# Climate Change Scenarios for the Congo Basin

## Climate Change Impacts on the Congo Basin Region

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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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*"Climate Change Impacts on the Congo Basin Region"*
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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**

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| | |
|---|---|
| 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.

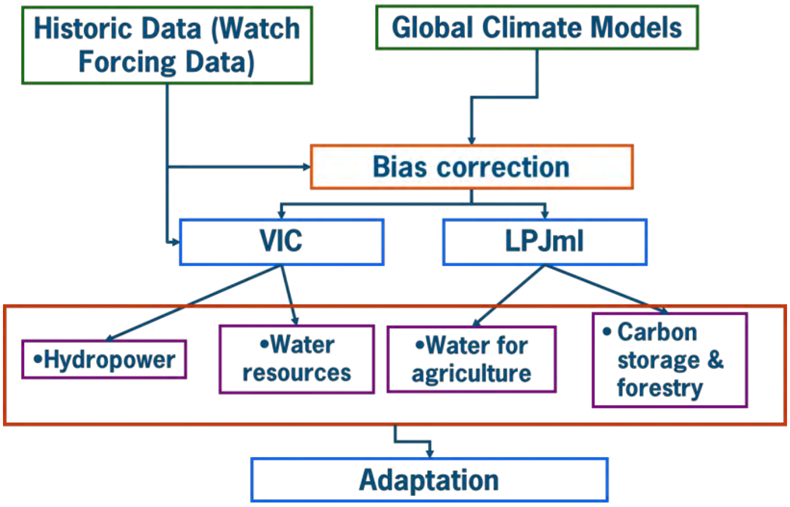



Figure 1. Modelling Framework used within the Climate Change Scenarios for the Congo Basin project.

## 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.

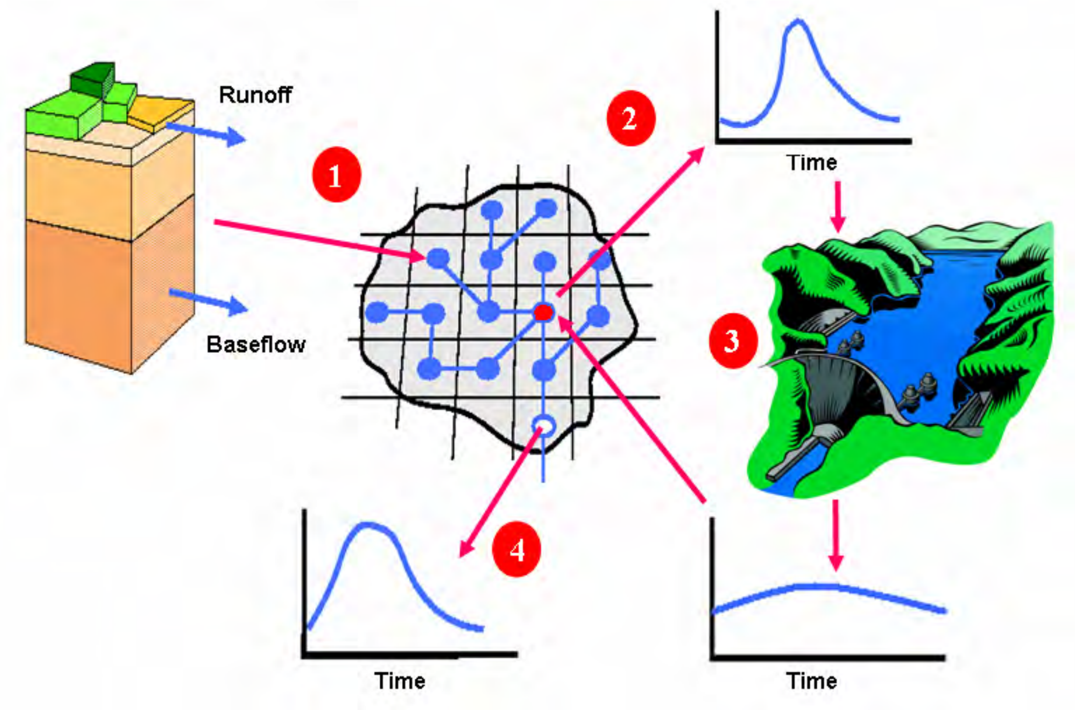



**Figure2. Schematic Coupling of 1) hydrology (Liang et al. 1994, Cherkauer et al. 1999, Su et al. 2005, Adam et al. 2007), 2) routing (Lohmann et al. 1998), and 3) reservoir (Haddeland et al. 2006a,b,c) models.**

## 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

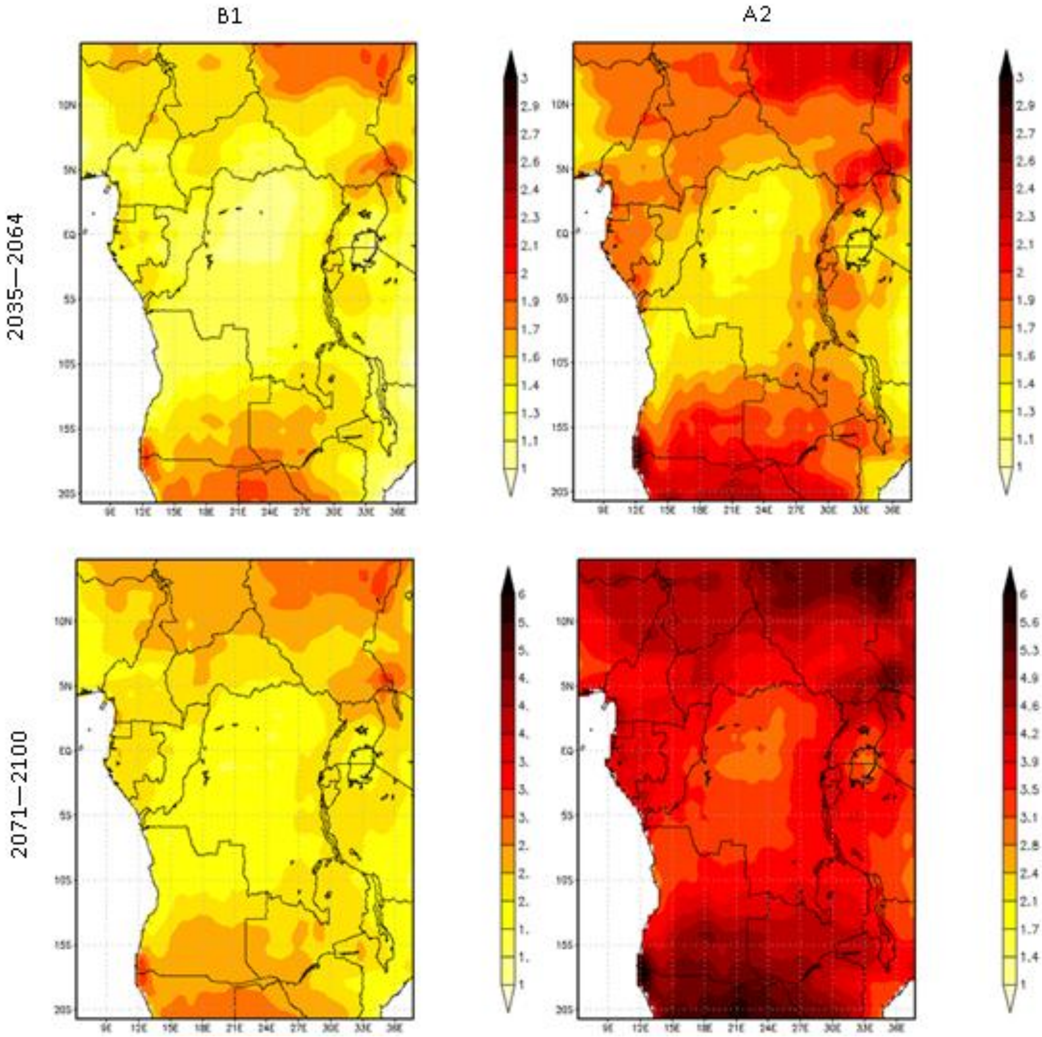



Figure 3. Temperature change [°C] comparing the years 1971 – 2000 with 2035 – 2064 and with 2071 – 2100 for both the A2 as the B1 scenario.

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.

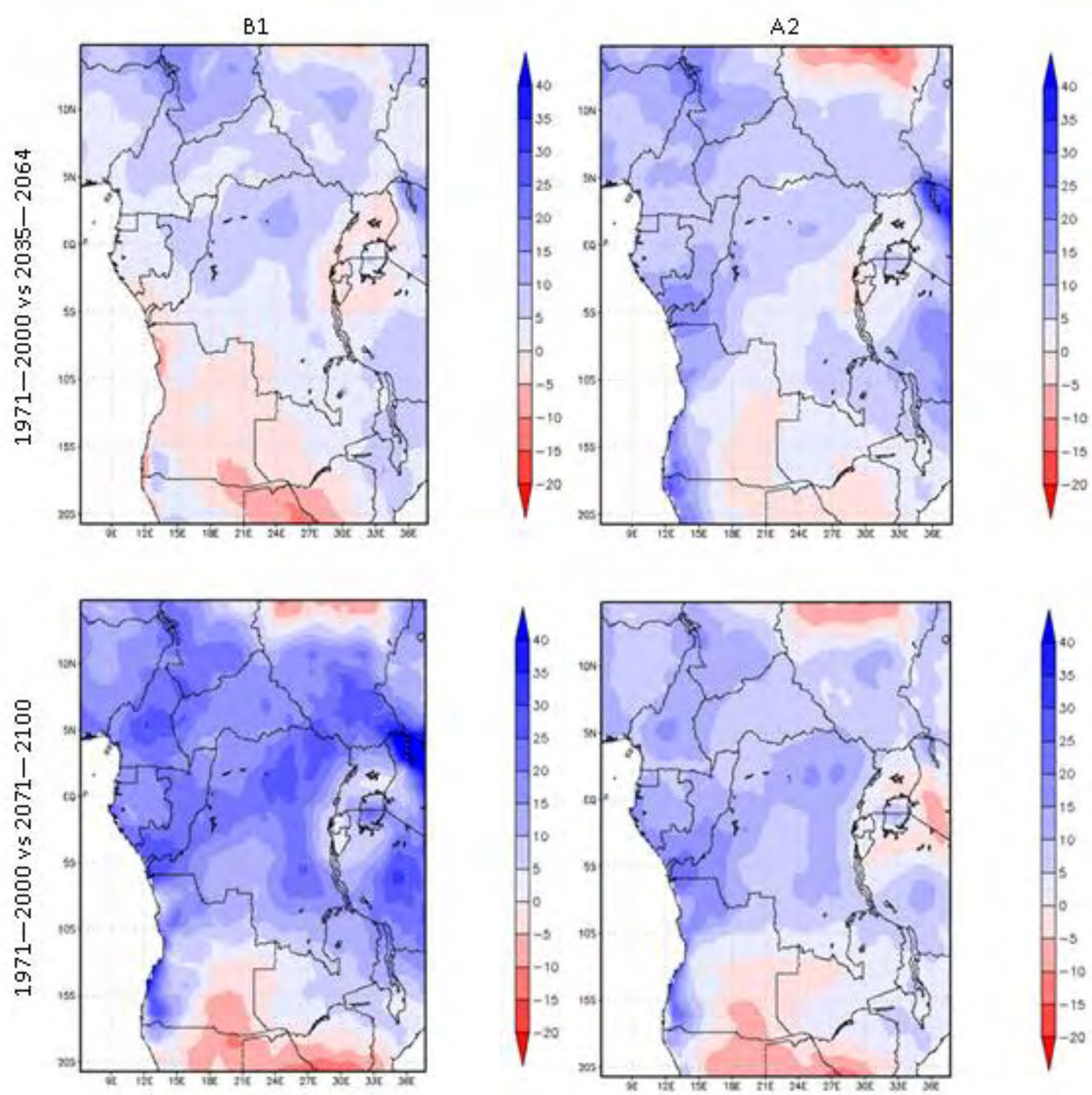



**Figure 4. Precipitation changes (%) for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline 1971-2000.**

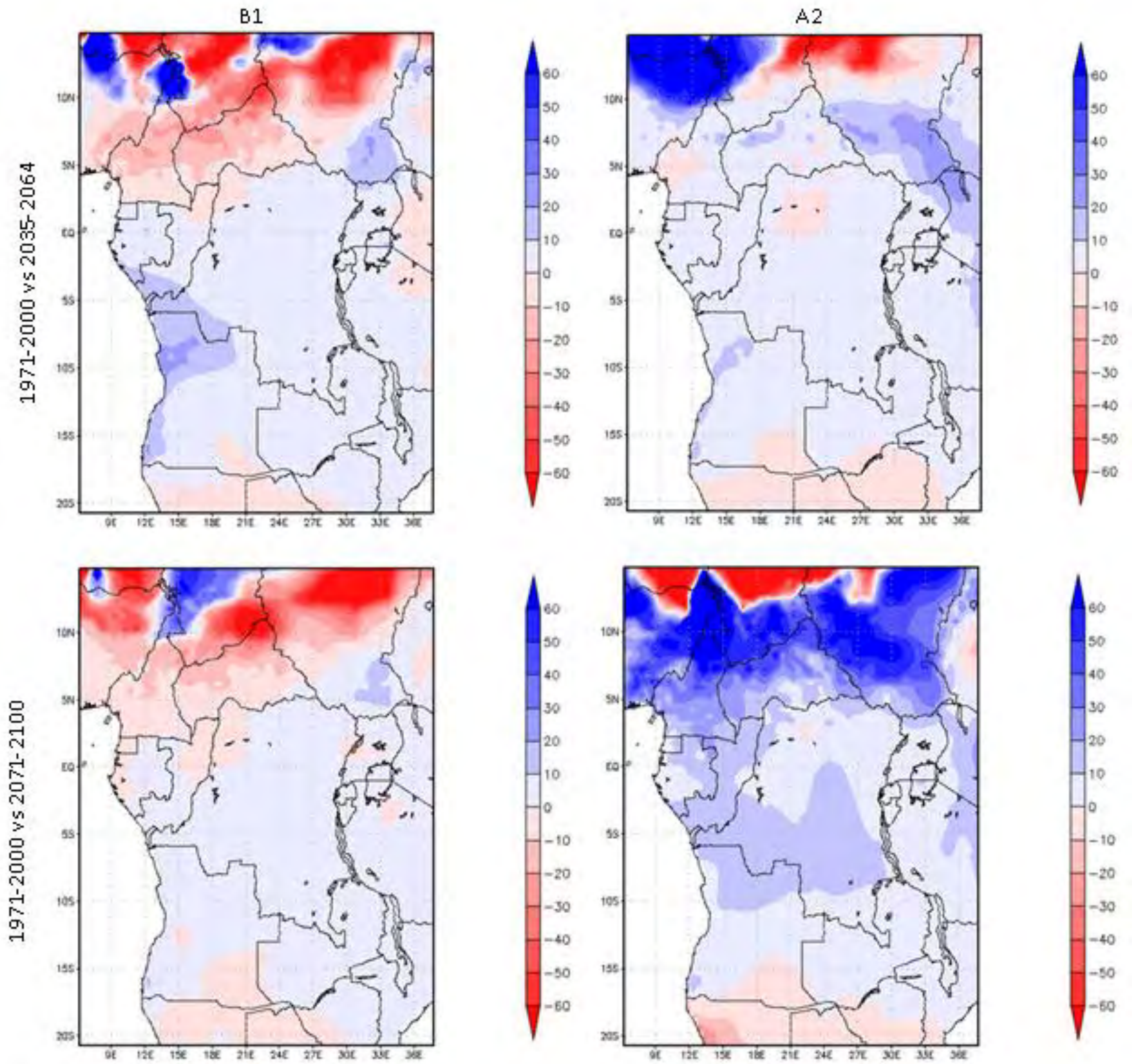



Figure 5.Changes (%) in precipitation for December, January and February for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline period 1971-2000.

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.

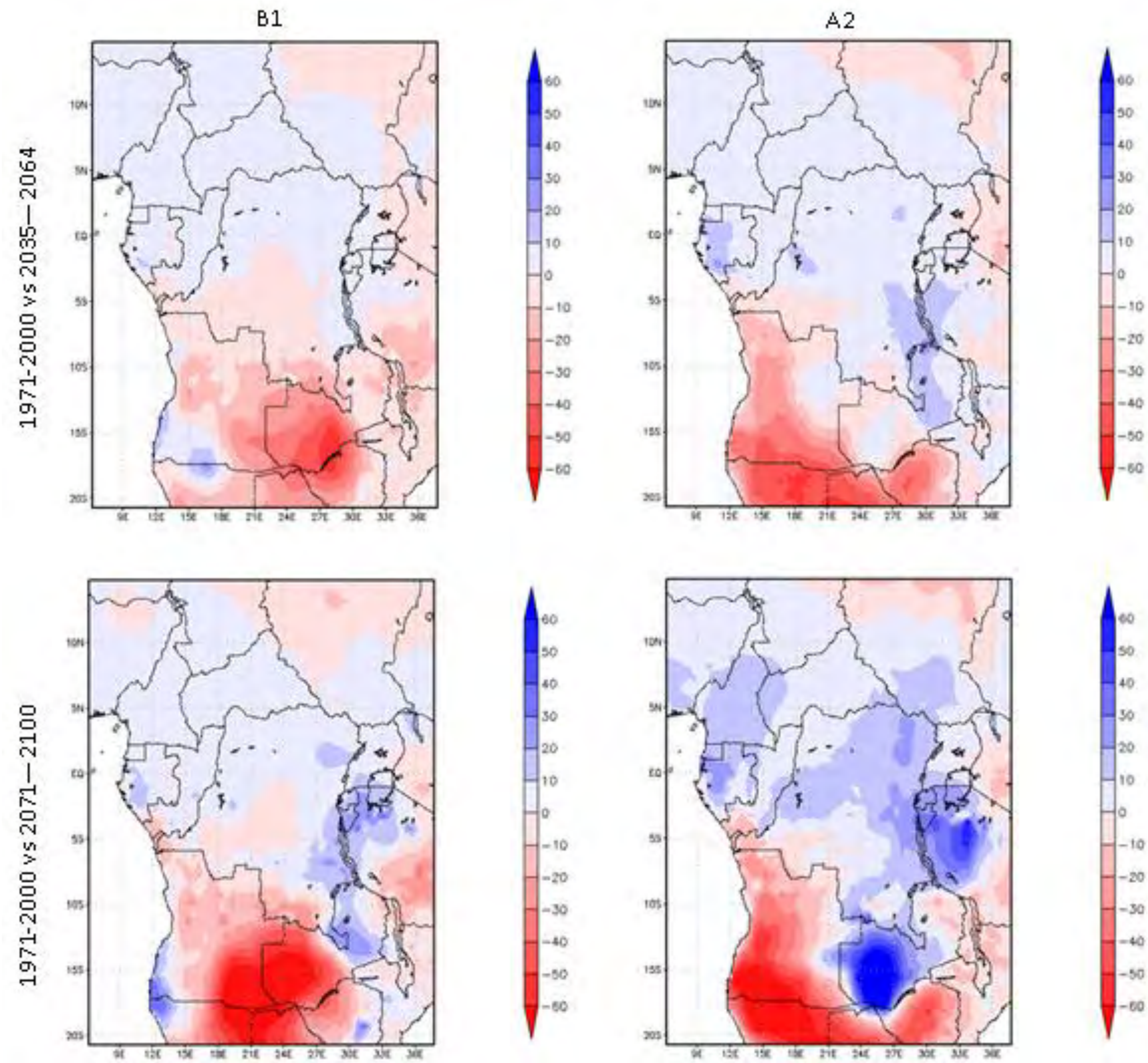



**Figure 6.Changes (%) in precipitation for June July, and August for scenario B1 (left) en A2 (right) for the 2035-2064 (upper) and 2071-2100 (lower) periods compared to the baseline period 1971-2000.**

# 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 21$^{st}$ 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 21$^{st}$ 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 21$^{st}$ 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 21$^{st}$ 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).

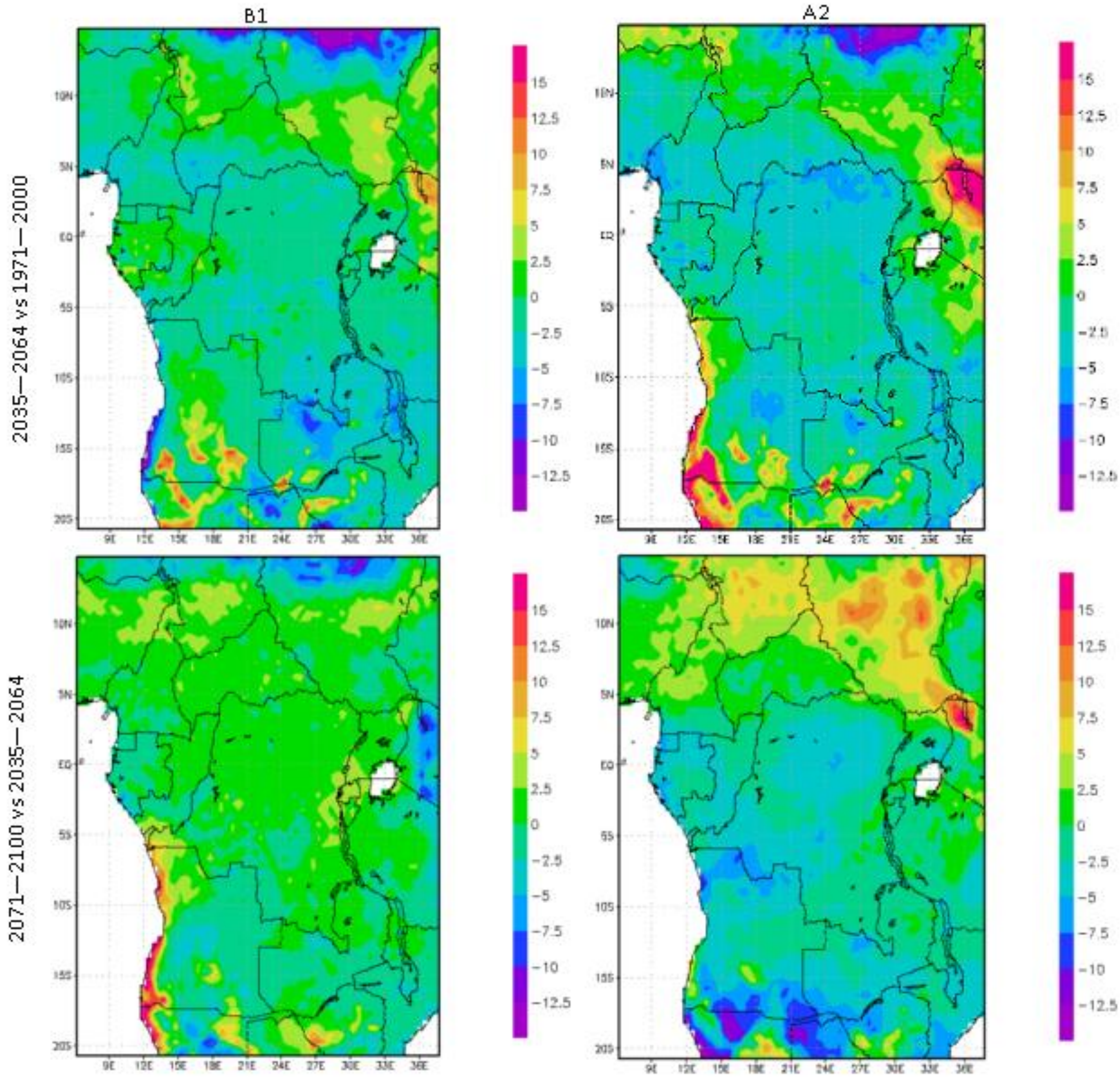



**Figure 7. Relative changes in the evapotranspiration for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.**

### 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 $21^{st}$ 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 $21^{st}$ 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 $21^{st}$ 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 $21^{st}$ 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 $21^{st}$ century, in the Sahellian region the precipitation decreases and consequently the green water consumption declines. The decline continues throughout the second half of the $21^{st}$ the century.

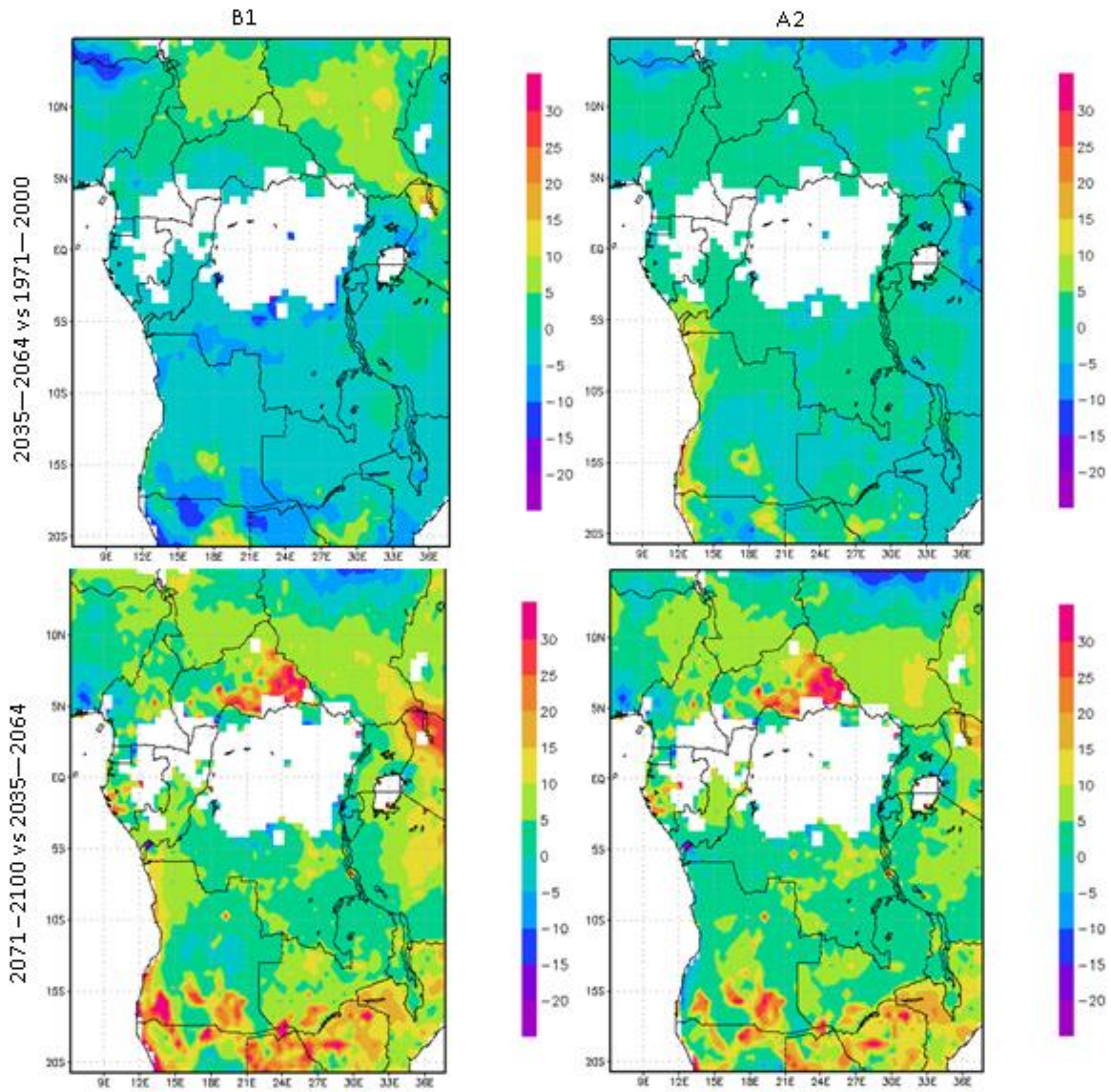



**Figure 8. Relative changes in the green water consumption for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.**

### 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.

<u>*Scenario A2*</u>

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 21$^{st}$ 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 21$^{st}$ 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.

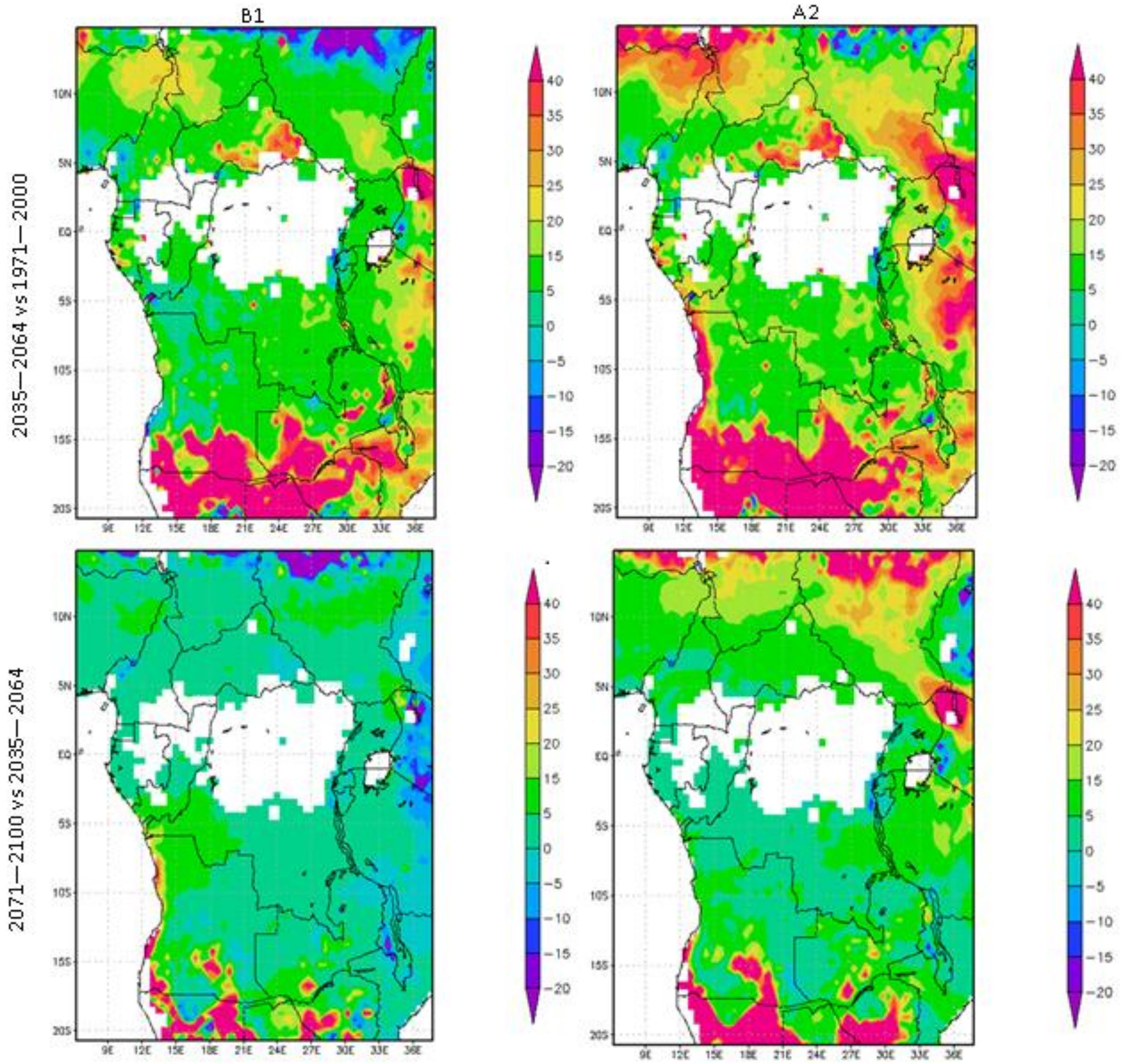
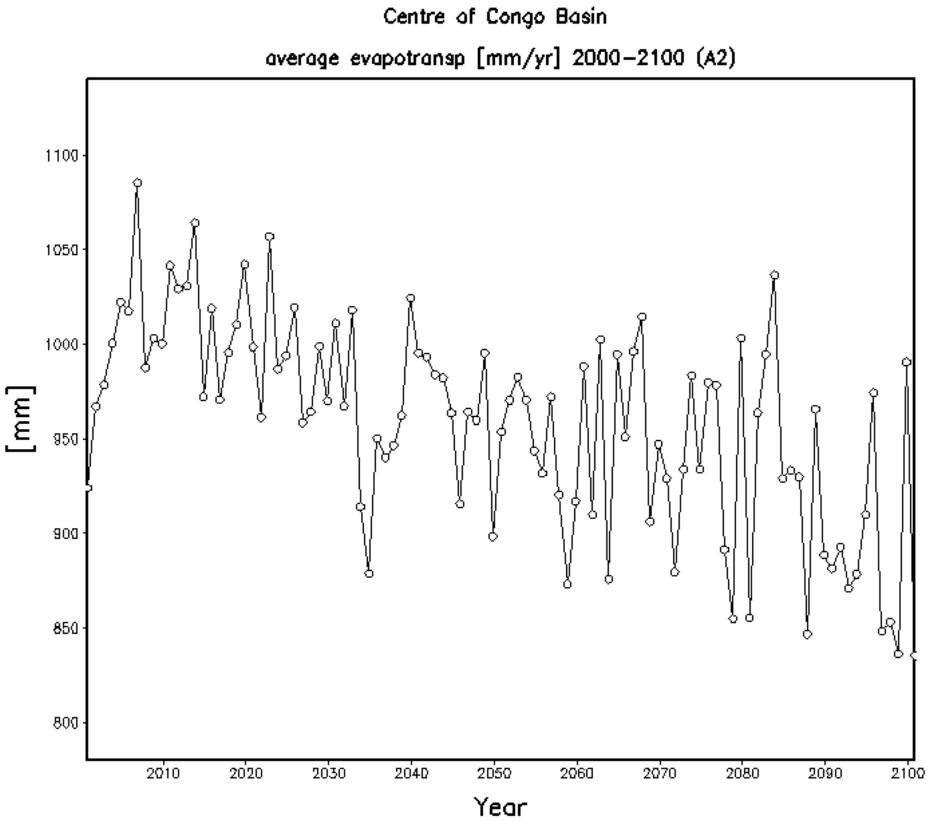



**Figure 9. Relative changes in water stress for the periods (2035-2064) – (1971-2000) and (2071-2100) – (2035-2064) for the B1 and A2 scenarios, respectively.**

## 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.



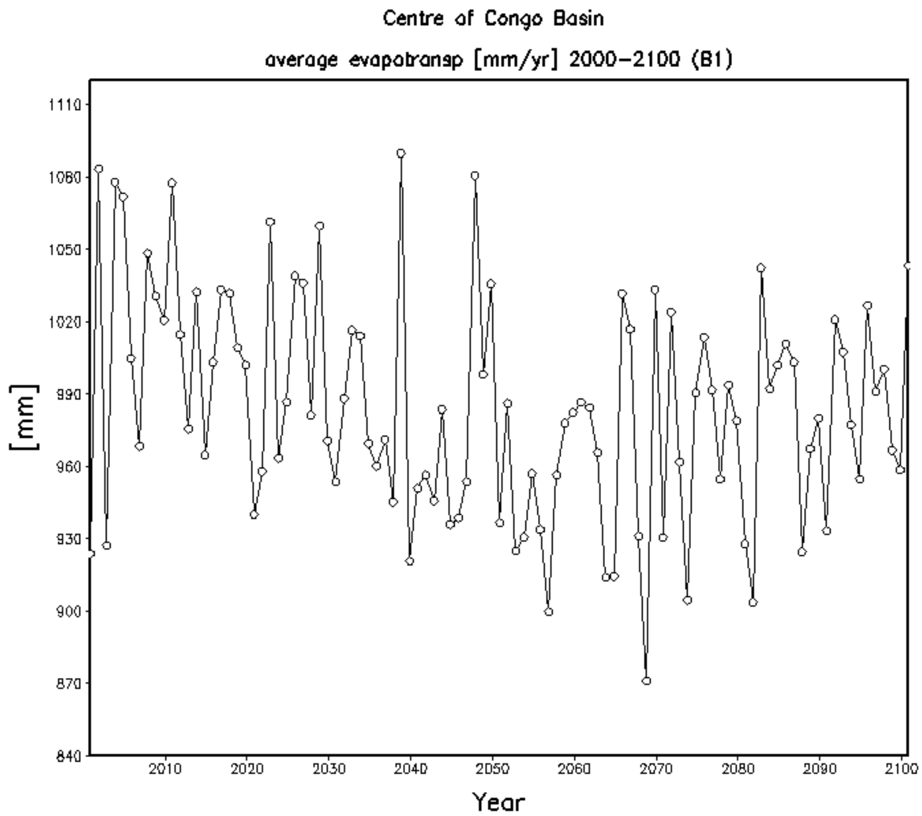
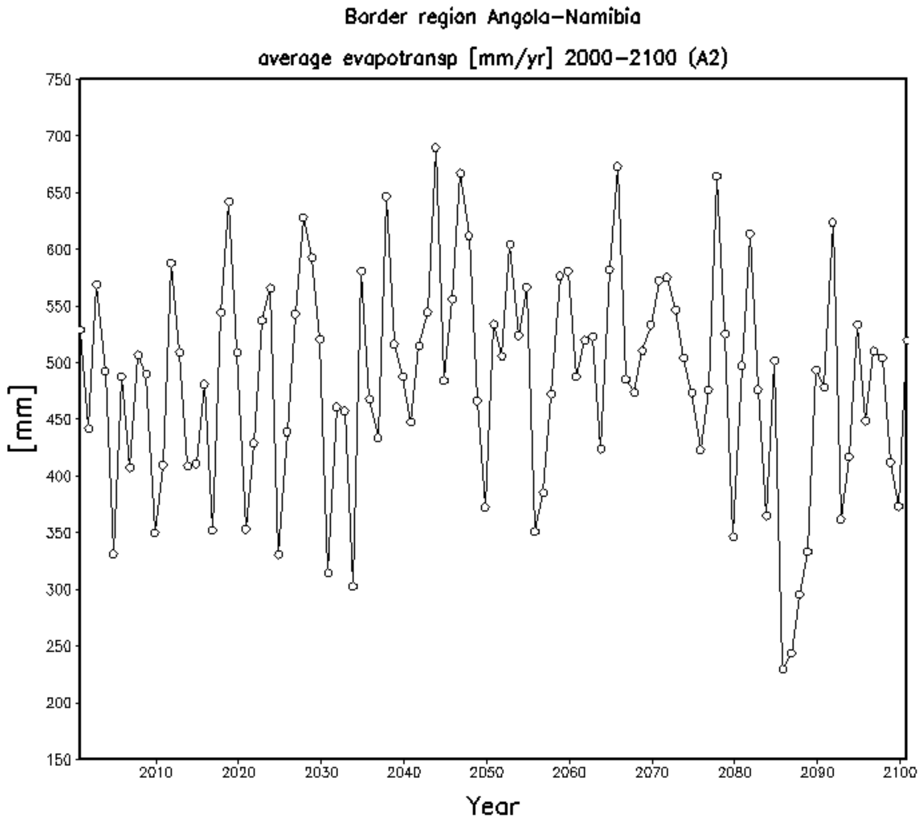




**Figure10. Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the Congo basin.**



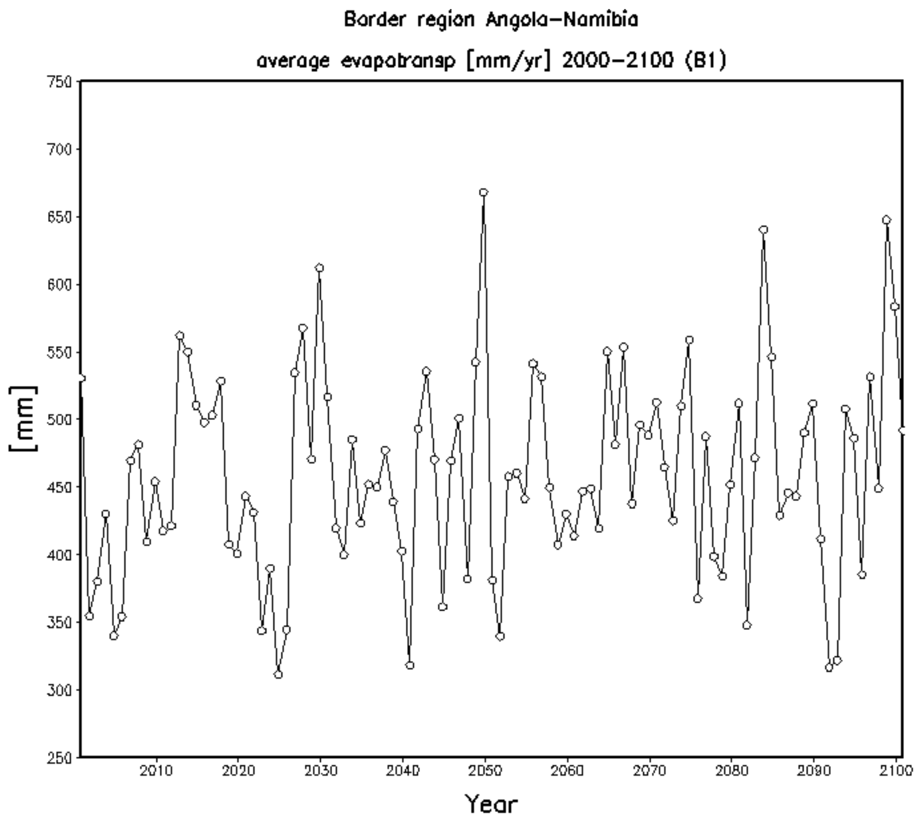
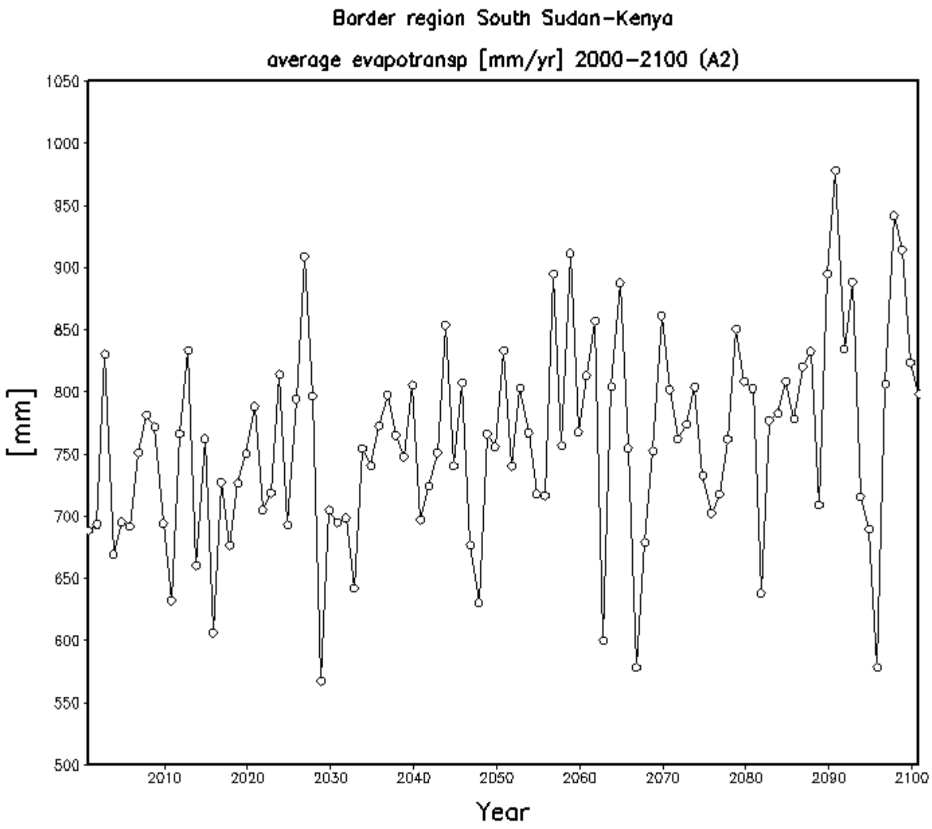




**Figure11 Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the Angola-Namibia border region.**



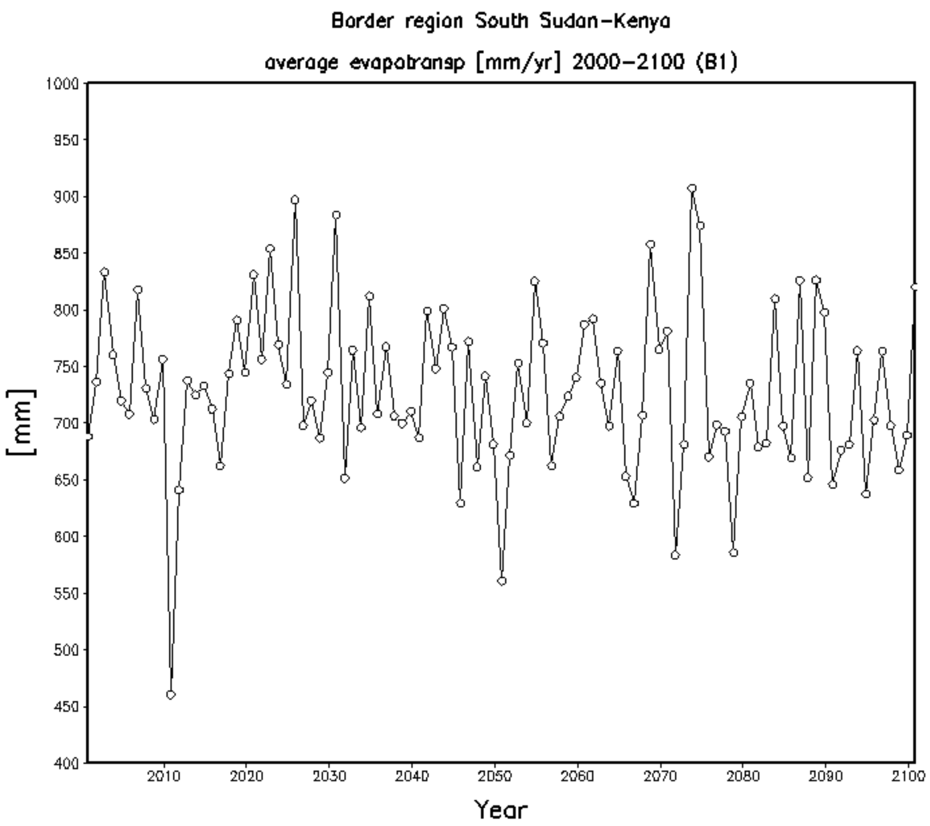




**Figure12. Average area evapotranspiration values for respectively the A2 and B1 scenarios for the centre of the South Sudan Kenya border region.**

# 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.

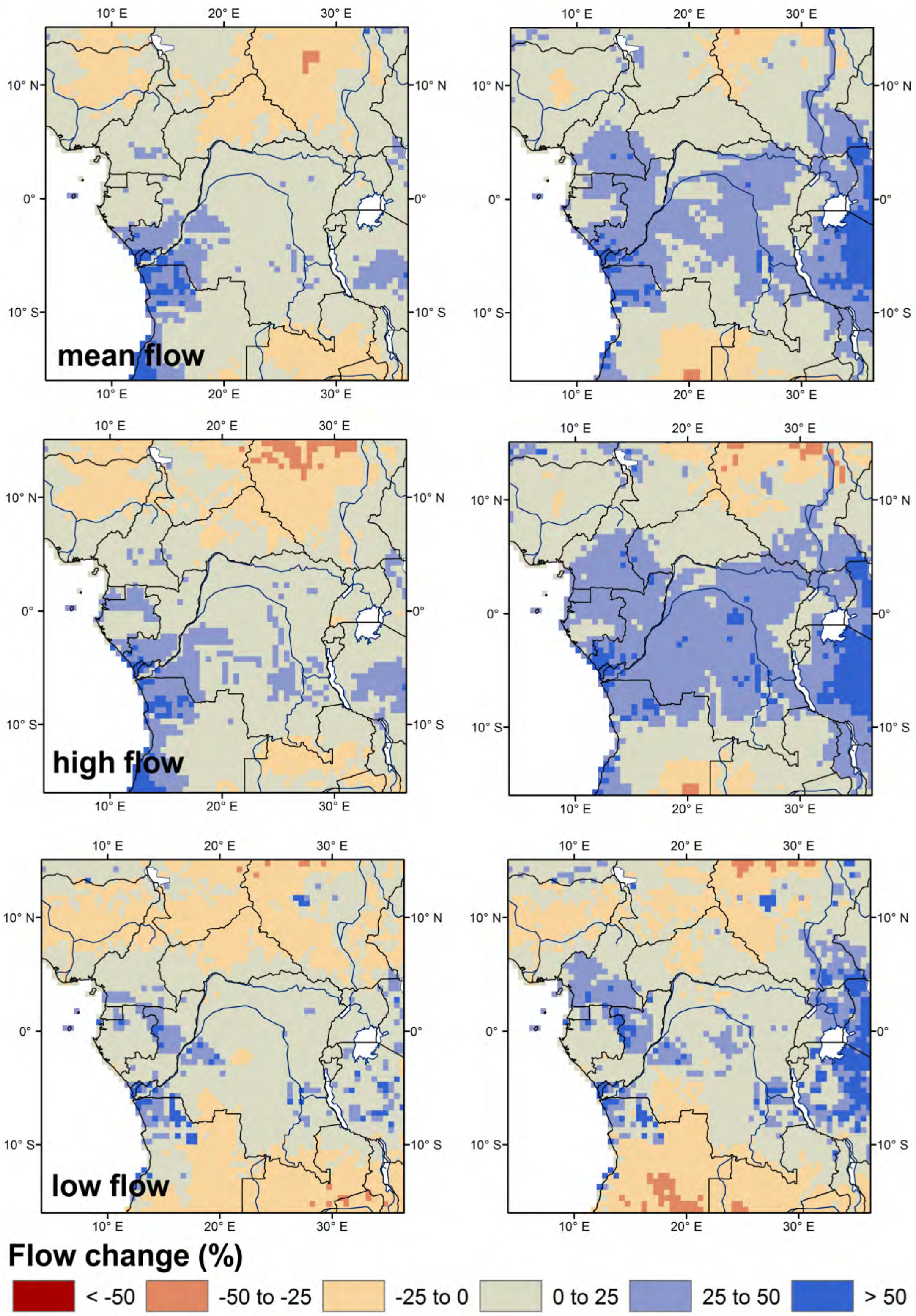



**Figure13. Projected changes in mean flow (a), high flow (Q95) (b) and low flow (Q10) (c) for 2071-2100 relative to 1971-2000 averaged for the three different climate model (GCMs) for both the high (A2) and low (B1) emissions scenario.**

## 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.

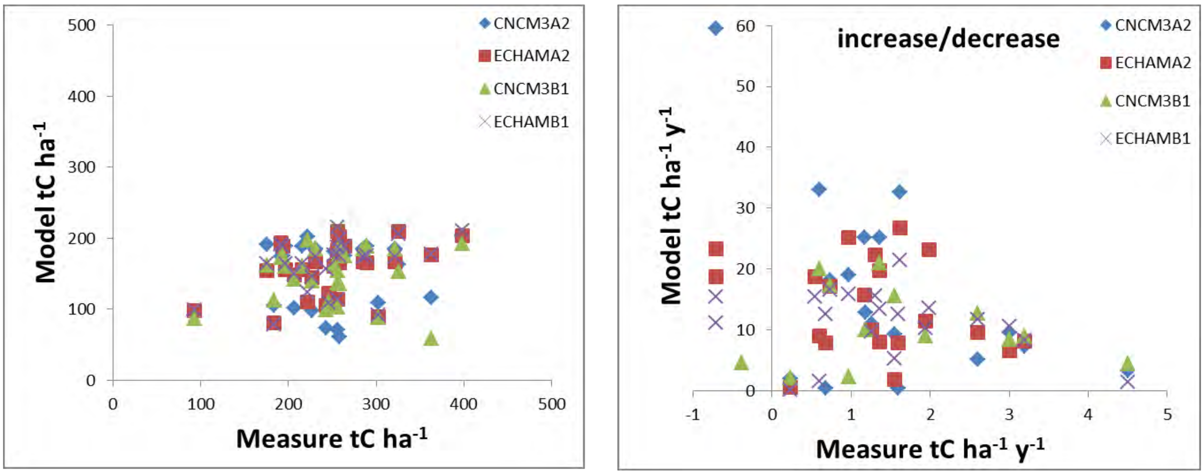



**Figure15. (left) Comparison of predicted and measured standing biomass in selected biomass plots as published by Lewis et al (2009), using two different models and two different climate change scenarios. (right) The same, but now for biomass change as measured and modelled over the measurement intervals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

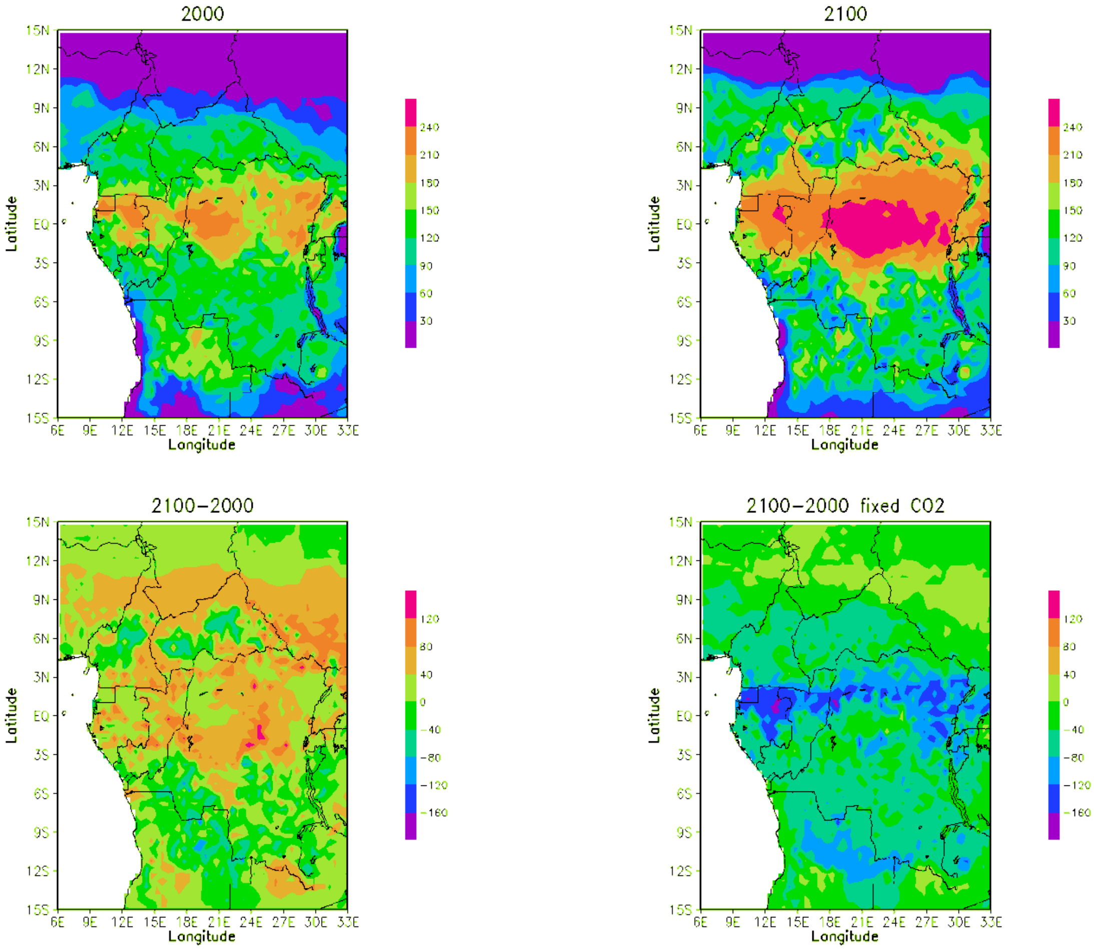



**Figure 16. Maps of vegetation carbon (tC ha$^{-1}$) as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing $CO_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row,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

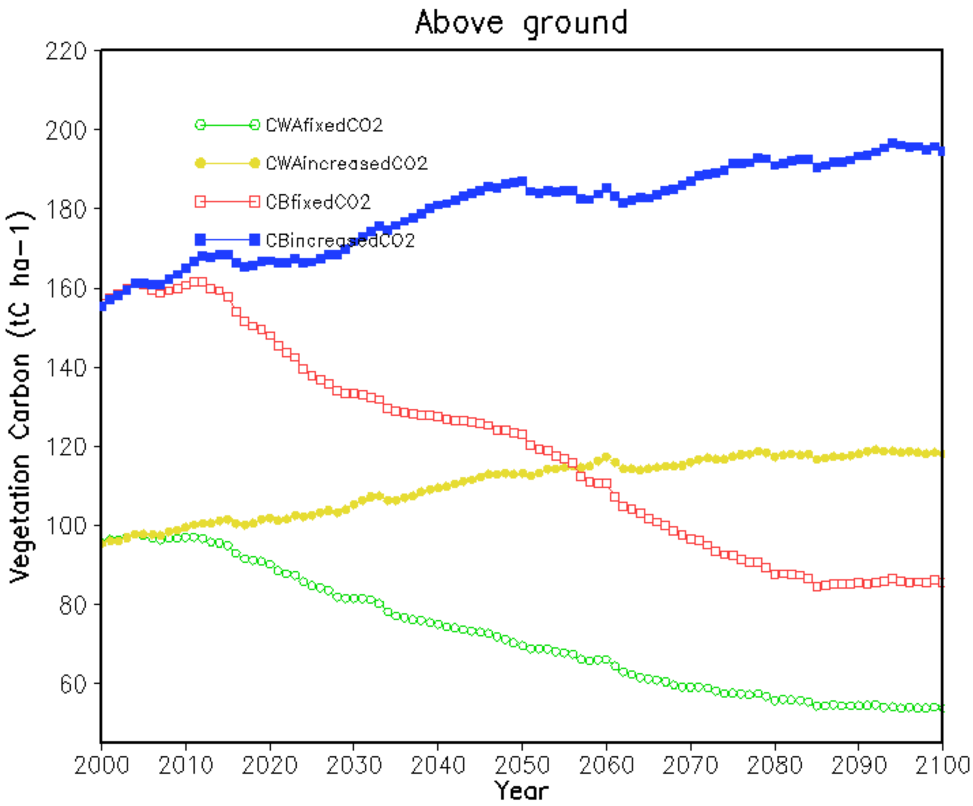



**Figure 17. Modelled time evolution using the high emission scenario (A2) of the vegetation carbon over the 21st century. Shown are the time series for the Central Western African area (i.e. the full areas shown in the maps) as well as the time series for the Congo Basin rectangular area, as defined 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.

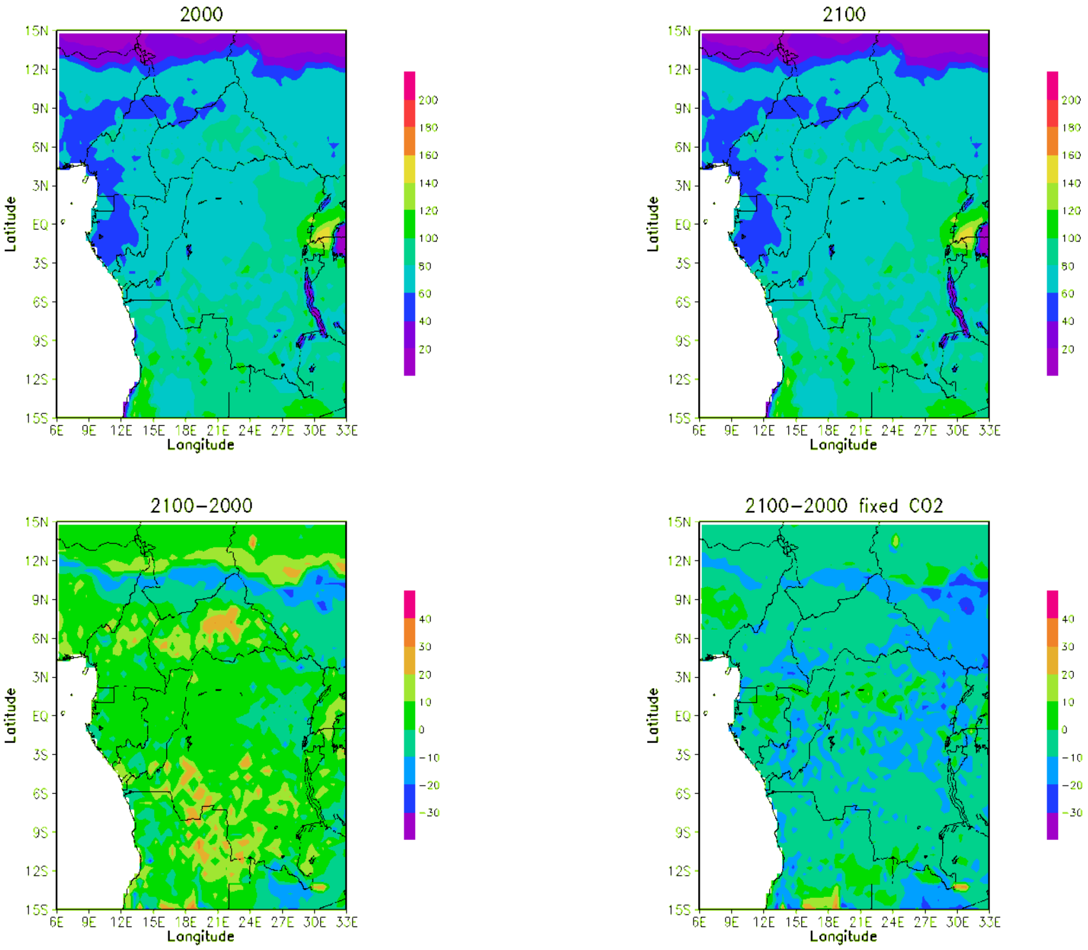



**Figure 18. Maps of soil carbon (tC ha$^{-1}$) as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing $CO_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.**

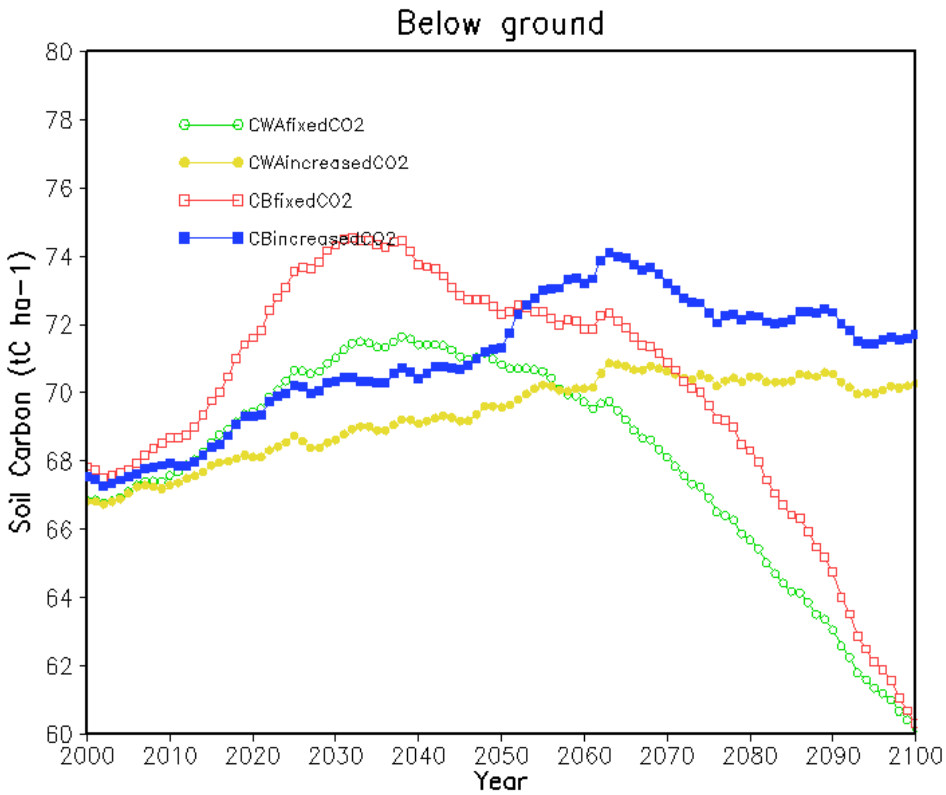



**Figure 19. Modelled time evolution using the high emission scenario (A2) of soil carbon over the 21st century. Shown are the time series for the Central Western African area (i.e. the full areas shown in the maps) as well as the time series for the Congo Basin rectangular area, as defined in the methodology.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

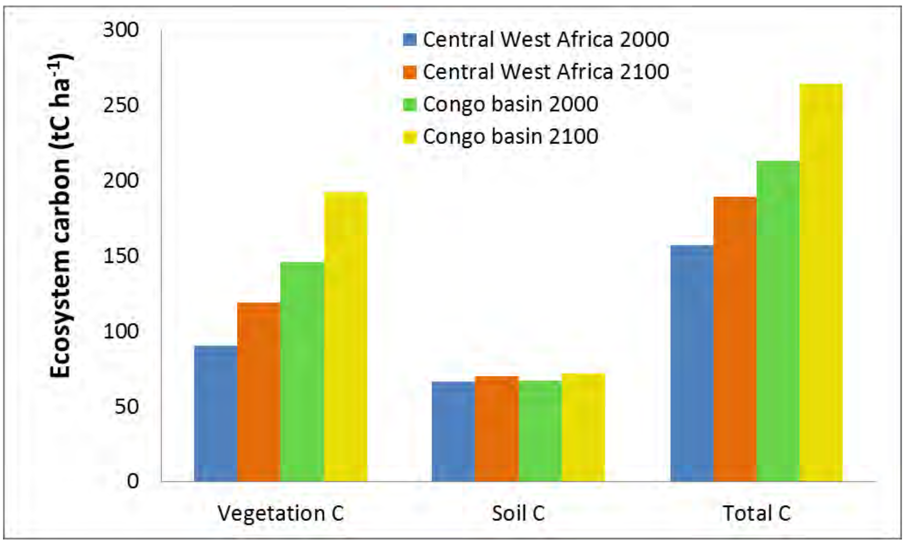



**Figure 20. Bar chart summarising the simulated changes over the 21st century in aerially integrated totals of vegetation, soil and total ecosystem carbon over the wider and restricted region, assuming increasing $CO_2$.**

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.

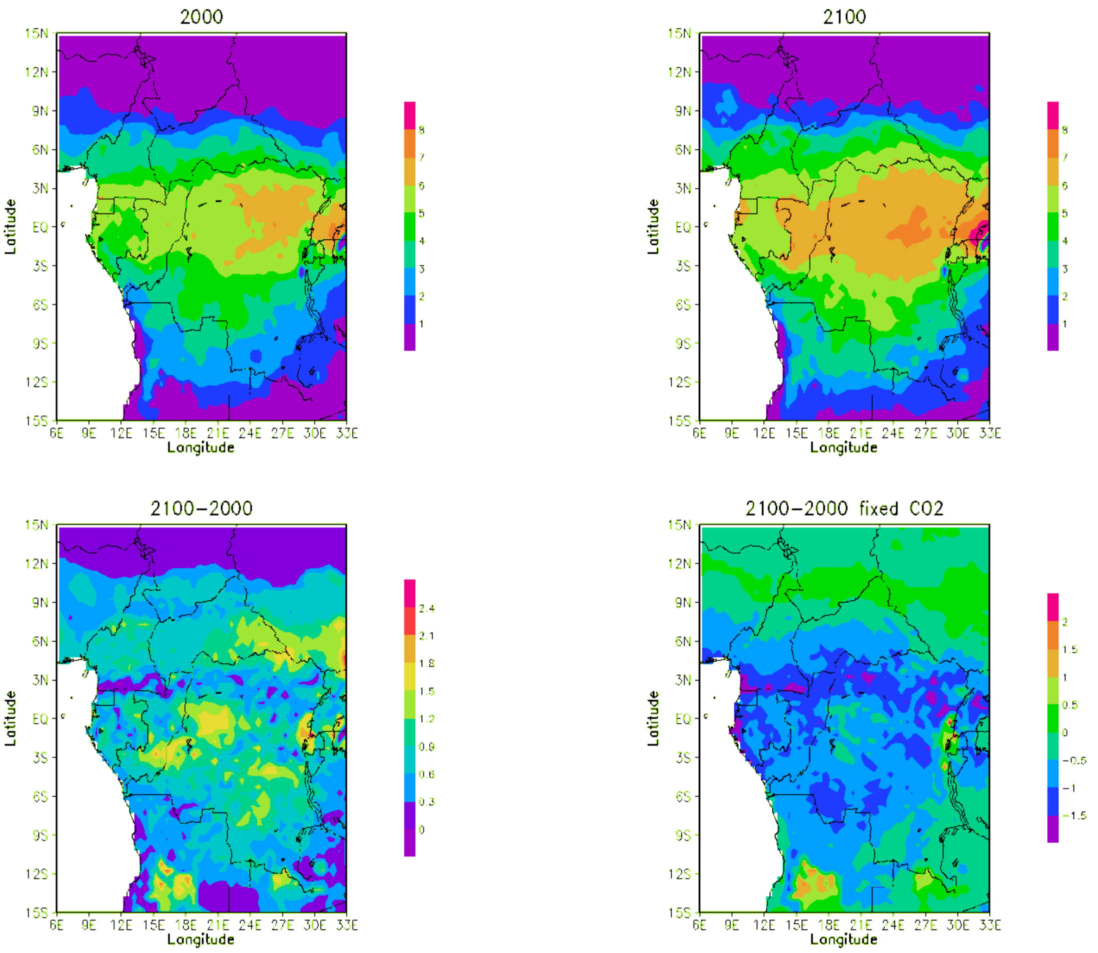



**Figure 21. Maps of Net Primary Productivity (NPP, gC m$^{-2}$) for plant functional type *Tropical Evergreen Forest* as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing $CO_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.**

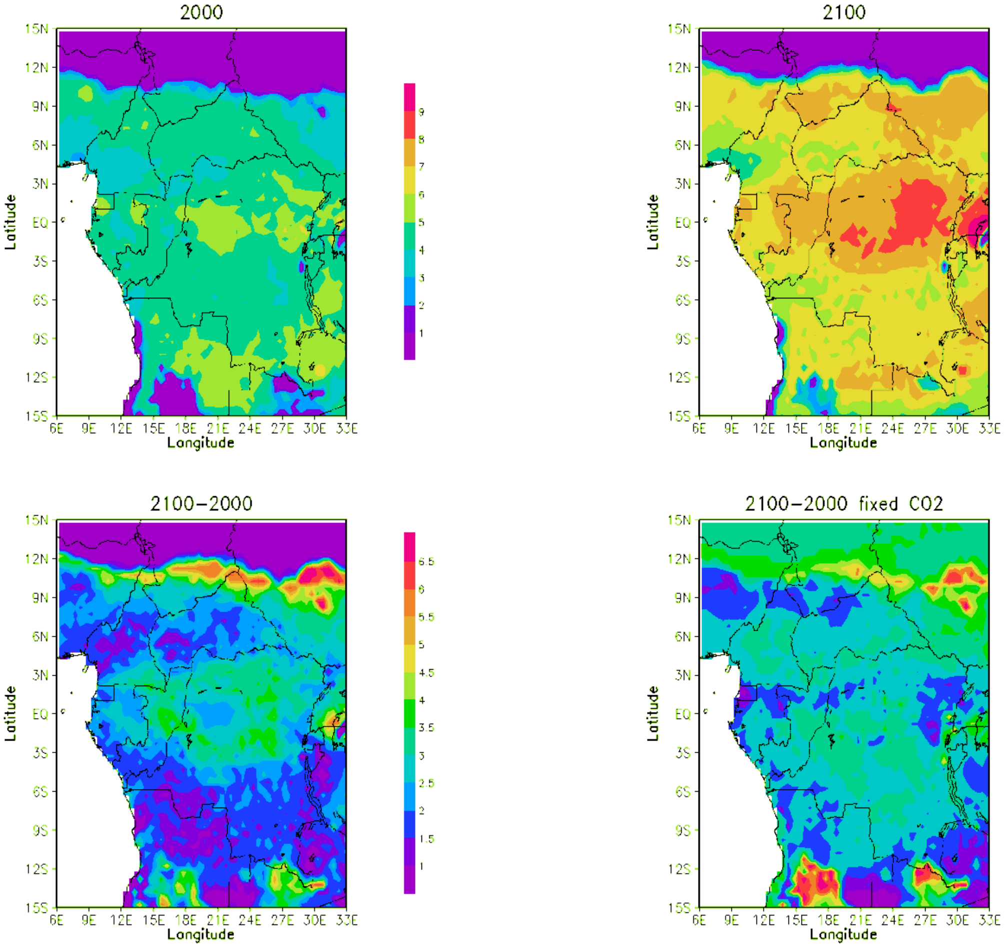



**Figure 22. Maps of Net Primary Productivity (NPP, gC $m^{-2}$) for plant functional type *Seasonal Forest* as modelled using the high emission scenario (A2) for the years 2000 and 2100 as well as the changes over this period with and without considering increasing $CO_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.**

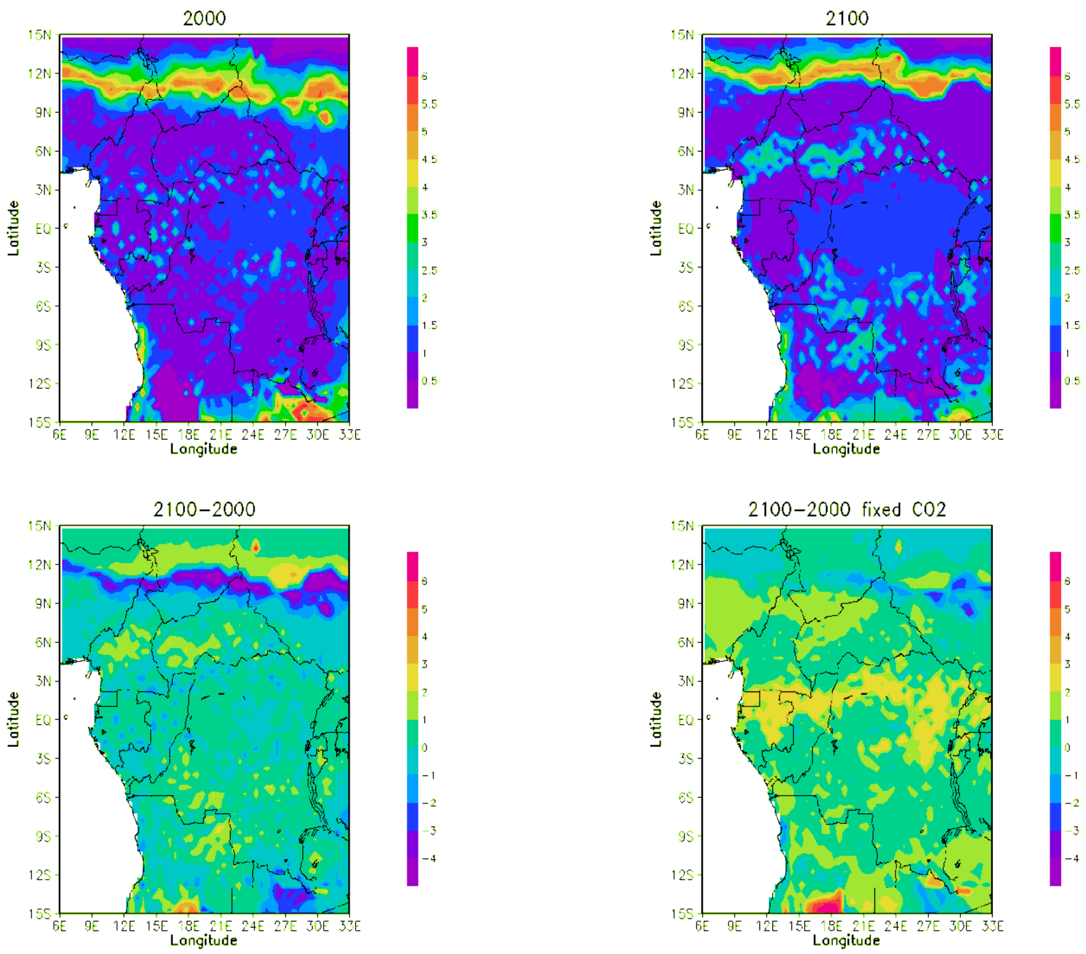



**Figure23.Maps of Net Primary Productivity (NPP, gC m$^{-2}$) for plant functional type *Natural Grassland* as modelled** using the high emission scenario (A2) **for the years 2000 and 2100 as well as the changes over this period with and without considering increasing $CO_2$ concentrations. NOTE that colour scaling is different top row, stocks and bottom row, changes.**

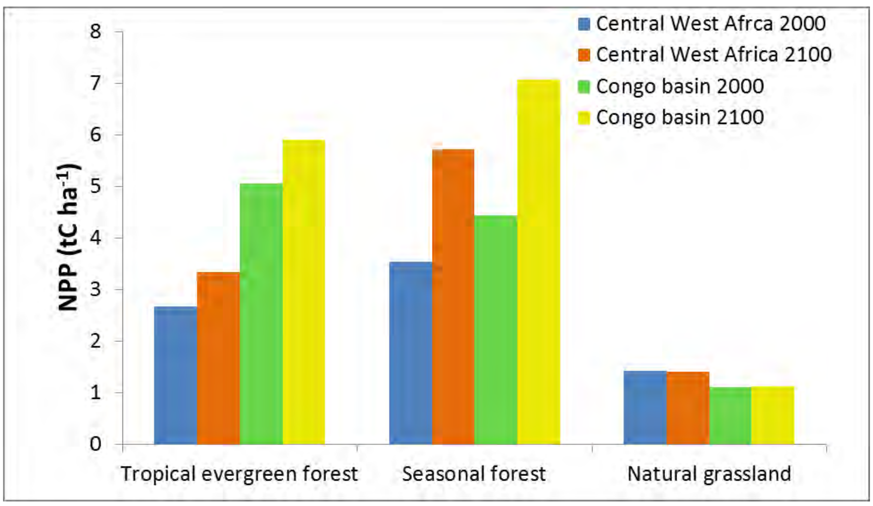



**Figure 24. Bar chart summarising the simulated changes over the 21$^{st}$ century in aerially integrated total NPP of the three most important plant functional types, over the wider and restricted region.**

## 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

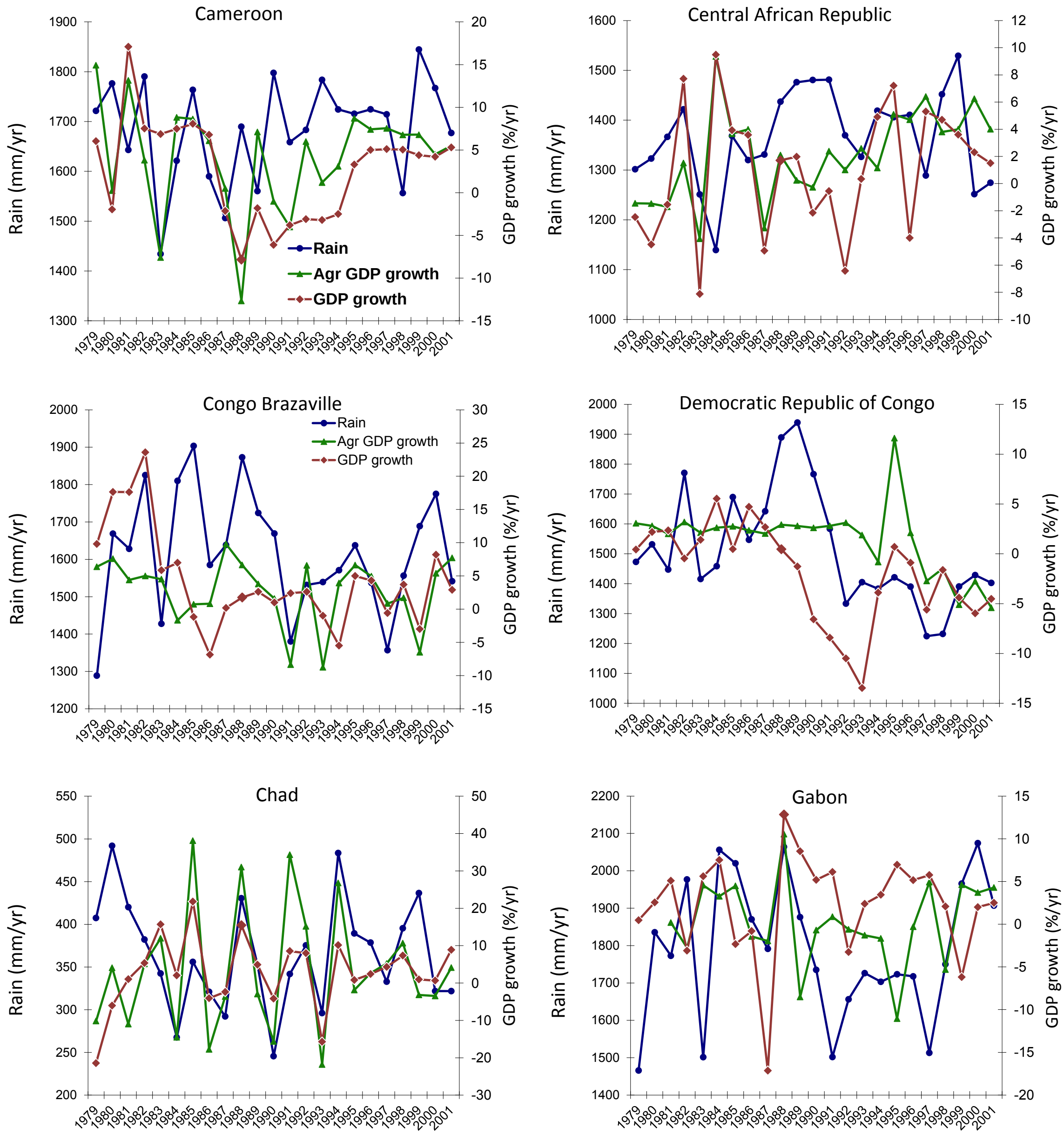



Figure 25. Relation between rainfall (blue line) and total economic growth (red line) and agricultural economic growth (green line) for six countries within the COMIFAC region.

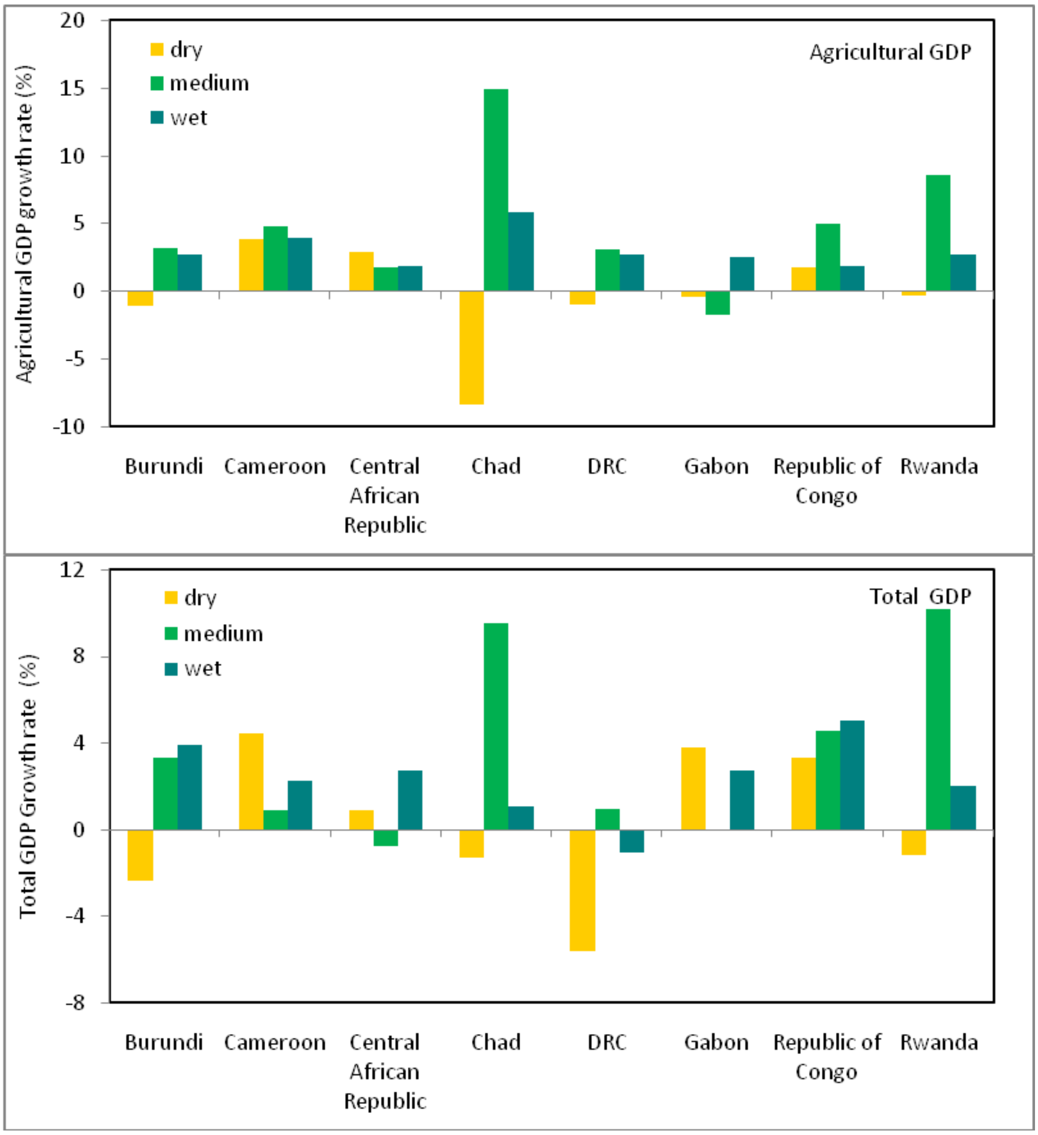



**Figure26. Average total and agricultural economic growth for the period 1979-2001 for dry, medium and wet years. Wet, medium and dry years were determined based on the country average total annual rainfall. For example for GDP growth during the dry years the GDP figures were average for the 33% driest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

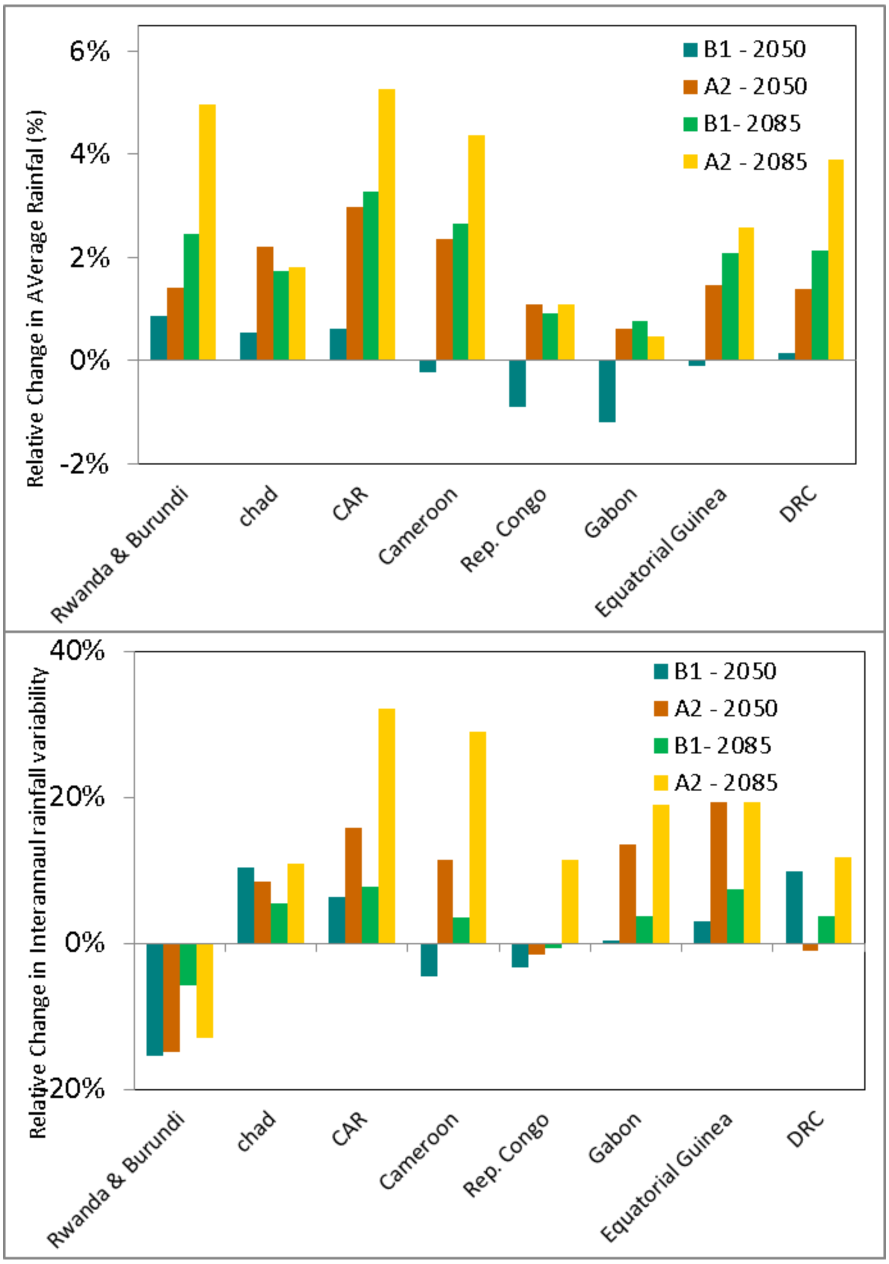



**Figure27. Relative future changes in average annual rainfall and interannual rainfall variability for the different Comifac countries. Changes are shown for two different periods: 2036-2065 (2050) and 2071-2100 (2085) and two different emission scenarios. Changes shown are the average of 5 or 6 different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