Quantification and Reduction of Predictive Uncertainty for Sustainable Water Resources Management (Proceedings of Symposium HS2004 at IUGG2007, Perugia, July 2007). IAHS Publ. 313, 2007.

Modelling regional climate change and the impact on surface and sub-surface hydrology in the Volta Basin (West Africa)

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Abstract In order to estimate the effect of an anthropogenic influence on the water balance in the Volta Basin, located in West Africa, joint regional climate–hydrology simulations were performed using the mesoscale meteorological model MM5 and the hydrological model WaSiM. The regional climate simulations show a decrease in rainfall at the beginning of the rainy season, an increase at the height of the rainy season and a clear increase in temperature. A mean delay in the onset of the rainy season accompanied with an increase in inter-annual variability of precipitation in the early stage of the rainy season was delineated. Due to the increase in potential evaporation, following the increase in temperature, most of the surplus rainfall evaporates. The highest sensitivity of the hydrological model to changing meteorological input conditions is found for direct runoff. Changes in the components of the hydrological cycle only seldom exceed the simulated present-day inter-annual variability.

Key words joint modelling; climate–hydrology modelling; West Africa; Volta Basin

INTRODUCTION

The Volta Basin located in West Africa (Fig. 1) covers an area of around 414 000 km^2. The countries that share over 80% of the basins' area are Burkina Faso and Ghana. Over the past decades, temperature has increased in West Africa whereas precipitation decreased (e.g. LeBarbe *et al.*, 2002; Servat *et al.*, 1998; Nicholson, 1993, 2001; Hulme *et al.*, 2001). Generally, the climate of the Volta Basin can be described as semi-arid to sub-humid. Mean annual potential evaporation is lower than 1500 mm in the south, but exceeds 2500 mm in the north of the basin (Oguntunde, 2004). Mean annual precipitation ranges from less than 300 mm in the north to more than 1500 mm in the south.

Joint regional climate–hydrology simulations were performed to investigate the impact of a future climate scenario on the hydrology of this climate sensitive region. Within the resolution of most GCMs (Global Circulation Models), it is not possible to achieve an explicit representation of mesoscale forcings. Therefore, the direct use of GCM output is restricted to a coarsely resolved analysis of hydrology, and often applied for global or continental-scale investigations of the hydrological cycle. A downscaling of GCM output data is advisable, especially in order to use them as input for high-resolution, distributed hydrological modelling.

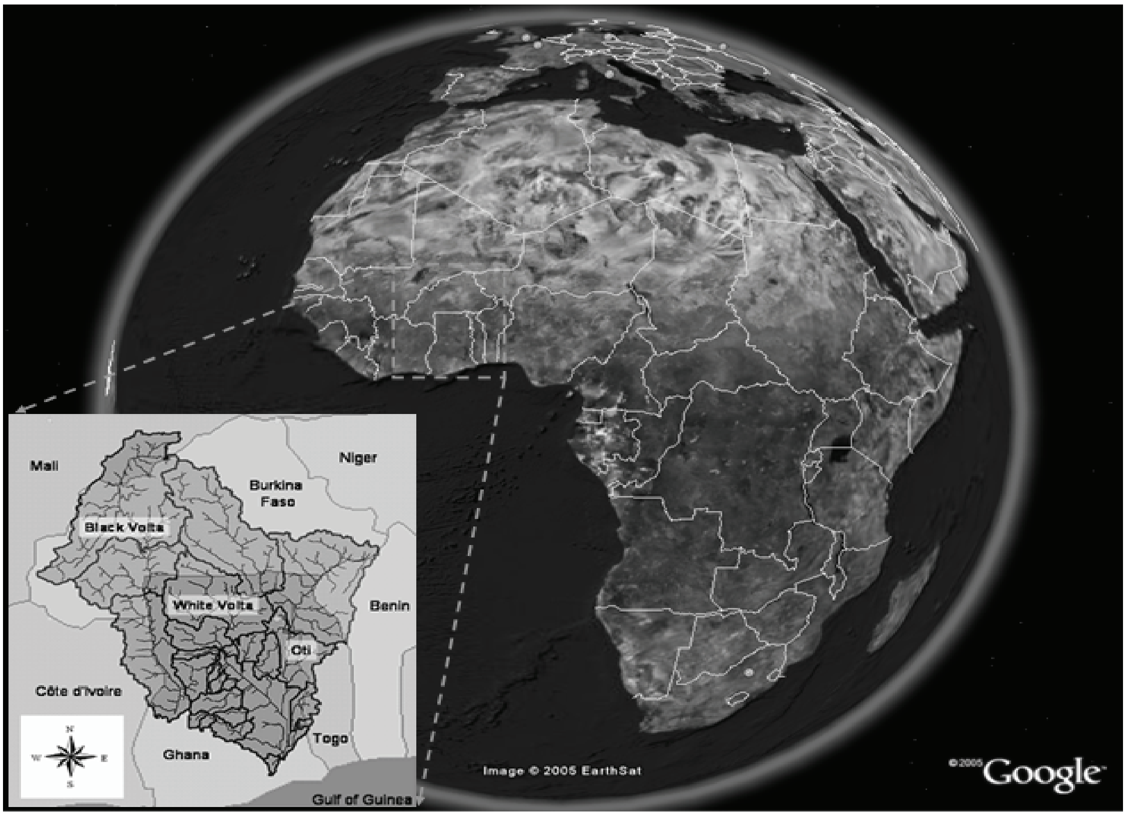

Fig. 1 Location of the Volta Basin and main tributaries. Image reproduced by permission Google Earth^{TM} mapping service/EarthSat.

A process study for the Rhine basin by Kleinn (2002) is one example of combining a dynamical downscaling approach and hydrological simulations. This study also included a comparison of the dynamically downscaled precipitation fields with those derived by two different methods of statistical downscaling. Hay *et al.* (2002) found that due to the relatively coarse resolution of their regional climate model (54 km), a statistical bias correction of the regionally downscaled data had to be performed to achieve reasonable results. For a mid-latitudinal environment represented by the Ammer catchment in Germany, a dynamical downscaling approach combined with a bias correction method yielded reasonable results describing the model's sensitivity to global climate change (Kunstmann *et al.*, 2004). A study by Schaefli (2005) demonstrates the influence of a regionally changing climate on hydropower production, following a statistical-dynamical downscaling approach. For European and other mid-latitudinal regions, impacts on extreme events, like floods, or impacts on hydropower production, are more important, while in West Africa, the importance of climate change impact analysis lies rather in an assessment of endangered water availability.

MODELS

Regional Climate Model – MM5 For the performance of the regional climate simulations the nonhydrostatic mesoscale meteorological model MM5 was chosen (Grell *et al.*, 1995), incorporating the Reisner Graupel scheme to parameterize gridscale (Reisner *et al.*, 1998) and the Grell scheme for sub-gridscale precipitation (Grell & Kuo, 1991). Furthermore, the Hong-Pan planetary boundary layer scheme was chosen (Hong & Pan, 1996) in combination with the Oregon State University land surface model to enable feedback mechanism simulation between soil moisture/ vegetation and atmosphere.

Hydrological Model – WaSiM For the present study, the demand to the hydrological model was a high degree of transferability of the model to differing climate conditions. This cannot be achieved with a simple rainfall–runoff model based on empirical relationships. Consequently, despite the high degree of parameter uncertainty due to low data availability, the use of a physically-based model was essential. For this study the physically-based, distributed hydrological model WaSiM was chosen. The physical part of the model is the simulation of the unsaturated zone, whereas discharge generation is parameterized. A model description can be found in Schulla (1997) and Schulla & Jasper (2002).

SIMULATION SETUP AND MODEL CALIBRATION

Regional Climate Simulations – Set-up The MM5 simulations were performed using a one-way nesting approach, nesting three model domains. The horizontal resolution of the three domains was 81 km for larger West Africa, 27 km for the second domain and 9 km for the smallest, covering twice as much as the Volta Basin (800 000 km^2). A vertical discretization of 25 layers was chosen. The initial and boundary fields of the climate runs were derived from a transient ECHAM4 (Roeckner *et al.*, 1996) global climate model run from 1860 to 2100. Two time slices (1991–2000 and 2030–2039) of the scenario IS92a (Houghton *et al.*, 1995) were used. A more detailed description of the set-up, validation and results of the regional climate simulations on which this study is based can be found in Jung & Kunstmann (2007).

Hydrological Simulations – Set-up and Adaptations The resolution of WaSiM used in this study is 1×1 km^2 for the horizontal, and 24 h for the temporal resolution. In the vertical, the soil is represented by 20 layers of an equal thickness of 1 m each. The hydrological model WaSiM has not been used in a catchment of a comparable size, nor in a semi-arid environment before. Several subcatchments were defined and set-up depending on data availability and quality for the 1960s, which was chosen as the calibration period. For details on set-up, model adaptations and input data refer to Jung (2006).

Hydrological Model Calibration The calibration period for this study covers the years 1962–1969, but daily observational discharge data was available only for the hydrological year 1968/69 (in West Africa: March 1968–February 1969). For this study, the nonlinear parameter estimation tool PEST (Doherty, 2002) was applied in combination with the manual trial-and-error method. An application of PEST for parameter estimation of WaSiM is discussed in Kunstmann *et al.* (2005).

Following Hartmann & Bardossy (2005), the transferability of a hydrological model is strongly improved if the calibration is performed on a monthly or annual time scale in addition to the diurnal timescale. As transferability is essential for the simulation of future climate scenarios' impact on hydrology, a similar approach was

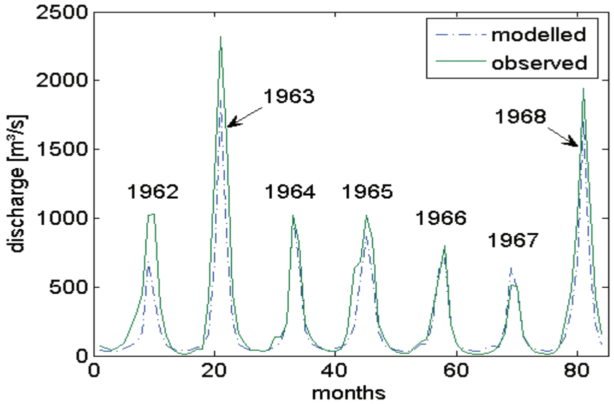

Fig. 2 Observed *vs* modelled monthly discharge at Bamboi gauge.

applied within the present study, calibrating on a daily basis for 1968/69 and on a monthly basis for the period 1962–1969. Therefore, a combined Nash-Sutcliffe criterion from both the daily calibration and the monthly calibration was calculated, as described in Jung (2006). Figure 2 demonstrates a good performance for WaSiM over the period of monthly calibration for the Bamboi gauge. The set-up of WaSiM for the Volta Basin, as well as necessary adaptations to the model and the calibration procedure are described extensively in Jung (2006).

Joint Modelling Procedure The coupling of the two models MM5 and WaSiM was done in a simple one-way approach. The meteorological input files that are needed as input by WaSiM are derived from the MM5 model outputs. Thereby each grid point of the MM5 model grid is defined as a WaSiM input station.

MODEL VALIDATION

A detailed view of the 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, 2006). A validation of the coupled modelling system was performed for the year 1968, running WaSiM with MM5, re-analysis driven, simulation output data. The resulting subcatchment runoff curves were then compared to observational data. The Nash-Sutcliffe Efficiency (NSE) values are summarized in Table 1 for selected subcatchments for the calibration runs, as well as for the coupled model simulation. Most probably the poor calibration result of the Pwalugu gauge is due to inaccurate observed runoff data.

Table 1 NSE for calibration run and joint MM5-WaSiM simulation, for the year 1968 (based on daily observations), and NSE for calibration run based on monthly observations for 1962–1969.

Gauge	Bamboi	Dapola	Nawuni	Pwalugu	Saboba
Daily calibration	0.95	0.82	0.84	0.30	0.85
Coupled run	0.92	–0.48	0.79	0.26	0.9
Monthly calibration	0.84	0.85	0.79	0.33	no monthly discharge data

IMPACT OF GLOBAL CLIMATE CHANGE IN THE VOLTA BASIN

Regional climate change signals

The results of the regional climate simulations are described in detail in Jung & Kunstmann (2006). Temperature change shows a clear signal of increase in the future simulations over the entire annual cycle. In contrast, rainfall shows a rather heterogeneous change, with months with increasing precipitation, most pronounced at the height of the rainy season, and decreasing rainfall amounts at the beginning of the rainy season. In connection to the decrease in rainfall at the beginning of the rainy season, it was also found that the mean onset dates are delayed in the future by 9.6 days in the north and 3.5 days in the south of the basin. In addition to the delay in the onset of the rains, it was demonstrated that interannual variability increases, especially in the early rainy season. Nevertheless, aridity, expressed through the de Martonne aridity index (de Martonne, 1920) showed hardly any change.

Impact of regional climate change on hydrology

Figure 3 reveals that most of the surplus rainfall reaching the Volta Basin contributes to an increase in evapotranspiration. This is easily explained by higher temperatures in the future climate scenario which lead to higher potential evaporation and, in the case of available soil moisture, to an increase in actual evapotranspiration. Therefore only a small amount of surplus rainfall runs off as additional direct runoff. The annual cycle of runoff with respect to climate change shows, first of all, a shift in the month of discharge maximum from August to September (Fig. 4).

Runoff in August is slightly lower for 2030–2039. In September, it is higher for the simulated future scenario due to the strong increase in precipitation. The low response signal of discharge in April is explained by the small rainfall deficit (in terms of rainfall amount) and the dry soils at the end of the dry season. Due to these factors, 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, as well as evapotranspiration, compared to the future run. A more detailed analysis of the joint modelling results can be found in Jung (2006).

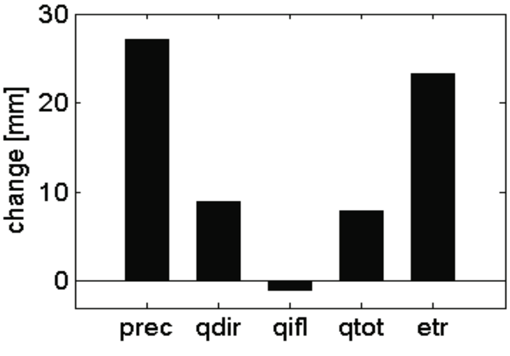

Fig. 3 Changes (2030–2039 *vs* 1991–2000) of precipitation (prec), direct runoff (qdir), interflow (qifl), total runoff (qtot) and evapotranspiration (etr) for the entire Volta Basin.

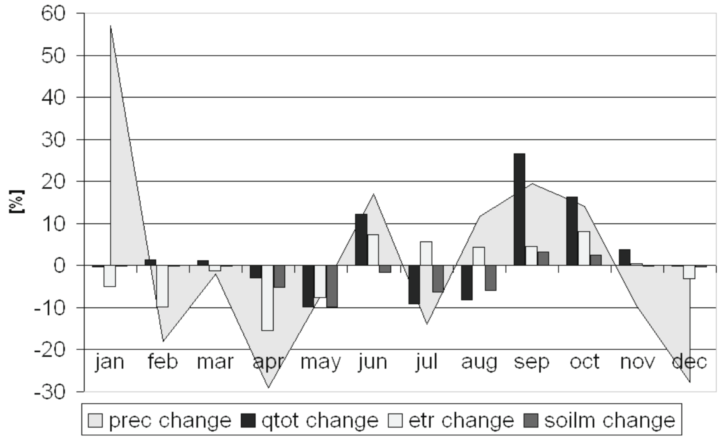

Fig 4 Monthly changes in precipitation (prec), total runoff (qtot), evapotranspiration (etr) and soil moisture (soilm) [%], (2030–2039 *vs* 1991–2000).

Climate change *versus* inter-annual variability

Analysis of the significance of a precipitation change signal with respect to the regions' simulated climate variability is essential for an assessment of the reliability and uncertainty of a detected signal of change. For this purpose, the signal to noise ratio (SN) was analysed, as discussed in Jung (2006). A value of SN > 1 indicates a detected change signal that lies outside the simulated interannual variability (noise). The annual cycle of the SN ratio for precipitation, evaporation and runoff is illustrated in Fig. 5.

Total runoff only exceeds a SN of 1 in February. This is not a significant signal due to the small amounts of runoff generally observed in the dry season. Precipitation shows a SN ≥ 1 in April and June for the basin. Due to the increase in rainfall in June, evapotranspiration shows a signal higher than interannual variability in this month. A delay in the onset of the rainy season is found, connected with a very good signal-to-noise ratio of 1.8 for the Sahelian region. Finally the strongest SN value was found for temperature, which clearly showed a change signal larger than inter-annual variability (Jung & Kunstmann, 2007).

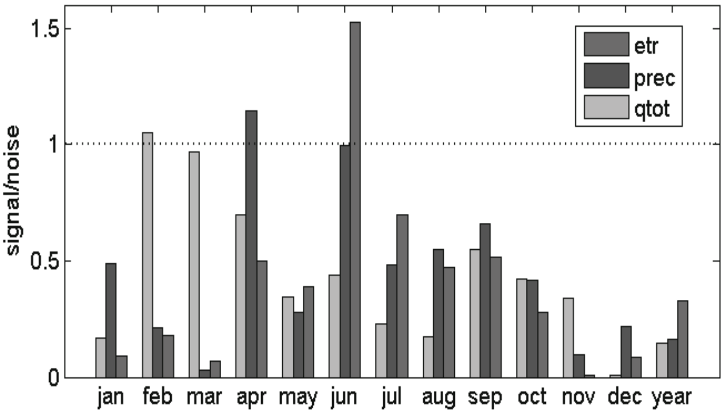

Fig. 5 Signal-to-noise ratio for evapotranspiration (etr), precipitation (prec) and total runoff (qtot). Above the dashed line: change signal exceeds inter-annual variability.

SUMMARY AND CONCLUSIONS

In order to investigate the impact of changing atmospheric conditions on surface and subsurface hydrology on the basis of environmental modelling, a suitable model cascade is needed. For the region of the Volta Basin, ECHAM4 outputs (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. The downscaled outputs were coupled one-way to the physically-based, distributed hydrological model WaSiM using a spatial resolution of 1 km. The analysis of this joint climate–hydrology modelling approach shows a very heterogeneous response of river runoff to changes in climate variables. A small increase in annual rainfall was observed which lead to an increase in discharge. Nevertheless, most of the rainfall surplus was found to evaporate due to an increase in temperature and consequently in potential evaporation. At the beginning of the rainy season, a striking rainfall decrease was found in connection with a delay in the onset of the rainy season but it did not have strong impacts on runoff. The largest percentage change was observed for infiltration excess (direct runoff), but the impact was strongly dependent on actual and past rainfall intensities, soil moisture and evapotranspiration. As a central topic, the climate change signal for several variables was examined with respect to simulated interannual variability via the signal-to-noise ratio. This was done to determine whether the modelled change signal should be seen as a clear sign of simulated climate change, or if it lies within the range of the regions' interannual variability. It can be concluded that there are only small changes in the runoff regime of the Volta between the two simulated time slices, and that the changes are predominantly within the range of the interannual variability. Nevertheless, the physically-based model WaSiM proved its capability to reproduce meaningful results for the different hydrological variables and their interactions.

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