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Using multiple climate projections for assessing hydrological response to climate change in the Thukela River Basin, South Africa

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ABSTRACT

This study used climate change projections from different regional approaches to assess hydrological effects on the Thukela River Basin in KwaZulu-Natal, South Africa. Projecting impacts of future climate change onto hydrological systems can be undertaken in different ways and a variety of effects can be expected. Although simulation results from global climate models (GCMs) are typically used to project future climate, different outcomes from these projections may be obtained depending on the GCMs themselves and how they are applied, including different ways of downscaling from global to regional scales. Projections of climate change from different downscaling methods, different global climate models and different future emissions scenarios were used as input to simulations in a hydrological model to assess climate change impacts on hydrology. A total of 10 hydrological change simulations were made, resulting in a matrix of hydrological response results. This matrix included results from dynamically downscaled climate change projections from the same regional climate model (RCM) using an ensemble of three GCMs and three global emissions scenarios, and from statistically downscaled projections using results from five GCMs with the same emissions scenario. Although the matrix of results does not provide complete and consistent coverage of potential uncertainties from the different methods, some robust results were identified. In some regards, the results were in agreement and consistent for the different simulations. For others, particularly rainfall, the simulations showed divergence. For example, all of the statistically downscaled simulations showed an annual increase in precipitation and corresponding increase in river runoff, while the RCM downscaled simulations showed both increases and decreases in runoff. According to the two projections that best represent runoff for the observed climate, increased runoff would generally be expected for this basin in the future. Dealing with such variability in results is not atypical for assessing climate change impacts in Africa and practitioners are faced with how to interpret them. This work highlights the need for additional, well-coordinated regional climate downscaling for the region to further define the range of uncertainties involved.

1. Introduction

As more and more evidence and acceptance of the existence of climate change comes about (Lettenmaier, 2009), more analysis is needed on assessing the possible impacts of future climate change on hydrological systems. Methods used for assessing hydrological impacts have evolved over time from simple sensitivity-based studies to more advanced ways of using outputs from climate models (e.g. Kaczmarek et al., 1996; Hay et al., 2000; Bergström et al., 2001; Middelkoop et al., 2001; Andréasson et al., 2004; Lenderink et al., 2007). The use of future climate projections from global climate models (GCMs) is now the norm, but these must first be regionally downscaled before they are used in hydrological models (Arnell et al., 2003; Graham et al., 2007b).

In earlier studies, analysis was often focussed on results from only one or a few regionally downscaled climate projections. This was due to lack of availability to such projections, which in turn reflected the relatively high demands in terms of computing and processing needed to produce and distribute them. With time and enhanced computing facilities, availability to climate projections has improved. However, the highest concentration of such datasets still remains in the developed world (Christensen et al., 2007; van der Linden and Mitchell, 2009), but this is also changing.

The objective of this study was to use a number of currently available regionally downscaled climate projections to assess hydrological effects on the Thukela River Basin in the province of KwaZulu-Natal, South Africa. Of primary interest was to evaluate

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Fig. 1. Location map for Thukela River Basin.

if the climate projections provide a consensus for hydrological response over the basin, or not.

Projections of climate change from different downscaling methods, different future emissions scenarios and different global climate models were used as input to simulations in one-way coupling to a hydrological model to assess climate change impacts. A total of 10 hydrological change simulations were made, resulting in a matrix of hydrological response results. This matrix includes dynamically downscaled climate change projections from the same regional climate model (RCM) using an ensemble of three global climate models (GCMs) and three global future emissions scenarios, and statistically downscaled projections using results from five GCMs with the same future emissions scenario.

The Thukela River Basin is located in the province of KwaZulu-Natal in South Africa, as shown in Fig. 1. Covering a catchment area of 29,200 km^2, the river has its headwaters in the highlands of neighbouring Lesotho and flows into the Indian Ocean. Elevations range from sea level to over 3000 m, with a basin-wide mean of 1300 m. The present climate is moderate and relatively wet for South African conditions and falls within the summer rainfall region. Mean annual precipitation varies from 650 to 1520 mm $year^{-1}$. Conditions are generally good for farming, which is extensive over much of the basin.

2. Methods and data

Global climate models (GCMs) are used to estimate future climate change at global scale. They are developed to simulate the complex interactions between atmosphere, ocean and biosphere. Using assumptions of how the concentration of greenhouse gases will change in the future, GCMs can be used to estimate the future evolution of climate due to anthropogenic effects. However, the coarse horizontal resolution of most GCMs (~200–300 km grid squares) limits the direct use of their outputs in impact models such as catchment-based hydrological models, which are typically used at scales of 10–50 km. The large discrepancy in scale between the GCM scale and regional impacts can be addressed by use of regional downscaling.

There are two primary methods used for regional downscaling. One is referred to as *dynamical downscaling*, which is based on regional climate modelling (RCM). It uses advanced numerical models that are similar to GCMs, but applied at much finer scales over limited areas. The other is *statistical downscaling*, which relies on a variety of statistical methods coupled to local and regional observations. Statistical downscaling (SD) is much less demanding than dynamical downscaling in terms of computing needs, but the quality of the outcomes are strongly dependent on the quality of the available observations and the level of sophistication used in the downscaling.

In both GCM and RCM climate projections, a historical control period is defined for comparison of results to observations (often 1961–1990), but this period represents only a possible realisation of climate that should not be expected to match exactly with observations. What should match during this period, however, is the historical concentration of greenhouse gases in the atmosphere. Thus, the results do not represent the day-to-day evolution of observed weather, but rather climate statistics such as seasonal, monthly and daily mean and standard deviations should be realistically reproduced for decadal scales (e.g. 20–30 year time periods).

Both RCM and SD projections were used in this study as described in more detail below. Outputs from the regional climate projections were input into a hydrological model to perform simulations to assess hydrological change. A number of key variables were then summarised to describe changes in hydrology and water availability. The SD projections were previously used in a nationwide setup to evaluate hydrological effects over all of South Africa (Hewitson and Tadross, 2010). Use of the RCM projections is limited to the Thukela Basin, as presented here.

2.1. Hydrological modelling

This study used the ACRU Agrohydrological Model for hydrological modelling. ACRU is a multi-purpose, daily time-step, physically-based conceptual model that has been developed over some 30 years at the University of KwaZulu-Natal in South Africa (Schulze and Pike, 2004). ACRU is sensitive to land management and changes thereof (Tarboton and Schulze, 1990; Jewitt et al., 2004), as well as to climate input and changes thereof (Schulze, 2000, 2005; Perks, 2001; Forbes et al., 2010). As it was developed for South African conditions, it is well-suited for use in assessing hydrological impacts of climate change for the Thukela River Basin. The model's hydrological output (e.g. runoff, peak discharge) has been widely verified under a range of climate conditions, as have its internal state variables, such as soil moisture content (for a review, see Warburton et al., 2010). Input parameters to the ACRU model are not typically calibrated to produce a good fit. Rather, input parameters are estimated from the physical characteristics of the catchment using available geo-physical information. The model inputs and configuration used for this study originate from Schulze (2005), as briefly outlined below.

The Thukela River Basin was delineated into 258 subcatchments that reflect topography, soil properties, land cover and water management. The ACRU model requires daily rainfall and daily reference potential evaporation (A-pan equivalent); the latter can be computed from daily minimum and maximum temperature if not provided explicitly. Representative rainfall stations were chosen for each of the subcatchments and daily rainfall was extracted from a rainfall database compiled for South Africa by Lynch (2004). As daily A-pan observations were not available for the catchment, the Hargreaves and Samani (1985) daily A-pan equivalent reference evaporation equation was used to estimate daily values. Daily minimum and maximum temperatures were extracted from a spatial database of daily temperatures for South Africa (Schulze and Maharaj, 2004) at a point closest to the centroid of each subcatchment representing the median altitude of the subcatchment. Lapse rate corrections for altitude were applied to temperature inputs.

The ACRU model revolves around a daily multi-layer soil water budget using surface layer characteristics and two active soil layers. The "natural" land use (Acocks, 1988) of each subcatchment was taken to be the dominant baseline vegetation of that catchment. Monthly values of the water use coefficient, interception per rainday, root distribution, a coefficient of infiltrability and index of suppression of soil water evaporation by a litter/mulch layer for each of the Acocks' Veld Types found in the Thukela Basin were obtained from Schulze and Pike (2004). Use of natural conditions