Impacts of Lateral Boundary Conditions on Regional Climate Projections over West Africa

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Abstract

Climate simulation and projections using regional climate models (RCMs) are sensitive to the choice of lateral boundary conditions (LBCs) which often are derived from global climate models (GCM). These LBCs used to drive RCMs describe the atmospheric conditions at the boundaries regarding atmospheric dynamics as well as atmospheric physics, including wind, atmospheric pressure, temperature and humidity. Understanding the impact of each component of LBCs is important for understanding and reducing the uncertainty in and improving the accuracy of RCM climate simulations and projections. In this study, the ICTP Regional Climate Model Version 4 (RegCM4) is used to investigate the impact of LBC on projected future changes of regional climate in West Africa. To examine this, present, future and several modified experiments are conducted with various combinations of LBCs and other climate change factors (including CO2 concentration and sea surface temperature (SST)) using RegCM4, and differences among the experiments are compared to identify the most important drivers for RCMs. The LBCs are derived from the global climate model ECHAM5.

When driven by changes in all factors, the RegCM4-produced future climate changes include drier conditions in Sahel and wetter conditions along the Guinean coast. The impact of CO2 concentration alone (in the RCM context) or atmospheric dynamics alone is not significant. Changes in the atmospheric humidity alone at the domain boundary lead to a wetter Sahel due to the northward migration of rain belts during summer. This impact, although significant, is offset and dominated by other factors that have a stronger impact. Changes of atmospheric temperature at the domain boundaries alone lead to a drier future over most of the model domain. This, when combined with SST changes over Ocean, produces a future prediction that closely resemble the changes caused by all factors combined. Further analysis demonstrates that the changes of moisture flux convergence dominate the projected precipitation changes. Moreover, it is founded that the response of the RCM climate to different climate change factors is primarily linear in that the projected changes driven by all factors combined are close to the sum of projected changes due to each individual factor alone. Findings from this study may be region-dependent, which will be examined in follow-up studies.
Chapter 1

Introduction

The term “climate change” refers to a significant and lasting change in the long-term statistical distribution of any weather patterns globally or regionally. Changes in the atmospheric concentration of GHGs, aerosols, land cover and solar radiation alter the energy balance of the climate system and are drivers of climate change. Increase in the atmospheric concentration of GHGs appears to be the predominant cause of recent climate change. The fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) estimated that the global atmospheric concentration of CO2 increased from a pre-industrial value of about 280pp, to 379ppm in 2005 (IPCC, 2007), and the concentration is currently approaching 400ppm. This elevated CO2 concentration is mainly due to the increased fossil fuel burning. For the six illustrative SRES emission scenarios (B1, A1T, B2, A1B, A2, A1FI), the projected concentration of CO2 in the year 2100 ranges from 540 to 970 ppm. The climate change due to anthropogenic forcing has led to a rise in extreme weather events such as floods and droughts, with significant consequences in all sectors. As climate change continues in the future, regional assessments of the impact of future climate changes has to rely on future climate changes projected by regional climate models. This dissertation investigates the impact of CO2 concentration increase on regional climate in West Africa, and how different factors influence future climate trend simulated by a regional climate model.

West Africa is the westernmost region of the African continent that includes much of countries of Benin, Burkina Faso, Cape Verde, Chad, Ivory Coast, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sudan and Togo in approximately 6.1 million square km. Generally, West Africa is from the area close to 10°E axis toward its western border surrounded by the Atlantic Ocean, and from the Guinea Coast to
the northern border along the Sahara desert. It contains the semi-arid, transitional zone named Sahel that is located between the dry Sahara desert and the humid Gulf of Guinean Cost in West Africa.

1.1 Climate in West Africa

The annual precipitation in West Africa decreases from 1500mm near the Guinea Coast around 5°N to about 100mm along the border of Sahara at about 20°N. Except for the coastal region, rainfall over most of West Africa takes place during the boreal summer with a rainfall maximum in August. The summer monsoon, linked to the northward migration of the Intertropical convergence zone (ITCZ) during boreal spring and summer, is the dominant climate characteristic in West Africa (Sultan and Janicot 2003; Sultan et al. 2003; Gu and Adler 2004; Hagos and Cook 2007) and brings most of its rainfall as a main moisture source for this region. The abundant monsoon rainfall strongly supports the agricultural activities in this area (Sultan et al. 2005). Since most of the inhabitants live in rural areas and practice agriculture, understanding the variability and changes of climate are critically important to the region.

During the past few years the Sahel region became a meteorologically spotlight region, at least in part because of major experiments aimed to better understand rainfall variability in the region (Nicholson, 2013). These include the AMMA (African monsoon multidisciplinary analysis) experiment in 2006 (Janicot et al., 2008; Redelsperger et al., 2006), the associated model intercomparison project ALMIP (Boone et al., 2009), the AMMA Catch Experiment that extended AMMA southward into Benin (Lebel et al., 2009), and the JET2000 Experiment that focused on the African Easterly Jet (Thorncroft et al., 2003).

A primary role of the West African monsoon system is transporting moisture into West Africa from the Atlantic. It is unclear whether West African summer monsoon is primarily connected to the ITCZ movement, or changes in higher-level circulation features, or both.
In the classic ITCZ migration scenario, rainfall is associated with a surface feature ITCZ. This zone, moving northward into West Africa in the boreal summer and southward into southern Africa in the austral summer, crosses the equatorial region twice. This movement, also known as the monsoon trough, creates a rainy season across central portions of the continent to the south of the Sahara. Rain production is assumed to result from local thermal instability, promoted by the low-level wind convergence within the ITCZ zone. Sultan and Janicot (2000) performed an observational analysis of the discontinuity in the northward migration of the ITCZ. They showed that the latitudinal shift is associated with the occurrence of a westward-travelling monsoon depression pattern over the Sahel. A number of early papers suggested that the Sahel drought in the late 20th century was linked to an anomalous southward displacement of the ITCZ (Nicholson 2009; Nicholson 2013).

On the other hand, some researchers mainly focused on the scenario that interannual variability of precipitation in West Africa is linked to changes in higher-level circulation feature that includes African Easterly Jet (AEJ) (Cook 1999; Grist and Nicholson, 2001), the Tropical Easterly Jet (TEJ) (Nicholson and Grist, 2003), and low-level westerly jet, the African Westerly Jet (AWJ) (Nicholson and Webster, 2007) over the continent and the West African Westerly Jet (WAWJ) over the Atlantic (Grodsky et al., 2003; Pu and Cook, 2010). The West African Monsoon is supported by moist southerly wind from the Gulf of Guinea. The moisture transport related with the WAWJ, which appears as a near-surface wind maximum over the equatorial Atlantic, is the important moisture source for the Sahel region (Pu and Cook, 2010a). Thus, stronger jet and wetter conditions tend to happen together (Pu and Cook, 2010b). Although the transport does not extend into the Sahel, the speed of the jet shows significant decadal and interannual variability that corresponds to rainfall variability in the West African Sahel (Grodsky et al., 2003). Development of the AWJ, lied in the lower troposphere with a core at roughly 850mb, is limited to wet years in the Sahel. AWJ is derived by inertial instability that develops as a response to pressure gradient (Nicholson and Webster, 2007). Druyan and Koster (1989)
showed that moisture transport by low-level westerlies had a stronger influence on model rainfall over the sub-Sahara as an important moisture source for West Africa. On the contrary, the AEJ, lied in the mid-troposphere at 650 to 700mb, is a moisture sink for the West African monsoon (Cook 1999).

1.2 Historical climate trend

Sahel was the subject of many studies in the 1970s and 1980s because of the long period of drought that had serious negative impact on the region and the controversial issue of desertification. From the 1950s to the 1980s, West Africa experienced a drying trend. Following copious Sahel rainfall in the 1950s, the drought onset in the late 1960s and became the most severe in the mid-1980s. Rainfall has been below the century long mean almost every year since late 1960s. Since then, seasonal rainfall over the Sahel has recovered a bit, however rainfall barely exceeded the long-term mean. Drier condition continued to dominate, at least until the end of the 1990s in Sahel (Nicholson et al. 2000; Le Barbe et al. 2002, Lebel and Ali 2009, Lebel et al., 2009).

The relationship between the regional/global SST and Sahel rainfall variability was studied extensively. Some authors (Folland et al., 1986; Lamb 1978; Semazzi et al., 1988; Ward 1992; Fontaine and Janicot 1996; Hoerling et al., 2006) related interannual and longer-term Sahel rainfall variability to occurrences of Atlantic and/or contrasting pattern of SST anomalies, and also showed that the worldwide SST anomalies modulate summer Sahel rainfall through changes in tropical atmospheric circulation (Lamb 1983; Newell and Kidson 1984).

A dry condition during 1997 was suggested to result from the impact of El Nino (Nicholson et al. 2000). Although the El Nino-Southern Oscillation phenomenon (ENSO) has been shown to be one of the major determinants of the interannual variability of rainfall in the Tropics, their connection is still controversial. Some studies suggest that ENSO seems to be
particularly related to the summer rainfall in sub-Sahara West Africa (Moron and Ward, 1998; Mariotti et al., 2011), and in part of eastern and southern Africa (Janowiak, 1988; van Heerden et al., 1988; Nicholson, 1996). The teleconnections between the West African monsoon and the tropical sea surface temperature have been assessed at the interannual to multi decadal time scales based on IPCC/CMIP3 models (Joly et al., 2007; Joly and Voldoire, 2009). The studies showed that most models produced a reasonable simulation of the ENSO-monsoon teleconnection, even though many models are still unable to capture the main modes of SST-West African monsoon rainfall covariability. Wolter et al. (1989) suggested that summer rainfall decreased during El Nino years over the Sahel due to the enhanced eastward wind, and increased during La Nina years. On the contrary, some studies found that the impact of ENSO was insignificant (Nicholson and Kim, 1997).

1.3 Future climate projections

Future climate changes in West Africa simulated by global climate model (GCM) have been studied based on a range of greenhouse gases (GHG) emission scenarios. While generally a future warming trend is agreed upon, there is no clear consensus concerning the future precipitation and water cycle changes in West Africa (Druyan 2011).

Hulme et al. (2001) found slight drying trend in the second half of the 21st century with little GHG impact using the seven AR3 models and three additional HadCM2 simulations. On the contrary, Maynard et al. (2002) and Kamga et al. (2005) found a consistent wetter climate in the late 21st century with increased monsoon precipitation over West Africa using the Meteo-France climate model ARPEGE-Climat AOGCM, and a wetter Sahel with an increase in moisture convergence based on NCAR Climate System Model, respectively. Hoerling et al. (2006) also found wetter summer over the Sahel in the first half of 21st century under A1B scenario due to SST gradients between North Atlantic and South Atlantic. They suggested that the relationship
between present SST and Sahel rainfall will dominate the projection of precipitation change. However, Biasutti et al. (2008) disagreed with Hoerling et al. (2006), and suggested that the Sahel rainfall and SST is not a simple linear relationship that characterized the past. Also they showed very uncertain Sahel rainfall in future under A1B scenario from Coupled Model Intercomparison Project 3 (CMIP3). Some researchers showed inconclusive projection between early 21st century and late 21st century. For example, Johns el al. (2003) projects an initial tendency towards wetter summer in 2029-2059, subsequently weakened or reversed back to little significant changes by 2069-2099 using HadCM3. Also, Held et al. (2005) showed somewhat consistent projection that some moistening or at least a cessation of the drying trend during the first few decades of 21st century, but rapid drying trend afterward for the A1B and A2 scenarios using the Geophysical Fluid Dynamics Laboratory (GFDL) AOGCM. Haarsma et al. (2005) projected opposite future changes depending on region. They produced a precipitation enhancement over northwest Sahel and some precipitation reductions over the southern edge of the Sahel, and a decreased frequency of prolonged droughts using Community Climate Model Version 3 (CCM3) coupled with an ocean model under the A2 emission scenario. Cook and Vizy (2006) showed that projections differ among GCMs. They chose three top GCMs among 18 based on the quality of their present-day modeling over West Africa in summer, but three of them showed qualitatively different projections, Geophysical Fluid Dynamics Laboratory (GFDL) model simulated severe drying across the Sahel in the later part of the twenty-first century, while Model for Interdisciplinary Research on Climate (MIROC) projected quite wet conditions throughout the twenty-first century. In the Japanese Meteorological Research Institute (MRI) simulation, which is considered the best in reproducing the rainfall dipole pattern in West Africa, warming in the Gulf of Guinea leads to more modest drying in the Sahel due to a doubling of the number of anomalously dry years by the end of the century. These disagreed projections indicate that the most accurate GCMs in simulating present-day climate do not necessarily provide the most reliable future projection over West Africa. Caminade and Terray (2010) also reviewed A1B
scenario predictions for the Sahel using 21 CMIP3 coupled models, and found no clear consensus for African rainfall trends.

General circulation models (GCMs) are used to investigate possible trends in the past and future global climate. However, GCMs have limited capability in representing local conditions because of their coarse spatial resolution, typically in the range of 150–400 km, which is not sufficient to support detailed analysis at the local level. In order to quantify details of projected climate changes, regional climate models (RCMs) are commonly used, forced with GCM output. However, the studies using RCMs did not find clear trend in future projections in West Africa.

Jung and Kunstmann (2007) found a warmer and wetter situation in 2030–2039 than in 1991–2000 using mesoscale meteorological model MM5 driven by ECHAM4. Vigaud et al. (2011) also found a substantial increase of rainfall over the Guinea Gulf and eastern Sahel in the 2030s compared to 1980s under the A2 scenario using the Weather Regional Forecast (WRF) model driven by the ARPEGE-CLIMAT GCM output. On the contrary, a warmer and drier future condition due to reduced total vegetation cover is predicted for West Africa using regional climate model REMO driven with the ECHAM5 output (Paeth et al. 2009). With the same GCM forcing of ECHAM5, Mariotti et al. (2011) projected a drying trend over West Africa at the end of the twenty-first century from RegCM3. Alo and Wang (2010) projected a dipole pattern of future precipitation with a decrease over Guinea Coast and an increase over Sahel during the summer compared to the present period using ICTP Regional Climate Model Version 3 (RegCM3) driven by the NCAR CCSM when the atmosphere-vegetation feedbacks was included. Patricola and Cook (2010) found a very mixed precipitation change signal for West Africa in the second half of the 21st century, characterized by drier June-July, followed by copious rainfall until the end of the summer from Weather Research and Forecasting (WRF) driven by some AOGCMs under A2 scenario. The ENSEMBLES (van der Linden and Mitchell 2009) project simulated the 1990-2050 climate using nine RCMs, and their ensemble mean showed reduced summer precipitation over most of West Africa during 1990-2050. However, the projected
precipitation trends over the Sahel using four ensembles during two periods of 2011-2030 and 2031-2050 are controversial.

While RCMs are able to provide finer future climate changes prediction with the desired fine spatial resolution, the requirement of lateral boundary conditions (LBCs) causes complications and additional uncertainties, hence the choice of LBCs is crucial on downscaling (Xue et al., 2007; Liang et al., 2008; Yu & Wang, 2013). LBCs driving the RCM reflect several aspects of the large scale climate forcing, including atmospheric dynamics and physics. This study examines the impact of different components of the LBCs on the RCM climate simulation, focus specifically on how each influences the RCM-simulated future climate trend in West Africa. Through comparison of future climate projections among the several sensitivity tests, we try to identify the dominant LBC component(s) that has the most significant impact on RCM-produced future climate changes.

The next chapter describes the models used (RegCM4.1.1/CLM3.5), and experimental design. Chapter 3 presents the model performance, and chapter 4 shows result and discussion about RCM simulated future changes in precipitation, evapotranspiration, moisture flux convergence and surface temperature, and LBC factors contribution on the future change. Finally, a summary and conclusion are provided in chapter 5.
Chapter 2

Model description and Experimental design

2.1 Model description

The International Center for Theoretical Physics (ICTP) regional climate model version 4.1.1, a recent version of RegCM4 employed in this study is a hydrostatic, compressible, sigma-p vertical coordinate model on an Arakawa B-grid in which wind and thermo-dynamical variables are horizontally staggered (Giorgi et al. 2012). RegCM4 has been applied for studying climate of various regions (e.g., United states by Mei et al. 2013; East and South Asia by Gu et al., 2012) and has been shown to perform well in its simulation of precipitation over West Africa (Yu and Wang 2013; Adeniyi 2013). The model dynamics are similar to that of the hydrostatic version of the Pennsylvania State University Mesoscale Model version 5 (MM5, Grell et al. 1994). Also, the basic model dynamics have remained the same as that of the previous version of RegCM2 and RegCM3 (Giorgi et al. 1993a,b; Pal et al., 2007). In case of model physics, the radiative transfer scheme adopted from the NCAR Community Climate Model 3 (CCM3; Kiehl et al. 1996); the planetary boundary layer process developed by Holtslag (Holtslag et al. 1990); the large-scale precipitation scheme is parameterized using the subgrid explicit moisture (SUBEX) scheme of Pal et al. (2000), the ocean flux scheme developed by Zeng et al. (1998), were not significantly changed in RegCM4 compared to RegCM3 (Pal et al. 2007; Giorgi et al. 2012). Additionally in RegCM4, an dust emission scheme for sub-grid emissions by different types of soil, and the soil texture distribution has been updated by Laurent et al. (2008), however neither aerosol, nor dust option used in this study.

The choice of convective parameterization and land-surface model has a strong impact on the simulation results, especially to project reasonable precipitation based on experimental
The model provides 5 options of cumulus convection parameter, Kuo-type scheme of Anthes (1977), Grell (1993), Betts-Miller (1986), MIT scheme (Emanuel 1991, Emanuel & Zivkovic Rothman 1999) and Tiedtke (1989), and two options of a land surface model, the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al. 1993) and the Community Land Model version 3.5 (CLM3.5) (Tawfik & Steiner 2011). Since the earliest versions of the RegCM, land surface processes have been represented via the BATS as the land surface scheme. The RegCM3, an earlier version of the model using BATS, produced reasonable seasonal mean, annual cycle, and inter-annual variability of climate in West Africa when driven by ERA-40 reanalysis (Pal et al. 2007), NCEP/NCAR Reanalysis data (Alo and Wang 2010), and ECMWF reanalysis (Sylla et al. 2010). Steiner et al. (2009) incorporated CLM3.5 into RegCM3 as an alternative land surface scheme (Steiner et al. 2009; Tawfik & Steiner 2011). It contains one vegetation layer, ten unevenly spaced vertical soil layers, and up to five snow layers with an additional representation of trace snow. Up to four different land cover types (glacier, lake, wetland, and vegetated) are contained in each grid, and the vegetated portion of the grid cell can be divided into up to 16 different plant functional types. Compared to BATS and previous version of CLM, CLM3.5 is a more advanced package with modification of canopy integration scheme, canopy interception, new frozen soil scheme, soil water availability to plants, a resistance term to reduce excessive soil evaporation, a TOPMODEL-based model for surface and subsurface runoff, a groundwater model for determining water table depth, and the introduction of a factor to simulate nitrogen limitation on plant productivity (Oleson et al. 2008).

Thus, CLM3.5 can grasp more detailed characteristics of land surface, especially for the vegetation cover. The Emanuel convection scheme (Emanuel 1991) and the CLM3.5 land surface scheme are chosen based on model performance in this specific domain. In this study, we use a more recent version of the model (RegCM4.1.1), with a 50 km horizontal resolution over the domain from 20°S to 35°N, 32°W to 53°E and 18 levels in the vertical direction from the surface to 50 hPa.
2.2 Experimental design

RegCM-projected future climate changes result from changes in the CO2 concentration and initial and boundary conditions (BCs). The BCs from Reanalysis or GCM include variables pertaining to sea surface temperature (SST) (ts), atmospheric physics such as air temperature (t) and humidity (qv), and atmospheric dynamics including zonal wind (u), meridional wind (v), geopotential height, and surface air pressure (ps). In this study, boundary conditions from MPI-ECHAM5 (The fifth generation European Community-Hamburg atmospheric Model) with 6-hourly output are used to drive RegCM4.1.1 under SRES A1B scenario run (A1B) to predict future climate changes. The work is based on a pair of present day versus future simulations and a large number of additional experiments designed to quantify the impact of different aspects of BCs. The present and future simulations differ in CO2 level, SST and LBCs. Therefore, the difference between present and future experiments reflects future change resulting from the combined effects of CO2, SST and LBC changes. To separate the impact of each factor, several sensitivity experiments are conducted to examine the future changes driven by each factor. This will allow us to figure out the dominant factor by comparing the future changes and results from the sensitivity experiments. In total, this leads to 9 sets of experiments, fut, prs, fdppts, fdpp, fpd, PrsfutCO2, fdtpp, ffpdqv using the RegCM4 driven by boundary conditions derived from the MPI-ECHAM5 model. Details of these experiments are listed in Table 1.

The future (fut) and present (prs) RCM simulations are driven directly by the future (2089-2099) and present (1989-1999) MPI-ECHAM5 LBCs, SST and CO2 concentration respectively, as was routinely done in previous studies. On the contrary, for the other experiments, we used various combinations of future and present MPI-ECHAM5 LBCs. The fdppts is driven by the combination of future dynamics, present physics and SST with future CO2 concentration, fdpp is driven by the combination of future dynamics and SST, present physics
under future CO2 scenario, fppd is driven by a combination of future physics, SST and CO2 level while present dynamics, PrsfutCO2 is the RCM simulation induced by the present LBCs and SST under future CO2 concentration. The fdtpp is driven by future dynamics and present Physics similar to fdpp except that the future air temperature is used. The fppdt experiment is driven by future SST and physics with present dynamics and air temperature. The fppdqv is driven by the same combination of factors with fppd but with present day atmospheric specific humidity.

Differences among the present, future and sensitivity experiments can show the future changes induced by the impact of a single factor or the combination of several factors, while the difference between the future and present experiments (fut-prs) shows the total future changes caused by the effects of all factors combined. For example, the only difference between fut and fdpp (fut-fdpp) is future or present physics factor because both are induced by the same future dynamics and SST under A1B scenario. So the difference between Fut and fdpp reflects the climate change caused by the effect of physics only. As a result, through the comparison of Fut-fdpp and Fut-prs, we can examine the difference between the effect of physics factor alone and all factors. Hence, we can separate the effects of the physics factor from others. Other different combinations are listed in Table 2 to examine the effect of CO2 alone, SST alone, air temperature alone, dynamics alone, specific humidity alone, and various combinations. Comparing the differences between Fut-Prs with other differences (i.e. Fdpp-prs, Fut-fd(t)pp…..), we can identify the dominant factors among the Dynamics (u,v,ps), Physics (t,qv), SST and CO2 level.

The first year of the simulation is discarded as the model spin up to eliminate the impact of initial conditions, and we present the results based on JJA averages over the last 10 years of the simulations, during 1990-1999 and 2090-2099.
Chapter 3

Model performance

When driven by initial and lateral boundary conditions from MPI-ECHAM5, the coupled RegCM4.1.1/CLM3.5 produces the present and future precipitation patterns that are consistent with the MPI-ECHAM general circulation model projection. Precipitation changes projected by the GCM (Fig.1a) and RCM (Fig. 1b) show similar signal in part of the model domain, with a decrease of up to 3-4 mm/day over the northwestern Sahel and an increase of 1-3 mm/day along the Guinean Coast. Although the RCM projects a slightly stronger drying future changes than the GCM especially over the Sahel region, the pattern of change is very similar. However, over the inland region such as Cameroon and Central Africa, GCM and RCM produce opposite future changes of precipitation. The GCM results suggest increasing precipitation over the areas, while the RCM produces a decrease by up to 4mm/day. These opposite trends between RCM and the driving GCM are the topic of a follow up study.

To evaluate the model performance over the domain of interest, precipitation from the RCM driven by MPI-ECHAM5 during 1990-1999 is compared to the monthly observational data from the University of Delaware. This gauge-based observation data is appropriate to compare with RCM simulation since it has fine spatial resolution of 0.5°, although its coverage is land only. Three maximum precipitation regions are located along the rain belt between the Equator and 15N over the Africa. One is centered over the western cost of Sahel, one is located in the Nigeria and Cameroon coastal region, and one is over the western Ethiopia (Fig. 2a). The RCM driven with MPI-ECHAM5 reproduces the observed JJA precipitation reasonably well (Fig. 2b), with some underestimation (by up to 3mm/day) over the three precipitation maxima locations and overestimation of precipitation by up to 5mm/day especially in West and Central Africa, and Ethiopia highland (Fig.2c).
The focus of the following analysis is on future changes of summer precipitation, surface temperature, moisture convergence, low-level circulation, evapotranspiration, and net radiation. A Student t-test was conducted to determine the statistical significance of the summer future changes at the 5% level.
Chapter 4

Future climate changes

4.1 Changes Due to All Factors Combined

Fig. 3 shows future precipitation and its changes in JJA simulated by RCM driven with MPI-ECHAM5 LBCs, where regions with trend significant at the 5% level are stippled. The RCM driven by MPI-ECHAM5 future LBCs and increased atmospheric CO2 level produced much lower precipitation during 2090-2099 than the corresponding present-day climate simulation (Fig. 3a). Compared to its present day (1990-1999) climatology, RCM with MPI-ECHAM5 projects decreases in Sahel, Central Africa, and northwestern part of Ethiopia, with the only major region of precipitation increase along the Guinean coast (Fig. 3b). The Guinean coast shows about 2mm increase of precipitation, but the projected changes in the region does not pass the 5% significance test. Precipitation over the Sahel, Central Africa and northwestern part of Ethiopia is projected to decrease significantly by up to 4mm/day.

The reduced precipitation over the Sahel and central Africa is consistent with the change of vertical wind velocity. As shown in Fig. 4e, elevated CO2 level, SST and LBCs impacts together cause the alternation of zonally averaged vertical wind velocity from 10W-10E, with a strong increased downward motion over the Sahel (5-15N), which hinders cloud formation thus diminishing precipitation. The decrease of precipitation over the Sahel limits moisture source to evaporate, thus ET decreases over the region. The region where ET decreases (over the western coast of Sahel, northern Angola and Congo River Basin) shows higher increase of 2-m air temperature because of reduced evaporative cooling (Fig. 4a, 4b). The 2m air temperature over the whole Africa increases, with warming larger than 5°C found in the sub-Saharan West Africa, Sahara desert, northwestern part of Ethiopia, northern Angola and Congo River Basin. Fig. 4c shows a considerable decrease of moisture flux convergence over the Sahel by up to 3mm/day.
As both precipitation and ET decrease, the decrease of moisture flux convergence means the amount of decrease of precipitation is primarily caused by changes in large scale moisture transport.

On the contrary, the increase of precipitation along the Guinean coast and Ethiopia highland and strong increase of net radiation cause an increase of ET with abundant moisture source, leading to a relatively weaker magnitude of warming of 2m air temperature by up to 3°C due to evaporative cooling (Fig. 3b, 4a, 4b). The moisture flux convergence over the Guinean coast decreases, indicating that the increment of ET is stronger than increase of precipitation over the area, thus the increase of precipitation is due to abundant water source with an increase of net radiation (Fig. 4b, 4c, 4d).

An increase of net radiation (by up to 25 W/m2) is simulated by the experiment using RCM with MPI-ECHAM5 LBCs in Sahel, Central Africa, and northwestern part of Ethiopia, while a decrease is found over East Africa (Fig. 4d). ET is a large component of the surface energy budget. In wet regions where ET is not limited by water, increase of net radiation leads to increase of ET. The increase of net radiation over the Guinean coast and Central Africa corresponds to the areas of ET increase (Fig. 4b, d). The net radiation increases probably because of precipitation decrease therefore decrease of cloud. Note that less cloud leads to increase of solar radiation and decrease of net long-wave radiation, although this decrease may be offset by the increase of CO2 concentration.

4.2 Contribution of different factors to future change

The changes in Figures 3-4 result from the radiative and physiological effects of elevated CO2 and LBCs concerning physics and dynamics, i.e., all factors combined. In comparison with the future precipitation changes caused by all factors combined (Fig. 3b), the precipitation difference in Fig. 5 shows the contribution from each factor. The experiments are selected to show
the impact of single or combined factors. As presented in Table 2, Fig. 5a-e show the impact of each individual factor (CO2, SST, air temperature, humidity mixing ratio and dynamics respectively), while the six plots in Figures 6a-e show the differences induced by the various combinations of these factors. Fig. 6a presents the impact of t and qv together, 6b the impact of dynamics and air temperature, 6c the impact of dynamics and qv, 6d the merged impact of CO2, dynamics and SST combined, 6e the effects of CO2, SST and humidity mixing ratio, and 6f the combination of SST and air temperature. Comparing the differences in Fig. 5, 6 and the future change of precipitation in Fig. 3b (Fig. 4) will allow us to identify the factors that have dominant impact on future precipitation changes. Figs. 7-14 present the future changes of 2m-air temperature, evapotranspiration (ET), moisture convergence and net radiation driven by single factor (7,9,11,13) or combined factor (8,10,12,14), respectively. They follow the same sequence as in Fig. 5 and 6.

**4.2.1 Future climate changes by individual factor**

**4.2.1.1 CO2 & Dyn**

The difference between the PrsfCO2 and Prs shows the impact of radiative and physiological effects of future increase of CO2 level (Fig. 5a). The impact of CO2 leads to a wetter condition by up to 2mm/day over the West Africa, Guinean coast and Central Africa. However, over most of the domain, these changes are not significant. Most value of future changes of 2-m air temperature (Fig. 7a), ET (Fig. 9a), moisture flux convergence (Fig. 11a), net radiation (Fig. 13a) induced by CO2 alone do not pass the 10% significance test either. The impact of future dynamics causes similar increase over the Guinean Coast and western Nigeria with a decrease in Ethiopia highland, Kenya and Uganda (Fig. 5e). The slight decrease of precipitation over East Africa is consistent with the future changes caused by all factors combined (Fig. 3b). The only area where the impact is significant is East Africa. The future changes of ET
and net radiation over the area are also consistent with the precipitation changes (Fig. 9e, 13e). The slight precipitation decrease shown in East Africa is consistent with a similar ET decrease and some increase of net radiation over the region due to less cloud formation. The changes of 2m-air temperature and moisture flux convergence that reflect impact of the dynamics factor alone are also negligible (Fig. 7e, 11e).

Overall, the impact of CO2 and dynamics LBCs are not significant. Differences in Fig. 6b,c,d driven with combined effects of multiple factors that include CO2 or Dyn also confirm the results from single factor experiments that the impact of CO2 and Dynamics is insignificant. For example, the combined effects of Dyn+t (Fig. 6b), Dyn+qv (Fig. 6c), and CO2+Dyn+SST (Fig. 6d) are similar to the t alone (Fig. 5c), qv alone (Fig. 5d), and SST alone (Fig. 5b), respectively.

### 4.2.1.2 QV

The future changes induced by qv alone are clearly opposite to those caused by all factor combined (Fig. 5d, 3b). The qv factor is the only one that favors wet conditions over inland regions such as the Sahel and Central Africa. As a result of changes in the qv factor alone, precipitation increases by up to 3mm/day over the Sahel, Central Africa and Ethiopia highland while deceases along the Guinea Coast by up to 2mm/day. The wetter condition over the Sahel due to qv changes is due to the copious rainfall produced by the northward migration of rain belt during the summer. The precipitation increase of about 2mm/day over the Sahel and Central Africa driven by qv alone is well connected with increase of ET and moisture flux convergence by up to 0.7mm/day and 3mm/day, respectively (Fig. 11d). The increase of moisture flux convergence is the dominant reason for the increase of precipitation. A slight decrease of 2m-air temperature over the Sahel region results from the cooling impact of increased ET (Fig. 7d, 9d). A relatively strong net radiation decrease of 15-25 W/m2 over the Sahel region is likely due to the cloud impact that blocks the incoming solar radiation (Fig. 13d). While the impact of qv is
significant, its effects are more than offset by some other factors since precipitation changes towards the opposite direction when all factors are included.

### 4.2.1.3 SST & T

The single impact of SST and T show drier future changes over the Sahel and Central Africa with different magnitudes (Fig. 5b, 5c). The pattern of the SST impact, drier over the Sahel and Central Africa and wetter along the Guinean Coast, is similar to precipitation changes caused by all factors. However, the future change driven by SST alone has a less severe dry signal (up to 3mm/day) over the Sahel and a much stronger wet signal (over 5mm/day) over the Guinean Cost, Atlantic Ocean and eastern coast compared to the future change caused by all factors combined (Fig. 5b, 3b). The enormous wet signal over ocean is due to the use of future warmer SST but unchanged atmospheric temperature at the domain boundary, which reduces the atmospheric stability over the Ocean. The wet conditions along the coastal region result from warmer SST leading to more evaporation as a source of moisture transported from the ocean towards the land.

The future change caused by air temperature alone shows a serious drying pattern across the whole domain, with especially strong signal over Atlantic Ocean, West Africa, Central Africa, Ethiopia highland and eastern coast (Fig. 5c). This is caused by the warmer air at the boundaries leading to warmer air within the domain that lies above unchanged SST, increasing atmospheric stability and suppressing precipitation.

All changes derived from experiments that include SST changes or air temperature changes (but not both), as evident in Figures 5b, 5c, 6a, 6b, 6d and 6e, show extremely strong wet or dry signals especially over the Ocean. This is due to changes in atmospheric stability caused by inconsistency between SST and air temperature, as alluded to above. Thus, separating the SST
and air temperature might not be a best option for modeling. The two should be both included or both excluded in any given experiment.

The change of moisture flux convergence is consistent with precipitation change caused by SST alone over Guinean coast, Central Africa and Ethiopia highland (Fig. 11b). Increase of moisture flux convergence along the western coast and Ethiopia highland by up to 5 mm/day dominates the precipitation increase over the areas, and decrease of moisture flux convergence over the Central Africa is responsible for decrease of precipitation in the region too. A similar statement is also true to the effects of air temperature alone -- decrease of moisture flux convergence caused by t alone in sub-Saharan are responsible for the decrease of precipitation (Fig. 11c). The net radiation increases over the Sahel, Guinean coast and Central Africa as a result of SST impact, which contributes to an increase of 2m-air temperature by up to 2°C (Fig.13b, 7b). The increase of net radiation shown in Fig. 13b is probably caused by less clouds associated with the precipitation decrease over the Sahel and Central Africa. In case of the impact of t alone, net radiation and ET show consistent changes that follow the decrease of precipitation over most of the domain, with increase of net radiation across the domain due to increased solar radiation resulting from less clouds and decrease of ET over the semi-arid and arid regions due to the reduced water availability (Fig. 9c, 13c).

4.2.2 future climate changes by combined factors

It appears from Fig. 5 and Fig. 6 that the response of the RCM climate to different factors in LBC is fairly linear. The differences driven by combined factor closely matches the sum of differences driven by each single factor. For example, the impact of SST in Fig. 5b is derived from the difference between fdpp and fdppts, and the impact of t in Fig. 5c is calculated from the difference between fdtpp and fdpp. Even though the experiment that is used to calculate the differences are not the same as those in Fig. 6f (fppdqv-prs), the sum of Figs. 5b and 5c (Fig. 15c)
is largely similar in both the magnitude and the spatial pattern to Fig. 6f. Also, the sum of the difference attributable to \( qv \) and that to \( \text{dyn} \) (Fig. 15a) is consistent with the difference driven by \( \text{Dyn} \) and \( qv \) combined in Fig. 15b.

The linearity may arise from the long-term average that smoothing the variability of precipitation changes. So the variance of 10 year JJA precipitation has been examined to check whether the linearity or additivity is also valid for climate variability. The sum of variance driven by each individual factor, dynamics and \( qv \), shows increase over the West Africa and central Africa while decrease along the Guinean coast (Fig. 16a). The interannual variability driven by single factors, \( qv \) and dynamics is fairly consistent to that of combined factors, \( \text{dyn}+qv \) (Fig. 16b). It indicates that the extreme events driven by dynamics and \( qv \) is going to decrease over the west Africa in the future, also the linearity is valid not only for the average of precipitation change, but also in variance of precipitation change. However, the variances between the sum of variance driven by single factor, SST and \( t \), and variance driven by combined factor, SST+\( t \), shows some difference especially over the Guinean coast and along the 15°N (Fig. 16c, 16d). While the impact of combined SST+\( t \) leads to the increase of precipitation variability only except small region in Guinean coast, the sum of individual impact of SST and \( t \) causes decrease of precipitation variability over the Guinean coast, central Sahel and Ethiopia highland. The inconsistency of variance between impact of sum of individual factor and combined factor is quite huge compared to the similar pattern between mean precipitation change between sum of single impacts and combined impact. It indicates that the linearity of western Sahel and central Africa region is still valid, but the linearity of some region such as Guinean coast is probably due to the smoothing from long-term average.

The change of precipitation response to the change of other variables such as 2m-air temperature, ET, moisture flux convergence and net radiation for combined factor is similar to the relationship of them as shown in above in 4.1 and 4.2.1 (Fig. 6, 8, 10, 12, 14). The increase or decrease of precipitation affects ET changes and influences the magnitude of 2m-air temperature
through evaporative cooling. In all cases, changes of moisture flux convergence are the dominant contribution to changes of precipitation.

Changes of precipitation caused by the combination of SST and t (Fig. 6f) shows the most similar pattern with future changes caused by all factors (Fig. 3b). Based on Fig. 6f, the future changes of precipitation are almost determined by the combined effects of SST+t. As such, among the boundary conditions for regional climate system models, SST and air temperature are the dominant factors for regional climate predictions using regional models driven by global climate models. This is at least the case of the RegCM4.1.1-CLM3.5 model when driven by MPI-ECHAM5.
Chapter 5

Summary and conclusions

This study aims to evaluate the impact of various ICBC components in driving future climate projection using RegCM 4.1.1-CLM3.5 model, and identify the most critical ones. When driven by MPI-ECHAM5 over West Africa during JJA period. The designed present and future climate experiments support the comparison among three types of future climate changes. The first is driven by all factors combined, including CO2, SST and LBCs (air temperature, humidity mixing ratio and dynamics) as was routinely done in previous studies. The second was induced by each individual factor alone. The third is driven by several combined factor in ICBC.

It is found that the RCM simulation driven by all factors combined projects a drier condition in Sahel and central Africa and wetter Guinean coast over West Africa domain. For the Sahel region, decrease of large-scale moisture convergence led to the decrease of precipitation. A suppression of moisture confirmed by increase of downward vertical wind velocity and decrease of ET is well connected to the precipitation reduction. The decrease of ET causes increase of 2m-air temperature in the area. Also increase of net radiation is shown in Sahel due to probably reduced cloud impact that increases the incoming solar radiation. The opposite effect of increase of long wave radiation is offset by increase of CO2 concentration. For the Guinean coast, increase of net radiation led to the increase of ET with abundant moisture source that is consistent with the increase of precipitation.

The future climate changes driven by an individual factor of CO2 or dynamics is weak, and do not pass the 10% significance test. The impact of qv alone shows completely opposite effects to the impact of all factors combined. Its wetter future condition over Sahel is due to the summer monsoon produced by northward migration of rain belt. The increase of moisture flux convergence is the dominant reason for the found increase of precipitation and increase of ET,
which has cooling impact on 2m-air temperature. The qv is an important driving factor for future climate change, however its impact is somewhat offset by other stronger factors (primarily SST and air temperature). The future precipitation changes driven by SST alone show wetter conditions along the Guinean coast and Atlantic Ocean due to copious evaporation from the nearby ocean with warmer SST impact, while modest drier condition is projected in the Sahel. The decrease of precipitation over the Sahel and central Africa is accompanied by the decrease of cloud formation, thus increase of net radiation and 2m-air temperature. Air temperature LBC alone can lead to e serious drying trend over the whole domain because of stable atmosphere induced by warmer air temperature. The decrease of precipitation and water availability suppress the ET amount and cloud formation, thus lead the increase of net radiation with larger incoming solar radiation. The dominance of change of moisture flux convergence on the change of precipitation is shown in both SST and air temperature impact. In case only one of the SST or air temperature changes is included, the model shows extremely wet or dry signals caused by atmospheric instability derived from the inconsistency of the two factors. Therefore, both SST and air temperature should be included or excluded for realistic simulations.

It is also found that the future change driven by several factors combined is almost same as the sum of future changes driven by each individual factor, even though the source of differences are not from the same experiments. The linearity might be an indication that there is little interaction among different aspects of the LBCs. Alternatively, the linearity is probably due to the long-term average that smoothes out the variability of precipitation changes. The future change driven by combined factor also follows same response between precipitation and other variables, such as moisture flux convergence dominates the change of precipitation. The combination of SST+t is found to be the most dominant factor driving regional climate changes in this region and in this model. However, the other ICBC factors have also some impact on the future projection and they are still required for more accurate simulations. Since the combined
factors show complicated and unclear impact on future projection, further research is necessary to improve the understanding of impact of LBCs.
Fig. 1 Future changes of precipitation from (a) MPI-ECHAM5, (b) RegCM driven by MPI-ECHAM5
Fig. 2 JJA Precipitation (in mm/day) over 1990-1999 from (a) University of Delaware dataset, (b) simulated by RCM driven by ECHAM5, and the (c) biases compared with the observation data.
Fig. 3 JJA Precipitation (in mm/day) over (a) 1990-1999, (b) 2090-2099 and (c) future changes simulated by RCM driven with ECHAM5 LBCs. Regions with value passing 0.05 significance test are stippled.
Fig. 4 Future changes of JJA averaged (a) 2m air temperature (in °C), (b) ET (in mm/day), (c) moisture flux convergence (in mm/day), (d) net radiation (W/m²), (e) downward vertical wind velocity from 10W-10E (Pa/s). Only regions with value passing 0.05 significance test are plotted.
Fig. 5 Future precipitation changes driven by single factor between the modified experiments. (a) PrsfCO2-Prs (impact of CO2 only), (b) fdpp-fdppts (impact of SST only), (c) fdtpp-fdpp (impact of t only), (d) fut-fdtpp (impact of q only), (e) fut-fppd (impact of dyn (u,v,ps) only)
Fig. 6 Future precipitation changes driven by combined factor between the modified experiments (a) fut-fdpp (impact of t and q), (b) fut-fppdt (impact of dyn and t), (c) fut-fppdqv (impact of dyn and q), (d) fdpp-prs (impact of CO2, dyn and SST), (e) fppdt-prs (impact of CO2, SST, and q), (f) fppdqv-prs (impact of ts and t)
Fig. 7 Same as Fig. 5 except 2m air temperature
Fig. 8 Same as Fig. 6 except 2m air temperature
Fig. 9 Same as Fig. 5 except ET
Fig. 10 Same as Fig. 6 except ET
Fig. 11 Same as Fig. 5 except Moisture convergence
Fig. 12 Same as Fig. 6 except moisture convergence
Fig. 13 Same as Fig. 5 except Net Radiation
Fig. 14 Same as Fig. 6 except net radiation
Fig. 15 Sum of change of 10 year averaged JJA precipitation driven by (a) individual factor, qv and dyn, (b) combined factor, qv and Dyn, (c) individual factor, SST and t, (d) combined factor, SST and t
Fig. 16 Variance of 10 year JJA precipitation changes driven by (a) sum of individual impact of $q_v$ and dyn, (b) combined impact of Dyn+$q_v$, (c) sum of individual impact of SST and $t$, (d) combined impact of SST+$t$. 
# Table 1: Specifics of experiments

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<th>Present LBC component</th>
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Table 2 Future change of precipitation for each experiment difference

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