WPS4290

Policy Research Working Paper 4290

The Impacts of Climate Change on Regional Water Resources and Agriculture in Africa

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July 2007

Abstract

This paper summarizes the methods and findings of the hydrological assessment component of the project studying likely impacts of climate change on water resources and agriculture in Africa.

The first phase of the study used a version of a conceptual rainfall-runoff model called WatBal (Water Balance) applied to gridded data to simulate changes in soil moisture and runoff across the whole continent of Africa rather than to any particular catchment or water resource system. The model inputs were the climate variables of the 1961–90 climatology and physiological parameters (such as soil properties and land use) derived from global datasets for each of the 0.5^{o} latitude/longitude cells across the continent. The primary model output comprised a time series (monthly time step) of simulated runoff for all the grid cells for each of the districts in the countries of interest.

The second phase of the study extended the hydrology analyses to update the above hydroclimatic series to the year 2000 using updated input data. To ascertain the possible impacts of climate change within the districts being investigated this study used synthetic or GCM-based climate change scenarios as input to the WatBal model. The WatBal model was used to determine the impact of these different scenarios on runoff and actual evaporation and hence flow in the districts under study. The generated hydroclimatic series and scenario analyses were used as inputs into various Ricardian regressions in other analyses measuring likely impacts of climate change on the agricultural economies of Africa.

This paper—a product of the Sustainable Rural and Urban Development Team, Development Research Group—is part of a larger effort in the group to mainstream climate change research. Copies of the paper are available free from the World Bank, 1818 H Street NW, Washington, DC 20433. Please contact Pauline Kokila, room MC3-446, telephone 202-473-3716, fax 202-522-1151, email address pkokila@worldbank.org. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at strzepek@colorado.edu. July 2007. (62 pages)

THE IMPACTS OF CLIMATE CHANGE ON REGIONAL WATER RESOURCES AND AGRICULTURE IN AFRICA[1]

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[1] An earlier version of this Working Paper was published as CEEPA Discussion Paper number 13.

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The authors wish to thank Rashid Hassan, Ariel Dinar and James Benhin for their comments. All errors and views expressed are the authors' and do not reflect those of the World Bank or CEEPA.

This paper was funded by the GEF and the World Bank. It is part of a larger study on the effect of climate change on agriculture in Africa, managed by the World Bank and coordinated by the Centre for Environmental Economics and Policy in Africa (CEEPA), University of Pretoria, South Africa.

SUMMARY

This report summarizes the methods and findings of the hydrological assessment component of the project studying likely impacts of climate change on water resources and agriculture in Africa. The study employed a version of a conceptual rainfall-runoff model called WatBal (Water Balance), applied to gridded data to simulate changes in soil moisture and runoff across the whole continent of Africa rather than to any particular catchment or water resource system. The model inputs were the climate variables of the 1961–1990 climatology and physiological parameters (e.g. soil properties and land use) derived from global datasets for each of the 0.5^{o} latitude/longitude cells across the continent. The primary model output comprised a time series (monthly time step) of simulated runoff for all the grid cells for each of the districts in the countries of interest.

The first phase of the hydrology component generated the following data at district level: runoff (in mm); relative soil moisture storage - z (0–1): 1 is fully saturated; potential evapotranspiration (in mm); actual evapotranspiration (in mm); temperature (in degrees Celsius); precipitation (in mm) and streamflow (in m^3). This data was generated for the 11 countries in the study on a monthly time step from 1961 to 1990. Additional results included a river density index (indicator of stream frequency and hence surface water availability within each district) and the area irrigated (an estimate of the percentage area irrigated within each district.)

The second phase of the study extended the hydrology analyses to update the above hydroclimatic series to the year 2000 using updated input data. To ascertain the possible impacts of climate change within the districts being investigated this study used synthetic or GCM-based climate change scenarios as input to the WatBal model. A subset of the 20 scenarios produced by the Climate Research Unit (CRU) for which data are available at 0.5º x 0.5º for the globe was employed to represent a range of equally plausible future climates with differences attributable to the different climate models used and to different emission scenarios that the world may follow. This study derived 16 scenarios using four different models (i.e. CSIRO2, HadCM3, CGCM2, ECHAM and PCM) based on four different emission scenarios (i.e. A2 & B2). The WatBal model was used to determine the impact of these different scenarios on runoff and actual evaporation and hence flow in the districts under study. The generated hydroclimatic series and scenario analyses were used as inputs into various Ricardian regressions measuring likely impacts of climate change on the agricultural economies of Africa.

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ACRONYMS AND ABBREVIATIONS

ADAPT	ADAPTation to changing environments in river basins
ADDS	Africa Data Dissemination Service
CRU	Climate Research Unit
EDC	European Data Centre
FAO	Food and Agriculture Organization
FRIEND	Flow Regimes from International Experimental and Network Data
GEF	Global Environment Facility
GRDC	Global Runoff Data Centre
GRID	Global Resources Information Database
IIASA	International Institute for Applied Systems Analysis
IGBP	International Geosphere-Biosphere Program
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
STN-30p	Simulated Topological Network (30-minute spatial resolution)
TRMM	Tropical Rainfall Measuring Mission
UNESCO	United Nations Educational Scientific and Cultural Organization
UNH	University of New Hampshire
USAID	United States Agency for International Development
USGS	United States Geological Survey
WMO	World Meteorological Organization
WBM	Water Balance Model

1. Introduction

Although considerable research efforts are being made, current understanding of the regional impacts, magnitude, and rate of climate change remain uncertain. Nevertheless, it is generally accepted that climate change will in many places adversely affect farming, fishing, forestry and many other industries that rely on weather and natural ecosystems. The African continent is particularly susceptible to climate change because it includes some of the world's poorest nations. Furthermore, high spatial and temporal variability in rainfall, as well as high evaporation rates, already place great stress on agricultural systems from which 70% of the continent's population derive their livelihoods. One of the most significant impacts of climate change is likely to be on the hydrological system, and hence on river flows and regional water resources. This will be particularly true in arid and semi-arid areas of Africa where water resources are very sensitive to climate variability, particularly rainfall.

The GEF/World Bank project, *Regional climate water and agriculture: Impacts on and adaptation of agro-ecological systems in Africa*, is an investigation of the sensitivity of agricultural systems to climate change and an economic assessment of various adaptation strategies. The principal method adopted for the study is the Ricardian approach, which measures the effect of climatic variables on agriculture (Mendelsohn et al. 1994). The method is based on the assumption that, by examining the relationship between climatic data and a variety of geographical, agricultural, economic and demographic factors on land value and farm revenue, it is possible to isolate the intrinsic value of climate. The approach presupposes that farmers at any given location have optimized their farming systems (i.e. crops grown and inputs) to maximize their land value and/or farm revenue. Thus, the approach investigates farmers' adaptation to local climate across a range of conditions by observing the relationship of farm values to climate. Basically, with this approach, regression relationships are derived to determine the links between climate variables (e.g. temperature and precipitation) and land values and farm revenues across different locations. In theory, by directly measuring farm prices or revenues it is possible to take into account not only the direct impacts of climate on yields, but also potential adaptations to climate change (e.g. the indirect substitution of different crops and different inputs, and even the introduction of different activities) (Mendelsohn et al. 1994). The implications of climate change for land values and farm revenues can then be deduced.

Politically defined 'districts' are the primary unit for collection of socio-economic, environmental and geographical data for the Ricardian approach (i.e. the independent variables in the regression equations) and they are the basis of all analyses. In the current project, the approach is being applied to selected districts in 11 countries, representing a broad spectrum of climatic conditions (Figure 1; Table 1). Multi-disciplinary teams of researchers in each country have collected the data required for the analyses.

This report describes the methods and results of hydrological analyses to provide inputs for use in the Ricardian assessment of climate change impacts. The reported analysis is conducted in two phases. The principal objectives of the first phase of the study were to

i. develop an approach that enables flow and runoff to be derived for the 'districts' of interest;

ii. develop time series (1961–1990) of runoff and flow for the 'districts' which will provide a baseline for climate change scenarios; and

iii. provide hydrologically relevant parameters that can be used as independent variables in the Ricardian analyses.

The objectives of the second phase were to

i. extend the time frame for the hydroclimatic series from 1990 to the year 2000, using the same modeling methodology used in Phase I and updated input data from the Climate Research Center at the University of East Anglia to calibrate and simulate the hydrological model up to the year 2000;

ii. provide results for the new district boundaries for Cameroon and Egypt (which have changed since the Phase 1 results were compiled) for the 1961–1990 period as well as for the proposed future analyses; and

iii. provide climate change scenario analyses for the same hydroclimatic variables at district level.

2. Methodology

The objective was to apply a hydrological model across the whole continent of Africa rather than to any particular catchment or water resource system. The model inputs were the climate variables of the 1961–1990 climatology and physiological parameters (e.g. soil properties and land use) derived from global datasets for each of the 0.5^{o} latitude/longitude cells across the continent. The primary model output comprised a time series (monthly time step) of simulated runoff for all the grid cells. For each of the districts in the countries of interest the runoff was computed as the areal weighted average of the runoff generated on all the cells that lay within that district. When a district lay entirely within a cell the runoff was assumed to be the same as that across the cell. No attempt was made to disaggregate data within cells. The runoff was also accumulated and 'routed' via a drainage network to simulate flow. This enabled flow into and out of each district to be estimated.

2.1 Model description

To address scientific issues at the continental scale, hydrological models must characterize the dispersed nature of climate and hydrology over space and time while avoiding excessive complexity. In the current study, simplification was required not only to ensure reasonable computing time, but also to develop a generic form of the model applicable to a wide range of conditions across the continent.

The model used is a version of a conceptual rainfall-runoff model called WatBal (Yates 1996), which can be applied to gridded data. The model simulates changes in soil moisture and runoff. It is essentially an accounting scheme based on a conceptualized, one-dimensional bucket that lumps together both the root and upper soil layer. The model comprises two elements. The first is a water balance component that describes water movement into and out of a conceptualized basin (Figure 2). The second is the calculation of potential evapotranspiration, which, in the gridded version of the model, is computed using the FAO Penman-Monteith approach (Monteith 1965). The simplified representation of soil moisture dynamics has been shown to adequately represent runoff changes due to climate fluctuations (Yates & Strzepek 1994; Yates1997).

The model was applied to a regular latitude/longitude grid covering the whole continent. Each of the 0.5° cells (which have an area ranging from about 2500 km^2 to 3100 km^2) depending on latitude) is regarded by the model as a small catchment. The model parameters, which define the size of the store and the rate of water removal from it, are derived in part from physical characteristics and in part by calibration. The inputs are monthly rainfall and climatic data required to estimate potential evapotranspiration. Water enters the soil moisture store through precipitation and is removed either by evapotranspiration, surface runoff or subsurface runoff. The water balance component of the model comprises three parameters related to i) surface runoff, ii) sub-surface runoff and iii) maximum catchment water-holding capacity. The monthly soil moisture balance is written as:

$$CS_{\max}\frac{dz}{dt} = P_{eff}(t) - R_s(z,P,t) - R_{ss}(z,t) - E_v(z,Pet,t) \tag{1}$$

where:

P_{eff} = effective precipitation (length/time)

R_s = surface runoff (length/time)

z = relative storage (length) ($0 \le z \le 1$)

P = precipitation (length/time)

R_{ss} = subsurface runoff (length/time)

P = precipitation (length/time)

Ev = evapotranspiration (length/time)

Pet = potential evapotranspiration (length/time)

CS_{max} = maximum catchment storage (length)

In the gridded version of WatBal, the relative importance of water storage on the hydrological regime of a cell is expressed as:

$$CS_{\max} = S_{\max}.AWC_{mult} \tag{2}$$

where:

S_{max}	=	the maximum water holding capacity of the soil (mm)
AWC_{mult}	=	maximum rooting depth (m)

S_{max} is expressed as millimeter of water stored per meter depth of soil and is dependent primarily on the type of soils in the cell. AWC_{mult} is dependent on the type of vegetation and hence is primarily a function of land use within the cell. The storage variable, z, is given as the relative storage state and is a value between 0 and 1. Consequently, when CS_{max} is multiplied by z, it gives the volume of water stored in the cell at any given time.

As recommended by the UN Food and Agriculture Organization (FAO), potential evapotranspiration is computed using the Penman-Monteith method (FAO 1992). A non-linear relationship (based on Kaczmarek 1993) is used to compute actual evapotranspiration from potential evapotranspiration.

$$E_v(z, Pet, t) = Pet\left(\frac{5z - 2z^2}{3}\right) \tag{3}$$

As z decreases the ratio of actual to potential evapotranspiration declines (Figure 3).

Surface runoff (R_s) is described in terms of the storage state, z, and the effective precipitation, $P_{eff.}$. Epsilon (ε), a calibration parameter, allows surface runoff to vary non-linearly with storage (Yates 1996).

$$R_s(z,P,t) = z^{\varepsilon} P_{eff} \tag{4}$$

Sub-surface runoff (R_{ss}) is a function of the relative storage state, multiplied by a coefficient α.

$$R_{ss} = \alpha \ z^2 \tag{5}$$

Total runoff for each time step is the sum of the two runoff components:

$$R_{total} = R_s + R_{ss} \tag{6}$$

More details of the model theory are presented in Yates (1996).

2.2 Data requirements

The modeling process is highly data intensive because of the number of cells (ca. 16,000) across Africa. The data types required for this study can be broadly divided into four types: geographical data, climate data for model input, physiological data and model calibration data. This section describes the data sources and, where necessary, the steps taken to prepare them for use in this study. A summary of exact data sources is provided in Table 2.

2.2.1 Geographical data

The district boundaries for each of the countries investigated in this study came from a variety of sources. Shape files were provided by USAID, FEWS, EDC-International Program and the US Geological Survey under the Africa Data Dissemination Service (ADDS) and Yale University. The Ghana and Kenya maps were provided by UNESCO (1997) through the UNESCO/GRID-Sioux Falls and Yale University. Land use data was obtained from the Land Use group at IIASA in Vienna. IIASA's dataset consists of 13 classes, aggregated into six classes (Figure 4; Table 3).

A digitized river network was used to estimate the river density index for each of the districts (Section 2.6). The network used was the 'Rivers of Africa' coverage obtained from the FAO geonetwork website. This coverage was developed by FAO as part of the Atlas of Water Resources and Irrigation in Africa. An irrigated area map of Africa indicating (as proportional coverage within a 0.5^{o} grid) where irrigation infrastructure and equipment has been installed in the past was also obtained from FAO (Figure 5). The map, also obtained from the geonetworks website, was used to estimate the percentage of each district with potential for irrigation (Section 2.7).

2.2.2 Climate data

Average monthly rainfall and the climate variables required to compute potential evapotranspiration (i.e. wind speed, vapor pressure, temperature and cloudiness) were taken from a database provided by the Climate Research Unit (CRU), University of East Anglia, Norwich, UK. These data, provided on a 0.5^{o} grid, represent the World Meteorological Organization's (WMO) standard reference 'baseline' for climate change impact studies. Most climate change scenarios (i.e. plausible descriptions of how things may change in future) are expressed as anomalies from this baseline (see Section 3).

2.2.3 Physiological data

The physiological data required were obtained from a number of geographically referenced datasets.

The soil water holding capacity (S_{max}) was taken from FAO's geonetwork. Values are dependent largely on soil texture. For areas of open water, values are set at 1000 mm. The original dataset was organized at the 0.08^o scale. The data were aggregated (by taking the numeric mean) into 0.5^o grid cells.

A gridded drainage network at 0.5^o resolution was used to simulate flow paths for routing runoff generated within cells to the oceans. The network, based on topography, attributes an 'average flow' direction to each grid cell (Figure 6). This is the direction that any runoff generated within the cell will move. Where rivers exist, the drainage network broadly corresponds to the river network (Figure 6). The simulated topological network used was the STN-30p network developed by the University of New Hampshire (Fekete et al. 2000). This dataset has been validated against several independent atlases and station-based attribute sources (Vörösmarty et al. 2000).

2.2.4 Model calibration data

The model was calibrated against simulated average monthly runoff generated on a 0.5^o grid by the University of New Hampshire (UNH) (see Section 2.3). The mean annual runoff is shown in Figure 7. The equivalent data are available for each month of the year. Several 'holes' were discovered in the gridded datasets developed by UNH, including nine holes in the continental land mass of Africa. It was not clear why these holes occurred. They did not correspond to water bodies or other natural features. Consequently, they were 'filled' with assumed runoff values of zero.

2.3 Model calibration

In WatBal, hydrological processes are simulated, as described above (Section 2.1), on the basis of a conceptual approximation. Consequently, it is necessary to adjust or optimize parameters until the model output is an acceptable estimate of the observed runoff regime. In order to do this it is necessary to have runoff data against which to calibrate parameter values. In the gridded version of the model, three parameters are calibrated:

Alpha (α) has units of mmd^{-1} and is directly related to soil water storage. Regions with higher runoff coefficients generally have higher values of alpha (i.e. boreal forests and tropical rain forests) while regions with lower runoff coefficients generally have lower values for alpha (i.e. deserts and dry forests).

Epsilon (ε) is unitless and defines the functional form of surface runoff, which depends on the magnitude of the precipitation event and the relative storage (see Equation 4). *Smaller* values of epsilon represent an *increase* in the contribution of surface runoff; therefore, smaller epsilons are generally associated with smaller soil moisture capacities and greater surface runoff (e.g. tundra and chaparral). Regions with larger baseflows and flatter runoff hydrographs generally have a higher contribution of runoff from sub-surface flow. Higher values of epsilon tend to reduce the contribution from surface runoff.

AWC_{mult} has units of meters and, as described above (Section 2.1), is directly related to land use. The greater the rooting depth of vegetation, the higher the value of AWC_{mult}. Higher values of AWC_{mult} tend to reduce the contribution from surface runoff.

In the current study, observed flow data (i.e. discharge from gauging stations) were obtained from some country teams. These were supplemented with additional data obtained from the Southern Africa FRIEND database (Table 4). Initially, it was intended to calibrate the model parameters using both these datasets. However, it was decided not to do this for several reasons:

i. The limited geographical distribution of the available flow data.

ii. The limited time available to assess data quality.

iii. The non-trivial nature of the required task and the considerable time it would have taken to define the cells contributing to any specific station.

iv. The numerous complications of using flow to validate runoff data (e.g. caused by the presence of wetlands, lakes, reservoirs and the abstraction of water by people).

Consequently, given the limited resources available for this study, it was decided to calibrate against an existing runoff dataset. Hence, for the calibration, simulated runoff data obtained from the CD of runoff fields were used. These were developed by the University of New Hampshire (UNH) and the Global Runoff Data Center (GRDC) (Fekete et al. 2000). The data on this CD have been endorsed by WMO, UNESCO and the IGBP (International Geosphere-Biosphere Program) and they are believed to be the best global runoff data currently available. There are three datasets available on the CD:

i. Simulated runoff data derived from a climate driven Water Balance Model (WBM) which is very similar to WatBal.

ii. Observed river discharge data from approximately 130 gauging stations, located on mainland Africa, predominantly in West Africa.

iii. A composite dataset derived by estimating inter-station runoff (i.e. difference in flow between two gauging stations on the same river) and applying correction coefficients (based on the ratio of observed and simulated runoff) to the simulated runoff.

The composite data (iii. above) underestimates runoff from some grid cells. This is because in areas where flow is reduced by evaporation from wetlands, lakes or reservoirs, inter-station flow may be significantly diminished or even negative. Since the UNH correction was applied to all cells located 'upstream' of a gauging station (i.e. not just those for which evaporation is high) the 'corrected' runoff tends to be significantly less than occurs in reality. For this reason it was decided to calibrate the WatBal model against the simulated UNH runoff (i. above). Thus the model was calibrated against existing model output rather than observed data. Clearly this is not ideal, but was the best that could be achieved given the constraints of limited time and resources.

The three parameters (i.e. alpha, epsilon and AWC_{mult}) were calibrated for each cell by simulating runoff for 30 years (1961–1990) and minimizing the root mean square error of the WatBal simulated average monthly runoff and the UNH simulated runoff data. This approach tends to maximize the 'goodness of fit' of the total volume of runoff, but will not necessarily produce a good fit in periods of extreme high and/or low runoff events. However, since this study is primarily concerned with water resources, it was felt that total volume was the most important aspect of the runoff regime to simulate correctly. A genetic mutation algorithm (Frontline Systems Inc. 2003) was used to optimize the parameters. This approach enables the whole of the 'solution space' to be searched and generally allows solutions to be obtained more rapidly than alternative optimization methods. The AWC_{mult} parameters were constrained to lie within a range 0.1m to 5.0m depending on the likely rooting depth of vegetation within the specified land use class (Table 3).

Using a dedicated computer, parameter calibration took approximately 15 seconds per grid cell. Thus the total time for calibrating parameters for all cells in Africa was three days. A comparison between average annual runoff generated using WatBal and the UNH runoff data, at the scale of 'food production units' (of which there are 97 in Africa) shows a reasonable fit (Figure 8).

2.4 Runoff simulation

When the model was calibrated it was run to estimate runoff, on a monthly time step, for all grid cells for the period 1961–1990. The cell data were then converted to runoff in each district. The percentage of each district's area in each associated grid cell was determined using a blank global 0.5 x 0.5 degree grid and geoprocessing tools in ArcView. This enabled the weighted average runoff produced by the grid cells contributing to runoff within any given district to be determined. For example, at any given time step, all districts in the same grid cell will have the same runoff. However, if a district was divided across a number of grid cells (as illustrated in Figure 9), runoff for that district was calculated based on the percentage area of the district in each of the grid cells.

2.5 Flow simulation

The flow routing model uses the STN-30p drainage network (Section 2.2.3) shown in detail for Burkina Faso in Figure 10. The drainage network shows the direction of flow in each grid cell and which upstream cells are contributing to its flow. Runoff from each grid cell is accumulated along the drainage network, providing the stream flow in each grid cell (Figure 11). After stream flow had been calculated in each grid cell, the same weighted average procedure as described in Section 2.4 was used to disaggregate the stream flow to each district. Since the drainage network represents directions of flow rather than actual rivers, and because the volumes have been weighted by percentage area, the flow values computed are indicative of, rather than an estimate of actual, flow within a district.

2.6 River density index

A river density index is an indicator of stream frequency and hence surface water availability within each district. It is possible that this could be a geographical feature that significantly influences land value and/or farm revenue. Consequently it was determined for each of the districts in the following ways:

i. The area of districts provided in the coverages obtained from each country was converted from acres to square kilometers. Kenya and Zimbabwe did not have area data included in their dataset, so the area was calculated using tools in ArcView.

ii. The river length was calculated in ArcView using the FAO's Rivers of Africa dataset. The calculation process involved converting the river shape file into a very small grid (0.001^{o}), summing the grids within each district, and converting the grid sum into a length. The river length represents the total amount of all river segments in a district.

iii. The river density index was calculated by dividing the river length in the district by the area of the district. Values were multiplied by 1000 to give integer values. The higher the value, the easier it is to access river water in the district.

Examples of the river density index are shown for districts in Burkina Faso in Figure 12.

2.7 Area irrigated

The extent of irrigation within a district is another factor that is likely to influence land value and farm revenue. Consequently, an estimate of the percentage area irrigated within each district was derived from the FAO's irrigated area map of Africa (Section 2.2.1). It was calculated using the weighted average estimate of grid cell contribution to the area of each district, determined when computing runoff (Section 2.4). Examples of the percentage of area irrigated are shown for districts within Burkina Faso in Figure 13.

3. Modeling climate change impacts on streamflow

3.1. Generation of climate change scenarios

To ascertain the possible impacts of climate change within the districts being investigated in this study, it is proposed to use synthetic or GCM-based climate change scenarios as input to the WatBal model. This would provide insight into the changes in hydroclimatic variables that can be expected under different climate change scenarios. It is recommended that the project use the 16 scenarios (or a subset of the 16) produced by the CRU for which data are available at 0.5º x 0.5º for the globe. These scenarios represent a range of equally plausible future climates (expressed as anomalies of the baseline 1961–1990 climate) with differences attributable to the different climate models used and to different emission scenarios that the world may follow. The ten scenarios are derived by using five different models (i.e. CSIRO2, HadCM3, CGCM2, ECHAM and PCM) in conjunction with two different emission scenarios (A2, B2, Figure 14). The WatBal model can be used to determine the impact of these different scenarios on runoff and actual evaporation and hence flow in the districts.

The analysts used the TYN SC 2.0: Global 0.5° x 0.5° Gridded Climate Change Dataset. The primary purpose for which TYN SC 2.0 was constructed was to provide environmental modelers with some of the inputs they require to run their models. The control scenario represents the evolution of surface climate over the 21st century under the assumption that the mean climate remains fixed at 1961–1990 levels. The 20 climate change scenarios are made up of all permutations of five **models**[3] with four SRES emissions scenarios (A1FI, A2, B2, B1, Figure 14).

The month-to-month and year-to-year variations are superimposed on top of the averaged climate changes taken from the models; these variations are taken from the gridded observations in **CRU TS 2.0**.[4]

[3] http://www.cru.uea.ac.uk/%7Etimm/grid/TYN_SC_2_0_text.html#Models.
[4] http://www.cru.uea.ac.uk/%7Etimm/grid/CRU_TS_2_0.html.

The companion dataset CRU TS 2.0 may be used in conjunction with TYN SC 2.0 to provide complete time series for the period 1901–2100. The control scenario for the 21st century may be duplicated into the 20th century, which provides a time series for the period 1901–2100 without any long-term climate change.

The purpose of providing 20 different futures is to enable environmental modelers to represent the uncertainty in climate impacts arising from two distinct sources of uncertainty: uncertainty in the future emissions of greenhouse gases, and uncertainty in climate modeling. Each of the 20 permutations should be treated as equally likely. Between them, the 20 scenarios cover 93% of the possible range of future global warming estimated by the IPCC (Intergovernmental Panel on Climate Change) in their Third Assessment Report (Houghton et al. 2001). The control scenario may be useful for tuning models, and for establishing baselines.

The TYN SC 2.0 dataset comprises monthly grids of modeled climate, for the period 2001–2100, and covering the global land surface at 0.5 degree resolution. There are five climatic variables available: cloud cover, diurnal temperature range, DTR, precipitation, temperature, vapor pressure. There is one control scenario and there are 20 climate change scenarios which should all be treated as equally likely.

Definition

Each datum (x) in any scenario is defined by the following equation:

$$x_{vgsiym} = o_{vim} + o'_{viym} + (p_{vgsim} * t_{gsy}) \tag{7}$$

The calculated value must be checked to ensure that it lies within the permissible range. If the value is out of range it must be corrected to the minimum or maximum permissible value, as appropriate.

The symbols used in the above equation are given in the two tables below Tables 5a and 5b: main characters in the first table, subscript characters in the second table. The ‘units’ given in the first table presume that the climate variable is precipitation; for other climate variables substitute the relevant unit wherever ‘mm’ appear. The ‘file type’ given in the first table is a backwards reference to the ‘ingredients’ table, Table 5b.

Procedure

The unpacking of the raw files into the scenario dataset comprises: employing the above equation to combine the information in the raw files into scenario data, and checking that the scenario data lie within the permissible range.

The sequence of operations that might be performed in carrying out the unpacking is summarized below. This is given as an example and is not prescriptive: the user is at liberty to use any sequence that satisfies the above equation. As an example we show how to obtain, for the 0.5° grid-box (363, 286) containing Norwich (52° 38' N, 1° 19' E), the projection of precipitation in July 2081 under the scenario given by using the climate model HadCM3 to represent the A2 emissions scenario. Convert the response pattern into a normalized response pattern (p).

Example: the change in precipitation in 2070–2099, relative to 1961–1990, is -23.9 mm; the amount of global warming, i.e. 3.931°C, is used to convert this into the change in precipitation per degree of global warming, i.e. -6.1 mm °C^{-1}. Obtain the time series of local climate change ($p * t$); this varies only at century time scales.

Example: the normalized pattern, i.e. -6.1 mm °C^{-1}, is multiplied by the amount of global warming in 2081 under the HadCM3 A2 scenario, i.e. 3.734°C^{-1}, to give an anomaly of -22.7 mm.

Add the interannual and multidecadal variability (o') derived from the observed period (1901–2000). Example: the long-term change of -22.7 mm is modified by the residual (from the ‘residual’ file: iavar.1901–2000.pre) for July 1981, i.e. +16.3 mm, to give a combined anomaly of -6.4 mm.

Add the mean climate (o) from the observed period (1961–1990). Example, the combined anomaly of -6.4 mm is added to the climatological mean of 56.9 mm to give a combined precipitation of 50.5 mm.

Check that the value lies within the permissible range. Negative precipitation is clearly nonsensical, so the minimum permissible precipitation is 0 mm.

The ‘scenario selector’ file was designed to inform our own Fortran software, and contains the names of the ‘response pattern’ and ‘global warming’ files to use for each scenario, and the value by which to divide the pattern files to obtain responses expressed in units per degree of global warming. These values are duplicated in Table 6 for clarity. It may be noted that the pattern files for ECHam4 are already stored in units per degree of global warming.

The ‘minimum’ and ‘maximum’ files were included in order to simplify the additions that had to be made to an existing code base. They are not likely to be convenient if writing one’s own software. The same effect can be achieved by applying the values in Table 7 to every grid-box.

3.2 Climate change results for case studies

The results were as follows:

i. WatBal, the water model, was run for base climate at a monthly time step for 1961–1990, producing 360 values for every district. We developed a ‘monthly average’ base for January to December by averaging over the period 1961–1990 (the standard IPCC base) for each of the 12 months. The monthly ‘average’ base values are the first set of data giving for all results for climate change.

ii. For climate change, we ran ten climate change scenarios, described in the previous section: five models for A2 and B2 monthly for the 100 years 2001–2100, producing 1200 monthly values. As requested by the economic modelers we developed decadal average values (monthly) for precipitation , temperature and streamflow.

We provided this data in two formats:

i. Absolute value for the base case and ten sets of decadal average *absolute* values of precipitation, temperature and streamflow.

ii. Absolute value for the base case and ten sets of decadal average *changes* from the *base* for values of precipitation (% change from base), temperature (delta T in degrees from base) and streamflow (% change from base).

Data are provided for all districts, not just those identified for analysis using the Ricardian approach (Section 1). Consequently, data are provided for 1421 political districts in total. The data are stored in individual Excel spreadsheets for each country. Within each spreadsheet the different data types (e.g. runoff, relative soil moisture storage, etc.) are stored in separate sheets, with the districts identified by a unique district number. The district numbers were obtained from the ArcView coverages provided by each country.

All of these data are available from the following website for each case study nation and for the remaining African Nations and subset of Middle Eastern nations:

http://www.joyfullyfit.net/downloads/GEF/

For each nation and the rest of Africa and the Middle East there are 60 files: ten scenarios, three variables and two formats (absolute and changes). With each file approximately one megabyte in size, the total size of the directory is above 600 megabytes.

3.3 Africa-wide analysis of climate change results

With data provided for 1421 political districts in total it is difficult to present any results or make any general conclusions. The authors therefore undertook an Africa-wide analysis with average results for 49 African nations. The results for decadal average changes for 2050 and 2100 in annual values for precipitation, temperature and streamflow are presented in Tables 8, 9, and 10.

Even with this aggregation the data is overwhelming so to give some idea of the spatial variability of the climate change impacts a series of four figures was produced. These figures represent the Africa-wide highest and lowest average impact on streamflow for 2050 and 2100 (see Figures 15 to 18).

Two interesting insights can be gleaned for the results presented:

i. The possible range of Africa-wide climate change impacts on streamflow increases significantly between 2050 and 2100. The range in 2050 is from a decrease of 15% to an increase of 5% above the 1961–1990 base for a range of 20%. For 2100 the range is from a decrease of 19% to an increase of 14% for a range of 33%.

ii. For southern Africa for all four scenarios almost all countries except South Africa experience significant reduction in streamflow. And even for South Africa the increases under the two high scenarios are modest at under 10%.

To provide some additional insights into the change in precipitation, temperature and streamflow over the ten decades from 2001 to 2100 for the ten scenarios for each of the 49 African Nations analyses, 174 figures were prepared, 12 of which were randomly selected and are presented in Appendix A.

4. Concluding remarks

In Phase I, the following monthly time series have been derived for the years 1961–1990 for each of the politically delineated districts in the 11 countries of the study:

- Runoff (mm)
- Relative soil storage (0-1)
- Potential evapotranspiration (mm)
- Actual evapotranspiration (mm)
- Temperature (^{o}C)
- Precipitation (mm)
- Streamflow (m^3)

A river density index and the percentage area irrigated have also been derived for each district. These data are available for the country teams to validate, and for the derivation of appropriate independent variables for use in the Ricardian analysis.

These results are provided for all districts, not just those identified for analysis using the Ricardian approach (Section 1). Consequently, data are provided for 1421 political districts in total. The data are stored in individual Excel spreadsheets for each country. Within each spreadsheet the different data types (e.g. runoff, relative soil moisture storage, etc.) are stored in separate sheets, with the districts identified by a unique district number. The district numbers were obtained from the ArcView coverages provided by each country.

In Phase II, the climate change impact analysis was performed. Ten climate change scenarios, and five models for A2 and B2 were run through the hydrologic model to produce monthly results for 100 years: 2001–2100 producing 1200 monthly values. As requested by the economic modelers, the 1200 monthly values were processed into decadal average values (monthly) for precipitation, temperature and streamflow. This data was provided in two formats:

i. Absolute value for the base case and 10 sets of decadal average *absolute* values of precipitation , temperature and streamflow.

ii. Absolute value for the base case and 10 sets of decadal average *changes* from the *base* for values of precipitation (% change from base), temperature (delta T in degrees from base) and streamflow (% change from base).

REFERENCES

FAO (Food and Agriculture Organization), 1992. Expert consultations on revision of FAO methodologies for crop water requirements. Land and Water Development Division, FAO of the UN, Rome, Italy.

FAO (Food and Agriculture Organization). Atlas of Water Resources and Irrigation in Africa. FAO of the UN, Rome, Italy.

Fekete BM, Vörösmarty CJ & Grabs W, 2000. Global composite runoff data set (v1.0). Complex Systems Research Center, University of New Hampshire, Durham, New Hampshire, US. http://www.grdc.sr.unh.edu/

Frontline Systems, Inc., 2003. Genetic Mutation Algorithm. **http://www.solver.com/developer.htm#Solver%20DLL%20Platform**

Houghton JT et al., (eds), 2001. *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Kaczmarek Z, 1993. Water balance model for climate impact analysis. *ACTA Geophysica Polnica* 41(4): 1–16.

Mendelsohn R, Nordhaus W & Shaw D, 1994. The impact of global warming on agriculture: A Ricardian Analysis. *American Economic Review* 84: 753–771.

Monteith JL, 1965. Radiation and crops. *Experimental Agricultural Review* 1: 241–251.

New M, Hulme M & Jones P, 1999. Representing twentieth-century space-time climate variability. Part I: Development of a 1961–90 mean monthly terrestrial climatology. *Journal of Climate* 12: 829–856.

UNESCO, 1997. Southern Africa FRIEND (Flow Regimes from International Experimental and Network Data), *Technical Documents in Hydrology No. 15*, UNESCO, Paris.

Vörösmarty CJ, Fekete BM, Meybeck M & Lammers RB, 2000. Global system of rivers: Its role in organizing continental land mass and defining land-to-ocean linkages. *Global Biogeochemical Cycles* 14(2): 599-621.

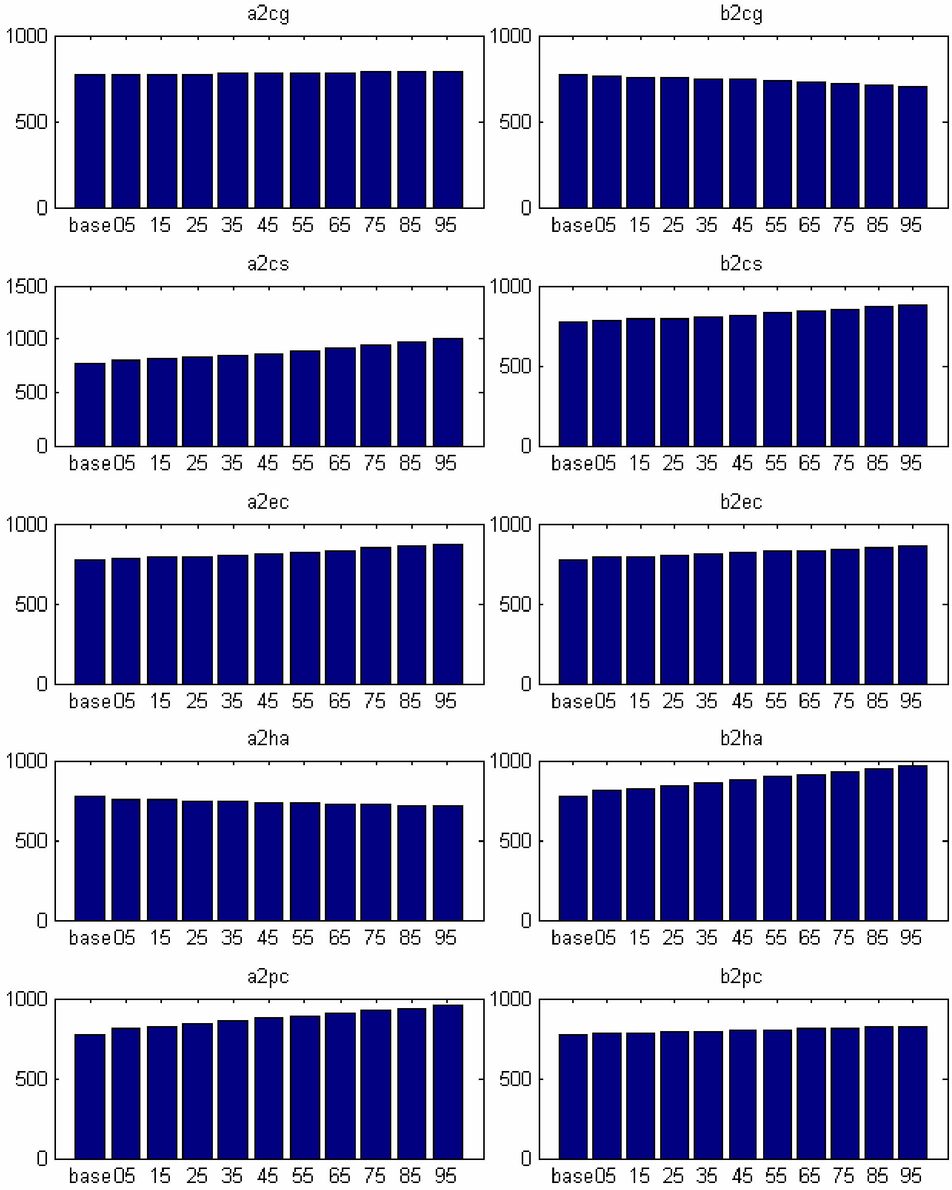
Yates D, 1996. WatBal: An integrated water balance model for climate impact assessment of river basin runoff. *International Journal of Water Resources Development* 12(2): 121–139.

Yates D, 1997. Approaches to continental scale runoff for integrated assessment models. *Journal of Hydrology* 201: 289–310.

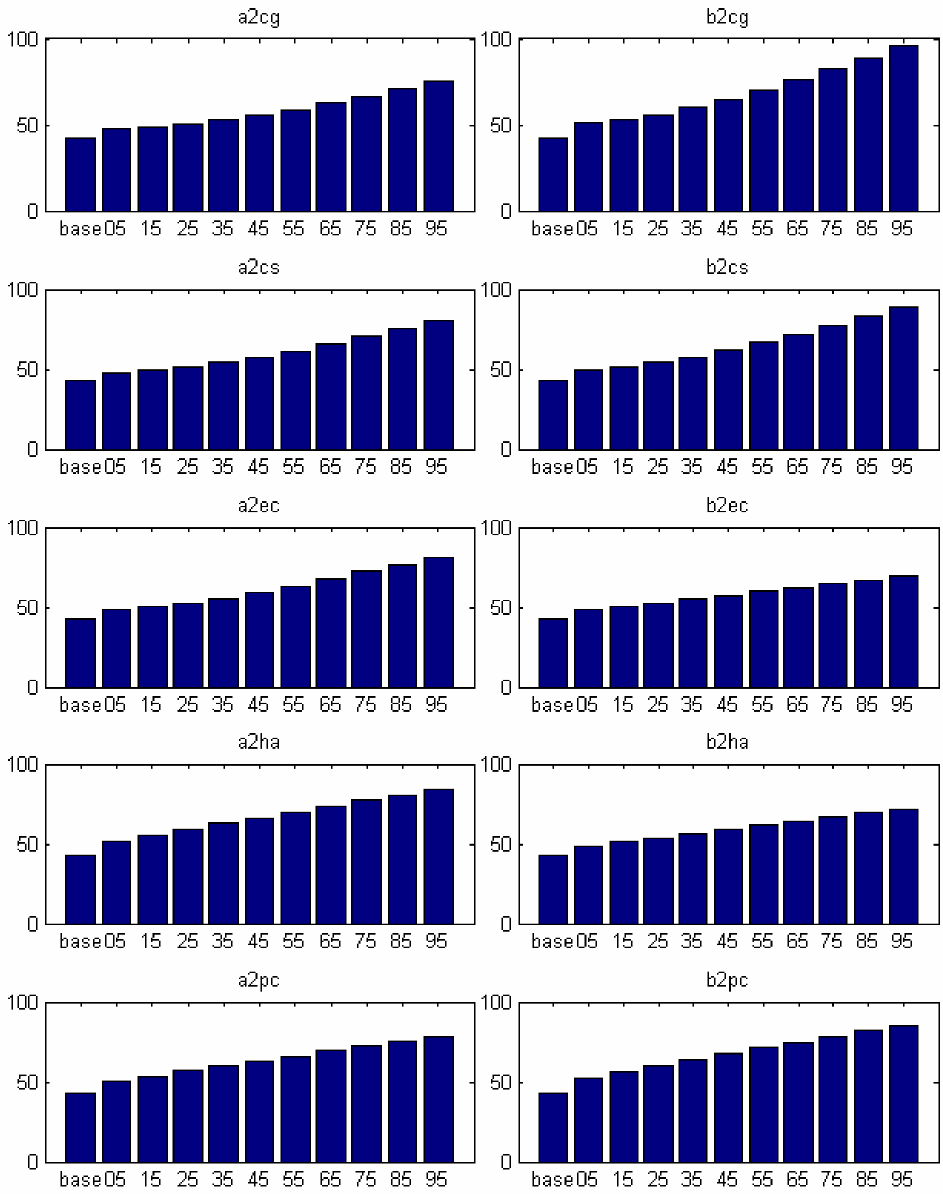
Yates D & Strzepek K, 1994. Comparison of models for climate change assessment of river basin runoff. WP-94-46, IIASA, Laxenburg, Austria.

APPENDICES: Sample results from analyses of climate change scenarios

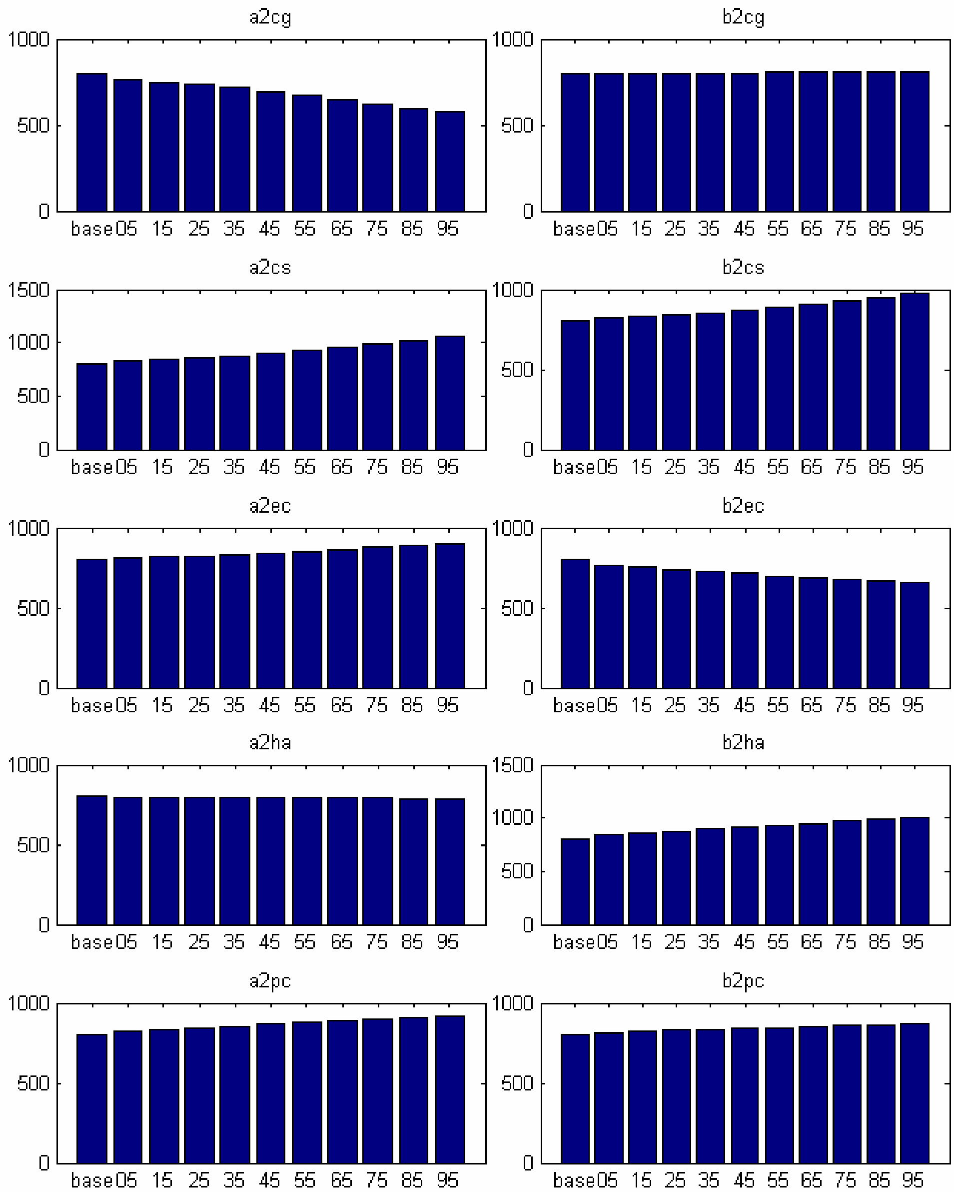
A1: Burkina Faso precipitation



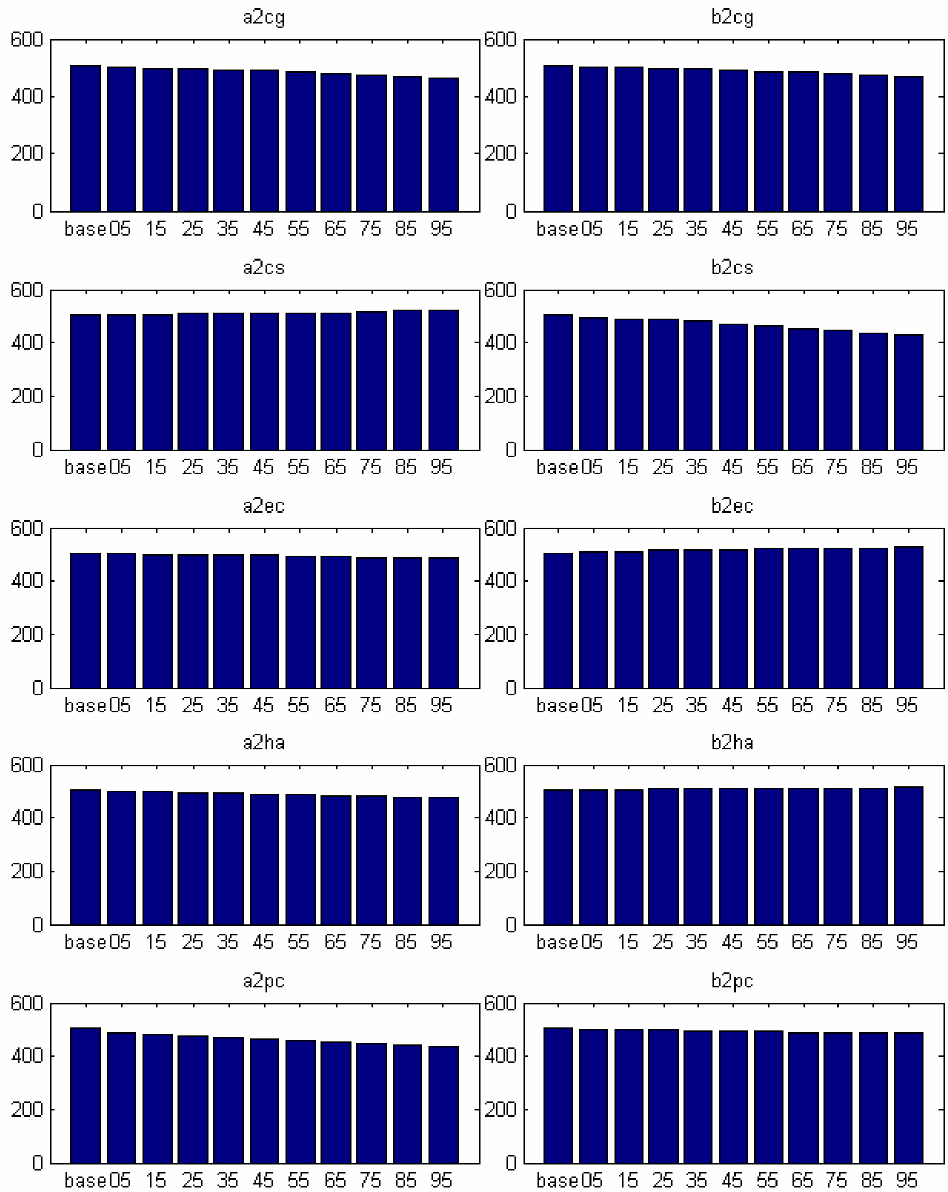
A2: Egypt precipitation



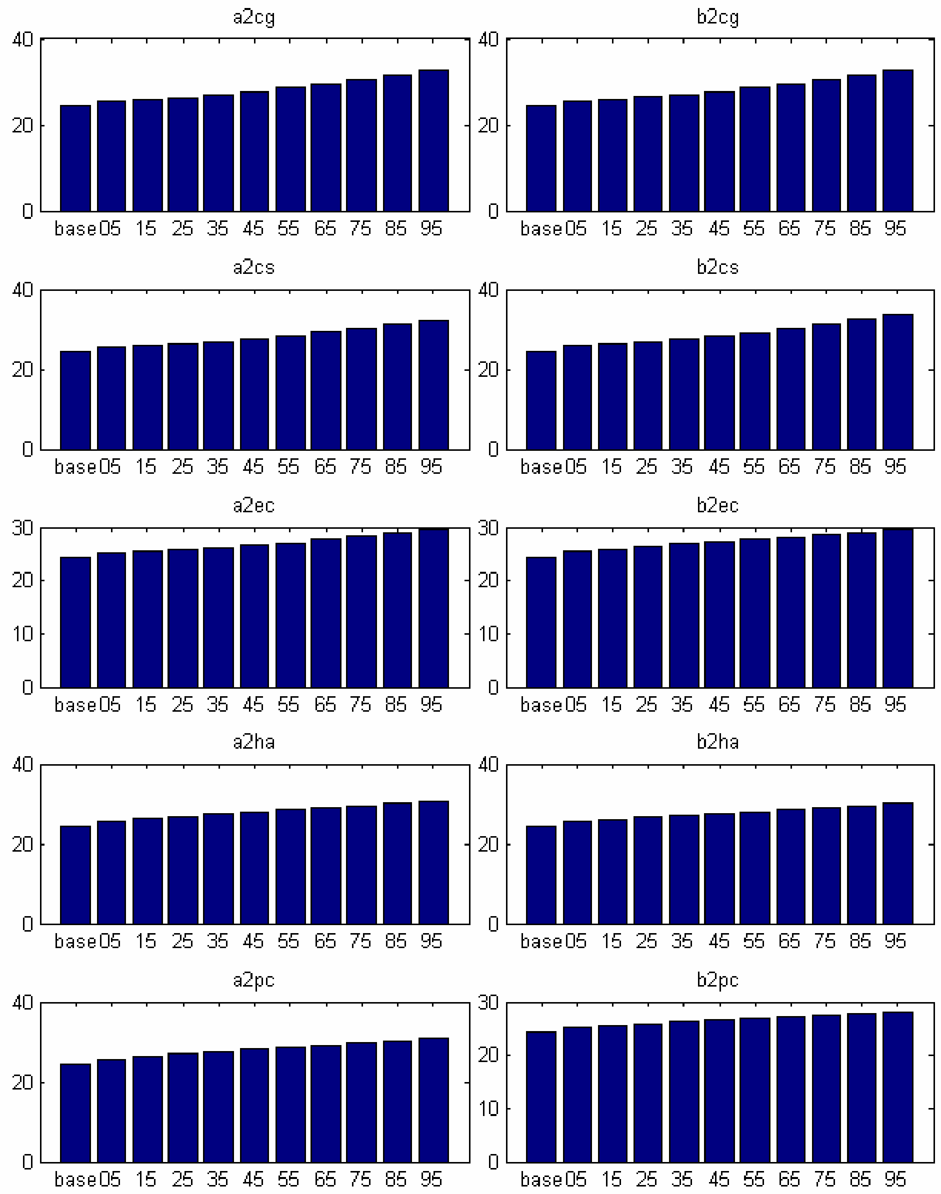
A3: Ethiopia precipitation



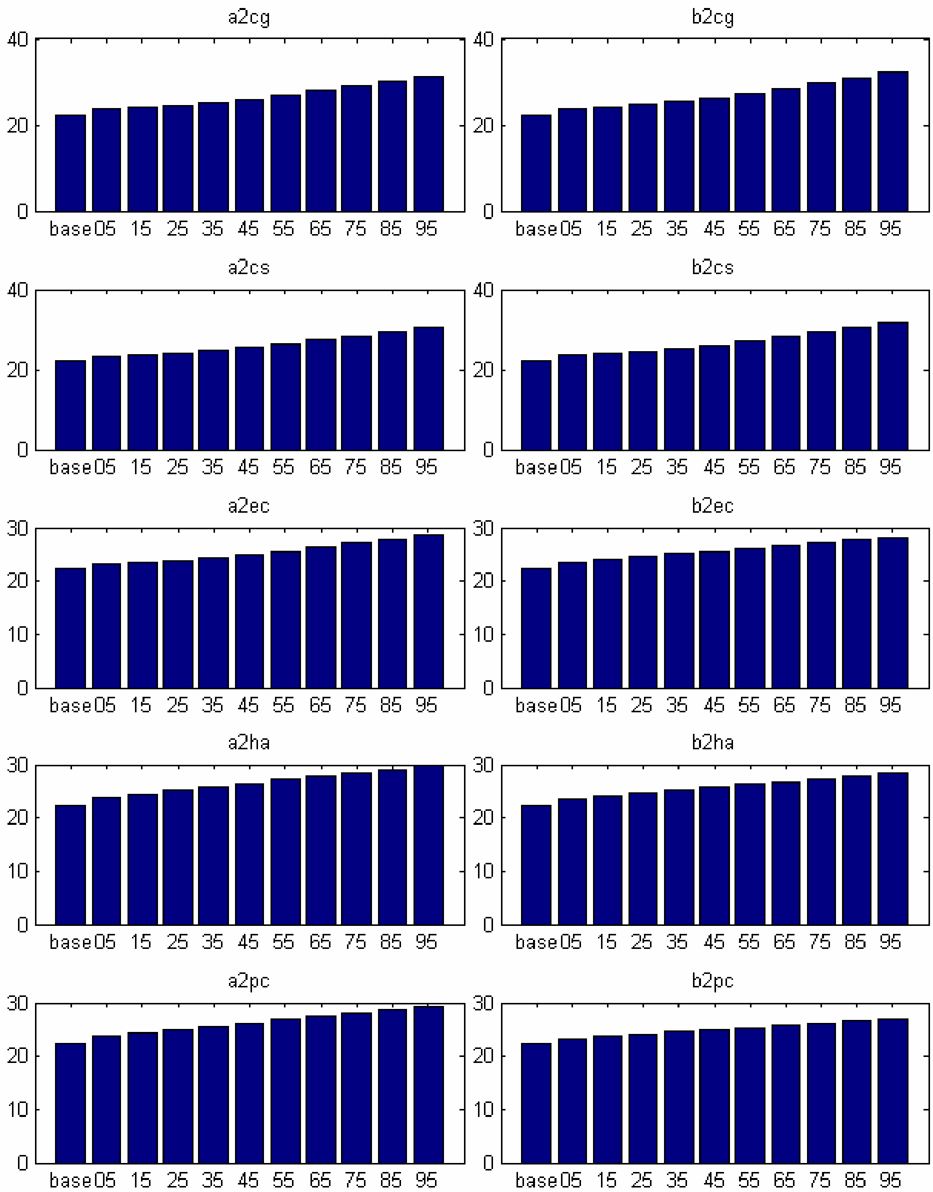
A4: South Africa precipitation



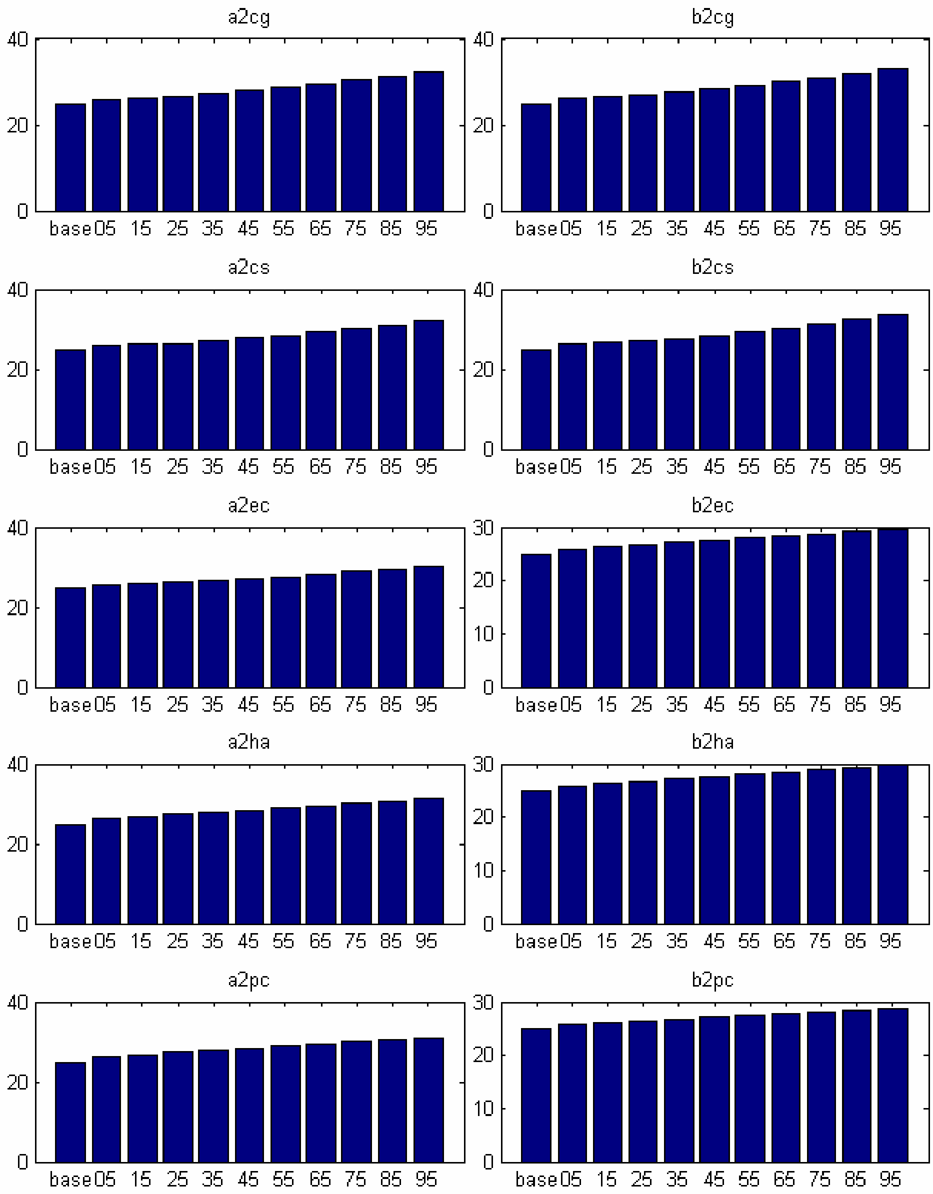
A5: Cameroon temperature



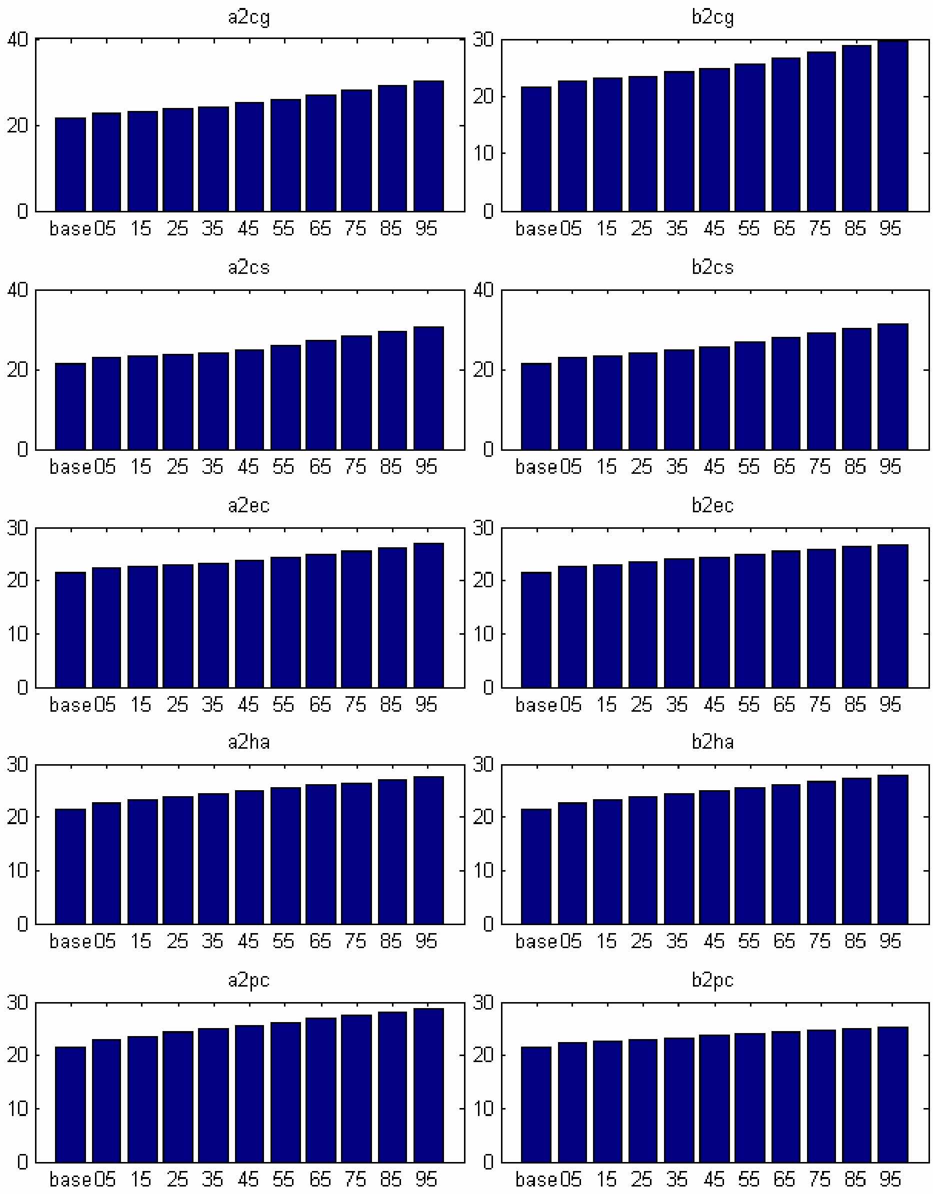
A6: Egypt temperature



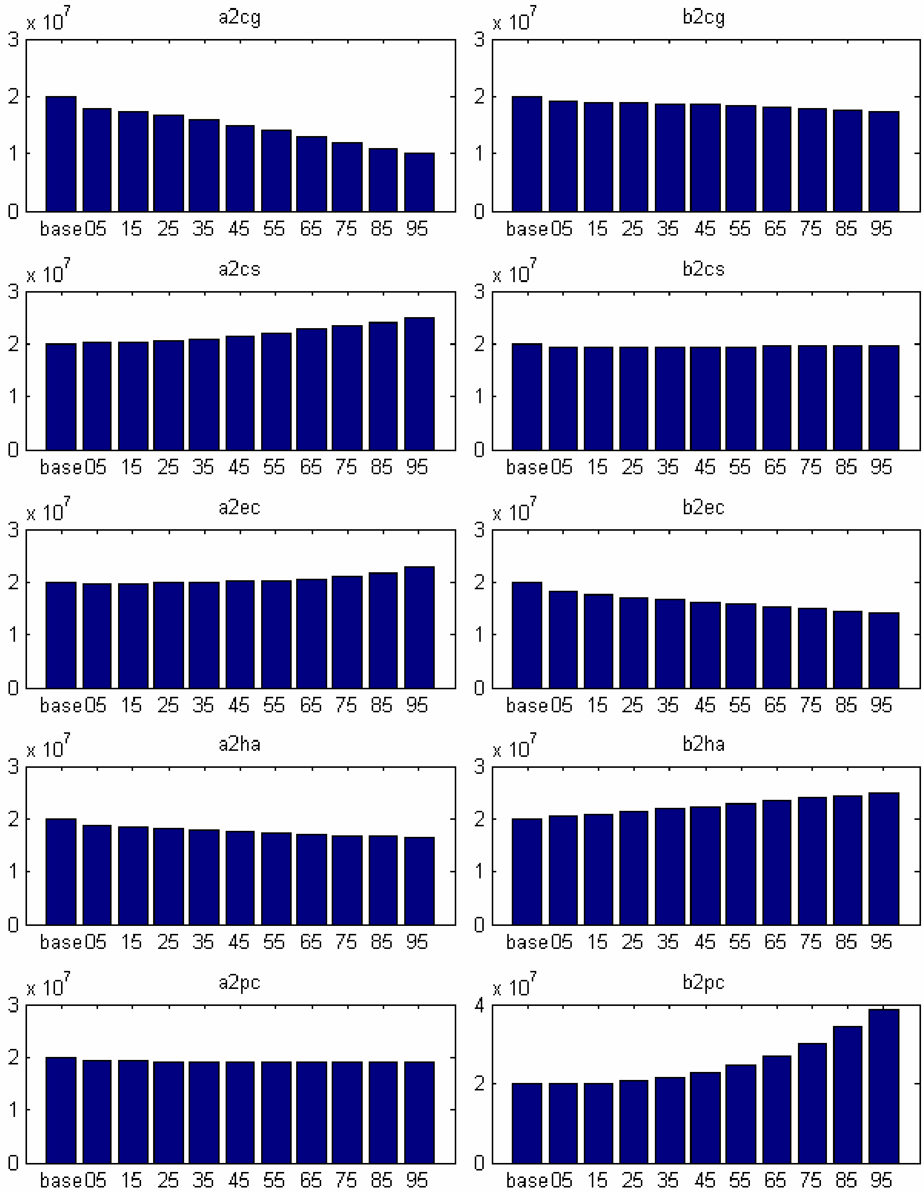
A7: Kenya temperature



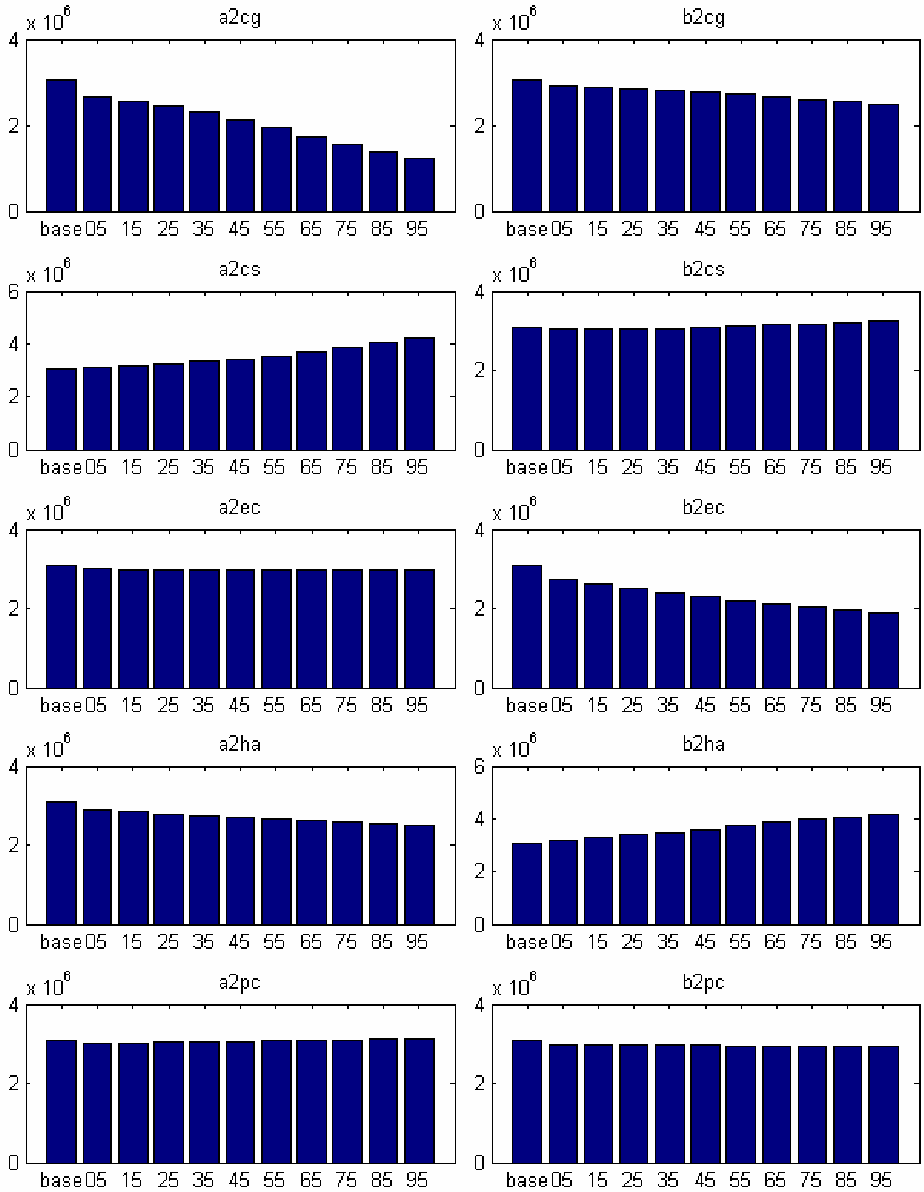
A8: Zambia temperature



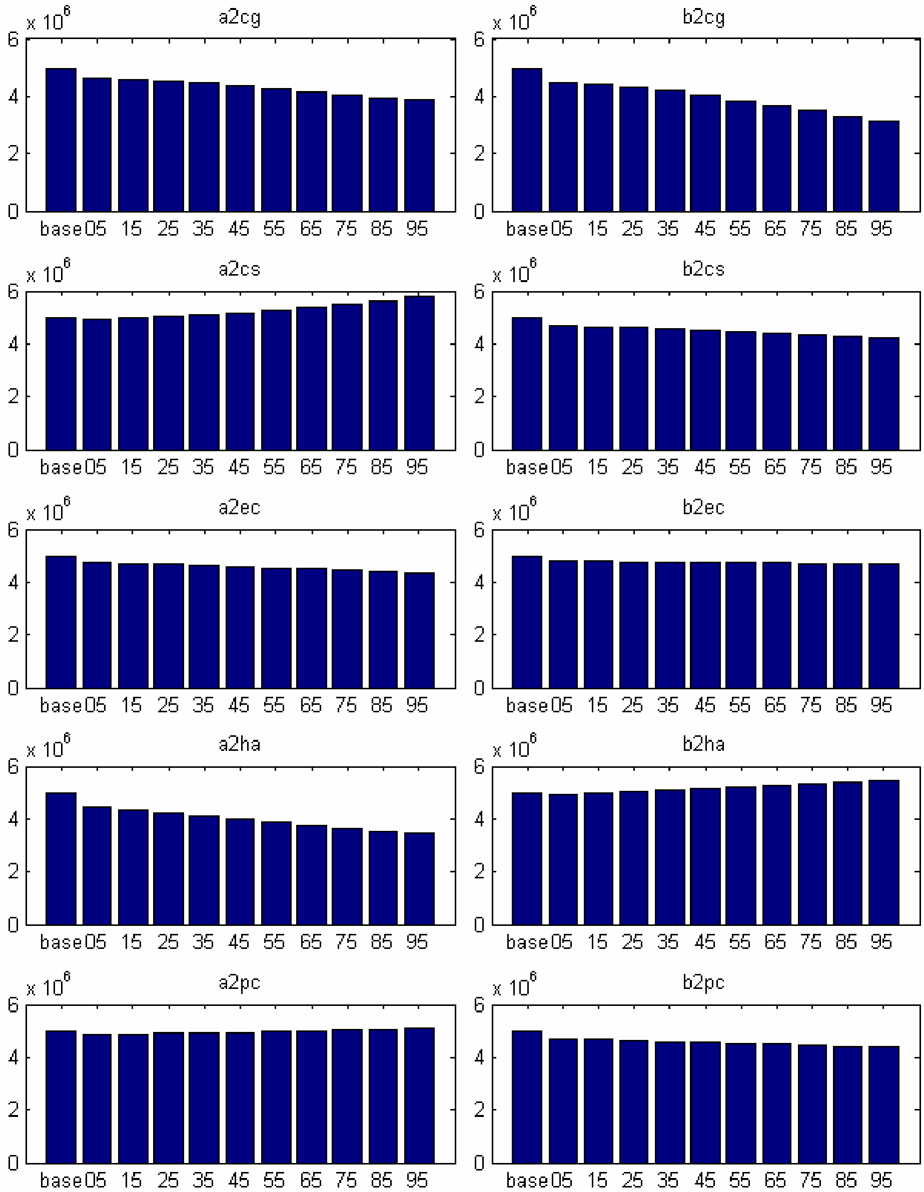
A9: Egypt flow



A10: Ethiopia flow



A11: Ghana flow



A12: Zimbabwe flow

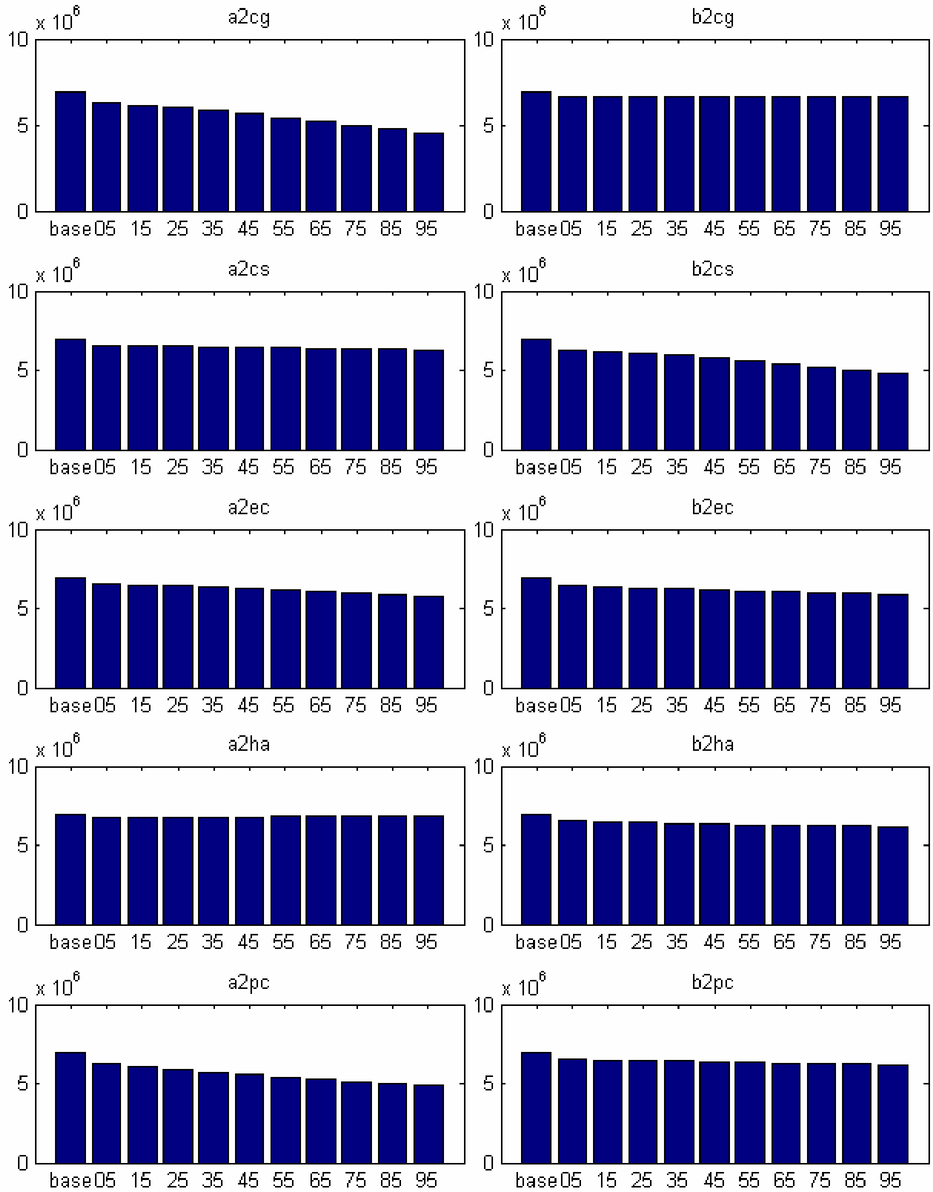


Table 1: Summary of districts in each country

Country	Area (km^2)	Nos. of districts	Nos. of districts selected by country teams*
Burkina Faso	273,719	301	50
Cameroon	466,307	58	50
Egypt	982,910	27	18
Ethiopia	1,132,328	65	62
Ghana	239,981	110	60
Kenya	584,429	72	43
Niger	1,186,021	36	30
Senegal	196,911	320	72
South Africa	1,221,943	372	32
Zambia	754,773	72	61
Zimbabwe	390,804	60	40

* Where no number is shown the districts for the Ricardian approach have yet to be identified.

Table 2: Sources of data used in this study

Data	Description	Source
District boundaries	Politically defined district boundaries – shape files	USAID, FEWS, EDC-International Program and the U.S. Geological Survey under the Africa Data Dissemination Service (ADDS) and Yale University. Ghana and Kenya map provided by UNESCO (1997) through UNEP/GRID-Sioux Falls and Yale University.
Land use	13 land classes - 0.5^{o} grid.	International Institute for Applied Systems Analysis (IIASA) - obtained directly by personal comm.
Rivers of Africa	Digitized map of African rivers – polylines	**http://www.fao.org/geonetwork/srv/en/metadata.show?id=12&currTab=summary**
Irrigation potential	Global map of irrigated areas – 0.5^{o} grid	**http://www.fao.org/waicent/faoinfo/agricult/agl/aglw/aquastat**
Maximum soil moisture capacity	Values between 0 and 1,000 mm – 0.08^{o} grid.	**http://www.fao.org/geonetwork/srv/en/metadata.show?id=5018&currTab=summary**
Precipitation, temperature, vapor, wind speed, pressure and cloudiness	CRU-CL 1.0 dataset. A dataset of mean monthly surface climate over global land areas, excluding Antarctica. Interpolated from station data to 0.5 degree lat./long. for a range of variables: precipitation and wet-day frequency, mean temperature and diurnal temperature range (from which maximum temperature and minimum temperature can be determined), vapor pressure, sunshine, cloud cover, ground-frost frequency and windspeed – 0.5^{o} grid (New et al. 1999)	**http://ipccddc.cru.uea.ac.uk/asres/baseline/climate_download.html**
Drainage network	Topographically generated drainage lines (polylines) for each 0.5^{o} grid cell. Named STN-30p	University of New Hampshire CD - UNH/GRDC Composite runoff fields V1.0.
Calibration runoff	Simulated runoff (average monthly totals in mm) 0.5^{o} grid	University of New Hampshire CD - UNH/GRDC Composite runoff fields V1.0.

Table 3: IIASA land use classes and the six classes derived by aggregation in this study

IIASA land classes	Aggregated land classes	Allowed range for AWC_{multi}
Grassland	Grassland	0.1-1.5 m
Mosaics including crops Wetlands Water and coastal fringes	Bush/savanna	0.1-2.5 m
Woodland Forest	Forest	0.1-5.0 m
Cropland Intensive cropland Urban	Cultivated land	0.1-2.0 m
Desert, bareland	Desert	0.1-2.0 m
Ice Cold desert Tundra	Tundra	0.1-1.0 m

Table 4: Summary of the number of gauging stations for which flow data were provided by the country teams

Country	Number of gauging stations for which data were provided	Supplementary data from the FRIEND database*
Burkina Faso	19	
Cameroon		
Egypt	3	
Ethiopia		
Ghana	29	
Kenya		
Niger	6	
Senegal	13	
South Africa	29	21
Zambia	1	20
Zimbabwe	32	21

* The Southern Africa FRIEND database comprises flow for SADC countries only (UNESCO 1997)

Table 5a: Definitions

Symbol	Variable	Units	File
x	Scenario datum	mm	-
o	(Observed) climatology	mm	'Climatology'
o′	(Observed) residual	mm	'Residual'
p	Response pattern	mm $°C^{-1}$	'Response pattern', modified by 'scenario selector'
t	Global warming	°C	'Global warming'

Table 5b: Definitions

Symbol	Variable
v	Climate variable
g	Climate model (GCM)
s	SRES emissions scenario
i	Grid-box
y	Year
m	Month

Table 6: Climate sensitivity

°C	PCM	CGCM2	CSIRO2	HadCM3	ECHam4
A1FI	3.045	4.382	4.855	4.863	1.000 (use A2)
A2	2.462	3.548	3.938	3.931	1.000
B2	1.894	2.462	3.139	3.070	1.000
B1	1.541	2.023	2.592	2.521	1.000 (use B2)

Table 7: Climate change variables

Climate variable	Units	Minimum	Maximum
Temperature	°C	None (in theory -273.15)	None
Precipitation	mm	0.0	None
Diurnal temperature range	°C	0.1	None
Vapor pressure	hPa	0.0	None
Cloud cover	%	0.0	100.0

Table 8a: Precipitation

	A2- Scenarios									
	cg-a2		cs-a2		ec-a2		ha-a2		pc-a2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	102%	105%	97%	93%	102%	105%	101%	102%	103%	106%
Kenya	106%	116%	109%	123%	113%	134%	110%	124%	106%	115%
Senegal	102%	105%	101%	102%	98%	96%	91%	79%	93%	85%
Burkina Faso	101%	103%	96%	91%	112%	130%	106%	115%	105%	113%
South Africa	96%	92%	97%	92%	101%	104%	93%	85%	98%	96%
Cameroon	100%	99%	99%	96%	106%	116%	101%	104%	104%	110%
Zambia	95%	88%	105%	113%	101%	105%	101%	102%	100%	99%
Zimbabwe	92%	82%	103%	107%	114%	140%	99%	97%	96%	91%
Egypt	131%	179%	153%	227%	136%	190%	146%	211%	139%	193%
Ethiopia	87%	72%	100%	101%	112%	132%	109%	122%	105%	112%
Niger	118%	146%	107%	117%	138%	196%	117%	144%	128%	169%

Table 8b: Precipitation

	B-2 -Scenarios									
	cg-b2		cs-b2		ec-b2		ha-b2		pc-b2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	104%	107%	98%	96%	100%	100%	106%	110%	103%	105%
Kenya	104%	109%	105%	109%	116%	129%	108%	115%	106%	110%
Senegal	106%	110%	102%	103%	99%	98%	95%	91%	88%	80%
Burkina Faso	101%	103%	96%	91%	112%	130%	106%	115%	105%	113%
South Africa	102%	104%	97%	94%	100%	102%	91%	86%	97%	96%
Cameroon	100%	99%	99%	96%	106%	116%	101%	104%	104%	110%
Zambia	98%	96%	106%	110%	100%	102%	98%	97%	101%	102%
Zimbabwe	91%	86%	107%	113%	111%	122%	96%	94%	100%	99%
Egypt	131%	179%	153%	227%	136%	190%	146%	211%	139%	193%
Ethiopia	87%	72%	100%	101%	112%	132%	109%	122%	105%	112%
Niger	131%	155%	107%	113%	157%	202%	124%	143%	131%	154%

Table 9a: Temperature

	A2- Scenarios									
	cg-a2		cs-a2		ec-a2		ha-a2		pc-a2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	3.5	8.5	3.5	8.7	3.2	8.0	3.7	9.2	2.2	5.2
Kenya	3.0	7.4	3.4	8.2	2.8	7.2	3.6	8.7	2.2	5.4
Senegal	3.9	9.6	3.5	8.7	3.3	8.5	4.0	9.9	2.4	5.9
South Africa	3.6	9.0	3.5	8.6	3.4	8.6	3.9	9.6	2.3	5.6
Burkina Faso	3.7	9.2	3.9	9.5	3.3	8.3	3.9	9.7	2.4	5.7
Cameroon	3.4	8.3	3.4	8.3	3.1	7.9	3.7	9.2	2.2	5.2
Zambia	3.6	8.8	3.4	8.3	3.5	9.0	4.1	10.0	2.2	5.4
Zimbabwe	3.7	9.2	3.4	8.2	3.4	8.7	4.3	10.6	2.3	5.6
Egypt	3.7	9.2	4.1	10.0	3.3	8.3	3.9	9.6	2.7	6.5
Ethiopia	3.3	8.0	3.6	8.7	3.2	8.0	3.8	9.4	2.3	5.5
Niger	3.9	9.5	4.1	9.9	3.2	8.2	4.0	9.8	2.5	6.1

Table 9b: Temperature

	B-2 -Scenarios									
	cg-b2		cs-b2		ec-b2		ha-b2		pc-b2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	2.9	5.1	3.7	6.6	3.2	5.7	3.7	6.5	2.2	3.8
Kenya	2.7	4.7	3.6	6.3	2.8	4.9	3.6	6.3	2.3	3.8
Senegal	3.3	5.8	3.7	6.5	3.4	6.0	4.0	7.0	2.5	4.2
South Africa	3.2	5.6	3.6	6.5	3.5	6.1	3.9	6.9	2.4	4.0
Burkina Faso	3.1	5.4	4.0	7.1	3.3	5.8	3.8	6.7	2.4	4.0
Cameroon	2.9	5.1	3.5	6.3	3.1	5.6	3.7	6.5	2.2	3.8
Zambia	3.0	5.3	3.5	6.2	3.6	6.4	4.2	7.3	2.2	3.8
Zimbabwe	3.3	5.7	3.3	5.9	3.5	6.2	4.5	7.9	2.3	3.9
Egypt	3.4	6.1	4.2	7.5	3.5	6.2	4.0	7.0	2.8	4.7
Ethiopia	2.9	5.1	3.7	6.6	3.1	5.6	3.8	6.7	2.3	4.0
Niger	3.4	6.0	4.2	7.4	3.2	5.8	4.0	7.0	2.5	4.3

Table 10a: Streamflow

	A2- Scenarios									
	cg-a2		cs-a2		ec-a2		ha-a2		pc-a2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	88%	77%	81%	63%	104%	116%	90%	85%	92%	87%
Kenya	80%	67%	97%	100%	107%	128%	95%	98%	95%	97%
Senegal	104%	92%	101%	85%	110%	101%	92%	66%	108%	115%
South Africa	80%	62%	82%	67%	105%	119%	82%	69%	84%	70%
Burkina Faso	83%	70%	79%	61%	108%	130%	91%	88%	94%	94%
Cameroon	89%	77%	89%	76%	110%	127%	93%	88%	99%	99%
Zambia	85%	69%	100%	104%	92%	87%	88%	77%	94%	91%
Zimbabwe	82%	66%	96%	97%	93%	91%	83%	69%	91%	84%
Egypt	75%	50%	92%	87%	107%	124%	97%	99%	100%	114%
Ethiopia	69%	41%	90%	81%	112%	138%	101%	106%	97%	97%
Niger	92%	150%	83%	66%	99%	103%	86%	75%	95%	101%

Table 10b: Streamflow

	B-2 -Scenarios									
	cg-b2		cs-b2		ec-b2		ha-b2		pc-b2	
	2050	2100	2050	2100	2050	2100	2050	2100	2050	2100
Ghana	95%	94%	80%	69%	103%	109%	99%	102%	91%	88%
Kenya	81%	74%	91%	89%	112%	126%	94%	95%	94%	95%
Senegal	113%	114%	100%	92%	113%	114%	97%	83%	105%	96%
South Africa	90%	86%	79%	67%	106%	115%	82%	74%	80%	70%
Burkina Faso	94%	92%	79%	69%	110%	122%	102%	107%	92%	90%
Cameroon	91%	85%	87%	79%	115%	128%	93%	90%	102%	104%
Zambia	93%	90%	100%	102%	91%	88%	85%	77%	95%	94%
Zimbabwe	90%	85%	98%	100%	92%	90%	80%	71%	92%	90%
Egypt	81%	70%	88%	82%	111%	124%	96%	96%	114%	193%
Ethiopia	75%	62%	88%	82%	118%	135%	100%	102%	96%	95%
Niger	100%	133%	84%	75%	104%	118%	94%	94%	94%	90%

Figure 1: District boundaries in each of the countries for which the Ricardian analysis is being conducted

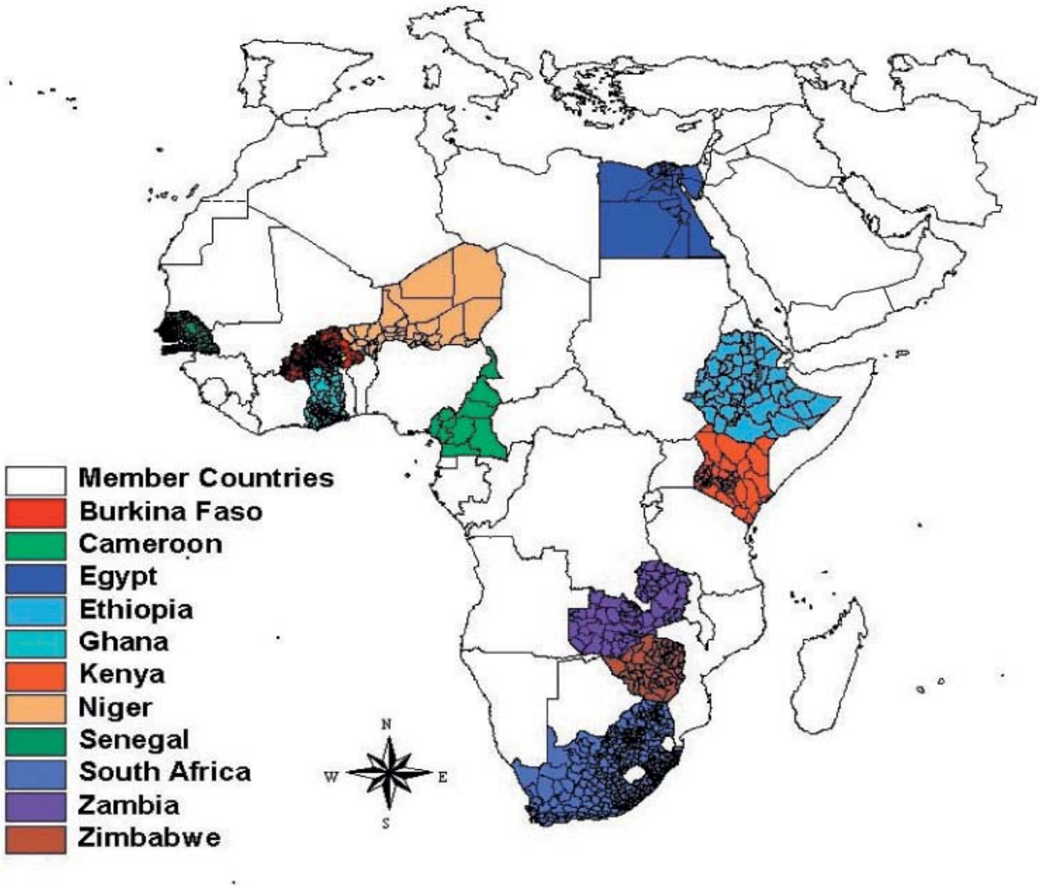


Figure 2: Simplified version of the WatBal model that is used to compute gridded runoff

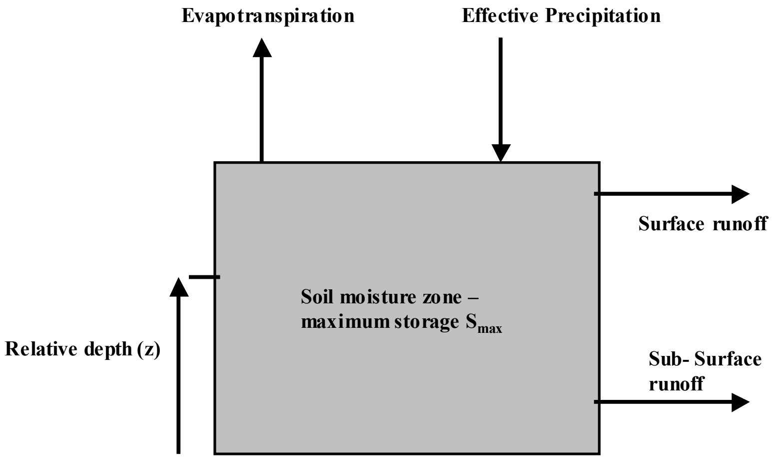


Figure 3: Ratio of actual to potential evapotranspiration as the relative depth (z) declines (i.e. the catchment gets drier)

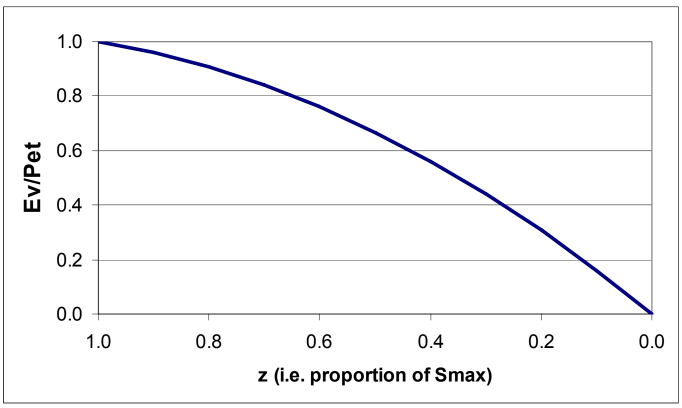


Figure 4: Land use classification for Africa (aggregated from IIASA land use classification)

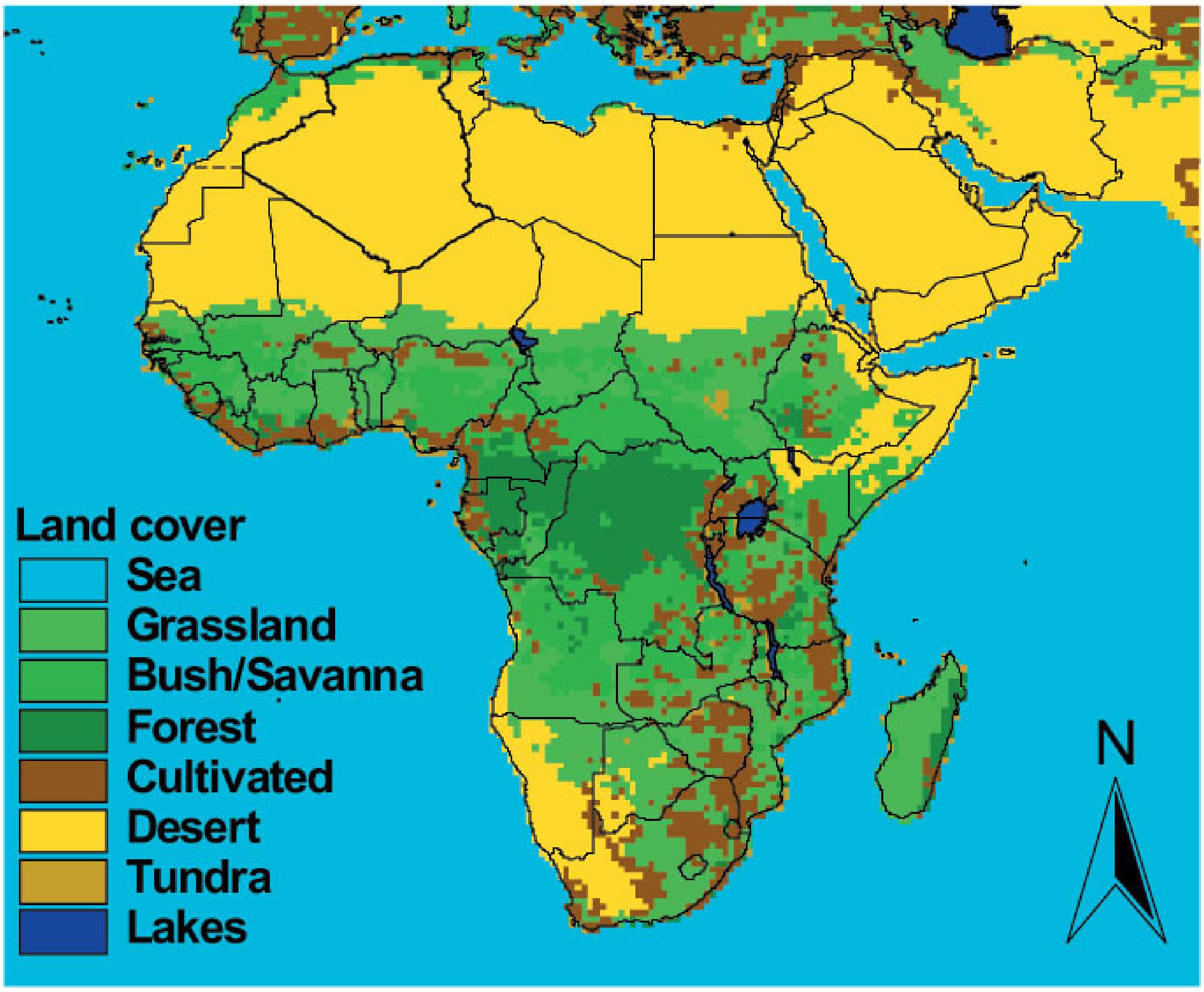


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Figure 5: Potential irrigated area, based on density of formal irrigation infrastructure for the whole of Africa and for Egypt, showing high potential downstream of the Aswan Dam and particularly in the Nile Delta (from FAO – Atlas of Water Resources and Irrigation in Africa)

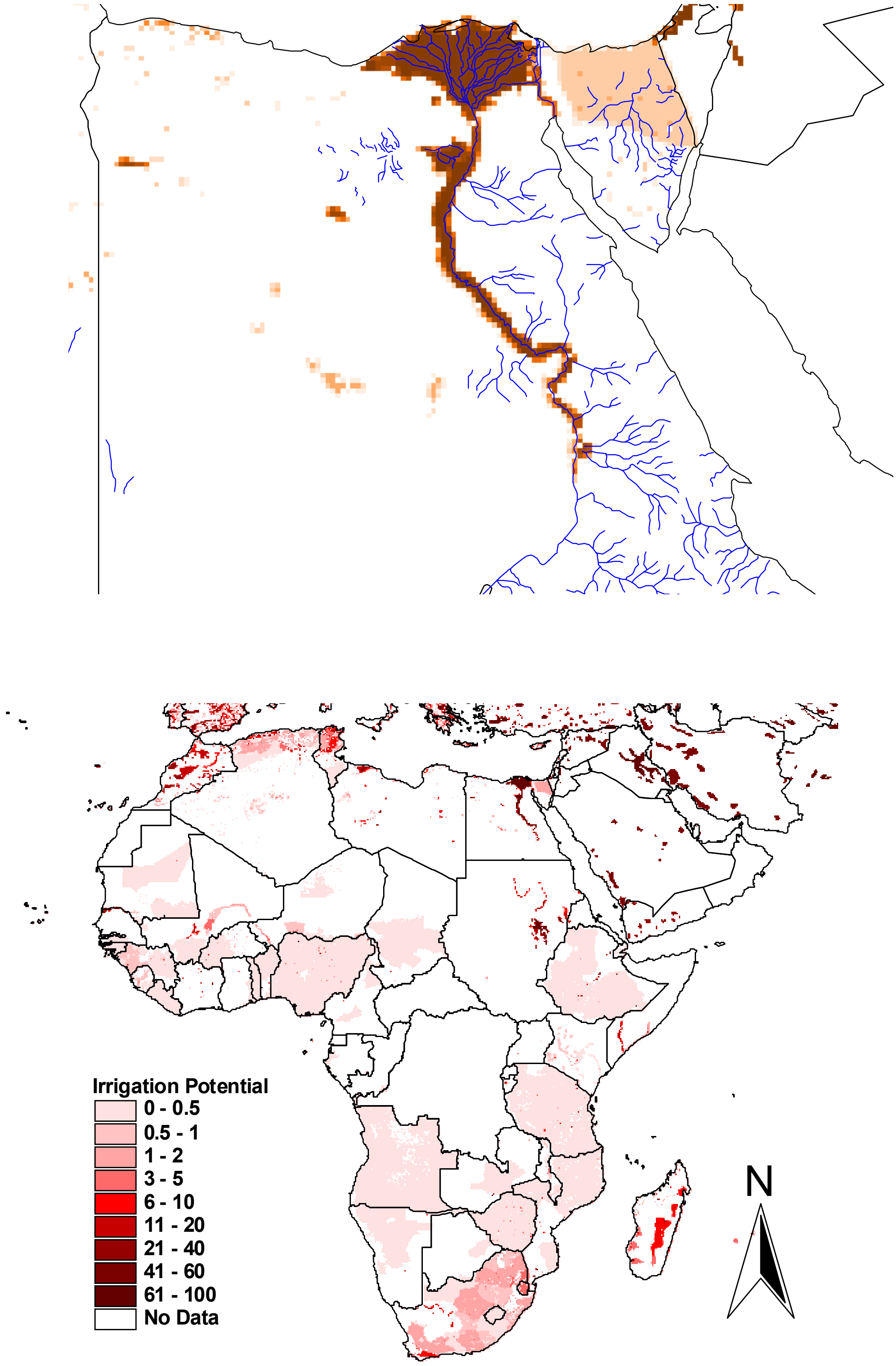


Figure 6: Topographically derived drainage network for Ghana (shows the 0.5° grid and the FAO river network)

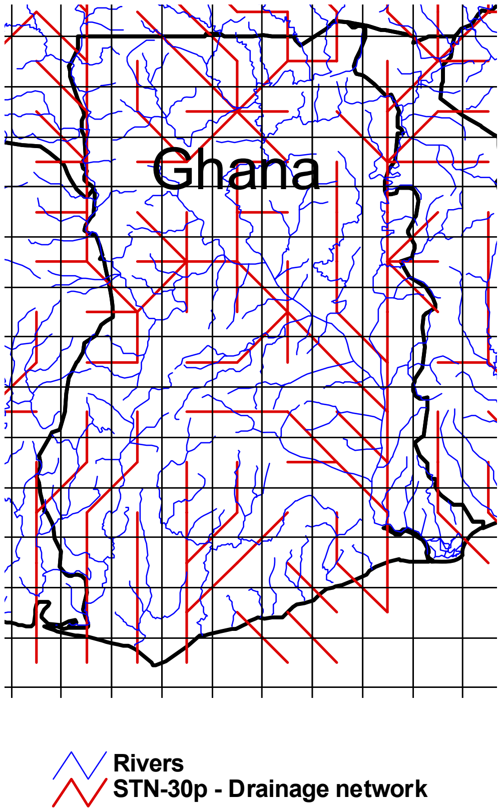


Figure 7: Mean annual runoff gridded at 0.5° latitude/longitude resolution
(from University of New Hampshire)

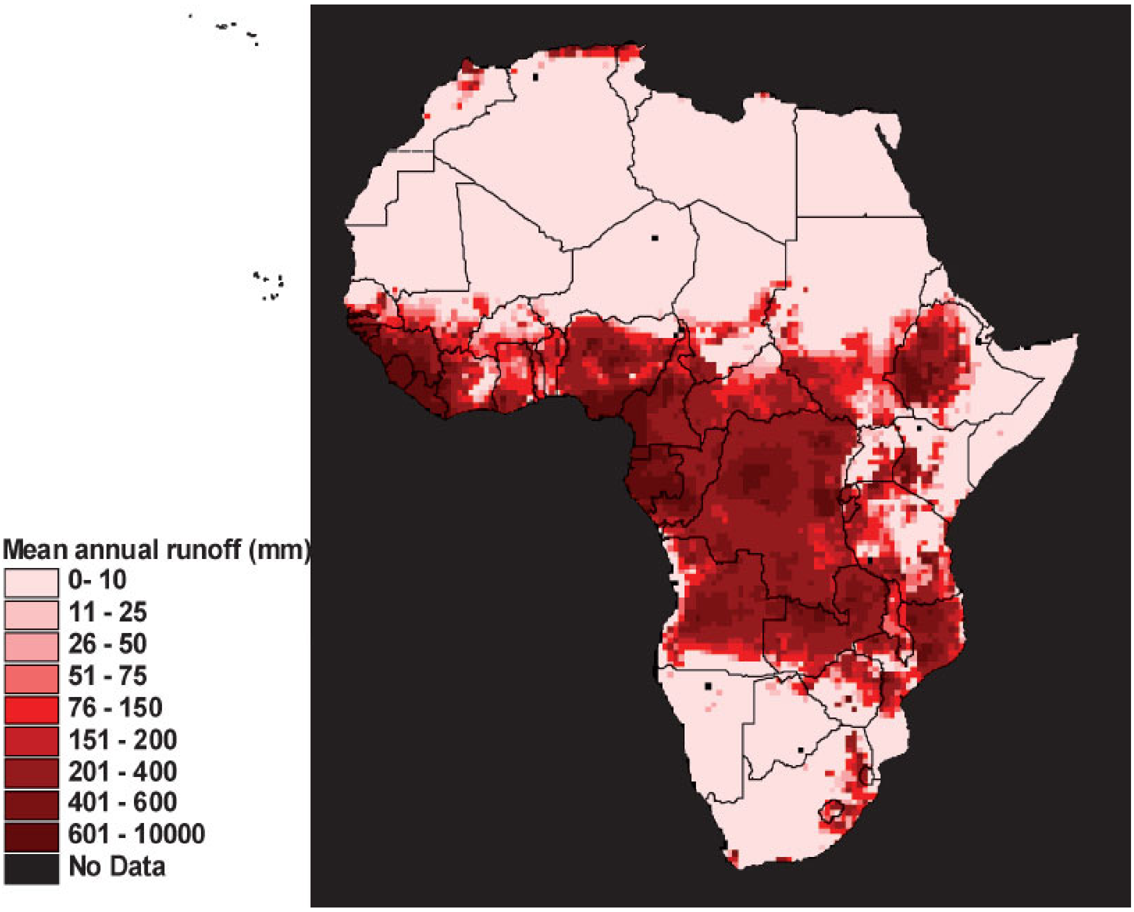


Figure 8: Comparison of runoff generated by WatBal and the UNH data for 97 'food production units' in Africa

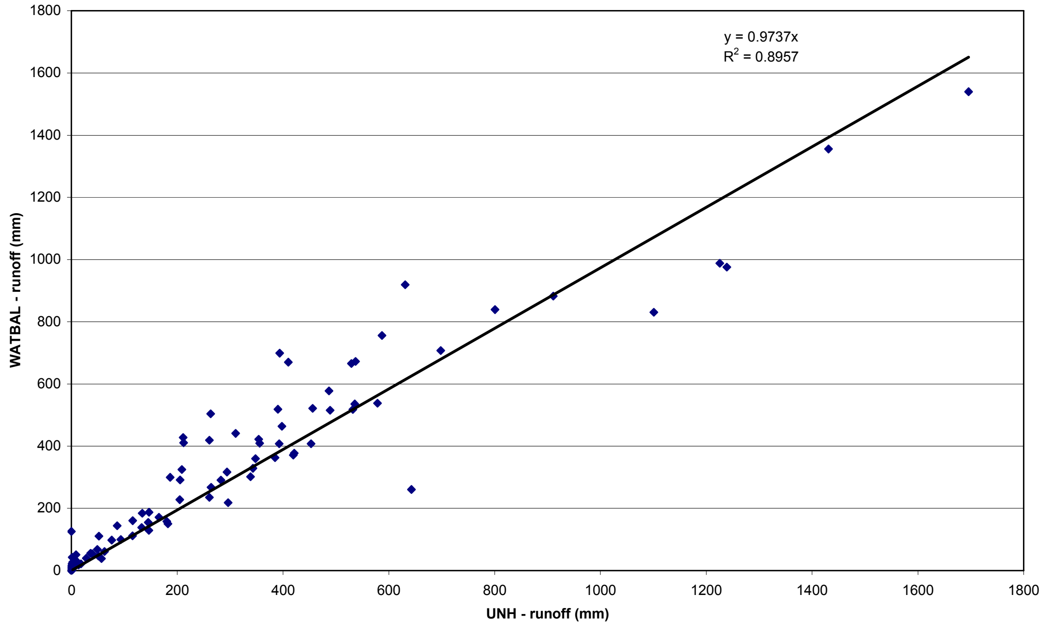


Figure 9: Burkina Faso: An example of how districts can be divided over a number of grid cells

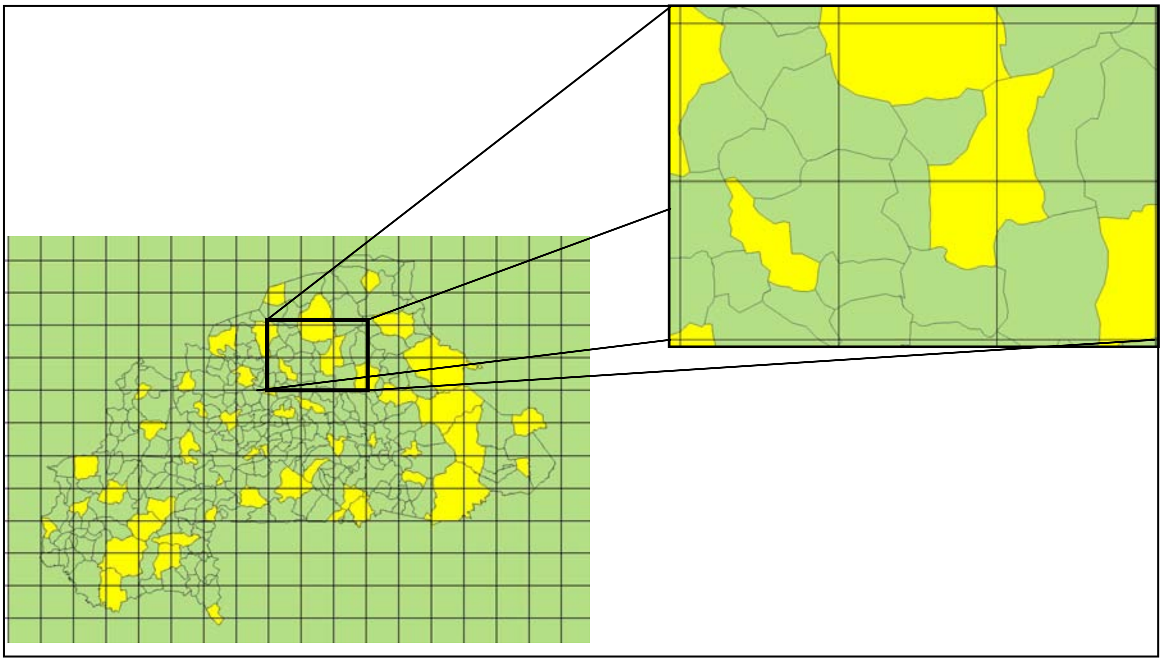


Figure 10: Details of the drainage network used for streamflow routing in Burkina Faso (Districts shown in orange are those in which surveys are being conducted to obtain data for use in the Ricardian approach.)

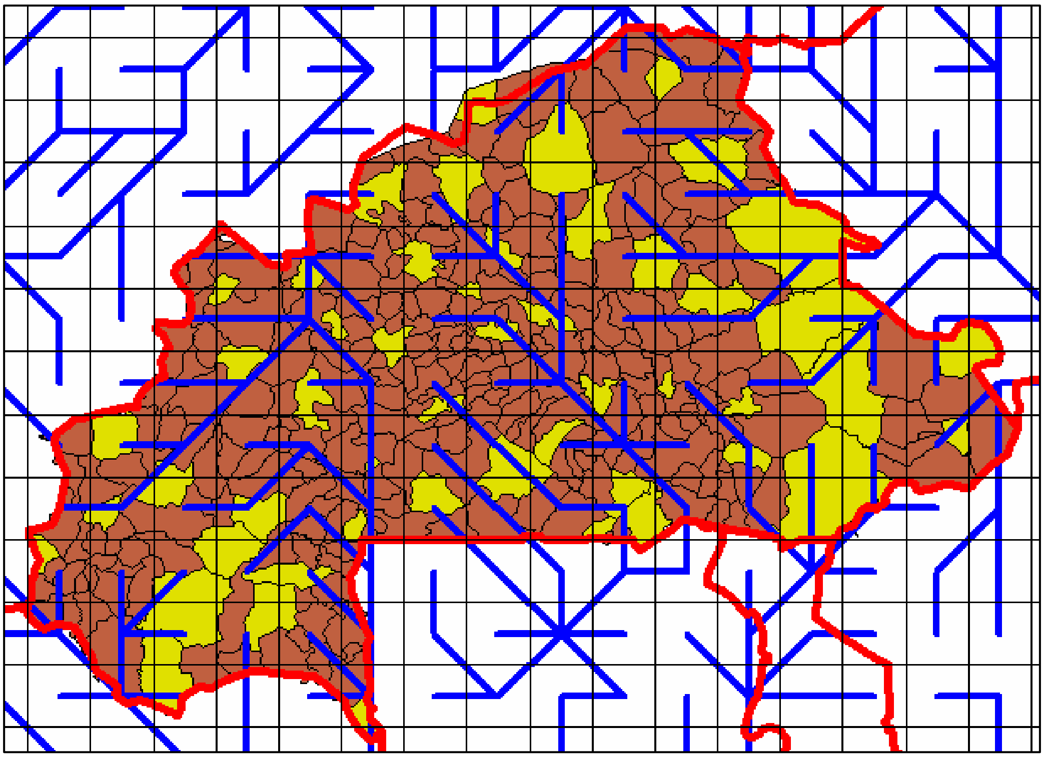
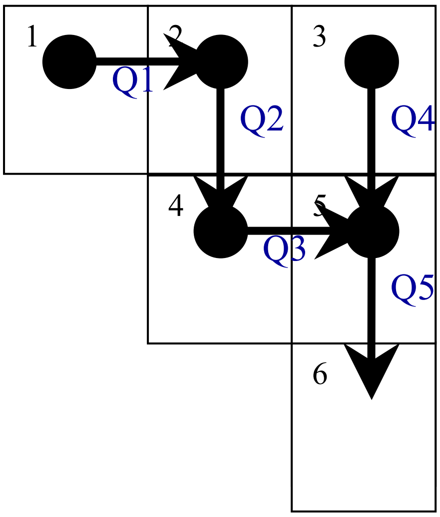


Figure 11: Example of runoff accumulation to generate flow in the drainage network



Q1 = R1
Q2 = Q1 + R2
Q3 = Q2 + R3
Q4 = R4
Q5 = Q3 + Q4 + R5

1-6 = cell numbers
Q = Flow out of grid cell
R = Runoff generated in grid cell

= flow direction

Figure 12: Burkina Faso: River density index by district

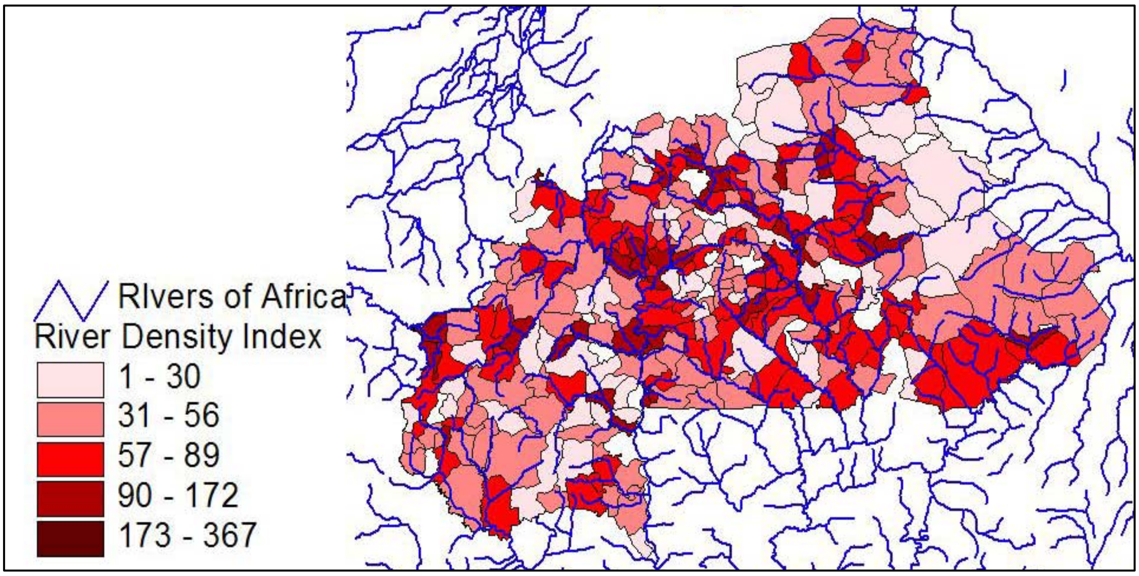


Figure 13: Burkina Faso: Average percentage irrigated by district

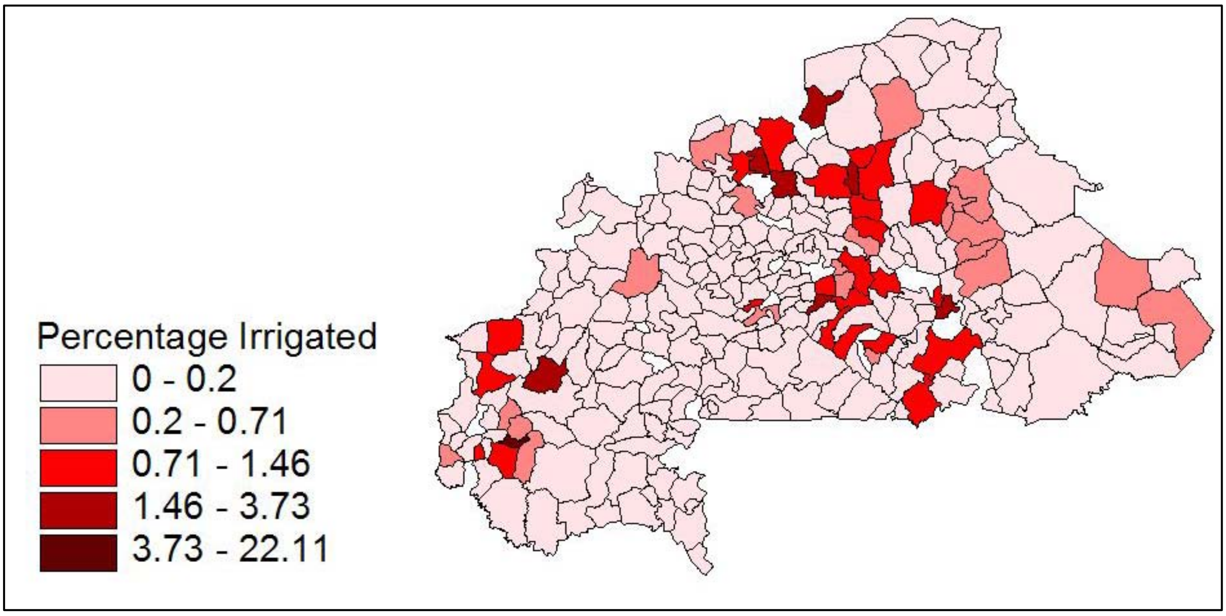


Figure 14. Climate change scenarios available from the CRU

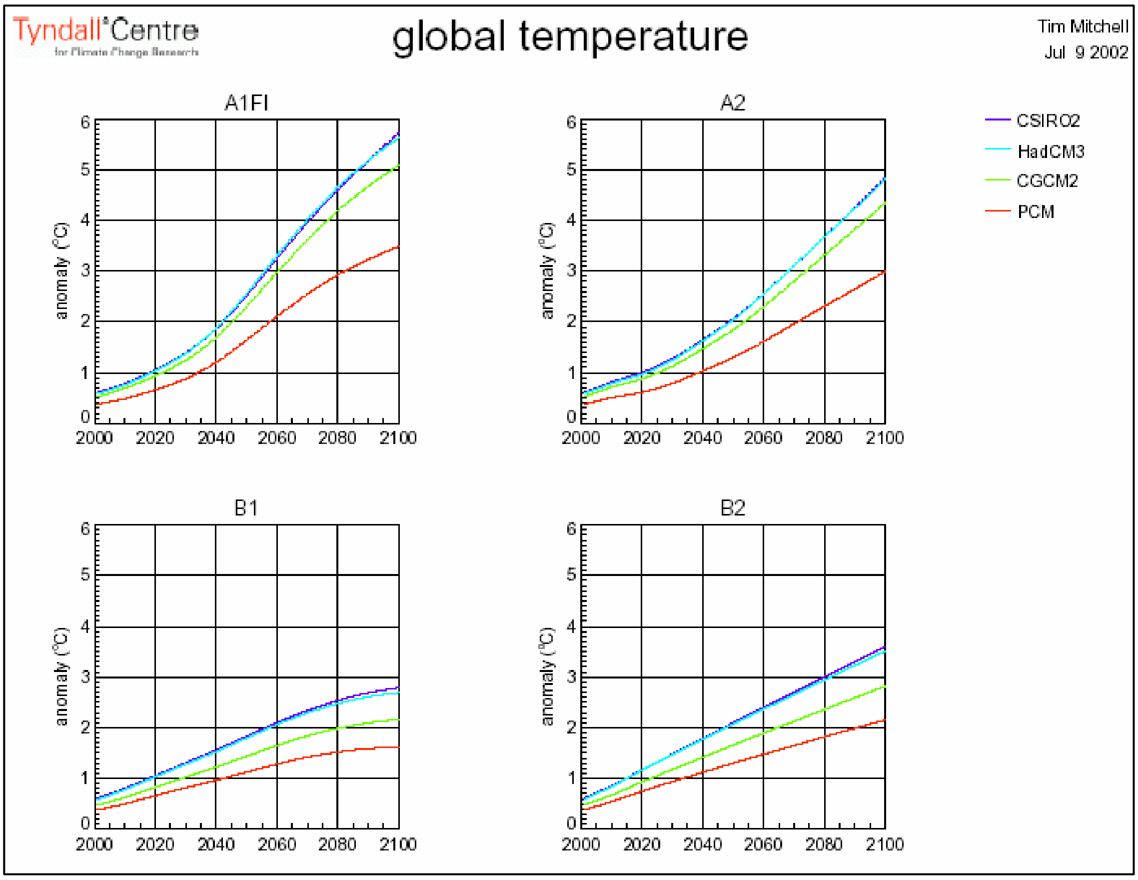


Figure 15: Low 2050 streamflow impacts Africa-wide 85% of base

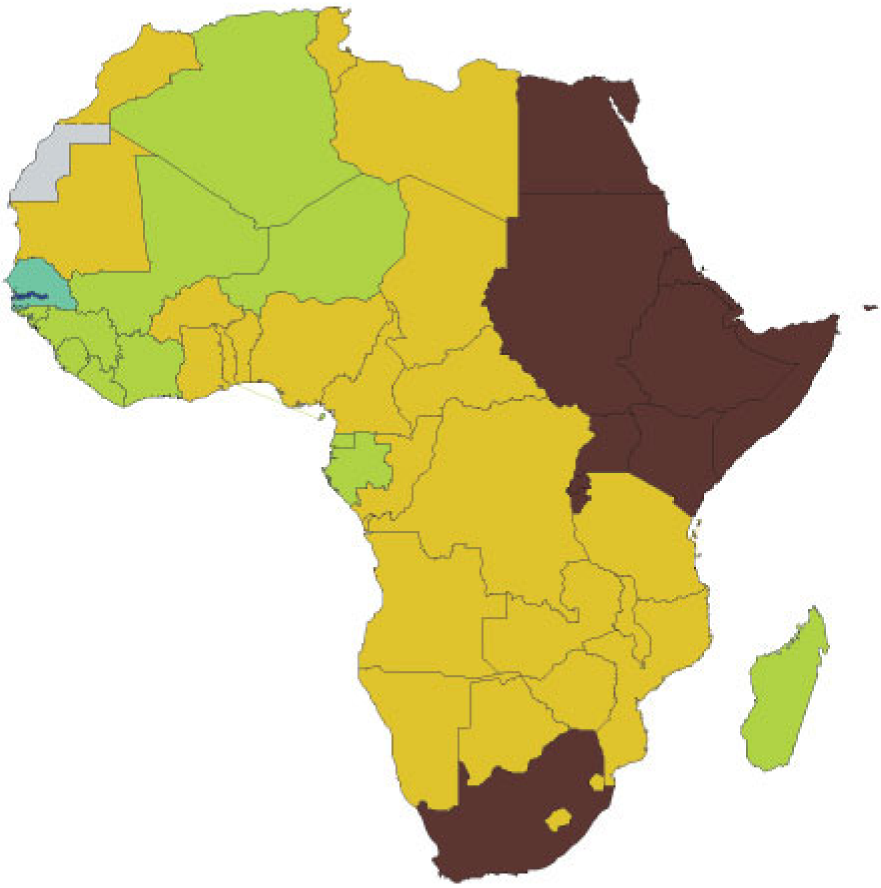


Figure 16: High 2050 streamflow impacts Africa-wide 105% of base

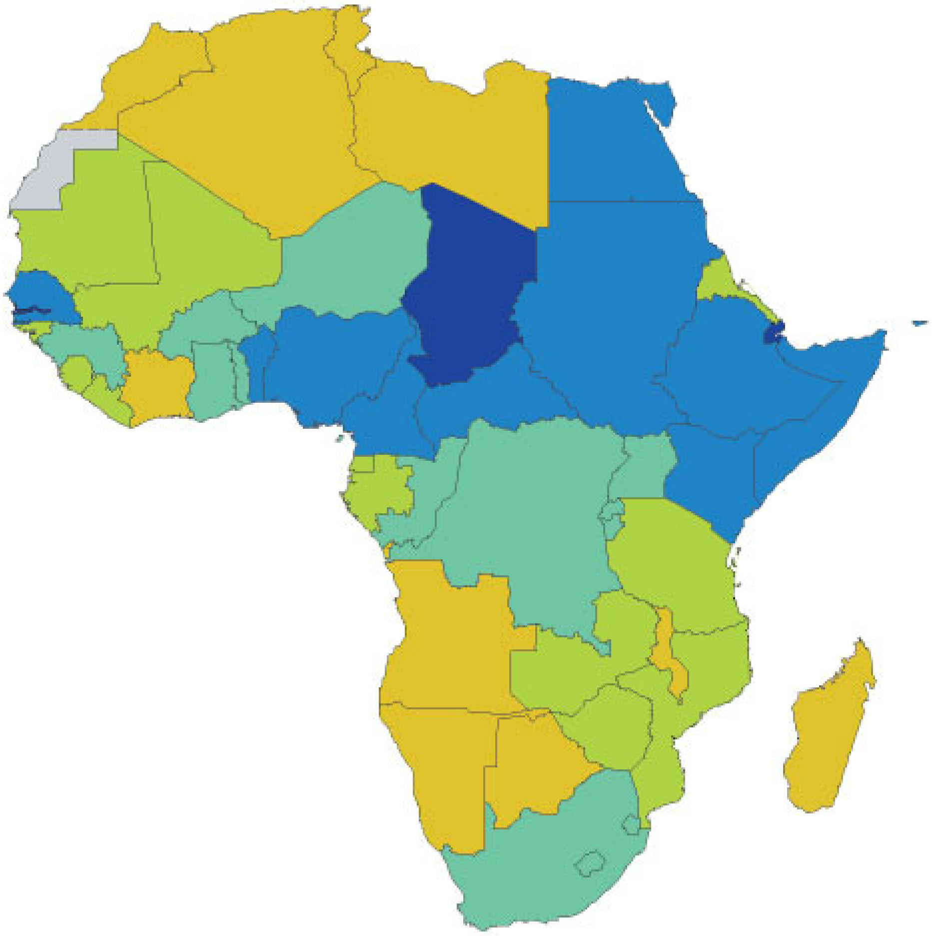


Figure 17: Low 2100 streamflow impacts Africa-wide 81% of base

Figure 18. High 2100 streamflow impacts Africa-wide 114% of base

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