  Hydrology Research | 43.3 | 2012

Joint climate–hydrology modeling: an impact study for the data-sparse environment of the Volta Basin in West Africa

Gerlinde Jung, Sven Wagner and Harald Kunstmann

ABSTRACT

The Volta Basin in West Africa is a region sensitive to water shortage. Future climate conditions therefore may put additional stress on the competition for the scarce water resources between industry, agriculture, and households. For an investigation of the sensitivity of the hydrological regime to global climate change in the data-sparse and poorly gauged region of the Volta Basin, joint regional climate–hydrology simulations were performed. MM5 was used as a regional climate model to downscale two time slices of a global ECHAM4 simulation to a resolution of 9 km. These regional climate simulations were used to drive a physically based, distributed hydrological model at 1 km resolution. The performance of the model components and the joint model system was evaluated for different historical periods. Results show that discharge in the Volta Basin reacts highly sensitively to precipitation differences. The pronounced rainfall decrease at the beginning of the rainy season is not transferred to discharge changes. During the rainy season most of the surplus rainfall evaporates due to a strong increase in evaporation as a consequence of higher near-surface air temperatures. The average change signal in precipitation, as well as surface and subsurface hydrology variables, lies in most variables within the range of inter-annual variability, but regionally stronger signals are also observed.

Key words | climate change, hydrological modeling, West Africa

Gerlinde Jung* (corresponding author)
Sven Wagner
Harald Kunstmann
Karlsruhe Institute of Technology (KIT),
Institute for Meteorology and Climate Research (IMK-IFU),
D-82467 Garmisch-Partenkirchen,
Germany
E-mail: *gjung@marum.de*

*Present address:
MARUM,
Center for Marine Environmental Sciences,
Department of Geosciences,
Klagenfurter Strasse,
University of Bremen,
D-28334 Bremen,
Germany

INTRODUCTION

The Volta Basin (see Figure 1) covers an area of 414,000 km^2. The countries with the largest share on the basins' area are Burkina Faso (42.07%), Ghana (40.25%) and Togo (6.25%). The Akosombo Dam in the south of the basin (built in 1965) led to the formation of one of the largest artificial lakes in the world, Lake Volta. Hydropower generation at the Akosombo Dam is the major energy source in Ghana and led to settlement of energy- and water-demanding industries in southern Ghana. Still, agriculture is the main economic sector in most of the Volta Basin. A growth in irrigated areas and the building of smaller dams can be observed to be triggered by an increasing population, especially in the Burkinabè and the northern Ghanaian part of the basin where water is scarce. The increase in agricultural activities and ongoing industrialization, as well as an increasing living standard of the urban population in the south, led to competing water demands for energy production, households and agriculture. This conflict is especially intensifying when the increasing demands in hydropower, as well as in water for irrigation purposes meet suboptimal climatic conditions as in extremely dry years. The region is characterized by very weak infrastructure. Hydrological and meteorological observation information accordingly has a very limited spatial and temporal density. Hydrological climate change impact analysis has to cope with this constraint.

This introductory section gives an overview on climate and hydrological conditions and trends in the Volta Basin, as well as a description of recent modeling approaches and possible modeling uncertainties. The next section gives an overview over the models used and the model set-ups, and the procedure of the joint modeling approach, as

doi: 10.2166/nh.2012.044

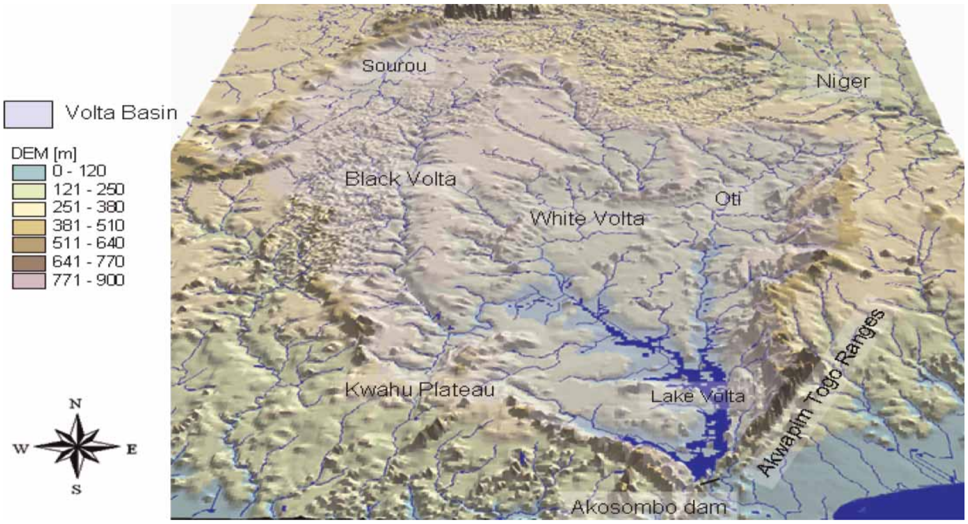

Figure 1 | The Volta Basin.

well as the calibration and validation of the models. The third section describes and discusses the simulation results including an analysis of the signal-to-noise (SN) ratio of the difference between the two time slices with respect to inter-annual variability. This part is followed by a section giving a summary and conclusions.

The climate of the Volta Basin

The climate of the Volta Basin can be described as semi-arid to sub-humid. The rainfall regime with its dry and rainy seasons is strongly influenced by the West African Monsoon. Around 80% of annual rainfall occurs from July to September with the monsoonal rains (Oguntunde 2004). Mean annual precipitation ranges from less than 300 mm up to more than 1,500 mm and shows a strong north–south gradient, with higher rainfall amounts in the tropical south and smaller amounts in the semi-arid north of the basin. In general, precipitation intensities and annual rainfall amounts in West Africa show a strong inter-annual, inter-decadal and even intra-seasonal variability (Laux *et al.* 2009). Mean annual temperature in the Volta Basin lies between 27 and 36 °C in the northern part, with an annual range of 9 °C (Oguntunde 2004). In the south of the basin the annual temperature range is around 6 °C, from 24 °C in August to 30 °C in March (Hayward & Oguntoyinbo 1987). Mean annual potential evaporation is lower than 1,500 mm in the south, but exceeds 2,500 mm in the north of the basin. Evapotranspiration accounts for approximately 80% of the rainfall amount during the rainy season (Oguntunde 2004).

Hydrology, geology, soils and landcover

The main tributaries to Lake Volta are the Black Volta (in Burkina Faso it is called Mohoun), the White Volta (Nakanbè) and its main tributary the Red Volta (Nazinon) and the Oti (Pendjari) river in the East. The runoff coefficient is relatively low in the Volta Basin. On average only 9% of rainfall becomes river discharge. For the Black Volta catchment it is only 4.9%, for the White Volta it is 7.1% and for the Oti 13.5%. The high nonlinearity of the rainfall–runoff response in this region is demonstrated by Andreini *et al.* (2000). As a response to the high inter-annual variability in precipitation, runoff is even more variable in time, as expressed through the coefficient of variation. While rainfall in the Volta Basin has a mean coefficient of variation of 7%, for river discharge it is 57% (Andreini *et al.* 2000). This finding indicates the high sensitivity of runoff with respect to rainfall and implies that relatively small differences in annual precipitation can cause large differences in river flow (Obeng-Asiedu 2004). Observations of river runoff of the Volta River before the building of the dam have shown a high seasonal variability. Mean discharge in the driest month was approximately 240 times less than mean peak flows (Andreini *et al.* 2000). In the Burkinabè part of the basin most of the rivers even run dry during the dry season, where the Mouhoun is the only permanent river. During the rainy season large areas of adjacent flood-plains are subject to regular shallow flooding of less than 100 cm (van de Giesen 2001). A tributary of the Mohoun with a specific behavior is the Sourou. The Sourou joins the Mohoun after flowing through a north–south trough, the so-called Sourou depression. The Sourou depression naturally regulates the runoff of the Mohoun. During the rainy season, when discharge of the Mohoun exceeds a certain level, water from the Mouhoun flows to the Sourou depression and is stored there. In low-flow times it takes up its normal flow and feeds the Mohoun (Shahin 2002). In 1984 a regulation mechanism was installed to control the flow and to allow storage of up to 0.25 km^3 of flood flow water and give some of the surplus water back to the Mohoun in the dry season (Bro 2001). This leads to a very low runoff coefficient of less than 3% at the Mohoun (Black Volta) downstream of Sourou, at the gauge Boromo (Shahin 2002).

Land cover in the Volta Basin is dominated by savannah-type vegetation. From south to north a transition from guinea savannah via shrub savannah to Sudan savannah occurs. Several studies demonstrated the high influence of land cover type on runoff processes. Chevallier & Planchon (1993), for example, investigated runoff processes in the small Booro–Borotou basin, in a savannah environment in the Ivory Coast and detected a dominant influence of vegetation on the high variability of infiltration.

The soils of Burkina Faso are predominantly of lateritic type. In the southern part of the basin the soils are mainly lixisols. The aggregate stability at the surface is low and soils are prone to erosion if vegetation cover is removed (Adams *et al.* 1996). The other main group of soils in the Volta Basin are the arenosols, mainly to be found in the northern, arid part of the basin. These soils are characterized by high infiltration rates.

The main geological systems of the basin are a Precambrian platform and a sedimentary layer, which covers a large area in the Ghanaian part of the basin. A detailed description of the geohydrology can be found in van der Sommen & Geirnaert (1988) and, with a special emphasis on the Ghanaian part of the basin, in Agyare (2004). Burkina Faso is dominated by crystalline and metamorphic rocks of the West African shield, formed primarily from Precambrian platform rocks, which are essentially impermeable. Fractures and channels, that enable the transmission and storage of groundwater, only developed through tectonic movements (Shahin 2002). A detailed geohydrological map of the Volta Basin was set up and analyzed by Martin & van de Giesen (2005). The groundwater aquifer system is characterized by two different aquifer types. One is of reservoir type, which means it is characterized by a weathered mantle of high porosity, but low permeability. This type provides the main aquifer storage (Adams *et al.* 1996). The second aquifer type found in fractured bedrock has low porosity and high permeability.

It is generally assumed that the aquifer systems in the basin are highly discontinuous with individual compartments in which isolated groundwater circulation occurs (Amisigo 2005). Surface water and groundwater are regarded as separate resources with little or no interaction. Groundwater flow to rivers in the basin is assumed to be insignificant, because mean monthly evapotranspiration exceeds mean monthly rainfall for most of the year for the entire basin. Therefore groundwater loss in the dry season would likely be more due to evapotranspiration than to base-flow to rivers (van der Sommen & Geirnaert 1988). Groundwater recharge was found to be spatially heterogeneous and it seems to derive largely from excess rainfall (van der Sommen & Geirnaert 1988). According to Martin & van de Giesen (2005), recharge is comparably low and no recharge at all is observed below an annual rainfall of 170 mm for sandstone aquifers and below 380 mm for weathered rock aquifers. For the Mohoun catchment in Burkina Faso, another study assumes that groundwater recharge accounts for approximately 16% of annual rainfall (Bro 2001). For the subcatchment of the Nakanbè 13.4% is assumed.

Trends in temperature, rainfall and runoff in the Volta Basin and in West Africa

Decreasing rainfall amounts and increasing temperatures have been observed and analyzed in West Africa over the past few decades in a variety of studies, such as, for example, in LeBarbé *et al.* (2002). A striking decrease in annual rainfall in the Sahel region occurred with a decrease of around 20–40% from 1931–60 to 1968–97 (Nicholson 2001). These trends do not match observed global ones, which rather show an increase in precipitation over land areas (even though not strictly significant) (Solomon *et al.* 2007). For the Volta region a trend analysis was performed by Neumann *et al.* (2007) to investigate present trends of temperature, precipitation and river runoff. The results indicated a stable trend of increasing temperatures and a weak trend of a decrease in precipitation. For river discharge no clearly stable trend was determined. The observed trend showed a discharge reduction in the dry season, but an increase in the wet season. The reasons had to be left open. Not only a lack of rainfall and increasing temperatures, but also enhanced irrigation, could lead to a negative trend in river discharge, especially during the dry season. On the other side, the building of additional dams and reservoirs can lead to an increase in discharge in the dry season, but to a decrease in the wet season.

Review of joint climate-hydrology modeling

Since global and regional climate and meteorology models increasingly simulate reliable scenario outputs, the demand to use these for an impact analysis in hydrology has grown in recent years. Still, the majority of the model coupling is done one-way, feeding the respective hydrological model with the output of the atmospheric model simulations. Some studies were performed that directly use the global climate model (GCM) output for an impact analysis on land surface hydrology. But the limiting factor of using GCM output for hydrological impact modeling is its more or less coarse resolution. Within the resolution of most GCMs, that are used nowadays it is not possible to achieve an explicit representation of mesoscale meteorological forcings. In the smaller scale simulations, where a higher resolved topography and land cover are available, lee effects, orographic enhancement of convection and land–atmosphere interactions are accounted for in more detail.

Andersson *et al.* (2006) studied the impact of climate change on the African catchment of the Okavango River (Namibia) using climate change signals directly derived from GCM simulations. Results showed that the impact of climate change in that region is larger than the impact of different scenarios of irrigation strategies and deforestation. An analysis of the hydrological sensitivity to climate change for nine large, continental river basins (none of them in Africa) using the statistically downscaled data of four GCMs was, for example, performed by Nijssen *et al.* (2001). They found a decrease in annual discharge in most basins, despite a precipitation increase, but a varying seasonal runoff behavior between catchments in higher and lower latitudes. Another example of statistically downscaled impact analysis was performed by Salathé (2005) for the simulations of streamflow of the Yakima River in the USA. They derived the global climate change signal from three different GCMs and two different scenarios (A2 and B2) and found a clearly good and sufficient performance using input from the global circulation model ECHAM4 with a simple statistical downscaling method.

A dynamical downscaling approach, combined with a bias correction method yielded reasonable results for the models' sensitivity to global climate change for the mid-latitudinal environment of the Ammer catchment in Germany (Kunstmann *et al.* 2004). Another example for a dynamical downscaling approach and coupled hydrological simulations with the aim of analyzing the impact of global climate change is a process study for the Rhine basin by Kleinn (2002). This study also included a comparison of the dynamically downscaled precipitation fields to the ones derived by two different methods of statistical downscaling. Both statistical downscaling methods did not provide satisfactory results, as precipitation amounts were underestimated by over 45%. Studies of Bergstroem & Forsman (1973) and Schäfli (2005) both demonstrate the influence of a regionally changing climate on hydropower production. Both follow a statistical–dynamical downscaling approach, using the information derived from regional climate simulations for a perturbation of the meteorological time series that serve as input to the hydrological model. Within the framework of the PRUDENCE project (prudence.dmi.dk) some coupled climate–hydrology simulations were performed as well. Hagemann & Jacob (2007), for example, used the output of 10 RCMs under the assumption of the A2 scenario, in a resolution of 50 km, to drive a global-scale discharge model at 0.5° resolution. They demonstrated that the ensemble mean was better than any single model when compared to observations, but a wide spread was observed for the different model runs. Graham *et al.* (2007a) used a conceptual semi-distributed rainfall–runoff model for climate impact studies, driving the model with different RCM model outputs with different underlying GCMs and climate scenarios. They investigated the role of different methods of transferring the data from the RCM to the hydrological model and found that this did not alter the mean results, but the seasonal behavior. Graham *et al.* (2007b) also analyzed RCM ensemble simulations and drove hydrological models with these data. They found that the choice of GCM had a larger impact on the hydrology model results than the respective choice of RCM and even emission scenario.

Review of hydrological modeling in West Africa

In lower latitudes the use of most hydrological models is limited by the fact that they were mainly developed for temperate conditions and are, for example, not easily transferable to other zones (Klemes 1993). This is especially true for simple lumped empirical or conceptual models due to their lack of physics representation. But also physically based models incorporate a number of empirical assumptions for these physical processes that cannot be calculated explicitly. Another limiting factor for reliable hydrological simulations, especially in developing countries like in West Africa, is insufficient data availability. Especially with physically based models with their high degree of parameter need, only a few studies were performed so far. Simple rainfall–runoff models are often the better choice in data-sparse regions, as the comparison of three models of diverse complexity of Giertz & Diekkrueger (2003) shows. In a study on parameter stability by Niel *et al.* (2003) a lumped hydrological model was applied to 17 west and central African catchments to study parameter stability related to climate change studies. They found that non-stationarity in rainfall or runoff series does not imply non-stability of the model parameters. The physically based, distributed MIKE SHE model was successfully applied to the large Senegal river basin and extensively validated in a modeling study of Andersen *et al.* (2001). Also semi-distributed empirical models showed reasonable results for rainfall–runoff modeling for different West African catchments in a study of Paturel *et al.* (2003). Recently a study with a semi-distributed modeling platform (Dezetter *et al.* 2008) investigated the effects of using different hydrological modeling approaches and input grids on the simulation of runoff for 49 West African catchments. The results demonstrated that the highest sensitivity was found with respect to the choice of soil datasets, but nevertheless no single data–model combination yielded the best results for all catchments under consideration. Amisigo *et al.* (2008) set up a statistical model (NARMAX) for several sub-catchments of the Volta Basin and demonstrated a good performance of monthly streamflow prediction.

As was demonstrated, regional downscaling of GCM outputs was performed for West Africa in a number of studies, as well as hydrological simulations, but the approach of a joint dynamical downscaling–hydrological modeling for climate impact studies was, to our knowledge, not performed for a West African environment before. The main objective of this approach is to analyze the impact of different climate conditions on the hydrology in the semi-arid Volta Basin. This is especially important to be investigated in a region where agricultural and industrial development are both highly dependent on water availability.

Discussion of uncertainties

One point to be mentioned, when talking about joint modeling, is the increase in uncertainties, because every simulation inherits some uncertainties; an increasing number of models in use also means an increasing uncertainty. One uncertainty that is always apparent in data-sparse regions like West Africa is the uncertainty that is caused by the sparseness of station data (Giorgi *et al.* 2001; Washington *et al.* 2004). In particular, if data are spatially interpolated, strong errors can be introduced when only a few stations are available, though interpolation is indispensable to obtain hydrological model input. This also influences model calibration and validation results. In climate modeling, generally the uncertainty that lies within the assumptions that were made for the chosen emission scenario is to be mentioned. Another source of uncertainty lies within the conversion of these scenarios' assumptions to atmospheric concentrations and radiative effects (Giorgi *et al.* 2001). Then there is the uncertainty in the global climate model (Bengtsson 2003), and when additionally regional models are applied for downscaling, in the regional climate model as well. First this is a model-intrinsic uncertainty that is due to imperfect knowledge or representation of physical processes, limitations due to numerical approximations of the physical equations and assumptions or simplifications that have to be included to parametrize subgridscale processes. The domain choice, as well as the spatial resolution, is other sources of uncertainty in limited area modeling (Kotlarski *et al.* 2005). As for the RCM, there is additionally some uncertainty lying in the hydrological model itself, dependent on the physics description and the numerics. The data transmission from the regional climate model to the hydrological model is also a source of uncertainty due to the interpolation of the climate model output.

SIMULATION SET-UP AND MODEL CALIBRATION

Regional climate modeling

Model description and set-up – MM5

The nonhydrostatic mesoscale meteorological model (MM5) was used to perform the regional climate simulations (Grell *et al.* 1995). MM5 is a multi-nesting-capable model that offers a large variety of physics parameterizations for subgridscale processes, making it applicable to climatic and dynamic conditions around the globe. The used cloud–radiation scheme incorporates short-wave and long-wave interactions with clear sky and explicit clouds (Grell *et al.* 1995). Following the results of Kunstmann & Jung (2003), who tested different model set-ups of MM5 for the same region, the following parameterization schemes were used. Interaction with cloudy skies is simulated by a cloud parameterization scheme. The Reisner graupel scheme is used to parameterize gridscale precipitation. This scheme is based on the mixed phase scheme of Reisner *et al.* (1998) and includes the calculation of cloud water, cloud ice, rain water, snow, supercooled water, melting of snow, graupel and ice particle number concentration. For sub-gridscale precipitation, the Grell scheme was used (Grell & Kuo 1991). Additionally a shallow convection scheme is implemented to account for shallow, non-precipitating convection that is forced by sub-grid scale processes (Grell *et al.* 1995). The Hong–Pan PBL scheme, based on a nonlocal boundary layer vertical diffusion scheme of Troen & Mahrt (1986) was used in the present study (Hong & Pan 1996) in combination with the Oregon State University land surface model (OSU-LSM). This fully developed one-dimensional SVAT (Soil–Vegetation–Atmosphere Transfer) model in MM5 version 3 enabled MM5 to be utilized as a regional climate model, because then it was possible to account for feedback mechanisms between soil moisture/vegetation and atmosphere. The importance of these feedback mechanisms was demonstrated in Kunstmann & Jung (2007) for the region of the Volta Basin.

The MM5 simulations were performed using a one-way nesting approach, involving the nesting of three model domains. The horizontal resolutions of the three domains were 81 km for the first domain, with an extension over larger West Africa (D1), 27 km for the second domain (D2) and 9 km for the smallest domain (D3), the larger Volta region, covering twice as much as the Volta Basin (~800,000 km^2). A vertical discretization of 25 layers was chosen. The model top level was set to 30 hPa to account for the higher tropopause level in the tropics. The initial and boundary fields of the climate runs were derived from a transient ECHAM4 (Röckner *et al.* 1996) global climate model run from 1860–2100. In the present study the scenario IS92a was used (Houghton *et al.* 1995). The underlying assumption of an annual increase in CO_2 of 1% per year leads to an effective CO_2 doubling time of about 90 years (May & Röckner 2001). Two time slices of 10 years were simulated: 1991–2000 for the present-day climate and 2030–2039 for the future climate. Moreover the simulated differences between the two time slices were analyzed with respect to inter-annual variability. A detailed description of set-up, validation and results of the regional climate simulations on which this study is based can be found in Jung & Kunstmann (2007).

Regional climate model validation

Two simulations of one year length each were performed within this study and validated. These simulations were run with the afore-mentioned configuration, using reanalysis data of the National Center for Environmental Prediction (NCEP) for the year 1997, and reanalysis data of the European Centre for Medium-Range Weather Forecasts (ECMWF) for the year 1968 as input. The years that were chosen for the validation were an extremely wet year, 1968, and with 1997 a comparably dry year, representative for the climate of the 1990s.

As an instrument of quantification of the modeling error, the *RMSE* (Root Mean Square Error) defined as

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(x_{\text{mod}} - x_{\text{stat}})^2}{N}} \quad (1)$$

was calculated for the modeled monthly mean value (in the case of temperature) or the monthly sum (in the case of precipitation) at the nearest grid point x_{mod}, compared to the respective station value x_{stat}. N denotes the number of x_{mod} and x_{stat}, respectively.

In the case of precipitation, additionally a normalized *RMSE*:

$$RMSE_{\text{norm}} - \sqrt{\frac{\sum_{i=1}^{N}(x_{\text{mod}} - x_{\text{stat}})^2/N}{\bar{x}_{\text{stat}}}} \quad (2)$$

was defined to account for the strong latitudinal and interannual dependence of absolute rainfall amounts in West Africa. For precipitation 108 observational stations were available for the year 1968, whereas for 1997 only data from 59 stations could be used. The $RMSE_{\text{norm}}$ and the *RMSE* values for precipitation for the nearest and, to account for the spatially highly heterogeneous nature of precipitation, also for the mean over the four nearest gridpoints are summarized in Table 1. A more detailed view on the performed validation of MM5 showed a weak performance of MM5 considering rainfall along the coast, but a sufficient accuracy for the Volta Basin itself (Jung & Kunstmann 2007).

Hydrological modeling

As the aim of this study was to consider climate change impact in a data-sparse environment, a high degree of transferability was demanded from the hydrological model. First, transferability between different subcatchments was necessary because data availability was not sufficient for calibration in all subcatchments. Second, the transferability to different climatic conditions was requested to apply the model for climate change scenarios. Additionally, a high degree of physics in the model was demanded for, because the analysis aimed at physically based process understanding, to gain insight into the processes of importance for runoff generation and the regional hydrological cycle. Consequently, the use of a physically based model was essential. The hydrological model that was used to fulfill these demands is the water balance simulation model (WaSiM) (Schulla & Jasper 2002).

Table 1 | *RMSE* and $RMSE_{\text{norm}}$ for precipitation, for the nearest gridpoint (1 GP) and the mean over the four nearest gridpoints (4 GP)

	1968 1 GP	4 GP	1997 1 GP	4 GP
RMSE (mm)	98.67	106.11	101.29	106.86
$RMSE_{\text{norm}}$ (–)	0.84	0.8992	1.22	1.24

Hydrological model description – WaSiM

WaSiM is a physically based hydrological model, suitable for flood modeling as well as for long-term water balance simulations. It is designed for applications in mesoscale and large scale basins (spatial resolutions between tens of meters and kilometers) and temporal resolutions from hours to one day. WaSiM is a deterministic, fully distributed, modular model for the simulation of the terrestrial water balance using physically based algorithms for the vertical fluxes and lateral groundwater fluxes. Other lateral fluxes like surface runoff and interflow are treated in a lumped manner.

Potential evaporation (ET_{pot}) is calculated using an approach of Penman–Monteith (Monteith 1975; Brutsaert 1982). When the simulation is performed with a daily time step, this calculation is split into two terms, ET_{pot} for the bright day and for the night, to account for a daily cycle. To determine the actual evapotranspiration, the first step is to reduce potential evaporation by the amount of water equal to interception storage. In the following, a further reduction of potential evaporation is performed, dependent on the actual suction of the soil, considering soil and plant physiological properties. A simple bucket approach is used to calculate interception storage. In the calculation of infiltration, macro pore flux can be approximated by using a generally higher effective hydraulic conductivity of the soil matrix. For the calculation of vertical soil water movement in the unsaturated zone, the spatially and temporally discretized one-dimensional Richards equation is solved for each grid cell. Hydraulic head and hydraulic conductivities are dependent on soil moisture. These relationships are parameterized through an approach after van Genuchten (1976). Through the introduction of a recession constant for vertical hydraulic conductivity, indicating a recession with depth, the generation of interflow is enabled. Groundwater recharge in WaSiM is defined as the remaining vertically percolating water. Soil heat flux is considered to be a fixed fraction of net incoming radiation. A two-dimensional groundwater flow module is dynamically coupled to the unsaturated zone module. The simulation of lateral fluxes within the aquifers is based on the mass balance equation and Darcy's law. Baseflow, which is defined as the groundwater-derived part of river discharge, can only be generated when groundwater levels reach the river bed or lake bottom level. Re-infiltration of surface water into groundwater occurs if groundwater drops below river water level. This situation is an advantage when simulating the hydrology of semi-arid regions. Direct runoff and interflow are routed with respect to flow times that are calculated following the Manning–Strickler equation (Maidment 1993). The routing is done by a kinematic wave approach, using different flow velocities for different water levels in the channel. Retention is simulated with a simple linear storage approach for direct runoff, as well as for interflow.

Within this study, IDW (inverse distance weighting) interpolation was used for an interpolation of observational station data in the calibration runs. For the application within a climate change impact study, where the meteorological input is derived from the regional climate model, and therefore is already available on a regular grid, a bi-linear interpolation method was used.

The hydrological model WaSiM has not been used in a catchment of a comparable size in a semi-arid environment before. It has been applied primarily in small, mid-latitude, largely mountainous catchments (Niehoff 2001; Kleinn 2002; Schulla & Jasper 2002; Kunstmann *et al.* 2004; Kunstmann & Stadler 2005). Adaptations, to account for the specific conditions in the large and extraordinarily flat Volta catchment located in a semi-arid to sub-tropical environment, can be found in Jung (2006). A similar set-up has been used within the study of Wagner *et al.* (2009) for the White Volta catchment, a subregion of the entire Volta Basin. A socio-economic model was coupled to WaSiM in Ahrends *et al.* (2008) and applied for the small subcatchment of the Volta Basin, the Atankwidi catchment.

Hydrological model set-up

WaSiM was used at a resolution of 1×1 km^2 and with a time step of 24 h. The temporal resolution was restricted by the availability of calibration data. No data below a resolution of 1 d was available. In the vertical, the soil is represented by 20 layers of an equal thickness of 1 m.

A subset of gauges was chosen to define the subcatchments to be simulated (Figure 2). These gauges were selected on the basis of data availability and data quality for the 1960s, which was chosen as the calibration period. The reasons to choose this period were twofold. First, in the 1960s the data quality and also quantity was better than from the 1980s up to 2000. Second, at this time the river flow was not as much influenced by artificial changes as today, because many smaller, but also some larger, dams were built during and following the drought period of the 1980s. For the demarcation of Lake Volta further gauges had to be set at the smaller tributaries to Lake Volta where no gauging stations were available. Another surplus gauge had to be set, to define the subcatchment at Sourou due to the above-described specific flow characteristics of the Sourou depression, to allow a handling of river extractions, dependent on discharge levels, within the model (Jung 2006).

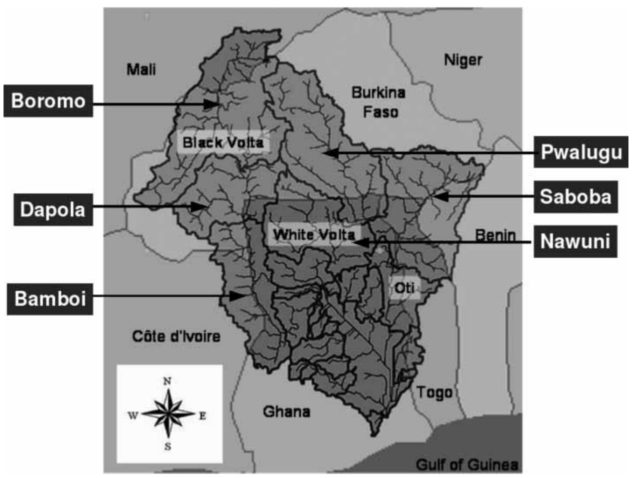

Figure 2 | WaSiM set-up: subcatchments and flow net structure.

A hydro-geological map was derived by Martin & van de Giesen (2005). Information on horizontal hydraulic conductivities, storage coefficient and aquifer thickness were classified for each geohydrological unit. The values of hydraulic conductivities and aquifer thicknesses were provided by Martin & van de Giesen (2005); for storage coefficients these soil-specific values were taken from general (not subcatchment-specific) literature (Maidment 1993). Land-use data was obtained from Vescovi (2001). The land-use-specific parameters were, where possible, taken from Grell *et al.* (1995) to achieve a best possible consistency with MM5, otherwise from Schulla & Jasper (2002). Soil texture from the global FAO (United Nations Food and Agriculture Organization) soil map (FAO 1971–1981) was used within the simulations. The van Genuchten parameters for tropical soils were taken from Hodnet & Tomasella (2002). The remaining soil hydraulic properties were either obtained from Maidment (1993) or Schulla & Jasper (2002).

Hydrological model calibration

Hydrological modeling in the Volta Basin has to cope with the often sparse availability of observation data for calibration and validation, but also for parameter input. The parameter values were either taken from the literature, or calibrated within the bounds found in literature, and not from on-site measurements, as described before. The calibration period was strongly constrained by data availability (1 year of daily observational data, 6 years of monthly data).

The calibration period for this study covers the years 1962–69. Daily observational discharge data was available only for the hydrological year 1968/69 (in West Africa: March 1968–February 1969). The remaining years (1962–67) were covered by monthly datasets. 120 stations with rainfall data were available, 20 stations for temperature, 18 for relative humidity, 19 for wind velocity and 12 for sunshine duration.

For this study the nonlinear parameter estimation tool, PEST (Doherty 2002), was applied in combination with the manual method. PEST uses a gradient-based nonlinear parameter estimation algorithm following Gauss–Marquardt–Levenberg, which is a least-squares fitting method. An advantage of PEST is its easy implementation for different kinds of script-based models. An application of PEST for parameter estimation of WaSiM is discussed in Kunstmann *et al.* (2005).

According to Hartmann & Bárdossy (2005), the transferability of a hydrological model is improved if the calibration is performed on a monthly or annual timescale in addition to the daily timescale. Because transferability is essential for the simulation of future climate scenarios' impact on hydrology, a similar approach was applied within the present study. As daily data was only available for the hydrological year 1968/69, the model was calibrated on a monthly basis for the rest of the calibration period. A combined Nash–Sutcliffe criteria (*NSM*) from both the daily calibration (NSM_{day}) and the monthly calibration (NSM_{month}) was calculated and weighted with a factor α, dependent on the importance to be given to the respective criteria (Equation (3)). Within the present study more weight was assigned to the daily calibration and α was set to a value of 0.8.

$$NSM = 1 - \alpha \underbrace{\left(\frac{\sum_i (x_{i,\mathrm{sim}}(d) - x_{i,\mathrm{obs}}(d))^2}{\sum_i (x_{i,\mathrm{obs}}(d) - \bar{x}_{\mathrm{obs}}(d))^2} \right)}_{NSM_{\mathrm{day}}} + (1-\alpha) \underbrace{\left(\frac{\sum_i (x_{i,\mathrm{sim}}(m) - x_{i,\mathrm{obs}}(m))^2}{\sum_i (x_{i,\mathrm{obs}}(m) - \bar{x}_{\mathrm{obs}}(m))^2} \right)}_{NSM_{\mathrm{month}}} \quad (3)$$

Figure 3 demonstrates a reasonable performance for WaSiM over the period of monthly calibration for the gauge Bamboi. The *NSM* values for calibrated gauges of the hydrological year 1968/69 and the monthly values for the time period of 1962–69 are summarized in Table 2.

Joint climate–hydrology modeling

Procedure

The coupling of the two models MM5 and WaSiM was done in a strict one-way approach, as illustrated in Kunstmann *et al.* (2008). The meteorological input fields that are needed as input by WaSiM are derived from the MM5 model outputs. Soil moisture is not transferred from the meteorological to the hydrological model, but simulated independently in both models. The soil and vegetation descriptions in the SVAT model of MM5 are primarily

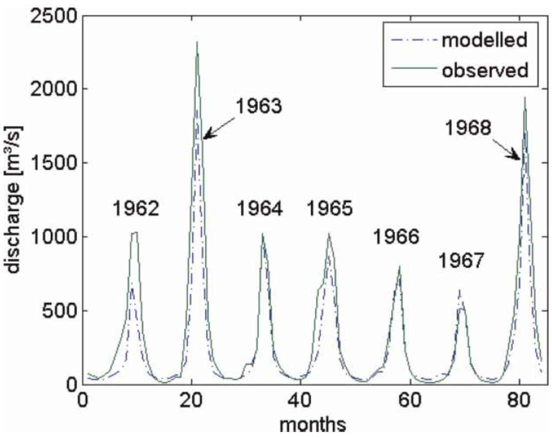

Figure 3 | Monthly values of observed and simulated discharge ($m^3\ s^{-1}$) for the years 1962–1969, Bamboi.

Table 2 | Nash–Sutcliffe efficiencies for monthly and daily calibration of WaSiM, daily: 1968/69, monthly: 1962–1969

Gauge	Bamboi	Boromo	Dapola	Nawuni	Pwalugu
NSM_{day}	0.95	0.31	0.82	0.84	0.3
NSM_{month}	0.84	0.74	0.85	0.79	0.33

designed to account for the fact that the soil provides a memory of atmospheric processes and therefore to account for land-surface–atmosphere feedbacks in general, whereas the higher resolved calculations in the hydrological model give more detail on soil moisture properties, needed for a sophisticated simulation of surface and subsurface hydrology and runoff processes.

In the data processing each gridpoint of the MM5 model grid is defined as a WaSiM input station. The transferred meteorological variables convective and nonconvective precipitation, 2 m temperature and mixing ratio, the 10 m horizontal wind components u and v, and global radiation are extracted from the MM5 output fields. Within a coupling routine from these variables, relative humidity and total precipitation are calculated and all variables are averaged (in the case of rainfall summed up) to the WaSiM input time-step of a day. The data are then transferred to the WaSiM gridpoints. A bias correction was not performed, as this was not feasible for the study area and model resolution. For the region of West Africa we face the specific situation that data availability is extremely limited compared to studies in North America or Europe. For bias correction and/or statistical postprocessing of RCM raw data output, long time series and a comparatively dense station network is mandatory. Furthermore, in this study the performed climate simulations have a comparably high spatial resolution of 9 km. Therefore, traditional evaluations and bias-correcting algorithms using data like CRU (Climate Research Unit) or ERA40 data might not be appropriate, due to a scale mismatch. Data that were needed by both MM5 and WaSiM were, as far as possible, equalized as mentioned before. This concerned land-use class parameters like LAI, albedo, etc, as well as soil characteristics like wilting point and saturated soil moisture content. Also land-use data and classification were the same in WaSiM and MM5.

Joint modeling validation

A validation of the coupled modeling system was performed for the year 1968, running WaSiM with MM5 output data (which was driven by reanalysis data from the National Center for Environmental Prediction (NCEP)). The resulting subcatchment hydrographs were then compared to observation data. The Nash–Sutcliffe criteria (*NSM*) values for this run are summarized in Table 3 for all subcatchments where observation data was available, for the calibration run, as well as for the coupled model simulation.

For most gauges the coupled run performance is comparable to station-driven simulations. For Saboba a better performance can be evaluated for the coupled run, with a direct comparison of hydrographs (Figure 4). Mainly, this is due to the better representation of the spatial rainfall distribution within the coupled simulation. As mentioned earlier, WaSiM, when run with observational data, produces erratic rainfall amounts due to spatial interpolation, especially in the subcatchment Saboba due to the sparseness of rainfall measurement stations. Saboba is the second-largest subcatchment (55,817 km^2), but has only six observational stations contributing to rainfall interpolation

Table 3 | Nash–Sutcliffe efficiencies for calibration and coupled model simulation of WaSiM (1968/69)

Gauge	Bamboi	Boromo	Dapola	Nawuni	Pwalugu	Saboba
Calib.	0.95	0.31	0.82	0.84	0.3	0.85
Coup.	0.92	−0.73	−0.48	0.79	0.26	0.9

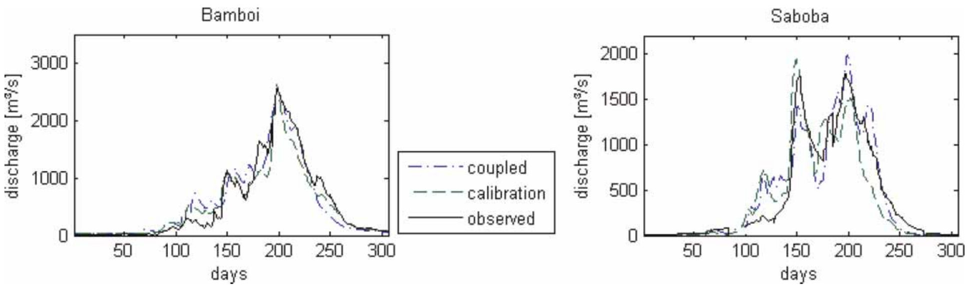

Figure 4 | Observed and simulated discharge (Q_{total}) ($m^3 s^{-1}$) (calibration run and joint MM5–WaSiM run), left: Bamboi, right: Saboba, 1968.

within the subcatchment. A slight overestimation of rainfall in the MM5 simulations for the year 1968 in the very north of the basin (Jung & Kunstmann 2007) leads to quite poor model performance for the gauges downstream of that area, Boromo and Dapola, in the coupled run. One bias that is obviously not due to the driving meteorological input fields, because it is found in both the calibration and the coupled run for the gauge Saboba, is the strong overestimation of runoff at the onset of the rainy season. This is most likely due to an insufficient representation of the soil moisture dependence of the saturated hydraulic conductivity, or due to an overestimation of soil moisture.

SENSITIVITY TO GLOBAL CLIMATE CHANGE IN THE VOLTA BASIN

Regional climate modeling results

Jung & Kunstmann (2007) give a detailed analysis of the change signal found in various parameters of the regional climate simulations for the two time slices (1991–2000 and 2030–2039) used in this study. The simulated temperature showed an increase of about 1.2–1.3 °C in the future simulations and it is clearly exceeding inter-annual variability. It was also shown that the signal was similar to the observed trend of the last century, globally, as well as in West Africa. Rainfall neither shows a general increase nor decrease. Nevertheless, precipitation amounts show a pronounced decrease in April of more than 20%. It was also demonstrated that changes in precipitation only for two months exceeded inter-annual variability, in April for the Sahel region and June for the Guinea Coast region. Additionally, it could be delineated that the rainfall decrease in April is connected to a delay in the onset of the rainy season. For the Volta Basin annual mean temperature and precipitation change patterns are illustrated in Figures 5 and 6. Temperature increases are stronger in the northern part of the basin and lowest in the south near the coast and over Lake Volta. Relative precipitation change shows a much more heterogeneous pattern, with changes up to ±10%. Increases of rainfall occur most pronounced in two bands north of Lake Volta and over the lake itself. In the rest of the basin area, precipitation tends to decrease. Because the simulated time slices spanned only two 10-year periods due to constraints in computational time and the high resolution of the model set-up, the resulting differences between the two time slices, even when clearly demonstrated to lie outside the range of interannual variability, might still be within

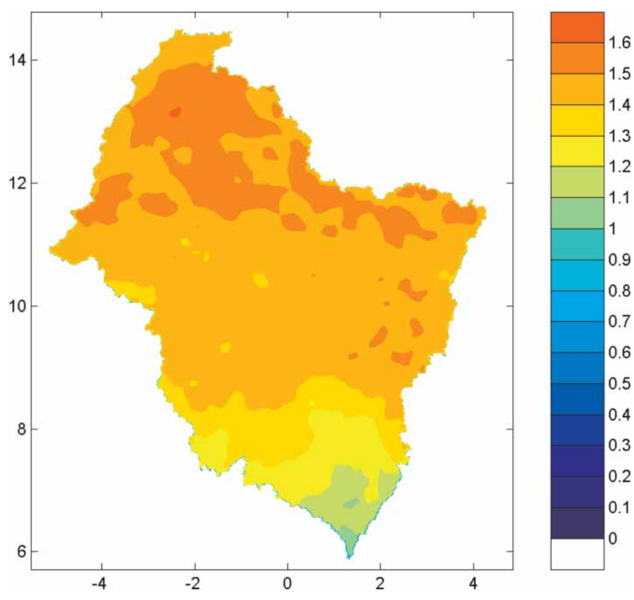

Figure 5 | Annual mean temperature change (°C) (2030–2039 vs 1991–2000).

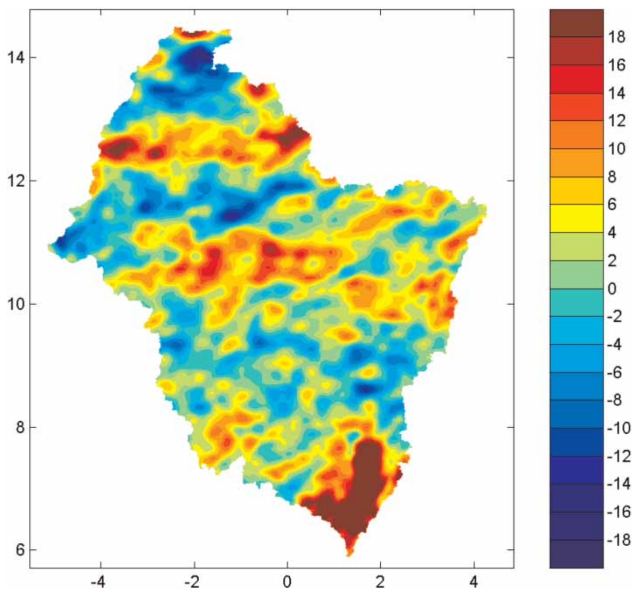

Figure 6 | Annual mean precipitation change (%) (2030–2039 vs 1991–2000).

the range of interdecadal variability and not completely be connected to global climate change.

Impact of differences in regional climate on hydrology

The average rainfall change signal in the Volta Basin is rather small for the considered regional climate model simulations. However, an investigation of the impact of the differences in regional climate on hydrology is ingenious, because of the significant increase in temperature and consequently in potential evaporation, as well as because of the spatial and temporal heterogeneity of the simulated climate change signal. The abbreviations of the variables that are analyzed and presented in the following are summarized in Table 4.

Table 4 | Used variables and abbreviations

ET_{pot}	Potential evaporation
ET	Actual evapotranspiration
P	Precipitation
Q_{direct}	Direct runoff/infiltration excess
$Q_{interflow}$	Interflow + baseflow
Q_{total}	Total runoff ($=Q_{direct}+Q_{interflow}$)
θ	Soil moisture

Mean hydrological response in the Volta Basin

Discharge change from the present-day coupled simulation (1991–2000) to the future scenario coupled simulation (2030–2039) does not show a linear response to differences in precipitation. Figure 7 shows that most of the surplus rainfall reaching the Volta Basin evaporates, demonstrated by increased evapotranspiration values. This is due to higher temperatures in the future climate scenario that lead to higher potential evaporation and, in the case of sufficient soil moisture availability, to an increase in actual evapotranspiration. Therefore, only a small amount of surplus rainfall runs off as additional direct runoff and interflow. Interflow shows hardly any difference. Due to the small amount of

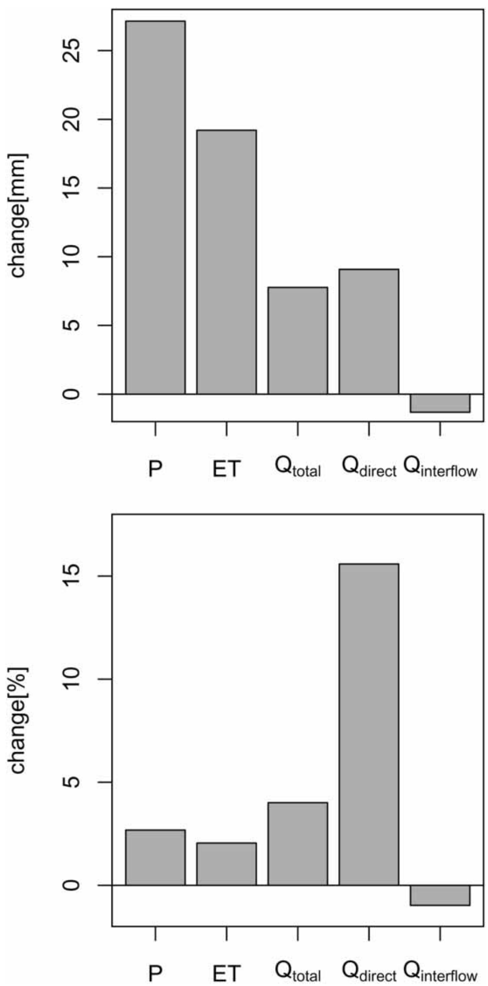

Figure 7 | Mean annual changes (2030–2039 vs 1991–2000) in the most important hydrological variables for the entire Volta Basin. Top: absolute values (mm), bottom: relative to (1991–2000) (%).

direct runoff in general, and the sensitive reaction towards rainfall events in the case of high soil saturation, the percentage difference is largest for direct runoff, with a difference of 16.5%.

The annual cycle of runoff shows a shift in the month of discharge maximum from August to September (Figure 8). Runoff in August is only slightly lower for 2030–2039 (7.3 mm less than in 1991–2000). In September it is higher for the simulated future scenario (26.1 mm greater than in 1991–2000) due to the strong increase in precipitation. This can be explained by the finding that in the present-day time-slice runoff peaks in August for half of the years and in September for the rest of the years. In contrast, in the future simulation all years show a peak runoff in September. The respective annual rainfall peak occurs in August in seven out of the ten years in the 2030–2039 time slice, whereas in the present-day simulation it is more variable, with three years showing peak rainfall in July and five in August. The large percentage decrease in precipitation in the Volta Basin in April does not show a corresponding signal in river runoff.

Figure 9 illustrates the differences in runoff, evapotranspiration and soil moisture for the simulated time slices for the total catchment. The small response signal in April can be explained by the small rainfall deficit in terms of rainfall amount and the extremely dry soil at the end of the long dry season. The small amount of surplus rainfall in the present-day reference state simulation (1991–2000) is most likely infiltrated and leads to a higher soil moisture amount in April in the present-

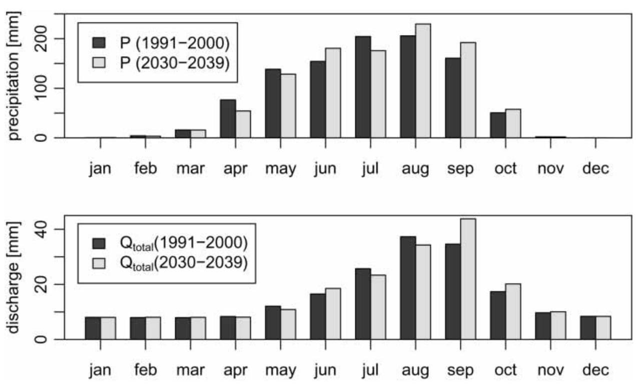

Figure 8 | Monthly decadal mean amounts of precipitation (top) and discharge (bottom) (mm) (1991–2000 and 2030–2039, entire Volta Basin).

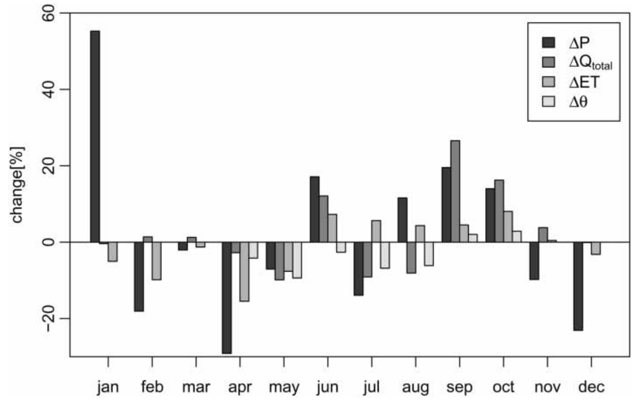

Figure 9 | Monthly mean changes in precipitation (*P*), runoff (Q_{total}), evapotranspiration (*ET*) and soil moisture (*θ*) (%) (2030–2039 vs 1991–2000, entire Volta Basin).

day simulation compared to the future run. By higher potential evaporation due to an increase in temperature, the soil moisture deficit is enhanced in the future time slice. This holds true also for May. In June, a clear increase in discharge follows the increase in precipitation. In July the opposite is observed. In both months the percentage difference in rainfall exceeds the difference in river runoff. In August discharge shows a decrease though rainfall increases, whereas in September both signals show an increase, leading to a delay in the peak runoff with respect to the peak rainfall amount. September and October uniformly show an increase in both variables. In November, an increase in runoff together with a decrease in precipitation can be observed.

These features can be explained through an additional consideration of soil moisture and evapotranspiration. Soil moisture is strongly determined by past amounts of rainfall and evapotranspiration. For the variability of the runoff response signal rainfall is more important, because evapotranspiration increases in all months, in which water availability is sufficient (June–November). The months with the highest increase in potential evaporation, April and May, show a decrease in actual evapotranspiration due to the lack of soil moisture. There are two reasons why the increase in precipitation in August is not leading to an increase in runoff. First, after the rainfall deficit in July soil moisture is lower and a higher amount of rainfall infiltrates in August. Second, the evapotranspiration increase consumes most of the surplus rainfall. The opposite signal in November can be explained by higher soil moisture amounts, resulting from the increase in precipitation in September and October, leading to a reduction of infiltrated rainwater. Consequently, even though an increase in evapotranspiration can be observed, river runoff increases as well, despite a decrease in rainfall.

Spatially distributed hydrological response

The spatial structure of the hydrological response of climatic differences in the Volta Basin is considered for annual mean evapotranspiration and total runoff. Evapotranspiration (not illustrated here) shows a pattern of relative differences, which is very similar to the one in precipitation with a similar order of magnitude (compare with the previous section). This is most likely due to the fact that actual evapotranspiration in the Volta Basin is basically limited by water availability and hence an increase in potential evaporation caused by higher temperatures has almost no effect on actual evapotranspiration. Also the response in total runoff (Figure 10) strongly follows the pattern in rainfall change. But the percentage changes are of a much higher order of magnitude, reaching values of up to ±50%, confirming the commonly noted observations of the coefficient of variation of discharge always being much larger than the one of precipitation in the Volta Basin, as described in the first section.

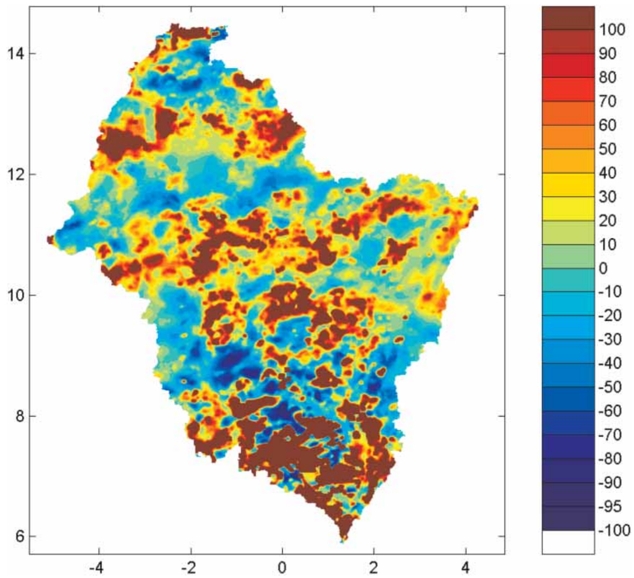

Figure 10 | Annual mean total runoff change (%) (2030–2039 vs 1991–2000).

Climate change versus climate variability

A central question that has to be taken into account in climate change studies is whether the derived climate change signal lies within the range of inter-annual variability. To analyze this, the signal-to-noise ratio was, according to Jung & Kunstmann (2007), defined as

$$SN = \frac{|\bar{X}_{\text{fut}} - \bar{X}_{\text{pres}}|}{\sigma} \quad (4)$$

with $\bar{X}_{\text{fut}}$ and $\bar{X}_{\text{pres}}$ the mean monthly or annual value of a certain variable for the future and the present time slice, respectively, and σ the standard deviation (of monthly and annual values, respectively) of this variable for the present time slice. A value of $SN > 1$ indicates a detected change signal that lies outside the simulated inter-annual variability (noise) and can be regarded as either larger scale variability or a climate change signal. The annual cycle of the SN ratio for precipitation, evaporation and runoff are summarized in Table 5. Total runoff only exceeds a SN of 1 in February, which is not a significant signal due to the small amounts of runoff generally observed in the dry season. Precipitation shows a $SN \geq 1$ in April and June for the basin. Due to the increase in rainfall in June, evapotranspiration shows a signal higher than inter-annual variability in this month. The SN values for direct runoff exceed 2 in February and

Table 5 | Signal-to-noise ratio for selected hydrological variables

	P	ET	Q_{total}	Q_{direct}	$Q_{\text{interflow}}$	θ
January	0.49	0.09	0.17	0.48	0.3	0.1
February	0.21	0.18	**1.05**	**2.48**	0.7	0.08
March	0.03	0.07	0.97	**2.18**	**1.04**	0.09
April	**1.14**	0.5	0.7	0.46	0.74	0.93
May	0.28	0.39	0.35	0.27	0.41	0.61
June	**1.0**	**1.53**	0.43	0.69	0.18	0.11
July	0.48	0.7	0.23	0.16	0.29	0.38
August	0.55	0.47	0.18	0.75	0.45	0.32
September	0.66	0.52	0.55	0.7	0.36	0.17
October	0.41	0.28	0.42	0.54	0.33	0.12
November	0.09	0.01	0.34	0.59	0.19	0.02
December	0.22	0.09	0.01	0.26	0.11	0.1
Year	0.16	0.33	0.15	0.35	0.05	0.19

March. This demonstrates the complexity and high nonlinearity of the hydrological system in the Volta Basin, where small precipitation differences (with also comparably small *SN* values) lead to a signal in infiltration excess that is clearly exceeding inter-annual variability. Responsible for that is the small inter-annual variability of direct runoff for these months, as well as the properties of the soil matrix that reduces permeability of very dry soils and is therefore inhibiting the infiltration of even small amounts of water. For both spatially distributed precipitation and runoff, the *SN* ratio shows the largest values predominantly in those areas, where a strong relative increase is observed (compare Figures 11 and 12). For total runoff, the *SN* value exceeds the threshold value of 1 in a wider area, caused by the very sensitive reaction of runoff to precipitation differences, leading to a much larger signal in runoff difference, as discussed in the previous section.

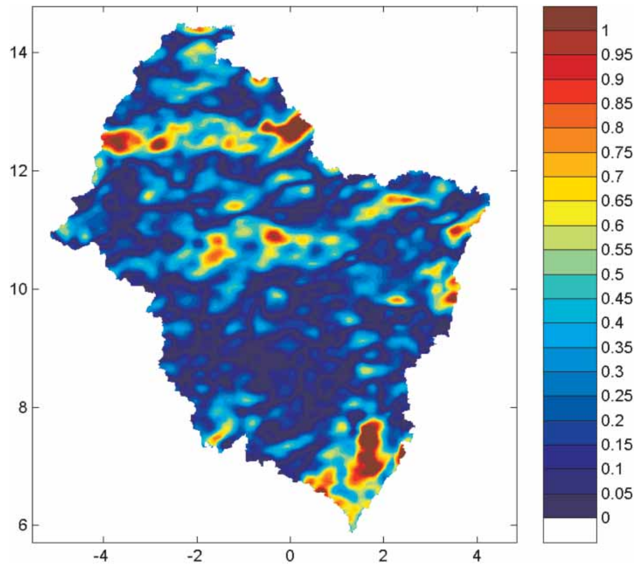

Figure 11 | Signal-to-noise ratio (SN) for precipitation.

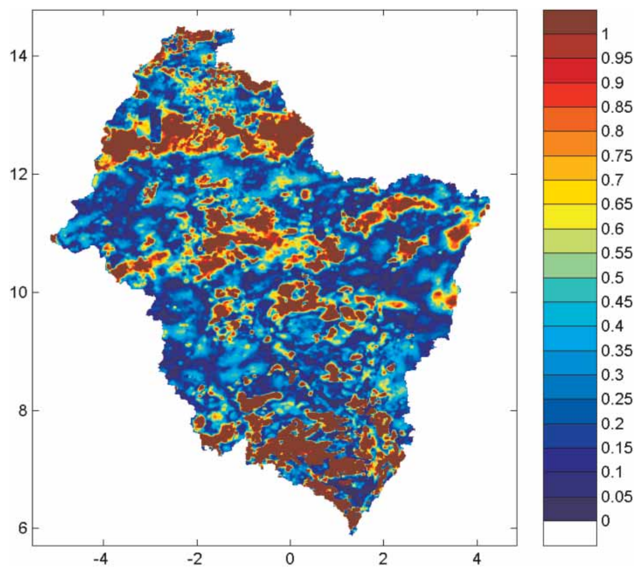

Figure 12 | Signal-to-noise ratio (SN) for total runoff.

SUMMARY AND CONCLUSIONS

Within this study ECHAM4 data (scenario: IS92a) for two 10-year time slices (1991–2000) and (2030–2039) were dynamically downscaled with the mesoscale meteorological model MM5 to a resolution of 9 km. This model output then served as input for the physically based, distributed hydrological model WaSiM, that was run at a resolution of 1 km for the entire Volta Basin. In this study the focus was set to a high resolution regional climate change impact assessment that allows us to account for the high spatial rainfall variability in the region. Uncertainties in the analysis remain due to the fact that only two 10-year time slices of one emission scenario were considered and only one GCM simulation was downscaled with one selected RCM. Thus, the modeling experiment has to be considered as one of various possible realizations of future climate.

The modeling study demonstrated a reasonable performance of the hydrological model WaSiM in representing the hydrology of the Volta Basin under present-day climate conditions, using observational as well as simulated meteorological data.

The analysis of the joint climate–hydrology modeling approach shows a very heterogeneous response of river runoff to changes in climate variables. A small increase in rainfall was observed, that led to a nonlinear increase in discharge. Nevertheless, most of the rainfall surplus was found to be evaporated, due to an increase in temperature and consequently in potential evaporation. The largest percentage difference was observed for infiltration excess (direct runoff), which was strongly dependent on actual and past rainfall intensities, soil moisture and evapotranspiration. For the different gauges, varying response signals could be delineated, but still explainable through the most important variables of the hydrological cycle. For several variables, the change signal was examined with respect to the simulated inter-annual variability. Therefore the signal-to-noise ratio was calculated in order to determine whether the modeled change signal might be seen as a sign of simulated climate change, or whether it lies within the range of the regions' (simulated) inter-annual variability. In some regions, most of all in those with larger increases in precipitation, the simulated signal is significantly larger than the inter-annual variability. This holds true for precipitation, and is even stronger for discharge.

It is concluded that, considering average values for the entire Volta Basin, there are generally only small changes in the runoff regime between the two simulated time slices, and differences are predominantly within the range of inter-annual variability. If considering the spatially distributed highly resolved variables, some stronger signals outside the range of inter-annual variability are found for precipitation, as well as for discharge. An overall large sensitivity of the discharge to small differences in precipitation and other meteorological variables was found that underlines the regions' sensitivity to water shortages.

ACKNOWLEDGEMENTS

This work was funded by the German Federal Ministry of Education and Research (BMBF) within the framework of the GLOWA-Volta project. The financial support is gratefully acknowledged. The authors are grateful to Dr. Richard Knoche and Dr. Renate Forkel (KIT) for providing preprocessing tools elementary for the performance of the regional climate simulations with MM5. We furthermore would like to express our gratitude to Dr. Boly and Dr. Somé of INERA (Institute Nationale de l'Environnement et de la Recherche Agricole) in Burkina Faso, as well as Michael Tanu from the Meteorological Service in Legon/Ghana and their staff members for their hospitality and aid in accessing meteorological and hydrological data. The authors would also like to acknowledge the valuable contributions of two anonymous reviewers.

REFERENCES

Adams, W. M., Goudie, A. S. & Orme, A. R. 1996 *The Physical Geography of Africa*. Oxford University Press, Oxford.

Agyare, W. A. 2004 *Soil Characterization and Modeling of Spatial Distribution of Saturated Hydraulic Conductivity at Two Sites in the Volta Basin of Ghana*. Ecology and Development Series no. 17. Cuvillier Verlag, Göttingen.

Ahrends, H., Mast, M., Rodgers, C. & Kunstmann, H. 2008 Coupled hydrological-economic modelling for optimised irrigated cultivation in a semi-arid catchment of West Africa. *Environ. Modell. Software* **23** (4), 385–395.

Amisigo, B., van de Giesen, N., Rogers, C., Andah, W. & Friesen, J. 2008 Monthly streamflow prediction in the Volta Basin of West Africa: a SISO NARMAX polynomial modelling. *Phys. Chem. Earth Parts A/B/C* **33** (1–2), 141–150.

Amisigo, B. A. 2005 *Modelling Riverflow in the Volta Basin of West Africa: A Data-driven Framework*. Cuvillier Verlag Göttingen.

Andersen, J., Refsgaard, J. C. & Jensen, K. H. 2001 Distributed hydrological modeling of the Senegal River Basin – model construction and validation. *J. Hydrol.* **247**, 200–214.

Andersson, L., Wilk, J., Todd, M. C., Hughes, D. A., Earle, A., Kniveton, D., Layberry, R. & Savenije, H. H. G. 2006 Impact of climate change and development scenarios on flow patterns in the Okavango River. *J. Hydrol.* **331**, 43–57.

Andreini, M., van de Giesen, N., van Edig, A., Fosu, M. & Andah, W. 2000 *Volta Basin Water Balance*. ZEF – discussion papers on development policy 21. Center for Development Research (ZEF), Bonn.

Bengtsson, L. 2003 *Climate Modelling and Prediction – Achievements and Challenges*. Available from: www.clivar.org accessed: January 2006

Bergstroem, S. & Forsman, A. 1973 Development of a conceptual deterministic rainfall-runoff model. *Nordic Hydrol.* **4**, 147–170.

Bro, C. 2001 *État des lieux des ressources en eau du Burkina Faso et de leur cadre de gestion*. Ministere de l'environnement et de l'eau, Burkina Faso.

Brutsaert, W. 1982 *Evaporation into the Atmosphere*. Kluwer, Dordrecht.

Chevallier, P. & Planchon, O. 1993 Hydrological processes in a small humid savanna basin (Ivory Coast). *J. Hydrol.* **151**, 173–191.

Dezetter, A., Girard, S., Paturel, J., MaheE, G., Ardoin-Bardin, S. & Servat, E. 2008 Simulation of runoff in West Africa: is there a single data-model combination that produces the best simulation results? *J. Hydrol.* **354**, 203–212.

Doherty, J. 2002 *PEST Model-Independent Parameter Estimation*. Watermark Numerical Computing, Brisbane, Australia.

FAO 1971–1981 *Soil Map of the World*. United Nations Food and Agriculture Organization, UNESCO, Paris.

Giertz, S. & Diekkrueger, B. 2003 Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). *Phys. Chem. Earth* **28**, 1333–1341.

Giorgi, F., Hewitson, B., Christensen, J., Hulme, M., Storch, H. V., Whetton, P., Jones, R., Mearns, L. & Fu, C. 2001 Regional climate information – evaluation and projections. In: *Climate Change 2001: The Scientific Basis*. eds J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson. Cambridge University Press, Cambridge Published for the Intergovernmental Panel on Climate Change.

Graham, L., Andréasson, J. & Carlsson, B. 2007a Assessing climate change impacts on hydrology from an ensemble of regional climate models, model scales and linking methods – a case study on the Lule River basin. *Climatic Change* **81**, 293–307.

Graham, L., Hagemann, S., Jaun, S. & Beniston, M. 2007b On interpreting hydrological change from regional climate models. *Climatic Change* **81**, 97–122.

Grell, G. A., Dudhia, J. & Stauffer, D. R. 1995 *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*. NCAR technical note, NCAR/TN-398+STR.

Grell, G. A. & Kuo, Y.-H. 1991 Semiprognostic tests of cumulus parameterization schemes in the middle latitudes. *Mon. Weather Rev.* **119** (1), 5–31.

Hagemann, S. & Jacob, D. 2007 Gradient in the climate change signal of European discharge predicted by a multi-model ensemble. *Climatic Change* **81**, 309–327.

Hartmann, G. & Bárdossy, A. 2005 Investigation of the uncertainty of hydrological modelling for climate change impact assessment. In: *Regional Hydrological Impacts of Climatic Change – Impact Assessment and Decision Making*. IAHS Publ. 295 eds T. Wagener, S. Franks, H. V. Gupta, E. Bøgh, L. Bastidas, C. Nobre & C. de Oliveira Galvão. pp. 283–293 Centre for Ecology and Hydrology, Wallingford, UK.

Hayward, D. & Oguntoyinbo, J. 1987 *Climatology of West Africa*. Hutchinson, London.

Hodnet, M. G. & Tomasella, J. 2002 Marked differences between van Genuchten soil-water retention parameters for temperate and tropical soils: new water-retention pedo-functions developed for tropical soils. *Geoderma* **108**, 155–180.

Hong, S.-Y. & Pan, H. L. 1996 Nonlocal boundary layer vertical diffusion in a medium-range forecast model. *Mon. Weather Rev.* **124**, 2322–2339.

Houghton, J. T., Filho, L. G. M., Bruce, J., Lee, H., Callander, B. A., Haites, E., Harris, N. & Maskell, K. 1995 Radiative forcing of climate change and an evaluation of the IPCC IS92 emission scenarios. In: *Climate Change 1994*. Cambridge University Press, Cambridge.

Jung, G. 2006 *Regional Climate Change and the Impact on Hydrology in the Volta Basin of West Africa*. PhD Thesis, University of Augsburg, Germany.

Jung, G. & Kunstmann, H. 2007 High-resolution regional climate modelling for the Volta Basin of West Africa. *J. Geophys. Res. – Atmos.* **112**, d23108.

Kleinn, J. 2002 *Climate Change and Runoff Statistics in the Rhine Basin: A Process Study with a Coupled Climate-runoff Model no. 14663*. ETH Zürich.

Klemes, V. 1993 *Hydrology and Water Management in the Humid Tropics*. Cambridge University Press, Cambridge.

Kotlarski, S., Block, A., Bahm, U., Jacob, D., Keuler, K., Knoche, R., Rechid, D. & Walter, A. 2005 Regional climate model simulations as input for hydrological applications: evaluation of uncertainties. *Adv. Geosci.* **5**, 119–125.

Kunstmann, H. & Jung, G. 2003 Investigation of feedback mechanisms between soil moisture, land use and precipitation in West Africa. In: *Water Resources Systems – Water Availability and Global Change*. eds S. Franks, G. Blöschl, M. Kumagai, K. Musiake & D. Rosbjerg. IAHS Publ., 280, pp. 149–159 Centre for Ecology and Hydrology, Wallingford, UK.

Kunstmann, H. & Jung, G. 2007 Influence of soil-moisture and land use change on precipitation in the Volta Basin of West Africa. *J. River Basin Mngmnt.* **5** (1), 9–16.

Kunstmann, H., Jung, G., Wagner, S. & Clottey, H. 2008 Integration of atmospheric sciences and hydrology for the development of decision support systems in sustainable water management. *Phys. Chem. Earth Parts A/B/C* **33** (1–2), 165–174.

Kunstmann, H., Krause, J. & Mayr, S. 2005 Inverse distributed hydrological modeling of alpine catchments. *Hydrol. Earth Syst. Sci. Discuss.* **2**, 1–43.

Kunstmann, H., Schneider, K., Forkel, R. & Knoche, R. 2004 Impact analysis of climate change for an alpine catchment using high resolution dynamic downscaling of echam4 time slices. *Hydrol. Earth Syst. Sci.* **8** (6), 1030–1043.

Kunstmann, H. & Stadler, C. 2005 High resolution distributed atmospheric–hydrological modelling for Alpine catchments. *J. Hydrol.* **314** (1–4), 105–124.

Laux, P., Wagner, S., Wagner, A., Jacobeit, J., Bárdossy, A. & Kunstmann, H. 2009 Modelling daily precipitation features in the Volta Basin of West Africa. *Int. J. Climatol.* **29** (7), 937–954.

LeBarbé, L., Lebel, T. & Tapsoba, D. 2002 Rainfall variability in West Africa during the years 1950–90. *J. Climate* **15**, 187–202.

Maidment, D. R. 1993 *Handbook of Hydrology*. McGraw-Hill, New York.

Martin, N. & van de Giesen, N. 2005 Spatial distribution of groundwater production and development potential in the Volta river basin of Ghana and Burkina Faso. *Wat. Int.* **30** (2), 239–249.

May, W. & Röckner, E. 2001 A time-slice experiment with the ECHAM4 AGCM at high resolution: the impact of horizontal resolution on annual mean climate change. *Climate Dyn.* **17**, 407–420.

Monteith, J. L. 1975 *Vegetation and the Atmosphere* vol 1 *Principles*. Academic Press, London.

Neumann, R., Jung, G., Laux, P. & Kunstmann, H. 2007 Climate trends of temperature, precipitation and river discharge in the Volta Basin of West Africa. *J. River Basin Mngmnt.* **5** (1), 17–30.

Nicholson, S. E. 2001 Climatic and environmental change in Africa during the last two centuries. *Climate Res.* **17**, 123–144.

Niehoff, D. 2001 *Modellierung des Einflusses der Landnutzung auf die Hochwasserentstehung in der Mesoskala*. PhD Thesis, Universität Potsdam Available from: http://opus.kobv.de/ubp/volltexte/2005/26/, accessed: January 2006.

Niel, H., Paturel, J.-E. & Servat, E. 2003 Study of parameter stability of a lumped hydrological model in a context of climatic variability. *J. Hydrol.* **278**, 213–230.

Nijssen, B., O'Donnell, G. M., Hamlet, A. F. & Lettenmaier, D. P. 2001 Hydrologic sensitivity of global rivers to climate change. *Climatic Change* **50**, 143–175.

Obeng-Asiedu, P. 2004 *Allocating Water Resources for Agricultural and Economic Development in the Volta River Basin*. Peter Lang Publishing Series: Europäische Hochschulschriften, Frankfurt am Main.

Oguntunde, P. G. 2004 *Evapotranspiration and Complementarity Relations in the Water Balance of the Volta Basin: Field Measurements and GIS-based Regional Estimates*. Ecology and Development Series no. 22. Cuvillier Verlag, Göttingen.

Paturel, J. E., Ouedraogo, M. & Mahe, G. 2003 The influence of distributed input data on the hydrological modelling of monthly river flow regimes in West Africa. *Hydrol. Sci. J.* **48** (6), 881–890.

Reisner, J., Rasmussen, R. M. & Bruintjes, R. T. 1998 Explicit forecasting of supercooled liquid water in winter storms using the MM5 mesoscale model. *Q. J. Roy. Meteorol. Soc.* **124**, 1071–1107.

Röckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dumenil, L., Esch, M., Giorgetta, M., Schlese, U. & Schulzweida, U. 1996 *The Atmospheric General Circulation Model ECHAM4: Model Description and Simulation of Present Day Climate*. Tech. rep., Max Planck Institute for Meteorology, no. 218, Hamburg, Germany.

Salathé, E. P. 2005 Downscaling simulations of future global climate with application to hydrologic modelling. *Int. J. Climatol.* **25**, 419–436.

Schäfli, B. 2005 *Quantification of Modelling Uncertainties in Climate Change Impact Studies on Water Resources: Application to a Glacier-fed Hydropower Production System in the Swiss Alps*. PhD Thesis, École Polytechnique Fédérale de Lausanne, EPFL.

Schulla, J. & Jasper, K. 2002 Model Description WaSiM-ETH. Tech. rep. ETH Zürich.

Shahin, M. 2002 *Hydrology and Water Resources of Africa*. Water Science and Technology Library, vol 41. Kluwer, Dordrecht.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M. & Miller, H. 2007 *Climate Change 2007: The Physical Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Troen, I. & Mahrt, L. 1986 A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. *Boundary-Layer Meteorol.* **37** (1), 129–148.

van de Giesen, N. 2001 Characterization of west African shallow flood plains with L- and C-band radar. *Remote Sensing Hydrol.* 365–367. IAHS Publ., 267, eds: Manfred Owe, Kaye Brubaker, Jerry Ritchie & Albert Rango Centre for Ecology and Hydrology, Wallingford, UK.

van der Sommen, J. J. & Geirnaert, W. 1988 On the continuity of aquifer systems on the crystalline basement of Burkina Faso. In *Estimation of Natural Groundwater Recharge*. NATO ASI Series Mathematics and Physical Science, vol. 222. D. Reidel, Dordrecht, pp 29–45.

van Genuchten, M. T. 1976 A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Am. J. Soil Sci.* **44** (5), 892–898.

Vescovi, F. D. 2001 Classification of African complex environments based on a contextual spatial approach (SPARK). In: *Proc. International workshop on Geo-Spatial Knowledge Processing for Natural Resource Management*, University of Insubria, Varese, Italy, 28–29 June (A. Belward, E. Binaghi, P. A. Brivio, G. A. Lanzarone & G. Tosi, eds.). Artestampa, Varese, pp. 371–375.

Wagner, S., Kunstmann, H., Bárdossy, A., Conrad, C. & Colditz, R. 2009 Water balance estimation of a poorly gauged catchment in West Africa using dynamically downscaled meteorological fields and remote sensing information. *Phys. Chem. Earth*. **34** (4–5), 225–235.

Washington, R., Harrison, M. & Conway, D. 2004 *African Climate Report – A Report Commissioned by the UK Government to Review African Climate Science, Policy and Options for Action*. Tech. Rep. DEFRA, London. Available from: http://www.g8.utoronto.ca/environment/africa-climate.pdf

First received 4 May 2010; accepted in revised form 3 January 2011