pastoral productivity and incomes, with much of this movement being at a national level, building on histories of seasonal migration in the region (Selby and Daoust 2021).

Human health

Human health and mortality outcomes in the Sahel region have improved over the past two decades, with all G5 countries experiencing an increase in life expectancy at birth and a decline in infant, child and adult mortality rates, although outcomes remain below global averages (WHO, 2021). While health expenditure has increased in the past two decades in all G5 countries, to an average of $36 per capita in 2016 (from $26 in Niger to $56 in Mauritania), this remains lower than West and Central African and broader sub-Saharan African averages (World Bank, 2021). Key health indicators remain poor. In 2019 the mortality rate for children under five years old was an average of 90 per 1,000 live births in the G5 countries (from 73 in Mauritania to 114 in Chad), compared to a world average of 38 (World Bank, 2021). Health systems in the region are affected by insufficient health centres, staff, financial and material resources and equipment (especially in rural areas), gaps in geographic accessibility and quality of care, and high costs of private services (Ridde and de Sardan, 2013; de Sardan and Ridde, 2015). Many health centres across the region have been closed or have reduced their services due to insecurity, and international agencies providing basic services have withdrawn from some areas, restricting access to care for millions of people and increasing vulnerability to health risks (Kwasi et al., 2019; OCHA, 2021).

Biodiversity and ecology

The G5 countries contain numerous parks and protected areas, including many UNESCO (natural) heritage and Ramsar sites (wetlands of international importance) alongside other national parks. These are home to a vast range of plant life and mammal, bird, reptile, fish, and plant species, including many vulnerable and threatened species. Such parks include: the W-Arly-Pendjari Complex, a UNESCO world heritage site (Burkina Faso and Niger, zone 3), the Aïr and Ténéré Natural Reserves UNESCO site (Niger), the Kokorou-Namga Complex (Niger), Aïr Gueltas (Niger), other lakes, ponds, and oases, and sites along the Niger river (Ramsar Convention, 2021), the Arly National Park (Burkina Faso), Pô-Nazinga-Sissili Complex (Burkina Faso), the Ounianga lakes (Chad), and the Banc d'Arguin National Park (Mauritania).

These ecosystems face a range of human pressures and threats. These include land clearance and conversion of natural habitats into agricultural fields and pastures, agriculture-related erosion and siltation, invasion by 'alien' species due to agricultural expansion, overgrazing of livestock, (often illegal) wood collection and timber harvesting, and illegal hunting. Wetlands have also been negatively affected by overexploitation and contamination of waterbodies, changes in water resources resulting from human activities (e.g., dams), and rainfall variations (Adams et al., 2014; Brito et al., 2014; Brito et al., 2016; Melcher et al., 2018; Ramsar Convention, 2021; UNESCO, 2021a, 2021b, 2021d). These point to the potential effects of future climate adaptation practices, including water infrastructure development and agricultural intensification.

Although large-scale agricultural expansion is generally linked to a reduction in tree cover in the Sahel region, small-scale farmland management can safeguard trees in semi-arid areas, challenging simplistic generalisations about farming and deforestation (Brandt et al., 2018), reflecting the ecological and land management knowledge (e.g., agroforestry practices) of farmers in these environments (Bayala et al., 2014) and pointing to directions for adaption to climate risks. Efforts to manage sustainable livelihood activities within protected areas have been implemented in some Sahel countries, with varying outcomes. For instance, the W-Arly-Pendjari Complex includes hunting reserves in Burkina Faso where regulated sustainable hunting is permitted (UNESCO, 2021d). In Mauritania's National Park of Banc d'Arguin, conservation efforts include limiting fishing activities to sustainable fishing by residents, but these are undermined by inadequate economic opportunities for subsistence fishers (Trégarot et al., 2020). In Burkina Faso, people's willingness to take part in sustainable forest management and conservation activities is directly related to security of land use rights, pointing to the importance of socioeconomic security to ecosystem protection, as well as adaptative capacities in response to climate risks (Brännlund et al., 2009).

Energy

Large-scale resource and energy development is central to socio-economic development in the Sahel region, and will have important implications for climate resilience, adaptation and mitigation. Oil production is an important source of export revenue in Chad and Niger, and oil and gas exploration and production in Mali and Mauritania highlight the sector's continued significance for Sahelian economies (IEA, 2021; Kwasi et al., 2019; OECD/SWAC, 2014). Solar, wind power (particularly in Mauritania) and hydropower (especially in Mali) are expanding in the region, which is viewed as a prime site for the expansion of renewable energy, such as solar energy development and production (IEA, 2021; Kwasi et al., 2019). The African Development Bank's 'Desert to Power' initiative in the Sahel – part of its 'New Deal on Energy in Africa' and a key pillar of the 'Great Green Wall' Initiative – aims to build the world's largest solar zone and expand solar power generation capacity (AfDB, 2021). The Sahel region also holds reserves of metals and minerals critical to clean energy technologies, such as copper, zinc, titanium and manganese (IEA, 2021). While these sectors occupy central roles in national economies, they can also contribute to socio-economic disruptions through large-scale environmental damage, land enclosure and impacts on agricultural, livestock and fishing activities.

2.1 Key risk factors in the report

The interpretation of climate projections in this report is informed and framed by six factors that explore the interlinkages between climate risk and socioeconomic trends:

- Economic sectors and growth
- Infrastructure and energy
- Livelihood systems
- Population and demographic trends
- Disaster risks
- Conflict dynamics

These risk factors are contextualised and assessed across six key themes: water resources, agriculture and pastoralism, aquaculture and fisheries, settlements and infrastructure, human health and mortality, and biodiversity and ecology. This report aims to understand how these trends and risks interact with changes in a future climate.

Focus Box 2: Risk-informed development

There is increasing recognition that development is exposed to multiple, intersecting threats (Opitz-Stapleton et al., 2019). However, identifying risks to development programming is often the result of single threat analysis, meaning that it fails to be risk-informed (Opitz-Stapleton et al., 2019). In order to be risk-informed, programme decision making must undertake multi-threat analysis that considers how different threats merge with existing and changing socioeconomic contexts to create complex risk (Opitz-Stapleton et al., 2019). In practice, this means that climate-resilient development must not only consider threats to programme outcomes from climate and environmental degradation, but also economic and financial instability, cyber and technology, transboundary crime and terrorism, geopolitical volatility, conflict and global health pandemics (Opitz-Stapleton et al., 2019).

Risk-informed development requires us not only to think about risks to development but also risks from development (Opitz-Stapleton et al., 2019). Development outcomes are uneven, creating opportunities for some and risks for others. Risk-informed development must account for trade-offs inherent in development choices, including climate adaptation and mitigation (Opitz-Stapleton et al., 2019). Such decisions are inherently political, involving the redistribution of resources and navigating unequal power structures (Eriksen et al., 2015).

Image location: Maaden, Mauritania

3 Climate in context: current and future climate in the Sahel region

3.1 Baseline climate for the Sahel region

3.1.1 Climate overview

The Sahel is a semi-arid region in Africa which stretches from Senegal in West Africa to Sudan and Ethiopia in East Africa. It is bordered by the Sahara Desert to the north, and tropical forests to the south. The climate of the Sahel region is influenced by the interaction of the Atlantic Ocean and the Sahara – the annual cycles of precipitation and temperature depend on the way in which humid ocean air masses interact with the dry and hot desert interior.

The Sahel has a semi-arid tropical climate. The climate is typically hot, sunny, dry and fairly windy all year long. Conditions in the North of the Sahel are similar to, but less extreme than, those of the Sahara Desert to the north. Conditions to the far south are tropical with similarities to the climate of inland West Africa.

The main driver of climate variability in the region is the West African Monsoon (WAM) (see Focus Box 3) generating a large annual cycle in rainfall across the region. Rainfall varies sharply in the meridional (North-South) direction, but much less in the zonal (East-West) direction. A zonal rain band moves northwards in the summer, producing a single rainy season, with the majority of annual rainfall falling between June and September. Annual mean rainfall decreases from more than 1000 mm in the south of the region (in the southern extents of Burkina Faso and Chad), to less than 200 mm in the north of the region (Biasutti et al., 2019). There is also significant interannual climate variability in precipitation with totals fluctuating considerably from season to season. Annual average precipitation amounts, and temperatures are shown in Figure 3. These maps represent the average annual values over the 30-year baseline climate period (1981-2010).

Temperatures are high throughout the year, and the region rarely experiences cold temperatures. The annual mean temperature for the Sahel region is approximately 25°C. During the hottest periods, temperatures reach between 25°C and 37°C, and during the coolest periods temperatures rarely drop below 13 °C (see Figure 4).

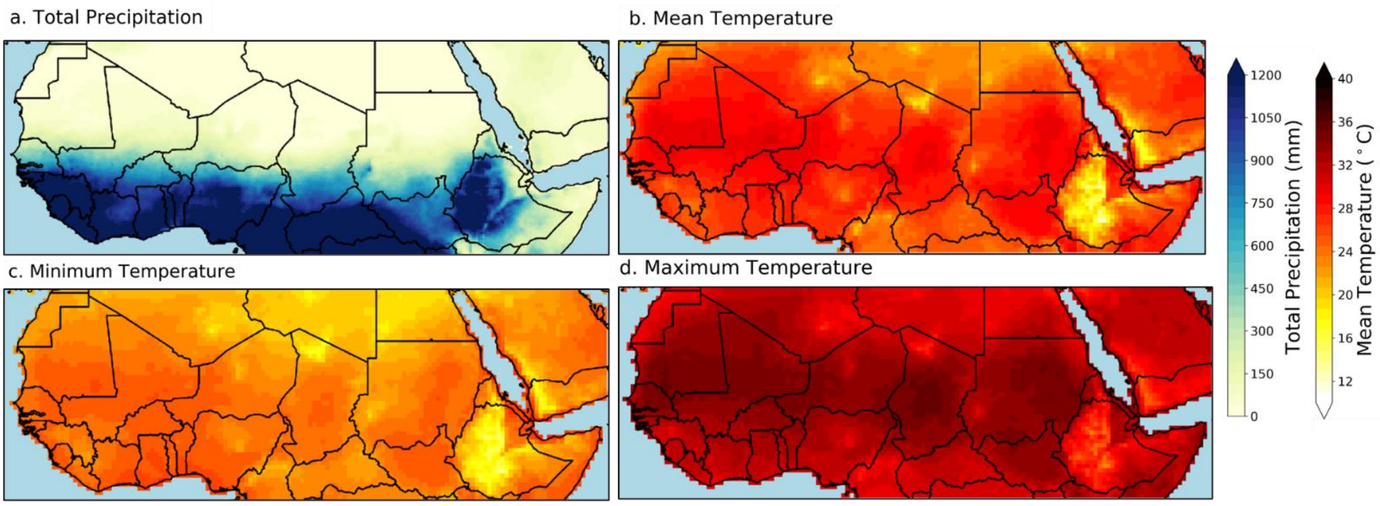


Figure 3: Baseline climate for the Sahel region for the period 1981-2010. Maps show climatological average values of annual mean a) total precipitation (mm/year), b) mean temperature (°C), c) minimum temperature (°C), and d) maximum temperature (°C). Temperature and precipitation data is from the WFDEI and CHIRPS datasets respectively.

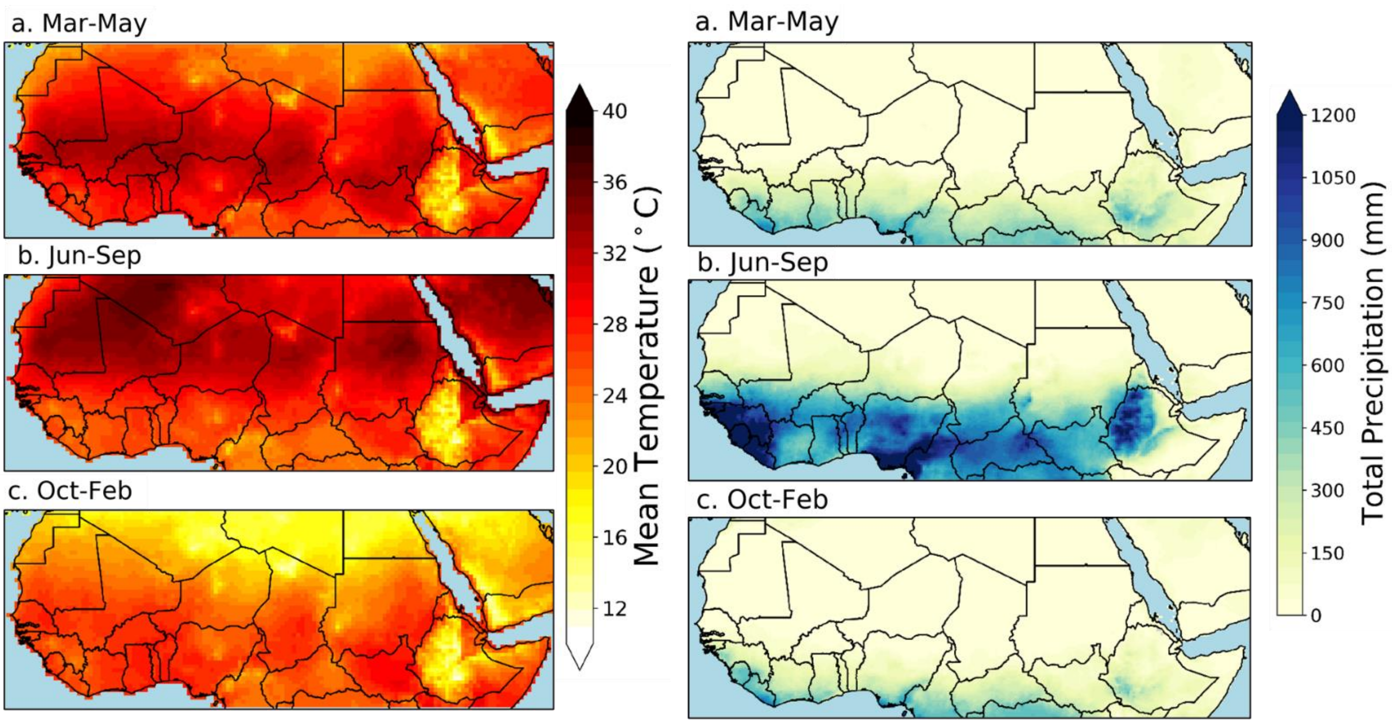


Figure 4: Left three plots: seasonally averaged mean temperature for the Sahel region over the baseline period (1981-2010). Right three plots: seasonal total precipitation for the Sahel region over the baseline period (1981-2010). Temperature and precipitation data is from the WFDEI and CHIRPS datasets respectively.

Focus Box 3: West African Monsoon

Monsoons are prevailing low-level winds which define seasons in tropical regions where they are active. Although there are cases of dry monsoons, these phenomena are commonly associated with intense rainfall, usually constituting the largest fraction of rainfall over the year, in a period which correspond to the hemispheric summer months. These systems can be seen as a mechanism to distribute energy toward the poles from the more insolate tropical regions (Biasutti et al., 2018), with land conformation, orography, state of the ocean and subtropical weather systems among the factors contributing to their evolution in space and time.

The West African Monsoon (WAM) is a system of south-westerly winds which form in the Gulf of Guinea. In the period from May to September the WAM brings rainfall toward the southern coast of West Africa extending to the northern edge of the Sahel (20°N), and from the western coast of Africa (15°W) to the western foothills of the Ethiopian highlands (30°E). On the coast and in the Sahel: rainfall starts along the coastal areas at the beginning of May and continues with strong intensity until the end of June, where a sudden drop in the coastal area is replaced by the start of rainfall over the Sahel region.

This shift is an actual spatial displacement of rainfall system known as the West African monsoon jump (Sultan and Janicot, 2003; Cook, 2015) in which the rain band moves by ~5-10° to the north within few days. This is the start of the rainy season over the Sahel, which continues until the beginning of September, after which another shift brings the rainfall back to the coast, where it persists until October.

Changes in sea surface temperature (SST) have been identified and reproduced in modelling studies (Folland et al,1986; Giannini et al. 2008; Biasutti 2019) as a driving factor of rainfall in the Sahel. The occurrence of persistent droughts in the 1970s to 1990s was attributed to anthropogenic emissions causing positive North Atlantic SST anomalies and associated regional changes in precipitation (IPCC AR6, 2021; Biasutti and Giannini, 2006; Biasutti et al., 2008; Greene et al., 2009). The recovery of the rains in the 1990s may be due to natural variability (Mohino et al., 2011) or a forced response to increased greenhouse gases (Biasutti et al., 2019; Haarsma et al., 2005) or reduced aerosols (Nicholson , 2013; Ackerley et al., 2011).

Future changes in the WAM system are are likely to be driven by similar factors of natural and human-induced climate change, though the relationship between these is complex (Wang et al., 2021; IPCC AR6, 2021). Other robust changes are the increase on extreme precipitation days and the increase of consecutive dry days mainly driven by the warmer, moister atmosphere (and so a larger atmospheric moisture content).

The IPCC AR6 report (2021) predicts that the WAM will increase in mean precipitation (medium confidence) in addition to medium confidence of increase in daily precipitation intensity, extremes and consecutive dry days. On the timing of the monsoon, there is high confidence of a delayed onset (Dunning et al., 2018) and medium confidence of a delayed retreat (lower confidence on its increased in duration). Spatially, projections also indicate greater increases in the eastern central Sahel and a decrease in the west (Wang et al, 2021, IPCC AR6, 2021) (see section 3.2).

Some of these changes have already been identified in the recent historical record, with associated larger variations of rainfall experienced at local scales, which could be a indication of a new climatic regime (IPCC AR6, 2021).

There are a number of winds that affect the Sahel region:

- The West African Monsoon (WAM) (see Focus Box 3)
- The Harmattan winds are characterised by a dry wind blowing from a north-east / easterly direction over north-west Africa. The winds are both dry and relatively cool, which contrasts against the humid heat of the tropics. Hot, dry continental air masses originating from the high-pressure system above the Sahara Desert give rise to the dusty Harmattan winds over most of West Africa from November to February. The winds carry great quantities of dust from the Sahara Desert and often in sufficient quantity to form a thick haze.

The West African coast is also home to the Canary Current. The Canary Current is part of the North Atlantic Gyre, a clockwise ocean-current system in the North Atlantic Ocean. Approximately 500 m deep (Wooster et al., 1976) the current is characterised by relatively cool surface temperatures produced by upwelling caused by offshore winds from the continent (Mittelstaedt, 1991). As the current flows around the Canary Islands, it helps reduce the heating effect of the Sahara to the east.

3.1.2 Large-scale climate drivers

Movement of the Intertropical Convergence Zone (ITCZ)

The ITCZ is a ring around the Earth where air masses from each hemisphere converge. It appears as an area of deep convection where intense precipitation is frequent. The ITCZ does not always occur in the same place but moves north and south of the equator seasonally, following the path of the sun. In the Sahel region, seasonal distribution of rainfall has previously been linked to the movement of the ITCZ however, new research challenges the ITCZ paradigm, which assumes tropical rainfall to be mainly associated with localised convection (Nicholson, 2018). The spatial and temporal patterns of rainfall during the equatorial rainy seasons in Africa are now understood to be more complex than purely an association with localised convective activity; for example, in the Sahel, the progression of the ITCZ in the Sahel is complicated by its interaction with the surface heat over the Sahara Desert. It is acknowledged that a deeper understanding of the seasonal cycle in the equatorial regions of Africa still needs to be developed.

West African Monsoon (WAM)

The WAM is a significant large-scale climate driver in the Sahel region and brings with it high variability in precipitation intensity. See Focus Box 3 for a detailed overview of the WAM, its variability, how it has been observed to change in the past, and how it may change in the future with climate change.

Atlantic Multidecadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO)

The two main teleconnections for the Sahel region are the Atlantic Multi-decadal Oscillation (AMO) and El Niño Southern Oscillation (ENSO). These large-scale drivers strongly influence the year-to-year variability of rainfall and affect the timing of the WAM . Anomalous sea surface temperatures (SSTs) associated with ENSO have been shown to cause increased rainfall over the Sahel, especially in the east (Joly & Voldoire, 2009). The AMO has also been shown to be a good predictor of drought events in the region where a cold AMO phase coincides with reduced rainfall over the region due to the impact on SSTs which affect the WAM (see Focus Box 3 on the WAM) (Martin & Thorncroft 2014; Ndehedehe et al., 2020).

3.1.3 Observed climate trends

Over the Sahel, near surface temperatures have already increased since the pre-industrial era (IPCC AR5, 2014). Collins (2011) shows statistically significant warming of between 0.5°C and 0.8°C between 1970 and 2010 over the region using remotely sensed data, with a greater magnitude of change in the latter 20 years of the period compared to the former. The IPCC Interactive Atlas (2021) shows that the Sahara and West Africa regions (which together cover the Sahel region) have been warming at a rate of 0.27 and 0.42 °C per decade between 1980 and 2015, with greater increases in the east compared to the west.

Since the 1980s rainfall totals in the Sahel have been increasing (Leduc et al., 2001), however, the characteristics of wet season rainfall have also changed, with increases in the frequency and intensity of extreme rainfall. Wet season rainfall also appears to be shifting to later in the year, particularly in the central Sahel regions away from the west coast (Wang et al., 2021; Biasutti, 2019; Dunning et al., 2018; Taylor et al., 2017) (see Focus Box 3 on WAM).

Focus Box 4: Weather, climate variability and climate change

The weather varies from day to day and season to season, with the statistics of these variations constituting the climate. These statistics are typically defined over a 30-year period. Climate change can then be characterised as the difference in these statistics between two 30-year climate periods. This will include the annual climate range through the year, from one period to another, as well as changes in the frequency, intensity and duration of extreme events, such as heavy rainfall and high temperatures.

Climate varies naturally over shorter periods of several years, and this natural variability can accentuate or dampen longer-term climate change signals. Both average conditions and the variability around that average can change and can result in increase in events that in the past were rare or extreme. It can also lead to situations where climate change increases the frequency of both heavy rainfall events and the occurrence of very dry conditions

Source: IPCC (2021).

3.2 Future climate for the Sahel region

Temperature

Temperatures in Africa are projected to rise faster than the global average increase during the 21st century (IPCC AR6, 2021). Diffenbaugh and Giorgi (2012) identify the Sahel and tropical West Africa as hotspots of climate change for both RCP4.5 and RCP8.5 pathways[6], and unprecedented climates are projected to occur earliest (late 2030s to early 2040s) in these regions (Mora et al., 2013).

Average daily minimum and maximum temperatures are also projected to increase into the 2050s at approximately the same rate as daily mean temperatures indicating that hot extremes will increase in frequency and intensity, and cold extremes will decrease in frequency and intensity. For the region as a whole, there is high confidence in an increase in the number of days per year above 35°C, and high confidence in an increase in the number of days above 40°C, with a number of days above these thresholds exceeding 40 days per year by 2050, presenting a considerable risk to heat stress (IPCC Interactive Atlas, 2021[7]).

Precipitation

Projected Sahel precipitation change is quantitatively uncertain; however, a consensus emerges when considering the direction of change (Monerie et al. 2016; Fontaine et al. 2011a; Biasutti, 2013; Monerie et al. 2012). Summer (June-September) precipitation associated with the WAM (see Focus Box 3 on WAM) is projected to increase. Spatial projections of monsoon precipitation indicate the existence of a precipitation gradient[8] (see Appendix B) across the region, where there is medium confidence in precipitation increase in the central Sahel and decrease the far west, especially on the coast of Mauritania (IPCC AR6, 2021; Monerie et al. 2016; Almazroui et al. 2020; Biasutti, 2013; Monerie et al. 2012; Fontaine et al. 2011b; Roehrig et al. 2013; James et al. 2015; Diallo et al. 2016; Akinsanola and Zhou, 2019; Dunning et al. 2018). This evolution is also projected in CMIP6 climate model simulations under the high-emission SSP5-8.5 scenario (Monerie et al. 2020a; O'Neill et al. 2016). The zonal contrast in precipitation changes strengthens with warming (Monerie et al. 2012) is reproduced by most of the climate models and seen with numerous emission scenarios (Monerie et al. 2016; Fontaine et al. 2011a; Biasutti, 2013; Akinsanola and Zhou, 2018; Monerie et al. 2020b; Biasutti, 2019).

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[6] The RCP8.5 Representative Concentration Pathway (van Vuuren et al., 2011) represents a future pathway of on-going and substantial increases in future global emissions of greenhouse gases. Other pathways represent stabilisation or reduction of future emissions, however there is little difference in the projected climate change between these pathways in the 2050s time period. Analysis of the RCP4.5 scenario was also conducted, and results were broadly consistent with those presented here for RCP8.5. Note that RCP8.5 refers to CMIP5 model projections - the CMIP6 equivalent is SSP585 (O'Neill et al., 2016).

[7] https://interactive-atlas.ipcc.ch/

[8] Sahel precipitation gradient: although this signal exists across the whole West Africa and Sahel region, for the Sahel, the gradient is weaker and less certain (lower confidence) compared to West Africa where the gradient is stronger and more certain (higher confidence). Though the signal to the northeast Sahel (zone 2 especially) appears substantial (see Figure B1 in Appendix B), the arid climate of the zone means that the large % change represents a comparatively small change in absolute precipitation.

The IPCC (AR6, 2021) note that the east and west Sahel are likely to experience delayed rainfall onset, potentially causing reduced length of the rainy season. Indeed, changes in seasonality of the WAM are projected, with high confidence of delayed onset (by 5-10 days) and medium confidence of its delayed retreat (Dunning et al, 2018; Biasutti et al., 2013).

Rainfall variability (both sub-annually and sub-seasonally) will also increase across the region (high confidence, IPCC AR6, 2021). Models are very broad scale and so too coarse to adequately resolve local convective rainfall events, however the dynamics of the hydrological system mean that in a warmer climate the frequency and intensity of heavy precipitation events and pluvial flooding are becoming more common (IPCC, 2021; Tabari, 2020).

Maximum 1 and 5-day precipitation are good indicators for extreme precipitation events. Projections indicate an overall increase in 1 and 5-day precipitation, with a spatial pattern across the region that is consistent with the west-east precipitation asymmetries noted in the IPCC (AR6, 2021). Largest increases (+40%) are projected for the west, and no change or smaller increases (0-10%) are projected for the east. Projections are particularly uncertain for the northwest (low confidence) but are more certain in the southeast (medium-high confidence) (IPCC Interactive Atlas, 2021).

Number of consecutive dry days are projected to slightly reduce in the arid north of the Sahel, consistent with moderate increases in total precipitation. In the far western Sahel, consistent with reduced rainfall, consecutive dry days are projected to increase however, no robust signal exists between the models (low confidence; IPCC AR6, 2021).

Although rainfall is projected to have moderate increases across the region, evaporation is also projected to increase alongside precipitation; increasing variability and temperatures may therefore offset any increases in total annual precipitation (IPCC AR6, 2021).

Overall, precipitation projections are highly variable amongst the models. For example, the CORDEX-Africa ensemble identifies two contrasting but physically plausible future rainfall scenarios over the Sahel, one where mean precipitation decreases significantly over the region in summer, and the other where summer precipitation is projected to increase. (Dosio et al., 2020).

CMIP6 models show better simulations of the WAM than previous CMIP5 models (see Focus Box 3) (Almazroui et al., 2020; Wang et al., 2021). CMIP6 models also project increases in heavy precipitation (anomalies in the annual maximum daily rainfall) across different levels of warming (Seneviratne & Hauser, 2020).

Oceans and coasts

The Sahel region has a small stretch of coastline limited to Mauritania to the far west of the region. Impacts on coastal areas from climate change are likely to be significant and further impact areas inland. Around the West African coast there is high confidence that sea surface temperatures will increase, with the increase for the mid-century under SSP5-8.5 projected to be between 0.6–1.9°C. Subsequently, there is also high confidence that marine heatwaves will increase over the 21st century alongside increasing deoxygenation (IPCC AR6, 2021).

The coast of Mauritania is an important area for upwelling. The Canary Current travels southward off the coast of Mauritania and the characteristic upwelling of the current is vital for productivity and biodiversity of the marine ecosystem. Ocean warming around the coast of West Africa has implications for the Canary Current. Most observations suggest that the current has warmed since the early 1980s, and that the primary production of the current has decreased over the past two decades (medium confidence, IPCC AR5, 2014). This warming trend is projected to continue with a decrease to the upwelling system over the 21st century, although this change is expected to be relatively moderate (Sylla et al., 2019). Temperature increases in the Canary Current have already resulted in changes to important fisheries species (IPCC AR5, 2014).

Changes in ocean currents are relevant for the Sahel region because they can have implications for distributions and movements of commercial fish stocks in and out of territorial waters, with implications for coastal livelihoods. As warming is projected to continue in the Canary Current, synergies between increases in water temperature and ocean acidification could influence a number of biological processes. Since the industrial period, ocean uptake of CO_2 has resulted in ocean acidification, corresponding to a 26% increase in acidity (IPCC AR5, 2014). Even in areas of cold water upwelling, such as along the coast of Mauritania, ocean acidification is projected to continue to increase in the 21st century, the extent of which is dependent on future global emissions (virtually certain; IPCC AR6, 2021).

Increasing ocean acidification has a number of detrimental effects on ecosystems, especially when occurring alongside SST increases and deoxygenation, though the impacts on specific taxa and across trophic levels is varied and not well understood.

There is very high confidence of an increase in relative sea level around the coast of Mauritania projected by CMIP5 (RCP8.5) and CMIP6 (SSP5-8.5) climate model simulations to the order of 0.3m by the 2050s (IPCC Interactive Atlas, 2021). Much of the Sahel coastline is low-lying, for example the capital of Mauritania (Nouakchott) has an elevation of between -1m and +1m, so Sea Level Rise (SLR), especially when combined with coastal storms (though there is no consensus on the direction of change for storm activity in the region), is likely to have detrimental impacts such as erosion and damage to coastal infrastructure.

IPCC AR6 (2021) concludes that for sandy coasts, such as along the coast of Mauritania, there is high confidence of an increase in coastal erosion with most sandy coasts in region projected to experience shoreline retreat through the 21st century (IPCC AR6, 2021), with high confidence of an increase in coastal flooding. In addition, there is high confidence that SLR will cause greater frequency of saltwater intrusion into coastal aquifers, which can corrode construction materials, and when combined with urbanisation is causing groundwater level rise and associated flooding both on the coast and at inland locations, with close proximity to affected aquifers (e.g., Trarza aquifer). Saltwater intrusion also impacts aquifers by contaminating drinking water sources (Agoubi, 2021; Mohamed et al., 2017).

Wind speed and wind energy potential over West Africa are projected to have significant increases (medium confidence), though the signal is less clear for regions over the northern Sahel.

3.3 Spatial analysis zones approach

To assess the scale and direction of projected climate trends it is useful to spatially aggregate gridded climate data over climatologically similar regions. As the Sahel region represents a large, meteorologically diverse area, it is not useful to average the climate data over this large region, as the resulting values will not reflect the climate diversity. Nor is it always useful to average the climate data by country borders, as these do not reflect the climate diversity and some countries may experience a range of climate types. Therefore, the region is divided into six sub-regional analysis zones that reflect the different climate types using a combination of the Köppen-Geiger climate classifications (Figure 5) and the Natural Earth7 country borders (v4.1.0)[9].

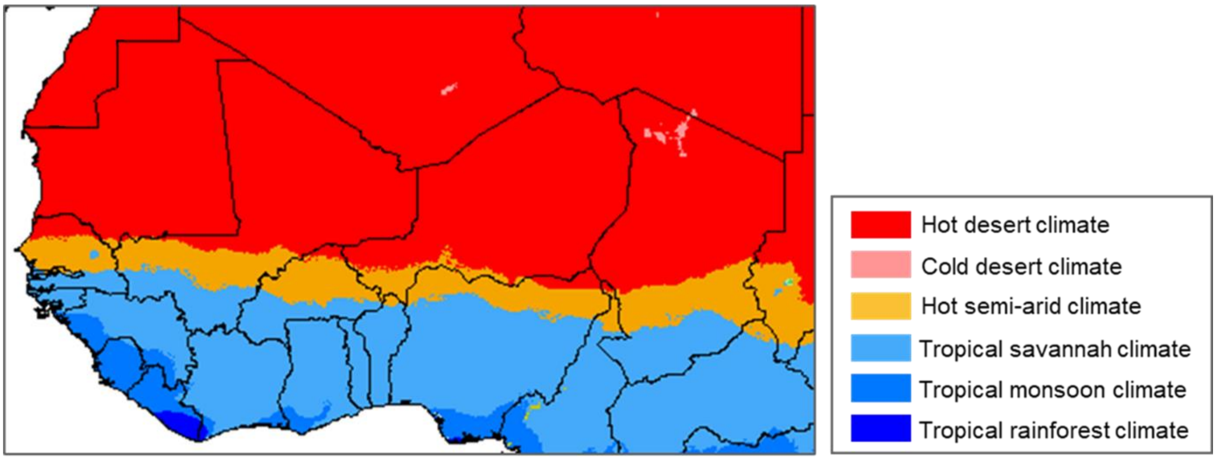


Figure 5: Köppen-Geiger climate classification map of Sahel and West Africa region, adapted from Beck et al. (2018).

Although climate type was the dominant metric used to establish spatial analysis zones, additional information was considered to ensure climate analysis would also capture relevant socio-economic information while still providing a robust overview of the climate. This included livelihood zones, maps of major farming systems and isohyet lines[10] which indicate approximate precipitation thresholds (examples shown in Figure B1 in Appendix B). Precipitation was a key consideration as it is a major controlling factor on the socio-economics of the region. Therefore, in addition to the aforementioned metrics, baseline and projection maps of precipitation were also used, the latter to ensure that zone selection accounted for potential future projected asymmetries in precipitation across the region (see section 3.2 and Figure B2 in Appendix B).

The final zones shown in Figure 6, follow the three traditional latitudinal boundaries of the Köppen-Geiger climate classification for the region, but differ slightly in that the central band (zones 3 and 4) extend further into the 'hot desert climate region' to follow agricultural boundaries dictated by the approximate 200mm isohyet, which demarcates the boundary between nomadic pastoralism and rainfed and irrigated agriculture. These zonal bands are then split into eastern and western zones to capture differences associated with potential future precipitation gradients. Finally, the southern borders of zones 5 and 6 are drawn as somewhat arbitrary boxes, extending to the southern edges of Burkina Faso and Chad but covering a larger geographical area than those countries alone in order to facilitate more robust climate analysis (Figure 6).

[9] https://www.naturalearthdata.com/

[10] Isohyet lines are approximate lines of average rainfall over a given period drawn a map and are used to spatially identify approximate extents of rainfall thresholds. For example, 200m isohyet and 600mm isohyet. Though isohyet lines are generally an oversimplification of rainfall conditions which across the Sahel have large interannual variability (see Figure B2 in Appendix B), they are a useful metric for livelihood mapping such as understanding approximate areas where certain agriculture types can exist.

The six zones used for the spatial analysis are shown in Figure 6. The majority of Mauritania and the northern half of Mali (zone 1) and the northern two thirds of Niger and northern third of Chad are regions of hot desert climate (zone 2), with zone 1 also including the only coastal area in the region. Zone 3 is the far south of Mauritania, the southwest of Mali, the northeast of Burkina Faso and the far southwest of Niger. Zone 4 is the southern third of central Niger and the southern half of Chad. Both zone 3 and 4 are the mixed rainfall zones where precipitation total varies from approximately 200-600mm per year. Zones 6 and 5 are the tropical zones where rainfall is generally over 600mm per year. These zones cover the southwest half of Burkina Faso and the southern third of Chad. Other countries are included within these zones, but this report will focus on the climate risks for the G5 Sahel countries, making references to other countries where relevant (See Doherty et al., 2022, for West Africa climate risks). Table 1 relates the countries to the spatial analysis zones for reference.

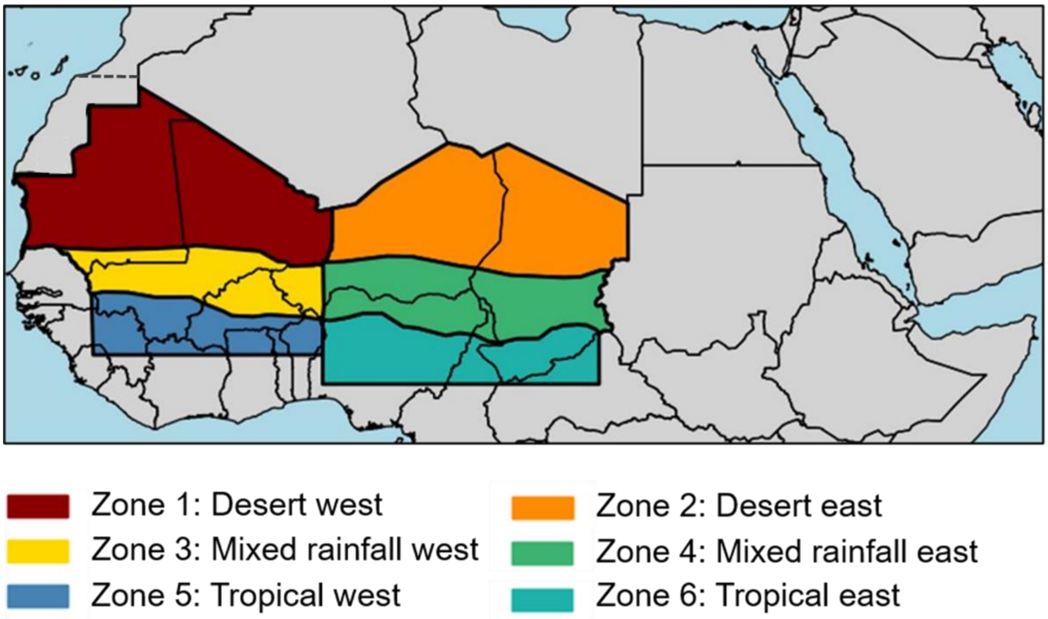


Figure 6: The six spatial analysis zones across the Sahel region.

Table 1: Countries in the Sahel region and the spatial analysis zones (defined in Figure X) that cover them.

Country	**Climate analysis zones that cover the country**
Mauritania	Zones 1 and 3
Mali	Zones 1, 3 and 5
Burkina Faso	Zones 3 and 5
Niger	Zones 2, 3 and 4
Chad	Zones 2, 4 and 6

Baseline and future climate data analysis is conducted in each of these six spatial analysis zones. Here, the baseline is the period 1981-2010, and the future period is 2041-2070 (the ‘2050s’). The analysis focuses specifically on temperature and precipitation climate variables (more detail and plots are provided in Appendix B). For other relevant climate variables and metrics, such as sea level rise and sea surface temperature, information is gathered from relevant scientific literature. Further analysis in the following sub-sections, summaries of the baseline climate and future projections, and their relevance to the socio-economic context, are presented for each of the six spatial analysis zones.

3.4 Baseline and future climate in the Sahel region by zone

In this section the climate in context analysis for the baseline and future climate is presented by zone. Summaries of the findings are presented in the zone summary infographics on the following two pages.

Zone summary: **Baseline climate in context**

Zone 1: Desert west: Northern Mauritania and Mali

Current climate:
Dry and hot with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

- Desert or pastoral region with sparse rural population
- Coastline in Mauritania enables commercial fishing and mineral exports
- Livelihoods based on mobile camel and goat herding, and trans-Saharan trade

Zone 2: Desert east: Northern Niger and Chad

Current climate:
Dry and hot with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

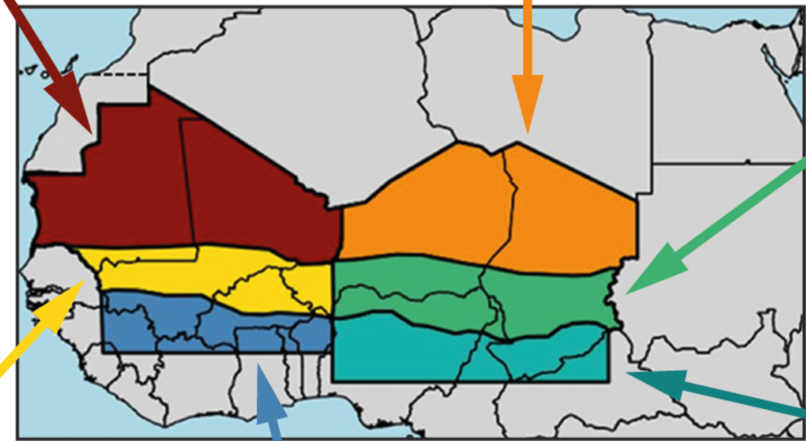
- Covers south-central Sahara, encompassing central Saharan highlands of Adrar, Aïr, Tibesti, and Ennedi
- Zone includes oasis areas of significance such as Ounianga (Chad)
- Predominantly pastoral livelihoods

Zone 4: Mixed rainfall east: South-eastern Niger and central Chad

Current climate:
Seasonal climate with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

- Pastoral and agro-pastoral livelihoods
- Irrigated crops cultivated along the Niger and Komadougou-Yobé rivers in Niger
- Cultivation around Logone and Chari rivers which flow through Chad
- Rainfed agriculture to the south of the zone
- Lake Chad provides fishing livelihoods, flood recession cultivation, and important trade



Zone 3: Mixed rainfall west: Southern Mauritania, Mali, southwest Niger, and northern Burkina Faso

Current climate:
Seasonal climate with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

- Livelihoods largely based on agro-pastoralism and millet and sorghum cultivation
- Niger Delta and Niger Bend of the Niger River, spanning over multiple countries, provide irrigated agriculture

Zone 5: Tropical east: Southern Mali and Burkina Faso

Current climate:
Seasonal climate with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

- Zone includes city Bamako (Mali) and key towns of Sikasso (Mali) and Bobo Dioualasso (Burkina Faso)
- Mixed agriculture with cultivation and small-scale irrigation
- Sedentary livestock rearing is common in households
- Gold mining is a key source of income in some locations

Zone 6: Tropical west: Southern Chad

Current climate:
Seasonal climate with warm, wet summers and cooler, drier winters

Geographic and socio-economic context:

- Livelihoods focused on mixed agriculture including cultivation
- Cultivation around Logone and Chari rivers which flow through Chad and feed into Lake Chad, including flood-plain rice cultivation
- Livestock raising, e.g., goats
- Movements of transhumance herders between Cameroon and Central African Republic

Zone summary: **Future climate trends and relevant risks**

Zone 1: Desert west: Northern Mauritania and Mali

Future climate trends:

- Hotter throughout the year, larger increases during hottest months
- Wetter on average, little change in dry season, slightly wetter in rainy season
- Sea level rise along Mauritania coast and increasing sea surface temperatures

Relevant risks:

- Risk of extreme human and livestock heat stress, impacting nomadic pastoralism
- Increased seasonal rainfall variability further exacerbating agricultural stresses
- Flooding events threatening livestock, agriculture and human health
- Coastal risks for Mauritania including saltwater intrusion into aquifers, flooding events, and coastal erosion. Also, increasing ocean temperatures, acidification and deoxygenation pose risks for coastal fisheries.

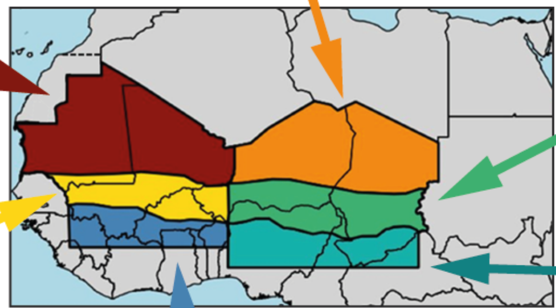
Zone 2: Desert east: Northern Niger and Chad

Future climate trends:

- Hotter throughout the year, larger increases during hottest months
- Wetter on average, little change in dry season, slightly wetter in wet season

Relevant risks:

- Heat stress risks, particularly at night, including heatwaves, are a major concern to animals, especially for livelihoods dependent on the climate-sensitive practice of nomadic pastoralism
- Increasing seasonal rainfall variability impacts oasis agriculture, such as in Ounianga in the Ennedi (Chad)
- Increasing frequency and intensity of heavy rainfall events leads to flooding, threatening livestock



Zone 3: Mixed rainfall west: Southern Mauritania, Mali, southwest Niger, and northern Burkina Faso

Future climate trends:

- Hotter throughout the year, larger increases during hottest months
- Annual average rainfall may increase or decrease. Projected little change in dry season, slightly wetter in rainy season

Relevant risks:

- Heat-related risks, particularly in urban environments such as Niamey (Niger), where the Urban Heat Island effect could further exacerbate heat-stress health risks
- Delayed onset of the wet season threatens rainfed agricultural systems
- Increased rainfall variability impacts flooding events along the Niger River, further impacting associated agriculture, fishing, and water availability

Zone 4: Mixed rainfall east: South-eastern Niger and central Chad

Future climate trends:

- Hotter throughout the year, larger increases during hottest months
- Wetter on average, little change in dry season, wetter in rainy season

Relevant risks:

- Heat-related risks, particularly in urban environments such as Zinder (Niger), and N'Djamena (Chad), especially at night time.
- Delayed onset of the wet season impacts rainfed agricultural systems and pastoralists
- Flooding events from increased frequency and intensity of heavy rainfall events can result in livestock deaths and loss of agriculture, further exacerbating urban flooding from the Chari and Logone rivers that feed Lake Chad
- Rainfall change impacts river flows and lake levels, particularly for Lake Chad, impacting livelihoods, agriculture and fisheries

Zone 5: Tropical east: Southern Mali and Burkina Faso

Future climate trends:

- Hotter throughout the year, larger increasing during hottest months
- Wetter on average, particularly in the rainy season

Relevant risks:

- Heat-related risks, such as in Bamako (Mali) and key towns of Sikasso (Mali), and Bobo Dioualasso and Ouagadougou (Burkina Faso) further exacerbate heat-stress health risks
- Delayed onset of wet season impact rainfed agricultural systems, causing scarcity of water for crops and livestock
- Increased rainfall variability impacts river flows and groundwater recharge, especially for the River Niger, which is already sensitive to flooding in the rainy season

Zone 6: Tropical west: Southern Chad

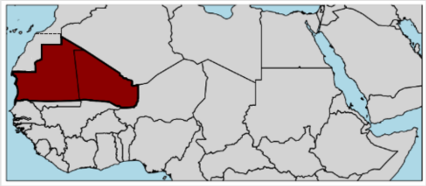
Future climate trends:

- Hotter throughout the year, larger increases during hottest months
- Wetter on average, particularly in the winter season

Relevant risks:

- Heat-related risks, such as in Moundou (Chad), especially at night
- Delayed onset of the wet season impacts rainfed agricultural systems
- Heavy rainfall events can result in livestock death and loss of agriculture
- Increased rainfall variability impacting river flows and groundwater recharge, such as within the Chad River Basin and Logone and Chari Rivers, also impacting agriculture, pastoralism and fishing

3.4.1 Zone 1 – Desert west: Northern Mauritania and Mali



Baseline climate for Zone 1

Zone 1 covers the majority of Mauritania and the northern half of Mali and is bordered by Western Sahara and the North Atlantic Ocean to the west and Algeria to the North. Zones 2 and 3 borders zone 1 to the east and south respectively. This zone covers the arid western Saharan regions of Mauritania and Mali north of the approximate location of the 200mm isohyet. In Mauritania it encompasses the regions north of approximately 16.2°N, covering all of the country except the southernmost areas in the east and centre of the country which lie east of the town of Bababé, just east of the Senegal River. Zone 1 covers the northern half of Mali. This zone includes the town of Timbuktu and the northernmost reaches of the Niger Bend. In Mauritania, it includes the capital, Nouakchott and the main port of Nouadhibou, as well as the desert towns of Akjout, Atar, Chinguett and Oudane, and the important mining area around Zouerate.

Zone 1 is hot and dry, characterised by a seasonal pattern of a warm and relatively wet summer period and a cooler and dryer winter period. The highest temperatures occur during the early part of the summer season (June-September) with mean daily temperatures reaching 35°C (with temperatures ranging from ~25°C to 40°C) in June. Lowest temperatures occur in December and January during the winter season (ONDF) where mean daily temperatures are approximately 20°C (with temperatures ranging from ~12°C to 27°C). There has been an observed warming trend in mean, minimum, maximum temperature over the duration of the baseline period. This zone experiences very little rainfall in the winter months, with most of the annual rainfall falling between June and September, although this rarely exceeds 100mm.

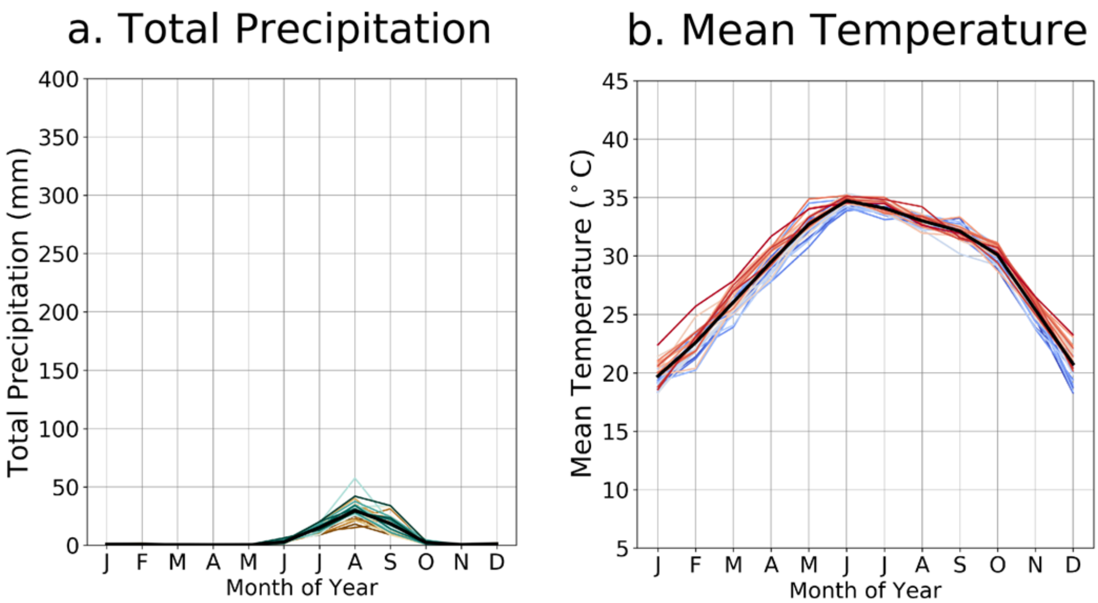


Figure 7: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 1. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 1

Most of zone 1 is classified as desert or pastoral, with the southernmost areas of zone 1 in Mauritania and eastern Mali extending into the agro-pastoral area in some livelihood classification systems. The rural population of zone 1 is sparse, and livelihoods are based predominantly on mobile camel and goat herding, and trans-Saharan trade, with contributions from other activities, such as oasis agriculture and, in certain locations, employment in the mining sector. Historically, tourism has provided some employment, but this sector has been severely affected by armed conflict and insecurity. In the region of the Niger Bend in Mali, zone 1 extends into areas of flood recession agriculture. In Mauritania, zone 1 includes coastal areas where commercial fisheries and mineral exports are important economic activities.

Future climate projections for Zone 1

In zone 1, climate model projections show high confidence in a projected increase in temperatures of 2.5-4°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 7). Temperatures are projected to increase in all months with some models indicating larger increases in mean daily temperature over the hottest months of the year (June – August). Minimum and maximum daily temperatures are also projected to increase, reaching or exceeding temperatures of 30°C and 45°C respectively in the hottest months, posing a risk to human and livestock heat stress (June-August). There is uncertainty in projections of precipitation, with most models projecting an increase in annual mean precipitation by up to 20% (+0-20mm) and fewer projecting a decrease. For seasonal precipitation, projections show medium confidence in little change in the dry seasons, with marginally larger changes projected for the rainy season (June-September). Where change in rainfall is more uncertain: the majority of models indicate a change of between -50 and +50mm (Appendix B). Into the

2080s a similar precipitation trend emerges, and temperatures continue to increase (+4-7°C) in all months, though models have less agreement in both temperature and precipitation. In other scenarios (RCP4.5), temperature anomalies are smaller (1.5-3°C), but precipitation trends remain similar. Spatially in Zone 1, there is very good agreement across the models for moderately cooler temperatures close to the west coast and warmer temperatures in the east. There is much less agreement across the models for precipitation changes, though generally there is a pattern of drier conditions in the far west and wetter conditions in the southeast into the 2050s.

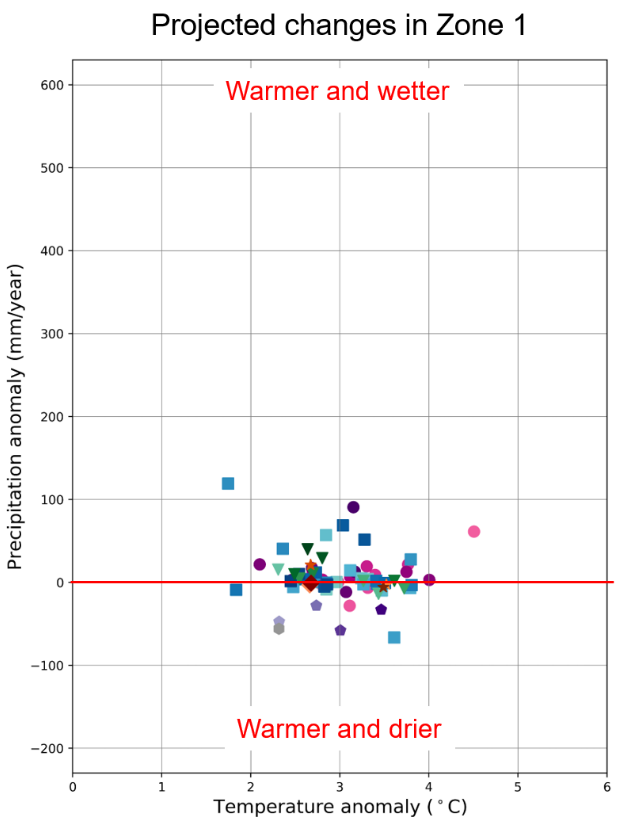


Figure 8: Projected change in average annual precipitation and temperature in Zone 1 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in urban environments, such as Bababé, Akjout , Atar , Chinguett, and Oudane in Mauritania. In the capital of Mauritania, Nouakchott, the urban heat island (UHI) effect[11] could further exacerbate heat-stress related health risks, particularly at night-time (IPCC AR6, 2021; see section 4.5). Heatwaves are still poorly understood in the arid and semi-arid regions of

[11] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

the Sahel, but these regions are especially vulnerable to heatwave due to the dependence on climate-sensitive practices, such as nomadic pastoralism (transhumant camel and goat-herding) where heat stress to animals is a major concern (Guigma et al., 2020; see section 4.2). Heat stress will also affect physical labour activities in the zone, which may be particularly impactful for outdoor workers such as those employed in mines (Kjellstrom et al., 2014; see section 4.5).

Furthermore, projections indicate that across zone 1, except for the far west, daily maximum temperatures will consistently exceed 40˚C in the hottest months (June-August), with some climate models projecting maximum temperatures up to 45˚C. These temperatures will also be exceeded earlier in the year and for longer through the year. Currently, these temperatures are rarely reached.

Though little agriculture occurs in this arid zone, increasing temperatures and temperature extremes are likely to impact oasis agriculture in the inland areas where productivity is already low. This may impact crops such as sorghum, millet and date palms. Though these crops are fairly resilient to changes in climate, any changes may be impactful especially when combined with changes to water availability (see section 4.2).

Precipitation is projected to have little change or very small increases, and rising temperatures are very likely to offset any additional water availability through increases evaporation rates (see section 4.1).

In the coastal region of Mauritania, precipitation is projected to have little change or small decreases, potentially exacerbating water stress for coastal cities and towns including the capital Nouakchott. Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate agricultural stresses.

Flooding events from heavy precipitation can result in livestock deaths and loss of agriculture, and heavy precipitation events are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding due to increased runoff.

There is very high confidence of an increase in relative sea level projected by CMIP5 (RCP8.5) and CMIP6 (SSP5-8.5) to be on the order of 0.3m by the 2050s (IPCC Interactive Atlas, 2021). SLR is also highly likely to cause greater frequency of saltwater intrusion into coastal aquifers (namely the Trarza and Benichab aquifers) causing groundwater level rise and so when combined with more intense precipitation events, flooding both on the coast and at inland locations with proximity to affected aquifers (Agoubi, 2021; Mohamed et al., 2017). The latest IPCC AR6 (2021) states that for sandy coasts such as along the coast of Mauritania, there is high confidence of an increase in coastal erosion with the vast majority of sandy coasts projected to experience shoreline retreat through the 21st century (IPCC AR6, 2021). This has further impacts for coastal flooding (see section 4.4).

Heavy precipitation and flooding is likely to cause spread of water-borne diseases, stressing health systems. In addition, contamination of freshwater resources through aquifer saltwater intrusion will also impact the availability of potable water in Nouakchott (Mauritania) and the surrounding area (see section 4.5).

Increasing ocean acidification has a number of detrimental effects on livelihoods on the Mauritania coast including impacts on fisheries, especially when occurring alongside Sea

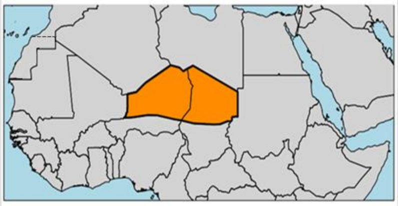
Surface Temperature (SST) increases and deoxygenation, though the impact on specific taxa is varied. Overall, negative effects on marine organisms may include changes to physiology and so reduced abundance, especially for calcifying organisms (such as molluscs) as acidification prevents larvae formation (Doney et al., 2020) - the impact of this at higher trophic levels is less certain but potentially significant for the health of fisheries (see section 4.3).

The impacts of increasing SSTs to the Canary Current are not well understood. Most observations suggest that the current has warmed since the early 1980s, and that the primary production of the current has decreased over the past two decades (medium confidence, IPCC AR5, 2014). This warming trend is projected to continue with a decrease to the upwelling system over the 21st century, although this change is expected to be relatively moderate (Blindoff et al., 2019; Sylla et al., 2019). Temperatures increases in the Canary Current has already resulted in changes to important fisheries species (IPCC AR5, 2014).

Zone 1 contains the northwest extent of the Niger River Basin (NRB). Though rainfall in this area is still very low (<300mm) compared to southern tropical parts of the basin meaning agriculture is limited to occasional seasonal pastureland employing traditional and mechanised irrigation techniques from groundwater sources (Ogilvie et al., 2016). Increasing interannual variability and uncertainty in water availability may impact groundwater recharge (see section 4.1).

The IPCC AR6 report (2021) projects that there is low confidence in the direction of change relating to dust storms in the Sahel however changes in dust storm activity, especially in arid regions like zone 1 may have implications for human mortality and health, including respiratory conditions, and dust-borne pathogens (see section 4.5).

3.4.2 Zone 2 – Desert east: Northern Niger and Chad



Baseline climate for Zone 2

Zone 2 contains the northern half of Niger and Chad in the eastern Sahel and is bordered by Sudan to the east and Algeria and Libya to the North. Zone 2 covers the south-central Sahara, encompassing the central Saharan highlands of the Adrar in Mali, the Aïr in Niger, and the Tibesti and Ennedi in Chad.

The region’s current climate is very similar to Zone 1: dry and hot, characterised by a seasonal pattern of warm and relatively wet summer period followed by rapidly decreasing temperatures and a cooler and dryer winter period. The highest temperatures occur at the beginning of the summer (June-September) season with mean daily temperatures reaching 33°C (ranging from 25°C to 40°C) in June/July. Lowest temperatures occur in December and January during the winter season (October-November) where mean daily temperatures are approximately 18°C (ranging from ~10°C to 26°C). There has been a small observed warming trend in mean, minimum, maximum temperature over the duration of the baseline period (1980-2010). This zone experiences very little rainfall in the winter months, with most of the annual rainfall total falling between June and September, although this rarely exceeds 100 mm.

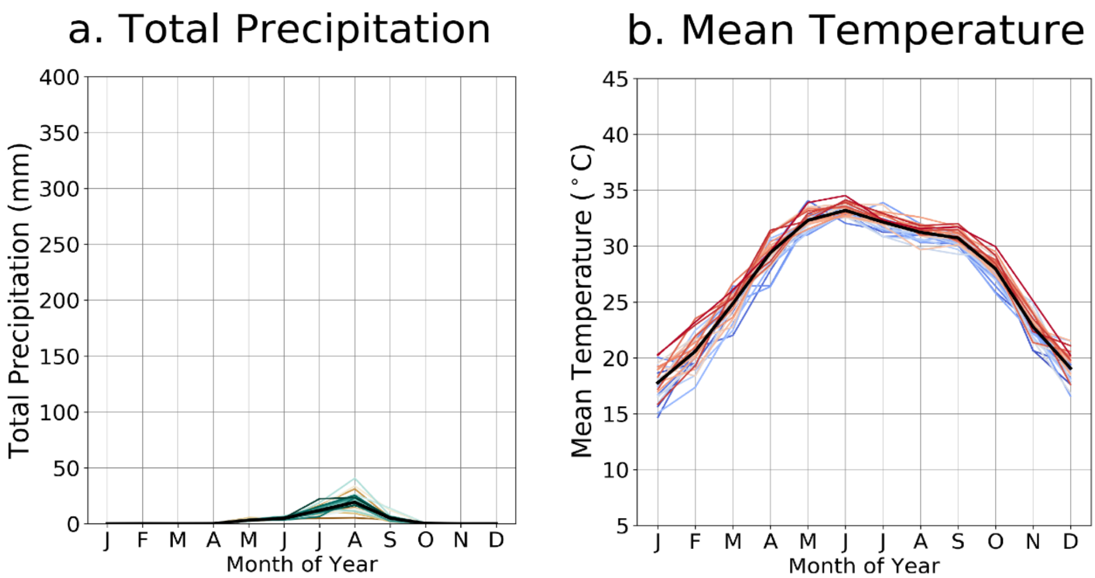


Figure 9: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 2. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 2

While most of Zone 2 is arid or hyper-arid, it contains important oasis areas such as the World Heritage Site of Ounianga in the Ennedi region of Chad. Zone 2 is entirely characterised by areas classified as pastoral and arid. Pastoral areas cover the southernmost latitudes of Zone 2, and parts of western Niger and eastern and northern Chad coincident with or are adjacent to upland areas. These uplands experience more rainfall than the Saharan lowlands, producing runoff that feeds the adjacent areas.

Future climate projections for Zone 2

In Zone 2, climate model projections show high confidence[12] in an increase of 2.5-4°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 9). Temperatures are projected to increase in all months, with some models indicating larger increases in mean daily temperature over the hottest months of the year. Mean daily minimum and maximum temperatures are also projected to increase (with greater increases between July and October), reaching or exceeding temperatures of 28°C and 45°C respectively in some

[12] High confidence is assigned when the majority of models agree on the direction of change.

models in the hottest months (June-August). There is uncertainty in precipitation projections, but most models show an increase in annual mean precipitation by up to 30% (+0-30mm) and fewer indicate a decrease. For seasonal precipitation, projections show medium confidence of little change in the dry seasons, with marginally larger changes projected for the rainy season (June-September) where change in rainfall is more uncertain. The majority of models indicate a change of between -50 and +50mm (Appendix B). Into the 2080s a similar precipitation trend emerges (under RCP8.5), and temperatures continue to increase (+4-7°C) in all months, though models have less agreement in both temperature and precipitation. In other scenarios (RCP4.5), temperature anomalies are smaller (1.5-3°C), but the precipitation trends remain similar. Spatially in zone 2, there is very good agreement across the models showing generally homogenous temperatures across the zone. There is much less agreement between the models for precipitation changes though generally there is a pattern of marginally drier conditions in the north and wetter conditions in the south into the 2050s.

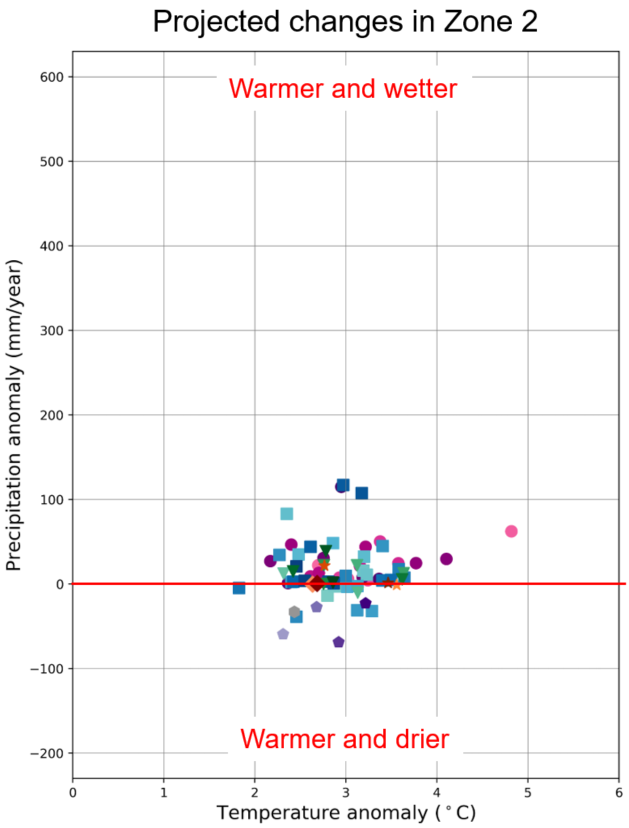


Figure 10: Projected change in average annual precipitation and temperature in Zone 2 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in the few urban environments in zone 2 (Agadez (Niger), Faya (formerly Largeau, Chad)) where the Urban Heat Island (UHI) effect[13] could further exacerbate heat-stress related health risks, particularly at night-time (IPCC AR6, 2021). Heatwaves are still poorly understood in the hyper-arid and arid regions of the Sahel, but these regions are especially vulnerable to heatwave due to the dependence on climate-sensitive practices, such as nomadic pastoralism (transhumant camel and goat-herding), where heat stress to animals is a major concern (Guigma et al., 2020; see section 4.2).

Furthermore, projections indicate that across zone 2 daily maximum temperatures will consistently exceed 40˚C in the hottest months (June-August). These temperatures will also be exceeded earlier in the year and for longer through the year, presenting an increased risk of heat stress. Currently, these temperatures are rarely reached.

Though very little agriculture occurs in this arid zone, increasing temperatures and temperature extremes are likely to impact oasis agriculture such as in Ounianga in the Ennedi region of Chad where perennial lakes are sustained by continuous flow from groundwater, balancing the effect of extremely high evaporation rates (Creutz et al., 2016). Future increases in temperatures may be impactful to this key oasis (and to pastoralism undertaken here) by disturbing the balance between groundwater influx and evaporation.

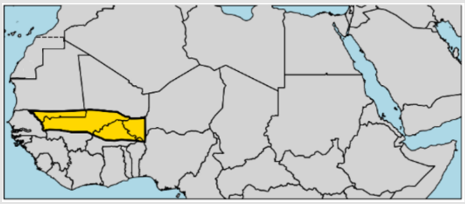
Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate stresses to nomadic pastoral livelihoods (see section 4.2).

Heavy precipitation events, which can lead to flooding and result in livestock deaths, are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding due to increased runoff (see section 4.2).

The IPCC AR6 report (2021) projects that there is low confidence in the direction of change relating to dust storms in the Sahel; however, changes in dust storm activity, especially in hyper-arid regions like zone 2, may have implications for human mortality and health, including respiratory conditions, and dust-borne pathogens (see section 4.5).

[13] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

3.4.3 Zone 3 – Mixed rainfall west: Southern Mauritania, Mali, southwest Niger, northern Burkina Faso



Baseline climate for Zone 3

Zone 3 covers the southernmost parts of central and eastern Mauritania, the south-central region of Mali, the northern half of Burkina Faso, and the westernmost part of Niger and is boarded by Senegal to the west. The western boundary of this zone follows the River Senegal and the Senegal-Mauritania border before taking an eastward direction at the latitude of the River Gambia. Zone 3 includes the Nigerien capital Niamey. The town of Gao (Mali) and the city of Ouagadougou (Burkina Faso) lie on the boundaries between Zones 1 and 3, and Zones 3 and 5, respectively.

The region is characterised by a moderately wet summer period (June-September) in which temperatures decline from hot to warm, rising moderately again at the start of winter (October-February), after which cooler and dryer conditions prevail. The highest temperatures occur towards the end of the spring (MAM) season with mean daily temperatures reaching 35°C (ranging from 27°C to 40°C) in May. Lowest temperatures occur in December and January during the winter season, where mean daily temperatures are approximately 24°C (ranging from 16°C to 32°C). There has been a small observed warming trend in mean, minimum, maximum temperature over the duration of the baseline period, especially in the winter and spring seasons. This zone experiences very little rainfall in the winter months, with much of the annual rainfall total falling between June and September – amount of total rainfall during this season is highly variable each year although it rarely exceeds 200mm.

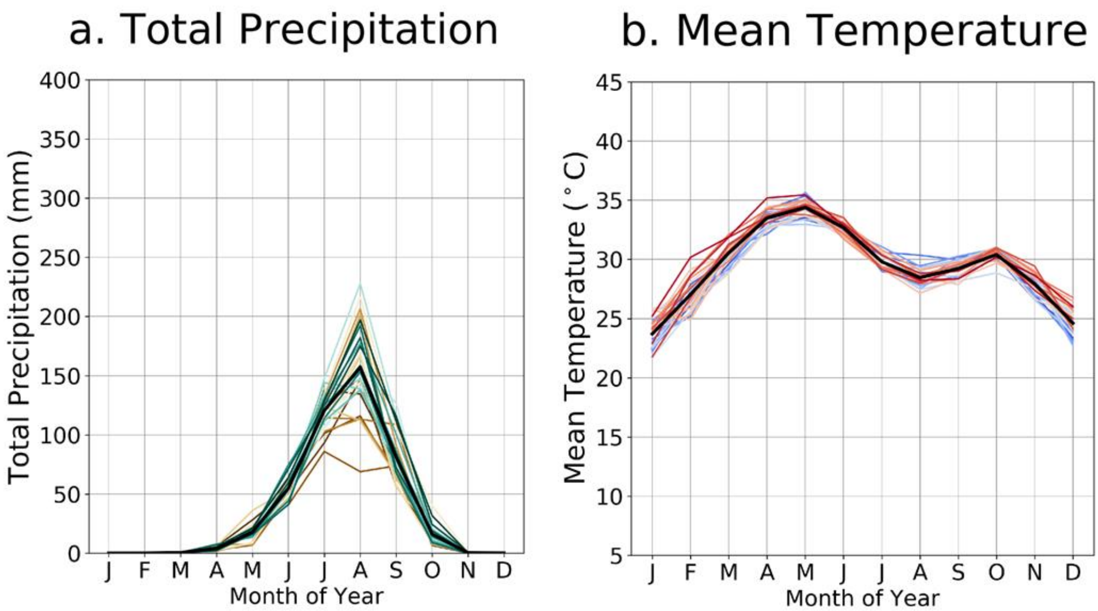


Figure 11: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 3. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 3

Livelihoods in Zone 3 are largely based on agro-pastoralism and the cultivation of millet and sorghum. In central and eastern Mali, this zone includes most of the area characterised by irrigated agriculture in the region of the inland Niger Delta and Niger Bend, which extends into western Niger to the east. Zone 3 extends into the northernmost parts of the zone of mixed rainfed agriculture. The highly variable nature of rainfall in the Sahel, and the latitudinal positions of different rainfall zones, mean that these livelihood zones are highly dynamic on timescales of years to decades.

Future climate projections for Zone 3

In Zone 3, climate model projections show high confidence[14] in an increase of 2-4°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 11). Temperatures are projected to increase in all months, with some models indicating larger increases in mean daily temperature over the hottest months of the year. Mean daily minimum and maximum temperatures are also projected to increase reaching or exceeding temperatures of 28°C and 40°C respectively in the hottest months (May/June). There is uncertainty in the direction of the projected trend in annual precipitation with more climate models projecting an increase of up to 25% (+0-75mm) and some projecting a small decrease. For seasonal precipitation, projections show medium confidence of little change in the dry seasons, with marginally larger changes projected for the rainy season (June-September). Change in rainfall is particularly

[14] High confidence is assigned when the majority of models agree on the direction of change.

uncertain and may increase or decrease (+/-50%) (Appendix B). Into the 2080s model projections (under RCP8.5) become increasingly uncertain for both temperature and especially precipitation, although trends are similar with a small number of climate models showing extreme increases for the summer. In general, temperatures continue to increase with a signal of +4 -7°C in all months. In other scenarios (RCP4.5), temperature anomalies are smaller (1.5-3°C) as are precipitation changes, with similar trends and more agreement between models. Spatially in zone 3, there is very good agreement between the models showing generally homogenous temperatures across the zone. There is much less agreement across the models for precipitation changes though generally there is a pattern of marginally drier conditions in the far west and wetter conditions in the east into the 2050s.

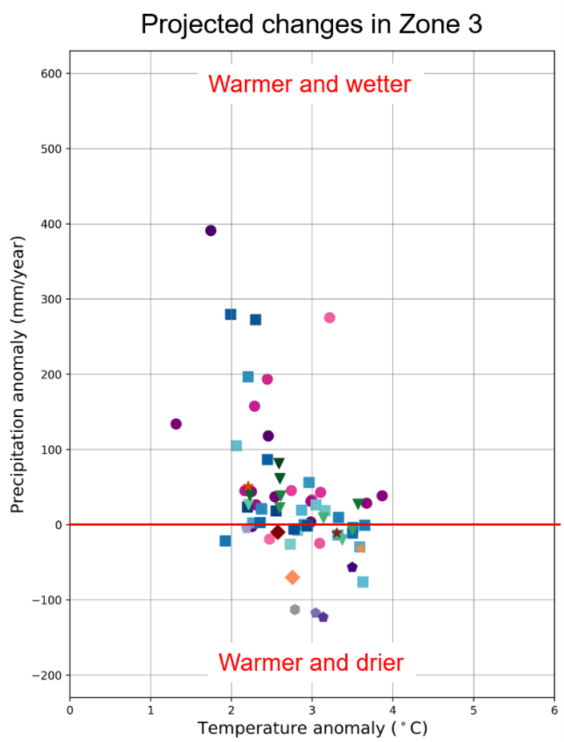


Figure 12: Projected change in average annual precipitation and temperature in Zone 3 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in the urban environments in zone 3, including the capital city of Niamey (Niger) where the Urban Heat Island (UHI) effect[15] could further exacerbate heat-stress related health risks, particularly at night-time (IPCC AR6, 2021). Heatwaves are expected to increase across the Sahel and in semi-arid regions such as zone 3, populations are especially vulnerable due

[15] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

to the dependence on climate-sensitive practices such as rainfed agriculture and pastoralism. Heat stress to key crops such as sorghum and millet as well as animals is a major concern for the region (Guigma et al., 2020), see section 4.2).

Furthermore, projections indicate that across zone 3 daily maximum temperatures will consistently exceed 40˚C in the hottest months (March-May). These temperatures will also be exceeded earlier in the year and for longer through the year, presenting an increased risk of heat stress. Currently, these temperatures are rarely exceeded.

Rainfed agropastoral systems and pastoralists are particularly vulnerable to delayed onset of the wet season, as this causes scarcity of pasture and water for crop production and livestock rearing. There is high confidence in the delay of the West African Monsoon and associated rains.

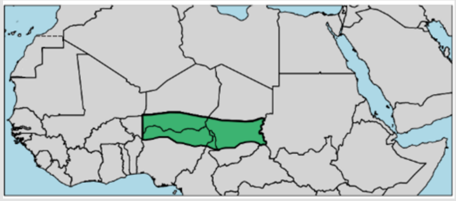
Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate agricultural stresses (see section 4.2). Flood events from heavy precipitation can result in livestock deaths and loss of agriculture, and heavy precipitation events are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding in Niamey due to increased runoff and flooding from the River Niger (see section 4.2).

Precipitation is projected to have small increases and rising temperatures are very likely to offset any additional water availability through increased evaporation rates (see section 4.1). Zone 3 may also be vulnerable to the projected spatial asymmetries of the WAM (see Focus Box 3) where the western regions may receive less rainfall than the east, though projections are especially uncertain for inland Sahel compared to West Africa.

Zone 3 contains Inland Niger Delta (IND); part of the Niger River Basin (NRB) in central Mali) which is sensitive to flooding in the rainy season, though risk is highly related to land use within the basin and the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). Floodplains of the IND support a large amount of agriculture and pastoralism including rice production and livestock grazing as well as fishing, and water availability is dependent on the annual inundation of the delta (Morand et al., 2012). With increasing interannual variability in precipitation, this inundation may be less reliable (Thompson et al., 2021). Increasing interannual variability and uncertainty in water availability may also impact groundwater recharge, though this is less clear in the semi-arid regions compared to the tropics (see section 4.1).

Increasing precipitation projections may coincide with increases in hydroelectricity production along the River Niger (Oyerinde et al., 2016); however, greater interannual variability (and associated frequency of flood and drought events) will affect the reliability of hydropower generation and dam storage. Therefore, it is likely that a tailored approach will be needed at country-level or smaller for management of hydropower in the 2050s (see section 4.4). In addition, increasing frequency of intense rainfall events are likely to impact water quality downstream, for example due to run-off of agrochemical pollutants into rivers (Aliyu et al., 2015) (see section 4.1).

3.4.4 Zone 4 – Mixed rainfall east: South-eastern Niger and central Chad



Baseline climate for Zone 4

Zone 4 covers south-eastern Niger and south-central Chad. Outside of the G5 area, Zone 4 extends into northern Nigeria and is boarded by Sudan to the east. The region is characterised by a moderately wet summer period (June-September) in which temperatures decline from hot to warm, rising moderately at the start of winter (October-February), after which cooler and dryer conditions prevail. The highest temperatures occur in the spring (March, April, May) season with mean daily temperatures reaching 33°C (ranging from 25°C to 40°C) in April/May. Lowest temperatures occur in December and January during the winter season where mean daily temperatures are approximately 23°C (ranging from 15°C to32°C). There has been a small observed warming trend in mean, minimum, maximum temperature over the duration of the baseline period. This zone experiences very little rainfall in the winter months, with most of the annual rainfall total occurring between June and September, amounts of total rainfall during this season is highly variable each year although it rarely exceeds 250mm.

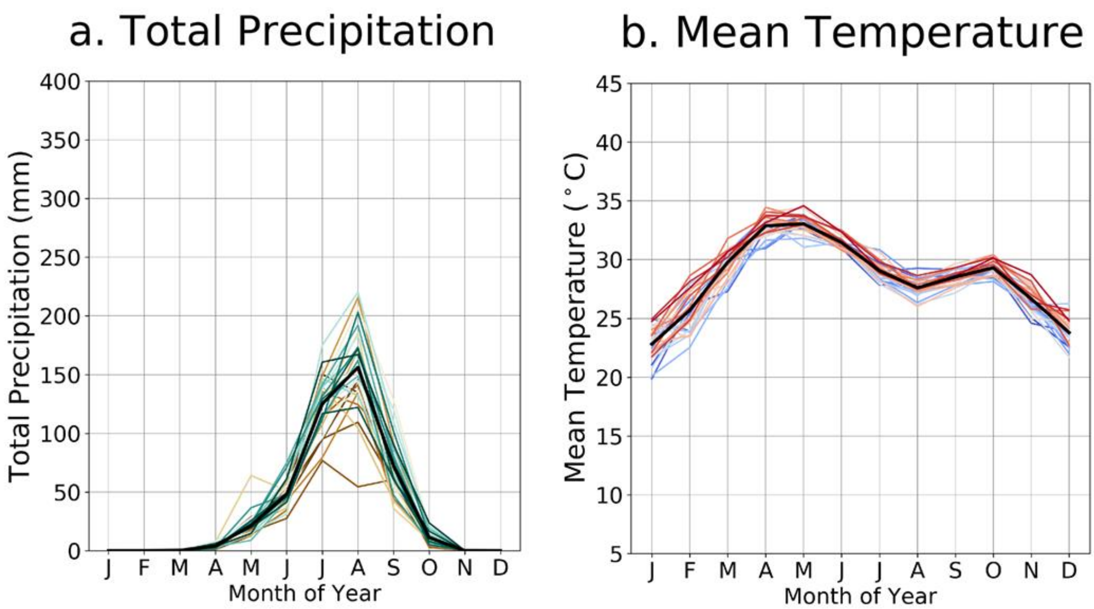


Figure 13: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 4. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 4

Zone 4 coincides with the zone of pastoral and agro-pastoral (rainfed sorghum and millet) livelihoods with irrigated crops cultivated along the Niger river (rice) and around the Komadougou-Yobe river along the Niger-Nigeria border leading into Lake Chad in the east. Crops include cereals, legumes, and vegetables (especially peppers). Across south-central Chad, Zone 4 encompasses the main pastoral agro-pastoral zones, as well as part of the zone of rainfed agriculture to the south and cultivation around the Logone and Chari rivers leading into Lake Chad. Zone 4 also covers flood recession cultivation and fishing livelihoods on Lake Chad, in both Niger and Chad, and important trade networks around the lake (although livelihoods and trade around Lake Chad and Niger Bend and Delta have been significantly disrupted by ongoing armed conflict).

Future climate projections for Zone 4

In Zone 4, climate model projections show high confidence[16] in an increase of 2-4°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 13). Temperatures are projected to increase in all months, with some climate models indicating larger increases in mean daily temperature over the hottest months of the year. Mean daily minimum and maximum temperatures are also projected to increase, exceeding temperatures of 25°C and 40°C respectively in the hottest months (April/May). There is uncertainty in the direction of the projected trend in annual precipitation, but the majority of models show that annual mean precipitation is projected to increase by up to 25% (+0-100mm). For seasonal precipitation, projections show medium confidence of little change in the dry seasons, with larger changes projected for the rainy season (June-September). Change in rainfall is particularly uncertain but more climate models show increases of up to 20% (+0-100mm) (Appendix B). A small number of projections indicate increases of over 100% (over +200mm) in the rainy season. Into the 2080s (under RCP8.5) model projections become increasingly uncertain in both temperature and especially precipitation and more so during the rainy season. Temperatures continue to increase with a signal of +4-6.5°C in all months. The majority of models indicate that summer rainfall will increase but anomalies range from +0 to over +300% (up to +500mm) with little model consensus. In other scenarios (RCP4.5), temperature anomalies are smaller (1-3°C) as are precipitation changes - trends remain similar and there is more agreement between models. Spatially in Zone 4, there is very good agreement between the models showing generally homogenous temperatures across the zone. There is much less agreement

[16] High confidence is assigned when the majority of models agree on the direction of change.

between the models for precipitation changes though generally there is a pattern of marginally drier conditions in the east and wetter conditions in the west into the 2050s.

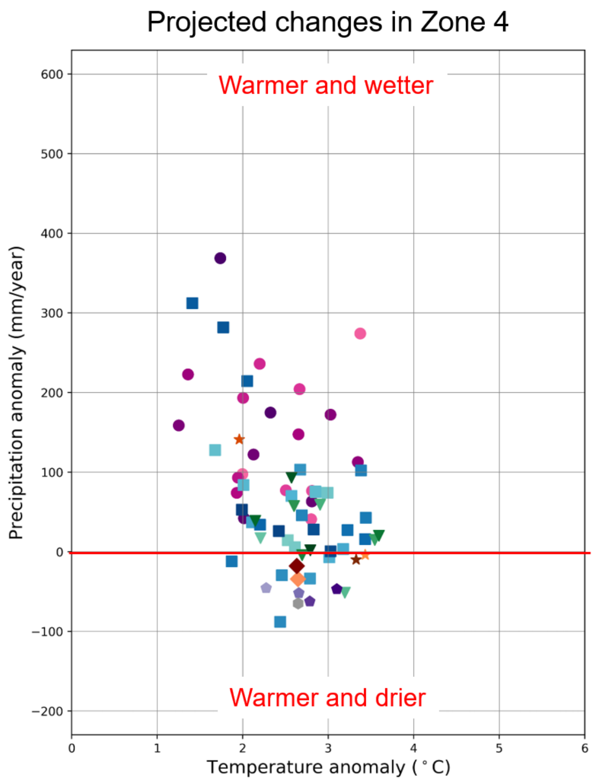


Figure 14: Projected change in average annual precipitation and temperature in Zone 4 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in the urban environments in zone 4, including Zinder (Niger) and the capital city of N'Djamena (Chad) where the Urban Heat Island (UHI) effect[17] could further exacerbate heat-stress related health risks, particularly at night-time (IPCC AR6, 2021). Heatwaves are expected to increase across the Sahel and in semi-arid regions such as zone 4, populations are especially vulnerable due to the dependence on climate-sensitive practices such as rainfed agriculture and pastoralism. Heat stress to key crops such cereals, legumes and vegetables as well as animals is a major concern for the region (Guigma et al., 2020), see section 4.2).

[17] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

Furthermore, projections indicate that across zone 4 daily maximum temperatures will consistently exceed 40˚C in the hottest months (March-May). These temperatures will also be exceeded earlier in the year and for longer through the year presenting an increased risk of heat stress. Currently, these temperatures are rarely exceeded.

Rainfed agropastoral systems and pastoralists are particularly vulnerable to delayed onset of the wet season as this causes scarcity of pasture and water for crop production and livestock rearing. There is high confidence in the delay of the WAM and associated rains.

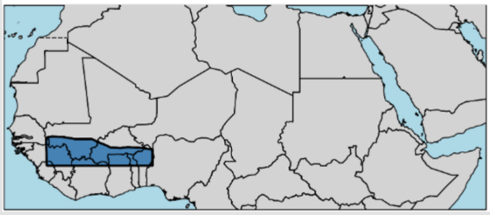
Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate these agricultural stresses (see section 4.2). Flooding events from heavy precipitation can result in livestock deaths and loss of agriculture, and heavy precipitation events are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding in N'Djamena (Chad) due to increased runoff and flooding from the Chari and Logone Rivers that feed nearby Lake Chad (see section 4.2).

Precipitation is projected to have small increases and rising temperatures are very likely to offset any additional water availability through increased evaporation rates (see section 4.1). However, zone 4 may also be affected by the projected spatial asymmetries of the WAM (see Focus Box 3), where the eastern regions may receive more rainfall than the west, though projections are more uncertain for the central inland Sahel compared to West Africa.

Zone 4 contains Lake Chad and the major rivers that feed it (the Chari and Logone) (see Focus Box 7 on Lake Chad Basin). This area is sensitive to flooding in the rainy season, though risk is highly related to land use within the basin and the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). N'Djamena is especially vulnerable due to the increased runoff associated with city infrastructure and the large population.

Projected rainfall change is significant in zone 4 due to the impact rainfall changes have on river flows and lake levels, particularly for Lake Chad (see Focus Box 7) where shallow lake depth is highly sensitive to increased temperatures and evaporation, affecting water depth, quality, nutrients and extent which in turn impacts livelihoods (e.g., floodplain agriculture and fisheries) more (Ogutu-Ohwayo et al., 2016).

3.4.5 Zone 5 – Tropical east: Southern Mali and Burkina Faso



Baseline climate for Zone 5

Zone 5 covers southern half of Burkina Faso and the far south of Mali and extends into the northern regions of Guinea, Côte d'Ivoire, Ghana, Togo and Benin, and into the far west of Nigeria. Zone 5 includes Mali's capital city of Bamako, and the key regional towns of Sikasso and Bobo Dioualasso, while Burkina Faso's capital city of Ouagadougou is located along the boundary between Zone 5 and 3. The northern boundary of Zone 5 follows the transition from the Sudano-Sahelian zone to the more humid Sudanian zone.

The region is characterised by a wet summer period in which temperatures decline from hot to warm, rising moderately again at the start of winter, after which cooler and dryer conditions prevail. There are only small differences between the highest and lowest temperatures throughout the year (6°C). The highest temperatures occur in the spring (MAM) season with mean (minimum, maximum) daily temperatures reaching 31°C (25°C, 38°C) in April. Lowest temperatures occur in December and January during the winter season (ONDF) where mean (minimum, maximum) daily temperatures are approximately 25°C (18°C, 30°C). This zone experiences significantly less rainfall in the winter months, with most of the annual rainfall total occurring between June and September, sometimes exceeding 300mm.

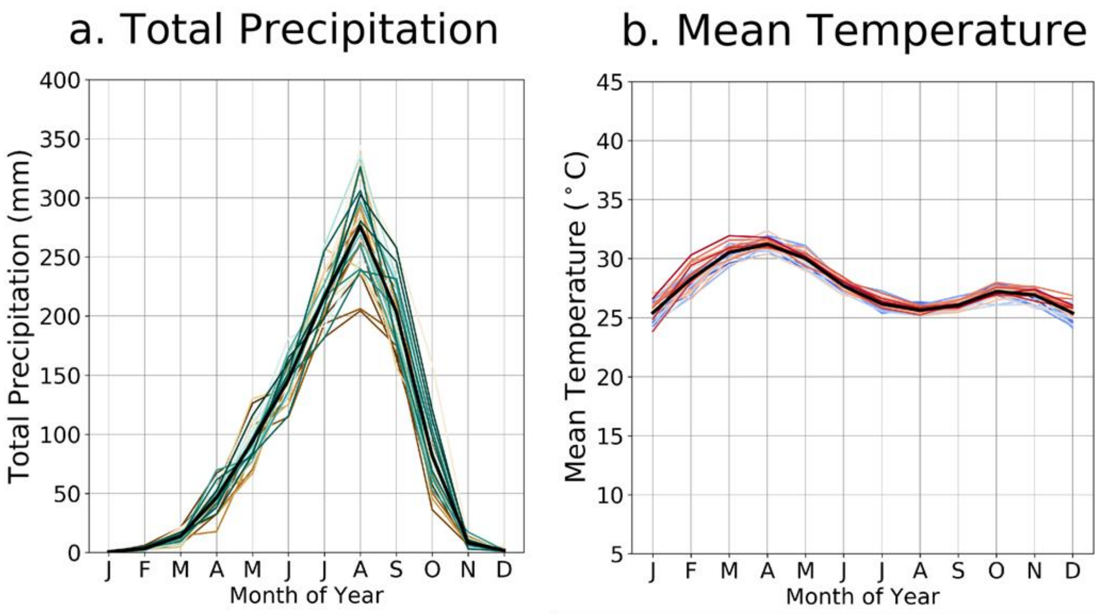


Figure 15: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 5. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 5

Zone 5 is characterised by mixed agriculture, including the cultivation of cereals (maize, sorghum), cotton, tubers, legumes (peanuts, cowpea) and fruit and vegetables, supported in places by small-scale irrigation using groundwater and seasonal surface water sources. Sedentary livestock rearing is an activity of most households. Gold mining (artisanal) is a key source of income in some locations.

Future climate projections for Zone 5

In Zone 5, climate model projections show high confidence[18] in an increase of 2-3.5°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 15). Temperatures are projected to increase in all months, with some models indicating larger increases in mean daily temperature over the hottest months of the year. Mean daily minimum and maximum temperatures are also projected to increase, with temperatures exceeding 25°C and 40°C respectively in the hottest months (April/May).

There is uncertainty in the direction of the projected trend in annual precipitation, but the majority of the climate models show that annual mean precipitation is projected to increase by up to 15% (+0-80mm). For seasonal precipitation, projections show medium confidence of little change in the spring season (March-May), and small increases in the winter season (October-February) with most models indicating increases of up to 50% (+0-80mm). Larger increases are projected for the rainy season (June-September) and projections are more

[18] High confidence is assigned when the majority of models agree on the direction of change.

uncertain, but more models show increases of up to 20% (+0-80mm) in this season (Appendix B). Into the 2080s (under RCP8.5) model projections become more uncertain in both temperature and precipitation. In general, temperatures continue to increase with a signal of +3.5-6.5°C in all months. There is a lot of uncertainty in the direction of the projected trend in annual precipitation with more climate models projecting an increase and some projecting a decrease. In other scenarios (RCP4.5), temperature anomalies are smaller (1-3°C) as are precipitation changes - trends remain similar and there is more agreement between models. Spatially in Zone 5, there is very good agreement between the models showing generally homogenous temperatures across the zone. There is much less agreement between the models for precipitation changes into the 2050s.

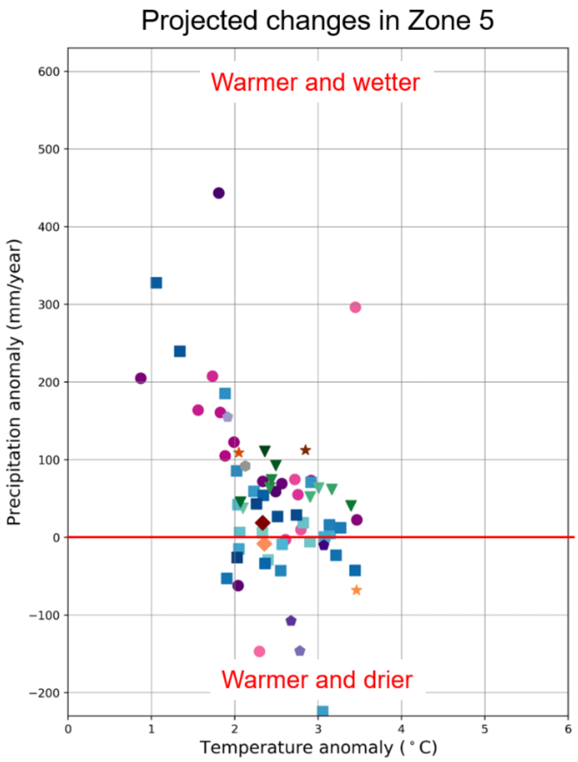


Figure 16: Projected change in average annual precipitation and temperature in Zone 5 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in the urban environments in zone 5, including Mali's capital city of Bamako, and the key regional towns of Sikasso and Bobo Dioualasso, and Burkina Faso's capital city of Ouagadougou where the Urban Heat Island (UHI) effect[19] could further exacerbate heat-stress

[19] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

related health risks, particularly at night-time (IPCC AR6, 2021). Heatwaves are expected to increase across the Sahel, and populations using rain-fed agriculture may be especially vulnerable. Heat stress to key crops, such as cereals (maize, sorghum), cotton, tubers, legumes (peanuts, cowpea) and fruit and vegetables, is a major concern for the region as well as the impact of heat stress on sedentary livestock (Guigma et al., 2020), see section 4.2). Cotton crops are especially sensitive to increasing temperatures and begin to fail at 35˚C (Cunningham et al., 2021). Heat stress will also affect physical labour activities in the zone, which may be particularly impactful for outdoor workers such as artisanal mine workers (Kjellstrom et al., 2014) (see section 4.5).

Furthermore, projections indicate that across zone 5 daily maximum temperatures will consistently exceed 40˚C in the hottest months (March-May). These temperatures will also be exceeded earlier in the year and for longer through the year presenting an increased risk of heat stress. Currently, these temperatures are rarely exceeded.

Rainfed agropastoral systems in the zone are particularly vulnerable to delayed onset of the wet season as this causes scarcity of water for crop production and livestock rearing. This may also put more pressure on irrigated agriculture. There is high confidence in the delay of the WAM and associated rains.

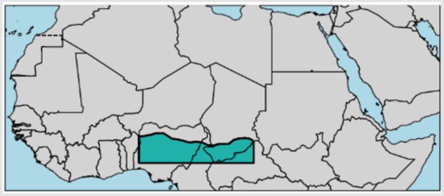
Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate these agricultural stresses (see section 4.2). Flooding events from heavy precipitation can result in livestock deaths and loss of agriculture, and heavy precipitation events are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding in Bamako due to increased runoff and flooding from the River Niger (see section 4.2).

Precipitation is projected to have small increases, and rising temperatures are very likely to offset any additional water availability through increased evaporation rates (see section 4.1). Zone 5 may also be vulnerable to the projected spatial asymmetries of the WAM (see Focus Box 3) where the western regions may receive less rainfall than the east, though projects are more uncertain for the western Sahel compared to West Africa.

Zone 5 contains the River Niger, which is sensitive to flooding in the rainy season, though risk is highly related to land use within the basin and the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). Floodplains of the Niger River Basin (NRB) supports a large amount of agriculture, some pastoralism and fishing. With increasing interannual variability in precipitation river flows and groundwater recharge may be affected (Thompson et al., 2021). Ground water is especially important in this zone because it is heavily used in small-scale irrigation for agriculture (see section 4.2).

Increasing precipitation projections may coincide with increases in hydroelectricity production along the River Niger (Oyerinde et al., 2016) but greater interannual variability (and associated frequency of flood and drought events) will affect the reliability of hydropower generation and dam storage. Therefore, it is likely that a tailored approach will be needed at country-level or smaller for management of hydropower in the 2050s (see section 4.4). In addition, increasing frequency of intense rainfall events are likely to impact water quality downstream, for example due to increased runoff of agrochemical pollutants into river systems (Aliyu et al., 2015) (see section 4.1).

3.4.6 Zone 6 – Tropical west: Southern Chad



Baseline climate for Zone 6

Zone 6 covers the far south of Chad and extends into central Nigeria, a northern portion of Cameroon, northern Nigeria and the northeast of the Central Africa Republic.

The region is characterised by a wet summer period (June-September) in which temperatures decline from relatively hot to warm, rising moderately again at the start of winter (October-February), after which cooler and dryer conditions prevail. There are only small differences between the highest and lowest temperatures throughout the year (5°C). The highest temperatures occur in the spring (March-May) season with mean (minimum, maximum) daily temperatures reaching 30°C (ranging from 25°C to 37°C) in April. Lowest temperatures occur in December and January during the winter season where mean daily temperatures are approximately 25°C (ranging from 17°C to, 30°C). This zone experiences significantly less rainfall in the winter months, with most of the annual rainfall total occurring between June and September, sometimes exceeding 300mm.

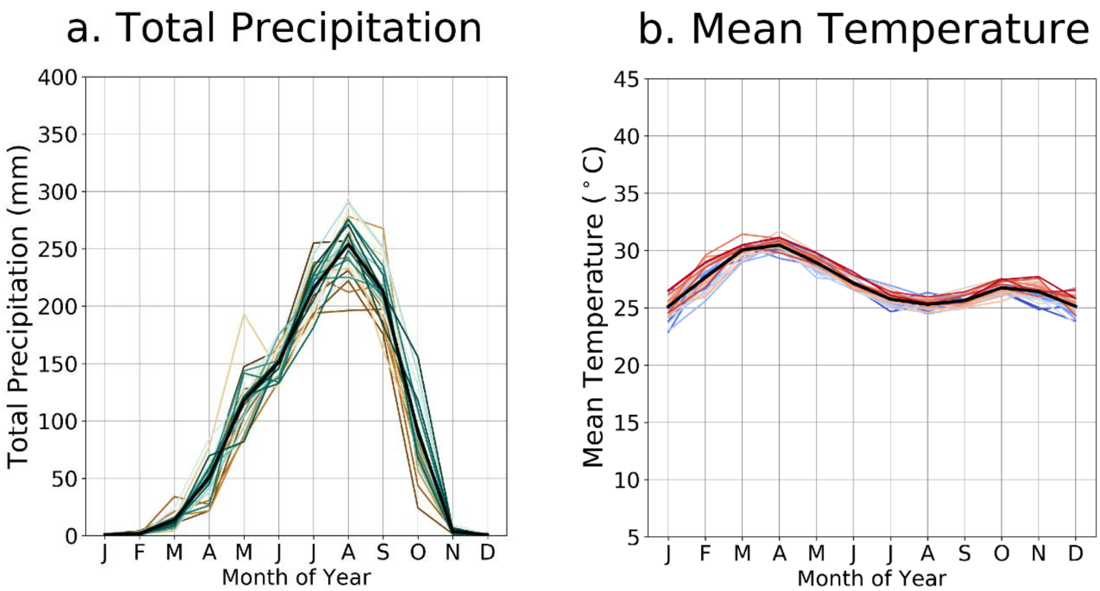


Figure 17: Observations of a. total monthly precipitation and b. average daily mean temperature over the baseline period (1981-2010) for Zone 6. Each line is one individual year. Colours show the ordering of the years from brown-blue (total precipitation) and blue-red (mean temperature) – this highlights the presence, or lack of, a trend over the baseline period. The bold black line indicates the average of the 30-year period. Observational dataset: CHIRPS and WFDEI for precipitation and temperature respectively. Similar plots for baseline minimum and maximum temperature shown in Appendix B.

Socio-economic context for Zone 6

Zone 6 is essentially an eastern counterpart to Zone 5, in which livelihoods are strongly focused on mixed agriculture, including the cultivation of cereals, tubers, and legumes. This includes cultivation around the Logone and Chari rivers, which feed into Lake Chad, including flood-plain rice cultivation. There is some raising of livestock (especially goats) in this zone, alongside movements of transhumance herders between Cameroon and Central African Republic.

Future climate projections for Zone 6

In Zone 6, climate model projections show high confidence[20] in an increase of 1.5-3.5°C in annual mean temperatures in the 2050s relative to the 1981-2010 baseline (Figure 17). Temperatures are projected to increase in all months, with some climate models indicating larger increases in mean daily temperature over the hottest months of the year. Mean daily minimum and maximum temperatures are also projected to increase, with temperatures exceeding 25°C and 40°C respectively in the hottest months (April/May). There is uncertainty in the direction of the projected trend in annual precipitation, but the majority of the climate models show that annual mean precipitation is projected to increase by up to 20% (+0-100mm). For seasonal precipitation, projections show medium confidence of little change in the spring season (March-May), and moderate increases in the winter season (October-February) rainfall with most models indicating increases of up to 40% (+0-75mm). Smaller increases are projected for the rainy season (June-September) and projections are more uncertain, but more models show increases of up to 30% (+0-200mm). Into the 2080s (under RCP8.5), climate model projections become more uncertain in both temperature and precipitation. In general, temperatures continue to increase with a signal of +3-6°C in all months. There is a lot of uncertainty in the direction of the projected trend in annual precipitation with more climate models projecting an increase and some projecting a decrease. In other scenarios (RCP4.5), temperature anomalies are smaller (1-2.5°C) as are precipitation changes - trends remain similar and there is more agreement between models. Spatially in Zone 6, there is very good agreement between the climate models, which show generally homogenous temperatures across the zone. There is much less agreement between the models for precipitation though generally there is a pattern of marginally wetter conditions in the east into the 2050s.

[20] High confidence is assigned when the majority of models agree on the direction of change.

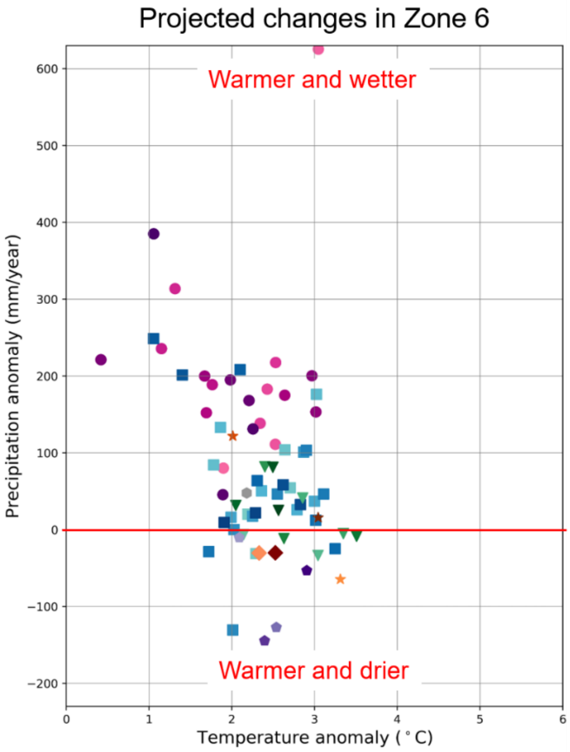


Figure 18: Projected change in average annual precipitation and temperature in Zone 6 from a selection of climate models. Each dot shows the difference between the average projected values in the 2050s and the average values in the current climate, for each climate model. The red line indicates the zero axis i.e., no change in precipitation. Similar plots for projected trends in seasonal means are in Appendix B.

Rising temperatures in this already hot region will increase the risk of heat-related risks, particularly in the urban environments in zone 6 including Moundou (Chad) where the Urban Heat Island (UHI) effect[21] could further exacerbate heat-stress related health risks, particularly at night-time (IPCC AR6, 2021). Heatwaves are expected to increase across the Sahel, and populations using rain-fed agriculture in this zone may be especially vulnerable. Heat stress to key crops, such as cereals (maize, sorghum), cotton, tubers and legumes (peanuts, cowpea), is a major concern for the region as well as the impact of heat stress on sedentary livestock (Guigma et al., 2020), see section 4.2). Cotton crops are especially sensitive to increasing temperatures and begin to fail at 35˚C (Cunningham et al., 2021). Heat stress will also affect physical labour activities in the zone which may be particularly impactful for outdoor workers such as those employed in mines or urban construction (Kjellstrom et al., 2014) (see section 4.5).

Furthermore, projections indicate that across zone 6 daily maximum temperatures will consistently exceed 40˚C in the hottest months (March-May). These temperatures will also be

[21] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

exceeded earlier in the year and for longer through the year presenting an increased risk of heat stress. Currently, these temperatures are rarely exceeded.

Rainfed agropastoral systems in the zone are particularly vulnerable to delayed onset of the wet season as this causes scarcity of water for crop production and livestock rearing. This may also put more pressure on irrigated agriculture. There is high confidence in the delay of the WAM and associated rains.

Interannual variability of amounts and timings of the seasonal rains will remain large in the future and is projected to increase across the Sahel relative to the present-day, resulting in a higher frequency of wetter and drier years relative to the mean, which could further exacerbate these agricultural stresses (see section 4.2). Flooding events from heavy precipitation can result in livestock deaths and loss of agriculture, and heavy precipitation events are projected to increase in frequency and intensity. Intense rainfall events may also exacerbate urban flooding in Bamako (Mali) (see section 4.2). Projected increased runoff may also exacerbate pollution downstream (into Lake Chad, zone 5), especially with greater use of agro-chemicals in farming.

Precipitation is projected to have small increases, and rising temperatures are very likely to offset any additional water availability through increased evaporation rates (see section 4.1). However, zone 6 may also be affected by the projected spatial asymmetries of the WAM (see Focus Box 3), where the eastern regions may receive more rainfall than the west, though projections are more uncertain for the central inland Sahel compared to West Africa.

Zone 6 contains part of the Chad River Basin and Logone and Chari Rivers which are sensitive to flooding in the rainy season, though risk is highly related to land use within the basin and the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). Floodplains of the Logone and Chari rivers support a large amount of agriculture including rice, some pastoralism and fishing. The region also sees movements of transhumance herders moving between Cameroon and the Central African Republic. With increasing interannual variability in precipitation river flows and groundwater recharge may be affected (Thompson et al., 2021). Ground water is especially important in this zone because it is heavily used in small-scale irrigation for agriculture (see section 4.2).

Image location: Bamako, Mali

4 Climate change risks and interpretation for the Sahel region

This section examines key climate related risks as relevant to the critical development themes and sectors. The sectors addressed are water resources, agriculture and pastoralism, aquaculture and fisheries, settlements and infrastructure, human health and mortality, and biodiversity and ecology. Coastal risks are addressed for Mauritania in the context of these key sectors.

The following discussion focuses on the geographical distribution of potential climate change impacts and related risks, including risks arising from the interaction of direct climate change impacts with socioeconomic and demographic trends. However, it must be stressed that risks and impacts will be experienced differently by different individuals and population groups as a result of socially differentiated exposure and vulnerability, even within the same area or location (see Focus Box 5). Vulnerability to climate change and its impacts will vary based on a suite of related factors such as gender, economic and employment status, livelihood, age, disability, political marginalisation, ethnicity, and the availability of key services such as water, power, finance, and hazard early warning systems.

The recent historical record provides us with abundant evidence relating to the nature and outcomes of climate hazards and climate-related disasters. Much of this evidence is inconsistent or contradictory, particularly in relation to the links between climate, conflict and migration. To a very large extent, this is because outcomes associated with hazards, such as drought, water scarcity and other manifestations of climate variability, are highly context specific. For example, conflict in the Sahel has been associated with both rainfall deficits and surpluses (Salehyan and Hendrix 2014, Abroulaye et al. 2015, Hendrix and Salehyan 2015), and convincing evidence for drought as a driver of conflict is lacking, although it may act as a trigger for conflict where more fundamental social, economic and political drivers establish the preconditions for conflict (Thébaud and Batterby 2001, Benjaminsen 2008, Turner 2011, Benjaminsen et al. 2012, Rayleigh 2010). Existing research shows similarly complex links between climate-related changes and migration (see Selby and Daoust 2021).

Nonetheless, caution needs to be exercised when using the past as a guide to the future. The evidence represented by the above sources represents approximately half a century during a period of relative global climatic stability. As global temperatures increase, the impacts of climate change will become more severe, and hazards of unprecedented magnitude will become more likely. New hazards may emerge in some regions, such as periodic episodes of heat and humidity that exceed human tolerances, as discussed as discussed in Section 4.5. Shifts in regional climate may occur rapidly, altering the distribution of key resources such as water and productive or habitable land. Where climatic and environmental stresses have previously represented one set of factors influencing decisions about migration, or influencing but not driving conflict dynamics, unprecedented hazards and large shifts in climatic and environmental conditions may become much more important as drivers of social and economic change. Perhaps counterintuitively, the high degree of historical climatic and environmental variability in the Sahel, and the highly dynamic nature of human responses to this variability, may mitigate against such large societal disruptions in societies that are accustomed to coping with and adapting to change. Nonetheless, the potential for future risks to be very different from those experienced in the region during the historical period needs to be considered in policy and planning.

4.1 Water resources

<u>Summary of risks relevant to water resources and water dependant services</u>

- Annual temperature increases and temperature extremes across the Sahel region could increase evaporative water losses and reduce surface runoff and groundwater recharge, presenting risks to water availability.
- Economic growth and diversification, including agricultural expansion and mining, and large-scale climate adaptation responses, will increase demand for water and place additional pressure on water resources.
- Projected increases in intense rainfall events and associated flooding pose risks to water infrastructure and supply systems and water quality, particularly in urban areas.
- Projected increases in sea level around the coast of Mauritania present risks of saltwater intrusion into coastal aquifers, contaminating freshwater resources.
- Existing patterns of social marginalisation and inequality, including those associated with gender and income, will shape risks resulting from changes in water availability and access.
- Climate-related risks to water availability, demand, supply and quality in the Sahel region will be mediated by transboundary water management dynamics, including both conflict and cooperation.

4.1.1 Risks to water availability

Changes in water availability in the Sahel will result from changes in total renewable water resources, changes in non-renewable water resources, and changes in water demand. Changes in internal total internal renewable water resources will be influenced by changes in precipitation and temperature. Existing studies and projections suggest a mixed and uncertain future for water resources in the central and eastern Sahel, where projections indicate that higher temperatures are likely to be accompanied by higher rainfall and increased rainfall intensity. However, projected small changes or declines in rainfall in the western Sahel suggest that this region is likely to experience an overall decline in water availability.

Changes in total (overall) renewable water resources will also depend on changes in water entering a country, which may be affected by climatic changes and by changes in abstraction and water management in upstream countries (see Section 4.1.3). Changes in non-renewable water resources are likely to be driven predominantly by abstraction of groundwater. The amount of water available for any given consumer may also be influenced by changes in demand, with increases in demand affecting per capita availability and availability for actors such as business, industry and agriculture. Furthermore, changes to water availability and capacities for adaptation will be shaped by patterns of differentiated vulnerabilities (see Focus Box 5), which will need to be considered in water management and planning.

Precipitation is projected to increase in the central Sahel (zones 2, 4 and 6) and decrease in the most westerly longitudes (zones 3 and 5), especially along the coast of Mauritania (zone 1) (medium confidence, IPCC AR6, 2021) (see section 3.2). Much of the projected increase occurs in the wet season (June-September), although increases in the winter (October-February) season are indicated in zones 5 and 6 (southern Burkina Faso and Chad). This is consistent with a projected shift in the seasonality of the rainy season, associated with the delayed onset of the West African Monsoon (high confidence) and its delayed retreat (medium confidence) (Dunning et al., 2018; Biasutti et al., 2013). This could mean more abundant water resources in the later part of the year, especially in zones 5 and 6. Additionally, maximum rainfall amounts are projected to increase, with the largest increases (+40%) in the east (zones 2 and 4) and no change or smaller increases (0-10%) in the west (zones 1 and 3). Moderate increases (10-20%) are projected for the south (zones 5 and 6). Projections are especially uncertain for the north and west (zones 1, 2 and 3) (low confidence; IPCC Interactive Atlas, 2021).

The trend in the Sahel towards longer dry periods between rainfall events, and for rainfall to occur in fewer, more intense precipitation events (see Focus Box 6) may have implications for groundwater recharge. According to the IPCC AR6 report (2021), there is medium confidence that increased precipitation intensities will enhance groundwater recharge in the tropics, which may be relevant to zones 5 and 6. However, even where rainfall is projected to increase, projected annual temperature increases across the whole Sahel region, with more frequent and extreme maximum temperatures sustained for longer periods, will increase evaporative water losses, acting to reduce surface runoff and groundwater recharge. Increased evaporation of surface water negatively affects river flows, groundwater reserves, lakes, and reservoirs. Increased evaporation, combined with greater interannual variability (IPCC AR6, 2021), means that water availability may remain similar to current levels or decline by the 2050s.

Economic growth and diversification will likely increase demand for water, as will any expansion of agricultural zones. This will place additional pressure on groundwater resources, which may already be negatively impacted by climate change, for example where the impacts of higher temperatures dominate over increases in rainfall (possible in Zones 2, 4, 5 and 6), or where they combine with reduced rainfall (potentially in Zones 1 and 3). The agricultural sector accounts for the largest proportion of water withdrawals in most G5 countries (FAO AQUASTAT, 2021; see Section 2).

Large-scale responses to climatic and environmental change may affect water demands and resources. For instance, the 'Great Green Wall' initiative involving the restoration of 100 million hectares of 'degraded' land across 11 countries including the G5 by 2030, includes large-scale reforestation and vegetation regeneration efforts as well as water harvesting, retention, and conservation measures (UNCCD, 2020). Such adaptation measures will likely involve increased demands on water resources.

Mining has affected and will continue to affect water resources in the Sahel region. Mining of uranium in Niger, gold in Burkina Faso, and iron ore, gold and copper in Mauritania consumes millions of litres of water daily, leading to groundwater depletion and contamination of drinking water (BGR and GIZ, 2018; Destrijcker and Diouara, 2017; Melcher et al 2018). The expansion of industrial activities, such as mining, driven in part by the need for resources for global energy transitions, will also increase water demand in certain locations. Mining activities may also expand due to pressure on agricultural livelihoods encouraging a movement into mining.

A number of strategies and measures may be pursued to address reductions in water availability. Given the relatively small proportion of available renewable surface water resources that are currently used, increased water capture and storage is one practical option, for example employing dams including small-scale sand dams, reservoirs, cisterns including underground cisterns, and domestic water harvesting systems. Facilitating groundwater recharge is another, for example by concentrating runoff in specific recharge zones or through appropriate land management. For example, Bargués-Tobella et al. (2020) propose maintaining or promoting tree cover in dryland areas as a means of enhancing groundwater recharge and countering the potential negative impacts of increased rainfall intensity on groundwater resources. Considering the asymmetries in projected changes in precipitation, with projected increases in the central and eastern Sahel, and small changes or declines in the west, may be important for regional water management and planning, for example in the planning of future irrigation systems and in the conservation of groundwater.

Focus Box 5: Gender and other social vulnerabilities to climate change

Existing patterns of social marginalisation and inequality, such as gender, income, and disability, significantly shape vulnerability to climate impacts and will in turn shape vulnerability to future climate risks. The impacts of any changes in water availability, for instance, will be shaped by broader systems of socioeconomic marginalisation and inequality. Gender is a particularly prevalent and powerful source of differential climate vulnerability. For instance, women may be particularly affected by gendered responsibilities for water provision and the gendered impacts of household water insecurity (Dickin et al., 2021; Doka et al., 2014). Access to drinking water varies widely between urban and rural populations within Sahelian countries: for instance, 64% of Mali's rural population and 49% of Niger's rural population have access to safe drinking water compared to nearly 100% of urban populations in both countries (FAO AQUASTAT, 2021). Climatic changes will likely intensify existing inequalities in access to water sources and irrigated land. In Mali, for instance, water-rich land is allocated primarily to large-scale farmers and elites rather than to small-scale farmers and local communities (Hertzog et al., 2012). Furthermore, women often face significant barriers to accessing irrigation water, with water access linked to gendered land tenure rights (Alou et al., 2015). These differentiated vulnerabilities and inequalities need to be taken into account in water management and planning, including adaptation planning.

The impacts of projected climatic changes on livelihoods, settlements, and infrastructure, including rainfall extremes, flooding, heat extremes, and coastal hazards, will present particularly severe risks for populations who already face conditions of vulnerability, including conditions of poverty. In urban areas, for instance, inhabitants of informal settlements experience high levels of poverty, already limited and inadequate access to basic services (e.g. water, sanitation, wastewater, waste management) (Baron and Bonnassieux, 2021; OECD, 2021) as well as social, economic, and political marginalisation and, in some cases, forced displacement by government authorities (McDougall, 2021). Populations who already face conditions of vulnerability are also likely to be particularly affected by climate-related risks to health associated with flood risks, heat extremes, and changes in the prevalence of communicable and non-communicable diseases.

Unequal access to resources, economic opportunity and participation in decision-making mean that men and women have different exposure to, and differing capacities to respond and adapt to, climate risks. Those with the resources to respond to and prepare for future climate hazards will be better equipped to navigate the climate crisis. However, those resources are rarely distributed equally at the state, community, and household levels. Specifically, gender inequalities within the Sahel region pose a significant challenge for resilience and adaptation strategies as state and global institutions put interventions in place to support at-risk populations (McOmber, 2020). These issues increase the burdens on women and limit their ability to respond and adapt to changing climate risks. For example, women face particular barriers to adaptation strategies in the agriculture sector (including farming and pastoral activities), linked to gendered inequalities in rights of access to natural and financial resources (including land), market opportunities, and decision-making power at household and community levels – although they play crucial roles in ensuring household resilience in response to environmental and food crises (Alou et al., 2015; Deubel and Boyer 2017; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Doka et al., 2014).

Furthermore, evidence from the Sahel and other geographic contexts shows that women are more likely to face barriers to mobility in response to environmental shocks and climatic variability, and that and for women, migration presents increased physical and social vulnerability (Deubel and Boyer 2017; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Drees and Liehr, 2015). Similarly, poverty-affected individuals and households are particularly affected by both migration pressures and barriers to movement, and young people are the most likely to move in response to climatic pressures (Selby and Daoust, 2021).

4.1.2 Risks to supply systems and water quality

Rainfall variability (both annually and sub-annually) is projected to increase into the 2050s. An anticipated increase in the intensity of heavy rainfall events, which may become more intermittent, has the potential to result in increased runoff and flooding (see Focus Box 6). Flood risks may be exacerbated (or ameliorated) by changes in land use change. More intense rainfall events and increased risks associated with flash flooding pose risks to water supplies and water quality, particularly in urban areas. As noted above, population movements of the kind that have been experienced historically and more recently in the Sahel have the potential to add further acute pressure on water infrastructure and supply systems in certain locations.

An increase in the frequency of intense rainfall events may increase the likelihood and extent of flooding and impact runoff in river and lake catchments such as the Lake Chad Basi and Niger River Basin, including the inland Niger Delta in central Mali, affecting downstream water quality, for example due to increased runoff of agrochemical pollutants into river systems (Aliyu et al., 2015) (see Focus Box 7). Flood risk and associated contamination risks will be strongly mediated by land use within these basins, and by the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016).

There is very high confidence of an increase in relative sea level around the coast of Mauritania (Zone 1) projected by CMIP5 (RCP8.5) and CMIP6 (SSP585) climate models by the 2050s (IPCC Interactive Atlas, 2021). Sea Level Rise (SLR) is highly likely to cause a greater frequency of saltwater intrusion into coastal aquifers, contaminating freshwater resources. Agoubi (2021) shows that the entire coastal zone of Mauritania is affected by saline contamination, extending tens of kilometres inland and impacting both the Trarza and Benichab aquifers. This has direct impacts on the population and especially the capital Nouakchott where, in addition to freshwater contamination, SLR is causing groundwater level to rise and thus exacerbating flooding risk. Much of the city is currently less than 1m above sea level (Mohamed et al., 2017).

Groundwater resources have been affected by rapid urbanisation in multiple locations in the Sahel, which has resulted in groundwater contamination and presents challenges to groundwater management (Hassane et al., 2016). Population movements of the kind that have been experienced historically and more recently in the Sahel have the potential to add further acute pressure on water infrastructure in certain locations. Such movements may become more likely as a result of climate extremes, such as droughts, floods and (as climate change intensifies) heat and humidity extremes, and the impacts of climate change on food production.

Water-related insecurities in the Sahel region have been linked to poor management and distribution of water resources, rather than a lack of water (Alagidede and Alagidede 2016). This results from insufficient investment to improve water distribution networks and maintain and expand water infrastructure, inefficient governance structures and institutions, and the lasting impacts of decades of structural reforms (ibid). The urban population of the Sahel is projected to increase dramatically (see Section 4.4), meaning there is an urgent need for improved water infrastructure. This infrastructure will need to be well adapted to increased rainfall intensity if it is to deliver safe water to growing urban populations in the face of enhanced flood risk that may be exacerbated by rapid, and in many cases unplanned, urbanisation. Investment in robust water infrastructure that can withstand floods and reduce associated risks of contamination will be necessary in some locations, such as the coastal settlements of Zone 1.

4.1.3 Risks associated with transboundary water management

Water resources in the Sahel are shared across national boundaries. Trends and risks associated with water availability, demand, supply and quality are mediated not only by national trends and policies, but also by transnational and regional water management dynamics. These dynamics in turn may be affected by climate change. The existing evidence base provides examples of both cooperation and conflict in relation to transboundary water management during episodes of water stress. Nonetheless, caution should be exercised in using historical evidence to draw conclusions about likely future responses to transboundary water management issues, given that the nature and magnitude of future climate change impacts on water resources may be very different from those experienced to date. Reliance on transboundary water resources in the Sahel means that water availability and use is shaped by development and population dynamics in neighbouring countries, as well as joint institutional, consultative and development mechanisms (Nijsten et al., 2018; Sahel Irrigation Initiative, 2017).

Transboundary water resources have the potential to trigger conflict between states, as illustrated by the Senegal-Mauritania border conflict of 1989, when cross-border movements of famers and herders in response to low river levels contributed to ethnic clashes (Comas et al., 2012). However, while tensions over water may have acted as a trigger for this conflict, it had deeper roots in policies that had undermined customary land use arrangements (Bloch and Foltz, 1999). This example emphasises the need to understand and address the underlying drivers of conflict, and to avoid the simplistic ‘securitisation’ of climate change via a narrow and exclusive focus on proximate causes associated with climate hazards.

Nonetheless, low river and lake levels have the potential to result in allocation issues, while high levels that necessitate the opening of dams may be associated with downstream flood risks. The construction of dams may disrupt flood regimes that are important for flood recession agriculture or cut off sediment supplies that contribute to soil fertility. The expansion of hydropower development, including as a climate change mitigation strategy, has the potential to increase risks associated with these phenomena. The contributions of renewable energy sources to power generation in the Sahel is increasing, currently accounting for nearly 20% of power generated. Hydropower is the principal source of renewable power, accounting for 12% in the region and nearly 40% in Mali (IEA, 2021).

Transboundary water management can also lead to cooperation between neighbouring states, building on existing regional institutional arrangements (Devlin and Hendrix, 2014). For instance, the Lake Chad Basin Commission was established in 1964 to manage the Basin's shared water resources. The focus of the Commission was expanded to encompass security issues following conflict between Chad, Niger and Nigeria over access to and control of lake waters, tributaries and islands in the 1980s and 1990s (Galeazzi et al., 2017; on transboundary tensions see Okpara et al., 2015).

While future climate change related stresses may be more challenging than in the past, with significant impacts on existing transboundary management systems, these may be associated with responses involving both conflict *and* cooperation. Planning for possible future climate-related changes in potential transboundary water flows, in the context of anticipated changes in management, use and demand (e.g. dam construction, hydropower and demographic change), should be a priority for regional water management bodies.

4.2 Agriculture and pastoralism

Summary of risks relevant to agriculture and pastoralism

- More frequent, severe and protracted extreme temperatures as well as increases in rainfall extremes may increase the likelihood that tolerance thresholds will be exceeded for certain crops and livestock and may in turn lead to crop loss and livestock mortality.
- Increases in rainfall variability and in the length of dry periods may combine with increased evapotranspiration driven by higher temperatures to reduce soil moisture and groundwater recharge, and to increase drought severity and irrigation demand, while a projected delayed onset to the wet season may result in shorter growing seasons.
- Rainfall deficits, amplified by higher temperatures, will increase periodic water stress and may result in reduced runoff, river flow and lake levels, adversely impacting widespread rainfed and flood-recession agriculture.
- The vulnerability of farmers and pastoralists to climate variability and change has increased as a result of government policies (e.g., changes in land tenure, agricultural expansion), reduced access to water and pasture , and the disruption of transhumance routes by infrastructure development and industrial activity, which also reduce their ability to deploy adaptive strategies.
- Adaptation responses may have adverse environmental impacts (e.g. via agricultural intensification, greater exploitation of natural resources such as forests and water), as well as social impacts (e.g. exclusion and the privileging of certain groups or activities).Where climate can be linked with conflict in the Sahel it is, at most, a trigger or mediating factor for conflicts driven by deeper political and economic causes rather than by climate change or environmental degradation.

4.2.1 Risks to agricultural productivity and livelihoods

Smallholder agriculture, mobile pastoralism and agropastoralism represent the principal livelihood activities and sources of food security across the Sahel. Changing climatic conditions may advantage certain farming systems, crop types and agricultural locations, and disadvantage others. Risks include crop losses, disruptions to planting and harvesting seasons, increased irrigation needs, and the intensification of existing inequalities in access to land and water sources. Agricultural activities and sectoral changes are directly affected by government policies and programmes, including those related to agricultural expansion and land rights, which will in turn mediate the impacts of climate change on agricultural livelihoods. Most agricultural activities in the Sahel rely on rainfall or surface water, although in some parts of the region, especially in arid areas, groundwater may be the only permanent water resource. Groundwater is used primarily for small-scale irrigation, which makes a significant contribution to agriculture and food security and is associated with the production of high-value crops (Sahel Irrigation Initiative, 2017).

Rainfed agriculture dominates in southern Mali (Zones 3 and 5), the southernmost regions of Niger and Chad (Zones 4 and 6), and most of Burkina Faso (Zones 3 and 5). North of these rainfed agricultural zones is a zone of mixed agropastoralism that characterises south-central Mali, Niger and Chad and southern Mauritania (Zones 3 and 4). Beyond this, in the more arid regions to the north (zones 1 and 2), mobile pastoralism dominates. Flood recession and irrigated agriculture around lakes and rivers is found in Zones 1, 3 and 4. In Zone 1, agriculture occurs in the region of the Niger Bend, where it is based on flood recession cultivation. Agriculture is largely absent from Zone 2. The main crops in Zone 3 are millet and sorghum. In Zone 4, irrigated rice is grown along the Niger river, with cereals, legumes and vegetables (especially peppers) grown around the Komadougou-Yobe river along the Niger-Nigeria, which flows into Lake Chad to the east. In Zones 4 and 6, cultivation also occurs around the Logone and Chari rivers, which flow into Lake Chad, where flood recession cultivation is practiced. Rainfed cultivation occurs in the southern-most regions of Zone 4. Zones 5 and 6 are characterised by mixed agriculture including the cultivation of cereals (maize, sorghum), cotton, tubers, legumes (peanuts, cowpea) and fruit and vegetables, supported in places by small-scale irrigation using groundwater and seasonal surface water sources.

Lake Chad (zone 4) is particularly susceptible to evaporative water losses because of its shallow depth. With projections of increasing precipitation, it is projected to continue to recover in terms of water availability (see Focus Box 3), although the impact of human activities, such as land use change or irrigation withdrawal across Lake Chad Basin, for example along the Chari and Logone rivers (Zhu et al., 2019), may negate any increases in water availability in these catchments. Irrigation demands are likely to increase as progressively higher temperatures result in greater evapotranspiration, reduced soil moisture, and increased water requirements for certain crops.

Climate projections indicate very high confidence in annual temperature increases across the Sahel region. To the south, zones 3, 4 and 5 show a marginally greater increase in projected annual temperatures compared to zones 1 and 2 in the north and zone 6 in the southeast (2-3.5°C compared to 1.5-3°C). Daily maximum temperatures will consistently exceed 40˚C in the hottest months across all zones, with some models projecting maximum temperatures up to 45˚C in zones 1 and 2. These temperatures will also be exceeded earlier in the year and for longer through the year, and heat extremes will increase in frequency and intensity. Extreme high temperatures and sustained periods of high temperatures are likely to increase heat stress on crops and may result in tolerance thresholds being crossed for certain crop types. Some crops, such as sorghum and millet, tend to be fairly resilient, but others, such as cotton (grown in zones 5 and 6), fail at temperatures over 35˚C. High temperatures and increased evapotranspiration will reduce groundwater recharge and soil moisture content. This may be offset to an extent by increased rainfall, except in zone 1 and the west of zone 3. However, water stress will increase during dry episodes, which may become more frequent and protracted as a result of changes in rainfall variability. Higher temperatures will make droughts more severe when they do occur. Oasis agriculture may be more resilient due to the reliance on ground water (occurring in zones 1 and 2). However, risks to these systems may increase due to greater evapotranspiration and increased demand.

Across the central and eastern Sahel there is medium confidence in small increases in annual total precipitation, with the majority of projected change occurring in the wet season, although winter season increases are indicated in zones 5 and 6 (southern Burkina Faso and Chad). Increases of up to 80mm are projected in zone 5 (50% increase) and 75mm in zone 6 (40% increase). Projections indicate a shift in the rainy season with high confidence of delayed onset to the West African Monsoon (WAM) (by 5-10 days) and medium confidence of its delayed retreat (Dunning et al, 2018; Biasutti et al., 2013). Projected spatial gradient changes in the WAM (see Focus Box 3) into the 2050s include precipitation increases in the central Sahel (zones 2, 4 and 6) and decreases in the far west (zones 3 and 5), especially on the coast of Mauritania (zone 1) (medium confidence; IPCC AR6, 2021). For rainfed agriculture, which dominates in zones 3-6, high sensitivity to changes in rainfall mean the western zones (3 and 5) could face increased risks of water scarcity and require additional planning for irrigation systems and groundwater conservation. Although projection signals indicate a moderate increase in total precipitation (smallest in zone 1 and small decreases only seen in the far west and near the coast), this does not necessarily mean more water availability, as rising temperatures in all zones combined with increased evaporation and greater interannual variability (IPCC AR6, 2021) may mean that water availability will be similar to current levels or become less available in the 2050s, therefore remaining a key concern for agriculture.

Rainfall variability (both annually and sub-annually) is projected to increase into the 2050s, with increased intensity of heavy rainfall events which may become more intermittent, especially in the west (Biasutti, 2019), potentially causing damage to crops, increased land degradation (e.g., soil erosion through increased runoff, see Focus Box 6), and increased risk of flooding that results in livestock mortality. The IPCC AR6 report (2021) notes that in the western Sahel (zones 1, 3 and 5), the number of consecutive dry days per year will also increase. In the east, extreme rainfall events may be more frequent, and the number of consecutive dry days is projected to decrease (low confidence, IPCC AR6, 2021). Changes in rainfall variability affect agricultural scheduling and increase the risk of crop losses resulting from inadequate rainfall following planting, protracted dry periods during the growing season, and extreme rainfall events and floods that damage crops and affect harvesting. Though total rainfall may increase, delays in wet season onset mean a potentially shorter growing season, requiring changes in crop management and planting practices to mitigate reductions in crop development (Dunning et al., 2018; Biasutti and Sobel, 2009).

Extreme high temperatures and sustained periods of high temperatures, combined with changes in rainfall, may increase the need for irrigation to support agricultural production. Large-scale irrigation schemes in the Sahel have often been unsuccessful, and the expansion of irrigation in the region has mostly involved small-scale private irrigation (Sahel Irrigation Initiative, 2017; Torou et al., 2013; Van Der Wijngaart et al., 2019). Irrigated land accounted for less than 1% of cultivated land in Burkina Faso, Chad, and Niger in 2018, 3% in Mali, and 10% in Mauritania in 2018 (FAO AQUASTAT, 2021), although these figures may not capture all small-scale private irrigation. Increased irrigation is identified as central to agricultural and economic development in the Sahel region (Sahel Irrigation Initiative, 2017). However, this will be shaped by and may intensify patterns of differentiated vulnerability and existing inequalities in access to water sources and irrigated land (see Focus Box 5), including inequalities in access to water-rich land and irrigation waters among women and men, and among wealthier and poorer farmers (Alou et al., 2015; Hertzog et al., 2012).

Previous research shows that the effects of climatic changes on agricultural production are highly variable across G5 countries and agroecological zones within the same country, depending on existing climatic conditions and agricultural production (e.g., technical and infrastructural) factors (Yobom and Le Gallo, 2021). For instance, average temperature increases during the growing season are found to have positive impacts on cereal production in Chad, Mali, and Mauritania, negative impacts in Burkina Faso, and insignificant impacts in Niger, while precipitation declines have positive impacts on cereal production in Chad, Mali, Mauritania, and Niger, and insignificant impacts in Burkina Faso (Yobom and Le Gallo, 2021). The effects of climatic changes also vary by crop type. In Chad, for instance, higher temperatures during the growing season have positive effects on maize, millet and sorghum production, but negative effects on rice and wheat production, while higher rainfall has positive effects on maize, millet, sorghum and rice (Yobom and Le Gallo, 2021).

According to the IPCC AR6 report (2021), there is medium confidence that increased precipitation intensities will enhance groundwater recharge in the tropics, which may be relevant to zones 5 and 6 in the south of the region, but this is less clear in more arid regions in the north (zones 1 and 2) (see also discussion of water resources). This could enhance groundwater resources available for irrigation and agricultural development. Extreme rainfall and floods can also result in soil erosion. Projected increased runoff (see Focus Box 6) may also exacerbate pollution downstream, especially with greater use of agro-chemicals in farming.

Floodplains of the Inland Niger Delta (IND) in central Mali (zone 3), part of the Niger River Basin (NRB), support a large amount of agriculture and pastoralism, including rice production and grazing of livestock, but this is dependent on the annual inundation of the IND. With increasing interannual variability in precipitation, this inundation may be less reliable (Thompson et al., 2021). Risk of flooding in major river basins such as the Niger River Basin and Chad River Basin (CRB) are projected to increase, though risk is highly related to land use within the basins and vegetation response to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). With projections of increasing precipitation, Lake Chad is projected to continue to recover in terms of water availability (see Focus Box 7), though the impact of human activities, such as land use change or irrigation withdrawal across the Lake Chad Basin, for example along the Chari and Logone rivers (Zhu et al., 2019), may negate increases in water availability, impacting agriculture.

Changes in soil moisture are an important consideration for ecological and agricultural drought but are complex to project. To a large extent, changes in soil moisture follow the same trends as precipitation, although varying evapotranspiration is also a factor. Projections indicate overall decreases in soil moisture across the majority of Mauritania, Mali and the northern half of Burkina Faso (zones 1 and 3), increasing the potential for agricultural and ecological drought in the region (low-medium confidence; IPCC AR6, 2021), with direct impacts on agricultural productivity. Other zones show little to no change in annual average soil moisture overall.

It is important to note that climatic changes may present risks not only to rural populations, given that agricultural activities are not restricted to rural areas in the Sahel region. Urban and peri-urban agriculture, including cultivation (e.g., subsistence or semi-commercial field cropping, commercial gardening), have increased along with urbanisation (Amadou et al., 2012; Dossa et al., 2011a, 2011b, 2015; Robineau and Souland, 2017).

Agricultural and pastoral livelihoods and productivity in the Sahel region are affected not only by climate change but also by government policies and programmes. As discussed in Section 2, these include agricultural support programmes (e.g., credit, input distribution) and changing market prices (Benjaminsen et al., 2010; Daouda 2015; Nilsson et al., 2020) as well as changes to governance systems and agricultural development frameworks, including land tenure systems and large-scale land acquisitions by private investors (Bouaré-Trianneau, 2013; Ickowicz et al., 2012; Leonhardt, 2019; Marega and Mering, 2018). Future risks to agricultural livelihoods will be shaped by the interaction of projected climate changes and these political and economic factors.

4.2.2 Risks to pastoralist livelihoods

Livestock herding is the predominant means of subsistence in Zones 1 and 2, the north-east part of Zone 3, and the northern areas of Zone 4. Sedentary livestock rearing is most common at the household level in Zones 5 and 6. Pastoralists face risks from climate change that are strongly mediated by the political and economic environments in which they operate. Climatic changes may threaten access to water sources and pasture, and influence and constrain mobility options. Pastoralists have modified their seasonal transhumance movements in recent decades, in response to climatic and other factors. Pastoralist activities and sectoral changes are directly affected by government policies and programmes, including those related to agricultural expansion and land rights, which will in turn mediate the impacts of climate change on pastoralist livelihoods.

In recent decades, seasonal transhumance movements – linked to seasonal rainfall, vegetation patterns, and water availability – in Sahelian countries have become longer and more dispersed and have moved southward, potentially due to the expansion of agricultural areas in transhumance corridors, environmental changes, increasing herd sizes, and transborder cattle markets (Kiema et al., 2014; Leonhardt, 2019; Moutari and Giraut, 2013; Touré et al., 2012). Risks facing herders include difficulties accessing drinking water, due primarily to high demand and encroachment of farmland, increasing fees or taxes to access water points and pasture, toll charges and checks along transhumance routes, and diseases and parasites (Bonnet and Guibert, 2014; Kiema et al., 2014; Koutou et al., 2016; Leonhardt, 2019; Moutari and Giraut, 2013; Zoma-Traoré et al., 2020). Herders may have more difficulty accessing water-rich pastureland, compared to agro-pastoralists (Koutou et al., 2016). Roads, urban development and mining also disrupt pasture areas and transhumance routes in the Sahel region (Leonhardt, 2019). Loss of pasture due to land fragmentation and access restrictions negatively impacts livestock nutrition, milk production, physical health, reproduction and mortality (Hiernaux et al., 2014; Okpara et al., 2016). In response to these challenges, some pastoralists have turned to agricultural production or agropastoralism, although this is a challenge for 'landless' livestock keepers (Bonnet and Guibert, 2014; Zoma-Traoré et al., 2020).

Pastoralists already face multiple threats to their livelihoods from land tenure changes and agricultural expansion that restrict their mobility and access to water, pasture and migration routes. Governments ofG5 countries have established policy frameworks to enhance the security of pastoral systems and reduce conflicts between herders and farmers, through land and resource access management, pastoral infrastructure and mobility rights (Bonnet, 2013; de Haan, 2016; Leonhardt, 2019; Touré and Benkahla, 2014). However, these are not fully applied in practice, privilege the individual rights of agricultural landholders while maintaining precarious pastoral land rights, and tend to prioritise systems with strong 'productive' potential (e.g., agropastoralism) (Leonhardt, 2019; Touré and Benkahla, 2014). This undermines pastoralists' ability to deploy the strategies they have traditionally used to navigate climatic variability and uncertainty and makes them more vulnerable to climate hazards. It is important to emphasise that pastoralism developed in the Sahara-Sahel region as a response to large and rapid changes in environmental conditions associated with a transition to a more arid and variable climate from the 4th millennium BCE onwards (Kuper and Kröpelin, 2006). As a livelihood strategy that has developed over millennia as an adaptation to the particular climatic and environmental conditions of the Sahel, pastoralism embeds a significant amount of adaptive capacity that could play a key role in adaptation to climate change now and into the future (Krätli et al., 2013; Brooks et al. 2020). While policies are emerging that seek to support pastoralism, these are unevenly implemented and, historically, pastoralists' vulnerability has been driven predominantly by often hostile policies that inhibit adaptive strategies (Bloch and Foltz, 1999; Thébaud and Batterbury, 2001).

Climate projections indicate very high confidence in annual temperature increases across the whole Sahel region. In zones 1 and 2 where nomadic pastoralism is dominant, extreme temperatures may result in heat stress for animals as well as herders themselves (Herrero et al., 2016). High temperatures also increase evaporation, which reduces water availability. In oasis agriculture especially (occurring in the north Sahel zones 1 and 2), this may increase risks to transhumance herders through lack of drinking water for herders and livestock. Extreme high temperatures may also be associated with increases in livestock mortality associated with heat-stress.

Projected changes in the spatial gradient of the WAM (see Section 4.2.1) combined with increasing temperatures could have highly detrimental effects on pastoral livelihoods near to the coast (IPCC AR6, 2021). However, projected moderate increases in total precipitation do not necessarily mean more water availability, as rising temperatures in all zones combined with increased evaporation rates and greater interannual variability (IPCC AR6, 2021) may mean that water availability will remain a key issue for pastoralism. These changes in precipitation, alongside projected increases in annual and sub-annual rainfall variability (Biasutti, 2019) and increasing frequency of extreme rainfall events in the eastern Sahel and increasing number of consecutive dry days in the west (low confidence; IPCC AR6, 2021), may also influence the factors that mediate pastoralists' vulnerability. Just as wet conditions in the 1950s and 1960s encouraged the northward expansion of agriculture, so any further 'greening' of the Sahel resulting from projected increases in rainfall may facilitate additional expansion of agriculture into pastoral areas. A northward shift of the monsoon belt may also increase the prevalence of livestock diseases, with impacts on herds.

Increased precipitation intensities may enhance groundwater recharge in zones 5 and 6 in the south of the region (medium confidence, IPCC AR6, 2021), which could enhance groundwater resources available for livestock watering. In the arid and semi-arid regions of the Sahel (zones 1 and 2 especially), dust storms may affect pastoral livelihoods by causing injury to livestock (IPCC, 2019b).

The impacts of climatic changes on livestock activities are not restricted to rural areas in the Sahel region. As discussed in 4.2.1, urban and peri-urban agriculture have increased along with urbanisation, involving the integration of cultivation and livestock (Amadou et al., 2012; Dossa et al., 2011a, 2011b, 2015; Robineau and Souland, 2017). Many urban and peri-urban residents (including in capital cities such as Bamako) own animals such as sheep, goats and cattle as a source of income and food security (Amadou et al., 2012; Crump et al., 2019; Dossa et al., 2011a, 2011b, 2015; Pica-Ciamarra and Tasciotti, 2018). In Niger, up to 40% of urban households own livestock (Pica-Ciamarra and Tasciotti, 2018).

Focus Box 6: Desertification

Despite the scientific evidence that drought in the Sahel is associated principally with the response of the monsoon to changes in ocean surface temperatures (Folland et al. 1986, Giannini et al., 2003, 2008; Biassuti 2019), the belief that the Sahel is experiencing systematic regional-scale desertification because of poor land management, and that the Sahara is consequently 'marching south' persists among policymakers and the public, both within and beyond the region (Benjaminsen and Hiernaux, 2019). The concept of 'desertification' is often mobilised as part of narratives linking environmental and climate change to insecurity and conflict, particularly in relation to pastoralists (UNEP, 2007; Benjaminsen, 2019). While certain areas may be affected by local anthropogenic land degradation, there is no evidence that the Sahel is experiencing systematic, regional-scale desertification (Behnke and Mortimore, 2016). Rather, vegetation responds to changes in the strength and position of the monsoon, which in turn is modulated by large-scale changes in surface temperature patterns (see Focus Box 3 WAM). Following the droughts of the 1970s, 1980s and 1990s, rainfall and vegetation recovered in much of the Sahel, and climate projections indicate increases in rainfall over most of the Sahel over the coming decades, although high climatic variability will continue to be a fundamental characteristic of the region (Olsson et al., 2005; Doblas-Reyes et al., 2021). However, the recovery has been more significant over the central Sahel than over the western Sahel, consistent with climate projections that indicate increased rainfall in these areas and little change or declining rainfall in the west (Doblas-Reyes et al., 2021). To the extent that anthropogenic drivers of the historical droughts can be identified, these are located outside the Sahel and are associated with the suppression of North Atlantic sea-surface temperatures by industrial aerosols originating in the global north (Biassuti and Giannini 2006, Giannini and Kaplan 2018, Marvel et al. 2020). An understanding of these factors by donors as well as governments is critical to the development of successful development and adaptation policies in the Sahel.

4.2.3 Risks related to livelihood adaptations

Across the Sahel region, people involved in agriculture have adopted a range of adaptive strategies in response to environmental and climate-related changes, including changes in temperature and precipitation trends. However, these adaptation responses are not universally available, may intensify existing inequalities, and may themselves present risks of harmful impacts on local environments.

Existing adaptation strategies include income diversification (e.g., use of forest resources, wage labour), adjustments to agricultural practices (e.g., farm inputs, new crop varieties and cropping strategies, agroecology), water conservation and small-scale irrigation, and soil conservation practices (Barbier et al., 2009; Bello, 2016; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Epule et al., 2017; Magrath, 2020; Maisharou et al., 2015; Marega and Mering, 2018; Okpara et al., 2016). In the Lake Chad region, for instance, responses to changing flood patterns include adjustments to agricultural practices (e.g., mixed cropping, timing of land preparation, planting, and harvesting, intensification and/or extensification) and water harvesting (e.g., digging canals, wells, or ponds) (Okpara et al., 2016), as well as the integration of flood recession cultivation and fishing activities (Okpara et al., 2016; Rangé and Abdourahamani, 2014). For livestock owners, coping strategies include income diversification (e.g., small trade), reducing herd sizes (e.g., through the sale of animals), changes in livestock species, changes in mobility patterns, construction of water points, and increasing involvement in agricultural activities (Bonnet and Guibert, 2014; Ickowicz et al., 2012; Koutou et al., 2016; Valerio, 2020; Zoma-Traoré et al., 2020).

However, these adaptation responses are not equally accessible and may exacerbate existing vulnerabilities and inequalities (see Focus Box 5). Barriers to the adoption of agricultural and pastoral adaptation strategies include insufficient financial resources, insecure land tenure systems, limited access to technical and technological information, and fragmented institutional coordination capacities (Maisharou et al., 2015). Women face particular barriers to adaptation strategies in the agriculture sector (including farming and pastoral activities) (Alou et al., 2015; Deubel and Boyer 2017; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Doka et al., 2014). This highlights the importance for adaptation planning in agricultural sectors to address existing systems of differential vulnerability and inequalities in access to adaptation resources and capacities.

Future adaptive responses associated with agricultural and pastoral livelihoods in response to climate-related changes – including annual temperature increases and increasing frequency and intensity of hot extremes, increases in annual total precipitation, increases in rainfall variability and extreme rainfall events or in number of consecutive dry days (discussed in 4.2.1) – may present risks of negative impacts on local environments, especially in conjunction with future climatic changes. These include the intensification of agricultural activities and effects on land and soil quality as well as disruptions to existing patterns of land use (e.g. livestock grazing), the use of farm inputs (e.g., fertilisers) and potential increases in water pollution, increased water use for irrigation and livestock, increased use of forest resources for income diversification, reduced or increased herd sizes, and more. While adaptation initiatives may also have positive environmental impacts (through water and soil conservation, agroecology, or other initiatives), potential risks of 'maladaptation' should also be considered.

4.2.4 Risks related to mobility and migration

The impacts of climatic changes on agricultural livelihoods, including farming and herding, and associated socioeconomic pressures, may contribute to risks related to displacement and migration. For some populations, these changes might contribute to increased pressures to move or underpin changes in existing mobility patterns, while for others, the impacts of climate-related changes might constrain possibilities for mobility. However, it is important to avoid problematising mobility and migration as risks to be 'managed' or 'controlled'. Rather, migration should be viewed as simultaneously part of a wider set of adaptive responses and as involving social losses (see Selby and Daoust, 2021).

While some studies find that environmental and climate-related changes are associated with increased migration in the Sahel region (Bertoli et al., 2020), other studies of G5 countries find no association between climatic factors (e.g., rainfall) and migration (Grace et al., 2018) or report that climatic factors (e.g., temperature and precipitation anomalies) are associated with *decreased* migration, potentially due to negative effects on agricultural outputs which 'trap' people in place (Gray and Wise, 2016). Thus, responses to risks related to mobility associated with climate change should consider not only those who move, but also those who cannot move due to socioeconomic or other barriers to mobility, especially for populations 'trapped' in situations of extreme vulnerability. Internal and short-term or seasonal migration may be used as a strategy to access land, markets, or new labour or income opportunities (Deubel and Boyer 2017; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Drees and Liehr, 2015; Okpara et al., 2016; Sydney, 2019). For instance, changes to pastoral economies, associated with the expansion of agricultural land, changes in land management, and monetisation and commercialisation of pastoral resources and economies in the Sahel region have been associated with migration from rural areas to towns and cities, especially among young men (Ancey et al., 2020). Patterns of mobility and immobility associated with climate change will likely intensify existing patterns of differential vulnerability and inequalities in possibilities for mobility (see Focus Box 5), with evidence from the Sahel and other geographic contexts pointing to uneven climate-related migration pressures *and* barriers affecting women and poverty-affected individuals and households (Deubel and Boyer 2017; Djoudi et al., 2013; Djoudi and Brockhaus, 2011; Drees and Liehr, 2015; Selby and Daoust, 2021).

Climatic changes including annual temperature increases and increasing heat extremes, increases in annual precipitation, increases in rainfall variability and extreme rainfall events, or in number of consecutive dry days, may lead to changes in existing mobility patterns, especially among pastoralists. At the same time, agricultural expansion, including in response to climate change, alongside land access reforms, may also lead to changes in mobility and in turn affect existing livelihood systems, including by presenting barriers to pastoralist mobility. In recent decades, the timing and locations of seasonal transhumance movements in Sahelian countries have changed in response to the expansion of agricultural areas and environmental change, among other factors (Kiema et al., 2014; Leonhardt, 2019; Moutari and Giraut, 2013; Touré et al., 2012). However, mobility patterns are also affected by policy or institutional barriers, such as water, pasture and transhumance route fees, taxes and checks (Bonnet and Guibert, 2014; Kiema et al., 2014; Koutou et al., 2016; Leonhardt, 2019; Moutari and Giraut, 2013; Zoma-Traoré et al., 2020).

Precipitation changes in the Sahel region – increases in annual precipitation (including winter season increases in zones 5 and 6, in southern Burkina Faso and Chad), projected spatial gradient changes in the WAM (see Section 4.2.1) – could present new or expanded opportunities for agricultural livelihoods, and in turn affect patterns of migration.

Changes in mobility and migration patterns may present future risks, including tensions between communities (see section 4.2.5) as well as risks associated with rapid urbanisation, including the growth of informal settlements and widening demands for housing, water, electricity and other basic services, as well as the intensification of existing inequalities in access to these services (see section 4.4). Importantly, movement *itself* is not the risk, but rather inequalities in adaptation support, mobility and resettlement support, land tenure systems, inadequate service systems, and so on.

4.2.5 Risks of conflict associated with complex drivers

Climate change may contribute to the dynamics of conflict through impacts on livelihoods, displacement, and the intensification of existing inequalities. However, the major underlying drivers of violent conflict are related to social, political and economic factors, and addressing these is essential and increasingly necessary as climate stressors increase.

While farmer-herder conflicts are often attributed to resource scarcity resulting from desertification (see Focus Box 6) or (more recently) climate change (Parker, 1991; Mazo, 2009), the roots of these conflicts often lie in development policies that promote agricultural expansion and changes to land tenure systems, constrain pastoralists' mobility, and result in tensions between farmers and herders over land and pasture (Benjaminsen et al., 2012; Benjaminsen and Ba, 2019; Bonnet, 2013; ICG, 2020; Marega and Mering, 2018; Turner et al., 2014). For example, in the Inland Niger Delta region of Mali (at the boundary between Zones 1 and 3), the large-scale conversion of dry season pasture to rice fields contributed to increasing land-use conflicts between farmers and herders (Benjaminsen et al., 2012; Benjaminsen and Ba, 2019), while rent-seeking by government officials through land conflict resolution processes and arbitrary fines for herders grazing livestock contributed to pastoralists' decisions to join armed groups (Benjaminsen and Ba, 2019). In Mauritania, land tenure reforms undermined systems of customary access in the Senegal river valley (Bloch and Foltz, 1999), contributing to the violence that precipitated the Senegal-Mauritania border conflict in 1989 (Niasse, 2005). While this conflict has been blamed on desertification (Parker, 1991), the proximate cause appears to have been low river levels following the construction of the Diama (Mauritania, Senegal) and Manantali (Mali) dams and the introduction of irrigated rice (Comas et al., 2012). Dams have negatively impacted flood-related cropping and the role of flood plains as dry-season refuges for pastoralists (Degeorges and Riley, 2006), and changes in land use and land cover associated with agricultural expansion and land clearance are identified as contributing to changing flood patterns along the Niger River (Aich et al., 2015). In eastern Niger, the creation of public wells and boreholes became the focus of conflicts over access to water (Thébaud and Batterby, 2001).

While the ultimate drivers of conflict in the Sahel are rooted in development policy, political marginalisation, land tenure reforms, and the expansion of agriculture into pastoral zones, climate change and variability may trigger conflict where these factors have created the preconditions for it. Conflict between herders and farmers, and between different pastoral groups in the Sahel can occur in contexts of both scarcity and abundance (Benjaminsen et al., 2012; Abroulaye et al., 2015). Nonetheless, there remains the potential for climate change to increase the risk that latent conflicts, whose roots lie in social, political and economic factors, will be triggered in the event of a climate hazard such as a drought or flood. Changes in rainfall variability may result in changes to mobility patterns, in the timing of certain movements, and in the likelihood of conflict. For example, the risk of conflict may be increased if pastoralists move into cultivated areas before crops are harvested, either because the timing of their movements has changed, or because the growing season has shifted. It is therefore vital that governments in the Sahel develop and effectively implement policies that support pastoral livelihoods and facilitate the peaceful interaction of different interests in areas used by different livelihood groups, in the context of dynamic and evolving climatic and environmental conditions.

There is some evidence that climate has played a role in recruitment to armed groups, although again this is as a 'trigger' in contexts where social, economic and political factors are the underlying drivers of conflict. For example, the droughts of the 1970s and 1980s precipitated the migration of young men from northern Mali to Algeria and Libya where they were exposed to revolutionary ideology and returned to participate in the Tuareg rebellion (Benjaminsen, 2008). However, the roots of this conflict are to be found in political marginalisation, while the rebellion was facilitated by the regional proliferation of weaponry. It is feasible that climate change may feed into regional conflict through comparable indirect mechanisms in the future, and that climate change impacts may erode livelihoods and opportunities to an extent that joining insurgent groups appears relatively more attractive (*cf* Van Baalen and Mobjörk, 2018).

The roots of farmer-herder conflicts often lie in development policies that promote agricultural expansion and changes to land tenure and conflict resolution systems and constrain pastoralists' mobility and access to land and water resources. Rather than treating climate change as a driver of conflict, governments, policy makers and the international donor community should address the underlying social, economic and political factors that make climate change likely to trigger deeper-rooted conflicts. Addressing the impacts of climate change is an urgent priority but doing alone so will not be sufficient to reduce the potential for conflict.

While disruptions to agricultural livelihoods may contribute to conflict dynamics, conflict will also intersect with climatic changes to negatively affect livelihoods. For example, renewed conflict in Western Sahara as of November 2020 has further constrained herders' access to pasture in the context of anomalously low rainfall since 2017, precipitating an exodus of Sahrawi pastoralists and agro-pastoralists to north-western Mauritania (Zone 1) (SADR 2021). Conflict and insecurity across the Sahel region, as well as restrictions on movement and border closures in response to armed activity, have disrupted agricultural and livestock production, movement and trade, and in turn affected crop yields, food prices, livelihoods and food security (FAO, 2019; FEWS NET, 2017; van Lookeren Campagne and Begum, 2017). In Niger's Diffa region, for instance, emergency measures imposed since 2015 include restrictions on movement and access to cultivation areas in the Koumadougou River area, restrictions on fuel and fertiliser purchases, and closure of markets, disrupting the production and sale of red peppers, the region's key crop (van Lookeren Campagne and Begum, 2017). At the same time, patterns of population displacement have affected agricultural production. For instance, the presence of large internally displaced or refugee populations may lead to increases in cultivated areas (Nilsson et al., 2020). The disruption of cross-border movement has significantly affected agricultural and livestock activities, given the economic importance of cross-border trade and labour movements within the Sahel and neighbouring countries (e.g., between Niger and Nigeria) (FEWS NET, 2017).

4.3 Aquaculture and fisheries

Summary of risks relevant to aquaculture and fisheries

- Projected temperature increases may reduce oxygen levels and increase evapotranspiration and temperatures of inland freshwater bodies as well as increasing sea surface temperature, negatively affecting fish health and fish stocks.
- Projected changes in rainfall patterns may increase flooding and runoff, with detrimental consequences downstream for lake and river fisheries.
- Human-caused factors, including agricultural and industrial water use, pollution, dam construction, and government regulations on fisheries, may interact with climate change to further increase risks to inland fisheries.
- Changes to water sources and fish stocks may constrains existing adaptive livelihood strategies, especially for poverty-affected individuals and households.
- Projected sea level rise may present risks to coastal fisheries infrastructure, such as ports, harbours, launching and landing sites, and processing facilities.

4.3.1 Risks to terrestrial aquaculture and fisheries

Terrestrial aquaculture and fisheries face multiple interacting risks due to climate change, in particular rising temperatures and changing rainfall patterns, acting in combination with other human activities in the region.

Annual and daily maximum temperatures are projected to increase across the Sahel region, with hot extremes increasing in frequency and intensity. Increases in the temperatures of freshwater bodies, particularly in shallow lakes such as Lake Chad (see Focus Box 7), reduces oxygen levels and vertical mixing. This may affect nutrient availability and water column stability and lead to an increased susceptibility of fish to disease (Ogutu-Ohwayo et al., 2016). Temperature increases may also increase evapotranspiration. In Lake Chad, increased evapotranspiration and changing lake levels have affected the lake's water quality and temperature, with knock-on effects on fish stocks (FAO, 2012; Roessig et al., 2004; Wedemeyer, 1996).

Projected changes in rainfall patterns have implications for river flows and lake levels. There is medium confidence of small increases in total annual precipitation across the region. Rainfall variability (both annual and sub-annually) is projected to increase, with increased intensity of heavy rainfall events, which may become more intermittent in the west and more frequent in the east (Biasutti, 2019). In river systems such as the Inland Niger Delta, which covers much of central Mali (zones 3 and 5), fish recruitment and survival during the dry season is highly dependent on seasonal flood extent in the preceding wet season. Increasing interannual variability in precipitation may mean this is less reliable (Thompson et al., 2021) and could impact artisanal fisheries in this region. More extreme heavy rainfall events will impact major river systems, such as the River Niger Basin and the Lake Chad Basin, which may experience more frequent flooding events and increased runoff. These impacts are likely to have detrimental consequences downstream for lake and river fisheries including increased mixing which leads to reduced light levels and can impact water chemistry (Ogutu-Ohwayo et al., 2016), including eutrophication of water bodies in agriculture-dominant areas of catchments and possible contamination. Where the impacts of higher temperature on runoff dominate over the impacts of increased rainfall, and where rainfall does not increase significantly, freshwater bodies may experience reductions in areal extent and depth, with negative impacts on fish recruitment and survival.

Human-caused factors may interact with climate change to further increase risks. Observations show that inland fisheries and aquaculture activities have been negatively affected by changes in water bodies linked to the depletion of surface waters due to rising domestic, agricultural, and industrial (e.g., mining) demands, pollution of rivers and other surface water resulting from urban waste and agricultural activities (e.g., pesticides and fertilisers). Degradation of aquatic ecosystems are also attributed to changing flood patterns due to upstream dam construction (Melcher et al., 2018; Morand et al., 2012). Overfishing has negatively affected fish stocks in the region, in terms of numbers, biodiversity, and fish size (Melcher et al., 2018).

Changes to water bodies and reduction in fish stocks may contribute to increased competition among and between groups who depend on fisheries for their livelihoods, increasing the risk of conflict. This risk maybe greater where there is new or recent adoption of livelihoods based on fisheries, for example by pastoralists or cultivators. Adaptive livelihood strategies that have been applied, primarily the mixing of fishing and farming activities and engaging in seasonal migration (Béné et al., 2003; Djoudi et al., 2013; Morand et al 2012; Okpara et al., 2016; Rangé and Abdourahamani, 2014), may be constrained in the context of projected climate change for the region. The impacts of climate-related changes on fisheries and aquaculture may present particular challenges for poverty-affected individuals and households, given existing economic barriers to fishing livelihoods, such as water access and boat rental costs. Government regulations have been shown to affect engagement in fishing livelihoods, for example, around Lake Chad high water access charges imposed by local authorities and inequalities in access to fishing rights present barriers to certain fishers (Fougou and Lemoalle, 2019; Okpara et al., 2016). Fishing livelihoods across the Sahel region have also been restricted by ongoing insecurity, including actions of armed groups and military responses (Melcher et al., 2018; van Lookeren Campagne and Begum, 2017).

The construction of fishponds is a potential response to a reduction in the productivity of natural water bodies, although the construction and maintenance of ponds may be limited by water availability, which is also likely to be impacted by higher temperatures, increased evapotranspiration, reduced groundwater recharge and, in some locations, periodic or long-term reductions in rainfall – as well as increased water demands associated with activities such as irrigation development. Support for the development or strengthening of local and community governance mechanisms to manage fish stocks through catch allocations and access agreements, and to resolve conflicts, may also be desirable.

4.3.2 Risks to marine fisheries

Marine fish stocks are vulnerable to a complex mixture of interacting climate change impacts. Around the West African coast (Mauritania, zone 1), sea surface temperatures (SSTs), marine heatwaves and deoxygenation are projected to increase over the 21st century (IPCC AR6, 2021). Increasing ocean acidification poses a number of detrimental effects on ecosystems, particularly when occurring alongside SST increases and deoxygenation, including impacts on the physiology, behaviour and population dynamics of individual species (IPCC AR5, 2014). Marine calcifying organisms are particularly vulnerable to physiological changes due to acidification; for example, acidification prevents mollusc larvae formation (Doney et al., 2020) and for phytoplankton which are a primary food source within most marine food webs. The impact of this at higher trophic levels is less certain but potentially significant for the health of fisheries.

The warming trend observed over recent decades in the Canary Current (IPCC SROCC, 2019) is projected to continue, with a decrease to the upwelling system over the 21st century, although this change is expected to be relatively moderate (Sylla et al., 2019). Primary production in the current has decreased over the past two decades (medium confidence, IPCC AR5, 2014). Increasing SSTs in the Canary Current have resulted in changes to important fisheries species, for example, increasing suitability for Sardinella aurita which had led to rapid expansion of the fishmeal industry in Mauritania over recent years and placed pressure on fish stocks (IPCC AR5, 2014; Corten, 2014; Corten et al., 2017).

Together, these climate-driven changes have the potential to affect both the abundance of economically valuable marine resources, and their geographic distribution. Increased SSTs have mostly negative implications for marine productivity and fisheries, including changes to dominant fish species and species composition of catches (Belhabib et al., 2016). Changes in ocean currents have important implications because these can affect geographic distributions and movements of commercial fish stocks in and out of territorial waters, making their exploitation by a given country (in this case Mauritania) more challenging and may result in implications for coastal livelihoods.

There is high confidence that sea level will continue to rise around the coast of Mauritania (zone 1) over this century (IPCC Interactive Atlas, 2021), posing a range of risks for marine fisheries. This includes the potential for reducing access to resources integral to the fishery industry, such as ports, harbours, launching and landing sites, and coastal processing facilities. While there is no consensus on the projected direction of change for storm activity in the region, any increases in storm activity may also increase risks to fishing vessels and fisher safety, particularly for fishers with limited financial resources, as well as potential damage to coastal defences.

Following intense growth in Mauritania's fisheries since the 1960s, concerns have been raised about overfishing, with some fish stocks (notably those with high commercial values) being exploited at rates 30 to 40% higher than sustainable yields (Meissa and Gascuel, 2015; Trégarot et al., 2020). Fisheries agreements with the European Union have been criticised for contributing to the overexploitation of Mauritania's fish stocks and failing to support local fisheries and workers, despite commitments to shared decision-making and sustainable fisheries development (Corten, 2014; Nagel and Gray, 2012). This points to the importance of considering not only potential impacts of climate change *within* the Sahel region but also impacts on fisheries within Europe and other demand regions, which may have significant implications for fisheries (e.g., overexploitation) in Mauritanian waters.

While it may be possible to adapt coastal infrastructure associated with fisheries, this will require significant investment. Adapting to declines in fish stocks and to changes in their distributions is likely to be more challenging. Effective monitoring of fish stocks and the conditions that mediate the abundance and health of key species is prudent, so that stocks can be managed sustainably and investment in the fisheries sector can be informed by an understanding of the viability of different resources and associated activities.

Focus Box 7: Lake Chad

Lake Chad is located in the Sahelian zone of west-central Africa, at the conjunction of Chad, Cameroon, Nigeria and Niger (zones 2 and 4). The lake provides food and water to ~50 million people and supports unique ecosystems and biodiversity (Pham-Duc, et al., 2020). Lake Chad, once the sixth largest lake in the world, decreased in area by more than 90% between the 1960s and 1980s (Gao et al., 2011). In recent decades it has become a symbol of climate change, signified by its dramatic ‘shrinking’ – although narratives of a ‘disappearing’ lake (and its links to conflict) have been widely critiqued (e.g., Daoust and Selby 2021; Magrin, 2016; Vivekananda et al. 2019). While some studies link precipitation and temperature variations to changing river flows into the lake (e.g., Coe and Foley 2001; Nour et al. 2021), others identify irrigation withdrawals as the major cause of recent low river flow and the lake’s minimal recovery since the 1970s-80s (Mahmood and Jia 2019; Zhu et al. 2019).

The lake’s unique shape and depth, which enables its division into two smaller lakes, further increased its vulnerability to water loss (Gao et al., 2011). The lake saw a partial recovery in response to increased Sahelian precipitation in the 1990s but still faces great uncertainty on its current variability under climate change. However, since the 1990s the lake’s total surface area has been relatively stable and in recent years it has expanded to a total area (including open water and water under vegetation) of ~12,000 km^2, despite a slight decrease in the northern pool (GIZ and LCBC, 2013; Lemoalle and Magrin, 2014; LIS 2020; Pham-Duc et al., 2020; Vivekananda et al. 2019). Since the 2000s, groundwater, which contributes to ~70% of the lake’s annual water storage change, is increasing due to water supply provided by its two main tributaries (Pham-Duc et al., 2020; Vivekananda et al. 2019). Pham-Duc et al. (2020) conclude that Lake Chad has not been shrinking over recent decades and the lake recovers seasonally its surface water extent and volume and remains relatively stable.

Rainfall levels have increased across the Lake Chad basin since the 1990s (Adeyeri et al., 2019, 2020; Okonkwo et al., 2014; Zhu et al., 2019). However, this could change with future climate change in the region with increasing mean temperatures and variable rainfall. Nonetheless, the lake remains much smaller in area than it originally was, and Gao et al. (2011) conclude that under current climate and water use, a full recovery of the lake is unlikely. In response to the ‘shrinking’ of Lake Chad, regional actors have proposed an inter-basin water transfer to ‘refill’ Lake Chad to channel water from the Oubangui River in the Congo Basin to the Chari River and Lake Chad (Adeniran and Daniell 2020). However, the project has been criticised for its potentially limited effects on lake levels (especially given its current stability), potential ecological and livelihood destruction, security concerns, and cost (CIMA International, 2011; Magrin, 2014; Sayan et al., 2020).

Fisheries, agriculture, livestock production and other goods and services provided by the Lake Chad Basin, have been undergoing a steady decline since the 1970s due to the major environmental changes resulting from climate change and human stream-flow modifications

(UNEP-GIWA, 2004). Increased evapotranspiration with increasing temperatures with climate change affects the lake's water quality and temperature, with knock-on effects to the immune function of fish (FAO, 2012), rates of bacterial infections in aquaculture systems (Wedemeyer, 1996), and presence of certain fish pathogens and transmission rates of certain parasites (Roessig et al., 2005). Parasitism and disease outbreaks can cause increased fish mortality, slower growth rates and lower marketability and economic returns of fish (Harvel et al., 2002).

Impacts on fish biodiversity will also have serious consequences for livelihoods and wellbeing of the communities dependent upon fisheries. However, communities around Lake Chad have engaged in long-standing forms of adaptation to environmental changes, including changing lake levels and flood patterns, including shifting between farming (including flood recession cultivation), pastoral, and fishing activities (Magrin and Pérouse de Montclos, 2018; Okpara et al., 2015; Rangé and Abdourahamani, 2014).

Furthermore, ongoing insecurity and military responses in the Lake Chad region (and not only environmental change) have significantly affected agricultural, pastoral, and fishing livelihoods. In Niger and Chad, emergency measures imposed since 2015 as part of military operations against Boko Haram include restrictions on crop planting, fishing, herding, and other movement, on forms of everyday transport, and on access to fields, fishing areas, and markets (Magrin and Pérouse de Montclos, 2018; van Lookeren Campagne and Begum, 2017).

4.4 Settlements and infrastructure

Summary of risks relevant to settlements and infrastructure

- Population growth and rapid urbanisation, combined with higher temperatures and in some locations possible declines in rainfall, will contribute to increasing pressure on services such as water, energy and health services.

- Climate extremes will result in periodic disruption to infrastructure services, particularly where infrastructure is already fragile and overstretched, notably in rapidly expanding urban centres and informal settlements.

- Increased flood risk and damage will combine with increasing demands on fragile and inadequate infrastructure to amplify risks associated with complex disasters in urban contexts, through damage to housing, schools, health facilities, roads, water, power and communications infrastructure, and food stocks.

- Population movement associated with climate-related changes such as extreme heat, drought, flooding, agricultural failure, livelihood disruptions and changes to economic industries may contribute to longer-term changes in the regional distribution of populations and urban settlements.

4.4.1 Risks of inadequate service provision

The urban population across the G5 countries is projected to rise to nearly 89 million by 2050, with urban populations projected to account for, on average, 50% of the population in the five countries, ranging from 28% of Niger's total population to 73% in Mauritania (UN Habitat, 2021). The rapid growth of urban settlements has increased housing, water, electricity and basic service demands, and wide gaps exist in access to these basic utilities and services. Water-related risks in cities in the region include insufficient coverage of water and sanitation services, aging or insufficient water infrastructure, water pollution and contamination, and waterborne diseases (Maazaz, 2021; OECD, 2021). The limited reach of government water supply networks in urban centres, alongside poor infrastructure and maintenance challenges, mean that most urban water users rely on a patchwork of private water sources such as boreholes, water pumps, water porters and water vendors (Maazaz, 2021). Population growth and rapid urbanisation will result in increasing pressure on services such as water, energy and health services. This pressure is likely to be amplified by climate change. Higher temperatures, coupled in some locations with possible declines in rainfall, will increase water demands for irrigation, livestock and domestic consumption in both rural and urban areas. Higher temperatures and worsening temperature extremes will increase energy demands for cooling in the domestic, industrial and health sectors. Worsening climate extremes will result in periodic disruption to these services, particularly where infrastructure is fragile and overstretched. This is most likely to be the case where urban populations are increasing rapidly. Such rapid increases in urban populations in turn may be driven by migration in response to the impacts of climate change in rural areas, as people seek employment as an alternative to agriculture made more difficult by climate change or migrate away from areas where climate change impacts otherwise make life more precarious.

Policy and planning in the Sahel need to address the increased demand for services resulting from a combination of rapid population growth (particularly in urban areas) and climate change, and the increasing risks to services and related infrastructure that are associated with climate change and intensifying climate hazards.

Focus Box 8: Jobs and employment

Generating employment is a political priority in Sahel countries facing large youth bulges. Climate change poses risks to employment in current sectors such as agriculture and tourism. It may also limit options for economic diversification and employment in new sectors, especially where those sectors are temperature-sensitive or water-intensive. Another climatic risk to jobs is from heat extremes, which are likely to reduce labour productivity in summer months, particularly in working environments without access to artificial cooling. There are also likely to be opportunities to create jobs in the green economy as part of responses to climate change, particularly in new industries generating renewable energy. The challenge is to identify new, labour-intensive economic opportunities with low carbon and water input requirements.

Investment in the green economy offers opportunities for generating new employment, although there are no reliable estimates for the number of potential green jobs in the Sahel region. Renewable energy generation tends to create more employment per MWh than oil or coal generation. Creating well-paid employment in high-tech sectors is politically attractive, although the total numbers of jobs in renewable energy will be relatively modest and offer little to semi-skilled workers (Cote, 2019). There is greater scope for semi-skilled job creation in labour-intensive sustainable agriculture and off-farm value addition to agriculture.

4.4.2 Risks from rainfall extremes and flash flooding

Rainfall variability (both annually and sub-annually) is projected to increase into the 2050s, with increases in the intensity of heavy rainfall events, which may become more intermittent in the west and more frequent in the east (Biasutti, 2019).

More extreme heavy rainfall events will impact settlements and infrastructure through increased runoff (see Focus Box 6) and flooding, especially when combined with land use change such as urbanisation. Risks associated with flooding will continue to increase as urban populations grow and rainfall extremes become more intense, resulting in greater runoff and flash flooding. Floods damage housing, schools, health facilities, roads, water, power and communications infrastructure, and can destroy food stocks and affect food distribution. Increased flood risk and damage will combine with increasing demands on fragile and inadequate infrastructure to amplify risks associated with complex disasters in urban contexts. People may migrate to urban centres in response to the impacts of climate change in rural areas, only to face increased climate-related risks in these new urban contexts.

Settlements close to major rivers and lakes are particularly vulnerable, such as capital cities Bamako (Mali, zone 3), Niamey (Niger, zone 3), situated on the River Niger, and N'Djamena (Chad, zone 4) situated near the Logone and Chari Rivers. City infrastructure is particularly vulnerable to flooding, especially N'Djamena in the east of the region where monsoon rainfall is projected to be above that in the west. Urban centres such as Niamey (Niger, Zone 3) and N'Djamena (Chad, Zone 4) have been severely affected by flooding in recent years, with intensifying flood risks linked to increasing precipitation as well as deforestation and soil erosion around urban areas (Descroix et al., 2015; Nouaceur, 2020).

The impacts of projected climatic changes on settlements and infrastructure, including via rainfall extremes, flooding, heat extremes, and coastal hazards, will present particularly severe risks for populations who already face conditions of vulnerability (see Focus Box 5). These include populations experiencing poverty and those living in informal settlements, with the latter accounting for 66% of urban populations in the G5 countries (UN Habitat, 2021). Informal settlements often located on the peripheries of cities, with already limited and inadequate water, sanitation, wastewater, and waste management services, transport and road infrastructure, and land titles (Baron and Bonnassieux, 2021; OECD, 2021). Informal settlements are often constructed on land at high risk of flooding, meaning that the highest risk is borne by the poorest members of society (Issaka and Badariotti, 2013).

Rainfall extremes have implications for hydropower generation, which is increasingly important in the Sahel. Projected increases in precipitation may coincide with increases in hydroelectricity production (Oyerinde et al., 2016). However, greater interannual variability (and frequency of flood and drought events) will affect the reliability of hydropower generation and dam storage. A tailored approach will be needed for the management of hydropower, with planning at the national and sub-national level accommodating increases in rainfall variability and considering downstream risks associated with dams, including potentially increased risks of flooding when water is released from reservoirs during periods of high rainfall, and of downstream water scarcity during dry periods.

Flash flooding and river flooding can also have severe impacts on health and health systems, as discussed in Section 4.5.1.

4.4.3 Risks associated with heat extremes

Climate projections indicate very high confidence in annual temperature increases across the whole Sahel region. Zones 3, 4 and 5, in the central and southwest of the region, show a marginally greater increase in the range of projected annual temperatures compared to zones 1 and 2 in the north and 6 in the southeast (2-3.5°C compared to 1.5-3°C). Daily maximum temperatures will consistently exceed 40˚C in the hottest months across all zones, with some climate models projecting maximum temperatures up to 45˚C in desert zones 1 and 2. These temperatures will also be exceeded earlier in the year and for longer through the year - currently, these temperatures are rarely reached. Nonetheless, temperatures more than 50°C are known to have already been experienced in the region and have been identified in historical climate records from north-western Mauritania.

Heat extremes pose direct and indirect risks to urban infrastructure, particularly electricity generation and distribution systems. Direct impacts include the overheating of electricity generators, transmission lines and substations, which can result in power outages (Burillo et al., 2017). Indirect impacts include increased electricity demand for cooling, which is likely to occur when infrastructure is most at risk from extreme high temperatures, amplifying the risk of power outages (Salimi and Al-Ghamdi, 2020). Power outages have knock-on effects on other sectors such as communications and health (via disruption to health services and equipment). Increases in sustained and extreme high temperatures could have major impacts on infrastructure, such as on electric power reliability (e.g., reduction in the cooling ability of nuclear electricity plants and reduced solar photovoltaic efficiency) or transport networks (e.g., buckling railways, roads and runways). This is especially impactful in urban areas due to the exacerbation of temperatures due to the Urban Heat Island (UHI) effect[22] (IPCC AR6, 2021).

Heat extremes may also threaten hydroelectric power generation through their impacts on streamflow via increased evapotranspiration and reduced surface runoff. Higher temperatures in general mean that periods of drought are more likely to coincide with heat extremes, amplifying drought severity. Risks of periodic disruption to hydropower associated with severe drought are therefore likely to increase.

Heat extremes also pose significant direct risks to human populations, as discussed in Section 4.5.

4.4.4 Risks from sea-level rise and coastal hazards

[22] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

There is very high confidence of an increase in relative sea level on the coast of Mauritania (zone 1) projected to be of the order of 0.3m by the 2050s (IPCC Interactive Atlas, 2021). There is high confidence of an increase in coastal erosion with the vast majority of sandy coasts in the region projected to experience shoreline retreat through the 21st century (IPCC AR6, 2021) and therefore high confidence of an increase in infrastructure damage (such as sea wall failure) and coastal flooding.

Nouakchott, Mauritania's capital (Zone 1) and home to about a third of the country's population, faces risks associated with its rapid expansion and coastal location. Nouakchott's elevation varies between –1m and +1m above mean sea-level, making it vulnerability to periodic coastal flooding associated with high tides and storm surges. While there is no consensus on the direction of change in storm activity in the region, higher sea-levels will increase risks associated with high tides and storm surges. Extreme sea level events are projected to increase with high confidence (IPCC AR6, 2021).

Flooding associated with storm surges and high tides may be exacerbated further by increases in runoff due to urbanisation and the expansion of hard surfaces, and the degradation of natural coastal defences as a result of sand extraction for construction. Both natural and engineered coastal defences are at risk from coastal storms and storm surges.

In addition, rising sea levels have resulted in saltwater intrusion and the elevation of the groundwater table in the vicinity of Nouakchott. This results in saturation of the ground, which means runoff stays on the surface (Mohamed et al., 2017; Niang, 2014). Sea-level rise is thus increasing flood risks associated with rainfall and surface runoff, by preventing the infiltration of runoff in the vicinity of affected aquifers such as the Trarza aquifer (Agoubi 2021). Nouakchott, Mauritania is particularly at risk from combinations of high tides/storm surges and extreme rainfall and high runoff over land. These risks may be offset to some extent by reduced runoff implied by projections of higher temperatures, with the greatest projected reductions in precipitation occurring in the far western coastal areas of Zone 1. However, this area will remain at high risks from individual extreme rainfall and runoff events, particularly where these combine with high tides or storm surges. In the medium to longer term, sea-level rise may result in the permanent inundation of parts of the city and surrounding areas.

Saturated soils also pose an increasing challenge in terms of drainage and wastewater management, and saltwater intrusion into coastal aquifers and groundwater can result in the corrosion of infrastructure.

4.4.5 Risks associated with wind regimes, dust storms and sand mobilisation

There is low confidence in the direction of change relating to sand and dust storms in the Sahel (IPCC AR6, 2021). However, the impacts on infrastructure could be significant, for example reducing efficiency of solar power, preventing the use of roads and railways through the movement of sand dunes, impeding air travel through reduced visibility, and impacts on mechanical equipment (IPCC, 2019b).

Wind speed and wind energy potential are projected to increase significantly (medium confidence), increasing the potential for infrastructure damage, although the signal is less clear for the northern Sahel.

Settlements, including cities such as Nouakchott (Mauritania, Zone 1), and smaller settlements in parts of the Sahel, face risks associated with the movement of mobile sand dunes (Berte et al., 2010; Bodart and Ozer, 2009; Gómez et al., 2018; Niang, 2014). While climate change may influence dune mobility via its impacts on vegetation cover and wind regimes, dunes are dynamic features of the Sahelian landscape and their advancement towards settlements is not necessarily an indicator of progressive or systematic desertification (see Focus Box 6).

4.4.6 Risks associated with disasters, displacement and population movements

While urban populations are steadily increasing due to regional population growth and rural-urban migration, urban areas may experience sudden influxes of people displaced by drought, flooding, agricultural failure, and conflict. By the 2050s, extreme heat may also trigger population movements. Climate may interact with conflict, both within and outside the G5 countries, to affect internal and cross-border population movements.

For example, anecdotal reports indicate an influx of people to northern Mauritania from Western Sahara that started following several years of below normal rainfall from 2017, and accelerated after November 2020, when the 29-year ceasefire between Morocco and the Frente Polisario, the Sahrawi independence movement, broke down (SADR, 2021). Mauritania already hosts over 65,000 Malian refugees in Mbera camp in the southeast of the country (WFP, 2021). The population of Mbera camp has been displaced principally by conflict, although there are suggestions that the drying of lakes in Mali and the resulting impacts on livelihoods may have played some role in displacement (UNHCR, 2021). In August 2020, floods affected over 700,000 people across the Sahel, destroying thousands of homes and affecting people who had already been displaced.

Intensification of risks such as those described above may combine with the emergence of new hazards and long-term shifts in climatic and environmental conditions to influence population movements. New hazards may include the emergence of combined extremes of heat and humidity approaching or exceeding the limits of human tolerance, as discussed below (see section 4.5). This tolerance threshold is associated with wet-bulb temperatures (WBT) above 34°C, characterised by Andrews et al. (2018) as representing ‘extreme risk.’ Im et al. (2017) identify a WBT of 35°C as representing the limit of human survivability, while Kang et al. (2019) characterise WBT above 29°C as extremely dangerous. The area of extreme risk associated with such combinations of heat and humidity is projected to cover increasingly large parts of the Sahel as global mean surface temperature increases beyond 1.5°C (Andrews et al., 2018). The occurrence of such extremes could result in population movements to areas outside the zone of extreme risk. This would mean movements of people out of eastern Mauritania, parts of central Mali and Niger, and most of central Chad as warming approaches 2°C above pre-industrial temperatures (Andrews et al., 2018). At 3°C of warming above pre-industrial, most of the Sahel is in the zone of extreme risk, with exceptions being the coastal areas of Mauritania, southwestern Mali and Burkina Faso, the southernmost extremity of Chad, and upland areas in the north of Mauritania, Mali and Niger (Andrews et al., 2018). This would result in extreme pressure on settlements in these areas.

Shifts in the monsoon and consequently in agroclimatic and vegetation zones may also influence the distribution of population, as people move south and to urban centres during dry periods, and north during humid periods. During dry periods, existing settlements may experience increases in their population, increasing pressure on infrastructure and services, and resulting in other socio-economic impacts. For example, Hill (1989), quoting Davies and Thiam (1987), describes how an influx of migrants into towns in Mali following the 1984-85 drought resulted in a fall in the daily wage rate of construction workers from 300 FCFA ($1) to 50 FCFA ($0.18). Hill (1989) also describes the congregation of 20,000 people, mostly pastoralists, around the town of Gao in Mali (Zone 3) during the drought of 1973.

Wetter conditions in the Sahel and southern Sahara may facilitate the northward expansion of agriculture and pastoralism, resulting in the development and growth of settlements in more northerly regions, with associated infrastructure requirements. However, as occurred in the 1950s and 1960s, this expansion may further marginalise pastoralists and establish a foundation for additional rural-urban migration during subsequent drought periods (Heyd and Brooks 2009). Any northward expansion of settlement and agriculture during wet periods may not be viable in the longer term if the northward extension of the monsoon is not sustained. Such expansion therefore may increase the risk of economic and social disruption on a large scale, systemically increasing risk. Agricultural and settlement expansion into areas that may become more productive as a result of changes in monsoon behaviour therefore needs to be approached with extreme caution.

Settlements, infrastructure and associated planning in the Sahel will need to accommodate a population that is both growing and highly dynamic, and whose movements and distribution will inevitably vary as climatic conditions and associated environmental opportunities wax and wane in the highly variable Sahelian environment. Mobility and the dynamic nature of the relations between urban and rural populations need to be understood and accommodated, as they are fundamental to Sahelian livelihood and economic strategies.

4.5 Human health and mortality

<u>Summary of risks relevant to human health and mortality</u>

- Increases in the intensity, frequency and duration of heat extremes, including wet-bulb temperatures marking the upper limit for human survival, pose a considerable threat to human health and life, through risks including dehydration, heat-stroke, reduced productivity, interaction with respiratory conditions, and impacts on water quality.
- Flood events present risks to human health associated with death and injury, water-borne diseases, contamination of water supplies, and damage to medical infrastructure and disruption of medical services, as well as displacement, food insecurity and malnutrition, and psychological impacts.
- Increasing precipitation and flood risks may lead to increases in the prevalence of communicable waterborne diseases such as cholera, as well as being a direct cause of death.
- The health and mortality impacts of these climate-related changes will be especially great for already vulnerable populations, including elderly people, people with existing health conditions, outdoor labourers, residents of informal urban settlements, and poverty-affected individuals and households.

4.5.1 Risks from heat extremes

Africa is projected to show greater increases in projected extreme temperatures than any other region in the world (Coffel et al., 2018; Rohat et al., 2019). The intensity and frequency of extreme temperatures (including heatwaves and concurrent heatwaves) will increase as global temperatures rise (IPCC AR6, 2021). Across the Sahel region, in all zones, there is high confidence in an increase in the number of days above 35°C and high confidence in an increase in the number of days above 40°C, with the number of days above these thresholds exceeding 40 days per year by 2050 (IPCC Interactive Atlas, 2021). Daily maximum temperatures will consistently exceed 40˚C in the hottest months across all zones, with some models projecting maximum temperatures up to 45˚C in desert zones 1 and 2. Extreme temperatures above 50°C have been recorded in northern Mauritania near the border with Western Sahara (Zone 1), and in southern Algeria in the area near the Mauritanian border. The likelihood of such temperatures occurring in northern Mauritania and potentially in other parts of the Sahel will increase as a consequence of climate change, and their occurrence in the historical record suggests that the climate projections may underestimate extreme high temperatures.

Daily minimum temperatures (which are generally assumed to be representative of night-time temperatures) are projected to consistently exceed 25˚C in the hottest months across all zones with some climate models projecting maximum temperatures up to 30˚C in desert zones 1 and 2. These temperatures will also be exceeded earlier in the year and for longer through the year. Currently, these temperatures are rarely reached.

Heat extremes have been shown to have significant impacts on human health in the Sahel, especially among elderly people and those with other health conditions such as cardiovascular disease (Ebi et al., 2017). Impacts of heat extremes include dehydration, heat-stroke, reduced productivity, exacerbation of respiratory conditions, and indirect impacts on human health via water quality. These risks may increase significantly as a result of climate change, which will result in significant increases in the magnitude, frequency, and duration of heat extremes. Extreme heat has been linked with an increased risk of occupational injuries and with adverse birth outcomes (Kuehn and McCormick 2017, Ebi et al., 2017). Power outages during episodes of extreme high temperature can increase health risks via their impacts on the functioning of health services and cooling systems, reducing the capacity of health services to cope, and amplifying the impacts of extreme heat in urban environments. Such outages can be caused by the direct impacts of heat extremes on transmission infrastructure and are made more likely by demand surges associated with powered cooling. In addition, increases in minimum temperatures further indicate greater risk for heat-related stress as persistent high temperatures at night-time during heat waves have been shown to have greater impacts on human health than high daytime temperatures alone (Nissan et al., 2017; Mcgregor et al., 2015). These risks will be particularly acute for poverty-affected individuals and households with limited access to cooling technologies (e.g., air conditioning).

Heat extremes can increase greenhouse gas emissions through energy demands for cooling in the form of air conditioning. Increased energy demand during heat extremes can also increase the risk of power outages, further exacerbating heat-related health risks and undermining the capacity of health services. The need for cooling, and the impacts of heat extremes, can be reduced through urban design and policy responses. Traditional architecture in arid and semi-arid North Africa incorporates elements to enhance thermal comfort, including covered outdoor spaces and shade, passive cooling elements that encourage air circulation, the situating of kitchens on rooftops or upper floors to avoid additional heating within the home, and the use of materials such as adobe with good thermal insulation properties (Ahmad et al., 1985). The use of local materials and techniques can reduce the need for emissions-intensive material such as cement.

Extreme hot temperatures may also enhance pressure on displacement and conflict, relating also to food security and nutrition, which in turn further impacts human health and mortality. At the same time, these may present additional barriers to mobility. While some studies find that environmental and climate-related changes are associated with increased migration in the Sahel region (Bertoli et al., 2020), other studies report that climatic factors including temperature anomalies are associated with decreased migration, potentially due to negative effects on agricultural outputs which ‘trap’ people in place (Gray and Wise, 2016).

4.5.2 Risks from extreme wet-bulb temperatures

Across all zones in the Sahel there is medium confidence in small increases in annual total precipitation. Evaporation rates generally increase with precipitation and high confidence in increasing temperatures means the risk of dangerous combinations of temperature and humidity (typically measured in terms of wet bulb temperatures) is increased, particularly in zones 2, 4, 5 and 6 (IPCC AR6, 2021). The humid tropical climate of Zones 5 and 6 makes these areas particularly susceptible to dangerous wet bulb temperatures[23] in the range 29-35°C, with significant effects on heat-related mortality (Coffel et al., 2018).

Wet bulb temperatures above 34°C pose severe risks to human health and productivity (Andrews et al., 2018). A wet-bulb temperature of 35°C has been proposed as an upper limit for human survivability (Im et al., 2017) while wet bulb temperatures above 29°C are extremely dangerous (Kang et al., 2019). Wet-bulb temperatures approaching 35°C have been recorded in southern Mali and southern Mauritania, and values of in excess of 29°C have been recorded throughout the southern parts of the western and central Sahel.

Andrews et al. (2018) identify regions of low, moderate, high, and extreme risk of occupational heat exposure in the shade during the hottest part of the day, based on projected wet-bulb temperatures associated with increases in global mean surface temperature of 1.5°C, 2°C, and 3°C. Low, moderate, high and extreme risk are associated with periodic wet bulb temperatures above 25°C, from 26°-29°C, from 30°-33°C, and above 34°C respectively.

Under global warming of 1.5°C, all Sahel zones are high risk, with areas of extreme risk in northeast and southwest Mauritania, eastern Niger, and central Chad. Areas of extreme risk expand at 2°C to eastern and central Mauritania, much of northern Mali, and western and central Chad. At 3°C, areas of extreme risk cover most of the G5 countries, except for western coastal Mauritania, the far southwest of Mali and Burkina Faso, southern Chad, some of the northern highland areas of Chad and Niger, and the far northeast of Mali (Andrews et al. 2018).

In cities close to rivers and lakes, such as Timbuktu, Bamako (Mali, zone 1 and 3 respectively), Niamey (Niger, zone 3) and N'Djamena (Chad, zone 4), proximity to water means humidity is likely be higher, increasing the likelihood of critical wet bulb temperatures in these urban areas during the hottest months when evaporation is highest. In urban areas, these risks may be exacerbated further by the Urban Heat Island (UHI) effect[24] which can increase temperatures by 2-3°C relate to surrounding rural areas (IPCC AR6, 2021).

If global mean surface temperature increases in excess of 1.5°C, extreme wet bulb temperatures could have significant impacts on the availability and distribution of habitable and productive areas within the Sahel, with serious consequences for human health and mortality, and potentially significant implications for population movements.

[23] Wet bulb temperature refers to the temperature that an air parcel would reach when fully saturated. When wet bulb temperatures reach 35°C – the average temperature of human skin – evaporative cooling of the body is much less efficient and so the body accumulates temperature. Studies suggest that 35°C is therefore the limit of human tolerance for heat stress (Coffel et al., 2018).

[24] The UHI effect refers to increased temperatures in urban areas such as cities and towns due to the high concentration of surfaces that absorb and retain heat, specifically concrete and tarmac. Additional feedbacks causing increased temperatures include reduced winds, air pollution and reduced evapotranspiration due to lack of vegetation. UHIs are especially dangerous for heat stress as temperatures remain high throughout the night.

Focus Box 9: Limits to adaptation

The rate and magnitude of climate change in the coming decades may exceed the limits to adaptation of some socio-economic systems (Adger et al., 2009). The limits to climate adaptation involve a complex set of thresholds that can be physical or social. In a social context, the limit to adaptation comes when no adaptation actions are available or sufficient to manage risks to a level considered tolerable to achievement of objectives (Dow et al., 2013). Physical limits to adaptation occur when climatic conditions are such that a living entity cannot survive, or a system or process cannot be sustained, at a given location or in a given context, and no interventions are possible or physically practical to enable it to do so.

For the Sahel region, where the climate is already harsh, climate change, even at relatively low levels, has the potential to exceed limits to adaptation in some regions at some periods of the year. A key example of this is associated with thermal stress. A wet-bulb temperature (air temperature measured by a saturated thermometer) of 35 °C marks the upper survivable physiological limit for humans, although much lower values have series health and productivity consequences.

Wet-bulb temperatures approaching 35°C have been recorded in southern Mali and southern Mauritania (Zone 1), and values around or in excess of 30°C[25] have been recorded across the southern regions of the western and central Sahel. It is conceivable that the 35°C threshold will be breached in these and other areas as the region warms.

4.5.3 Changes in the prevalence of communicable and non-communicable diseases

While progress has been made in providing access to water in the region, progress in access to sanitation services has been slower, with poor access to safe drinking water and improved sanitation increasing the risk of waterborne diseases, such as Hepatitis A and typhoid fever as well as diarrhoea (gastroenteritis) and malaria (Alagidede and Alagidede, 2016). In 2016, the average mortality rate attributed to unsafe water and sanitation and lack of hygiene in the G5 countries was 66 per 100,000 people (ranging from 39 in Mauritania to 101 in Chad), compared to a world average of 14. In 2019, communicable diseases and maternal, prenatal, and nutrition conditions accounted for an average of 58% of deaths in the five countries (ranging from 53% in Mauritania to 63% in Chad), compared to a world average of 33% (World Bank, 2021). In 2016, the average mortality rate attributed to air pollution in the region was 223 per 100,000 people (ranging from 170 in Mauritania to 280 in Chad), slightly higher than the world average of 211 (World Bank, 2021). Dust carried by the wind has been associated with poor air quality and increased respiratory infections in parts of the Sahel region (Jenkins and Gueye, 2018; Ozer, 2008).

Increasing precipitation and flood risks may lead to increases in the prevalence of communicable waterborne diseases such as cholera, as well as being a direct cause of death. Increases in rainfall and flooding may contribute to increases in malaria prevalence in some

[25] https://news.climate.columbia.edu/wp-content/themes/sotp-foundation/dataviz/heat-humidity-map/.

locations (and spatial changes in rainfall could contribute to southward movements of malaria prevalence), although rising temperatures could contribute to a decrease in malaria transmission (Diouf et al., 2021; Ermert et al., 2012). Extreme high temperatures could have impacts on the prevalence of heat impacts on respiratory and cardiovascular diseases. Populations who already face conditions of vulnerability, including poverty, will be particularly affected by climate-related disease risks (see Focus Box 5). For instance, residents of informal settlements in the Sahel region already face greater risks associated with waterborne diseases (Alagidede and Alagidede, 2016).

The IPCC AR6 report (2021) projects that there is low confidence in the direction of change relating to dust storms in the Sahel, but changes in dust storm activity may have implications for human mortality and health via increased prevalence of respiratory conditions, and dust-borne pathogens.

4.5.4 Flood risks to human health

Flood events present risks to human health associated with death and injury, water-borne diseases, contamination of water supplies, and damage to medical infrastructure and disruption of medical services, as well as displacement, food insecurity and malnutrition, and psychological impacts. Intensifying flood risks in the Sahel region have been linked to both climatic variability *and* to changes in land use and land cover.

Severe flooding increases risks to human health in the Sahel region, including as a direct cause of death. In recent years, parts of the Sahel region have experienced severe flooding, especially along the Niger River (Guinea, Mali, Niger, Benin, Nigeria) and in urban centres such as Niamey (Niger) and N'Djamena (Chad). In 2020, over 70 people died and 90 were injured due to flooding in Niger, while over 40 people died and over 100 were injured in Burkina Faso (United Nations, 2020). Rainfall variability (both annually and sub-annually) across the Sahel is projected to increase into the 2050s, with greater intensity of heavy rainfall events which may become more intermittent in the west and more frequent in the east (Biasutti, 2019). Increases in flood risk associated with increases in the intensity of extreme rainfall events, and in the coastal zone of Mauritania with sea-level rise, are likely to increase risks to human health through a variety of mechanisms. In addition to death and injury during flood events, floods are associated with water-borne diseases, and biological and chemical contamination of water supplies and soils that can adversely affect human health. Flood damage to transport infrastructure and health facilities can mean that access to and quality of medical services are adversely impact when they are needed most.

Flooding can also result in the loss of food stocks, livestock, housing and other assets, increasing poverty and food insecurity and driving displacement and migration. Impacts on mental health are also significant, considering the psychological impacts (trauma) of flooding and its consequences. These risks can be expected to increase as a result of climate change and may be exacerbated by demographic trends and underinvestment that amplify pressures on fragile infrastructure and drive increases in population density in locations such as informal settlements that are highly vulnerable to flooding. Risk of flooding is especially high in major river basins such as the Niger River Basin (including Inland Niger Delta) and Lake Chad Basin though risk is highly related to land use within the basin (e.g., urban areas) and the response of vegetation to flood regimes (Hiernaux et al., 2021; Hassan et al., 2020; Aich et al, 2016). The impacts of flooding will be particularly acute for poverty-affected individuals and households. Food insecurity and malnutrition, resulting primarily from displacement due to ongoing insecurity in the Sahel region, as well as environmental crises such as flooding and droughts, have severe impacts on health outcomes. Roughly 8.3 million people are experiencing crisis or emergency-level food insecurity in Mali, Burkina Faso, Niger, and Chad, and 1.2 million children across the G5 countries are severely malnourished (OCHA, 2021).

While climate change may contribute to increased risks associated with flooding, local changes in flood patterns and intensifying flood risks in the Sahel region have been linked to both climatic variability *and* to changes in land use and land cover, such as agricultural expansion, land clearance and deforestation, and soil erosion (Aich et al., 2015; Descroix et al., 2015; Nouaceur, 2020; OCHA, 2021).

For coastal areas (zone 1, Mauritania), there is very high confidence of an increase in relative sea level. The city of Nouakchott which has an elevation of between -1m and +1m is likely to have increased frequency of storm surges and increasingly extreme sea level events causing coastal flooding. SLR is also highly likely to cause greater frequency of saltwater intrusion into coastal aquifers (namely the Trarza and Benichab aquifers) causing groundwater level rise and therefore flooding both on the coast and at inland locations with proximity to affected aquifers (Agoubi, 2021; Mohamed et al., 2017). The contamination of freshwater resources (including drinking water sources) due to coastal flooding may also reduce the availability of potable water in Nouakchott and the surrounding area causing water related risks to health.

4.6 Biodiversity and ecology

Summary of risks relevant to biodiversity and ecology

- Increases in extreme high temperatures and delays to the onset of the wet season may adversely affect the development and biodiversity of certain plant and animal species through impacts on growing seasons, increased heat stress, and changes to water availability.
- Increased water stress and reduced runoff may have adverse impacts on wetland and other ecosystems that act as reservoirs of biodiversity in the Sahel, with water bodies at the edge of lake, wetland and delta systems at particular risk.
- Climate-related environmental risks affecting species behaviour, abundance and distribution will be intensified by anthropogenic pressures such as pollution, ecosystem fragmentation and destruction, and the disruption of migration routes.
- Coastal and marine ecosystems in Mauritania face risks from increasing sea levels and changes in water temperatures, chemistry, circulation and oxygen content, combined with anthropogenic pressures associated with fishing, mineral extraction, urban development and coastal infrastructure.
- Conservation and restorations programmes may have adverse impacts on local livelihoods by limiting activities based on the exploitation of natural resources (e.g., subsistence fishing), in turn intensifying existing patterns of inequality and vulnerability.

4.6.1 Risks to unique ecosystems

Environmental conditions in the Sahel are mediated by the behaviour of the West African Monsoon (see Focus Box 3), with vegetation cover responding to changes in the strength and position of the monsoon rain belt over periods ranging from years to millennia. Following the persistent drought conditions of the 1970s and 1980s, rainfall and vegetation recovered in much of the Sahel from the mid-1990s onwards, although this recovery has been more significant over the central Sahel than over the western Sahel (Olsson et al., 2005, Doblas-Reyes et al., 2021). There is no scientific evidence to support narratives of progressive desertification in the Sahel and the steady southward encroachment of the Sahara (Brooks, 2004, Benjaminsen and Hiernaux, 2019) (See Focus Box 6); rather, drought conditions in the Sahel are manifestations of interannual to decadal-scale climate variability mediated by anthropogenic aerosols and increased atmospheric greenhouse gas concentrations (Biasutti and Giannini, 2006, Giannini and Kaplan, 2018, Marvel et al., 2020).

Changes in temperature may have significant direct impacts on plant and animal species, and therefore on ecosystems and biodiversity, in addition to impacts related to increased evapotranspiration and associated reductions in runoff and soil moisture. Climate projections indicate very high confidence in annual temperature increases across the whole Sahel region. Zones 3, 4 and 5 in the central and southwest areas of the region show a marginally greater increase in the range of projected annual temperatures compared to zones 1, 2 in the north and 6 in the southeast (2-3.5°C compared to 1.5-3°C). Daily maximum temperatures will consistently exceed 40˚C in the hottest months across all zones, with some models projecting maximum temperatures up to 45˚C in desert zones 1 and 2. Climate change means that these temperature thresholds will be exceeded more frequently, for longer, and earlier in the year. Increases in the frequency and severity of heat extremes may exceed the tolerances of plant and animal species and ecosystems. push species beyond tolerable limits. A study by Batisti and Naylor (2009) concluded that, by the end of the 21st century, and earlier in some parts of, the Sahel, growing season temperatures are expected to exceed those of the hottest seasons in the historical record. This suggests unprecedented stress on species and ecosystems as well as people, crops and livestock.

Across all of the Sahel zones, there is medium confidence in small increases in annual total precipitation with the majority of projected change occurring in the wet season (June-September), although increases in the winter (October-February) season are indicated in zones 5 and 6 (the southern extents of Burkina Faso and Chad). In these zones, increases of up to 80mm (50%) and 75mm (40%) are projected respectively, indicating an extension of the summer wet season into winter. Although projection signals indicate a moderate increase in total precipitation, this does not necessarily mean more water availability; rising temperatures in all zones combined with increased evaporation rates and interannual variability may mean that water availability does not increase and may reduce, impacting ecosystems and biodiversity.

Projections indicate a shift in the seasonality of the rainy season with high confidence of delayed onset to the WAM (by 5-10 days) and medium confidence of its delayed retreat (Dunning et al, 2018; Biasutti et al., 2013). Though total rainfall may increase, delays of the wet season onset mean a potentially shorter growing season for deciduous plants, impacting plant development and overall biodiversity (Dunning et al., 2018; Biasutti and Sobel, 2009) (see WAM Focus Box 3).

Reduced moisture availability, resulting from higher mean and extreme temperatures and greater evapotranspiration, will increase stress on ecosystems, in particular aquatic or wetland ecosystems (e.g., rivers and lakes, streams, oases, marshes, and pools) that are 'hotspots' of biodiversity in the Sahel region. Such changes can have large impacts on wetland ecosystems. For example, Lake Faguibine, the northernmost of the lakes of the inland Niger Delta, dried almost completely following the droughts of the mid-1970s, and the wetland ecosystem was replaced by forest on the former lake bed, with profound impacts on local livelihoods (Thom and Wells, 1987; Brockhaus et al., 2013). Future reductions in moisture availability, coupled with increases in water diversion and abstraction, may have the potential to drive similar changes in certain locations, for example on the periphery of wetland areas or in oasis zones.

A variety of water bodies exist throughout the Sahel and Sahara, including freshwater oases, saline lakes, and temporary or permanent pockets of water fed by drainage channels or springs known as *gueltas.* These features exist alongside numerous dry lake beds (palaeolakes) dating from previous Saharan humid episodes. The nature and status of these various features is determined by a complex interaction of precipitation, evaporation, topography and geology (Eggermont et al., 2008; Grenier et al., 2009). These features can be viewed in the context of long-term responses to the desiccation of the Sahara between approximately 7000 and 4000 years ago (with humid conditions persisting longer in certain locations), mediated by the above factors and their impact on groundwater. The extent to which climate change threatens these water bodies and their associated ecosystems is unclear and likely to vary considerably. Water bodies fed by fossil groundwater, such as the

Ounianga lakes in Chad, may be less vulnerable to climate change (but potentially susceptible to any large-scale abstraction of non-renewable groundwater). Gueltas fed by runoff and springs are likely to be more vulnerable, depending as they do on surface runoff and related groundwater discharge.

Many of these features house rare and unique relict species and ecosystems from previous humid episodes. For example, Guo and Dumont (2014) report two species of crustacea in freshwater environments from Ounianga and Tibesti in northern Chad (Zone 2), one of which was previously unknown to science. In the same region, Dumont and Vershuren (2005) report multiple odonata species (which include dragonflies and damselflies) including some that are rare or unique west of the Nile. Trape (2013) describes six species of relict fish and a relict toad species in lakes and gueltas near Ounianga Serir (northern Chad). Relict crocodile populations have been identified Chad and Mauritania, associated with 78 localities in the latter, most commonly in permanent gueltas and seasonal pools (Brito et al. 2011).

Increases in rainfall may have beneficial or adverse effects on Sahelian ecosystems, with potential risks related to increased runoff as well as flooding. Increasing precipitation intensity and extremes may lead to direct damage to plants, soil erosion and degradation and loss of biodiversity if animal and plant life are not resilient to more frequent flooding or if breeding cycles are regularly adversely impacted.

There may also be impacts to migration patterns. In major river systems such as the Niger River Basin and the Lake Chad Basin, where land and aquatic biodiversity is high, increasing variability and frequency of extreme events may cause biodiversity changes or loss and associated changes to ecosystem services. The projections of total soil moisture are less clear but an important consideration for ecological drought. Projections indicate that the majority of Mauritania, Mali and the northern half of Burkina Faso (zones 1 and 3) will have decreases in soil moisture (low confidence; IPCC AR6, 2021).

Projected increased runoff may also exacerbate pollution downstream, especially with greater use of agro-chemicals in farming, affecting animal and plant life and reproductivity. Floodplains of the Inland Niger Delta (part of the River Niger Basin) support a large amount of agriculture such as rice production but are dependent on the annual inundation of the delta. With increasing interannual variability in precipitation, this may be less reliable and so change the ecological structure of floodplains (Thompson et al., 2021).

The amount of precipitation increases in drier zones (northern Sahel zones of 1 and 2, up to +30mm) are unlikely to change biodiversity or ecosystems in the area without major irrigation infrastructure such as dams. In other zones, precipitation increases are also unlikely to cause major spatial shifts in ecological ranges, however, although extension of the wet season and additional rainfall in the winter season in the southern Sahel zones 5 and 6 may allow growth of some different plant species.

Around the West African coast (zone 1, Mauritania), there is high confidence that sea surface temperatures (SSTs) will increase, with the increase for the mid-century projected to be between 0.6–1.9°C. Subsequently, there is also high confidence that marine heatwaves will increase over the 21st century alongside increasing deoxygenation (IPCC AR6, 2021). Increasing ocean acidification has a number of detrimental effects on ecosystems, especially when occurring alongside SST increases and deoxygenation.

Ecosystems will be made more vulnerable to these climate related stresses by local anthropogenic stresses related to land use, the exploitation of ecological resources, ecosystem fragmentation and environmental pollution. Anthropogenic stresses are likely to grow as a result of economic development and demographic trends. Future climate adaptation practices, including water infrastructure development and agricultural intensification, may contribute to intensified negative effects on water bodies and wetlands (e.g., overexploitation, contamination, reduced flows to rivers, lakes and wetlands as a result of dam building).

The potential impacts of climate change on agricultural and fishing livelihoods and national agricultural economies may contribute to the expansion of other economic activities such as mining – which have significant impacts on ecosystems and can impede protection efforts. Resource extraction activities, including mining and oil and gas extraction, present significant threats to Sahelian ecology (Brito et al., 2014; Brito et al., 2018; Melcher et al., 2018; Ramsar Convention, 2021; UNESCO, 2021d). In Niger, for instance, exploration and exploitation permits for uranium, oil, and gold present threats to the Air and Ténéré ecosystems (UNESCO, 2021a). Just two years after nominating Lake Chad for UNESCO world heritage status, the Chadian government withdrew its application after signing production-sharing agreements with several oil companies for renewed production around the lake, despite warnings of impacts on the lake's waters (Gouby, 2020). And in Mauritania, the Banc d'Arguin National Park is threatened by offshore oil exploration, water extraction for mining, overfishing, illegal fishing, mechanical shellfish harvesting, urban development, and increasing tourism due to new road infrastructure (UNESCO, 2021b; Ramsar Convention, 2021). These will interact with threats associated with sea-level rise, increase water temperatures, ocean acidification and changes in water chemistry and circulation.

4.6.2 Risks to specific plant and animal species

Environmental changes associated with temperature and rainfall changes – as well as adaptation responses (e.g., agricultural or irrigation expansion) – will likely have differing impacts on different species. For instance, some bird species may be negatively affected by conversion of wetlands to cultivation or loss of tree cover, while other species may benefit from increased food availability or new habitats (Adams et al., 2014).

High temperatures, and especially sustained high temperatures, are likely to cause heat stress on plants (or extend beyond tolerable limits for certain plants) and wildlife, particularly in the central and southern Sahel (Zones 3, 4, 5 and 6) where the tropical and mixed rain climate supports a huge variety of plant and animal life. For arid desert zones (northern Sahel zones 1 and 2), extreme temperatures threaten extreme heat stress for both plants and animals (Herrero et al., 2016), especially in the far west coastal region where precipitation is also projected to decrease.

The effect of increasing temperatures strongly impacts both inland and coastal fisheries, particularly in shallow lakes such as Lake Chad. For example, increases in water temperature have significant impacts on aquatic life, such as increasing susceptibility of fish to disease, changes in nutrient availability for phytoplankton, and disturbances or increases to water column stability (stratification) that impacts mixing and primary productivity in lake ecosystems (Ogutu-Ohwayo et al., 2016). Increased sea surface temperatures have mostly negative implications for marine productivity, including changes to dominant fish species and species composition and diversity (Belhabib et al., 2016).

Changes in ocean currents are important to understand for Mauritania (Zone 1) as these can influence distributions and movements of fish species in and out of territorial waters, with implications for seabird and marine mammal health and diversity due to changes or imbalances to predator-prey relationships. Increasing ocean acidification also has several detrimental effects on ecosystems, especially when occurring alongside sea surface temperature increases and deoxygenation, though the impacts on specific taxa are not well understood (IPCC AR5, 2014). Overall, negative effects on marine organisms may include changes to physiology, resulting in reduced abundance, especially for calcifying organisms (for example, acidification prevents mollusc larvae formation (Doney et al., 2020)) and for phytoplankton which are a primary food source within most marine food webs. The impact of this at higher trophic levels is less certain but potentially significant for marine ecosystems.

4.6.3 Environmental protection and management

The G5 countries contain numerous parks and protected areas, including many that are listed as UNESCO (natural) heritage sites or Ramsar sites (wetlands of international importance) alongside other national parks, which are home to a vast range of plant life and mammal, bird, reptile, fish, and plant species, including many vulnerable and threatened species. Aquatic ecosystems around waterbodies, including rivers and lakes, and permanent, semipermanent and temporary streams, oases, marshes, and pools – are 'hotspots' of biodiversity in the Sahel region and provide refuges for ecological restoration during recovery periods from severe drought period. Indeed, over very long timescales, these 'refugia' act as reservoirs of biodiversity during arid climatic phases, from which the greater Saharan region is repopulated during humid phases. The loss of such ecosystems thus has the potential to disrupt ecological cycles associated with successive Sahara arid and humid phases that have pertained for at least 2.5 million years and possibly 7 million years or more (Kröpelin, 2006; Schuster et al., 2006; Carranza et al., 2008)

These ecosystems provide habitats for numerous species of birds, mammals, fish, and plants, including vulnerable and endangered species, as well as playing important roles in water supplies, flood control, and groundwater recharge (Brito et al., 2014; Ramsar Convention, 2021), pointing to their importance in mitigating environmental risks (e.g., flooding, evapotranspiration, water needs) associated with climate change. Mountain ecosystems, including the Aïr mountains in Niger and the Adrar mountains in Mauritania, are also important spaces of vertebrate and vegetation biodiversity (See section 2, Anthelme et al., 2008; Brito et al., 2014).

On a larger scale, the 'Great Green Wall' (GGW) initiative, which covers the G5 countries, involves (as noted in Section 4.1) the restoration of 100 million hectares of 'degraded' land across 11 countries by 2030 through large-scale reforestation, 'land restoration', vegetation regeneration efforts, watershed management, and other measures. GGW intervention areas cover 1.7 million ha in Mauritania, 3 million ha in Chad, 13.3 million ha in Burkina Faso, 44.4 million ha in Mali, and 47.3 million ha in Niger (UNCCD, 2020). While GGW activities have contributed to large-scale reforestation, dune fixing, assisted natural regeneration, and training and job creation (UNCCD, 2020), GGW interventions often focus on technical goals (e.g., numbers of trees planted or hectares 'restored'), often exclude particularly vulnerable demographic and livelihood groups (e.g., women heads of household, pastoralists), and can lead to the enclosure of sites benefiting powerful individuals (Turner et al., 2021). This highlights the potential risks associated not only with climate change effects but also climate mitigation initiatives (e.g., reforestation or afforestation) responses.

Conservation efforts should also consider potential risks to local livelihoods, as ‘conservation’ practices may be used to legitimise forms of state control and ‘rent-seeking’. For instance, marine conservation efforts such as restrictions on fishing in the National Park of Banc d’Arguin along Mauritania’s coast have been undermined by inadequate economic opportunities for subsistence fishers (Trégarot et al., 2020). In Mali, the state Forest Service’s practice of arbitrary fines for herders grazing livestock in the name of ‘fighting desertification’ has been identified as part of a broader system of state oppression of pastoralist communities, which contributes to pastoralists’ decisions to join armed groups (Benjaminsen and Ba, 2019).

The protection of ecosystems and biodiversity in the Sahel region is constrained by weak environmental management systems, including insufficient national funding to biodiversity conservation, limited high-level political support from national governments, a lack of dedicated legislation and institutions, limited institutional power of environment ministries, weak organisational structures and processes for implementing environmental initiatives, and poor coordination across relevant sectors (e.g. environment, forests, agriculture, energy, land-use planning, rural development, administration) and across regional, national, and local scales (Brito et al., 2016; Melcher et al., 2018; UNCCD, 2020). Many protected areas and ecosystems in the Sahel region cross national borders and require regional and international coordination efforts for the implementation and management of biodiversity conservation (Brito et al., 2016).

Image location: Niger

5 Summary

This report considers the exposure and vulnerability to current climate and climate change within the Sahel region. It sets out a broad range of climate-related risks for the region to support development planning.

The climate of the Sahel is characterised by semi-arid tropical conditions determined by the meridional progression of the West African Monsoon (WAM) in summer. Conditions in the northern extents of the Sahel are similar to, but less extreme than, the Sahara Desert to the north. Conditions to the far south are tropical with similarities to the climate of inland West Africa. Climate projections for the 2050s show very high confidence in a substantial warming trend. There is less confidence around the direction of changes in average rainfall, but climate modelling suggests an increase in mean rainfall across most of the region, occurring mostly during the summer season associated with the West African Monsoon. Spatially, rainfall is projected to increase in the central and eastern Sahel and decrease in the far west, especially on the coast of Mauritania. The onset of the WAM is projected to be delayed, affecting and duration of the rainy season. Interannual variability of rainfall is also projected to increase as is the frequency and intensity of extreme heavy rainfall events. The combination of increasing temperatures and increasingly variable seasonal rainfall, together with exposure to sea level rise and coastal storms (the coast of Mauritania), means that climate change will increase stress on existing vulnerable populations in the next few decades.

The key risk identified in this report include risks to: water resources, agriculture and pastoralism, aquaculture and fisheries, settlements and infrastructure, human health and mortality, and biodiversity and ecology. Coastal risks are addressed for Mauritania in the context of the key risks mentioned above. However, climate presents just one element of risks and multiple stresses across the region. Climate change will undoubtably test the resilience of human and agricultural systems, yet not all problems across the region will be driven by climate change. Climate risks are not isolated threats; how they interact with, and compound other sources of risk can be difficult to disentangle. For example, conflict and migration across the region are more complex issues caused by a multitude of factors spanning beyond climate change. It is important to consider the climate risks presented within this report in the context of development objectives and the wide range of intersectional risks that include socio-economic stresses and other drivers of change.

Nevertheless, long-term climate risks themselves will present considerable challenges, both in terms of average climate conditions which require adaptation to new ways of living, and through climate extremes and shocks, such as droughts, that exacerbate pre-existing and complex compounding risks. Development that accounts for climate risks includes low and no-regrets investments in adaptation and resilience aligned to development goals, such as sustainable agricultural intensification, environmental stewardship, social protection, water supply and sanitation and health, all of which support broader development aspirations. This kind of incremental adaptation develops climate resilience within systems and generates widespread benefits for people across a range of plausible climate futures. However, in some areas and localised hot spots where pressures combine for example water, agriculture, infrastructure, health and ecology, systems are already under stress, and in some instances functioning at the limits of climate tolerance. As climate change pushes systems further, acting as a 'risk-multiplier', transformational adaptation may be required to develop entirely new approaches to job creation and environmental management where existing ways of doing business or livelihoods are no longer viable.

The climate risks identified in this report demonstrate that climate change already impacts development. The region contains fragile and vulnerable states and landscapes, where climate risks amplify pre-existing pressures, particularly around water, agriculture and aquaculture, infrastructure, health and ecology. These can, in turn, compound the problems facing development, such as poverty, employment and gender equity. If the climate risks outlined in this report are considered within the context of the wider intersectional issues the region faces, it is possible to ensure that such risks can be effectively managed in development planning, and development goals can still be achieved despite the considerable challenges of a changing climate.

Image location: Mali

6 References

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