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CORDEX and CMIP5 Model based biophysical and socio-economic Extreme Climate Change impacts in Northern Hemisphere Sub-Sahara Africa

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603864-HELIX

Executive Summary

Sub-Sahara Africa is one of the most vulnerable regions of the world to adverse impacts of increased levels of global warming and climate change. The regional climate conditions are generally marginal, most areas being arid-and-semi arid and basic livelihoods including subsistence farming and water resources being replenished by decreasing rainfall across the region from West to East Africa. Persistent droughts occurring for several successive years are a serious threat to food and water productivity and availability, essential for livelihoods in the region.

Climate change model projections provide good suggestions as to what might happen in the future and within the framework of HELIX, these model indicators supported by observed trends and observed and anticipated impacts will be consolidated into decision information products and baselines for specific sectors, policy makers and stakeholder long term decision support. In Sub Sahara Africa region, impacts of climate extremes are manifested in many forms. In this deliverable, these impacts are reported as current status, starting with indications of climate change warming to various levels from both CMIP5 and CORDEX models; and how the impacts are reflected in water resources, crop modeling, immigration and conflict alongside a region wide climate and hunger Index.

Within the framework on on-going HELIX Sub-Sahara Africa focused research, the new generation of high resolution climate model projection outputs and systematically corrected model data sets will be used to derive improved impact models for food and water resources as critical sectors which must be strategically informed for guidance of improved sector polices and action plans addressing the needs of vulnerable communities of the region as well as technical cooperation program activities between the Sub-Sahara Africa and its development partners including the European Union.

Introduction

Increasing levels of global warming and therefore extreme climate change and implications on socio-economic welfare of communities worldwide is currently an issue of great societal concern and must be addressed urgently. Of the alterations in the statistical distribution of observed weather patterns, including biotic processes, variations in solar irradiance, geological factors (e.g., plate tectonics and volcanic eruptions), and the influence of human activities, the role of human activities has drawn significant interest within the scientific community in an attempt to understand the possible direction of future climate. With the build-up of temperature data from the immense geological evidence and the available instrumental records, the community of scientists is now in a position to assess changes in the mean weather as well as alterations in the frequency of extreme weather conditions based on longer-term data records and impacts of recent climate extremes. One of the most commonly studied alterations in the observed climate characteristics relates to incremental temperature, often termed as global warming.

There is no better source of evidence and extend of climate change than is available in the Fifth Assessment (AR5) report of the intergovernmental panel of climate change. AR5 is the single most authoritative consolidated source of the extend of climate change and implications at global and to some extend regional levels. Useful chapters and authors in AR5 include Cubasch *et al*., (2013) and Bindoff *et al*., (2013) among others. Extreme climate change in form of warming is likely have a negative effect on the yield of major cereal crops across Africa, with strong regional variability in the degree of yield reduction. Sub-Saharan Africa is predicted to experience decreases of 19% for maize yields, 68% decrease for bean yields and a small increase for fodder grass with a 5 degrees C warming (Bindoff et al., 2013). Therefore within the framework of HELIX regional focus for Sub-Sahara Africa, the extent to which these impacts can occur and implications of regional and sub-regional socio-economic welfare and policy issues for sustainable development are ultimate targets within the final deliverables and outcomes of Africa focus work packages.

Global warming, and the associated climate change, is bound to affect virtually all aspects of the socio-economic fabric of countries and economic grouping of regions. Adverse impacts include disruption of ideal conditions for production of food overall agricultural productivity and food security, hydrological balance and surface water resources; livestock and wildlife; and public health of communities. Impacts of increasing levels of climate extremes and changes are expected to be most severe in Sub-Sahara Africa where conditions are generally arid-and-semi-arid lands (ASALs) where livelihoods and water resources (Fekete et al., 2004) are depend on seasonal rainfall. Modelling and simulation of the adverse effects consequential to the shifts in the observed weather parameters is paramount in understanding the future impacts of climate on these socio-economic sub-sectors. With this information, policy makers, businesses and other decision makers would be better placed to prepare to cope with, and assist others to adapt to, future modifications in climate under higher levels of observed temperature and global warming.

Coherent information of the future climate conditions may be obtained through dynamical modelling exercises premised upon the Representative Concentration Pathways (RCPs) of the Intergovernmental Panel on Climate Change of 2014 (IPCC-2014) which are consistent with a wide range of possible changes in future anthropogenic greenhouse gas (GHG) emissions. Based on future emission levels, four RCP scenarios exist: RCP 2.6 that supposes global annual GHG emissions reach the summit between 2010 and 2020 and decline substantially thereafter; RCP 4.5 that presupposes emissions reach the summit around 2040 before declining, RCP 6 that envisions emissions peaking around 2080, then declining; whereas emissions continue with an upward trend throughout the 21st century in the RCP 8.5 scenario.

The global community seeks to limit the warming arising from GHG emissions to 2^{o}C. When will the 2^{o}C threshold be exceeded? Is it conceivable that the warming can reach 4^{o}C, or even 6^{o}C, and what would the world look like with these higher values? What is the degree of uncertainty in simulated temperature using an array of global models? These are some of the questions that the High-End cLimate Impacts and eXtremes (HELIX) project seeks to address. The overall objectives of the Pathways to Specific Warming Levels Work Package of the HELIX project are to:

1. Characterize uncertainty in the times at which existing climate model simulations reach specific warming levels (SWLs) and levels of other relevant targets such as forcing, CO2 concentration and sea level rise.
2. Improve the consistency between the treatment of climate in integrated assessment models (IAM) and state-of-the-art global climate models, and assess the impact of this on policy.

3. Estimate alternative greenhouse gas emissions, concentrations, and forcing pathways that lead to similar SWLs, including clear narratives on aspects of the economic and technical feasibility of these pathways.
4. Calculate the effect on the timing of reaching specific climate targets of additional biogeochemical feedbacks not typically included in the current generation of complex earth system models (ESMs) or IAMs.

Climate Model Change Projections in NHSSA: CMIP5 and CORDEX

The **H**igh-**E**nd c**L**imate **I**mpacts and e**X**tremes (HELIX) venture is a collaborative project funded by the European Commission (Number 603864) and comprises ten work packages, namely Stakeholder Engagement and Outreach (WP 1); Pathways to Specific Warming Levels (WP 2); High resolution Specific Warming Level timeslices and regional downscaling (WP 3); Global Biophysical Impacts (WP 4); Global-scale Assessment of Socio-Economic Impacts (WP 5); Project Management (WP 6); Regional Focus: Europe (WP 7); Regional Focus: Sub-Saharan Africa (Northern Hemisphere) (WP 8); Regional Focus: South Asia (WP 9); and Risk Management of Tipping Points (WP 10).

The HELIX project has 16 partners based in 14 countries, namely, the University of Exeter (UNEXE) in the United Kingdom; Met Office of The United Kingdom; University of East Anglia (UEA) in the United Kingdom; Stichting VU-(VUMC VU) in the Netherlands; Joint Research Centre - European Commission (JRC) in Belgium; the World Food Programme (WFP) in Italy, Universite De Liege (ULG) in Belgium; Centre National De La Recherche Scientifique (CNRS) in France; Sveriges Meteorologiska Och Hydrologiska Institut (SMHI) in Sweden; Potsdam Institut Fuer Klimafolgenforschung (PIK) in Germany; University College London (UCL) in the United Kingdom; the Technical University of Crete (TUC) in Greece; the IGAD Centre for Climate Prediction and Application (ICPAC) in Kenya; Bangladesh University of Engineering and Technology (BUET) in Bangladesh; the Foundation for Innovation and Technology Transfer (FITT-IITD) in India; and Agence Nationale De La Meteorologie Du Senegal (ANACIM) in Senegal. The partners contributing directly to Africa focus work and deliverables are ANACIM, CNRS, ICPAC, Met Office, ULG and WFP.

The CMIP5 Model Concept and Approach

This report addresses the Pathways to Specific Warming Levels (the second Work Package, WP 2, of HELIX) through the use of the fifth phase of the Coupled Model Intercomparison Project (CMIP5) models (Taylor et al., 2012). CMIP5 is a framework and analogue of the Atmospheric Model Intercomparison Project (AMIP) for global coupled ocean-atmosphere general circulation models under the auspices of CLIVAR and the World Climate Research Program, and is supported by the Program for Climate Model Diagnosis and Intercomparison with output from 29 global coupled ocean-atmosphere general circulation models (coupled GCMs) that include interactive sea ice. The goal of CMIP5 is to detect anthropogenic effects in the climate record of the past century and to project future climatic changes due to human production of greenhouse gases and aerosols. The CMIP model output entails simulations forced by both historical, paleoclimate CO2 levels that serve as pre-industrial "control runs" and future scenarios, with annually-incremented levels of CO2 levels.

Model uncertainty necessitates the employment of a number of coupled GCMs to simulate the physical climate system with a limited number of external boundary conditions such as the solar irradiance and atmospheric concentrations of radiatively active gases and aerosols. Bias-corrected data from ten out of the original 29 models are employed (Table 1: The models applied are bolded in the table). Two RCP scenarios are considered: the RCP 4.5 scenario that envisions an increase in GHG emissions up to 2040 before declining, and the RCP 8.5 scenario where emissions continue with an upward trend throughout the 21st century.

Table 1: The CMIP5 Modelling Groups or Centres

Serial	Modeling Center (or Group)	Institute ID
1	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM
2	Beijing Climate Center, China Meteorological Administration	BCC
3	Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research)	INPE
4	College of Global Change and Earth System Science, Beijing Normal University	GCESS
5	Canadian Centre for Climate Modelling and Analysis	CCCMA
6	University of Miami – RSMAS	RSMAS
7	National Center for Atmospheric Research	NCAR
8	Community Earth System Model Contributors	NSF-DOE-NCAR
9	Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC
10 11	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS

Serial	Modeling Center (or Group)	Institute ID
12	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE
13	EC-EARTH consortium	EC-EARTH
14	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University	LASG-CESS
15	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP
16	The First Institute of Oceanography, SOA, China	FIO
17	NASA Global Modeling and Assimilation Office	NASA GMAO
18	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL
19	NASA Goddard Institute for Space Studies	NASA GISS
20	National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA
21	**Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)**	**MOHC** **(additional realizations by INPE)**
22	Institute for Numerical Mathematics	INM
23	Institut Pierre-Simon Laplace	IPSL
24	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC
25	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC
26	**Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)**	**MPI-M**
27	**Meteorological Research Institute**	**MRI**
28	Nonhydrostatic Icosahedral Atmospheric Model Group	NICAM
29	Norwegian Climate Centre	NCC

The models used in this report are bolded.

(Source: http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.docx)

The datasets applied in the HELIX project are obtained from the East Africa climate database and the ISI-MIP subset of the CMIP5 ensemble that encompasses decadal hindcasts and projections simulations, long-term simulations, and prescribed SST simulations for models that are especially computationally-demanding. The detailed information supported by a comprehensive analysis of confidence and uncertainty is produced through simulations for the sub-Saharan Africa focus region in the Northern Hemisphere (NHSSA) region shown in Figure 1.

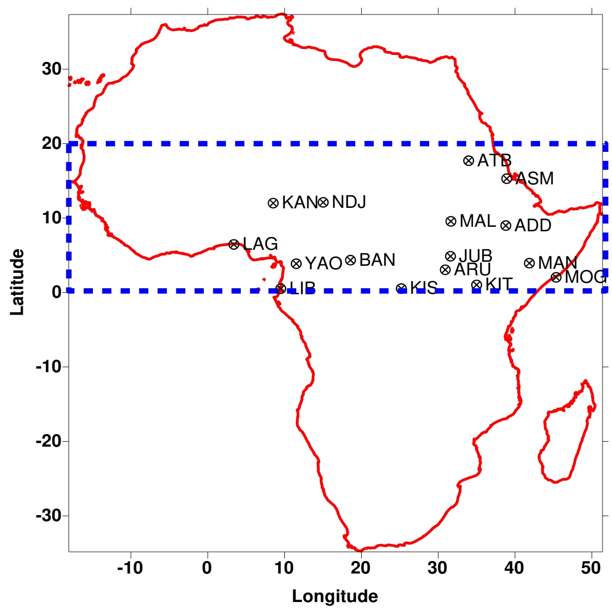


Figure 1: The Sub-Saharan Africa focus region in the Northern Hemisphere as a broken rectangle and the locations of Addis Ababa (ADD), Arua (ARU), Asmara (ASM), Atbara (ATB), Bangui (BAN), Juba (JUB), Kano (KAN), Kisangani (KIS), Kitale (KIT), Lagos (LAG), Libreville (LIB), Malakal (MAL), Mandera (MAN), Mogadishu (MOG), Ndjamena (NDJ), and Yaounde (YAO).

The methodology encompasses model verifications of hindcast datasets against observations for stations within various areas of NHSSA, bias correction, and decadal projections guided by the RCP 4.5 and RCP 8.5 scenarios. In Figure 1 is also the locations of some of the stations considered in the results indicated in this report. These stations are Addis Ababa (Ethiopia), Arua (Uganda), Asmara (Eritrea), Atbara (Sudan), Bangui (Central African Republic), Juba (South Sudan), Kano (Nigeria), Kisangani (Democratic Republic of Congo), Kitale (Kenya), Lagos (Nigeria), Libreville (Gabon), Malakal (Sudan), Mandera (Kenya), Mogadishu (Somalia), Ndjamena (Chad), and Yaounde (Cameroon). Spatiotemporal temperature variations are analysed as near surface average, minimum, and maximum air temperatures. The GrADS tool is used in post-processing data from the NetCDF CMIP5 files.

Africa-CORDEX Domain and Regional Models

The Coordinated Regional Climate Downscaling Experiment (CORDEX) was initiated by the World Climate Research Program (WCRP) to spearhead the generation and provision of regional climate downscaled climate change projections in various parts of the world (Giorgi *et al*., 2009), with special focus on Africa for various reasons including the overall vulnerability of Africa to climate change, low climate modeling capacity and low adaptive capacity of most of the continent to extreme climate changes like implications of $4^{o}C$ and $6^{o}C$ warming which are of interest to HELIX. In addressing this need for Africa, a large number of climate modeling institutions and centres worldwide availed their regional climate models (RCs) to participant in generation of regional model climate change projections for Africa. Figure 2 below is the Africa CORDEX domain (with HELIX focus sub-region of NHSSA delineated). Most of the Africa CORDEX regional model outputs and post-processed data was facilitated by Sverirges Meteorologiska Och Hydrologigiska Institut (SMHI-Sweden-HELIX partner No. 8).

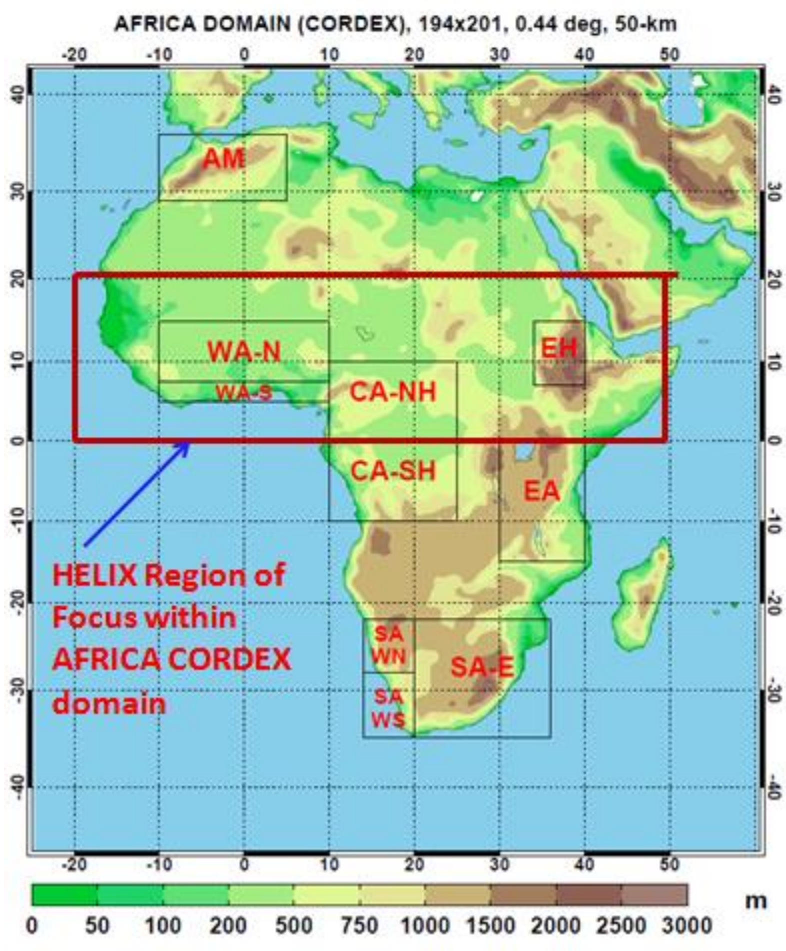


Figure 2: Africa CORDEX Domain and HELIX focus region of Northern Hemisphere Sub-Sahara Africa.

Africa CORDEX and Sample High Downscaled Results

Africa CORDEX Regional model downscaling objective is quite similar to dynamical model downscaling applications applied in the other regions of the World (Giorge *et al*., 2009), namely:

- Evaluate and improve dynamical and statistical regional climate downscaling (RCD) techniques over Africa;
- Produce a new generation of RCD-based climate projections for Africa;
- Foster communication between the climate modeling and impact communities and enhance the engagement of scientists from developing countries in climate change research.
- Within the frame work of Africa CORDEX a substantial amount of work has been done within the auspices of University of Cape Town climate Systems Analysis group (CSAG-UCT) collaboration with START capacity developments, training and research in expanded understanding of climate change and other drivers of global change at local, national and regional scales in Africa.

In conformity with HELIX project intension that results and outputs from other Africa CORDEX initiatives such as CSAG-UCT and START be taken advantage of, within this deliverable as indication of what CORDEX archives in addressing needs of high resolution climate change projections at sub-regional levels. Figure 3 shows CORDEX model performance in capturing of annual cycle of rainfall in various parts of the HELIX focus areas in Sub-Sahara Africa.

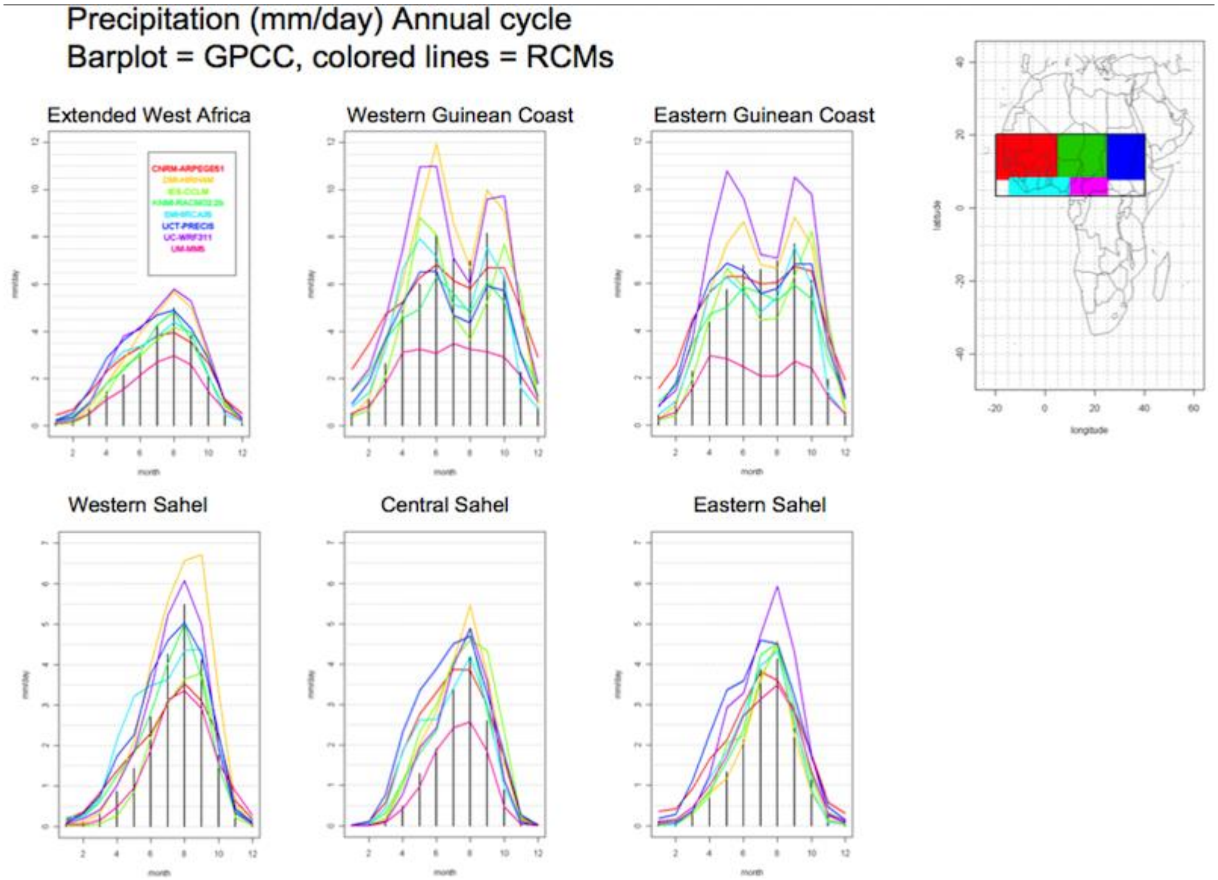


Figure 3: Africa CORDEX regional model representation of observed annual cycle of rainfall in various parts of HELIX focus sub-regions in NHSSA (Source: CSAG-UCT: http://www.csag.uct.ac.za/research/cordex-old/cordex-africa-2/).

From these results, there is apparent difference in performance skill (in terms of capturing magnitudes and timing of the seasonal peaks). Differences and inconsistencies like this prompt climate scientists to adopt techniques believed to improve the usability of model outputs. This is one reason why bias correction was applied in HELIX version of Africa CORDEX models, the bias correction work which was completed during August 2015 was led by Technical University of Crete.

Bias Corrected AFRICA CORDEX model Outputs for HELIX

Raw Africa CORDEX model data

The raw RCM output was retrieved from the repositories of Earth System Grid Federation (ESGF) for Africa domain CORDEX models. Details of the model variables are provided in Table 3 below.

Available Bias Corrected data at RCP85. The available bias-corrected datasets are noted with X (Source: TUC-HELIX partner No.12)

	AFRICA CORDEX MODEL VARIABLE name	HUSS	PS	PR	TAS	TASMAX	TASMIN	WIND	RSDS	RLDS
1	AFR-44_CCCma-CanESM2_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
2	AFR-44_CNRM-CERFACS-CNRM-CM5_r1i1p1_CLMcom-CCLM4-8-17_v1_day	X	X	X	X	X	X	X	X	X
3	AFR-44_CNRM-CERFACS-CNRM-CM5_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
4	AFR-44_CSIRO-QCCCE-CSIRO-Mk3-6-0_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
5	AFR-44_ICHEC-EC-EARTH_r12i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
6	AFR-44_ICHEC-EC-EARTH_r1i1p1_KNMI-RACMO22T_v1_day	X	X	X	X	X	X	X	X	X
7	AFR-44_ICHEC-EC-EARTH_r3i1p1_DMI-HIRHAM5_v2_day	X	X	X	X	X	X	X	X	X
8	AFR-44_IPSL-IPSL-CM5A-MR_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
9	AFR-44_MIROC-MIROC5_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
10	AFR-44_MOHC-HadGEM2-ES_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
11	AFR-44_MOHC-HadGEM2-ES_r1i1p1_CLMcom-CCLM4-8-17_v1_day	X	X	X	X	X	X	X	X	X
12	AFR-44_MOHC-HadGEM2-ES_r1i1p1_KNMI-RACMO22T_v1_day	X	X	X	X	X	X	X	X	X
13	AFR-44_MPI-M-MPI-ESM-LR_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
14	AFR-44_MPI-M-MPI-ESM-LR_r1i1p1_CLMcom-CCLM4-8-17_v1_day	X	X	X	X	X	X	X	X	X
15	AFR-44_NCC-NorESM1-M_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X
16	AFR-44_NOAA-GFDL-GFDL-ESM2M_r1i1p1_SMHI-RCA4_v1_day	X	X	X	X	X	X	X	X	X

Reference Dataset Used

The reference dataset used for the bias correction is the hybrid dataset of Watch Forcing Data - WFD (Weedon et al., 2010) and the Watch Forcing Data methodology applied to ERA-Interim data (WFDEI) (Weedon et al 2014) used in the Inter-Sectoral Impact Model Integration and Intercomparison Project ISI-MIP which combines forcing data of WFD (1901-1978) and WFDEI.GPCC (1979-2012) (Warszawski et al 2014).

Bias Correction Methodology

The bias correction methodology applied to the precipitation data is the one described in Grillakis et al., (2013). For the rest of the climate variables, the same methodological principles are applied on different type of transfer functions due to differences in the data types. The period 1981-2010 was used as bias correction reference period.

Reference Grid

The rotated pole RCM grid (i.e. the same grid to the raw RCM data) over Africa was used as reference grid. The observational datasets were interpolated on the reference grid prior the bias correction procedure.

Bias Corrected CORDEX Data Reference Syntax

The names of the bias corrected files are changed according to the following example:

Unprocessed:

tas_AFR-44_MOHC-HadGEM2-ES_historical_r1i1p1_CLMcom-CCLM4-8-17_v1_day_19491201-20051230

Bias corrected:

tasAdjust_AFR-44_MOHC-HadGEM2-ES_rcp85_r1i1p1_CLMcom-CCLM4-8-17_v1-TUC-MSBC-WFDWFDEI-1981-2010_day_19491201-20051230

New global attributes have been added to the files

:bc_method = " Grillakis, M. G., Koutroulis, A. G., & Tsanis, I. K. (2013). Multisegment statistical bias correction of daily GCM precipitation output. Journal of Geophysical Research: Atmospheres, 118(8), 3150-3162";

:bc_method_id = " TUC-MSBC-WFD/WFDEI-1981-2010" ;

:bc_observation = " Watch Forcing Data and Watch Forcing Data Era Interim dataset created by ISI-MIP2 for the ISI-MIP2 modeling needs; See the ISI-MIP2 Simulation Protocol at https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/research/rd2-cross-cutting-activities/isi-mip/for-modellers/isi-mip-phase-2/simulation-protocol" ;

:bc_observation_id = " WFD/WFDEI" ;

:bc_period = "1981-2010" ;

:bc_info = " TUC-MSBC-WFD/WFDEI-1981-2010" ;

Variable attribute 'long_name' is modified by appending 'Bias-Corrected' at the beginning, for example, tasminAdjust: long_name = "Bias-Corrected Air Temperature"

HELIX Africa Domain Bias Corrected Results: Rainfall and Temperature

Probably, the only common modeling attribute in the set of Africa CORDEX model configurations was the horizontal grid resolution of 50 by 50 km. Probably all regional models used similar topography, but the boundary base fields were provided by different global models and each regional model has generally a unique dynamics and physics concept implemented in a manner depending on the modeling philosophy of model developers. Therefore, we can expect differences in model results. Figures 4 and 5 shown results from ensembles of CORDEX model precipitation and temperature, before and after bias correction for current climate and future climate change (cc) time slice 2046 – 2075 over the HELIX focus domain of Africa.

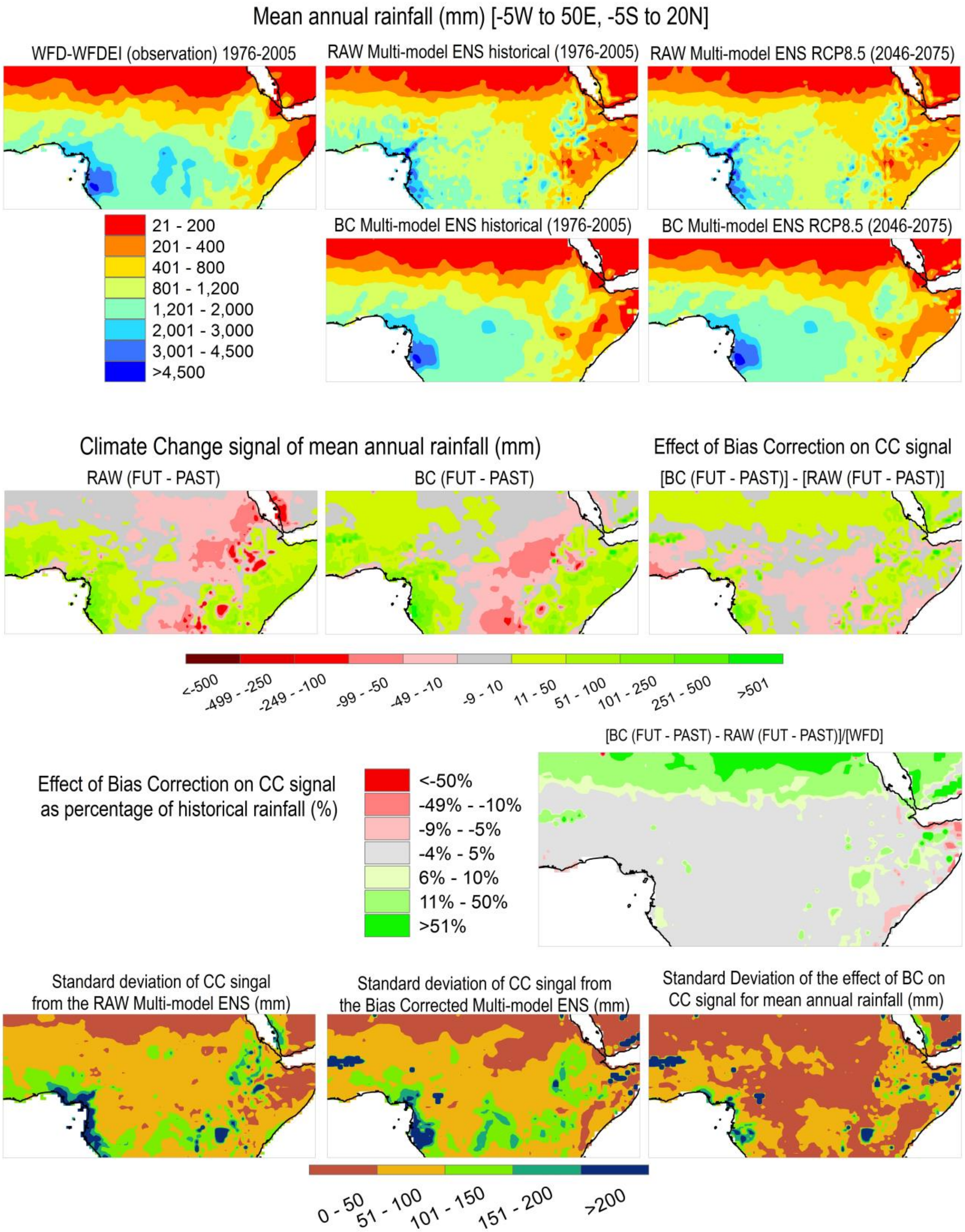


Figure 4: CORDEX Africa model rainfall over HELIX focus domain, historical and future climate change patterns before and after HELIX bias correction.

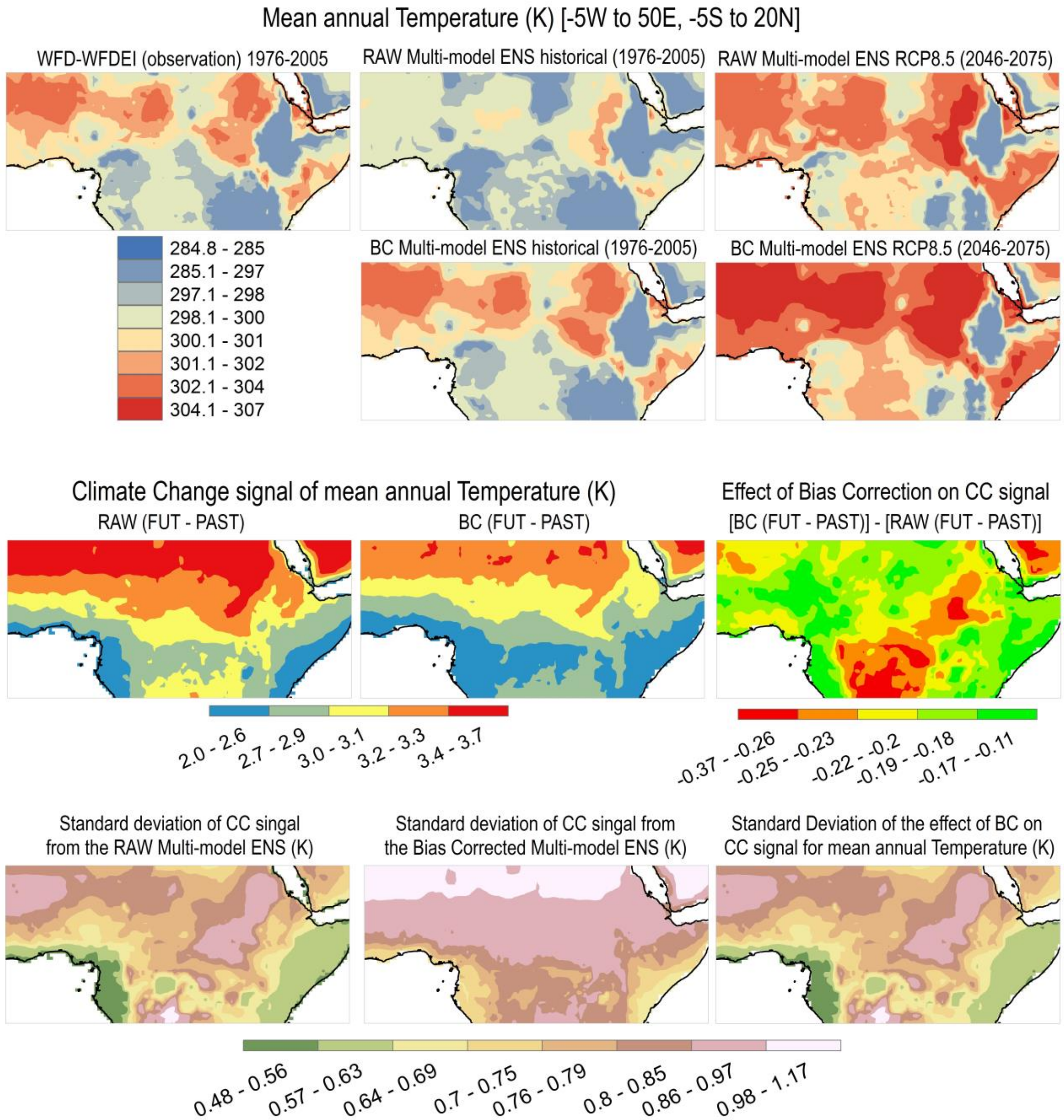


Figure 5: CORDEX Africa model mean temperature over HELIX focus domain, historical and future climate change patterns before and after HELIX bias correction.

For both rainfall and temperatures, bias correction provides a climate change signal of lower variability and therefore more consistent and coherent in space and time. The usefulness of these bias-corrected CORDEX data sets will be fully evaluated and assessed when the data sets are applied in running of impacts models, in particular crop models (Maize) and stream flow responses, in particular the White Nile source river systems in Interior East Africa great lakes region.

Climate Change Model for Potential Bio-Physical Impacts in HELIX NHSSA Region

Projected Trends over Eastern Africa

Projected Temperature Trends

Figure 6 shows the simulated projection of the seasonal variation of mean, maximum and minimum temperatures of historical (1971-2000), RCP 4.5 (2011-2040) and RCP 8.5 (2071-2100) periods at Kitale, Kenya, averaged from the MPI-M, MRI and HadGEM2 models. The models are able to simulate the annual pattern nearly as the observed temperature, capturing the two peaks in the year. However, the actual values are not captured.

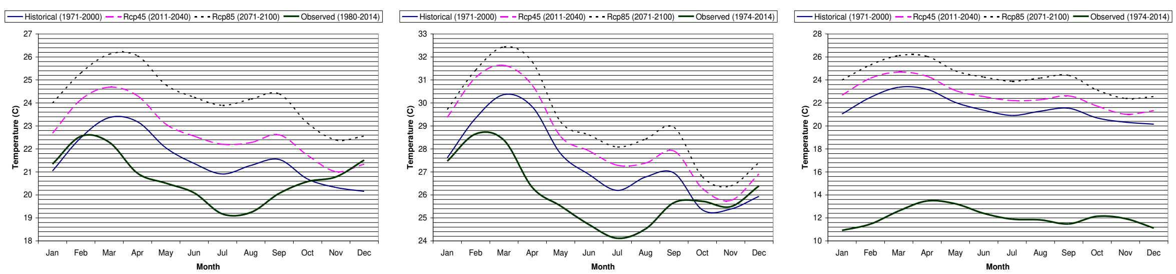


Figure 6: Simulated seasonal variation of mean (left), maximum (centre) and minimum (right) temperatures (°C) of historical 1971-2000 (blue, solid), RCP 4.5 2011-2040 (pink, dashed) and RCP 8.5 2071-2100 (black, dotted) projected at Kitale, Kenya, averaged from the MPI-M, MRI and HadGEM2 models. Observed values for 1980-2014 (green) are shown.

Figure 7 Shows the historical, current and projected near-surface annually averaged screen height mean, maximum and minimum air temperatures as well as the nine-year moving average trends at Kitale, Kenya, from the Max-Planck-Institut für Meteorologie (MPI-M), Meteorological Research Institute (MRI) and Met Office Hadley Centre (HadGEM2) models based on the RCP 4.5 and RCP 8.5 scenarios for the period 1850 to 2100. These models were used because of the better quality of simulated temperature values being in closer proximity to the observed values.

The three sets of graphs show the temperature cycles between 1850 and the present, before steadily increasing after 2005 based on the assumed increase in CO2 from human activities. The annual mean dry bulb temperatures average 22½ °C over the 155 year period before steadily increasing. The annual average maximum and minimum temperatures averaged over the same period are 27¼ °C and 14¼ °C, respectively.

In the RCP 4.5 scenario, which presupposes that emissions reach the summit around 2040 before declining, the simulated temperatures increase dramatically until the year 2050 before attaining oscillatory stability. Over the 45-year period, the mean dry bulb temperature, the maximum temperature and the minimum temperature all increase by about 2°C, on average. This translates to an annual incremental rate of 0.04°C. At this rate, the 2 °C incremental threshold is attained in the year 2050.

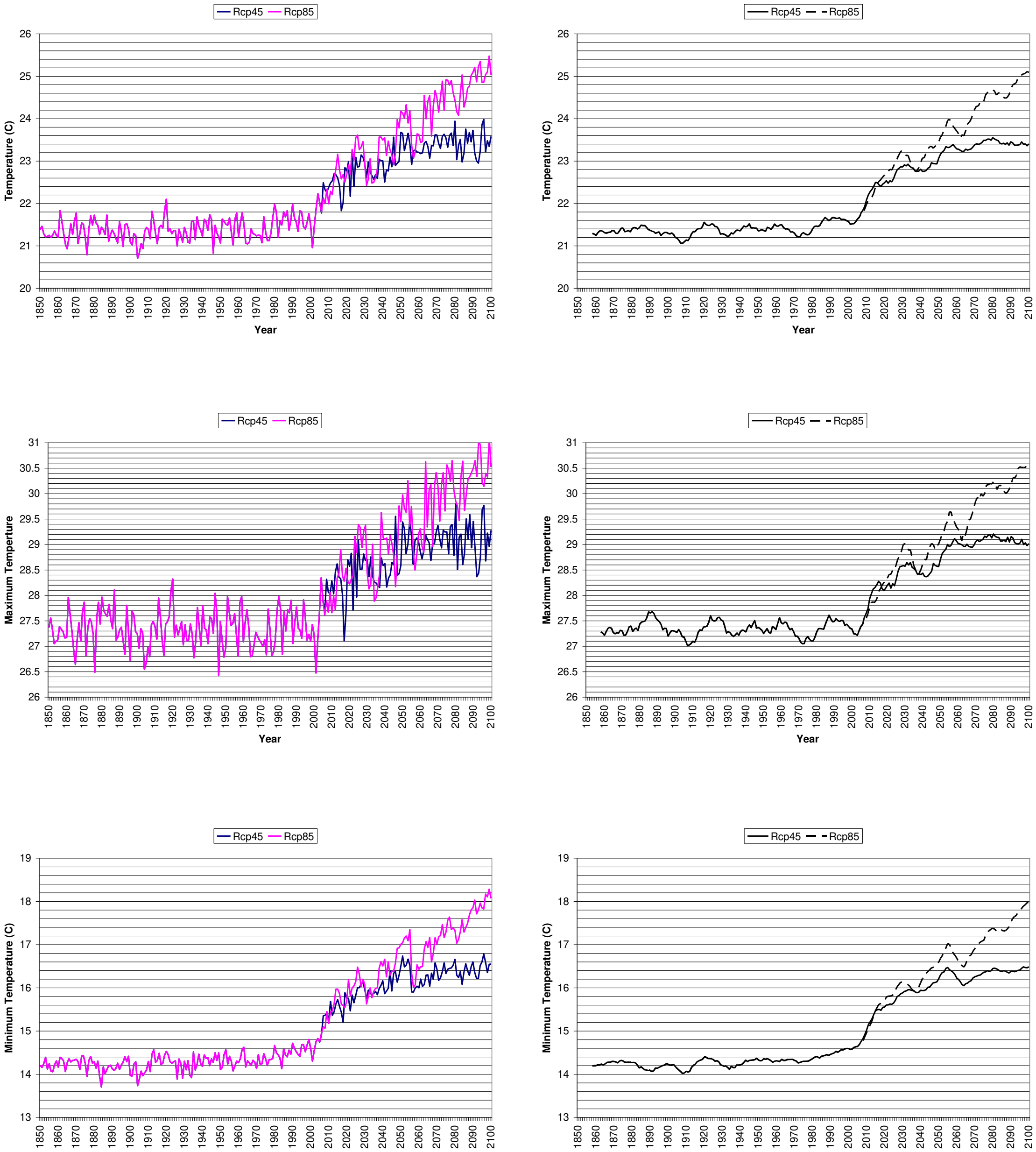


Figure 7: Simulated mean (top), maximum (middle) and minimum (bottom) temperatures (°C) of historical, current and projected conditions (left panel) and nine-year moving average trend (right panel) at Kitale, Kenya, averaged from the MPI-M, MRI and HadGEM2 models based on the RCP 4.5 (blue/solid) and RCP 8.5 (red/dashed) scenarios for the period 1850 to 2100

In the RCP 8.5 scenario where emissions continue with an upward trend throughout the 21st century, the simulated temperature increases at the mean rate of 0.034°C per year. The maximum and minimum temperatures record similar simulated annual incremental rates. At this rate, a sustained (average) 2°C incremental threshold is attained in the year 2060 while a 4°C incremental threshold is attained at the close of the century in the year 2100.

Projected Trends over Central Africa

Temperature Trends

Figure 8 shows the simulated seasonal variation of mean, maximum and minimum temperatures of historical (1971-2000), RCP 4.5 (2011-2040) and RCP 8.5 (2071-2100) projected at Libreville, Gabon, averaged from the MPI-M, MRI and HadGEM2 models. The model cluster is unable to simulate the annual variation in the observed temperature, not capturing the climatological two peaks in the year and their actual time occurrence.

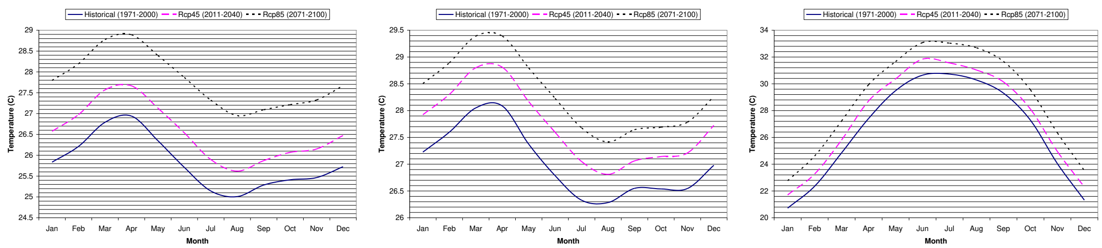


Figure 8: Simulated seasonal variation of mean (left), maximum (centre) and minimum (right) temperatures (°C) of historical 1971-2000 (blue, solid), RCP 4.5 2011-2040 (pink, dashed) and RCP 8.5 2071-2100 (black, dotted) projected at Libreville, Gabon, averaged from the MPI-M, MRI and HadGEM2 models

Figure 9 illustrates the historical, current and projected near-surface annually averaged screen height mean, maximum and minimum air temperatures as well as the nine-year moving average trends at Libreville, Gabon, from the Max-Planck-Institut für Meteorologie (MPI-M), Meteorological Research Institute (MRI) and Met Office Hadley Centre (HadGEM2) models based on the RCP 4.5 and RCP 8.5 scenarios for the period 1850 to 2100.

The three sets of graphs show the temperature cycles between 1850 and the present, before steadily increasing after 2005 based on the assumed increase in CO_2 from human activities. The annual mean dry bulb temperatures average 25½ °C over the 155 year period before steadily increasing. The annual average maximum and minimum temperatures averaged over the same period are 26¾ °C and 24½ °C, respectively.

In the RCP 4.5 scenario, which presupposes that emissions reach the summit around 2040 before declining, the simulated temperatures increase dramatically until the year 2050 before attaining oscillatory stability. Over the 45-year period, the mean dry bulb temperature, the maximum temperature and the minimum temperature all increase by about 2°C, on average. This translates to an annual incremental rate of 0.04°C. At this rate, the 2°C incremental threshold is attained in the year 2050.

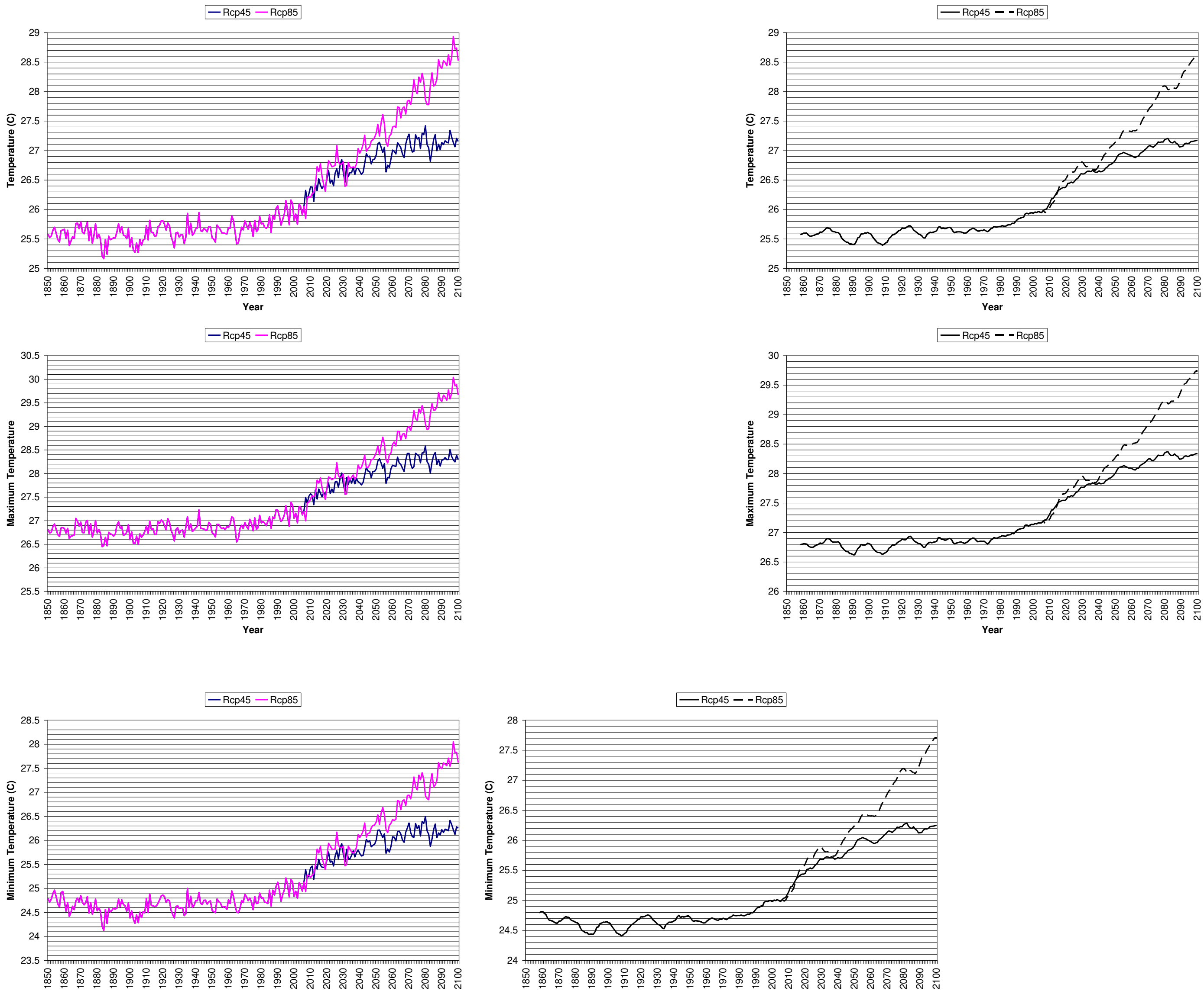


Figure 9: Simulated mean (top), maximum (middle) and minimum (bottom) temperatures (°C) of historical, current and projected conditions (left panel) and nine-year moving average trend (right panel) at Libreville, Gabon, averaged from the MPI-M, MRI and HadGEM2 models based on the RCP 4.5 (blue/solid) and RCP 8.5 (red/dashed) scenarios for the period 1850 to 2100

NHSSA Temperature Projection Spatial Patterns

Figure 10 shows the projected rise in the simulated mean, maximum and minimum temperatures over the Northern Hemisphere Sub-Saharan Africa region for the RCP 4.5 and RCP 8.5 scenarios using the MPI model. The changes are based on ten-year averages of simulation products for 1996 to 2005 period for the historical observations, 2040 to 2049 for the RCP 4.5 scenario, and 2091 to 2100 for the RCP 8.5 scenario.

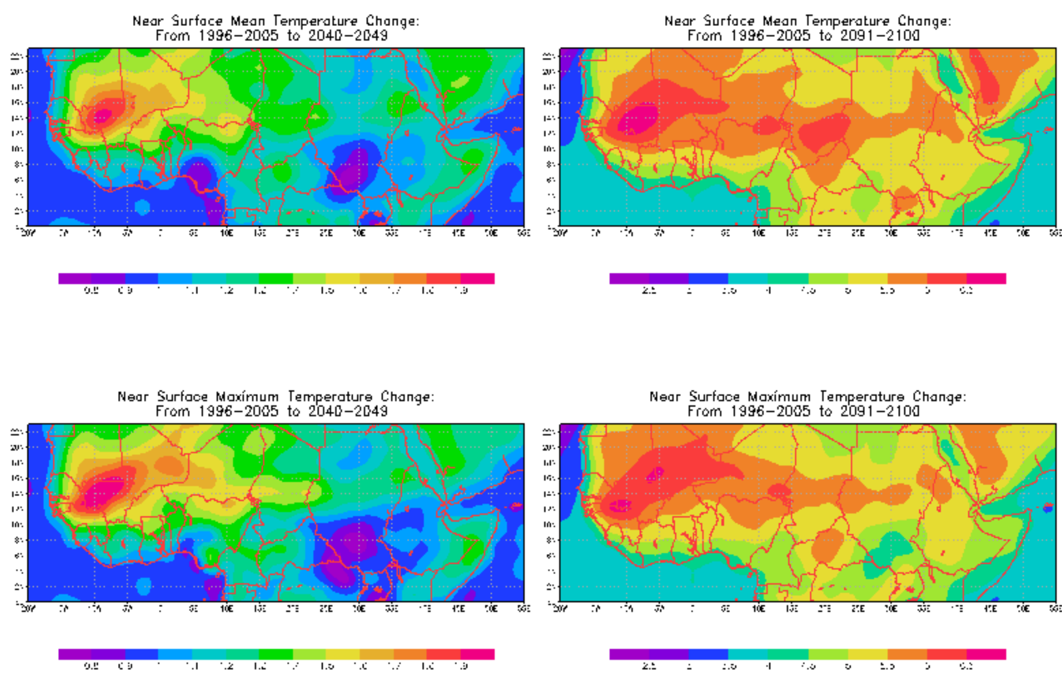
The results show that the near-surface mean air temperature for the period 2040 to 2049 is projected to increase due to the envisaged increase in the greenhouse gases under the RCP 4.5 scenario by between

0.8°C and 2.0°C over the area. The lowest increase is projected to occur over traditionally rainy portions of Uganda, the South Sudan and the Gulf of Guinea regions while the highest increase will occur in the traditionally drier southern portions of Mauritania Mali, and Guinea.

The results further show that the ten-year averaged near surface mean temperature is projected to increase by 2.5°C and 7.0°C in the period from 2091 to 2100. Substantial temperature increase is expected to occur over the western Africa region in southern Mauritania and southern Mali, and extending eastward into Chad and the Central African Republic. The rest of the region is expected to experience increments of between 4.5 and 5.5°C.

Figure 10 also shows an increment in maximum temperature based on the RCP 4.5 scenario of between 0.8°C and 2.0°C over the 2040 to 2049 period as compared to the 1996 to 2005 period. The smallest increments are expected over the South Sudan, eastern parts of the Democratic Republic of Congo and parts of Uganda, as well as southern portions of Nigeria and the Gulf of Guinea. The highest increment in maximum temperature is expected to occur over much of Mauritania, Mali and Guinea.

In the RCP 8.5 scenario, the increase in maximum temperature ranges between 2.5°C and 7.0°C over the SSA region in the period 2091 to 2100 compared to 1996 to 2005. The highest projected increase of between 6.0°C and 7.0°C is in the Sahel region. The increase in maximum temperature over the rest of the region ranges between 4.5°C and 5.5°C, with the lowest values over South Sudan, eastern parts of Kenya and southern Somalia.



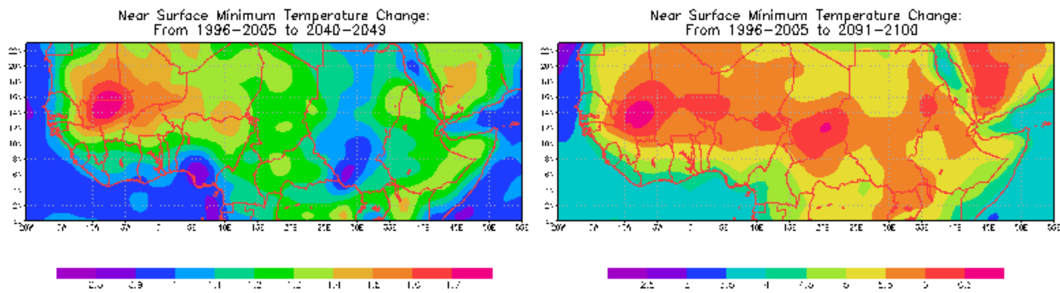


Figure 10: Projected rise in mean (top), maximum (centre) and minimum simulated temperatures (bottom) between historical (1996-2005) and RCP45 (2040-2049, Left Panel) and RCP85 (2091-2100, Right Panel) over the Sub-Saharan region in the Northern Hemisphere using the MPI model.

The results further show that near-surface minimum temperatures over the NHSSA are projected to increase by between 0.8°C and 2.0°C, with the highest increment in the western parts of the Sahel zone, centred over southern Mauritania, Mali, Guinea and Burkina Faso regions, basing on the RCP 4.5 scenario in the period between 2040 and 2049, inclusive, relative to the historical base period of 1996 to 2005. The lowest increased minimum temperature is expected over southern Nigeria, Gulf of Guinea, parts of South Sudan, parts of southern Uganda and eastern Kenya/southern Somalia.

Simulations over Sub-Saharan Africa for the RCP 8.5 scenario over the period 2091 to 2100 relative to the period 1996 to 2005 show a projected increase in minimum temperature of between 2.5°C and 7.0°C. The highest increase is in the Sahel and neighbouring regions extending from southern Mauritania to northern Ethiopia, southern South Sudan, northern Uganda and North-western Kenya. Eastern parts of Kenya, much of Somalia, and southern parts of West Africa are expected to experience minimal increases in minimum temperature.

Recent Rainfall Trends in NHSSA and Biophysical Impacts

As pointed out earlier in section 2.3 and Figure 3 therein, CORDEX regional models hardly agree on the magnitude and timing of seasonal rainfall in the various sub-regions of sub-Sahara Africa. While the consistency and accuracy of climate change models representing realistically the present day climate baselines and future changes are the greatest concern of HELIX focus in Africa, it is important to keep track of how observed climate trends, such as year to year rainfall have been in the region for the recent climatological period. Figures 11 and 12 show interannual variability and linear trends of annual rainfall totals in Western Kenya and Northern Ghana areas. Although these two areas are in climatically different zones and rainfall processes are substantially different, these results reveal notable rainfall decrease, for example a decrease of about 100mm for both sub-regions during the more than 38 years of observed records in both cases. This decreasing trend of regional rainfall has been noted by researchers and pointed out as East Africa Climate Change paradox. For HELIX impacts and modelling in the region, it is sufficient to note that decreasing rainfall has wide range on adverse implications in the NHSSA region. Most of agriculture is rainfed, and water resources and environmental productivity are replenished by rainfall. Therefore decreasing rainfall imply decreased agricultural productivity and therefore a threat to food production as well as fresh water for current and future generations. Both East and West Africa sub-regions of NHSSA are water and food insure.

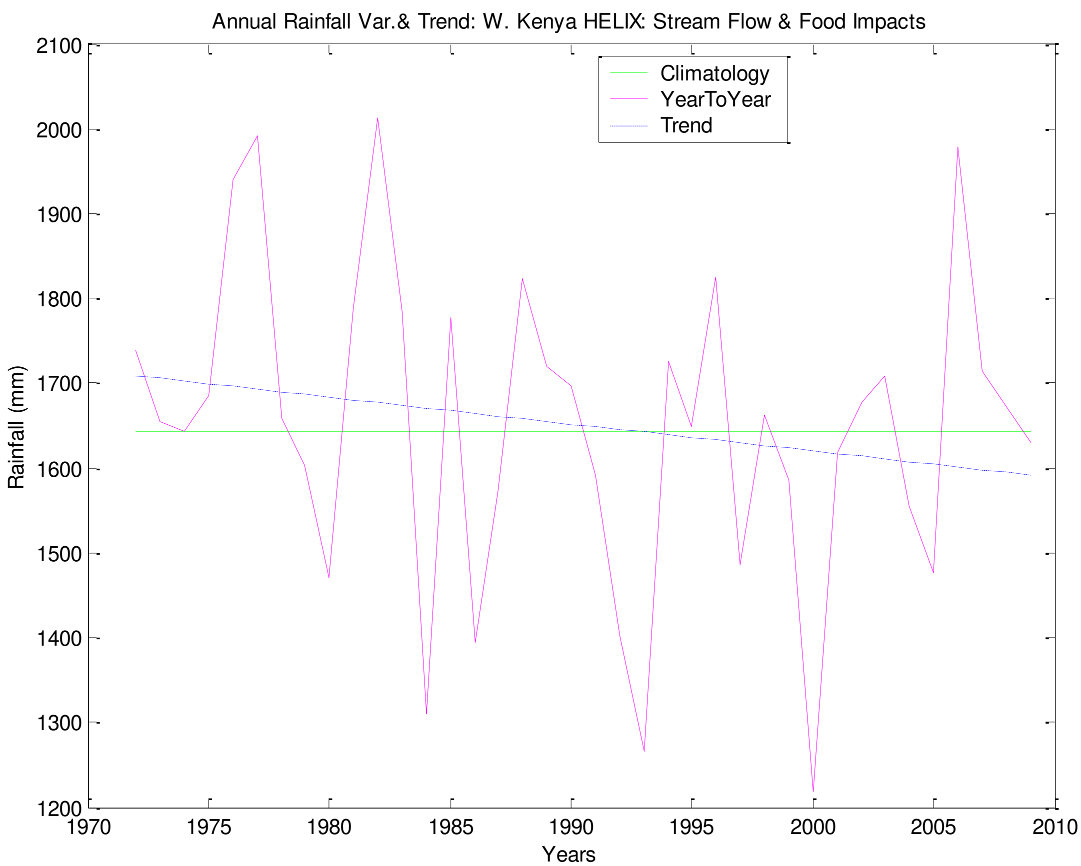


Figure 11: Interannual variability and trends of total rainfall in Western Kenya sub-region of HELIX focus for food and water resources.

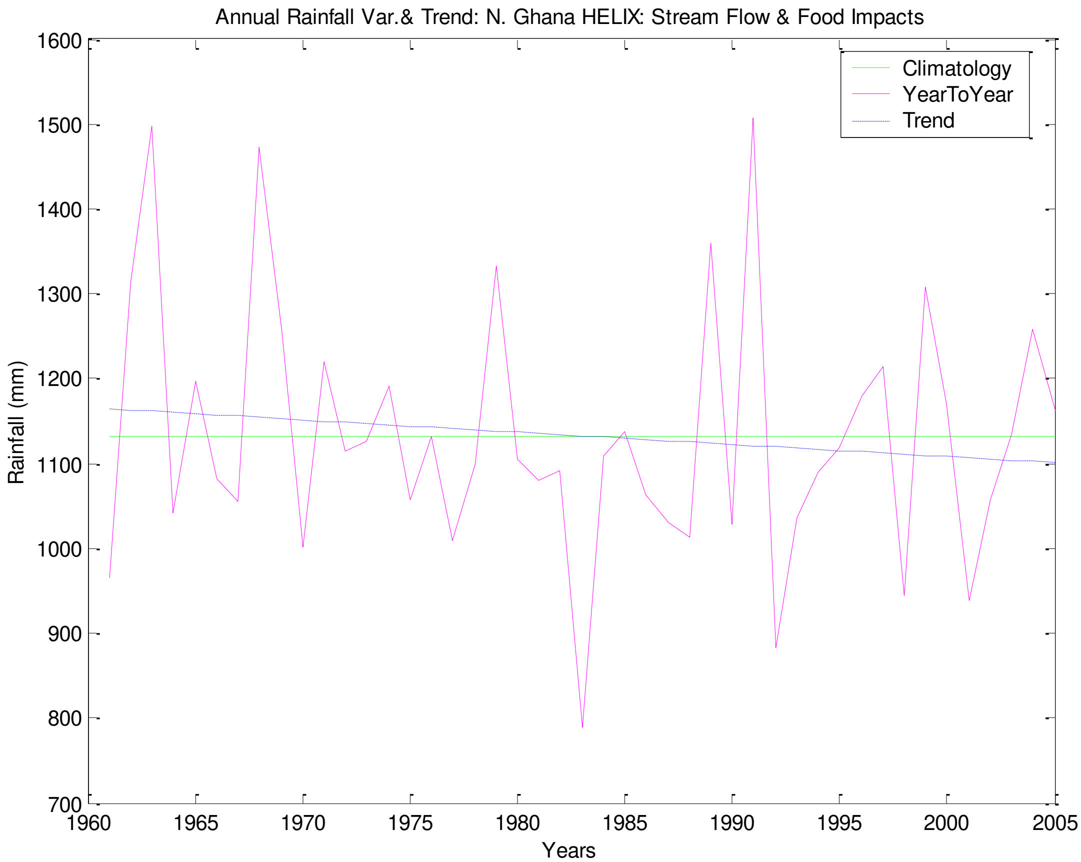


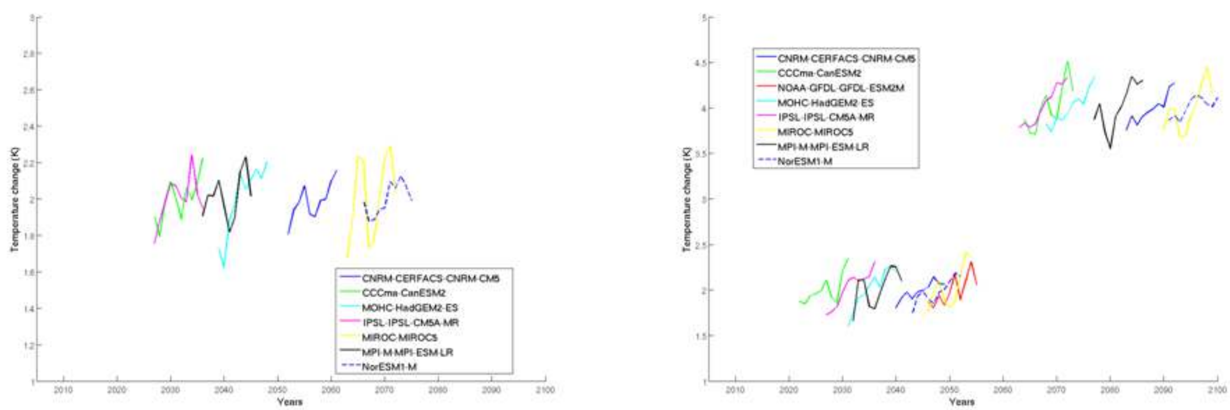
Figure 12: Interannual variability and trends of total rainfall in Northern Ghana sub-region of HELIX focus for food and water resources.

Northern Hemisphere Sub-Sahara Africa ORCHIDEE-Crop model for Food Security Impacts

The crop modelling has been performed using the ORCHIDEE-Crop model based at NCRS. ORCHIDEE-Crop is a currently unreleased specific development of the ORCHIDEE land surface model. ORCHIDEE is a land surface model with river routing, carbon fluxes and an interactive biomass scheme. For more details on the development of ORCHIDEE see, (Ducoudré et al., 1993; Viovy, 1996; Polcher et al., 1998; Krinner et al., 2005). ORCHIDEE as part of the IPSL climate model was used as in the IPCC AR5 (Guenet et al., 2013). The sample results shown in this section are the potential areas for tropical maize productivity, the model being driven by un-bias-corrected CORDEX data from various regional models.

Methods and Input Data in ORCHIDEE Crop Model

The simulations are all 20 year simulations where the first 10 years are used to spin up the soils and the final 10 are analysed. Hereafter the times mentioned are for analysis unless otherwise stated. The historical time period for all simulations is 1996-2005 which is the final 10 years of the CMIP5 historical simulations. For both the RCP4.5 and RCP8.5 simulations the 10 year global average mean temperatures of +2/4 K were found and used to define the periods of analysis. For the 8 GCMs which were used in CORDEX Africa these time slices are shown in Figures 13a and b.



a) With RCP 4.5 CC scenario **b) With RCP 8.5 CC scenario**

Figure 13: Temperature and time slices from several GCMs simulating (a) RCP 4.5 and (b) RCP 8.5 where average temperatures are +2 or +4 K.

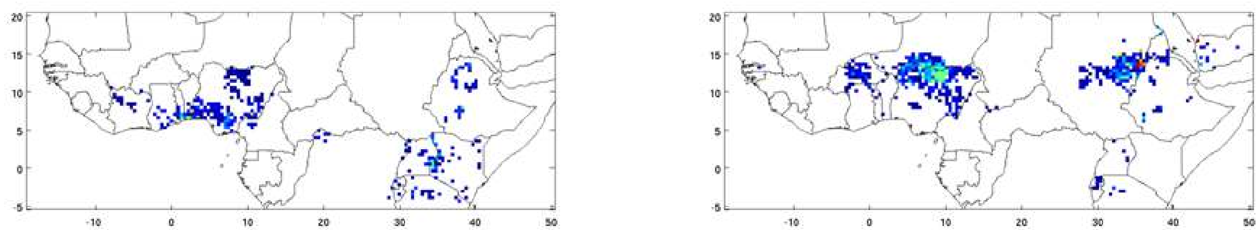
There are 8 GCMs used in CORDEX Africa, these 8 GCMs were each used to drive a varying number RCMs resulting in 12 output experiments. Table 4 below shows the available simulations. Models are listed by their most used names.

Table 4: The climate models data sets used in CORDEX model for ORCHIDEE crop model in whole NHSSA region.

GCM	CCLM	KNMI	SMHI
CNRM-CERFACS-CNRM-CM5	Y		Y
CCCma-CanESM2			Y
NOAA-GFDL-GFDL-ESM2M			Y
MOHC-HadGEM2-ES	Y	Y	Y

IPSL-IPSL-CM5A-MR			Y
MIROC-MIROC5			Y
MPI-M-MPI-ESM-LR	Y		Y
NCC-NorESM1-M			Y

The simulation area used for the HELIX simulations has the following limits and is shown in Figure 14 below, covering the geographical area within 2. 5^{o}N – 5^{o}S and 18^{o}W – 50^{o}E. To prevent signals in the simulations being swamped by noise from regions where the crops aren't grown, the analysis is restricted to grid cells where the cultivated area of the crop being analysed is over 5% of the grid cell.



a) Cultivated area over 5% maize

b) Cultivated area over 5% sorghum

Figure 14: NHSSA cultivated crop areas with over 5% crop growing for impacts with ORCHIDEE crop model (a) maize growing areas, (b) Sorghum growing areas.

The experiments have been grouped in several different ways to analyse the outputs from the models. Singleton groups are not displayed in the table 5 below as any singleton can be produced.

Table 5: Grouping of GCMs and RCs in climate model analysis for ORCHIDEE Crop model

Model	GCM group	RCM group	RCP 4.5 2K	RCP 8.5 2K	RCP 8.5 4K
CNRM cclm	cnrm	cclm	Medium	Late	Mid Late
CNRM smhi	cnrm	smhi	Medium	Late	Mid Late
CanESM smhi	Singleton	shmi	V Early	V Early	Early
GFDL smhi	Singleton	smhi	No data	Late	No data
HadGEM cclm	hadgem	cclm	Early	Early	Early
HadGEM knmi	hadgem	Singleton	Early	Early	Early
HadGEM smhi	hadgem	smhi	Early	Early	Early
IPSL smhi	Singleton	smhi	V Early	Early	Early
MIROC smhi	Singleton	smhi	Late	Late	Late
MPI cclm	mpi	cclm	Early	Early	Mid Early

MPI smhi	mpi	smhi	Early	Early	Mid Early
NorESM smhi	Singleton	smhi	Late	Late	Late

Results of Calibrated ORCHIDEE Crop Model

The crop model has been calibrated using WFDEI observational data, however as the CORDEX Africa inputs haven't been bias corrected it is not expected that they will produce accurate yields in these simulations. As this is the case the historical simulations from each model are treated as control simulations and relative changes are calculated. For each output the entire set of options listed in the table above are available, in this report the results are from all data. The results are given with GCMrcm naming. To show the issue with uncorrected data the raw yields and the differences are shown in Figure 15.

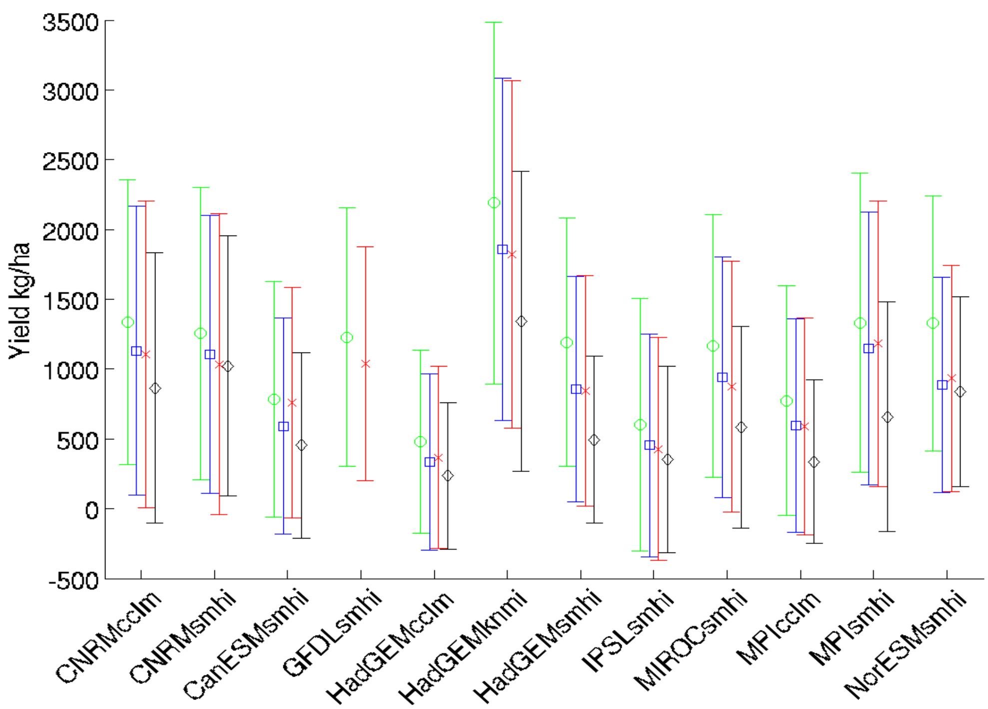


Figure 15: Average yields from the 275 selected maize cells for all simulations with the following colours. Historical = Green circle, RCP4.5 2 K = Blue square, RCP8.5 2 K = Red x, RCP8.5 4 K = Black diamond.

The yield for each grid cell and each model was subtracted from the mean historical yield from that cell on a per model basis. This created a distribution of yield changes about the mean historical yield. Figure 4 shows this distribution using all models. As can be seen from Figure 16, the amount of damage done by 2 K increase in temperature is not significantly altered by arriving earlier as part of RCP 8.5 however the longer term damages when 4 K is reached are significant with an average yield loss across all highly cultivated cells of over 500 kg/ha.

For each grid cell in each historical run a mean and standard deviation of yield were calculated, a yield below 1 standard deviation below the mean was defined as a mild crop failure and one below 1.5 standard deviations was defined as a severe crop failure. The ratio of crop failures was then calculated by dividing the crop failure rate on a per cell basis by the crop failure rate in the historical simulation. This defines the historical rate as 1 without any uncertainty. Figure 17 shows the mild and severe crop failure rate for all data. This plot shows the impact of variability, and that the crop failure rate is expected to increase significantly under 2 or 4 K climate change.

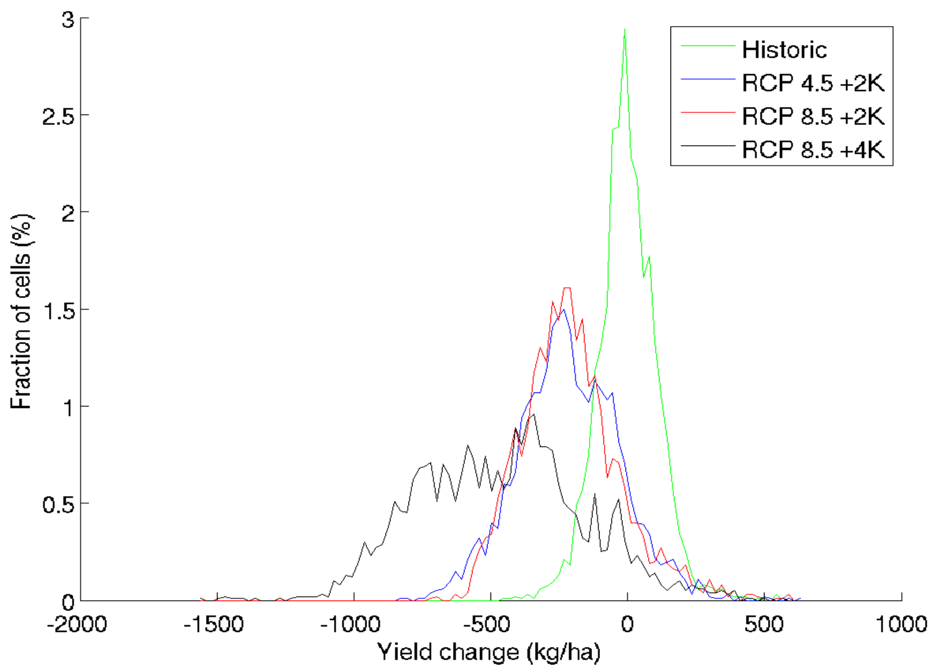
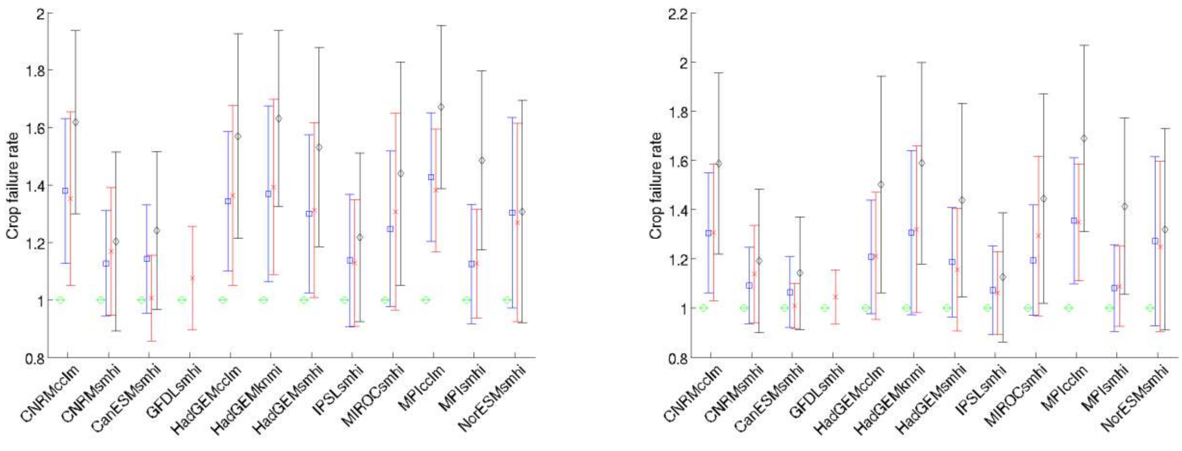


Figure 16: Average yield change from the 275 selected maize cells for all simulations.



a) b)

Figure 17: Difference in mild (a) and severe (b) crop failure rates for all simulations with the same colour scheme as used in Figure 15.

Summary and Conclusions from ORCHIDEE Crop model

The ORCHIDEE-Crop model has been used to analyse the impacts of +2/4K temperatures on tropical maize grown throughout Northern hemisphere Sub-Saharan Africa. The input data from CORDEX-Africa were not bias corrected which means they cannot be compared directly with each other nor with observations. Instead a comparison with historical self approach was taken and the results are internally consistent.

The analysis focused on regions where the cultivated area for a crop was significant, this prevented unrealistic areas from swamping the real signal. The results in Figure 4 show that reaching 2K reduces yield by about 250 kg/ha across highly cultivated areas with little difference between the RCP4.5 and RCP8.5 simulations, this indicates that the 'no if but when' approach used in HELIX is important. When reaching the high end changes of +4K the yield losses are more significant with some crops losing 1000 kg/ha in annual average yield. The results in Figure 5 show that mild and severe crop failure rates increase under climate change, this increase in crop failures not only put livelihoods at risk but indeed lives too. In particular the +4K simulations lead to a nearly 50% increase in severe crop failures.

The methods used here could be improved in several ways.

- Longer future climate simulations
- Focus instead on high end climate
- Lower cultivated area requirement

- Use of bias corrected inputs to enable comparison across models and with observations

Hydrological Impacts of Extreme Climate Changes with linkage to Sources of the While Nile within the NHSSA HELIX focus

Introduction

Implications of Extreme climate warming in water resources over the Sub-Sahara Africa region is an issue of strategic importance to both the region and its development partners. The river systems in the great lakes region of East Africa, especially the river systems draining into Lake Victoria are the source of White Nile. White Nile is an essential transboundary freshwater for the eastern half of the NHSSA region, supporting millions of people in the region. The Nile as a whole is the only fresh water resource for Egypt. The Lake Victoria, and the system of rivers draining into it, especially River Nzoia (In Western Kenya) and River Kagera (whose source is highlands of Burundi and flows through Rwanda and Tanzania into L. Victoria) as well as the out-flowing White Nile therefore form an important focus of HELIX on impacts of climate extremes and change to large scale water resources of strategic importance to many nations within and outside the region. Early results for hydrological SWAT model of River Nzoia, as the second most important tributary of the White Nile are captured in this report. River Nzoia basin covers an area of 12676 km^2, with the main source being Mt Elgon on the Kenya-Uganda bounder.

Nzoia SWAT Model and Stations with Daily Rainfall Records

SWAT is a hydrological model used in many hydrological studies and applications. It has been used for hydrological modeling of the Nzoia by several authors including Githui et al., (2009) who also provide a good description of SWAT model. In hydrological terms, SWAT model is based on the water balance equation. Figure 18 shows the digital elevation models (DEM) for Nzoia and other river systems within the Lake Victoria White Nile basin. In input data consists of daily for 39 years 1972 to 2010. From these data sets, a 30 year climatology is constructed as well as two selected cases, a wet year (1982), and dry year (2000). These are used to drive SWAT stream flow for the basin so as to investigate the likely stream flow response and difference view of current climate extremes and changes. Figure 19 shows the SWAT model DEM for Nzoia basin only alongside the rainfall stations whose daily rainfall records are used in the hydrological model within the basin.

River Nzoia Stream Flow Response to Climate Extremes

The table below summarizes the long term mean annual flow of all river systems flowing into Lake Victoria. From hydrological gauge records, it is noted that River Nzoia flow is very important for fresh water available in the lake and also the contribution to the total White Nile flow.

The Annual Mean flows (cumecs) of the Major Rivers of the Lake Victoria basin and their Relative Ranking of Contribution to the total flow into the lake.

River Basin	Sio	Nzoia	Yala	Nyando	North Awach	South Awach	Sondu	Gucha-Migori	Mara	Grumeti	Mbalageti	E. Shore Streams
Annual mean m^3/s	11.6	117.5	38.4	18.3	3.8	6.0	43.0	59.2	38.2	11.8	4.3	18.9
Rank	15	2	6	12	20	17	4	3	7	14	19	11
River Basin	Sim iyu	Magogo Moame	Nyashishi	Issanga	S. Shore Streams	Biharamulo	W. Shore Streams	Kagera	Bukora	Katonga	N. Shore Streams	
Annual Mean m^3/s	39.8	8.5	1.7	31.1	26.1	18.2	21.1	266.0	3.3	5.2	1.5	
Rank	5	16	22	8	9	13	10	1	21	18	23	

Using SWAT model driven by daily rainfall, Nzoia flow is found to exhibit an annual cycle pattern, with peak flow centered on the months March-April-May. From our results using daily rainfall for stations in Figure 19, the long term mean flow is to the order of $800m^3$. It can be as low as 500m3 for during dry years, for example during year 2000 and can be as high as $1200m^3$ during wet years, for example year 1982. Figure 20 summarizes these annual cycle patterns of the flow. One of the most notable change signal in area rainfall is a decreasing trend. Figure 21 is a good illustration of this decreasing trend during the 39 years 1972 to 2010. The March-April-May period is also the long rainfall season in Equatorial East Africa and this decreasing trend in observed rainfall is a well-known mode.

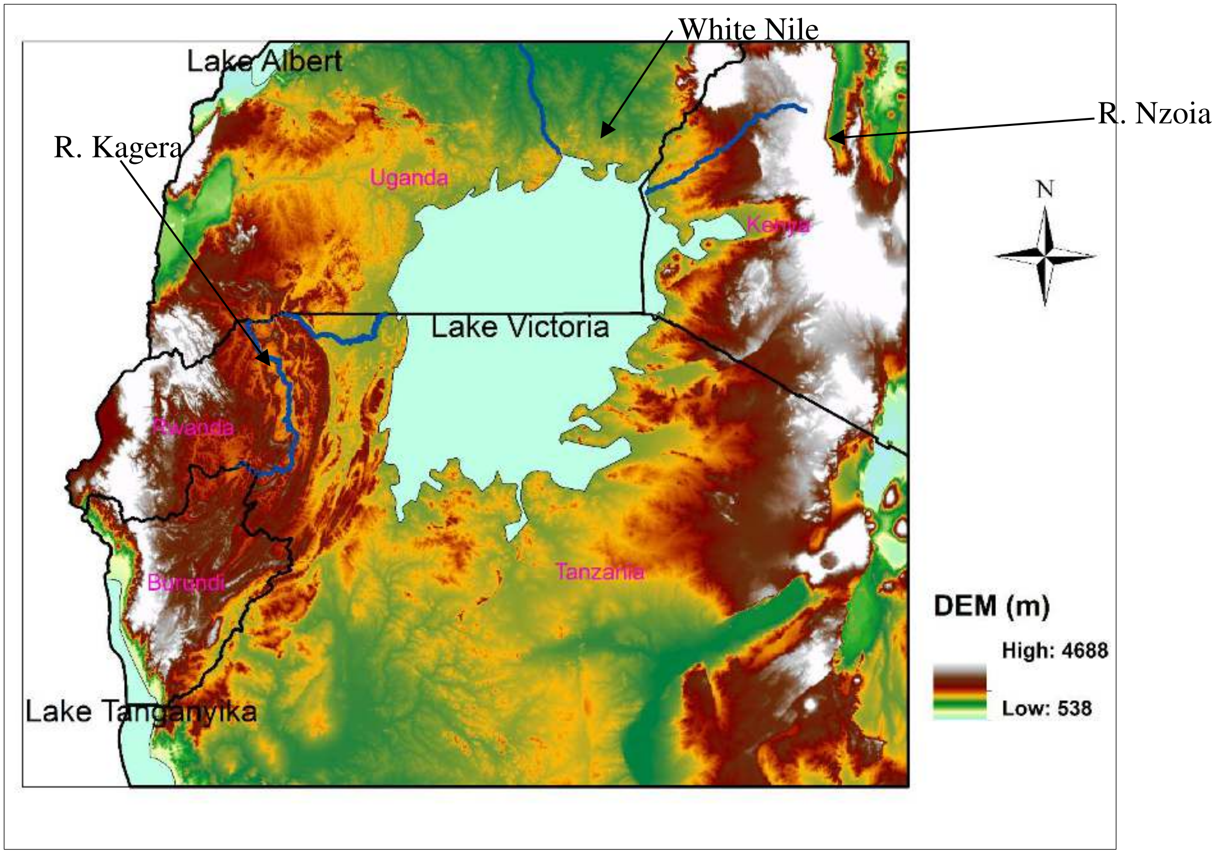


Figure 18: The digital elevation models (DEMs) of White Nile, Kagera and Nzoia Rivers within the Lake Victoria Basin as examples of Large Scale Water Resources within NHSSA climate change impacts on water resources.

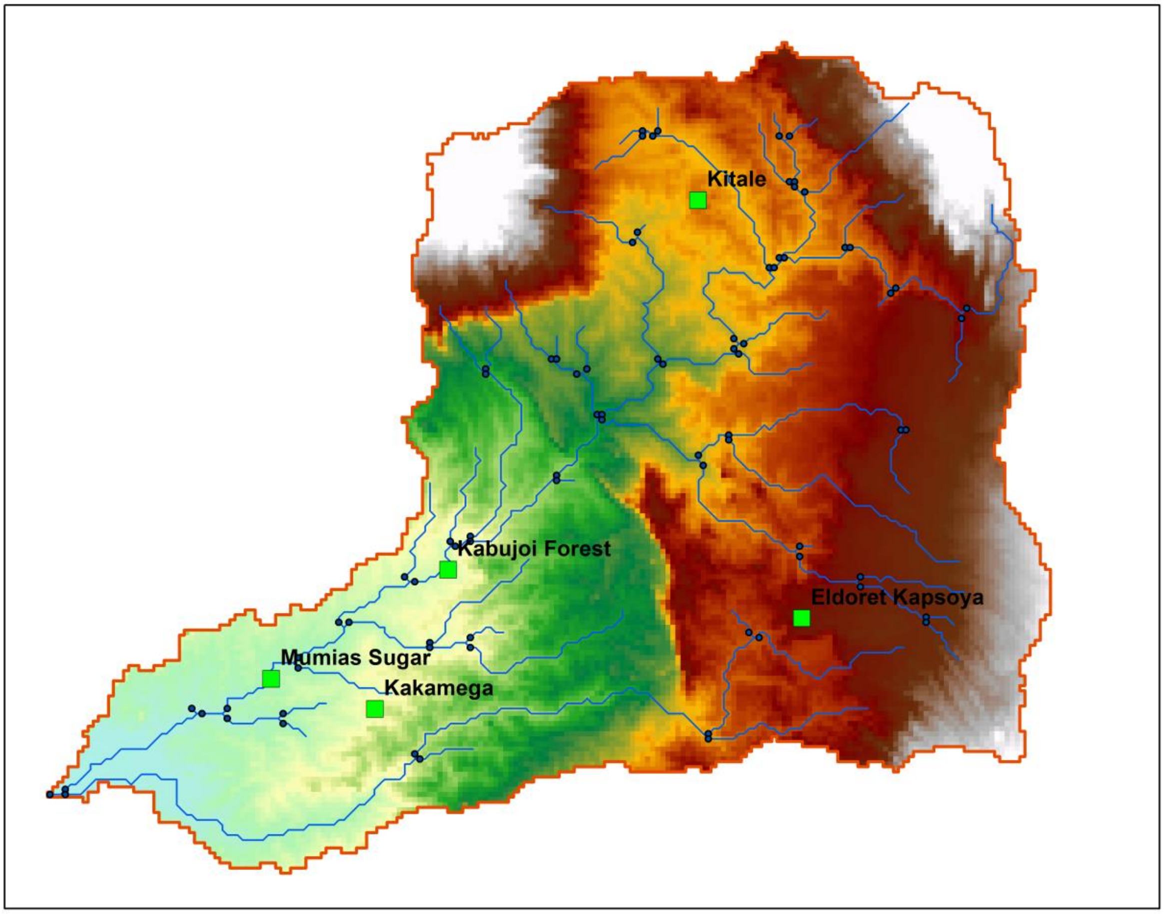


Figure 19: The digital elevation model (DEM) for Nzoia Basin and stations with daily rainfall records used in HELIX W. Kenya and White Nile SWAT model for stream flow impacts.

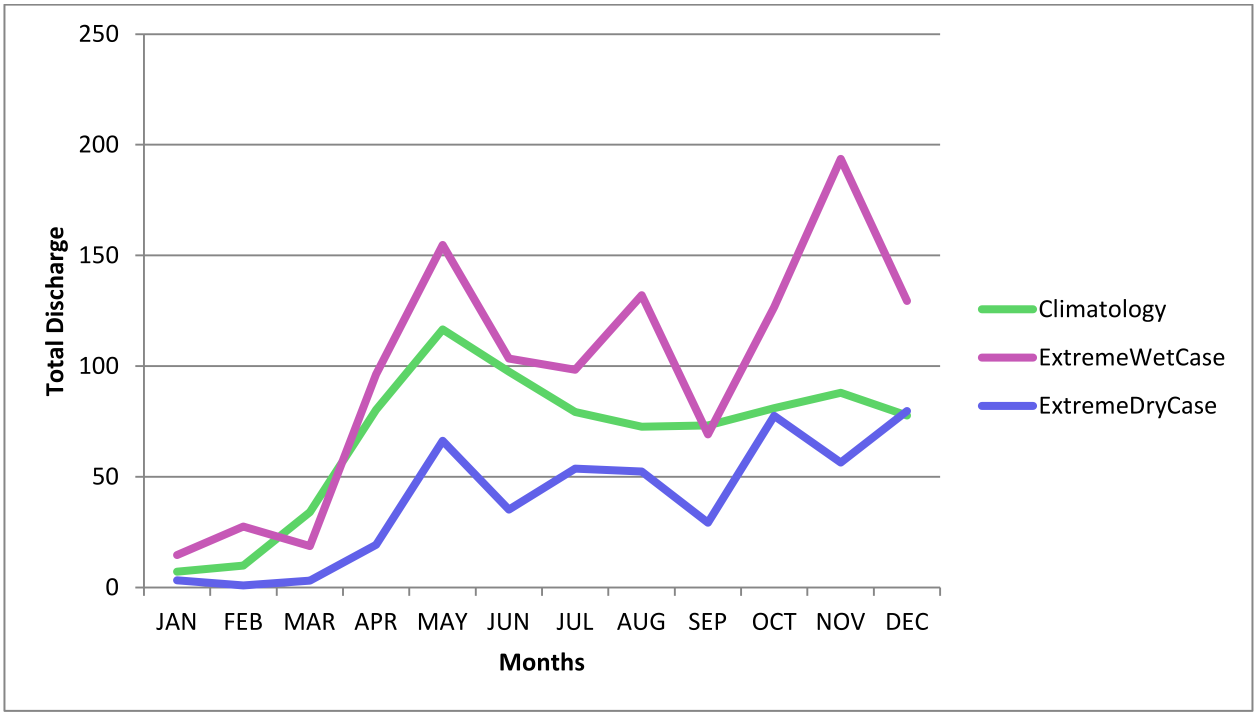


Figure 20: SWAT Model: River Nzoia Annual Flows and Response to Climate Extremes. River Nzoia, a Major Tributary of the White Nile in HELIX W. Kenya Water Resources.

Summary and Conclusions

Nzoia river is the second most important river and therefore fresh water resource for Lake Victoria and the White Nile. Its annual flow, as modeled using SWAT model driven by rainfall indicates that the water yield can be nearly half the climatological base line when dry conditions prevail. In this part of NHSSA, total annual rainfall shows a decreasing trend and therefore fresh water yields in the catchment basins forming the large scale river system like the whole of the Nile, during the near- and long- term future is an issue of concern for societal welfare within and outside the region. This result and its implications on regional and international issues like water rights and treaties will be carefully modeled with internally consistent HELIX climate change model and decisive conclusion with policy implications drawn during the final phase of the project.

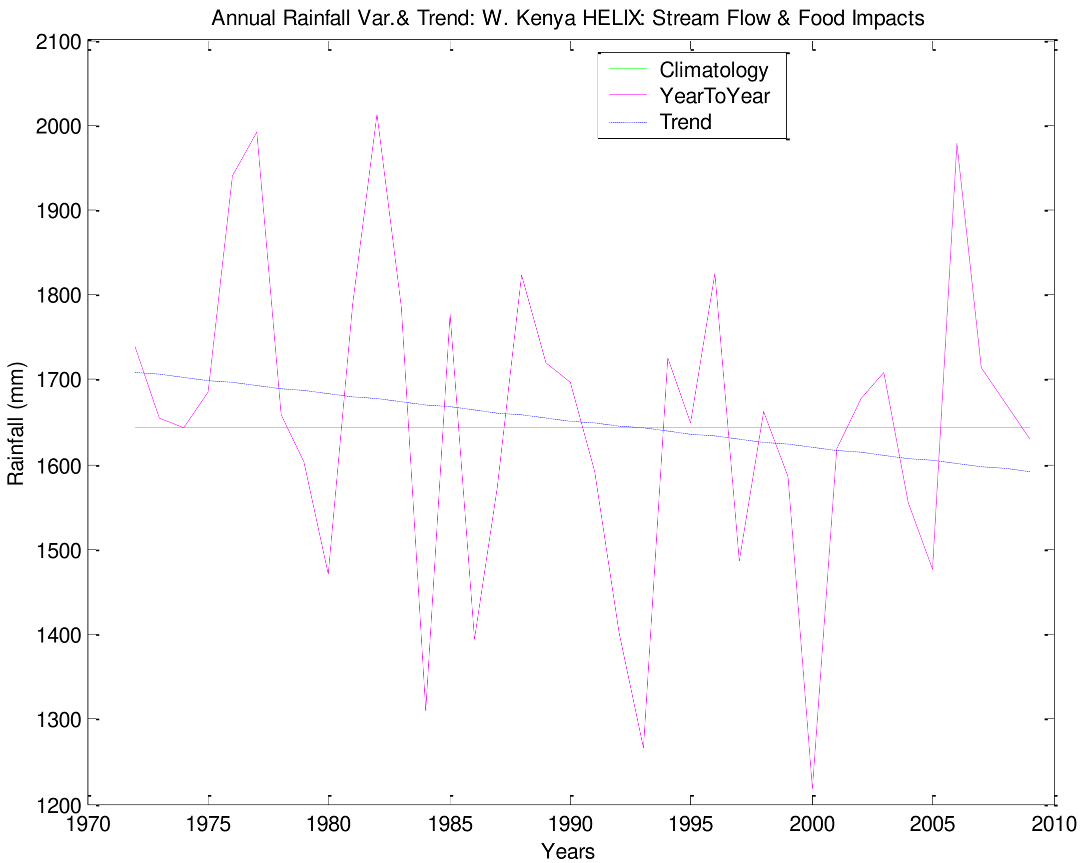


Figure 21: Interannual variability and annual rainfall trend over Western Kenya Nzoia basin within HELIX focus on regional water resources impacts.

Impact of Vulnerability and Resilience to Environmental Changes on Mobility Patterns in Sub-Sahara Africa: West Africa Case Study

Introduction

The northern hemisphere of sub-Saharan Africa (NSSA) is witnessing a variety of impacts of climate extremes and change, including sea level rise, soil salinization, floods, drought, and desertification, while simultaneously suffering other forms of environmental degradation. Together, these environmental changes are significantly influencing migration patterns in and out of the sub-regions of NSSA. Research carried out within the framework of the HELIX project, for which regional foci are West and East Africa, analyzes *vulnerability* and *resilience* to environmental changes as they affect and are affected by mobility patterns in the region.

As a point of departure, this research approaches migration from the view that the impact of environmental changes cannot be isolated from political, social, economic and other demographic pressures that together drive human mobility. In regions where natural resources form the foundation of livelihoods and food security (e.g. fishing, pastoralism and agriculture), the relationship between environmental changes and socio-economic vulnerabilities is of particular concern. This research therefore draws from distinct case studies in order to grasp the variegated and cumulative vulnerability and resilience among local populations as they relate to internal and intra-regional migration.

West and East Africa are among most dynamic regions in which to examine the human impacts of climate change. From the Sahel to the coasts, it faces the many manifestations of climate change, including sea level rise, soil salinization, floods, drought, desertification, intensifying winds and heat waves (IPCC 2014; DARA 2013). Moreover, the consequences of climate change are only one part of current processes of environmental degradation affecting the region. Taken together, these environmental changes are significantly influencing mobility patterns. While environmental degradation acts as one driver of regional mobility, it cannot be isolated from other political, social, economic and demographic pressures that together shape migration patterns (Black et al. 2011).

Within the framework of HELIX task CCT1b.2 on migration and conflict, case studies have been completed in West Africa, which serve as the basis of the present document. Further studies are planned for the East and Horn of Africa.

Objectives

The aim of the on-going research aims to provide an analysis of *vulnerability* and *resilience* to environmental changes in relation to mobility patterns in West Africa. The 2014 IPCC report defined *vulnerability* as “the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt” and *resilience* as “the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.”

Outcomes are based on extensive field research experience relevant to environmental changes and migration. Each case study takes a distinct methodological and disciplinary approach to analyze impacts of environmental degradation on the vulnerability and resilience of communities, households, and individuals and their relationship with migration in NSSA as a crucial HELIX focus region. The objective is to reflect the diversity of environmental migration in the region specifically tied to slow-onset environmental changes by touching upon different environmental stressors, economic sectors tied to natural resources, and the heterogeneity of vulnerability and resilience among local populations as it affects their mobility responses. In addition to demonstrating the complexity and diversity of the environment-migration nexus across the region, several connective threads run throughout these case studies that are of critical importance to African policymakers as well as governments and strategic development partners including the European Union (EU) : the importance of local perceptions of environmental changes and of differentiated and cumulated vulnerabilities within each studied population as they determine mobility decisions and outcomes for resilience.

Preliminary results

Vulnerability, resilience and mobility in West Africa

Current environmental trends in West Africa

A significant increase in the frequency and intensity of natural disasters in West African countries has been observed in recent decades and attributed to global warming (IPCC 2012). Floods, droughts, strong winds and heat waves are the most tangible extreme weather events affecting populations (DARA 2013). According to the most recent data from the International Disaster Database of the Centre for Research on the Epidemiology of Disasters (CRED 2015), natural disasters such as droughts and floods have affected over 28 million people in West Africa from 2010 to 2014. Strong coastal erosion and sea level rise are further compounding the vulnerability of populations along the entire coast, from Mauritania to Nigeria (UEMOA 2010). Desertification and soil erosion are continuously augmenting as a result of the aforementioned climatic events (Stringer et al. 2011), adding pressure to food insecurity and therefore exacerbating further the vulnerability of local populations.

A recent study on livelihood security in West Africa led by the United Nations Environment Programme identified 19 ‘climate hotspots’ severely affected by natural disasters and climate change (UNEP 2011). These hotspots are mainly located in the central part of the Sahel, Niger, Burkina Faso, northern and coastal Ghana, as well as in northern Togo, Benin and Nigeria and often straddle international borders, highlighting that risk management requires an inter-state response. These areas have been heavily hit by floods in recent years and also recorded significant increasing temperature and a substantial increase in the frequency of droughts. The latter primarily affect the most arid countries (Mauritania - Mali - Niger), which account for nearly 90% of drought victims (50 million cumulative people) since 2000 in West Africa (Gemenne et al. 2014). These recent changes are affecting the livelihoods of millions of people who depend directly on natural resources.

The agricultural sector employs 60% of the workforce while it contributes only 35% of GDP (Abdulai et al. 2013). The national economies in this sub-region of NSSA are particularly vulnerable to climate change because the populations are heavily dependent on rain-fed agriculture. The effects of climate change are strongly felt by rural communities, regardless of their geographical position and the reporting rainfall zone. A majority suffers from a decrease in the length of the rainy season due to a delay of the starting date and an earlier end, an increase in extreme rainfall events and dry periods within the rainy seasons that may compromise agricultural production. A majority of farmers in the Sahelian arid zone believe that precipitation changes have occurred during the last 20-30 years, while in wetter areas (Guinean zone) effects were felt during the last decade (Ozer and Perrin 2014).

According to UN estimations, the population of West Africa increased from 86 million in 1961 to 340 million people in 2014, and is expected to increase to 815 million people by 2050 (FAO 2014). Mainly cities will be affected by rapid demographic growth, partly because of rural-urban migration trends (Foresight 2011). In sub-Saharan Africa, 70% of rural-to-urban migrants move into slums where population are particularly vulnerable (UN Habitat 2010). The urban population accounted for 16% (14 million) of the total population in 1961, 47% (159 million) in 2014 and is expected to reach 66% (534 million) in 2050 (FAO 2014). Urban areas are not equipped to absorb such population growth, while simultaneously they are increasingly threatened by global environmental change (Foresight 2011) and their resilience capacities decrease. The annual floods reflect the explosive growth of cities, poverty and the lack of urban planning policies. Human activities are responsible for the increased flooding due to urban sprawl in risk areas (floodplains of rivers, depression areas, axes serving as natural outlet of the water, etc.). Nouakchott, Ouagadougou, Cotonou, Dakar, and Niamey are some examples of cities more and more regularly affected by flooding, as are a large number of primary and secondary cities of all countries of the West African Region (Ould Sidi Cheikh et al. 2007; and Descroix al. 2013). According to the newest report from the Intergovernmental Panel on Climate Change, the cities of developing countries with health services, housing and disposal systems of good quality water will more easily adapt to climate change (IPCC 2014), but this unfortunately is not the case among West African cities.

In 2005, 168 countries signed the Hyogo Framework for Action (HFA) and agreed to establish action plans to reduce the risks of natural disasters by 2015 (UNISDR 2011). According to UNISDR, more than half of African countries have established frameworks but as these countries have minimal resources to devote to it, few have actually implemented policies and plans to reduce disaster risk.

Current projections suggest that Sub-Saharan Africa will be the most affected by extreme climate change, along with small island states, coastal and deltaic regions (Gemenne 2011). The fifth assessment report (AR5) of the IPCC mentions that temperatures could rise by 3°C to 6°C in some parts of Africa, including the Sahel, by 2100 (IPCC 2014), which is likely to be accompanied by a significant increase in natural disasters. The recurrence of extreme events makes people more vulnerable. Adverse effects are expected on major crop production and livestock, the availability of drinking water, and will probably cause the collapse of the fishing industry. In addition, climate change contributes to food insecurity and worsening health problems (IPCC 2014). Faced with these threats, policy responses are urgently needed because the effects of global warming are a serious obstacle to development and regional resilience.

Environmental context as a driver of migration in West African sub-region of NSSA

Environmental context as a driver of migration has attracted the interest of scientists and policy makers in the last three decades (Oliver-Smith 2012). While findings of studies show consensus that environmental factors play a role among many interacting causes of migration, there is a debate as to their importance (Perch-Nielsen et al., 2008). It is a combination of factors (economic, political, demographic, social and environmental) that explains human migrations (Black et al., 2011). In West Africa, population movements, including displacement, are caused by economic crises, armed conflict, generalized violence, violations of human rights, large-scale development projects, environmental change and natural disasters (Ferris and Stark 2012). The relation between environmental change and migration is still complicated because the impacts are mostly indirect (Mortreux and Barnett, 2009; Foresigh 2011). For example, rainfall variability affects migration via livehood systems (Warner and Afifi, 2014).

The analysis of the environment-migration nexus literature allows us to distinguish forced migrations from voluntary migrations in response to environmental change, people who flee a disaster from people who gradually leave because of environmental degradation, internal migrations from international migrations, permanent migrants from temporary migrants *(Bates, 2002; Gemenne, 2011b; Renaud et al., 2011). On the other hand, environmental changes include a set of different processes: rapid onset hazards, loss of ecosystem services and slow onset hazards that consist in accelerated or gradually degradation of ecosystems (Renaud et al., 2011). The term 'environmental migration' is complex because there is a set of environmental influences (Gray and Bilsborrow, 2013) and environmental change might affect human mobility in various way (Jónsson, 2010). In response to rainfall variability, four patterns of migration are distinguished (Warner and Afifi, 2014): (1) households that use migration to improve their resilience (successful migration), (2) households that use migration to survive, but not flourish, (3) households that use migration as a last resort and erosive coping strategy and (4) households that cannot use migration and are struggling to survive in their areas of origin. Whether migration is a forced movement or adaptation strategy will depend on a number of factors such as the type of climate shock, the characteristics of the affected population and the capacity of institutions (local, national and international) to prevent the effects adverse climatic shocks (Coniglio and Pesce 2010).

The concept of immobility is fairly new (Black et al., 2013) and very important because environmental change increase the vulnerability of people and make them less able to migrate in some cases. Several studies showed that migration decreased during the severe drought-years in the 1970s' and 1980s' in Burkina Faso (Henry et al., 2004) and in Ghana (Van der Geest, 2011). This can be explained by the fact that migration requires financial resources that cannot be mobilized in times of crisis. Some studies proved that it is not generally the poorest people who migrate (Tacoli, 2009). In some cases, the migrants themselves increase the vulnerability of their communities of origin because they represent a depletion of the workforce, skills and wealth for their community of origin (Cissé et al., 2011). Sometimes, migration have conversely positive impacts on origin communities and on the environment in the origin area. Migrants reduce the vulnerability of their communities of origin through remittances and information (Adger et al., 2002; Tacoli, 2011). Thanks to skills transfer, migrants share new techniques of management of soil fertility and as they left, they alleviate the pressure on local resources. This kind of positive feedback helps to maintain the original populations in place by improving both their live conditions and their environment.

Floods are among the most frequent natural disasters in the West African sub-region of NSSA and cause population displacement. The number of people affected by floods in West Africa has increased steadily since 1980. According to statistics from the EM-DAT data (CRED 2015), floods have affected (without necessarily moving) 13.6 million people in West Africa over the 2004-2013 period. In total, 600,000 people were affected by the 2009 floods in Burkina Faso, Ghana, Niger, Senegal and Sierra Leone. According to estimates by the Internal Displacement Monitoring Centre (IDMC), in Nigeria, 6,818,000 people were displaced due to natural disasters between 2008 and 2012. The devastating floods of September and October 2012 caused the displacement of 6,112,000 people which is 3.6% of the total population in this country. Thousands of homes, bridges and other infrastructure as well as large agricultural areas were completely devastated (IDMC 2013). According to estimates, the number of people threatened by coastal flooding will dramatically increase along the Gulf of Guinea, the Senegalese and Gambian coasts (UNESCO 2012). In West Africa, 40% of the population live in coastal cities and it is expected that 500 km of coastline between Accra and the Niger Delta will become megacities of more than 50 million people by 2020 (Hewawasam 2002). Studies have shown that among African port cities most exposed to sea level rise, six of them (Lagos, Abidjan, Lomé, Conakry, Dakar, and Accra are in West Africa () (Nichols et al. 2008). Sea level rise can also cause soil salinization and thus damage land, agricultural productivity and food security.

Although most mobility due to natural disasters occurs within national boundaries, studies have shown that rural communities affected by drought and slow-onset events can cross borders especially where borders are more permeable such as the Sahel (Seck 1996; Findley 1994). Mobility due to economic, social and political vulnerability can have indirect effects on resilience to environmental factors, just as environmental factors may aggravate existing and fragile social, political, and environmental conditions. For example, the drought that affected the Sahelian region in 2012, combined with the political instability and conflict occurring in the north of Mali, displaced hundreds of thousands of people to the drought-affected communities in the south and in neighbouring countries. A special feature of West Africa is its unusually high level of intra-regional migration, with the highest number of mobile peoples of any region in the world. According to the bilateral migration matrix, developed by the World Bank (2010a), over 58% of migration flows in West Africa take place within the sub-region. The importance of intra-regional migration in West Africa can be partly explained by the creation in the late 1970s of an area of free movement of people within the Economic Community of African States West (ECOWAS). In fact, migration between West African countries are mostly from neighboring countries (World Bank 2010b). It is the only sub-region of Africa where intra-regional migration is greater than outward migration (34.5%, mainly to Europe) (Ndiaye and Robin 2010). With some 8.4 million people, West Africa also has the largest stock of migrants of any sub-region in the world (UN DESA 2009). Despite these statistics, lack of reliable data on population dynamics in the region (and especially as they relate to environmental migration) makes it difficult to assess vulnerability and mobility on a regional scale. It is thus essential that governments cooperate in order to collect reliable data upon which policymakers can shape long-term strategies. Political, social and environmental crises existing in the region will be exacerbated by the effects of climate change in the coming years, likely leading to more frequent migration (IOM 2014).

Case studies

The impact of perceptions of extreme rainfall changes on population movements in West Africa

Climate change has been affecting the economic and social vulnerability of populations for decades, particularly in West Africa where the populations are largely dependent on rain-fed agriculture (Juana et al. 2013). Economic losses, damages to water resources, decreases in crop production and mortality are some of the direct and/or indirect impacts that must be mentioned (Crétat et al. 2014; Meehl et al. 2000; Mouhamed et al. 2013). Are such impacts due to increasing frequency of extreme events and climate variability, to growing vulnerability or to both (Easterling et al. 2000)? It is currently difficult to answer this question without thorough empirical evidence. What is more certain is that populations must adapt to environmental changes. In arid and semi-arid areas, adaptation strategies to climate change implemented by farming communities vary from area to area and depend on a multitude of factors, including cultural ones (Adger et al. 2009; Nielsen and Reenberg 2010). Temporary or permanent migrations are part of these households' adaptation strategies to maintain their standard of living through the diversification of livelihoods (McLeman and Hunter 2010; Wouterse and Taylor 2008).

There is an increasing number of studies about impacts of environmental changes on migration but they are based on objective determination of environmental changes. Populations' migratory responses are made based on their perceptions of environmental changes and their own vulnerability to them; thus, taking into account the perception of change by local populations can improve the understanding of the environment-migration nexus and help to understand the magnitude and character of future migration patterns.

This study therefore compared the perceptions of rainfall changes experienced by people in different climatic zones of West Africa with the actual trends recorded in the same period. Then, assuming that migration decisions are made based on the perception of changes rather than changes themselves, the second objective was to assess migration intentions as direct responses to future climate change in order to investigate and establish the importance of migration in this region in the coming decades.

Methods

A request by keywords was carried out using the Scopus and Google Scholar databases since 2000 to find studies on perceptions of rainfall change in West Africa. A distinction was made between studies in arid zone (300-500 mm) and in semi-arid zone (500-900 mm). Results of studies were compared with real climate trends available in the literature. The data on the intention to migrate was taken from socio-economic surveys of the AMMA[1] project conducted in five West African countries between November 2007 and June 2008. Questions related to intentions to migrate, either temporarily or permanently, in response to three potential situations – a drought, a more arid climate and a more humid climate – were posed to 1342 households distributed in two climatic zones (Mertz et al. 2011). We analyze the main strategies considered by respondents in case of rainfall change and assess the place of the intention to migrate among them.

Findings

Perception of rainfall change vs observed trends in West Africa

Literature review shows that the most important change felt by the West African populations is a decrease in total annual rainfall but populations also perceived a decrease in the length of the rainfall season (late onset date and early cessation date), an increase in dry spells during the rainy season and in periodic droughts and irregular rainfall.. These perceptions have the same trends in the two climatic zones but are somewhat more pronounced in the arid zone than in the semi-arid zone.

There is an overall pessimistic perception of rainfall change. Results show that population believe there has been change in rainfall while such change in rainfall trends are not clearly reflected in climatic data *(New et al., 2006, Lebel and Ali, 2009). Despite variation in observed changes in rainfall across and within the sub-region, populations share similar perceptions of environmental stress; differences between observations and perceptions may thus be characterized as a reflection of a progressive decrease in socio-economic conditions (resulting notably from a loss of profitability in agricultural sector) due to other factors co-occurring with climate change (demographic pressure, environmental degradation) (Müller et al., 2014). West African people become increasingly vulnerable because of its population growth and poor infrastructure, and it will be increasingly difficult for them to be resilient even in the face of even low intensity changes (Müller et al., 2014).

[1] African Monsoon Multidisciplinary Analyses

Intention to migrate in case of rainfall changes

In response to a drought, a drier climate or a wetter climate, migration is rarely the first adaptation strategy currently implemented by the surveyed population, but the intention to migrate is an important one should the situation worsen (or rather be perceived to worsen). In case of drought, respondents currently give priority to selling their livestock but several strategies are often considered together. Temporary migration has been cited as the first strategy in case of a drought by 24% of respondents and in total, 29% of respondents intend to use temporary migration in response to a drought in the future. In the case of a drier climate, the first two cited strategies are search of new crop varieties and livestock sales. About 11% of respondents indicated that they would resort to temporary migration and 30% to permanent migration in response to a future drier climate; and temporary and permanent migration would be the first strategy for 6% and 13% of households respectively. The intention to migrate also exists but is less important in the case of a wetter climate, with only 2% and 4% of respondents saying that they would migrate temporarily or permanently in this case. When counting people who intend to migrate temporarily in a rainfall deficit situation (drought and/or drier climate), 36% of respondents plan to adopt this strategy. In total, taking into account temporary and permanent migration, more than 51% of respondents plan to migrate if rainfall conditions deteriorate in the future. However, some people who do not intend to migrate may not have a choice in the future and may have to use migration as a survival strategy. Conversely, the intention to migrate may not translate into actual movements: people who intend to migrate may find themselves unable to do so, lacking the necessary means (e.g. financial, social, and human capital).

Conclusion and policy implications

While researchers and stakeholders often consider the effects of climate change on the vulnerability and resilience of affected populations, this case study highlights the importance of taking into account populations' *perceptions* of climate change as it can affect their adaptation responses. This means that, positing the possibility of a perfectly rational decision to migration in response to perfect information on the actual climate event, that decision is not actually in the populations' capacity to make, as it is their perceptions of change driving behavior (stay or move) rather than actual change. The conclusion of this study raises the need for better information reaching vulnerable populations, in order to allow to make better informed policy choices.

Environmental Mobility and Fishing Communities in Guet Ndar, Saint-Louis (Senegal)[2]

Context

Senegal's coast, like many other coastal West African countries, is threatened by climate change impacts of coastal erosion, sea level rise, flooding, soil salinization, and increasing storm surges (Salem 2013). Concomitantly, the Senegalese coastal waters have witnessed changes in currents, stronger waves, depletion of fish stocks and decreases in maritime bio-diversity. These visible impacts of climate change have been compounded by man-made environmental degradation, including overfishing by national and foreign industrial vessels, and local changes to infrastructure, such as the opening of a breach in 2003 that

[2] The research leading to these results has received funding from the European Union Seventh Framework Programme *FP7/2007-2013* under *grant agreement* n° 603864.

displaced dozens of villages in the Langue de Barbarie along Senegal's northern coast (Tacoli 2011). These environmental changes threaten the livelihoods of the approximately 600,000 people directly or indirectly working in the Senegalese fishing industry (FAO 2008), augmenting and diversifying existing mobility patterns. Yet Senegalese fishermen's mobility responses and their effects on local resilience capacities have received little attention.

Methods

In order to examine the migratory patterns associated with man-made environmental degradation and climate change impacts in West African fishing communities, a qualitative case study was undertaken in Guet Ndar,[3] an overcrowded fishing quarter in Saint-Louis, Senegal. Along with an extensive literature review and document analysis, the primary tools of investigation were qualitative, in-depth interviews and focus groups with fishermen (migrant and non-migrant), women working in the local fishing industry, and leaders of fishing associations. Local and national stakeholders, experts, community leaders, and researchers were also consulted in Dakar and Saint-Louis. The qualitative data was collected over a five-week period during the summer of 2014. Participants were selected using a network-sampling strategy, and insofar as possible maximum variation, in which respondents reflected different occupations, ages, men and women and geographical locations (and thus the differences in perceived and actual environmental threats) within Guet Ndar.

Findings

In 2008, UN-Habitat designated the city of Saint-Louis as the most threatened by sea level rise in all of Africa. The fishing quarter of Guet Ndar in Saint-Louis is particularly vulnerable to environmental degradation. This stems, firstly, from the quarter's location between the Senegal River on its eastern limits and the Atlantic Ocean to its west, leaving it with no territory to expand into as the sea advances. Piles of rubble and debris where homes once stood line the coast. Currently, those who live on the 'front lines' of Guet Ndar are forced to build their own makeshift barriers to protect their homes from coastal erosion and sea level rise. In the south of Guet Ndar, women's working spaces for fish processing are now tightly cramped areas, wedged between the sea on one side and a cemetery on the other. In turn, some women have resorted to performing their work beside their homes, or commuting to a newly constructed space north of Guet Ndar near the Mauritanian border. Compounding local vulnerability, the quarter is one of the most densely populated districts in all of West Africa, with more than 25,000 inhabitants occupying an area of 1 km long and 300 m wide according to regional statistics (CLUVA 2013; Ateliers 2010). The local impacts of climate change only exacerbate overcrowding, with coastal erosion forcing the growing population into an ever-smaller space. Furthermore, without an agricultural production scheme, almost all households rely on fishing in one form or another. The local population is also heavily reliant on fish for their own subsistence, being a hallmark of the daily local diet in traditional dishes such as Thiéboudienne. Guet Ndar's inhabitants are therefore especially vulnerable to the impacts of climate change and environmental degradation as they threaten their local livelihood strategies, their lands, and their food security. Interestingly, however, only two respondents in the study attributed environmental changes in Guet Ndar in any way to climate change. Respondents cited overfishing by foreign vessels and other unintended consequences of man-made changes to the environment (i.e. the opening of a breach in 2003 to decrease

[3] Interviews were also conducted in rural villages in the south of the Langue de Barbarie and two urban neighborhoods to the north of Guet Ndar: Ndar Toute and Goxum Baccc.

flood risks in the city) as being the primary causes of environmental degradation, and thus the key challenges facing Guet Ndarians alongside urban overcrowding.

Mobility Patterns

As local livelihoods become increasingly difficult to maintain, building on a long history of fishing migration throughout West Arica, many Guet Ndarian fishers respond by traveling northward to Mauritania (cf Sall and Morand 2008), where infrastructure and livelihood opportunities are markedly better. While some fishermen fish irregularly just across the Senegalese-Mauritanian border or obtain one of 400 licenses granted annually to fishermen to bring catches back to Senegal, the danger of fishing irregularly stemming from conflicts with the Mauritanian coast guards historically and contemporarily led most respondents to obtain contracts with Mauritanian factories. Lacking a strong fishing tradition, factory representatives are sent to the quarter to recruit the highly experienced Guet Ndarian fishermen. The primary international destinations of Guet Ndarian fishermen are the Mauritanian cities of Nouakchott and Nouadhibou. Although retired respondents had fished outside of Guet Ndar in Mauritania, Guinea, Guinea-Bissau, among others, the diminishment of local fish stocks due to climate change and overfishing has increased fishing migration to Mauritania and for longer durations. Whereas retired fishermen had travelled for short periods and seasonally in the past, currently active fishermen are spending 10 months or more outside of Guet Ndar. Moreover, those who stay in Guet Ndar and fish locally no longer abstain during maritime reproductive months because of the diminished returns the rest of the year and a lack of local infrastructure to preserve their catches, which in turn exacerbates maritime resource depletion.

Fishermen preferred to remain in Guet Ndar, however, fishing migration allowed men to support their families living in the community and area of origin. Money earned by fishermen in Mauritania is sent primarily through informal channels to relatives who stay behind in Guet Ndar. These remittances supplement household income and provide for basic necessities such as food, water and shelter, demonstrating the importance of migration for improving household resilience in the community of origin by decreasing residents' reliance on the local economy. However, currency exchange rates weakened remittance potential and, additionally, differences among migrant fishermen led to varying levels of remittances. Irregular fishermen often have their equipment confiscated, are jailed and/or fined by the Mauritanian coast guard, losing any earnings or assets in the process.[4] Poorer artisanal fishermen who take up contracts with Mauritanian factories must pay off the debts they accumulate when taking on loans for fishing equipment (boats, nets, motors, etc.), which decreases their remittance capacities. Only the more successful fishermen, who own their own, larger boats (*pirogues* of 25m) and therefore are able to generate larger catches, are able to send greater sums back to Guet Ndar. Importantly, the last group is able not only to provide their families with basic necessities, but also to relocate their families out of Guet Ndar and away from the encroaching sea. In a gradual process (sometimes taking more than a decade), remittances are used to construct homes in other coastal districts perceived to be safer from sea level rise and coastal erosion. Although local authorities have made gestures towards establishing residential developments for Guet Ndarians at danger of displacement, homes in these areas are often costly and relocation remains out of reach for the most vulnerable households to climate change and environmental degradation, placing them at risk of becoming 'trapped populations' (Foresight 2011).

[4] Respondents who obtained a license to fish in Mauritania and return with their catches to Senegal also reported the same problems, citing corruption among Mauritanian coast guards.

Conclusions and Policy Implications

Driven by residential destruction, demographic pressures and concomitant economic strife caused by maritime resource degradation, urban fishermen and their families are highly vulnerable to the current impacts of climate change, which will only exacerbate migratory pressures in the future. In order to protect these vulnerable coastal populations, firstly local and national governments must intervene to mitigate and adapt to the effects of climate change but also to limit degradation caused by man-made environmental changes (e.g. overfishing by foreign trawlers, unsustainable fishing practices, and breach openings). As is, outside of makeshift barriers, departure is often seen as the only solution for those who are able to do so.

Environmental degradation is already significantly influencing both internal and international mobility patterns in Saint-Louis, Senegal. However, Guet Ndarian households' vulnerability varies and so does their capacity for migration and building resilience. Active fishermen are able (if not always willing because of precarious conditions) to move up the coast in order to sustain their livelihoods, while those who are retired, elderly or whose occupations are land-based are less able to enact migration as an adaptation strategy and therefore rely on household members' labor migration.

But while most fishermen are able to embark on international labor migration in one form or another, only the most successful fishermen are currently able to relocate their families within Senegal. The findings from case of Guet Ndarians therefore demonstrates the importance of integrating livelihood strategies and socio-economic status variations into vulnerability and resilience assessments and local, national and intra-regional adaptation plans. Policies and government initiatives must also make relocation available to the most vulnerable households, those in imminent danger of displacement and those without the capital to move out of harm's way. However, any efforts to relocate fishing families must be accompanied by infrastructure that recognizes their dependence on the sea, making commuting to work accessible for example. Furthermore, policy interventions that seek to limit the need for international migration must ask how the local fishing sector can be developed to absorb excess labor supply and to address inadequate fish stocks, such as through investment in preservation and processing factories and the halting or mitigating of unsustainable fishing practices, both commonly cited solutions among Guet Ndarian respondents.

Lastly, the connections between internal and international mobility patterns exposes the importance of addressing environment-related population movements with integrated local, national and regional solutions. As demonstrated by empirical investigation, these mobility responses are highly interrelated as international migration can facilitate internal relocation through remittances, and therefore call for cooperation among different levels of government and between countries. Although Senegal and Mauritania recently upped the number of annual licenses granted for people to bring fish back across the Senegal-Mauritanian border from 300 to 400, further increases could improve local populations' resilience capacities by stimulating the local economy, improving food security, and ameliorating precarious living and working conditions for migrant fishermen as well as local actors in the fishing sector. However, ongoing conflicts between the Mauritanian coast guard and Senegalese fishermen must be addressed to facilitate migration as adaptation.

The settlement dynamics of populations vulnerable to erosion in Cotonou's coastal zone (Benin)

Context

In the 21st century, the effects of global warming could be particularly disastrous for coastal areas, among others those located on the Gulf of Guinea in West Africa. The coast of Cotonou, the economic capital of Benin, has recorded significant coastal erosion for several decades, mainly due to the obstruction of the littoral transit by the harbour built in 1962 and the decrease in sedimentary inputs from the west due to diverse coastal protection structures. Moreover, sand quarries carried out directly on the beach have amplified erosion. Like most other coastal nations, a high proportion of the population is located on the coast. The vulnerability is exacerbated by rapid demographic growth and inadequate resources for urban development. In the future, the process will very likely be amplified by sea level rise and more frequent storms as consequences of global warming (Ozer et al. 2013).

This study examined population dynamics in a section of the coastal zone of Cotonou that is exposed to rapid erosion. The aims were to determine the vulnerability of populations in the risk zone and to analyze the responses of the authorities in order to underline the needs in the context of climate change, since global warming is responsible for sea level rise that accelerates the shoreline erosion process.

Methods

In order to assess the eroded area in the six kilometres directly east of the harbour infrastructures and to observe the human settlement dynamics next to the sea, multi-temporal analyses of very high-resolution satellite images from Google Earth (2002, 2011 and 2013) were carried out. We completed the analyses with field missions in September 2012, September 2013 and July 2014. These fieldworks consisted of discussions with institutional actors, local authorities and researchers and of twenty interviews with affected populations.

Findings

Between 1963 and 1997, the coastline retreated by 400 meters at the east of the harbour of Cotonou (CODJIA, 1997). Diachronic analyses of satellites images show that the sea eroded approximately 75 ha of land between 2002 and 2013. This corresponds to a coastline retreat of 125 meters in 12 years. Coastal erosion is observed up to the Nigerian border, which is 27 km east of Cotonou, with an erosion of 30 meters in 10 years recorded at the border.

In some zones, one observes a progressive replacement of parcelled/standing houses by makeshift houses between 2002 and 2011. Furthermore, between 2011 and 2013 images reveal a rapid destruction of some of these newly constructed houses.

Migrants and trapped populations

Results from fieldwork show that people with sufficient financial and/or social capital left the coastal zone when their houses were threatened by the sea. According to evidence, they relocated inland, usually to the peripheral areas of Cotonou. People remaining in the risk zone were mainly fishermen and precarious populations. Fishermen (or their parents) are native to the region of Grand-Popo (on the coast 90 km to the West of Cotonou) and arrived in the coastal zone of Cotonou in the 1970s in order to have better living conditions and more employment opportunities. However, since their arrival, they made successive displacements along the coastal zone due to the encroachment of the sea. Due to loss of assets and capital allocation for constructing a new home, their vulnerability increased with each move. There are two groups of precarious populations in the zone. On the one hand, there are people who lost their homes to the sea, causing them to fall into poverty. On the other hand, there are poor people who moved *into* the risk zone because they had no money to pay rent elsewhere in the city. Both groups feared being displaced by the sea. Unlike fishermen who want to stay near the shoreline for their economic activities, the precarious populations want to leave the coastal area but lack the financial capital and social networks to do so. Results highlight an increasing vulnerability of populations as the sea continues to advance and a concomitant decrease in their resilience capacities, forcing the poorest people to stay in the risk zone, they become 'trapped' populations (Foresight 2011). Without sufficient resources or other viable alternatives, people's only adaptation strategy is to continually move within the risk zone.

Authorities' responses

In the national strategy to implement the UN Framework Convention on Climate Change, Benin proposed two adaptation options: 1) stabilizing the coastline by building groynes (rigid hydraulic structures built from an ocean shore in coastal engineering that interrupts water flows and limits the movement of sediment therefore reducing erosion), and 2) relocating activities, communications, transport, hotel infrastructures and communities out of the risk zone. Under the pressure of associations, all marine sand quarries were closed in March 2009. Since May 2014, seven groynes were built in the most exposed zone for a cost of 45.4 milliards FCFA, financed by several investors (essentially Islamic States Funds). At a scale of a groyne, positive effects are observed at the west of the structure but negative effects (fast erosion) appear at the east. However, the problem is transferred to the east of the zone where the seven groynes are placed, to the neighbouring municipality. The installation of such protection structures restores confidence to investors who are starting to build new standing houses in the zone protected by the groynes.

Conclusion and policy implications

There is a lack of habitat regulations and land use planning addressing settlement in the risk zone. Some laws and decrees have not been respected and others are inadequate and should be revised or updated. Additionally, there is little awareness among the local populations of existing legal mechanisms and regulations. Although the Cotonou town council wants to solve the erosion problem whilst avoiding the displacement of their residents, they have few resources within their reach. They place their hopes on the groynes but realize that their effectiveness will only be proven over time, and, furthermore, that even then the problem will be transferred to the neighboring municipality. Meanwhile, local authorities try to persuade fishermen to relocate away from the sea but do not offer compensation or assistance. However, they turn a blind eye to informal settlements because they have no alternative to propose.

In addition to the need for local solutions, coastal erosion is not confined to this zone and so the development of international cooperation with other countries in the Gulf of Guinea is necessary. Benin, like the other ten coastal countries of West Africa, has adopted a master plan for coastal development with the support of the West African Economic and Monetary Union (UEMOA) but implementation of the recommendations must be consistent within the region. Consultation with affected populations is also needed (Teka and Vogt 2010).

General conclusions and Policy Recommendations

Climate change's effects on mobility in West and East Africa, as well as outside of NSSA, cannot be isolated to a singular outcome. Environmental degradation, whether resulting from slow-onset changes or sudden shocks, affects populations' vulnerability and resilience capacities in complex manners. These complexities stem from, and result in, variegated and cumulative vulnerability and resilience among and within African populations. Firstly, the presence of multiple environmental trends and shocks vary geographically within the whole Northern Hemisphere Sub-Sahara Africa. While desertification and droughts are of prime importance for some communities, floods, coastal erosion and sea-level rise are the main hazards which have livelihoods and migration implications in other areas. Even within local populations affected by the same climatic threats, their vulnerability and likelihood to migrate is affected by their socio-economic status (with those having some form of financial and social capital more able adapt locally and/or through migration), their dependence on natural resources, and their demographic characteristics (age, gender, etc.). Together, cumulated vulnerabilities increasingly shape differentiated mobility outcomes and consequential capacities for resilience.

A holistic comprehension of how environmental vulnerabilities compound pre-existing vulnerabilities is essential in order to provide useful responses. Given the aforementioned differentiated vulnerabilities and capacities for resilience, there is no one-size-fits-all solution. Policy must be adapted and implemented according to particular populations and needs. Strategies will need to take into account geographical and climatic variations, but also socio-economic differentiated vulnerability in order to build resilience. However, that does not preclude the need for regional cooperation. While the particularity of threats may be local, climate change stimulates internal and international migration that will affect all the countries of Africa.

However, it is not only that policy must take into account differences among and within local populations in terms of their vulnerability and subsequent migration decisions, policymakers must also consider vulnerability as it is *perceived* by those affected. We cannot therefore treat environmental mobility as a strictly rational behavior based on actual vulnerability, as if local populations perceptions of environmental threats and changes necessarily correspond with meteorologically observed climatic trends or their causes. Furthermore, perceived vulnerability among local populations must be analyzed in terms of all of its components (environmental, political, economic, demographic, etc.) as they together inform people's subsequent (im)mobility behaviors and intentions. Building resilience among local populations therefore requires assessing perceived *and* actual vulnerability as well as educating local populations about current and expected changes to their natural environments, which can facilitate better-informed mobility decisions.

As the relationship between vulnerability and mobility outcomes varies among and within the presented case studies, so too does the impact of environmental mobility on individual, household and community resilience. Again here it important to consider how people's mobility decisions are based on their expectations of the outcomes of these movements. While migration may be perceived to increase individual and household resilience to socio-environmental changes, it may in fact place them at further risk in the destination area. Furthermore, regional rural-to-urban migration does not always provide better conditions for migrants, who may struggle to find employment in destination areas and often move into slums and makeshift housing in urban peripheries. These living conditions can exacerbate risk to environmental and health hazards.

However, migration can also offer a significant tool with which local populations can increase their resilience to socio-environmental changes. In conclusion, regional authorities must work together to build the resilience of sending communities to climatic shocks, but they must also facilitate migration as an adaptation strategy by, for example, recognizing the developmental potential of remittances. In addition, to avoid adverse migration outcomes, they must prepare destination areas (especially coastal urban centers) to receive internal and international migrants but they must also better inform those living and migrating to risk zones about the potential risks of (im)mobility in and out of these areas. These policy interventions may help decrease the potential for the creation of 'trapped' populations (Foresight 2011), be they trapped in areas of origin, in transit, or in destination areas.

Forthcoming work in the East and Horn of Africa

Following the results of the conclusion of the West African case studies and review, a distinct but complementary set of case studies will be undertaken in the East and Horn of Africa. In broad terms, the goal of these studies will be to assess the impact of dryness and successive drought events on mobility patterns of rural communities, agro-pastoralists and rain-fed agriculture-dependent populations in particular, with a view to exploring the dynamics underlying the varying points at which coping strategies are employed, migration among them.

Case studies in Ethiopia and central Tanzania where rural populations are reliant on natural resources and are vulnerable to precipitation and temperature changes (agricultural, pastoral, and agro-pastoral livelihoods) have been explored, in order to build a richness of the regional analysis envisaged.

Migration related to successive drought cycles

An exploration of mobility related to successive drought cycles is envisaged as a basis for understanding how extreme climates may erode livelihoods and compounded vulnerability of rural agro-pastoral and agricultural communities. Among rural households which derive most of their income from agricultural activities, assuming varying levels of income and access to capitals, and that migration is one possible household strategy, the assertions that remain to be explored include: [H.1.] During reported drought period, households are more likely to have a household member migrate as a coping strategy; [H.2.] for vulnerable households this has little effect on long-term resilience and/or erodes the effectiveness other household coping strategies; [H.3.] During dry years, households of varying vulnerability levels (a combination of vulnerability indicators based on the multivariate vulnerability index (MVVI)) may make different migration decisions; [H.4.] Different forms of migration (e.g. circular and seasonal migration versus permanent, internal versus international) have different impacts on household capacities and resilience to further shocks; and [H.5.] Households reporting multiple idiosyncratic shocks over time (i.e., for whom livelihoods are eroded and insecurity) a) make different migration decisions and b) have different livelihoods outcomes. Household inclusion in resilience-building programs[5] and the presence of negative social and political externalities (e.g. conflict) should also be assessed against migration outcomes and the multivariate vulnerability index.

This research seeks to build on understandings of the linkages between drought and livelihoods choices, by further exploring rural populations' characterization of their natural environment as well as their perceptions of environmental and climatic changes. A better understanding of these dynamics - always framed within a deeper understanding of vulnerabilities and opportunities of varying socio-economic, gender, generational and ethnic groupings – serves as a basis to environmental and climate stress influence migration and mobility both directly through environmental hazard events (e.g., the drought and famine crises since 1984), conceived as similar to shocks, as well as how environmental changes indirectly affect migration patterns through their effect on economic and political drivers of migration.

Perceptions versus measured impacts in responding to dryness and drought shocks

Scholars from the natural sciences often struggle to include the nuances of human activities, non-linearity and human choices in biophysical models. Yet regional models for the consequences of high-end warming scenarios mean little without including the human response to the biophysical changes occurring around them. For millions of people across the developing world whose livelihoods depend directly on natural resources, recent changes in local climates and perceptions of these changes are paramount to an understanding of livelihood choices and household risk coping strategies.

Using qualitative research and climate perception surveys this research seeks to build on research carried out in West Africa, described above, to develop a more appropriate characterization of drought in East and the Horn of Africa that integrates socio-cultural points of view with observed weather and climate data. This research seeks to answer the question of: how do perceptions and narrative characterizations of drought among rural agricultural communities of East and West Africa compare to measured precipitation and temperature data?

Research objectives

The goal of this work is threefold. First, to build on previous research exploring indices and variable sets for drought that combine perceptions of drought with measurable drought indicators.[6] Next, to work towards a more comprehensive and appropriate set of variables for "drought" that can be used in research linking climate change to livelihoods choices, with an emphasis on migration. Finally, to contribute to a bridging between natural science and social science in climate change research, by aiding in a better integration of human systems into climate change scenarios.

A qualitative narrative is envisaged to be compared to a set of accepted measurable rainfall and temperature indices. In the post-mission phase, the work established with the support of UNU colleagues

[5] These are defined as locally implemented social and political programs that influence in household resilience. These will include participation in informal and semi-formal credit cooperatives, key government poverty reduction and rural development initiatives and a small number of externally-funded climate change adaptation/resilience building projects.

[6] C.f. Gray & Mueller 2012, for example, for which a weighted drought measure was constructed using both reported drought periods from interviewees (perceived drought) combined with measured rainfall data.

will seek to build on research developing a set of variables that together more comprehensively represent a human-centered characterization of "drought" than perceptions or weather data alone.

Methods

Census data and survey data[7], is used to establish a baseline analysis of changes in socio-economic conditions, consumption, sources of income, out-migration[8] and self-reported household response to shocks[9] are assessed selected sites since 1984, a year of significance due to the severe drought and famine crisis in 1983-85 in today's Ethiopia and Eritrea. This thirty year time horizon is chosen as a benchmark to begin to assess long-term changes in climate and other environmental changes (soil quality, rainfall variability) and second to use the 1984 drought as a point of reference after which migration patterns have emerged.

The methodology for developing a multivariate vulnerability indices (MVVI) as well as qualitative information is adapted from on-going innovative research in the domains of risk assessment, assessing non-economic loss and damage and vulnerability mapping (c.f. IOM 2015; Warner et al. 2012)

The Hunger and Climate Vulnerability Index in Sub-Sahara Africa

Introduction

The Hunger and Climate Vulnerability Index (HCVI), has been developed to illustrate the complex interactions between food security and climate change. The analysis is based on the definition of vulnerability to climate change from the Intergovernmenal Panel on Climate Change. In this case, vulnerability is defined as the relationship between the degree of climate stress on populations (exposure), the degree of responsiveness to stress (sensitivity), and the ability of populations to adjust to the climatic changes (adaptive capacity). Indicators are selected based on their relevance to food security through rigorous statistical analysis. A total of 17 indicators were chosen for exposure (demographics, climate-related hazard frequency and intensity), sensitivity (agricultural and environmental profiles), and adaptive capacity (socio-economics, infrastructure and governance). Details of the methodology for developing the index can be found in Krishnamurthy et al. (2014).

Following the development of the index, as described in Krishnamurthy et al. (2014), it was then adjusted to use gridded climate model data for the exposure to climate-related hazard component of the index. A

[7] Use of the Ethiopia Rural Household Survey (EHRS) of the Ethiopian Government and the International Food Policy Research Institute is envisaged.

[8] Defined in most available survey as a household member who has moved out of the district of survey enumeration, most commonly for labor opportunities or marriage, since the previous survey was enumerated.

[9] Includes pests, illness in the family and other idiosyncratic shocks; natural hazards and drought in particular are subsets and in focus for the purposes of this research.

selection of Global Climate Model runs from the CMIP5 database (REF) were inputted into the index and the results for the HELIX Sub-Saharan Africa (North of the equator) region are shown below.

The Hunger and Climate Vulnerability Index

In order to evaluate the climate change impact on food security through the index, the first step is to generate the baseline values of vulnerability in the present day. Figure 22shows the categories of vulnerability, computed using the Index, for the baseline period across the region. The data used in this case was the WATCH forcing reanalysis dataset (REF).

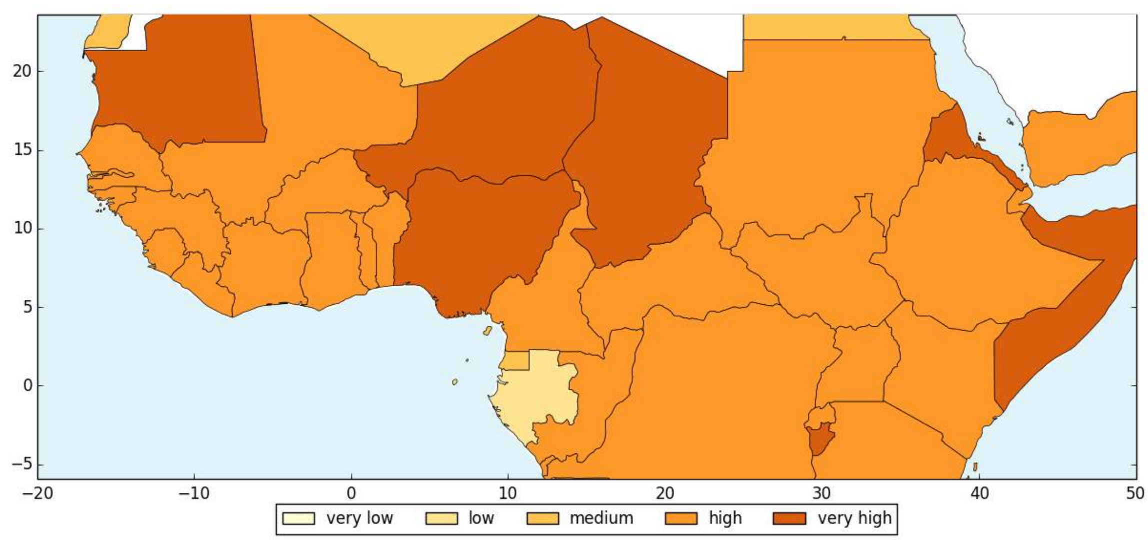


Figure 22: Present day Hunger and Climate Vulnerability Index. (Krishnamuthry et al., 2014).

Figure 22 Highlights the fact that in the present day the vulnerability to food insecurity from climate is high or very high in most countries within the region.

Projections of the Hunger and Climate Vulnerability Index Sub-Saharan Africa

The Index was then re-calculated using data from a sub-set of the CMIP5 GCM runs, relevant to the HELIX project. These three runs were IPSL CM5-MR, GFDL ESM2M and HadGEM2-ES. The methodology for adapting and running the Index with climate model data can be found at Richardson et al., (2015).

For each of the three GCMs the Index was calculated using two Representative Concentration Pathways (RCPs). The first RCP 2.6, is consistent with a global average temperature rise of approximately 2 °C. The second, RCP 8.5, is consistent with a global average temperature rise of approximately 4 °C by the end of the century. These results are shown in

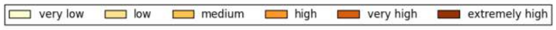


Figure 23 for the 2050s, and Figure 24: for the 2080s.

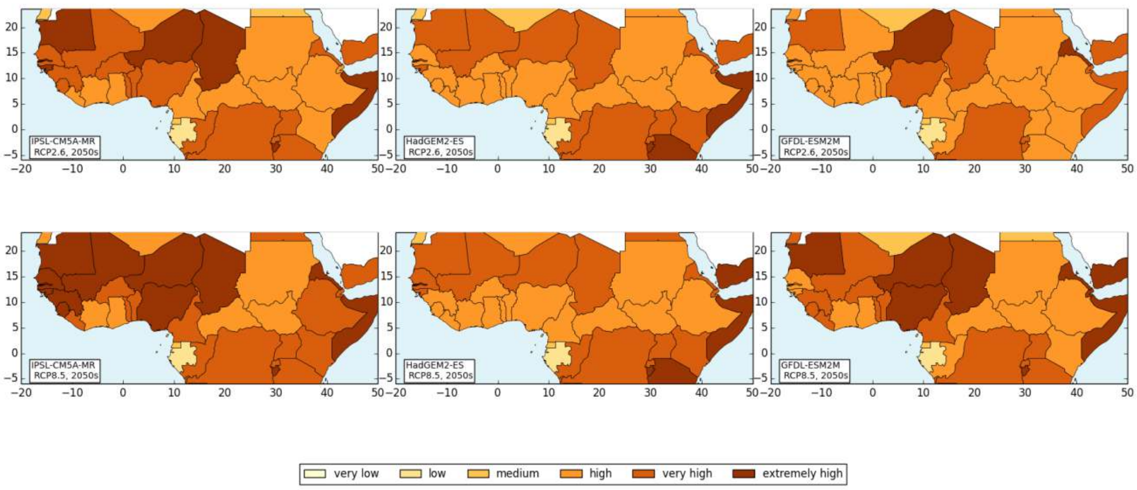


Figure 23 Future projections for the 2050s of the HCVI2 for the HELIX subset of CMIP5 models; IPSL-CM5-MR is shown in the left column, HadGEM2-ES in the middle column, and GFDL-ESM2M in the right column. The top two rows show the RCP2.6 scenario, the bottom two rows show the RCP8.5 scenario.

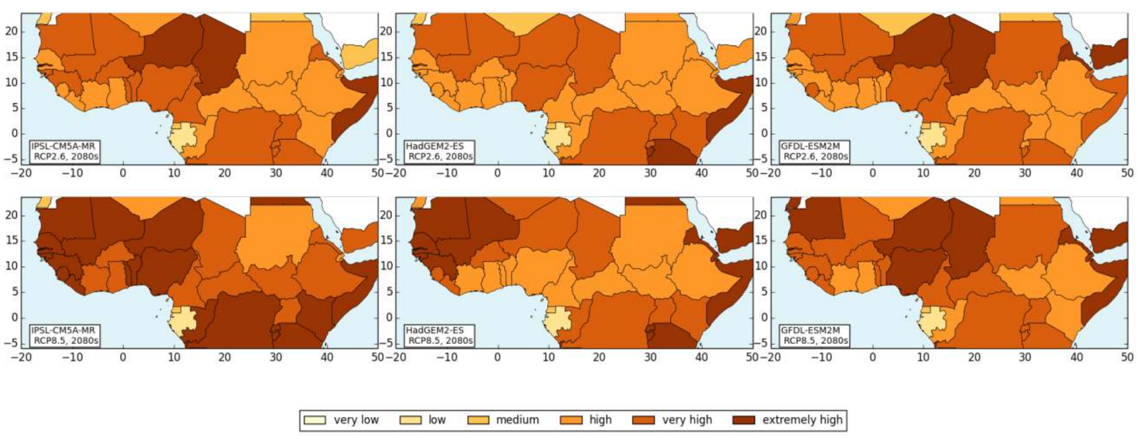


Figure 24: Future projections for the 2080s of the HCVI2 for the HELIX subset of CMIP5 models; IPSL-CM5-MR is shown in the left column, HadGEM2-ES in the middle column, and GFDL-ESM2M in the right column. The top two rows show the RCP2.6 scenario, the bottom two row shows the RCP8.5 scenario.

All six of the projections show a similar pattern for food insecurity, but IPSL shows the largest increases, followed by HadGEM2. By the 2050s, the two RCP scenarios show a similar levels of increase, although the levels of vulnerability to food insecurity are slightly higher for RCP 8.5 than RCP 2.6. This is true for all three of the climate models, although the absolute levels are different between the models. However, by the 2080s there is a larger difference between the two RCPs. The projections for RCP 2.6 show little change from the 2050s, but the projections of the index for RCP8.5 show further increases in food insecurity.

These results are consistent with those found for the Index across all models globally. The message remains that under either RCP vulnerability to food insecurity increases by the 2050s, due to the amount of climate change the earth system is already committed to. After this time, the level of increase in vulnerability to food insecurity depends strongly on the RCP. Under RCP 2.6 food insecurity remains steady at the 2050 levels. Under RCP 8.5 it continues to increase further. This means that to maintain current levels of food security, and to prevent climate change increasing the number of food insecure people, both adaptation and mitigation are required. Adaptation is required to address the challenges of the climate change we are already committed to. Mitigation is required to prevent the level of climate change exceeding our ability to adapt.

WP8: ISIMIP maize yields for Sub-Saharan Africa

Introduction

This document shows total maize yield (rainfed simulated yield over present-day rainfed land combined with irrigated simulated yield over present-day irrigated land) from Inter-Sectoral Impacts Model Intercomparison Project (ISIMIP). There are seven crop models used in this inter-comparison, each driven by three CMIP5 Global Climate Models (IPSL-CM5A-MR, HadGEM2-ES and GFDL-ESM2M; these are the three driving GCMs from ISIMIP that also appear in the HELIX subset of models).

Maize Yield data and Impacts

The maize yield data is masked to only show areas which grow maize in the present-day (more than 5% of the grid cell). The estimate of the fraction of the grid cell growing maize from the Monfreda dataset over areas shown in Figure 2left panel) is used to create this mask, and is interpolated onto the ISIMIP 0.5 x 0.5 grid as shown in Figure 2Right right panel).

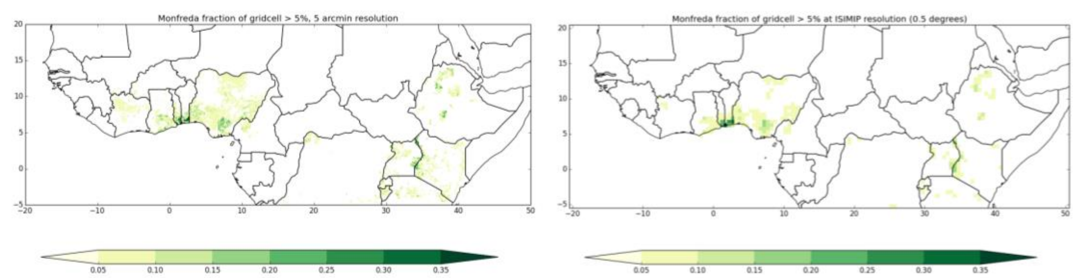


Figure 25: Left panel – Fraction of the grid cell growing maize, representative of year 2000 (Monfreda *et al.*, 2008). Grid cells with less than 5% of the cell growing maize have been masked. Right panel – the Monfreda maize data from the left panel on the ISIMIP grid (0.5° x 0.5° grid).

The masked total maize yield simulated from the ISIMIP ensemble over the baseline period (1981 – 2010) is shown in Figure 25. The projected yield, absolute change and percentage change in yield compared to the baseline (Figure 26**:**) from the ISIMIP ensemble for the RCP2.6 and RCP8.5 scenarios and the 2050s and 2080s time periods are shown in Figure 26 to Figure 3.

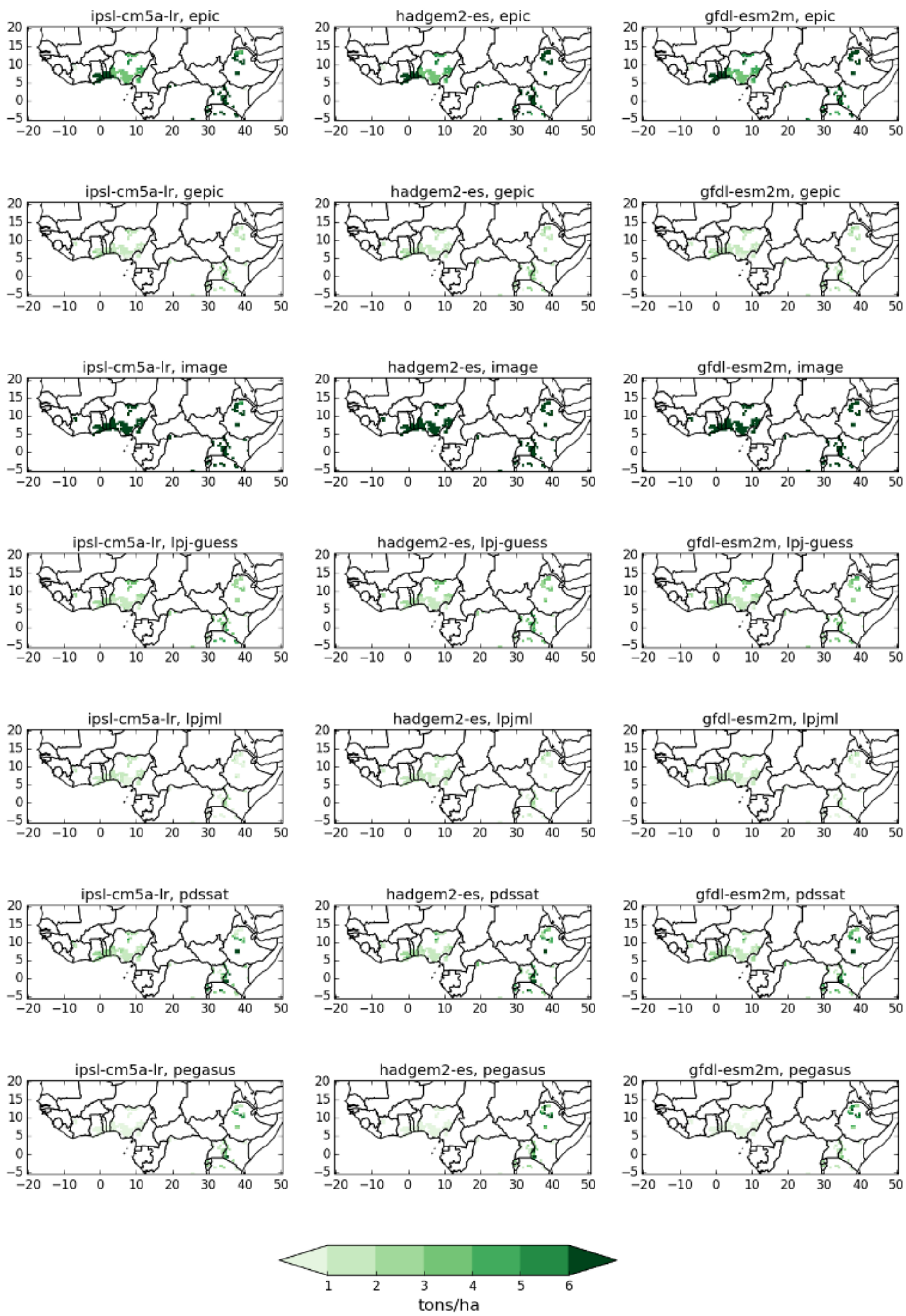


Figure 26: Maize yield over the baseline (1981 – 2010) period in the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

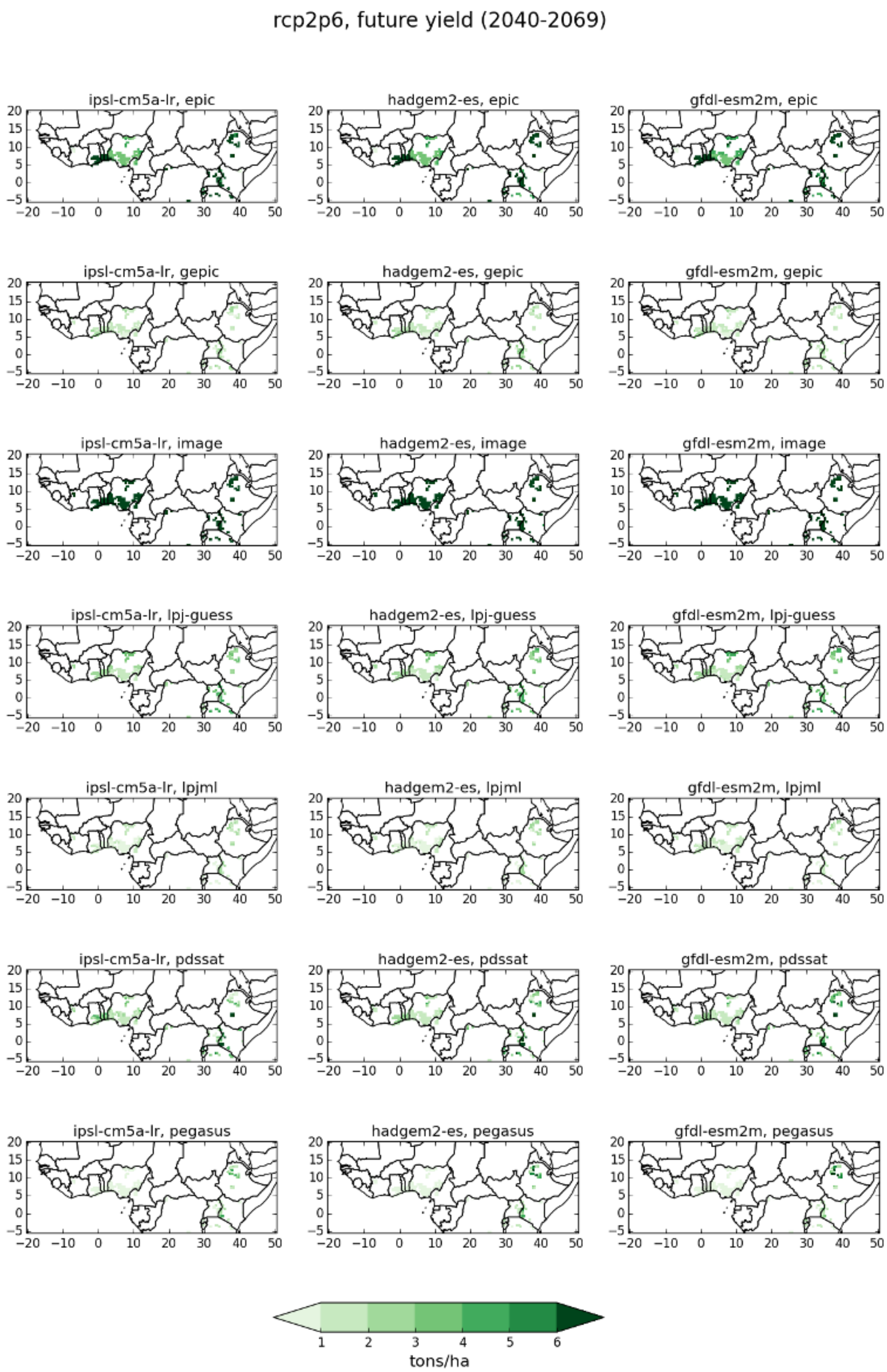


Figure 27: Projected maize yield for the RCP2.6 scenario and 2050s time period for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

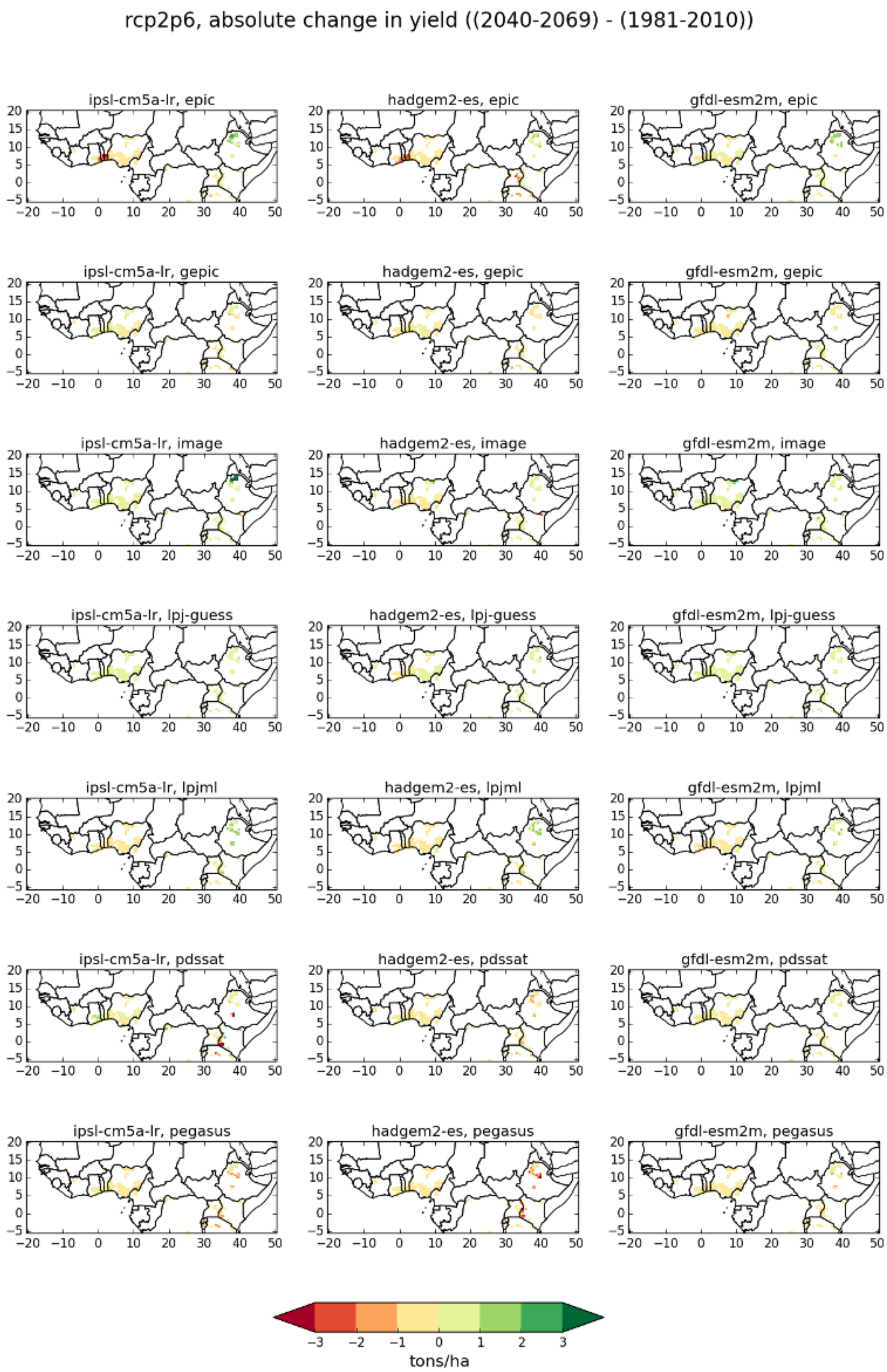


Figure 28: Absolute change in maize yield between the 2050s and baseline period (Figure 26: for the RCP2.6 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

rcp2p6, percentage change in yield ((2040-2069) - (1981-2010))

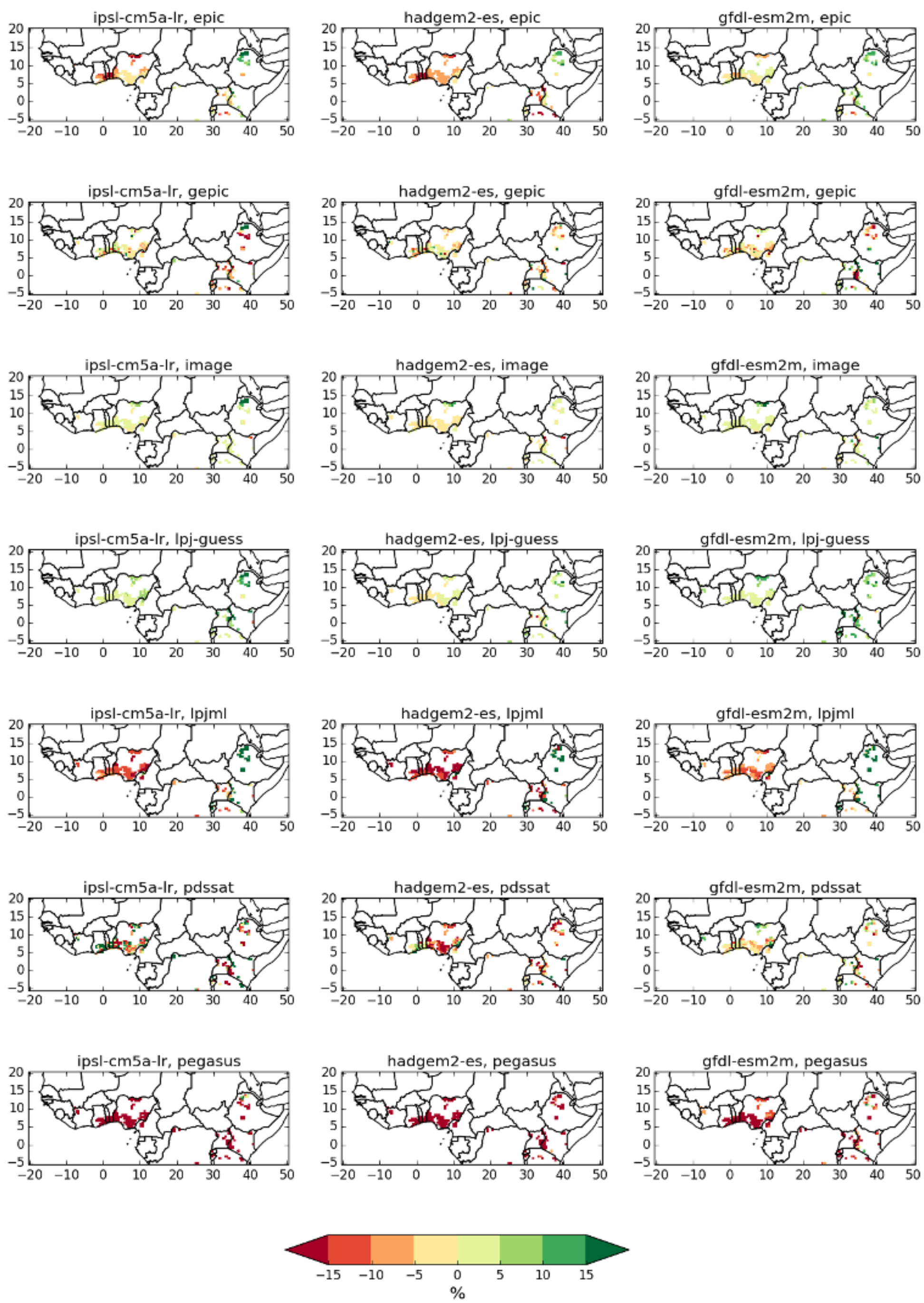


Figure 29: Percentage change in maize yield between the 2050s and baseline period for the RCP2.6 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

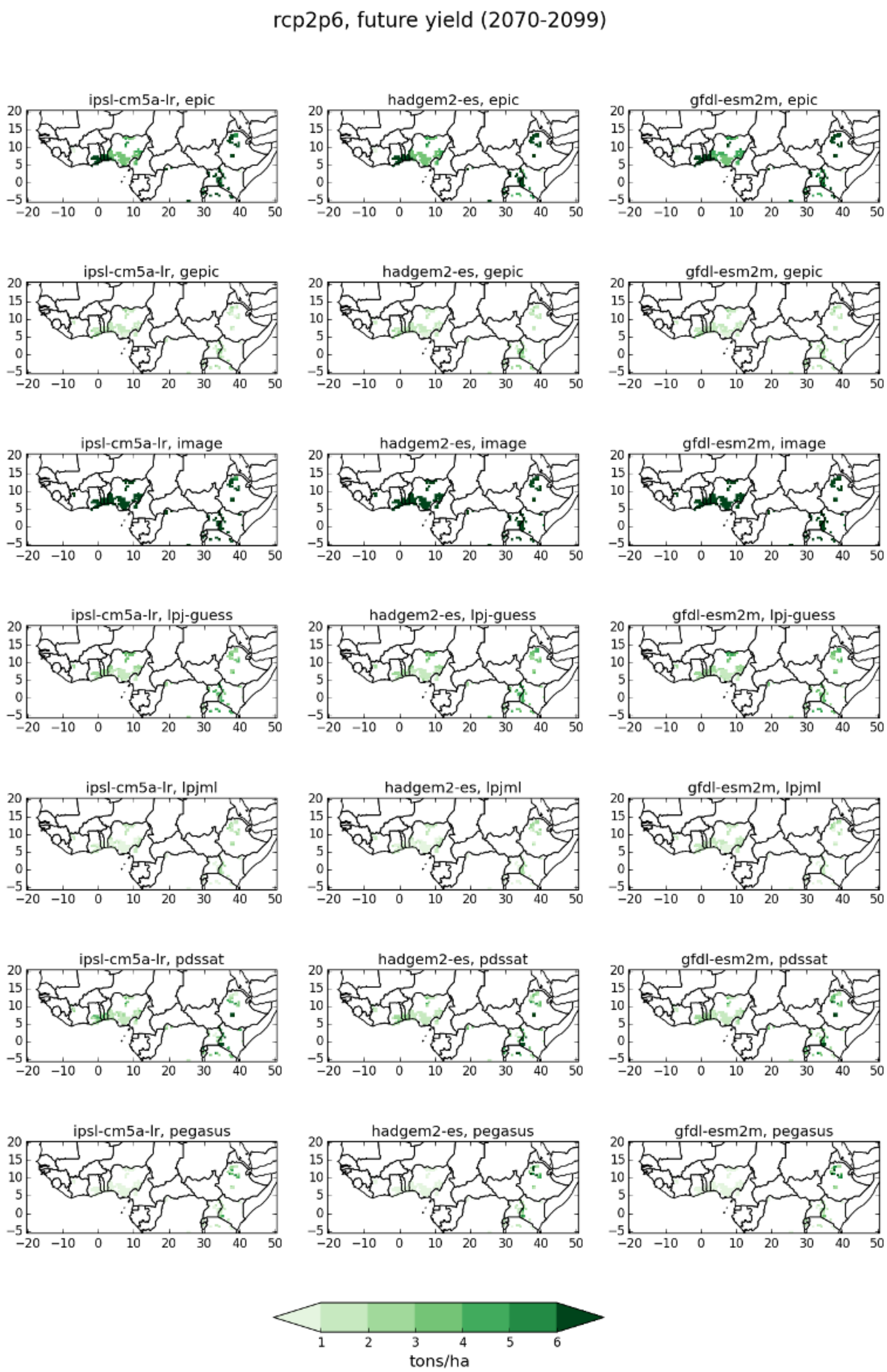


Figure 30: - Projected maize yield for the RCP2.6 scenario and 2080s time period for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

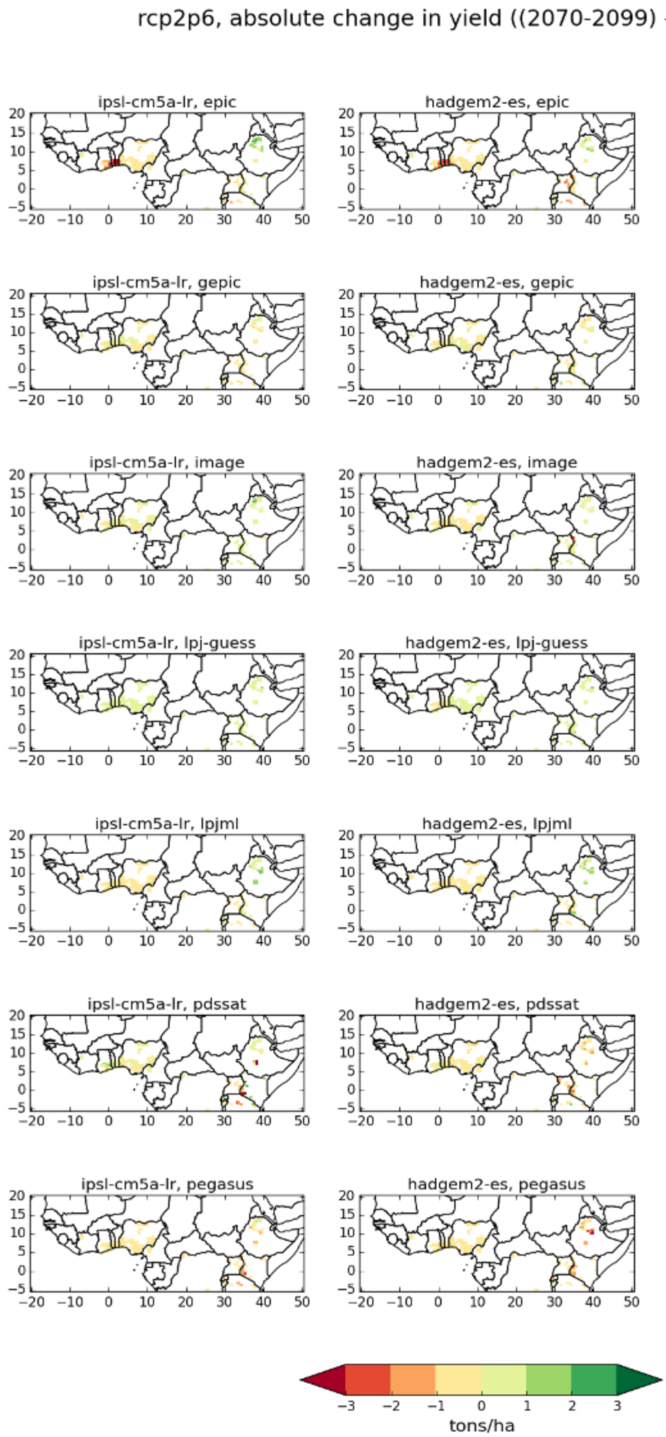


Figure 31:– Absolute change in maize yield between the 2080s and baseline period for the RCP2.6 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

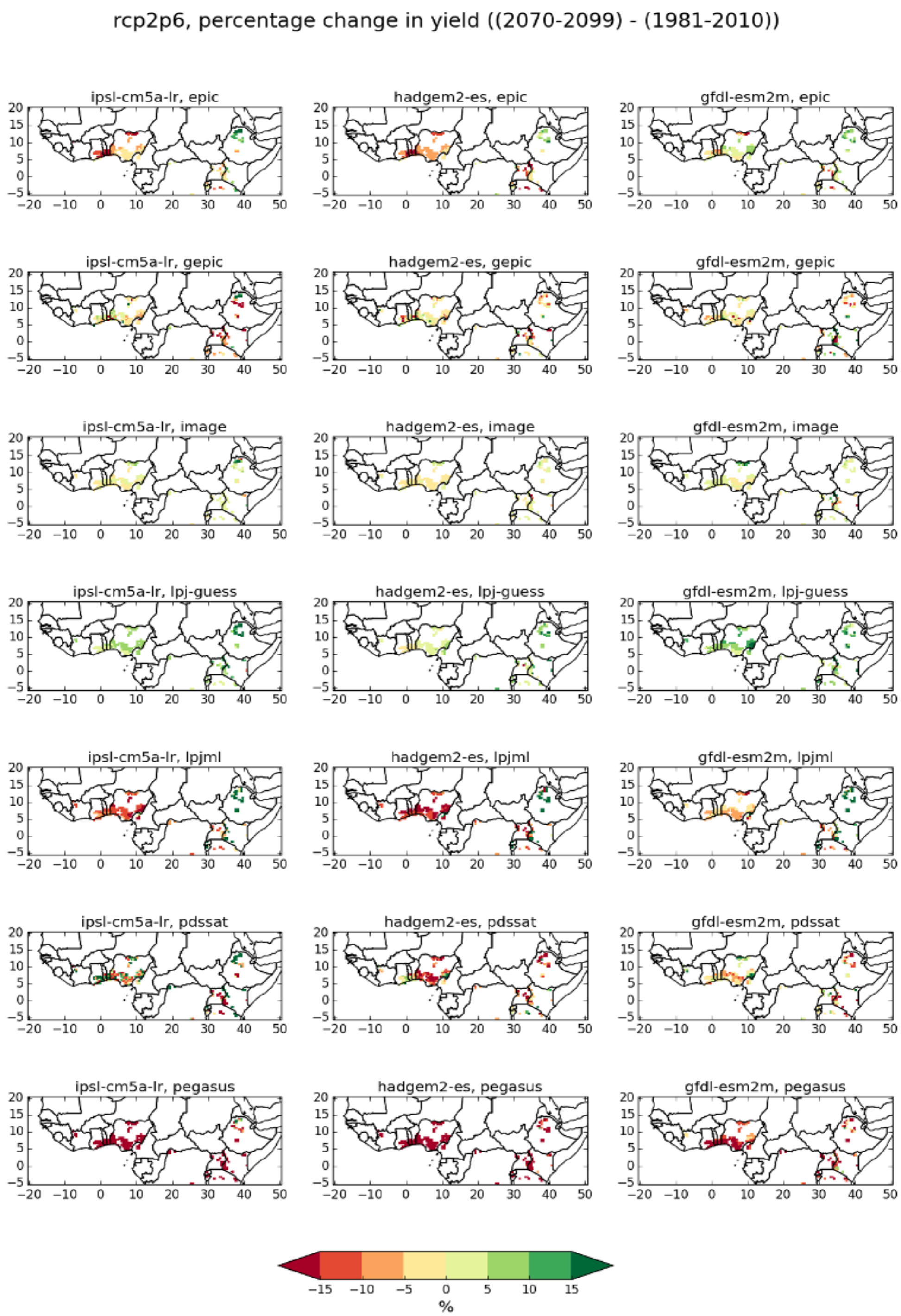


Figure 32:– Percentage change in maize yield between the 2080s and baseline period for the RCP2.6 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

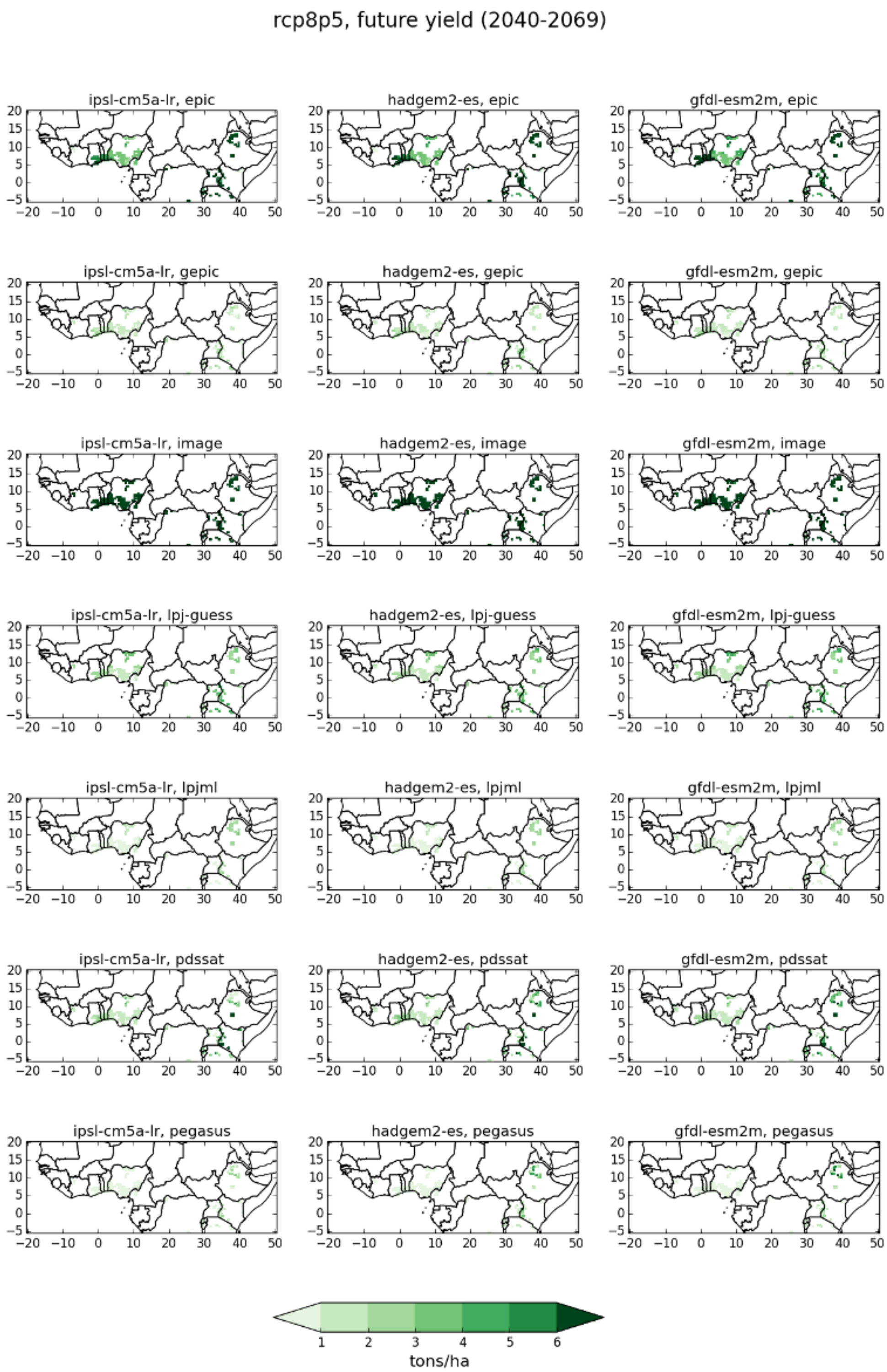


Figure 33: - Projected maize yield for the RCP8.5 scenario and 2050s time period for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

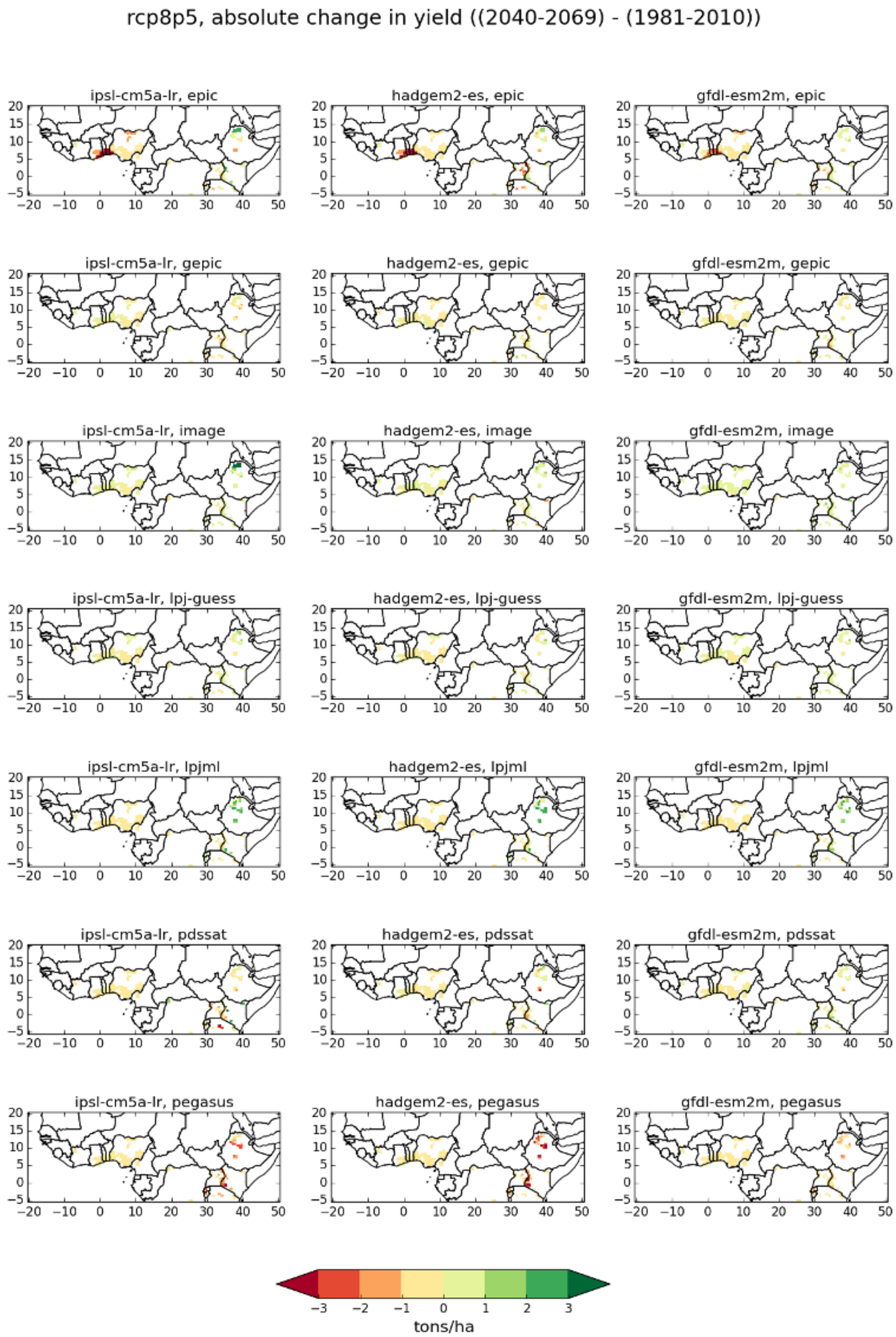


Figure 34:– Absolute change in maize yield between the 2050s and baseline period for the RCP8.5 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

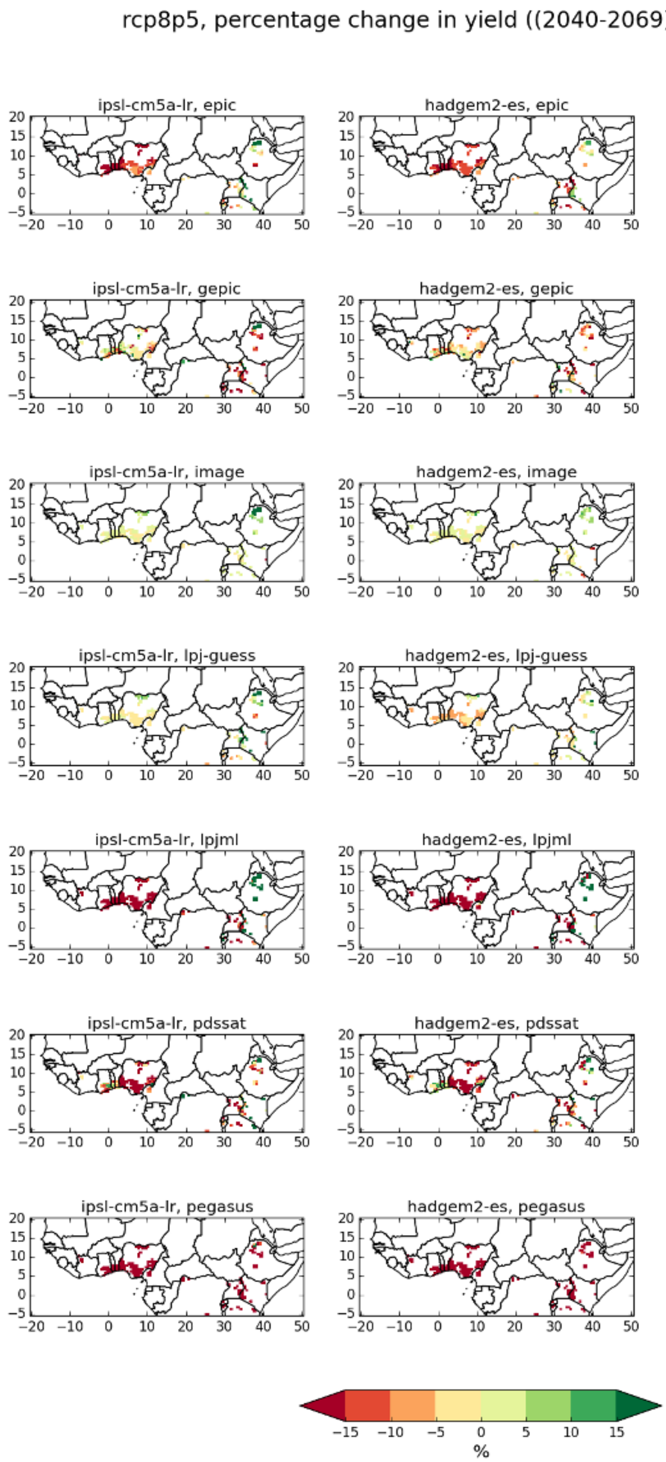


Figure 35:– Percentage change in maize yield between the 2050s and baseline period for the RCP8.5 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

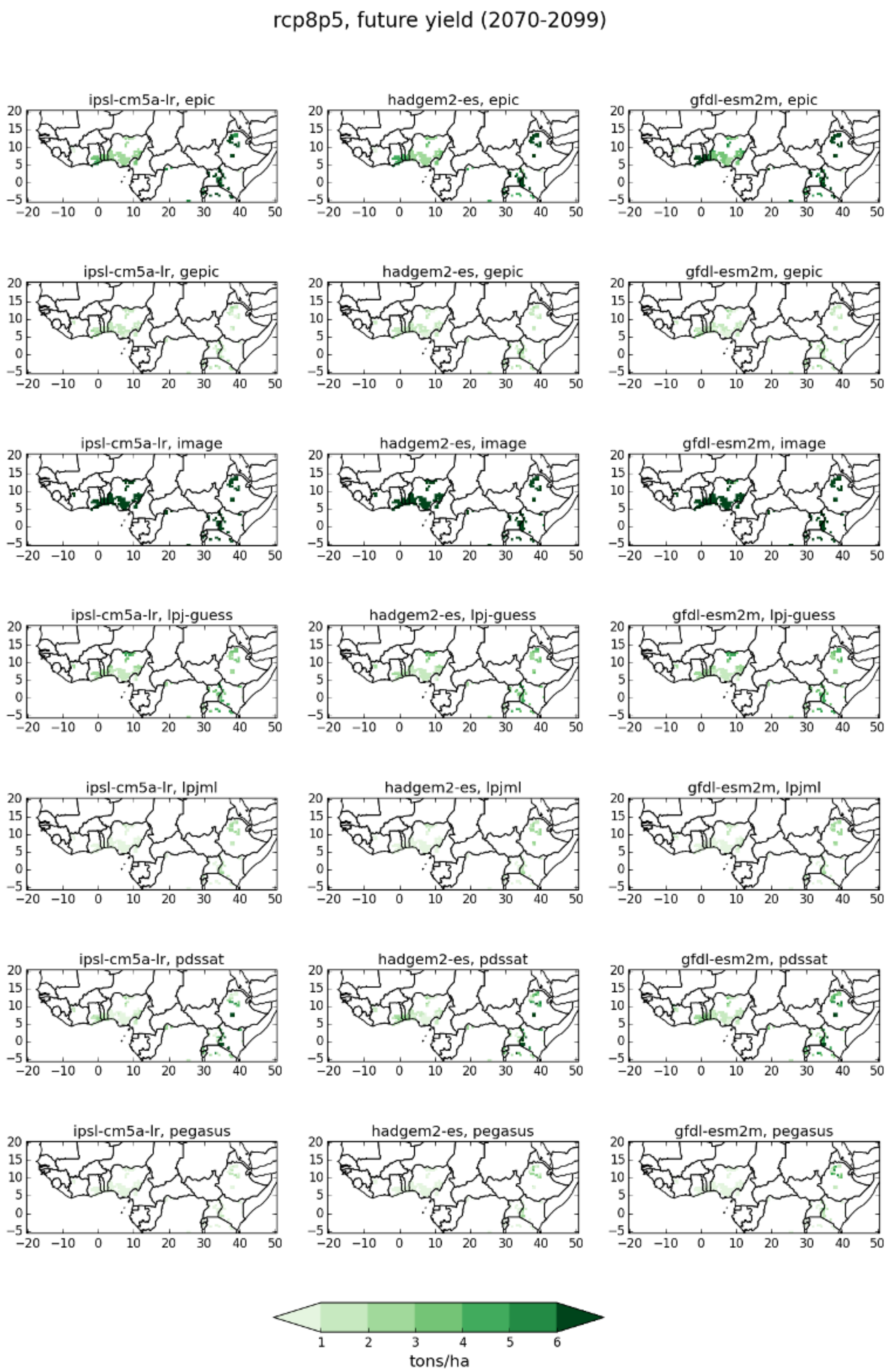


Figure 36: - Projected maize yield for the RCP8.5 scenario and 2080s time period for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

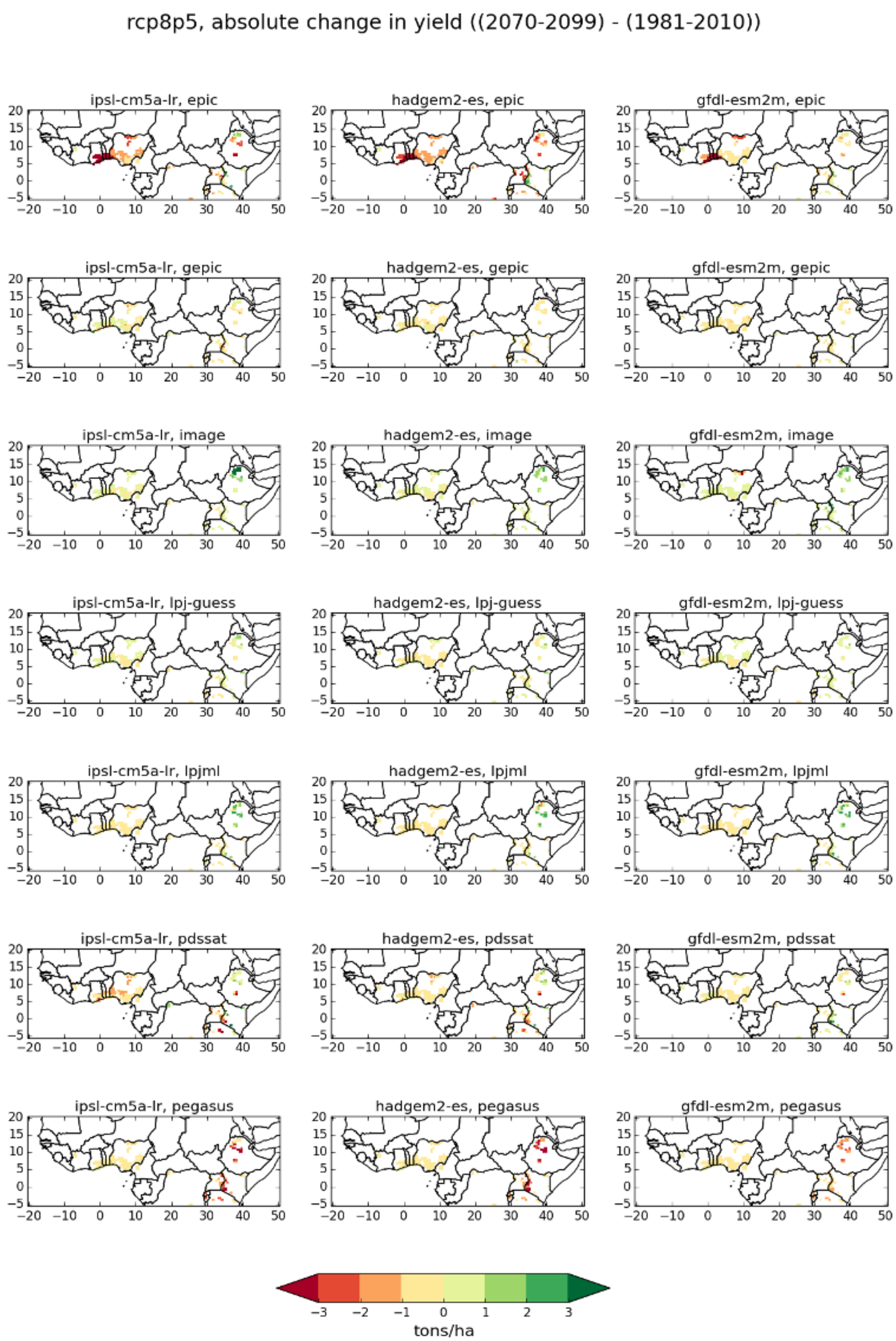


Figure 37:– Absolute change in maize yield between the 2080s and baseline period for the RCP8.5 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

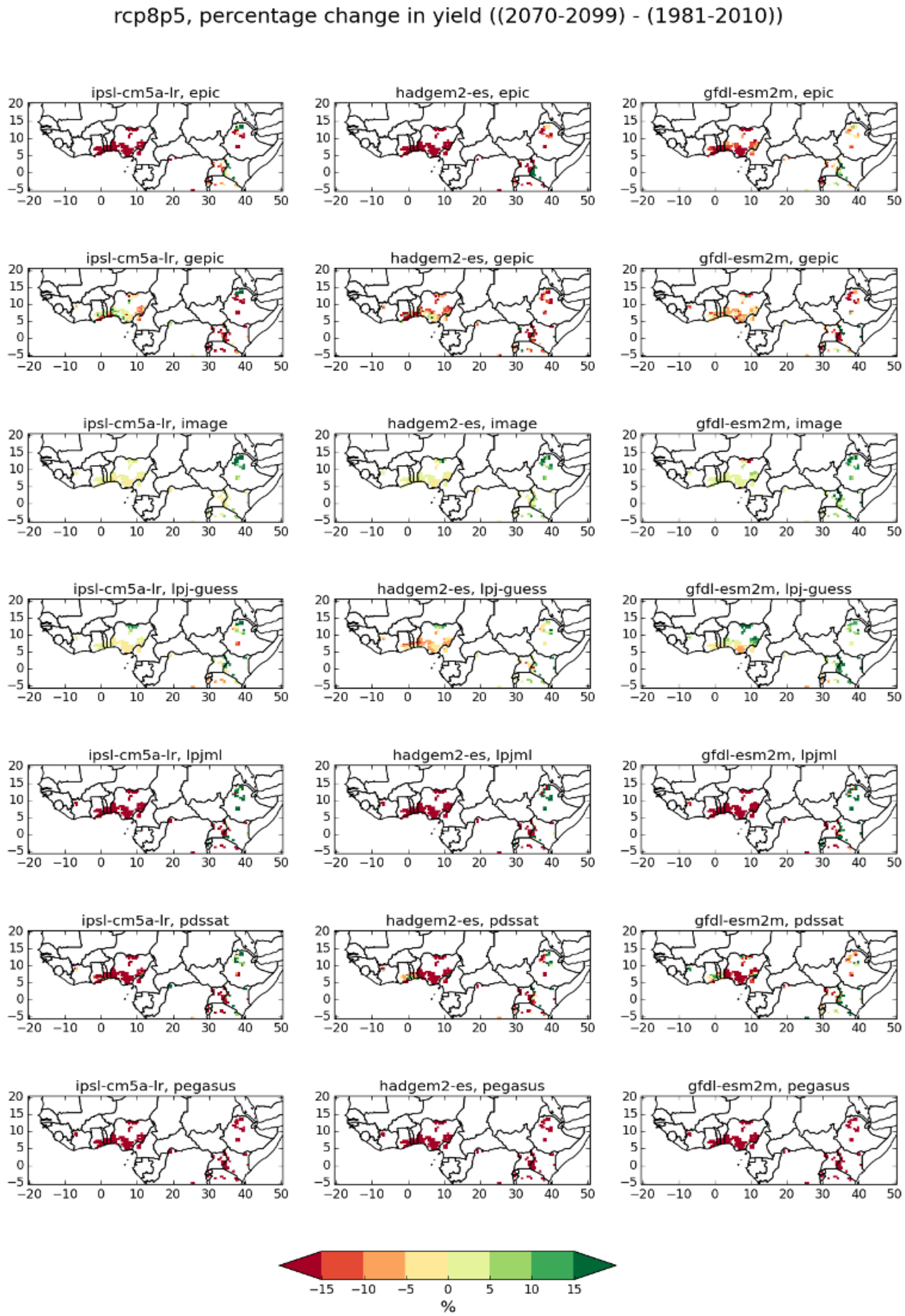


Figure 38:– Percentage change in maize yield between the 2080s and baseline period for the RCP8.5 scenario for the seven impacts models (rows) for each of the HELIX CMIP5 models (columns).

Conclusions and Policy Recommendations

Model simulations show that the current observed near-surface dry bulb mean, maximum and minimum temperature cycles are likely to embrace an increasing trend in the coming decades. The results show large simulated increments in the temperature over the Northern Hemisphere Sub-Saharan Africa (NHSSA) region, with the largest increments in projected temperature expected to occur over the Sahel region. Over the NHSSA region, temperature is projected to increase by about 2°C by the 2040s and by between 4°C and 7°C by the close of the century.

On migrations within the Sub-Sahara Africa, following the West Africa case study, it was found that while researchers and stakeholders often consider the effects of climate change on the vulnerability and resilience of affected populations, this case study highlights the importance of taking into account populations' *perceptions* of climate change as it can affect their adaptation responses. This means that, positing the possibility of a perfectly rational decision to migration in response to perfect information on the actual climate event, that decision is not actually in the populations' capacity to make, as it is their perceptions of change driving behavior rather than actual change. There is need for improved information reaching vulnerable populations to support their long term policy choices.

Impacts from the hunger and climate vulnerability index in the whole region indicates that vulnerability to food insecurity increases by the 2050s, due to the amount of climate change the earth system is already committed to. After this time, the level of increase in vulnerability to food insecurity depends strongly on the RCP. Under RCP 2.6 food insecurity remains steady at the 2050 levels. Under RCP 8.5 it continues to increase further. This means that to maintain current levels of food security, and to prevent climate change increasing the number of food insecure people, both adaptation and mitigation are required. Adaptation is required to address the challenges of the climate change we are already committed to. Mitigation is required to prevent the level of climate change exceeding our ability to adapt.

The projected increase in temperature is bound to have far-reaching repercussions on the expected climate over the Sub-Saharan region, which could impact on the agro-based economies of the countries concerned, including impacting upon the hydrological and surface water resources, agricultural and food security, livestock and wildlife, health and well-being, and energy and industrial production sectors.

Acknowledgments

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References

Abdulai, J., Nelson, G.C., Thomas, T.S., Zougmore, R. and Roy-Macauley, H. (eds.). 2013. “West African agriculture and climate change: A comprehensive analysis”. *IFPRI Research Monographs,* Washington DC. Available at: http://www.ifpri.org/publication/west-african-agriculture-and-climate-change, last access: 20/05/2014.

Adger, W Neil, S. Dessai, M. Goulden, M. Hulme, I. Lorenzoni, D.R. Nelson, L. Otto Naess, J. Wolf, and A. Wreford. 2009. "Are there social limits to adaptation to climate change?" *Climatic change* 93 (3-4): 335-354.

Akponikpè, P.B. Irénikatché, P. Johnston, and E.K. Agbossou. 2010. "Farmers’ perception of climate change and adaptation strategies in Sub-Saharan West-Africa." 2nd International Conference: Climate, Sustainability and Development in Semi-arid Regions August.

Ateliers (Les Ateliers Internationaux de Maîtrise d’oeuvre urbaine). 2010. "Saint-Louis 2030: New African Metropolis." Accessed 14.02.2015. http://www.ateliers.org/IMG/pdf/2__dossier_analyse_eng.pdf.

Barnett, T. P., 1999: Comparison of near-surface air temperature variability in 11 coupled global climate models. *J. Climate*, **12**, 511-518.

Bindoff N, and co-authors, 2013: Detection and Attribution of Climate Change: from global to regional, AR5, chapter 10.

CLUVA, (Climate change and vulnerability of African cities). 2013. "Saint-Louis, Senegal." Accessed 13.02.2015. http://www.cluva.eu/CLUVA_publications/CLUVA Climate-change-and-vulnerability-of-African-cities-Saint-Louis.pdf.

Codjia, C.L. 1997. "Application de la télédétection à l'étude des changements urbains et des transformations du littoral à Cotonou (Bénin)." *Universités francophones. Actualité scientifique)*:299-306.

Coniglio, N. and G. Pesce. 2010. "Climate Variability, Extreme Weather Events and International Migration", *COMCAD Arbeitspapiere-Working Papers*, No 92. Available at: http://www.unibi.de/tdrc/ag_comcad/downloads/Coniglio-Pesce_Climate-Variability-Extreme-Weather-Events-International-Migration.pdf, last access: 18/05/2014.

Covey, C., K.M. AchutaRao, U. Cubasch, P. Jones, S. J. Lambert, M.E. Mann, T.J. Phillips, and K.E. Taylor, 2003: An Overview of Results from the Coupled Model Intercomparison Project (CMIP) *Global and Planetary Change,* **37**, 103-133 (http://www.elsevier.nl/locate/gloplacha)

CRED. 2015. Available at: http://www.emdat.be/, last access: 20/02/2015.

Crétat, J., E. K. Vizy, and K. H. Cook. 2014. "How well are daily intense rainfall events captured by current climate models over Africa?" *Climate Dynamics* 42 (9-10):2691-2711.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cubasch, U., R. Voss, G. C. Hegerl, J. Waszkewitz, and T. J. Crowley, 1997: Simulation of the influence of solar radiation variations on the global climate with an ocean-atmosphere general circulation model. *Climate Dynamics*, **13**, 757-767.

DARA. 2013. "Indice de réduction des risques (RRI) en Afrique de l'Ouest. Analyse des conditions et des capacités de réduction des risques de catastrophes. Le Cap-Vert, la Gambie, le Ghana, la Guinée, le Niger et le Sénégal". Available at: http://daraint.org/risk-reduction-index/, last access: 07/05/2014.

Descroix, L. *et al*. 2013. "Impact of drought and land-use changes on surface-water quality and quantity: The Sahelian Paradox." In P. Bradley (ed.), *Current perspectives in contaminant hydrology and water resources sustainability*, INTECH, pp. 243-271.

Diessner, C.. 2012. "It will rain if god wills it: local perceptions of climate change in the Futa Tooro of northern Senegal." University of Missouri--Columbia.

Dieye, A. M., and D.P. Roy. 2012. "A Study of Rural Senegalese Attitudes and Perceptions of Their Behavior to Changes in the Climate." *Environmental management* 50 (5): 929-941.

Ducoudré, N. I., K. Laval, and A. Perrier (1993), **SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land-atmosphere interface within the LMD atmospheric general circulation model**, Journal of Climate, 6, 248– 273

Easterling, D. R., J.L. Evans, P. Ya Groisman, T.R. Karl, K. E._ Kunkel, and P. Ambenje. 2000. "Observed Variability and Trends in Extreme Climate Events: A Brief Review*." *Bulletin of the American Meteorological Society* 81 (3):417-425.

FAO, (Food and Agriculture Organization of the United Nations). 2008. "Vue générale du secteur des pêches national: La République du Sénégal." Accessed 12.02.2015. ftp://ftp.fao.org/Fi/DOCUMENT/fcp/fr/FI_CP_SN.pdf.

FAO. 2014., "FAOSTAT" Available at: http://faostat.fao.org, last access: 17/05/2014.

Fekete B. M., C.J. Vorosmarty, J.O. Roads, C.J. Willimot, 2004: Uncertainties in Precipitation and their Impacts on Runoff Estimates. Journal of Climate, 17:294 – 304.

Ferris, E. and C. Stark. 2012. "Internal Displacement in West Africa: A Snapshot", the Brookings Institute, LSE. Available at: http://www.brookings.edu/research/papers/2012/01/ecowas-ferris-stark, last access: 18/05/2014.

Findley, S. E. 1994. "Does drought increase migration? A study of migration from rural Mali during the 1983-1985 drought." *International Migration Review*: 539-553.

Gemenne, F. 2011. "Climate-induced population displacements in a 4 C+ world" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369(1934), pp. 182-195.

Gemenne, F., J. Blocher, F. De Longueville, N. Perrin, S. Vigil Diaz Telenti, C. Zickgraf, and P. Ozer. 2014. Catastrophes, Changement climatique et Déplacements forcés: Dynamiques régionales de mobilité humaine en Afrique de l'Ouest. Nansen Initiative.

Giorgi F, Jones C, Asrar G, 2009: Addressing climate information needs at the regional level:the CORDEX framework. World Meteorol Organ (WMO) Bull 58(July):175–183

Githui, F., W. Gitua, F. Mutua and W. Bauwens, 2009: Climate Change impact on SWAT simulated streamflow in western Kenya. In. J. Climatol., 29, 1823-1834

Grillakis, M. G., Koutroulis, A. G., & Tsanis, I. K. (2013). Multisegment statistical bias correction of daily GCM precipitation output. Journal of Geophysical Research: Atmospheres, 118(8), 3150-3162.

Guenet, B., Moyano, F. E., Vuichard, N., Kirk, G. J. D., Bellamy, P. H., Zaehle, S., and Ciais, P.: **Can we model observed soil carbon changes from a dense inventory? A case study over England and Wales using three versions of the ORCHIDEE ecosystem model** (AR5, AR5-PRIM and O-CN), Geosci. Model Dev., 6, 2153-2163, doi:10.5194/gmd-6-2153-2013, 2013.

IDMC. 2013. "Global estimates 2012. People displaced by disasters". Available at: http://www.nrc.no/arch/_img/9675115.pdf, last access: 17/05/2014.

IOM. 2014. “West and Central Africa”. Available at: https://www.iom.int/cms/west-africa, last access: 17/05/2014.

IOM. 2015. “Migration, Environment and Climate Change: Evidence for Policy (MECLEP).” Geneva: IOM. Available http://environmentalmigration.iom.int/migration-environment-and-climate-change-evidence-policy-meclep

IPCC. 2012. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation.* A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

IPCC. 2014. “Climate change 2014: Impacts, Adaptation and Vulnerability”. Available at: http://ipcc-wg2.gov/AR5/, last access: 06/05/2014.

Jones, P. D., M. New, D. E. Parker, S. Martin, and I. G. Rigor, 1999: Surface air temperature and its changes over the past 150 years. *Rev. Geophys.*, **37**, 173-199.

Juana, J. Sharka, Z. Kahaka, and F.Nathan Okurut. 2013. "Farmers’ perceptions and adaptations to climate change in Sub-Sahara Africa: a synthesis of empirical studies and implications for public policy in African agriculture." *Journal of Agricultural Science* 5 (4): p121.

Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), **A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system**, Global Biogeochemical Cycles, 19, GB1015, doi:10.1029/2003GB002199.

Lazcko, F. and C. Aghazarm. 2009. *Migration, Environment and Climate Change: Assessing the Evidence,* International Organization for Migration, Geneva, Switzerland.

McLeman, Robert A, and Lori M Hunter. 2010. "Migration in the context of vulnerability and adaptation to climate change: insights from analogues." *Wiley Interdisciplinary Reviews: Climate Change* 1 (3):450-461.

Meehl, G. A., G. J. Boer, C. Covey, M. Latif, and R. J. Stouffer, 2000: The Coupled Model Intercomparison Project (CMIP). *Bull. Amer. Meteor. Soc.*, **81**, 313-318.

Meehl, G. A., T. Karl, D. R. Easterling, S. Changnon, R. Pielke Jr, D.Changnon, J. Evans, P. Ya Groisman, T. R. Knutson, and K. E. Kunkel. 2000. "An Introduction to Trends in Extreme Weather and Climate Events: Observations, Socioeconomic Impacts, Terrestrial Ecological Impacts, and Model Projections*." *Bulletin of the American Meteorological Society* 81 (3): 413-416.

Mertz, O., C. Mbow, A. Reenberg, and A. Diouf. 2009. "Farmers’ perceptions of climate change and agricultural adaptation strategies in rural Sahel." *Environmental Management* 43 (5): 804-816.

Mertz, O., S. D'haen, A. Maiga, I. Bouzou Moussa, B. Barbier, A. Diouf, D. Diallo, E. Dapola Da, and D.Dabi. 2012. "Climate variability and environmental stress in the Sudan-Sahel zone of West Africa." *Ambio* 41 (4): 380-392.

Mouhamed, L., S. B Traore, A. Alhassane, and B. Sarr. 2013. "Evolution of some observed climate extremes in the West African Sahel." *Weather and Climate Extremes* 1:19-25.

Müller, C, K Waha, A Bondeau, and Heinke J. 2014. Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development. Global Change Biology.

Ndiaye, M. and N. Robin. 2010. "Les migrations internationales en Afrique de l'Ouest". *Hommes & Migrations* (4), pp. 48-61.

Nielsen, J. Østergaard, and A.Reenberg. 2010. "Cultural barriers to climate change adaptation: A case study from Northern Burkina Faso." *Global Environmental Change* 20 (1):142-152.

Ouédraogo, M., Y. Dembélé, and L. Somé. 2010. "Perceptions et stratégies d'adaptation aux changements des précipitations: cas des paysans du Burkina Faso." *Science et changements planétaires/Sécheresse* 21 (2): 87-96.

Ould Sidi Cheikh, M.A., P. Ozer and A. Ozer. 2007. "Risques d'inondation dans la ville de Nouakchott (Mauritanie)". *Geo-Eco-Trop* 31, pp. 19-42.

Ozer, P. and Perrin, D. 2014. "Eau et changement climatique. Tendances et perceptions en Afrique de l'Ouest". In A., Ballouche and N. A., Taïbi (Eds.), *Eau, milieux et aménagement. Une recherche au service des territoires* . Angers, France: Presses de l'Université d'Angers : pp. 227-245

Ozer, P., Y-C Hountondji, F. de Longueville, M. Victoire Bessan, and A.Thiry. 2013. "Impact de l'érosion littorale dans les villes côtières africaines: de la procrastination des pouvoirs publics à la migration forcée des plus précaires. Cas de Cotonou, Bénin."

Polcher, J., McAvaney, B., Viterbo, P., Gaertner, M.-A., Hahmann, A., Mahfouf, J.-F., Noilhan, J., Phillips, T., Pitman, A.J., Schlosser, C.A., Schulz, J.-P., Timbal, B., Verseghy D., and Xue, Y. (1998) **A proposal for a general interface between land-surface schemes and general circulation models**. Global and Planetary Change, 19:263-278.

Salem, M-C. Cormier. 2013. "L'aménagement du littoral: un enjeu crucial pour les pêcheries artisanales." *Artisans de la mer: une histoire de la pêche maritime sénégalaise <ird-00827404>*:136-145.

Sall, A., and P. Morand. 2008. "Pêche artisanale et émigration des jeunes africains par voie piroguière." *Politique africaine* 109 (1):32-41.

Tambo, J. Akpene, and T. Abdoulaye. 2013. "Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna." *Regional Environmental Change* 13 (2): 375-388.

Taylor, Karl E., Ronald J. Stouffer, Gerald A. Meehl, 2012: An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc., 93, 485–498.

Teka, Oscar, and Joachim Vogt. 2010. "Social perception of natural risks by local residents in developing countries—The example of the coastal area of Benin." *The Social Science Journal* 47 (1): 215-224.

Tschakert, P. 2007. "Views from the vulnerable: understanding climatic and other stressors in the Sahel." *Global Environmental Change* 17 (3): 381-396.

UNFCCC (United Nations Framework Convention on Climate Change). 2014. “Institutional arrangements for national adaptation planning and implementation. 2014 Thematic Report.” Available at: http://unfccc.int/files/adaptation/application/pdf/adaption_commitee_publication_-_web_high.pdf*

Viovy, N. (1996), **Interannuality and CO_2 sensitivity of the SECHIBA-BGC coupled SVAT-BGC model**, Physics and Chemistry of The Earth, 21, 489– 497

Warner, K., T. Afifi, K. Henry, T. Rawe, C. Smith, and A. De Sherbinin 2012. “Where the Rain Falls: Climate Change, Food and Livelihood Security, and Migration.” United Nations University Institute for Environment and Human Security.

Warner, K., W. Kälin., S. Martin., Y. Nassef., S. Lee., S. Melede., H. Entwisle Chapuisat., M. Frank and T. Afifi. 2014. “Integrating Human Mobility Issues within National Adaptation Plans.” UNU-EHS Publication Series. Policy Brief n°9, June 2014. Available at: http://www.ehs.unu.edu/file/get/11786.pdf

Warszawski L, Frieler K, Huber V, et al (2014) The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): project framework. Proc Natl Acad Sci U S A 111:3228–32. doi: 10.1073/pnas.1312330110

Weedon GP, Balsamo G, Bellouin N, et al (2014) The WFDEI meteorological forcing data set: WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. Water Resour Res n/a–n/a. doi: 10.1002/2014WR015638

Weedon GP, Gomes S, Viterbo P, et al (2010) The WATCH forcing data 1958–2001: A meteorological forcing dataset for land surface and hydrological models. Watch. Ed. Watch Tech. Rep. 22.

West, C. Thor, C. Roncoli, and F. Ouattara. 2008. "Local perceptions and regional climate trends on the central plateau of Burkina Faso." *Land degradation & development* 19 (3):289-304.

Wouterse, F. and J. Edward Taylor. 2008. "Migration and income diversification: Evidence from Burkina Faso." *World Development* 36 (4): 625-640.