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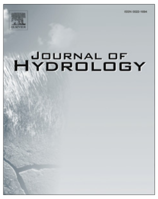

Comparing ensemble projections of flooding against flood estimation by continuous simulation

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SUMMARY

Climate impact studies focused on the projection of changing flood risk are increasingly utilized to inform future flood risk policy. These studies typically use the output from global (GCMs) and regional climate models (RCMs). However the direct application of GCM/RCM output is controversial as often significant biases exist in predicted rainfall; instead a number of alternative 'correction' approaches have emerged. In this study an ensemble of RCMs from the ENSEMBLES and UKCP09 projects are applied, via a number of application techniques, to explore the possible impacts of climate change on flooding in the Avon catchment, in the UK. The analysis is conducted under a continuous simulation methodology, using a stochastic rainfall generator to drive the HBV-light rainfall run-off model under a parameter uncertainty framework. This permitted a comparison between the projections produced by differing application approaches, whilst also considering the uncertainty associated with flood risk projections under observed conditions.

The results from each of the application approaches project an increase in annual maximum flows under the future (2061–2099) climate scenario. However the magnitude and spread of the projected changes varied significantly. These findings highlight the need to incorporate multiple approaches in climate impact studies focusing on flood risk. Additionally these results outline the significant uncertainties associated with return period estimates under current climate conditions, suggesting that uncertainty over this observed record already poses a challenge to develop robust risk management plans.

1. Introduction

Recent severe flood events in the UK have raised public and political awareness of flooding impacts and the potential climate change projections that suggest the global hydrological cycle will intensify with continued greenhouse-gas induced global warming (Karl and Trenberth, 2003). Moreover, flooding events in Australia, Pakistan and Thailand have further enhanced the perception that changes to hydrological extremes may be increasing and will have the greatest impact on human society. Observed precipitation trends in the UK indicate that an intensification of winter precipitation has occurred across many regions, with similar patterns becoming evident in spring and autumn (Jones et al., 2012; Maraun et al., 2008). However the identification of similar trends in observed flow records is much more difficult, owing to the affects of local anthropogenic influences and significant natural variability (Wilby et al., 2008; Villarini et al., 2011).

According to the IPCC fourth assessment report (AR4), continued warming of the global climate system is anticipated to alter the large scale hydrological cycle; with increasing temperatures, atmospheric moisture content is expected to increase according to the Clausius–Clapeyron relation (Trenberth et al., 2005). With increased atmospheric moisture content, the absolute potential water content, pool of precipitable water and potential for intensive precipitation will also increase (Kundezwicz et al., 2005). Aside from changes to accumulative rainfall amounts, continued warming is also anticipated to alter rainfall distribution; consequently even when total rainfall remains constant or decreases, incidents of heavy rainfall may increase. Therefore the widely held hypothesis is that the hydrological cycle will intensify and become more volatile with further greenhouse-gas induced global warming (Kyselý and Beranová, 2009).

The latest generation of climate models suggest that heavy precipitation or the proportion of total rainfall from heavy events will increase over most areas during the 21st century (IPCC, 2012). The projection of more frequent heavy precipitation events across most regions is also anticipated to increase the risk of rain-generated

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flooding. Indeed estimated damages from flooding are anticipated to increase over large parts of Europe through the next century (Feyen et al., 2012). In the UK, regional studies indicate that heavy precipitation events will increase during winter, spring and autumn, with low confidence associated with summer projections (Fowler and Ekström, 2009; Smith et al., 2013). Similar studies focused on producing future flood projections suggest that peak flows will largely increase through the 21st century. However, significant spatial variability is found, with the change signal varying in direction and magnitude across different regions (Bell et al., 2007). The perceived threat of increased flooding has led the UKs Department of the Environment, Food and Rural Affairs (Defra) to name flooding as the most significant threat posed to the UK by climate change.

In response to these concerns, climate change impact studies focused on future flood risk have received considerable effort in recent years. The projection of future river discharge in climate impact studies requires the coupling of global climate models (GCMs) and/or regional climate models (RCMs) with hydrological models. In recent years there have been significant improvements in climate modelling, particularly with regards to RCMs as they transfer the large scale signal from GCMs to scales closer to the catchment scale (Teutschbein and Seibert, 2012). However there are still significant uncertainties associated with the use of RCM output in hydrological impact studies. When cascading climate to impact simulations these uncertainties include the choice of climate model structure, emissions scenario, downscaling and correction techniques, and hydrological modelling uncertainty (Prudhomme et al., 2010; Cloke et al., 2012).

A common approach that has emerged in response to these uncertainties is to employ a suite of climate models as an ensemble of predictions, as opposed to more deterministic, single model methods. Indeed, multi model approaches that attempt to represent these uncertainties using a model ensemble are now recommended and widely used (Prudhomme et al., 2010; Fowler and Ekström, 2009; Teutschbein and Seibert, 2010). Although the use of model ensembles has emerged as a possible way to represent uncertainty, the direct use of climate model output is still not recommended in flood impact studies as model deficiencies currently preclude this (Prudhomme et al., 2010; Teutschbein and Seibert, 2010). There will undoubtedly be further improvements in the representation of precipitation within RCMs as model resolution continues to improve. However significant challenges in applying their output to hydrological impact studies will remain for the foreseeable future (Cloke et al., 2012). In response to these uncertainties a number of methods for deriving synthetic or corrected meteorological time-series from RCM output have been proposed. These approaches assume that although RCM outputs are partially unrealistic, owing to significant biases displayed when compared to observed data (Christensen et al., 2008; Smith et al., 2013; Teutschbein and Seibert, 2010), they still contain valuable information about real precipitation, and therefore can provide a basis to quantify future climate changes (Maraun et al., 2010).

Among the approaches used to produce more realistic precipitation fields are a number of statistical downscaling techniques (Fowler et al., 2007). These include various delta change or change factor approaches; such methods use the size and direction of changes in future precipitation from a baseline simulation, as opposed to using climate model output directly (Kay et al., 2006). Various forms of the change factor methodology have been used ranging from simplistic approaches, typically using changes to monthly mean or seasonal precipitation totals to develop change scenarios (Anandhi and Frei, 2011; Prudhomme et al., 2010; Kay and Jones, 2012), to more sophisticated approaches using changes to statistical variables within a weather generator (Kilsby et al., 2007). Studies by Cameron et al. (2000) and Cameron (2006) used a change factor methodology under a continuous simulation methodology. This was achieved via the coupling of a stochastic rainfall generator with a rainfall-runoff model. Estimated changes in monthly precipitation were then used to derive a variety of climate scenarios and perturb the inputs of the modelling framework.

Applying Model Output Statistics (MOS) or bias correction has also emerged as a useful tool in allowing climate model output to be utilised in climate impact studies (Maraun et al., 2010; Bell et al., 2007; Cloke et al., 2012). Such approaches primarily remove the systematic error present in RCM precipitation by correcting this to more closely replicate observed behaviour. The reduction of errors in modelled precipitation therefore allows realistic flow regimes under observed conditions to be replicated via cascading these results through rainfall-runoff models; this is then thought to allow for a greater confidence in assessing the impacts of future changes on flow regimes (Wood et al., 2004; Maraun et al., 2010). However Cloke et al. (2012) highlighted the difficulties in using MOS in climate impact studies, with MOS having a clear effect on the change signal when compared with using RCM output directly. Issues relating to stationarity were also highlighted; the assumption that the statistical relationships between observed and modelled variables do not change in the future may not be valid. It was therefore suggested that if MOS approaches were to be applied, alternative approaches should also be used.

The increased application of climate models in hydrological impact studies has led to the development of various application techniques, from simple scaling approaches to complex statistical methods. However, the emergence of differing methods introduces further uncertainty as comparing the performance of different approaches is difficult to achieve (Fowler et al., 2007). This has led to the suggestion that multiple ensemble techniques should be employed to provide a more robust understanding of future flood risk (Cloke et al., 2012). Others have questioned the need for such elaborate measures, suggesting that coping with uncertainty in the observed record already poses a significant challenge (Wilby and Dessai, 2012). This paper compares a number of application procedures to ascertain their influence on the resulting change signal. Uncertainty in the observed record is also assessed, permitting a discussion as to the value of using climate model output to inform flood risk decision making.

An ensemble of RCMs from the UKCP09 and ENSEMBLES projects are applied via a number of application techniques to explore the possible effect of climate change on flooding in the Avon catchment, in the UK. Each of the ensemble approaches are applied under a continuous simulation methodology similar to that outlined by Cameron et al. (2006). In total three application approaches are applied: (1) a quantile change factor approach (2) Model Output Statistics (MOS) or bias correction (3) a direct forcing approach. Each approach is used to assess changes to extreme flows for the 2061–2099 time-period. Flood events with return periods of up to 200 years are considered in this study due to the continuous simulation approach, focusing particularly on the 10, 25, 50, 100 and 200 year events. The aim of the study is to conduct a climate change impact assessment that accounts for multiple sources of uncertainty in the RCM's themselves and how they are applied under different assumptions. An evaluation of the influence that the selected joint ensemble-application approach has on projected extreme flows is quantified. In addition to the assessment of future changes, we quantify the uncertainty in predictions over the observed record period. This permits a comparison between future flow projections and current uncertainties in the quantification of flood risk return periods. The implications of this comparison and the resultant uncertainties, in terms of informing flood risk management and adaptation, are then discussed.