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An evaluation of how downscaled climate data represents historical precipitation characteristics beyond the means and variances

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ABSTRACT

Precipitation is the main driver of the hydrological cycle. For climate change impact analysis, use of downscaled precipitation, amongst other factors, determines accuracy of modelled runoff. Precipitation is, however, considerably more difficult to model than temperature, largely due to its high spatial and temporal variability and its nonlinear nature. Due to such qualities of precipitation, a key challenge for water resources management is thus how to incorporate potentially significant but highly uncertain precipitation characteristics when modelling potential changes in climate for water resources management in order to support local management decisions. Research undertaken here was aimed at evaluating how downscaled climate data represented the underlying historical precipitation characteristics beyond the means and variances. Using the uMngeni Catchment in KwaZulu-Natal, South Africa as a case study, the occurrence of rainfall, rainfall threshold events and wet dry sequence was analysed for current climate (1961–1999). The number of rain days with daily rainfall > 1 mm, > 5 mm, > 10 mm, > 20 mm and > 40 mm for each of the 10 selected climate models was, compared to the number of rain days at 15 rain stations. Results from graphical and statistical analysis indicated that on a monthly basis rain days are over estimated for all climate models. Seasonally, the number of rain days were overestimated in autumn and winter and underestimated in summer and spring. The overall conclusion was that despite the advancement in downscaling and the improved spatial scale for a better representation of the climate variables, such as rainfall for use in hydrological impact studies, downscaled rainfall data still does not simulate well some important rainfall characteristics, such as number of rain days and wet-dry sequences. This is particularly critical, since, whilst for climatologists, means and variances might be simulated well in downscaled GCMs, for hydrologists, downscaled climate data still needs to represent the underlying historical precipitation properties, such as consecutive wet days, number of rain days and their seasonal and monthly distribution during the downscaling process. This then calls for an improvement in the downscaling process by incorporating rainfall drivers such as cyclones, so as to capture better, these rainfall characteristics important to hydrologists.

1. Introduction

A key challenge for water resources management is how to incorporate potentially-significant but highly uncertain rainfall information when modelling the potential impacts of climate change on water resource. The most relevant meteorological variables for evaluating hydrological responses to climate change are precipitation and temperature (Bronstert et al., 2007; Xu et al., 2009). For freshwater resources, precipitation constitutes the most important driver of hydrological processes (Schulze, 2005b; Kundzewicz et al., 2008). Precipitation is however, considerably more difficult to predict than temperature, mostly due to its high spatial and temporal variability (Maraun et al., 2010). Most climate change studies in southern Africa (e.g. Schulze, 2005c; Graham et al., 2011; Schulze, 2011; Warburton et al., 2012) have used means and variances to compare downscaled Global Climate Model (GCM) to historical rainfall. For example, recently, Hughes et al. (2014) used skill tests (based on means and variances) to assess whether downscaled GCMs were able to realistically reproduce precipitation distribution statistics, patterns of seasonality, and extremes. To date, only a few studies from southern Africa, (see e.g. Cockcroft et al., 1987; Thomas et al., 2007) have looked at other rainfall characteristics important to hydrologists, such as rainfall events and sequence of raindays. Due to the relationship between the hydrological and climate systems, any change in climate will affect hydrological variables, particularly precipitation (Arnell, 1999; Warburton and Schulze, 2005). Therefore the ability of downscaled precipitation to characterise historical precipitation is essential for regional and local scale hydrological studies (Pervez and Henebry, 2014).

GCMs provide a “broad-brush” view of how variables (such as temperature and rainfall patterns) might change in response to rising concentrations of anthropogenic greenhouse gases (Graham et al., 2007). GCMs,

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however, cover much larger spatial scale than is usually needed in climate change impact studies (Mearns et al., 2003; Tebaldi et al., 2005). Downscaled GCM modelling, on the other hand, focuses relatively small areas in detail, at a higher spatial resolution than that offered by GCM simulations. Downscaling, hence, is aimed at generating more locally relevant climate data for improved understanding of the spatial and temporal long-term weather patterns at meso and microscales (Graham et al., 2007).

Downscaling methods are now widely being employed to either statistically disaggregate GCM output to finer spatial scales or dynamically generate fine scale climate simulations (Xu, 1999b; Nikulin et al., 2012; Wilby and Dawson, 2013), of 1 km spatial resolution or less. This enables incorporation of downscaled outputs in hydrological models at local scales better suited to impact assessments. Statistical downscaling uses average climate variables from GCMs to estimate point scale meteorological variables (such as station precipitation, temperature and wind speeds) (Diaz-Nieto and Wilby, 2005; Wilby and Dawson, 2013). On the other hand, in dynamical downscaling, high resolution Regional Climate Models (RCMs) are run over a limited area with boundary conditions coming from observation-based datasets (Nemeth, 2010; Kienzle et al., 2012). Whilst much research has been dedicated to downscaling methods, both approaches have inherent limitations (see, e.g. Xu, 1999b; Schulze, 2000; Tabor and Williams, 2010). Principally, the mismatch between GCMs and hydrological models occur on the scale(s) at which climate and terrestrial impact models interface. These mismatch limitations, which affect both the temporal and spatial dimensions, have important implications for the credibility of impact studies derived from the output of climate change models (Wilby and Wigley, 1997).

Table 3-1
Example of some key rainfall characteristics that may be considered important by hydrologists (for climate change impact analysis) and are normally not considered by climatologists.

Hydrological variables	Justification why variables are important	References
Daily rainfall characteristics		
Wet/dry sequences	Antecedent soil moisture conditions, runoff generation	Stokes et al. (1997); Schulze et al. (2001)
Number of rain days	Saturation capacity, runoff generation antecedent soil moisture conditions, runoff generation, base flow or ground water recharge	Nel and Sumner (2008); Schulze (2010)
Number of dry days	Antecedent soil moisture conditions, infiltration capacity, runoff generation	Frei et al. (2006); Schulze (2010); Tadross et al. (2011)
Probability distribution of daily rainfall	flood forecasting + design rainfalls + projections of surface water availability/changes to streamflow	Li et al. (2013); Kwak et al. (2015)
Sub-daily rainfall characteristics		
Threshold events	Runoff generation	Prudhomme and Reed (1998); Hay et al. (2002)
Rainfall intensity	Rainfall erosivity + runoff generation	Coutinho et al. (2014); Masson and Frei (2014)
Rain rates	Peak rain rates + runoff generation	Wenninger et al. (2008); Munyaneza et al. (2012)
Rain event depth & duration	Interception losses + runoff generation + frequency analysis for return periods	Meusburger et al. (2012); Smithers and Schulze (2004)
Inter event time	Interception losses + hydrological drought indices + soil moisture modelling	Bulcock and Jewitt (2012); Dunkerley (2015)
Frequency of extreme events	Short design rainfall estimates + design flood estimations + peak discharge + streamflow volumes + runoff timing + rainfall-intensity-duration-frequency relationships	Smithers and Schulze (2004); Yilmaz et al. (2014); Asadieh and Krakauer (2015)

In spite of the limitations, the resolution of downscaled GCM climate data has improved remarkably. For instance, over the last 5 years, a proliferation of regional studies using downscaled products at 25–50 km spatial resolution has been undertaken (e.g. Endris et al., 2013; Lutz et al., 2013; Kothe et al., 2014; Panitz et al., 2014). Micro-scale downscaled products at ultra-high resolution simulations (of up to 1 km) have been used in a limited number of studies in southern Africa (e.g. Engelbrecht et al., 2011; Tadross et al., 2011; Landman and Beraki, 2012; Winsemius et al., 2013). Generally, the studies have shown that downscaled products simulate seasonal mean and annual cycle precipitation quite robustly, although individual models sometimes exhibit significant biases in some sub-regions and seasons. This bias/uncertainty in outputs from the regional climate models is a measure of unexplained variation. The uncertainty, results partly from measurement errors and partly from inadequate understanding of the climate hydrological system processes (Lehmann and Rillig, 2014). Despite that uncertainty, less attention has been given to other rainfall characteristics, such as number of raindays or length of wet/dry spells, variables which are critical in examining hydrological impacts of climate change.

Advances in downscaling, and hence improved spatial resolution raises the question of whether such high resolution simulations provide a better representation of the climate variables, such as rainfall (Schulze, 2000; Hewitson, 2010; Tadross et al., 2011) for use in hydrological impact studies. The emerging question is thus, "What is the added value of high resolution downscaled rainfall?" In downscaling, most climatologist have focused on the statistical representativeness by way of "means and variances" of rainfall. Hydrologists, however, may be interested in (say) the length of the wet/dry sequences, beyond the means and variances. This brings into focus the differences between what climatologists may consider as an adequate simulation of rainfall (means and variances) and rainfall characteristics of concern to hydrologists (e.g. see Table 3-1 below).

A follow-up question would be, "How well do the downscaled climate data represent the historical rainfall beyond the means and variances?" This type of uncertainty is addressed in this study.

Uncertainty is a feature of any hydro-climatic planning study, whether climate change is explicitly included or not (Schulze and Perks, 2000; Tadross et al., 2005). Accounting for, and disclosing, uncertainty is an established component of good hydrological planning practice (Xu, 1999a; Fowler et al., 2007). Historical precipitation data, however, is subject to inherent uncertainties, both spatially (not enough raingauges) and temporally (short records, limited records, errors) (Mason et al., 1999; Mazvimavi, 2010). Nevertheless, to have confidence in the downscaled GCM precipitation output, it needs to represent the historical precipitation regimes and characteristics reasonably well. If climate models cannot simulate the characteristics of historical rainfall, then there would be limited confidence in the ability of the GCMs to predict the future. All the same, the ability of the downscaled GCMs to represent historical rainfall characteristics is regarded as a necessary but not sufficient requirement for the GCMs to be useful in climate projections.

Use of downscaled GCM precipitation for climate change impact studies in other world regions has been shown to add value to climate change projections (e.g. Durman et al., 2001; Frei et al., 2006; Buonomo et al., 2007; Schmidli et al., 2007). Durman et al. (2001) reported that, compared to the driving GCM, downscaled outputs could capture an intensification of precipitation, which led to an improved representation of daily precipitation distribution. Frei et al. (2006) established that downscaled precipitation can reproduce many features of precipitation distribution over regions of complex topography. Additionally, according to Giorgi and Mearns (2002) there is evidence that the skill of downscaled rainfall in simulating the spatial pattern and temporal characteristics of precipitation increases with increasing model resolution. Maraun et al. (2010) reporting on studies in Britain, stated that for a given downscaled model, downscaling skill was