Impact of climate change on the hydroclimatology of Lake Tana Basin, Ethiopia

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[1] Climate change has the potential to reduce water resource availability in the Nile Basin countries in the forthcoming decades. We investigated the sensitivity of water resources to climate change in the Lake Tana Basin, Ethiopia, using outputs from global climate models (GCMs). First, we compiled projected changes in monthly precipitation and temperature in the basin from 15 GCMs. Although the GCMs uniformly suggest increases in temperature, the rainfall projections are not consistent. Second, we investigated how changes in daily temperature and precipitation might translate into changes in streamflow and other hydrological components. For this, we generated daily climate projections by modifying the historical data sets to represent the changes in the GCM climatologies and calculated hydrological changes using the Soil and Water Assessment Tool (SWAT). The SWAT model itself was calibrated and validated using the flows from four tributaries of Lake Tana. For the Special Report on Emissions Scenarios A2 scenario, four of the nine GCMs investigated showed statistically significant declines in annual streamflow for the 2080–2100 period. We interpret our results to mean that anthropogenic climate changes may indeed alter the water balance in the Lake Tana Basin during the next century but that the direction of change cannot be determined with confidence using the current generation of GCMs.

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1. Introduction

[2] In recent years, concern has increased over climate change caused by increasing concentrations of carbon dioxide and other trace gases in the atmosphere. A major effect of climate change is likely to be alterations in hydrologic cycles and changes in water availability. Increased evaporation, combined with changes in precipitation, has the potential to affect runoff, the frequency and intensity of floods and droughts, soil moisture, and available water for irrigation and hydroelectric generation. In addition, watershed hydrology is affected by vegetation types, soil properties, geology, terrain, land use practices, and the spatial pattern of interactions among these factors and with climate [e.g., *Richey et al.*, 1989; *Laurance*, 1998; *Schulze*, 2000; *Fohrer et al.*, 2001; *Zhang et al.*, 2001; *Huang and Zhang*, 2004; *Brown et al.*, 2005, *van Roosmalen et al.*, 2009; *Tu*, 2009].The findings of the *Intergovernmental Panel on Climate Change* (*IPCC*) [2007] suggest that developing countries like Ethiopia will be more vulnerable to climate change because of their economic, climatic and geographic settings. According to *IPCC* [2007], the population at risk of increased water stress in Africa is projected to be between 75 and 250 million and 350–600 million by the 2020s and 2050s, respectively. Moreover, yields from rain-fed agriculture could be reduced by up to 50% in countries that depend mainly on rain-fed agriculture.

[3] The economy of Ethiopia mainly depends on agriculture, and this in turn largely depends on available water resources. Given that a large part of the country is arid and semiarid and highly prone to drought and desertification, this represents a significant risk. Also, the country has a fragile highland ecosystem that is currently under stress due to increasing population pressure. The Blue Nile River Basin is one of the most sensitive basins to changing climate and water resources variability in the region [*Kim and Kaluarachchi*, 2009]. But the effects of climate change on water availability (with respect to water resources analysis, management, and policy formulation in the country) in the Lake Tana Basin have not been adequately addressed. Hence, it is necessary to improve our understanding of the problems involved due to the changing climate.

[4] Assessing the impact of climate change on streamflow, soil moisture, groundwater, and other hydrological parameters essentially involves taking projections of climatic variables (e.g., precipitation, temperature, humidity, and mean sea level pressure) at a global scale, downscaling these global-scale climatic variables to local-scale hydrologic variables, and computing hydrological components for water resources variability and risk of hydrologic extremes

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in the future. Projections of climatic variables globally have been performed with general climate models (GCMs), which provide projections at large spatial scales. Such large-scale climate projections must then be downscaled to obtain smaller-scale hydrologic projections with appropriate linkages between the local climates. A number of studies have investigated downscaling methods for establishing a connection between coarse-resolution GCMs and hydrologic models [e.g., *Wilby et al.*, 1998, 2000; *Hay and Clark*, 2003; *Wood et al.*, 2004; *Benestad et al.* 2008].

[5] There are limited climate change impact studies in Ethiopia [*Tarekegn and Tadege*, 2006; *Kim and Kaluarachchi*, 2009; *Abdo et al.*, 2009, *Melesse et al.*, 2009]. But much of the previous research focused on the influence of climate variability, and change in the region has been based on a limited number of GCMs. Making a conclusion about the effect of climate change on the watershed hydrology using a particular GCM may not give a clear representation of the future changes. High uncertainty is expected in climate change impact studies if the simulation results of a single GCM are relied upon [*IPCC*, 1999, 2007].

[6] The first comprehensive study of the potential impacts of climate change on the Nile River, incorporating results from 11 GCMs and two emission scenarios, was conducted by *Beyene et al.* [2010]. The results they reported for the Blue Nile subbasin are relevant for the Lake Tana region. First, they noted that projections of rainfall change for the subbasin differed substantially between the different GCMs. Second, they reported multimodel results for the Special Report on Emissions Scenarios (SRES) A2 scenario that showed that annual rainfall in the Blue Nile subbasin increased by 15% in the 2010–2039 period, decreased by 2% in the 2040–2069 period, and again increased by 6% toward the end of the century (2070–2100). The combined changes in rainfall and potential evapotranspiration led to increased modeled streamflow in the 2010–2039 and declines in the 2040–2069 and 2070–2100 periods.

[7] *Beyene et al.*'s [2010] results are particularly interesting because they do not align with the common assumption that fractional changes in rainfall and potential evaporation will be roughly linear with increasing global temperature [e.g., *Arnell and Osborn*, 2006]. This "pattern-scaling" assumption has been used, for example, by *Kingston and Taylor* [2010] to investigate the effects of global warming from 0.5°C to 6°C in the River Mitano catchment in the Upper Nile Basin in Uganda. Thus, the results of Beyene et al., if verified, have potentially far-reaching implications for the study of climate change impacts.

[8] A different approach to modeling changes in the Lake Tana catchment was taken by *Taye et al.* [2010]. They used a frequency perturbation downscaling approach to assess changes in daily climate as modeled by 17 GCMs and propagated these through two hydrological models. They did not find any clear trends in rainfall or outflows for the catchment, noting that half of the GCMs projected increase, whereas the other half projected decrease in outflow. Taye et al. investigated changes for only one time period (2046–2065).

[9] Different studies have been conducted to assess the impact of climate change on hydrology in different parts of the world [*Gleick and Chalecki*, 1999; *Neff et al.*, 2000; *Groisman et al.*, 2001; *Chang*, 2003; *Novotny and Stefan*, 2007; *Kim and Kaluarachchi*, 2009; *Abdo et al.*, 2009]. Many of these studies indicated water resource variability associated with climate change. We note that a few studies have quantified the combined effects of future climate and land use changes on hydrology [*Tu*, 2009; *van Roosmalen et al.*, 2009; *Quilbé et al.*, 2008], which is a key study area for the future.

[10] In this study, we investigated the possible effects of climate change on water resources in Lake Tana Basin, Ethiopia, by analyzing outputs from GCM models. To get an indication of the consistency of the projected changes in the region, we first compared projected changes in precipitation and temperature across 15 models for two seasons and three time periods. We then investigated how changes in daily temperature and precipitation might translate into changes in streamflow and other hydrological components, using outputs from nine climate models for two time periods (2046–2065 and 2080–2100). We generated daily climate projections by modifying the historical data sets to represent the changes in the GCM climatologies. The physically based Soil Water Assessment Tool (SWAT) model was used to determine the impact of climate change on the surface and groundwater resources availability in the Lake Tana Basin. The SWAT model was calibrated and validated using historical data from four rivers that flow into Lake Tana: Gumera, Gilgel Abay, Megech, and Ribb rivers [*Setegn et al.*, 2009a].

2. Materials and Methods

2.1. Study Area

[11] Lake Tana occupies a wide depression in the Ethiopian plateau. The lake is shallow, oligotrophic, and freshwater, with weak seasonal stratification [*Wood and Talling*, 1988; *Wudneh*, 1998].The lake is believed to have been formed because of damming by lava flow during the Pliocene [*Mohr*, 1962], but the formation of the depression itself started in the Miocene [*Chorowicz et al.*, 1998]. Lake Tana Basin comprises a total area of 15,096 km^2 (drainage plus lake area). It is rich in biodiversity with many endemic plant species and cattle breeds, contains large areas of wetlands, and is home to many endemic birds and cultural and archeological sites. This basin is of critical national significance as it has great potentials for irrigation, hydroelectric power, high value crops and livestock production, ecotourism, and more. Lake Tana is located in the country's northwest highlands (latitude 12°0′N, longitude 37°15′E) (Figure 1). The lake is a natural type that covers a 3000–3600 km^2 area at an elevation of 1800 m and with a maximum depth of 15 m. It is approximately 84 km long and 66 km wide. It is the largest lake in Ethiopia and the third largest in the Nile Basin. Gilgel Abay, Ribb, Gumera, and Megech are the main rivers feeding the lake, and they contribute more than 90% of the inflow *Setegn et al.*, 2009a]. The lake is the main source of the Blue Nile River, which is the only surface outflow for the lake. The climate of the study area varies from humid to semiarid. Most precipitation occurs in the wet season (locally called Kiremt) from June to September. The two other seasons are known as Bega (normally dry, from October to February) and Belg (normally mild, from March to May). About 70% of annual precipitation is concentrated in Kiremt. The annual precipitation has an increasing trend from northeast to southwest. Figure 2 shows the basin-wide monthly rainfall average. The estimated mean annual precipitation of the study area ranges from 1200 to

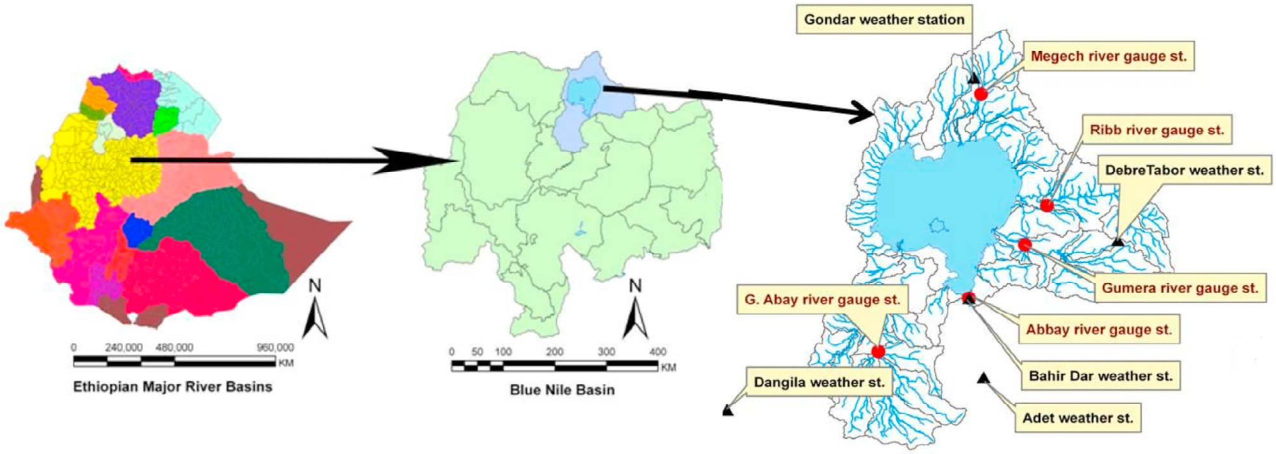

Figure 1. Location map of the study area. Lake Tana is located between 12°0′N latitude and 37°15′E longitude.

1600 mm on the basis of data from 1961 to 2000 depending on the studies [*Gamachu*, 1977; *Conway*, 1997, 2000; *United Nations Educational, Scientific and Cultural Organization*, 2004; *Kim et al.*, 2008; *Setegn et al.*, 2009a]. Because of the summer monsoon occurring between June and September, more than 80% of the annual flow occurs from July to October and flows to the downstream countries because of the absence of storage capacity. The mean annual rainfall of the catchment area is about 1280 mm. The air temperature shows large diurnal but small seasonal changes with an annual average of 20°C. The observational record from 1980 to 2000 shows a seasonal variation of less than 2°C. The annual mean actual evapotranspiration and water yield of the catchment area are estimated to be 773 and 392 mm, respectively [*Setegn et al.*, 2009a].

2.2. Description of Global Climate Models

[12] Global climate models, also known as general circulation models, numerically simulate changes in climate as a result of slow changes in some boundary conditions (such as the solar constant) or physical parameters (such as the greenhouse gas concentration) [*Abbaspour et al.*, 2009].

[13] GCM output data were obtained from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set. The details of the models used in this study are listed in Table 1. Two data sets were downloaded.

[14] 1. The first data set consisted of monthly precipitation and average surface air temperatures for 15 GCMs. These data were used to quantify the range of the projected climate changes for the region. A single run was downloaded for each of the SRES B2, A1B, and A2 scenarios, and data were extracted for the pixel containing the observation stations. Changes were calculated for three periods: 2010–2039, 2040–2069, and 2070–2100. The changes are expressed as the differences between the scenarios and a 1950–1999 baseline from the Climate of the 20th Century Experiment (20C3M) runs. The statistical significance of the changes for each scenario or time period "ensemble" was assessed using a Wilcoxon signed rank test. This is a nonparametric alternative to the better-known *t* test and tests the assumption that the ensemble members are drawn from a continuous, symmetric distribution with zero median (i.e., no change in the ensemble median) against the alter-

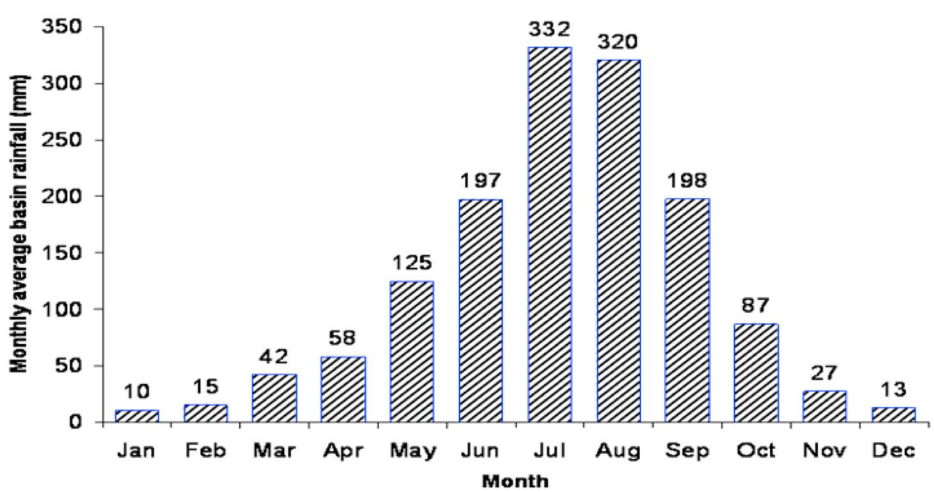

Figure 2. Upper Blue Nile basin monthly average rainfall (1960–2002).

Table 1. Details of the Different GCMs Used in This Study[a]

Center	Model	Approximate Atmospheric Resolution
Bjerknes Centre for Climate Research, Norway	Bergen climate model (BCM2.0)	2.8° × 2.8°
Canadian Centre for Climate Modelling and Analysis, Canada	Coupled global climate model (CGCM3)	3.75° × 3.7°
Centre National de Recherches Meteorologiques, France	CNRM-CM3	2.8° × 2.8°
Commonwealth Scientific and Industrial Research Organisation, Australia	CSIRO Mark 3.0	1.9° × 1.9°
Max-Planck-Institut für Meteorologie, Germany	ECHAM5/MPI-OM	1.9° × 1.9°
Meteorological Institute of the University of Bonn, Germany	ECHO-G	3.75° × 3.7°
Geophysical Fluid Dynamics Laboratory, United States	CM2.0-AOGCM	2.5° × 2.0°
	CM2.1-AOGCM	2.5° × 2.0°
Institute for Numerical Mathematics, Russia	INMCM3.0	5.0° × 4.0°
Institut Pierre Simon Laplace, France	IPSL-CM4	3.75° × 2.5°
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	2.8° × 2.8°
National Center for Atmospheric Research, United States	Parallel climate model (PCM)	2.8° × 2.8°
	Community climate system Model, version 3.0 (CCSM3)	1.4° × 1.4°
Hadley Centre for Climate Prediction and Research, Met Office, United Kingdom	HadCM3	3.75° × 2.5°

[a] *IPCC* [2007].

native hypothesis that the distribution does not have zero median.

[15] 2. The second data set consisted of daily data that were extracted from the outputs of nine models. These data were used to modify historical data sets, which were then input to the SWAT model to compare runoff in the region for a base period (1980–2000) with two future periods (2046–2065 and 2080–2100). This required daily climate data. These nine models were selected because the modeling groups had provided daily precipitation and minimum and maximum temperature outputs to CMIP3.

2.3. Description of Selected Climate Change Scenarios

[16] A set of scenarios assists in the understanding of possible future developments of complex systems. They are images of the future or alternative futures. But they are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. Scenarios help in the assessment of future developments in complex systems that are either inherently unpredictable or have high scientific uncertainties [*IPCC*, 2007].

[17] The Special Report on Emissions scenarios [*IPCC*, 2000] are grouped into four scenario families (A1, A2, B1, and B2) that explore alternative development pathways, covering a wide range of demographic, economic, and technological driving forces and resulting greenhouse gas emissions. In this study three SRES scenarios (A1B, B1, and A2) were used. These scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse and aerosol precursor emissions. Each scenario assumes a distinctly different direction for future developments. The SRES A1B emissions scenarios (a scenario in the A1 family) describes "a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies" [*IPCC*, 2000]. The SRES A2 emissions scenarios describe a very heterogeneous world with high population growth, slow economic development, and slow technological change. B1 describes "a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in materials intensity, and the introduction of clean and resource efficient technologies" [*IPCC*, 2000].

2.4. Downscaling of Global Climate Models to Watershed Level

[18] The question of how to generate climate time series with sufficient realism for use in hydrological models based on GCM outputs has been the subject of much research (see *Fowler et al.* [2007] for a recent review). The choice of method will depend on the details of the research question. For example, dynamical downscaling using regional climate models is likely to produce more robust results in areas where there is significant variation in local topography. On the other hand, running a regional model using an ensemble of GCM outputs requires significant effort. In situations where different GCMs within the ensemble project significantly different climate changes, dynamical downscaling will probably not provide any extra certainty, and such an effort will bring little benefit.

[19] This study generated daily climate projections by modifying the historical data sets to represent changes in the GCM climatologies. This is different from the approach more usually thought of as "statistical downscaling" [e.g., *Benestad et al.* 2008], where scenarios are created as a function of the daily outputs from GCM themselves. The historical modification approach was used because hydrological models often perform poorly when applied to data sets with distributions of daily climate data that are different from their training data, and statistical downscaling techniques often result in distributions that are noticeably different from observed time series (e.g., linear techniques can generate time series with compressed variance).

[20] Our historical modification procedure used the changes in ranked GCM daily rainfalls and temperatures to scale the ranked historical station daily rainfalls and temperatures. In summary, the method involved calculating the difference between the daily cumulative frequency distributions (CFDs) of a GCM output variable for a present-day period and a future period, and then applying these differences to an observed data set. This simple "downscaling" technique has been used in several hydrological climate impact studies [e.g., *Wood et al.*, 2002; *Harrold and Jones*, 2003; *Taye et al.*, 2010]. It provides a good com-

promise between the requirement to produce realistic time series and the desire to represent the effects of climate change across different weather situations as these are simulated in the GCMs. In addition, the method is easy to implement and fast to run. It is a good solution for producing climate change scenarios for impact assessments.

[21] The details of our historical modification procedure were as follows. Cumulative frequency distributions for daily precipitation and maximum and minimum temperatures were first calculated for the GCM outputs, both for a base period (1980–2000) and for two scenario periods (2046–2065 and 2080–2100). The CFDs were calculated independently for each month of the year, using data from that month of the year and the preceding and subsequent months. The differences between the base period CFD and the scenario period CFDs were then determined for the cumulative frequencies 0.05, 0.15, 0.25…1.0. Absolute differences were calculated for minimum and maximum temperature CFDs, while for precipitation the changes were derived as ratios with respect to the present period values. Because fractional changes in the low-rainfall end of the CFDs may be large, all GCM rainfall values <0.1mm/d were considered to be zero, and zero values were omitted from the CDF calculations. The extremes of the CFDs (e.g., 0.001, 0.999) were deliberately not sampled: the time windows used are not long enough to define the tails of the CFDs or changes in them. The changes in the CFDs sampled at cumulative frequencies 0.05, 0.1, 0.15, … 0.95 were then linearly interpolated and extrapolated to cover the entire cumulative frequency range (0–1). Finally, the historical data were ranked and modified to reflect the changes in the GCM CFDs for each scenario and time period. The result is "downscaled," daily climate time series.

2.5. SWAT Model Description

[22] The Soil Water Assessment Tool model is one of the watershed models that play a major role in analyzing the impact of land management practices on water, sediment, and agricultural chemical yields in large complex watersheds. It is widely applied in many parts of the world. It is a public domain model developed by *Arnold et al.* [1998]. SWAT uses hydrologic response units (HRUs) to describe spatial heterogeneity in terms of land cover, soil type, and slope within a watershed. The SWAT system is embedded within a geographic information system that can integrate various spatial environmental data including soil, land cover, climate, and topographic features. Currently, SWAT is embedded in an ArcGIS interface called ArcSWAT. The simulation of the hydrology of a watershed is done in two separate divisions. One is the land phase of the hydrological cycle that controls the amount of water, sediment, nutrient, and pesticide loadings to the main channel in each subbasin. The second division is the routing phase of the hydrologic cycle that can be defined as the movement of water, sediments, nutrients, and organic chemicals through the channel network of the watershed to the outlet. In the land phase of the hydrological cycle, SWAT simulates the hydrological cycle on the basis of the water balance equation

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right), \quad (1)$$

in which SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day i (mm), t is the time (days), R_{day} is the amount of precipitation on day i (mm), Q_{surf} is the amount of surface runoff on day i (mm), E_a is the amount of evapotranspiration on day i (mm), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the amount of return flow on day i (mm).

[23] The different components of the SWAT model application to the Lake Tana Basin are described by *Setegn et al.* [2009a, 2009b]. More detailed descriptions of the different model components are listed in work by *Neitsch et al.* [2005]. A comprehensive review of SWAT model applications is given by *Gassman et al.* [2007].

2.5.1. SWAT Model Input

[24] For the setup of the SWAT model we have used a 90 m resolution digital elevation model (DEM) for the delineation of the watershed and to analyze the drainage patterns of the land surface terrain. Subbasin parameters such as slope gradient and slope length of the terrain and the stream network characteristics such as channel slope, length, and width were derived from the DEM. The SWAT model requires different soil textural and physicochemical properties such as soil texture, available water content, hydraulic conductivity, bulk density, and organic carbon content for different layers of each soil type. Land use is one of the most important factors that affect runoff, evapotranspiration, and surface erosion in a watershed. The soil and land use data were used for the definition of the HRUs. In this study, the weather variables used for driving the hydrological balance are daily precipitation and minimum and maximum air temperature. The daily river discharges data were used for model calibration and validation. The details of the input data used for the setup of the SWAT model are documented by *Setegn et al.* [2009a].

2.5.2. Setup, Calibration, and Evaluation of SWAT Model

[25] The model setup involved five steps: (1) data preparation, (2) subbasin discretization, (3) HRU definition, (4) parameter sensitivity analysis, and (5) calibration and uncertainty analysis. The steps for the delineation of the watershed include DEM setup, stream definition, outlet and inlet definition, watershed outlets selection, and definition and calculation of subbasin parameters. Artificial stations were located during the setup of the SWAT model. This was aimed at quantifying quantity of water fluxes into the lake, which could be used in analyzing the water balance of the lake.

[26] Twenty-six hydrological parameters were tested for sensitivity analysis for the simulation of the streamflow in the study area. The data for the period 1981–1992 were used for calibration, and data for the period 1993–2004 were used for validation of the model in the four tributaries of Lake Tana Basin. Periods 1978–1980 and 1990–1992 were used as "warm-up" periods for calibration and validation purposes, respectively. The warm-up period allows the model to get the hydrologic cycle fully operational.

[27] The calibration and uncertainty analysis were done using three different algorithms, i.e., sequential uncertainty fitting (SUFI-2) [*Abbaspour et al.*, 2004, 2007], parameter solution (ParaSol) [*van Griensven and Meixner*, 2006], and generalized likelihood uncertainty estimation (GLUE)

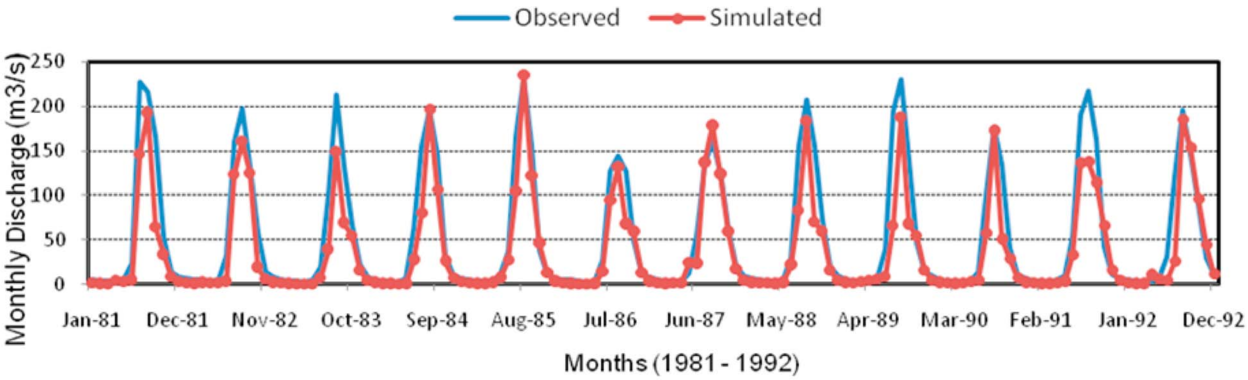

Figure 3. Time series of measured and simulated monthly flow at Gilgel Abay River station for the calibration period (1981–1992).

[*Beven and Binley*, 1992]. The details of the methods and application can be found in work by *Setegn et al.* [2009a].

3. Results and Discussion

3.1. Hydrological Model Calibration and Validation

[28] The parameter sensitivity analysis was done using the ArcSWAT interface for the whole catchment area. Twenty-six hydrological parameters were tested for sensitivity in the study area. The most sensitive parameters considered for calibration were soil evaporation compensation factor, initial Soil Conservation Service curve number II value, base flow alpha factor, threshold depth of water in the shallow aquifer for "revap" to occur, available water capacity, groundwater "revap" coefficient, channel effective hydraulic conductivity, and threshold depth of water in the shallow aquifer for return flow to occur. The details of the sensitive flow parameters and their fitted values are documented by *Setegn et al.* [2009a]. SUFI-2, GLUE, and ParaSol methods were used for calibration of the SWAT model in Gilgel Abay, Gumera, Ribb, and Megech inflow rivers. The comparison between the observed and simulated streamflows indicated that there is a good agreement between the observed and simulated discharge, which was verified by higher values of coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE). Model predictive performances for calibration and validation periods of all inflow rivers discharge for all calibration and uncertainty analysis methods are summarized by *Setegn et al.* [2009a]. Figure 3 shows the time series comparison between measured and simulated monthly flow at Gilgel Abay River gauge station during calibration and validation periods. *Setegn et al.* [2009a] indicated that the water balance of the upland watershed is well represented. The results indicated that 65% of the annual precipitation is lost by evapotranspiration in the basin during calibration as compared to 56% during the validation period. Surface runoff contributes 31% and 25% of the water yield during calibration and validation periods, respectively, whereas groundwater contributes 45% and 54% of the water yield during calibration and validation periods, respectively.

3.2. Changes in Monthly GCM Climate Variable Outputs

[29] In our analysis we have split the data into a wet season (June–September) and a dry season (October–May) so that the results are easier to interpret from the perspective of possible impacts. Projected changes in seasonal mean temperature at the location of Adet station are shown as box plots in Figure 4. Changes in seasonal precipitation are shown in Figure 5. The Adet station can be taken to be representative of all stations in the study region because the study region is relatively small compared to the GCM's resolution. Temperature changes are given in degrees Celsius and precipitation changes are given as a percentage change of the base period mean (e.g., a change of 100% would imply a doubling of precipitation). This way of expressing changes has become a de facto convention. The results from Figures 4 and 5 are summarized in Tables 2a, 2b, 3a, and 3b.

3.2.1. Surface Air Temperature

[30] Figure 4 and Tables 2a and 2b show that the GCM runs project a range of temperature changes for the region, with a significant spread among GCMs for any given scenario or time period ensemble. Even so, all the projected changes are for regional warming, and all ensembles show statistically significant changes in median temperature using the signed rank test (see section 2.2). Additionally, the ranking of the changes for the three scenarios is consistent with what we expect: the temperature changes increase with time, and for any given time period, the smallest changes are for the lowest-emission SRES B1 scenario and the largest changes are for the highest-emission SRES A2 scenario.

3.2.2. Precipitation

[31] In contrast, the precipitation changes shown in Figure 5 and Tables 3a and 3b do not suggest that there is any consensus among GCMs regarding rainfall changes for the region. None of the 18 ensembles examined showed statistically significant changes in median precipitation using the signed rank test. This is not to say that individual GCMs do not project large precipitation changes, especially in the ensembles with larger global warming (the 2070–2100 periods for SRES A1B and SRES A2). However, there is no consensus among the GCMs used in this study about the sign of the precipitation change in the region.

3.3. Impact of Climate Change on Streamflow

3.3.1. Changes in Rainfall as a Function of Frequency

[32] The changes in daily rainfall for four GCMs for the SRES A2 scenario, 2080–2100 compared to 1980–2000, are shown in Figure 6 as a function of cumulative frequency.

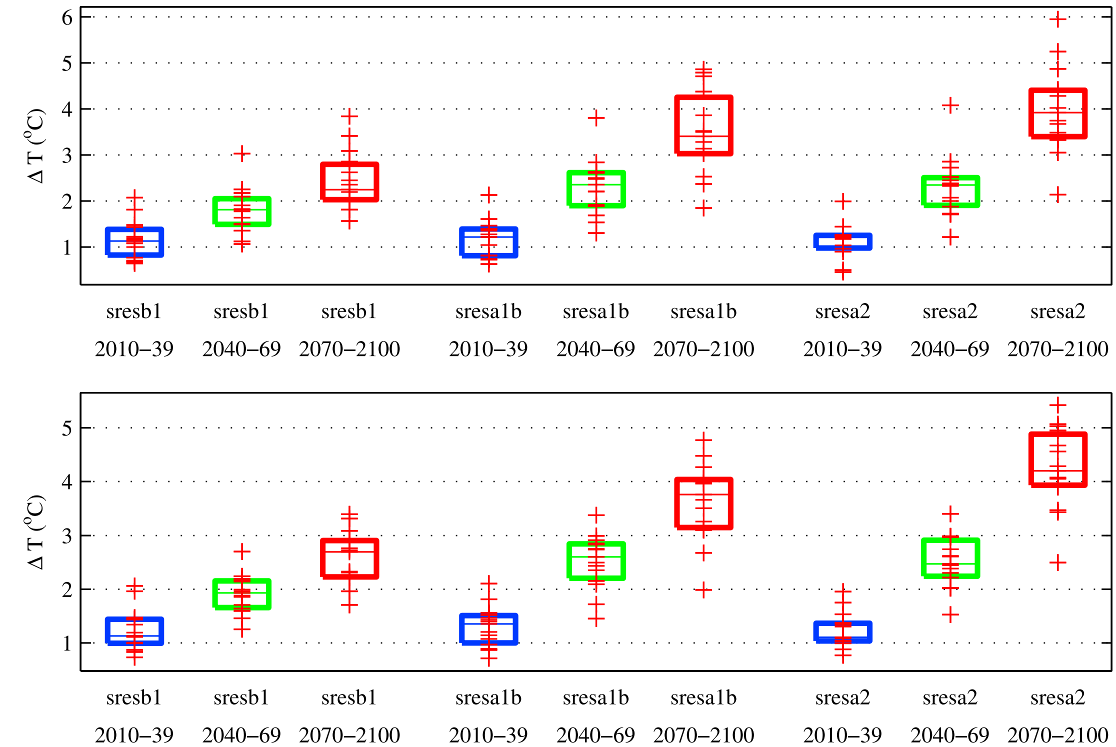

Figure 4. Projected changes in mean temperature at the location of Adet station for three SRES scenarios and time periods, calculated from monthly GCM outputs: (top) changes in wet season temperature and (bottom) changes in dry season temperature. The results for the individual GCMs are shown as pluses, and the boxes show the 25th, 50th, and 75th percentiles.

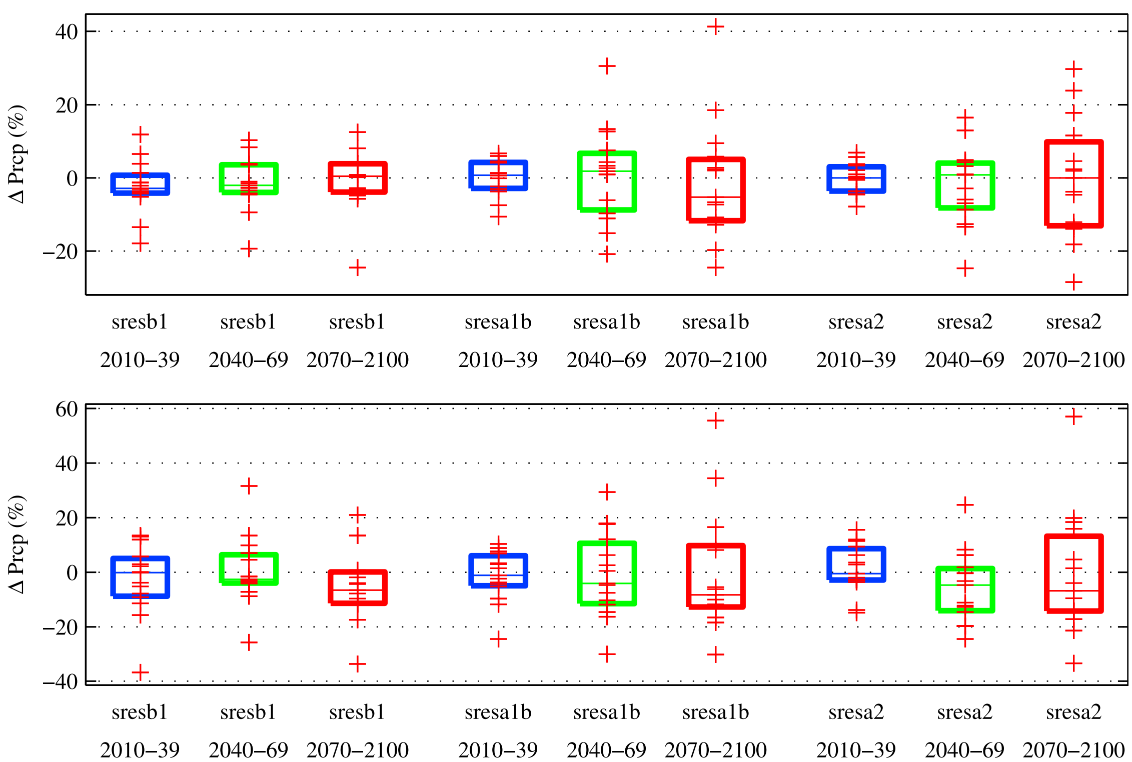

Figure 5. Projected changes in mean precipitation at the location of Adet station for three SRES scenarios and time periods, calculated from monthly GCM outputs: (top) changes in wet season temperature and (bottom) changes in dry season temperature. The results for the individual GCMs are shown as pluses, and the boxes show the 25th, 50th, and 75th percentiles.

Table 2a. Ranges of Projected Changes Given as 25th–75th Percentiles in Wet Season Surface Air Temperature for the Study Region for the GCM Ensembles[a]

	Temperature Changes, Wet Season		
Scenarios	2010–2039	2040–2069	2070–2100
SRESB1	0.8°C–1.4°C	1.5°C–2.1°C	2°C–2.9°C
SRESA1B	0.8°C–1.4°C	1.9°C–2.6°C	3°C–4.4°C
SRESA2	1°C–1.3°C	1.9°C–2.5°C	3.4°C–4.4°C

[a]The changes in the ensemble medians are all statistically significant.

Table 3a. Ranges of Projected Changes Given as 25th–75th Percentiles in Wet Season Precipitation for the Study Region for the GCM Ensembles[a]

	Precipitation Changes, Wet Season		
Scenarios	2010–2039	2040–2069	2070–2100
SRESB1	−4%–1%	−4%–4%	−4%–4%
SRESA1B	−3%–4%	−10%–8%	−12%–6%
SRESA2	−4%–3%	−9%–4%	−13%–12%

[a]In no cases are the changes in median statistically significant.

Figure 6 shows that for some GCMs, the changes are not uniform across the rainfall distribution. The most extreme cases are the CSIRO Mk3 (where smaller rainfall amounts increase by over 50% but higher rainfalls decrease by 15%) and the INM CM3 model (where there is a small decline in smaller rainfall amounts but higher rainfalls increase by 50%). The results from both Geophysical Fluid Dynamics Laboratory (GFDL) models (not shown in Figure 6) show 40%–50% declines in smaller rainfall amounts but little change in higher daily rainfalls. The other models show less dramatic variations in rainfall change across the distribution; the MPI and Canadian Centre for Climate Modelling and Analysis model results (shown in Figure 6) are representative.

[33] When downscaling using historical-modification, it is preferable to modify ranked distributions (rather than the simpler case of applying a mean change to all values) in situations where the changes simulated by a GCM are systematically different across the variable's distribution. We consider that the large differences in rainfall changes across the rainfall distribution in 6 of the GCMs examined justifies our approach of modifying ranked values, rather than using a single modifier value.

3.3.2. Annual and Seasonal Streamflow Change

[34] River discharge is an important hydrological component that is greatly influenced by climate and land use. Figure 7 shows the projected effect of climate change on annual streamflow, as output from the SWAT model. The numbers of models showing statistically significant declines in mean annual flow for the different time periods and scenarios are shown in Table 4. For the most extreme climate change scenario, SRES A2 for the 2080–2100 period, five of the nine models show statistically significant declines in annual flows. The results from the hydrological modeling for the wet-season (June–September) streamflow in the Gilgel Abay River are shown in Figure 8 for each downscaled GCM. Again, reduced streamflow is the dominant result.

[35] Even though declining streamflow is the dominant result from the nine GCMs downscaled in this study, we note that this cannot be taken as a general result. Unfortunately, it seems that, by chance, the nine GCMs used in this study are those that show a precipitation decrease. In particular, the study did not include the National Center for Atmospheric Research community climate system model or Met Office HadCM3 GCMs, both of which show precipitation increases in the region. However, both the Institut Pierre Simon Laplace CM4 model and Max-Planck-Institut für Meteorologie (MPI) EHCAM5 model show small (<10%) increases in wet season precipitation for 2070–2100, but the SWAT modeling using downscaled daily data shows declines in 2080–2100 wet season streamflow. Most of the models show similar trends in both the 2046–2065 and 2080–2100 periods.

[36] Although the number of GCM outputs examined in the hydrological modeling study is smaller than in the seasonal rainfall and temperature studies shown in Figures 4 and 5, we can still draw out some important points. First, the directions of the streamflow changes generally follow the changes in rainfall. This is expected given the fact that local evapotranspiration does not dominate the water cycle in the wet season. But we also see that the streamflow changes are larger in magnitude than the rainfall changes. We interpret these aspects of the modeling results to imply that runoff changes in the region could be significant even though the GCMs do not agree on the direction of the precipitation change.

3.4. Impact of Climate Change on Soil Moisture, Actual Evapotranspiration, and Groundwater

[37] In this section we discuss changes in actual evapotranspiration (AET), soil moisture (SW), surface runoff (SRO), and groundwater (GW) that are of the most important components of the hydrological cycle. Our intention is to understand how the changes in climate variables can affect the different hydrological components of the basin that control the final streamflow.

[38] The results from using the nine downscaled GCM models in SWAT on the possible impact of climate change on the annual changes in actual ET, soil moisture, surface

Table 2b. Ranges of Projected Changes in Dry Season Surface Air Temperature.

	Temperature Changes, Dry Season		
Scenarios	2010–2039	2040–2069	2070–2100
SRESB1	1°C–1.4°C	1.6°C–2.2°C	2.2°C–2.9°C
SRESA1B	1°C–1.5°C	2.2°C–2.8°C	3.1°C–4.1°C
SRESA2	1°C–1.4°C	2.2°C–3°C	3.9°C–4.9°C

Table 3b. Ranges of Projected Changes in Dry Season Precipitation

	Precipitation Changes, Dry Season		
Scenarios	2010–2039	2040–2069	2070–2100
SRESB1	−9%–6%	−4%–7%	−11%–1%
SRESA1B	−5%–7%	−12%–12%	−13%–10%
SRESA2	−3%–9%	−15%–2%	−14%–16%

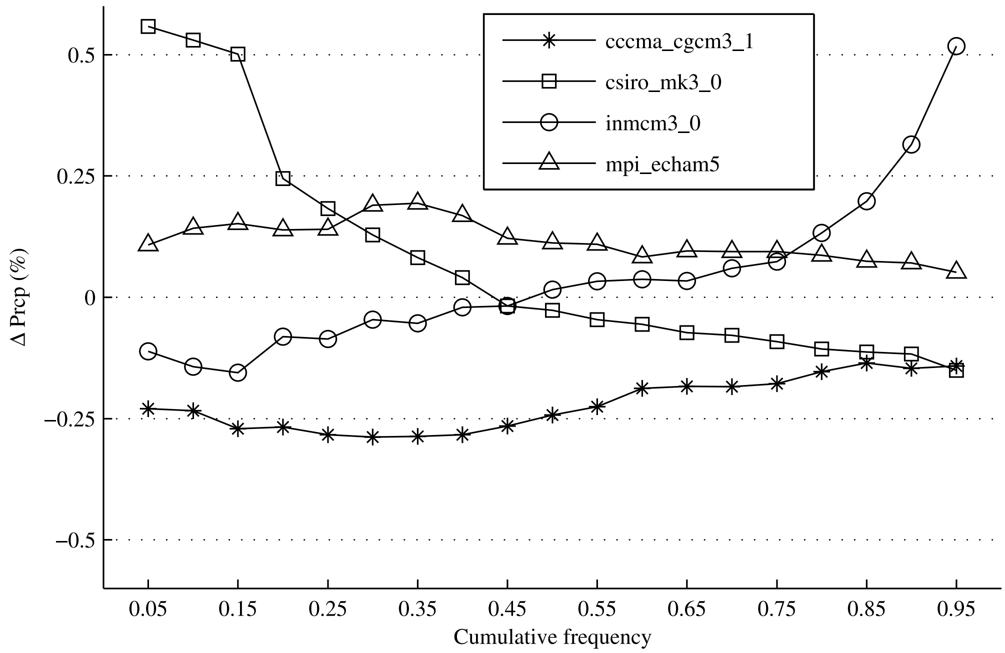

Figure 6. Changes in wet season daily rainfall at the location of the Adet station from four GCMs as a function of cumulative frequency. Note that this is for rain days (rain >0.1 mm/d) only. Changes are for SRES A2 scenario, 2080–2100, expressed as percentage changes on a 20C3M 1980–2000 base period.

runoff, and groundwater for the periods of 2046–2065 and 2080–2100 are shown in Figure 9. The results indicated that AET increases considerably in many models but especially for the GFDL model attributed to the increase in the air temperature. It was observed that soil moisture showed little change (between 0% and −2% decreases) for all models. Groundwater flow is reduced for all downscaled models. Surface runoff reduces for many of the models.

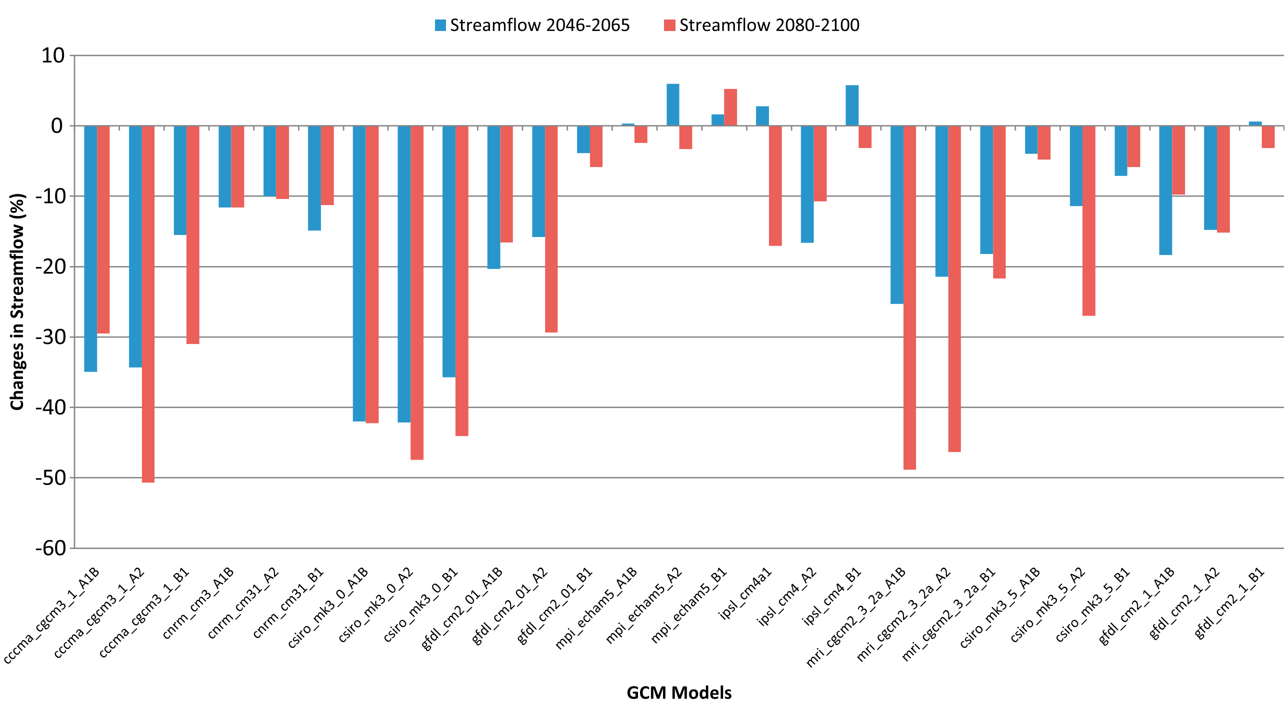

Figure 7. Change in annual streamflow due to changes in daily precipitation and temperature derived from nine GCM models under A1B, A2, and B1 scenarios for the periods 2045–2065 and 2080–2100 expressed as a percentage of streamflow in the base period 1980–2000.

Table 4. Number of the Nine Downscaled GCM Time Series That Showed a Statistically Significant Decline in Annual Streamflow in the SWAT Model Results[a]

	Time Period	
Scenarios	2046–2100	2080–2100
SRESB1	1/9	2/9
SRESA1B	3/9	3/9
SRESA2	2/9	5/9

[a]None of the nine downscaled GCM time series showed a statistically significant increase in annual streamflow.

[39] The increase in ET is probably due to increased air temperatures. The study also used the Hargreaves method [*Hargreaves et al.*, 1985] to calculate evapotranspiration that depends on minimum and maximum temperatures. This is consistent with previous studies, which have shown that a significant variation in AET is expected to follow changes in air temperature [*Abbaspour et al.*, 2009]. The changes in modeled groundwater flow clearly influenced the changes in streamflow. This is consistent with the work of *Setegn et al.* [2009a], who indicated that 60% of the streamflows in the inflow rivers of Lake Tana are base flow and that future reduction in groundwater might contribute to reduced streamflow in the basin. Moreover, *Setegn et al.* [2009a] have indicated that more than 60% of the hydrological loss in the present system is through evapotranspiration. This shows that the increase in evapotranspiration for the future scenarios may play a significant role in the reduction of streamflows in the GFDL and MPI models.

3.5. Sources of Uncertainty and Other Considerations

[40] In this study, we have used the same land cover data as the present time. Such a study should not be considered as a realistic actual scenario because the latter would require including the impact of future land use change. We are conducting further investigations regarding the combined effect of climate and land use change. We note also that in the present study there is no consideration of changes in soil parameters that could influence the soil properties of the watershed. This may explain the low response of soil moisture to the changes to climate in this study.

[41] Another area of uncertainty that warrants more research is the combined effect of land cover–land use dynamics and climate change on streamflows and other components of the hydrological cycle. Considering both land use and climate change in the analysis will also raise the question of the effect of climate change on land use changes and vice versa. Unless we quantify the proportion of the land use changes due to human variability and those caused by the changing climate (rainfall and air temperature) variability, understanding the combined feedback to the water resources variability will be misleading.

[42] There is much uncertainty in our modeling results. This is a combination of uncertainties in the GCM outputs as a result of the downscaling, hydrological parameter uncertainty, and neglect of land use changes or potential changes in soil properties. Any or all of these factors may cause the results to deviate from reality. However, even so, we are dedicated to perusing a thorough investigation of the combined effect of climate and land use or land cover on the hydrological processes and water resources in the study area, and we believe this study is an important first step in this direction.

4. Conclusion

[43] A major effect of climate change is likely to be alterations in hydrologic cycles and changes in water availability. The possibility of water resources reduction is a major threat in the study area. In this study, we investigated the sensitivity of water resources to changing climate in the Lake Tana Basin, Ethiopia.

[44] We compared projected changes in precipitation and temperature across 15 GCM models for two seasons to get an indication of the consistency of the projected changes in the region. All individual GCMs projected temperature increases in the region for all time periods and emission scenarios. The interquartile ranges of the projected temperature increases for 2070–2100 for the three emission scenarios show 2.0°C–4.4°C in the wet season and 2.2°C–4.9°C

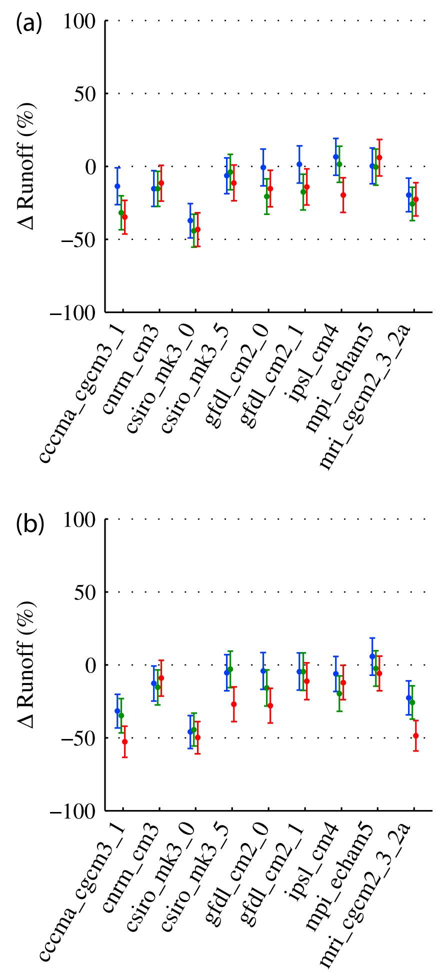

Figure 8. Projected changes in wet season runoff in the Gilgel Abay River compared to the base period 1980–2000, calculated with the SWAT model: (a) changes to 2046–2065 and (b) changes to 2080–2100. Colors denote the SRES scenario used: blue, B1; green, A1B; red, A2. Changes are expressed as percentages of the base period (1980–2000) wet season runoff.

in the dry season. The changes in ensemble median were statistically significant for each of the time period and scenario combinations we examined.

[45] The ensemble of GCMs we examined includes models that project increases and decreases in seasonal precipitation. The interquartile ranges of the projected rainfall changes for 2070–2100 for the three emission scenarios show −13% to +12% in the wet season and −14% to +16% in the dry season. For no time period or scenario ensemble did we find a statistically significant change in median seasonal precipitation, and we were not able to draw any definite conclusions about probable rainfall changes in the region.

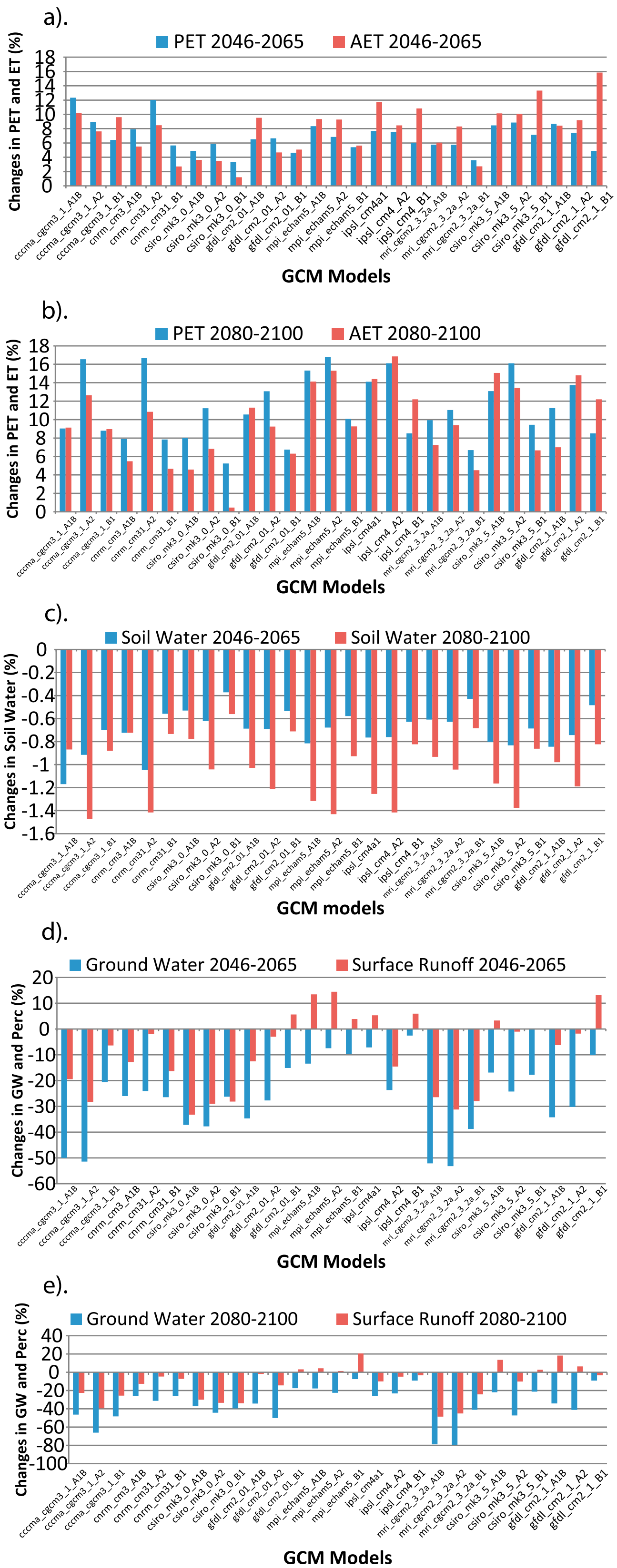

Figure 9. Annual changes in potential and actual evapotranspiration (PET and AET, respectively), soil moisture, surface runoff, and groundwater due to changes in climate for the 2046–2065 and 2080–2100 periods: (a) changes in PET and AET for 2046–2065, (b) changes in PET and AET for 2080–2100, (c) changes in soil water content for 2046–2065 and 2080–2100, (d) changes in surface runoff and groundwater for 2046–2065, and (e) changes in surface runoff and groundwater for 2080–2100.

[46] We also investigated how changes in temperature and precipitation might translate into changes in streamflows and other hydrological components using downscaled outputs from four climate models. Although the GCM sample examined was smaller, we note important aspects of the results. First, the direction of streamflow change generally followed the direction of changes in rainfall. This is expected, given that local evapotranspiration does not dominate the water cycle in the wet season. But we also saw that the fraction changes were larger than the rainfall changes. The hydrological response to evapotranspiration, soil moisture, and groundwater was also examined, and it was found that changes in groundwater flow may be a significant component of the modeled changes in streamflow.

[47] We interpret the different aspects of the hydrological response to imply that changes in runoff and other hydrological variables in the region could be significant even though the GCMs do not agree on the direction of the change. This implies that climate change may well impact on the surface and groundwater resources of the Lake Tana Basin and that the lake may experience a change in water balance due to a change in river inflow in the forthcoming decades.

[48] The effect of climate change has the potential to cause a great agricultural drought unless there is ample water available for irrigation. However, a reduction in rainfall may cause reduced groundwater recharge, which would significantly reduce its contribution to streamflow. Lake Tana is highly sensitive to variations in rainfall as well as variations in river inflows and evaporation. *Setegn et al.* [2009a] showed that inflow river discharge to Lake Tana contributes over 90% of the lake inflow. It is thus very likely that changes in river inflow would also change the volume of the lake and the water balance, which could ultimately adversely impact the lake ecosystem. Furthermore, Lake Tana is the source of the Blue Nile that contributes more than 7% of the total annual Nile River flow, and any possible change in the basin may contribute to the reduction of Nile flow.

[49] Finally, we note that a significant deficiency in the current study is that the scenarios used did not consider potential changes in land use or land cover. Hence, we strongly recommend a thorough investigation of the combined effect of climate and land use or land cover change on

the hydrological processes and water recourses variability, which are so important for the economy and livelihoods of people in the study area.

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