

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

# Projected impacts of climate change on groundwater and stormflow in a humid, tropical catchment in the Ugandan Upper Nile Basin

**D. G. Kingston and R. G. Taylor**

Department of Geography, University College London, Gower Street, London, WC1E 6BT, UK

Received: 28 February 2010 – Accepted: 10 March 2010 – Published: 17 March 2010

Correspondence to: D. G. Kingston (dgkingston@hotmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

**HESSD**

7, 1913–1944, 2010

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

The changing availability of freshwater resources is likely to be one of the most important consequences of projected 21st century climate change for both human and natural systems. However, substantial uncertainty remains regarding the precise impacts of climate change on water resources, due in part to uncertainty in GCM projections of climate change. Here we explore the potential impacts of climate change on water resources in a humid, tropical catchment (the River Mitano) in the Upper Nile Basin of Uganda. Uncertainty associated with GCM structure and climate sensitivity is explored, as well as from parameter specification within hydrological models. This is achieved by running pattern-scaled GCM output through a semi-distributed hydrological model (developed using SWAT) of the catchment. Importantly, use of pattern-scaled GCM output allows investigation of specific thresholds of global climate change including the purported 2°C threshold of “dangerous” climate change. In-depth analysis of results based on HadCM3 climate scenarios shows that annual river discharge first increases, then declines with rising global mean air temperature. A coincidental shift from a bi-modal to unimodal discharge regime also results from a projected reduction in base-flow (groundwater discharge). Both of these changes occur after a 4°C rise in global mean air temperature. These results are, however, highly GCM dependent in both the magnitude and direction of change. This dependence stems primarily from projected differences in GCM scenario precipitation rather than temperature. GCM-related uncertainty is far greater than that associated with climate sensitivity or hydrological model parameterisation.

## 1 Introduction

Changing availability of freshwater resources is likely to be one of the most important consequences of projected 21st century climate change, critically affecting the potential for sustainable development of life and livelihoods (Kundzewicz et al., 2007; Todd

**HESSD**

7, 1913–1944, 2010

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



et al., 2010). Historical (20th century) periods of wetter and drier conditions in the Upper Nile region have demonstrated the vulnerability of human and natural systems to changes in the availability of freshwater resources (Tate et al., 2004; Conway, 2005). Projections of 21st century climate suggest an overall intensification of the global hydrological cycle, with substantial changes expected to result in the hydrology of the Upper Nile region (Sene et al., 2001; Arnell, 2003; Tate et al., 2004).

Throughout the Upper Nile Basin, river discharge sustains surface water levels upon which there is substantial dependence for fisheries (e.g. Nile Perch and Tilapia) and hydro-electric power generation (Bugenyi, 2001; Mwanja, 2004). Domestic water supplies depend primarily upon dispersed groundwater abstraction and spring discharges. Piped water supplies drawing from Lake Victoria, the world's second largest lake in area, are restricted to cities such as Kampala, Kisumu and Jinja. Similar to most of sub-Saharan Africa, almost all arable land is presently rainfall-fed (Giordano, 2006; Fischer et al., 2007); irrigation is restricted to commercial agriculture (e.g. fresh-cut flowers) primarily for export. Substantial increases in demand for freshwater are projected as a result of population growth not only for domestic purposes but also to increase food production through expansion of irrigation (Taylor et al., 2004, 2009; Carter and Parker, 2009).

Given the magnitude of projected climate changes and the role of water in the socio-economic development of the Upper Nile Basin, there is a clear need for improved understanding of the potential impacts of these changes on the availability of freshwater resources. However, many existing assessments of water resources (past and projected) do not directly consider soil water (i.e. water transpired by plants) or groundwater, focusing instead on mean annual river flow (e.g. Kamga 2001; Legesse et al., 2003; Messenger et al., 2006; Wit and Stankiewicz, 2006; Elshamy et al., 2009). This focus remains despite the fact that soil water sustains almost all agricultural production in equatorial Africa, and groundwater comprises 75% of all safe sources of drinking water in sub-Saharan Africa (Taylor et al., 2009). Furthermore, freshwater resources defined in terms of mean annual river discharge fail to indicate the proportion of freshwater

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



available ephemerally in channels as stormflow (i.e. runoff) and that which is more evenly distributed in time and space as groundwater. As such, a quantitative understanding of the impacts of climate change on both catchment stores (i.e. soil water, groundwater) and flows (i.e. river discharge) is of critical importance to the development of effective strategies for management and adaptation to climate change (Mileham et al., 2009; Nyenje and Batelaan, 2009; Taylor, 2009).

This paper addresses an urgent need for improved understanding of projected climate change impacts on water resources in the Upper Nile Basin, and the uncertainty associated with such projections of hydrological change. This analysis is achieved through hydrological modelling of the River Mitano, a catchment in southwestern Uganda that drains into Lake Edward. The catchment features one of the longest continuous records of river discharge in Uganda. We resolve both surface and sub-surface contributions to river discharge. Following calibration, the hydrological model is forced with a range of climate change scenarios, designed to allow investigation of uncertainty between different GCMs and climate sensitivities. This represents an advancement of previous research into climate change impacts on surface and sub-surface hydrology in the Mitano River Basin (Mileham et al., 2009), which did not consider uncertainty between different GCMs or climate sensitivities. Furthermore, the scenarios explored herein permit direct investigation of the impacts of specific (and policy relevant) thresholds of climate change on water resources including the hypothesised 2°C threshold for “dangerous” climate change.

## 2 Study catchment

The River Mitano catchment is located just south of the equator in southwestern Uganda (Fig. 1), and is the primary contributor to the larger Ntungwe Basin. The main river channel is well incised along the catchment’s western border and flows from an area of relatively high elevation (2500 m a.s.l.) in the south to the depression containing Lake Edward (975 m a.s.l.) in the northwest. The gauging station, 20 km upstream of

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Lake Edward (and run by the Ugandan Directorate of Water Resources Management), represents a catchment area of 2098 km<sup>2</sup>. The water balance of Lake Edward is uncertain, but the Mitano is thought to account for approximately 10% of river flow input to the lake using values from Hurst (1927), Viner and Smith (1973) and Lehman (2002), as cited in Russell and Johnson (2006). Westward flowing tributaries in eastern and northeastern parts of the catchment drain areas of considerably lower relief that represent the eastern boundary of drainage induced by the downfaulting of the western arm of the East African Rift System during the Mid-Pleistocene (Taylor and Howard, 1998). Incised valleys characterise a runoff dominated regime whereas areas of low relief promote infiltration and give rise to substantial baseflow (Taylor and Howard, 1999). Mean annual precipitation for the period 1965–1979 ranges from 963 mm at Rwaishmaire (30.13° E, 0.83° S) in the east of the Mitano Basin to 1699 mm at Sabiano (29.63° E, 1.38° S) in the south. Similar to the rest of the Upper Nile Basin, monthly precipitation follows a bimodal regime with dominant modes occurring from March to May and September to November; these are known as “short rains” and “long rains”, respectively (Basalirwa, 1995).

Land use in the River Mitano catchment is primarily agrarian (79%). Agriculture takes place principally on small land holdings, with the most common crops comprising banana (matoke), tea, millet, cassava, sugarcane, and groundnuts. As rain falls during every month of the year within the inner tropics, crops are entirely rainfall-fed. Grasslands dominate the remainder of the catchment (17%), with small areas of forest plantations and wetlands also present. Domestic water supplies in rural areas derive invariably from groundwater via handpumped wells and protected springs. Discrete aquifers occur within deeply weathered Precambrian crystalline rocks including gneiss, schist and phyllites of the Bugando-Toro Formation. The town of Rukungiri (population approximately 14 000) is the only urbanised area in the catchment and obtains its water supplies from a series of deep boreholes drawing from aquifers within coarse-grained, weathered clasts at the base of the saprolite (unconsolidated regolith) and fissures in the underlying crystalline bedrock (saprock).

## HESSD

7, 1913–1944, 2010

### Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Data and methods

Baseline meteorological data for the hydrological model of the Mitano River Basin comprise monthly minimum and maximum temperature, precipitation totals and wet days obtained from the CRU TS 3.0 data set (Mitchell and Jones, 2005). With a gauged catchment area of 2098 km<sup>2</sup>, the Mitano occupies part of four 0.5° grid cells from this global climate data set. Monthly data for these grid cells were disaggregated to daily resolution, following procedures outlined in Todd et al. (2010). Station-based daily precipitation data that provide the basis for the coefficient of variation used to generate daily data were obtained from five gauging stations within the River Mitano catchment (operated by the Ugandan Meteorology Department). Station-based daily temperature data (for setting the standard deviation of the generated daily data) were obtained from a weather station in the town of Mbarara approximately 50 km east of the catchment. The Hargreaves method of estimating potential evapotranspiration was applied instead of more data intensive methods such as Penman Monteith and Priestley-Taylor.

Future climate scenarios for temperature and precipitation were generated using the ClimGen pattern-scaling technique described in Todd et al. (2010). Scenarios were generated for a prescribed warming of global mean temperature of 0.5, 1, 1.5, 2, 2.5, 3, 4, 5, and 6 °C using the UKMO HadCM3 GCM, and for 2 °C warming with six additional GCMs: CCCMA CGCM31, CSIRO Mk30, IPSL CM4, MPI ECHAM5, NCAR CCSM30, and UKMO HadGEM1.

The hydrological model used to investigate climate change impacts in the River Mitano catchment was developed using the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998). This is a physically based, semi-distributed hydrological model that operates on a daily time step. Different versions of SWAT have been widely used throughout the world for agricultural and water resources applications (Gassman et al., 2007). Here, AVSWAT-X 2005 was used (Di Luzio et al., 2004). The Mitano model was calibrated for the 1961–1990 baseline period (with a preceding 3-year model spin-up period) using daily river discharge data from the single gauging station within the

Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



catchment. A further 15 years of data (1991–2005) were used to validate the model. Catchment topography was determined from the Shuttle Radar Topography Mission (SRTM) 3 arc second dataset (Farr et al., 2007). Land-cover data were derived from the Africover dataset generated by the Food and Agriculture Organisation of the United Nations (FAO) (available online at <http://www.africover.org/index.htm>, accessed 29 January 2010). Land-use classifications from this dataset were matched with appropriate land cover groupings within the SWAT internal database. The FAO soil map of the world (FAO, 1990) was used as the basis for soil parameters within the hydrological model.

## 4 Hydrological model calibration and validation

The SWAT hydrological model was run at a daily time step, but model calibration (and subsequent analyses) were undertaken on a monthly basis as daily data derive from a weather generator (discussed in Todd et al., 2010). Initial model runs, following basic adjustment of model parameters, resulted in reasonable agreement between monthly observed and simulated discharge. However, the resultant Nash-Sutcliffe efficiency was  $-0.09$  indicating that the model was slightly less useful than the observed long-term monthly mean discharge as a basis for prediction. This reflects the occasionally very poor month-to-month performance of the model, with substantial monthly flow events either missing or erroneously introduced in the modelled time series. Even in the context of possible errors in the observed discharge data of  $\pm 15\%$  (Mileham et al., 2008), errors are large and contrast strongly with the good agreement between observed and simulated monthly means and flow duration curves.

Autocalibration routines were employed with the aim of improving the agreement between the model and observations. AVSWAT-X 2005 includes the ParaSol autocalibration routine (van Griensven and Meixner, 2007) or, alternatively, can be coupled to the SWAT-CUP (Calibration, Uncertainty and Prediction) programme for autocalibration

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



using either the SUFI-2, ParaSol or GLUE routines (Abbaspour et al., 2007). None of these routines resulted in satisfactory improvement of the hydrological model. It is thought that this is because there are some model-observation divergences within the 1961–1990 calibration period that are simply too large to be resolved by an autocalibration routine.

Following the unsuccessful application of autocalibration routines, a more extensive manual calibration was undertaken. This calibration was undertaken by manually varying the ten most sensitive parameters in the hydrological model (Table 1). These parameters were identified using the automated sensitivity analysis procedure within SWAT (which is based on a combination of a Latin Hypercube and one-factor-at-a-time sampling strategy: van Griensven et al., 2006). This resulted in improved agreement between observed and simulated monthly river flow (Fig. 2a and b). Furthermore, comparison of results from a simple baseflow separation procedure (Arnold et al., 1995) of modelled and observed discharge reveals an approximately similar ratio between baseflow and quickflow in both series (with a modelled baseflow fraction of 58% and observed of 65%). Although the absolute numbers are different, these derived baseflow fractions are similar to previously defined graphical baseflow separation of observed and modelled Mitano discharge (modelled baseflow fraction: 43%, observed: 50%; Mileham et al., 2008). Despite these improvements, occasional poor month-to-month sequencing remains (Fig. 2c), as reflected in the low (albeit slightly higher) Nash-Sutcliffe coefficient of 0.06 for the period 1961–1990. For similar reasons to those discussed above, renewed application of autocalibration routines was again unsuccessful.

Further investigation was undertaken to determine the cause of the variable model performance, specifically with respect to the input data used. Observed (station-based) precipitation data were available for five stations within the Mitano Basin for the 1965–1980 period. These five stations are not included in the CRU TS 3.0 data set; the CRU station nearest to the Mitano that is available during the calibration period is located approximately 35 km south of the basin. The mean rainfall across these five stations was

Projected impacts of  
climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



compared to the CRU TS 3.0 data used to drive the hydrological model. Differences between the mean station-based rainfall and the mean CRU TS 3.0 rainfall across the four Mitano grid cells correspond well with the differences between observed and modelled river flow (correlation coefficient 0.47; Fig. 3), particularly given consideration of the approximate 2 week lag time between precipitation occurrence and river discharge (Mileham et al., 2008). This correspondence provides an explanation for the strong agreement between mean monthly observed and modelled river discharge but occasional poor month-to-month sequencing. This is because it could be expected that rainfall at a location 35 km away would have a similar overall climatology to the Mitano River Basin, but that there would be some difference in month-to-month rainfall totals, due to the high spatio-temporal variation in the occurrence of precipitation events.

The role of the disaggregation of monthly data to a daily time-step was also investigated by running the disaggregation procedure multiple times to determine the sensitivity of the hydrological model to the random sequencing of rainfall events within each month. Results suggested that the model is not sensitive to this sequencing, with similar performance of model month-to-month and 30-year monthly mean river flow.

The correspondence between observed and simulated discharge over the 1991–2005 validation period is similar to that of the 1961–1990 calibration period (Fig. 2c). The fifteen-year mean monthly modelled runoff agrees relatively well with observed values though performance is slightly poorer than that of the calibration period with an underestimation of river discharge during the September–November second rainy season. This may be due to the closest rainfall station to the Mitano River Basin in the CRU TS 3.0 data set becoming unavailable from 1996 onwards, with the new nearest available rainfall station approximately 115 km from the basin. Similar issues of poor month-to-month sequencing again occur in the validation period, although the Nash-Sutcliffe value of 0.13 is slightly higher than that of the calibration period.

The model therefore adequately simulates long-term monthly mean discharge including the relative contributions of quick and slow flow to river discharge but is less reliable in terms of month-to-month sequencing. The latter may be due to the model

## HESSD

7, 1913–1944, 2010

### Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



being run with gridded rainfall data of questionable accuracy over the Mitano Basin. The climate change scenario runs will be evaluated within this context.

5 Simulation of climate change scenarios

5.1 Prescribed warming on HadCM3

5 Prescribed change climate scenarios for the River Mitano catchment show that temperature increases at a near-linear rate between scenarios, with a 6 °C rise in global mean temperature resulting in increases of between 7 and 9.6 °C in monthly temperature over the catchment. The largest increases occur from May to July (8.6 to 9.6 °C increase for the 6 °C scenario), whereas the smallest take place from September to December (7.2 °C increase for the 6 °C scenario). Precipitation also changes at a near-linear rate, with annual increases of 2.1 and 6.7% from the baseline for the 2 to 6 °C scenarios. At a monthly resolution, however, both increasing and decreasing linear trends occur, most of which are within ±9% of the baseline for the 6 °C scenario: greater changes occur in March (+13%), May (−46%), June (+19%), July (+54%) and August (+25%).  
10 These trends in monthly precipitation totals are mirrored by those in the number of wet days per month.

The impacts of prescribed increases in global mean temperature on the hydrological regime of the River Mitano comprise increases in mean annual river discharge up to the 3 °C scenario, followed by decreases (to a level lower than the baseline) for rises in global mean air temperature of 4 to 6 °C. Substantial changes in intra-annual river discharge are associated with the non-linear response in annual river discharge to increasing global mean air temperature (Fig. 4). For the 0.5–3 °C scenarios, small decreases in river discharge are projected during the first wet season (March–May) whereas large increases in discharge are projected during the second wet season (October–December). From 0.5–2 °C, these seasonal changes in discharge have a negligible influence on mean annual river discharge (<1% change from baseline)  
25

Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

AbstractIntroduction

ConclusionsReferences

TablesFigures

◀▶

◀▶

BackClose

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



but for the 2.5 and 3 °C scenarios, increases in annual river discharge are >8% from baseline. For the 4–6 °C scenarios, projected decreases in March–May river discharge are more substantial, eliminating the March–May seasonal peak so that the River Mitano flow regime shifts from bimodal to unimodal. This shift is associated with projected decreases in annual river discharge of >12% from baseline for the 6 °C scenario.

The SWAT model divides contributions to river flow into three categories: surface (i.e. overland) flow, lateral flow (i.e. quickflow within the upper soil profile), and groundwater flow (i.e. return flow from shallow aquifers). For the Mitano, surface flow is relatively unimportant, contributing approximately 1% of total annual river flow for the baseline period, compared to 38% and 61% for lateral and groundwater flows, respectively. Although surface flow remains unimportant on a monthly basis (i.e. <5% of the total), the relative importance of lateral and groundwater flow varies, with a 55:45 ratio during the first wet season, a 20:80 ratio during the June–July dry season, and a 45:55 ratio during the second wet season (Fig. 5). Whilst annual contributions vary by only small amounts with increasing global mean temperature (for the 6 °C scenario lateral flow increases to 41% whilst groundwater flow decreases to 54%), changes in monthly contributions are more marked (Fig. 5). Changes in monthly contributions occur primarily in the first half of the year (February–July), with the groundwater component of river flow progressively decreasing with increasing global mean temperature. Although the absolute magnitude of lateral flows at this time of year remain similar, reductions in the groundwater component increase the importance of lateral flow to the extent that it comprises between 70–85% of total runoff in March–May under the 6 °C scenario. As such, these results suggest that decreasing groundwater flow is the primary cause of reduced early season river flow in the 4–6 °C scenarios.

Analysis of the relative importance of changing precipitation versus temperature (and hence evapotranspiration) was performed by running the SWAT model with scenario temperature and holding precipitation constant, and vice versa (Fig. 6). Although precipitation decreases at the end of the first wet season (i.e. May), projected reductions in early season river flow result primarily from increasing temperature and in turn,

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



evapotranspiration. This finding is in contrast to the increases in late-season river flow, which are primarily linked to rising precipitation. Combined with the changing lateral flow and groundwater contributions to river flow, these results suggest that increasing evapotranspiration (rather than reduced precipitation) limits the amount of water penetrating the soil profile and replenishing the shallow groundwater store during the first wet season. This change leads to the reduced contribution of groundwater to river flow and the overall decrease in discharge.

## 5.2 2°C warming across 7 GCMs

The 2°C prescribed warming scenarios from seven different GCMs project contrasting changes in climate over the River Mitano catchment. Although all GCMs show a rise in temperature of close to 2°C in all months, the rise in air temperature on an annual basis ranges from approximately 1.8°C for the NCAR GCM to 2.7°C for the MPI GCM (Fig. 7a). This apparent contradiction can be explained by the fact that each GCM has a different pattern of global temperature change, meaning that while the global average temperature change is the same between GCMs, regional patterns are not. Differences between GCMs are even more apparent for precipitation. Projected change in mean annual precipitation varies from a 23% increase (NCAR) to a 23% decrease (CSIRO). On a monthly basis, some GCMs project lower or greater precipitation in all months whereas others project a mixture of increasing and decreasing precipitation over the course of the year (Fig. 7b).

The results from the 2°C scenarios show substantial disparities between GCMs, with little consistency in either magnitude or direction of change, for either seasonal or annual discharge (Fig. 8). For example, the CSIRO GCM projections result in reductions in river discharge at 2°C that are greater than those from the HadCM3 GCM at 6°C. In contrast, the NCAR GCM projections result in increased river discharge in all months that, in some situations, is double that of the baseline. There is, however, no particular clustering of GCMs. The results show that the NCAR and CSIRO projections lead to

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the greatest increase and decrease, respectively, in river discharge (although it is not possible to label these two GCMs as outliers, because the seven GCMs used here are drawn from a larger population of 23 CMIP-3 GCMs).

5 Resolution of the climate change signal for each of the GCMs derived from changing temperature and precipitation independently reveals consistency in the 2°C temperature signal between GCMs (Fig. 9a). This signal results in a slight decrease in March–May river discharge. It is clear from the precipitation-only climate change signal that changes in precipitation are the dominant driver of changing river flow for the 2°C scenario (Fig. 9b). It is also clear that differences in the precipitation climate change signal  
10 between GCMs are far greater than those in the temperature climate change signal, with different GCMs giving rise to both positive and negative changes in discharge in all months.

### 5.3 Parameterisation uncertainty

15 In the absence of quantitative estimates of uncertainty in model parameterisation from an autocalibration routine, a manual assessment was undertaken to provide an indication of model parameterisation uncertainty. This analysis was undertaken by manually varying the ten most sensitive parameters in the hydrological model (Table 1). Each parameter was varied by a small amount ( $\pm 10\%$ ) and the model re-run with baseline climate data. The model was then run using the same perturbed parameter set with  
20 scenario climate data: the HadCM3 2°C prescribed warming was used as an exemplar scenario. The difference between the reference and perturbed runs was then compared between baseline and scenario situations. If the difference between the reference and perturbed runs was greater for the scenario than the baseline, the model parameterisation was considered as a possible cause for additional uncertainty in climate change projections (and vice versa).  
25

Results of the uncertainty analysis (Fig. 10) indicate that model parameterisation generally imparts little additional uncertainty to the climate change projections based on the HadCM3 2°C prescribed warming scenario. Differences in the

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



reference-perturbed percent anomaly between baseline and scenario runs are below 5%, with the most sensitive parameters relating to evapotranspiration and soil water capacity.

## 6 Discussion

In this paper we assess the projected impacts of climate change on river discharge and contributions to flow (runoff, baseflow) in a humid tropical catchment in the Upper Nile Basin. Importantly, this assessment includes evaluation of the range of uncertainty in this assessment due to climate sensitivity, choice of GCM, and hydrological model parameterisation. The primary outcome of these results is the overwhelming dependence upon the GCM used for climate change projections, in agreement with the findings of previous studies (e.g. Chiew et al., 2009; Prudhomme and Davies, 2009). Furthermore, we show that single-GCM evaluations of climate change impacts are likely to be wholly inadequate and potentially misleading as a basis for the analysis of climate change impacts on freshwater resources.

Despite the substantial uncertainty associated with choice of GCM, a number of additional important issues are highlighted by our results from the River Mitano catchment. For example, river discharge, at least on an annual basis, may not respond linearly to increases in global mean air temperature (i.e. a combination of linear changes in monthly river flow can give rise to a non-linear annual response). This finding emphasises two key issues: firstly, the potential for thresholds of climate change associated with impacts on water resources (i.e. 3 °C here), and secondly, the importance of investigating changing water resources on an intra-annual basis.

A further important finding is that whilst there is great uncertainty in the precipitation climate change signal between GCMs, the temperature signal is very consistent. As such, high confidence can be placed in the projections of increased evapotranspiration in the River Mitano catchment during the first wet season as this result is consistent across all GCMs and scenarios examined. This is of interest because the results of

### Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



simulating different warming scenarios using HadCM3 demonstrate the implications that increased evapotranspiration can have for the groundwater contribution to river discharge. Confidence can therefore be placed in the assertion that irrespective of the magnitude or direction of future changes in precipitation, the proportion of precipitation that contributes to Mitano river discharge via groundwater flow will decrease as a result of increasing temperature. Furthermore, such a change would likely result in an altered seasonal distribution of river flow, affecting local and regional groundwater resources, and consequently agricultural and domestic water availability.

The projected changes in groundwater contributions to river flow and subsequent shift in annual regime (under HadCM3 scenarios) demonstrate the importance of understanding the interaction between changing temperature (and thus evapotranspiration) and precipitation for river flow in areas where there is a seasonal switch between P-PET deficit and surplus. Our ability to understand this balance is, however, constrained by the substantial uncertainty regarding estimation of both baseline and scenario PET. Although the relative advantages and disadvantages of many different methods of estimating historical PET from meteorological data have been widely considered (e.g. Vorosmarty et al., 1998; Lu et al., 2005), relatively little attention has been given to how representative different PET methods remain when transferred from baseline to scenario climatology. Indeed, recent work (Kingston et al., 2009) shows that different methods of estimating PET can produce markedly different climate change signals. This tendency can be demonstrated for the Mitano Basin by a brief comparison of baseline: scenario PET ratios for the commonly used Hargreaves, Penman-Monteith and Priestley-Taylor methods of calculating PET (Table 2). Substantial differences are found in the PET climate change signal between the three methods, with this difference (for the HadCM3 2 °C scenario) most apparent during May, where the increase in PET ranges from 9–17% between methods.

Whilst further uncertainty in the climate change signal for the Mitano Basin is likely to arise from the parameterisation and structure of the hydrological model used, the findings presented here indicate that such uncertainty is much smaller than that associated

**Projected impacts of climate change**

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



with choice of GCM, climate sensitivity, and PET algorithm. Despite this, it should be noted that only a limited and subjective assessment of model parameter uncertainty has been conducted, so these findings should be taken as indicative rather than definitive. Future work will aim to treat model uncertainty in a more objective and probabilistic manner by using, for example, autocalibration routines.

## 7 Conclusions

Investigation of uncertainty in future river discharge of the River Mitano Basin based on results from different GCMs, climate sensitivities and hydrological model parameter specification reveals the overwhelming dependency of hydrological projections on the GCM used. This dependence stems primarily from projected differences in GCM scenario precipitation rather than temperature. Within this overriding constraint, however, a number of interesting results have emerged. These include non-linear responses in annual discharge to increasing global temperature, the importance of the precipitation–evaporation balance for determining the direction of changes in river discharge, and subsequent impacts on groundwater contributions to river discharge.

The above findings represent an important basis for interpretation of previous climate change-hydrology studies and for designing future studies of possible climate change impacts on river flow. However, the utility of the results with respect to future changes in Mitano river discharge remain limited by the large uncertainty between GCMs. This is a key research gap, given the likely changes to the groundwater regime of the Mitano (and wider region), and the importance of groundwater as a hydrological resource. As such, there is an urgent requirement for research to develop from the current approach of equal probability ratings assigned within an ensemble of opportunity of GCMs. Alternative approaches include development of reliability ratings for GCMs, and more widespread generation of probabilistic climate change scenarios and GCM output–impact model couplings (e.g. Manning et al., 2009). However, the challenge of objectively undertaking such tasks remains difficult.

### Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



*Acknowledgements.* This work was supported by a grant from the UK Natural and Environmental Research Council (NERC) under the Quantifying and Understanding the Earth System (QUEST) programme (Ref. NE/E001890/1).

References

5    Abbaspour, K. C., Yang, J., and Maximov, I.: Modelling hydrology and water quality in the pre-ailpine/alpine Thur watershed using SWAT, *J. Hydrol.*, 333, 413–430, 2007.

    Arnell, N. W.: Effects of IPCC SRES\* emissions scenarios on river runoff: a global perspective, *Hydrol. Earth Syst. Sci.*, 7, 619–641, 2003, <http://www.hydrol-earth-syst-sci.net/7/619/2003/>.

10    Arnold, J. G., Allen, P. M., Muttiah, R., and Bernhardt, G.: Automated Base Flow Separation and Recession Techniques, *Ground Water*, 33, 1010–1018, 1995.

    Arnold, J. G., Srinivasan, R., Muttiah, R., and Williams, J. R.: Large area hydrologic modelling and assessment, Part 1: model development, *J. Am. Water Resour. As.*, 34, 73–89, 1998.

    Basalirwa, C. P. K.: Delineation of Uganda into climatological rainfall zones using the method of principal component analysis, *Int. J. Climatol.*, 15, 1161–1177, 1995.

15    Bugenyi, F. W. B.: Tropical freshwater ecotones: their formation, functions and use, *Hydrobiologia*, 458, 33–43, 2001.

    Carter, R. C. and Parker, A.: Climate change, population trends and groundwater in Africa, *Hydrolog. Sci. J.*, 54, 676–698, 2009.

20    Chiew, F. H. S., Teng, J., Vaze, J., Post, D. A., Perraud, J. M., Kirono, D. G. C., and Viney, N. R.: Estimating climate change impact on runoff across southeast Australia: Method, results and implications of the modelling method, *Water Resour. Res.*, 45, W10414, doi:1029/2008WR007338, 2009.

    Conway, D.: From headwater tributaries to international river: Observing and adapting to climate variability and change in the Nile basin, *Global Environ. Chang.*, 15, 99–114, 2005.

    Di Luzio, M., Srinivasan, R., Arnold, J. G., and Neitsch, S. L.: ArcView interface for SWAT User's Manual, Texas Water Resources Institute, TWRI Report TR-193, 351 pp., 2002.

    Elshamy, M. E., Seierstad, I. A., and Sorteberg, A.: Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios, *Hydrol. Earth Syst. Sci.*, 13, 551–565, 2009, <http://www.hydrol-earth-syst-sci.net/13/551/2009/>.

30

Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



- Farr, T. G., Rosen, P. A., Caro, E., et al.: The shuttle radar topography mission, *Rev. Geophys.*, 45, RG2004, doi:10.1029/2005RG000183, 2007.
- Food and Agricultural Organisation of the United Nations (FAO): FAO-UNESCO Soil Map of the World: Revised Legend, World Soil Resources Report 60, FAO, Rome, Italy, 1990.
- 5 Fischer, G., Tubiello, F. N., van Velthuisen, H., and Wiberg, D.: Climate change impacts on irrigation water requirements: effects of mitigation, 1980–2080, *Technol. Forecast. Soc.*, 74, 1083–1107, 2007.
- Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G.: The soil and water assessment tool: Historical development, applications and future research directions, *T. ASABE.*, 50, 1211–1250, 2007.
- 10 Giordano, M.: Agricultural groundwater use and rural livelihoods in sub-Saharan Africa: A first-cut assessment, *Hydrogeol. J.*, 14, 310–318, 2006.
- Kamga, F. M.: Impact of greenhouse gas induced climate change on the runoff of the upper Benue river (Cameroon), *J. Hydrol.*, 252, 145–156, 2001.
- 15 Kingston, D. G., Todd, M. C., Taylor, R. T., and Thompson, J. R.: Uncertainty in the potential evapotranspiration climate change signal, *Geophys. Res. Lett.*, 36, L20403, doi:10.1029/2009GL040267, 2009.
- Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., Oki, T., Şen, Z., and Shiklomanov, I.: The implications of projected climate change for freshwater resources and their management, *Hydrolog. Sci. J.*, 53, 3–10, 2008.
- 20 Legesse, D., Vallet-Coulomb, C., and Gasse, F.: Hydrological response of a catchment to climate and land use changes in tropical Africa: case study South Central Ethiopia, *J. Hydrol.*, 275, 67–85, 2003.
- Lu, J. B., Sun, G., McNulty, S. G., and Amataya, D. M.: A comparison of six potential evapotranspiration methods for regional use in the southeastern United States, *J. Am. Water Resour. As.*, 41, 621–633, 2005.
- 25 Manning, L. J., Hall, J. W., Fowler, H. J., Kilsby, C. G., and Tebaldi, C.: Using probabilistic climate change information from a multimodel ensemble for water resources assessment, *Water Resour. Res.*, 45, W11411, doi:10.1029/2007WR006674, 2009.
- 30 Messenger, C., Gallée, H., Brasseur, O., Cappelaere, B., Peugeot, C., Séguis, L., Vauclin, M., Ramel, R., Grasseau, G., Léger, L., and Girou, D.: Influence of observed and RCM-simulated precipitation on the water discharge over the Sirba basin, Burkina Faso/Niger, *Clim. Dynam.*, 27, 199–214, 2006.

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Mileham, L., Taylor, R. G., Thompson, J. R., Todd, M. C., and Tindimugaya, C.: Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa, *J. Hydrol.*, 359, 46–58, doi:10.1016/j.jhydrol.2008.06.007, 2008.

5 Mileham, L., Taylor, R. G., Todd, M. C., Tindimugaya, C., and Thompson, J. R.: The impact of climate change on groundwater recharge and runoff in a humid, equatorial catchment: sensitivity of projections to rainfall intensity, *Hydrolog. Sci. J.*, 54, 727–738, 2009.

Mitchell, T. D. and Jones, P. D.: An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, 25, 693–712, 10 2005.

Mwanja, W. W.: The role of satellite water bodies in the evolution and conservation of Lake Victoria Region fishes, *Afr. J. Ecol. Suppl.*, 42(1), 14–20, 2004.

Nyenje, P. M. and Batelaan, O.: Estimating the effects of climate change on groundwater recharge and baseflow in the upper Ssezibwa catchment, Uganda, *Hydrolog. Sci. J.*, 54(4), 15 713–726, 2009.

Prudhomme, C. and Davies, H.: Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 2: future climate, *Climatic Change*, 93, 197–222, 2009.

20 Russell, J. M. and Johnson, T. C.: The water balance and stable isotope hydrology of Lake Edward, Uganda-Congo, *J. Great Lakes Res.*, 32, 77–90, 2006.

Sene, K. J., Tate, E. L., and Farquharson, F. A. K.: Sensitivity of the impacts of climate change on White Nile flows, *Climatic Change*, 50, 177–208, 2001.

Tate, E., Sutcliffe, J., Conway, D., and Farquharson, F.: Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100, *Hydrolog. Sci. J.*, 49, 563–574, 2004.

25 Taylor, R. G.: Rethinking water scarcity: role of storage. *EOS, Trans. Am. Geophys. U.*, 90(28), 237–238, 2009.

Taylor, R. G., Barrett, M. H., and Tindimugaya, C.: Urban areas of sub-Saharan Africa: weathered crystalline aquifer systems, *Urban Groundwater Pollution*, 24, 155–179, 2004.

30 Taylor, R. G. and Howard, K. W. F.: Post-Palaeozoic evolution of weathered landsurfaces in Uganda by tectonically controlled weathering and stripping, *Geomorphology*, 25, 173–192, 1998.

Taylor, R. G. and Howard, K. W. F.: The influence of tectonic setting on the hydrological characteristics of deeply weathered terrains: evidence from Uganda, *J. Hydrol.*, 218, 44–71, 1999.

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Taylor, R. G., Koussis, A. D., and Tindimugaya, C.: Groundwater and climate in Africa – a review, *Hydrolog. Sci. J.*, 54, 655–664, 2009.
- Todd, M. C., Osborn, T., and Taylor, R. G.: Quantifying uncertainty in the impact of climate change on water resources at river basin and global scales – a unified approach, *Hydrol. Earth Syst. Sci. Discuss.*, in preparation, 2010.
- 5 van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., and Srinivasan, R.: A global sensitivity analysis tool for the parameters of multi-variable catchment models, *J. Hydrol.*, 324, 10–23, 2006.
- 10 van Griensven, A. and Meixner, T.: A global and efficient multi-objective auto-calibration and uncertainty estimation method for water quality catchment models, *J. Hydroinform.*, 9, 277–291, 2007.
- Vörösmarty, C. J., Federer, C. A., and Schloss, A. L.: Potential evaporation functions compared on US watersheds: Possible implications for global-scale water balance and terrestrial ecosystem modelling, *J. Hydrol.*, 207, 147–169, 1998.
- 15 Wit, M. and Stankiewicz, J.: Changes in surface water across Africa with predicted climate change, *Science*, 311, 1917–1921, 2006.

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

**Table 1.** The ten most sensitive parameters in the SWAT model of the Mitano River Basin.

Sensitivity rank	SWAT parameter name	Parameter description
1	CH_K2	Hydraulic conductivity of channel
2	CH_N2	Manning's n for main channel
3	SURLAG	Surface runoff lag coefficient
4	SOL_AWC	Soil water capacity
5	CANMX	Maximum canopy water storage
6	ESCO	Soil evaporation coefficient
7	CN_2	Curve number
8	SOL_Z	Soil depth
9	SOL_ALB	Moist soil albedo
10	GWQMN	Threshold level for baseflow in shallow aquifer

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

**Table 2.** Percent change in monthly PET from baseline to HadCM3 2 °C scenario.

	Hargreaves	Penman-Monteith	Priestley-Taylor
Mean monthly change	6.7	6.4	9.6
Max monthly change	9.3	14.9	17.0
Min monthly change	4.7	1.5	6.0

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor

Title Page

## Abstract

## Introduction

## Conclusions

## References

## Tables

## Figures



▶

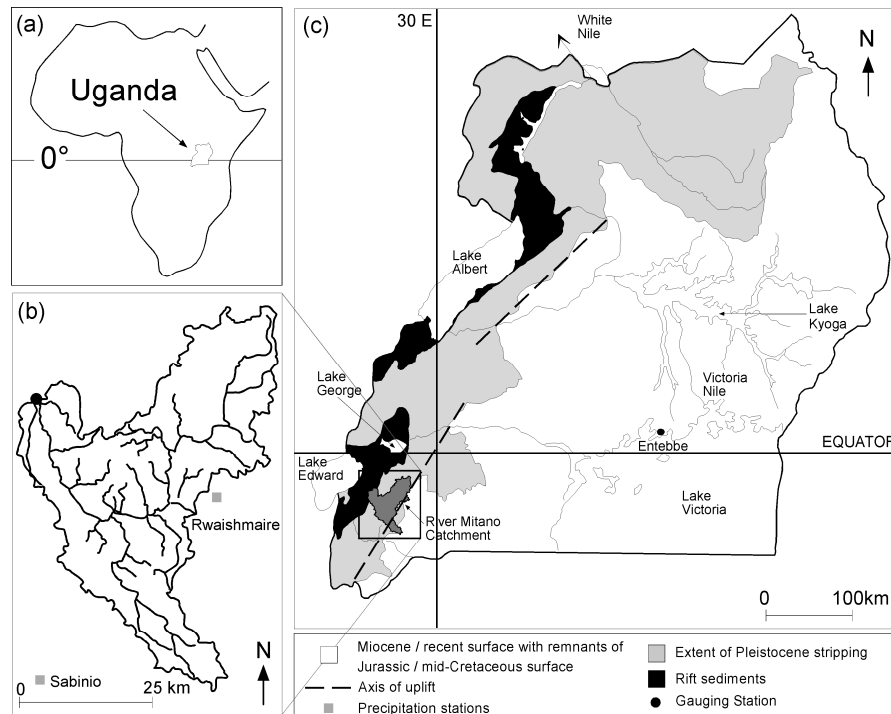
[Back](#)

Close

Full Screen / Esc

[Printer-friendly Version](#)

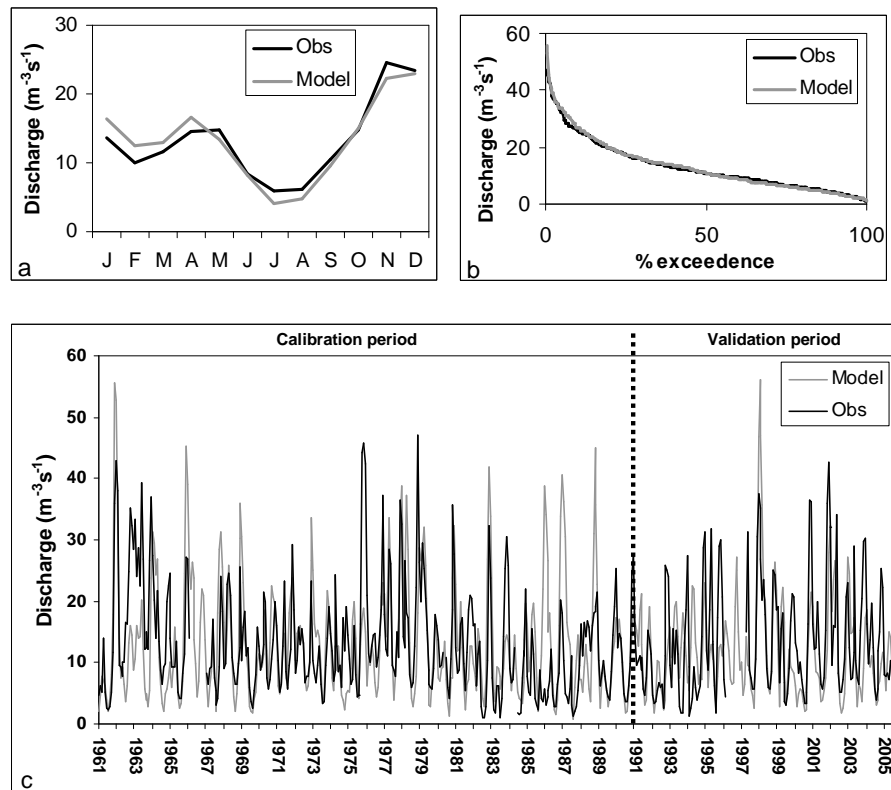
## Interactive Discussion



**Fig. 1.** (a) Location of the River Mitano Basin; (b) detailed map of the catchment drainage system; and (c) the location of the basin relative to the weathered land surfaces of Uganda (adapted from Taylor and Howard, 1999).

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 2.** Comparison of 1961–1990 modelled and observed (a) monthly mean flow; (b) flow duration curve; and (c) 1961–2005 month-to-month sequencing.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

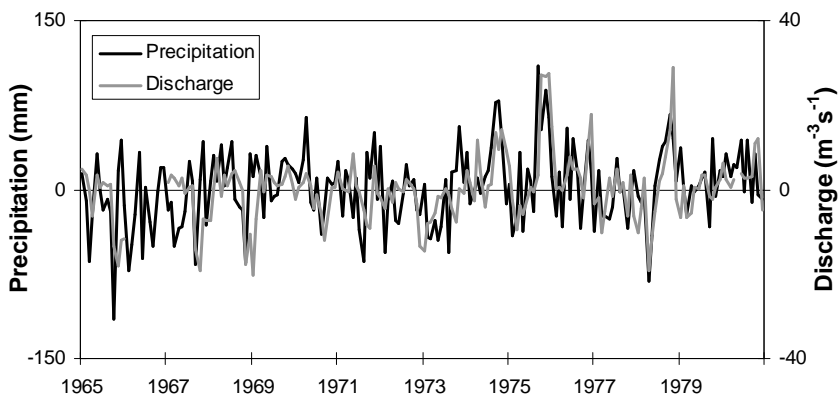
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 3.** Comparison of difference in monthly precipitation between CRU TS 3.0 and station-based records with modelled-observed differences in river flow for 1965–1980.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

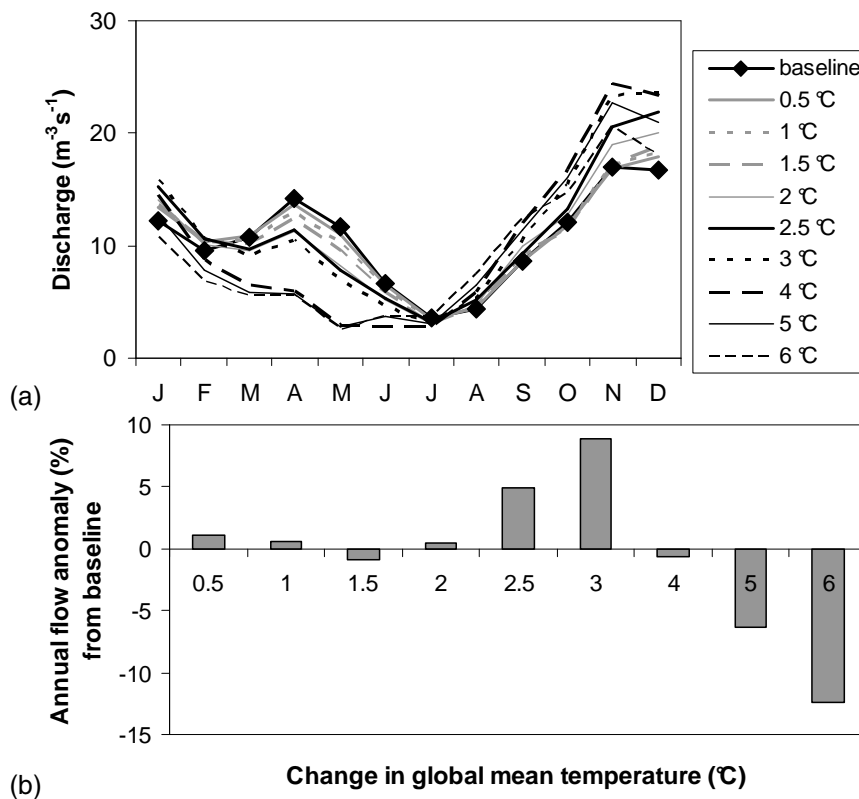
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 4.** Climate change signal in (a) monthly and (b) annual discharge for HadCM3 prescribed warming scenarios.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

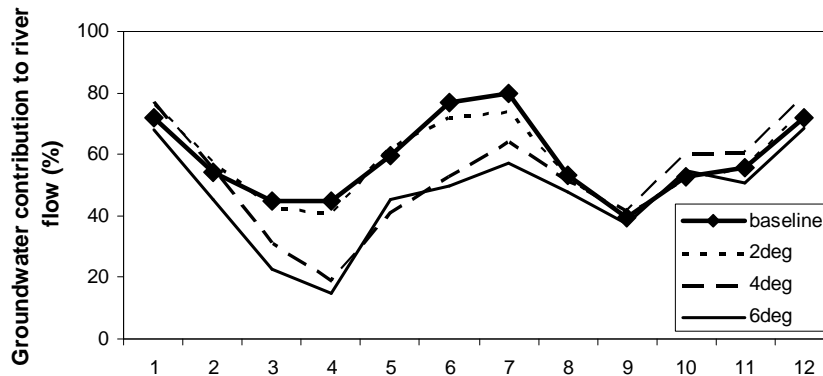
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 5.** Groundwater flow contribution to Mitano discharge for HadCM3 prescribed warming scenarios.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

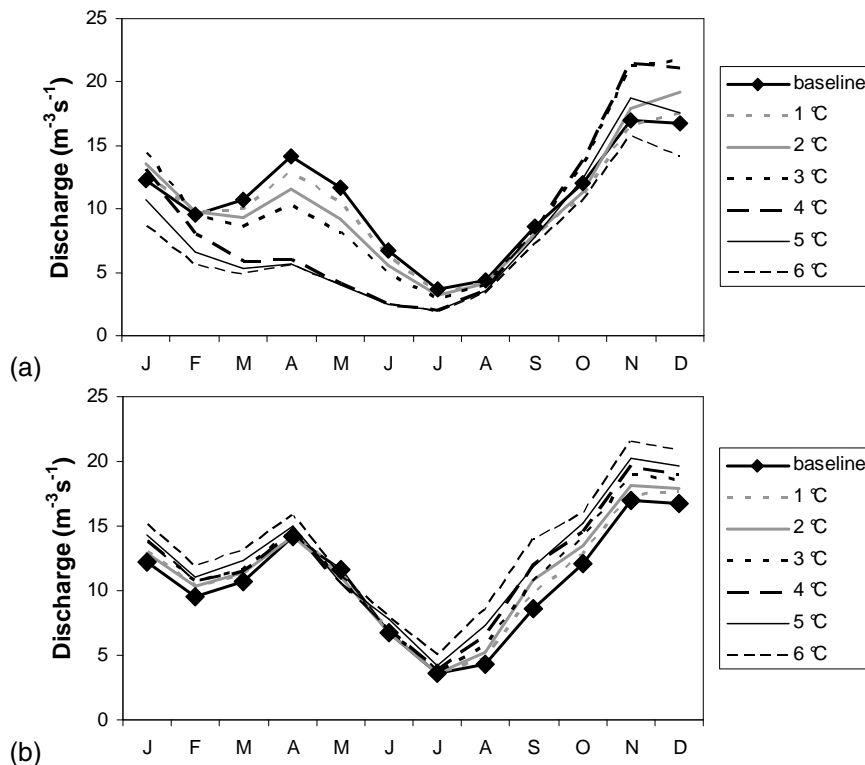
Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 6.** (a) Temperature and (b) precipitation only climate change signals for HadCM3 prescribed warming scenarios.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

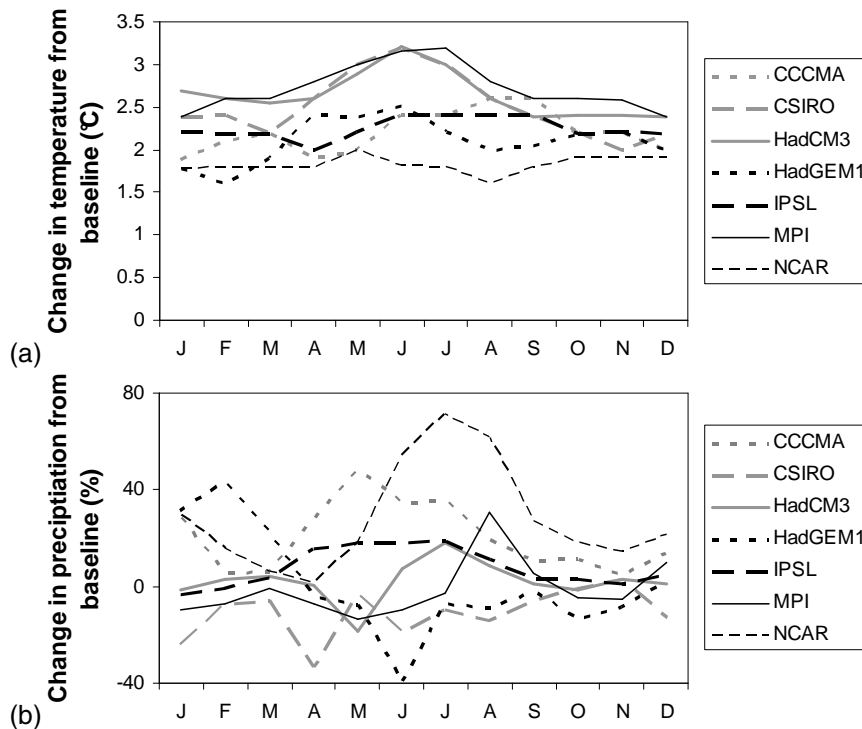
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 7.** Comparison of baseline and scenario (a) temperature and (b) precipitation for the 2°C prescribed increases in global mean temperature across 7 GCMs.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

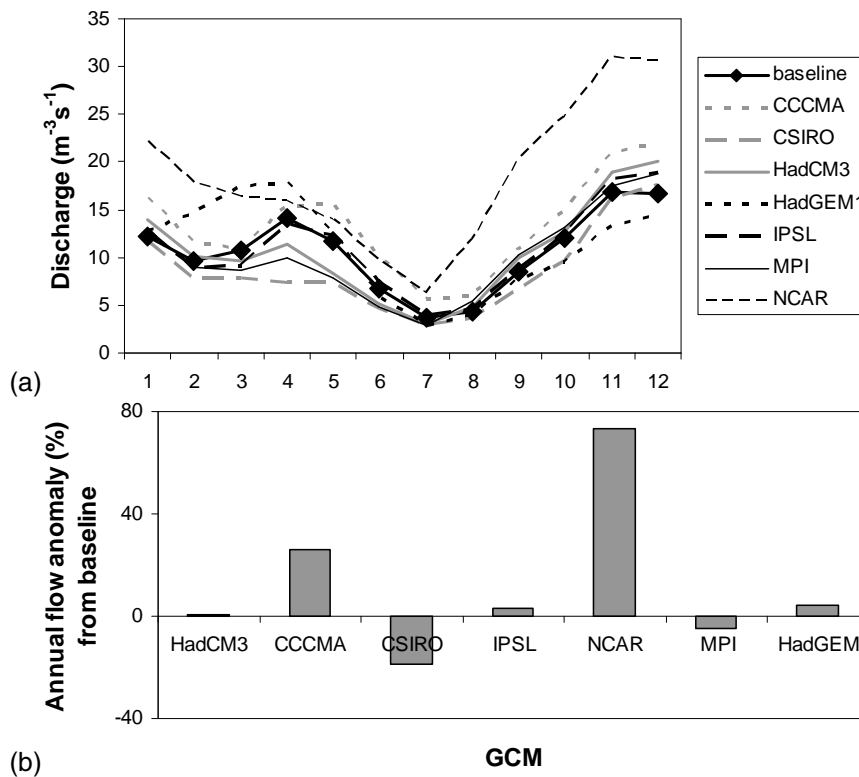
Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 8.** Climate change signal in (a) monthly and (b) annual discharge for the 2°C prescribed warming scenario across 7 GCMs.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

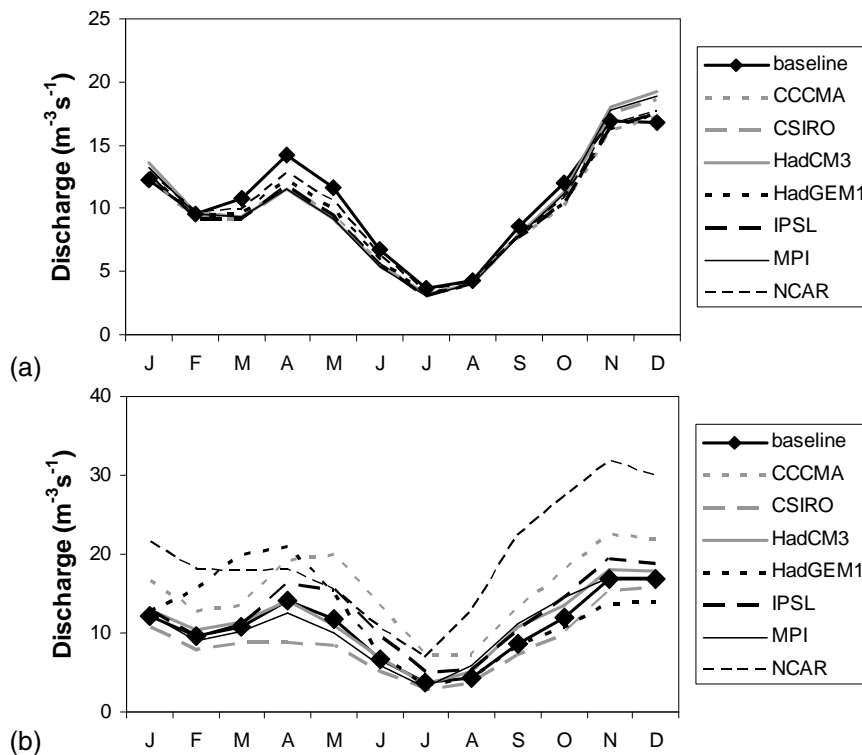
Printer-friendly Version

Interactive Discussion



## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 9.** (a) Temperature and (b) precipitation only climate change signals for 2°C prescribed warming scenarios across 7 GCMs.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

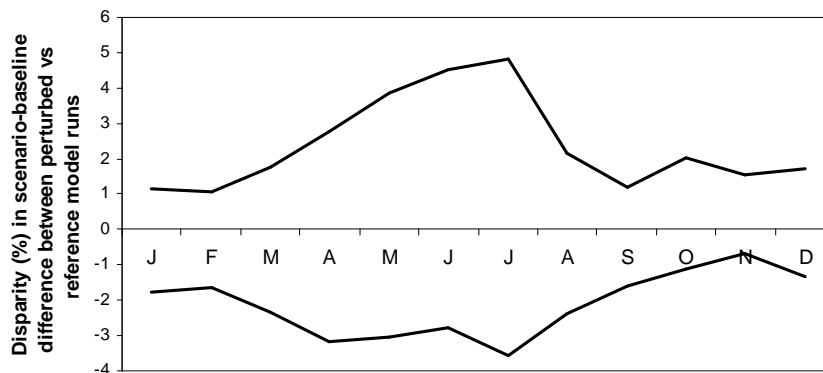
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Projected impacts of climate change

D. G. Kingston and  
R. G. Taylor



**Fig. 10.** Model parameter uncertainty for HadCM3 2°C scenario: maximum extent of the disparity between the scenario-baseline difference in the perturbed parameter versus reference model runs.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)
