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Blue Nile flow sensitivity to projected climatic change until 2100

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Abstract The sensitivity of Blue Nile flows (which contribute the bulk of the Nile water) to changes in future rainfall during the June–September rainy season based on output from three General Circulation Models (GCMs) was determined up until 2100. The study attempted to quantify uncertainties arising from: (a) use of different GCMs; (b) different greenhouse gas emissions scenarios; and (c) downscaling coarse-scale GCM output to a finer-scale required for hydrological modelling. A multidimensional stochastic rainfall generator was developed to produce high-resolution gridded rainfall data required by the distributed hydrological model (Nile Forecast System). The assessment also incorporated future evapotranspiration changes over the basin, although in a more simplistic way. Two of the GCMs (Canadian Climate Centre's CGCM2 and UK Hadley Centre's HadCM3) led to reductions in future mean flow and Q5 (daily flow exceeded 5% of the time) during the rainy season, whilst use of the third GCM (Max Plank Institute's ECHAM4) led to general increases in future mean flow and Q5. Changes were more pronounced by the 2050s and 2080s.

Key words Blue Nile; climate change; downscaling; stochastic; uncertainty

INTRODUCTION

To date, several investigators have carried out climate change impacts assessments for the Nile basin. These include the studies of Riebsame *et al*. (1995); Conway & Hulme (1996); Yates & Strzepek (1998), and Sene (2000). Due to data limitations, nearly all these studies adopted the standard mean delta change approach to impacts assessment (see Carter *et al*., 1994) whilst hydrological extremes (e.g. flood frequency assessment) and quantification of uncertainties have been largely omitted—a key requirement by the Intergovernmental Panel on Climate Change (IPCC, 2001).

The aim of this study is to undertake an investigation of the sensitivity of Blue Nile flow to climate change in accordance with IPCC recommendations. The study employed three GCMs, forced with two sets of greenhouse gas emissions scenarios; the output from which was downscaled using a multidimensional stochastic rainfall generator. The scenarios were used in conjunction with a distributed hydrological model known as the Nile Forecast System—NFS (Schaake *et al*., 1996; Elshamy, 2006) to assess the impacts of climate change on both mean flow as well as the flow exceeding 5% and 1% of the time during the wet season (June–September), which is the main rainy season in the region (Gissila *et al*., 2004). Use of three different GCMs and two emissions scenarios will allow appreciation of climate model uncertainties whilst the statistical downscaling model will enable quantification of downscaling uncertainties.

BLUE NILE DATA AND STUDY AREA

The area of the Blue Nile River Basin to Khartoum (Sudan) is approx. 275 000 km^2, which is larger than the entire UK. The river basin (Fig. 1) contributes around 65–80% to the total annual flow component of the main Nile at Khartoum, with the remaining sourced from the White Nile (Sutcliffe & Parks, 1999; Sene *et al*., 2001). Daily rainfall data records of adequate length and regularity are restricted to just six stations (Fig. 1) and a 10-year period (1992–2001). Annual rainfall totals for the six stations (see Fig. 1) vary from 541 mm to 2005 mm and monthly variations range from 20 mm (February) to 360 mm (August).

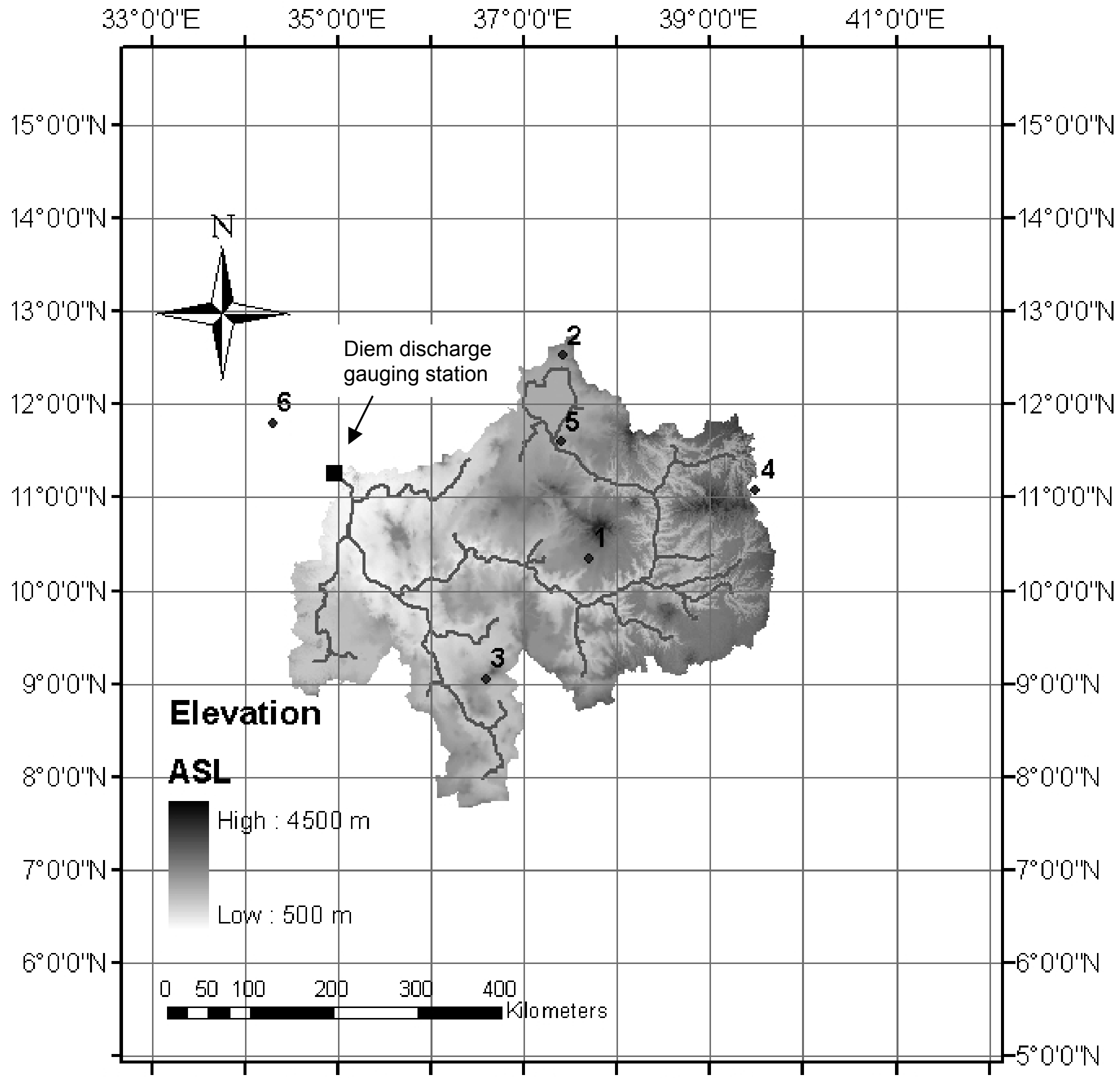

Fig. 1 The Blue Nile Basin and location of rainfall stations and Diem discharge gauging station ((1) Debre-Markos; (2) Gonder; (3) Nekemte; (4) Kembolcha; (5) Abay Lake Tana; (6) Roseires).

Mean monthly observed potential evapotranspiration (PET) data based on the Penman-Monteith formula and interpolated to a 0.20° (20 x 20 km) resolution are available within the NFS database. PET varies from a low of 75–100 mm range during July and August when cloud cover and humidity are highest, to a maximum of 225 mm during March–May driven by relatively high levels of incident solar radiation, windspeed and humidity. Daily flow values at Diem station (see Fig. 1) were available for the study. The complete record spanning 1966–2001 was available although the shorter record coinciding with available daily rainfall data (spanning 1992–2001) was used for model calibrations. Blue Nile average monthly flow at Diem varies from less than 200 $m^3 s^{-1}$ prior to May to approx. 5500 $m^3 s^{-1}$ during August.

METHODOLOGY

A major study requirement was production of high resolution climate change scenarios to be fed into the NFS. It was decided to downscale coarse-scale GCM rainfall only, to the required resolution (20 × 20 km and daily time-step) based on the technique of Widmann *et al*. (2003). The study was carried out in four steps: (i) gather Blue Nile Basin historical daily rainfall data and GCM monthly rainfall data over a baseline period; (ii) elect several GCMs on the basis of their performance in simulating current climate; (iii) calibrate a stochastic rainfall generator; and (iv) use rainfall generator to generate 50 traces of baseline and future rainfall and feed both baseline and future rainfall data into the NFS to determine future Blue Nile flow changes.

GCM selection and downscaling

GCM selection was based on model ability to simulate historical baseline rainfall and a number of GCMs were tested for their adequacy. The mean monthly GCM-simulated rainfall over 1992–2001 simulated by three different GCMs: (i) CGCM2 (the Canadian Climate Modelling Centre); (ii) ECHAM4 (Max Planck Institute for Meteorology, Hamburg); and (iii) HADCM3 (UK Hadley Centre), compared well with observational data over the same period. Two sets of greenhouse gas (GHG) emissions scenarios were used; the SRES A2 and B2, which make different assumptions about future global socio-economic conditions (see IPCC, 2000). Downscaling of GCM-simulated rainfall was carried out using the method of histogram matching (Rosenfeld *et al*., 1993) to compare the frequency distributions of GCM outputs and local rainfall statistics. Statistical relationships were derived between GCM outputs and three statistics: (i) probability of a wet day given a previously wet day (P_{WW}); (ii) probability of a wet day given a previously dry day (P_{WD}); and (iii) daily rainfall amount on a wet day (M_{RR}). The daily statistics were obtained from synoptic station data block-krigged to the NFS model resolution of 20 km for cells containing a recording gauge. Months where missing values exceeded the 10-day threshold were discarded. Separate relationships were derived for each selected GCM. In all cases, the regression equations were able to explain a significant amount of variation with R^2 values exceeding 0.70.

Multidimensional stochastic rainfall generator

The gridded rainfall data required by the NFS was generated by setting up a multidimensional stochastic rainfall model based on the Turning Bands procedure (Mantoglou & Wilson 1982; Mantoglou, 1987). The rainfall generator uses Monte Carlo simulation to generate synthetic sequences of daily rainfall having the same spatial and temporal structure of the historical rainfall. Results from the validation (not shown here due to lack of space) showed all three GCMs to be reproducing the observed mean rainfall adequately.

Potential evapotranspiration

It was not possible to produce PET scenarios based on the Penman-Monteith approach due to lack of data. Instead, monthly mean baseline and future temperature simulated by all three GCMs was used with the Thornthwaite formula (Thornthwaite, 1948) to determine current and future monthly mean PET and the corresponding percentage changes which were applied to the observational PET data set. No stochastic modelling of PET uncertainty was performed and composite PET scenarios (constructed by averaging the A2 and B2 scenarios) were used rather than individual A2 and B2 scenarios.

A limitation of this approach is that compared to the relatively detailed assessment of Nile flow response to future rainfall changes, the simplistic way in which the PET scenarios were incorporated would only allow limited insight to Nile sensitivity to future PET.

Hydrological modelling

The NFS is an operational distributed hydro-meteorological forecasting system designed for forecasting Nile flows at designated key points within the Nile basin (Nile Forecast Center, 2002). The core of the NFS is a conceptual distributed hydrological model (Johnson & Curtis, 1994; Schaake *et al*., 1996) including soil moisture accounting, hillslope and river routing, lakes, wetlands, and man-made reservoirs within the basin. The NFS requires as input, daily gridded rainfall and potential evapotranspiration. Three basic models are normally executed at every grid cell: (i) water balance model; (ii) hillslope model; and (iii) channel routing model (Nile Forecast Center, 1999). While the NFS includes an optional data assimilation procedure, it is specifically designed to be capable of both forecasting and simulation of the Nile Basin and is able to accurately reproduce the flow regime over long periods without state updating. Further details of the NFS and its evaluation in long term simulations are provided in Nile Forecast Center (1999) and Elshamy (2006).

Model performance over the baseline period was assessed by feeding the generated rainfall sequences based on each of the three GCMs through the NFS and comparing simulations with observations over the baseline period (1992–2001) at Diem gauging station (see Fig. 1). Because of the importance of wet season flows to water resources planners, the results will focus on the wet season (June–September). Three sets of flow statistics over the wet season; mean daily flow and Q5 and Q1 (a daily flow value exceeded 5% and 1% of the time of the four wet months, respectively) were adopted. Results showed that mean flow and Q5 were well simulated by the model. However, the model had difficulty in reproducing the very high flows (with Q1 based on simulated flows higher than that based on observed data). This indicates that the combined modelling procedure might be generating unrealistically high maximum flows.

RESULTS AND DISCUSSION

Three 30-year future time periods until 2099 were considered: (i) 2010–2039; (ii) 2040–2069; and (iii) 2070–2099 and these will be referred to as the 2020s, 2050s and 2080s. Other terminology used in presenting the results includes using the initial letter from the GCM name and the initial number from the time-period of interest. For example, C2 represents CGCM 2020s, H8 represents HadCM3 2080s, etc.

Rainfall and PET changes

Figure 2 shows the future change (percentage from baseline) in areal rainfall for three future time periods based on three GCMs forced with both the A2 and B2 GHG emissions scenarios. Changes are shown for two parameters, mean daily areal wet season rainfall and mean daily areal rainfall exceeded 5% of the time (P5—a daily areal rainfall value exceeded 5% of the time of the four wet months). By considering only the inter-quartile range in the box plots, it can be concluded that a relatively modest change (general increase) in rainfall is expected by the 2020s for all GCMs. By the 2050s, some rather different patterns are emerging; the CGCM indicates drier conditions whilst both the ECHAM and HadCM3 indicate wetter conditions. The ECHAM in particular indicates very wet conditions; especially under the B2 scenario. By the 2080s, some rather large changes in rainfall are to be expected for both the CGCM and the ECHAM. The ECHAM B2 scenario in particular, indicates a very wet future by the 2080s whilst the CGCM A2 results in very dry conditions. The HadCM3, on the other hand, still provides relatively modest changes (increases).

Forcing the GCMs with the two different GHG emissions scenarios has an effect in most cases and especially by the 2080s. GHG emissions for the A2 scenarios continue to rise by the 2080s whilst under the B2 scenario, they are stabilized at 2050 levels (IPCC, 2000). Differences in emission levels for the two time periods explains the larger rainfall changes by the 2080s for both the CGCM and HadCM3. ECHAM shows differences between both emissions scenarios for both the 2050s and the 2080s, with larger rainfall increases under the B2 scenario. It is not clear why this happens as differences should be more marked by the 2080s as the two emissions scenarios diverge significantly towards the end of the century. This might simply be an anomaly given the ECHAM rainfall simulation over the baseline period was found to be less accurate than the other GCM-based rainfall. A comparison of changes in P5 outside the inter-quartile range reveals greater variability in extreme rainfall changes.

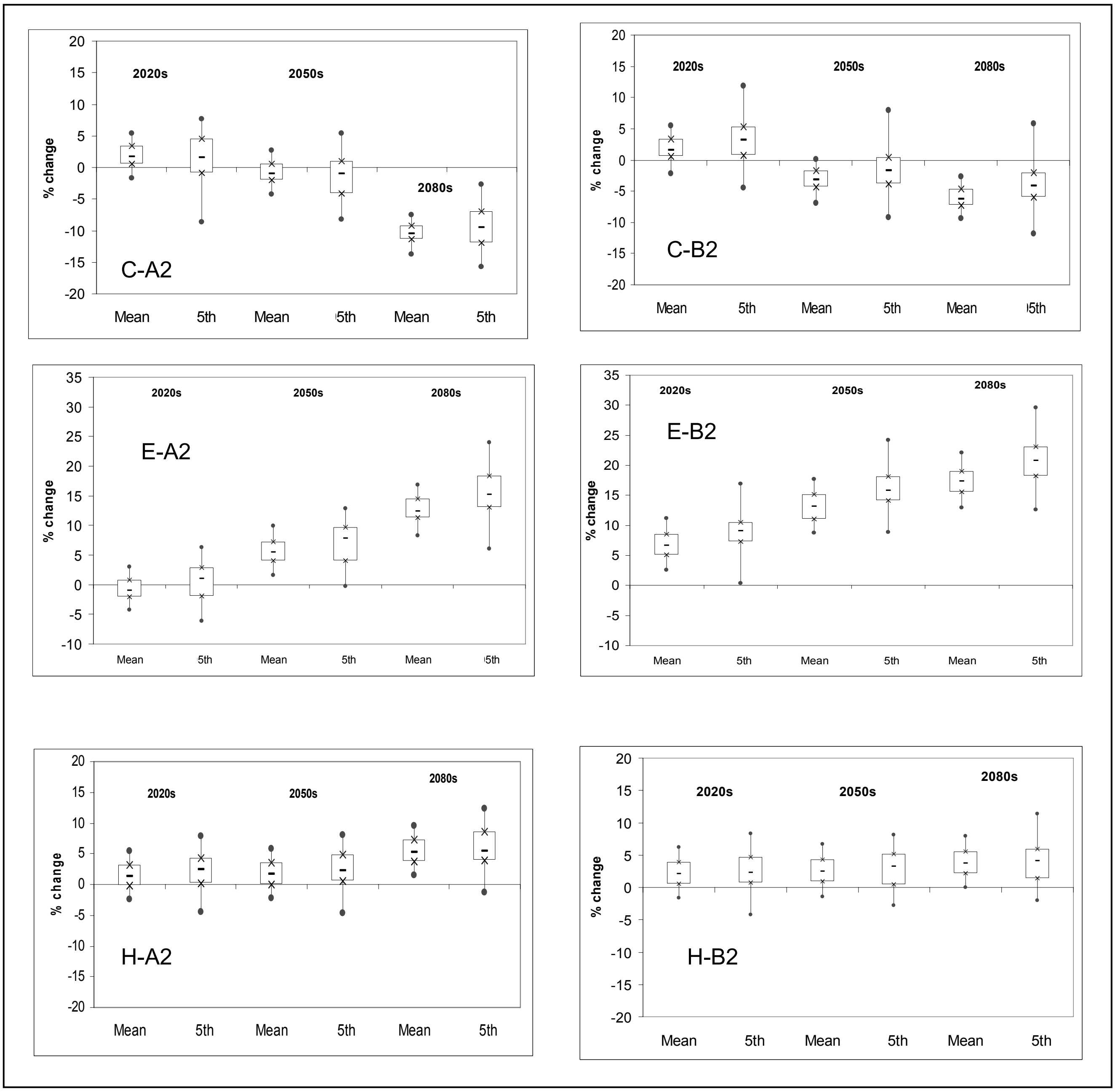

Fig. 2 Percentage change in Blue Nile basin areal rainfall (from baseline) for A2 and B2 GHG emission scenarios over the wet season (June–September). (5th = Areal daily rainfall exceeded 5% of the time during wet season).

The range of changes expected (within the inter-quartile range) for the 2050s and 2080s are summarized in Table 1. The median values in bold indicate that the percentage change in mean areal rainfall could vary from –10.5% (CGCM A2 2080s) to +17.3% (ECHAM B2 2080s). However, in addition to considering uncertainties in GCMs and future GHG emissions, the inclusion of downscaling uncertainties indicates greater variability; % change in mean areal rainfall varies from –11.4% (CGCM A2 2080s) to +19% (ECHAM B2 2080s). The percentage changes in P5 show greater variability (ranging from –12% to +23%).

Table 1 Percentage change (from baseline) in rainfall during wet season.

Scenario	% change in mean areal rainfall			% change in P5 (rainfall exceeded 5% of the time)		
	Median	75th Percentile	25th Percentile	Median	75th Percentile	25th Percentile
SRES A2						
C5	–1.1	0.59	–2.0	–1.0	1.0	–4.1
C8	**–10.5**	–9.2	**–11.4**	**–9.4**	–6.9	**–12.0**
E5	5.5	7.2	4.1	7.8	9.7	4.1
E8	12.4	14.5	11.3	15.2	18.4	13.1
H5	1.6	3.6	0.078	2.3	4.8	0.5
H8	5.3	7.3	3.7	5.5	8.7	4.0
SRES B2						
C5	–3.2	–1.7	–4.3	–1.7	0.5	–3.9
C8	–6.3	–4.6	–7.2	–4.1	–2.0	–6.0
E5	13.1	15.2	11.1	15.8	18.1	14.2
E8	**17.3**	**19.0**	15.6	**20.7**	**23.1**	18.2
H5	2.5	4.3	0.95	3.2	5.2	0.5
H8	3.7	5.5	2.2	4.1	6.0	1.4

Direct comparisons with other studies are difficult due to only very few published Blue Nile impacts assessments. Detailed climate scenarios were developed for Africa by Hulme *et al.* (2001) until 2100, based on output from seven GCMs. For the June–August season by the 2050s and 2080s (A2 scenario), they noted that the median value of rainfall generated by all seven GCMs was expected to change by +5%–16% and +8–24%, respectively. The general wetting trend reported by Hulme *et al.* is also observed in the current study according to two of the GCMs. Yates & Strzepek (1998) used six GCMs to construct climate change scenarios for the Nile basin. Results from the first generation versions of atmosphere–ocean coupled models CGCM, ECHAM and HadCM revealed annual changes (from baseline) in rainfall for the Blue Nile of –8.8%, +23.3% and +54.6%, respectively. This is a similar trend to that observed in the present study, with CGCM indicating drier conditions.

PET is set to rise under all scenarios with the largest increase according to the ECHAM model of +15 to +30% (2050s) and up to 90% increase in the northern part of the basin by the 2080s. The CGCM model results in more modest increases of 0 to +5% (2050s) to +15% to +30% (2080s). Projected HadCM3 increases lie between those estimated by the CGCM and ECHAM.

Flow changes

Figure 3 shows the future change (percentage from baseline) in flow at Diem station for the wet season (June–September). Changes are presented in a similar format to rainfall changes presented as box-plots earlier. The flow change results also includes another peak flow metric; Q1 (difference in flow exceeded 1% of the time).

By considering only the inter-quartile range in the box plots, it can be concluded that some rather significant changes are to be expected in flow during all three time-

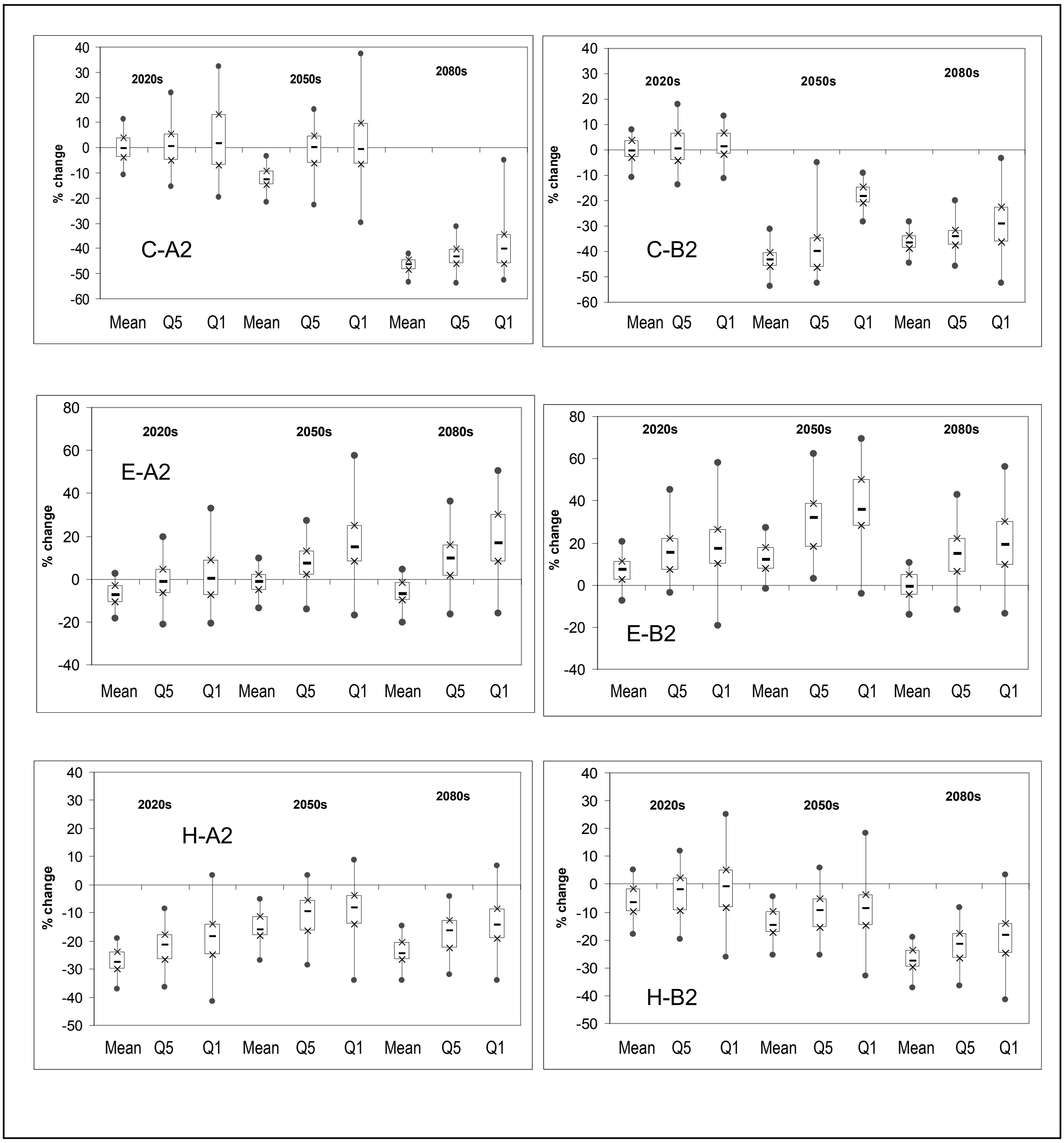

Fig. 3 Percentage change in discharge (from baseline) of Blue Nile flow (at Diem) for A2 and B2 GHG emissions scenarios over wet season (June-September). (Q5 & Q1 = daily flow exceeded 5% & 1% of the time during wet season, respectively).

periods, which is in contrast to the moderate rainfall changes. The CGCM indicates drier conditions driven by the rainfall scenarios. The marked difference between projected flow reductions under the CGCM A2 and B2 scenarios for the 2050s is noteworthy. Results highlight the high sensitivity of flow changes to rainfall changes (see rainfall scenarios in Fig. 3). Results from HadCM3 suggest that although a wetter future is expected (Fig. 3), flow is set to decrease, especially by the 2080s. This is because increased PET across the basin leads to flow reduction even though rainfall increases by a small amount.

The full range of changes expected (within the inter-quartile range), including the median changes for the 2050s and 2080s, are summarized in Table 2. The median values in bold indicate that the percentage change in mean flow could vary from –46.6% (CGCM A2 2080s) to +12.4% (ECHAM B2 2050s). Q5 shows similar reductions but a greater increase (32.1% increase under the ECHAM B2 2050s). To reveal the effects of downscaling uncertainty on the assessed impacts, we need to examine the full range of results within the inter-quartile range in Table 2. This leads to greater variability as expected and percentage change in mean flow could vary from –48.5% (CGCM2 A2 2080s) to +17.9% (ECHAM B2 2050s). This large variation corresponds to limits within the 75th and 25th percentiles and would be even greater had results been presented in between the 90th and 10th percentiles.

The results presented in this study are in general agreement with what other investigators have noted. Riebsame *et al.* (1995) reported that GCM scenarios provided widely diverging pictures of possible future river flows, from a 30% increase to a 78% decrease; larger reductions were expected as is the case in the present study. Yates & Strzepek (1998) reported a range of changes for a doubling of CO_2 concentrations; mean annual flow was expected to change by –19% (CGCM1), +41% (ECHAM1) and +133% (HadCM1). Although the sign of changes is consistent with findings from the present study, the flow sensitivity appears to be much greater, especially under the HadCM1 scenario due to the large projected increase in rainfall.

Table 2 Percentage change (from baseline) in flow during wet season.

Scenario	% change in mean flow			% change in Q5 (flow exceeded 5% of the time)		
	Median	75th Percentile	25th Percentile	Median	75th Percentile	25th Percentile
SRES A2						
C5	–12.5	–9.0	–14.6	0.1	4.9	–6.3
C8	**–46.6**	–44.7	**–48.5**	**–43.4**	–40.2	–46.0
E5	–1.3	2.1	–4.9	7.6	12.9	2.0
E8	–6.6	–1.8	–9.7	9.7	15.9	1.6
H5	–15.9	–11.3	–18.0	–9.6	–5.6	–16.5
H8	–24.4	–20.4	–26.5	–16.5	–12.6	–22.5
SRES B2						
C5	–43.4	–40.2	–46.0	–40.1	–34.6	**–46.1**
C8	–36.6	–33.7	–38.6	–34.2	–31.6	–37.4
E5	**12.4**	**17.9**	8.0	**32.1**	**38.6**	18.1
E8	–0.6	4.9	–4.4	15.1	22.3	6.5
H5	–14.6	–9.8	–17.1	–9.5	–5.1	–15.7
H8	–27.5	–23.7	–29.9	–21.6	–17.8	–26.6

CONCLUSIONS

This study assessed Blue Nile flow response to uncertainties in: (i) future GHG emissions; (ii) GCMs; and (iii) downscaling GCM output to a finer spatio-temporal scale. The findings indicate that considerable variations in Blue Nile flow sensitivity arise as a result of GHG emissions uncertainties and choice of GCM. In the Blue Nile case study area, one GCM indicates a drier future, whilst two others indicate wetter futures, which agrees with what has been noted by previous investigators. Uncertainties introduced by the downscaling procedure were also quantified and shown to be significant. Under the majority of the scenarios, it was shown that future Blue Nile flow is generally expected to reduce, despite small increases in future rainfall; this is because of large projected increases in PET which offsets small increases in rainfall. This warrants a more detailed examination of the effect future PET changes may have on Blue Nile flow. A further limitation of the study is that it did not consider additional sources of uncertainty including sampling and hydrological model uncertainties, which can also be significant (Nawaz & Adeloye, 2006).

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REFERENCES

Carter, T. R., Parry, M. L., Nishioka, S. & Harasawa, H. (1994) Technical guidelines for assessing climate change impacts and adaptations. Intergovernmental Panel on Climate Change, University College London, Centre for Global Environmental Research, Tsukuba.

Conway, D. & Hulme, M. (1996) The impacts of climate variability and future climate change in the Nile Basin on water resources in Egypt. *Water Resour. Dev.* **12**, 277–296.

Elshamy, M. E. A. M. (2006) Improvement of the hydrological performance of land surface parameterization: an application to the Nile Basin. PhD Thesis, Imperial College of Science, Technology, and Medicine, University of London, UK (unpublished).

Gissila, T. Black, E., Grimes, D. I. F. & Slingo, J. M. (2004) Seasonal forecasting of the Ethiopian summer rains. *Int. J. Clim*. **24**, 1345–1358.

Hulme, M., Doherty, R. New, M. & Ngara, T. (2001) African climate change: 1900–2100. *Clim. Res*. **17**, 145–168.

IPCC (2000) IPCC Special Report–Emissions Scenarios, Summary for Policymakers. Intergovernmental Panel on Climate Change (http://sres.ciesin.org/index.html).

IPCC (2001) Climate change 2001: Impacts, adaptation and vulnerability. In: *Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (ed. by J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken & K. S. White). Cambridge University Press, Cambridge, UK.

Johnson, P. A. and Curtis, P. D. (1994) Water balance of Blue Nile River Basin in Ethiopia. *J. Irrig. Drain. Engng.* **120**, 573–589.

Mantoglou, A. & Wilson, J. L. (1982) The Turning Bands Method (TBM) for simulating random fields using line generation by a spectral method. *Water Resour. Res*. **18**(5), 1379–1394.

Mantoglou A. (1987) Digital simulation of multivariate two- and three- dimensional stochastic processes with a spectral Turning Bands Method. *Math. Geol.* 1**9**(2), 129–149.

Nawaz, N. R. & Adeloye, A. J. (2006) Nawaz, N. R. & Adeloye, A. J. (2006) Sampling uncertainty of climate change impacts. *Climatic Change* **78**(2–4), 257–292.

Riebsame, W. E., Strzepek, K. M., Wescoat, J. L. Jr., Perrit, R., Graile, G. L., Jacobs, J., Leichenko, R., Magadza, C., Phien, H., Urbiztondo, B. J., Restrepo, P., Rose, W. R., Saleh, M., Ti, L. H., Tucci, C. & Yates, D. (1995) Complex river basins. In: *Climate Changes, International Impacts and Implications* (ed. by K. M. Strzepek & J. B. Smith), 57–91. Cambridge University Press, Cambridge, UK.

Rosenfeld, D., Wolff, D. B. & Atlas, D. (1993) General probability-matched relations between radar reflectivity and rain rate. *J. Appl. Met.* **32**(1, 50–72.

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

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

Sene, K. J. (2000) Theoretical estimates for the sensitivity of White Nile flows to land use and climate change. *Hydrol. Sci. J.* **45**, 125–145.

Schaake, J. C., Koren, V. I., Duan, Q. Y., Mitchell, K. & Chen, F. (1996) Simple water balance model for estimating runoff at different spatial and temporal scales. *J. Geophys. Res.-Atmos.* **101**(D3), 7461–7475.

Sutcliffe, J. & Parks, Y. P. (1999) *The Hydrology of the Nile*. IAHS Special Publ. 5, 57–87. IAHS Press, Wallingford, UK.

Thornthwaite, C. W. (1948) An approach toward a rational classification of climate. *Geogr. Rev.* **38**, 55–94.

Widmann, M., Bretherton, C. S. & Salathé, E. P. Jr. (2003) Statistical precipitation downscaling over the Northwestern United States using numerically simulated precipitation as a predictor. *J. Clim.* **16**(5), 799–816.

Yates, D. & Strzepek, K. (1998) Modelling the Nile Basin under climatic change. *J. Hydrol. Engng* **3**(2), 98–108.