Analysing regional climate change in Africa in a 1.5°C, 2°C and 3°C global warming world

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Key Points:

The African continent has to expect an increase in hot nights and longer and more frequent heat waves.

Daily rainfall intensity is expected to increase towards higher global warming scenarios for the African Sub-Saharan coastal regions.

Major changes of the analysed climate indices for Africa could be prevented by keeping below the 1.5°C/2°C global warming thresholds.
Abstract

At the 21st session of the UNFCCC Conference of the Parties (COP21) in Paris, an agreement to strengthen the effort to limit the global temperature increase well below 2 °C was decided. However, even if global warming is limited, some regions might still be substantially affected by climate change, especially for continents like Africa where the socio-economic conditions are strongly linked to the climatic conditions. In the paper we will discuss the analysis of indices assigned to the sectors health, agriculture and infrastructure in a 1.5°C, 2°C and 3°C global warming world for the African continent. For this analysis an ensemble of ten different GCM-RCM simulations conducted in the framework of the COordinated Downscaling EXperiment for Africa was investigated. The results show that the African continent, in particular the regions between 15°S and 15°N, has to expect an increase in hot nights and longer and more frequent heat waves even if the global temperature will be kept below 2°C. These effects intensify if the global mean temperature will exceed the 2°C threshold. Moreover, the daily rainfall intensity is expected to increase towards higher global warming scenarios and will affect especially the African Sub-Saharan coastal regions.

1 Introduction

The willingness of the global community in enhancing efforts to limit global mean warming to well below 2°C is the key outcome of the 2015 Paris Agreement and can be seen as a major breakthrough in the series of climate summits Falkner (2016). It nevertheless has to be recognized that the Paris goals are ambitioned and require a tremendous global mitigation effort in order to have a chance to be met (Schellnhuber et al., 2016). And recent studies showed that even substantially limiting global mean warming to about 2°C above pre-industrial levels will still lead to substantial climate change impacts in specific regions and for specific sectors (e.g. Jacob & Solman, 2017; Vautard et al., 2014). In order to support the implementation of the Paris Agreement key questions to be answered for decision makers therefore are: What does a global mean warming well below 2°C actually mean for a specific region/sector? Are there regions/sectors that even when the Paris goals would be reached are still suspect to substantial and robust consequences of climate change? What harmful climate change impacts on specific regions/sectors can be prevented if the Paris goals are reached?

In our study, we would like to present answers to the questions above raised from an African perspective by analysing potential impacts of regional climate change for various sectors under different thresholds of global warming – namely 1.5°C, 2°C and 3°C - as a proxy for the strength of global mitigation efforts. We set our regional focus over the African continent as Africa is supposed to be a climate change hotspot with a high exposure to future climate changes and a low adaptation capacity resulting in a very large vulnerability to future climate change (e.g. IPCC AR5). The flowering of many sectors in Africa directly depends on climate and climate variability resulting in a potentially large sectoral impact of climate change over most parts of Africa (e.g. Lerner-Lam, 2007). Examples are the widely spread rainfed agricultural systems, the fragile infrastructure as well as various health issues related to climate such as malnutrition after droughts; heat waves but also malaria outbreaks (e.g. Kjellstrom et al., 2014).

While in earlier times African continent was rather outside the focus of the international climate and climate impact research community, this has changed substantially in the course of the CMIP5 (Taylor et al., 2011) and especially COordinated Downscaling EXperiment (CORDEX) (Giorgi & Gutowski, 2015) community efforts. Given the fact that Africa is in the centre of the CORDEX-activity, numerous simulations for current and future African
climate conditions are available and have been analysed and published in coordinated ways within the CORDEX-Africa initiative (e.g. Abba Omar & Abiodun, 2017; Abiodun et al., 2017; Diallo et al., 2016; Dosio, 2017; Dosio & Pantiz, 2016; Fotso-Nguemo et al., 2017; Pinto et al., 2015; Sylla et al., 2016). Most of the studies are available for West, East and Southern Africa and fewer for Central Africa and related to precipitation characteristics.

For West and Central Africa projected changes in precipitation are widespread between different regional climate models (RCMs) (e.g. Haensler et al., 2013; Sylla et al., 2016) resulting in a high uncertainty regarding future changes in hydrological responses in West Africa (e.g. Yira et al., 2017). The uncertainty in simulating precipitation response in the RCMs over western and partly also central Africa might be linked to the individual convective schemes of the individual models (Klutse et al., 2016). Also the representation of the land surface (e.g. Dosio & Panitz, 2016; Saeed et al., 2013) and the simulation of vegetation response (e.g. Erfanian et al., 2016; Wu et al., 2016) seem to play a dominant role regarding future precipitation in the low latitude regions of Central and West Africa. Most CORDEX-models generally project an increase in annual mean precipitation over eastern Africa (e.g. Souverijns et al., 2016) caused by thermodynamical changes in moisture content and local/mesoscale feedbacks rather than due to changes in the general circulation. For Southern Africa a general and consistent decrease in precipitation is projected by the CORDEX-ensemble (Pinto et al., 2015) connected to an increase in consecutive dry days. With respect to extreme precipitation indices, Abiodun et al. (2017) found in CORDEX-Africa projections a decrease in the wet days and an increase in dry spells and widespread extreme events for cities in northern, western, eastern and southern Africa.

Regarding temperature extremes, a study based on the CORDEX-ensemble from Russo et al. (2016) shows that under the RCP8.5 Scenario more than 50% of the land area of Africa will be affected by heat waves on a regular basis at the end of this century which are very unusual today. Applying the same heat wave magnitude index, Dosio (2017) showed that especially the subtropical regions and eastern Africa are projected to be affected by increased heat waves. The approach of analysing climate change and related impacts over Africa independent of time but linked to specific levels of warming were also adopted earlier. Examples are general circulation model (GCM) ensemble based analyses of hydrological responses in the frame of the ISIMIP initiative (Schewe et al., 2014), African flood risk (Alferie et al., 2017) or shifts in southern African climate zones (Engelbrecht & Engelbrecht, 2016). Déqué et al. (2016) used a small RCM ensemble to analyse projected climate changes over western and eastern Africa in a 2°C and 3°C global warming world.

Our analysis adds unique and policy relevant information to the existing literature. The major added value of our study is that in contrast to others (e.g. Déqué et al., 2016) we base our pan-African analysis on data of the largest possible but still consistent ensemble of high-resolution regional climate change projections compiled within the CORDEX-Africa activity. We further analyse projected climate change signals for a series of sector-specific climate indices for three different, policy-relevant levels of global mean warming, namely 1.5°C, 2°C and 3°C compared to pre-industrial times. This type of analysis is suited provide answers to the above mentioned key questions related to the Paris agreement.

The paper is structured as follows: Initially, the model data, the observational data and the methods used in the work are described in Section 2. Subsequently, the findings are described in Section 3 and a summary and a discussion follow in Section 4. Finally, the article will close with the concluding remarks and outlook in Section 5.
2 Materials and Methods

2.1 Climate model ensemble

The focus of our study is on the high mitigation scenario RCP2.6 for the 1.5°C global warming scenario, and to relate it consistently to a 2°C and 3°C warmer world. Only the RCP2.6 CMIP5 simulations provide a stabilization of the global mean temperatures at the middle of the century indicating an equilibrium state of the simulated climate system (see Figure 1 of Vautard et al., 2014, for global mean temperature increase in RCP2.6 emission scenarios). We use daily temperature and precipitation data of the freely available regional climate change projections of the CORDEX-Africa ensemble for the RCP2.6 and RCP8.5 emission scenarios to analyse projected changes for the different warming levels. To have comparable ensembles for the 1.5°C period (derived from the RCP2.6 simulations) and the 2°C and 3°C periods (derived from the RCP8.5 simulations), we only select data of RCMs that provide data for both scenarios forced with the identical GCM. The resulting ensemble comprises of ten downscaled climate change projections (see Table S1 in supporting information). The data of the projections is available for the whole African continent at a horizontal resolution of about 50 x 50 km covering the time from 1950 to 2100. The applied RCMs in this work were already evaluated in numerous studies (e.g. Abba Omar & Abiodun, 2017; Diasso & Abiodun, 2017; Haensler et al., 2011; Klutse et al., 2016; Pinto et al., 2016; Teichmann et al., 2013).

2.2 Identifying warming periods

See Text S1 in supporting information

2.3 Analysed indices and study region

We concentrate on projected changes for a series of praxis-relevant climate indices based on daily maximum and minimum temperatures as well as on daily precipitation data. Altogether three temperature related indices and four rainfall related indices are analysed. The selection of indices is made in order to reflect the climate change information needs of multiple sectors but at the same time being solely dependent on climate data only. For the temperature case we focus on heat indices relevant from a health perspective. For rainfall we analyse dry and wet extremes, both important for multiple sectors (agriculture, infrastructure, disaster risk management). We specifically focus our rainfall related analyses to indices characterizing the rainy season(s) (RS) hence providing baseline information for the agriculture and energy management planning. A list of the analysed indices with a short definition and the link to the respective sectors is provided in Table 1.

The analyses are generally conducted for the pan-African continent for temperature related indices and for African Sub-Saharan regions for rainfall related indices. In order to be able to reflect the large differences in the climate characteristics and especially the rainfall and rainy season characteristics, we defined a series of sub-regions reflecting different rainfall regimes (one vs two rainy seasons; winter vs summer rainfall) and climate zones (Figure 1).
2.4 Determining rainy seasons

See Text S2 in supporting information

2.5 Defining robust changes

The climate indices are calculated individually for each of the ten ensemble members for the respective scenario. Also the respective climate change signals for each of the indicators and warming thresholds are calculated on an individual ensemble member basis. These individual climate change signals are combined to ensemble signals by providing the respective median of the projected changes as well as measures for the ensemble spread which are the central 66% of change as well as minimum and maximum change (Haensler et al., 2013). As a proxy for robustness of the ensemble projection of change for a specific indicator, weanalyse the standard deviation during the historical period for each of the individual ensemble members. If at least 66% of the ensemble members project changes larger than one standard deviation of the respective present climate conditions, the projected changes are referred to as robust. In case that more than 66% of the simulations project changes larger than twice the standard deviation of present climate conditions, the projections are considered as “strongly robust”. This method assesses the robustness of the changes of indicators projected by the ensemble on hand, described in section 2.1. It does not allow for statements on the representativeness of the sub-ensemble used in this study with respect to the full CORDEX-Africa ensemble of simulations.

2.6 Calculation of ensemble histograms

See Text S3 in supporting information

2.7 Observational data

The WATCH data set (Weedon et al., 2014) is utilised as reference data for the current climate state of the respective temperature and rainfall related indices. This data set provides consistent daily temperature and rainfall data at a spatial resolution of 0.5°x0.5° based on the European Centre for Medium-range Weather Forecasts (ECMWF) ERA-40 reanalysis data.

3 Results

In order to help assessing the impact of the global temperature increase on the African society and economy, sector relevant temperature and rainfall indices were analysed for the a possible global temperature increase of 1.5°C, 2°C and 3°C. For the in-depth analysis, four focus regions representing typical African climates and rainfall regimes (as defined by Trewartha, 1954) were selected: West Africa (WA) showing a semi-arid to tropical savannah climate with one rainy season (RS), Equatorial Africa (EQA) representing a tropical savannah to equatorial climate with two RS, the Greater Horn of Africa (GHA) having a desert climate with two RS and the Western Cape region of South Africa (WCR) exhibiting a Mediterranean climate with winter RS (see Figure 1). The changes of the indices were described by means of ensemble medians. RS related indices are only discussed for Sub-Saharan regions. Furthermore, the changes of indices were tested regarding their robustness.

3.1 Mean annual hot nights (HN)

For the 1.5°C global warming scenario the model ensemble projects a robust increase of 20 to 150 annual HN for the African continent (Figure 2a) and for the 2°C global warming scenario
a very robust increase of 40 to 200 in annual HN towards the equator (Figure 2b). In particular the equatorial regions between 15°N and 15°S are affected by a strong increase of annual HN for the 2°C global warming scenario. These regions become even more affected under the 3°C global warming scenario showing a very robust increase of 100 to 300 (and partly more at equatorial west Africa) annual HN (Figure 2c). This implies for the focus regions an increase of about 50, 75 and 130 HN in WA (Figure 2d), 85, 140 and 235 annual HN in EQA (Figure 2e), 65, 105 and 170 HN in GHA (Figure 2f) and an increase of about 20, 35 and 60 HN in the WCR (Figure 2g) for the 1.5°C, 2°C and 3°C global warming scenario, respectively. The ensemble ranges of the boxplots are relatively wide for WA and EQA and relatively narrow for WCR (Figure 2d-g).

3.2 Mean annual heat waves days (HWD)

For today’s climate, the number of annual HWD in Africa shows a range between 1 to 3 days with lower numbers in the west central Africa (Figure 3a). For the 1.5°C global warming scenario, the model ensemble simulates a robust increase of up to 8 annual HWD for the African continent with higher number and very robust signals in the regions of about 20°N, at the equator and at the GHA with up to 10 annual HWD (Figure 3b). The aforementioned regions and southern Africa experience an increase of 4 to 10 annual HWD and an expansion of areas with very robust signals for the 2°C global warming scenario (Figure 3c). The number of annual HWD increases by up to 16 days at the equator and at the GHA for the 3°C global warming scenario (Figure 3d). This means for the focus regions that WA experiences an increase of about 3, 5 and 7 HWD (Figure 3e) and similar values for EQA (Figure 3f), the GHA exhibits an increase of about 5, 7 and 10 HWD (Figure 3g) and the WCR exhibits an increase of about 2, 3 and 5 HWD (Figure 3h) for the 1.5°C, 2°C and 3°C global warming scenario, respectively. All focus regions show wider ensemble ranges for the 3°C than for the 1.5°C and 2°C global warming scenario. Moreover, WCR exhibits the narrowest ensemble ranges for the three global warming scenarios of all focus regions (Figure 3e-h).

3.3 Heat waves (HW)

The analysis of HWD provides already an overview of the changes under the different global warming scenarios, but the HWD are more general per definition since the index counts three or more consecutive days. For a more detailed statement of the heat wave duration and frequency it is more appropriate to apply a histogram with distinct duration classes. Therefore, an analysis of HW for the GHA is carried out exemplarily. The GHA was chosen because this region shows the strongest increase of HWD for the 1.5°C and 2°C global warming scenario (Figure 3a/b). The model ensemble projects for the GHA a clear increase in the HW frequency as well as in the HW duration in the timeframe of 30 years for all three global warming scenarios. Moreover, there is an increasing trend in the HW duration and HW frequency towards higher global warming scenarios and, in particular, the GHA will experience HW durations which did not occur at all in the past (Figure 3i).

3.4 Mean length of rainy season (LRS)

In Africa there are climate regions determined by one RS such as north and south of the Equator and by two RS such as in central Africa, Guinea Coast and Greater Horn of Africa. The climate regions exhibiting the longest LRS from 180 to 300 days are located between 15°S and 15°N with an exception of GHA exhibiting 100 to 160 days (Figure 4a). The Sahel region counts LRS of 80 to 140 days and southern Africa between 100 and 200 days. For simplicity the spatial change of the total LRS is analysed for the different global warming.
scenarios. The model ensemble projects small changes in LRS for the 1.5°C and 2°C global warming scenario (Figure 4b,c). For the 3°C warming scenario, a reduction of 5 to 10 days is simulated by the model ensemble for the West African coastal region at the Gulf of Guinea as well as for parts of southern Africa (Figure 4d). The modelled changes of LRS are not robust. The focus regions with one RS show mainly a small decrease in the LRS for the different warming scenarios (Figure 4e,j). Similar changes are indicated for first RS of EQA and GHA (Figure 4f,h). However, the EQA region and the GHA show a small increase in the length of the second RS (Figure 4i). The WCR ensemble ranges of the three global warming scenarios are wider, even the central range, than the ones of the other focus regions indicating a higher variability of the different model ensemble members (Figure 4j).

3.5 Mean sum of rainfall during rainy season (SRRS)

The main rainfall in Africa occurs during rainy seasons with the highest rainfall amount at the equator and at the Guinea Coast and the lowest amount in the Saharan regions (Figure 5a). For the 1.5°C and 2°C global warming scenario a small decrease of about 5 to 20% in SRRS over southern Africa and partly over East Africa is projected by the model ensemble (Figure 5b,c). A small increase of 5 to 20% in SRRS is simulated from the Greater Horn of Africa to Kenya. The above described pattern is also simulated for the 3°C warming scenario but with partly larger changes in SRRS (Figure 5d). Over the west coast of southern Africa the SRRS decreases up to 30% and from the Greater Horn of Africa to Kenya the rainfall amount increases up to 50%. The modelled changes of SRRS are fulfilling not the criteria of the robustness. On the regional scale the model ensemble projects for WA and EQA small changes between -10 to 10% in the SRRS for all three global warming scenarios (Figure 5e-g). The WCR shows a small decrease up to 9% in SRRS for the 1.5°C and 2°C, but a decrease of 20% rainfall mount for the 3°C global warming scenario (Figure 5j). The GHA experiences only small changes between -5 to 5% in the first RS (Figure 5i), but an increase in SRRS between 15% and 20% in the second RS under the 1.5°C and 2°C global warming scenario (Figure 5i). However, the increase of SRRS in GHA intensifies with 40% in the second RS for the 3°C global warming scenario (Figure 5i). The ensemble ranges for the 3°C global warming scenario are wider than the ones for the 1.5°C and 2°C global warming scenario.

3.6 Mean dry days during rainy season (DDRS)

Days with less than 1 mm daily rainfall may occur during RS. Under today’s climate conditions, these dry days occur very often with 100 to 140 days between 15°S and 15°N and with 40 to 100 days in southern Africa (Figure 6a). The model ensemble projects small changes of DDRS mainly between -5 and 5 days for the 1.5°C and 2°C warming scenario and a moderate increase of 5 to 15 days between 15°S and 15°N for the 3°C warming scenario (Figure 6b-d). The modelled changes of DDRS are not robust. As a result, the focus regions show only small changes in DDRS as well. However, in EQA there is a slight trend of more DDRS recognisable for both RS for the higher global warming scenarios (Figure 6f,g). The opposite trend is simulated by the model ensemble for the first RS in the GHA showing a decrease in DDRS (Figure 6h). The WCR ensemble ranges of the three global warming scenarios, in particular the central range, are wider than the ones of the other focus regions indicating a higher variability of the different model ensemble members (Figure 6j). Additionally, dry spells during the rainy seasons were analysed by means of histograms for the selected regions, but the model ensemble projects only small changes for the different global warming scenarios (not shown).
3.7 Extreme daily rainfall intensity during RS (ERIRS)

In this analysis, extreme rainfall is defined as the 99th percentile of daily rainfall during the RS. For the 1.5°C and 2°C global warming scenario the model ensemble simulates mainly an increase in ERIRS of 1 to 6 mm per day for the Sub-Saharan African continent and a strong increase up to 20 mm per day for the coastal regions of West Africa, Greater Horn of Africa and southeast Africa (Figure 7a,b). This increase in ERIRS becomes even more intense (more than 20 mm per day) for coastal regions for the 3°C global warming scenario (Figure 7c). Nevertheless, the modelled changes are not robust. The focus regions show different changes in extreme rainfall depending on their geographical location. The regional climate model ensemble projects almost no changes in ERIRS for the WCR (Figure 7i) and an increase of 1 to 4 mm per day for WA for all warming scenario (Figure 7d). A similar increase in ERIRS is simulated for both RS with a rising trend towards the higher global warming scenarios for EQA (Figure 7e,f). The GHA shows a moderate increase in ERIRS of 4 to 7 mm per day for both RS for the 1.5°C and 2°C warming scenario and a strong increase of 11 to 14 mm per day for both RS for the 3°C warming scenario (Figure 7g,h). The ensemble ranges of the boxplots increases towards the higher global warming scenarios for WA, EQA and GHA (Figure 7d-h). The widest ensemble ranges exhibit the WA and the narrowest ones WCR (Figure 7d,i).

4 Summary and discussion

In this work a regional climate model ensemble consisting of ten different ensemble members (six GCMs and three RCM in various combinations) was used to analyse the potential change of temperature and rainfall related indices under a 1.5°C, 2°C and 3°C global warming scenario for the CORDEX-Africa domain. For the discussion, the analysed indices were assigned according to their relevance to the specific sectors health, agriculture and infrastructure as collective term for traffic infrastructure and electricity grids.

The mean annual hot nights (HN), the mean annual heat wave days (HWD) and heat waves (HW) affect the human health and the human mortality and can thus be assigned to the health sector (Lui et al., 2017; Patz et al. 2005; Phalkey & Louis, 2016; Schmidt et al., 2016). For the 1.5°C and 2°C global warming scenario the model ensemble projects a moderate to strong increase in mean annual HN and for the 3°C global warming scenario a very strong increase in mean annual HN for central Africa (15°S-15°N). Furthermore, the projected increase in the mean annual HN is indicated as robust to strongly robust. The considerable increase in the number of HN might be to some extent a result of the low daily temperature variability in this region on the one hand and the threshold of the 90th percentile of daily maximum temperature which is easily exceeded in the global warming scenarios on the other hand. The results of the mean annual HWD are quite similar to the ones of HN concerning the impact of global warming scenarios on HWD. The model ensemble simulates a slight to moderate increase in HWD in the regions around 15°N, at the equator and for southern Africa under the 1.5°C and 2°C global warming scenario, respectively, and a strong increase in the HWD for the 3°C global warming scenario. The increase in the aforementioned regions is indicated as strongly robust.

To receive more detailed information of the global warming effect on the HW characteristic, the HWs occurring in the GHA are analysed by means of a histogram, exemplarily. The histogram shows an increase in the HW frequency and HW duration regarding a 30-years period towards higher global warming scenarios. It means that the model ensemble projects a field mean median of 24.2 events in a 30-years reference period of HW lasting between 3 and
7 days (all numbers are rounded to one fractional digit for readability). For the same HW category the models simulate almost three times higher number of events for the 1.5°C, more than three times for the 2°C and almost four time higher number of events for 3°C global warming scenario compared to a 30-years reference period. Moreover, the model ensemble projects the occurrence of HW with longer durations for the global warming scenarios in comparison to the reference period. For instance, the category of HW durations between 43 and 47 days shows zero events in the reference period, but 0.1, 0.6 and 1.5 events in the GHA region for the 1.5°C, 2°C and 3°C global warming scenario, respectively. Consequently, we can conclude that 1218 HW (1.5 x 812 gridboxes for the GHA region) with durations between 43 and 47 days are detected as ensemble median in a 30-years period in the 3°C global warming scenario. This could mean that either at least one event is simulated for all gridboxes or certain gridboxes experience a couple of HW events with duration between 43 and 47 days in a 30-years period.

Our results correspond to the work by Dosio & Panitz (2017) showing that rising temperatures simulated by an RCM ensemble using a RCP4.5 and RCP8.5 emission scenarios lead to increasing numbers of warm nights (90th percentile) in the CORDEX-Africa region. Russo et al. (2016) found in 50% of regional climate projections applying RCP8.5 emission scenario heat waves which are unusual under the present climate and become regular by 2040 (i.e. under higher temperatures). Based on the findings, the health related temperature indices will compromise the human health and increase human mortality rates on the African continent, in particular in the regions between 15°S and 15°N as well as in southern Africa, even for the 1.5°C and 2°C global warming scenario. A strong intensification of this effect is expected for the 3°C global warming scenario.

The length of RS (LRS), the daily sum of rainfall (SRRS), the number of dry days (DDRS) and the extreme rainfall (ERIRS) during the RS are important for the production of crops. Moreover, the annual HWD and HW have also an impact on the prosperity of crops. Therefore, these rainfall and temperature indices are relevant to the agriculture sector (e.g. Crookes et al., 2017; El Chami & El Moujabber, 2016; Msowoya et al., 2016; Sultan & Gaetani, 2016). As the HWD and HW were already discussed in the health sector, in this paragraph only the rainfall indices will be discussed. The projected changes of the RS rainfall indices were tested regarding their robustness, but they are not robust. Nevertheless, it seems to be worth discussing the changes in order to identify possible tendencies. RS related indices are only considered for Sub-Saharan regions. Small changes of the total LRS are simulated by the model ensemble for all global warming scenarios. Whereas most regions of the African continent exhibit a small decrease in the total LRS, there are two focus regions such as EQA and the GHA showing a small increase in the second RS. The model ensemble projects a decrease in SRRS of about 5 to 20% over south western Africa and over East Africa and an increase in SRRS of 5 to 20% from the GHA to Kenya for the 1.5°C and 2°C global warming scenario. The areas with a decrease in SRRS become drier (up to 30%) and the ones with an increase in SRRS become wetter (up to 50%) under the 3°C global warming scenario. This means for the WCR a decreasing trend of SRRS up to -20% and for the second RS of GHA an increasing trend of SRRS up to 40% towards higher global warming scenarios. Consequently, when small changes in LRS coincide with a decrease or an increase in SRRS, there must be changes in the rainfall intensities (i.e. in rainfall extremes) in the respective regions. For the 1.5° and 2°C global warming scenario the model ensemble project a moderate to strong increase in ERIRS of up to 20 mm per day over the coastal regions of West Africa, Greater Horn of Africa and southeast Africa. These regions will experience severe ERIRS with partly more than 20 mm per days under the 3°C global warming scenario.
This results in an increase in ERIRS for the GHA of 11 to 14 mm per day for both RS. The opposite extreme index, i.e. dry days (DDRS), shows for the Sub-Saharan regions small changes mainly between -5 and 5 days for the 1.5°C and 2°C warming scenario and with moderate increase of 5 to 15 days between 15°S and 15°N for the 3°C warming scenario.

The agriculture sector in Africa has to expect more intense ERIRS mainly at the coastal regions except for south western Africa for the 1.5°C and 2°C global warming scenario. This coincides with an increase in HWD and with longer and more frequently HW in particular between 15°S and 15°N of the African continent. The aforementioned impacts will be stronger under the 3°C global warming scenario. Therefore, it seems to be reasonable to plant specific crops being resistant to long-lasting high temperatures and extreme rainfall.

Extreme daily rainfall (ERIRS) may damage non-asphalted streets and may cause overloading of canalisations if available. Long-lasting heat waves (HW) can stress the electricity grids due to the usage of air conditions (Climate Service Center Germany (GERICS) and KfW Development Bank, 2015). Therefore both indices are relevant to the sector infrastructure. For the 1.5°C and 2°C global warming scenario the model ensemble projects a moderate increase in ERIRS and more frequent and longer HW for the African coastal regions between 15°S and 15°N. These findings become much more intense for the 3°C global warming scenario. Moreover, the regions with an increase in ERIRS will expand from the coastal regions towards the interior of the continent. Consequently, in the aforementioned regions the electricity grids should be prepared for higher demands due to longer and more frequent HW, and non-asphalted streets should be surfaced due to more intense ERIRS.

A main driving factor for the projected increase in ERIRS by the model ensemble is the increased moisture availability at the 850 hPa level. While the moisture increases slightly till moderately for the 1.5°C and 2°C global warming scenario respectively, the increase is much more intense for 3°C global warming scenario. The majority of the ensemble member simulates an increase in specific humidity over the oceans and the African continent. However, they simulate also a decrease in specific humidity over southwest Atlantic Ocean and coastal regions of southwest Africa in the austral summer (Dec.-Feb.) (not shown). This may explain why the southwest Africa becomes drier.

This work contains an analysis of regional climate changes for the pan-African and Sub-Saharan African continent under 1.5°, 2°C and 3°C global warming scenarios using identical GCM-RCM combinations for all three global warming scenarios. Therefore the derived climate change signals are not affected by applying different GCM-RCMs experiments. In total ten GCM-RCM ensemble members consisting of six different GCMs and three different RCMs covering the CORDEX-Africa domain are used. We acknowledge that the usage of a subset of the available regional climate experiments from the CORDEX-Africa database may not reflect the total potential range of climate changes. Thus, it would be reasonable to enlarge the number of ensemble members by conducting more RCP2.6 regional climate simulations to obtain more confidence in the findings. In addition, we expect that the uncertainty of the results due to the usage of ten ensemble members is not higher than the modelling uncertainties caused by missing physical processes and feedbacks in the existing regional climate simulations, such as deficiencies in the representation of sea surface temperatures in GCMs or missing interactions between atmosphere and ocean in RCMs (e.g. Cabos et al., 2017; Weber et al., 2017).
5 Conclusions and outlook

This analysis revealed substantial differences between 1.5°C/2°C and 3°C global warming scenarios and the resulting indices of climate change which are related in this study to the sectors health, agriculture and infrastructure for the pan-African and Sub-Saharan African continent. In detail the continent, in particular the regions between 15°S and 15°N, has to expect an increase in hot nights and longer and more frequent heat waves even if the global temperature will be kept below 2°C. These effects intensify if the global mean temperature will exceed the 2°C threshold. Furthermore, the daily rainfall intensity is expected to increase towards higher global warming scenarios and will affect especially the African Sub-Saharan coastal regions. A lot of harmful climate change impacts such as the loss of human lives and economics costs could be prevented if warming is limited below 2°C. This paper provides only a first analysis on this kind and further investigations should follow. Now it is time to combine CORDEX-Africa data with models/applications from the climate change impact side in order to provide more impact assessment tailored information. Future analysis has to be conducted more on the regional scale and specifically for different sectors which means local knowledge has to be included in the investigations. The climate model data for such analysis is freely available via the Earth System Grid Federation (ESGF). This kind of studies would be very beneficial for policy and decision makers and would allow developing sustainability strategies for the pan-African and Sub-Saharan African continent.

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Table 1: Analysed climate indices and their application in the respective sectors

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<th>Indicator</th>
<th>Definition</th>
<th>Sector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean annual hot nights (HN)</td>
<td>90&lt;sup&gt;th&lt;/sup&gt; percentile of daily minimum temperature of the reference period 1971-2000 [days]</td>
<td>Health</td>
</tr>
<tr>
<td>Mean annual heat waves days (HWD)</td>
<td>Number of periods of three or more consecutive days with daily maximum temperature above the 95&lt;sup&gt;th&lt;/sup&gt; percentile of the reference period 1971-2000, but with at least 25°C [N] (Liu et al., 2017)</td>
<td>Health, Agriculture</td>
</tr>
<tr>
<td>Heat waves (HW)</td>
<td>Number of consecutive days with daily maximum temperature above the 95&lt;sup&gt;th&lt;/sup&gt; percentile of the reference period 1971-2000, but with at least 25°C [days]</td>
<td>Health, Agriculture, Infrastructure</td>
</tr>
<tr>
<td>Mean length of rainy seasons (LRS)</td>
<td>[days]</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Mean sum of rainfall during rainy seasons (SRRS)</td>
<td>[mm]</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Mean number of dry days during rainy seasons (DDRS)</td>
<td>Days with daily rainfall amount less than 1 mm [days]</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Extreme daily rainfall intensity during rainy seasons (ERIRS)</td>
<td>99&lt;sup&gt;th&lt;/sup&gt; percentile of daily rainfall of the reference period 1971-2000 [mm]</td>
<td>Infrastructure, Agriculture</td>
</tr>
</tbody>
</table>
Figure 1: Orography of the CORDEX-Africa domain showing the focus regions West Africa (WA), Equatorial Africa (EQA), the Greater Horn of Africa (GHA) and the Western Cape Region of South Africa (WCR).
Figure 2: Projected changes of mean annual hot nights [days] by the regional model ensemble: Spatial distribution of median for a) 1.5°C, b) 2°C and c) 3°C global warming scenario. Dotted areas indicate the exceedance of the single standard deviation; hatched areas indicate the exceedance of the double standard deviation. Ensemble minimum/maximum (light colour), 17th and 83rd percentile (dark colour) and median (grey) as field means for the focus regions d) West Africa, e) Equatorial Africa, f) Greater Horn of Africa and g) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario.
Figure 3: a) Mean annual heat wave days [N] calculated from the WATCH data set for reference period (1971-2000). Projected changes of mean annual heat wave days [N] by the regional model ensemble: Spatial distribution of median for b) 1.5°C, c) 2°C and d) 3°C global warming scenario. Dotted areas indicate the exceedance of the single standard deviation; hatched areas indicate the exceedance of the double standard deviation. Ensemble minimum/maximum (light colour), 17th and 83rd percentile (dark colour) and median (grey) as field means for the focus regions e) West Africa, f) Equatorial Africa, g) Greater Horn of Africa and h) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario. i) Ensemble median of heat waves durations and frequencies for the Greater Horn of Africa.
Figure 4: a) Mean rainy season length [days] calculated from the WATCH data set for reference period (1971-2000). Projected changes of mean rainy season length [days] by the regional model ensemble: Spatial distribution of median for b) 1.5°C, c) 2°C and d) 3°C global warming scenario. Ensemble minimum/maximum (light colour), 17th and 83th percentile (dark colour) and median (grey) as field means for the focus regions e) West Africa, f) Equatorial Africa rainy season one, g) Equatorial Africa rainy season two, h) Greater Horn of Africa rainy season one, i) Greater Horn of Africa rainy season two and j) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario.
Figure 5: a) Mean rainfall during rainy seasons [mm rs-1] calculated from the WATCH data set for reference period (1971-2000). Projected changes of mean rainfall during rainy seasons [%] by the regional model ensemble: Spatial distribution of median for b) 1.5°C, c) 2°C and d) 3°C global warming scenario. Ensemble minimum/maximum (light colour), 17th and 83rd percentile (dark colour) and median (grey) as field means for the focus regions e) West Africa, f) Equatorial Africa rainy season one, g) Equatorial Africa rainy season two, h) Greater Horn of Africa rainy season one, i) Greater Horn of Africa rainy season two and j) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario.
Figure 6: a) Mean dry days during rainy seasons [days] calculated from the WATCH data set for reference period (1971-2000). Projected changes of mean dry days during rainy seasons [%] by the regional model ensemble. Spatial distribution of median for b) 1.5°C, c) 2°C and d) 3°C global warming scenario. Ensemble minimum/maximum (light colour), 17th and 83rd percentile (dark colour) and median (grey) as field means for the focus regions e) West Africa, f) Equatorial Africa rainy season one, g) Equatorial Africa rainy season two, h) Greater Horn of Africa rainy season one, i) Greater Horn of Africa rainy season two and j) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario.
Figure 7: Projected changes of mean 99th percentile daily rainfall [mm day\(^{-1}\)] by the regional model ensemble: Spatial distribution of median for a) 1.5°C, b) 2°C and c) 3°C global warming scenario. Ensemble minimum/maximum (light colour), 17th and 83rd percentile (dark colour) and median (grey) as field means for the focus regions d) West Africa, e) Equatorial Africa rainy season one, f) Equatorial Africa rainy season two, g) Greater Horn of Africa rainy season one, h) Greater Horn of Africa rainy season two and i) Western Cape Region. The colours of the boxes indicate the 1.5°C (green), 2°C (blue) and 3°C (red) global warming scenario.