Chapter 3
Climate Change over West Africa: Recent Trends and Future Projections

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Abstract The West African climate has evolved in recent decades to respond to elevated anthropogenic greenhouse gas (GHG) forcing. An assessment of its recent trends and future changes is presented here based on various data sources (observations and models), along with an extensive review of recent literature including the latest Intergovernmental Panel on Climate Change report. A gradual warming spatially variable reaching 0.5 °C per decade in recent years is observed. In addition, the Sahel has recovered from the previous drought episodes (i.e., 1970s and 1980s); however, the precipitation amount is not at the level of the pre-drought period. Although these features are common across the different data sources, their magnitudes differ from one source to the other due to a lack of reliable observation systems. Projected climate change indicates continuous and stronger warming (1.5–6.5 °C) and a wider range of precipitation uncertainty (roughly between −30 and 30 %) larger in the Sahel and increasing in the farther future. However, the spatial distribution unveils significant precipitation decrease confined to the westernmost Sahel and becoming greater and more extensive in the high level GHG forcing scenario by the end of the 21st century. This coexists with a substantial increase in both dry spell length and extreme precipitation intensity. West Sahel is thus the most sensitive region to anthropogenic climate change. The rest of West Africa also experiences more intense extremes in future climate but to a lesser extent. It is also reported from other previous studies that the projected rainy season and the growing season will

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become shorter while the torrid, arid and semi-arid climate conditions will substantially extend. It is thus evident that in a "business as usual" World, most countries in West Africa will have to cope with shorter rainy seasons, generalized torrid, arid and semi-arid conditions, longer dry spells and more intense extreme precipitations. Such conditions can produce significant stresses on agricultural activities, water resources management, ecosystem services and urban areas planning. However, some GHG mitigation (i.e., a mid-level forcing) could help to reduce the stress.

Keywords Anthropogenic climate change · Recent trends · Sahel precipitation recovery · Projections · Uncertainties · Extreme events

3.1 Introduction

In the timeline of the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5), global warming resulting from enhanced anthropogenic greenhouse gases (GHGs) forcing on global climate is scientifically well established (IPCC 2013). In fact, global near-surface air temperatures have increased at a rate unequal to any other periods on record including paleo periods (Hartmann et al. 2013; Karl et al. 2015). Such increases have substantial consequences on precipitation and its variability, especially drought and flood episodes in both the tropics and the subtropics (Zwiers et al. 2013; Giorgi et al. 2014a).

It is thus common that the developing countries' low-income populations are likely to be affected by factors related to global warming, making West Africa one of the regions in the world that are most vulnerable to climate change. This is particularly true for rural areas where agriculture is the most prominent instrument for securing income and overcoming poverty (Boko et al. 2007). This region experiencing exponential population growth is already facing the consequences of climate change through gradual land degradation and loss of croplands and ecosystem services (Lambin et al. 2003; Leh et al. 2013; Carney et al. 2014) and high water stress and scarcity (Schewe et al. 2014), along with recurrent and localized droughts and flash floods (Douglas et al. 2008; Dai 2013). These conditions, expected to be exacerbated in the future, constitute significant threats to water resources, agricultural activities and ecosystem services (Lobell et al. 2011; Anyamba et al. 2014).

While local populations have difficulties adapting to such present-day conditions, the absence of governmental politics that would help to alleviate the consequences of future climate change adds another degree of vulnerability for rural inhabitants. Therefore, reliable adaptation methods are urgently needed in order to address the negative impacts of climate change and this requires the understanding of recent trends and the elaboration of robust climate change scenarios for the West African domain.

In this chapter, recent trends and future projections for the West African climate system are investigated by reviewing findings from the latest IPCC report and using various observation products and a multi-model ensemble based on the newly generated COordinated Regional climate Downscaling EXperiments (CORDEX; Giorgi et al. 2009) simulations.

3.2 Recent Trends in Climate Change over West Africa

This section examines recent trends in seasonal (May-September) mean temperature and precipitation over West Africa for the period ranging from 1983 through 2010. To this end, various observation products including data from the University of Delaware (UDEL 0.5° × 0.5° resolution; Legates and Willmott 1990), from the Climatic Research Unit of the University of east Anglia (CRU 0.5° × 0.5° resolution; Harris et al. 2014) and from the African Rainfall Climatology (ARC 0.1° × 0.1° resolution; Novella and Thiaw 2013) are used to account for uncertainties in different observed products (Nikulin et al. 2012; Sylla et al. 2013a). The latest IPCC report findings and highlights are also reviewed and compared with key studies that explore similar topics.

In recent decades, a clear warming in both CRU and UDEL is trending over most West Africa (i.e., Fig. 3.1). These trends are statistically significant at the 90 % level. The Gulf of Guinea and west Sahel, for instance countries such as

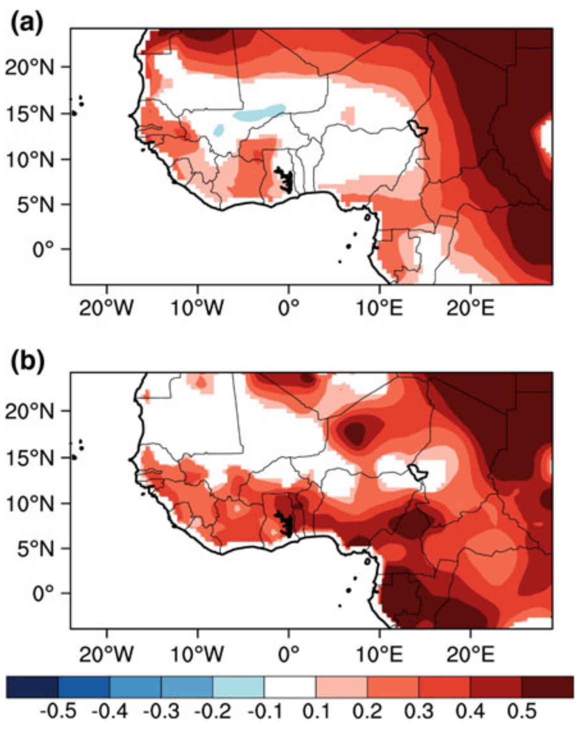

Fig. 3.1 Linear trends in mean seasonal (May–September) temperature over West Africa for the period 1983–2010. Only areas where the trend is statistically significant at the 90 % level are shaded. *Temp* stands for Temperature, *CRU* for Climate Research Unit and *UDEL* for University of Delaware. **a** CRU Temp trend: 1983–2010. **b** UDEL Temp trend: 1983–2010

Ghana, la Cote d'Ivoire, Guinea and Senegal experience the most significant and warmest signals ranging from 0.2 °C to more than 0.5 °C per decade. This is consistent with the last IPCC report (IPCC 2013) and a recent study from Padgham et al. (2015) stating that the whole of West Africa has recorded in recent decades a warming of between 0.3 and 1 °C. In contrast, southern Sahara and northern Sahel (e.g., southern Mauritania, Mali and Niger and northern Burkina Faso) show no significant changes. While these patterns are common to both observation products (CRU and UDEL), it is worth highlighting the point that the two data also have substantial differences. For example, in southern Mali and a larger part of Nigeria and Niger, UDEL unveils a more significant positive trend while CRU exhibits no significant trend, making it difficult to unambiguously assess the recent changes in temperature patterns in these regions during the last decades.

For the precipitation (Fig. 3.2), a tendency towards a significant increasing trend of about 0.2–1.0 mm/day per decade occurs along the Sahel band. This positive

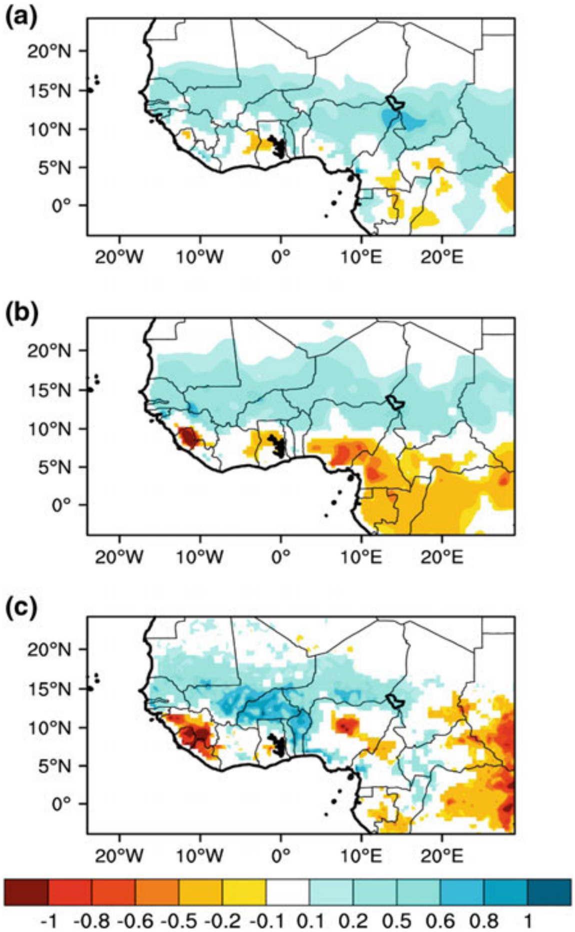

Fig. 3.2 Linear trends in mean seasonal (May–September) precipitation over West Africa for the period 1983–2010. Only areas where the trend is statistically significant at the 90 % level are shaded. *Precip* stands for Precipitation, *CRU* for Climate Research Unit, *UDEL* for University of Delaware and ARC for African Rainfall Climatology. **a** CRU Precip trend: 1983–2010. **b** UDEL Precip trend: 1983–2010. **c** ARC Precip trend: 1983–2010

precipitation trend, statistically significant at the 90 % level, covers countries such as Senegal and Burkina Faso but also the southern half of Mauritania, Mali, Niger and Chad. The precipitation increase is more spatially extended in UDEL and larger in magnitudes in ARC. However, the general pattern is similar in all the three observation products, making it a robust signal. Another common feature is the significant negative trend around a few areas in the orographic regions and a portion of the Gulf of Guinea. Overall, this indicates that the Sahel has experienced wetter conditions while the orographic regions and a small part of the Gulf of Guinea have recorded drier conditions in recent years.

Such a result is consistent, to some extent, with recent studies (Nicholson 2005; Hagos and Cook 2008; Mahe and Paturel 2009; Riede et al. (2016) (this issue)). For example, Lebel and Ali (2009) noted that precipitation over central Sahel has increased by about 10 % during the period that ranges from 1990 through 2007 compared to 1970–1989, while in the west Sahel, the deficit remains unchanged. In another study, Druyan (2011) found that since the last few decades (1990s and 2000s).

Seasonal precipitation accumulations over the Sahel have recovered but do not reach the levels of the period preceding the drought episodes of the seventies and eighties. As a matter of fact, IPCC (2013) reports a drying trend over West Africa in a longer time series ranging from 1951 to 2012. Recently, a more extensive study by Ibrahim et al. (2014) reveals that in the last two decades, not only have the annual precipitation totals increased, but also the rainy days have been more frequent, leading to the partial recovery of precipitation amount. This recent precipitation recovery in the Sahel is due, to a great extent, to the direct influence of higher levels of anthropogenic greenhouse gases in the atmosphere, along with changes in anthropogenic aerosol precursor emissions (Haarsma et al. 2005; Ackerley et al. 2011; Biasutti 2013; Dong and Sutton 2015), although natural variability might have played an important role (Mohino et al. 2011). In addition to the wetter precipitation trend, the prevalence of a higher interannual variability, a delayed onset and an early retreat of the monsoon season in recent years over West Africa have been reported (Biasutti and Sobel 2009; Sylla et al. 2010a; Diallo et al. 2013; Seth et al. 2013; Hartmann et al. 2013).

3.3 Projected Climate Change over West Africa

According to the latest IPCC (2013) report, the present-day warming and the increased variability of precipitation are likely to be exacerbated in future climate with large regional variations and different degrees of confidence. However, mean precipitation shows substantial uncertainties as the Coupled Models Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) Global Climate Models (GCMs) disagree in both direction and magnitude of change. In this regard, IPCC (2013) states that there is low to medium confidence in the robustness of projected regional precipitation change over Africa in general until a larger body of regional results become available through, for example CORDEX. We thus use the set of Regional

Climate Models (RCMs) participating in the CORDEX program and available for the West African domain (see Sylla et al. 2016) to assess future climate change over the region. Although there is inherent value in each group of models (GCMs and RCMs), using RCMs is probably more appropriate because of the presence of complex terrains, high variations of landcover and the mesoscale nature of precipitation over West Africa (Teichmann et al. 2013; Dosio et al. 2015; Sylla et al. 2015). The higher resolution in CORDEX (50 km compared to 100s km in CMIP5) would favor the gain of more detailed climate change information at the regional/local level. The CORDEX experiments have been described in detail by Jones et al. (2011). In addition, the outputs have been thoroughly validated over West Africa (Gbobaniyi et al. 2014; Klutse et al. 2015). For this assessment, a multimodel ensemble approach is carried out for the sake of robustness in the projections (Diallo et al. 2012; Sylla et al. 2013b; Haensler et al. 2013; Dosio and Panitz 2015).

In Fig. 3.3, the CORDEX multimodel long-term time series of seasonal (May-September) mean temperature and precipitation anomalies are shown along with the range of possible values for the Sahel, the Gulf of Guinea and whole West Africa during the historical (1970–2005) and the future (2006–2100) periods and for both RCP8.5 and RCP4.5. These RCP forcing scenarios are described in detail by Moss et al. (2010) and Riede et al. (2016). The anomalies are calculated with respect to the seasonal mean of the reference period 1976–2005. The CORDEX time series confirm IPCC findings, indicating that the regions have undergone significant warming in recent decades and that this is going to be amplified in the future regardless of the greenhouse gas (GHG) forcing scenario. This is the result of previous GHG emissions and also inertia in the climate system (IPCC 2013). Considering a "business as usual" (high level GHG) forcing scenario (RCP8.5) and a mid-level one (RCP4.5), the warming gradually increases and reaches its maximum on 2100. However, the temperature changes from the two forcing scenarios start to diverge only around 2050 and this divergence is maximal on 2100. The mid-level GHG forcing scenario yields to lesser warming while the high level forcing produces a greater warming. Thus, at the end of the century, possible warming over West Africa ranges from 1.5 to 6.5, with the Sahel experiencing the largest changes.

The mean precipitation change over West Africa and the two subregions (Fig. 3.3) shows a less evident trend and mostly oscillates between −10 and 10 %. In addition, climate change causes more precipitation variability with greater amplitudes (i.e., Fig. 3.3b, d, f). The range of possible precipitation changes spans both negative and positive values (mostly between −30 and 30 %), indicating that projected precipitation is highly uncertain over the region, consistent with IPCC (2013). It is interesting to note that the range of uncertainty gradually increases as the RCP forcing increases (i.e., as the time frame increases), suggesting that the different RCMs generate substantial different responses to a larger forcing. The largest uncertainty is found in the Sahel as in IPCC (2013), probably because of differences in the models' representations of the West Africa Monsoon and its interactions with deep convection (Fontaine et al. 2011; Sylla et al. 2011; Roehrig et al. 2013). However, considering the spatial pattern of change (i.e., Fig. 3.4), it is clear that

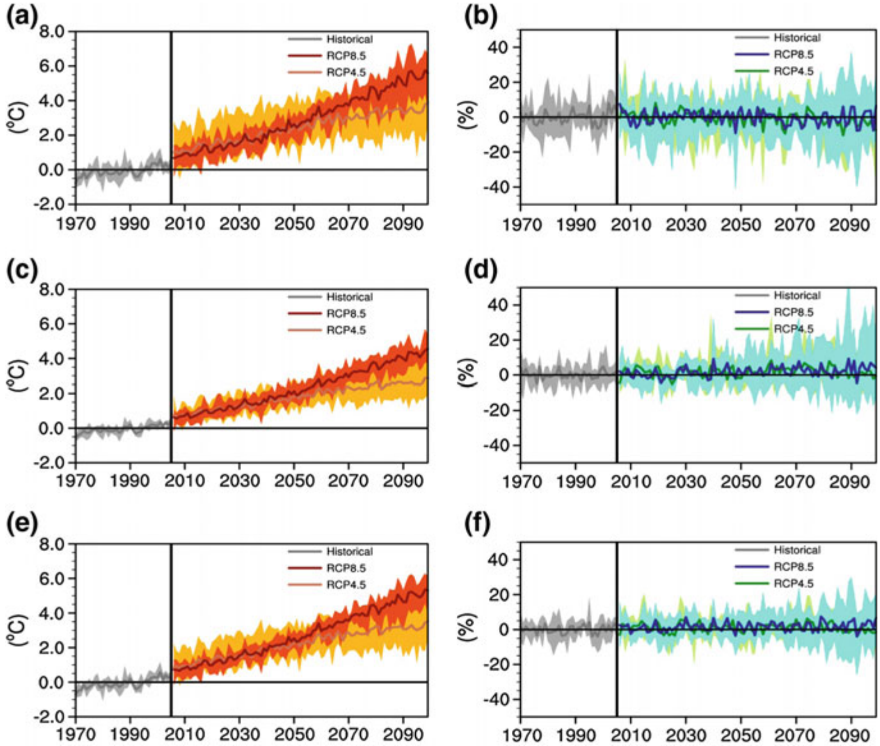

Fig. 3.3 Long-term time series (1970–2100) of seasonal (May–September) mean temperature (*left panels*) and precipitation (*right panels*) anomalies for the Sahel (*upper panels*), the Gulf of Guinea (*middle panels*) and the West Africa (*lower panels*) and for both RCP4.5 and RCP8.5 based on multimodel CORDEX simulations. The anomalies are calculated with respect to the seasonal mean of the period 1976–2005. The *shaded areas* denote ensemble maxima and minima. **a** Sahel temperature change. **b** Sahel precipitation change. **c** Guinea temperature change. **d** Guinea precipitation change. **e** West Africa temperature change. **f** West Africa precipitation change

although most of West Africa experiences no changes, a significant precipitation decrease of about 5–40 % prevails in the West Sahel. This precipitation reduction strengthens and further extends spatially to the East as the forcing increases from RCP4.5 to RCP8.5 and the time period shifts from 2036–2065 to 2071–2100. During the late 21st Century, it covers the whole of Senegal, southern Mauritania and Mali and northern Guinea. It is worth mentioning that a few precipitation increases (5–10 %) are also projected but to a lesser extent in some small areas in the Gulf of Guinea, covering Sierra Leone, Liberia and Cote d'Ivoire and over East Sahel in countries such as Niger and Chad. Similar results have been reported in different studies using either single or multiple RCM experiments and have been linked to changes in the West African Monsoon features such as the monsoon flow, African Easterly Jet and African Easterly Waves, but also Integrated Moisture Flux

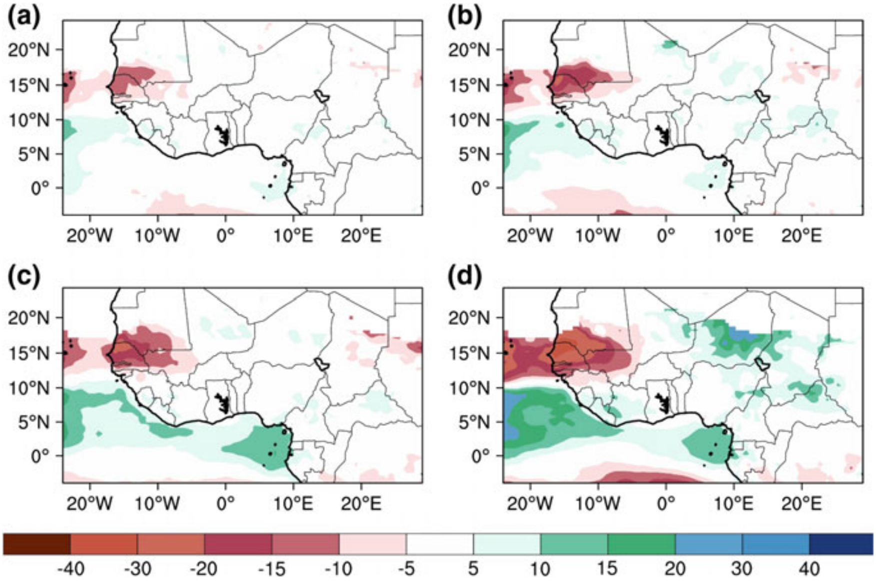

Fig. 3.4 Seasonal (May–September) mean Precipitation changes (RCP4.5/RCP8.5 minus Historical) from the multimodel ensemble mean of CORDEX simulations for the early (2036–2065) and the late (2071–2100) 21st Century. Changes *shaded* are statistically significant at the 90 % level. **a** Precip: RCP4.5 (2036/2065)—Historical. **b** Precip: RCP8.5 (2036/2065)—Historical. **c** Precip: RCP4.5 (2071/2100)—Historical. **d** Precip: RCP8.5 (2071/2100)—Historical

Divergence and Moist Static Energy (Diallo et al. 2012; Laprise et al. 2013; Abiodun et al. 2013; Teichmann et al. 2013; Mariotti et al. 2014; Sylla et al. 2015).

Although it is important to derive and understand changes in mean precipitation, extreme precipitation events have a much greater impact on natural systems and human activities (Parry et al. 2007). To characterize extreme events, two indices are considered here: the dry spell length and the total precipitation intensity of very wet days.

The dry spell length is calculated as the maximum number of consecutive dry days (i.e., days with precipitation lower than 1 mm). The total precipitation intensity of very wet days is the fraction of precipitation accounted for by the very wet days (wet days above the 95th percentile). While the dry spell length index measures drought occurrence (WMO 1986), total precipitation intensity of very wet days provides an indication of high intensity precipitation that can cause widespread flooding events (WMO 1989).

Changes in dry spell (i.e., Fig. 3.5) indicate a significant lengthening of maximum dry period primarily confined over West Sahel and, as with the mean precipitation, extends westwards as the radiative forcing (from RCP4.5 to RCP8.5) and the time frame (from 2036–2065 to 2071–2100) increase. Therefore, the largest and more extended changes covering almost all West Africa are found by the end of the 21st Century and for the high GHG forcing scenario, RCP8.5. In this case, increases

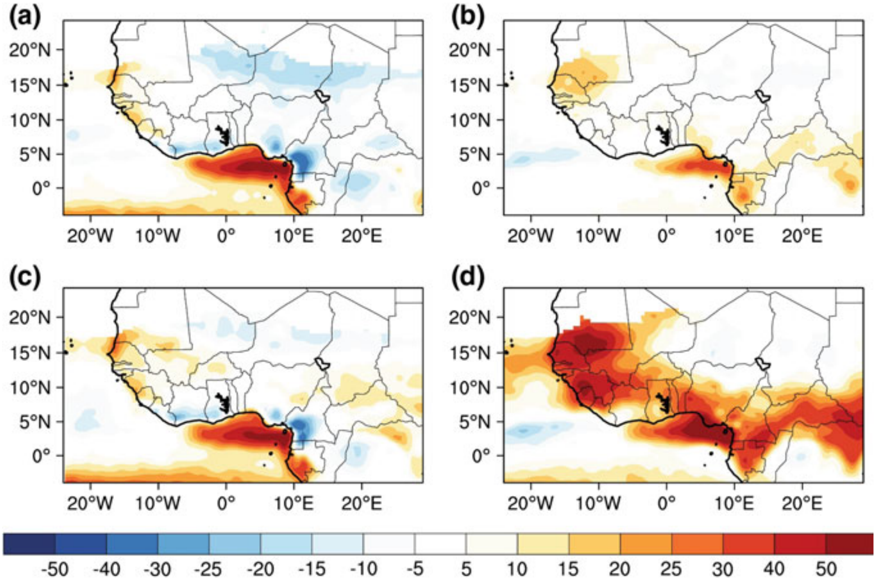

Fig. 3.5 Changes (RCP4.5/RCP8.5 minus Historical) in seasonal (May–September) mean maximum Dry Spell Length (DSL) based on multimodel ensemble of CORDEX simulations for the early (2036–2065) and the late (2071–2100) 21st Century. Changes *shaded* are statistically significant at the 90 % level. **a** DSL: RCP4.5 (2036/2065)—Historical. **b** DSL: RCP8.5 (2036/2065)—Historical. **c** DSL: RCP4.5 (2071/2100)—Historical. **d** DSL: RCP8.5 (2071/2100) —Historical

in the length of dry spell of around 30–50 % with respect to the reference period (1976–2005) are projected in many parts of West Africa in countries such as Senegal, Guinea and Sierra Leone, but also in southern Mauritania, Mali, Burkina Faso and Nigeria, and northern Cote d'Ivoire. Despite these dominant positive changes, few decreases in dry spell length occur in the mid-level forcing scenario (RCP4.5) along the Gulf of Guinea (southern Cote d'Ivoire, Ghana, Nigeria and Cameroon) and east Sahel (central Mali, Niger and Chad).

Projected very wet days intensity leads to different patterns following the fact that a mid-level or a high level GHG forcing scenario is considered (i.e., Fig. 3.6). In fact, in the former (RCP4.5) and for both future time periods (2036–2065 and 2071–2100), amid few regions with no significant changes, small decreases of 5–10 % prevail in most of West Africa. In particular, in areas along the Gulf of Guinea and east Sahel where a decrease in dry spell length occurred, a reduction in extreme precipitation intensity is also projected. This indicates that GHG mitigation can help minimize the effects of climate change over West Africa as it can significantly decrease the occurrence of extreme events. In the high level GHG forcing, a small tendency towards more extreme intensity (5–10 % of increase) is predominant during the early 21st Century; however, by the end of the century, substantial increases are widespread all over West Africa. Countries such as Senegal, Cote

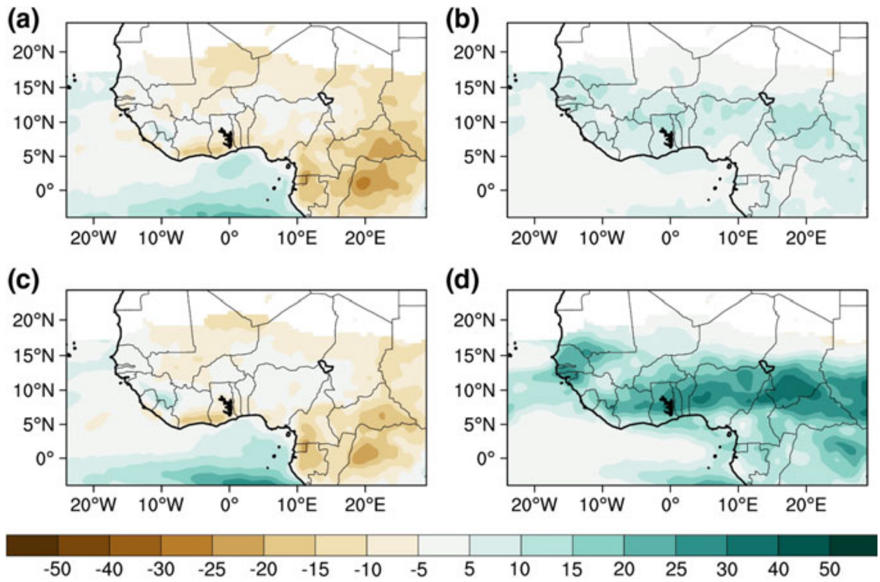

Fig. 3.6 Changes (RCP4.5/RCP8.5 minus Historical) in seasonal (May–September) mean intensity of precipitation events above the 95th Percentile (95Ptot) based on multimodel ensemble of CORDEX simulations for the early (2036–2065) and the late (2071–2100) 21st Century. Changes *shaded* are statistically significant at the 90 % level. **a** 95Ptot: RCP4.5 (2036/2065)—Historical. **b** 95Ptot: RCP8.5 (2036/2065)—Historical. **c** 95Ptot: RCP4.5 (2071/2100)—Historical. **d** 95Ptot: RCP8.5 (2071/2100)—Historical

d'Ivoire, Ghana, Benin, Togo, Nigeria and Chad will experience more intense future increase (more than 40 % of increased intensity compared to the reference period) while other countries such as Mali, Burkina Faso and Niger will undergo a moderate intensity increase of about 20 %. It is thus evident that for the high GHG forcing scenario, longer dry spells and more intense precipitation extremes will become more common over West Africa, with Senegal, Mali, Mauritania, Nigeria and Cote d'Ivoire being more prone to such changes.

The latest IPCC (2013) and Riede et al. (2016; this issue), along with previous studies using either GCMs or RCMs, have reported similar results on the amplification of annual and seasonal extreme events over West Africa as a response to future anthropogenic climate change (Sylla et al. 2010b; Lintner et al. 2012; Vizy and Cook 2012; Scoccimarro et al. 2013; Abiodun et al. 2013; Giorgi et al. 2014b). It was found that such increases of extremes are mostly driven by an intensification of the local hydrological cycle (Giorgi et al. 2011; Sylla et al. 2012) and that their changes may be largest before the mature monsoon season, i.e., around the onset of the rainy season over the Sahel, thus triggering greater impacts (Sylla et al. 2015).

In addition to the increase in dry spell length and intensification of wet extremes discussed above, the shortening of the Sahel rainy season is projected to be more pronounced (i.e., Sarr 2012; Ibrahim et al. 2014), the growing season length further reduced (i.e., Cook and Vizy 2012), the torrid, arid and semi-arid climate regimes generalized over West Africa, and the moist and wet climate zones much less extensive (Elguindi et al. 2014; Sylla et al. 2016). It is thus clear that West Africa is substantially vulnerable as these changes will not only threaten agricultural activities, water resources management and ecosystem services, but will also considerably disturb urban areas planning.

3.4 Conclusion and Outlook

West Africa is already facing the consequences of climate change. In this chapter, the recent trends and future scenarios are investigated by doing an extensive review of recent literature, including the latest IPCC report, and undertaking a thorough analysis of various observation products and the newly generated CORDEX multi-GCMs/multi-RCMs projections.

The results first confirm that the region has undergone warming in recent decades as a response to increased anthropogenic GHG forcing. This elevated GHG amount in the atmosphere, in addition to changes in aerosols concentration, has favored the Sahel to partially recover from its previous drought episodes. Although this is consistent across the various data sources and the available literature, one key problem is the magnitudes of such recent changes that vary considerably between the different data sources.

This is a direct consequence of lack of sufficient observed datasets, which has prompted the research centers collecting them to just interpolate from few stations. In fact, as stated by the latest IPCC report, there is not enough historical data to show observed trends over large areas of Africa. This situation is mostly due to a general decline of meteorological stations and the absence of reliable data transmission and storage. This not only prevents a thorough understanding of current trends but also induces considerable uncertainty about future climate conditions. Therefore, it is not surprising that in the last few years, some programs have emerged, among them the West African Science Service Center on Climate Change and Adapted Landuse (WASCAL). The main objective of such programs is to strengthen climate services through climate monitoring over West Africa in collaboration with national meteorological agencies. Investment in such programs must be a top priority for regional governments and international partners.

Projected climate change from multimodel CORDEX experiments confirms that temperature over West Africa will continue to rise by about 1.5–6.5 °C in the future. In addition, it shows that future precipitation changes can range between −30 and 30 % with respect to the reference period, indicating the existence of substantial uncertainties in projected precipitation over the region. The uncertainty range is larger in the Sahel and around the end of the 21st century, suggesting that the various GCM/RCM combinations respond to increasing GHG forcing very differently. Despite these uncertainties, some interesting patterns have emerged during the last three decades of the century (2071–2100) and consist of a significant decrease in mean precipitation, a lengthening of the dry spell and an increased intensity in extreme precipitation over west Sahel covering countries such as Senegal, Mauritania and Mali. These west Sahel countries, along with Cote d'Ivoire and Nigeria, are most prone to the combined increase of droughts and potential floods more pronounced in the high level GHG forcing. The other West African countries will also experience, to a lesser extent, the intensification of such extreme events. On top of these projected climate conditions, the recent literature has emphasized other important aspects of climate change over West Africa such as the reduction of the length of the rainy season and the growing season, increases in the intensity of extremes before the mature monsoon season, and an extension of torrid, arid and semi-arid conditions. It is worth mentioning that the use of a mid-level GHG forcing scenario has led to a small decrease in dry spell length and extreme precipitation intensity amid large areas with no significant changes. This suggests that mitigating anthropogenic GHG emissions could help minimize the effects of climate change over West Africa.

Although this analysis reaches promising results, a wide range of uncertainty still exists in available observation products and CORDEX projections, preventing a thorough assessment of climate change over the region. It is thus critical, on the one hand, to invest in extensive climate monitoring and data collection, and on the other hand, to undertake much more coordinated higher resolution (i.e. 10–25 km) climate change experiments within CORDEX, Phase 2 for a better assessment of recent trends and future climate conditions over West Africa.

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