Climatic Response of the Central African Dry Season to the RCP 8.5 Climate Change Scenario Using CMIP5 Ensemble

Alexander James Thompson

University of Michigan, B.S. Earth and Environmental Science

Abstract

Central African rainforests exist in relatively dry conditions for tropical forests and are therefore sensitive to changes in the hydrologic system. With few climate stations in the region, understanding of how climate change will impact the forests in this area is of considerable importance but is limited. This study analyzed changes in the West African monsoon to determine its projected effect on the intensity and duration of the Central African dry season using a CMIP5 model ensemble and RCP 8.5 climate change scenario. Simulations demonstrated that the later portion of the future Central African dry season will exhibit enhanced drying, specifically in Western Equatorial Africa. Simultaneously, projections show increased precipitation and low-level southwesterly flow consistent with an enhanced West African monsoon over the Sahel/Sahara region. Moisture advection to Northern Africa will likely reduce moisture available for Central African forests and lead to a more intense future dry season. Central African rainforest biomass and extent reductions will likely result from this increase in dryness. Historically, rainforest extent in this region has been sensitive to West African monsoon changes. The climate changes projected in this study suggest the possibility of future rainforest extent reductions.

Introduction

Anthropogenic climate change is projected to have profound impacts on ecosystems and human society. The impacts from climate change differ based on location, so examining these changes at the regional level is critical (Pachauri et al. 2014). There have been a limited number of studies that focus on the probable impacts of climate change on Central Africa, potentially due to the lack of climate stations in this region (James et al. 2013). Without abundant local climate station observations, it is difficult to understand how the climate has changed historically, and thus difficult to evaluate the accuracy of climate model simulations in the region. These model simulations provide valuable insight for understanding future changes, but their results have not been evaluated comprehensively and compared to modern observations. Consequently, there remains considerable uncertainty in the understanding of future climate change in Central Africa.

Central Africa is home to a large expanse of tropical rainforest that covers much of the western edge of Equatorial Africa (Figure 1). The Congo Basin rainforest, which comprises much of the tropical rainforest present in Central Africa, encompasses approximately 20% of the world's tropical rainforest and 70% of total plant cover on the African continent. The Congo Basin is one of the most biodiverse regions on Earth. It contains hundreds of species of mammals and fish and thousands of species of birds and plants (Bele et al. 2014). The Congo Basin also provides many important ecosystem services for human development. Resources such as bio-energy materials, timber, and agricultural lands are abundant in this region and the rainforest biomass serves as an important reservoir for sequestering carbon (Bele et al. 2014). The tropical rainforest in the basin may also influence climate through positive feedbacks. A warmer, drier climate could reduce forest extent through lack of available moisture and diminish the forest's ability to sequester carbon. This would contribute to further global warming as more carbon would remain in the atmosphere and would produce warmer, drier conditions (Bonan 2008). Due to lack of extensive infrastructure in the Central African region, the people living in this area may be especially vulnerable to future changes since they are reliant on the local resources in this region.

Central African rainforests exist in conditions that are nearing the edge of hydrological capacity for tropical rainforests (James et al. 2013). Palaeoecological studies of pollen indicate that in the past few thousand years drier conditions have led to less carbon-dense forests (Brncic et al. 2007). Observations support the idea that both increasing temperatures and drought conditions will likely impact forest health by decreasing the productivity of the forests and leading to greater instances of tree mortality (Clark 2004). Historically, Western Equatorial African rainforest extent has declined during prolonged intervals of regional-scale drought (Ngomanda et al. 2007). The enhanced vegetation index (EVI) values for these rainforests, which are derived from satellite images that quantify biomass volume, were observed to be lowest during the dry seasons (Viennois et al. 2013). Additionally, the aboveground biomass of Central Africa's tropical rainforest is reduced during dry seasons due to less net primary productivity (NPP). Primary productivity measures the rate at which plants produce chemical energy that can be used for growth, and net primary productivity is the difference between total primary productivity of plants and their respective respiration. These observations suggest that understanding the response of dry season intervals to climate change may be key for understanding the forest response to climate change (Viennois et al. 2013).

Central Africa has two distinct rainy seasons and one main dry season (Figure 2). Rainy seasons take place during the months of March, April, and May (MAM), and during the months of September, October, and November (SON). The main dry season occurs during the months of June, July, and August (JJA) and a minor dry season occurs during the months of December, January, and February (DJF). The Inter-Tropical Convergence Zone (ITCZ) is the source of much of the rainfall in Central Africa, and the timing of both the rainy and dry seasons corresponds with the north-south movement of the ITCZ. Rainy seasons in Central Africa correspond with a southward shift of the ITCZ, while the dry seasons correspond with a northward shift of the ITCZ. The Congo Basin region comprises one of three main regions of tropical convection. This region plays a role in planetary circulation, especially through its transition periods between rainy and dry seasons when rainfall is very high, and this accounts for a significant portion of global precipitation (Washington et al. 2013). Yet, the forests in this region experience significantly less precipitation per month and lower temperatures than the Amazon and Southeast Asian rainforests (Otto et al. 2013).

Besides local convective mechanisms, remote processes, such as the West African monsoon, also exert influence over the magnitude and pattern of rainfall in Central Africa. The West African monsoon forms in mid- to late-boreal spring and is characterized by strong winds that flow from the Atlantic Ocean toward Northern Africa. The monsoon is largely driven by the temperature difference between Northern Africa and the adjacent Atlantic Ocean. During the boreal spring and summer months, relatively warm surface temperatures over Northern Africa create a region of low pressure over the Saharan surface, which results in low-level convergence and advection of large quantities of moisture from the Atlantic and the ITCZ into Northern Africa (Cornforth 2013). Therefore, changes in the strength and timing of the West African monsoon can also influence patterns of rainfall in Central Africa. The Sahel region's rainfall comes from mesoscale convective systems and is sensitive to summer positioning of the ITCZ. In the late 20th century, the Sahel experienced a prolonged and severe drought, and modeling evidence suggests this drought was largely driven by an anomalously southward-displaced ITCZ due to regional changes in sea surface temperatures (Hulme et al. 2001; Giannini et al. 2003).

Since the 1990s, rainfall in the Sahel has increased (Roehrig et al. 2013). CMIP5 models accounting for the RCP 8.5 climate change scenario show an enhancement of the West African monsoon in the future. These models generally agree that the JAS months exhibit wet anomalies for precipitation throughout the Sahel region for the 21st century (Biasutti 2013).

This study explores the influence of the RCP 8.5 climate change scenario on the nature of the dry seasons in Central Africa. The movement of the West African monsoon is analyzed for its effect on intensity and duration of the Central African dry season. In particular, I investigate the possibility that enhancement of the West African monsoon may increase moisture advection to the Sahel/Sahara, reducing available moisture for Central Africa and intensifying dry season aridity. This mechanism has serious implications for the health of Central African rainforests and their resilience to drought.

Methods

Changes in precipitation, temperature, and winds were calculated during the JAS months and changes in monthly precipitation and evaporation were calculated for each month. All simulated plots for this study were performed using NCL software, with the exception of the rainforest extent plot, which was performed with ArcGIS software. The rainforest extent of Central Africa was generated using land cover data from the European Commission Joint Research Centre, and the layers used to reconstruct tropical rainforest extent were closed evergreen lowland forest, submontane forest, montane forest, swamp forest, and mangrove (Mayaux et al. 2003).

The twelve climate models used in this study are listed in Table 1. All twelve come from the Coupled Model Intercomparison Project phase 5 (CMIP5) archive at http://www.pcmdi9.llnl.gov/esgf-web-fe/. The models have resolutions as stated in the table;

however, the latitudes and longitudes were re-gridded for each model to a common 1° by 1° resolution for uniformity. Re-gridding was done using bilinear interpolation. Two time periods were then isolated to perform calculations on: historical (1980-1999), using historical values from each model, and future (2080-2099), using Representative Concentration Pathway 8.5 (RCP 8.5) climate change scenario values from each model. For each calculation, a difference was calculated from the historical time period to the future time period (future – historical). RCP 8.5 is a high emission scenario represented by a radiative forcing of 8.5 W m^{-2} and concentration of greenhouse gases in the atmosphere near 1370 ppm CO_2 equivalent by the year 2100 (van Vuuren et al. 2011). The RCP 8.5 scenario was chosen as a likely scenario to occur under business-as-usual conditions.

Results

Ten of the twelve models exhibit reduced future (2080-2099) precipitation relative to historical (1980-1999) conditions over some or all of Central Africa during the JAS months (Figure 3). Additionally, nine of these models simultaneously show increased precipitation in the Sahel/Sahara. Thus these nine models exhibit reduced precipitation in Central Africa and increased precipitation over the Sahel/Sahara. The model CNRM-CM5 shows the Northern African precipitation enhancement, but does not demonstrate Central African drying. Neither CESM1-CAM5 nor GFDL-ESM2M shows enhanced rainfall in Northern Africa; however, GFDL-ESM2M does show Central African drying, while CESM1-CAM5 does not. These three models are the only three in the ensemble that do not demonstrate reduced precipitation in Central Africa coupled with enhanced rainfall in Northern Africa.

When the precipitation responses from the twelve models in Figure 3 are averaged, several aspects of the multi-model plot come into clearer focus. To gain confidence in the projections from CMIP5 models, consistent changes across the ensemble are identified using multi-model ensemble averaging. First, the multi-model mean plot (Figure 4a) shows that the spatial pattern of the precipitation response in Central Africa is heterogeneous. In the west (5°N-10°S, 10°E-22°E), the overall signal is reduced precipitation by approximately 0.5 mm day^{-1}, but in the east (5°N-10°S, 22°E-34°E), the overall signal is a slight increase in precipitation by approximately 0.25 mm day^{-1}. Furthermore, Figure 4b shows that there is high model agreement that West Equatorial Africa will become drier during the JAS months in the future, meaning there is strong model evidence for drying since approximately 8 to 12 models exhibit this agreement. Comparing Figure 4a,b with Figure 1, which displays the geographic distribution of tropical rainforest, demonstrates that the regions experiencing reduced precipitation and model agreement of drying coincide with much of the tropical rainforest extent. Therefore, the decrease in precipitation and increase in drying will directly affect the Central African rainforest. Additionally, in the Sahel/Sahara region there is a clear zonal band of precipitation increase in Figure 4a,b, which is consistent with the enhancement of the West African monsoon. There is strong agreement showing increased precipitation across the models. This band is contained within 10°N and 15°N and extends as far west as the Atlantic Ocean (5°W) and continues east across the African continent (40°E). Simultaneously, there is a band of reduced precipitation in the Gulf of Guinea, just south of the area with increased precipitation, and nearly every model agrees with the decrease. These results signify a northward shift of the ITCZ and West African monsoon circulation.

The increase in the strength of the West African monsoon and the concurrent reduction in Central African precipitation is particularly pronounced during the second half of the monsoon season (JAS) (Figure 5). Thus, the timing of West African monsoon strengthening and Western

Equatorial African maximum drying is coincident. To highlight changes in the seasonal cycle of precipitation, Figure 5 shows the multi-model mean change in precipitation for each month averaged over Western (10°S – 5°N, 10°E – 22°E) and Central (10°S – 5°N, 22°E – 34°E) Equatorial Africa. In Figure 5a for Western Equatorial Africa, the two rainy seasons (MAM and SON) show increased precipitation and the main dry season (JJA) shows decreased precipitation. Specifically in the later portion of the dry season (JAS), the change in precipitation becomes further reduced, which signifies enhanced dryness during the dry season of Western Equatorial Africa. The drying in the JAS months specifically is this study's motivation for analyzing precipitation, temperature, and wind vector variable changes for the JAS month time interval. In Central Equatorial Africa (Figure 5b), the rainy seasons exhibit increased precipitation, while dry season precipitation neither increases nor decreases. Overall, these results show that the dry season in Western Equatorial Africa becomes drier, while the dry season in Central Equatorial Africa is not likely to change. Additionally, precipitation throughout Central Africa is increasing during the rainy seasons. The positioning of the ITCZ is south of the equator during the rainy seasons of Central Africa, so changes in the West African monsoon are unlikely to affect rainy season rainfall in Central Africa because the ITCZ is the main driver of monsoon precipitation.

Future drying during JAS in West Equatorial Africa is consistent with model projections of a northward shift of the ITCZ and strengthening of the West African monsoon over Africa during the late boreal summer season near the end of the 21st century (Biasutti 2013). Given that the distribution of Northern and Central African precipitation during the boreal summer is driven largely by the West African monsoon, the following figures analyze the projected dynamical changes in the monsoon. Figure 6 shows the mean change in near-surface air temperature between the future and historical time periods. Increased temperatures in the Sahel/Sahara region promote a stronger temperature difference between land and ocean, potentially enhancing the monsoon. Near-surface air temperatures demonstrate that the most intense warming, upwards of 6°C from historical to future, occurs in the Sahara. This intensity of warming is not seen over the ocean or any part of Central Africa, and creates a low-pressure zone that leads to increased wind flow towards the Sahara.

When analyzed for change from historical to future time periods in 850 millibar (mb) wind vectors and wind convergence, eleven of twelve models demonstrate anomalous southwesterly winds developing in the JAS months, which flow from the Gulf of Guinea into the Sahel/Sahara region (Figure 7). Flow convergence over the Sahel/Sahara region is consistent with the simulation of enhanced precipitation. In many of the models, there is a clear dipole response in convergence over Northern Africa, where anomalous divergence is occurring over the Guinea Coast and Southern Sahel and anomalous convergence is appearing over the Northern Sahel and Southern Sahara. These anomalies demonstrate that the main convergence zone associated with the monsoon has shifted northwards. Additionally, the projected changes in winds and convergence are consistent with future enhanced precipitation in the Sahel (Figure 4a). Overall, Figures 6 and 7 demonstrate that future increased warming of the Sahara leads to a low-pressure zone at the surface, and a subsequent enhancement of the West African monsoon circulation. The increase in moisture advection towards Northern Africa reduces moisture availability in Central Africa and is at least partially responsible for the projected decreases in JAS precipitation throughout Western Equatorial Africa (Figure 4a,b).

Discussion

Implications for Central African rainforests

Central African rainforests are sensitive to global and regional climate change as they are closely coupled with variability in climate due to changes in the hydrologic system (Lézine et al. 2013; Lewis et al. 2009). Central African rainforests exist near the hydrological limit for rainforests, and water is a limiting factor in their growth (James et al. 2013). Consequently, small changes in rainfall or intensity of the dry season can lead to larger changes in rainforest extent (Malhi et al. 2013). Central African rainforests are much drier than the rainforests of Amazonia, as they receive approximately 1000 mm less precipitation per year than the Amazon does (Otto et al. 2013). With such little precipitation, African rainforests are already close to the rainfall threshold that favors savanna over forest (Malhi et al. 2013). According to water deficit calculations by James et al. (2013), Central African rainforests are demonstrated to be near the transition to savanna. Water deficit values reflect the forest impact of having net evaporative losses for consecutive months. The cutoff point for a transition from rainforest to savanna occurs at approximately -400 mm month^{-1}, and Central African rainforests currently exist at approximately -300 mm month^{-1} (James et al. 2013).

Since Central African rainforests exist in a much drier local climate than other rainforests throughout the world, their viability is tied more closely to the length and intensity of the dry season compared to other forests (Malhi et al. 2013). Over the last two to three millennia, Central African forests have been climatically drier than they are in the present, and this produced forests that were more open, more fire-prone, and less carbon dense (James et al. 2013). During this extended dry period, significant changes in vegetation occurred as a result of the drier climate (Lewis et al. 2009). Forest biodiversity declined because only the rapidly dispersing and colonizing species were able to spread during the last millennium. This was due to forest retreat during more intense dry seasons (Lézine et al. 2013; Malhi et al. 2013). This vegetation change was marked by an increase in pioneer tree taxa, which greatly impacted the overall forest composition. If future anthropogenic forest clearance and burning during prolonged dry seasons occurs, plant species composition will likely suffer more severely in the future than it did during the last two to three millennia (Brncic et al. 2007).

Historically, Western Equatorial African tropical rainforest extent decreased during times of drought (Ngomanda et al. 2007). Decreased rainfall in the dry seasons likely made the Central African rainforests less productive and thus increased tree mortality, which led to a reduction in overall area of the rainforest (Clark 2004). In 2005, a severe drought greatly reduced the regional NPP in Central Africa, and this subsequently led to a decrease in global NPP (Zhao & Running 2010). Aboveground biomass present in rainforests is lower when NPP is reduced during drier dry seasons. This mechanism occurs because NPP, and thus growth, is reduced due to a limit on water availability (Lewis et al. 2013). Additionally, it is demonstrated that EVI values are lowest during the main dry season in Central Africa, in contrast to Amazonia (Viennois et al. 2013). Therefore, a drier dry season likely will lead to a reduction in rainforest biomass. There are also positive feedbacks that further exacerbate biomass reductions. Due to higher temperatures that accompany drier dry seasons, evapotranspiration will increase in the rainforests and reduce moisture availability. This will lead to further drying (James et al. 2013).

As they have been linked to reductions in rainforest biomass, periods of drought in the past have also been linked to movement of the West African monsoon. During the African Humid Period (AHP, 14.8 – 5.5 kyr), initial movement of the monsoon south led to a drier Sahara. Later in the AHP and in the Early Holocene, the rainbelt associated with the West

African monsoon shifted north, as this study suggests will occur in the future, and more moisture was delivered to the northern limit of the monsoon in the summer. This coincided with reduced rainfall in Central Africa due to a longer dry season (Shanahan et al. 2015). Thus the monsoon enhancement in the Holocene, which shifted rainfall patterns northward by a similar mechanism as presented in this study, led to longer, more intense dry seasons. Since climate change-induced rainforest retreat happened in Central Africa during the drier periods in the Holocene, it is certainly feasible that this could happen again with drier dry seasons (Malhi et al. 2013). Alternatively, between 1968 and 2007, aboveground carbon storage in trees tested by Lewis et al. (2009) increased by 0.63 Mg C ha^{-1} yr^{-1}. The West African monsoon was more subdued during this time period, as widespread droughts occurred in the Sahel/Sahara, and this study's results suggest that an opposite effect will occur in the future as the monsoon is enhanced and Central Africa again experiences drier dry seasons (Roehrig et al. 2013).

Further evidence also supports a reduction in Central African rainforest extent during an intensification of the dry seasons. Guan et al. (2015) analyzed precipitation changes and their effects on the vegetation of global rainforests in order to identify which forests may be vulnerable or resistant to future changes in the hydrologic system. In the study, Guan et al. (2015) found that above an annual rainfall threshold of 2000 mm year^{-1}, a rainforest can withstand the dry season without loss in biomass or reduction in extent, but below the threshold it cannot. Therefore, if a rainforest does not receive more than 2000 mm year^{-1}, it is more vulnerable to an intensification of the dry season, and its extent will be reduced as a result of biomass loss during the dry season. This quantitative threshold directly applies to Central African rainforests as 90% receive less than 2000 mm year^{-1} of rainfall (Guan et al. 2015). Thus, Central African rainforests are vulnerable to the intensifying dry season in the future, as this study suggests, and a reduction in rainforest extent and total biomass appears likely.

A direct relationship between water availability and vegetation has been established by literature on the topic of Central African climate change and its effect on the region's rainforests. Water availability and regional precipitation variability directly affect the response of rainforest vegetation in tropical forests globally (Guan et al. 2015; Ngomanda et al. 2007). Since Central African rainforests are demonstrated to be highly sensitive to drought, they exert a low buffering capacity in their ability to reduce the effects of drought from a more intense dry season in the future (Guan et al. 2015). Additionally, human factors such as deforestation, changes in the way land is used, and forest fires provide an added stress on the resilience of Central African rainforests (Guan et al. 2015). Deforestation in Central Africa has been historically less than West Africa and Madagascar, but increases in human population's proximity to the forests and agricultural activities throughout the forest's extent will increase deforestation rates and further exacerbate the reductions in rainforest biomass and extent (Mayaux et al. 2013). As the human population in Africa increases, the vulnerability of Central African rainforests to climate change will likely increase due to human activities such as deforestation.

Limitations

Potential limitations for the experimental method of this study exist. Using twelve models presents a limited focus on the overall climate system of Central Africa. Due to computational and theoretical limitations, each model represents certain earth system processes with a set of parameterizations. Parameterizations are used to represent complex processes within the models that are not well constrained. All models assume simplifications of understood physics and climate dynamics, and therefore bias can be associated with these simplifications. Involving more models in the ensemble would likely reduce the overall bias of the study's simulations. Of the twelve models used, many differ in their underlying physics and internal components, and this has potentially led to differing responses under homogeneous starting conditions. Based on the level of experimentation performed in this study, it is not clear as to why particular models respond similarly and others respond differently under the same conditions. Further exploration of the potential reasons for differences in model responses based on their internal physics should be performed in future studies, building off of the twelve models used in this study and adding additional CMIP5 models.

The limited number of climate stations in Central Africa also presents potential limitations for analyses of simulated results. In 2013, only three climate stations were operating and reporting to the Global Telecommunication System over the region of 5°S – 5°N, 12.5°E – 30°E, which has declined from nearly 60 in the 1980's (Washington et al. 2013). Without sufficient historical data on the climate of Central Africa it is difficult to assess the strength of models in simulating the region's climate, so limitations on the accuracy of future projections using climate models may exist.

Conclusion

Central Africa's response to future climate change has been sparsely examined, yet is important in understanding the effects global climate change will have on regional climate systems around the world. The climate of Central Africa is poorly understood due to few climate stations reporting historical data and few studies investigating how the region might respond to future changes (Washington et al. 2013; James et al. 2013). It is increasingly important to study Central Africa's tropical rainforest response to climate change because it is home to one of the most biodiverse regions on Earth (Bele et al. 2014). Additionally, Central Africa is one of three main convective regions in the terrestrial tropics, and thus its seasonal cycles contribute significantly to planetary circulation (Washington et al. 2013). The region is home to more than 60 million people who make their living from the ecosystem services provided by the rainforest (Mayaux et al. 2013). Beyond the region itself, resources such as timber, agricultural products, and bio-energy are important for human development worldwide (Bele et al. 2014). Also at the global level, positive forest feedbacks have the potential for amplifying climate change by carbon dioxide release, so therefore the health of the rainforest is critical to mitigating further warming (Bonan 2008).

This study has demonstrated through analysis of climate change scenario RCP 8.5 that Central Africa is likely, under business-as-usual emissions conditions, to experience drier dry seasons in the future and an increase in dry season intensity specifically in the JAS months. An important mechanism behind this drying is the intensification of the West African monsoon. Under future conditions, intense warming is likely to occur in Northern Africa, which will create a low-pressure zone over the land. The pressure difference between Northern Africa and the adjacent Atlantic Ocean will lead to stronger flow towards land and advection of moisture to the Sahel and Sahara regions. A northward migration of the ITCZ will aid in enhancing the West African monsoon at its northern limit, and thus will draw moisture away from Central Africa. The result is a drier dry season, especially in the Western Equatorial region, with its drying intensity increasing in the JAS months.

The intensification and elongation of the dry season has serious implications for the health of Central African rainforests. These rainforests are already nearing their hydrological limit, and a change in dry season intensity will likely lead to less carbon dense forests. During periods of historical drought, Central Africa's rainforests became less biodiverse and their geographic extent was reduced. The forests experienced these reductions in biomass most severely during the dry seasons. Finally, quantitative cutoff points for annual rainfall exhibits that African rainforests are vulnerable to a drier dry season, as they exist in much drier conditions than other rainforests around the world. With the likelihood of increasing human interactions, such as deforestation, with the rainforests of Central Africa, the forests' vulnerability to droughts will likely increase in the future.

Acknowledgements

The author acknowledges the WCRP from http://www.pcmdi9.llnl.gov/esgf-web-fe/ for providing the CMIP5 data and the European Commission Joint Research Centre for providing land cover data used in this study. The data for this study were analyzed using computing resources in the Department of Earth and Environmental Sciences at the University of Michigan. Acknowledgements and thanks also go to Turner Postdoctoral Fellow Christopher Skinner at the University of Michigan for his remarkable guidance and assistance in the creation of this study and its results, and to Professor Christopher Poulsen for his exceptional supervision and assistance in creation of this study. Additional thanks go to the Poulsen Climate Change Lab at the University of Michigan for supporting this project and for helping the author whenever needed.

References

Bele, M.Y., Sonwa, D.J., & Tiani, A. (2014). Adapting the Congo Basin forests management to climate change: Linkages among biodiversity, forest loss, and human well-being. *Forest Policy and Economics*, 50, 1-10. doi:10.1016/j.forpol.2014.05.010

Biasutti, M. (2013). Forced Sahel rainfall trends in the CMIP5 archive. *Journal of Geophysical Research: Atmospheres*, 118, 1613-1623. doi:10.1002/jgrd.50206

Bonan, G.B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, 320, 1444-1449. doi:10.1126/science.1155121

Brncic, T.M., Willis, K.J, Harris, D.J., & Washington, R. (2007). Culture or climate? The relative influences of past processes on the composition of the lowland Congo rainforest. *Philosophical Transactions of the Royal Society B*. 362, 229-242. doi:10.1098/rstb.2006.1982

Clark, D.A. (2004). Sources or sinks? The responses of tropical forests to current and future climate and atmospheric composition. *Philosophical Transactions of the Royal Society B*, 359, 477-491. doi:10.1098/rstb.2003.1426

Cornforth, R.J. (2013). West African monsoon 2012. *Royal Meteorological Society: Weather*, 68, 256-263. doi:10.1002/wea.2161

Giannini, A., Saravanan, R., & Chang, P. (2003). Oceanic forcing of Sahel rainfall on interannual to interdecadal time scales. *Science*, 302, 1027-1030. doi:10.1126/science.1089357

Guan, K. et al. (2015). Photosynthetic seasonality of global tropical forests constrained by hydroclimate. *Nature Geoscience*, 8, 1-6. doi:10.1038/ngeo2382

Hulme, M., Doherty, R., Ngara, T., New, M., & Lister, D. (2001). African climate change: 1900-

2100. *Climate Research*, 17, 145-168. doi:10.3354/cr017145

James, R., Washington, R., & Rowell, D.P. (2013). Implications of global warming for the climate of African rainforests. *Philosophical Transactions of the Royal Society B*. 368, 1-8. doi:10.1098/rstb.2012.0298

Janicot, S. et al. (2011). Intraseasonal variability of the West African monsoon. *Atmospheric Science Letters*, 12, 58-66. doi:10.1002/asl.280

Lewis, S.L. et al. (2009). Increasing carbon storage in intact African tropical forests. *Nature*, 457, 1003-1007. doi:10.1038/nature07771

Lewis, S.L. et al. (2013). Aboveground biomass and structure of 260 African tropical forests. *Philosophical Transactions of the Royal Society B*. doi:10.1098/rstb.2012.0295

Lézine, A., Assi-Kaudjhis, C., Roche, E., Vincens, A., & Achoundong, G. (2013). Towards an understanding of West African montane forest response to climate change. *Journal of Biogeography*, 40, 183-196. doi:10.1111/j.1365-2699.2012.02770.x

Malhi, Y., Adu-Bredu, A., Asare, R.A., Lewis, S.L, & Mayaux, P. (2013). African rainforests: Past, present, and future. *Philosophical Transactions of the Royal Society B*, 368, 1-10. doi:10.1098/rstb.2012.0312

Mayaux, P. et al. (2003). The land cover map for Africa in the year 2000. *European Commission Joint Research Centre*. http://www-gem.jrc.it/glc2000.

Mayaux, P. et al. (2013). State and evolution of the African rainforests between 1990 and 2010. *Philosophical Transactions of the Royal Society B*, 368, 1-10. doi:10.1098/rstb.2012.0300

Ngomanda, A. et al. (2007). Lowland rainforest response to hydrological changes during the last 1500 years in Gabon, Western Equatorial Africa. *Quaternary Research*, 67, 411-425. doi:10.1016/j.yqres.2007.01.006

Otto, F.E.L., Jones, R.G., Halladay, K., & Allen, M.R. (2013). Attribution of changes in precipitation patterns in African rainforests. *Philosophical Transactions of the Royal Society B*, 368, 1-10. doi:10.1098/rstb.2012.0299

Pachauri, R.K. et al. (2014). Climate Change 2014: Synthesis report. *Intergovernmental Panel on Climate Change*, 1-151.

Roehrig, R., Bouniol, D., Guichard, F., Hourdin, F., & Redelsperger, J. (2013). The present and future of the West African Monsoon: A process-oriented assessment of CMIP5 simulations along the AMMA transect. *American Meteorological Society,* 26, 6471-6505. doi:10.1175/JCLI-D-12-00505.1

Shanahan, T.M. et al. (2015). The time-transgressive termination of the African Humid Period. *Nature Geoscience*, 8, 140-144. doi:10.1038/ngeo2329

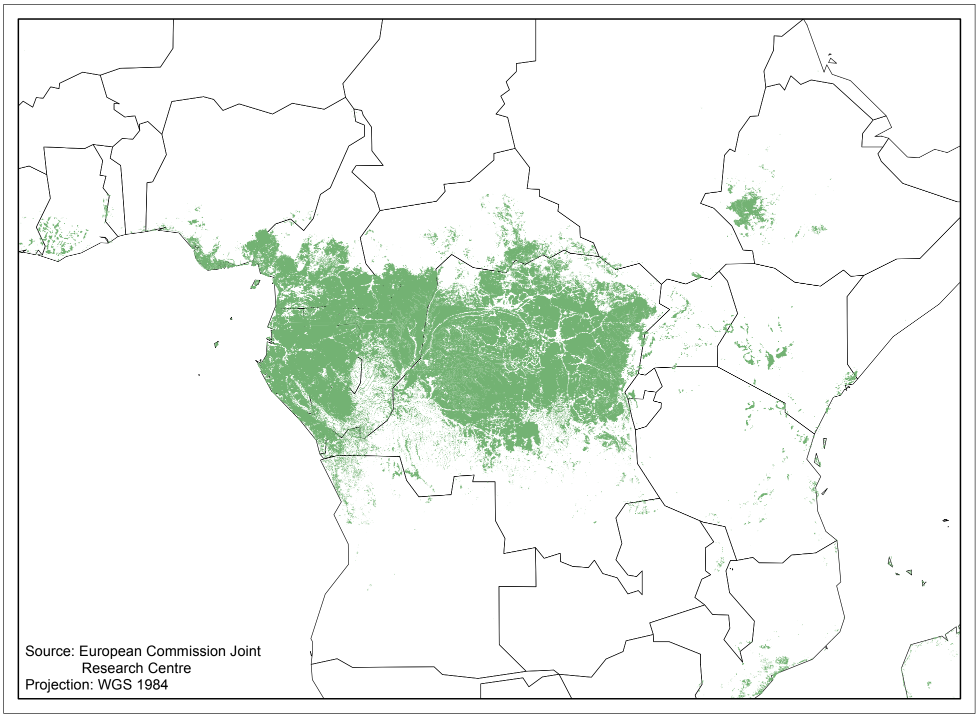
van Vuuren, D.P. et al. (2011). The representative concentration pathways: An overview. *Climatic Change*, 109, 5-31. doi:10.1007/s10584-011-0148-z

Viennois, G., Barbier, N., Fabre, I., & Couteron, P. (2013). Multiresolution quantification of deciduousness in West-Central Africa. *Biogeosciences*, 10, 6957-6967. doi:10.5194/bg-10-6957-2013

Washington, R., James, R., Pearce, H., Pokam, W.M., & Moufouma-Okia, W. (2013). Congo Basin rainfall climatology: Can we believe the climate models? *Philosophical Transactions of the Royal Society B*, 368, 1-7. doi:10.1098/rstb.2012.0296

Zhao, M. & Running, S.W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, 329, 940-943. doi:10.1126/science.1192666

Appendix



Source: European Commission Joint Research Centre
Projection: WGS 1984

Figure 1: Tropical Rainforest Extent in Central Africa
Geographic distribution of tropical rainforest throughout Africa. Land cover data used was downloaded from the European Commission Joint Research Centre. Layers used for forest analysis were closed evergreen lowland forest, submontane forest, montane forest, swamp forest, and mangrove (Mayaux et al. 2003).

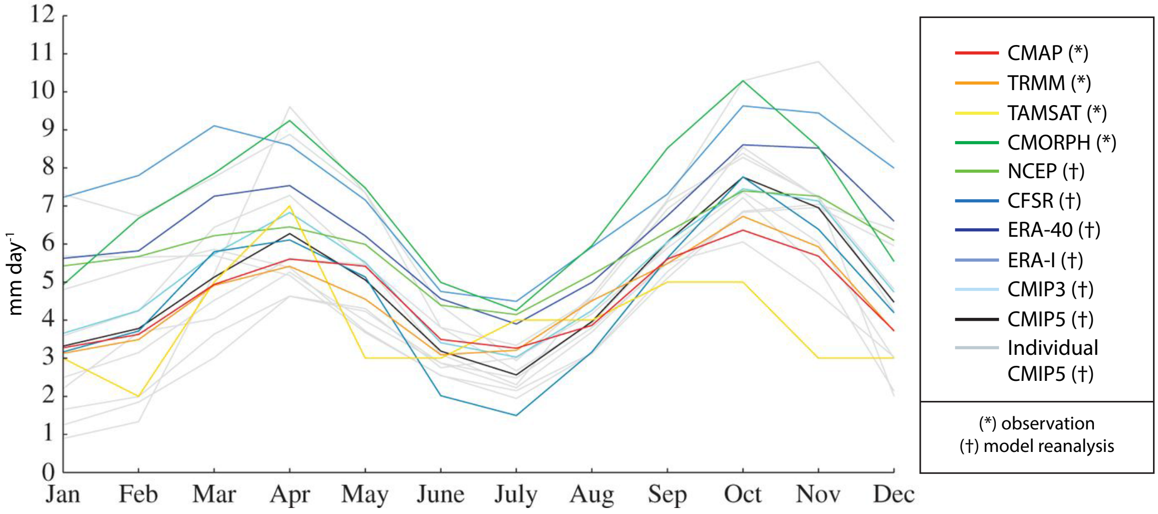


Figure 2: Reconstructed Historical Annual Precipitation Cycle in Central Africa
Long-term mean annual precipitation cycle in mm day^{-1} for Central Africa (5°S – 5°N, 12.5°E – 30°E) over time period 1961-1990 for NCEP, ERA-40, CMIP3, CMIP5; 1979-1990 for ERA-I, CSFR, CMAP; 1998-2011 for TRMM, TAMSAT; 2002-2011 for CMORPH. This figure was modified from Figure 2 of Washington et al. 2013.

Model	ACCESS1-0	ACCESS1-3	BNU-ESM	CanESM2
Resolution (Lat/Lon)	1.24°, 1.875°	1.24°, 1.875°	2.8125°, 2.8125°	2.8125°, 2.8125°

Model	CESM1-CAM5	CNRM-CM5	GFDL-ESM2M	GISS-E2-H
Resolution (Lat/Lon)	0.9375°, 1.25°	1.40625°, 1.40625°	2°, 2.5°	2°, 2.5°

Model	MIROC-ESM	GFDL-CM3	MIROC5	NorESM1-M
Resolution (Lat/Lon)	2.8125°, 2.8125°	2°, 2.5°	1.40625°, 1.40625°	1.875°, 2.5°

Table 1: CMIP5 Models Used With Their Respective Resolutions
All models come from CMIP5 archive. Model results were re-gridded to 1° by 1° resolution for uniformity in comparison throughout the study.

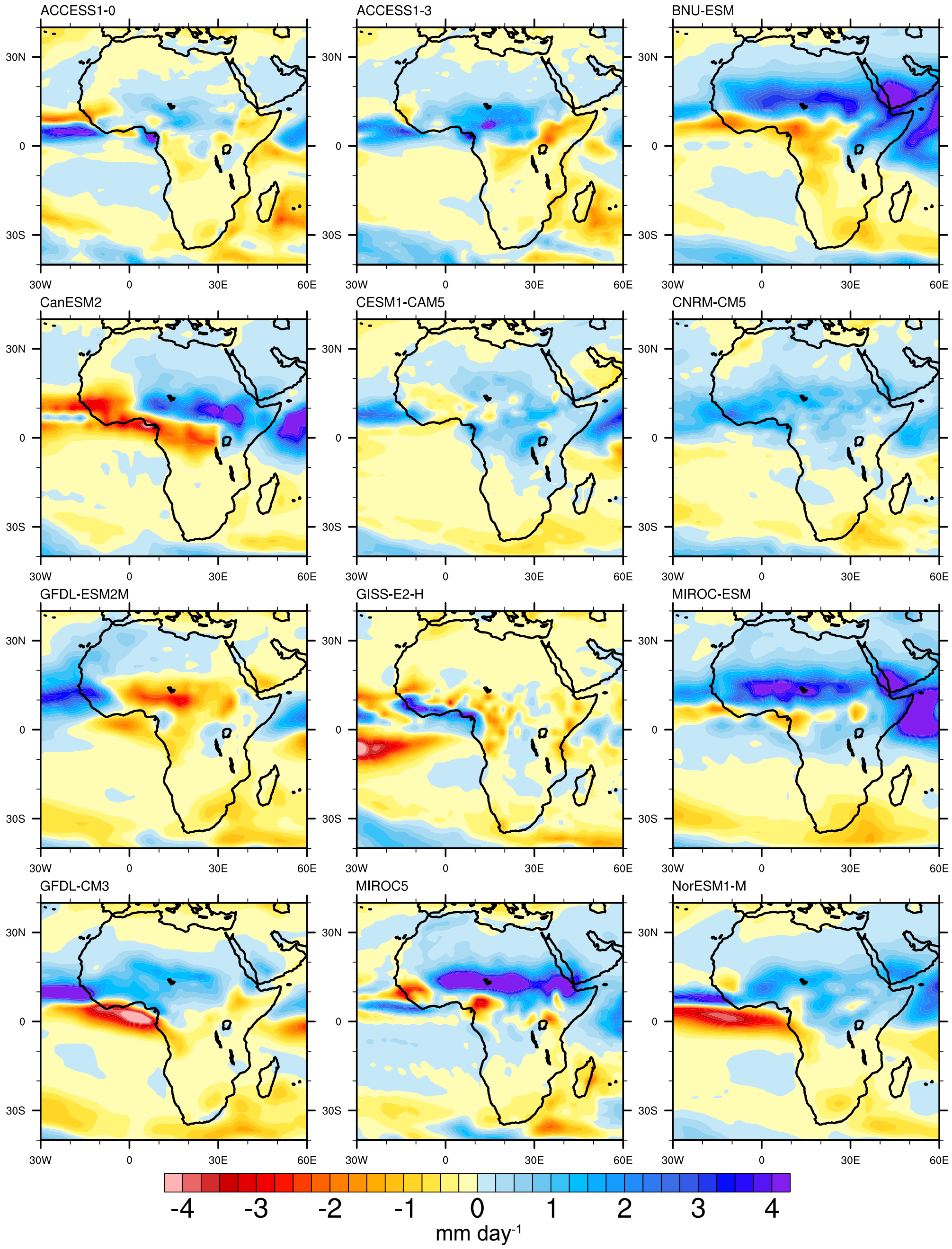
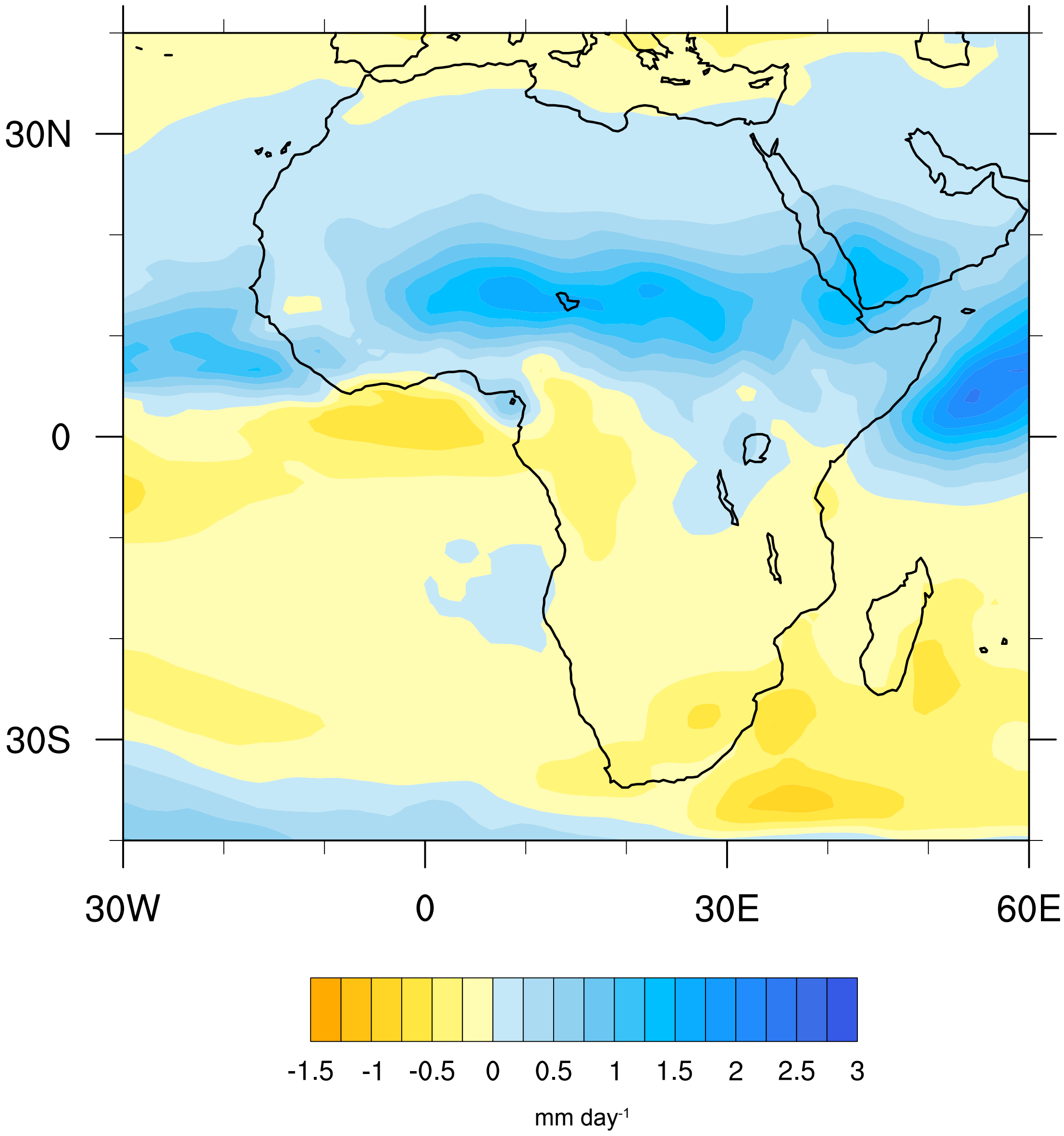


Figure 3: JAS Precipitation Change for Individual CMIP5 Models
Precipitation change in mm day^{-1} from historical (1980-1999) to future (2080-2099) time periods using the RCP 8.5 climate change scenario for the JAS months (July-September) over the African continent (40°S – 40°N, 30°W – 60°E). Positive values represent increased precipitation in future relative to historical (future – historical).

4a)



4b)

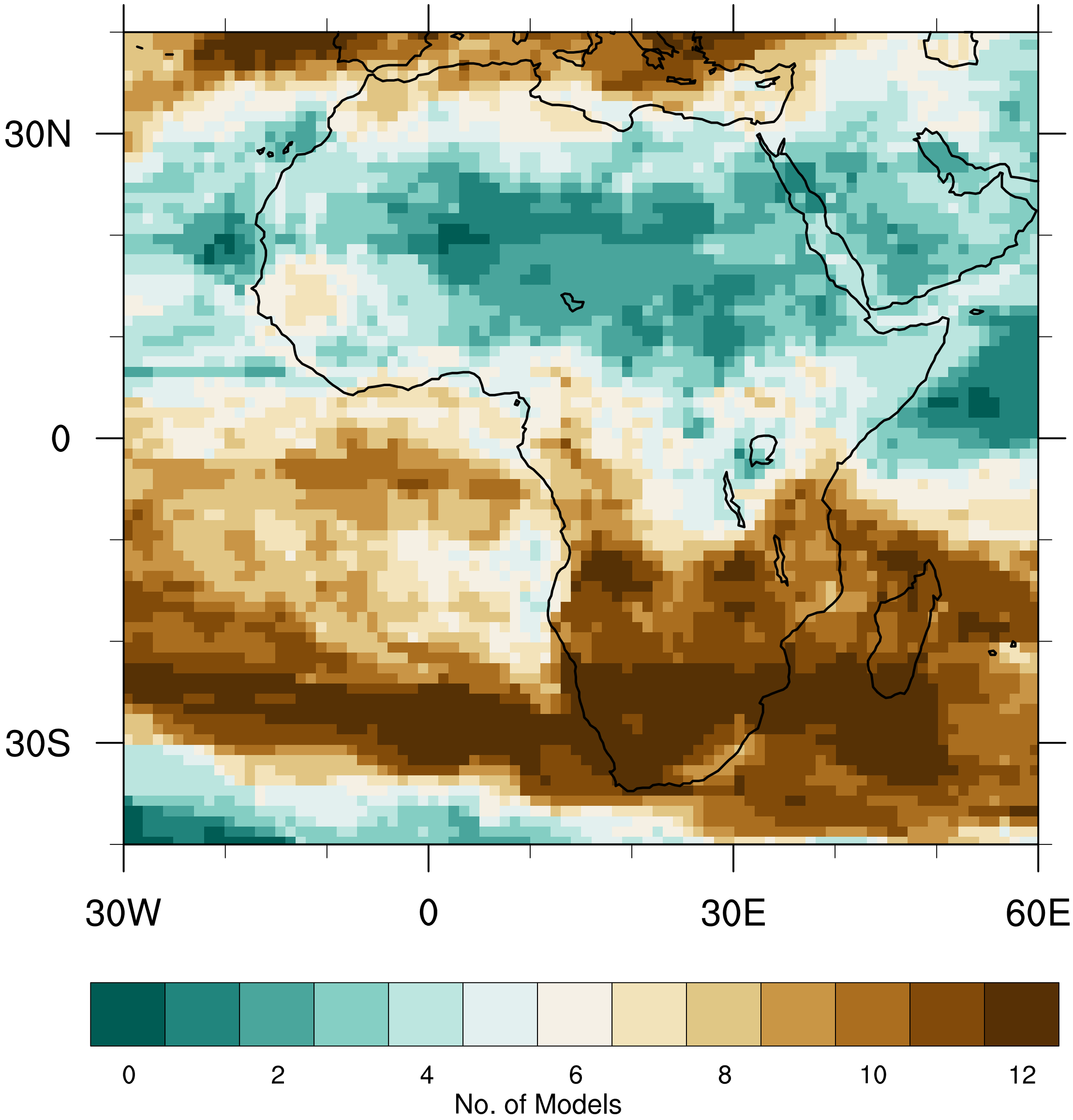
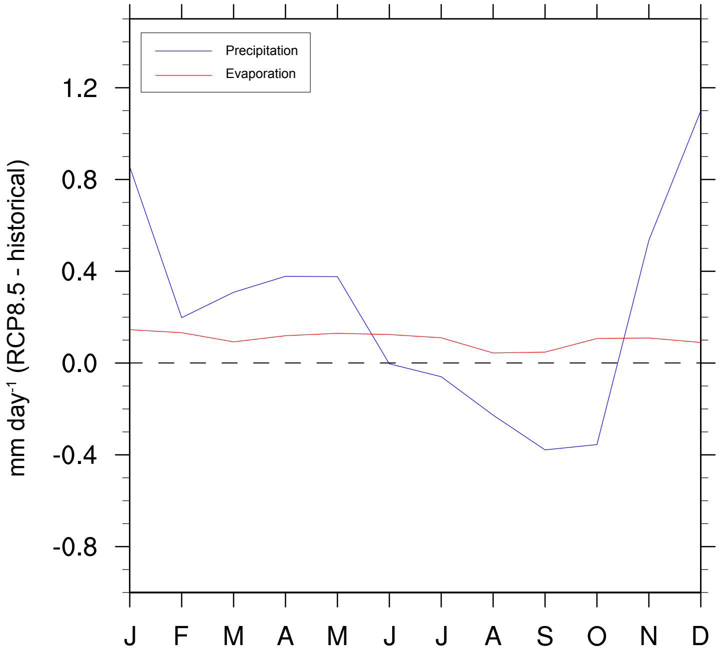


Figure 4: JAS Multi-model Precipitation Change
Multi-model precipitation change from historical period (1980-1999) to future (2080-2099) with RCP 8.5 scenario for the JAS months over the African continent (40°S – 40°N, 30°W – 60°E). 4a) Multi-model ensemble average precipitation change in mm day^{-1}. Positive values represent increased precipitation in future relative to historical (future – historical). Multi-model ensemble is average of results listed in Figure 3. 4b) Multi-model agreement showing number of models indicating drying in the future relative to historical per grid point.

5a)



5b)

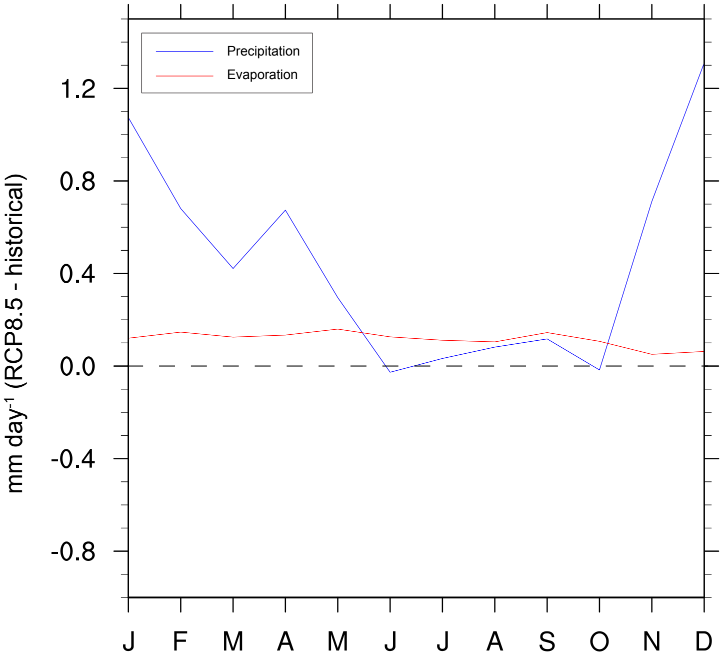
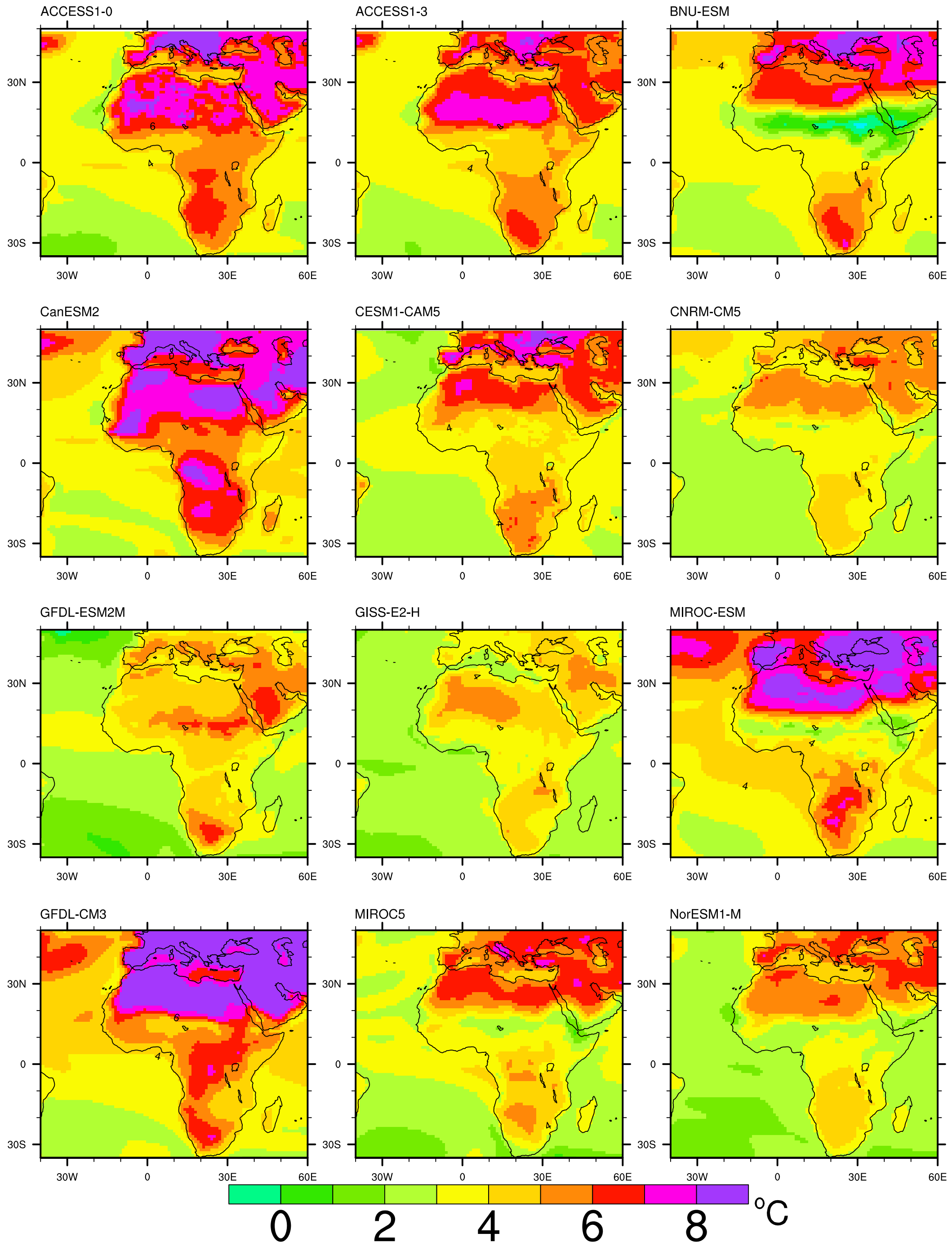


Figure 5: Difference in Annual Precipitation and Evaporation Cycle
Difference in annual precipitation cycle by month in mm day^{-1} from historical (1980-1999) to future (2080-2099) using the RCP 8.5 climate change scenario for 7a) Western Equatorial Africa (10°S – 5°N, 10°E – 22°E) and 7b) Central Equatorial Africa (10°S – 5°N, 22°E – 34°E). Positive values represent increased precipitation in future relative to historical (future – historical).

6a)


ACCESS1-0
ACCESS1-3
BNU-ESM
CanESM2
CESM1-CAM5
CNRM-CM5
GFDL-ESM2M
GISS-E2-H
MIROC-ESM
GFDL-CM3
MIROC5
NorESM1-M
30N
0
30S
30W
0
30E
60E
0
2
4
6
8
°C

6b)

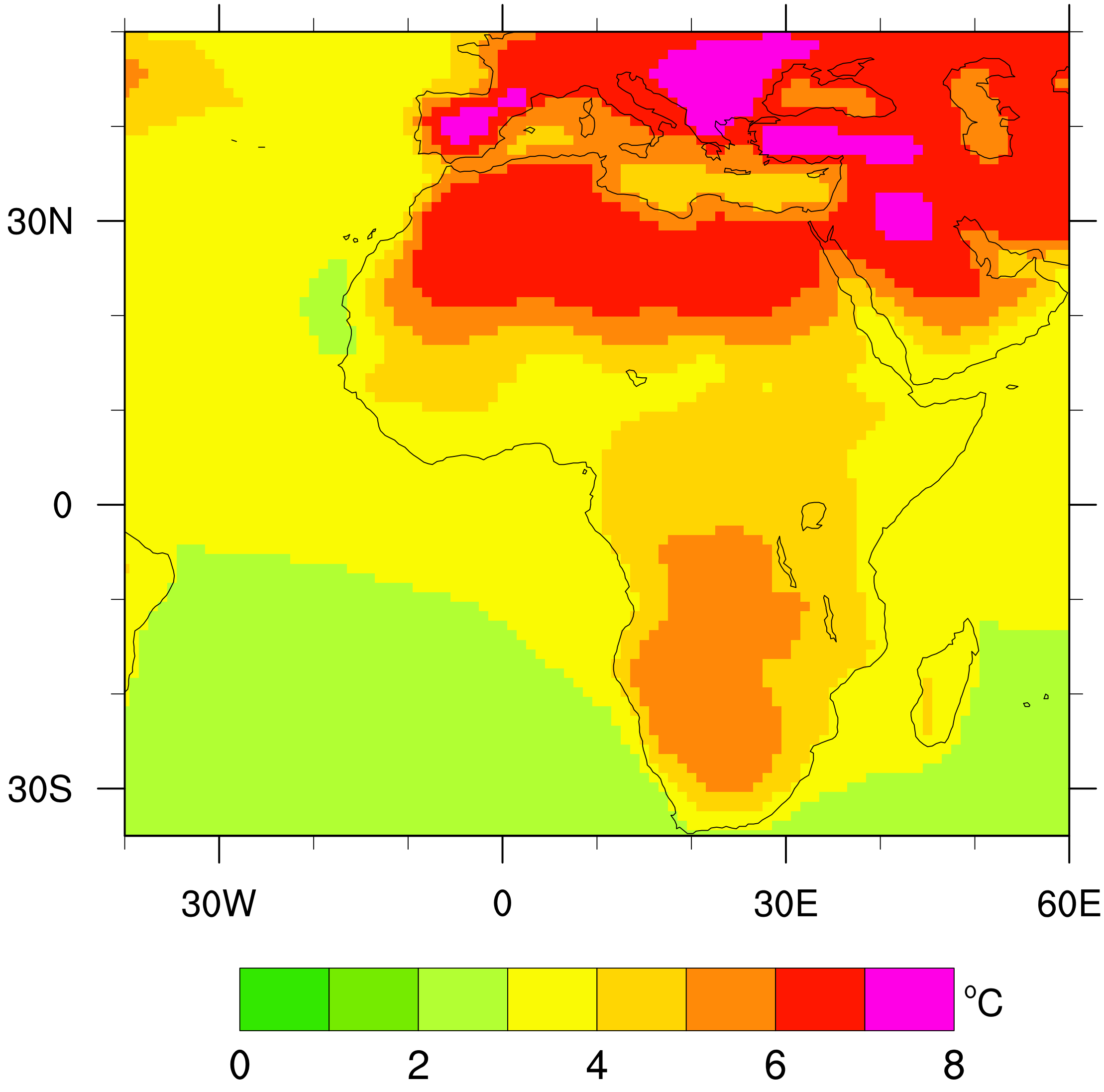


Figure 6: JAS Multi-model Ensemble Average Near-surface Air Temperature Change
Near-surface air temperature change in °C from historical (1980-1999) to future (2080-2099) time periods using the RCP 8.5 climate change scenario for the JAS months over the African continent and Atlantic Ocean (35°S – 50°N, 40°W – 60°E). Positive values represent increased temperature in future relative to historical (future – historical). 4a) Near-surface air temperature change for twelve CMIP5 models used in ensemble. 4b) Multi-model ensemble average near-surface air temperature change.

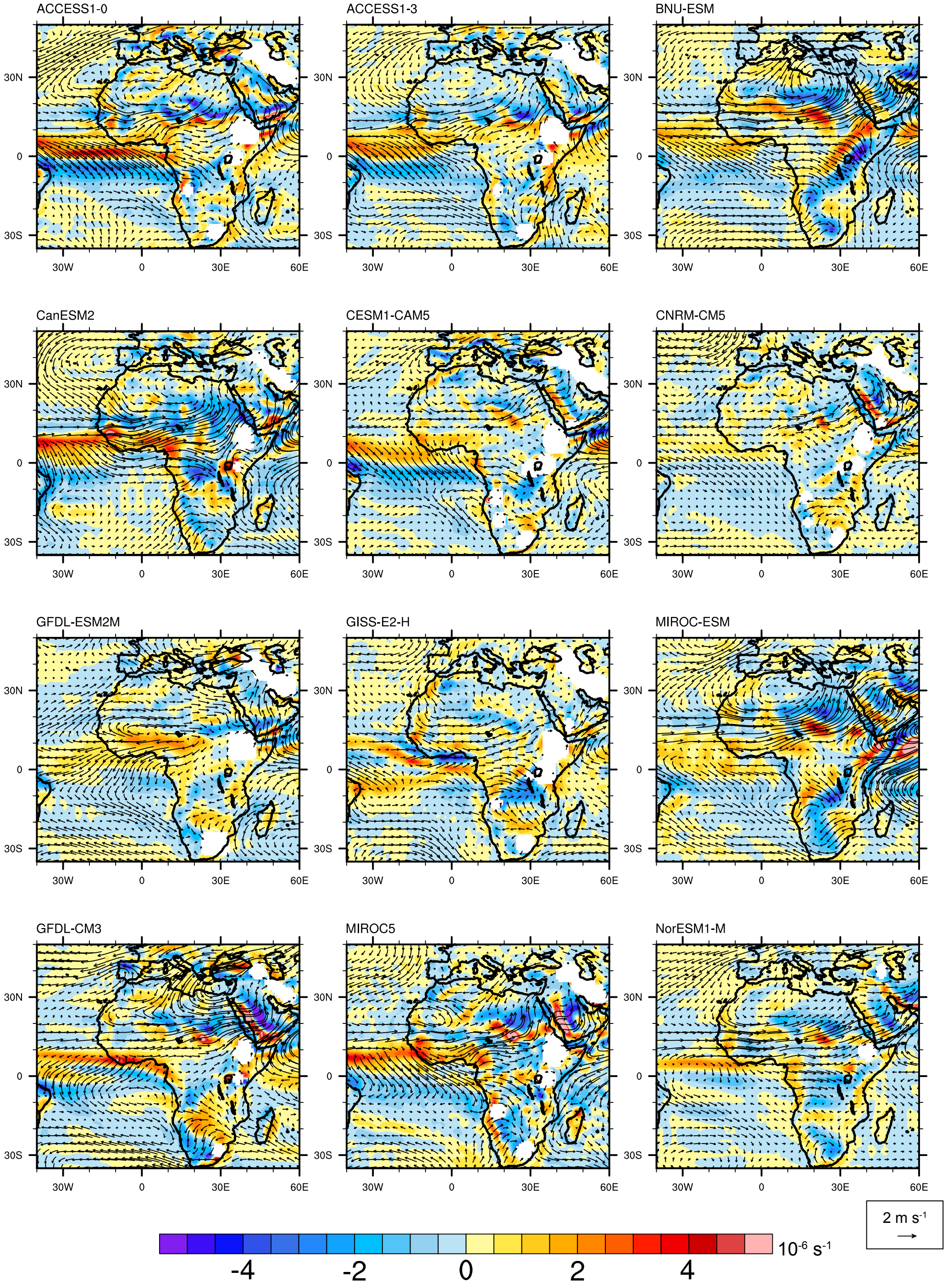


Figure 7: JAS 850 mb Wind Vectors Anomalies for Individual CMIP5 Models
Wind vector and divergence change from historical (1980-1999) to future (2080-2099) time periods using the RCP 8.5 climate change scenario for the JAS months over the African continent (35°S – 50°N, 40°W – 60°E). Arrows depict wind vector anomaly direction and size is proportional relative to reference arrow for 2 m s^{-1}. Divergence values have units of 10^{-6} s^{-1} and positive values represent divergence while negative values represent convergence. Areas with white shading indicate that the models show land surface at 850 mb over that area.