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What are the impacts of bias correction on future drought projections?

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SUMMARY

It is expected that anthropogenic greenhouse gas emissions will continue to change our climate, and in turn the characteristics of future drought. Assessments of the risks of future droughts, when at a global or a continental scale, are often based on simulations from General Circulation Models (GCMs). When raw GCM simulations are used, it is assumed that the future deviations from modelled historical climatology represent the future drought. On the other hand, it is known that raw GCM simulations are significantly biased for the variables that affect hydrology and a correction is needed before assessments can be performed. We investigate here whether drought assessments based on raw GCM simulations are biased and the typical extent of this bias. Our assessment is based on the use of monthly precipitation data from 18 CMIP3 GCMs, two popular bias correction alternatives and Australia as the study domain. A number of different precipitation drought attributes have been assessed. These include the Standardized Precipitation Index (SPI), multi-year rainfall statistics and a drought vulnerability statistic that measures the maximum deviation of a time series from its mean.

We find significant differences between droughts assessments using raw GCM simulations and using bias corrected sequences. Large increases in drought frequencies are projected for some parts of Australia. Both bias correction methods moderate these increases. This result is consistent across the three different drought statistics. The bias corrected drought projections also generally have slightly more agreement (smaller range of future changes) across the GCMs compared to the raw projections, which is a promising result for attempting to reduce model structural uncertainty. What this study shows is raw model simulations can lead to incorrect drought assessments even at continental scales and bias corrections should be applied.

1. Introduction

Anthropogenic climate change is now assessed as being "extremely likely" and is expected to lead to detrimental effects for human and natural systems both at regional and global scales (IPCC, 2013). One of the areas of concern is the impact of these changes on water resources systems (Jiménez Cisneros et al., 2014), particularly for parts of the world where water resources are already stressed due to population pressures, technological change and the variability introduced by large scale natural climate drivers (Vörösmarty et al., 2010). General Circulation Models (GCMs) are one method of assessing the likely impacts of increasing greenhouse gas concentrations on natural and human systems. Despite the skill of GCMs at a global scale, there remain concerns about their ability to model regional scale impacts (Fowler et al., 2007a) and to represent certain features of the climate system, such as precipitation (Chan et al., 2013), which form an important input to the modelling of water resources systems (Maraun et al., 2010).

Techniques to overcome the weaknesses of GCMs and which allow scientists to undertake impact assessments, are based on the assumption that some regional scale changes do not create global scale feedbacks and therefore may be corrected outside of the modelling of the GCM without affecting the accuracy of the global scale simulations (Pitman et al., 2012). Methods that correct GCM simulations at a regional scale include dynamical downscaling (regional climate modelling) or statistical downscaling. Given the significant differences in GCM simulated fields compared to observations, there is often a need for a pre-processing step before statistical or dynamic downscaling approaches can be used. This pre-processing step is referred to as bias correction, whereby the GCM or regional climate model results representing the current climate are corrected to match observations. The bias correction model over the historical period is assumed to be the same in future simulations, and can therefore be used to obtain the future projections

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(Buser et al., 2009). Bias correction has been shown to be a simple and effective method that can be quickly be applied over large areas, to multiple models or as pre or post-processing step for more sophisticated downscaling methods (Chen et al., 2013; Gudmundsson et al., 2012; Ines and Hansen, 2006; Johnson and Sharma, 2012; Li et al., 2010; Piani et al., 2010; Teutschbein and Seibert, 2012; Wood et al., 2004).

Hydrologic planning is strongly dictated by the frequency and magnitude of sustained low or high flow anomalies that affect water resources systems. The importance of these anomalies becomes even greater when the system is stressed and water demand is close to the overall availability in the system. Past assessments have evaluated such anomalies based on raw GCM simulations. However, most water resources assessments at a catchment scale require some post-processing or bias correction, before any evaluation (for drought or for other purposes) can be carried out. This contradiction lays the foundation for this research; the key question that is posed is whether bias correction is needed for drought assessment at the scale of a catchment, a region, or an entire continent.

To this end, we assess drought simulations across Australia using monthly precipitation simulations from 22 GCMs of the historical and future climate. We then repeat this assessment using the same GCMs, but after applying two established alternatives for bias correction. One of these alternatives, the Nested Bias Correction (NBC) (Johnson and Sharma, 2012) was designed specifically to correct low frequency variability bias in simulations. The other method, Quantile Mapping (QM) corrects distributional attributes of simulations instead of focusing on persistence related attributes. Our investigation uses these approaches to examine the differences that result with reference to a future climate. We then ask whether raw GCM simulations are indeed different from bias corrected simulations of drought, and if so whether there are clear advantages in using one of the two bias correction alternatives evaluated.

The remainder of this paper is as follows. In Section 2 the bias correction methodologies and the data sources used for the analysis are described. Section 3 discusses the drought and rainfall statistics that have been considered. Section 4 applies the technique to 20th century rainfalls over Australia to compare the modelling of drought using observed, raw GCM outputs and the bias correction techniques. In Section 5 comparisons of projected future changes in drought from the raw and bias-corrected GCM outputs are presented. The final section discusses the implications of the results for future drought assessment and draws conclusions that will be useful for water resources climate change impact assessment.

2. Bias correction of GCM precipitation

2.1. Background

Recent comparisons of bias correction methods (Gudmundsson et al., 2012; Johnson and Sharma, 2011; Teutschbein and Seibert, 2012) have shown that the assumptions of the correction method can affect their performance. Gudmundsson et al. (2012) found that nonparametric methods lead to the lowest errors, whilst Teutschbein and Seibert (2012) recommend power transformations or quantile mapping. Quantile mapping has been found in particular to be useful for correcting high rainfall totals of daily data (Themeßl et al., 2012). If year to year variability in rainfall is an important driver of the behaviour of a water resources system then it is necessary to consider biases in persistence as well as the distribution of the monthly rainfall data (Johnson and Sharma, 2011). The importance of this is highlighted by Rocheta et al. (2014) who have recently shown that the majority of GCMs in the Coupled Model Intercomparison Project 3 (CMIP3) underestimate interannual variability.

In practical terms, the effects of interannual and interdecadal precipitation variability manifest as periods of drought or abnormally wet conditions that can lead to flooding (Kiem et al., 2003; Pui et al., 2011; Verdon et al., 2004). Therefore correctly modelling low-frequency variability is the key to understanding possible changes to future water resources. Future drought assessments have found that larger areas of land are expected to have increased drought frequencies than decreases (Taylor et al., 2013) particularly for the later parts of the 21st century (Burke et al., 2006). Areas of the largest increases in drought frequencies are the Amazon, Central America and South Africa (Dai, 2013; Taylor et al., 2013) which is broadly consistent with the results from other studies (Burke and Brown, 2008; Orlowsky and Seneviratne, 2013) although the studies use different climate models and emission scenarios. These projections are also consistent with observed trends of drought frequency based on soil moisture anomalies (Orlowsky and Seneviratne, 2013).

A recent comprehensive study of global drought (Prudhomme et al., 2014) has been carried out as part of the Inter-Sectoral Impact Model Intercomparison Project (Warszawski et al., 2014). The analyses considered daily runoff and compared it to a daily drought threshold set at the 10th percentile of the daily values from the period 1976–2005. For large parts of the world, large increases in drought frequency were found particularly in Australia. The use of daily drought thresholds does not provide further guidance on longer term droughts due to interseasonal or interannual variability.

One of the problems with previous assessments of future drought frequencies is that generally they have not considered biases in the GCM precipitation simulations (e.g. Burke and Brown, 2008; Taylor et al., 2013). Wang and Chen (2014) used the Bias Correction and Spatial Disaggregation method of Wood et al. (2004) but did not assess the improvements in drought representation in the current climate or the effects of bias correction on the future projections. Prudhomme et al. (2014) also used bias corrected simulations and note that "statistical bias correction can influence the signal of the runoff changes". They go on to state that this uncertainty is believed to be smaller than the structural uncertainty associated with the choice of GCM or global impact model. Our study addresses this assumption directly by considering whether bias correcting GCM simulations improves the representation of historical drought statistics and then secondly if the bias correction leads to differences in the projected frequencies of future droughts. Changes at the individual grid cell are to be expected; specifically we are interested in whether bias correction leads to different estimates of drought at regional or continental scales.

2.2. Bias correction methods

Bias correction techniques have been developed to allow the direct use of GCM outputs for climate change impact assessment applications, whilst accepting that there are problems in the GCM modelling of rainfall (Johnson and Sharma, 2012). Bias correction approaches previously proposed include monthly (Wood et al., 2004) or daily (Ines and Hansen, 2006), quantile matching (Christensen et al., 2008; Gudmundsson et al., 2012) and simple monthly correction factors (Fowler and Kilsby, 2007). One of the weaknesses of all these approaches is that they only consider biases in the distribution of GCM simulations and not the persistence of the simulations. Biases in the representation of persistence translate to a poor characterization of interannual variability which can be particularly important when assessing the impacts of climate change on water resources availability and