CLIMATE SERVICE CENTER

CSC Report 11

Climate Change Scenarios for the Congo Basin

Final Report

On behalf of

Federal Ministry for the
Environment, Nature Conservation
and Nuclear Safety

of the Federal Republic of Germany

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

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Climate Service Center
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Acknowledgments

The project “Climate Change Scenarios for the Congo Basin” was a joint activity of the Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH, the Climate Service Centre (CSC) in Hamburg and the Wageningen University and Research Centre (WUR) in the Netherlands. It was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and run for the period from late 2010 to early 2013.

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Technical Preface

This final report summarizes the findings of the project “Climate Change Scenarios for the Congo Basin”. The report consists of four independent reports on the topics *regional climate change assessment*, *regional hydrological change assessment*, *regional impact assessment* and *identification of regional adaptation options*. The key findings of each report are condensed in the *executive summary* which is placed in the beginning of the report.

The final report should be cited as follows:
CSC (2013): *Climate Change Scenarios for the Congo Basin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

The respective reports should be cited as follows:
Report 1
Haensler, A., Saeed, F. and Jacob, D. (2013): Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections. In: Climate Change Scenarios for the Congo Basin. [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

Report 2
Beyene T., Ludwig F., Franssen W. (2013): The potential consequences of climate change in the hydrology regime of the Congo River Basin. *In: Climate Change Scenarios for the Congo Basin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

Report 3
Ludwig F., Franssen W., Jans W., Beyenne T., Kruijt B., Supit I. (2013): Climate change impacts on the Congo Basin region. *In: Climate Change Scenarios for the Congo Basin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

Report 4
van Garderen, Ludwig F. (2013): Climate change adaptation options for the Congo Basin countries. *In: Climate Change Scenarios for the Congo Basin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

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Climate Change Scenarios for the Congo Basin

Executive Summary

The African continent has an elevated susceptibility towards the stress caused by climate change combined with relatively low adaptation capacities as highlighted by the 4th Assessment Report (IPCC AR4) of the Intergovernmental Panel on Climate Change (IPCC). The forests of the Congo basin are the second largest continuous rainforest in the world, covering an area of approximately 1.8 Million km^2. The Congo forests are extremely important for storing carbon and their impact on the global water cycle through local water recycling. Nevertheless, there are only a limited number of studies focusing on climate change and the resulting impacts for the Congo basin. One of the major reasons for this is the lack of observational climate and hydrological data, which makes it difficult to evaluate the performance of modelling studies. The elevated vulnerability of the sectors agriculture / food security, water supply and ecosystems implicates that the concepts of sustainable management and the development strategies take climate change aspects into account and be adjusted if needed. In order to achieve that, the so far existing data from the sub-region are insufficient. It is thus of major importance to generate specific and solid sub-regional data on climate change, its impacts on key sectors of the Central African economy and ecology and on potential adaptation options to combat the effects of climate change.

Since 2008, the International Climate Initiative (ICI) of the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has been financing climate and biodiversity projects in developing and newly industrialising countries, as well as in countries in transition. The ICI is a key element of Germany's fast-start financing. It is in the framework of ICI that in 2009, BMU mandated the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH to implement the project "Climate Change Scenarios for the Congo Basin". The main aim of the project was to provide national and regional decision makers with relevant climate change scenarios for the countries in the greater river Congo basin region in order to allow these decision makers i) to adapt their management strategies related to natural resources (such as forests, water, agriculture) to climate change and ii) to strengthen the science base for their interest in the post-Kyoto negotiations context.

It was a joint project of GIZ, the Climate Service Centre (CSC) in Hamburg, Germany and the Wageningen University and Research Centre (WUR) in the Netherlands running from late 2010 to early 2013 with a total budget of 1.530.000€. GIZ as the lead implementing organisation was responsible for sub-contracting the internationally established research institutions for the scientific part of the project and for creating a link between these institutions and the respective countries of the sub-region. GIZ further facilitated the transfer of the results towards the decision makers of the COMIFAC member countries.

The scientific part was subdivided between CSC and WUR and a dedicated interdisciplinary workflow has been established – connecting projected climate changes and thereby resulting impacts on the hydrology, forestry and agriculture with direct and indirect monetary threats and chances, and finally giving advice with respect to management strategies and the political decision making process. A sketch of the workflow of the project is given in Figure 1.

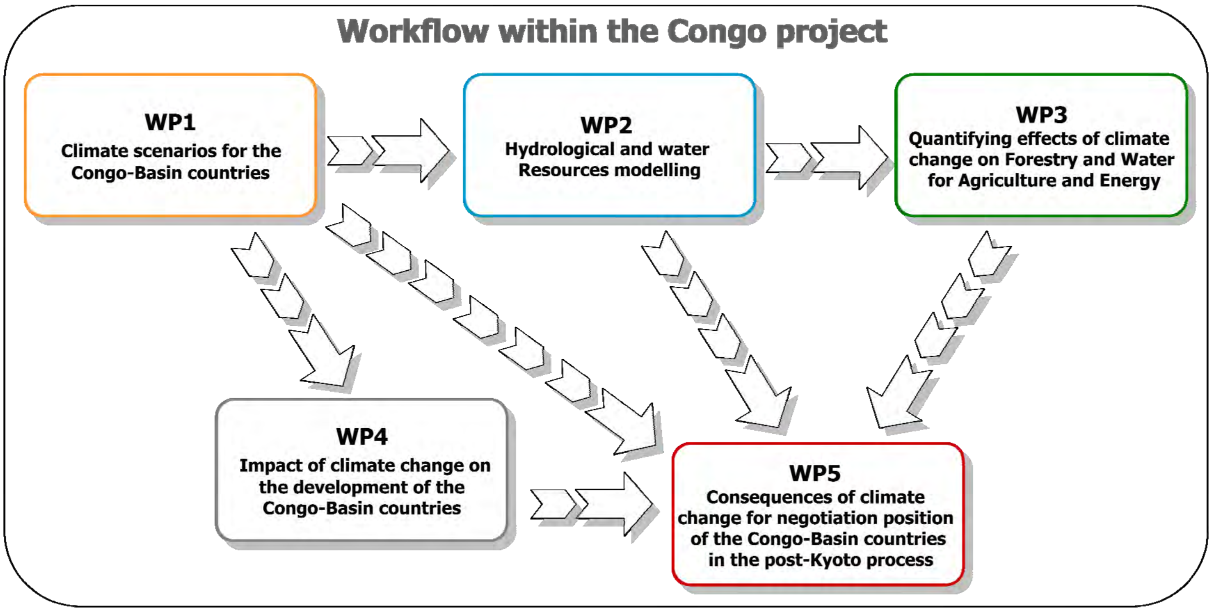

Figure 1: Interdisciplinary work-flow by work-packages (WP) of the project “Climate Change Scenarios for the Congo Basin”. WP1 was conducted by CSC; subsequent WPs 2-5 were conducted by WUR.

CSC was responsible for the regional climate change assessment. In a first step, available projections from state-of-the-art global climate models (from the CMIP3 and CMIP5 projects) have been analysed. Furthermore, recent projections from CMIP5 global climate models have been downscaled with regional climate models to enlarge the available dataset of independent climate change projections. Subsequently a dataset consisting of 77 different climate change projections from global and regional climate models was used for the regional climate change assessment. Out of this large ensemble, six representative projections were then used by WUR to conduct further simulations by feeding their results into two impact models, namely the Lund-Potsdam-Jena-managed land model (LPJml) and the distributed Variable Infiltration Capacity model (VIC). Based on these simulations, the impact of climate change on regional water availability, with its possible impacts on hydro-power generation potential, agricultural water use and productivity and the carbon stocks in the vegetation have been studied. On the basis of the model results, suitable adaptation and management options have been developed in the project. The major findings of the project are summarized in the subsequent paragraphs. A summary of the underlying data and models used in the different work packages is depicted in Figure 2.

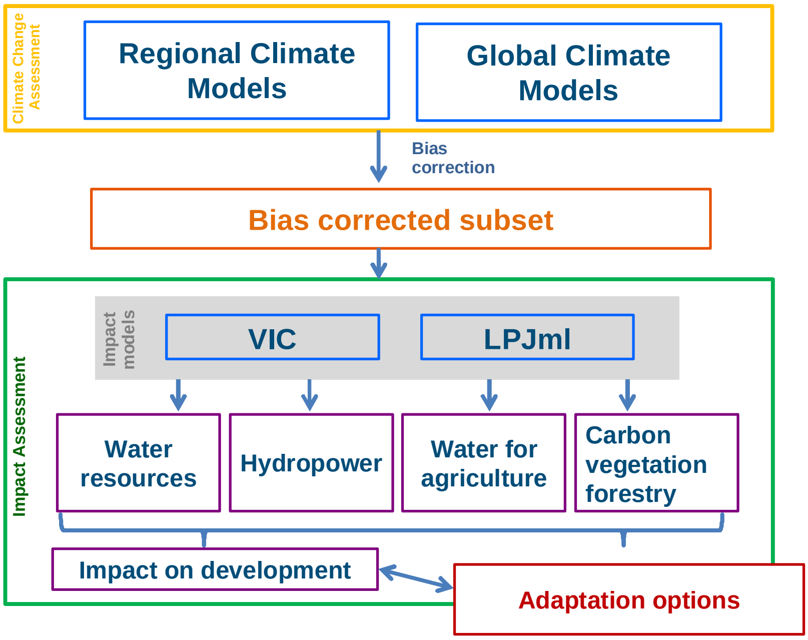

Figure 2: Modelling chain of the project “Climate Change Scenarios for the Congo Basin”

Regional Climate Change Assessment:

The climate change assessment described in this report was based on a unique large set of projections from global climate models from the CMIP3 project (database of the 4th IPCC assessment report) and the CMIP5 project (database of the upcoming 5th IPCC assessment report due in 2013). Moreover bias-corrected and statistical downscaled projections of the EU-WATCH project have been included along with the projections of regional climate models. Although most of the regional climate projections are developed within the framework of this project, a few simulations from the preliminary CORDEX Africa data archive are also considered for the analysis.

For the analysis of potential climate changes two potential future developments have been considered – a "*high*" emission scenario (combining climate projections following the SRES A2 and RCP8.5 emission scenarios) and a "*low*" emission scenario (combining climate projections following the SRES B1 and RCP4.5 and RCP2.6 emission scenarios). Altogether an ensemble of 46 different projections has been analysed for the case of the low emission scenario and an ensemble of 31 projections for the high emission scenario. This unique large dataset of different kind of projections (from global climate models, regional climate projections and statistically bias-corrected and downscaled global projections) allows the identification of robust patterns and associated ranges of projected changes for the first time over this region.

The major findings of the climate change assessment can be summarized as follows. For the near surface air temperature, all assessed models agree on a substantial warming towards the end of the century in all seasons of the year regardless of the underlying scenario. On an annual basis a warming in the range of +1.5 and +3°C for the low and in the range between +3.5 and +6°C for the high emission scenario can be considered to be likely towards the end of the 21st century. In general projected temperature increase is slightly above average in the northern parts of the region and slightly below average in the central parts. Also for temperature extremes (frequency of cold/hot days and nights) all models agree on a decrease/increase in the future. Especially the hot days and nights are projected to occur much more frequently in the future, particularly in the case of the high emission scenario. Since for the temperature related parameters all 77 analysed projections agree in the sign of the projected changes, therefore these changes can be considered to have a very large robustness.

For total precipitation the agreement between the assessed projections is not as high as for the temperature. For all zones some models project an increase in annual total precipitation and some project a decrease. If the full range of projected changes in annual total precipitation is considered, all models agree on a change not higher than ±30% towards the end of the 21st century for most parts of the domain with a general tendency of a slight increase in future annual total precipitation. However, in the dryer northern part, a larger increase in annual total precipitation (full range up to about +75%) is projected, mainly related to the northward expansion of the tropical convection zone, which was already described in the scientific literature. These findings are independent of the underlying emission scenario. If only the likely range is considered, projected changes in annual total precipitation are between ~ -10 to +10% (-10 to +30% in the north) and between -5 to +10% (-10 to +15% in the north) for the high and low emission scenarios respectively. This finding once again points to the conclusion that - on the basis of the assessed large ensemble of climate change projections – it is not likely that drastic changes in annual total rainfall will occur in the future over the greater Congo basin region.

Although the annual total precipitation amounts might not change dramatically, the rainfall characteristics are projected to undergo some substantial changes. An example for this is the likely increase in the intensity of heavy rainfall events in the future (likely range for most parts positive, up to ~ +30%). Also the frequency of dry spells during the rainy season is projected to substantially increase in the future over most parts of the domain. This indicates a more sporadic rainfall distribution in the future.

In summary the climate change assessment for the greater Congo basin did reveal that projected rainfall changes are unlikely to lead to a general water shortage in the region, however some prolonged and more frequent dry periods might become more likely in the future. This finding is independent of the underlying emission scenario. In terms of the projections in near surface air temperature, the projected warming is substantially larger under the high emission scenario, and therefore might also have a substantially larger impact on the living environment in the region.

Regional Climate Change Impacts Assessment:

It is impossible to use all 77 climate change scenarios for the impact analyses so instead we used a rather representative subset of climate scenarios. Most of the assessments were based on six different global climate change scenarios; however for some studies like the analysis of the forest carbon cycle only two global climate scenarios could be used. This difference in the number of GCM input data into the different assessments causes a limitation of this study that should be kept in mind when comparing the results of the different assessments to each other. However, differences in future climate change impacts that arise between the high and low scenario *within* the same assessment *can* be reliably compared.

Projected changes in rainfall and temperature will result in substantial changes in the hydrology of the Congo basin. Due to temperature increases evaporation potentially also increases. However projected changes in evapotranspiration in the region are not completely consistent in the different assessments. This is probably caused by the fact that different hydrological models were used and that different numbers of climate scenarios have been used as input for the hydrological models. For the climate scenarios analysed, the rainfall generally increased more than the evaporation and as a result the run-off increased up to 50%. Run-off and stream flow will especially increase in the wet season. This indicates that flood risks will increase significantly in the future throughout the basin. Floods will increase most in the central and western part of the Basin. While run-off and stream flow will clearly increase during the wet seasons, during the dry season the scenarios show conflicting results. Some scenarios indicate a drier dry season while others show higher flows during the dry season. What is clear from all model results is that the difference between wet and dry season will become larger compared to the current climate. Especially the wet extremes will become more frequent and more intense, which is also inline with the projected intensification of heavy rainfall events.

In general, our analyses shows that more water will be available for hydropower in the future. So on average, climate change will have a positive impact on potential electricity production. However, the rainfall variability will also increase which means, that in some years power production will be much lower compared to other years. Countries should therefore ensure that they have enough other sources of electricity to cover the reduced hydropower production during dry periods.

Climate change will have a range of different impacts on forest ecosystems. The higher atmospheric CO_2 concentrations might increase forest growth and carbon capture. Higher temperatures however will have negative impacts on forest growth and reduce the amount of carbon in the forests. The impact analyses show that as a result of climate change, the Congo basin is unlikely to see a decline in forest growth such as sometimes predicted for the Amazon basin. Instead, there could be a moderate increase in ecosystem carbon. Depending on how the climate will change there could be a shift in land cover of the different ecosystems. Based on the analyses a moderate expansion to the North and South of Evergreen forests into savannas and grasslands is the most likely future scenario. The model assessments show a large uncertainty range, highlighting the fact that collecting new data on, e.g., biomass in the central Congo basin and responses of forests to changing climate and CO_2 concentrations are essential to further narrow down prediction ranges.

In general, climatic conditions are currently not limiting agricultural production in the Congo basin region. Only on the (drier) edges of the region water limitation is sometimes reducing the potential agricultural productions. In the tropical climates too much rainfall and high humidity limits agricultural production through nutrient leaching and fungal growth. The impact of future climate on agricultural production will therefore be limited in the region. In most of the area the water stress will increase slightly in the future. However the agriculture will not suffer from structural water shortages. Only the agriculture in the savanna regions surrounding the Congo basin could potentially face water shortages in the future. In the southern savanna region the analysis indicates that more frequent droughts will affect agriculture production and water stress.

In several of the COMIFAC countries there is a clear correlation between annual rainfall and GDP growth. GDP and Agricultural GDP growth rates tend to be higher in years with above-average rainfall than in the dry years. The impact of climate variability on GDP growth is most pronounced during dry years. During below-average rainfall years growth is sometimes severely reduced and generally the drier the lower the GDP growth rate. All above-average rainfall years tend to have relatively similar economic growth rates. The correlation between rainfall and GDP growth rates is stronger in countries with lower and more variable rainfall. In most countries, agricultural GDP growth rates are affected stronger by climate variability than the total GDP growth rates. For example in the Democratic

Republic of Congo during dry years the growth was negative while during average and above average rainfall years the economic output of the agricultural sector is growing. In Chad, the situation is even more dramatic with large reductions in Agricultural productivity during dry years and rapid growth especially during the years with near average rainfall.

In terms of future climate change impacts on economic development our analysis shows that COMIFAC countries are especially vulnerable to a reduction in rainfall and a significant increase in interannual rainfall variability. Our results show that at a continental scale, climate change is likely to have a negative impact on the development in Africa. However the economies of central African countries are likely to be less affected by climate change compared to countries in West, East and Southern Africa. Nevertheless some climate change scenarios show large increases in climate variability and this could have a negative impact on development.

In conclusion, the region needs to prepare for a more variable climate and a more variable hydrological regime. Also the difference between seasons and between different years is likely to become larger in the future. The region needs to prepare for more intensive rainfall and probably more floods during the wet season. It is also clear that temperatures will increase in the future. Climate change adaptation should therefore focus on reducing the impacts of increased rainfall variability and higher temperatures.

Regional Climate Change Adaptation Options:

In terms of adaptation, first of all there is a need to improve preparedness for extreme weather events such as droughts and floods because these kinds of events will occur more often in the future due to climate change. In addition, in the agricultural and energy sector there should be risk spreading by diversification. Farmers should grow different crops and also different varieties to reduce impact of climate variability. Countries should be careful not to become fully dependent on hydropower because this makes them too vulnerable to droughts. Other sustainable energy sources such as solar and biofuel should also be promoted. To prevent forest degeneration and erosion there should be more attention on reforestation and agroforestry. Programs on food and water security should develop strategies to manage climate variability so they are prepared for both dry and wet periods. The knowledge of climate change impacts and adaptation is still very limited in the region and there is need for more capacity building and awareness raising.

Most of the COMIFAC member countries still have very big development challenges. The general income tends to be low and there are still high poverty rates. These immediate development needs are overall more important than climate change adaptation. However future development also creates opportunities for adaptation. To avoid wrong investments and to reduce future cost of adaptation, climate change adaptation should be integrated in future development plans. A more indirect impact of climate change on the Congo basin countries might arise from neighbouring countries in the north and south which are expected to be more severely affected by climate change. The climate change related increased variability in agricultural production might lead to increased migration from these countries into the Congo basin.

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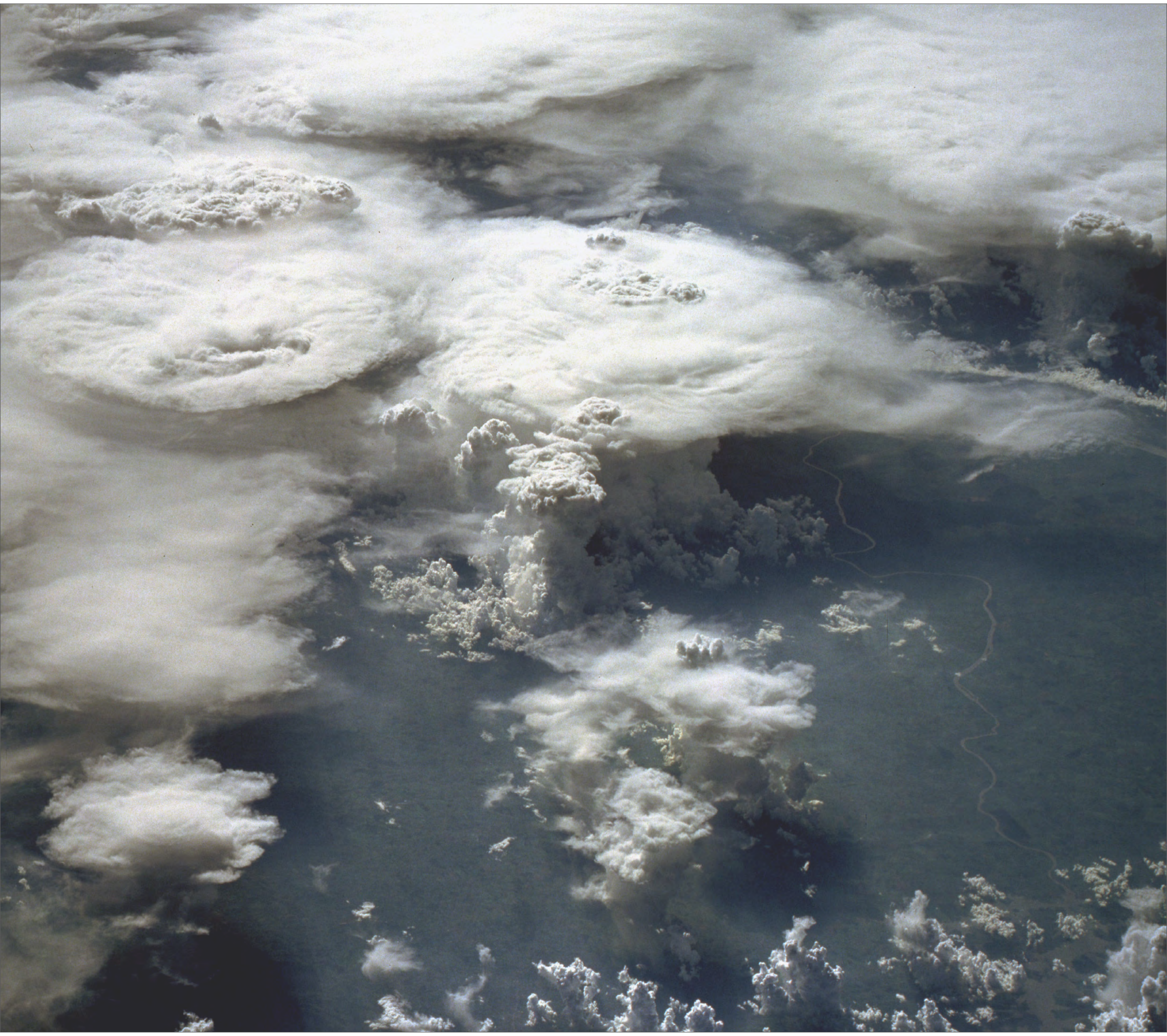
Climate Change Scenarios for the Congo Basin

Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections



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Climate Change Scenarios for the Congo Basin

Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections

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Hamburg, February 2013

On behalf of:
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
In cooperation with:
Gesellschaft für Internationale Zusammenarbeit (GIZ), Germany and Wageningen University, The Netherlands

This report should be cited as follows:
Haensler, A., Saeed, F. and Jacob, D. (2013): Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections. In: Climate Change Scenarios for the Congo Basin. [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

“Assessment of projected climate change signals over central Africa based on a multitude of global and regional climate projections”
Part of the series: “Climate Change Scenarios for the Congo Basin”
Authors: Andreas Haensler, Fahad Saeed, Daniela Jacob
Lay-out and Editing: Andreas Haensler
Date: February 2013

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany / Gesellschaft fur InternationaleZusammenarbeit (GIZ), Germany / Wageningen University, The Netherlands / Climate Service Centre, Germany.

Cover photo: “Series of mature thunderstorms” by the NASA Earth Observatory

Abstract

In the framework of the project “Climate Change Scenarios for the Congo Basin” (funded by the German Ministry for Environment, Nature Conservation and Nuclear Safety) a regional climate change assessment was conducted over the greater Congo basin region. The analysis was based on a state-of-the-art multi-model multi-scenario ensemble of global and regional climate change projections. Several parameters and indices related to temperature and precipitation were considered for the assessment of projected climate changes in extremes as well as in the mean state. The large size of the analyzed ensemble proved to be useful not only for quantifying the magnitude of projected changes, but also for analyzing their robustness.

The findings of the report indicate a substantial robust increase in mean temperature over the greater Congo basin region independent of the underlying emission scenario. Along with the mean temperatures, the temperature extremes are also projected to undergo a considerable change. For annual total precipitation the analyzed ensemble does not show a large change over the study area, again independent of the underlying emission scenario. However, rainfall characteristics are projected to change in the future. The projected change in the intensity of heavy precipitation events shows a robust increase over major parts of the study area. Similarly the number of dry spells during the rainy season is also likely to increase. These changes might have a substantial impact on the region’s agricultural and hydro-energy systems, even if the mean annual water availability stays constant. The potential impacts of the projected changes and possible strategies to adapt to these changes are estimated in subsequent studies of the project.

Table of content

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) projects in its fourth Assessment Report (AR4) that mean global temperatures are likely to rise between 1.1 and 6.4°C (with a best estimate of 1.8 to 4°C) above 1990 levels by the end of the current century associated with an likely increase in frequency and intensity of extreme climate events (floods, droughts, extreme temperatures etc.). However at regional level, the magnitudes of climate change signals and associated extremes can be substantially different as compared to the global average. Hence in order to develop adaptation and mitigation strategies, detailed analysis of magnitude of climate change and associated extremes are required at a regional scale. In the current report a synthesis of existing climate change projections for the greater Congo basin will be given. This region has been classified in AR4 to be a region with a less clear picture with respect to projected climate change, with some models projecting an increase in annual total precipitation while others a decrease (Christensen et al., 2007). Therefore further studies on a larger database are required to identify robust patterns of potential climate change over the region in order to build a reliable data base on which potential benefits and threads for the region resulting from possible climate change can be identified.

The Congo basin is predominately forested. The forests of the Congo region are the second largest rainforest in the world, covering an area of approx. 1.7 Million km^2. Due to their immense potential in storing carbon as well as through their impact on the global water cycle via local water recycling, they are supposed to have a substantial impact on the climate system. However, so far only a limited number of studies on potential impact of climate change over the Congo region are available. The lack of information with regard to future climate change has therefore made the region more vulnerable, and hence calls for a more in-depth and detailed study to estimate the possible future climate changes over the region.

In this report, a unique regional climate change assessment based on a large state-of-the-art ensemble of global and downscaled climate projections is presented. This dataset combines several kinds of projections (from global climate models, regional climate projections and statistically bias-corrected global projections) and allows for the first time to identify robust patterns and ranges of projected changes over the greater Congo basin region.

The report is structured as follows. The major climate characteristics of the greater Congo basin are introduced in section 2. Section 3 describes the underlying analysis concept and data sets. The performance of the selected datasets in simulating the regions climate characteristics is evaluated in section 4. Section 5 summarizes the projected climate change signals of the full ensemble of model simulations for several parameters over the Congo basin region. In section 6 the subset of climate change projections used for subsequent impact studies within the project is analyzed. The major findings of the report are finally summarized in section 7.

2. The general circulation and climate of the greater Congo basin region

2.1. Circulation characteristics

The climate of the African continent exhibits a zonal pattern in general, with varying distribution of seasonal precipitation. Northern and Southern regions of the African continent come under the influence of mid-latitude westerlies during winter. Therefore, these regions experience wet and dry conditions during winter and summer respectively. Moving further toward equator comes the deserts of Sahara and Namib in northern and southern hemisphere respectively, which are dominated by subtropical anticyclones throughout the year. These arid zones are separated by a wide belt of tropical climate and the greater Congo basin region is located within these tropics. A schematic of general patterns of winds and pressure over Africa is presented in Figure 1(a,b) for January and July/August. A more detailed description of characteristics of the climate and circulations of Africa can be found in Nicholson (1996).

The Congo basin has a typical tropical circulations mainly determined by the meridional flows of the Hadley cells. A schematic of the Hadley cell is shown in Figure 1(c). In a typical Hadley cell, the major driving force

of atmospheric circulation is solar heating causing rising motion near equator, poleward motion in the upper troposphere, sinking motion in the subtropics and an equatorward return flow in the lower troposphere. The equatorward return flow takes a northeast-southwest (southeast-northwest) direction in northern (southern) hemisphere due to the coriolis force, and therefore called as easterly trade winds. The region where the trade winds from north and south converge is known as the *InterTropical Convergence Zone* (ITCZ). Due to solar heating, the ITCZ is characterized by low surface pressures and generally rising air masses. Therefore this central region is affected by high-cloudiness and frequent convective rainfall events.
Along with the typical circulation of the Hadley cell, the upper tropospheric circulation is also influenced by the *Tropical Easterly Jet* (TEJ). TEJ can be identified by a zone of strong north-easterly winds in about 200hPa that is most pronounced during the boreal summer season and is centered during that time at around 15N. The origin of the TEJ can mainly be related to the presence of Tibetan anticyclone which is one of the main features during the south Asian summer monsoon season (McGregor, 1998).

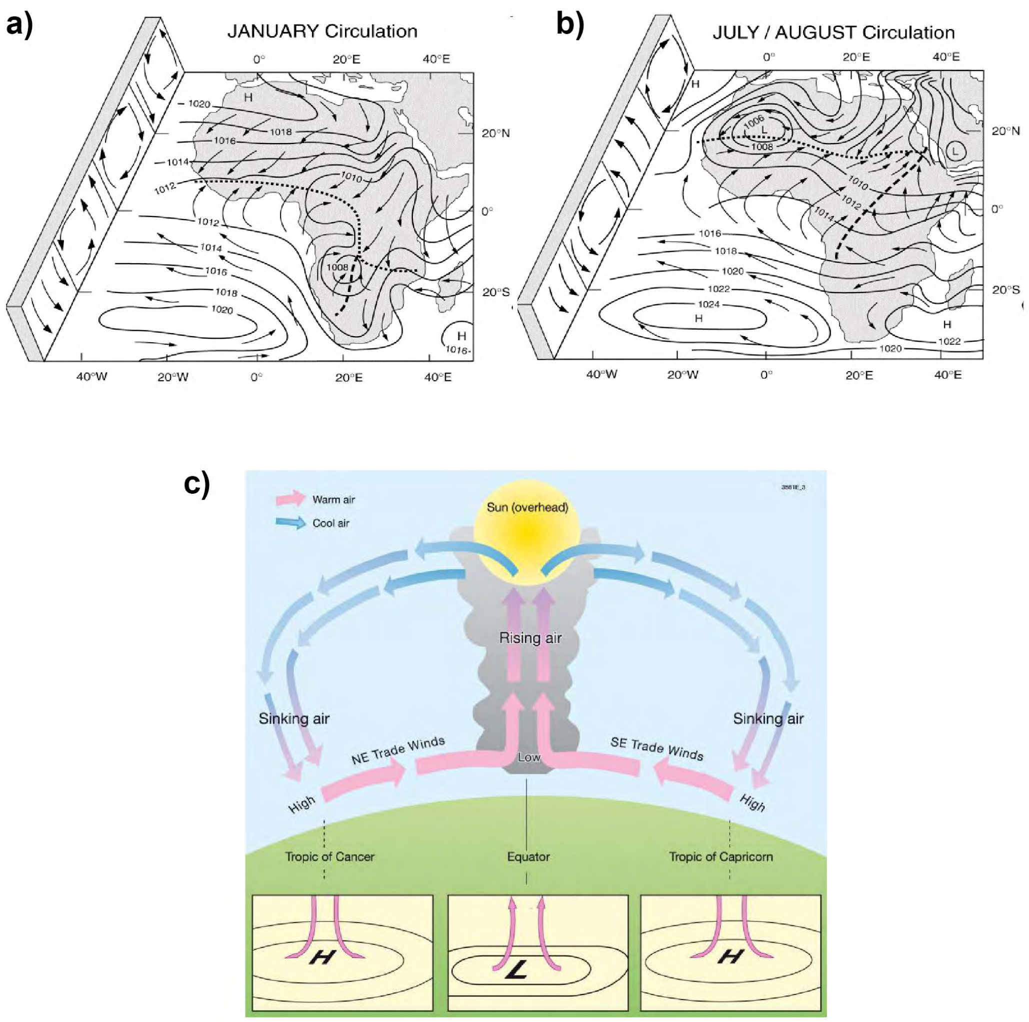


Figure 1: Schematic of the general near surface circulations and pressure patterns over Africa for (a) January (b) July/August from Nicholson (1996), where the dotted lines indicate the ITCZ. (c) Schematic of the atmospheric circulation in the subtropical and tropical regions.

Mid-tropospheric circulation over the region is further characterized by the occurrence of the *African Easterly Jets* (AEJ) at around 600hPa at both sides of the main convective belts of the ITCZ. They are supposed to be generated by the thermal gradients between the semiarid regions in the subtropics and the sub humid regions further towards the central tropics (Nicholson and Griest, 2003).

The above described system, however, is not a constant feature but varies throughout the course of the year. The ITCZ moves back and forth across the equator following the sun's zenith point. Over the greater Congo basin region the ITCZ reaches its northern (southern) most extent during the boreal (austral) summer season. The north and southward movement of the ITCZ (and also of the subtropical highs) leads to generally unimodal rainfall regimes in the northern and southern part of the greater Congo basin region, whereas a bimodal regime is present over the central regions. However the seasonal evolution of the circulation patterns is not uniformly distributed around the equator, but is influenced by the land surface characteristics, the ocean currents and the large scale atmospheric circulation.

A consequence of the seasonal movements of the circulation patterns is the development of a monsoon-like circulation, generally defined by an occurrence of a seasonal reversal wind system during the course of the year. Even though the central African region is largely influenced by easterly trade winds, also westerly flow carries humid air masses into the domain. These westerly flows are mainly forced by differential heating of ocean and land surfaces during a specific time in the year and therefore resulting in a monsoon effect (Leroux, 2001). The westerly monsoon flow can reach as far east as about 30°E, where the mountain range in the eastern part is located.

2.2 Precipitation and temperature characteristics

Due to steady solar heating in the tropics, most areas remain hot and therefore, seasonal climate variation is mainly determined by rainfall and the sequence of rainy and rain-free periods. Large parts of the available heat is used for evapotranspiration, therefore the tropical air masses are rich in humidity. The availability of large amounts of energy and moisture are a prerequisite for turbulent conditions in the lower layers of the atmosphere. Hence the region generally favors convective instability; therefore forming clouds with large vertical extent, causing storm showers.

Unfortunately the region of the greater Congo basin has a very limited number of meteorological stations for the quantitative description of the climatological rainfall and temperature characteristics. Due to this, only a few studies dealing with rainfall and rainfall changes in this region can be found in the earlier literature. Therefore, the following description of the rain distribution is taken from two textbooks dealing with the general climate of the tropical African region (Leroux, 2001; Bultot and Griffiths, 1972).

Generally the tropics can be separated into humid tropics (more than 2.000 mm rainfall a year), the intermediate tropics (between 1.000 and 2.000 mm rainfall a year) and the dry tropics with less than 1.000 mm a year. The rainfall is generally of convective nature. The greater Congo basin region is mainly classified as intermediate tropics, showing rainfall in the order of about 1.000 to 1.750 mm a year. Higher rainfall amounts are observed in the equatorial regions in the centre of the Congo basin with rainfall as high as 2.000 mm a year on average, including the coastal areas of Cameroon, where the highest rainfall amounts of the whole African continent are recorded (e.g. more than 11.000 mm a year at the slopes of Mount Cameroon; Wanji et al., 2003 - see Figure 2, upper right). However available observations in the region are sparse and also uncertain. To illustrate this, we included annual total precipitation amounts measured at several stations in the analysis. Compared to the gridded dataset (Watch Forcing Data (WFD); Weedon et al., 2011) a large discrepancy is visible in observed precipitation amounts along the coastal areas of the greater Congo basin region. In this region, the gridded data set shows at least 50% higher annual total precipitation amounts than the station data. Therefore, this uncertainty in the available observations should also be kept in mind, while evaluating the quality of the model simulations described in section 4.

As mentioned earlier the seasonal distribution of the rainfall in the greater Congo basin is characterized by either unimodal or bimodal rainfall regimes, caused by the north/south movement of the ITCZ during the course of the year. The unimodal regime is mainly limited to the northern parts of the basin and shows a maximum in the late boreal summer season (July to August). In the north-western parts this unimodal rainfall regime is often connected to the monsoon circulation. Also the southern parts of the Congo basin show unimodal rainfall behavior, however receiving the maximum rainfall in the boreal winter season (November to January). The majority of the Congo basin is characterized by a bimodal rainfall regime with a lower rainfall peak in the boreal spring season (March/April) and the main peak in October/November. However within the regions showing a bimodal regime, a clear difference in the rainfall occurring in-between the two main rainy seasons is visible. In the central parts the main dry season is from November to February, but the situation in the southern parts is reversed, resulting in a main dry season in the boreal summer (see Figure 2, bottom rows).

Apart from the studies describing the general link of the rain formation to the movement of the ITCZ and the effect of the monsoon circulation, there are very few studies available that describe the synoptic/mesoscale systems responsible for the generation of rain in the central African region. The same holds true for processes governing the interannual and interdecadal variation of rainfall in the region. Nicholson and Grist (2003) found out that the rainfall is more intense during seasons where the AEJs are developed at both side of the equator. Although, the northern AEJ seems to be established throughout the year, its southern counter part only develops during the second half of the year. Therefore both jets are in place during the September to November rainy season, which might be the explanation why more rainfall falls during this season. Focusing on the interannual rainfall variations, Balas et al., (2010) found a link between sea surface temperatures of the Atlantic, the pacific and the Indian Ocean to have an effect on rainfall over the Congo basin.

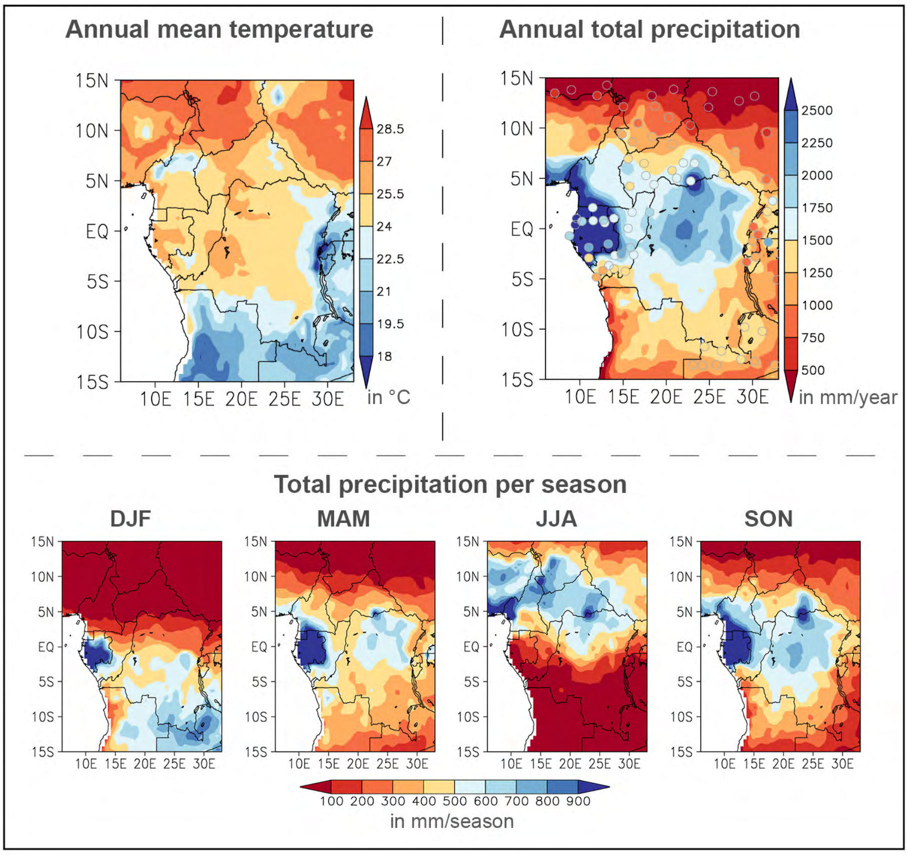


Figure 2: Maps of observed annual mean temperature and observed total annual precipitation (top row from left), as well as seasonal total precipitation for the four standard meteorological seasons (bottom row) as mean over the period 1961 to 1990. Depicted observations are taken from the WFD dataset (Weedon et al., 2011), which is on an annual basis similar to the better known CRU dataset (New et al. (2002)). In the annual total precipitation figure also station data (taken from the National Climatic Data Center (NCDC) at NOAA – http://www.ncdc.noaa.gov/land-based-station-data) has been included as circles, however not all of these stations cover the full 1961 to 1990 period (but at least for 15 years within this period).

As mentioned earlier, the scarcity of station measurements is the main hindrance in the assessment of past changes in the rainfall amounts and patterns. Available studies suggest that for the greater Congo basin, no clear and consistent change in rainfall patterns during the last decades is observed. Nicholson et al. (2010) found an interdecadal variability but with no significant changes in the long-term rainfall. The same conclusion is provided in the 4th Assessment Report of the IPCC (IPCC-AR4; Trenberth et al., 2007). Although for some regions a significant trend in precipitation has been shown (Aguilar et al., 2009), however this can not be transferred to the whole Congo basin simply because of the lack of station data. On the basis of the CRU dataset (New et al., 2002) a study by Djomou et al. (2009) found a decrease in precipitation for the equatorial area of Central Africa since the 1970s. However our own analysis of the CRU dataset averaged over the whole Congo basin (see Figure 6 in section 4.1.) did not reveal a substantial change in basin averaged annual precipitation amounts over the last century.

For temperature the situation is rather simple. Generally the temperature in the tropics is defined by rather warm annual mean temperature of about 24 to 25 ºC (see Figure 2, upper left) and only small seasonal amplitudes of about 2 to maximum 4 ºC. In the interior of the Congo basin this annual temperature amplitude is even as low as 1 ºC. The temperature seasonality throughout the greater Congo basin region follows a unimodal regime with maximum temperatures in the early months of the year (January to March) and minimum temperatures around July to September. With respect to observed long-term temperature changes over the region, the few available station data suggest a statistically significant warming over the region (IPCC, 2007), with an increase in warm extremes (e.g. warmest day seemed to increase by about 0.25 ºC per decade) and a decrease in the occurrence of cold spells (Aguilar et al., 2009). However, due to the scarcity in station data available robust statements can only be made for a limited area of the domain.

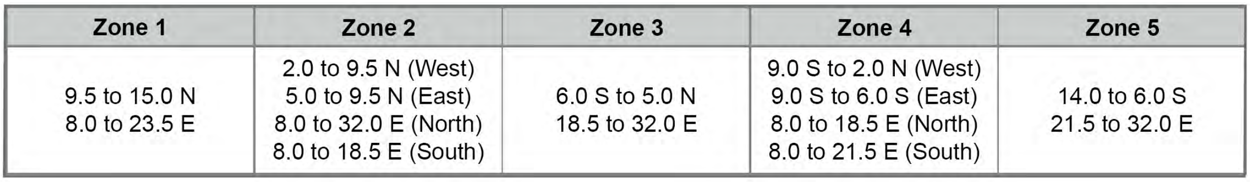
3. Introduction of the analysis concept

Normally, the information obtained from a climate model about future climate change is only presented as projection, without any information about the likelihood of such a projection (e.g. Cubasch et al. 2001). However when it comes to the development of adaptation and mitigation strategies, an estimation of the risks of failure of a proposed mechanism is required and therefore the likelihood of the projected climate changes needs to be estimated. The overall uncertainty associated with the model projections of future climate change can be assigned to the contribution from three different sources: i) from uncertainty in the development of future emissions of green house gases (GHGs) and other anthropogenic and natural factors that can affect climate, ii) from uncertainty arising from the natural internal climate variability and iii) from uncertainty inherent in the modeling systems in order to estimate the response of the climate system to a particular greenhouse gas forcing. The contribution of these three different sources to the overall uncertainty of the projected climate change signal changes with the time horizon of the projections (Hawkins & Sutton, 2009). The internal climate variability is the major source of uncertainty in projections with a future time horizon (lead-time) less than 10yrs, whereas the underlying emission scenario and the applied modeling systems are the major source of uncertainty in the long-term (centennial) climate change projections. As this report deals with the long-term projected changes in the climate system, uncertainty from natural internal climate variability can be considered to be less important. Therefore in order to cope with the uncertainties from the emissions and the model system, the approach which is normally adopted is to use a sufficiently large and independent multi-model ensemble of different greenhouse gas emission scenarios in order to provide ranges of probable future change with certain likelihood. This approach was also adopted in this study. The underlying emission scenarios are described in section 3.2. and the analyzed multi-model ensemble is presented in section 3.3.

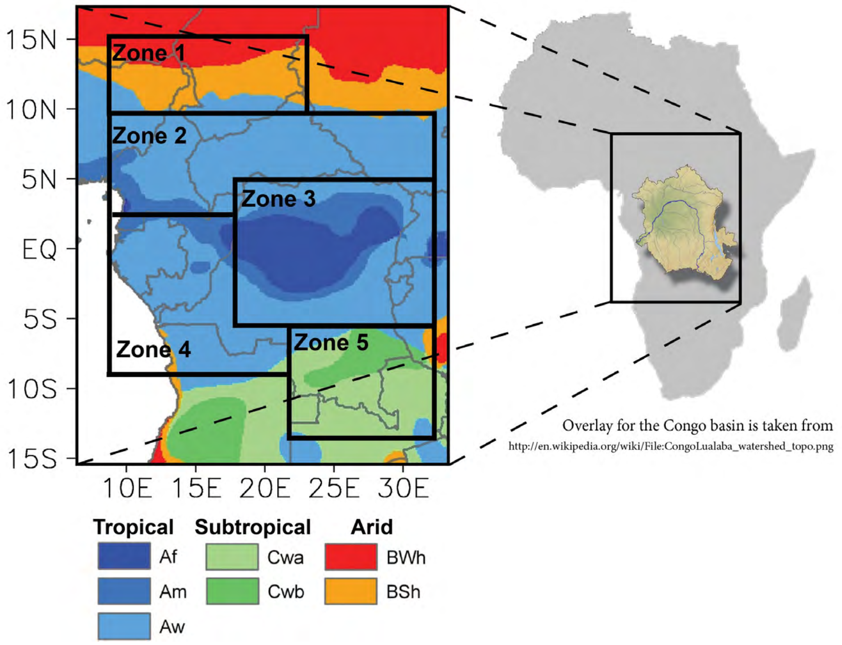
3.1. Subregions

The regional focus of the study is the central African region centered on the Congo basin (in this report generally referred to as greater Conge basin region; see Figure 3). A study domain of an area spanning from 15 ºN to 15 ºS and from 7 ºE to 35 ºE is defined. However, as already described in section 2, climate characteristics in this particular domain show a lot of variation. For example, the rainy season which changes from the JJA season in the northern parts to the DJF season in the southern parts, and from a unimodal regime (North and South) to a bimodal regime in the center. Moreover the predominant climate changes substantially, with moisture conditions in the centre of the domain compared to the northern and southern boundary regions.

Table 1: Details of the five subzones.



Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
9.5 to 15.0 N 8.0 to 23.5 E	2.0 to 9.5 N (West) 5.0 to 9.5 N (East) 8.0 to 32.0 E (North) 8.0 to 18.5 E (South)	6.0 S to 5.0 N 18.5 to 32.0 E	9.0 S to 2.0 N (West) 9.0 S to 6.0 S (East) 8.0 to 18.5 E (North) 8.0 to 21.5 E (South)	14.0 to 6.0 S 21.5 to 32.0 E



Overlay for the Congo basin is taken from http://en.wikipedia.org/wiki/File:CongoLualaba_watershed_topo.png

Figure 3: Map indicates the spatial extent of the study region, referred to as the greater Congo basin region. Colors in the left map highlight the different climates within this region – ranging from tropical climate types in the centre to even arid regions along the northern margins. The classification is based on the Koeppen-Geiger climate classification and the map is taken from Peel et al., 2007. In the map also the spatial extent of the 5 subzones is depicted (see Table 1 for details). The spatial extent of the Congo basin is depicted in the Africa map on the right.

This spatial climate variability can be taken into account by defining five subzones on which most of the subsequent analysis presented in this report was conducted. The spatial extent of these subzones is depicted in Figure 3, and the coordinates are given in Table 1. These zones represent some simplified climate zones based on the Koeppen Geiger climate classification (e.g. Peel et al., 2007 - also included in Figure 3). They further consider the north-south movement of the main rainy season. The northern most Zone 1 represents the semi-arid Sahel region (mainly classified as desert (BWh) and Steppe (BSh)). Zones 2 and 4 can be classified as predominantly tropical wet and dry climates (Aw) with a dedicated rainy season. The central Zone 3 spans around the tropical rainforest climates (Af) with large areas having a bimodal rain-regime. Finally the Zone 5 represents the subtropical climates in the southern parts of the greater Congo basin region. Of course these zones are just a rough approximation of the different climate states. However as some of the assessed global climate models (see section 3.3) are having a rather coarse horizontal resolution of up to 500 km, these very generalized zones seem to be justified.

3.2. Emission scenarios

Socio-economic and emission scenarios provide plausible descriptions of how the future may evolve with respect to a range of variables including socio-economic change, technological change, energy and land use, and emission of greenhouse gases and air pollutants (Van Vuuren et al. 2011). These future scenarios of forcing agents (e.g., greenhouse gases and aerosols) are fed in to the climate models as input, and the output of these climate models is further used in climate change analysis and hence, the assessment of impacts, adaptation and mitigation.

Several sets of scenarios including the IS92 scenarios (Legegett et al. 1992), the scenarios from the Special Report on Emission Scenarios (SRES) (Nakicenovic & Swart, 2000) and, more recently, the Representative Concentration Pathways (RCP) (van Vuuren et al. 2011) are used in climate research. In the subsequent section, a brief description of SRES and RCP scenarios is presented.

3.2.1. SRES – Emission scenarios

The greenhouse gas emissions scenarios described in the IPCC's **S**pecial **R**eport on **E**mission **S**cenarios published in 2000, have been used to make projections of possible future change and therefore, given the name SRES scenarios. IPCC Third Assessment Report (TAR) and Fourth Assessment Report (AR4), published in 2001 and 2007 respectively, were based on these SRES scenarios.

The fundamental motive behind SRES scenarios was to improve upon the earlier IS92 scenarios used in earlier IPCC Second Assessment Report in 1995. SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The scenarios encompass different future developments that might influence greenhouse gas (GHG) sources and sinks. There are total of 40 SRES scenarios with each one associated to a particular family. Therefore, scenario families may be thought of containing individual scenarios with common themes. Following is the brief description of each family.

A1: This scenario family describes a homogeneous future world with rapid economic growth. It assumes the global population to peak in mid-century and declines thereafter. Further major underlying themes are convergent world, capacity building, increased cultural and social interaction and a substantial reduction in regional differences in per capita income. There are three subsets of the A1 family which are distinguished by their technological emphasis: fossil intensive (A1F1), non-fossil energy sources (A1T), or a balance across all sources (A1B).

A2: These A2 scenarios are of a more heterogeneous world. Major underlying themes are independently operating self-reliant nations; continuously increasing population and regionally oriented economic development with per capita economic growth and technological change are more fragmented and slower.

B1: This B1 family describe a future world similar to A1, but with rapid changes in economic structures toward a service and information economy, with reduction in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on the global solutions to economic, social and environmental stability.

B2: This scenario family describes the more divided future world, but with more ecologically friendly approach. This family is characterized by a continuously increasing population, but at a slower rate than in A2. Other major underlying themes are emphasis on local solutions to economic, social and environmental stability; intermediate levels of economic development; less rapid and more fragmented technological change than in A1 and B1.

3.2.2. RCP – Emission scenarios

Among the research community, recently there has been an increasing interest in scenarios that explicitly explore the impact of different **climate-policies** in addition to the **no-climate-policy** scenarios such as SRES (Moss et al. (2010). The need for new scenarios prompted the IPCC to request scientific communities to develop a new set of scenarios for the assessment of future climate change. There a set of new scenarios is constructed containing emission, concentration and land-use trajectories referred to as "**R**epresentative **C**oncentration **P**athways" (RCPs). In its name, the word "representative" signifies that each of the RCPs represents a larger set of scenarios in the literature. This implies that this set of RCPs should be compatible with the full range of emission scenarios (with and without climate policy) available in the current scientific literature. The word "concentration pathway" emphasizes that these RCPs are not the final new, fully integrated scenarios (i.e. they are not a complete package of socio-economic, emission and climate projections), but instead are internally consistent sets of projections of the components of radiative forcing that are used for the input to climate models. The word "concentration" also emphasizes that instead of emissions, concentrations are used as the primary product of the RCPs, designed as input to climate models.

As mentioned earlier, the main criterion of the development of RCPs was that it should be based on the scenarios published in the existing literature, developed independently by different modeling groups, including extreme, intermediate, baseline and stabilization scenarios. A literature review revealed that scenarios can be found with a year 2100 radiative forcing from as low as 2.5 W/m^2 to between 8 and 9 W/m^2 and higher. Therefore, there was a need to construct RCPs scenarios in a way that it should not only cover this range, but also include intermediate scenarios as the majority of the scenarios in the literature lead to intermediate forcing levels. Four RCPs scenarios are selected during the course of the effort and are named according to radiative forcing target level for 2100. Following is the brief description of each scenario

RCP2.6: This scenario has also been referred to as RCP3PD representing the radiative forcing trajectory which goes to a peak level of 3 W/m^2 before 2100, followed by a decline (PD=Peak-Decline). The selected pathway declines to 2.6 W/m^2 by 2100 (Van Vuuren et al., 2007). AR4 identified only 6 scenarios that lead to forcing levels below 3 W/m2, however by now there are more than 20 scenarios in the literature which lead to similar forcing level as RCP2.6.

RCP4.5: This scenario describe the stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100 (Clarke et al. 2007). RCP4.5 corresponds to that category scenarios in AR4 which contains the far majority of the scenarios assessed, i.e. 118.

RCP6: This scenario is also similar to RCP4.5, with stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100 (Fujino et al. 2006). The number of mitigation scenarios leading to 6 W/m^2 in the literature is relatively low however, at the same time many baseline scenarios (no climate policy) correspond to this forcing level.

RCP8.5: This scenario corresponds to the rising radiative forcing pathway leading to 8.5 W/m^2 by 2100 (Riahi et al. 2007). This scenario leads to a forcing level near the 90th percentile for the baseline scenarios, however recently 40 scenarios with a similar forcing level are identified (Van Vuuren et al. 2011).

Figure 4, modified after Van Vuuren et al. (2011), shows the comparison among different RCP and SRES scenarios for CO2 emissions. The RCP 8.5 is representative of the high range of non-climate policy scenarios. The emission level of RCP6 is around 15GtC by the end of the century, which is similar to the most non-climate policy scenarios found earlier in the literature. The forcing pathway of the RCP4.5 scenario is of the same range of number of climate policy, as well as low-emissions reference scenarios, such as the SRES B1 scenario. The RCP2.6 represents the range of lowest scenarios, which requires stringent climate policies to limit emissions.

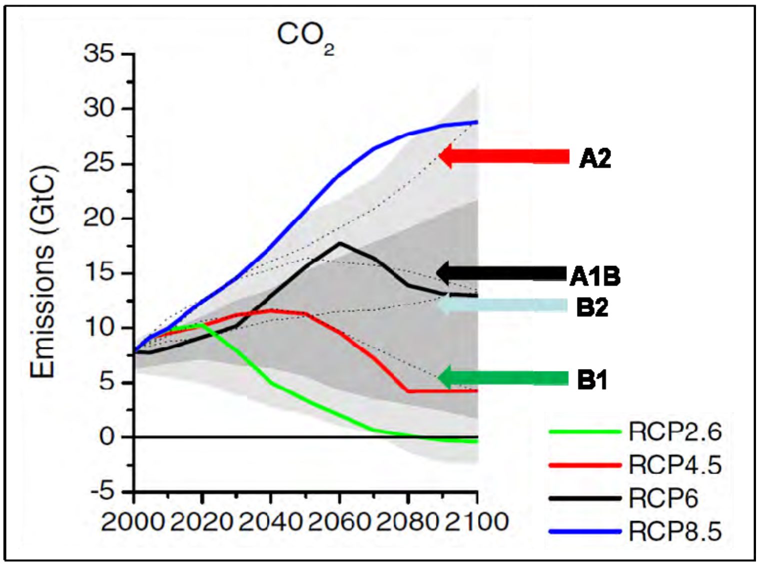


Figure 4: Comparison of emissions in the SRES and RCP emission scenarios – changed after Van Vuuren et al. (2011).

In the assessment described in subsequent sections of this report, the focus is on projected changes for high and low end emission scenarios only. To be able to analyze different generations of climate change projections (e.g. based on the SRES and the RCP emission scenarios) together, the different emission scenarios had to be grouped together. This grouping was conducted based on the projected emissions at the end of the century (see Figure 4). Climate change projections following the SRES - A2 emission scenario and the RCP 8.5 emission scenarios have been grouped into a "**high**" emission scenario ensemble. For the "**low**" emission scenario ensemble projections of the SRES –B1 emission scenario and the RCP2.6 and RCP4.5 emission scenarios have been grouped together. Available projections for following the A1B and B2 scenario have not been considered in the analyses. The number of projections available for each of the two scenario ensembles is indicated in Table 2.

3.3. Description of assessed climate projections ensembles

Climate change projections from four different data ensembles have been included and analyzed in this study. The four different data ensembles are referred to as **IPCC-AR4**; **CMIP5**; **WATCH** and **RCMs** and are described below.

3.3.1. Projections from global climate models

IPCC-AR4: The IPCC-AR4 ensemble refers to the climate change projections that built the base for IPCC-AR4. This ensemble consists of simulations conducted by different climate modeling groups around the world within the **CMIP3** project (**C**oupled **M**odel **I**ntercomparison **P**roject phase **3**). CMIP3 runs are basically the improved global model runs in which simulations are mainly conducted using more sophisticated SRES scenarios as compared to earlier CMIP runs and also more sophisticated General Circulation Models

(GCMs) that cover more processes important for the climate system. In the earlier CMIP runs, a straightforward approach of 1 degree C per year increase of CO2 was adopted. Therefore, the output from CMIP3 runs was highly rated as the best available multi-model dataset for future climate change projections existed for the whole globe for a multitude of different emission scenarios.

CMIP5: Similar to CMIP3, CMIP5 is the abbreviation of phase 5 of the Coupled Model Intercomparison Project. CMIP5 simulations basically aim to address the scientific question that arose in IPCC-AR4. Results of these climate change projections will be the basis of the Fifth Assessment Report (AR5) scheduled for publication in late 2013. As mentioned on the World Climate Research Project (WCRP) website (http://cmip-pcmdi.llnl.gov/cmip5/), CMIP5 promotes a standard set of model simulations in order to:

- evaluate how realistic the models are in simulating the recent past,
- provide projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and
- understand some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle.

3.3.2. Projections from bias-corrected global climate models

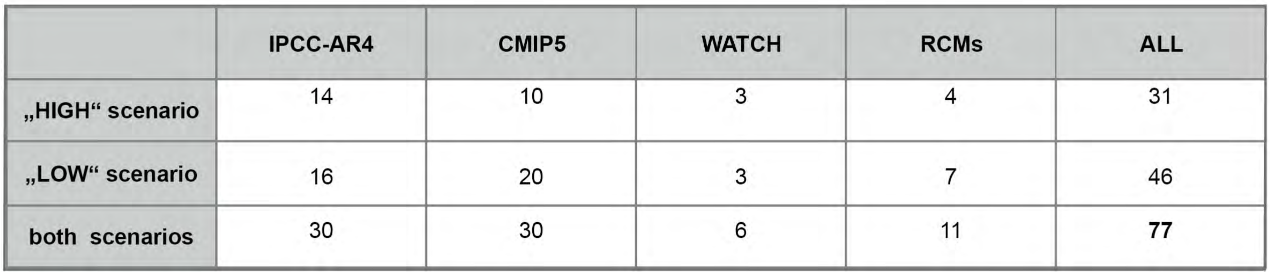
WATCH: The WATCH data was prepared in order to force the global hydrological modeling under the Integrated project **WAT**er and Global **CH**ange (WATCH, 2007-2011, Harding et al., 2011), funded under the EU FP6. The aim of the project was to estimate future changes in the global water availability. The data used within this study consist of bias corrected (and thereby statistically downscaled) climate change projections of three GCMs used in the CMIP3 project (ECHAM5, CNRM and IPSL) and for the two emission scenarios A2 and B1. Details on the WATCH data and the applied bias correction can be found in Hagemann et al. (2011) and Piani et al. (2010).

3.3.3.: Regional climate model projections

RCMs: Projections from two different regional climate models have been used. The models are the REMO model (Jacob, 2001) and the RCA4 model (Samuelsson et al., 2011). With both models transient regional climate change projections have been conducted over the so called CORDEX-Africa domain (see Giorgi et al., 2009 for domain description) using results from projections from several GCMs under different RCP emission scenarios. The REMO projections have been conducted within the project "Climate change scenarios for the Congo basin"; the RCA4 projections have been provided by SMHI via the preliminary CORDEX-Africa archive.

In the context of the present study, the multi-model dataset from CMIP5 GCM output and the RCM – projections may be considered as the latest state-of-the-art dataset available. However, also the older GCM datasets from the IPCC-AR4 archive and the WATCH project are still valid. In Table 2 an overview of the number of assessed projections per dataset and emission scenario group is provided. With a total number of 77different climate change projections, the current study is one of the most comprehensive studies so far existing.

Table 2: Number of projections available for the different data sets and the different scenario groups. As described in the text, the grouping in a "high" and a "low" emission scenario was motivated by the projected emissions at the en of the 21st century.



	IPCC-AR4	CMIP5	WATCH	RCMs	ALL
„HIGH" scenario	14	10	3	4	31
„LOW" scenario	16	20	3	7	46
both scenarios	30	30	6	11	**77**

3.4. Assessed parameters and indices

In this report the projected changes are analyzed for several parameters and indices. Generally projected changes are regarded for two 30 year periods in the future – one in the middle of the 21st century (2036 to 2065) and one at the end of the 21st century (2071 to 2100). However, for the subset of the IPCC AR4 data daily data for the projections were only available for two 20-year periods (2046 to 2065) and (2081 to 2100). All projected changes in this report are always with respect to the same reference period spanning from 1961 to 1990.

Table 3: Details of the analyzed parameters and indices

Parameter/Indices	**Short** (used in plots)	**Definition**	**Time period**	**Units** (values in brackets give the units of the projected changes)
Mean Temperature	-	Near surface air temperature	annual and seasonal	°C (in°C)
Number of cold nights	Cold nights	Number of days, with daily minimum near surface air temperature below the 10th percentile of daily minimum near surface air temperatures of the period 1961 to 1990	annual and seasonal	- (in %)
Number of cold days	Cold days	Number of days, with daily maximum near surface air temperature below the 10th percentile of daily maximum near surface air temperatures of the period 1961 to 1990	annual and seasonal	- (in %)
Number of hot nights	Hot nights	Number of days, with daily minimum near surface air temperature above the 90th percentile of daily minimum near surface air temperatures of the period 1961 to 1990	annual and seasonal	- (in %)
Number of Hot days	Hot days	Number of days, with daily maximum near surface air temperature above the 90th percentile of daily maximum near surface air temperatures of the period 1961 to 1990	annual and seasonal	- (in %)
Total precipitation	-	Surface total precipitation	annual and seasonal	mm/month (in %)
Total precipitation in the rainy season	P rainy s.	Surface total precipitation that falls in the rainy season	per rainy season	mm/rain season (in %)
Number of dry spells in the rainy season	N-Dry rainy s.	Number of periods in the rainy season with at least six consecutive days with daily rain amounts less than 1mm/day	per rainy season	No. (in %)
Duration of the rainy season	Length rainy s.	Length of the rainy season. The definition of the rainy season is described in Liebmann et al. (2012)	per rainy season	Days (in %)
Intensity of heavy rain events	-.	95th percentile of daily precipitation amounts, but only wet days (days with daily rain amounts of at least 1mm/day) are considered	annual and seasonal	mm/day (in %)
Frequency of heavy rain events	-	Number of days with daily precipitation amounts above the 95th percentile of daily precipitation amounts of the period 1961 to 1990 - defined as fraction of all days within the respective time period.	annual and seasonal	% (in %)
Maximum 10 day precipitation sum	Max. 10d rain	Maximum rainfall that occurs in 10 consecutive days	annual	mm/10 days (in %)

The set of analyzed parameters and indices consist of some basic parameters like the change in annual and seasonal mean temperature and annual and seasonal total precipitation amounts for the standard meteorological seasons (DJF – December to February; MAM – March to May; JJA – June to August; SON – September to November). On top of these basic parameters, some indices describing the changes in extremes have been included into the analysis. For temperature, the changes in the occurrence of cold and hot days and nights have been studied. For precipitation changes in the intensity and frequency of extreme precipitation events are analyzed. An extreme precipitation event is defined as the 95th percentile of daily precipitation amounts of wet days (more than 1mm rainfall a day). Another extreme parameter discussed in this report is the maximum 10day total precipitation amount. Since the different parts of the greater Congo basin region are characterized by rainy seasons occurring at different times of the year, some indices describing the characteristics of the rainy seasons have also been analyzed. To define a rainy season for each grid box in the assessed model simulations (and also in the WFD observation dataset used for evaluation of the model performance) a fixed onset and end date for the rainy season can not be used, but a method has to be defined that estimates the rainy season based on the specific rainfall characteristics. For this analysis the recently published method from Liebmann et al. (2012) was used, which defines the onset and end date of the rainy season based on the position of the absolute minima (onset) and maxima (end) of the cumulative (summed) deviation of the daily rainfall amounts from the long term mean. Once the onset and end dates of the rainy season are defined for the control and the future periods, projected changes in the mean duration of the rainy season as well as the total precipitation amounts in the rainy season can be analyzed. Finally projected changes in the frequency of dry spells within the rainy season (number of periods that have at least six consecutive days with rain amounts less than 1mm/day) are described. A summary of all analyzed parameters and a short definition is provided in Table 3.

3.5. Analysis of robustness of projected changes

A major aim of the report is not only to describe projected climate change signals over the greater Congo basin region, but also to assess the robustness of these signals. For this purpose, two measures that have been applied in IPCC-AR4 to identify robust changes are used in this study. The first measure is the agreement of the different model projections in the direction of change. A projected climate change signal is considered to be robust if at least 66% of the models agree in the direction of change (IPCC, 2007). The second measure considers the range of potential future changes derived from the different model projections. This is motivated by the fact that a climate change signal can be considered to be robust even though less than 66% of the model projections agree in the direction of change. This can be understood from the following example. Suppose there is a scenario in which 50% of the models are showing a 5% increase and the remaining 50% showing a 5% decrease in future precipitation. Although the first condition of robustness (agreement of 66% of the models) does not fulfil, however, such a small range (10% in this example) is quite convincing to believe that the signal of no change in precipitation is very robust. Similarly consider another case where 50% of the models are showing an increase of 100% and the remaining 50% of the models showing a decrease of 100% in future precipitation. This range (200% in this example) is definitely not considered sufficient to call it a robust signal of no change. Therefore, in general it is assumed that the smaller the overall range of projected future changes the more robust is the information about the future climate change. Nevertheless in this report no fixed threshold is assigned for the range to be classified as robust. Instead, the projected ranges and associated robustness are quantified relative to the absolute values of the respective parameter.

The second assumption of robustness becomes mostly important in regions where climate change projections of the assessed parameters are supposed to have only a small magnitude. Based on the findings of IPCC-AR4, this applies to projected changes in precipitation over many parts of the greater Congo basin region.

Considering the full range of the projected changes of the analysed model ensemble would, of course, allow some few outlier models to substantially impact the robustness assessment. Therefore a sub-range was introduced into the analysis which spans around the central 66% of the projected changes of the models. It is named the “likely” range of projected changes. According to IPCC (Mastrandrea et al., 2010), a change can be referred as “likely to occur” if at least 66% of all projected changes are within this area. As it is defined centred around the median (from 17th to the 83rd percentile), it does exclude potential outliers.

Of course the definition of such a sub-range is only valid if the analysed ensemble consists of a sufficient number of independent model projections. For the present study, due to the fact that a very large dataset is analysed that combines projections from GCMs and RCMs it can be assumed that the constraint is given.

However it has to kept in mind that the models are not totally independent but share some common features (see Masson and Knutti 2011). Also often RCM projections are considered to depend directly on the forcing GCM. However this dependence can be considered to be rather small in the greater Congo basin region, as it is located in the centre of the CORDEX domain (and therefore far away from the forcing fields at the boundaries) and also can be quantified to be a region, over which local processes (e.g. moisture recycling; Koster et al., 2004) plays an important role.

Using such a diverse and large ensemble minimizes the effect of inter-model dependencies. It has also to be mentioned that so far a perfect model ensemble with a large set of completely independent climate change projections simply does not exist.

4. Evaluation of the multi-model ensemble simulations with respect to observed climate

4.1. Annual and seasonal mean temperature and total precipitation

We start our analysis by evaluating the performance of the models in simulating the past climate. Even though data of only a few stations are available and included into the available observation datasets (e.g. CRU, New et al. (2002)), they still represent the best areal data source available for the greater Congo basin region for temperature and precipitation. Nevertheless, as a comparison with station data reveals, there remains a good portion of uncertainty in the observational dataset itself (see Figure 2, upper right panel). As already discussed above, on the basis of the rainfall distribution within the greater Congo basin region, the region can be subdivided into several zones (see Figure 3). Therefore, for each of the zones the performance of the models in simulating annual and seasonal mean temperature and precipitation is evaluated. The evaluation for these parameters is summarized in Figure 5, with observed and simulated mean temperature in the left column and simulated and observed total precipitation in the right column. The observed values are indicated by the horizontal magenta line. The bars represent the full range of simulated values separated for the different models (red bar - global IPCC-AR4; orange bar – global CMIP5; green bar– downscaled WATCH data; and blue bar – downscaled RCM-data) and all the models combined (grey bar). In the case of all models combined, the range which spans around 66% of all model simulations (centered on the median) is also highlighted by the darker colored subpart of the grey bars. The definition of this sub range is motivated by the concept of analyzing robust changes (introduced in section 3.5) which uses the same range (then referred to as the likely range) for defining agreement between models. Finally for the four analyzed ensembles the median of the respective ensemble is included in the figures with the black line.

In the case of temperature (left column in Figure 5) the intra-annual variation is rather small. A clear seasonal cycle is only observed for Zone 1 and Zone 5, whereas for Zone 3 only very little variation is visible. In general the simulations are able to represent the seasonal behavior of the observed temperature; however a substantial range is visible – especially in the global datasets (range up to 7.5°C in the IPCC-AR4 dataset in simulated annual mean temperature for Zone 1). The simulations of the WATCH project (3 GCMs) represent observed temperatures perfectly; however this is expected, as they have been bias corrected with the WFD observational dataset (which has identical values as the CRU dataset on a monthly basis - see section 3.3.2). If the simulations of all ensembles are considered in a combined way (grey bars), the observed values are always within the dark grey range, which is defined by the central 66% of all simulations. As this range is always substantially smaller than the full range of simulations, it can be inferred that most of the models have skill to adequately represent the observed seasonal temperature behavior in the region. However the majority of the models have a tendency to underestimate the observed temperature, indicated by the fact, that the median of all simulated temperatures is predominantly lower than observed temperature.

In the case of precipitation (right column in Figure 5) a larger intra-annual variation is present. For Zone 1 and Zone 5 a clear unimodal rainfall regime with the rainy season in the JJA and DJF season is visible. Closer to the equator (Zone 4 and 2) the rainfall regime is still more or less unimodal, however it extends over more seasons, and has only one clear dry season (DJF in Zone 2 and JJA in Zone 4). In the central part of the greater Congo region (Zone 3) a rather bimodal rainfall regime with more above average rainfall in the MAM and SON season with no clear dry season is observed. For all zones the observed seasonal variations are rather well captured by the simulations; however for precipitation, a substantial range is also visible in all datasets with largest values in the two global datasets. Also in the case of precipitation observed rainfall is always (apart from the JJA season in Zone 4) within the dark-grey range defined by the central 66% of all simulations. And like in the temperature case this range is mostly substantially lower than the full range of the simulations, again indicating substantial skill of the models in simulating total precipitation amounts. Considering the simulation of annual total precipitation amounts the models again nicely represent the observed values.

The fact that the sub-range of the central 66% of all model simulations is always substantially lower than the full range leads the conclusion that the large ranges seen in the global ensembles (IPCC-AR4 and CMIP5) is mainly caused by a few outlier models. As all the models get the seasonal cycles right (e.g. extremely dry seasons in Zone 1 and 5) and also keeping in mind the large uncertainty of the observational datasets, there is no reason for excluding these few outlier-models form the analysis.

With respect to the individual performance of the different ensembles, no general conclusion can be drawn. It can of course be noted that the ranges are substantially lower in the WATCH and RCMs ensembles: however this can also be related to the much smaller number of simulations in these ensembles (see Table 2). Better performance of the WATCH ensemble is not surprising, as it was bias corrected on the basis of the observational dataset included in the figures. For the case of the RCMs ensemble, it can be noted that it is generally located in the center of all simulations (apart from the precipitation simulations for Zone 3 and 4, where it is at the lower and upper end of the full range of all simulations) and rather close to the observed dataset. However a general conclusion that the application of RCMs would improve the simulations can not be drawn on the basis of this analysis, as the forcing GCMs are not explicitly highlighted in the CMIP5 ensemble.

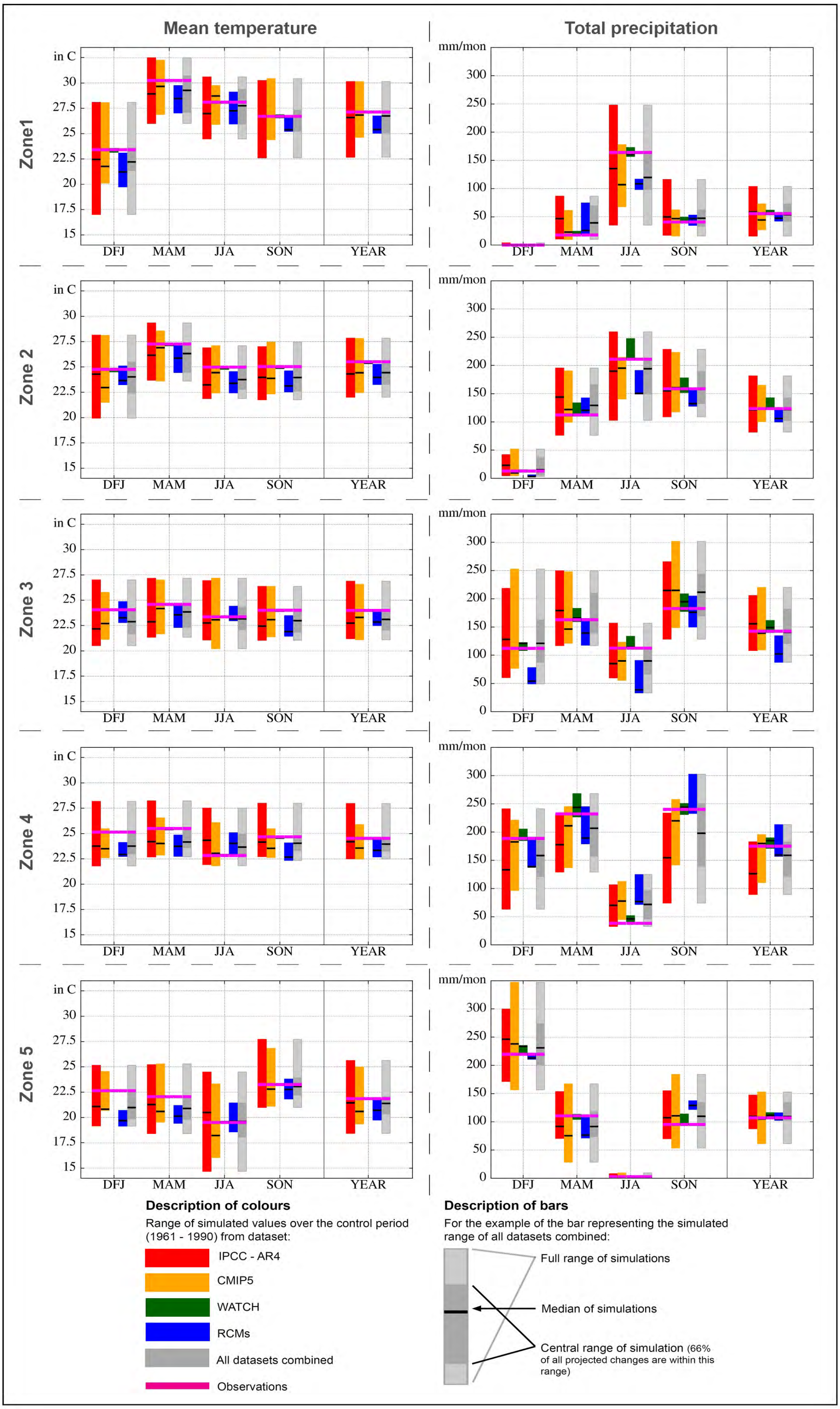


Figure 5: Mean annual cycle of temperature (left) and precipitation (right) for the five different sub-regions of the greater Congo basin region (as defined in Figure 2) for the period 1961 to 1990. The horizontal magenta line represents the observed values (CRU). The colored bars define the simulated ranges of the four different ensembles included in the analysis. The black lines are the median of the respective ensemble. The grey bar represents the range of all datasets together. Moreover, the sub-range defined by the central 66% of all simulations (darker-grey area) has also been included.

In order to assess if the observed long-term trends in annual mean temperature and precipitation are reasonably represented in the simulations, a longer time period has to be evaluated. Figure 6 shows the observed and simulated long-term development (only the IPCC-AR4 subset, as this was the only one available for the full 20th century) of annual mean temperature (upper panel) and precipitation (lower panel), both spatially averaged over the whole Congo basin (see Figure 3 for spatial extent). As already mentioned in section 2, the interannual variations in temperature and precipitation are rather low in the tropics (see also the CRU observations in Figures 2 and 6). For temperature a slight increase, starting around the early 1980s can be identified in the observations, whereas for precipitation no trend seems to be present. In general, the models tend to slightly overestimate the observed temperature increase (trend) during the past century over the Congo basin, which can be seen in the multi-model mean temperature curve. For precipitation all models agree on a rather constant precipitation evolvement during the last century.

For the whole period a substantial spread is visible in the GCM simulations for both quantities. However, as even the models with the largest deviation from the mean show a reasonable long-term behavior and interannual variability, there is again no reason for excluding these models from any further analysis. However it has to keep in mind that the magnitude of projected changes in the future of course depend on the selected dataset, and might change if only a subset of the available data is assessed (see section 6).

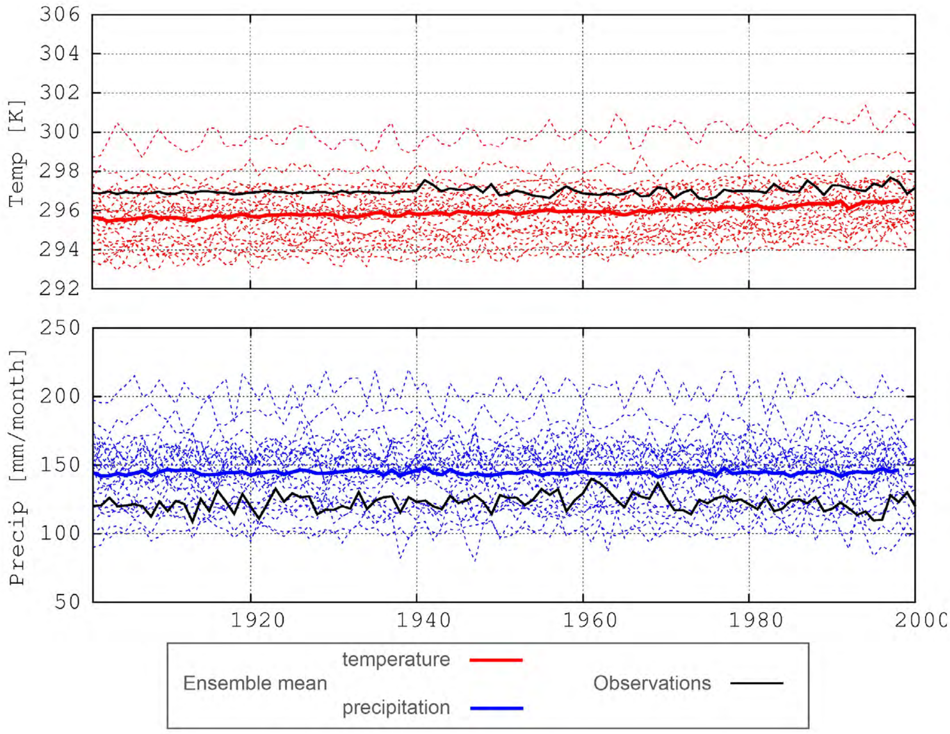


Figure 6: Long-term development of observed and simulated annual mean temperature and precipitation for the period from 1901 to 2000 spatially averaged over the Congo basin (see Figure 3 for spatial extent). The black line represents the observed values (CRU). The red and blue lines represent the simulated values over the historical period (AR4 only - dashed line: single model: thick line: multi model mean) for temperature and precipitation, respectively.

4.2. Extremes and indices

In addition an evaluation of the simulated intensity of extreme precipitation events (Figure 7, left column), as well as the 10 day maximum rainfall and some characteristics related to the rainy season (Figure 7, column 2-5) is presented. In the figures the color scheme is the same as used for the evaluation of annual and seasonal mean temperature and precipitation (see section 4.1). However the observations (indicated with the horizontal magenta lines) are no longer taken from the CRU dataset, but from the WFD (Weedon et al., 2011), which is available globally at 0.5 degree horizontal resolution at a daily time step. This higher temporal resolution is needed to calculate the precipitation indices and extremes; however the WFD dataset can still be compared to the CRU data, as they have identical monthly values.

The intensity of heavy precipitation (Figure 7, left column) shows for all zones a seasonal cycle similar to the seasonal cycle of total precipitation, with higher intensities during the rainy season. These seasonal cycles are captured by the ensemble of simulations, however for all seasons and zones the precipitation intensity of heavy precipitation events is strongly underestimated in the simulations, which is a feature very often observed in climate models (e.g. Fowler et al., 2007). The underestimation is strongest in Zone 4; however this is also the region where the underlying observation dataset differs strongly from station data, when annual total rainfall amounts are considered.

For the frequency of heavy rainfall events (not shown) the similar seasonal behavior as discussed for the intensity of heavy rainfall events is observed, with a higher frequency during the rainy seasons. In general the models tend to slightly overestimate the frequency of heavy rain events (pointing to too many precipitation days) for all seasons and zones. In this case the regional climate simulations seem to perform best. For the 10day maximum precipitation and the parameters of the rainy season no seasonal analysis has been conducted. In Figure 7 only one graph is therefore included per index and zone. For the maximum 10day precipitation amounts, rather large quantities are observed in the region with more than 350mm/10 days in Zone 4. Compared to the heavy rain intensity the model simulations better represent the observed maximum 10day precipitation amounts (right column in Figure 7), with the observations always within the central 66% of the simulations (apart from Zone 4, where simulated values are lower). However, it can be noted that the models show a very large spread (especially the larger IPCC-AR4 and CMIP5 ensembles), indicating a rather large degree of uncertainty with respect to this parameter.

Evaluation of rainy season indices includes the simulated total rainfall amount of the rainy season (Figure 7, 2nd column from left), the simulated number of dry-spells in the rainy season (Figure 7, 3rd column from left) and the simulated length of the rainy season (2nd column from right in Figure 7). For all zones, the major portion of the annual total rain falls within the rainy season (from 65% in Zone 3 to 95% in Zone 1) and the total rain amount in the rainfall season also corresponds nicely to the annual total rainfall in the respective zone (highest amounts in Zone 4 and lowest in the Zones 1 and 5). In general most models are well able to simulate the rainfall amount of the rainy season in all zones, with the observations always within the dark-grey range (defined by 66% of all simulations). As this darker grey range is substantially smaller as the full range, it can be concluded that the majority of the models have reasonable skill in simulating the rainfall amounts of the rainy season, and that the large ensemble ranges (again mainly in IPCC-AR4 and CMIP5) are caused by a few outliers.

The number of dry spells during the rainy season is generally underestimated by the models (especially in Zone 4), however the absolute differences are rather small. The length of the rainy season is simulated in good agreement with the observations in Zones 4 and 5, but overestimated in the remaining zones. Comparing the observed length of the rainy season between the different zones a slight variation is visible, with the longest rainy season in the Zones 2 and 4, whereas in the central Zone 3 the rainy season is slightly shorter. This is mainly due to the fact that in this zone a bimodal rainfall regime is observed, which means that there are two rainy seasons per year and therefore the mean length of each rainy season is slightly shorter.

Based on the evaluation of the agreement between observations and simulations it can be concluded that for most of the assessed parameters the majority of the models has a substantial skill in representing observed conditions. Worst overall performance is definitely visible in the simulation of the intensity of heavy rainfall events that is strongly underestimated in the model ensembles. However this is a known issue and mainly related to the coarse model resolution that dampens the extremes in the model simulations. On a first glance the horizontally higher resolved RCM simulations seem to have the same deficiencies as in the GCM simulations. However if a direct comparison between forcing GCM and nested RCM pair is conducted, a substantial improvement of the simulated heavy rainfall intensity is seen. Nevertheless this finding does not indicate a general added value of RCMs in the region, but is just valid for the given RCM/GCM combination and parameter.

The advantage of the large ensemble is definitely that a few less well performing models do not have the same weight in the analysis as if a smaller ensemble (including some of these outliers) would have been studied. This is also in line with findings from former studies (e.g. Gleckler et al., 2008) that show that the ensemble mean generally outperforms each of the single model simulations. But once more it has also to be kept in mind that the availability of observations is very limited in the region and the conclusion could have been different for the case of another observation dataset.

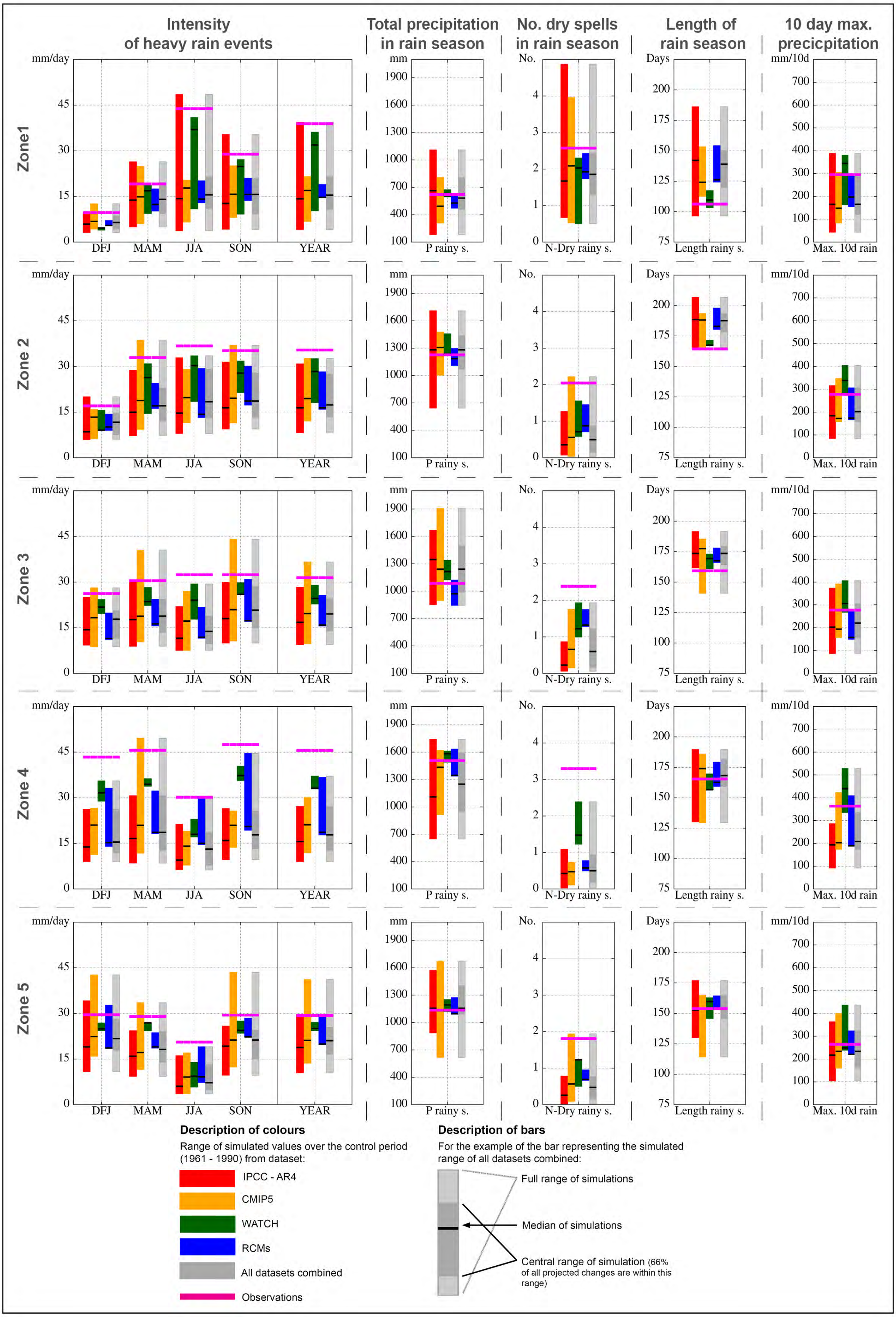


Figure 7: Same as Figure 5, but for several precipitation indices (see Table 2 for definition).

5. Analysis of projected changes

In this section the projected changes from the multi-model ensemble are assessed for the low and the high scenario for both of the two future time periods. Although, each dataset has been analyzed separately, the focus of the analysis in this report is on the projected changes of the full ensemble of available simulations. The issue of different signals from different sub-ensembles will only be tackled briefly in section 6. However, the material of the separate analysis of the different ensemble is available through the "Interactive Final Report Document" (available online under http://www.climate-service-center.de).

5.1. Projected changes in annual and seasonal mean temperature and total precipitation

A very common way to assess projected climate change signals over a specific region and for a given time period is in the form of spatial maps. This is especially useful if a region integrates not only several geomorphological, but also climatological features like the greater Congo basin region where a spatially heterogeneous climate change signal might be expected. Subsequently maps depicting the spatially heterogeneous climate change projections for mean temperature and total precipitation for different scenarios (low and high) and for different time periods of the year (whole year, standard seasons) are shown and discussed (Figure 8 to 11). In all of the figures, the respective median of the underlying dataset is shown for the control period as well as the projected changes. Each of the figures consists of 15 different panels which are sorted as follows: The left column represents the simulated mean over the control period (1961 to 1990), the central column the projected changes for the mid of the century (2036 to 2065) and the right column the projected changes for the end of the century (2071 to 2100). The top row depicts the respective values averaged over the whole year, and the subsequent rows for the four standard meteorological seasons. For the projected changes not only the median but also some information about the robustness of the projected climate change signal is included (see section 3.5 for details). Regions that have a robust climate change signal (based on agreement of direction of change) are marked with black stipples. However this measure was only applied if the median of projected changes is larger than ±0.5°C (in the case of temperature) or larger than ±5% for all other variables. Regions having a change signal within this range are generally depicted as white areas.

In general, the projected temperature increase (Figure 8 for the low emission scenario and Figure 9 for the high emission scenario) for both scenarios and both time periods is rather uniform over the greater Congo basin region. Only towards the end of the century a slightly larger increase in the less humid areas north and south of the Congo basin is visible. However under the high emission scenario, projected changes especially towards the end of the century, are substantially larger over all parts of the domain and remain in the range between about 4°C to more than 5°C (compared to 2°C to 3°C). All temperature changes projected for the two scenarios are robust in all seasons.

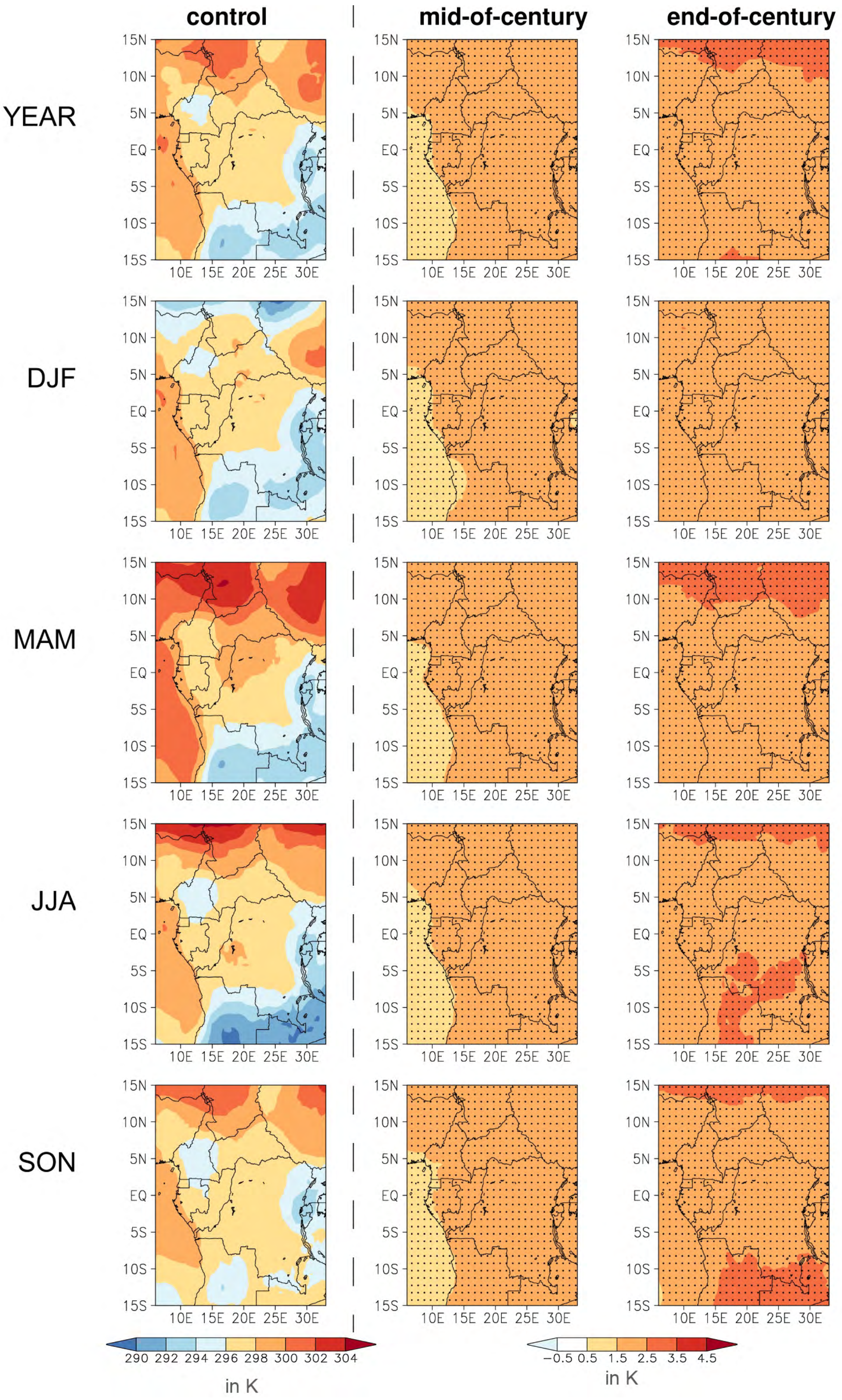


Figure 8: Maps of projected changes for mean temperature under the low emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

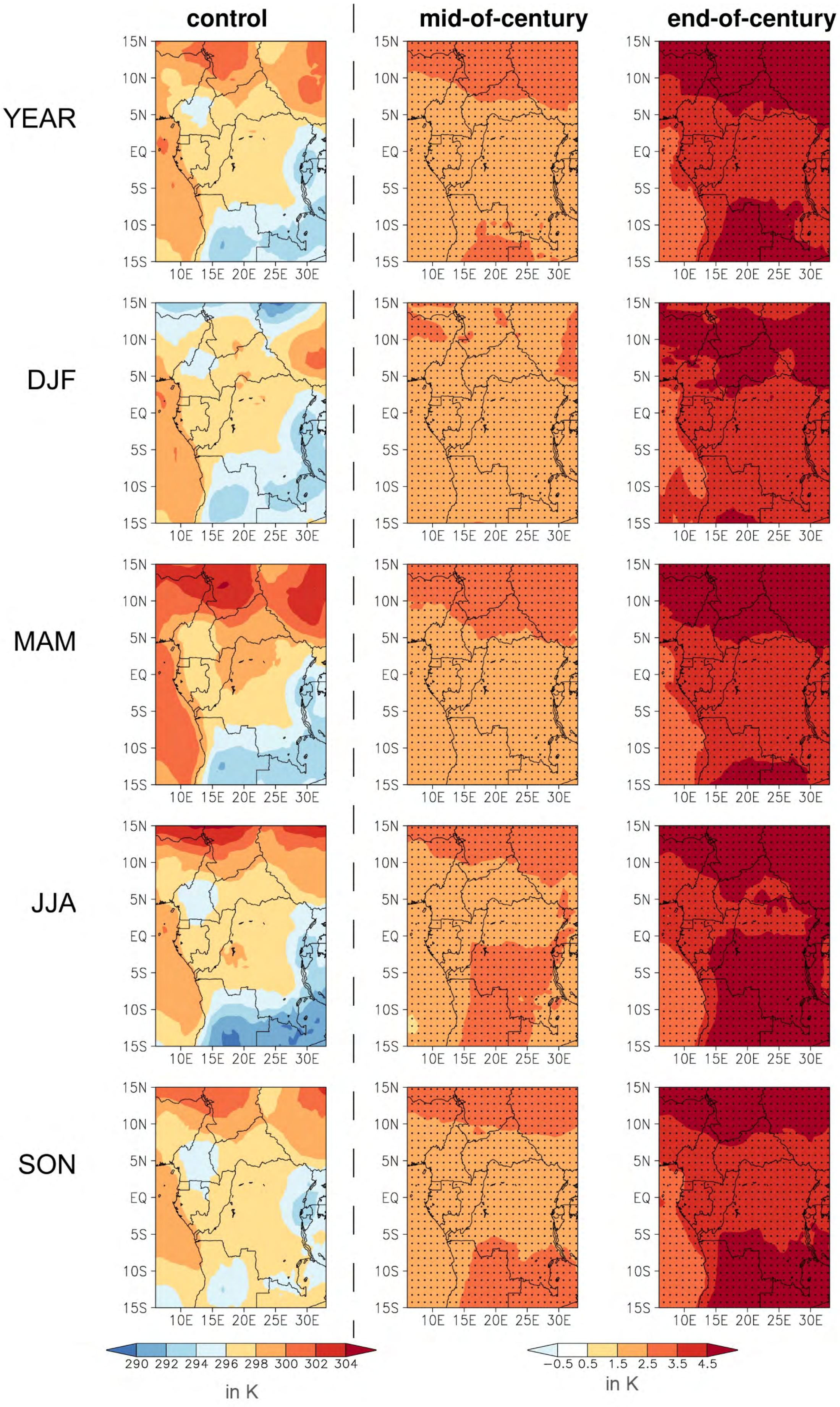


Figure 9: Maps of projected changes for mean temperature under the high emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

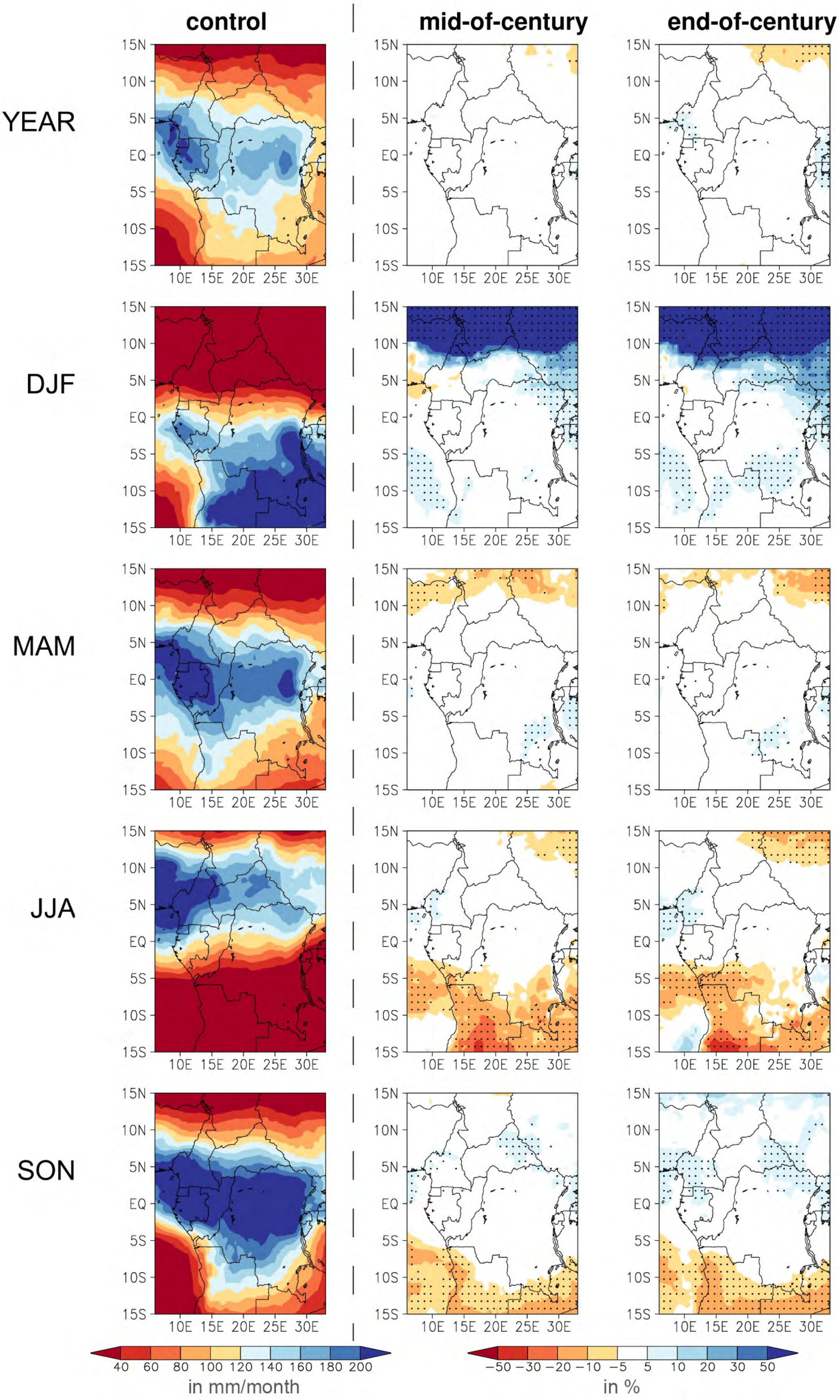


Figure 10: Maps of projected changes for total precipitation under the low emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

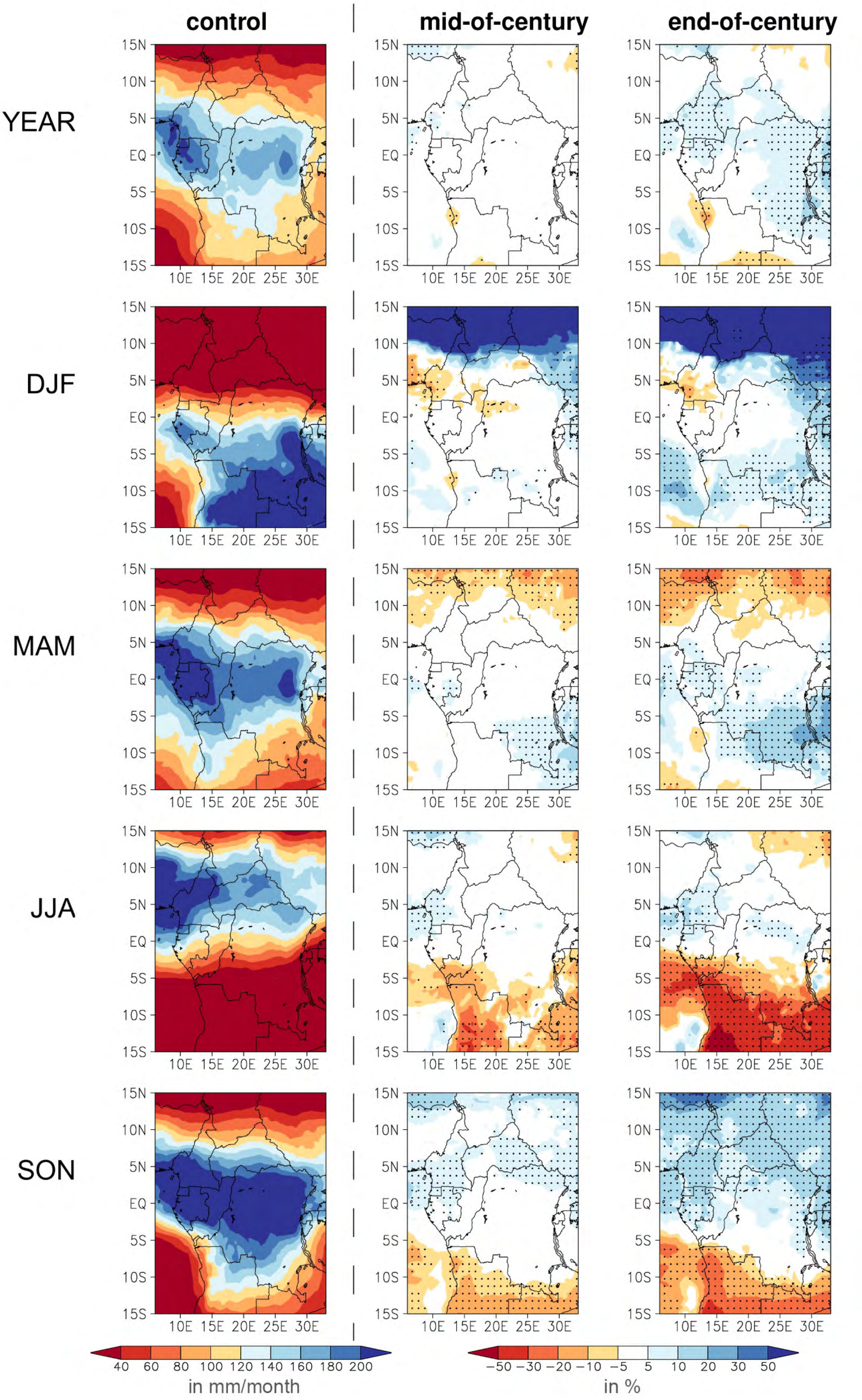


Figure 11: Maps of projected changes for total precipitation under the high emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

The same analysis was conducted for the projections of future total precipitation amounts (Figure 10 for the low emission scenario and Figure 11 for the high emission scenario). If only the annual average of projected changes is considered (upper row in the two figures) the median projection is for almost no change under the low scenario (Figure 10) and for a slight (but mostly robust) tendency for an increase in annual total precipitation (below +10%) in some of the central and eastern parts of the study area.

However if the changes for the different seasons are included in the analysis a more diverse picture is given. For the central part of the region generally no change at all (low scenario) or a moderate but robust increase (high scenario) in precipitation is projected for all seasons. In the southern parts of the domain a mostly robust decrease during the dry season in the JJA and SON seasons is visible for both scenarios, but substantially amplified under the high emission scenario. For the northern part a strong relative increase in rainfall is projected to occur during the dry season (DJF), however it has to be kept in mind that due to the very small rainfall amounts the high relative changes are not at all an indicator of a less-dry future.

So far only the median projection of change has been displayed in the maps, but of course if such a multitude of different model projections is analyzed it is not enough to simply focus on the median but also some analyses of the ensemble ranges of the projected changes have to be made. For this purpose the projected changes are again averaged over the five zones introduced in section 3.1. For each of the zones the full range of projected changes is assessed for both scenarios and the two time periods in the middle and the end of the 21st century (see Figure 12 – low scenarios – blue colored bars; high scenario – orange and dark-red colored bars; mid-of the-century – blue and orange bars; end-of-the-century – dark-blue and dark-red colored bars). In this approach, one has to keep in mind that the full range of the projected changes might be influenced by the extreme changes of a few models which may be considered as outliers. In order to avoid this, the so called likely range of projected changes (central 66% of the projected changes – see section 3.5 for details) is included. In the figures used in this report the likely range is indicated by the darker colored subareas of the respective bars.

The full and likely ranges of projected changes in annual and seasonal mean temperature (average over the respective zone) are depicted in Figure 12 (left column). It is obvious from the figure that especially towards the end of the century (red bars) a substantially stronger increase in mean temperature is projected under the high scenario, with an increase of at least +3°C (lower end of the red bars). While at the mid of the century the projected changes remain similar, the likely ranges of projected changes for the low and the high scenario do not overlap anymore at the end of the century. Here, the likely warming under the high emission scenario for all zones is about 2°C stronger than under the low scenario (projected increase in annual mean temperature for the high scenario always between +3.5 and +6°C versus +1.5 and +3°C under the low emission scenario – both at the end of the 21st century). The full range of projected changes is rather similar for both scenarios but changes from zone to zone (from about 2.5°C in Zone 4 to about 4.5°C in Zone 2, if the full range of projected annual mean temperature at the end of the century is regarded). If only the likely range is considered, the bandwidth of projected changes of annual mean temperature is substantially lower (about 1.5 to 2°C for annual mean temperature at the end of the century).

For the annual and seasonal mean total precipitation amounts the bandwidth of projected changes is largest in the dry regions (Zone 1) and/or seasons (DJF in Zones 1 and 2; JJA in Zone 5). Also for this parameter, the range in projected changes is substantially reduced, if only the central 66% (likely range) is considered. Although, even under the likely range some of the projections are for an increase and others for a decrease in total precipitation amounts, the rather small ranges (in the more humid Zones 2 to 4 always between about -10 to +10%; in the more arid Zone 1 between -15 to +30%; both in the case of annual total rainfall) in both scenarios indicate that it is very likely that total rainfall amounts will not change drastically in the future. This conclusion is independent of the underlying emission scenarios. As for all of the zones the median projection for annual total precipitation amounts is slightly positive (also for both of the scenarios) a tendency for a slight increase in annual total precipitation amounts is assumed. This conclusion of course is only valid on the basis of the analyzed multi-model multi-scenario data set, however due to its size and also due to the fact that different types of model projections have been analyzed, the finding seems to be rather robust.

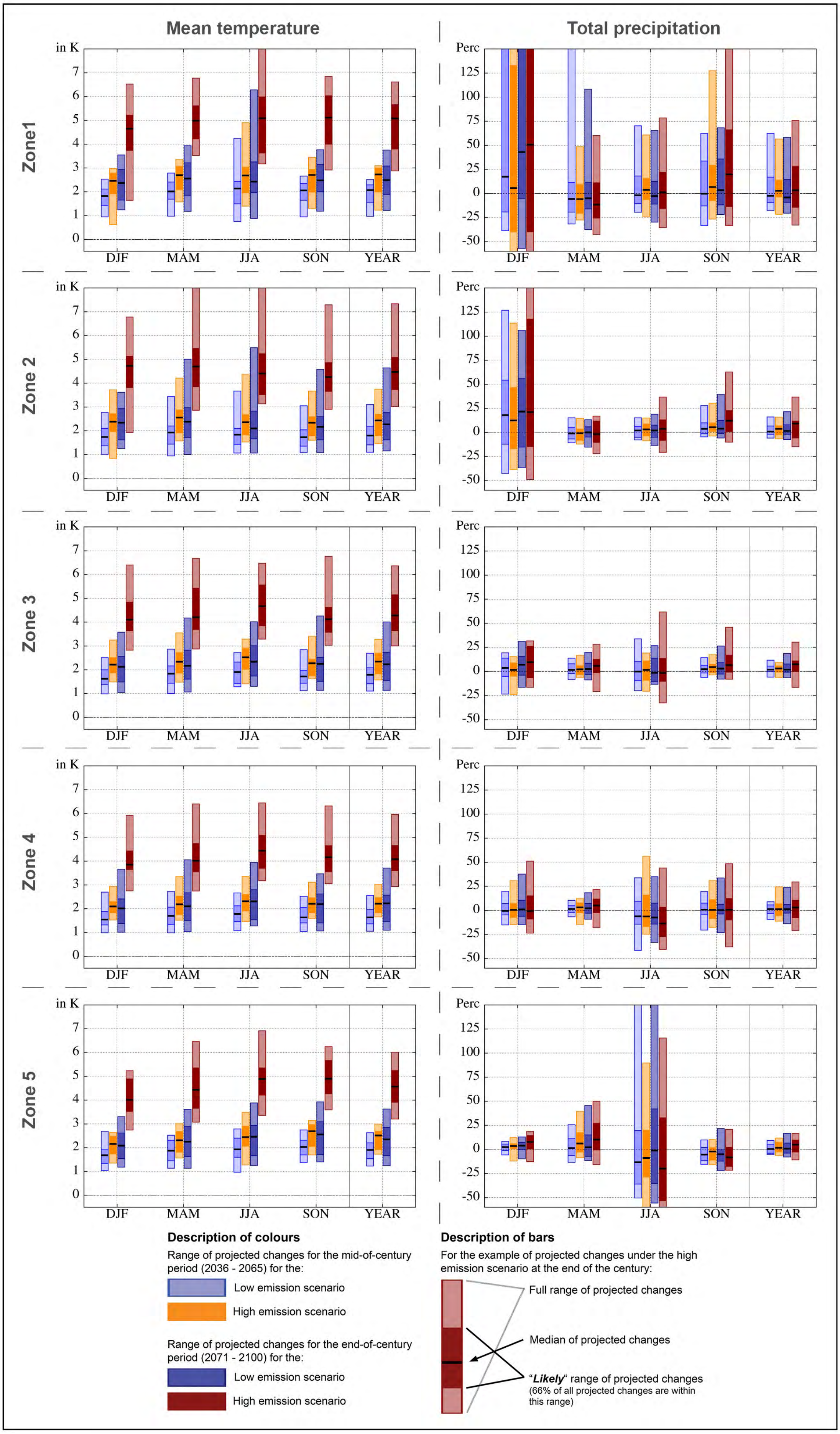


Figure 12: Full and likely ranges of projected changes for mean temperature (left column) and total precipitation (right column) averaged over the five subzones for both scenarios for different time periods.

The substantial differences between the full range and the likely range of projected changes visible for both parameters again indicate that a few outlier models project a substantially different climate change signal. This is most prominent for projected precipitation changes in the semi-arid region of the study area (Figure 12, upper right panel) where already slight differences in absolute rainfall amounts can lead to huge relative changes, depending on the simulated precipitation amounts during the control season. Therefore these large changes should not be overemphasized. Nevertheless the analysis again shows the importance of analyzing a large amount of different projections, as only then the influence of outlier models can be compensated.

5.2. Projected changes in extremes of temperature and precipitation

For the temperature based extremes the relative change in the annual mean number of cold days and nights and in the annual mean number of hot days and nights has been assessed (for definition see Table 3). In the Figure 13 the spatial distribution of the median of projected changes of the respective variable is depicted for the low (left part of the figure) and the high (right part of the figure) emission scenario and for both time periods (mid-of the-century – respective left column; end-of-the-century – respective right column). (Note that in Figure 13 the mean over the control period is not depicted as it would always be constant, due to the fact that the extremes are defined via the 10th and 90th percentile of daily minimum and maximum temperatures, respectively).

The median projection of change for the frequency of cold days and nights is for a decrease over all parts of the analyzed region and for both scenarios by about +8 to +12% (upper two rows in Figure 13). For the frequency of hot days and nights a substantial increase is projected under both scenarios (lower two rows in Figure 13), however under the high emission scenario the increase is substantially larger than in the low emission scenario (at the end of the century on average by up to +25%). For both variables, both scenarios and also for both time periods the projected increase of the median change is largest in the central parts of the domain (more than +50% in the case of the low scenario and more than +70% in the high emission scenario). For both the projected changes in cold as well as in hot extremes, the majority of the models agree on the direction of projected changes. Therefore the projected changes can be classified to be robust over the whole region.

The full and the likely ranges of the projected changes for the temperature based extreme indices for the different zones are depicted in Figure 18 (left column). All models agree on a slight decrease in the frequency of cold days and nights and for a substantial increase in the frequency of hot days and nights for both scenarios and for all zones in the future. This of course is a very robust signal. While in the case of the cold extremes no substantial difference is visible between the two scenarios, the projected changes for the hot extremes are amplified in the case of the high-emission scenario (e.g. for Zone 1 the likely range of projected changes in the frequency of hot days is for an increase by +12 to +26% under the low emission scenario, whereas it is between +22 to +46% in the case of the high emission scenario; both for the end of the century period).

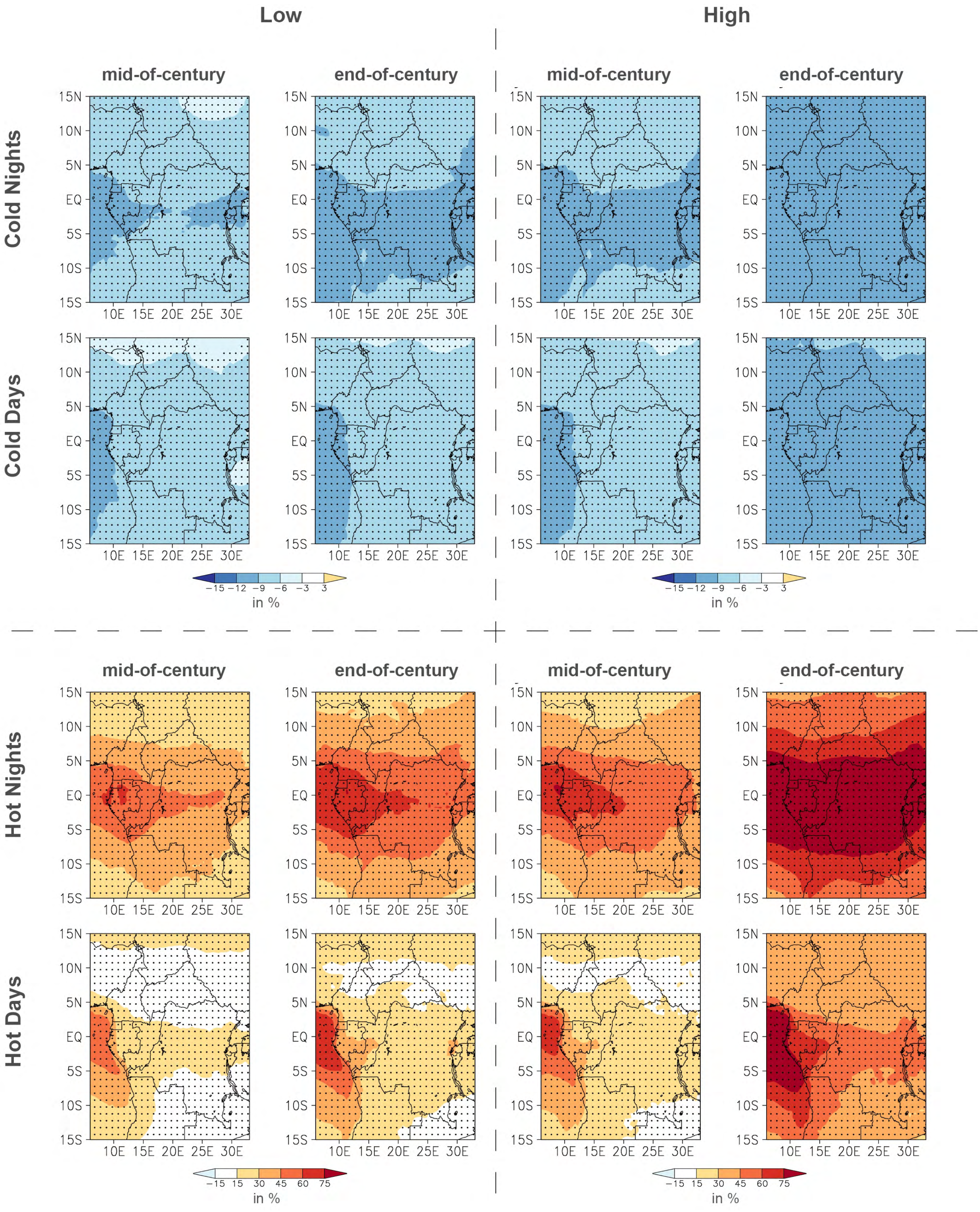


Figure 13: Maps of projected changes for the frequency of the occurrence of cold days and nights (upper two rows) and for the frequency of the occurrence of hot days and nights (lower two rows) under the low emission scenario for the middle of the century and the end of the century. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

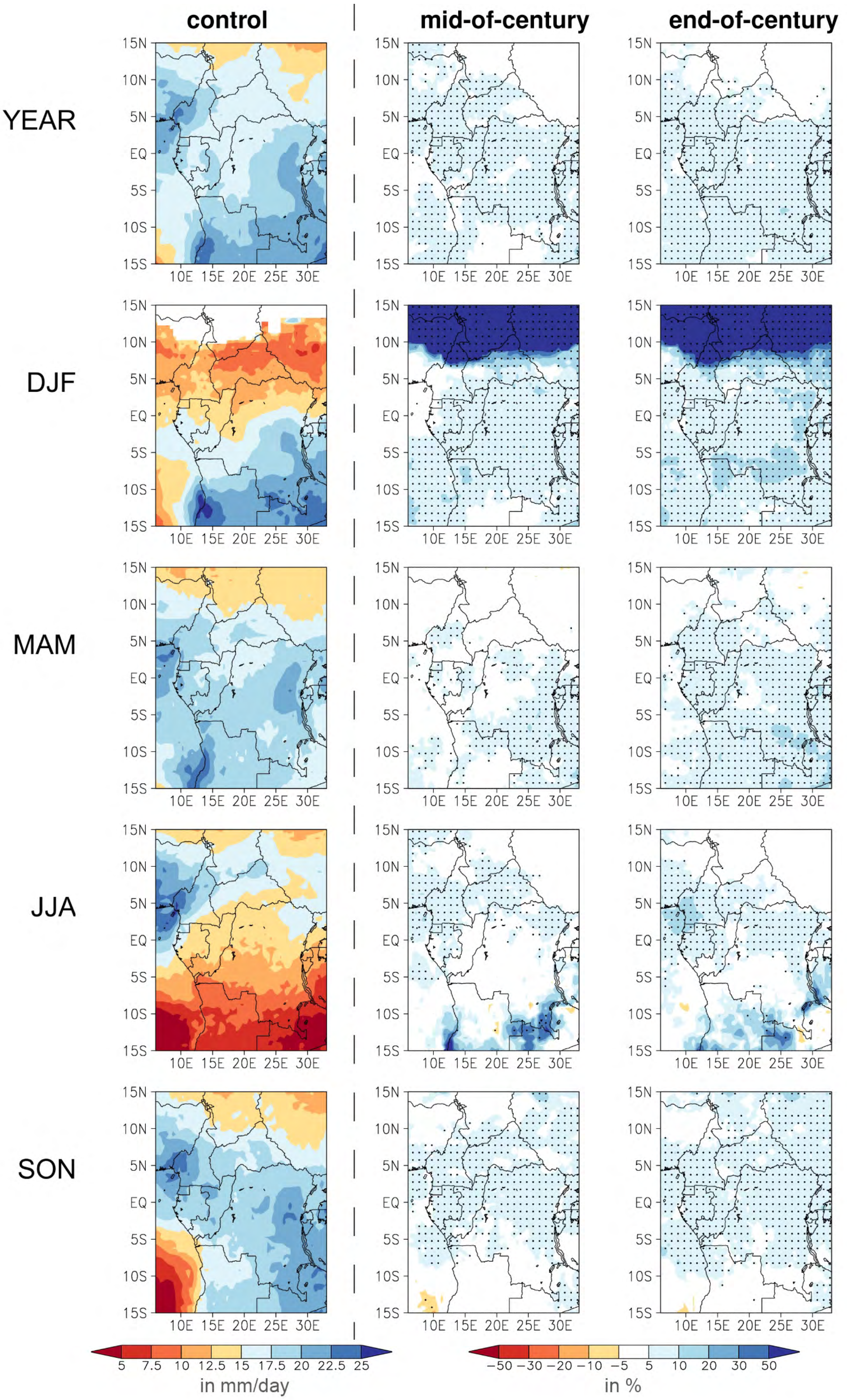


Figure 14: Maps of projected changes for the intensity of heavy rainfall events under the low emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

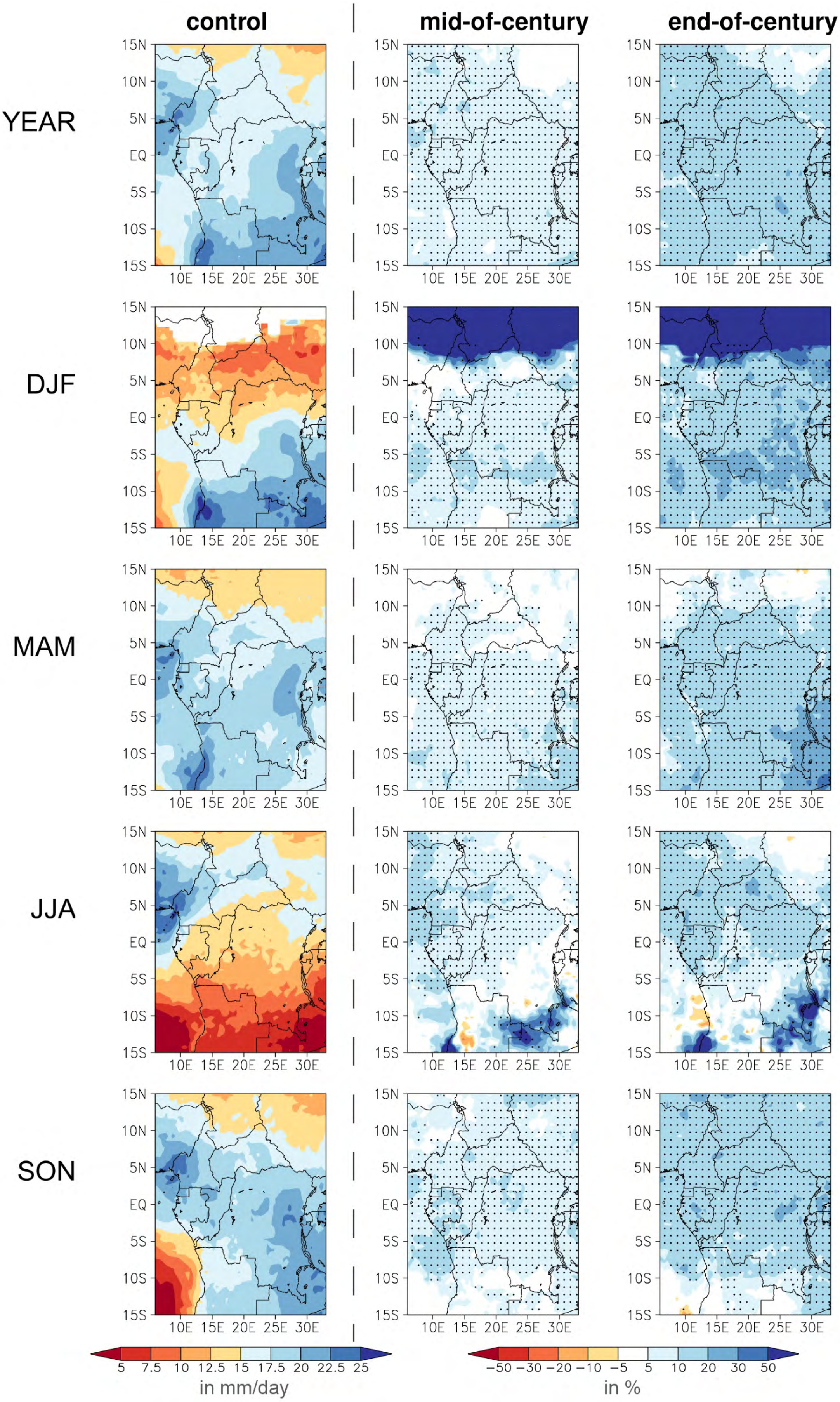


Figure 15: Maps of projected changes for the intensity of heavy rainfall events under the high emission scenario for different time periods. Stippled areas indicate regions with "robust" changes, over which at least 66% of all models project a climate change signal in the same direction.

The spatial patterns of the median projection of change of the intensity of heavy rainfall events are depicted in Figure 14 for the low emission scenario and in Figure 15 for the high emission scenario. The panels in the figures are arranged as described above for the annual and seasonal mean temperature and total precipitation figures (Figures 8-11). Towards the end of the 21st century the median projection of change in the intensity of heavy rainfall events is for a robust increase over most parts of the domain for both the low and the high emission scenario. This is not only true for change in the intensity of mean annual heavy rain events (upper row in figures), but also for the respective means of the different seasons. In general, the regions with robust changes in the increase of the intensity of heavy rain events are linked to the regions with higher rainfall intensity during the control period. Of course this is only true, if the projected very high increases over the very dry parts during DJF season in the northern part of the greater Congo basin region are neglected. If the two emission scenarios are directly compared to each other it can be concluded that the patterns are rather similar, but under the high emission scenario the projected changes are larger (up to about 10% stronger increase).

For the frequency of heavy rain events, no substantial change is projected over the whole region regardless of the considered emission scenario (not shown). As the frequency of heavy rainfall events is estimated with respect to all days of a year (no matter if it is raining or not) this finding combined with the projected increase in the intensity of heavy rainfall events and the rather small changes in total rainfall amounts (see section 5.1) indicates that the absolute number of rainfall events seems to be reduced in the future.

A general mostly robust increase is also projected for the 10-day maximum rainfall amounts for both scenarios (Figure 16, panels in upper row represent the median of projected changes under the low emission scenario, panels in bottom row under the high emission scenario, respectively) and most parts of the analyzed region. Like in the case of the intensity of heavy rain events also for the maximum 10 day rainfall amounts a substantially larger increase is projected under the high-emission scenario.

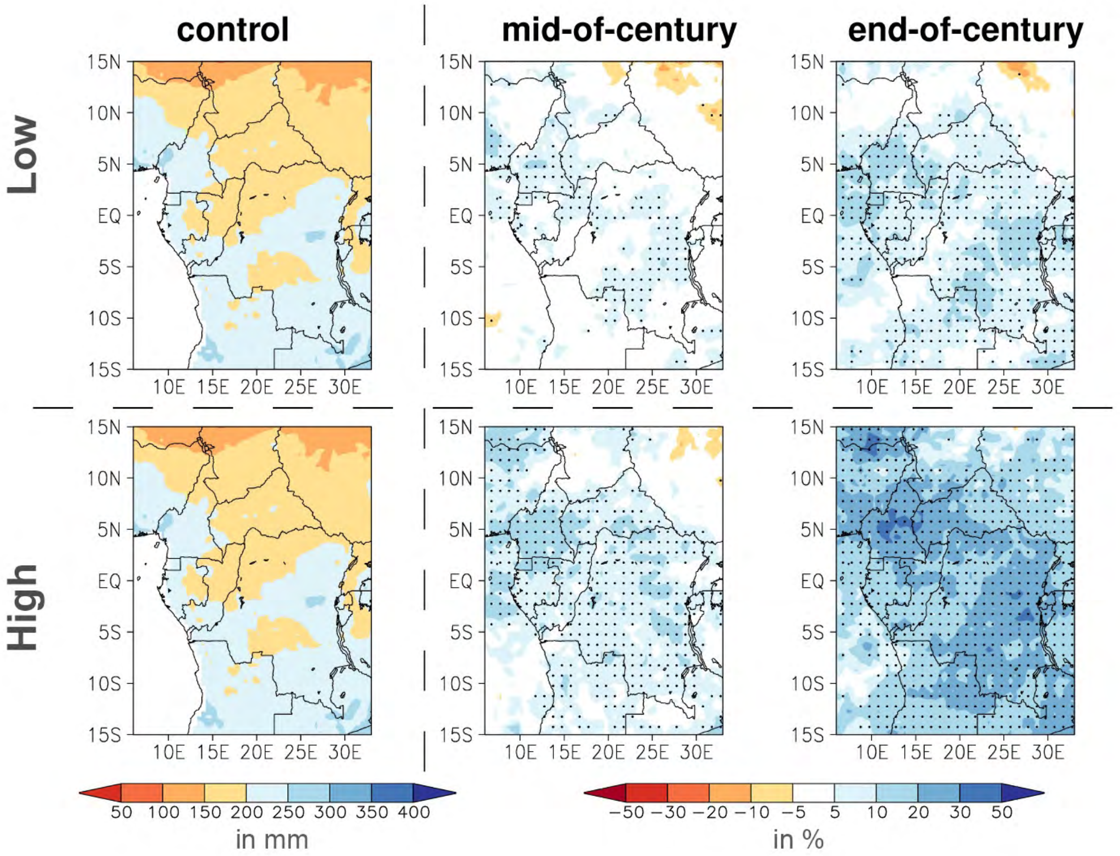


Figure 16: Maps of projected changes for the 10-day maximum rainfall amounts for the low (upper row) and high emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

The full range of projected changes for the precipitation extremes are depicted in Figure 17 (for the projected changes in the intensity of heavy rain events) and in Figure 18 (right panel – for the projected changes in the maximum 10day precipitation amounts). The full range of projected changes in the intensity of heavy rainfall events is very large, especially in the two northern zones and during the respective dry seasons. However this large range is caused by projected changes of a few outlier models only. Therefore the likely range is substantially smaller than the full range. If just the likely range is considered, a clear and robust tendency for an increase in the intensity of heavy rain events up to a maximum increase of about +25% is projected towards the end of the century. This holds true for both scenarios, although the likely range is slightly lower under the low emission scenario. Larger changes are only projected to occur during the respective dry seasons and can be neglected due to the minimum intensities observed during this time of the year. For the case of the maximum 10 day precipitation amounts, the full range (Figure 18, right panel) is substantially lower in the northern two zones compared to the full range of projected changes in the intensity of heavy rainfall events. Also for this parameter, the likely range indicates an increase in 10 day maximum rainfall amounts for the future. Under the high emission scenario the likely range of projected changes spans mainly between +10 to +30% at the end of the 21st century. Only for Zone 1, the range is slightly larger (from -6 to +40%). Under the low emission scenario projected changes for the maximum 10 day precipitation amounts are slightly lower.

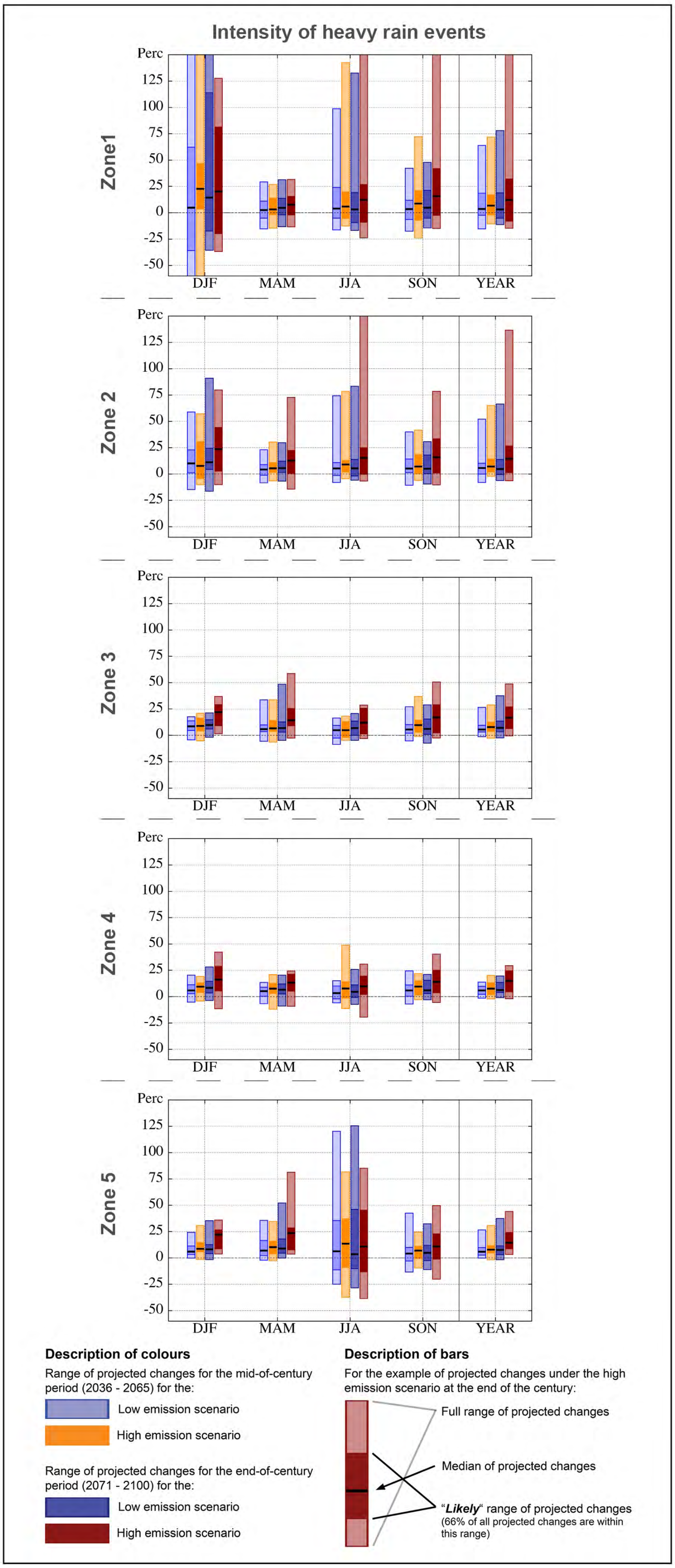


Figure 17: Full and likely ranges of projected changes for the intensity of heavy rainfall events

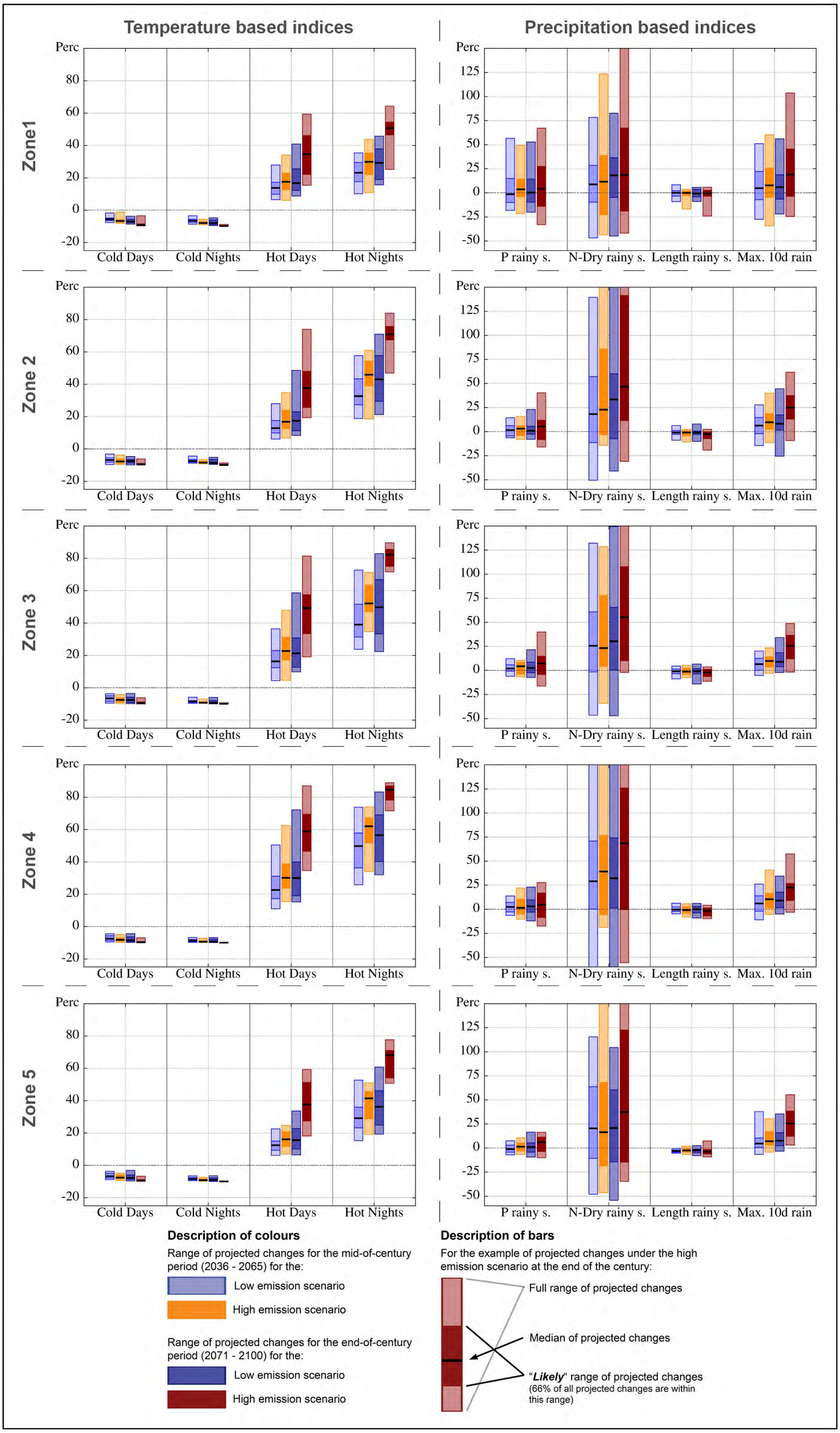


Figure 18: Full and likely ranges of projected changes for temperature based indices (left column) and precipitation based indices (right column) averaged over the five subzones for both scenarios for different time periods.

5.3. Projected changes for the rainy season

In Figures 19 and 20 the spatial distribution of the median of the projected changes for the total precipitation sum during the rainy season (upper row), the number of dry spells within the rainy season (central row) and the length of the rainy season (bottom row) are depicted for the low (Figure 19) and the high (Figure 20) scenario and for the two future time periods. Under the low scenario, the median projection of change for the rainy season total rainfall shows almost no change over the greater Congo basin region. Only at the coastal areas of Cameroon and in the east of the Democratic Republic of the Congo (DRC), a robust increase by about +5 to +10% is projected. Under the high emission scenario the median projection of change in rainy season rainfall amounts is for a slight increase over large parts of the domain. This increase is slightly larger in the southwest of Cameroon and the east of DRC. However one has to keep in mind that over large parts the projected changes are not robust. This indicates that there is a large fraction of models that project a decrease in rainy season rainfall amounts (see also below and Figure 18).

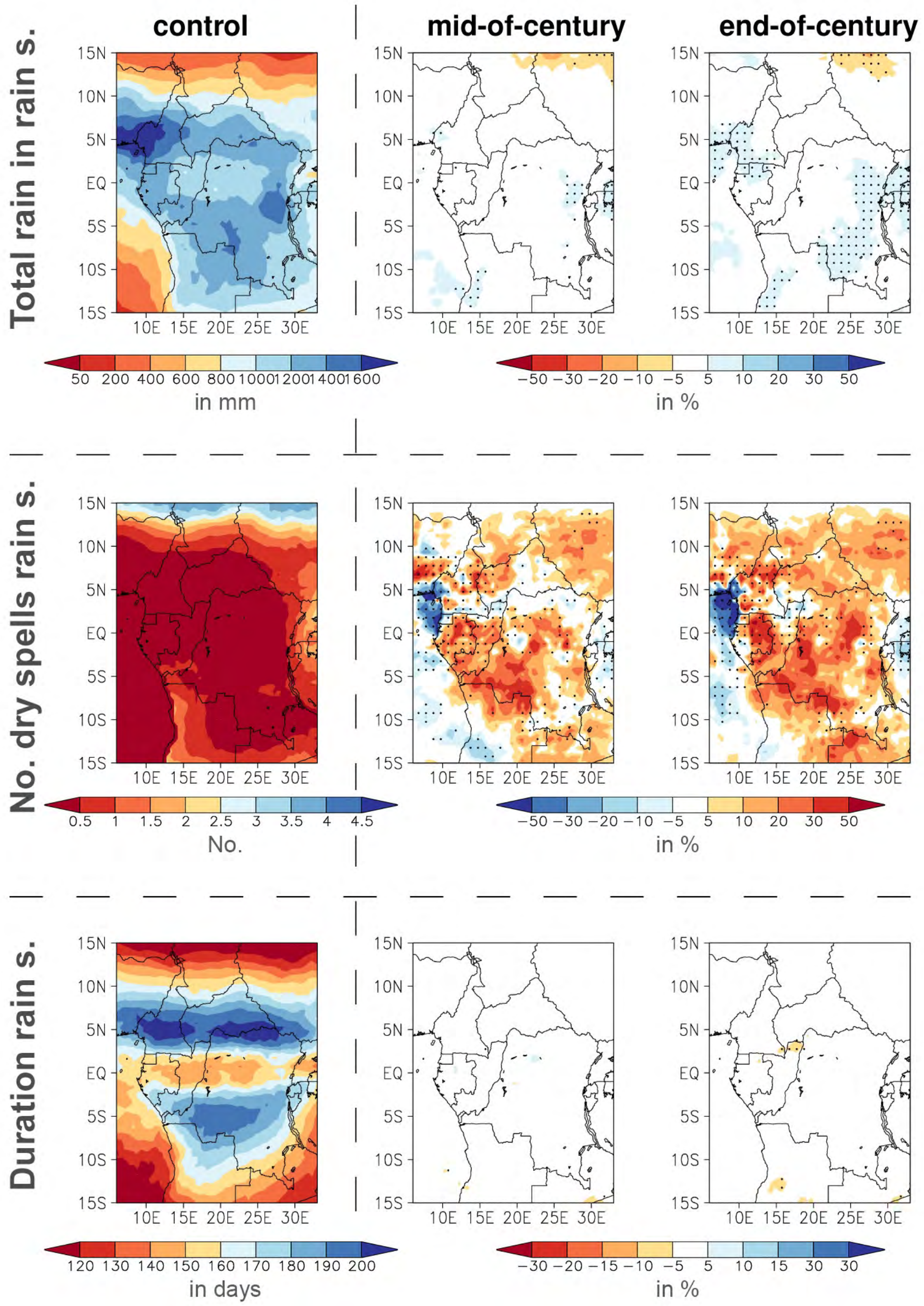


Figure 19: Maps of projected changes for the total precipitation amount during the rain season (upper row), the number of dry spells during the rain season (central row) and the duration of the rainy season (bottom row) under the low emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

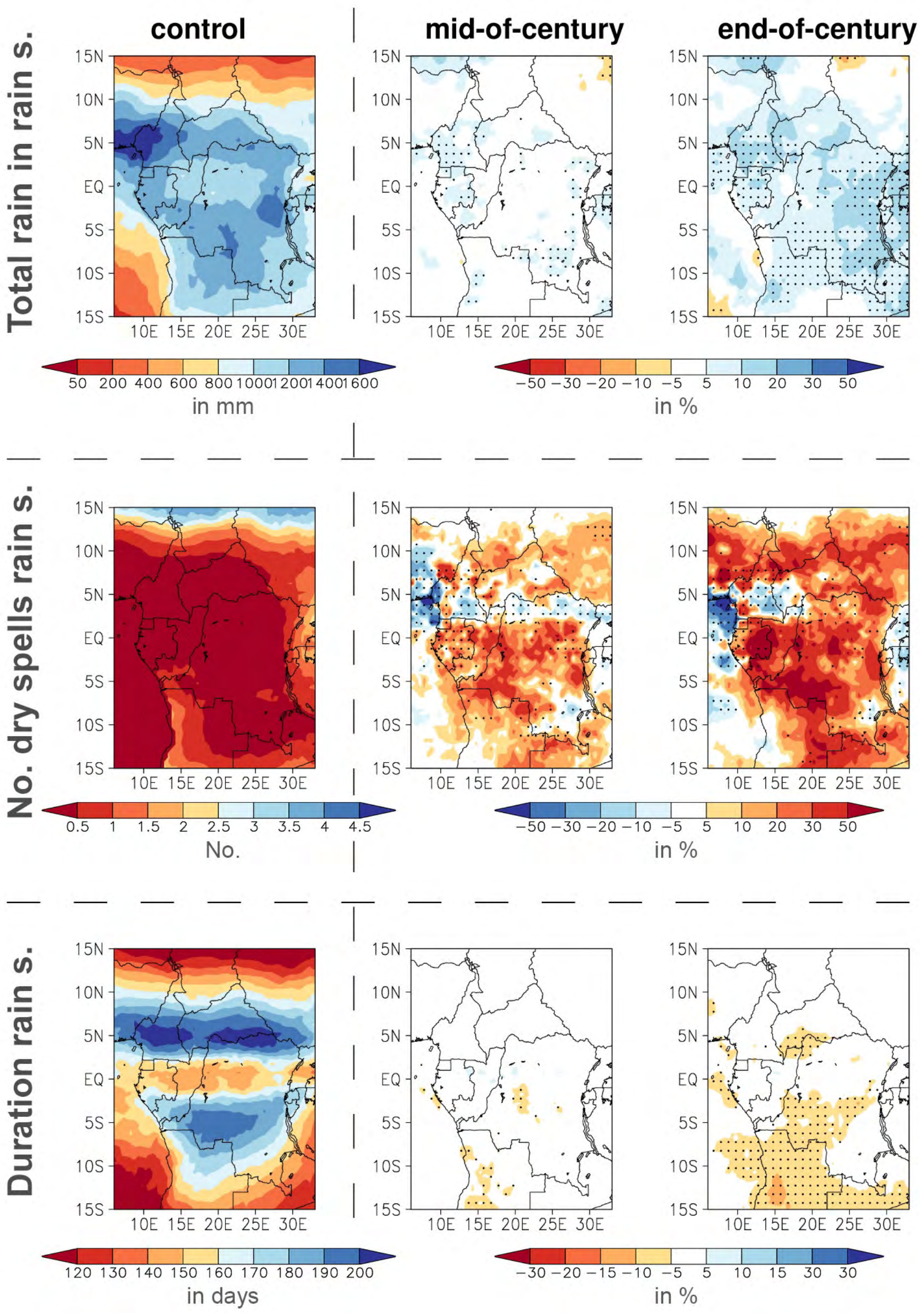


Figure 20: Maps of projected changes for the total precipitation amount during the rain season (upper row), the number of dry spells during the rain season (central row) and the duration of the rainy season (bottom row) under the high emission scenario for different time periods. Stippled areas indicate regions with “robust” changes, over which at least 66% of all models project a climate change signal in the same direction.

The median projection of change for the number of dry spells during the rainy season is for a rather large increase over major parts of the domain (especially under the high emission scenario and towards the end of the century – see Figure 19, centre row, right panel). However for both scenarios, a substantial decrease in the number of dry spells is projected over some parts in the south-east of Cameroon and the Gulf of Guinea region. However the uncertainty in the projected changes is rather large, as many regions with strong change signals are not marked with black stipples (and therefore no robust changes). Only very small changes are projected for the duration of the rainy season; however there is a tendency for a slightly shorter rainy season in the future for both of the scenarios. This tendency is little more pronounced under the high-emission scenario.

The full and likely ranges of the projected changes for the three rainy season parameters and for the five subzones are depicted in Figure 18 (left 3 panels in the right column). For the total rainfall in the rainy season, the likely range of possible changes rather small over the humid regions (from -9 to +18%) and slightly larger in the northern zone (from -14 to +27%) for both the scenarios. For all zones the likely range is enlarged under the high emission scenario.

Whereas for the duration of the rainy season all models agree on only a minor change (likely range always between ±5%, independent of the scenario – see Figure 18, second panels from right) a very large uncertainty is assigned to the projected relative changes in the number of dry spells (Figure 18, second panels from left). This is of course also partly due to the fact that during the control period only very few dry spells per rainy season (usually less then 3 dry spells) have been simulated and observed. Nevertheless, even though a large uncertainty also remains in the case of the “likely” changes, there seems to be a clear tendency for all zones and scenarios for an increase in the number of dry spells during the rainy season. This also points to the fact that rainfall is likely to occur more sporadic as under today’s conditions.

6. Description of projected changes in the subset of climate change projection used for the subsequent impact assessment studies

All the analyses on projected changes for different parameters presented so far have been conducted on the full multi-model multi-scenario data set of available global and downscaled climate change projections. Altogether this set of projections consists of data from 77 different simulations (46 for the low and 31 for the high emission scenario, see also Table 2). In an ideal case, all projections would now be used as input for subsequent impact assessment or adaptation studies. These studies are necessary as it is mainly the impacts of potential climate change and possible ways to adapt to them about which the people are most concerned about. The pure climate change signal itself is often an information which has less practical importance for practitioners.

However, for several impact assessments it is simply not possible to use such a huge amount of data - especially if also for the impact assessment itself a multi-tool approach is considered. Examples for this are hydrological, agricultural and forest models (all used within this project – see Beyene et al., 2013; Ludwig et al., 2013 and Van Garderen & Ludwig, 2013 for details) which require also a lot of computational resources themselves and cannot be easily repeated 77 times (e.g. once for every climate change information).
In most cases only a small subset of climate change projections is therefore used as input for climate change assessment studies. But of course this is dangerous, as a sub-selection of climate change projections might impacts on the range of the full ensemble of projected climate change signals. An example for this is given in Figure 21. Here the median of projected changes for annual mean temperature (left panel) and annual total precipitation (right panel) are shown for the two scenarios separately as well as the full range of the projected changes (low and high scenario combined) for each of the four ensembles and for all of the 77 projections - each averaged over Zone 3. For the case of all projections (respective right bars) also the likely range (darker area) is provided for both scenarios.

In the case of annual mean temperature the differences in projected changes among the four different ensembles are rather small. For all the four datasets the median projection of change is within the respective likely range of all projections for both of the scenarios. Some differences, however, are found in the case of projected changes for annual total precipitation (right panel). While the two datasets of GCM projections (AR4 and CMIP5) and the bias-corrected and downscaled WATCH dataset agree on a slight increase in precipitation under both scenarios (with median projection of change rather similar) the dataset of regional climate models (RCMs) mainly indicates a decrease in future precipitation amounts. This difference is especially pronounced under the high emission scenario. Due to the fact that the ensemble size of the regional models is rather low (compared to the full set of all other simulations) the median projections of the RCMs ensemble are outside the likely ranges of projected changes of all projections (darker grey area – in this case, the likely range of the low and high scenario overlap).

Coming back to the sub-selection needed for impact assessment studies this finding indicates that any results of subsequent studies would substantially differ if only the RCM ensemble projections would be used. But it has to be noted that this finding is only true for the variables and zone depicted in Figure 21. If other regions and variables are considered, the situation might look different. Figures for other zones and further parameters are available through the “Interactive Final Report Document” (available online under http://www.climate-service-center.de).

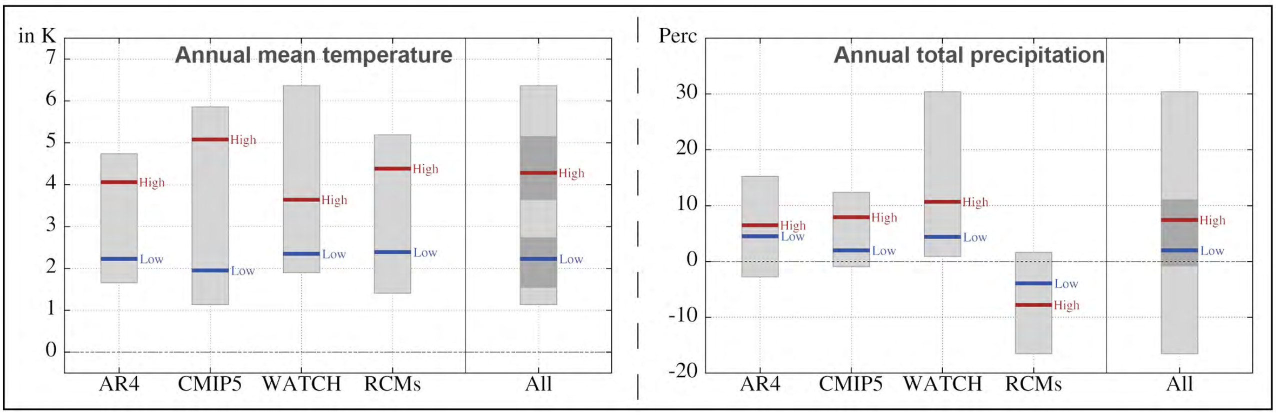


Figure 21: Comparison of the median of projected changes for the low (respective blue lines) and the high (respective red lines) emission scenario for the different datasets and all datasets combined (right bar in the respective column) for annual mean temperature (left part of figure) and annual total precipitation (right part of figure) for Zone 3. The light grey bars represent the full range of possible changes, combined for both scenarios. The dark-grey sub-ranges identify the respective likely ranges of the low and high emission scenarios. In the case of precipitation, the likely ranges overlap.

A common method to sub-select projections from a large ensemble is to use preferably projections of the models that perform best over a specific region (e.g. Johnson et al., 2011; Arnell, 2004). However it is of course subjective to define the criteria that divide good performing models from less good performing models. In practice, this simply depends on the number of projections that can be afforded to use as input in subsequent studies.

In the course of this project the projected climate change signal of the five best-performing models of the IPCC-AR4 dataset have been compared against the signal of the full IPCC-AR4 ensemble. The selection was based on a skill score (calculated from the observed and simulated probability density distribution), the correlation of the annual cycle and the mean bias for both 2m temperature and precipitation over then Congo basin (see Figure 3 for spatial extent). As observed data again the daily WFD was used. Details on the skill score method can be found in a paper by Perkins et al. (2007).

Figure 22 depicts a comparison of the mean projected changes for annual and seasonal mean temperature (left two columns) and annual and seasonal total precipitation (right to columns) for all models of the IPCC-AR4 dataset (respective left column) and the five best performing projections (below referred to as BPMs - respective right column) for the case of the high (SRES A2) scenario. In the case of projected temperature changes, an enhanced warming is observed for the subset of the BPMs over the regions north and south of Congo basin. However, a similar pattern of warming is observed over the central parts. For total precipitation over large parts of the Congo basin an opposite signal is projected in the BPMs as compared to the full ensemble of IPCC AR4 projections. These opposite signals are visible in the annual total precipitation as well as in the different seasons. It should be noted that these opposite signals are also statistically significant on the 95th confidence level; however it should be kept in mind that the size of the database for the statistical test substantially differs between the two datasets.

If the same subset of model projection is compared to the full IPCC-AR4 ensemble under different scenarios, the conclusion might be different. In the case of the more moderate A1B emission scenario and the low (B1) scenario, for example, differences between the full set and the subset of projected changes are smaller (total precipitation) or not existing (mean temperature).

Comparing the result of the five best performing models of the IPCC AR4 dataset to the full ensemble of the 77 projections analyzed in this report (e.g. Zone 3 in Figure 21) the five BPMs seem to be the one projecting the largest decrease in annual total precipitation, while the vast majority of the available model projections (including the BPMs of the CMIP5) have a tendency for an increase in total rainfall amounts. Therefore even though there is some justification for selecting the BPMs for subsequent studies, one has to be aware of the fact that they might cluster at one end of the distribution. Also the required independency of an ensemble consisting only of a few BPMs is questionable.

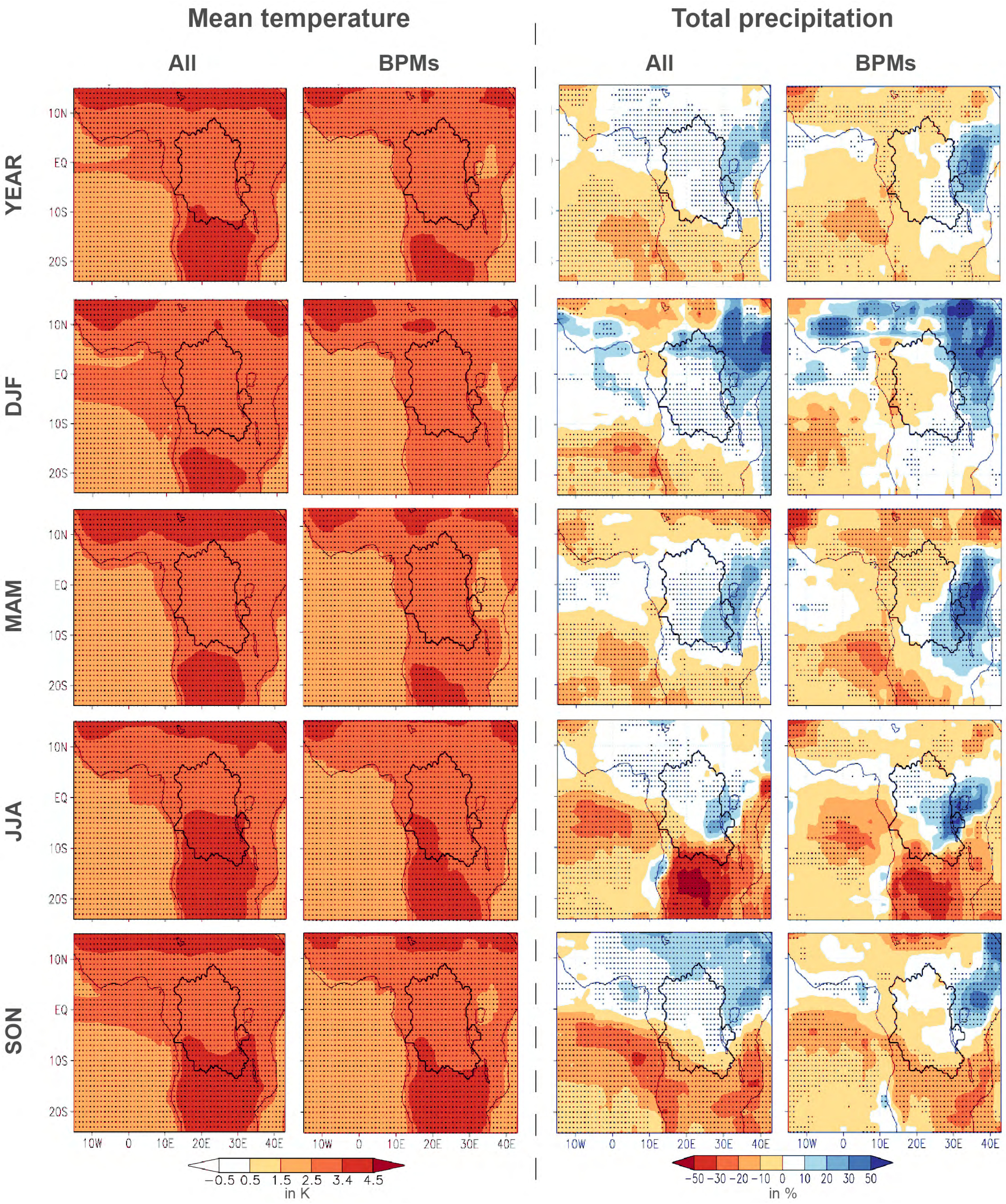


Figure 22: Comparison of projected changes of the five best performing models (BPMs) of the IPCC-AR4 dataset compared with all projections of the IPCC-AR4 dataset for mean temperature (left part) and total precipitation (right part) under the high (A2) emission scenario for the end of the century. Stippled areas indicate regions with statistical significant climate change signals on the 95th confidence level using a non-parametric Mann-Whitney U test.

The perfect subset of model projections would therefore be a set that on the one hand performs reasonably well when compared to observed climate data, but also has the potential to adequately represent the range of projected changes for all parameters, time scales, scenarios and over the whole region. Of course such a subset of projections will never exist; therefore it has to be prioritized if the performance over the control period or the ranges of projected changes is more important. For most of the impact assessment models the earlier is of higher importance, as only input data that well represent the observations allow to judge the performance of the impact models itself.

In the course of the project “Climate Change Scenarios for the Congo Basin” the subset of the bias-corrected and downscaled WATCH data was used as input for the subsequent studies (see Beyene et al., 2013; Ludwig et al., 2013 and Van Garderen & Ludwig, 2013 for details). This dataset comprises of three projections for the low and three simulations for the high scenario. Due to the fact that the dataset is bias-corrected, it performs for most of the variables best when compared to the observations (e.g. section 4).
In the subsequent section however it shall shortly be assessed how representative the projected changes of the WATCH dataset are when compared with the full range of projected changes of the full ensemble. For this purpose, histograms of projected changes of all models have been calculated over all zones and all parameters. These histograms define on the one hand the full range of projected changes (abscissa), and on the other hand the frequency of a projected change signal (ordinate). The projected changes of the simulations of the WATCH dataset (three projections for the low and for the three for the high scenario) are included by blue (low) and red (high) arrows. For selected zones and variables these histograms are depicted in the Figure 23. Note, that the histograms are summarizing projected changes at the end of the century compared to the control period. A complete collection of figures representing the histograms of projected changes of the whole ensemble and the respective changes in the subset of the WATCH projection, for all zones, variables and the two future time periods is available through the “Interactive Final Report Document” (available online under http://www.climate-service-center.de).

For the projected changes in annual mean temperature, the projections of the WATCH data subset span over a wide range, thereby representing the full range of available changes rather nicely, even though the subset is slightly shifted to the warm end of the histograms. For the number of cold days the range of projected changes of the WATCH subset is centered around the histogram maximum, indicating that the subsets is well inline with the majority of projected changes, even though the extremes are not represented. For the projected changes in annual total precipitation, the subset of the WATCH projections span from the maximum frequency towards the higher end of the histogram for Zone 1 and 3. In these zones, the subset of projected changes represents the whole ensemble of projected changes rather well. In the case of Zone 4 the projected changes of the selected subset are all assembled on the high end of the histogram (independent from the scenario), thereby probably overestimating the projected increase in annual total precipitation. The findings of the projected changes in the annual total precipitation can directly be transferred to the representation of projected changes of the intensity of heavy rain events. For the number of dry spells during the rainy season, the projected changes of the whole ensemble span over a huge range from a decrease by 50% to an increase up to 140%. This huge range is caused by the very small number of occasions of dry spells during the control period. Therefore it is not surprising that the subset of selected projections does not represent the full range of projected changes. For Zone 1 the subset of projected changes represents the range of the majority of changes of the full ensemble, whereas in Zones 3 and 4 the subset is more representing the lower bound of the full ensemble range. If all variables and zones are regarded (see collection of figures in the digital version), it can be noted that the projected changes of the subset of projections for the end of the century are for almost all of the zones and variable well within the range of the full ensemble of projected changes. Mostly the changes of the subset also span over a sufficiently large range to ably represent the majority of the projected changes in the full ensemble dataset. Exceptions to this are the projected changes in total precipitation (for both annual as well as during the rainy season) in Zone 4, over which the changes projected by the subset are all clustered at the high end of the full ensemble histogram. Another case for a mismatch between the full ensemble and the projections of the subset is for the frequency of heavy rain events. Here the projected changes of the subset are substantially large over all zones.

In summary it can be concluded that for many parameters the projected changes of the simulations of the WATCH dataset represents the full ensemble of projected changes nicely. However there are definitely regions where the WATCH dataset represents an outlier. This has to be kept in mind when interpreting the results of the subsequent studies compiled within this project. Especially over Zone 4, the projected precipitation increase in the WATCH dataset is notably larger than all other projections. This mismatch might be related to the applied bias correction. It was shown that the WFD strongly overestimates annual total precipitation over this region, as compared to station data. Therefore applying these data for bias correction might amplify the projected future precipitation amounts of the three GCMs in the WATCH ensemble to strongly.

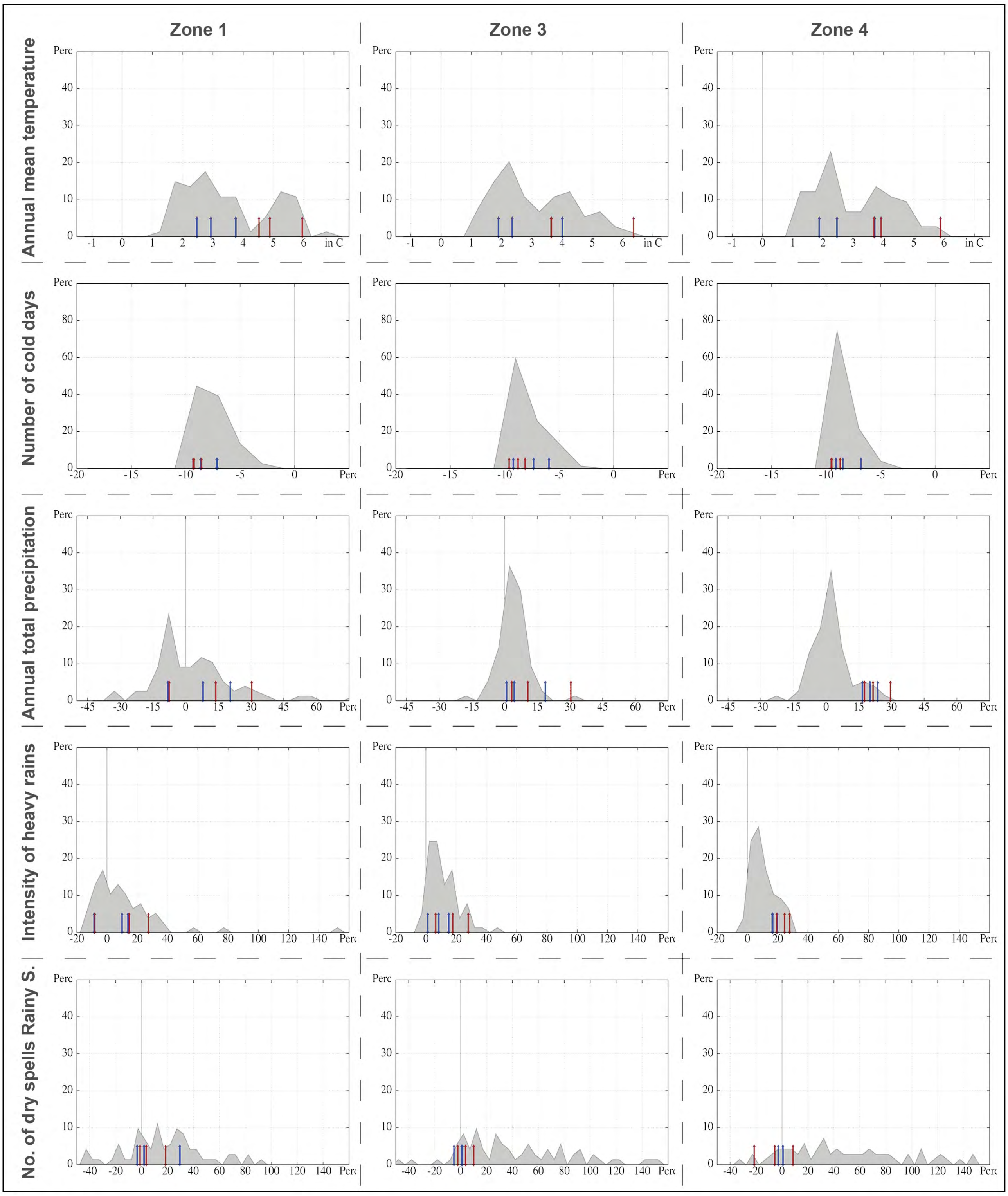


Figure 23: Histograms of all projected changes under the low and high scenarios. The blue (red) arrows indicate the projected changes of the selected subset for the low (high) emission scenario, respectively.

7. Summary and conclusion

The climate change assessment described in this report was based on a unique large set of projections from global climate models from the CMIP3 project (database of the 4th IPCC assessment report) and the CMIP5 project (database of the upcoming 5th IPCC assessment report due in 2013). Moreover bias-corrected and statistical downscaled projections of the EU-WATCH project have been included along with the projections of regional climate models. Although most of the regional climate projections are developed within the framework of this project, a few simulations from the preliminary CORDEX Africa data archive are also considered for the analysis.

For the analysis of potential climate changes two potential future developments have been considered – a “*high*” emission scenario (combining climate projections following the SRES A2 and RCP8.5 emission scenarios) and a “*low*” emission scenario (combining climate projections following the SRES B1 and RCP4.5 and RCP2.6 emission scenarios). Altogether an ensemble of 46 different projections has been analysed for the case of the low emission scenario and an ensemble of 31 projections in the case of the high emission scenario. This unique large dataset of different kind of projections (from global climate models, regional climate projections and statistically bias-corrected and downscaled global projections) allows the identification of robust patterns and associated ranges of projected changes for the first time.

The major findings of the climate change assessment can be summarized as follows. For the near surface air temperature, all assessed models agree on a substantial warming towards the end of the century in all seasons of the year regardless of the underlying scenario. On an annual basis a warming in the range of +1.5 and +3°C for the low and in the range between +3.5 and +6°C for the high emission scenario can be considered to be likely towards the end of the 21st century. In general projected temperature increase is slightly above average in the northern parts of the region and slightly below average in the central parts. Also for temperature extremes (frequency of cold/hot days and nights) all models agree on a decrease/increase in the future. Especially the hot days and nights are projected to occur much more frequently in the future, particularly in the case of the high emission scenario. Since for the temperature related parameters all 77 analysed projections agree in the sign of the projected changes, therefore these changes can be considered to have a very large robustness.

For total precipitation the agreement between the assessed projections is not as high as for the temperature. For all zones some models project an increase in annual total precipitation and some project a decrease. If the full range of projected changes in annual total precipitation is considered, all models agree on a change not higher than ±30% towards the end of the 21st century for most parts of the domain with a general tendency of a slight increase in future annual total precipitation. However, in the dryer northern part, a larger increase in annual total precipitation (full range up to about +75%) is projected, mainly related to the already earlier in the scientific literature described northward expansion of the tropical convection zone. These findings are independent of the underlying emission scenario. If only the likely range is considered, projected changes in annual total precipitation are between ~ -10 to +10% (-10 to +30% in the north) and between -5 to +10% (-10 to +15% in the north) for the high and low emission scenarios respectively. This finding once again points to the conclusion that - on the basis of the assessed large ensemble of climate change projections – it is not likely that drastic changes in annual total rainfall will occur in the future over the greater Congo basin region.

Although the annual total precipitation amounts might not change dramatically, the rainfall characteristics are projected to undergo some substantial changes. An example for this is the likely increase in the intensity of heavy rainfall events in the future (likely range for most parts positive, up to ~ +30%). Also the frequency of dry spells during the rainy season is projected to substantially increase in the future over most parts of the domain. This indicates a more sporadic rainfall distribution in the future.

In summary the climate change assessment for the greater Congo basin did reveal that projected rainfall changes are unlikely to lead to a general water shortage in the region, however some prolonged and more frequent dry periods might become more likely in the future. This finding is independent of the underlying emission scenario. In terms of the projections in near surface air temperature, the projected warming is substantially larger under the high emission scenario, and therefore might also have a substantially larger impact on the living environment in the region.

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The Potential Consequences of Climate Change in the Hydrology Regime of the Congo River Basin

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On behalf of
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

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This report should be cited as follows:
Beyene T., Ludwig F., Franssen W. (2013): The potential consequences of climate change in the hydrology regime of the Congo River Basin. *In: Climate Change Scenarios for the Congo Basin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

"The Potential Consequences of Climate Change in the Hydrologic Regime of the Congo River Basin"
Part of the series: "Climate Change Scenarios for the Congo Basin"
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Date: Feb 2013

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Cover photo: "An aerial view of a tropical river"@ thobo/ fotolia.de

ABSTRACT

Future climate change can potentially have a large impact on hydrological systems. Global warming can increase evaporation and cause changes in rainfall patterns. The current and future hydrologic regime of the Congo River Basin was simulated using the macro-scale hydrological model VIC. For the analyses a subset of 6 different climate scenarios was used. These scenarios were based on the bias corrected output of three GCMs in combination with a high (A2) and a low (B1) greenhouse gas emission scenario. The magnitude of precipitation changes differed between GCMs and emissions scenarios. However all the three GCMs projected moderate to high wetting conditions throughout the 21st century. The model simulations indicated that climate change will result in increased evaporation throughout the basin. On average, the increase in evaporation by the end of the century will be about 10% for the A2 emission scenario and 8% for the B1 Scenario. Average over the Congo basin, run-off is projected to increase by 15% by mid-century for the A2 scenario and 10% for the B1 scenario (Table 3). By the end of the century run-off is projected to increase with 27% for the A2 scenarios and 23% for the B1 scenario. For changes in run-off there were large differences between the 3 different climate models. Run-off is especially increasing in the central and western part of the Congo Basin. On the Northern, Southern and Western edges of the Basin, the results are considerably different. Here the increases are marginal and sometimes the run-off decreases. Due to the higher run-off also the river discharge is increasing. Near the river mouth, the multi model average increase in stream flow was 27% for the B1 scenario and 38% for the A2 scenarios for the end of the 21st century. However there are large uncertainties in the future changes in river flow. The ECHAM5 climate model showed the largest increase with a 73% higher discharge for the A2 scenario by the end of the century. The IPSL model only showed an increase of up to 18%. Changes in discharge depended on the season. All climate models showed increased discharge during the wet season. During the dry season, however, two climate models indicated a reduction in discharge for the 21st century. However for all model results the difference between wet and dry season will become larger compared to the current climate and especially the wet extremes are likely become more frequent and more intense. In conclusion due to a more variable climate also the hydrological regime will become more variable. The difference between seasons and between different years will increase in the future and there is the need to prepare for more hydrological frequent extremes in the future.

Keywords: Water resources; Lake Chad; future climate; scenarios; availability; climate change

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1.0 INTRODUCTION

Adverse effects of climate change with irregular distribution of precipitation in space and time, plays an important role in defining the hydrologic features of a river basin. It is projected that global warming will cause to heat up the Earth's average temperature by approximately 3^0C by 2080 (IPCC, 2007). The rising temperature will have a major effect on hydrologic processes, and will likely impact the local amount of precipitation. Recent advances in climate system and land surface hydrologic modelling contribute greatly to global and regional climate change impact assessment by using projected trends in future emissions scenarios (IPCC (2001, 2007). Climate change impact studies using 21st century climate change scenarios indicated that the African continent will warm up the most and consequences of such will have great effect on livelihoods (Arnell, 2004, Hulme *et al*., 2005), although predictions vary whether the African continent at large can expect more or less precipitation especially with regard to seasonal changes and variability (Conway 2011; Conway and Schipper 2011; IPCC, 2001).

Some of the earlier climate change studies for Africa using experimental data include: Hernes *et al*. (1995) and Ringius *et al*. (1996) who constructed climate change scenarios for the African continent resulting in 1.6°C temperature rise for areas over the Sahara and semi-arid parts of southern Africa, and 1.4°C for the equatorial African countries by 2050. These studies, together with Joubert *et al*. (1996), suggest a rise in mean sea-level around the African coastline of about 25cm by 2050. A more selective approach to the use of GCM experiments was taken by Hulme *et al*. (1999, 2001). However, these studies documented a bigger picture of future climate change impact across the continent; therefore it cannot be used to understand the implication of future climate change on the Congo River Basin (CRB) hydrologic system and water resources.

Implications of future climate change on freshwater systems will aggravate the impacts of other stresses, such as population growth, changing economic activity, land-use change and urbanization (Goulden *et al*., 2009). Water demand for irrigation, drinking water supply and hydropower will grow in the coming decades, primarily due to population growth and economic development of the equatorial Africa region (IPCC, 2007). Given the uncertainty in future climate change projections, the question how the changing climate will alter the hydrologic regime of the Congo River Basin remains. The Congo River basin is currently facing adverse effects of climate change. The consideration of climate change that pushes the Sahara and Sahel deserts (North) as well as the Kalahari Desert (South), towards the equator line, suggests a progressive strangulation of the Congo basin. This is evident in the North-West part of the Basin where water levels within the Ubangi watershed, one of the Congo's sub basins, have decreased significantly (Yolande Munzimi, 2008).

In addition to mean annual changes in climate variables, there is need for development of the global circulation models concerning future climate projections, demanding simulations of the current climate extremes within a certain level of confidence. For regional climate change studies, monthly or seasonal means from climate models have traditionally been the most common basis for analysis. They are on the other hand, not necessarily the most useful measures for climate impact assessment.Extremes are more sensitive than average in responding to global climate change. Although changes in long-term climatic means are important, extremes generally have the greatest and most direct impact on our everyday life, community and environment. Hence, detecting changes in extremes has become important in current climate research (Vincent and Mekis, 2006). Indices based on daily temperature and precipitation projections have been developed to provide some insights in the changes of climate extremes (Peterson *et al*., 2002). These indices are valuable when studying the impacts of climate change on regional activities, agriculture and economy. They are also helpful in monitoring climate change itself and can therefore be used as benchmarks for evaluating climate change scenarios.

Runoff regimes might change significantly as a result of climate change, adaptation strategies for water resources management are sought for to lessen the impacts on and vulnerability of a certain region. The search for these adaptation strategies depend upon reliable assessment climate change impacts on the future hydrologic regime of the river basin.This study assesses and evaluates the impact of projected climate change on the hydrologic regime and climate extremes of the Congo River basin. This specific river basin, despite its huge importance and implications to the regional hydrological cycle, has the least number of climate change impact studies in Africa to date (Wolf *et al*., 1999). Land surface hydrologic modelling, using bias-corrected and spatially downscaled climate data from three GCMs (CNCM3, IPSL, and ECHAM5) and two emissions scenarios (A2 and B1), were used to simulate historical and future hydrologic regimes.

2.0. DATA AND METHODOLOGY

In this chapter a brief description of the Congo River basin is given. The datasets used (historical and future) and hydrologic simulation models are explained below. The General Circulation Models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC, 2007) , are the major input for the future change in temperature, precipitation, evaporation, runoff and river discharge patterns analysis. The Future climate data consists of two emissions scenarios (A2 and B1) and three GCMs (ECHAM5, IPSL, and CNRM3). Data derived from the three GCMs were statistically bias-corrected and downscaled to the hydrologic model resolution. The details of the bias-correction and spatial downscaling technique is described in Piani *et al*. (2010).

2.1. THE CONGO RIVER BASIN

The Congo River originates in the highlands and mountains of the East African Rift system. It is located in Central Africa extending from latitude 09°15’N in the Central African Republic to 13° 28’S in Angola and Zambia, and from longitude 31° 10’E through the Great African Lakes in the East African Rift to 11° 18’E on the Atlantic Ocean (Figure 1). The Congo basin is shared between nine African countries: Angola, Cameroon, the Central African Republic, the Republic of Congo and the Democratic Republic of Congo which together make up for 92% of its total surface of 3,691,000 km^2. The basin comprises a population of approximately 77,344,991 inhabitants in 2005. The basins water resource is vital for local livelihoods, drinking water supply, food security and energy generation.

Figure 1 The Congo River basin and riparian countries sharing its water resources

The Congo River is the only major river to cross the Equator twice. In doing so, the basin lies in both the Northern and Southern Hemispheres causing it to receive year round rainfall from the migration of the Inter-tropical Convergence Zone (ITCZ) (Kundzewicz *et al*., 2007). After the north has its wet season in the spring and summer, the ITCZ moves south and the southern part of the basin receives large amounts of rain. This results in little seasonal variability in the Congo mainstream water flow.

The heart of Congo River basin enjoys an equatorial climate with no dry season whereas the far north and south benefit from a tropical climate. The annual average rainfall in the Congo River basin varies between 1,500 and 2,000 mm per year depending on the location of the sub-basins. As the singular river basin flows mainly in this equatorial part of Africa, the main stem exhibits a more constant flow compared to other African major rivers with an average of 45,000m^3/s.It does show some inter-annual variability with July and August being the months of low flow whereas December is the month of high flow. The tributaries from the South, such as the Kasai, have two periods of low water and two of high in the year, but the tributaries from the north, such as the Ubangi, have a single maximum. Consequently, the regime of the main river does vary from place to place (Shahin, 2002).

2.2. HISTORICAL AND FUTURE CLIMATE DATA

The reference historical observations from the newly available global WATCH (http://www.waterandclimatechange.eu/) and the forcing dataset (henceforth referred to as WFD) (Weedon *et al.*, 2011; Haddeland et al. 2011) were used to simulate the current status of the hydrologic regime of the Congo River basin. The dataset covers the period 1958-2001 and is based on the 40-years re-analysis of the European Centre for Medium-Range Weather Forecasts (ERA40; Hagemann *et al*., 2011). The ERA40 data were interpolated to 0.5°lat x 0.5°long and only considered over land points using the land-sea mask from the Climate Research Unit (CRU) dataset TS2.1. A correction for elevation differences between ERA40 and CRU was applied. For 2m temperatures, a correction of the monthly means with CRU data was performed. For precipitation, a correction of the monthly means with data from the Global Precipitation Climatology Centre full dataset version 4 was conducted. In addition, a gauge-undercatch correction following Adam and Lettenmaier (2003) was used, which takes into account the systematic underestimation of precipitation measurements that have an error of 10-50%. In this way, the WFD combined the daily statistics of ERA40 with the monthly mean characteristics of CRU temperature and gauge undercatch-corrected GPCC precipitation amounts.

When compared to FLUXNET data (http://www.fluxnet.ornl.gov/fluxnet/) a close correspondence between field measurements and the 180 WFD for all variables is demonstrated (Weedon *et al*., 2011). ERA40 data was used in different studies downscaledfor Africato characterize hydro-climatology of the continent and derive regional climate models. Afiesimama *et al*. (2006) and Anyah and Semazzi (2007) used RegCM3 to downscale the NCEP reanalysis, respectively, over West and East Africa. Galle´e *et al*. (2004) used ERA-15 to drive MAR (Modele Atmospherique Regional) over West Africa. Hudson and Jones (2002) and Tadross *et al*. (2006) used MM5 and PRECIS to downscale ERA-15 over South Africa. Pal *et al*. (2007) used ERA-40 to drive RegCM3 over the entire African domain. However, these reanalysis products exhibit significant biases over the African region (Trenberth *et al*., 2001; Diongue *et al*., 2002; Tadross *et al*., 2006), and errors introduced by the reanalysis large-scale boundary conditions are transmitted to the RCM (Noguer *et al*., 1998; Giorgi and Mearns 1999; Wang *et al*., 2004).
Global Circulation Models (GCMs) have a very coarse spatial resolutions in the order of 3.5° lat X 3.5°lonaverage grid size, which is different from most hydrological and land surface hydrologic model resolution. Hence, for GCMs grid-point projections to be useful or have a realistic representation of climate fields (precipitation and temperature) it is crucial for impact studies to do bias correction and spatial downscaling to the hydrologic model resolution (Hagemann *et al*., 2011). Individual GCMs model results can produce quite varying and even contradictory results for both control and future climate including disagreement with the observations. Thus, to reduce inherent uncertainties with climate data derived from GCMs, many climate change impact studies concluded that a multi-model ensemble of GCMs should be used to obtain a reliable impression of the spread of possible regional changes and their accompanying uncertainties (IPCC, 2007).

For this hydrologic assessment we used a sub-set of the climate scenarios analysed in chapter 1. In total 6 climate scenarios we used. The scenarios were a combination of 3 different global climate models and two different emission scenarios (table 2). Two different SRES emission scenarios were selected: a low (B1) and a high (A2) emission scenario.

Significant deviations are especially apparent for precipitation both in the control and future climate derived from GCMs.Simulated precipitation statistics are generally affected by a positive bias in the number of wet days, which is partly compensated by an excessive number of occurrences of drizzle, a bias in the mean, the standard deviation (variability), and the inability to reproduce extreme events (Piani *et al*., 2010). Therefore, it has been widely recognized that precipitation data needs to be bias-corrected before it can be used. Future projected climate change data at 0.5°lat x 0.5°long grid resolution and daily time step was produced following a statistical bias correction developed by Piani *et al*. (2010) as part of the EU-WATCH project. Daily time series from the three global circulation models and historical data were used for the VIC hydrologic model to complete a regional hydrologic analysis. We adopted a multi-model ensemble approach to measure the degree of shift and or change in the future hydrologic regime from historical climate.

2.3. OVERVIEW OF HYDROLOGIC SIMULATION MODEL

The current and future hydrologic regime change in the Congo River basin was simulated using VIC: a macro scale land surface hydrologic model, and then assessed. Description and implementation of the model is given in section 2.1.1

2.3.1. VIC –LAND SURFACE HYDROLOGIC MODEL

The Variable Infiltration Capacity model (VIC) is a macro-scale spatially distributed land surface hydrologic model that solves the energy and water budgets (Liang *et al*. 1994; Nijssen et al. 2001). It has been widely applied in land surface hydrologic simulation analyses on spatial scales ranging from watershed to global domain (Beyenne et al. 2009: Van Vliet et al. 2013). Besides historical hydrologic simulation, the VIC model has been used to assess the impact and implications of climate change on water resources in several research projects both at regional and global scale. Following the third IPCC Assessment Report (IPCC, 2001), this model has been used by Payne *et al*. (2004) studying climate change effects on the Columbia River, Christensen *et al*. (2004) studying effects on the Colorado River, and Van Rheenen *et al*. (2004) studying effects on California. Similarly, several recent studies involved implementation of the VIC model to analyse the effects of IPCC AR4 projections on hydrologic systems: Cuo *et al*. (2011) on the Puget Sound basin, Christensen and Lettenmaier (2007) on the Colorado River, and Beyene *et al*. (2009) on the Nile River basin. The model was calibrated for the Congo River basin and naturalized flows were compared to observed flows at three gauging station with records sufficient for plausible comparison.

A calibration procedure similar to that described in Nijssen *et al*. (1997) and Payne *et al*. (2004) was followed to assure a match between model-simulated and observed flows for the period in which historic streamflow observations were available (Appendix 1). The VIC was calibrated by adjusting parameters that govern infiltration and base flow recession to match simulated historic streamflow. Naturalized observed flow was obtained for different time periods based on the available observed data from the GRDC at three gauging stations: Congo Kinshasa, Brazzaville and Ouesso. The overlapping period of record between simulated and observed naturalized streamflow at each gauging station is shown in Appendix 1.Table 1summarizes the bias level at each gauging stations, the bias is mainly attributed to the fact that, the simulated flows were naturalized flows without reservoir or regulation effects considered.

For the future scenarios only the climate input data was changed. Land use was assumed to remain constant. Future land use change in the region is very uncertain and at the moment there are no good regional land use change scenarios available.

Table 1 Statistics of measured and simulated flow at three gauging stations in the Congo River basin

Gauging station	Mean Observed flow(m^3/sec)	Mean Simulated flow(m^3/sec)	Bias (%)
Congo-Kinshasa	46520	52260	12.5
Congo-Brazzaville	45670	50024	9.5
Ouesso-Congo	1838	2168	17.9

3.0 RESULTS AND DISCUSSIONS

The impacts of a changing climate in the hydrologic regime of the Congo River basin were assessed using climate data from three GCMs and two emissions scenarios. Runoff and evaporation changes were simulated using the physically-based VIC model. VIC was run on a daily time step with historical meteorological conditions (1960 -2000) and future climate change scenarios for the 21st century. Changes in temperature, precipitation, runoff and river discharge are analyzed over a 30year period centered at 2050 for the period (2036-2065), and at 2080 for period (2071-2100). Multi-model average and extremes in temperature and precipitation for each GCM and emissions scenarios were computed relative to the historical simulation (1960-2000).The percentage in evapotranspiration, runoff and river discharge were computed between the 1960-2000 historical periods and the future. Analysis was performed for monthly, seasonal and annual time steps.

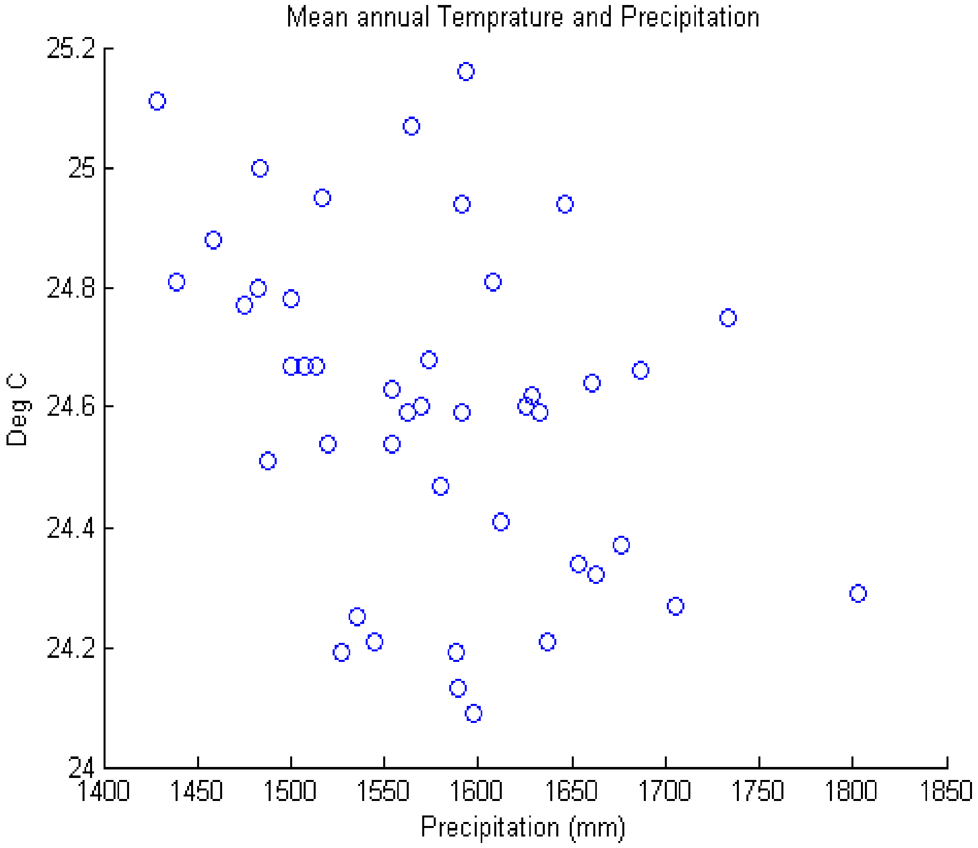

Figure 2 Scatter plot of annually averaged temperature and precipitation from EU-WATCH forcing data for the period 1958-2001.

3.1. CHANGES IN THE HYDROLOGICREGIME

Possible changes in the hydrologic regime, expressed in annual average changes in hydrologic climate derivers (temperature and precipitation) and derived hydrologic parameters (runoff, evaporation and river discharge) for the Congo River basin, are discussed below. Indices for future temperature and precipitation extremes are also included to visualize future trends in climate variables and derived hydrologic components. Hydrologic regime change signatures are summarized as graphical and tabular representation. Multi-model ensemble approach was used to quantify these changes.

3.1.1. MEAN TEMPERATURE CHANGES

Figure 2 (page 7) shows a scatter plot of annual mean temperature and precipitation for the historical period (1960-2000) averaged over the entire Congo River basin. Average annual temperature is about 25 °C st.div. 0.28 °C and average annual precipitation is 157 cm st.div. 8cm. The wettest year is 1961 (182 cm) and the driest year is 1998 (142 cm), the warmest is 1987 (25 °C) and the coldest is 1964 (24 °C) indicating that annually precipitation and temperature are not correlated. The GCMs and emissions scenarios used in the IPCC/AR4 Fourth Assessment Report (Table 2) to reproduce the observed seasonal cycle and 20th century warming in the Congo River basin, shows a higher warming for the 21st century. A plot of mean annual bias in temperature and precipitation can be found in Appendix 2.

Table 2 List of AOGCM simulations based on the IPCC SRES A1B and 20C3M

Model Name	Originating group	Model resolution
CNRM-CM3 (CNCM3)	Météo-France/Centre National de Recherches Météorologiques, France	T42L45
ECHAM5/MPI-OM (ECHAM5)	Max Planck Institute for Meteorology, Germany	T63L31
IPSL-CM4 (IPSL)	Institut Pierre Simon Laplace, France	2.5 X 3.75L19

For the global average, many GCM models simulate a warming rate of 0.6°C warming observed in the 20th century. At the regional and large river basin scale, like the Congo River basin, the warming rate could be dominated by changes in atmospheric circulation rather than greenhouse forcing. Nonetheless, the GCM models used in this study for control climate simulate a warming in the order of 0.5°C during the 20thcentury which is comparable to the global 20th century temperature trend (Table 3).

Comparison of future temperature projections per model (Ap. 2) displays a varying degree of warming; still a consistent upward trend across the river basin for the 21stcentury is visual. Rates of warming range from 0.5 to 2°C per decade from the minimum to maximum projections. The three GCMs show an increase in surface air temperature throughout the 21st century. The IPSL model shows the greatest increase in warming, under both the A2 and B1 emissions scenarios with more extensive warming under A2. The multi-model average warming, compared to the 1960 – 2000 historical mean, is 1.8°C (A2) 1.5°C (B1) in 2050 and 4.0°C (A2) 2.4°C (B1) in 2080.

Historical climate temperatures peak at 26°C in March and drops to 23°C in August and then increases back up to 25°C on November. For the climate control, all the GCMs captured the annual cycle very well with both amplitude and timing being well-simulated with more than 0.9 correlation coefficients. IPSL is slightly warmer (warm bias) than the historical observation (Ap. 3).

These monthly variability patterns are consistent in the future climate projections shown in Appendix 3. All models predict an increase in average annual temperature, ranging from 0.9°C to 6.3°C. The magnitude of seasonal increase however differs for each model. For example the warmest climate model IPSL, there is a difference of 1.2°C and 3.0°C in the month of November and April for A2 and 1.0°C and 2.9°C for July and March for B1 emissions scenarios.

Although there are no detailed comparable studies for the CRB, reviews from future temperature projection derived from Global Circulation Models (GCMs) show a general consensus on the rise of temperature across the African continent (IPCC, 2007, Bates *et al*., 2008). Future warming across the continent is projected ranging from 0.2°C up to 0.5°C per decade (Hulme *et al*., 2001). This warming will be greatest in the semiarid margins of the Sahara and central southern Africa. IPCC, 2007 summarized that from the various emission scenarios, large regions of Africa and more particularly the Sahel and part of southern Africa will experience warming in the range of 3 to 6°C by 2100.Together with the rising temperatures, significant changes in precipitations will severely affect North Africa, the Sahel and southern Africa. Precipitations might decline by more than 20% compared to levels of 1990. Depending on the scenario used, global annual mean surface air temperature for the period 2080-2099 is expected to increase 3 - 4°C compared with the 1980-1999 period. Even though less warming in expected around the equatorial and coastal areas (Christensen *et al.*, 2007), temperature may increase up to 9 °C in other parts of Africa (e.g. north Africa during the summer).

GCM driven temperature distribution for the A2 and B1 emission scenarios reproduced a spatial pattern for the CRB comparable to the historical data. The models show similar spatial temperature distribution for both emission scenarios, compared to the historical data, with exception of a band of warmer temperatures between 5-10N.

Table 3 Summary of changes in precipitation , evapotranspiration and runoff across the Congo River basin using climate change scenarios (30-year average changes not weighted) for the 2050s and 2080s, for SRES A2 (high) and B1 (low) emissions scenarios expressed as percentage change of the historical base simulation (1960 – 2000).

GCM	**Precipitation**				**Evapotranspiration**				**Runoff**			
	A2		**B1**		**A2**		**B1**		**A2**		**B1**	
	2050	2080	2050	2080	2050	2080	2050	2080	2050	2080	2050	2080
CNCH-CM3	8	12	10	6	8	11	8	9	12	15	10	9
ECHAM5	6	21	8	15	13	17	3	5	16	60	24	42
IPSL4	11	9	5	13	9	12	9	11	19	6	-3	20
Avg	8	14	8	11	10	10	7	8	15	27	10	23

3.1.2. MEAN PRECIPITATION CHANGES

Despite consistent trends in future temperature increases for the CRB, future precipitation projections are highly variable and uncertain. Precipitation has various modes of seasonality and inter-annual variability depending on the location of the specific sub-basins with respect to the Equator. Appendix 2 shows a time series of annual anomalies of precipitation (20th and 21st century). Despite the wider inter-model dispersion in the 21st century projections (outlying IPSL (dry) and CNCM3 (wet) GCMs, there is substantial evidence in support of an increase in the amount of precipitation throughout the 21st century. As illustrated in table3, there is a positive trend in the multi-model ensemble average precipitation changes by 2050 and 2080s. All the changes are significant relative to observed levels of decadal variability. The multi-model projected average annual precipitation increases by [15%(24cm) , 12%(20cm)] by 2050 and [23%(37cm) , 18%(28cm)] by 2080 for the [A2, B1] emissions scenarios compared to the historical annual mean of 1960-2000 . To allow a concise spatial interpretation and easy assessment of the spatial pattern of the projected changes, spatial maps of the distribution of hydrologic variables are shown in Appendix 4.5 and 6. Including the rate of changes in precipitation from the historical average for each time horizon in each panel for A2 and B1 emissions scenarios. The sharp precipitation increase in the Congo River basin emerges in the early part of the 21st century and in most cases is a reversal of the drier conditions experienced towards the end of the last part of 20th century (ERA40). It is important to note that the observed trend derived from the ERA40 historical data over the last decade of the 20th century is opposite to the long-term GCMs simulated trend. This can be due to the decadal variability which is opposed to the long-term trend in the GCM models, or due to GCM deficiencies in simulating regional specific hydro-climatologic characteristics. The current generation of models indicate that in the tropics precipitation maxima generally increase with a warmer (IPCC 2007 WG1 Ch.10). The multi-model projects in general a trend towards predominantly positive precipitation anomalies through the 21st century.

Although the three GCM models accurately simulate the spatial distribution of precipitation over the entire basin (Ap. 4), it also shows strong correlation when comparing the annual cycle to the ERA40 driven observation data. The monthly observed precipitation over the Congo River basin shows two peaks around October and November and a relative minimum on June and July (Ap. 3). This minimum is explained by Adegoke and Lamptey (2000) as a result of lower SST and divergence of specific humidity. The two peaks are connected a low-pressure system caused by the migration of the ITCZ resulting in instability in equatorial Africa during these periods.

The GCMs show two peaks but in some cases (*e.*g. ECHAM5) the second peak is shifted to November, as opposed to the historical max in October. Given this discrepancy, monthly variability of precipitation from the GCMs is strongly correlated to the ERA40 observations. There is a considerable global and regional consensus between observational and modelling studies, who are suggesting an increase in vertically-integrated atmospheric water vapour as the tropical wet climate continues to warm (Trenberth *et al.*, 2005; Zveryaev and Allan 2005). Related to this is a robust projection of precipitation increase in the deep tropics that feeds most of the Eastern Africa and Equatorial rain forest region, which has been detected in the current climate (Zhang *et al.*, 2007). The annual precipitation increase in the Congo River basin is in the order of 10% per °C for both emissions scenarios, which is comparable to the tropical climate projected precipitation increases of 7% per °C in precipitable water, which follows the Clausius-Clapeyron relationship (Vecchi and Soden 2007).

Table 4 Definitions of the indices of cold and warm temperature extremes and the indices of precipitation extremes used in this study. The abbreviation and definitions follow the standardization of the CCL/CLIVAR Working Group on Climate Change Detection (Peterson *et al.,* 2002)

Indices	Definition	Units
Txq10	Tmax 10th percentile	°C
Txq90	Tmax 90th percentile	°C
Tnq10	Tmin 10th percentile	°C
Tnq90	Tmin 90th percentile	°C
Pq10	10th percentile rainy amounts	mm/day
Pq90	90th percentile rainy amounts	mm/day
Px3d	Greatest 10 day total precipitation	mm
Pn10mm	Number of days (per year) with precipitation amount >10 mm	days

3.1.3. CHANGES IN CLIMATE EXTREMES

In this section we document future changes in temperature and precipitation extremes as simulated by three GCMs and two SRES emissions scenarios. Changes in warm and cold temperature extremes are compared to the corresponding changes in the maxima and minima of the annual cycle, that is, the mean temperature of the climatologically warmest and coldest seasons. Relative changes in extreme precipitation are compared to changes in annual mean precipitation. Changes in both seasonal and annual temperature and precipitation extremes are likely to have a greater impact on a range of biophysical and land surface systems than a change in the mean climatology. Sixteen of the 27 indices recommended by the ETCCDMI are temperature related and eleven are precipitation related. They are derived from daily maximum and minimum temperature and daily precipitation. A full descriptive list of the indices can be obtained from http://cccma.seos.uvic.ca/ETCCDMI/list_27_indices.html.

We have chosen four temperature and four precipitation indices (Table 4) for the purpose of this study. The indices were chosen primarily for assessment of changing regional climate aspects derived from GCMs which include changes in intensity, frequency and duration of temperature and precipitation events. In addition to assessing multi-model mean changes, analysis of extremes is also important in regions with greater susceptibility to climate change which is discussed in detail in the subsequent section. The probability of value range and occurrence of precipitation, evapotranspiration, temperature and runoff are shown for the entire Congo River basin.

A) TEMPRATURE-BASED EXTREMES

For temperature extremes analysis, we used percentile-based indices which include occurrence of, 10th percentile of minimum temperature (Tn10), 90th percentile daily minimum temperature (Tn90), 10th percentile in daily maximum temperature (Tx10), and 90th percentile daily maximum temperature (Tx90) (Table5 and 6). The percentile-based temperature indices sample the coldest and warmest deciles for both maximum and minimum temperatures. This enables the evaluation of the extent to which extremes are changing. In general when averaged over the entire Congo River basin, almost all of the temperature indices show significant changes during the 1960-2000 historical period.

Changes in the absolute temperature indices are more complex to assess as they do not necessarily appear as a simple shift in the distribution. However, in general the future period does appear warmer and wetter than the 1960-2000 periods. For five of the temperature and four of the precipitation indices we are also able to assess changes in seasonal values. Warming of minimum temperature extremes is apparent during all seasons although changes in JJA are generally more pronounced, with generally the least amount of changes in DJF. All the investigated temperature indices showed annual and seasonal variability. Consistent with the basin wide increases in mean annual temperature, both the annual and seasonal daily minimum temperature were found to become more extreme than the daily maximum temperature shown in Appendix 5.

Table 5 Mean indices of two future periods over the 1960 - 2000 baseline periods for the entire Congo River basin anomalies. Temperature threshold indices are in (°C), Px3d in mm and Px10mm in days for A2 emissions scenarios

Indices	**DJF**		**JJA**		**ANN**	
	2050	**2080**	**2050**	**2080**	**2050**	**2080**
Tx10	1.32	2.98	1.6	3.55	1.36	3.44
Tx90	1.31	3.24	1.44	3.5	1.40	3.58
Tnq10	1.40	3.57	1.90	4.3	1.77	4.10
Tn90	2.05	4.31	2.18	4.6	2.18	4.54
Pq10	0.2	0.06	0.12	0.03	0.01	0.00
Pq90	3.5	2.34	3.32	2.28	4.9	3.00
Px3d	34.43	47.3	37.40	43.0	21.42	34.71
Pn10mm	1.93	3.5	7.69	11.29	5.23	7.37

By 2080 the highest average increase in the 90th percentile daily maximum temperature was observed in the summer (JJA), 3.5 °C (A2) and 2.3 °C (B1) (Table 5 and 6). The summer, JJA, 90th percentile daily minimum temperature increased by a higher amount (4.6 °C and 2.8 °C) for A2 emissions scenario for the same period. Similarly, the 10th percentile daily minimum also showed a greater increase in summer than in winter: 3.6 °C (A2) and 2.1 °C (B1). In Appendix 5 shows the winter (DJF), summer (JJA) and annual (ANN) anomalies in the 90th percentile daily minimum and maximum and 10th percentile daily minimum and maximum temperatures for A2 future period 2071-2100.

Table 6 Mean indices of two future periods over the 1960 - 2000 baseline periods for the entire Congo River basin anomalies. Temperature threshold indices are in (°C), Px3d in mm and Px10mm in days for B1 emissions scenarios

Indices	**DJF**		**JJA**		**ANN**	
	2050	**2080**	**2050**	**2080**	**2050**	**2080**
Tx10	1.44	1.82	2.26	2.26	1.19	2.12
Tx90	1.05	1.87	2.07	2.07	1.26	2.06
Tn10	1.05	2.10	2.41	2.41	1.49	2.32
Tn90	1.76	2.76	2.77	2.77	1.83	2.86
Pq10	0.00	0.15	0.05	0.05	0.00	0.03
Pq90	2.22	2.90	2.61	2.89	2.92	3.85
Px3d	34.43	41.5	43.0	37.4	20.4	21.8
Pn10mm	1.93	2.02	7.6	10.7	3.71	4.51

Table 7 summarizes the linear trend analysis using Kendall's tau test with the associated level of significance for the extreme temperature indices investigated in this study. In all the seasons (DJF and JJA) and annual time scales, both the 10^{th} and 90^{th} percentile daily minimum and maximum showed increasing trends for the entire 21^{st} century (95% confidence level).The magnitude of the trends is also generally greater for minimum temperature both in JJA and annual time scale by 2080 (Table 7). Appendix 6 shows the seasonal results for the annual average changes trends in Minimum and maximum temperature for the entire future period (2010-2100), showing significant increase in minimum temperature as compared to maximum temperature. Maximum temperatures exhibit a similar pattern of change although the magnitude of warming is much when compared to the minimum temperature. This has led to a significant decrease in DTR during the entire 21th century (Ap. 6). Trends for the temperature indices are shown in Table 7.

Table 7 Kendall's tau test for statistical significance of temperature extremes

Temperature Indices	DJF		JJA		ANN	
	A2	B1	A2	B1	A2	B1
Txq10	0.74 (12)	0.61 (11)	0.78 (12)	0.67 (11)	0.81 (12)	0.72 (11)
Txq90	0.76 (11)	0.62 (10)	0.85 (11)	0.66 (11)	0.80 (11)	0.74 (10)
Tnq10	0.82 (19)	0.72 (17)	0.85 (20)	0.72 (17)	0.88 (19)	0.79 (17)
Tnq90	0.77 (17)	0.77 (15)	0.82 (18)	0.74 (16)	0.91 (16)	0.80 (15)

With warm extremes increasing and cold extremes decreasing, these series clearly indicate significant warming. The warmest day and night of the year is warming at a rate approximately comparable to the global average. The coldest day and night of the year in the Congo River basin is warming faster than the global average. The diurnal temperature range which is decreasing globally is decreasing at slightly higher rate within the entire Congo River basin (Ap. 6).

There are not many studies on extreme climate analysis of future climate change using the SRES scenarios for the Congo River basin domain. A study by Aguilar *et al.* (2009) using observed station data for the historical climate is one of the major works in this area. The study concluded that for the majority of the temperature indices, the Central region of central Africa exhibits the greatest warming. Trends in quarterly percentile indices time series, extracted from standard seasons, highlight some differences across the year. Central has significant trends in the four indices in all four seasons, with larger slopes on average during June–July–August (JJA). For Guinea, trends are larger between June and November for daytime metrics and larger during March–April–May (MAM) for nighttime values. No significant trends are found during December–January–February (DJF).

In summary, the mean, maximum and minimum values of daily maximum and minimum temperatures showed overall increasing trends. While the DTR was significantly decreased starting from the late 20th century. The maximum temperature has risen significantly since the 1990s, while the minimum temperature began to rise steadily in the late 1970s, and the trend became more prominent in the late 1990s and entire 21st century. Because of the asymmetry of maximum and minimum temperature variations, DTR experienced a significant decline, beginning late 20th century followed by the entire 21st century (Ap. 6).

B) PRECIPITTAION-BASED EXTREMES

The temperature percentile-based indices sample the coldest and warmest deciles for both maximum and minimum temperatures, enables evaluation of the extent to which extremes are changing. The precipitation indices in this category represent the amount of rainfall falling above the 90th representing very wet days or 90th percentile rainy amounts (Pq90) , 10th percentiles representing the highest bound of the dry days or 10th percentile rainy amounts (Pq10), three day maximum total precipitation (Px3d) and number of days in excess of 10mm threshold (P10mm). In the Congo River basin for two future periods centred at 2050 and 2080 under SRES A2 and B1scenarios, Pq10 shows little change in all seasons (DJF and JJA) and annual time scale, Pq90 shows significant increases from the mean historical climate.Px3d and P10mm show substantial increases in

DJF and JJA, with JJA changes relatively higher than DJF implying that in the Congo River basin there are heavier precipitation events in summer (JJA), and the chance of flood occurrence increases.
Time series and trends in precipitation-based indices of heavy precipitation (Px3d and P10mm) in the Congo River basin in DJF, JJA and ANN under SRES A2 scenario are shown in Appendix 5. The increasing spread in the models' future (21st century) projections is related to the sensitivity of the standard deviation the outlier (notably the CNRM-CM3 model). Notwithstanding a notable upward trend is projected by a large fraction of the multi-model ensemble across the Congo River basin.There is an increasing trend in JJA three day total precipitation (Px3d) and precipitation above 10 mm threshold (P10mm) using the A2 emissions scenarios by 2080 and with relatively weak signal in DJF. The trends in precipitation indices show two distinct characteristics, decreases in CDD (Consecutive Dry Days) and increases in CWD (Consecutive Wet Days). Heavy precipitation indices in general show significant increases both percentile based 90th percentile shown in tables and figures and (95% and 99%) not shown and intensity based indices Px3d and P10mm consistent with the global average projections from multi-model ensembles (IPCC, 2007). The results differ from E. Aguilar *et al.,* (2009) who analysed using historical climate, but our results are consistent with global projections. Aguilar *et al.*, 2009 explained why the calculated indices are likely associated with the decrease in total precipitation and concluded the length of the maximum number of consecutive dry days is increasing in Guinea and the length of the maximum number of consecutive wet days shows a significant decrease in Central.

The annual trend is dominated by JJA clear increasing trend (Ap. 5). Similar results are shown for B1, with relatively weak signal in future trend, despite increases in the mean distribution of px3d and P10mm (Table 4 and 5). Therefore, the present condition of heavy precipitation and floods in summer JJA in the Congo River basin is significantly changed in future. While in winter (DJF) it is possible that there will be less extreme precipitation. The mean values of both indices (Px3d and P10mm) are significantly shifted as compared to the historical 1960-2000 mean values (Table 4 and 5).

3.1.4. EVAPORATION

The VIC model in combination with six different climate scenarios was used to estimate the impacts of climate change on evaporation. As explained above, for the climate scenarios we used the bias corrected output of three different climate models using a low (B1) and a high (A2) emission scenario (*see* Table 2). The model simulation outcomes indicated that climate change will result in increased evaporation throughout the basin (Figure 3). The change is quiet evenly distributed throughout the basin but the increase in evaporation will be slightly higher towards the edges compared to the central Congo basin (Figure 3). On average, the increase in evaporation by the end of the century will be about 10% for the A2 emission scenario and 8% for the B1 Scenario (Table 3). The different climate models gave similar results (Figure 4) and for all six scenarios the evaporation increased.

Increased evaporation as a result of climate change is reported in many other studies, especially if the rainfall is increasing. Due to higher atmospheric temperatures, the water-holding capacity of the atmosphere is increasing which results in higher evaporative demand (Bates et al., 2008). The higher evaporative demand or potential evaporation results in higher evaporation in the Congo basin because also soil moisture is increasing as a result of higher rainfall (Table 3). It is important to note here that the VIC modelling framework used for this assessment does not include the direct impact of CO_2 enrichment on plant transpiration. Higher CO_2 concentrations reduce plant transpiration because the leaf stomata, through which transpiration takes place, have to open less in order to take up the same amount of CO_2 for photosynthesis (Lambers et al., 1998). It is thus possible that VIC over estimates the impact of climate change on total evapotranspiration. The LPJml model used in Chapter 3 does include this direct impact of CO_2 on plant evaporation and as a result the estimated evaporation in a changing climate tends to be lower for LPJml compared to the VIC model.

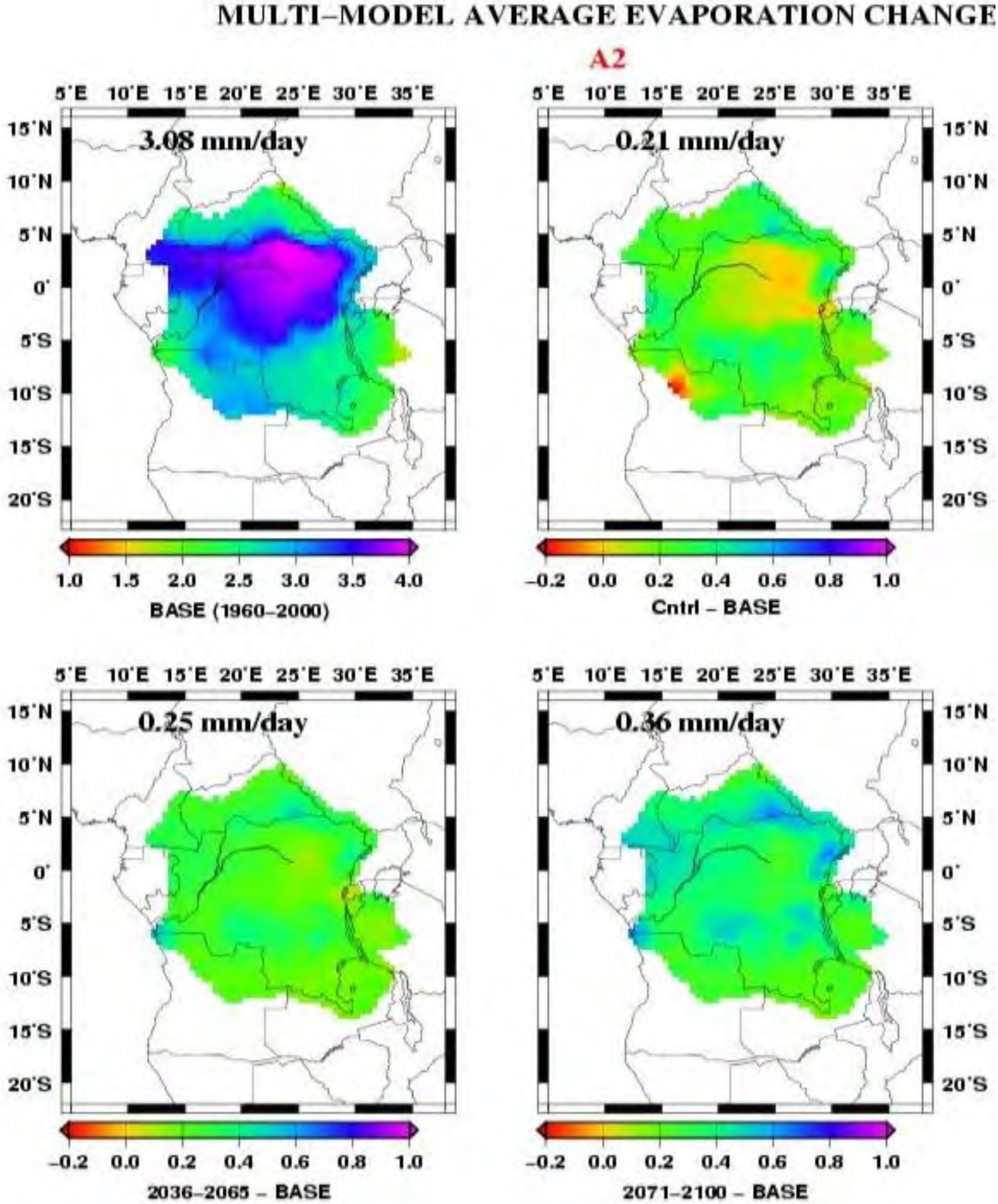

Figure 3 Spatial distribution of historic simulated evaporation (top let panel) and multi-model average projected changes in future evaporation. Results are shown for the control periods of the climate models versus the base line analyses using the Watch Forcing Data (top right panel). Result for the future periods are shown in the bottom left panel (2036-2065) and bottom right panel (2071-2100). For the future analyses the A2 emissions scenario was used.

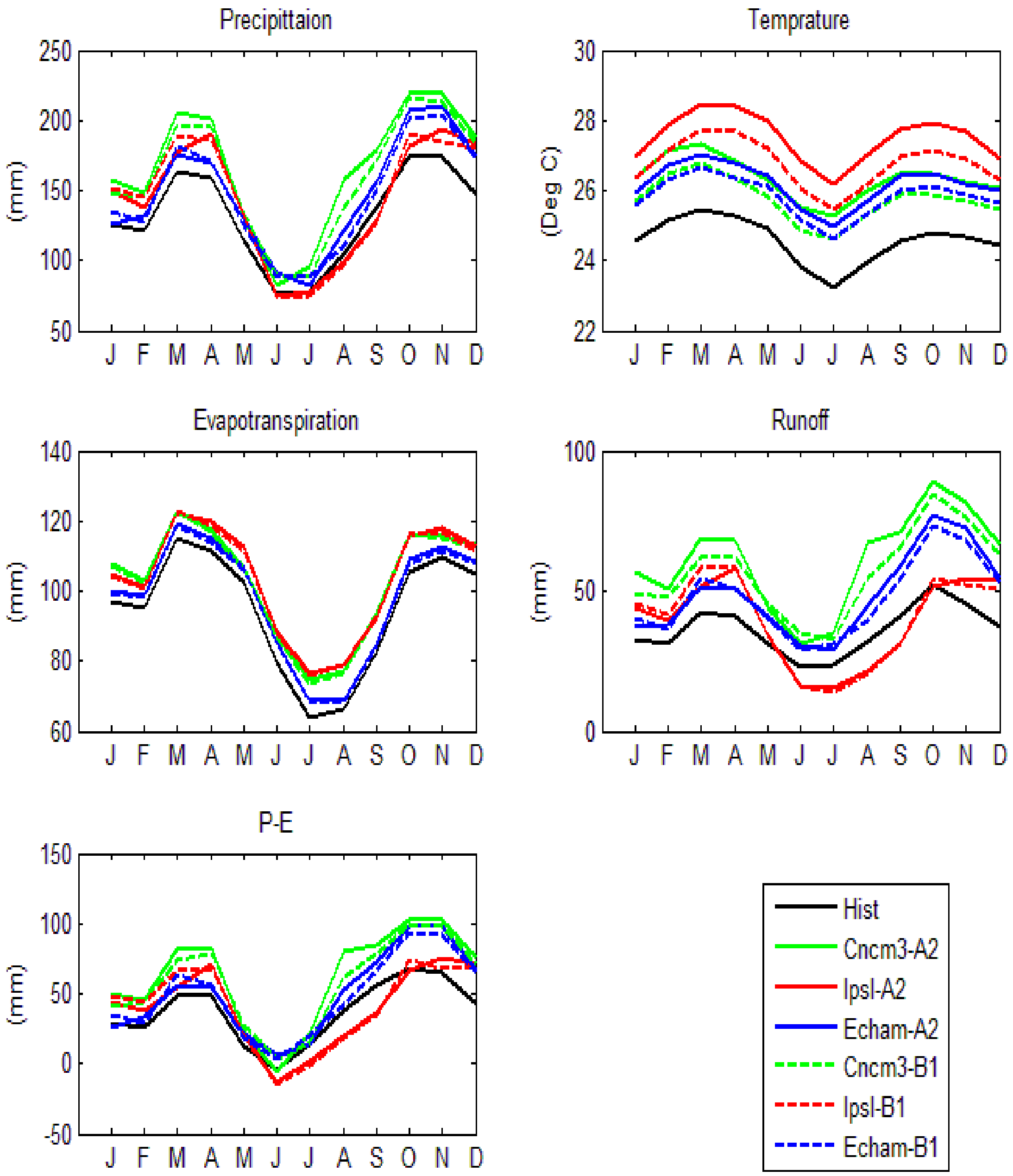

Figure 4 Mean seasonal cycle of precipitation, temperature, evapotranspiration, runoff, P-E, for each of the six climate scenarios All data area averaged over the Congo River basin for the period 2071-2100 (for historic period see annex..).

3.1.5. RUN-OFF

All the six climate change scenarios used in the analyses for this chapter show a basin average increase in both rainfall and evaporation (Table 3). However the total increase in rainfall tends to higher than the increase in evaporation and a result in most scenarios the run-off is increasing (Table 3). The increase in run-off is not evenly distributed throughout the basis (Figure 5). Run-off is especially increasing in central and western DRC and in Congo Brazzaville. Also the Cameroon part of the Congo basin shows a relatively high increase in run-off. On the Northern, Southern and Western edges of the Basin, the results are considerably different. Here the increases are marginal and sometimes the run-off decreases (Figure 5).

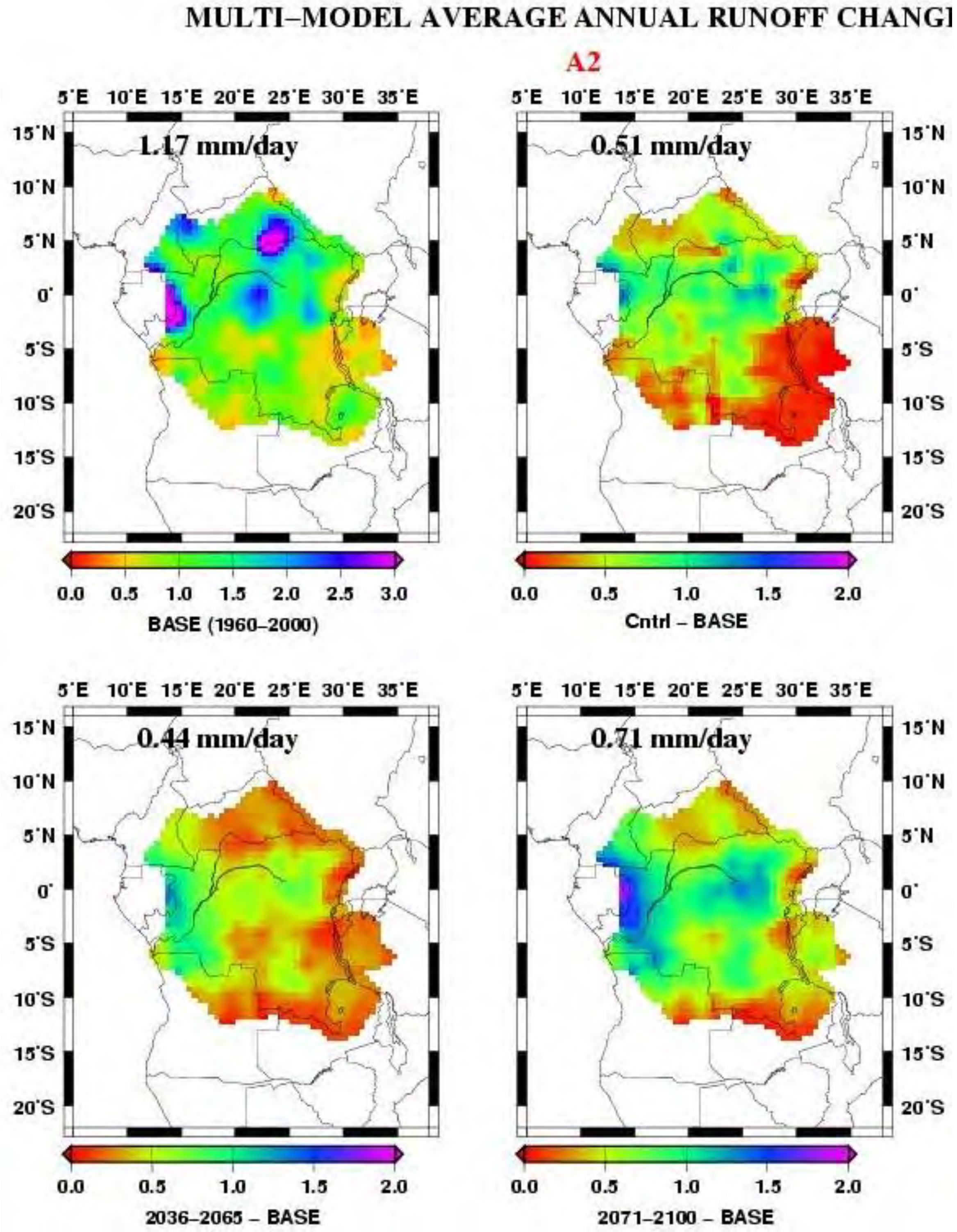

Figure 5 Spatial distribution of historic simulated run-off (top let panel) and multi-model average projected changes in future run-off. Results are shown for the control periods of the climate models versus the base line analyses using the Watch Forcing Data (top right panel). Result for the future periods are shown in the bottom left panel (2036-2065) and bottom right panel (2071-2100). For the future analyses the A2 emissions scenario was used.

On average, over the whole Congo basin, run-off is projected to increase by 15% by mid-century for the A2 scenario and 10% for the B1 scenario (Table 3). By the end of the century run-off is projected to increase with 27% for the A2 scenarios and 23% for the B1 scenario. For changes in run-off there was a large difference between the 3 different climate models used for the hydrological impact assessment (Table 3, Figure 4). The use of the ECHAM5 model results in the highest increase of run-off up to 60% by the end of the century for the A2 scenario. The IPSL4 model however showed a much lower increase in run-off. Depending on the time and the emission scenarios run-off increase is maximum 20% when the IPSL4 model outcomes were used. However, for mid-century using the B1 scenarios there even was a small decrease in run-off for the IPSL4 climate model (Table 3).

The changes in run-off also depend on the season. During the wet season all three climate models project an increase in run-off and the relative increase is also the highest (Figure 4) during the wet season. During the dry season, the IPSL4 and CNCM3 models project a reduction in run-off. The ECHAM5 model also showed an increase in run-off during the dry season. However, the increase in run-off during the dry season is lower than during the wet season, both in relative and absolute terms. For all three climate models the difference in run-off between dry and wet season are increasing indicating a more variable future hydrologic regime. Also on spatial scale the variability is increasing. Especially in the wetter central and western part of the Basin the run-off is increasing while at the drier edges the run-off is slightly increasing in some scenarios and decreasing in others.

Other previous studies on the impact of climate change on hydrologic characteristics of the Congo River basin show diverse results. Arnell (2003) showed a possible decrease in average changes in runoff over the Congo River basin by 2050, using a different set of climate models. Aerts *et al*. (2006) documented an increase in runoff of 12% in the Congo River basin by 2050 compared to the historical simulations. The African continent holds the lowest conversion factor of precipitation to runoff, averaging 15%. Although the equatorial region and coastal areas of eastern and southern Africa are humid, the rest of the continent is dry-subhumid to arid (IPCC, 2007). The dominant impact of global warming is predicted to be a reduction in soil moisture in subhumid zones and a reduction in runoff and current trends in major river basins indicate a decrease in runoff of about 17% over the past decade (Arnell, 2004, IPCC, 2007).

Table 8 Projected relative changes in annual average river flow at Congo-Kinshasa for two future periods expressed as percent change compared to the historical time period (1960-2000). For this analysis three different climate models were used in combination with a high emission scenario (A2) and a low emission scenario (B1).

Climate Model	2036-2065		2071-2100	
	A2	B1	A2	B1
CNCM3	20%	5%	27%	17%
ECHAM5	23%	28%	73%	46%
IPSL4	8%	1%	14%	18%
Multi-model average	17%	11%	38%	27%

3.1.6. DISCHARGE

Projected discharge or streamflow changes differ from those of runoff because runoff is a spatial quantity that is an integral part of the water balance at each hydrologic model grid cell and does not incorporate the time lag effects. Streamflow, however, is the culmination of hydrologic processes evaluated at a given location over time (Maurer *et al., 2008*). The VIC macro scale hydrologic model used in this study reproduced the observed discharges reasonably well for the Congo River basin at three of the gauging stations used in this study (Appendix 1). The long-term mean signatures of naturalized flow are higher than the GRDC observations. These deviations are partly due to the fact that the land surface hydrologic model used calculates naturalized flows and does not include water use for irrigation and other purposes by regulating reservoirs and dams. Our historical hydrologic simulation results using VIC are comparable to other global and regional studies in which Congo

River basin is one of the catchment. For example, a study by Sperna Weiland *et al. (2010*) reported ensemble routed naturalized flow of 46,990 m^3/sec with 8% bias level derived from 20th century (Control climate).

Before analysing the future impacts we compared the historical bias corrected output of the climate model with the simulations using the Watch Forcing Data (WFD) climate reference data set. These analyse showed that using the bias corrected data sets of the ECHAM5 and IPSL4 models represented the discharge analyses using the WFD data set (Figure 6). However for the CNCM3 data the bias correction still resulted in discharge which are much higher compared the analyses using the WDF.

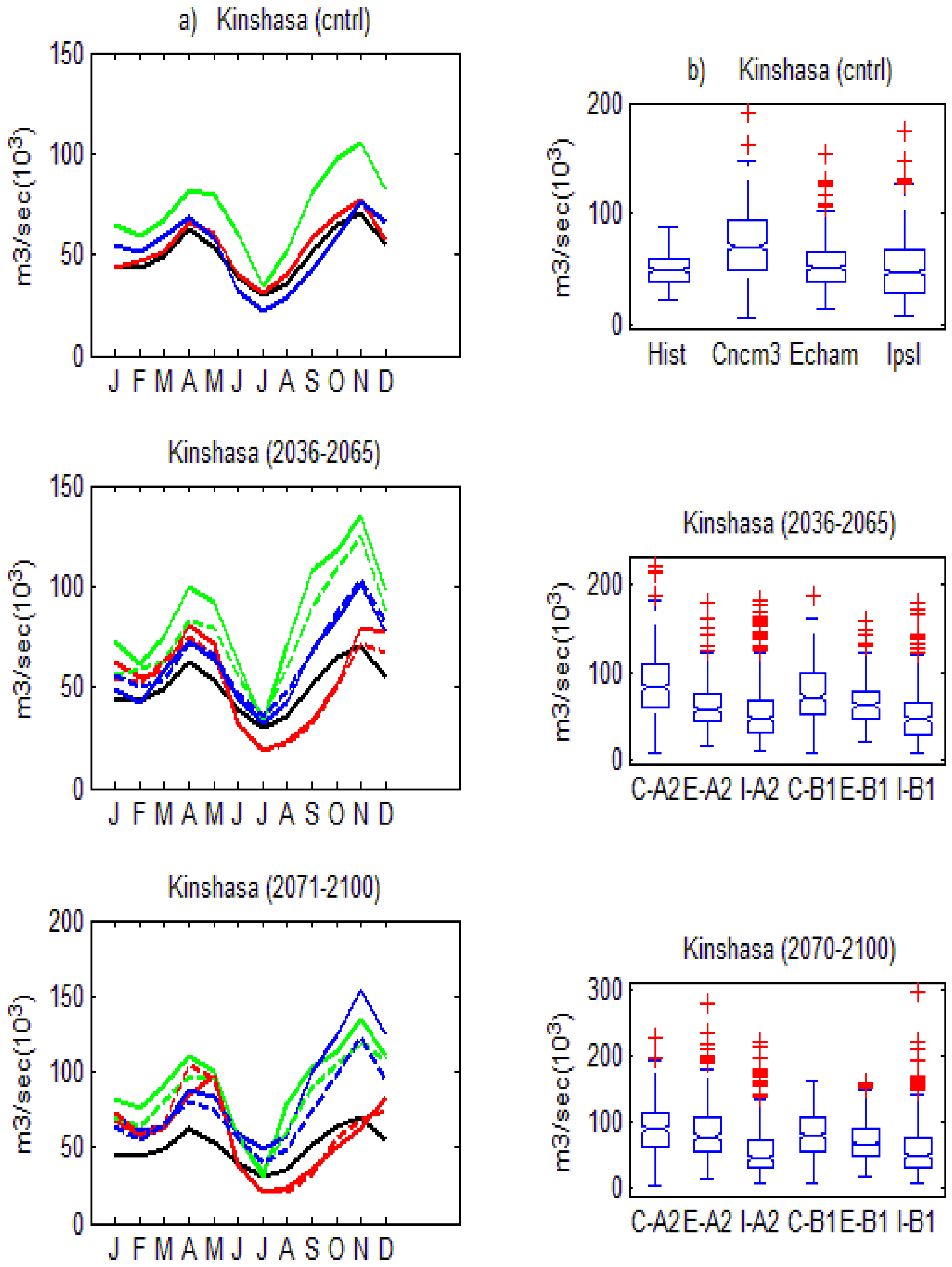

Figure 6 Historic and future simulated naturalized flow of the Congo River at Kinshasa. Top panels: derived from control climate and base simulation from three GCMs. for 2036-2065, bottom panels for 2071-2100. Observed flow from GRDC data is used as a reference flow. Straight lines are for the A2 scenario and dashed lines for the B1 scenario. For explanation of line colours see figure 4

Consistent with projected runoff changes, multi-model average annual flow at Kinshasa gauging station were projected to increase by [17% , 11%)] by 2050 for [A2 ,B1] emissions scenarios and [(38 % , 27 %)] by 2080 for A2 and B1 emissions scenario compared to the historical period (1960-2000) (Table 8). There was a large difference between the climate models in projected changes in discharge. The IPSL4 model showed the lowest increase in discharge with increases up to 18% by the end of the century. The ECHAM5 model showed the largest increase with a 73% higher discharge for the A2 scenario by the end of the century.

Increased changes in discharge are especially observed in the wet season. In October, November and December all analysed scenarios show an increase in discharge. In the dry season, however, both the CNCM3 and IPSL model indicate a reduction in discharge for the 21st century. Especially, the IPSL model shows a significant reduction in discharge from June until October. These results indicate that during the wet season river flows are likely to increase. During the dry season however results are more uncertain and flows could both increase and decrease. So while total water availability is likely to increase in the future this does not mean that droughts or low flow frequency will reduce in the future. For all scenarios the difference in discharge between the dry and wet season are increasing. This indicates that both wet and dry extremes could increase in the future.

4.0. SUMMARY AND CONCLUSION

Climate change will have a clear impact on the hydrological cycle of the Congo Basin. Climate change scenarios show an increase in temperatures of about 2 to 4 degrees by the end of the century. The six climate scenarios used in the hydrological analyses indicated increased rainfall across the basin. However the uncertainty in rainfall scenarios is much higher than for temperature and at the Northern, Southern and Eastern edges of the basin some scenarios show reduction in rainfall particularly during the dry season. Climate change also has an impact on the extreme rainfall. Especially the wet extremes will increase with climate change in the Basin.

These changes in rainfall and temperature resulted in significant changes in the hydrology of the Congo Basin. Due to temperature increases evaporation will also increase. The rainfall is however increasing much more than the evaporation and as a result the run-off could increase up to 50%. Run-off and stream flow will especially increase in the wet season. This indicates that flood risks will increase significantly in the future throughout the basin. Floods will however increase more in the central and western part of Basin.

While run-off and stream flow will clearly increase during the wet seasons during the dry season the scenarios show conflicting results. Some climate models indicate a drier dry season while other climate models also show higher flows during the dry season. What is clear from all model results is that the difference between wet and dry season will become larger compared to the current climate and especially the wet extremes will become more frequent and more intense.

In conclusion the region needs to prepare for a more variable climate and a more variable hydrological regime. Both the difference between seasons and between different years will become larger in the future. It is very clear that the region needs to prepare for more rainfall and probably floods during the wet season. The dry season could become both wetter and drier. In the drier parts of the basin it is more likely that dry seasons rainfall will decrease compared to the wet parts of the Basin.

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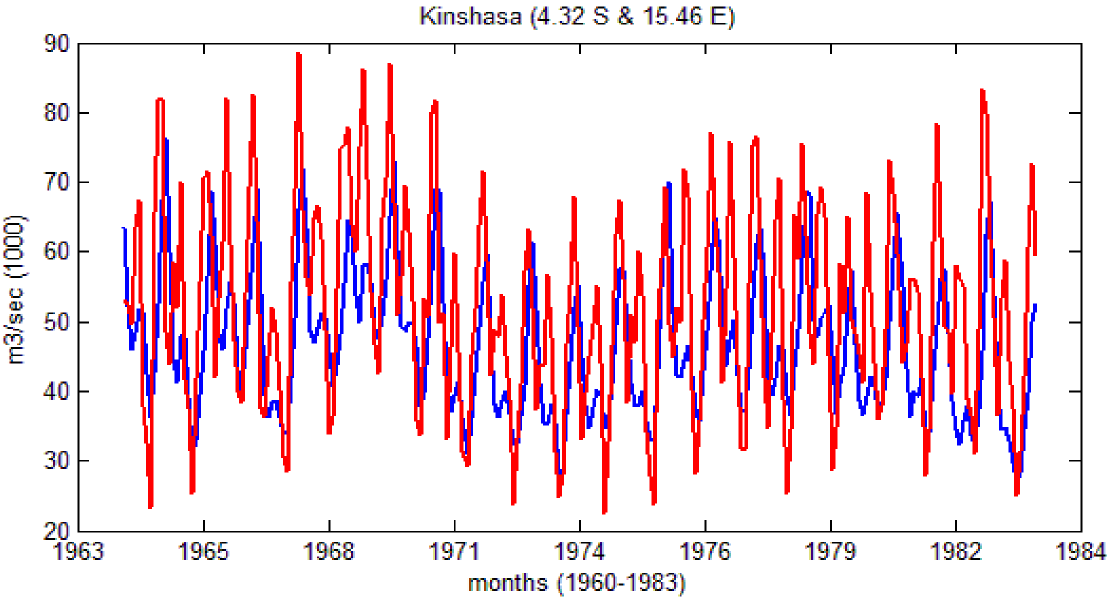
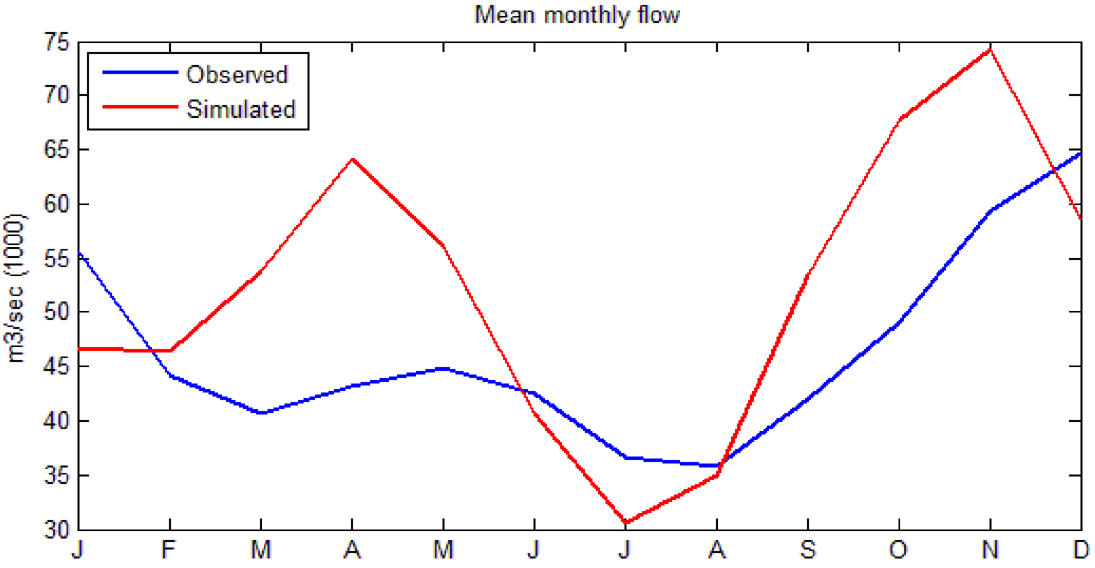
APPENDICES

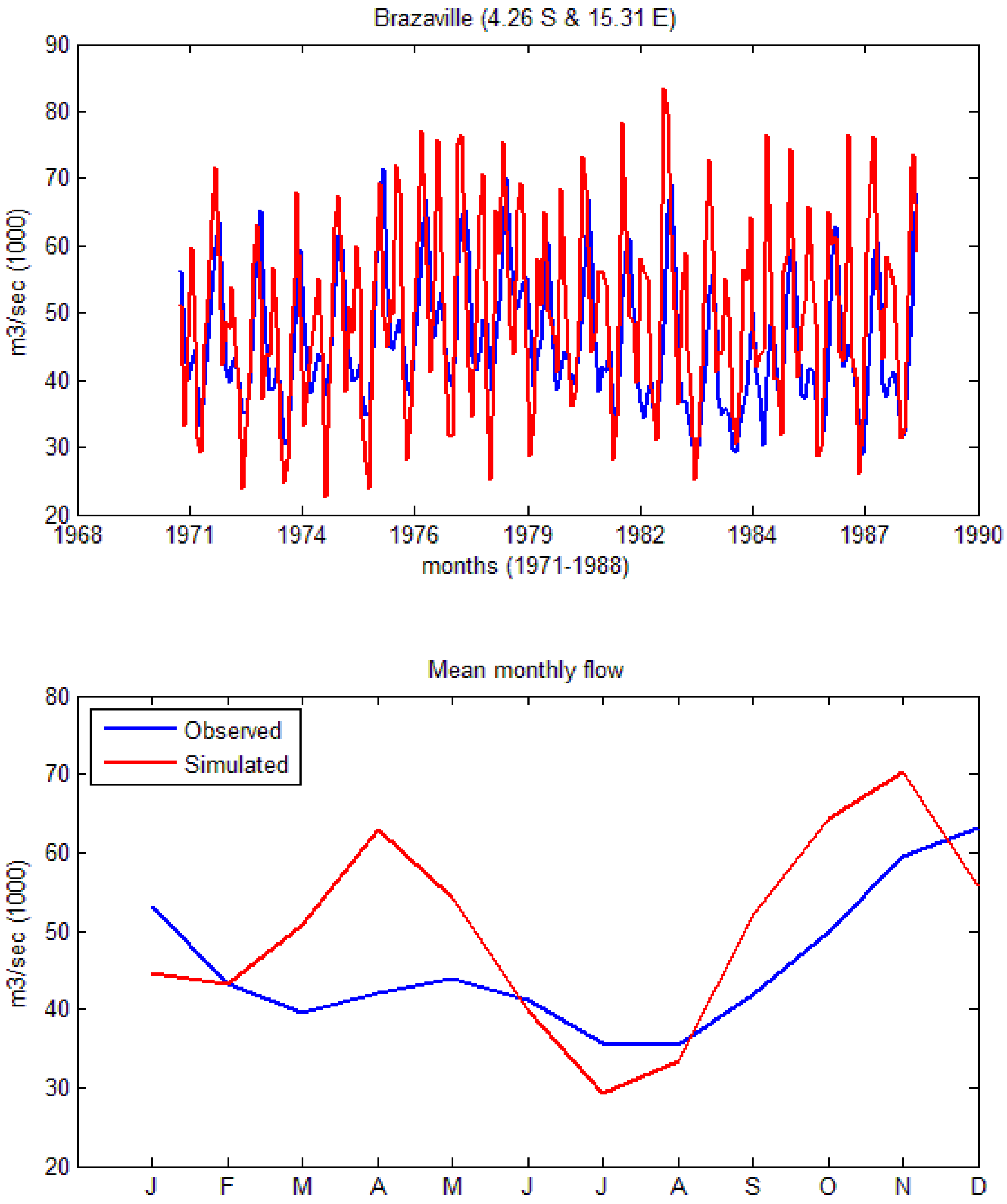
Appendix 1 Naturalized and observed Congo River flow

Naturalized and observed Congo River flow at Kinshasa gauging stations for the period 1962-1983.

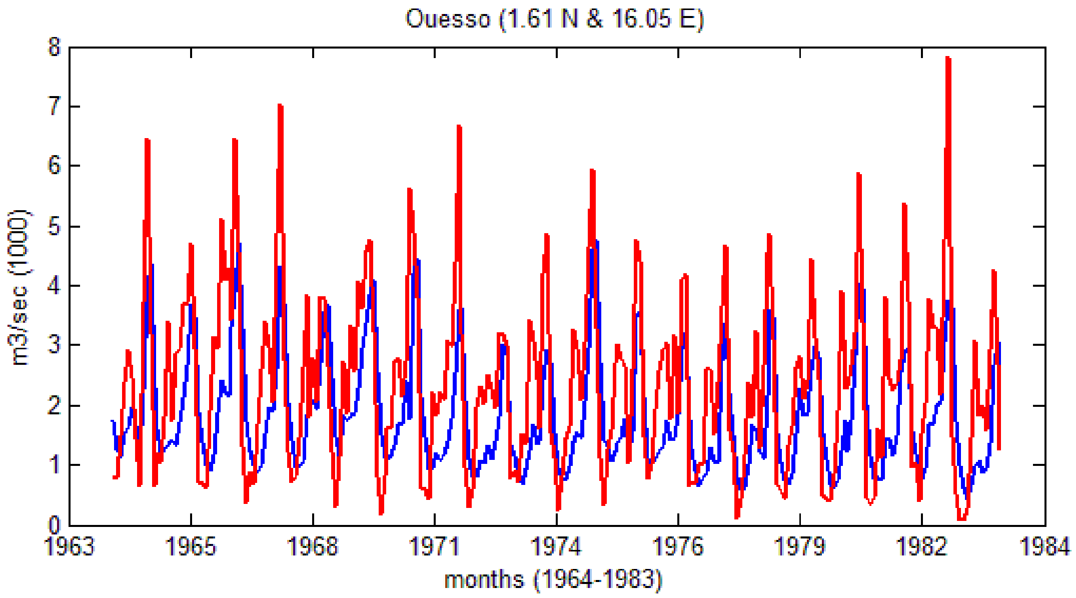


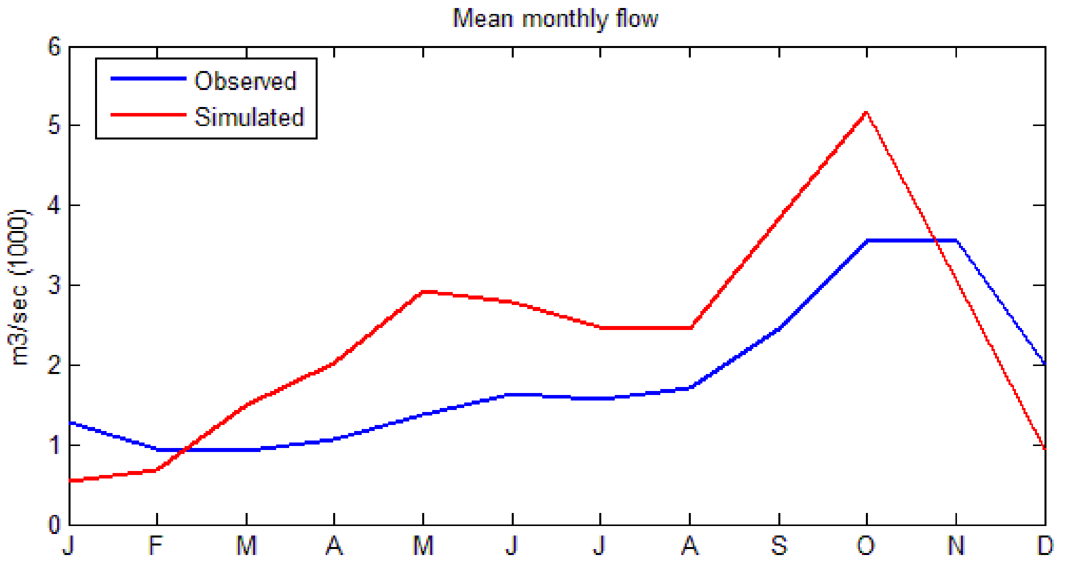


Naturalized and observed Congo River flow at Brazzaville gauging stations for the period 1970-1988



Naturalized and observed Congo River flow at Ouesso gauging stations for the period 1965–1983.Validationperiod shown excludes the period 1964–1983 used for model calibration

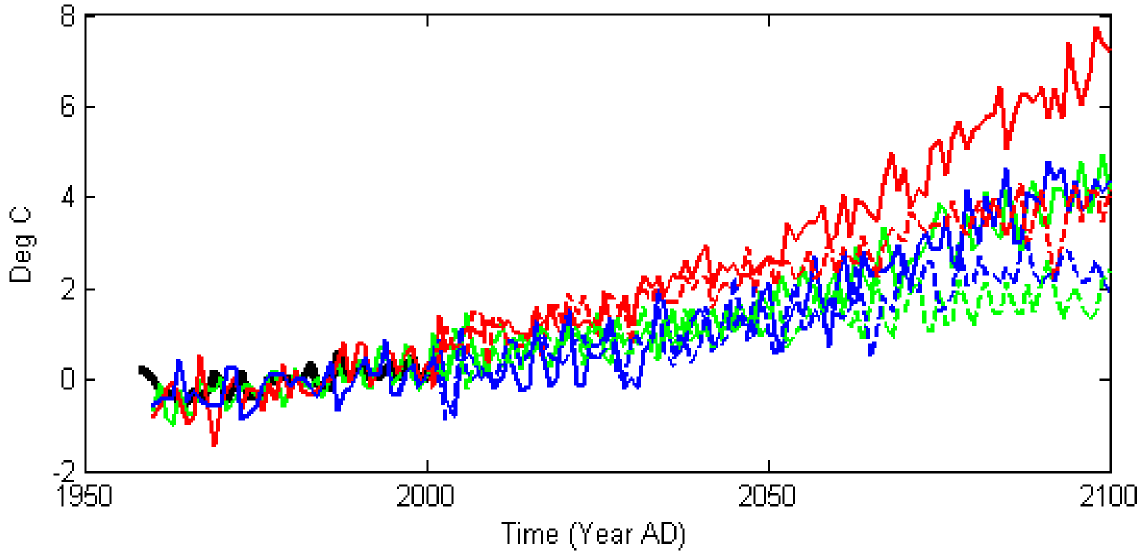




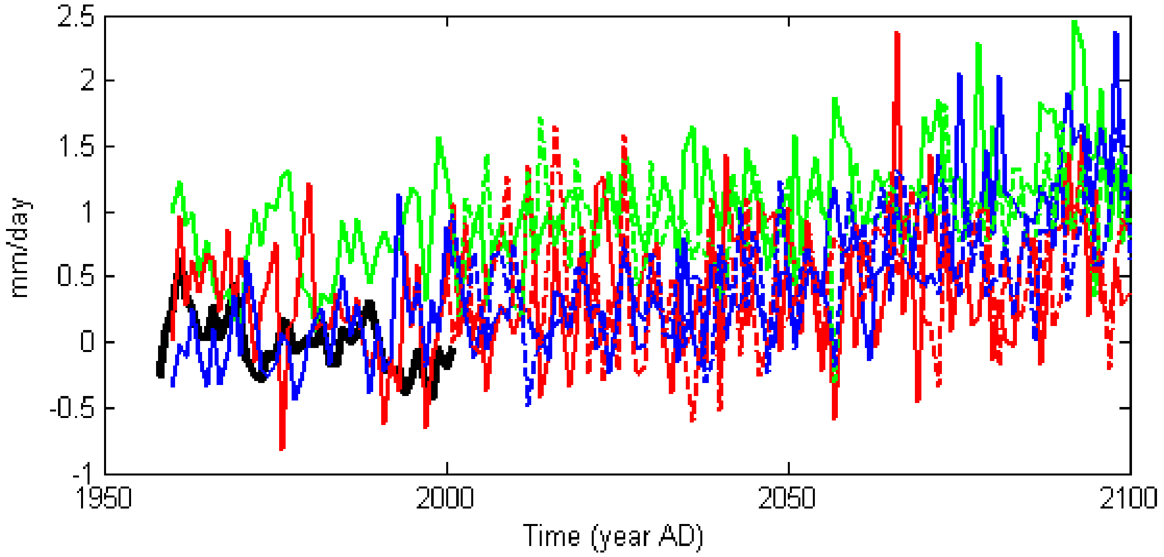
Appendix 2 Time series of mean annual temperature and rate of precipitation anomalies

Time series of mean annual temperature (a) and mean annual rate of precipitation (mm/day) (b) anomalies of three GCMs and two emissions scenarios. Note that while projections for temperature increase vary by the end of the century, all models show a clear upward trend. One of the GCMs shows different historical paths from 1960-2000.The thick black line indicates a time series of observed mean annual anomaly of historical (1960-2000) climate.

a) Temprature

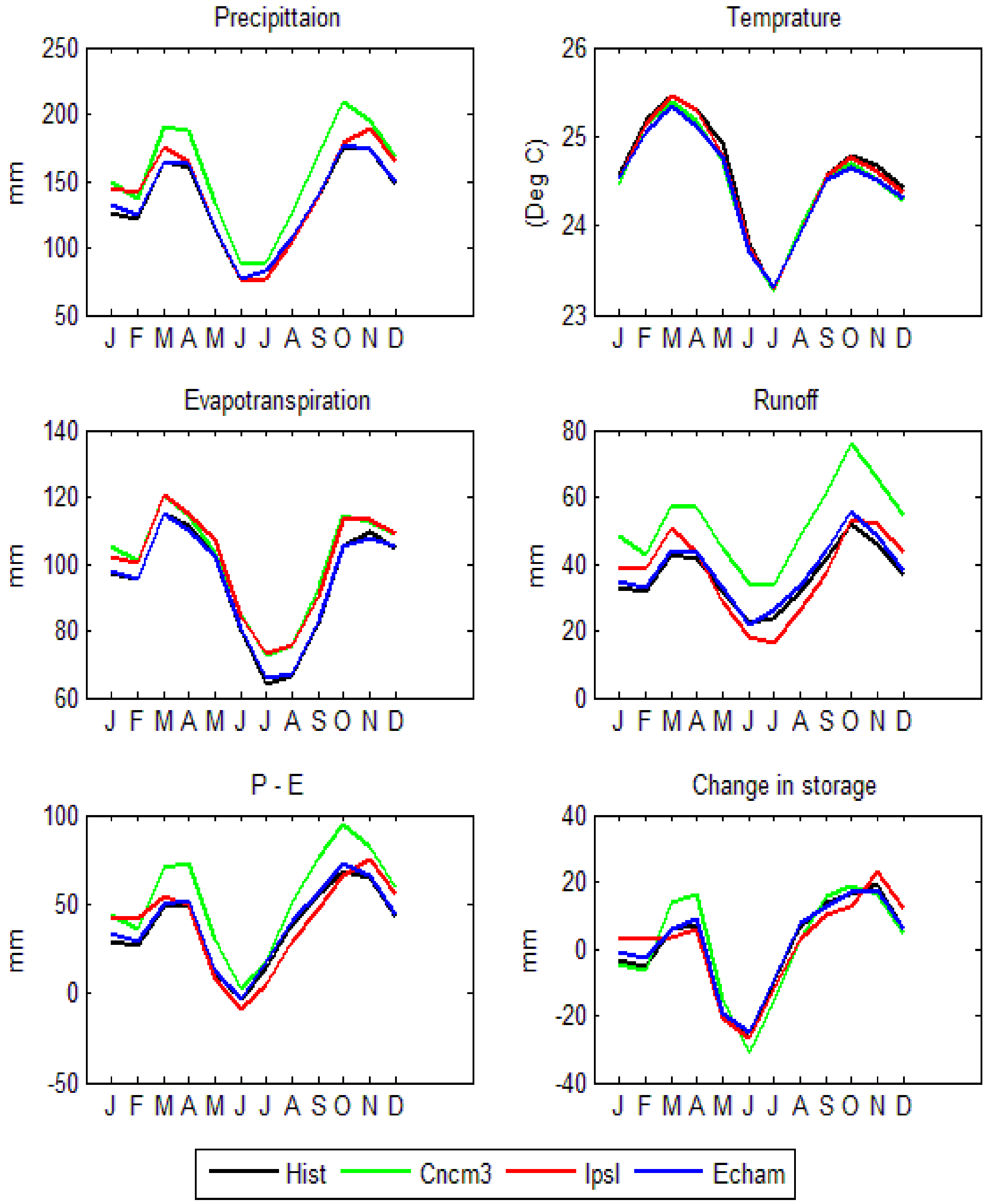


b) Precipitation

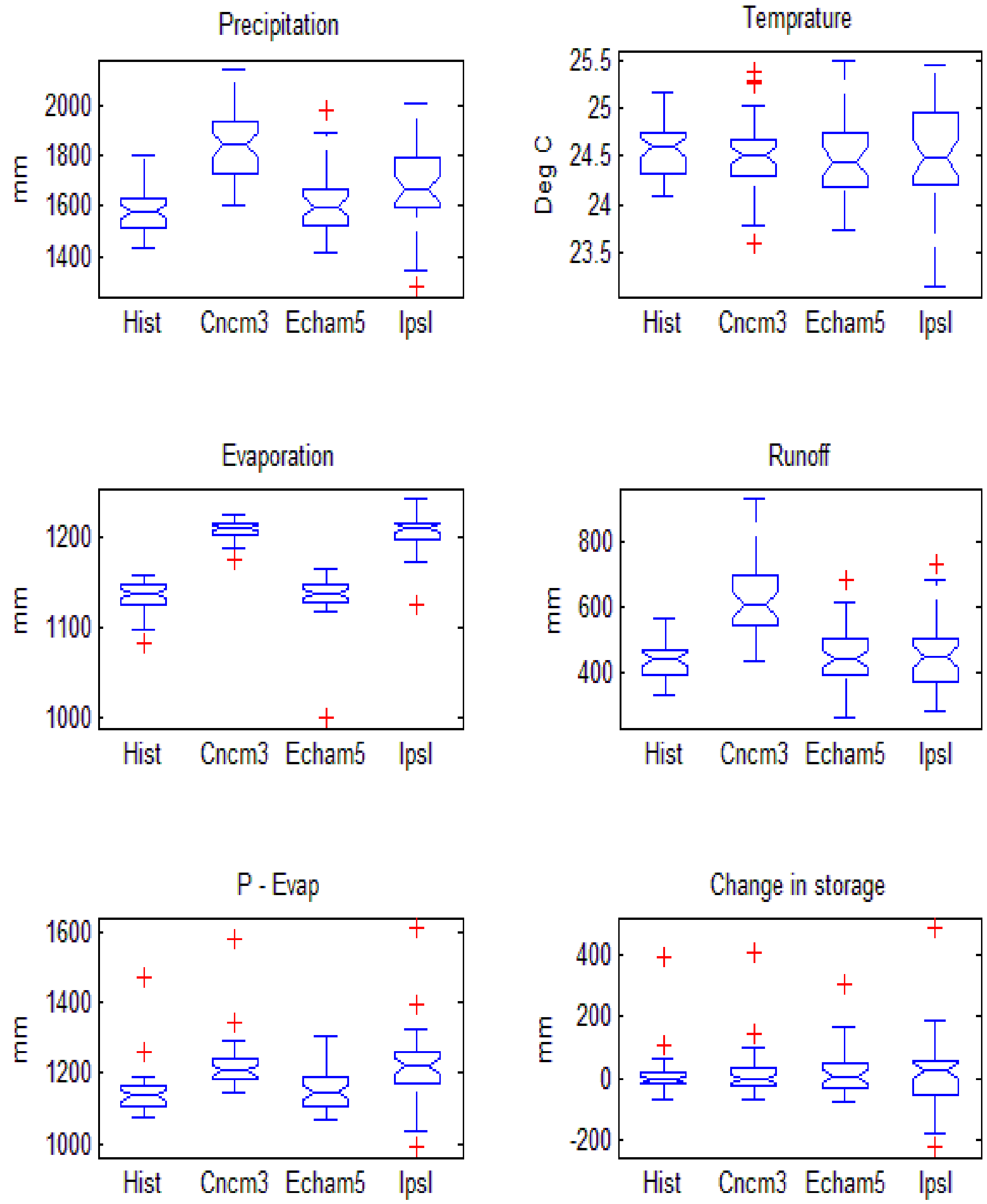


Appendix 3 Mean seasonal cycles and statistics, averaged over the Congo River basin

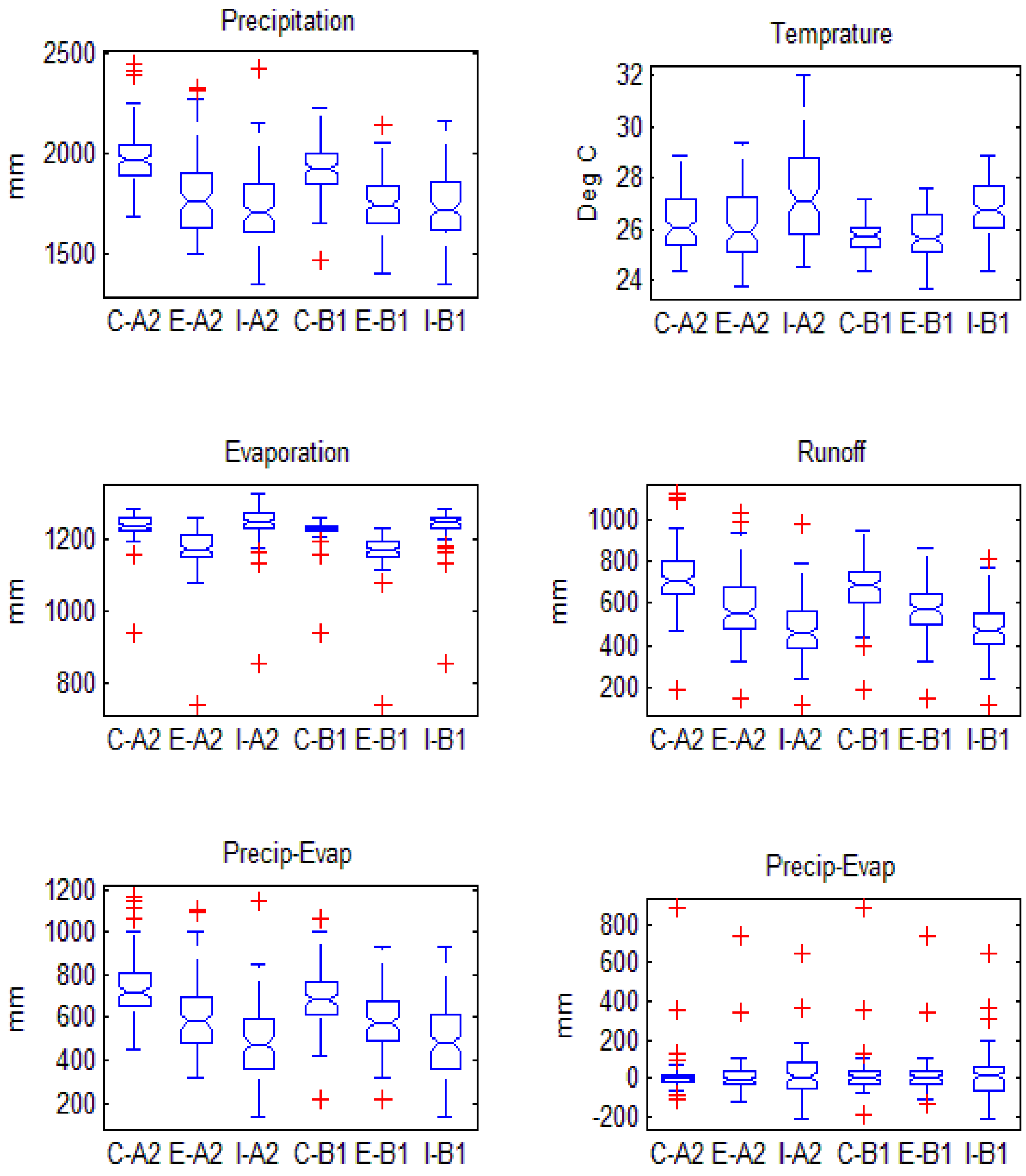
Mean seasonal cycle of precipitation, temperature, evapotranspiration, runoff, P-E, and change in storage for each GCM 20th century simulation, averaged over the Congo River basin.



Box plots for the annual statistics (precipitation, temperature, evapotranspiration, runoff, P-E, and change in storage) derived from three GCMs and two emissions scenario for future climate

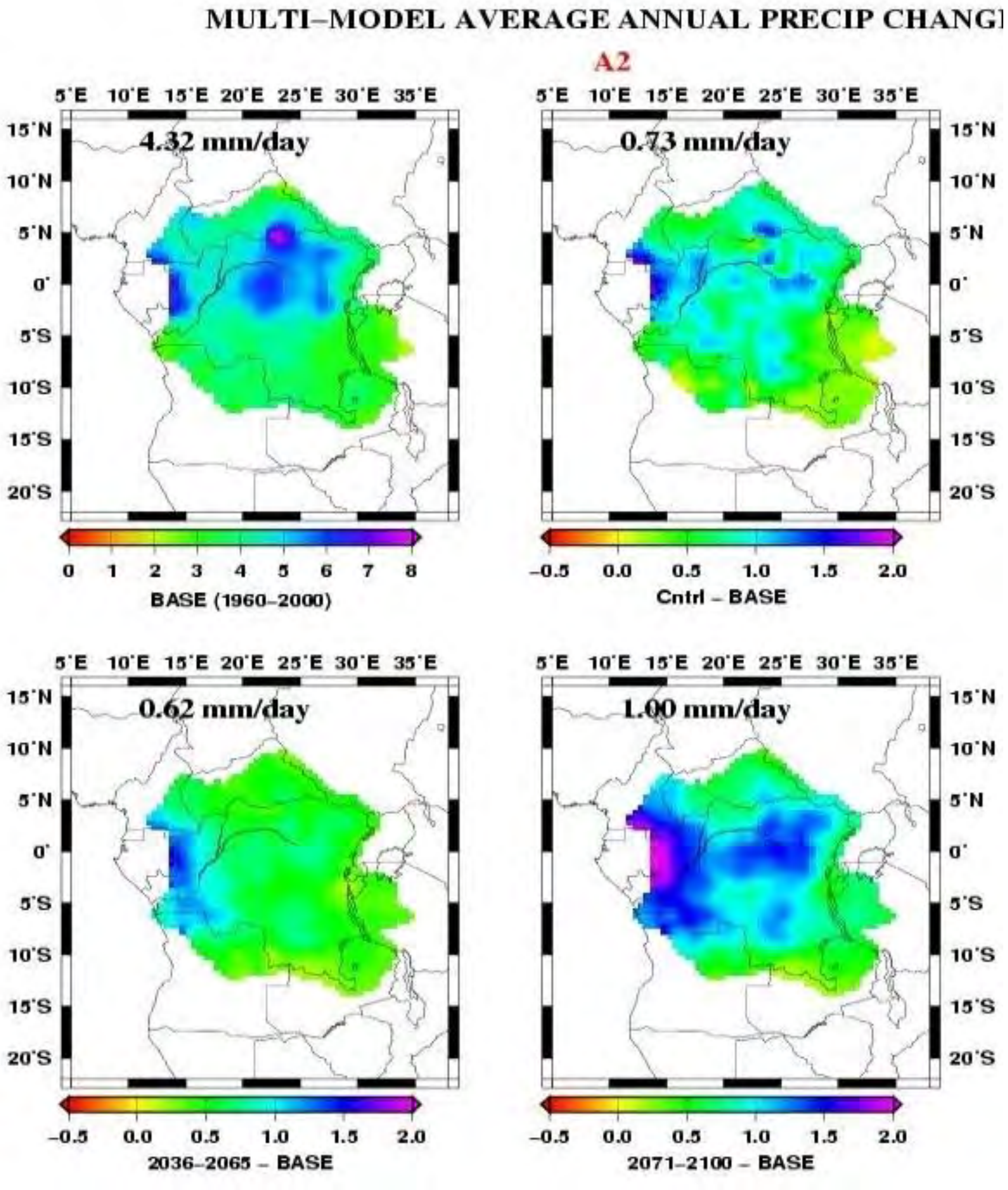


Box plots for the annual statistics (precipitation, temperature, evapotranspiration, runoff, P-E, and change in storage) derived from three GCMs and two emissions scenario for future climate



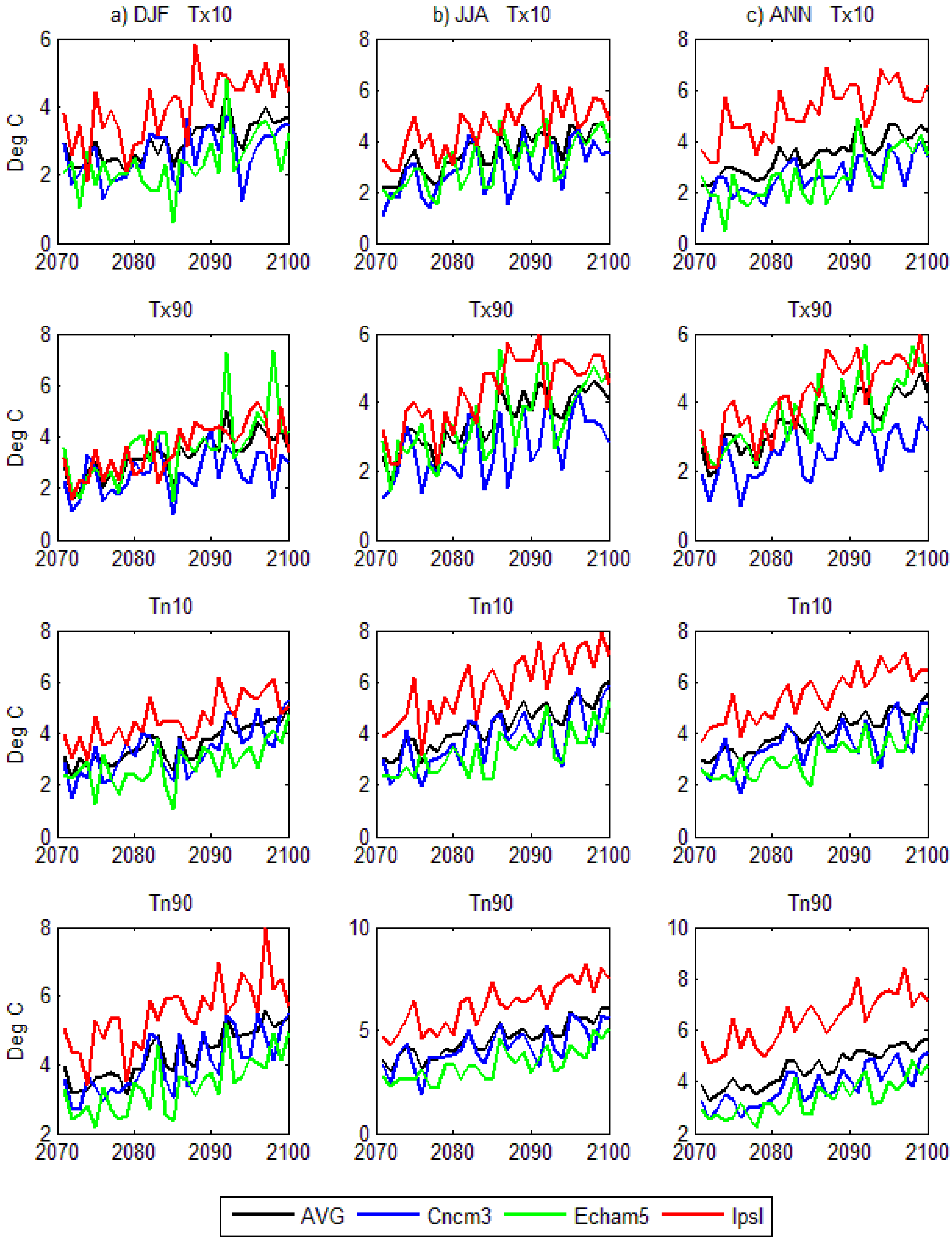
Appendix 4 Spatial distribution of multi-model average projected changes in precipitation

Spatial distribution of multi-model average projected changes in precipitation ; for the period 2036-2065, and 2071-2100, top left panel (Base) , top right (Control), bottom left panel (2036-2065) and bottom right panel (2071-2100) for A2 emissions scenario

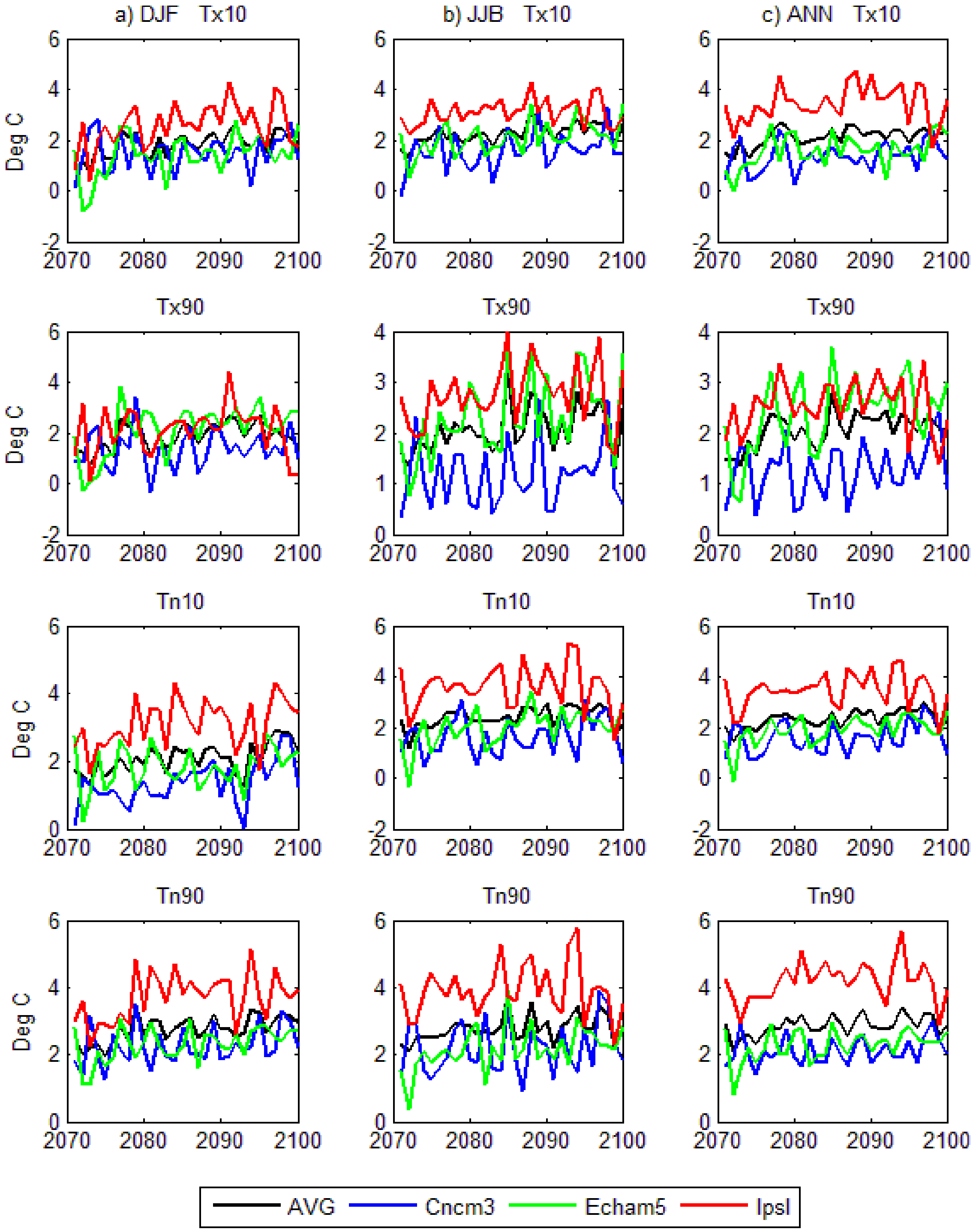


Appendix 5 Anomalies of the average annual temperature and precipitation

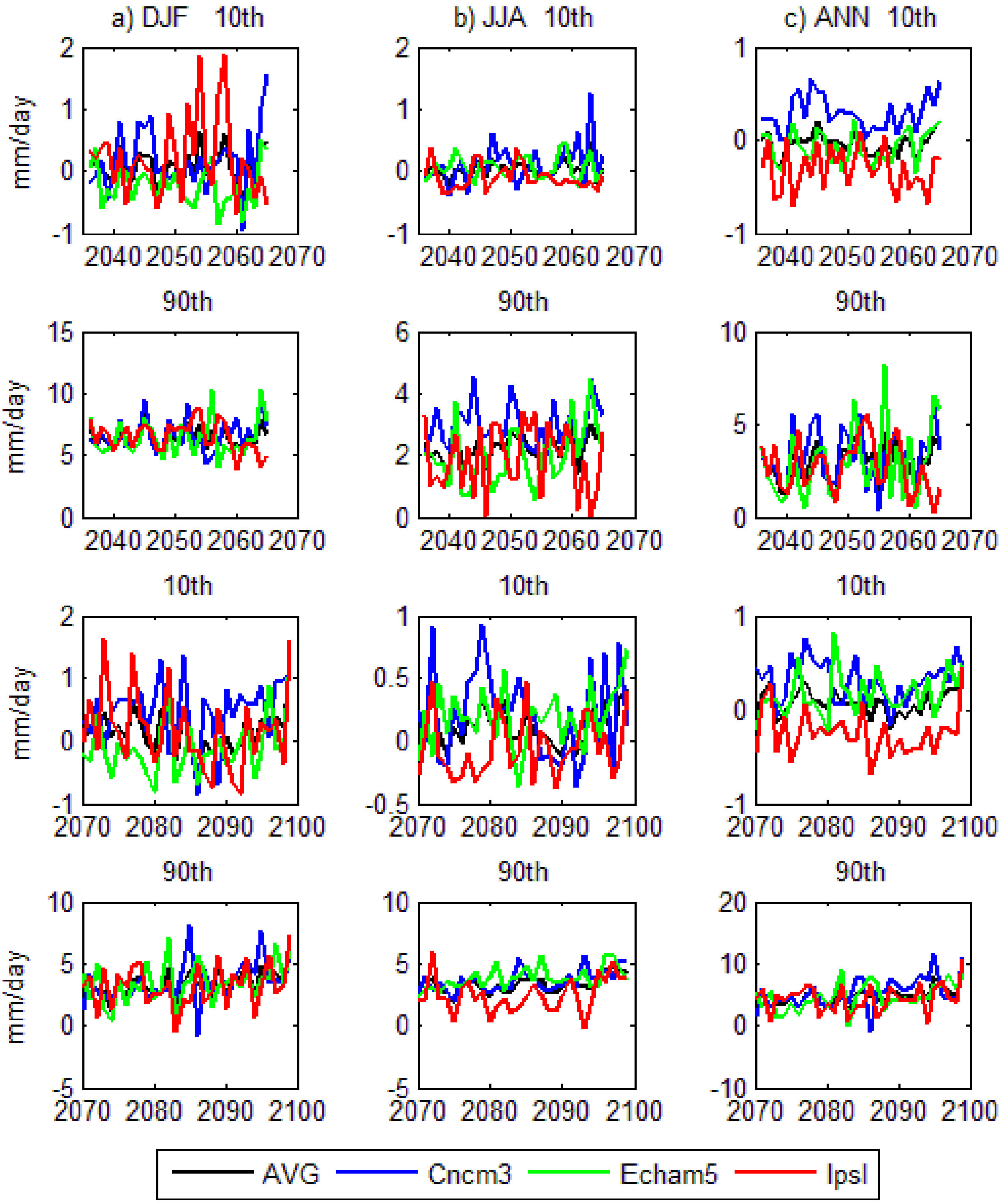
Anomalies of the Congo basin average annual (Tx10 and Tx90) 10th and 90th percentile of maximum temperature, and (Tn10 and Tn90) 10th and 90th percentile minimum temperature for the period 2070-2100 using the A2 emissions scenarios. The anomalies are relative to 1960–2000 mean values



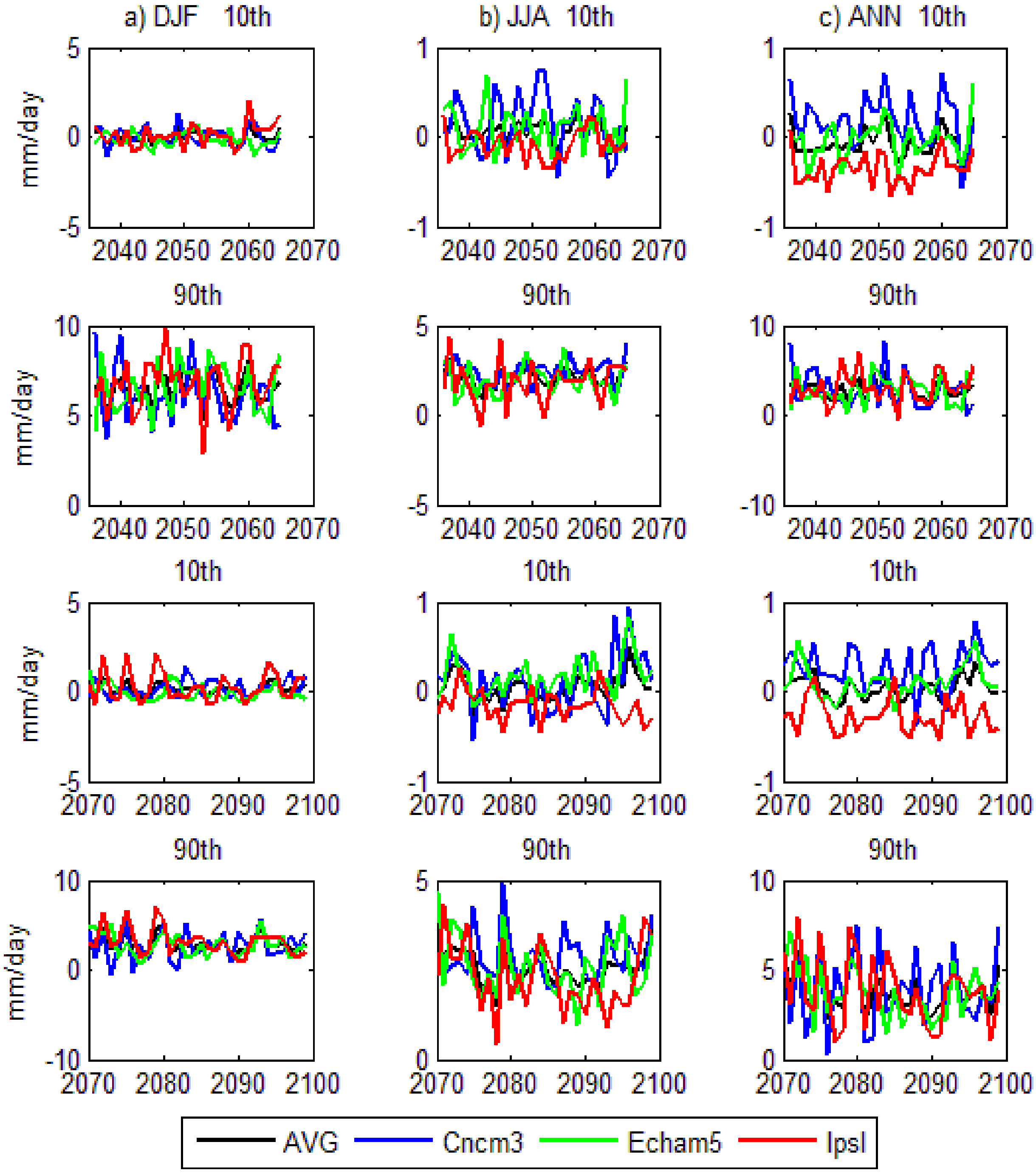
Anomalies of the Congo basin average annual (Tx10 and Tx90) 10th and 90th percentile of maximum temperature, and (Tn10 and Tn90) 10th and 90th percentile minimum temperature for the period 2070-2100 using the B1 emissions scenarios. The anomalies are relative to 1960–2000 mean values



Anomalies in precipitation extremes time series for three seasons (DJF, JJA and ANN) in the 10th and 90th percentile for two future periods using the A2 emissions scenarios. The anomalies are relative to 1960–2000 mean values

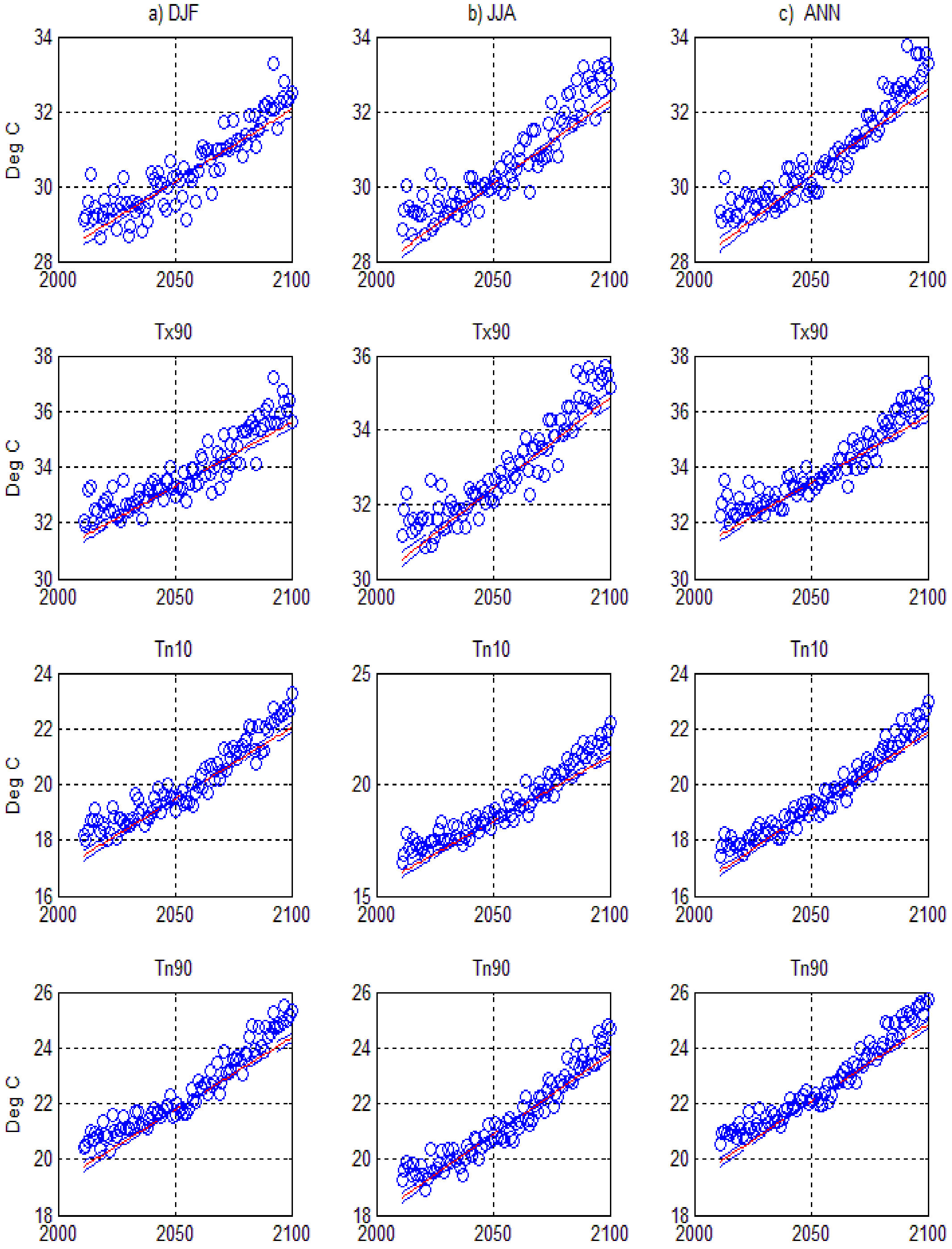


Anomalies in precipitation extremes time series for three seasons (DJF, JJA and ANN) in the 10th and 90th percentile for two future periods using the B1 emissions scenarios. The anomalies are relative to 1960−2000 mean values

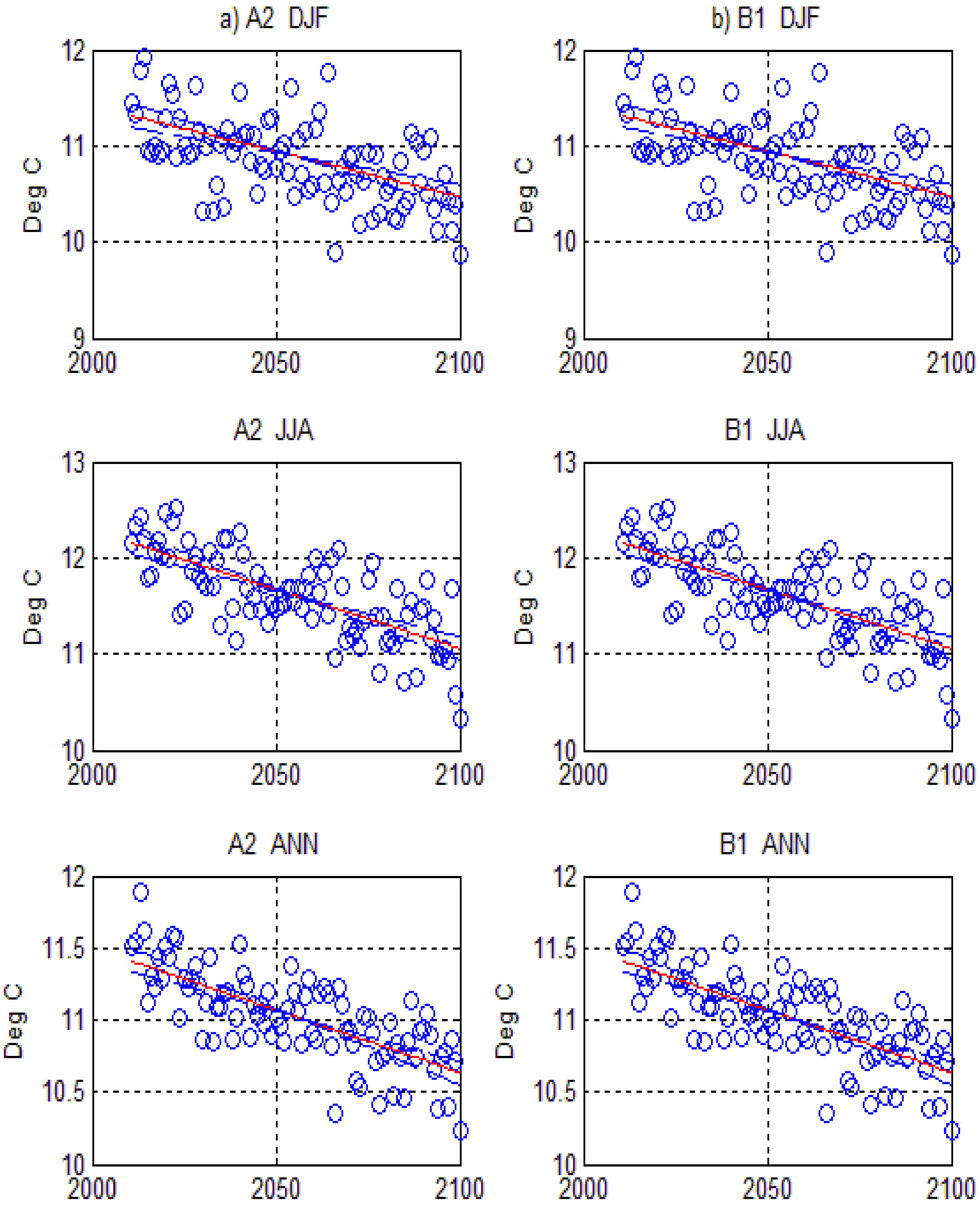


Appendix 6 Trends in temperature

Trends in temperature extremes in (DJF, JJA and ANN) in Tmax 10th and 90th percentile and Tmin 10th and 90th percentile for the period between 2010-2100 using A2 emissions scenarios. The red lines are linear trends.



Congo-river basin trends in diurnal temperature range (DTR), using A2 and B1 emissions scenario, for the time period 2010–2100.The red lines are linear trends


a) A2 DJF
b) B1 DJF
A2 JJA
B1 JJA
A2 ANN
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Climate Change Scenarios for the Congo Basin

Climate Change Impacts on the Congo Basin Region

Fulco Ludwig
Wietse Franssen
Wilma Jans
Bart Kruijt
IwanSupit

On behalf of
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

giz

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Eine Einrichtung der GKSS-Forschungszentrum Geesthacht GmbH

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This report should be cited as follows:
Ludwig F., Franssen W., Jans W., Beyenne T., Kruijt B., SupitI. (2013): Climate change impacts on the CongoBasin region. *In:Climate Change Scenarios for the CongoBasin.* [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

"Climate Change Impacts on the Congo Basin Region"
Part of the series: "Climate Change Scenarios for the Congo Basin"
Authors: Fulco Ludwig, Wilma Jans, WietseFranssen, Bart Kruijt, IwanSupit
Lay-out and Editing: Linda van Garderen
Date: Feb 2013

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany / Gesellschaft fur Internationale Zusammenarbeit (GIZ), Germany / Earth System Science and Climate Change group, Wageningen University, The Netherlands / Climate Service Centre, Germany.

Cover photo: "Evergreen cloud forest on the slopes of Mt. Rwenzori" @GuenterGuni/ istockphoto.com

ABSTRACT

This report presents analyses of climate change impacts in the Congo Basin on water for agriculture and hydropower, forest ecosystem functioning and carbon storage and impacts of climate variability and change on future economic development. To quantify the impacts of future climate we developed a modelling framework which links climate models with different impact models. Bias corrected climate model output was used to force the macro-hydrological model VIC and therefore it is necessary to use numerical models. For this project a modelling framework was developed which made it possible to link climate models with hydrological, agricultural and ecosystem models.

In general, our analyses shows that more water will be available for hydropower in the future. So on average, climate change will have a positive impact on potential electricity production. However the river discharge will also become more variable which will increase the flood risks and could make the power production less reliable. The increased flow variability however will make dam management more complicated because the balance between flood prevention and optimal power production will be more difficult to manage.

Climate change will have a range of different impacts of forest ecosystems. The higher atmospheric CO2 concentrations will probably increase forest growth and carbon capture. Higher temperatures however will have negative impacts on forest growth and reduce the amount of carbon in the forests. The impact analyses show that as a result of climate change, the Congo basin is unlikely to see a decline in forest growth such as is sometimes predicted for the Amazon basin. Instead there could be a moderate increase in ecosystem carbon. Depending on how the climate will change there could be a shift in land cover of the different ecosystems. Based on the analyses a moderate expansion to the North and South of Evergreen forests into savannas and grasslands is the most likely future scenario.

In general, climatic conditions are currently not limiting agricultural production in the Congo basin region. Only on the (drier) edges of the region water limitation is sometimes reducing the potential agricultural productions. In the tropical climates too much rainfall and high humidity limits agricultural production through nutrient leaching and fungal growth. The impact of future climate on agricultural production will therefore be limited in the region. In most of the area the water stress will increase slightly in the future. However the agriculture will not suffer from structural water shortages. Only the agriculture in the savanna regions surrounding the Congo basin could potentially face water shortages in the future. In the southern savanna region analyses indicate that more frequent droughts will affect agriculture production and water stress.

In several of the COMIFAC countries there is a clear correlation between annual rainfall and GDP growth. GDP and Agricultural GDP growth rates tend to be higher in years with above-average rainfall than in the dry years. The impact of climate variability on GDP growth is most pronounced during dry years. During below-average rainfall years growth is sometimes severely reduced and generally the dryer the lower the GDP growth rate. All above-average rainfall years tend to have relatively similar economic growth rates. The correlation between rainfall and GDP growth rates is stronger in countries with lower and more variable rainfall. In most countries, agricultural GDP growth rates are affected stronger by climate variability than the total GDP growth rates. In terms of future climate change impacts on economic development our analysis shows that COMIFAC countries are especially vulnerable to a reduction in rainfall and a significant increase in interannual rainfall variability. Our results show that at a continental scale, climate change is likely to have a negative impact on development in Africa. However the economies of central African countries are likely to be less affected by climate change compared to countries in West, East and Southern Africa. Also at macro scale the climate scenarios seem to be more favourable in the central African part compared to the rest of Africa. However some climate change scenarios show large increases in climate variability and this could have a negative impact on development.

In conclusion the climate change impacts on the different sectors shows that the main impacts will come from a more variable climate. No major impacts are expected in terms of water availability for agriculture and future carbon storage in the tropical forests. Also the average potential energy production from hydropower will not reduce. The most severe impacts will result from a more variable hydrological regime. This will result is higher flood frequency and will complicate future dam management.

Keywords: Climate change; water resources; agriculture; forestry; carbon stocks; GDP

Table of Content

LIST OF ACRONYMS

Ag-GDP	Agricultural Gross Domestic Product
AR4	Assessment Report 4
CAR	Central African Republic
CB	Congo Basin
CNRM-CM3	Centre National de Recherches Météorologiques - coupled model 3
CRB	Congo River Basin
CRU	Climate Research Unit
CWA	Central West Africa
DGVM	Dynamic Global Vegetation Model
ECHAM	European Centre Hamburg Model
ERA40	European Centre for Medium-Range weather forecasts
FAO	Food and Agriculture Organization
GCM	Global Circulation Models
GDP	Gross Domestic Product
GPCC	Global Precipitation Climatology Centre
GPCP	Global Precipitation Climatology Project
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM4	Institut Pierre Simon Laplace - coupled model 4
LPJml	Lund-Potsdam-Jena managed lands model
MPIOM	Max-Planck-Institut für Meterologie
NPP	Net Primary Productivity
PFT	Plant Function Types
REDD	Reducing deforestation and degradation
REDD+	Reducing deforestation and degradation plus conservation of biodiversity
SLA	Specific Leaf Area
SRES	Special Report on Emissions Scenarios
UNFCCC	United Nations Framework Convention on Climate Change
VIC	Variable Infiltration Capacity
WATCH	Water and Global Change
WFD	WATCH Forcing Data

1.0 INTRODUCTION

Due to increased greenhouse gas concentrations in the atmosphere, the climate around the world is changing. Already over the last decades the climate has significantly changed and there has been an increase in global temperatures of about 0.7C over the last century. The IPCC (2007) concluded that at least part of the increase in temperature is caused by human emissions of greenhouse gases. Not only temperatures are changing but also rainfall patterns are changing. Some regions have seen a reduction in rainfall will in other areas rainfall amounts have increased. Especially in Africa (in particular the Sahel) there is large decadal variability in rainfall; long periods of drier than average are followed by relatively wet periods. How climate change will affect this variability is still unclear.

In the future global warming is likely to increase. Depending on the emission scenario temperatures will increase between 1 and 6°C in the coming century, but it is likely to be between 2 and 4 °C (IPCC 2007). Temperature increase will not be uniform around the globe and tropical regions such as the Congo Basin will probably experience less warming than regions around the poles. The higher temperatures will have an impact on the hydrological cycle resulting in changes in evaporation, rainfall and run-off (Ludwig 2009). These changes can potentially have a large impact on the water, agriculture and energy sectors.

Africa is widely seen as the continent most vulnerable to climate change. Current climate variability already has a large impact on economies of developing countries. Large parts of the economy in Africa are highly climate sensitive in particular agriculture, infrastructure and water sector. Also African livelihoods are highly dependent on climate-sensitive natural resources such as dry land agriculture, forestry and local water resources. In addition there is often little protection against disasters from storms and floods and there is limited adaptive capacity in most African countries.

These conclusions, however, are mostly based on research in West, East and Southern Africa. There is very little known on the climate change impacts on the Central African Region. The project "Climate Change Scenarios for the Congo Basin" has the aim to fill this knowledge gap. Potentially this region could be very vulnerable to climate change. For example natural resources such as agriculture, forestry and hydropower are very important for the local economy. Changes in climate will affect forest functioning, hydropower production and agricultural systems.

Forests are not only important for the local population but they also play an important role in affecting global climate change. Forest clearing and degradation caused by expansion of agricultural land, urban development, logging and fires account for almost 20% of global greenhouse gas emissions. Reducing deforestation is extremely important for climate change mitigation. To stimulate developing countries to reduce emissions from forests, the Reducing Emissions from Deforestation and Forest Degradation (REDD) effort was started. REDD aims to provide financial value for carbon stored in forests and as a result create incentives for countries to reduce their emissions from forested lands.

However, not only land use change affects greenhouse gas emissions also climate change affects forest ecosystems and the amount of carbon stored in tropical forests. So climate change could potentially both increase and decrease carbon stocks in forests of the Congo Basin. It is therefore important to know how vulnerable the forest systems in Central Africa are to climate change and how this could affect the amount of carbon emitted or taking up by these systems.

Climate change will have a major impact on the hydrological cycle. Due to global warming clouds, atmospheric water vapour concentrations, rainfall and runoff patterns will change. The impacts of climate change on the water cycle in the Congo Basin are discussed in detail in a previous report of this project (Beyene et al 2013). These changes in the hydrological cycle can potentially have large impacts on the Agricultural and Energy sector.

Due to changes in rainfall and evaporation, run-off and streamflow patterns will change. This affects the water available at hydropower dams and could alter the amount of energy that can be produced. Not only the total stream-flow will change but also seasonal patterns and variability can change. This will also affect the potential power production of hydropower plants.

Water is essential for food production both for dryland and irrigated agriculture. Climate change affects both agricultural water demand and availability. Water available for dryland agriculture mainly depends on rainfall and soil evaporation. Higher future temperatures are likely to result into an increase in soil evaporation resulting in lower plant water availability. Rainfall changes differ across the Congo basin region. On the edges of the basin, where the rainfall is relatively low, some scenarios indicate a reduction in rainfall. In the centre of the region and along the Atlantic coast rainfall will probable increase. Across the region it is likely that rainfall intensity will increase. This will result in higher relative run-off and lower infiltration. Effects of climate change on water available for irrigation mainly depends on changes in run-off patterns.

This report presents a detailed analysis of climate change impacts in the Congo Basin on water for agriculture and hydropower and Forest ecosystem functioning and carbon storage. To quantify the impacts of future climate change it is necessary to use numerical models. For this project a modelling framework was developed which made it possible to link climate models with hydrological, agricultural and ecosystem models. The next part of the report discusses this modelling framework and explains the different components. Thereafter the climate change scenarios are discussed followed by the results of the impacts analyses.

2.0. MODELLING FRAMEWORK

To study the impacts of climate change on the different sectors in the Congo Basin a set of different models and datasets was used (Figure 1). The bases of the modelling framework are the model LPJml and VIC. LPJml is a coupled hydrology, agriculture and dynamic vegetation model (Bondeau et al., 2007; Sitch et al., 2003). LPJml integrates a representation of the coupled terrestrial hydrological cycle and carbon cycle, which makes it a very suitable tool to study the relationship between water availability and crop production. LPJml is also a dynamic vegetation model which makes it very suitable to simulate changes in the carbon cycle.

The Variable Infiltration Capacity (VIC) (Liang et al., 1994) is a grid-based macro-scale hydrological model. The model solves both the surface energy and water balance equations. The model represents subgrid variability in vegetation, elevation, and soils by partitioning each grid cell into multiple land cover (vegetation) and elevation classes. The soil column is commonly divided into three different soil layers. Surface runoff and baseflow are routed along the stream network to the basin outlet with an offline routing model. The model was recently expanded with a dams and reservoirs scheme (Haddeland et al. (2006). This reservoir scheme was further optimized to assess the impact of climate change on potential hydropower production.

The output of the different impact models (VIC and LPJml) was used to analyse impact on water agriculture, hydropower and carbon storage. For the water for agriculture, and forest carbon storage assessment, the LPJml model was used. For the hydropower assessment we used the macro-scale hydrologic model VIC (Liang et al. 1994).

Both the VIC and LPJml model use climate data as input. To simulate the current status of the Congo basin WATCH Forcing Dataset (henceforth referred to as WFD) was used (Weedon et al., 2011). This dataset covers the period 1958-2001 and is based on a 40-year re-analysis of the European Centre for Medium-Range Weather Forecasts (ERA40) in combination with measured temperature data from the CRU dataset TS2.1 and the GPCC version 4 dataset on measured rainfall. For more details on this dataset see our previous report (Beyene et al. 2013 and Wheedon et al. 2011). It is important to note here that available rainfall data for these regions is relatively scarce which the climate dataset for the Congo Basin region less reliable compared to other regions in the world.

To study the impacts of climate change bias corrected output of different climate models was used as input of the impact models. There are still a lot of uncertainties on how the climate will change in the future. First of all it is unclear how high the future emission will be. Secondly it is unclear how the climate system will respond to future changes in atmospheric greenhouse gases. To cover part of this uncertainty we used three different climate models and two different emission scenarios.

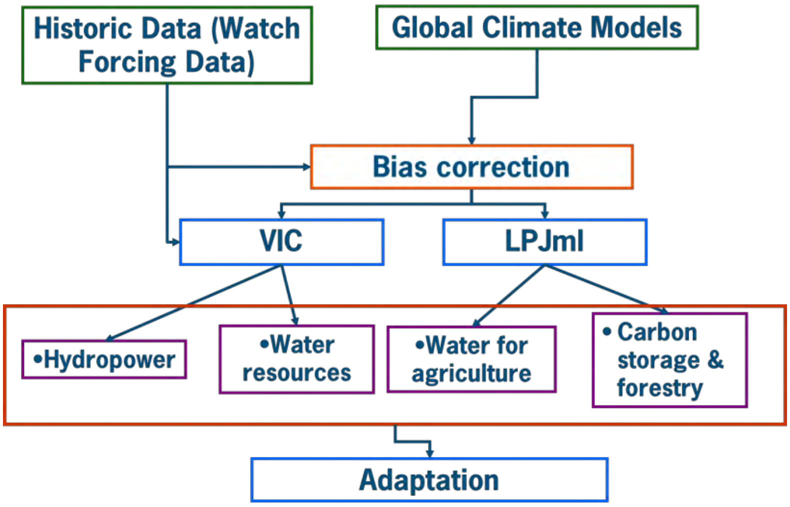


Figure 1. Modelling Framework used within the Climate Change Scenarios for the Congo Basin project.

2.1 The Lund-Potsdam-Jena managed lands model (LPJml)

2.11 Water for Agriculture analyses

We used results of the CNCM and ECHAM Global circulation Models as input for LPJml. The SRES A2 and the B1 scenarios of the IPCC were used. The A2 scenario represents a world of independently operating self-reliant nations, a continuously increasing population and a regionally oriented economic development. The CO_2 concentration increases from 369 ppm in 2000 to 771 ppm in 2090. The B1 scenarios represent a more integrated world that is more ecologically friendly. Global solutions to economic, social and environmental stability are emphasized. The CO_2 concentration increases less than in the A2 scenario, from 369 ppm in 2000 to 545 in 2090.

The evapotranspiration, green water consumption, water stress as well as the precipitation have been used in this study. For the time slots 1990-2010, 2035-2064 and 2071-2100 average values have calculated. The results for these timeslots have subsequently been compared which each other

Increasing temperature and the rising atmospheric CO_2 concentration have an opposite effect on the vegetation. The increasing temperature results in increasing soil evaporation whereas the rising CO_2 concentration reduces plant transpiration especially in the C4-plants. In the humid tropics, regions with abundant plant cover, the contribution of the transpiration to the evapotranspiration is large in comparison to the soil evaporation and the effects of the increasing temperatures are negated by the increasing CO_2 concentration. In the savannah and the Sahelian regions, vegetation is less abundant and soil evaporation contributes more to the evapotranspiration and consequently the increasing temperatures will lead to increasing evapotranspiration.

Note that LPJml calculates the actual evapotranspiration. As the water availability increases (resulting from increasing precipitation), the actual evapotranspiration increases. However, this does not mean that the water stress decreases. The water stress may increase as well. The increasing temperatures lead to a stronger atmospheric water demand which may be higher than the increasing water availability

2.12 Carbon Cycle

In order to model the likely changes in the regional carbon cycle as a consequence of climate change, we are also using the LPJml modelling framework. The general set-up has been described before, and in this section we will focus on aspects of modelling the carbon cycle.

The LPJml (Lund-Potsdam-Jena-managed-land, Sitch et al., 2003; Gerten et al., 2004) dynamic global vegetation model (DGVM) simulates the components of the ecosystem carbon cycle explicitly, using process-based equations. These components are: canopy photosynthesis, plant respiration, allocation of photosynthates over leaves, woody parts and roots, litterfall and mortality, and heterotrophic respiration.

Productivity

The simulation of photosynthesis is based upon the formulation by Farquhar and subsequent publications (Farquhar et al., 1980). In summary, photosynthesis primarily depends on absorbed radiation and CO_2 concentration inside the leaves, modulated by a photosynthetic capacity and temperature. CO_2 concentration inside the leaves is determined by the degree of water stress in the plant canopy. This water stress, in turn, depends on the balance of atmospheric demand for water vapour and supply of water by the soil, and this balance also determines the water use by the plants.

Photosynthetic capacity is a crucial parameter. Whilst in principle this depends on the nutrient (nitrogen) concentration inside leaves, the model approximates whole-canopy capacity from the total amount of absorbed light. This assumption originates from the notion that there is an optimum photosynthetic capacity that plants can achieve at a certain light level, where higher capacity would lead to too high maintenance costs. Of course, the amount of absorbed light does not only depend on the incoming light from the sky, but also from canopy leaf area, which in turn depends on photosynthesis of the ecosystem in the past. But because light absorption saturates at high levels of leaf area, this model principle does lead to stable and realistic photosynthetic capacities.

It should be noted, that the dependence of photosynthesis on temperature is uncertain. Especially, there is little empirical knowledge on the temperature above which photosynthesis will decline. Therefore, simulations with increasing temperatures should be evaluated with care.

Also, it has been shown that the sensitivity to soil water availability is uncertain, because information on rooting depth and activity of roots is scarce.

One uncertainty stands out, however. The productivity model is sensitive to atmospheric CO_2 concentrations, with increasing photosynthesis when CO_2 increases. However, much research in temperate regions, as well as ecosystem theory, shows that such positive response to CO_2 often does not occur in reality. This is likely caused by nutrient limitations and limited life time of carbon (i.e. minimum turnover) in ecosystems. For tropical biomes, there is very little information available to quantify such limitation, but it is likely that also here limitations will occur. Therefore, it is prudent to simulate effects of climate change both with and without consideration of increasing CO_2, and then evaluate the difference between both simulations.

Plant respiration is simulated as a fixed proportion of photosynthetic capacity multiplied with a factor that increases with temperature. Net Primary Productivity (NPP) is then the difference between total photosynthesis and plant respiration.

Allocation, litter and decomposition

The model simulates the allocation of carbon at an annual basis but in a dynamic way, maintaining a balance between leaf area and sap wood, and between roots and leaves, increasing the water and nutrient uptake capacity in those environments where these resources are scarce. The specific leaf area (SLA) is fixed per species group (PFT, see, below) and determines the carbon investment in foliage.

Litter fall is determined by simulated leaf area and leaf longevity and root turnover rate, while establishment and mortality are determined by PFT-specific self-thinning rules and stress factors.

Decomposition of litter and organic material in the soil determines heterotrophic respiration and depends on temperature, soil moisture and organic matter content itself.

Total vegetation carbon is determined as the net cumulative result of annual NPP, mortality and litter fall. Total soil carbon is calculated as the accumulated sum of litter and dead material input and decomposition.

Plant functional types

The model contains a number of parameters, such as those determining temperature sensitivity, moisture sensitivity, allocation and turnover. These parameters vary per ‘plant functional type’, or, species group. For the tropical biomes, these are: ‘Tropical Evergreen forest’ (broadly, rain forests), ‘Tropical raingreen forests’ (broadly, savannahs), and ‘tropical grasslands’ (broadly, C4 grasses). Although in reality there are many more relevant ecosystems and vegetation types, it is almost impossible to meaningfully define parameter sets for all these different types, because measurements of essential parameters are scarce, because it would only make sense to make this refinement if such data would be available for most or all of these types, and also because, despite obvious differences in physiognomy, the differences in physiology would probably not be such that they would lead to important differences in carbon dynamics

2.2 Variable Infiltration Capacity model (VIC)

The Variable Infiltration Capacity model (VIC) is a macro-scale spatially distributed land surface hydrologic model that solves the energy and water budgets at the land surface (Liang et al. (1994, 1996, and 1999)). It has been widely applied in land surface hydrologic simulation analyses on spatial scales ranging from watershed to global domain (Abdulla et al., 1996; Maurer, 2007; Maurer and Lettenmaier, 2003; Nijssen et al., 1997; Wood et al., 2002). Besides for historical hydrologic simulation, VIC model (Liang et al. 1994, 1996; Nijssen et al. 1997) has been used to assess the impact and implications of climate change on water resources in several research projects both at regional and global scale. Following the third IPCC Assessment Report (IPCC, 2001), Payne et al. (2004) studied climate change effects on the Columbia River, Christensen et al. (2004) studied effects on the Colorado River, and Van Rheenen et al. (2004) studied effects on California. Similarly, several recent studies involved implementation of the VIC model to analyse the effects of IPCC AR4 projections on hydrologic systems: Cuo et al. (2010) on the Puget Sound basin, Christensen and Lettenmaier (2007) on the Colorado River, and Hayhoeet al. (2007) on the north-eastern U.S, Beyene et al. (2009) on the Nile River basin. The model was calibrated for the Congo River basin and naturalized flows were compared to observed flows at three gauging station with records sufficient for plausible comparison. A calibration procedure similar to that described in Nijssen et al. (1997) and Payne et al. (2004) was followed to assure a match between model-simulated and observed flows for the period in which historic streamflow observations were available. VIC was calibrated by adjusting parameters that govern infiltration and base flow recession to match simulated historic streamflow with naturalized observed obtained from GRDC at three gauging stations Congo Kinshasa, Brazzaville and Ouesses gauging stations for different time periods based on the available observed data .The overlapping period of record between simulated and observed naturalized streamflow at each gauging station.

2.3 The Reservoir Routing Model

Reservoir operation is an important element in water resources planning and management. It consists of several control variables that defines the operating strategies for guiding a sequence of releases to meet a large number of demands from stakeholders with different objectives, such as flood control, hydropower generation and allocation of water to different users such as irrigation water demand. A major difficulty in the operation of reservoirs is the often conflicting objectives. Therefore, it is necessary to optimize reservoir operation in determining balanced solutions between the conflicting objectives and demands.

For the purpose of this study, we used retrospective and future climate change scenarios, to assess the effect of climate change on hydrologic and water resource and the intrinsic implications of reservoir operation in the CRB .We applied the Haddeland et al. (2006a, b, c) reservoir model which is intended to be used in regions like the CRB basin where details of operating and water management policies are not available. The reservoir model is applied to the 18 reservoirs listed in Table 1, some of which are currently operating and some of which are under construction. All of the reservoirs are used primarily for hydroelectric power generation. In the reservoir model, hydroelectric power generation is maximized for each operational year using an optimization scheme based on the SCEM-UA algorithm (Vrugt et al. 2003). This approach of maximizing hydropower for a single operational year is not completely applicable to reservoirs that are regulated on a multi-annual basis. Notwithstanding this deficiency, the model should provide an understanding of the effects of reservoir operation effects on downstream flows.

The operational year is identified for each reservoir and begins in the month when mean monthly simulated naturalized streamflow shifts to being less than mean annual streamflow (following Hanasaki et al. 2006). The reservoir model is operated at a daily time-step and determines reservoir releases, storage, and reservoir level. Reservoir evaporation is calculated using the Penman equation for potential evaporation, which is subtracted from reservoir storage each day. To maintain a reservoir water balance, daily precipitation is added to the reservoir surface. To improve parameterization of the model, we made several modifications to the Haddeland et al. (2006a,b,c) set-up as follows:

(a) Maximum Release: One of the limitations of the single purpose optimization scheme in the original implementation of the reservoir-routing model was that flood control was not implemented as one constraint, which is problematic given flooding problems in the lower Congo basin resulting from operations in the upper part of the basin. In the modified implementation, we applied flooding as one constraint applicable to combined releases from all reservoirs.

(b) Minimum allowable reservoir release: To estimate the minimum release from each reservoir, Haddeland et al. (2006a,b,c) use 7Q10, the seven-day ten-year recurrence interval low flow, which is calculated from naturalized simulated streamflow at each dam location. Depending on the availability of observed streamflow data, we set the minimum flow to the mean of dry-season (December to May) observed streamflow after reservoir construction.

(c) Reservoir filling: We needed to allow for new reservoirs to come on line before each operational year begins. During the filling period, reservoir discharge is maintained at minimum flow and the remainder of the inflow to the reservoir is used for reservoir filling until the reservoir reaches full storage capacity. This results in a filling period of 9-15 months for most of the reservoirs.

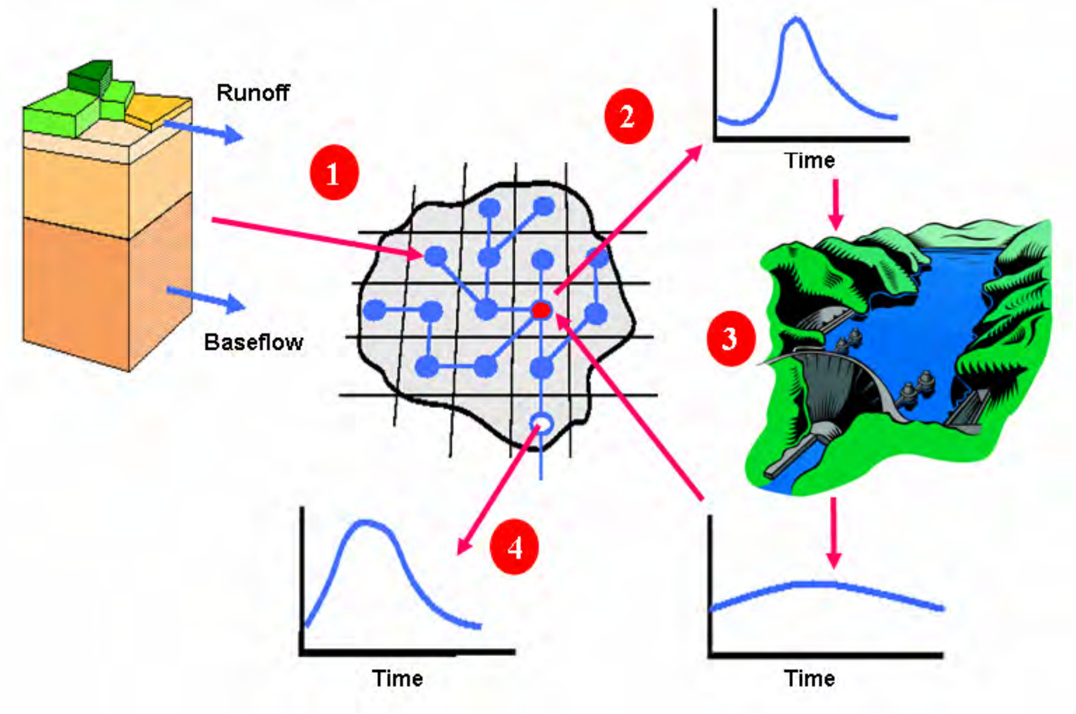


Figure2. Schematic Coupling of 1) hydrology (Liang et al. 1994, Cherkauer et al. 1999, Su et al. 2005, Adam et al. 2007), 2) routing (Lohmann et al. 1998), and 3) reservoir (Haddeland et al. 2006a,b,c) models.

2.3 Model simulation and focal reservoirs.

The VIC model was forced first with the reference data set the Watch Forcing Data (Wheedon et al. 2011) and thereafter with 6 different climate scenarios (see par3.1 for details on climate scenarios). Climate scenarios were run from 1961-2100. The VIC model was run for the complete COMIFAC region to also include basins around the Congo which are important for the region. To study the impact of climate change on hydropower production we selected five focal dams within the region. These dams were selected during the kick-off workshop of the project in November 2011 in Doula Cameroon. The Dams are: Inga, Song Loulouo, N'Zilo, Imboulou, and Moukouloulou.

3.0 CLIMATE CHANGE SCENARIOS

3.1 Climate Models and Scenarios

For this project the result of three different global climate model were used the ECHAM5/MPIOM, CNRM-CM3 and IPSL-CM4. These three GCMs were selected because of the availability of archived output on a daily time step. The three climate change models were run with different SRES emission scenarios (Nakicenovic, 2000). For this project we used a high emission scenario (A2) and a low emission scenario (B1). However it has to be noted that only for the analysis of the impacts on hydropower (section 5) and on economic development (section 7), the results of all the three GCMs were used. For the analysis of the forest carbon cycle (section 6) only the results of the ECHAM5/MPIOM climate model have been used. For the analysis of agricultural water use (section 4), the data of the ECHAM5/MPIOM and the CNRM models have been considered. The difference in numbers of GCM input in the different assessments results from the fact that various applications (water, runoff, carbon) show very different sensitivities to climate. Therefore some of the GCM inputs just did not deliver acceptable results in some of the assessments conducted with the impact models. These differences in the climatic input data (see Beyene et al. 2013 for details) causes a limitation of this study that should be kept in mind when comparing the results of the different assessments to each other. However, the differences that arise between A2 and B1-related impacts *within* the same assessment *can* be reliably compared.

Due to significant systematic biases in the ability of climate models to simulate observed temperature and precipitation, the output of the climate models was bias corrected. This bias correction is needed to produce suitable input data for the use in the impact models VIC and LPJml. In this project we used the bias correction method developed FP6 Water and Global Change (WATCH) project (Hagemann et al., 2011). The method is based on transfer functions which describe the relationship between the modelled and observed time series. These transfer functions are fitted at grid cell level and are used to adjust the probability distribution function of intensity for simulated variables (Piani et al., 2010). This method, however, does not correct for some changes in seasonal patterns like changes in the timing of the monsoon (Haddeland et al., 2012; Hagemann et al., 2011). The WATCH forcing dataset (WFD) is used as the reference (observed) data for the bias correction. The bias correction transfer function for each grid cell was derived for the 1960-1999 period and was subsequently applied to 1960-2100 assuming that biases in GCM output for the future period are similar for the control period. Before bias correction of precipitation and surface air temperature, a statistical downscaling was conducted on all forcing variables to produce fields at 0.5° x 0.5° spatial resolution (for details see Hagemann et al. (2011)).

3.2 Future Changes in Temperature

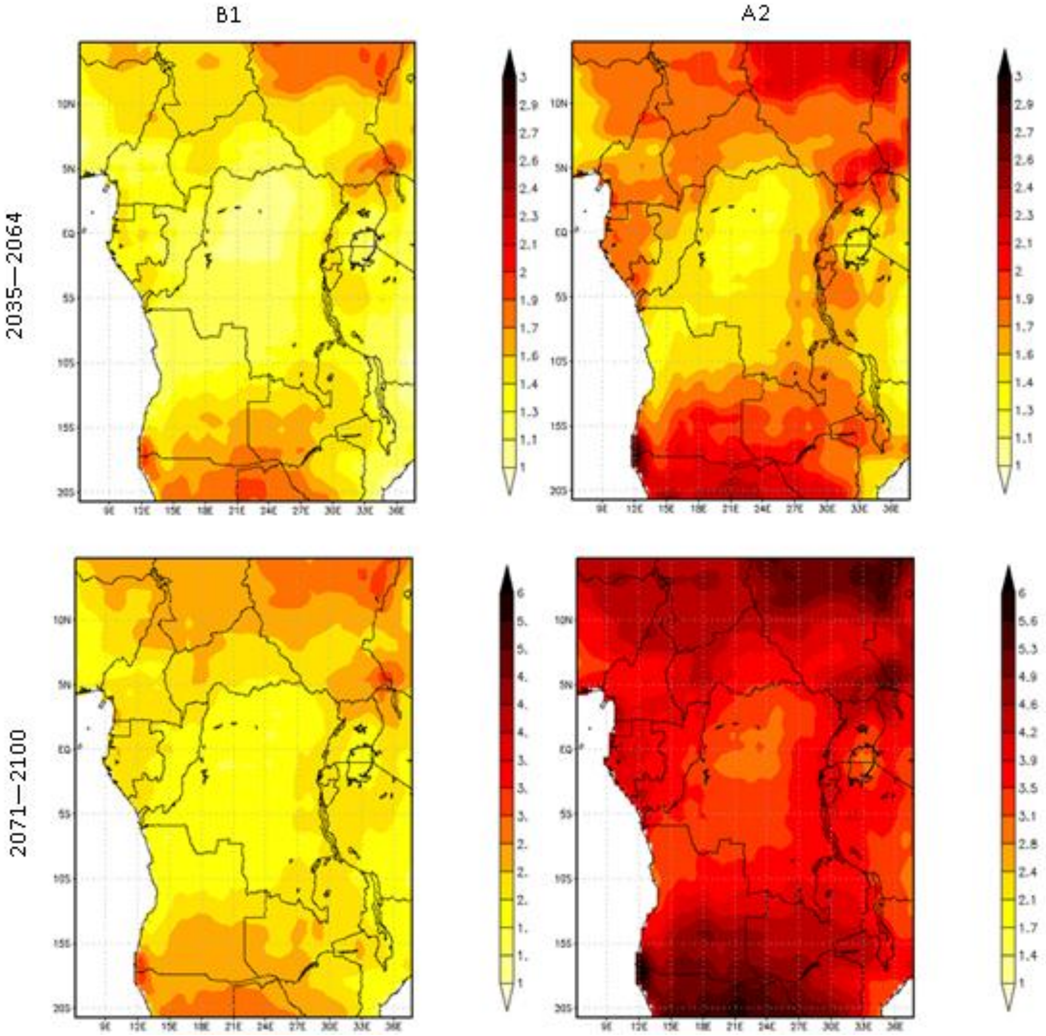


Figure 3. Temperature change [°C] comparing the years 1971 – 2000 with 2035 – 2064 and with 2071 – 2100 for both the A2 as the B1 scenario.

Due to climate change, temperatures will increase throughout the region. Globally temperature increases are the highest in the arctic and lowest in the tropics. Under the low emission scenario B1 the temperature increase in the region will be between 1 and 2°C by 2050 and between 1.5 and 3°C by 2100 (Figure 3). Under the high emission scenario A2 the temperature increases are much more dramatic. Already by 2050, the temperatures are increasing by 2.5°C in the Northern and Southern edges of the region. By the end of the century the temperature increases are between 3 and 5 °C under the high emission scenario.

Temperature increases are the lowest in the tropical climatic central part of the region. In the regions with a more semi-arid climate such as Chad the temperature increases are much higher. Temperature increases also tend to be higher in the highland compared to the lowlands. So temperature increases in Rwanda and Burundi are likely to be higher than the average for the region (Figure 3).

3.3 Future Changes in Precipitation

On average the rainfall is likely to increase in the Congo Basin (Figure 4). This increase is especially observed in the Central and Western part of the region. Especially near the mouth of the Congo River the Rainfall is projected to increase. By the end of the century an average increase of rainfall between 20 and 30% is projected.

At Southern, Northern and Easter edges of the region the impacts of climate change on precipitation are much more uncertain. Especially for Central and Northern Chad a reduction of precipitation is projected. Also for Burundi and Rwanda the changes in rainfall are unclear. Some scenarios show and increase while others show a reduction.

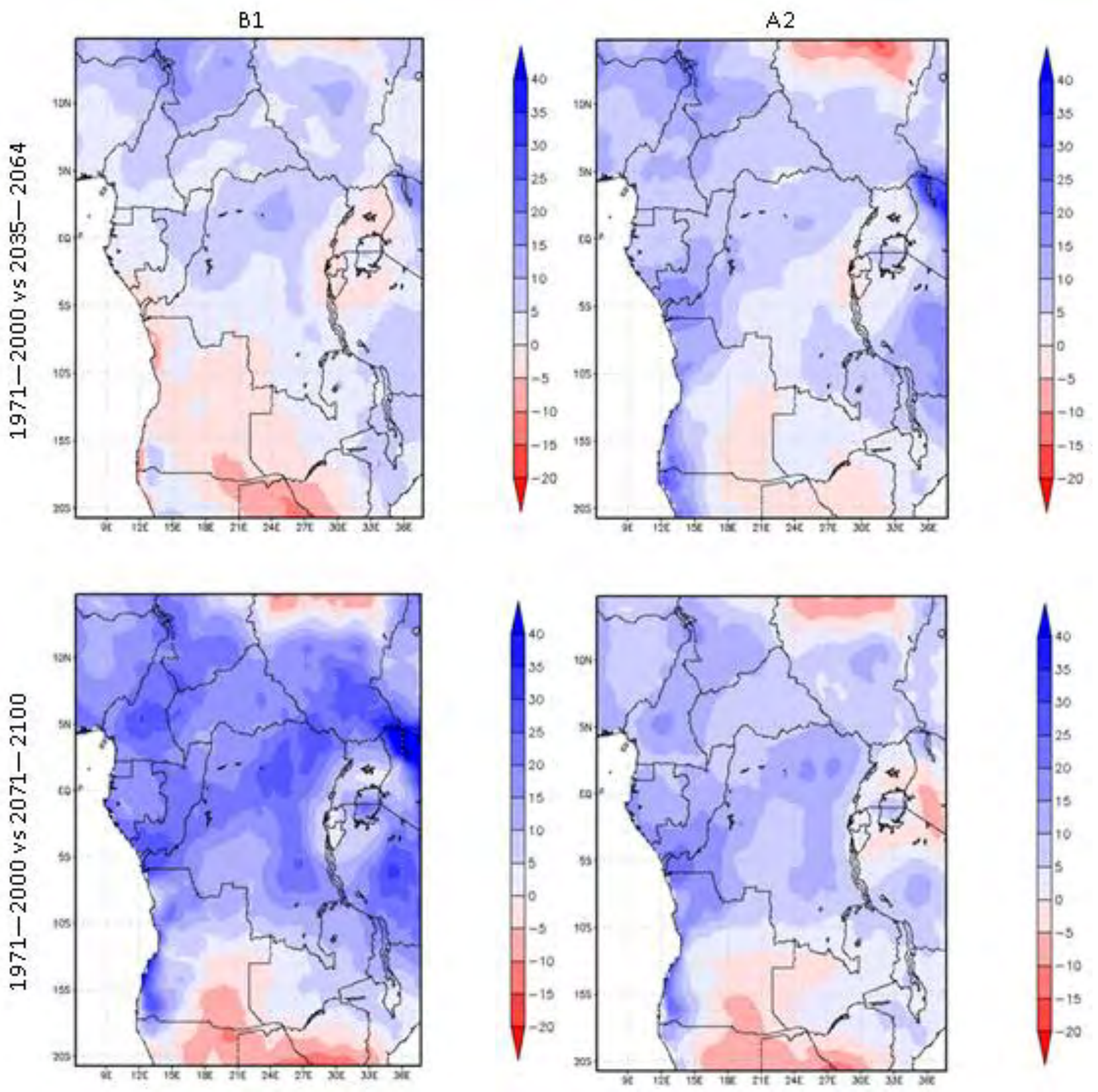


Figure 4. Precipitation changes (%) for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline 1971-2000.

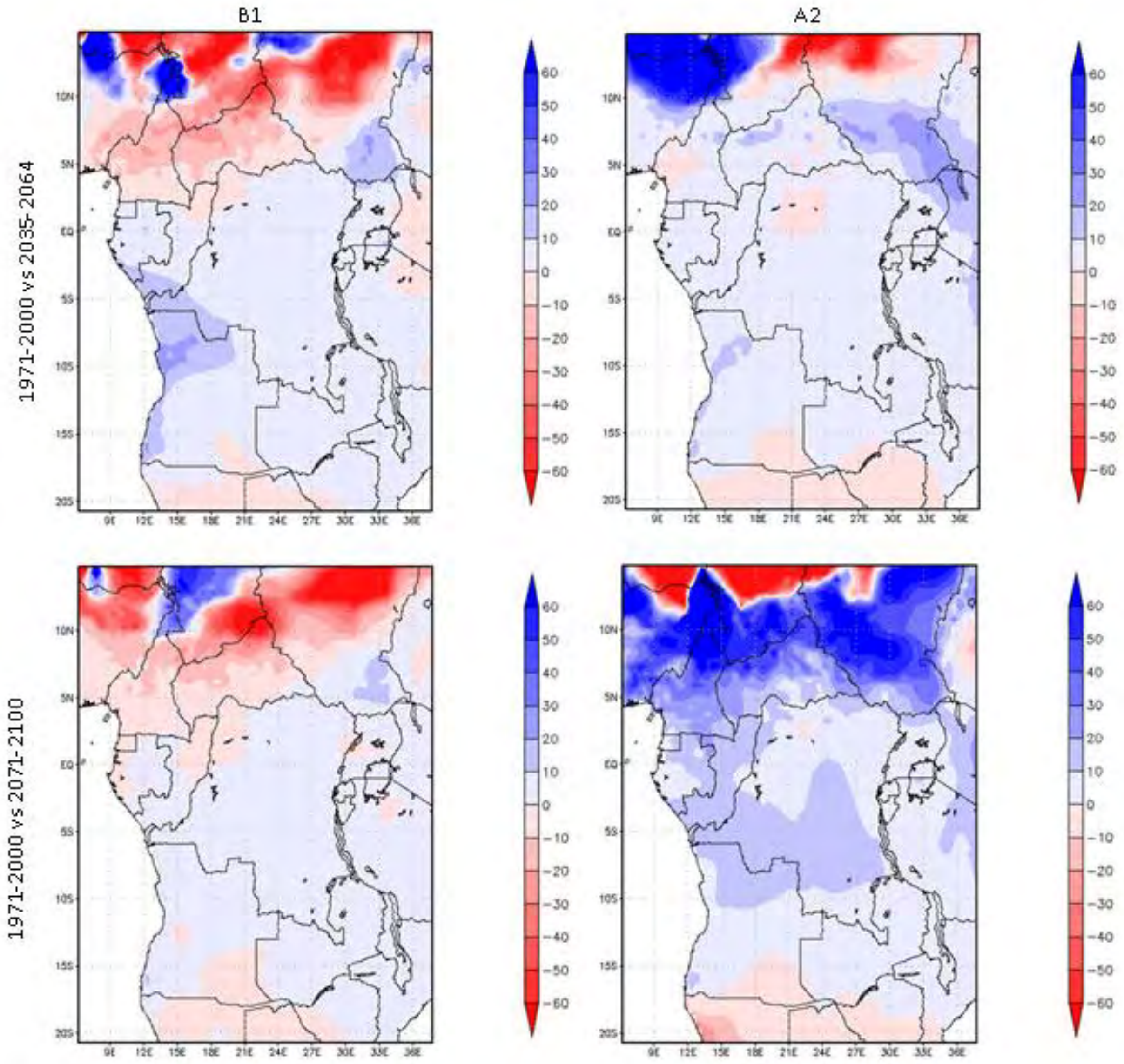


Figure 5.Changes (%) in precipitation for December, January and February for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline period 1971-2000.

Rainfall changes are not equal throughout the season. There is a general trend that especially in the dry season the rainfall is reducing. In the period December-February the rainfall is significantly reducing in Northern part of the region (Figure 5) while in the period June-August the rainfall in the Southern part is reducing (Figure 6). This trend of dry seasons becoming dryer and wet seasons becoming wetter is observed throughout the globe. This indicates that the climate will become more extreme. Also the higher temperatures will make the dry season even drier due to increased evaporative demand. In the Central part of the region rainfall is especially increasing during the December-February periods.

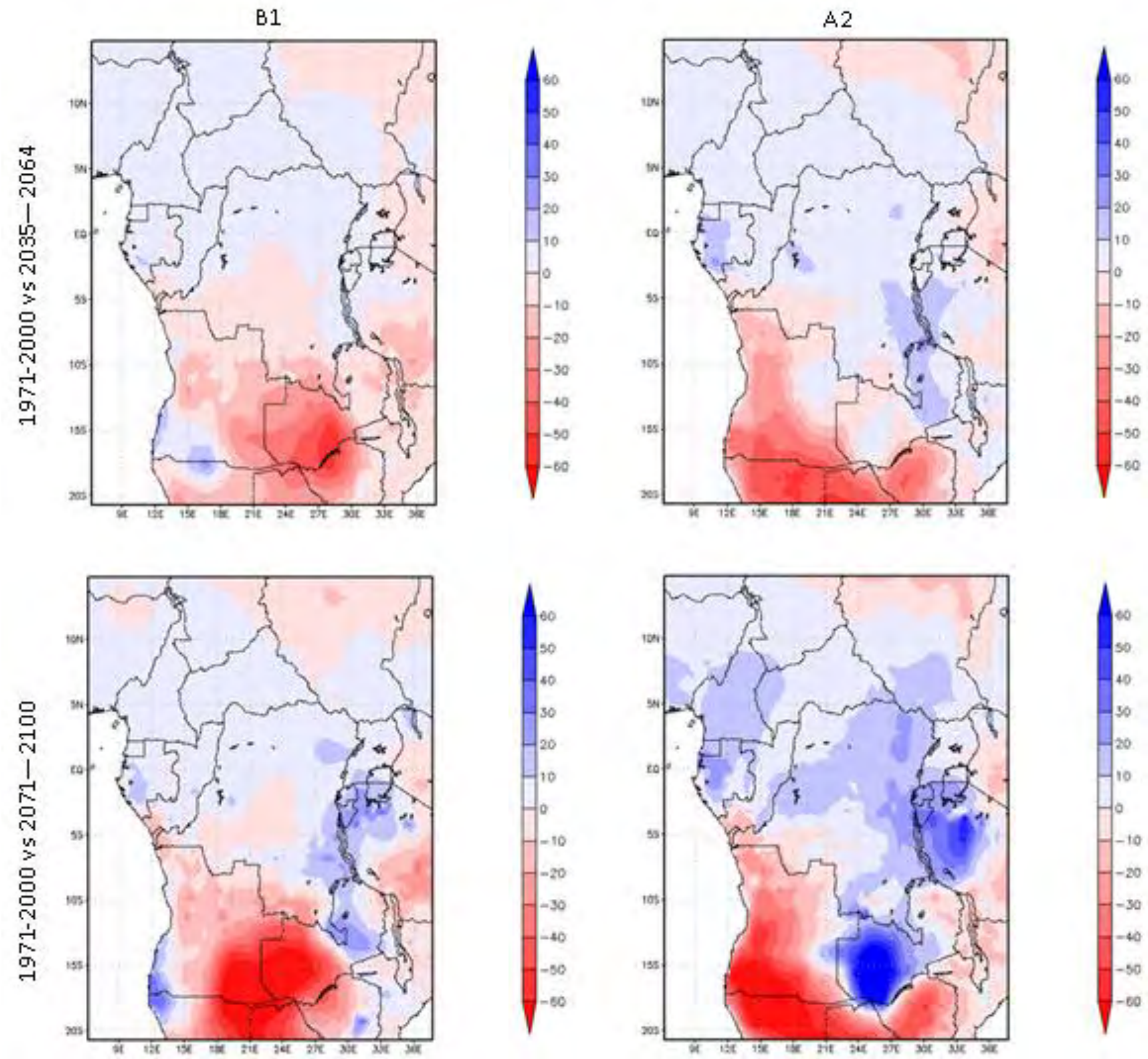


Figure 6.Changes (%) in precipitation for June July, and August for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline period 1971-2000.

4.0. IMPACTS OF CLIMATE CHANGE ON AGRICULTURAL WATER USE

4.1 Methodology

To assess the agricultural water use we used the following LPJml results: evapotranspiration, green water consumption, water stress and the precipitation. Figures 7-9 represent the relative changes in evapotranspiration, green water consumption and water stress. These parameters provide a good overview of possible changes in agricultural water use. For each parameter average values were calculated for the time periods: 1990-2010, 2035-2064 and 2071-2100.

Increasing temperature and the rising atmospheric CO_2 concentration have an opposite effect on the vegetation. The increasing temperature results in increasing soil evaporation whereas the rising CO_2 concentration reduces plant transpiration. In the humid tropics, regions with abundant plant cover, the contribution of the transpiration to the evapotranspiration is large in comparison to the soil evaporation and the effects of the increasing temperatures are negated by the increasing CO_2 concentration. In the savannah and the Sahelian regions, vegetation is less abundant and soil evaporation contributes more to the evapotranspiration and consequently the increasing temperatures will lead to increasing evapotranspiration.

Note that LPJml calculates the actual evapotranspiration. As the water availability increases (resulting from increasing precipitation), the actual evapotranspiration also increases. However, this does not mean that the water stress decreases. The water stress may increase as well. The increasing temperatures lead to a stronger atmospheric water demand which may be higher than the increasing water availability.

4.2 Analysis

4.2.1 Evapotranspiration

Evaporation is the process whereby liquid water is converted to water vapour (vaporization) and removed from the evaporating surface (vapour removal). Water evaporates from a variety of surfaces, such as lakes, rivers, pavements, soils and wet vegetation (FAO: http://www.fao.org/docrep/X0490E/x0490e04.htm)

Scenario A2

From 2000 to 2100, temperature and the CO_2 concentration increase. However, the evapotranspiration in the Congo basin, as well as some regions north and South in the humid tropics (e.g. Central African Republic, Cameroon, Nigeria, Central Angola) decreases between 2.5-7.5%. For the central region of the Congo Basin there is a clear downward in trend in area averaged evapotranspiration (Figure 10) . Since the soil evaporation in the humid tropics is small in comparison to the transpiration, this indicates that the transpiration is likely to decrease in the coming century as a result of the increasing CO_2 concentration. The effects of the increasing CO_2 concentration compensate the effects of increasing temperature. The decreasing evapotranspiration could also indicate that the water availability is decreasing, however, Figure 4 inidicates that in the period 1990-2100 the rainfall increases in central Congo basin region.

The evapotranspiration increases in the regions that border the humid tropical region i.e. the savannah region, including the coastal areas of Angola. In the savannah regions the vegetation is less dense than in the humid tropics and consequently the contribution of the evaporation to the evapotranspiration is much higher.

The highest increases are in the areas surrounding the central African region such Namibia, Botswana and Southern Zambia and the border region of Ethiopia, Kenya and South Sudan. Figure 11 presents the area averaged yearly evapotranspiration of the southern part of region for the period 2000 to 2100. Here, the evapotranspiration is significantly lower than in the Central Congo basin. There is also much more interannual variability in the evapotranspiration. From the middle of the 21st century up to 2100 the rainfall is increasing in this region resulting in higher evapotranspiration values. Figure 12 presents the area averaged yearly evapotranspiration of northern eastern part of the region between South Sudan and Kenya for the period 2000 to 2100. Note that the evapotranspiration in this region is higher than in the southern region (Figure 11), indicating that the water availability is higher and the upward trend indicates that more water becomes available as rainfall increases over time.

In the western Sahellian region (Niger, Western Chad) the evapotranspiration is increasing up to the middle of the 21st century as the rainfall increases. From 2050 and onwards, the evapotranspiration continues to increase, however the increase becomes smaller. In the Eastern Sahellian region the rainfall initially decreases and gradually increase at the end of the century. The evapotranspiration follows the same pattern as evapotranspiration is limited by rainfall.

B1 Evapotranspiration

In the first part of the 21st century the evapotranspiration in general decreases in the Congo basin. There are some regions where the evapotranspiration increases, however, these increases are small, less than 3%. The trend in the evapotranspiration is downward, however, around 2050 the temperature effects on the vegetation become stronger than the CO_2 influence and the trend changes direction and becomes positive (see Figure 10).

In the savannah region to the North of the Congo basin and in the Sahellian region, up to the middle of the 21st century the water availability increases as is suggested by Figure 4. Consequently the actual evapotranspiration increases. However, as time progresses the water availability declines and consequently the evapotranspiration also decreases.

In the savannah region to the South of the Congo basin region the evapotranspiration declines from the beginning of the century to the end as a result of declining rainfall. There are although some areas within this region (e.g. Angola – Namibia border region) that do not show a declining trend (Figure 11).

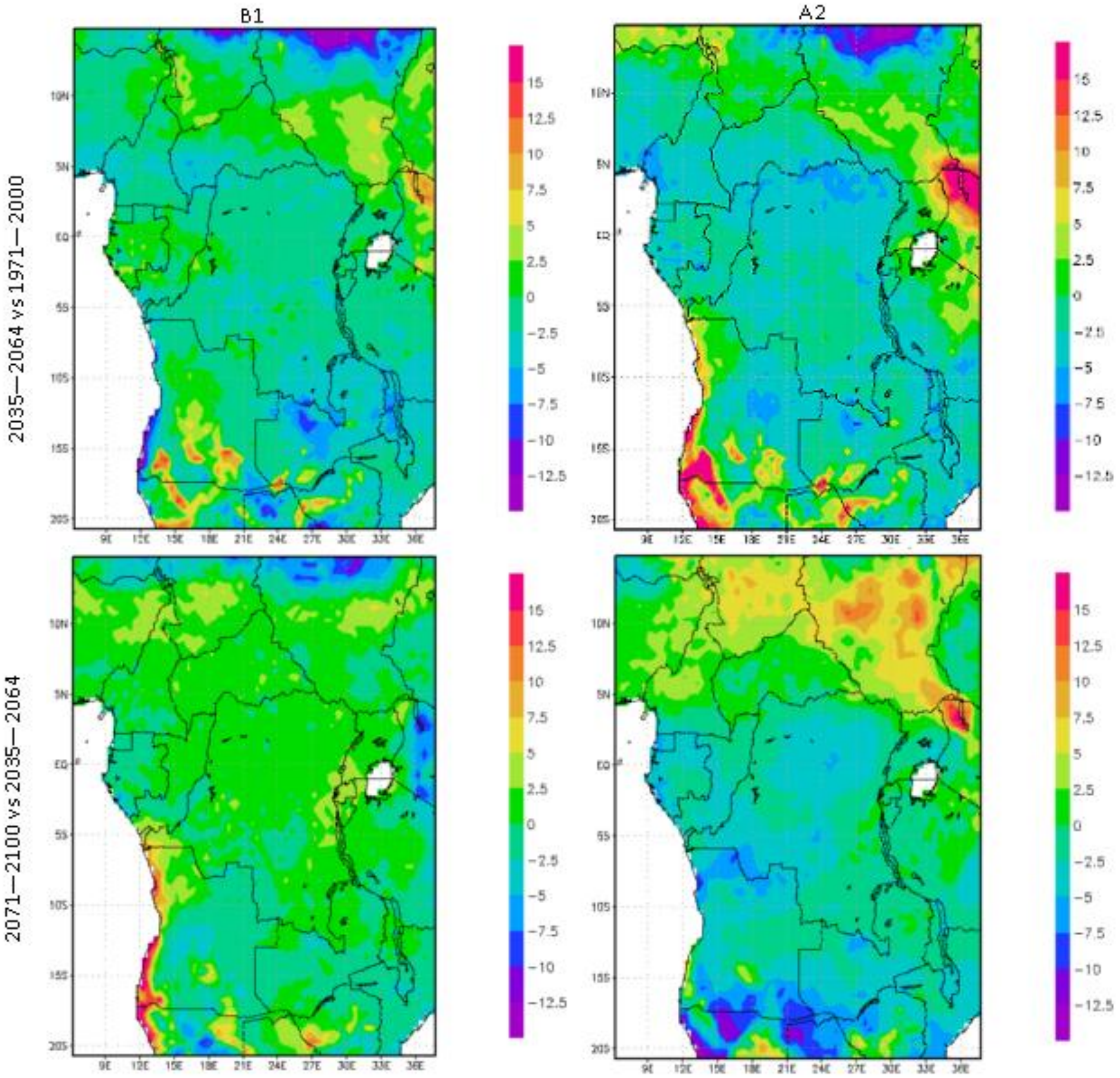


Figure 7. Relative changes in the evapotranspiration for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.

4.2.2 Green water consumption

Green water is defined as the fraction of water that is evapotranspirated, i.e. the water supply for all non-irrigated vegetation. Green water can be called either productive with respect to plant production (if transpired by crops or natural vegetation) or non-productive if evaporated from soil and open water. (source: http://www.tropentag.de/2002/proceedings/node34.html). In this study the agricultural green water consumption is defined as the total water amount evapotranspired by crops.

Scenario A2

Unfortunately there is little information on agricultural land use in the Centre of the Congo basin. For those regions where information is available it can be seen that from 2000 to 2050 the green water consumption increases. These increases are small, in the order of 0.5-5.0%. Higher increases 5-10% occur in the savannah regions to the North East and the South of the Congo basin, indicating that the water availability increases (Figure 8). As can be seen in Figure 4, in the first half of the 21st century the rainfall increases slightly. To the North of the Congo basin, in the Eastern Sahellian region (Sudan) the green water consumption decreases as result of the decreasing rainfall (See Figures 4). In the western Sahellian region the agricultural water consumption increases.

In the second half of the 21st century temperature and the CO_2 concentration further increase, however the green water consumption does not increase anymore. In fact, in several regions in the Congo Basin a decline is clearly visible. In the savannah regions to the North, in Chad and South Sudan, the green water consumption continues to increase. In the Southern savannah regions, however, the available water decrease as a result of declining rainfall.

Scenario B1

From the beginning of the 21st century except for the coastal regions in the Central Congo basin the green water consumption increases slightly (0-5%) due to a slight increase of the precipitation. The increase continues to the end of the 21st century. In the savannah region to the South of the Congo basin the green water consumption increases, however, as time progresses the green water consumption levels off or in some areas decline. This is caused by a decline of the precipitation in combination with an increasing CO_2 concentration. In the savannah region to the East and North of the Congo basin the green water consumption in the first half of the century initially increases, however in the second half the increases becomes gradually less (0-5%). In the first half of the 21st century, in the Sahellian region the precipitation decreases and consequently the green water consumption declines. The decline continues throughout the second half of the 21st the century.

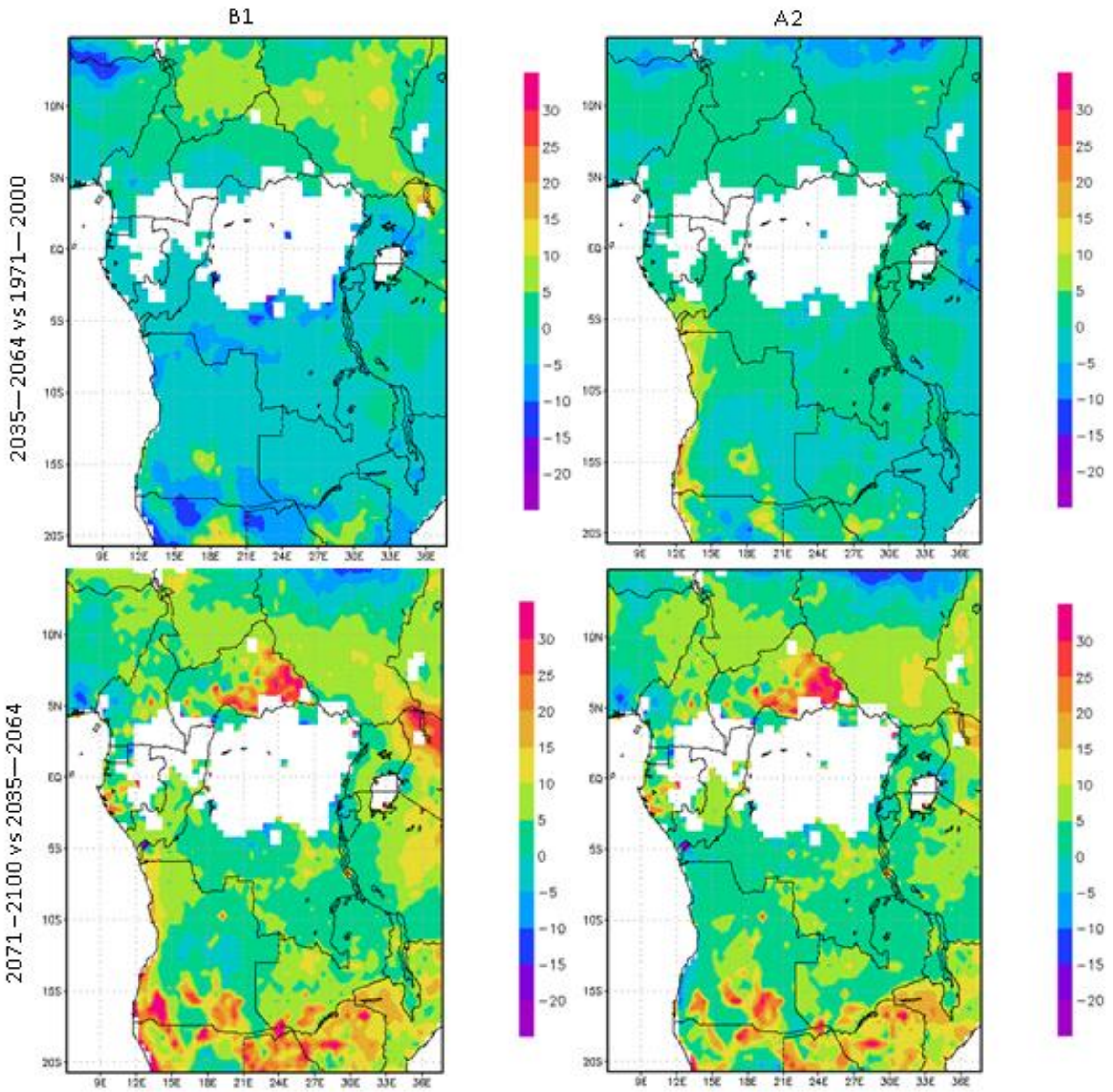


Figure 8. Relative changes in the green water consumption for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.

4.2.3 Water stress

The water stress is defined as the fraction of the water amount that is needed by the vegetation and the water amount that can be delivered by the soil. Related to the water stress is the water-use efficiency which is defined as the units of crop produced per unit of water.

Scenario A2

In the first half of the 21st century the water stress in the Congo basin will increase 5-15%, however towards the end of the century the water stress increase becomes less and settles around the 0-5% (see Figure 9). The reduction of this trend is caused by the increasing CO_2 concentration that causes the transpiration to decline. The water stress in the savannah regions surrounding the Congo basin, increase strongly in the first half of the 21st century. The second half of the century shows decreasing evapotranspiration, green water consumption and precipitation amounts, however, as a consequence of the increasing water- use efficiency (due to increasing CO_2 concentration) the water stress increases is much less in this region.

Scenario B1

In this scenario the temperature and the CO_2 concentration increase less than in the A2 scenario. In the southern savannah region the water stress increases strongly (Figure 9) in the first half of the 21st century. In the other savannah regions surrounding the Congo basin the water stress increases as well, however it is less than in the Southern savannah region. In the Congo basin itself, the water stress is similar to those observed in the A2 scenario in the same period, 10-15%. In the Congo basin and the savannah regions to the East and North, in the second part of the 21st century the water stress increases less than in the first half of the century. In some regions the water stress even declines. Only in the savannah region to the south of the Congo basin the water stress continues to increase. However, the areas where this happens are much smaller than in the A2 scenario.

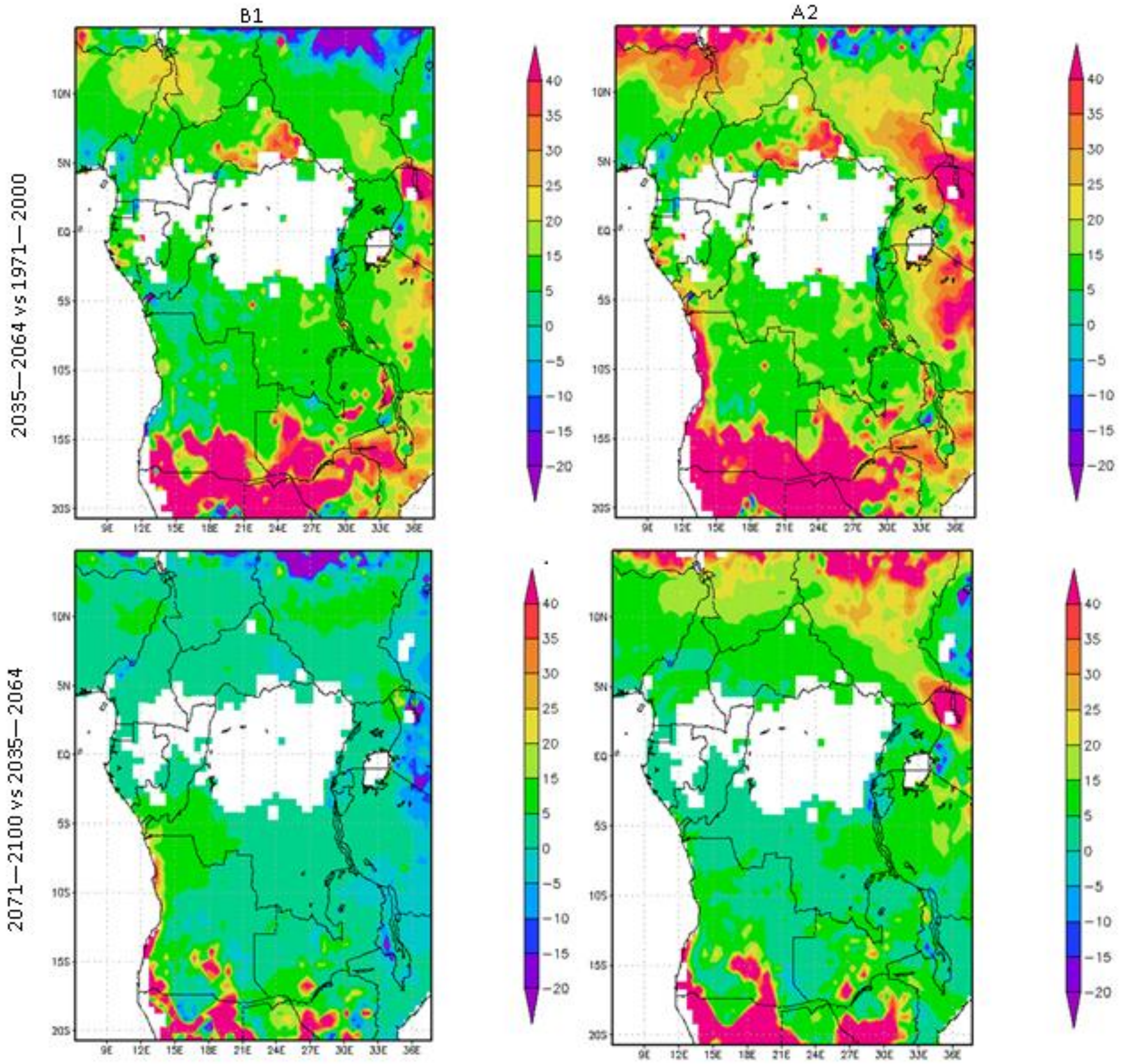


Figure 9. Relative changes in water stress for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.

4.3 Summary

In both scenarios the Congo basin becomes drier in the course of the 21st century. Water stress will increase slightly. However the agriculture will not suffer from structural water shortages. The increasing CO_2 will result in increasing water use efficiency of the natural vegetation as well as of the agricultural crops. The agriculture in the savannah regions surrounding the Congo basin initially will experience water shortages, however, as time progresses these shortages become less severe. Only in the Southern savannah region droughts will affect the agriculture. Note that the droughts in the A2 scenario are more severe than in the B1 scenario.

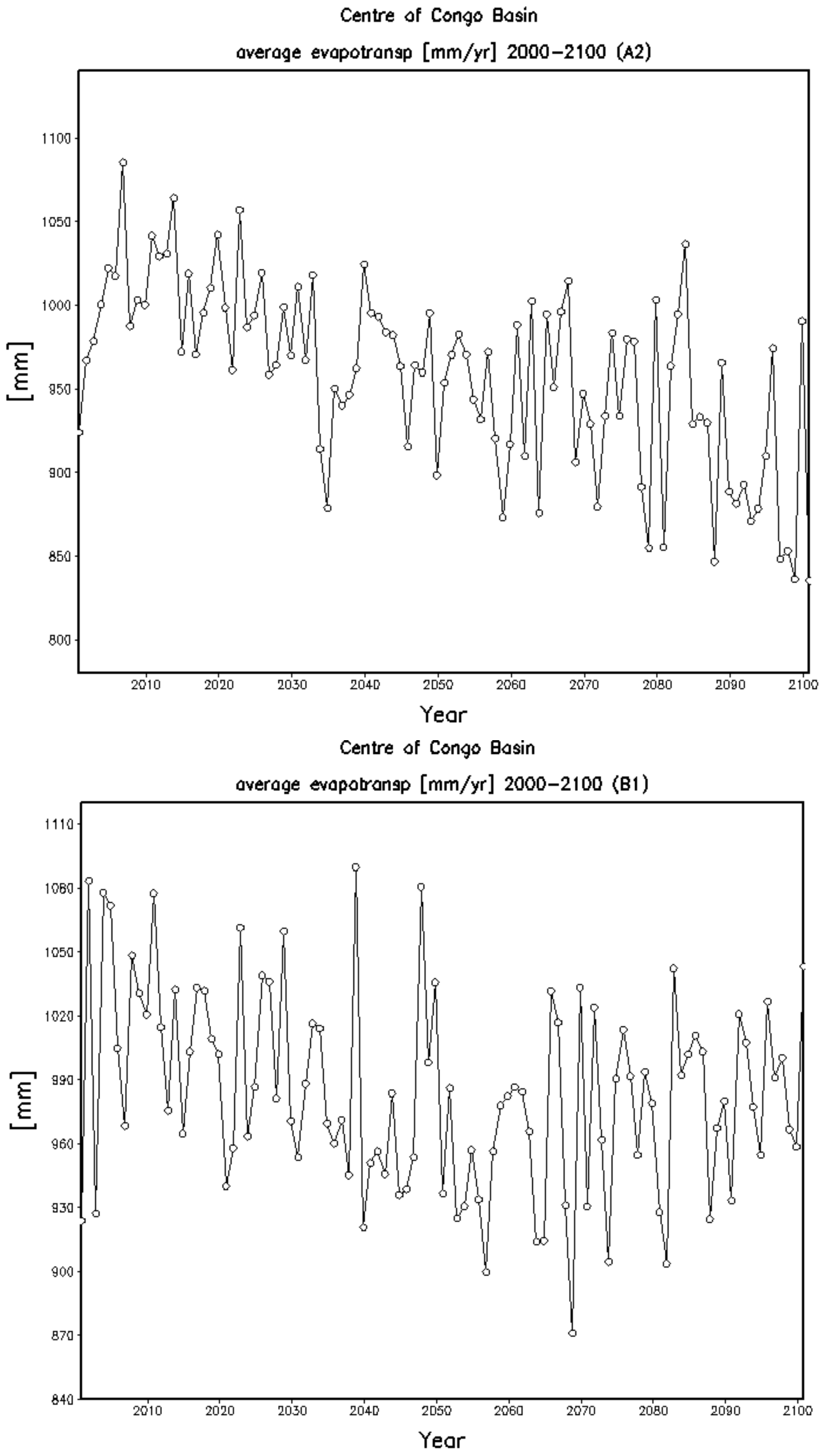


Figure10. Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the Congo basin.

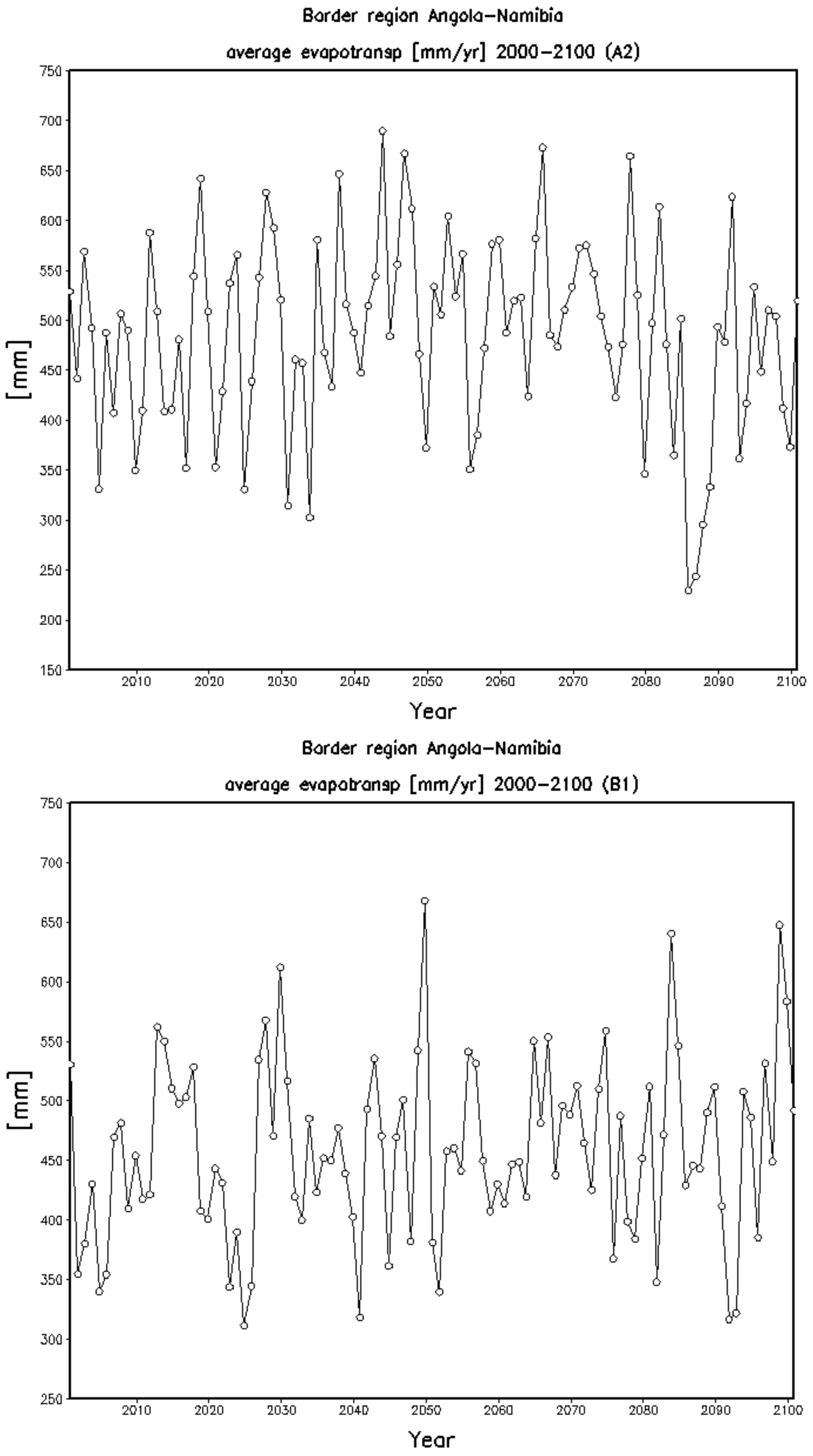
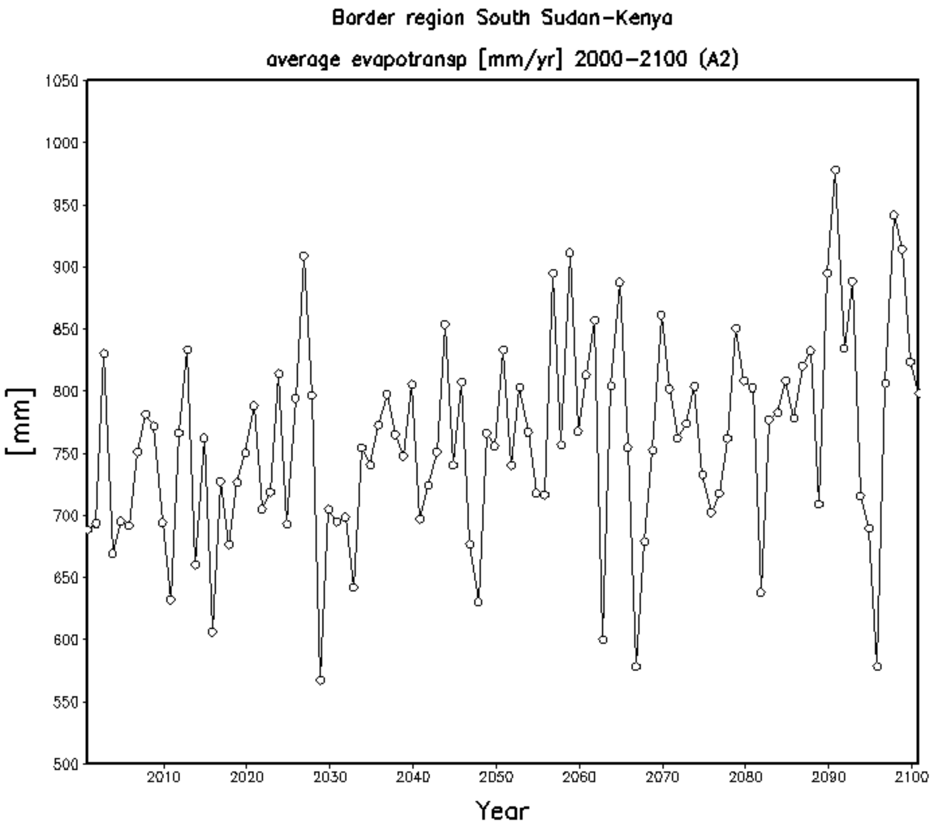


Figure11 Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the Angola-Namibia border region.



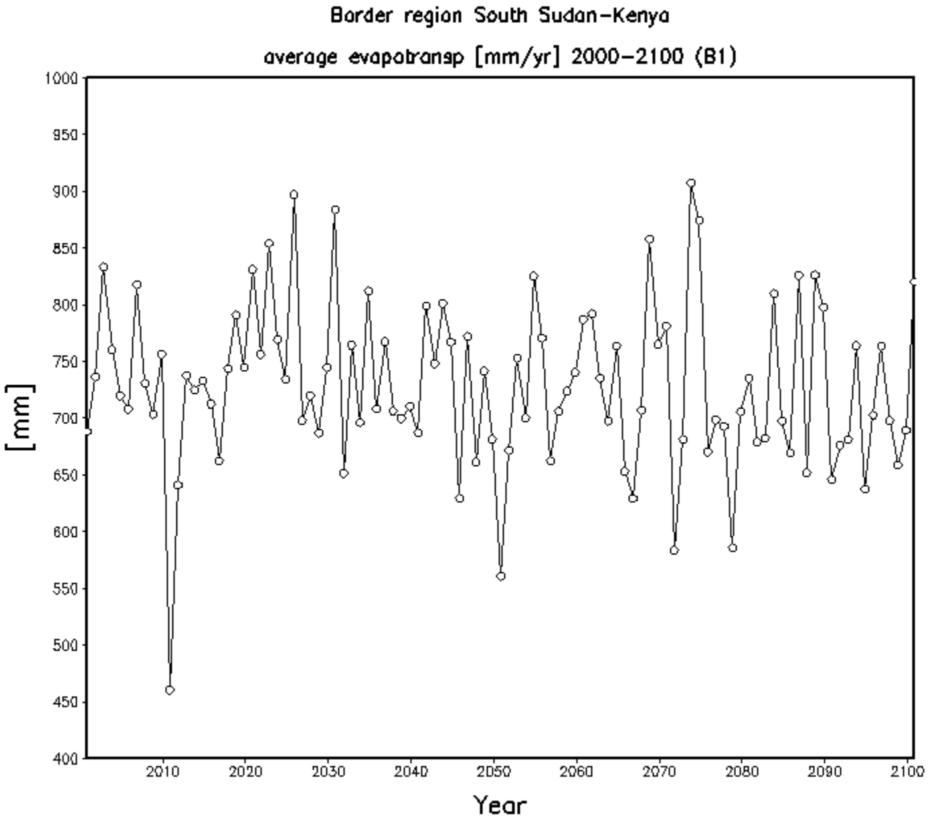


Figure12. Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the South Sudan Kenya border region.

5.0 IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES AND POTENTIAL HYDROPOWER PRODUCTION

5.1Climate change impacts on river flows and variability.

Climate change has a clear impact on future river flows within the Central African region. The average river flows are increasing in most parts of the region (Figure 13). Higher increases in flows are projected for the region near the Atlantic coast, in areas like western DRC and southern Congo Brazzaville. Areas were flows will increase are similar for the low (B1) and high (A2) emission scenario. Lower average flows are predicted for areas at the edges of the region. Of the COMIFAC countries especially for Chad and northern Central African Republic the river discharges are projected to decrease. For both these countries different climate models show conflicting results. Some of the climate models result in higher discharges while other show a clear decrease. These results indicate that in most parts of the region the water availability will increase. This indicates that also the total potential hydropower production will increase.

In addition to analysing the average flows we also looked at changes in high flows (Q95) and low flows (Q10) (Figure 13). High flows are increasing more than average flows in most parts of the region. Throughout large parts of the region high flows are increasing more than 25 percent for the high (A2) emission scenarios. The impact under the low (B1) scenario is less severe but also under the low emission scenarios high flows are increasing throughout most of the region.

Low flows are reducing particularly over the northern and southern part of the region. Low flows reduce over a larger area compared to the average flow (Figure 13). Especially in the areas on the edges of the Congo basin both the low flows *reduce* and the high flows *increase*. Also most of climate scenarios indicate an increase in flows during the wet season while during the dry season more scenarios show lower flows (see also Beyene et al. 2013).

Throughout the region the flow variability is increasing. Even in areas where both the high flow and the low flows are increasing the high flows are increasing more. This increase in variability has an impact on hydropower production. As flows will become more variable in the future the hydropower potential could become less reliable. While the total production potential is probably increasing in most areas, more frequent high and low flows could still cause more frequent situations when water availability is reducing power production.

The increased flow variability also has an impact on dam management. More frequent high flows will increase the risk that hydropower reservoirs are filling up beyond the maximum capacity. The risk that emergency releases are necessary will probably increase if dam management is not changed. To reduce these risks it might be necessary to release more water than necessary for power production before the wet season to reduce flood risks downstream. However if there rainy season then results in lower inflows than expected this could reduce power production.

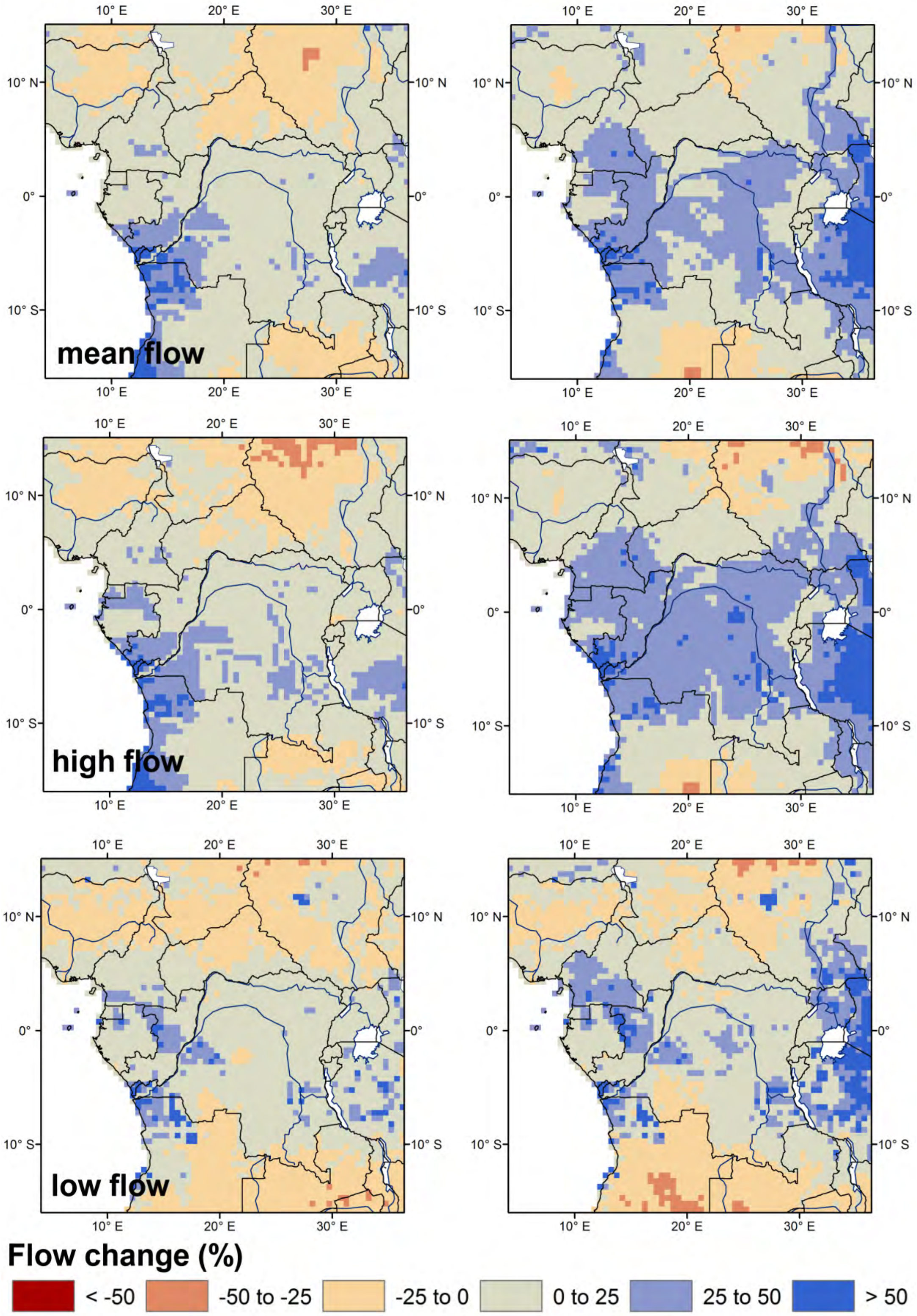


Figure13. Projected changes in mean flow (a), high flow (Q95) (b) and low flow (Q10) (c) for 2071-2100 relative to 1971-2000 averaged for the three different climate model (GCMs) for both the high (A2) and low (B1) emissions scenario.

5.2Hydropower dams.

Climate change is increasing the inflow in all the five focal dams analysed (Table 1). The magnitude of the change however is variable. In the Nzilo dam, the average flow is only slightly increasing. The average increase under the low emission scenarios is almost zero. By the end of the century the flow increases only 13% on average for the high emission scenario. Flow increases were highest for the Song LouLou dam with average increased flows up to 55% for the high emission scenarios by the end of the 21st century. The other three dams all show increased flows of about 10% for the low emission scenario for the 2035-2064 period and 30% by the end of the century for the high emission scenario.

Table 1. Average relative change in river flow for five different hydropower dams within the Comifac region for mid-century and the end of the 21st century for two different emission scenarios. The results are the average of three different climate models (in parentheses the max and minimum change).

Dam	Low emission scenarios (B1)		High emission scenarios (A2)	
	2035 – 2064	2071-2100	2035 – 2064	2071-2100
Moukoukoulou	10% (1 – 17%)	17% (7 – 29%)	13% (11 – 14%)	30% (16 – 53%)
N'Zilo	0.3% (-4.4 – 3.5%)	9% (6 – 15%)	6% (-2.5 – 14%)	13% (10 – 17%)
Song Loulou	18% (-6 – 45%)	50% (32–83%)	36% (20 – 51%)	55% (40 – 73%)
Inga	10% (1 – 18%)	18% (7 – 29%)	13% (12 –15%)	30% (17 – 53%)
Imboulou	10% (3 – 19%)	15% (6 – 29%)	13% (11 – 16%)	30% (16 – 57%)

Changes in flow are not equal over all seasons (Figure 14). In general the flow increases especially during the wet season. During the dry season the average flow increase is minimal and some climate model indicate a reduction in flow during the dry season. The Moukoukoulou, Inga and Imboulou dam all show increases in flow during April and May and for the November-December period. During the low flow period around August the average increase is the lowest. The IPSL climate models indicate lower flows especially in August and September. The CNRM model however indicates reduced flow in July. Also during February and March some of the climate models indicate a reduction of flow.

For the Nzilo dam flows are projected to decrease for the dry season while average flows are increasing for the wet season. During the peak flow season (January) all climate scenarios predict an increase. During the dry season all climate models indicate an increase. For the months between the peak flow and the dry season before the results are more mixed with some climate models indicating a lower flow and other showing an increase.

In conclusion from the six climate scenarios used in this impact analyses it seems unlikely that climate change will have a negative impact on potential hydropower production. The increased flow variability however will make dam management more complicated. Due to increased rainfall intensities (see Haensler et al. 2013) and higher peakflows flood risks are likely to increase. Management of the dams need to be adapted to reduce these risks.

Figure 14. Relative changes in river flow into hydropower reservoirs for five different dams in Central Africa for mid 21st century (left panel) and the end of the century (right panels). Each line (except red) shows the result of an individual climate model. Red lines show the average of the three different climate models. Dashed lines indicate a high emission scenario (A2) and straight lines a low emission (B1) scenario.

6.0 IMPACTS OF CLIMATE CHANGE ON FORESTS AND THE CARBON CYCLE

In this section we describe an analysis of the likely consequences of climate change on the Congo basin region for the carbon cycle. This includes an analysis of the size and the stability of stocks of carbon in the natural vegetation of this region over the upcoming century. We also study the potential shifts in broad classes of vegetation types, resulting from climate change.

Understanding the size, type and stability of carbon stocks over the coming century is important, because these stocks constitute a potentially important opportunity to mitigate climate change. As such, these stocks, if released will cause substantial rise of atmospheric CO_2 concentrations and if conserved have the potential of absorbing additional CO_2 from the atmosphere. Apart from their role in containing atmospheric CO_2, tropical forests represent a suite of ecosystem services locally, regionally and globally, relating to their role in maintaining water resources, containing erosion, providing food and many rare, naturally occurring chemicals, conserving biodiversity, stabilising climate, etc. The carbon stocks and annual carbon uptake rates are a coarse, but useful indicator of the vitality of tropical forests.

There are already several mechanisms being discussed within international treaties and in the UNFCCC to combine the conservation of forests and mitigation of climate change, through management and trading of carbon credits. One of the high-potential mechanisms currently debated is REDD+ (Reducing deforestation and degradation plus conservation of biodiversity), where, at country scale, incentives would be created to reduce deforestation and hence conserve carbon. A crucial aspect of these mechanisms, to be viable on any international ‘market’, is how durable the carbon is that is represented by the conserved forests. If, for any reason, the forests would disappear or degrade, this would put at risk the viability and value of the measures taken to conserve them. This includes forests and the biomass in the forests being threatened by changes in the climate, such as increased temperatures or reduced rainfall. Conversely, if forests could be expected to sequester important additional amounts of carbon, this would add to the viability and value of mechanisms such as REDD+.

Several studies have shown that another tropical rain forest biome, the Amazon basin, can indeed be threatened by climate-induced degradation (Cox et al., 2000; Nobre and Borma, 2009). For that basin, some (but not all) coupled climate-vegetation models suggest that, after an initial increase in biomass, the Amazon forests could rapidly decline as a result of enhanced droughts and a self-enhancing cycle of CO_2 emissions, accelerated climate change and temperature increase. Whether this will really occur is currently subject of intensive scientific studies. Obviously, it is an important question whether computer simulations would show the same pattern for the Congo basin.

Tropical forest carbon stocks are, apart from human-induced degradation, mainly sensitive to changes in rainfall and rainfall patterns (droughts), temperature changes (resulting in changes in photosynthesis and increased decomposition of organic material), and CO_2 change (potentially resulting in increased productivity). We are aware that vegetation models will likely be sensitive to increased radiation as well. Assuming that radiation will not substantially change we will study the changes in carbon stocks of the wider Congo basin over the coming century mainly with changes in rainfall, temperature and CO_2 in mind.

6.1 Simulations and Analysis

For the analysis we have used the LPJml model, applied to the Central-western African region (Lon 6-32; Lat -15-15), using climatic forcing from one of three climate models, generated under the IPCC's AR4 - A2 scenario (Haensler et al., 2013). Forecast runs were done for the period 2000-2100. Parameters were adopted as provided with the model's standard Plant Functional Types (PFTs). For further details on model set-up and spin-up we refer to other sections on this report.

To start with, modelled carbon stocks and changes in carbon stocks have been validated against measured data. For this, we used the series of biomass plot data collected at variable intervals in both West-Africa and margins of the Congo basin, published by Lewis et al. (2009). The LPJml model was used to predict biomass and biomass increment over the same periods for each of these plots.

On the basis of these validations and on the basis of expert judgement on the forecasted changes in vegetation and soil carbon, we selected the results associated with one climate model only (the ECHAM model).

Then the changes in vegetation carbon and soil carbon were analysed, for the given scenarios and periods. For every analysis two spatial domains have been selected: Central West Africa (CWA, Lon 6-32; Lat -15-15), and the Congo Basin (CB, Lon 9-28; Lat -5-5). For these domains, both the patterns of change as well as the regional totals in carbon stocks have been analysed.

To allow for the fundamental uncertainty associated with the effect of changing atmospheric CO_2 (the CO_2 fertilisation effect, see methodology section), simulations were each time done under two sets of conditions: while the climate (temperature, precipitation, radiation) was always assumed to change as predicted by the climate model, CO_2 was allowed to change as prescribed in one case, but kept constant in the other case.

Under the same conditions and simulations, the model forecasted the changes in spatial distribution of productivity per Plant Functional Type. This can be interpreted roughly as the viability of existence for each of these types. These distributions have also been analysed.

6.2 Results and Discussion

Figure 15 shows the results of the validation against measured biomass data. From this, it is clear that the model in its present set-up underestimates the measured biomass. This is a concern, because the source of this discrepancy is not well understood. However, especially the ECHAM model does show a reasonable correlation between modelled and observed stocks, such that it can be assumed that this model does capture sensitivities reasonably well. Where changes over time are compared between model and data, there is no clear correlation. Although this may seem discouraging, it should be realised that the model and the data refer to very different scales. Where the data are valid for individual plots in a very variable landscape, the model generates numbers for broad vegetation classes only and averages conditions over large grid points. This makes it highly unlikely that model and data would agree at a point-to-point basis, especially if time differences are considered.

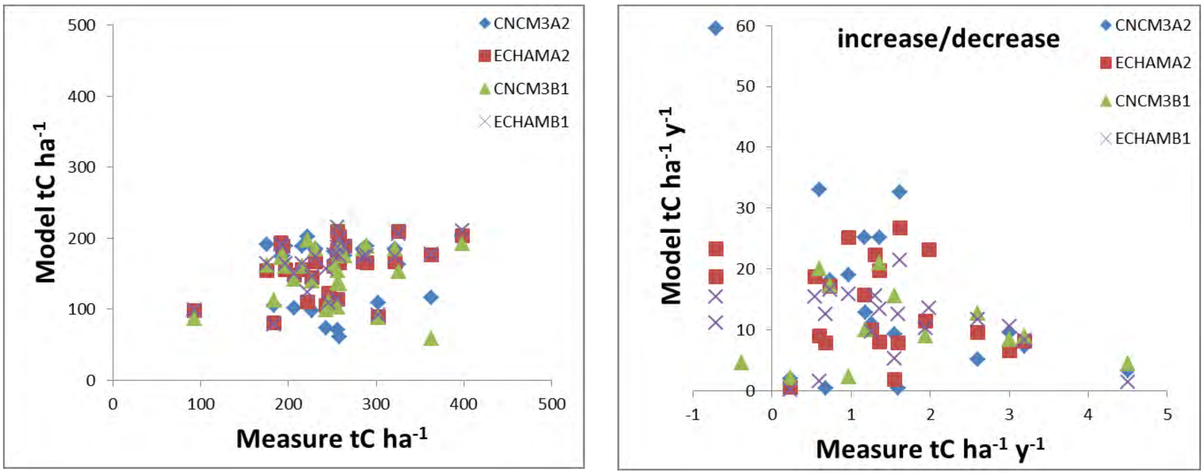


Figure15. (left) Comparison of predicted and measured standing biomass in selected biomass plots as published by Lewis et al (2009), using two different models and two different climate change scenarios. (right) The same, but now for biomass change as measured and modelled over the measurement intervals of each plot.

Figure 15 shows that the simulations predict an overall increase in vegetation carbon, especially in the central Congo basin. If however the effect of CO_2 rise is excluded the model, in contrast, predicts an overall decline in vegetation carbon, also mainly in the central basin. This is also reflected in Figure 16, where we see that only the first decades of the 21st century would show an increase in vegetation carbon , probably with only moderate temperature rise, but for the rest of that period a decline with constant CO_2, where the central basin declines fastest. Information on simulation results for the low emissions scenario (B1) can be found in the map/figure section of the digital (interactive) version of the final report.

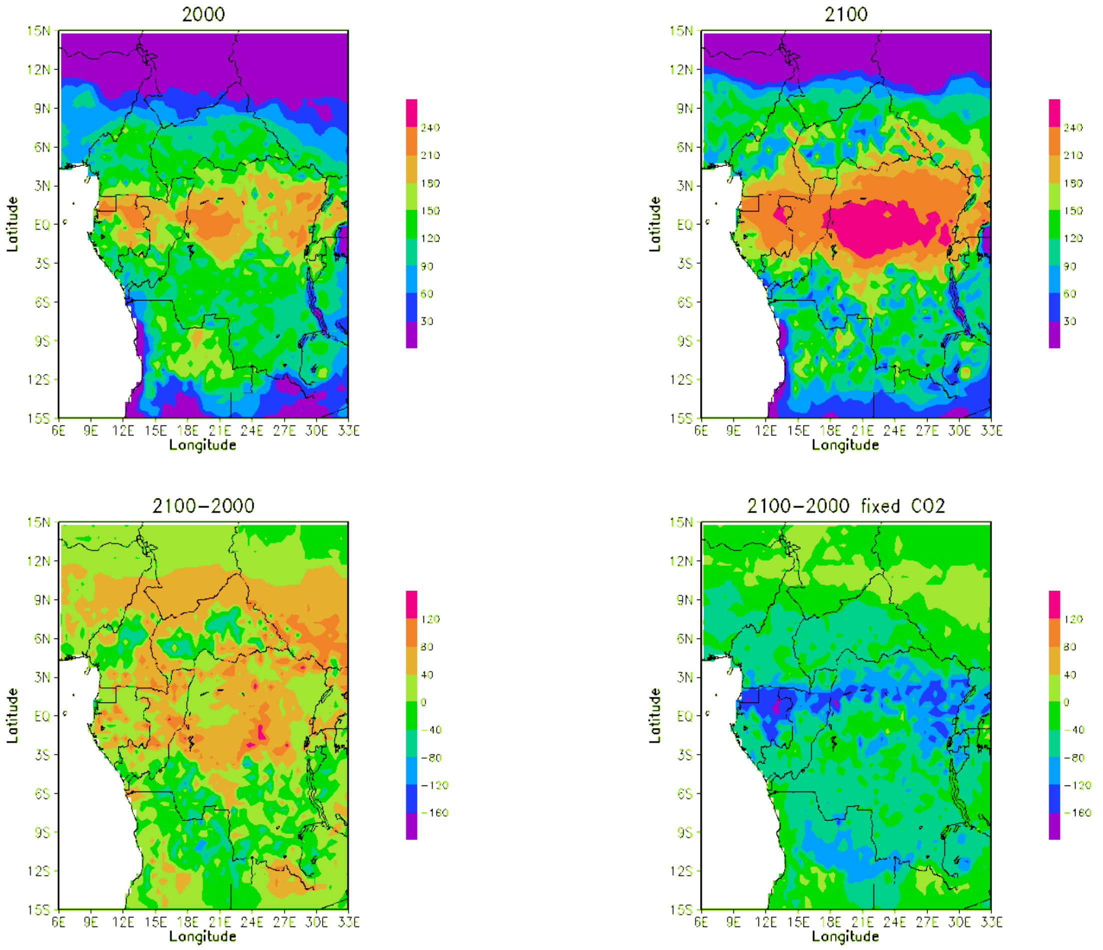


Figure 16. Maps of vegetation carbon (tC ha^{-1}) as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing CO_2 concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.

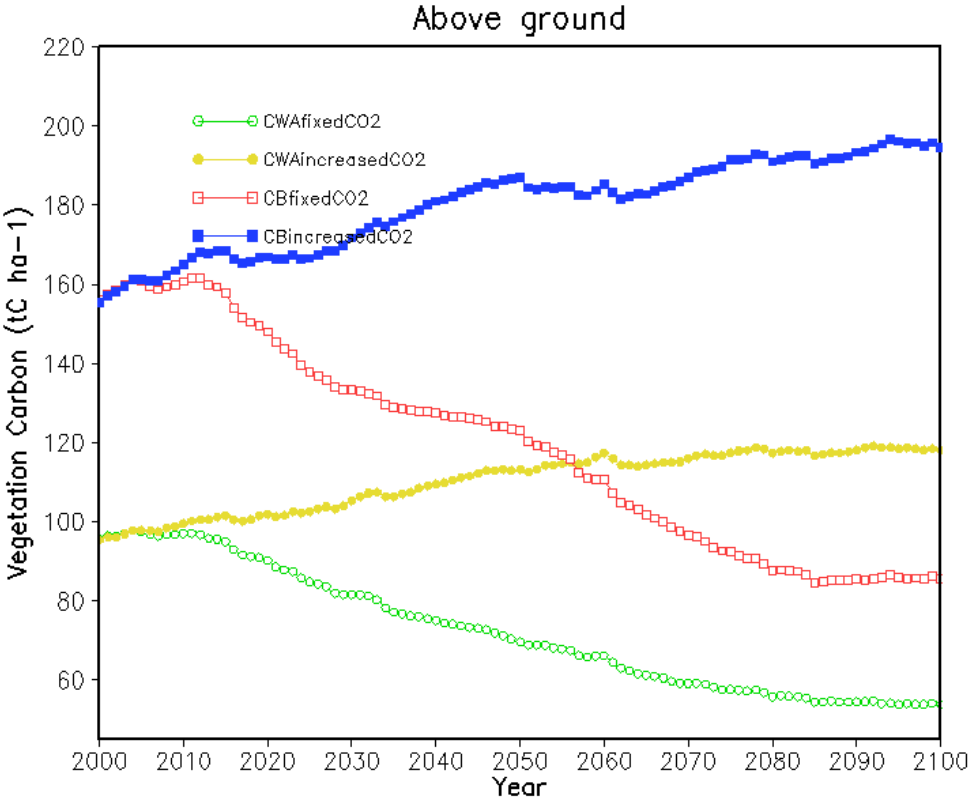


Figure 17. Modelled time evolution using the high emission scenario (A2) of the vegetation carbon over the 21st century. Shown are the time series for the Central Western African area (i.e. the full areas shown in the maps) as well as the time series for the Congo Basin rectangular area, as defined in the methodology. The graph also shows the same time series in the case where atmospheric CO_2 is kept constant.

Figure 18 shows that soil carbon may also be expected to increase with climate change and increasing CO_2, albeit not for the whole basin. For the northern savanna-Sahel transition a decline in soil carbon is simulated even under increasing CO_2. If CO_2 effects are excluded, a uniform decrease in soil carbon is simulated. Figure 19 does reflect these overall changes at century scale, but also shows a more complicated pattern in the time evolution of soil carbon. With increasing CO_2, especially the total soil carbon in the Central basin is simulated to peak in the second half of the century, followed by a decline. For simulations without a CO_2 effect, there is a strong peak in the first half of the 21st century, followed by steep decline. This non-linear behaviour is most likely caused by the simulated transfer of increased vegetation litter and dead woody material to the soil. If decline starts in the vegetation, this will first lead to accumulation of soil carbon, followed by decomposition. Even for the case where CO_2 is simulated to increase, vegetation productivity will lead to enhanced litter fall and turnover, leading to peaks in soil carbon that equilibrate afterwards. Finally, Figure 19 summarises the expected increases, with increasing CO_2, of carbon in the two components, showing that in all cases carbon increases in the vegetation are dominant. Information on simulation results for the low emissions scenario (B1) can be found in the map/figure section of the digital (interactive) version of the final report.

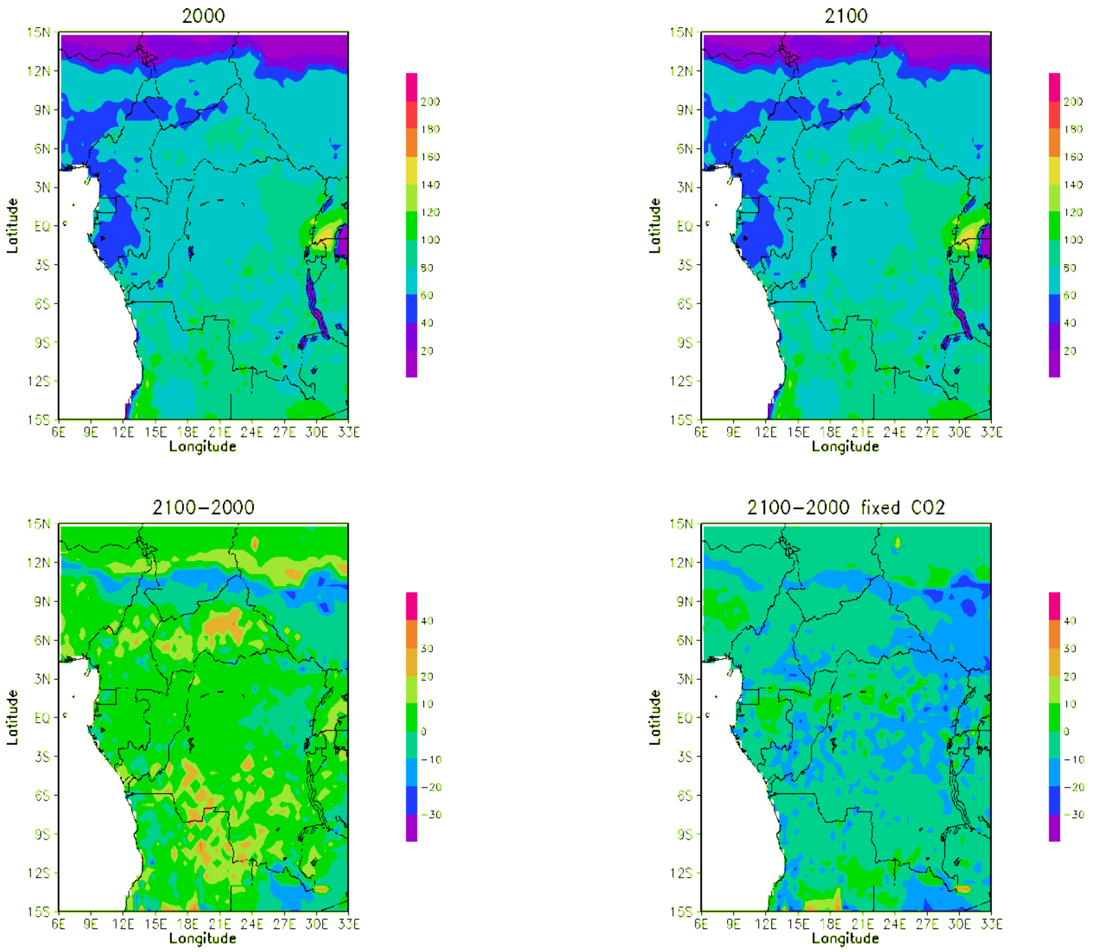


Figure 18. Maps of soil carbon (tC ha^{-1}) as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing CO$_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.

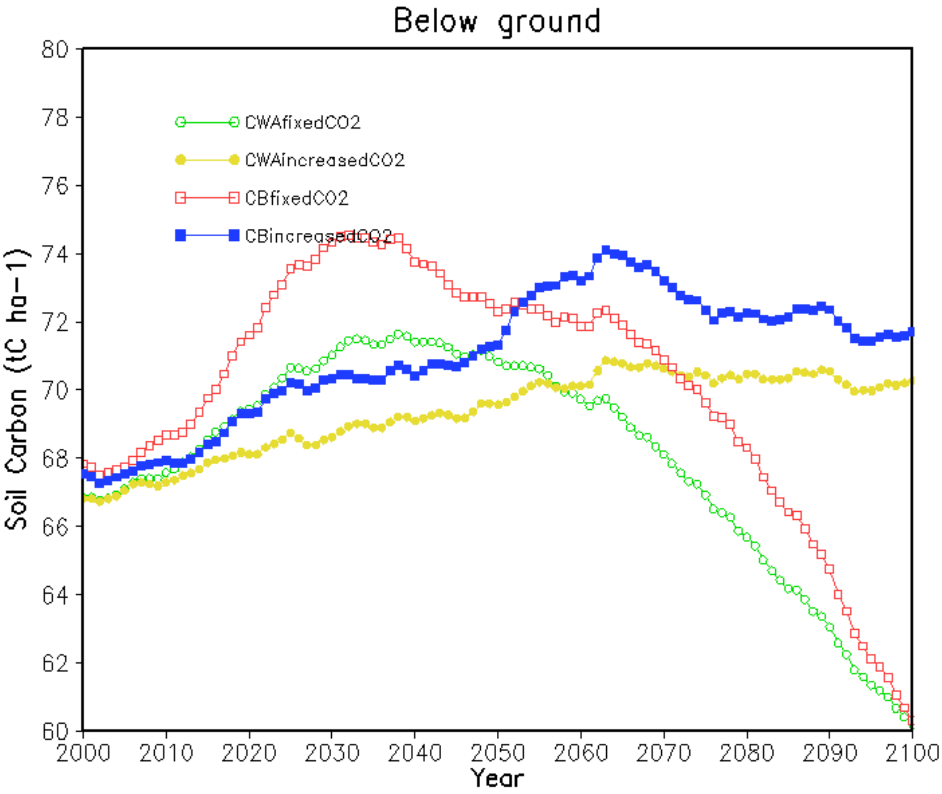


Figure 19. Modelled time evolution using the high emission scenario (A2) of soil carbon over the 21st century. Shown are the time series for the Central Western African area (i.e. the full areas shown in the maps) as well as the time series for the Congo Basin rectangular area, as defined in the methodology. The graph also shows the same time series in the case where atmospheric CO_2 is kept constant.

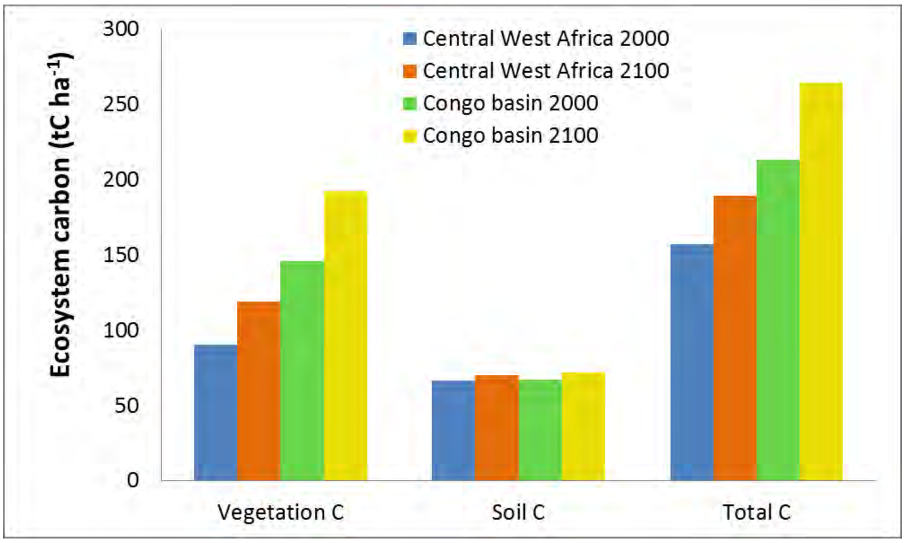


Figure 20. Bar chart summarising the simulated changes over the 21st century in aerially integrated totals of vegetation, soil and total ecosystem carbon over the wider and restricted region, assuming increasing CO_2.

Figures 21 to 23 show the likelihood of shifts in vegetation types, expressed as changes in NPP in the three dominant plant functional types represented by LPJml: Tropical evergreen forest, Tropical seasonal forest and Tropical grassland. The simulations illustrate that the simulated increases in NPP are mainly caused by expansion of the evergreen forest domain. For the seasonal forest, simulations also show an increased NPP in the equatorial region, but the main feature here is a sharp band of expansion towards the north. For the grasslands type, NPP is almost negligible in the central Congo regions, but the model shows a clear shift of grasslands towards the north. Where the effects of CO_2 are excluded, the model shows a decline of tropical evergreen forests in their areal domain, and also a decline in seasonal forests in that area, but still an increase in the northern and southern savanna regions, associated with a replacement of evergreen forest by seasonal forest. Such replacement effect is most clearly shown for grasslands in the case of no CO_2 effect, where the decline in tropical evergreen forest in the Central Congo region leads to modest replacement by grasslands.

Figure 24, finally, shows that in the case of increasing CO_2 all forests are expected to increase in productivity whereas the grasslands are expected to decline slightly. In the latter case, however, it should be realised that grasslands may be moving out of the model domain, so that although total productivity in this domain increases, total productivity in the grassland domain may in fact be increasing. Information on simulation results for the low emissions scenario (B1) can be found in the map/figure section of the digital (interactive) version of the final report.

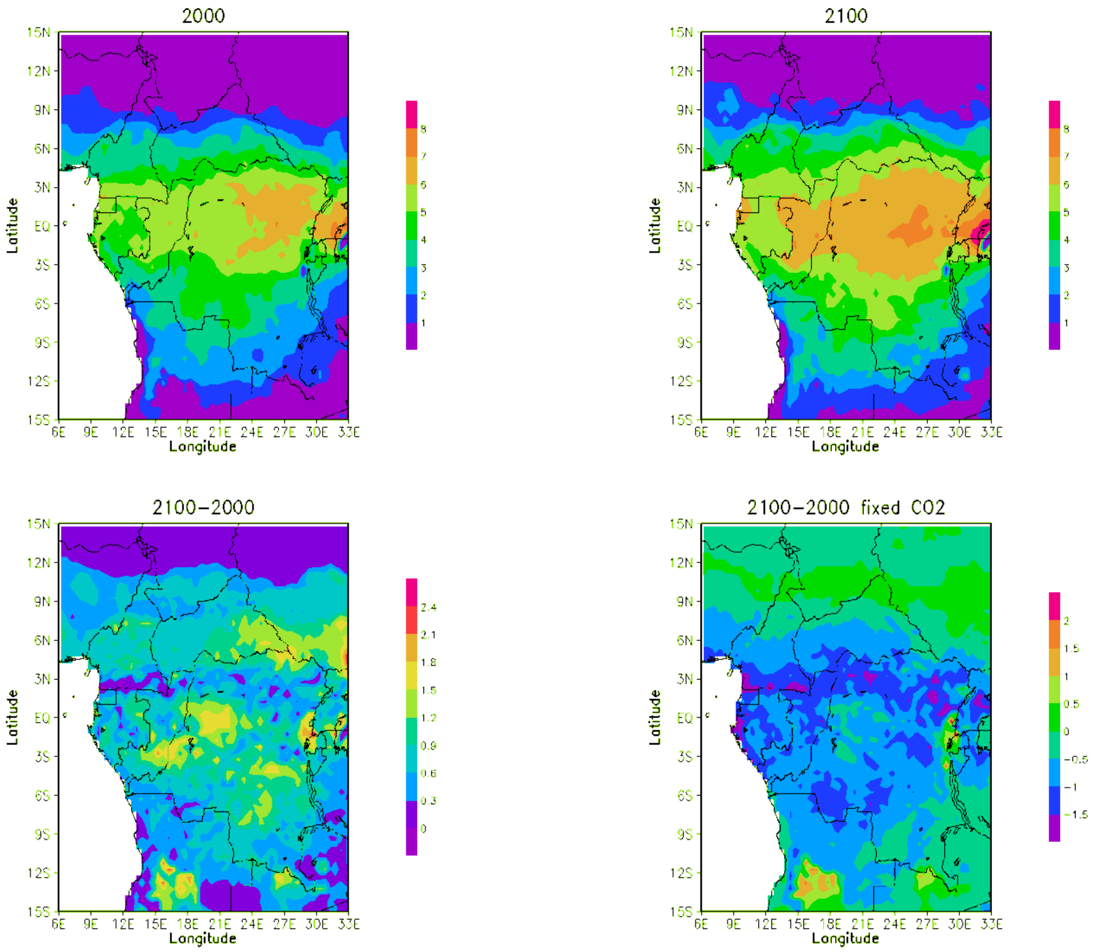


Figure 21. Maps of Net Primary Productivity (NPP, gC m^{-2}) for plant functional type *Tropical Evergreen Forest* as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing CO$_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.

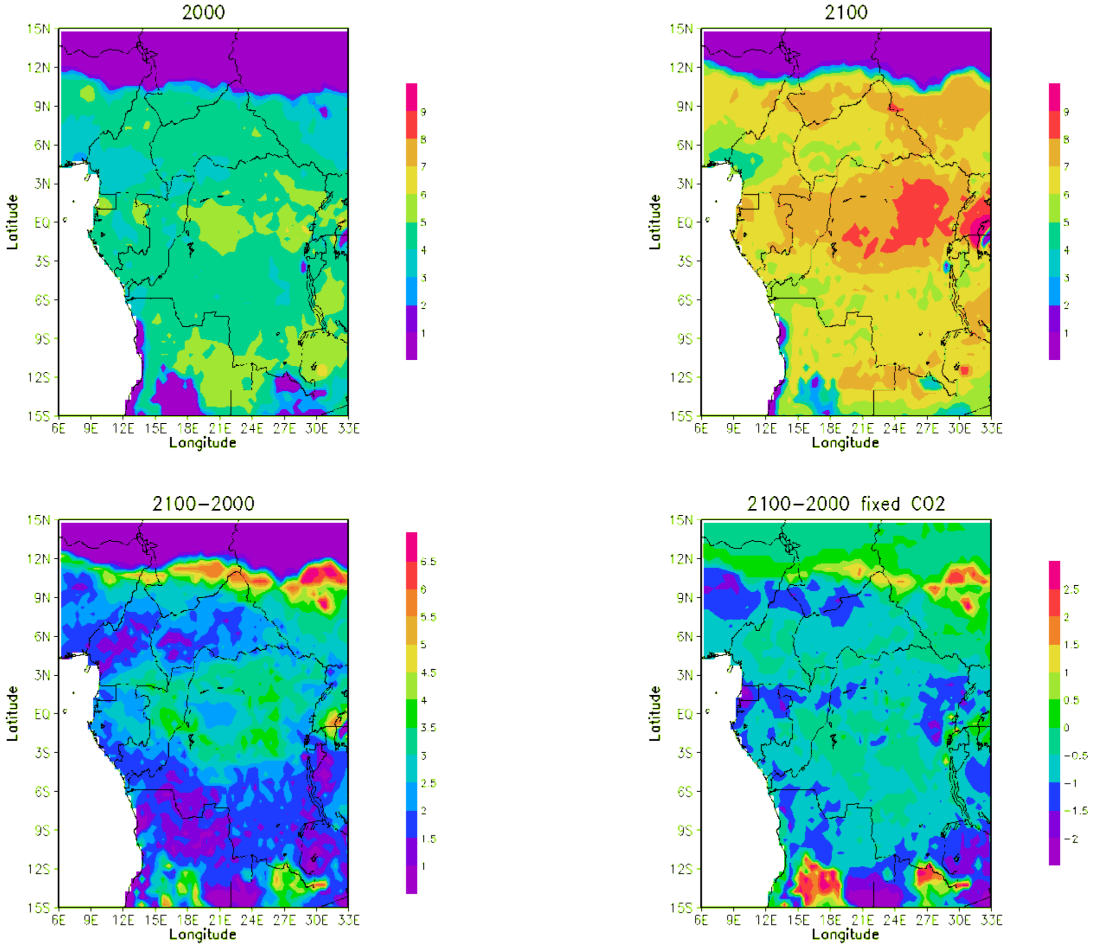


Figure 22. Maps of Net Primary Productivity (NPP, gC m^{-2}) for plant functional type *Seasonal Forest* as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing CO$_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.

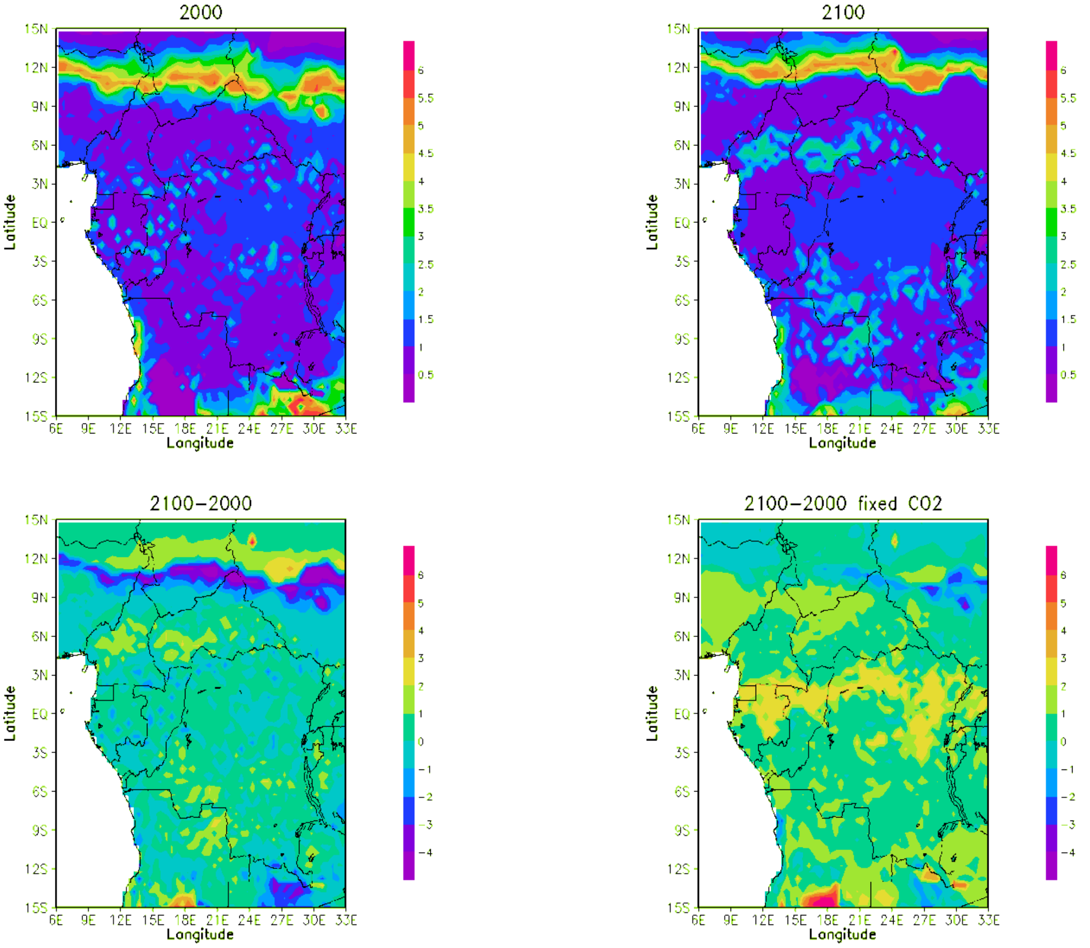


Figure23.Maps of Net Primary Productivity (NPP, gC m^{-2}) for plant functional type *Natural Grassland* as modelled using the high emission scenario (A2) **for the years 2000 and 2100 as well as the changes over this period with and without considering increasing CO$_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.**

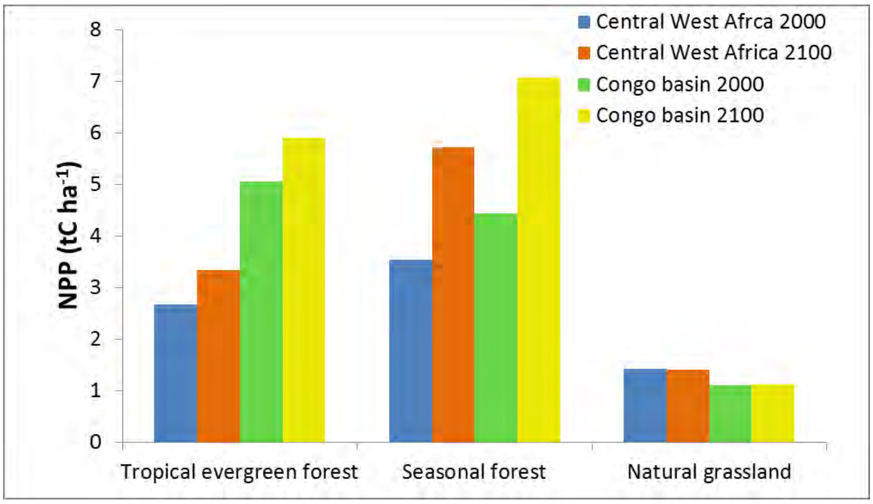


Figure 24. Bar chart summarising the simulated changes over the 21st century in aerially integrated total NPP of the three most important plant functional types, over the wider and restricted region.

6.3 Conclusions

It has to be stressed that the model results on carbon and vegetation are just that: dependent on all assumptions and flaws that may be present in the particular model used, and also dependent on the skill of the climate models underlying the forcing scenarios used. There is, however, one clear conclusion that can be drawn: the lack of understanding on CO_2 effects is responsible for major uncertainty. With inclusion of CO_2 effects, the forests are simulated to grow, without those effects, they are simulated to decline. Which assumption is closer to the truth is still unknown. It is reasonable to expect that there will be a moderate, or at least a temporary effect, of increased CO_2, such that it might be reasonable to estimate that real biomass increases are somewhere in the middle of the range shown here.

Apart from CO_2, it is likely that the decline in biomass is mainly the result of temperature increasing beyond the optimum that is prescribed in the model. Again, there is little empirical evidence to support the specification of temperature optima in tropical forests, so the decline may well be unrealistic. These results, as well as those for CO_2 dependence, are very similar to the analysis by Jupp et al. (2010) for the Amazon.

In summary, based upon these results, it may be expected that as a result of climate change, the Congo basin is unlikely to see a decline such as is sometimes predicted for the Amazon basin, but instead will see a moderate increase in ecosystem carbon, a moderate expansion to the North and South of Evergreen forests, associated by similar shifts in savannahs and grasslands. Much more research is needed, however, to substantiate the underlying model assumptions and reduce uncertainty in these simulations

From these findings it follows that the potential in the region to implement UNFCCC-REDD+ projects is still very uncertain, but probably sustainable and feasible. Because the model results do not predict large-scale, *climate-induced* forest and biomass degradation, the risks for *climate-induced* losses of carbon in a REDD+ project are small. At the same time, the simulations also suggest that especially the seasonal forests (savannahs) are at risk near their climatic boundaries. Combined with the generally recognised risks for uncontrolled deforestation, which was not accounted for in our simulations, this calls for well-planned and strong investment in conservation and sustainable management. The region clearly has a big potential to serve as an important carbon sink, and at the same time there seems to be scope for investments into forest-related biofuel production (from firewood to energy from forestry waste).

7.0 IMPACT OF CLIMATE VARIABILITY AND CHANGE ON ECONOMIC DEVELOPMENT

Climate change is likely to have the most severe impacts on developing countries. Many African countries already face a climate with unpredictable rainfall and future climate change is likely to increase water stress and make water availability and agricultural production less reliable. To estimate the impact of future climate change on economic development in African countries it is important to know to what extent recent economic growth is affected by climate variability. Some recent reports have indicated that climate variability can have a serious impact on economic growth. For example, the great floods during 2000 in Mozambique reduced economic growth from 8.2 % in 1999 to only 2% in 2000 (World Bank 2001). Another World Bank report estimated that floods and droughts experienced in Kenya during the 1997-2000 El-Nino - La Nina cycle resulted in damages worth 22% of annual GDP (World Bank 2004). These examples and a few national analyses (Grey and Sadoff 2006) indicate that economic and agricultural development in developing countries depends on climate variability. All previous studies however did not look at the Central African region where climate variability is different and could have a different impact on economic development.

To study the relationship between climate variability and development we used annual data on rainfall, and annual total GDP and agricultural GDP growth rates from 1979-2001 for most countries in Sub-Saharan Africa. We used the rainfall data base described by Miguel et al. 2004. The basis of the dataset is the rainfall database of the Global Precipitation Climatology Project (GPCP) of monthly rainfall estimates. This database contains rainfall estimates at 2.5 degrees latitude and longitude intersections. Estimates are based on actual station data and density of cold cloud cover. Yearly rainfall estimates are calculated as a sum of the monthly rainfall data. Yearly rainfall of each country is calculated as the average of all rainfall estimates of 2.5 degree longitude/latitude nodes located within each country. Data on total and agricultural GDP, GDP growth and GDP per capita were extracted from World Bank databases.

In several of the Comifac countries there is a relation between annual rainfall and GDP growth. This correlation is stronger in countries with lower and more variable rainfall. For example in Chad, dry years often coincide with years of low GDP growth (Figure 25). To analyse if year with below average (droughts) and above average (possible floods) year affect GDP growth we divided the years in three different groups. The 33% wettest year, the 33% driest years and a middle group. For each of the three groups the average total GDP and Agricultural GDP (Ag-GDP) growth rate was calculated. In most countries both the total and agricultural GDP growth rates were lower during dry years compared to medium and high rainfall years (Figure 26). For example in the Democratic

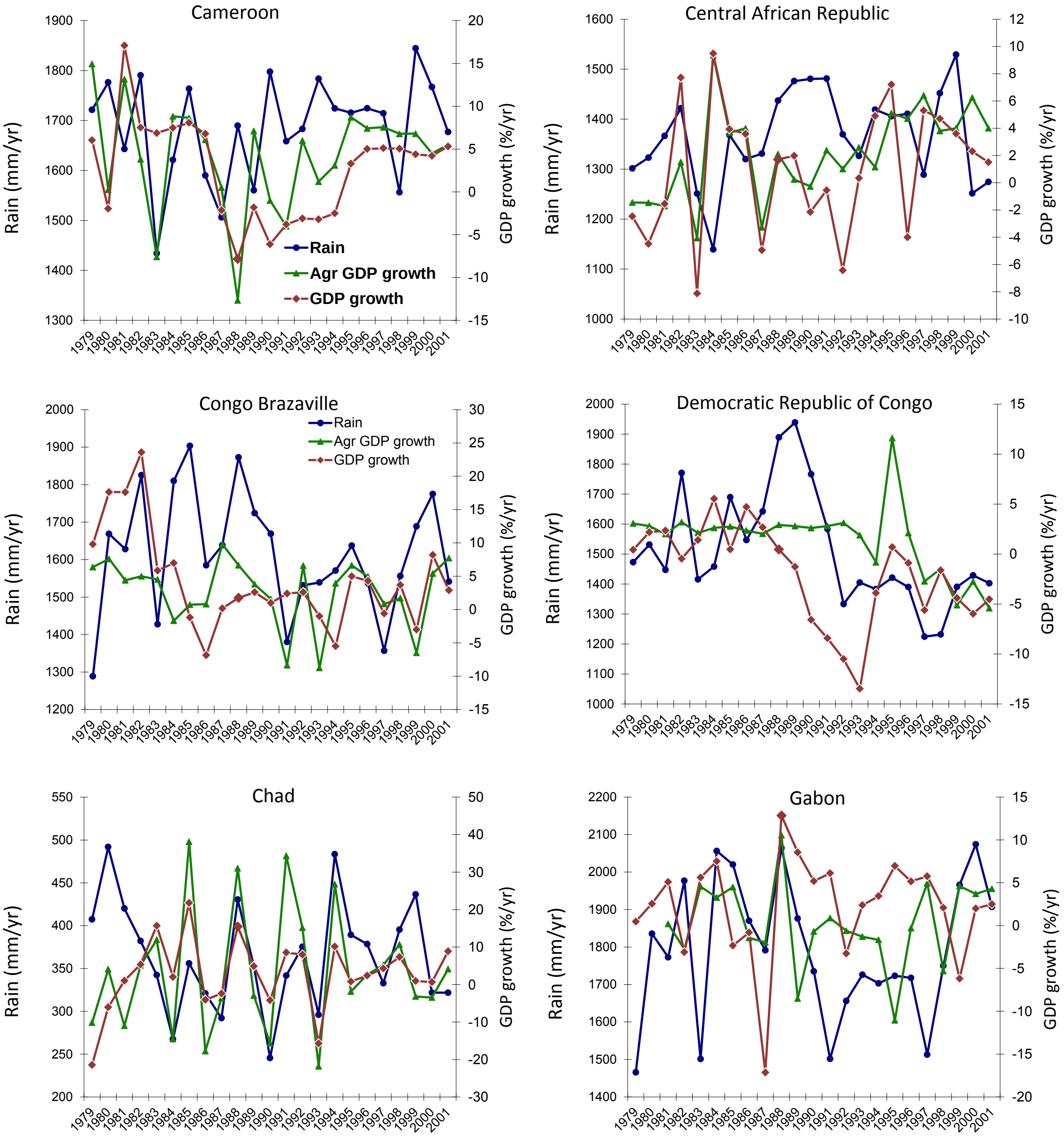


Figure 25. Relation between rainfall (blue line) and total economic growth (red line) and agricultural economic growth (green line) for six countries within the COMIFAC region.

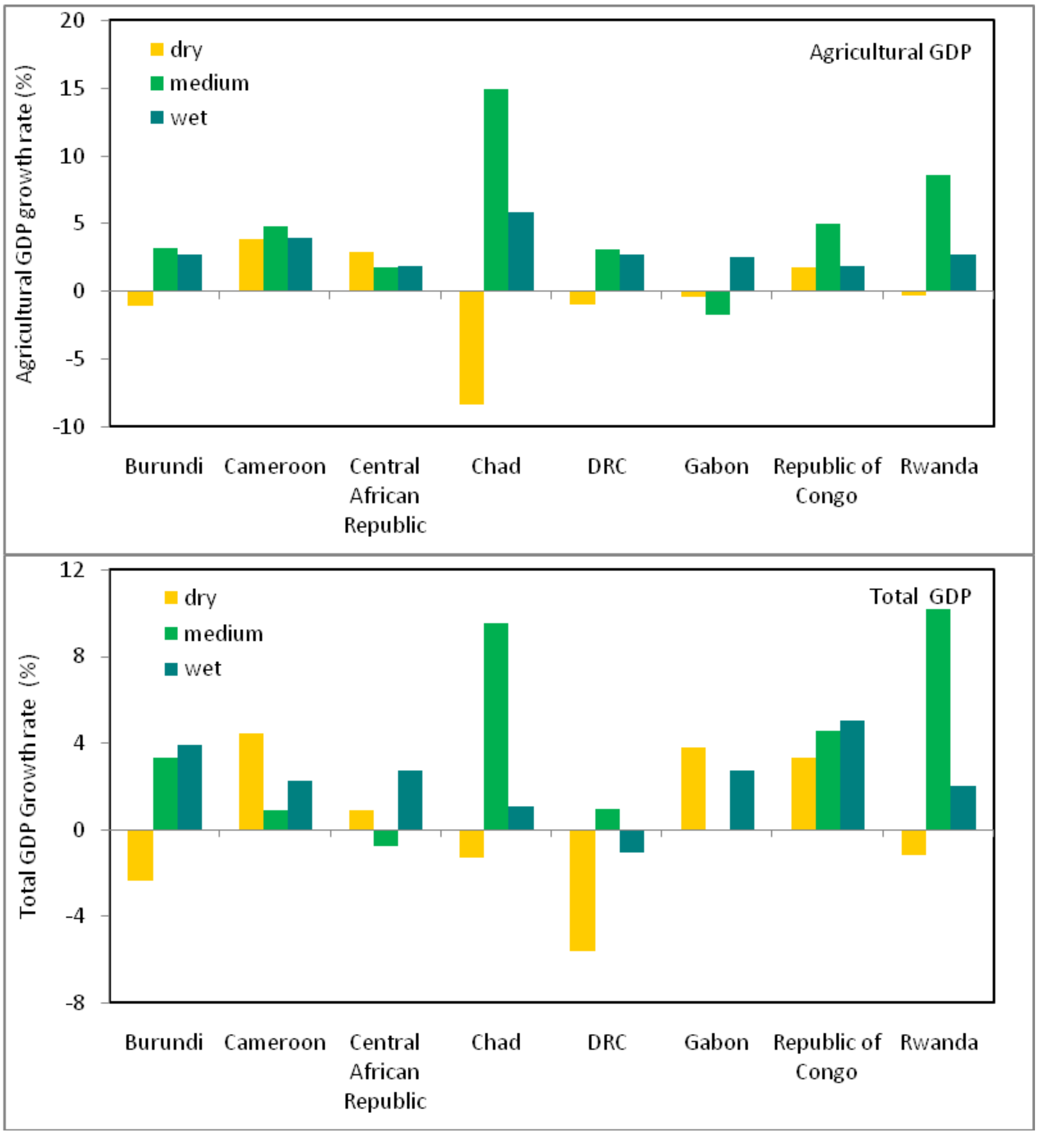


Figure26. Average total and agricultural economic growth for the period 1979-2001 for dry, medium and wet years. Wet, medium and dry years were determined based on the country average total annual rainfall. For example for GDP growth during the dry years the GDP figures were average for the 33% driest years.

Summarized, the analyses of the historic data showed that climate variability has in some countries clear impact on GDP growth rates. GDP and Agricultural GDP growth rates tend to be higher in years with above average rainfall than in the dry years. The impact of climate variability on GDP growth is most pronounced during dry years. During below average rainfall years growth is sometimes severely reduced and generally the dryer the lower the GDP growth rate. All above average rainfall years tend to have relatively similar growth rates.

For most of the Central African countries rainfed Agriculture is still an important driver of the economy. In countries with high interannual rainfall variability dry years result in crop failure and also reduce some other economic activities through for example reduction of available hydropower and water needed for industrial activities. Above average rainfall tends to have a positive impact on development largely through improved agricultural production. Only in very wet years does rainfall again reduce growth. This reduction is especially clear for total GDP growth and not for Agricultural production. The negative impact of high rainfall is usually through flooding which especially damages infrastructure (World Bank 2001) and probably does more harm to the industrial and services sector of the economy than on Agriculture. There is no doubt that flooding also has an impact on agricultural production but probably because flooding tends to be local, negative impacts of flooding on Agricultural production are compensated by higher production in non-flooded areas.

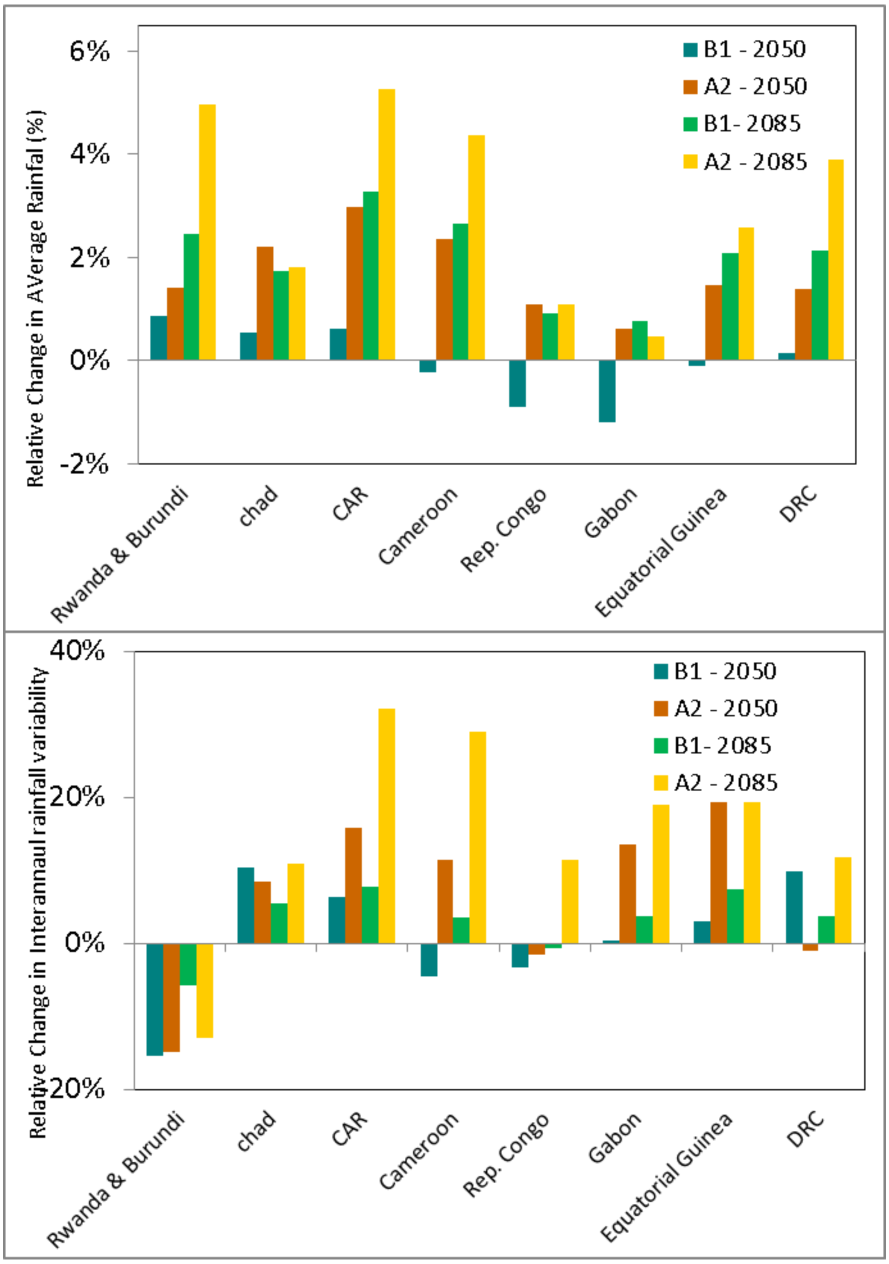


Figure27. Relative future changes in average annual rainfall and interannual rainfall variability for the different Comifac countries. Changes are shown for two different periods: 2036-2065 (2050) and 2071-2100 (2085) and two different emission scenarios. Changes shown are the average of 5 or 6 different climate models.

Figure28. Relative future changes in average annual rainfall and interannual rainfall variability for the different Comifac countries. Changes are shown for two different periods: 2036 - 2065 (2050) and 2071 - 2100 (2085) and two different emission scenarios. Changes shown are the average of 5 or 6 different climate models.

To determine if future climate change will affect economic development we analysed changes in future total rainfall and the interannual rainfall variability for the different countries. To do this we used 6 different climate models and two emission scenarios. A high emission scenario (A2) and a low end scenario (B1).

An average rainfall is increasing in all countries for almost all scenarios (Figure 27). Only for the B1 scenarios for mid-21st century there is a slight decrease projected for some countries. The increase averaged over the 5 or 6 climate models is in most cases not very high. The higher rainfall increases are up to 5% for the A2 scenario by the end of the century. While average over the models the rainfall is increasing in the region there were considerable differences between the different climate models (Figure 28). For example, for Chad the range is between -8% and +9% change in annual rainfall for the A2 scenario. For Gabon the range is between -10 and +13%. For none of the countries all scenarios agree on sign of change. There is always one or models which predicts either a decrease or an increase. This indicates that there is large uncertainty about the future changes in rainfall in the region (see also Haensler et al. 2013).

Climate change does not only affect the average rainfall it also changes the variability. Especially towards the end of the century the interannual variability is increasing throughout the Central African region (Figure 27). For the countries analysed only for Burundi and Rwanda the interannual variability was decreasing. The impact of climate change on interannual rainfall variability is much higher than the impact on changes in the total rainfall. Averaged over the different climate models, rainfall variability is increasing by 30% in Chad and Central African Republic for the A2 emission scenarios. Some individual climate models even project increased rainfall variability of up to 100% in some countries. Similar as with changes in total rainfall there is a large spread between the different climate models. Some models project small reductions in interannual rainfall variability while other show a doubling in variability (Figure 28).

The main question is how will these changes in total annual rainfall and interannual rainfall variability effect economic development. To answer this question we expanded our dataset including almost all countries in sub-saharan Africa. This gave us a larger dataset to estimate the parameters needed for our model.

The panel data regression analyses of the historical climate showed that also for the whole African continent climate variability has a clear impact on agricultural production and GDP growth rates. Results of the vulnerability analyses showed that throughout Africa a climate with increased rainfall variability would reduce GDP growth. The Sahel region is most vulnerable to changes in rainfall variability, a 50% increase in the standard deviation of annual rainfall would reduce GDP growth by 35%. In East and coastal West Africa a 50% higher standard deviation (s.d.) of annual rainfall would result in about 20% less growth. In Southern Africa the impact of increased rainfall variability are relatively small a 50% higher s.d would reduce growth by 7%. In general, African economies are much more vulnerable to a drier future climate than to increases in rainfall. A 10% reduction in rainfall could result in 12% lower GDP growth rate in Southern Africa and 43% in the Sahel region. Especially a combination of a drier and more variable climate has a large impact on GDP growth. A 10% reduction in annual rainfall combined with 25% higher s.d. will reduce growth rates to only 1% in the Sahel region. In East and Coastal West Africa, this drier and more variable scenario will result in a 30 to 40% reduction in GDP growth rates.

A small increase in rainfall general has a positive impact on economic growth. A climate with on average 10% more rainfall would result in higher GDP growth rates throughout Africa. However, the impacts are not linear and a 20% increase in annual rainfall of 20% results in GDP growth rates lower than historic growth rates in West Africa. In Sahel and East Africa projected growth rates for 20% increased rainfall are similar compared to a scenario with 10% higher rainfall.

Using projected changes in the mean and the interannual rainfall variability simulated with ECHAM5/MPIOM coupled atmosphere-ocean general circulation model there was on average a reduction in GDP growth for Southern and West Africa and the Sahel regions and hardly any change for East Africa. In Southern Africa, GDP growth reduced due to a projected decrease in rainfall. In West Africa, a more variable rainfall caused the reduction in GDP growth. For Southern Africa, for all countries a reduction in GDP growth was projected. In the other regions there were some clear differences between countries. For example in the Southern part of East Africa (Malawi and Mozambique) a reduction of rainfall is projected which results in lower projected GDP growth figures. In the Northern part of East Africa a slight increase of rainfall is projected in combination with generally lower rainfall variability this combination resulted in higher projected GDP growth rates for countries like Ethiopia and Kenya. In the coastal West African region, especially for countries on the western edge of the continent a reduction in mean rainfall and an increase in variability is projected. This resulted in projected reductions in GDP growth. For the countries on the Eastern side of West Africa a small increase in rainfall is projected which would have a positive impact on GDP growth.

The analysis of the historic data shows that climate variability has had a clear impact on historic GDP growth rates. In most countries outside the Central African tropical zone, GDP and Agricultural GDP growth rates are much higher in years with above average rainfall than in the dry years. During below average rainfall years growth is severely reduced and generally the dryer the lower the GDP growth rate. All above average rainfall years tend to have relatively similar growth rates. For most of the African countries rainfed agriculture is still one of the most important drivers of their economy. In countries with high interannual rainfall variability dry years result in crop failure and also reduce other economic activities through the reduction of available hydropower and water needed for industrial activities. For example, the drought in Kenya during the 1998-2000 La Nina in resulted in the reduction in hydropower worth $640 million (World Bank 2004). Above average rainfall tends to have a positive impact on development largely through improved agricultural production. Only in very wet years does rainfall again reduce growth. This reduction is especially clear for total GDP growth and not for Agricultural GDP. The negative impact of high rainfall is usually through flooding which especially damages infrastructure (World Bank 2001) and probably does more harm to the industrial and services sector of the economy than on agriculture. There is no doubt that flooding also has an impact on agricultural production but probably because flooding tends to be local, negative impacts of flooding on Agricultural production are compensated by higher production in non-flooded areas.

In terms of the impacts of future climate change, our analyses showed that GDP growth is especially vulnerable to relatively small reductions in rainfall. Already 10% less rainfall can significantly reduce growth without any adaptation. Also a more variable climate reduces average GDP growth rates.

More variable rainfall will result in more extreme dry and wet years when economic growth tends to be lower and fewer years with around average rainfall which is optimal for economic development.

Using the outputs from the ECHAM5 GCM model showed that future climate change can reduce GDP growth in Africa due to changes in rainfall patterns. Both in West and Southern Africa model projection show a reduction in GDP growth, in coastal west Africa and the Sahel this is due to more variable rainfall while in Southern Africa this is due to a reduction in annual rainfall. We have only used the outputs from one GCM models while different models tend to give different results for the African continent. However, the output of ECHAM5 model is representative of average model outputs. Most GCM models predict a drier future climate for Southern Africa (Christensen et al. 2007). Also for East Africa the ECHAM5 model outputs are consisted with model ensemble averages: increased rainfall for the Horn of Africa and Kenya and lower rainfall in the south-eastern countries like Mozambique and Malawi. For West Africa and the Sahel results are mixed with some models predicting increases in rainfall and other predicting a drying trend. Also the ECHAM5 model outputs did not show a clear picture for West Africa. For some countries there was a slight increase in rainfall while for sometimes neighbouring countries a reduction in rainfall was predicted.

An important assumption of our analyses is that impacts of historic climate variability are similar to the impacts of future variability. Whether this is the case or not probably depends on the individual country and which adaptation measurers will be taken. Due to continuing population growth water demands are likely to increase in the future. Also higher temperatures have the potential to increase water demands for irrigation and industrial cooling. However, some countries have during the last decades improved their economic performance in the industrial and services sector which are potentially less vulnerable to climate variability than agriculture (Vincent 2007). Although, also part of these sectors such as hydropower, tourism and transport can be vulnerable to climate variability.

Our results only show the impact of increased interannual rainfall variability. Increased greenhouse gas concentrations are also likely to increase within year rainfall variability i.e. rainfall periods become more concentrated and both the frequency and length of dry periods are likely to increase (IPCC2012). This will put an additional constraint on agricultural production because especially dryland crops depend on regular rainfall for optimal production.

For the central African region the model showed that economic growth is especially vulnerable to a reduction in rainfall and a significant increase in interannual rainfall variability. When we combine this with the future climate change scenarios results show that the impact of climate change is relatively small in central Africa compared to other regions in Africa (Table 2). The reason is that most scenarios show a small increase in annual rainfall for the Region. At the same time variability is also increasing. In Cameroon and Chad this has a negative impact on economic development. However these negative impacts of climate change are only very clear when the climate scenarios for the end of the century are used. By that time the economies have probably changed with a different sensitivity to climate change. In Rwanda and Burundi, due to projected reduction in climate variability and a small increase of total rainfall, there is a positive impact of climate change on economic development.

Table2. Climate change impact on relative changes in future GDP growth rates. Changes in GDP growth rates are based on change in average and variability of annual rainfall using parameters based on statistical analyses of historical data.

Time period	2036-2064		2071-2100	
Emission scenario	B1	A2	B1	A2
Burundi	2.1%	5.1%	6.1%	19.9%
Cameroon	-1.3%	2.4%	2.6%	-18.2%
Chad	-1.0%	2.3%	0.3%	-8.2%
Rwanda	3.8%	9.4%	3.1%	15.9%
Central African Republic	No detectable Signal of climate change			
DRC				
Gabon				
Republic of Congo				

Our results show that at a continental scale, climate change is likely to have a negative impact on development in Africa. However the economies of Central African countries are less vulnerable to climate change compared to countries in West, East and Southern Africa. Also at macro scale the climate scenarios seem more favourable the in the central African part. However some climate change scenarios show large increases in climate variability. In this Central African region, it is especially the increase in variability as a result of global warming which will have the most impacts on economic development.

8.0 GENERAL DISCUSSION AND CONCLUSIONS

For the climate change impact analyses presented above we used a subset of all the climate scenarios analysed by Haensler et al. (2013). For the impact analyses it was not possible to use all the climate scenarios available. The subset of climate change scenarios used however showed a representative spread of the all available climate scenarios. Using a larger set of climate scenarios could have improved the results. However, it is unlikely that a large number of scenarios would significantly change the conclusions of the impact analyses.

Result showed that as a result of climate change, in general, the water availability in the region will increase. In most parts of the region run off and river flows will be higher in the future. Although in the drier parts, especially in Chad, the river discharge could become lower. Not only the average flows will increase but especially the peak flows will become higher. This is the result of a combination of higher average rainfall and increased rainfall intensity. The main impacts of the higher peak flows are increased flood risks and it will affect the management of hydropower dams.

In general, climatic conditions are currently not limiting agricultural production in the Congo basin region. The water for agriculture analyses showed that it is unlikely that agricultural production will become water limited in Central Africa in the future climate. In the (drier) edges of the region water limitation is sometimes reducing the potential agricultural productions. The agriculture in the savanna regions surrounding the Congo basin could potentially face higher water shortages in the future. In the southern savanna region analyses indicate that more frequent droughts will affect agriculture production and water stress.

The main climate change impacts for the agricultural sector will come from a more variable rainfall and higher temperatures. The temperatures in the region are already higher and even higher temperatures could negatively affect crop production. In the tropical central Africa, too much rainfall and high humidity is currently limiting agricultural production through nutrient leaching and fungal growth. Higher temperatures and can increase diseases and fungal infections especially if the humidity remains high or will increase. More precipitation can potentially increase nutrient leaching and erosion.

Our analysis shows that water available for hydropower is likely to increase in the future. For all the dams analysed, average water availability will increase. On average, climate change will have a positive impact on potential electricity production. Especially during the wet season water inflows into the reservoirs will increase. The impact of climate change on dry season flows is uncertain. With climate change, however, river discharge will also become more variable with more frequent low and high flow periods. This will increase the flood risks and could make the power production less reliable. The increased flow variability will make dam management more complicated because the balance between flood prevention and optimal power production will be more difficult to manage.

Climate change will have a range of different impacts of forest ecosystems. The higher atmospheric CO_2 concentrations will probably increase forest growth and carbon capture. Higher temperatures however will have negative impacts on forest growth and reduce the amount of carbon in the forests. The impact analyses show that as a result of climate change, the Congo basin is unlikely to see a climate-induced decline in forest growth such as is sometimes predicted for the Amazon basin. Instead there could be a moderate increase in ecosystem carbon. Depending on how the climate will change there could be a shift in land cover of the different ecosystems. Based on the analyses a moderate expansion to the North and South of Evergreen forests into savannas and grasslands is the most likely future scenario. The model assessments show a large uncertainty range, highlighting the fact that collecting new data on, *e.g.* biomass in the central Congo basin and responses of forests to a changing climate and atmospheric CO_2 concentrations, are improve our understanding on climate change impacts on forests in the Congo basin.

Our results indicated that the potential in the region to implement UNFCCC-REDD+ projects is still uncertain, but probably sustainable and feasible. Because the model results do not predict large-scale, climate-induced forest and biomass degradation, the risks for climate-induced losses of carbon in a REDD+ project are small. At the same time, the simulations also suggest that especially the seasonal forests (savannas) are at risk near their climatic boundaries. Combined with the generally recognised risks for uncontrolled deforestation, which was not accounted for in our simulations, this calls for well-planned and strong investment in conservation and sustainable management. The region clearly has a large potential to serve as an important carbon sink, and at the same time there seems to be scope for investments into forest-related biofuel production (from firewood to energy from forestry waste).

In several of the COMIFAC countries we observed a clear correlation between annual rainfall and GDP growth. GDP and Agricultural GDP growth rates were higher in years with above-average rainfall compared to dry years. Dry years have more impact on GDP growth rates than wet years. Droughts tend to have a big impact on agriculture while floods tend to destroy more infrastructure. So with more infrastructure development flood vulnerability of the economy could potentially increase. Making future infrastructure more climate proof by ensuring that future floods will not wash away the infrastructure could reduce the impacts of future floods on economic development.

Our analyses on the impacts of future climate change on economic development showed that COMIFAC countries are especially vulnerable to lower future rainfall and a significant increase in interannual rainfall variability. Our results show that at a continental scale, climate change is likely to have a negative impact on development in Africa. However the economies of central African countries are likely to be less affected by climate change compared to countries in West, East and Southern Africa. The COMIFAC countries are less vulnerable due to the relatively high rainfall in the region which makes them the economies less sensitive to future changes. Also at macro scale the climate scenarios are more favourable central Africa to the rest of Africa. In some other regions of Africa, especially Southern the rainfall and water availability is projected to reduce or become much more variable (Christensen et al. 2007).

In conclusion, the climate change impacts on the different sectors shows that the main impacts will come from a more variable climate. No major climate change impacts are expected in terms of total water availability for agriculture and average total future carbon storage in the tropical forests. Also the average potential energy production from hydropower will not reduce. The most severe impacts will result from a more variable hydrological regime. This could result in more frequents droughts and dry periods within the growing season. Climate change will also increase future flood frequency and possibly severity. Future dam management will also become more complicated due to increased climate variability and increased frequency of days with high rainfall extremes.

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Climate Change Adaptation Options for the Congo Basin Countries

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On behalf of
Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
of the Federal Republic of Germany

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This report should be cited as follows:
van Garderen, Ludwig F. (2013): Climate change adaptation options for the Congo Basin countries. In: Climate Change Scenarios for the Congo Basin. [Haensler A., Jacob D., Kabat P., Ludwig F. (eds.)]. Climate Service Centre Report No. 11, Hamburg, Germany, ISSN: 2192-4058.

"Climate change adaptation options for the Congo basin countries"
Part of the series: "Climate Change Scenarios for the Congo Basin"
Authors: Garderen, Linda van, Fulco Ludwig
Lay-out and Editing: Linda van Garderen, Fulco Ludwig
Date: Feb 2013

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany / Gesellschaft fur Internationale Zusammenarbeit (GIZ), Germany / Wageningen University, The Netherlands / Climate Service Centre, Germany.

Cover photo: "A farmer watering his field of sugar cane" @ AlidaVanni/istockphoto.com

ABSTRACT

During the last decades, the importance and seriousness of climate change and it's impacts have become more and more understood. The climate is already changing and therefor adaptation to these changes need to be made. Central Africa needs to adapt to climate change just as much as the rest of the world. This report is focused on the COMIFAC countries, or the Congo River Basin countries: Cameroon, Equatorial Guinea, Sao Tome & Principe, Gabon, Republic of Congo, Central African Republic, Democratic Republic of Congo, Rwanda and Burundi. Based on the impact analyses of the previous chapter, this chapter discusses the most appropriate adaptation measures for the region. This chapter explains the basic principles of climate change vulnerability and adaptation such as adaptive capacity, forms of adaptation, the adaptation cycle, maladaptation, adaptation deficit and no-, low- and high regret adaptation options.

The second part of the report focusses on the different climate change adaptation options for central Africa within four sectors: Agriculture, Forestry, Water and Energy. Even though these four sectors are discussed there is also a strong overlap. In total 52 climate change adaptation measures are listed in the annex and discussed in the report. Most of the adaptation measures fit under a few basic climate change adaptation principles:

- Spreading of risk by diversification
- Buffer building by reforestation / agroforestry
- Preparedness for extreme weather events, droughts and floods.
- Food and water security
- Sustainable energy supply
- Education and awareness raising
- Effective management

Most of the COMIFAC member countries still have very big development challenges. The general income tends to be low and there are still high poverty rates. These immediate development needs are overall more important than climate change adaptation. However future development also creates opportunities for adaptation. To avoid wrong investments and to reduce future cost of adaptation, climate change adaptation should be integrated in future development plans.

Keywords: Climate Change, COMIFAC, Congo, River, Basin, Adaptation, Africa, Agriculture, Water, Energy, Forestry

ACRONYMS

CRB	Congo River Basin
CWP	Crop Water Productivity
COMIFAC	The Central African Forest Commission
GDP	Gross Domestic Products
IFRC	International Federation of Red Cross and Red Crescent
MTS	Modified Taugya System
NAPA	National Adaptation Programme of Action
NC	National Communications
NGO	Non-Governmental Organisations
PWS	Public Water System
REDD	Reducing Emissions from Deforestation and Forest Degradation in Developing Countries
RWH	Rain Water Harvesting
TWB	The World Bank
UNFCCC	United Nations Framework Convention on Climate Change
UKCIP	United Kingdom Climate Impacts Programme

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1. INTRODUCTION

Even with if highly effective mitigation measures are introduced in the near future the climate will continue to change in the coming century. So to reduce negative impacts of future climate change there is a need for adaptation. The IPCC (2007) defined adaptation as "actual adjustments, or changes in decision environments which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate'. Many previous reports have highlighted the need for adaptation especially on the African continent. However most of the work on adaptation in Africa has focussed on the Semi-arid zones and the Mediterranean part of the continent. Much less is known about adaptation in the Tropical zone of the continent focusing on the question: Which climate change adaptation measures are most efficient and applicable for the Congo basin region? This chapter aims to review the publications on climate change adaptation in the region and summarize important knowledge on climate change adaptation outside the region. This chapter first presents a framework for adaptation and then different adaptation options discussed. Through literature study, applicable adaptation measures from within and outside the COMIFAC region which are applicable inside the region have been summarized. The measures are explained and different practical examples are discussed.

2. Future climate change and potential impacts

Adaptation should focus reducing the negative impacts of future climate change. Climate change scenarios and potential impacts are discussed in detail in the previous chapters. From these analyses the most important climate change impacts are a future change in rainfall characteristics increasing the intensity of heavy precipitation events and an increased number of dry spells during the rainy season. In addition the average and extreme temperatures will increase in the future. This changes in temperatures and rainfall will results in an intensification of the hydrological cycle. This will result in more hydrological extremes (floods and droughts).

The six climate scenarios analysed in the hydrologic assessment indicated the run-off and river flows will especially increase in the wet season. While in the dry season several scenarios indicated a reductions in river flows. These changes will not reduce the total hydropower production potential but it will make hydropower production in the region less reliable. Low flow events will become more frequent causing periods will low power generation potential. Also the chance of dam failure and the need for emergency releases will increase due to more frequent extreme rainfall and high river flow events.

Agricultural production systems will mostly suffer from the higher temperatures. In tropical part of the region agricultural water stress will not increase due to climate change. In the savanna regions in both the northern and southern edges of the region future climate change could increase future water stress resulting in lower potential agricultural production. Agricultural systems will also be affected by a more variable future climate. Higher rainfall intensities increase erosion and flood risks. Dry spell during the wet season can potentially reduce crop production.

The most pressing adaptation needs for the different sectors but also for the whole economy will be to cope with a more variable future climate.

3. CLIMATE CHANGE VULNERABILITY AND ADAPTATION

During the last decades, the awareness of the potential seriousness of climate change and the impacts have rapidly increased. Ten to twenty years ago adaptation used to be connected with giving up avoiding climate change but it is now widely accepted as essential because it has become more and more likely that climate will continue to change in the future. So in addition to reducing greenhouse gas emission to reduce climate change will use need to adapt to future change to reduce climate change vulnerability

3.1. What is climate change adaptation?

To understand the what adaptation means, it is necessary to understand the concept of vulnerability to climate change. Vulnerability can be seen as the risk of exposure to a certain hazard. Each country, region or sector is exposed to different kinds of hazards. For example, the risk of the hazard of flooding due to sea level rise is higher in Cameroon than in Burundi, because Burundi has no coast-line.

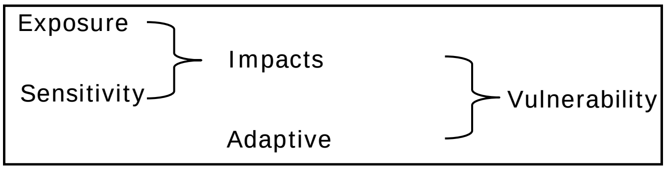

Figure 1. Vulnerability scheme

Vulnerability is the combination of impacts and adaptive capacity (Figure 1). So vulnerability can be high because of high impacts and / or low adaptive capacity. If an area is impacted by a certain hazard, and it is able to respond successfully to this by adjusting behaviour, resources or technologies, the area has enough adaptive capacity. With such adaptive capacity the area is not vulnerable to this specific hazard. However if there is no or little adaptive capacity the area is considered to be vulnerable (Parry and Intergovernmental Panel on Climate, 2007). Every area has a specific adaptive capacity to each existing hazard. For example, country A has a high adaptive capacity, meaning solutions available, to deal with heavy rainfall, country B does not and is therefore vulnerable to floods and erosion. The context determines the adaptive capacity of the area (Smit and Wandel, 2006).

Impact is the combination of exposure and sensitivity. Exposure is the absolute change in a particular climatic indicator, for example, a shorter rainy season, higher maximum temperatures or sea level rise. These changes can only cause an impact if the area is sensitive to the exposure. A country that has no coastline is not sensitive to sea level rise. Low sensitivity means low impacts. If on the other hand the area is very sensitive to a certain exposure (or change), the impact will be very high. For example agricultural systems are highly sensitive to changes in rainfall.

Still, an area is only vulnerable if there is no, or only little, adaptive capacity to deal with the consequences of these impacts (Figure 2). Wealth, infrastructure, knowledge, equity, etc. are indicators for adaptive capacity. Adaptation can be implemented as an act (building dams) or teaching how to act (education, etc.). In the many African countries, the adaptive capacity is relatively weak due to low economic wealth, limited education and weak institutions. However at community level there is sometimes a remarkably high level of resilience for different climate extremes. Different communities have developed skill to survive long term drought and can respond quickly to changing weather conditions.

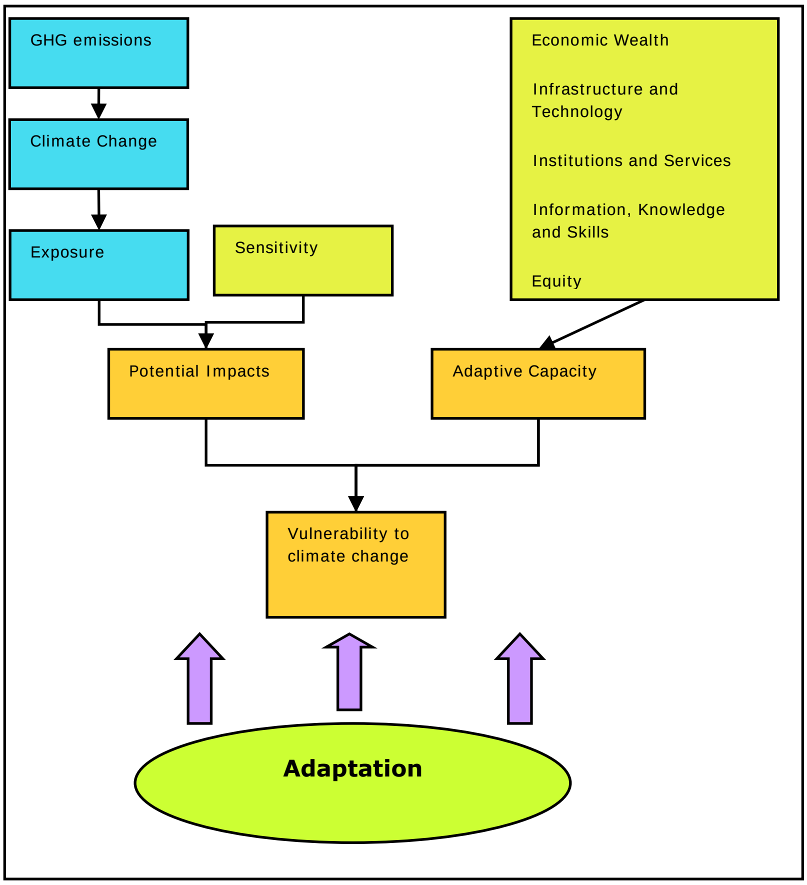

Figure 2. Adaptation framework

Historically, vulnerability has been approached from two points of view, the top-down and bottom-up-approach (Figure 3). The Bottom-up approach is often used more in social sciences studies, with focus on vulnerability of society or communities. It derives its data from studying the existing local social adaptive capacity to climate change. From that information the adaptation options are considered and the vulnerability of the area is analysed. This approach is often used by NGO's at community level.

The Top-Down approach is commonly used in climate change adaptation policies. It focuses on the physical science of climate change and biophysical vulnerability. To get data on what kind of climate change is to be expected; global climate change projections are used and then downscaled to the area for which the analysis is done. Based on that information an impact assessment is performed and the physical vulnerability of the area is assessed (Figure 3).

The two points of view should not be seen as opposite's but as complimentary. Within adaptation policy the physical vulnerability and social vulnerability should both be taken in account to create an effective package of adaptation measures (Dessai and Hulme, 2003). It is often difficult to use a large-scale analysis for local adaptation, thus especially for local adaptation the bottom-up approach was developed. The "Climate Change Scenarios for the Congo Basin" project follows a top-down approach because it aims at a large scale climate change analyses. For the Central African region limited climate change information is available and this project aimed to fill that information gap. This analyses aim at identifying the main changes in the climate system and possible future impacts for a large region. For these large scale analyses the top down approach is usually most appropriate.

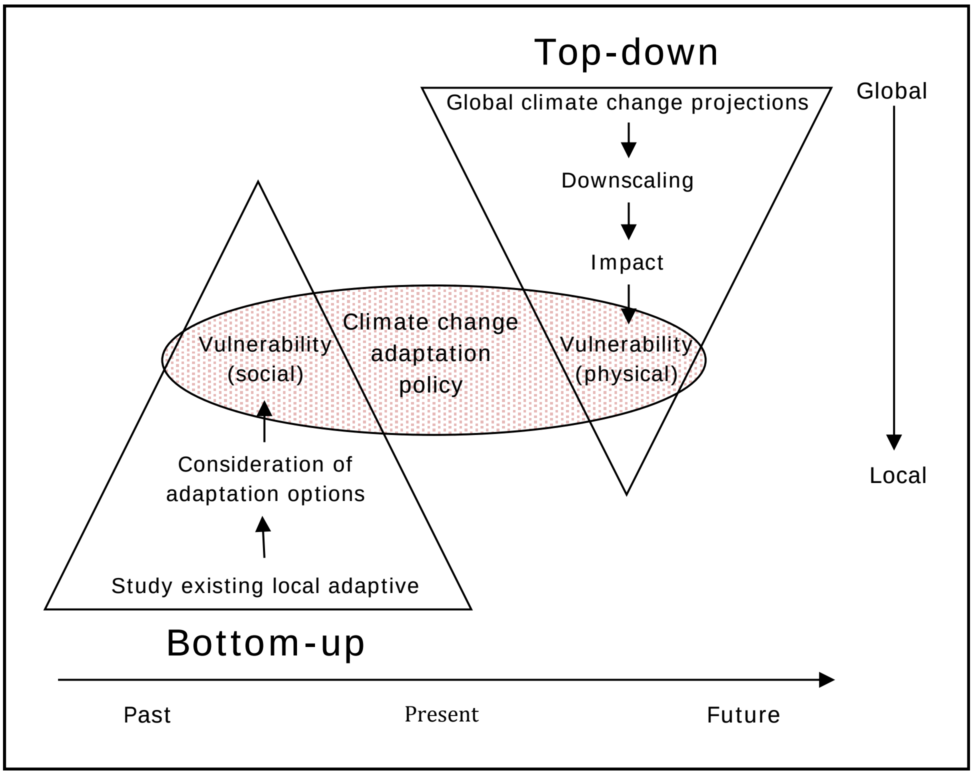

Figure 3. Top-down and Bottom-up vulnerability approaches for informing climate change adaptation policy (Dessai and Hulme, 2003)

To find out if an area is vulnerable, the coping range and adaptive capacity should be known. Figure 4 shows a schematic representation of vulnerability, coping range and adaptive capacity. For example, consider temperature as the climatic variable shown. The temperature is considered to be 'normal' as long as it stays within the dotted lines. If the variable crosses the dotted line but stays within the solid line, the 'boundary of adaptive capacity', one could speak of abnormalities but the population, or ecosystem, can deal with it by adapting . The resources and knowledge for adjustments are available, if used these kind of variations should not lead to great adverse impacts. If the temperature crosses the boundary of adaptive capacity, the population or ecosystem can no longer adjust to it with the available knowledge and / or resources it is provided with and therefore negative impacts are to be expected.

If it is known in advance that this extreme could happen, or the population who lived through such temperature extremes before and realises that it is possible to happen again, a choice can be made to prepare and gain the knowledge and / or collect the appropriate resources to adapt. As a result of this adaptation the adaptive capacity will increase. The solid lines move further away from each other (see Figure 4). Climate change could cause boundaries of adaptive capacity to be crossed. Climate change adaptation is focussing on moving the boundary to avoid or minimise the chance of crossing of it(Vincent, 2004). In conclusion, enlarging adaptive capacity will avoid (serious) impacts.

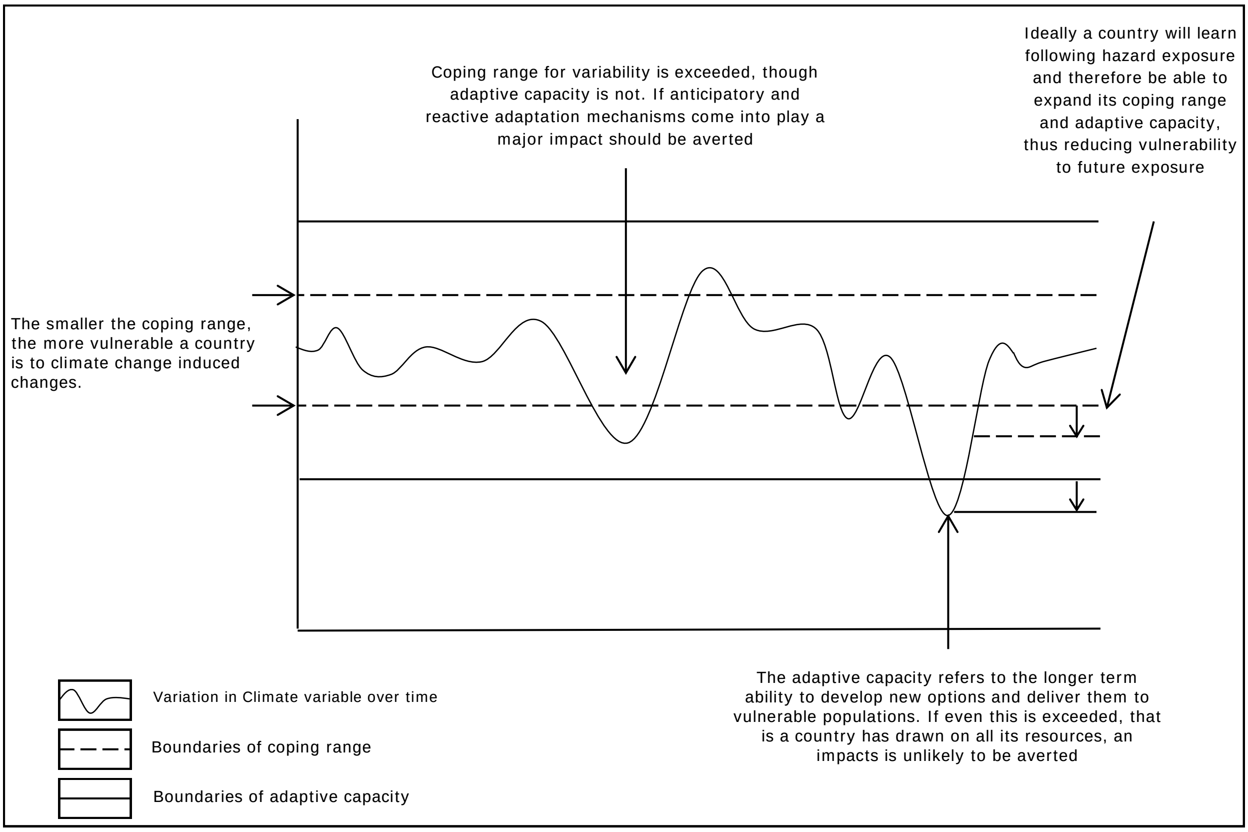

Figure 4. Framework of vulnerability, coping range and adaptive capacity (Vincent, 2004)

Climate change adaptation is complex, touching social, cultural as well as economic factors which need to be linked to the natural science of climate change, the physical changes (Sullivan and Huntingford, 2009). Although many communities, businesses and government institutions now realize that they need to adapt to climate change, how to do this is often unclear. To assist governmental institutions and businesses to adapt to climate change the adaption cycle was developed (Figure 5). For successful adaptation it is needed to know what to adapt to. Through a ‘climate change impact and vulnerability assessment’ the expected changes and the effects on the present state system, community or region can be mapped. After the impacts and the vulnerability of the area are known adaptation options can be designed and selected which is step two of the adaptation cycle. After selection of options, the adaptation measures should be evaluated. To deal with the residual vulnerability after the adaptation measures are implemented, the cycle can be followed again.

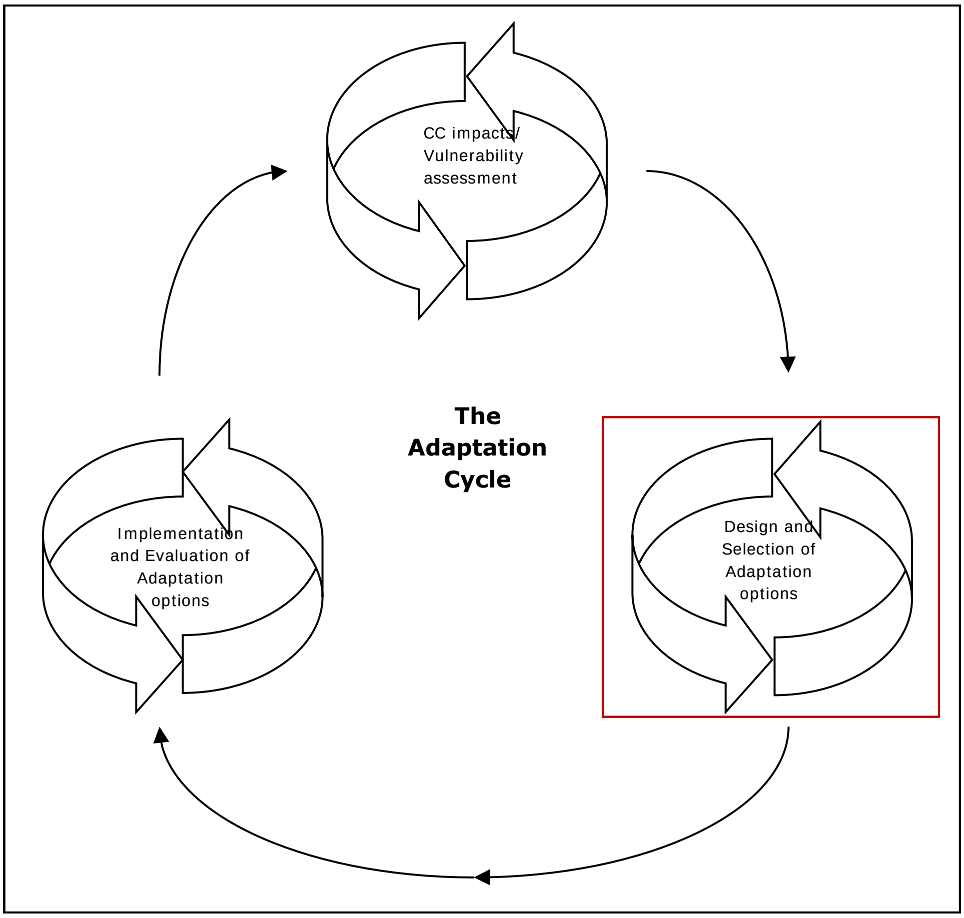

Figure 5. The Adaptation Cycle adapted from Goossen et al., 2011

The results first step of the adaptation cycle has been described in the in the previous chapters (Beyene et al., 2013; Haensler et al., 2013; Ludwig et al., 2013). This report is focussing on step two of the adaptation cycle (boxed in Figure 5). This report can be used to assist in the selection of climate change adaptation measures by providing a list of options from the Congo river basin area (see Chapter 4) as well as outside the Congo river basin region (see Chapter 5) which are implementable within the region.

There are different ways of adapting to changes, simple as well as complex activities are possible. Over time different structures to categorize these adaptation options have been developed. One could choose to *build adaptive capacity*: encouraging adaptation in the form of policy, education, financial stimuli, etc. Another strategy is to *deliver adaptation actions* which are ‘hard adaptation measures’: structural solutions like building dams, changing the irrigation system, etc. or ‘soft adaptation measures’: developing evacuation plans and seasonal climate forecast(Tompkins et al., 2009). In practise it is found most effective to combine both strategies, often soft measures are needed to activate hard measures ((De Loë et al., 2001)published, based on (Kates et al., 1985) and a more elaborate version in (Feenstra et al., 1998)). Climate change adaption measures can be categorized in three main categories:

1. *Accepting losses*

   This is basically the ‘doing nothing’ strategy. Within climate change adaptation assessments, the measures planned or implemented can be compared to this scenario.

   If for example the risk of floods increase, this means accepting the losses of crops, livelihoods and even lives, not acting in advance to prevent any losses from happening

2. *Preventing effects*

   Trying to protect the existing activities as they are and prevent losses or damages due to the climate change, measures are designed to prevent or lessen the effects.

   In case of flood risk increase, this usually means building dikes and other infrastructure. In case of higher water scarcity it can mean providing additional water to agricultural systems in order to avoid changes in the agricultural system.
3. *Changing uses and/or locations*

   If the activities as they used to be are no longer possible due to climate change, the use of the area could be changed. Activities can be moved to other areas or could be replaced by different activities.

   In the example of flood risk increase, this could mean moving the economic activity away from the river. In case of increased water scarcity or more frequent droughts this means changes land use by abandoning agriculture or a different crop

(Feenstra et al., 1998, Tompkins et al., 2009, UKCIP, 2011, Goulden et al., 2009)

Even though climate change adaptation is a well thought through concept, many adaptation actions are done without considering the action to be an adaptation to climate change at all. This spontaneous form of adaptation is called autonomous or unplanned adaptation. A simple thing such as carrying an umbrella because it might rain even outside of season, is a climate change adaptation measure. Though the individual who thought of bringing an umbrella was not specifically considering climate change. *Autonomous adaptation* occurs by itself, it is reactive. *Planned adaptation* is adapting by conscious intervention or preparation to climate change. It exists in the form of adaptation strategies and policies (Feenstra et al., 1998, Tompkins et al., 2009, The World Bank, 2009, Goulden et al., 2009).
It should be noted that what is considered spontaneous adaptation at one level may be seen as planned adaptation in another. On governmental level, actions are seen as autonomous adaptation if the people adapt without the governments interference. On the other hand, for the people themselves, that same action might be a planned adaptation measure, implemented after carefully considering climate change impacts on their personal situation (Feenstra et al., 1998).
The difference of these two views can be seen as the difference between private and public adaptation. If adaptation is initiated by individuals, households or private companies the adaptation is private. If the adaptation is initiated by the government, irrelevant which level of government, it is public adaptation (MacCarthy and Intergovernmental Panel on Climate Change, 2001, The World Bank, 2009).

If climate change adaptation measures are not adequately designed and implemented to manage the climate change impacts, an adaptation deficit or adaptation gap is created (Figure 6). The deficit represents the additional effort needed to correct the lack of climate change adaptation. During the acceleration of climate change, this deficit has the potential to grow over time and thus the cost of adaptation will grow over time(The World Bank, 2009, Schipper et al., 2008).

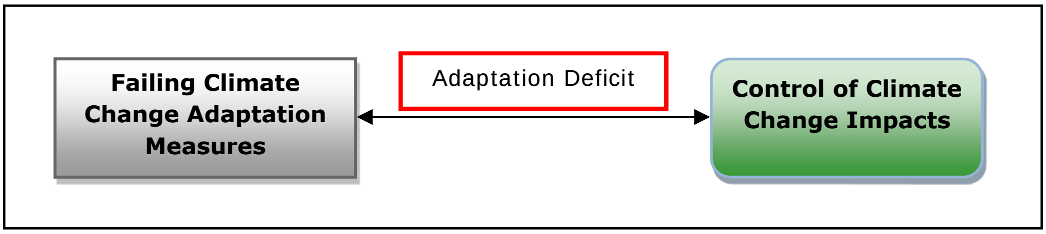

Figure 6. Schematic resemblance of adaptation deficiency

It is possible that a measure which was initially chosen to reduce vulnerability to climate change hazards, eventually turns out to increase vulnerability, this is called maladaptation (De Loë et al., 2001, Schipper et al., 2008, The World Bank, 2009, Barnett and O'Neill, 2010). Most of these measures are designed for short-term benefits but have a negative impact in the long term. For example, the use of air-conditioning in response to health impacts of heat-waves. The benefits of this type of adaption are direct, unfortunately the higher energy demand for using the air-conditioning will eventually cause more CO2 to be released in the atmosphere increasing the warming effect on the earth, thus this is a maladaptation. Maladaptation can be defined in 5 types (Barnett and O'Neill, 2010):

1. Increasing emissions of greenhouse gases.(see example above)
2. Disproportionately burdening the most vulnerable.
   When the adaptation measure increases vulnerability for those who are most at risk (minority groups or low-income households, etc.)
   In a river valley, the richer area is in the hills while the poorer area is in the valley close to the river. When the flood risks increases the government wants to implement an adaptation measure to protect the population. They place a protection dam in the centre of the valley. This protect the rich areas from floods but increase flood risk in the lower value. The poor part is there disproportionately affected even though they are the most vulnerable.
3. High opportunity costs
   When the costs (economic, social and environmental) are higher than an alternative measure
4. Reduce incentive to adapt,
   When an adaptation actions is causing people to experience less incentives to adapt by, for example, penalising early actors.
   For example government often decide to financially support farmers that are struggling to survive period of drought through drought assistance programme. Without these programmes some companies that would have gone bankrupt without droughts, were now maintained due to this financial support. The best farmers which prepare properly for the do not use the support system. This is an example were farmers are supported not to adapt but depend on the finances given by the government.
5. Path dependency
   If a large adaptation measure requires, for instance, capital commitment than cannot be changed in the future. It reduces flexibility to react to unforeseen adverse effects

Therefore, during the adaptation selection procedure, possible negative effects should be seriously considered preventing maladaptation.

3.2. Adaptation measures

In the process of choosing adaptation measures, the most effective measure with the lowest risk is often preferred and the adaptation measures can be ordered in no-regret, low-regret, win-win, flexible / adaptive management and high-regret options. Each of these groups has pro’s and con’s which should be carefully considered (for examples see table 1).

No-regret options: Adaptation measures that already have a net socio-economic benefit independent without climate change. This form of adaptation is not affected by the uncertainties connected to future climate change. These measures deal with the current climate variability while also building up adaptive capacity for future climate change. Thus the measures are justified (cost-benefit) for present and future projected climate. The measures are mainly near-term and are likely to be implemented because they are at least cost-neutral.

Low-regret options: Adaptation measures with relatively low costs that may have relatively high benefits. These measures are aiming at a maximal return on investment even though the certainty of a correct future climate change projection is low.

Win-win options: These adaptation measures have also other benefits, this could be an adaptation and a mitigation effect or it could be for other reasons implemented but also function as an adaptation measure. No-regret and Low-regret measures can also be win-win if they also add to other outcomes.

Flexible / adaptive management options: Incremental adaptation measures instead of large plans that need to be implemented at once. This management form reduces the 'wrong-risk'. If certain measures turn out to be non-beneficial they can be altered due to the fact that they are part of a (large) group of smaller measures. The course of the whole adaptation management can even be altered when new knowledge, experience or technologies become available.
High-regret options: These options are considered the large-scale options. Examples are resettling parts of the population or building a large dam. Due to the uncertainty in climate change projections, these expansive and mainly irreversible options should be considered with care and awareness of the risks. Tough risky, it is possible that in certain cases this would be the best possible solution (UKCIP, 2011;The World Bank, 2009).

It is important to stress that the differentiation of what is no-regret, low-regret or high-regret is not constant and is variable over time and space. A certain measure may be high-regret in one part of the world, but low-regret in another. Also, in time a high-regret may become low-regret or vice versa (The World Bank, 2009).

Table 1 adaptation measure regret options (UKCIP en TWB)

Regret option	Explanation	examples
No-regret	options that will produce benefits with or without climate change.	Multi-cropping, Mixed farming and livestock systems, Conservation and sustainable use of natural resources (e.g. Land conservation)
Low-regret	Options that produce high amount of benefits with low risks	Meteorological / seasonal climate forecast, Extension services targeted to new crops / water saving technologies, Diversifying community sources of income
High-regret	Options that are mostly irreversible and by that will have high costs if the measure turns out to be unnecessary or not operative	Net water harvesting infrastructure, Resettlement of a community
Win-Win	*"When an option is enhancing adaptive capacity as well as contributing to other outcomes"*	Enhancing biodiversity, Reducing overall exposure to risk
Flexible management	*"Based on incremental adaptation in that way reducing risks associated with being wrong"*	Diversify business activity, Reduce pressure on areas and systems at risk, Long term flexible sustainability plan

3.3. Principles of adaptation

There are a few popular adaptation principles that form the basis for a variety of adaptation measures. *Diversification* is a principle used in almost every sector concerning climate change. One could think of diversification of income, diversification of cropping, etc. The strength of this principle is the spreading of risk. If one form of income fails, the other flow(s) of income remains to support the family or business. The same with crops, if due to climate change one species of crop fails, the other maintains and produces yield for the farmer to live on. Choosing the diversification with care can ensure an income. Diversification is an important adaptation measures because the future climate is uncertain and because with climate change often the climate becomes more variable. A more diverse system is often less vulnerable to high climate variability compared to a system with low diversity.
Reforestation in its simplest form is planting trees. The importance and diverse implementation possibilities of reforestation should not be underestimated. Forests provide food security and other livelihoods, trees provide shelter from storms as well as energy.
Management of land use, water, energy, forests, etc., will increase adaptive capacity. Knowing what is happening concerning these sectors and planning how the natural resources are used and the

expected climate change impacts within these sectors causes a country to be much more resilient. For example water management; by installing a water infrastructure transporting water from a water rich area to a water poor area. Land management to controlling were, for instance, trees must remain to protect agricultural land from storm, etc. Correct and effective management is of capital importance. *Education and awareness rising* is also important especially for improving adaptive capacity. Adaptation measures can be available but if the people are not aware of the dangers of climate change they will not change their lifestyle or accept implementation of adaptation measures. Also if professionals wish to support climate change adaptation are not educated and equipped, their efficiency will be low.

Financial aid is especially used by global or regional organisation and by developed countries to give incentives for climate change adaptation. Examples of financial aid are micro insurance, micro loans, etc. Limited financial resources make it difficult to implement such measures. Another important flow of financial aid is that of national government to local government. This flow needs to be secured to enable local governments to implement adaptation measures explicitly for their own region.

4. METHODS

The Congo River basin region is predominantly occupied by forest and agricultural land, the population and economy is heavily dependent upon these two sectors. The population has been, and still is, growing rapidly especially the urban centre. All these people need access to drinking water, energy and a safe living environment. Their city, village or land needs to be 'safe', the population must be protected against the effects of climate change on their environment. This report therefore focuses on four sectors: water, forestry, agriculture and energy. These sectors have been selected based on their size and their role in fulfilling basic needs for the people within this region. Also the present state of certain sectors such as water (for example drinkable water supply) is such that focus on how to cope with the coming climate changes is more than necessary.

Other sectors are not discussed within this report, not all existing sectors are important for this region, or the financial and political situation makes them less profitable to focus on for now. For instance, working with financial measures can only be done when monetary means are available, this is not always the case and therefore the focus is not on that sector. Institutional changes can be made but are of high complexity, not just practically but most definitely culturally. Institutions need to be up and running to be changed, to start new institutions the needed means must be available. There will be a short portion on institutions and management due to its importance, but they are integrated within the four chosen sectors.

The most effective climate change adaptation measures were searched review the existing literature. The measures were split in a group already used within the CRB, and measures applicable but not yet used within the CRB. Based on books and online available literature (both scientific and grey literature) the climate change measures were selected.

The measures selected are listed in the 'Climate Change Adaptation Table' (see appendix and also chapter 4). It includes the measures, a description, and a reason why it is applicable and, if available, a link to a practical example of the measure.

During the literature search we observed that little is known about this specific region concerning climate change and only a few publications were found which focus on the central African region. A big part of the information from within the region originates from the NAPA's and NC's found on the UNFCCC website, and publications from The World Bank and NGO's.

5. CENTRAL AFRICAN ADAPTATION OPTIONS

The analyses of future climate change showed that within Central Africa Climate Change will cause an increase in higher temperatures and more variable rainfall with more frequent extremes (Haensler et al., 2013). Adaption should focus mainly on extreme events such as heavy rainfall events and heat waves. The dry spells will be longer, the rainy season could become shorter but more intense. The changes, of which only the main line is described here, will impact the functioning of the region. The impact analyses shows that higher temperatures will have adverse effects on plant / crop growth, floods may increase due to the more intensive rainfall and river flows will become more variable. This chapter describes the possible adaptation measures to cope with the expected climate change impacts, for the sectors: Agriculture, Forestry, Water, Energy and Adaptive Capacity. These sector often interact with each other. For example water is used is used for agriculture and energy and deforestation affects the river systems. A complete overview of all the suggested adaptation options is given in the Adaptation Table (appendix 1).

5.1. Forestry

Within the CRB, there is still about 2 million km^2 of tropical and seasonal forest types. 30 million people of 150 ethnic backgrounds live in these forests. Though the forest contains about 4000 species of which 70% are endemic, about 60% of the forest is seen as industrially exploitable (CBFP, 2006). Climate change impacts can potentially increase the pressure on these systems. Climate change combined with bad forest management could have large impacts on the forest ecosystems and both the timber industry as well as the people depending on the forest for livelihoods. Changes in temperature and rainfall patterns may cause the evergreen forest to expand more to the north and south. Also the ecosystem carbon capture may increase, which in itself is a potentially positive effect of climate change (Ludwig et al., 2013).

Reforestation is a major part of both the climate change mitigation as well as the adaptation practises. Reforestation improves and diversifies sources of livelihoods, protects against soil erosion and soil / rock slides. It prevents loss of soil fertility. Trees can protect surrounding agricultural land from storms. Reforestation can balance the hydrology of catchments by improving infiltration of water and reducing loss of soil by erosion. Choosing to let reforestation be an obligatory part of the timber industry preserves natural woodlands and provides income and energy to those involved. During reforestation tree species could be used which are adapted to the expected future climate. This will make the forest more climate proof. By setting up a regional forest and agroforestry seed centre, the existing species and species that have their growth / yield optimum in the expected future climate (for each region) can be grown / collected and stored. In this way species can be chosen specifically for the local situation and can be provided for reforestation. If the seedlings (or seed beds) or partly grown trees are needed to be planted depends on the local situation. Seed banks have been set up in different African countries like South-Africa, Ethiopia, Niger, Kenya, etc. Seed banks can be national but also smaller community seed banks can significantly increasing adaptive capacity by reducing genetic erosion, conserve and enhance IN SITU diversity, maintenance of local genetic resources and seed security etc. Seed banks are not just for forestry, but also for agriculture, agroforestry, nature conservation, etc. (Worede, 2011, Albrecht and Monodi Oloo, 1993, Vercoe and Midgely, 1993) . The seed centre can hold an important task in the diversification of the forest. On could look at the diversification of tree species, as mentioned in precious paragraph, but also at de diversification by combining agriculture with forestry: agroforestry. For agriculture seed banks are important and will become more important in a changing climate as seed banks can facilitate in introducing new varieties.

Agroforestry is an old and proven method for diversification of income and spreading of risk to increase income and food security. By implementing for example the Modified Taungya System (MTS) both agricultural and forestry methods are used by the same farmer. The MTS stands for mixing trees and agricultural crops (see Figure 7). The first three years of using the MTS it is clearly an agroforestry system, as the trees grow and form a closed canopy, the farmer can focus on tending the trees to maturity after which it can be used for timber, energy, etc. The crops and tree cultivation are complementary, not competitive. There are varieties of complementary activities possible like small-scale trade, farming of poultry, bees or livestock keeping. To cope with climate change, the MTS provides food security, erosion control (the trees keep the soil together, less will be lost), soil fertility (trees have a fertilizing effect on their environment) and moisture balance as well as an addition source of fuel (wood), all of which are important in climate change adaption creating a buffer for the local environment when dealing with the changes. MTS has been successfully implemented in the Offinso forest district in Ghana, were it significantly improved the food production (Kalame et al., 2011).

Figure 7, example of MTS plantation in Ghana (www.fcghana.org)

Government officials also need to look at the present state of national forest management. To understand the state of the forest and the bottlenecks, a forest inventory can be done. Most of these inventories can be through remote sensing, using satellite images. But also on-ground monitoring of part of the forest can be an important part of it. A sustainable forest management plan connected to forest legislation can make a big difference, even more when management is based on a well-researched and continuously monitored forest inventory. Proper monitoring well ensures that climate change impacts are observed in time and that appropriate measures are taken in time.

Through forest management future energy supply, livelihoods and so on can be assured for due to the fact that the management has adapted to the changing climate. One cannot manage something of which the state and strengths and weaknesses are not known, on the other hand the magnitude of the forest can be a constraint in monitoring it. With this a balanced and well thought through plan should be designed how the inventory and monitoring of the forest can be done most efficiently keeping in account the capabilities present. There are already different monitoring systems in place however this systems could be improved also looking at possible climate change impacts(CBFP, 2006).

5.2. Agriculture

More than 80% of the rural communities depends on agricultural and forest activities contributing to large of the total economy of the region (Sonwa et al., 2012). Climate change is expected to put extra constraints on the agricultural sector. Increased interannual rainfall variability, greenhouse gas concentrations and more concentrated rainfall periods combined with longer dry spells will put dry land crops and rain fed agriculture under high pressure. The long dry spells initiate lack of water while during erratic rainfalls there may be floods that seriously damages any crop or pasture and thus weaken the economy (Ludwig et al., 2013). In this paragraph, suggestions are made that can assist in coping with these agricultural climate change impacts.

Diversification is a well-known and proven principle within climate change adaptation (see §2.2). Especially within the agricultural sector there are a lot of possibilities for this risk spreading practise. One could think of diversification in crops. Instead of cropping one species, a farmer could crop more species with different optimal climates. In this case the risk of crop failure is smaller due to the fact that if one crop fails, the other crops could yield well. This specific form of diversification is to deal with uncertain weather conditions: timing of the rains, temperatures, hours of sunshine / shade, etc. On the other hand it also limits the chance of overall maximum yields, as not all the crops will do equally well, they are picket out on the bases of yielding optimally in slightly different climatic circumstances. The exact crops chosen must be considered with care, taking in account present and expected future climate as well as the boundaries of optimal climatic conditions of the crops. Another form of diversification is diversification of income. Diversifying income by adopting an agro-sylvo-pastoral system, combining both livestock as well as crop cultivation could be effective in some regions. To ensure and income, even if crops fail, the farmer or family member could choose to participate in non-agricultural activities. It reassures a family of monetary income though it might also pressurise the family in time-management and task division (who will do the chores of the person who is now out working etc.).

In this region, the potential agricultural product is not reached on most of the field and farms. Improved land, nutrient, pest and weed management could dramatically increase agricultural production in the regions. When developing the agricultural sector it should include climate change adaptation, making the region “climate proof”. It is necessary to better integrate climate change adaptation into the different agricultural institutes and climate change adaptation needs to become part of the development (and development part of the adaptation).

Adaptation can also be implemented in small changes of current practices. A farmer can choose to crop a different variety, but remain farmer and operate as before. If the timing of the rainy season changes, the farmer could choose to change the timing of planting and harvesting. If crops do not reach normal yield, a farmer could choose to use extra fertilizer to strengthen the crop. To improve yield of pastures, the zero-grazing technique could be implemented. This means that the livestock will not graze in the pasture, but the grass is cut regularly and then fed to the animals. The yield of grass is higher, assuring food for the animals and so income for the farmers. However this technique requires more time investment. In respective of climate change agricultural production has to increase by improving management.

To be less dependent on rainwater, and to reduce the impact of shifting precipitation patters, farms can collect rainwater in the rainy season and use that in the times of drought. This is called rainwater harvesting. Also growing crops using irrigation techniques reduces the dependency on rainwater and thus reduces the risk of crop failure due to lack of rains.

The described techniques spread risks and can improve food and income security. It is possible that changing current practises is not sufficient. Adaptation measures on larger scales should than be considered. Changing the area under cultivation for example promoting clay soil farming. In clay soils water is kept longer by the soil structure and nutrients are more available. Building an irrigation infrastructure to transport water from water rich areas to water poor areas. Improved food stocking techniques helps in overcoming a time of shortage, these stocks should than be well managed and secured to prevent theft or loss of good food due to errors. A veterinary and phylosanitary services could be launched to provide farmers with helping hands in keeping livestock healthy and minimise loss of crops due to diseases. The services can also provide training to optimise for example livestock raising techniques.

The agricultural sector can be seen as flexible, there are many opportunities to adapt to the changing climate. As explained, not all of these measures need to be expensive or risky, but they do require careful research before implementing. Trying the cheapest option because it's the cheapest might eventually turn out to much more expansive due to losses and damages it could not prevent, which other more expensive options might have. Please take into account that situations differ per location, it is important to invest in research to determine the best options per local area. In the choice for adaptation options the free choice of farmers to or not to adapt should not be underestimated. Most farmers will not allow adaptation measures on their farm if there are not informed about climate change and the expected risks, and if they did not have the opportunity to be part of the process of selecting adaption measures. Including their knowledge of the local area and the farming practises can enrich the research for best adaptation measures significantly and increase the willingness of participation in the implementation of the measures.

5.3. Water

The Congo river has been known for being a stable, reliable source of surface water. Climate change will not stop the river from flowing, the opposite is more likely. The annual runoff of water could increase and therefore more water needs to be able to pass through the river system. The increase of both dry spells and erratic rainfall may cause the river to become more dynamic. More runoff will cause more soil degradation and will have adverse effects on the soil fertility and consequently on the food security. For human safety as well as the livestock branch of agriculture, providence of drinkable water must be assured. Today this is already troublesome in some areas due to rapid population growth, the effect of climate change such as longer dry spells will worsen the pressure even more. In the coming paragraphs the focus will be on water management, flood prevention, drought management and drinking water supply.

For the implementation of different adaptation measures and assures that the water sector can adapt to climate change there is a need for improved water management throughout the region. What the water sector needs most is solid management, this can be implemented in different forms. Local water boards with the responsibility to foresee, investigate and produce solutions for water related issues could be set in place. This water board could start out with collecting water data and creating awareness among the officials as well as the people what the present state of drinking water, surface water and groundwater is. Based on this information, a water source management plan could be written. It could therefore function as an implementing body for governmental legislation and planning as well as a communication vessel for the needs of the people concerning water towards water management and legislation. The actual tasks and framework of action can be locally determined based on the needs and possibilities in each country.

To prevent a shortage of water during times of drought a diverse group of soil water conservation techniques can be implemented. These techniques can include mulching, contour ridging, terracing, etc. (see Figure 8) In this way water is kept in the surface soil for a longer period of time and by that increase the Crop Water Productivity (CWP).Improving soil water holding capacity reduces the risks of dried out soils.

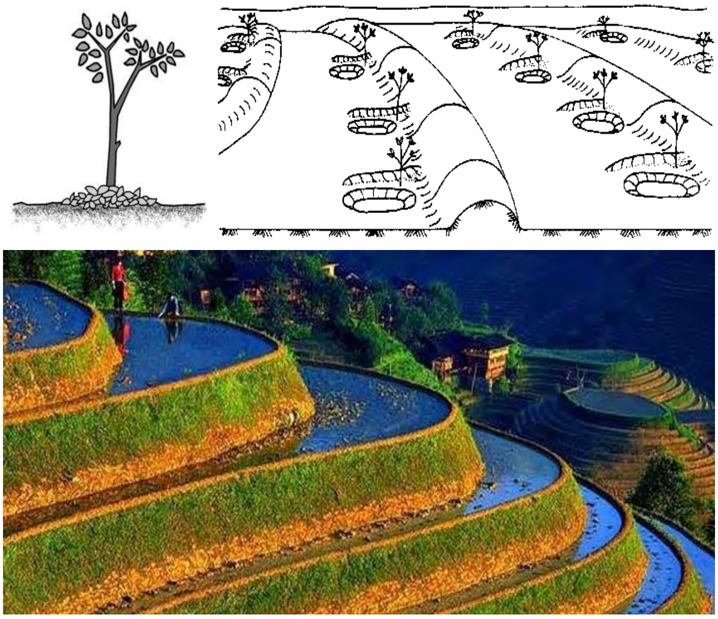

Figure 8, soil water conservation techniques. upper left is mulching (covering of area around plant), upper right is contour ridging and in the bottom is a picture of the terracing technique

Soil water conservation techniques might not be sufficient to overcome a longer period of drought. The reviving of rainwater harvesting (RWH), which is simple but effective, will cause annually enough water to be available (see figure 9). This technique is applicable in both small and large scale projects. Farmers could for example use this water for irrigating their crops especially fruits and vegetables.

Figure 9, small scale RWH in Ethiopia(www.waterworld.com)

During times of drought the supply of drinking water is even more pressurised than normally. Solutions to providing drinking water could be as simple as drilling more wells which can supply a community of clean drinking water taking into account possible lower water levels during the expected droughts. Storing water in times of abundance is easily applicable and can save the lives of many who are in need of drinking water in the times of drought. Storing of water can be organised per village, community or area and can thus be applied on different scales. A Public Water System (PWS) is an effective way of transporting drinkable water to the areas in need. A PWS is a large investment and often complex to manage, though many countries have partially implemented such a system. The key for climate change adaptation is here that when designing the drinking water supply systems they are developed to function under a range of future climate. The systems need to be capable to supply enough water also during periods of droughts and should be not be destroyed or polluted during floods

During the shorter rainy season, the amount of rain falling per day is expected to be increased which increases flood risk. To make the rivers and dredges able to handle the larger amount water they can be dredged or widened, allowing more water to be able to pass through. River systems should be able to carry more water during peak flows and there will be longer periods with low flows. In critical areas, river stabilisation techniques can be applied such as river bank design, dykes, dams, spaces reserved for overflow, etc. with great focus on human safety as well as taken in account the dynamics of the river in future year.

The logistics behind water transport are very important, although even more important may be that the water that is transported is of sufficient quality, so it can be used for human consumption. To reduce back pollution of water, building water treatment plants will improve clean water availability. This will have a positive effect on health and productivity of the population.

5.4. Energy

The main sources of energy which will be affected by climate change in the COMIFAC countries are biomass and hydropower. Our analyses shows that climate change will not reduce the total hydro power potential but energy supply could become less reliable due to more variable river flows (Ludwig et al., 2013). Also total biomass production will not reduce due to climate change but a more variable climate will increase the pressure on forest ecosystems (Ludwig et al., 2013).
The continuing population growth and development in the region will increase the energy demands. When increasing the energy supply in the region it is important to take climate change into account. Hydropower is an attractive source of energy in the region and there is definitely potential in to hydropower in the region. It is however important to realise the water availability in the future will become less variable. As a result energy supply from hydropower could become less reliable. It is therefore needed to develop a more diverse energy supply system to also guarantee power supply during droughts.

Hydropower energy does not only have to come from systems. There also many local opportunities for small hydro stations. These stations can provide energy for a significant number of households and could reduce biomass and charcoal use. A micro hydro station can be developed near small towns to provide the town with energy. The local communities can manage their dam themselves, for which education and training is necessary. Other forms of renewable energy sources such as solar or wind energy should also be promoted and can be excellent options for local energy supply. Starting up pilot project for different kind of renewable energy sources can clarify which kind is most efficiently usable for which area without the risk of investing in big projects that are not tested beforehand.

In addition to renewable energy source also recycling of waste can be a source of energy. An example is the forming of ‘Briquettes’ (see Figure 10) out of waste products (www.gvepinternational.org). Briquettes are pieces of charred sawdust, agricultural residues or charcoal waste, the sawdust is waste and can be purchased for small prices or can simply be collected from forest cutting location. Forming ‘Briquettes’ can be done with limited investments and technology (though providing machinery does significantly increase production) and therefore creates employment and income for the people.

Figure 10, Small business selling 'Briquettes' (www.gvepinternational.org).

It is important that the damage done to the forest and ecosystem, but also to human health, through the use of wood as biomass energy should be reduced. Planning and implementing a wood-energy programme that includes legislation for forest management to minimise the cutting of natural forest, but could also provide safe wood stoves for those who use open fire or other forms of unsafe (self-made) equipment and education to use, or promotion of, other forms of energy.

To cope with the increasing energy demand of a growing population, energy saving education plans can be considered to teach the population to use energy as efficient as possible. Through the local schools, radio and television programmes, and other form of communication the information can be brought to the people. Locating small energy businesses for (such as Briquettes salesmen) and elaborate their function with an information facility function to provide education on safe and efficient energy use. It is important activate people to want to make a change for by personal motivation.

In terms of dam management there is an important link between the water and energy sector. For optimal energy production there is the aim to have as much water as possible in the reservoirs. However if reservoirs are completely full and there is a lot of rainfall upstream lots of water needs to be released from the dam which can cause large scale flooding downstream. For example the water released from the Lagdo reservoir in Cameroon, in September 2012 caused large scale flooding downstream in Nigeria. To reduce the risk of flooding reservoirs should not be at full capacity before the wet season. However, this could reduce energy supply if there is lower than expected rainfall during the wet season. These trade-offs between reducing flood risk and optimising energy production will become more problematic to manage in the future due to climate change which will cause more variable river flows. However there is a great need to improve dam management plan to adapt to climate change.

5.5. Improving Adaptive Capacity

When changes are happening it is the way and capability of dealing with it that will determine the vulnerability and consequences (see chapter 2). The adaptive capacity within the CRB is generally low. Even if the population is aware of the climate change issues and willing to act, there are many other barriers to adaptation. Next to the political unrest in the area, lack of monetary and material provision, management, education and governance will keep the adaptive capacity low. The climate is already changing, lacks in adaptation is impacting the region. A few examples of adaptation measures are given within this paragraph concerning education, early warnings systems, infrastructure, management and awareness rising that higher the overall adaptive capacity to climate change.

Early warning system

"It is much more effective to evacuate people before a flood than to rescue people during the flood… It is much more effective to support farmers to find alternative livelihood options than to provide food aid when the harvest has failed." (IFRC, 2008)

A warned farmer can decide to cultivate a different crop because he now knows that the season will not fit the needed environment of the crops he would otherwise cultivate. Communities can be assisted in evacuation after they have been warned that due to heavy rainfall further upstream the river nearby will flood soon. Lives can be saved, incomes secured if an early warning system is up and operational including effective communication and action.

Due to scientific developments humanity is now able to better predict the future weather, extreme events. Knowing what to expect gives the advantage of being able to prepare for what it is that is coming. An early warning system is not just about knowing what might happen, but just as much about how to communicate and effectively respond to the gained knowledge. An effective early warning system combines science with problem solving and communication, it requires a collaboration of different sectors, specialists and organisations.

Early warning systems come in different forms and shapes, focussing on different scales (local, national, regional, global). Many specific early warnings systems exist, for example: hurricane warnings, tsunami warnings, drought warnings, etc. What kind of system is needed depends on the area and the characteristics in which the early warning system has to function.

Within central Africa, agriculture is one of the main income generators, the population is depended upon it for food security, income and other livelihoods. The agricultural systems are dependent upon the seasonal weather conditions and therefore installing an early warning system for weather conditions focussing on the agricultural sector, a hydro-agro-meteorological warning system, will reduce risks of crop failure and all its consequences. How to communicate the information most effectively is very much dependent on what kinds of media are available. Television, radio, mobile phones, newspapers but also a warning system by sending out volunteers to warn people personally and offer possible solutions or help with evacuation, depending on the need (NAPA Rep. of Burundi, 2007, NAPA Rep. of Rwanda, 2006).

Early warning systems are not something new, establishing and maintaining such have been part of national and international goals for several years. In central Africa, this has also been endeavoured, though socio-economic crisis and other forms of political unrest have caused most of these initiatives to end or be strongly limited. Reviving and improving early warning systems should be high on the priority list to reduce vulnerability to future extreme events.

Education and awareness rising

Making the population aware of climate change and possible impacts and opportunities that it brings, is an one of the most important things to do. If one does not know what the impact of a certain event may cause, this person will never think of adapting or allow changes suggested by government or other institutions which influence his or her life to happen. People have through time shown themselves creative to deal with problems, to know what will happen to the climate and how that will impact each of his or her personal lives will give range to that creativity and could cause people to come up with personal adaptation options. Lack of education on possibilities or effects of certain choices will cause people to choose mainly for short term solutions or to choose for option that are maladaptation options or leave adaptation deficits to deal with will come back to them at another time.

Management and integration

For successful climate change adaptation in the Water, Energy and Forestry and agricultural sectors improved management at different scales is necessary. However these sectors should not be managed in isolation. Climate change and future development will increase the linkages between the different sectors. The demand for water, agriculture and energy resources will increase while at the same the pressure will increase due to climate change. Improper managed hydropower dams can cause large scale flooding. While excessive water use by the agricultural sector could reduce energy production. When developing a new large dam for hydropower production not only the energy sector should be involved other plans can damage drinking water facilities, ecosystems and livelihoods downstream. Within forest management a certain area of forest might be fenced to protect the ecosystem, but if that forest was the basic provider of livelihoods to a small village, the consequence might be devastating for the local people. It is of utmost important to make integrated project plans when designing and implementing climate change adaptation measures.

Land management and land use planning has not yet been discussed before although it is very important to adapt future land use to climate change. Also improving local, national and international infrastructure increases adaptive capacity by enabling transport of food, water and other resources. Also if evacuation is necessary, a good roads systems will make this possible and diminishes the needed amount of time which increases the human safety and reduces economic damages. Also erosion control will become more important because increased extreme event will result in higher erosion risks. These examples discussed above show the importance of including different sectors in climate change adaptation.

Often the measures concerning climate change adaptation and the measures concerning development are not co-ordinated while often they have very similar goals. Development plans and climate change adaptation plans are written in separation. Climate change adaptation should not be the responsibility of only the department of environment because climate change can affect the whole economy, agriculture, infrastructure, national safety, food and water security. Therefore climate change adaptation should be seen as an important part of the different ministries. Development is a strong adaptation measure if climate change adaptation has been taking in account. Developing non climate change proof projects could be lost investments. The integrated approach is strongly recommended.

5.6.Mainstreaming and Funding Climate Change Adaptation.

Most of the COMIFAC member countries still have incredible development challenges. The general income tends to be low and there are still high poverty rates. To feed the growing population significant increases in agricultural production are necessary. Also in terms of water management there are still lots of challenges but also opportunities. For example the further development of hydropower in the Congo basin could provide a basis for further economic growth. These immediate development needs are overall more important than climate change adaptation. However future development also creates opportunities for adaptation. To avoid wrong investment and to reduce future cost of adaptation, climate change issues should be integrated in future development plans. This is especially the case in the water, energy, agriculture and forestry sectors. Ideally climate change adaptation should be mainstreamed into sustainable development. However this is easier said than done. Even the most developed countries with large R&D budget still struggle with mainstreaming climate change adaptation. The complexity of the problem, the long term horizon and the uncertainties make climate change adaptation a difficult issue to integrate into on-going governmental decision making.

Given that the ideal situation would be that climate change adaptation needs to be mainstreamed into climate change adaptation would go against the idea to develop separate adaptation projects. However, we would like you to argue that this is not case. There is need to develop adaptation projects to fulfil the most immediate adaptation needs and more importantly to learn how to integrated adaptation into sustainable development.

One on the most important next steps in the process would be to define adaptation projects which could be funded by the different donor programmes. The reports of this project provide a building block to define these projects. Given the limited capacity, knowledge and experience with climate change adaptation. An important aim of these projects should be building the capacity and know-how considering climate change in the region. This is probably as important as the immediate adaptation benefits of such projects.

6. CONCLUSION AND RECOMMENDATIONS

Within the region there is very limited documented knowledge and experience in relation to climate change adaptation. However there are many adaptation options which have been tested and described in other regions of the world which are useful for the COMIFAC countries. There is an urgent need to improve the knowledge base on climate change adaptation in the region. On-going activities should be better documented and there is need to develop experience, expertise and capacity in relation to climate change adaptation.

As a result of the lack of documented experience with adaptation in the region we can only give relatively general advice on the use of adaptation measures in the region. Most of the future climate change impacts will be felt through a more variable climate and adaption should thus focus on reducing the vulnerability to climate variability. . Adapting to *future* increased climate variability can be very well combined with improving management of the *current* climate variability. This can be done for example by spreading of risk through diversification and by improving the preparedness for extreme weather events, droughts and floods.

For the *Forestry* sector the most important adaptation measures should focus on the prevention of forest degradation. This means reforestation of areas where forest has disappeared due to either natural causes or human activities. Also increased introduction of agroforestry should be promoted to reduce erosion.

For the *Water* sector adaptation should focus on reducing flood vulnerability through development of flood prediction system, avoiding development in flood prone areas and building flood preventing infrastructure (dykes and levees) were needed. In addition it is important to adapt dam management policies. As river flow regimes will become more variable and extreme, on average less water should be stored in dams to prevent dam failure and avoid emergency releases which can cause floods downstream.

Adaption in the *Agricultural* sector should focus reducing vulnerability to higher future temperatures and increased climate variability. New varieties should be developed and/or introduced which are adapted to higher temperatures. Also pest and disease control will become more important in a warmer climate. To adapt to future climate variability programmes should be started to improve the management of the current climate variability. This can be done through *e.g.* diversification of farming systems and improved soil water and nutrient management.

For the *Energy* sector it is important to adapt to the lower reliability of future hydropower production. To do this there is a need for diversification in the energy sector. In addition to large hydropower plants more local energy production systems are needed. For example by using biofuels, solar energy and micro-hydropower plants.

Future climate change will affect water, energy and food security and many adaption options focusing on improving these resources securities. Already without climate change many of the COMIFAC countries have problems with water, energy and/or food security. It is important that measures and policies which are developed to improve these securities take into account climate variability and change.

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APPENDICES

Appendix 1 Adaptation measures table inside region

Adaptation table Legend:	Existing adaptation measures, previously published
Adaptation measure	Title / name of proposed measure
sector:	
A	*Agriculture*
F	*Forestry*
W	*Water*
E	*Energy*
M	*Management*
Description	What is the proposed measure practically about
Rationale	Why is this measure effective. In what for circumstances can this measure be used
Reference	Sources

Nr.	Adaptation Measure	Sector	Description	Rationale	Examples (UNFCCC and others)	Reference
1	**Agriculture**					
1.1	*Crop (species) selection*	*A*	*Cultivate crops more suited to the new climatic circumstances. For instance slower or quicker maturing varieties to cope with changes in rainy seasons. Drought or heat resistant crops.*	*Crops that are used up until now could possible no longer grow or deliver enough yield due to the new climatic circumstances. Changing to crops that are delivering satisfactory yield in the new situation is therefore reducing risk to crop failure and thus increases food security.*		*NAPA Burundi, NAPA Rwanda, Schulte-uebbing 2011, Feenstra et al., 1998*
1.2	*Introduction of species varieties*	*A*	*Diversify cropping by cultivating several crop species, all with a small difference in optimal climatic conditions.*	*Diversification of crops is a spreading of the risks concerning climate change damage.*		*NAPA Rwanda, Lipper et al., 2010*
1.3	*Crop timing*	*A*	*Switch seasons of cropping, alter times of sowing . Modify early and late planting dates.*	*adapt timing of cultivating to the altered climatic conditions so that the probability of a successful harvest in higher*	*Mixed cropping in Burkina Faso*	*Schulte-uebbing 2011, Feenstra et al., 1998*
1.4	*Change the area under cultivation*	*A / F*	*Move the area under cultivation to an area in which the future climate will be suitable*	*In this case loses of crops due to climate change can be avoided by cropping in an area that will be / remains suitable for that crop species*		*Schulte-uebbing 2011, Bwalya& Friedrich 2002*
1.5	*Expand area under cultivation*	*A / F*	*Expand are under cultivation to also cultivate crops that previously could not be cultivated*	*Changed climatic circumstances allow other crop species to be cultivated next to what is currently done. This diversifies crop species and thus spreads risk, gives a higher yield and thus a higher income*		*Schulte-uebbing 2011*
1.6	*Maximize agricultural activity on clay soils*	*A / W*	*Clay soils have a high water-holding capacity which can be taken advantage off during droughts and longer periods of dry spell*	*If the soils have a higher water-holding capacity, the efficiency of water use is higher, less water is lost due to evaporation or leaching and the crops can endure longer periods of dry spells than those cultivated on other soil material*		*Schulte-uebbing 2011, Dinar et al., 2008*
1.7	*Promote stocking techniques for agricultural products after harvesting*	*A*	*Store foods safely, protected from rot and pests, for times of need*	*If storage techniques that can prevent pests and / or rotting of foods, these foods can be stored successfully for a longer period of time providing food in case of lack.*	*Food storage in Egypt*	*NAPA Rwanda*
1.8	*Increased (N) fertilization*	*A*	*increase amount of fertilizer used, reuse of manure or inorganic fertilizer, or increase other methods of fertilization*	*increases fertilization enhances crop yields, the crops are less impacted by climate change than non fertilized crops for they have become stronger due to provided nutrition.*	*Nine-Maize Hole Planting in Kenya*	*Schulte-uebbing 2011, Lipper et al., 2010*

Nr.	Adaptation Measure	Sector	Description	Rationale	*Examples (UNFCCC and others)*	Reference
2	**Livestock**					
2.1	*promote zero-grazing breeding*	*A*	*Grassland management: instead of letting the animals graze, the grass is cut and then fed to the animals. This technique improves the grass utilization*	*More security of fed animals during droughts, increased productivity and resilience.*	*Goat breeding in Moroto and Nakapiripirit, Uganda*	*NAPA Burundi, Morrison 2003, Lipper et al., 2010*
2.3	*Promote agro-sylvo-pastoral systems*	*A/ F*	*Income diversification by promoting agro-sylvo-pastoral system: combining pastoralism and agriculture on household level, adapted to the new climatic conditions*	*Diversification of income sources, spreading the risks. For a pastoralist to also cultivate crops, and vice versa, highers the probability of food security and income during extreme weather events and change in climate*		*NAPA Rwanda, Lipper et al., 2010*
2.4	*Promote veterinary and phytosanitary services*	*A*	*"improving livestock health through the provision of veterinary services and treatment of animals for diseases". This also counts for stronger crops due to phytosanitary services*	*"By increasing the health of the animals the milk production increases. The efficiency improvement results in increased production and income but with a smaller more efficient herd causing a smaller impact on the resource base". For crops that withstand or survive pests, phytosanitary services should be put in place*	*Improving milk production in Cajamarca, Peru (Spanish website)*	*NAPA Rwanda, Lipper et al., 2010*
2.5	*Improving livestock raising techniques*	*A*	*Improve used and introduce new raising techniques for livestock increasing health, and thus survival rate, of the animals and increases the income of the farmer*	*teaching and promoting new techniques for growing food for the animals, zero-grazing techniques, building / maintaining shelter for the animals, water supply, etc. to improve health of the animals which improves lifetime of the animals and income for the farmer. Healthy animals can withstand climate changes better than less healthy animals*	*Goat breeding in Moroto and Nakapiripirit, Uganda*	*Schulte-uebbing 2011*
3	**Agroforestry**					
3.1	*Modified Taungya System (MTS)*	*F / A*	*MTS is an agroforestry system involving inter-planting trees (with edible fruits) with agricultural crops. Providing food security, reduces erosion and provides additional source of fuel wood / timber / fertilizer / etc.*	*"Mixing trees and shrubs with food crops provides an opportunity for farmers to improve their food security". Diversifying income spreads the risks. Trees improve soil fertility and soil moisture through increasing soil organic matter*	*The modified taungya system in Ghana's transitional zone*	*Schulte-uebbing 2011 --> Kalame et al., 2011, Roberts 2009, Lipper et al., 2010*
3.2	*Keeping trees as wind / protection breaks*	*F / A*	*planting and growing trees on strategic place to protect the crops from damages*	*"diminishes the effects of extreme weather event such as heavy rains, droughts and wind storms. Besides protecting crops, the trees also function as natural fertilizer for the crops through increasing soil organic mater and they have an erosion controlling effect*		*Schulte-uebbing 2011, Lipper et al., 2010*

Nr.	Adaptation Measure	Sector	Description	Rationale	Examples (UNFCCC and others)	Reference
4	**Forestry**					
4.1	*Reforest stripped mountainous massifs*	*F*	*Reforestation to reduce erosion, protection against drought and aridity, provide natural fertilization of the soil and provides food / timber*	*Besides the mitigation effect of reforestation, the technique also provides adaptation by providing more stability for food and income*		*NAPA Burundi*
4.2	*Seek local and exotic forest species resistant to dryness and to diseases*	*F*	*Adapting to the expected climatic conditions by choosing species that are well adjusted to such condition, those already locally present as well as 'new' exotic species to introduce.*	*Species that are cultivated up until now could possible no longer grow or produce enough yield due to the new climatic circumstances. Changing to tree species that are delivering satisfactory yield in the new situation is therefore reducing risk of losses for this sector*	*Domesticating wild fruit trees in Botswana*	*NAPA Burundi, Roberts 2009*
4.3	*Rehabilitate existing forest resources*	*F*	*seed or cuttings of existing natural trees and shrubs that have been lost due to deforestation or other factors, to rehabilitate natural resources for food and other livelihoods*	*To rehabilitate natural recourses is to provide the communities with variety of food sources. Variety in Nutrition will keep the population healthy and stronger to deal with climate change. Rehabilitate the natural resources strengthen the ecosystem (biodiversity), allowing it to be stronger in coping with climate change*	*Moringa trees in Senegal*	*NAPA Burundi*
4.4	*Restoration of existing woodlots*	*F / E*	*"replant the areas of destroyed woodlots"*	*Reforestation for timber production and wood energy, keeping the communities and companies to look for wood in different places. By that preserving natural woodlots, and providing income and energy for the community*		*NAPA Burundi*
4.5	*Forestation of catchments*	*F / W*	*"Forestation of catchments to contribute to eco-climate system restoration"*	*Afforest the catchment prevents erosion and loss of fertility and balances evaporation of water. It also lifts up the adaptive capacity to erratic rains, and other extreme weather events.*		*NAPA Burundi*
5	**Drinking Water**					
5.1	*Development of public water system (PWS)*	*W*	*building a drinking water system to villages and communities (pipelines, taps, etc.), supplying safe drinking water*	*If a drinking water infrastructure is developed, safe drinking water can transported from water sources to areas with few to no water sources during draughts.*		*NAPA CAR, Soa Tomé e Principe*
5.2	*Drilling drinking water wells*	*W*	*providing more available drinking water by drilling more drinking water wells*	*Times of drought, longer dry spells, etc. can be bridge by providing more available drinking water to the communities.*		*NAPA Congo rep*
5.3	*Development of water storage*	*W*	*storing water from different kinds of sources to supply water, also preventing flooding by erratic rains*	*Storing water in basins or catchments (rain-water, ground-water, etc.) will ensure water supply during times of drought and can prevent damage during erratic rain*	*Shallow water basins in Turkana, Kenya*	*Schulte-uebbing 2011, NAPA Congo rep*

Nr.	Adaptation Measure	Sector	Description	Rationale	Examples (UNFCCC and others)	Reference
6	**Agricultural Water**					
6.1	*Promotion of non rain-fed agriculture*	*A*	*Not depend only on the rainy seasons, other techniques such as irrigation techniques, rainwater harvesting, etc., can be promoted for cropping success*	*The timing and character of the rainy season(s) are likely to change. To be less depended on that rainy season, non rain-fed agriculture will help build food and income security*		*NAPA Rwanda, CAB international 2009*
6.2	*Expand area under irrigation*	*A*	*reduce area of rain-fed agriculture to non rain-fed by using irrigation methods . Irrigation water can bet taken from e.g. nearby rivers, rainwater harvesting or drop irrigation*	*providing sufficient water to the crops can boost yields by preventing water stress due climate change*		*Schulte-uebbing 2011*
6.3	*Reviving rain water harvesting*	*A / W*	*collecting and storing rain water to satisfy irrigation and animal husbandry in times of drought*	*"It reduces vulnerability to drought, the pressure on water points meant for drinking water and conflicts of drinking water utilization"*	*Water harvesting structures in northern Kenya*	*Schulte-uebbing 2011, Partow 2011, NAPA Rwanda, NAPA Burundi*
6.4	*Build irrigation infrastructure*	*A / W*	*"sharing irrigation water over agro ecologically and hydrologically diverse areas"*	*Investing in an irrigation infrastructure allows dry areas to be provided with water, causing farmers to be assured of water and by increasing adaptive capacity in the form of food security. Also conflicts for water can be reduces by transporting water from location with abundance to location with (possible) lack*		*Schulte-uebbing 2011, Rosegrant et al., 2010*

Nr.	Adaptation Measure	Sector	Description	Rationale	*Examples (UNFCCC and others)*	Reference
7	**Surface water**					
7.1	*Soil water conservation techniques*	*W*	*Mulching, contour ridging, terracing*	*these techniques increase crop water productivity (CWP) by using techniques such as mulching, contour ridging and terracing. Building of efficiency lessens risks*		*Schulte-uebbing 2011*
7.2	*Prevention and treatment of polluted water*	*W*	*endeavour to practically minimize water pollution and install water treatment plants to treat water and reuse*	*keeping clean and polluted water strictly apart, treat polluted water and reuse. Providing a more stabilized water production*		*NAPA Burundi*
7.3	*stabilisation of river dynamics of river courses*	*W*	*protecting the rivers surrounding landscape, communities and infrastructure by stabilization and correcting parts of the river that propose risk / danger. Including maintenance, building ridges i.e.*	*erratic rains can cause more water to flow through the rivers close to communities, infrastructure or protected landscapes. By maintaining, and correcting weak parts of the rivers, flooding will be prevented*		*NAPA Burundi*
7.4	*Widening and dredging of rivers*	*W*	*Apply basic river mechanics to allow higher flow of water through the rivers*	*allowing more water to run through the rivers will prevent or delay flooding*		*NC Congo*
8	**Energy**					
8.1	*Promotion of new and renewable energies*	*E*	*Implement other forms of energy sources such as bio-energy (biomass, biofuel (Bagasse or others)), Solar and Wind energy, Hydro-energy, etc.*	*Usage of other forms of energy, replacing wood energy and by that reducing deforestation, also produces more energy security, forms of income, etc.*	*GVEP International*	*NAPA Burundi, NAPA Sao Tomé e Principe, website GVEP*
8.2	*Promotion of hydropower (micro) stations*	*W / E*	*enlarging the electricity supply by building more hydropower stations. Small hydropower stations to promote living conditions of the rural population*	*The Congo River is a stable river, this can be used as energy source on different scales. Smaller hydropower stations can supply for a village or area. "without electricity, possibilities of production and improvement of the well-being of the population are inaccessible"*		*NAPA Burundi, NAPA Sao Tomé e Principe*
8.3	*development and construction of dams / dykes*	*W / E*	*Coastline / river basin protection from sea-level-rise by building dams / dykes*	*protecting communities, infrastructure, etc. from flooding by building dykes and dams. Possible to link with promotion of hydropower stations*		*NAPA Burundi, NC Gabon*
8.4	*Promotion of charring wood waste from logging companies (Briquettes)*	*F / E*	*To make briquettes from sawdust or other usable waste*	*replacing wood en charcoal energy reduces deforestation and pollution. Creating Briquettes out of waste is a sustainable energy source and can be made at low costs (depending on scale)*		*NAPA CAR, website GVEP*

Nr.	Adaptation Measure	Sector	Description	Rationale	Examples (UNFCCC and others)	Reference
9	**Land Management**					
9.1	*Make formerly swampy areas suitable for off-season maize cultivation*	*A / F*	*Due to longer dry spell, certain swampy areas can be used for cultivation*	*taking advantage of the changes is to use the now drier areas for cultivation of crops like Maize*		*Schulte-uebbing 2011*
9.2	*Erosion control*	*A / W*	*planting zone with trees and / or shrubs and replanting areas of destroyed woodlots. This will cause the soil to be less vulnerable to soil erosion due to, for example, erratic rainfall or floods. Trees and shrubs of choice are those adapted to new climatic circumstances*	*Plant cover prevents erosion by absorbing the kinetic energy of raindrops, it slows down the runoff and it keeps the soil surface porous.*	*Ngare or Mhindu ridging in Mozambique and Zimbabwe*	*NAPA Burundi, NAPA Congo rep, NAPA Rwanda*
9.3	*Construction of contour lines to control erosion*	*F / W / A*	*preventing erosion and deforestation by planting and cultivating in contour lines.*	*Implementing contour lines fixes the unstable grounds and slopes. Also plowing in contour lines on fields, perpendicular to the gentle slopes (works for gentle slopes only) prevents erosion by holding water containing solids*		*NAPA Burundi, Roose 1996*
9.4	*Improve (inter)national and local infrastructure*	*A / F / E*	*Increasing access to the market and other services by restoring or building roads, railways, etc.*	*improved infrastructure causes farmers to be able to sell off surplus after harvest. Food, wood and other basic needs can be transported further away and faster than previously. Increases adaptive capacity. People will be able to reach hospitals and other services quicker than previously*		*NAPA Congo rep, Feenstra et al 1998, NC Congo, Foster &Briceño-Garmendia 2010*
10	**Agricultural Management**					
10.1	*Promotion of non-agricultural activities*	*A*	*Set up and implement a plan to help people identify and / or develop other competences usable in non-agricultural jobs to generate income from other sectors than agriculture*	*diversification of income highers adaptive capacity, if the crops yield is not sufficient, the second income can still provide for basic needs*		*NAPA Rwanda*

Nr.	**Adaptation Measure**	**Sector**	**Description**	**Rationale**	*Examples (UNFCCC and others)*	**Reference**
11	**Water Management**					
11.1	*Installation of a technical body to coordinate the water sector*	*M W*	*creating a water board to take responsibility of the surface water and safety aspects of climate change adaptation and development. Goals are to provide clean drinking water to all inhabitants and to endeavour to create or maintain safety from flooding's i.e. Create an international collaboration for clean and safe Congo River Basin*	*installing bodies to manage and control priority measures will speed up the process of realisation. Good management practises should be taken in serious account. Including river mechanics and implementation of water management planning. See also adaptation points 7.3 and 7.4*	*Rand Water board South Africa*	*NAPA Burundi, Ashton 2002*
11.2	*Installation of national water data bank*	*M W*	*keeping water data organised to create awareness of the need of water in which areas. The possible uses of the water (drinking, irrigation).*	*water data bank could be established and maintained by the water board to create a scientific basis and awareness on what to be done and implementing water management*	*Regional water data bank project Middle East*	*NAPA Burundi*
11.3	*Develop and implement source protection plans for watersheds*	*W*	*develop and implement management plans containing basic zoning principles, demarcated protection zones, adequate natural buffering strips, land delineation, controlling land development and clarify land tenure and jurisdictional mandates. Create a broad level vision and strategy on regional watershed development*	*Poor land use practices is a threat to drinking water sources. By developing and implementing a proper land and water management plan (by for instance the water board), sprawl of the urban area and thus the slowly advancing beyond limits can be significantly reduces. This will safeguard public health and strengthen water sector investments*		*Partow 2011*
12	**Forest Management**				-	
12.1	*Make a forest inventory*	*M F*	*document the present situation of the forests*	*To know what has happened in the light of deforestation and biodiversity, and to apply adaptation measures, the present situation of the forests need to be know and clearly documented*		*NAPA Burundi*
12.2	*Work out / further develop sustainable forest management plans*	*M F*	*create, or further develop, forest management. Controlled / contracted allocation of forest management if needed due to the size of the forests. Management including, monitoring status of the forests, safeguard forest protection and afforestation areas, certification and verification forest concessions and Non-Timber Forest Products, promoting agroforestry, manage slash and burn agriculture, use of wood waste, energy efficiency, etc.*	*A sound forest management guarantees future energy supply, while simultaneously maintaining the natural resources base and stopping overharvesting of wood*		*NAPA Burundi, NAPA Congo rep, de Wasseige et al., 2010*
12.3	*Enhance the forest and agro-forest seed centre*	*M A / F*	*Organisation to keep germplasm collection, genetic resources, collaborate with other seeds centres around the world, support research activities such as silviculture, genetic variation, breeding systems, climatic analysis, etc.*	*A seed centre assists in preparing and go through climate changes by providing seedlings that are adapted to new climate, without losing the original genetic variation of the area through a genetic/seed database. It can provide seed security for local communities and create a healthy genetic variation which is also important for the crops and trees to be resistant against diseases.*	*Flood management in the Xai-Xai District, Mozambique*	*NAPA Burundi, Vercoe&Midgley 1993, Worede, 2011*

Nr.	**Adaptation Measure**	**Sector**	**Description**	**Rationale**	*Examples (UNFCCC and others)*	**Reference**
13	**Energy management**				-	
13.1	*Set up a national wood-energy programme*	*M F / E*	*creating a programme that educates and enables different and more efficient uses of wood-energy. Safe wood energy use for household, etc.*	*Educate and promote (make available) for example safe stoves, more efficient and safe than open fire.*	*Practical Action East Africa's programme*	*NAPA Burundi*
13.2	*Develop energy-saving programme*	*M E*	*promote energy efficiency in government, businesses, households, etc. Set goals for certain time frame*	*less use of energy for the same activities causes less energy to be spilled, higher sustainability, higher adaptive capacity*		*NAPA Burundi*
13.3	*Design and implement renewable energy pilot projects for conventional water utilities and community based water-supply systems*	*M W / E*	*"carry out a technical assessment to identify appropriate renewable energy technologies for operating conventional water treatment plants, based on the technical evaluation, implement the simplest and most appropriate renewable energy solutions selected"*	*"This measure will lower the financial burden of fuel oil costs for water treatment plants". Renewable energy will lower the pollution, higher adaptive capacity due to independence of non renewable energy sources*		*Partow 2011*
14	**Education**					
14.1	*Training in basic techniques and water management*	*M W*	*Education of water management techniques on different scales.*	*equipping officials and experts to practically run and implement a sustainable and climate change proof water management*		*NAPA Burundi*
14.2	*Training and sensitization of the population on the economic use of water and energy*	*W / E*	*Set up and implement and education plan for the population to educate in energy and water efficiency*	*Increase efficiency of the populations water and energy use increases adaptive capacity due to the fact that less water / energy is needed for the same activities. In case less is available due to climatic factors, this will not have the same effect on population as previously*		*NAPA Rwanda*
14.3	*Promoting awareness of bushfire risk*	*F*	*Radio and TV broadcasts on the adverse effects of climate change and the effect of bushfire and deforestation now and in the near future*	*Informing people, and by that raising the awareness of risks of bushfires, will cause people to be more aware of their actions and the consequences of such. This decreases the number of bushfires and other forms of deforestation*		*Schulte-uebbing 2011, NAPA Burundi*
15	**Early warning management**					
15.1	*Setting up hydro-agro-meteorological early warning system*	*A / F / W/ E*	*"Installation or rehabilitation of hydrological and meteorological station to master hydro meteorological information and early warning systems for control of climate change hazards" Including a communication protocol to communicated findings to those in need of it*	*Predictions enable, for instance, farmers to take specific adaptation measures against the adverse effect of climate change. This reduces the 'surprise' factor when it comes to climate change impacts and enables the people to prepare for what is coming. This measure enlarges the adaptive capacity greatly if the findings can also be effectively communicated*	*Point-to-point radio in Isiolo, Kenya*	*NAPA Rwanda, NAPA Burundi*

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ISSN 2192-4058

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