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# Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling

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ABSTRACT

*Study region:* The South Asia.

*Study focus:* This paper presents future climate and runoff projections for the South Asia region under the RCP8.5 scenario with climate change informed by 42 CMIP5 GCMs. Runoff is projected for 0.5° grids using hydrological models with future climate inputs obtained by empirically scaling the historical climate series.

*New hydrological insights:* The modelling results indicate that future runoff will increase throughout most of the region except in the far north-east and far north-west. The median projection shows increases in mean annual runoff of 20–30% in the Indian sub-continent for 2046–2075 relative to 1976–2005. The change in runoff is driven mainly by the change in precipitation, moderated (in wetter futures) or intensified (in drier futures) by higher temperature and potential evaporation. The paper also investigates the uncertainties of the projection due to scaling methods and selection of GCMs. The difference in runoff projections from different scaling methods is small relative to the large uncertainty in precipitation projections from the GCMs. Sub-selecting only the "better" performing GCMs shows marginal difference in the uncertainty range of projected runoff. For the broad scale projections presented here, it is best to use projections informed by all the GCMs to provide an indication of the full uncertainty range.

## 1. Introduction

Water security in South Asia will be under increasing stress owing to socio-economic growth and global climate change. It is forecasted that the population in South Asia will be more than 2.3 billion by 2050 (United Nations, 2015). The growth of population and expanding economies will result in an increase in water demand. Meanwhile, there is strong evidence that many parts of South Asia are experiencing long-term warming trends that will continue into the future (Hijioka et al., 2014). The changes in climate will have significant impacts on water availability. Moreover, the warmer future climate will increase evapotranspiration and hence increase demand for water in irrigated agriculture, urban centres and water-dependent ecosystems. Exacerbated by climate change, it is estimated that water scarcity could cost up to 6% GDP loss in South Asia by 2050 (World Bank, 2016).

As water impacts practically all sectors (people, agriculture, industries and ecosystems), there have been considerable research efforts on predicting or projecting water availability under future climate conditions (e.g. Devkota and Gyawali, 2015; Gupta and Deshpande, 2004; Immerzeel et al., 2010; Immerzeel and Bierkens, 2012; Nepal and Shrestha, 2015) to inform the development of effective adaptation options. For South Asia, most studies of hydrological response to climate change only investigate limited regions

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and climate scenarios. For example, Akhtar et al. (2008) simulated the hydrological response to climate change for three river basins (Astore, Gilgit and Hunza) in the upper Indus using two downscaling approaches driven by the HadAM3P GCM. One of the downscaling approaches was a form of statistical downscaling using the 'delta change' approach and another was dynamical downscaling using the PRECIS regional climate model at 25 km resolution. Lutz et al. (2014) assessed potential changes of water availability for the large basins in northern South Asia, with increased runoff projected for 2050 for the upper Ganges, Brahmaputra, Salween and Mekong primarily due to projected precipitation increases and for the Indus due to accelerated glacier melt in the upper basin.

The hydrological response to climate change is generally predicted using downscaled future climate projections to drive a hydrological model (Chiew et al., 2009a; Teng et al., 2012a). One of the key challenges in factoring climate change into water resources management lies in the uncertainty in the projections (Jiménez Cisneros et al., 2014; Lopez et al., 2009). The sources of the projection uncertainties could be from the GCMs, the downscaling approaches, or the hydrological models (Chen et al., 2011; Teng et al., 2012b; Vetter et al., 2016). The performance of GCMs over the South Asia region have been investigated by quite a few researchers (e.g., Chaturvedi et al., 2012; Freychet et al., 2015; Jourdain et al., 2013; Ogata et al., 2014; Palazzi et al., 2015; Saha et al., 2014). For example, Saha et al. (2014) found that the majority of the CMIP5 GCMs fail to simulate the post-1950 decreasing trend of Indian summer monsoon rainfall, as they did not capture the weakening monsoon associated with the warming of southern Indian Ocean and strengthening of cyclonic formation in the tropical western Pacific Ocean. Some studies have suggested placing more weight on or using only projections from the better performing GCMs As noted by Palazzi et al. (2015), however, it is challenging in selecting better performing GCMs for the region as none of GCMs can reproduce all the salient features (e.g. seasonal and annual rainfall amounts, distribution and trend, or the large scale atmospheric-oceanic drivers of rainfall in the region). Like the GCMs, the latest dynamic downscaling runs in the CORDEX regional climate model experiments also do not capture the observed monsoon precipitation trends or the correct magnitude of observed warming (Ghimire et al., 2015; Mishra et al., 2014). In any case, the uncertainty in climate projections (from GCMs and from downscaling approaches) must be adequately represented within the specific context and objectives of any hydrological modelling and integrated water resources management study.

This paper aims to present future climate (precipitation, temperature and potential evaporation) and runoff projections across South Asia, and the associated uncertainties and robustness of the projections from different considerations or treatments of climate change projections and hydrological modelling. The future runoff is projected using hydrological models with future climate inputs informed by 42 GCMs reported in the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (IPCC, 2013). The paper investigates (i) the sensitivity of runoff to changes in the climate variables, (ii) the projected runoff change resulting from different hydrological modelling approaches, (iii) the projected runoff change using different empirical downscaling approaches, (iv) the uncertainties of runoff projection within and across the GCMs, and (v) whether using a sub-set of the 'better' performing GCMs can reduce the uncertainties in the projection. The structure of the paper is as follows – Section 2 outlines the data and methods used; Section 3 presents and discusses the projected changes in the climate variables across South Asia; Section 4 presents the climate change impacts on runoff and water supply security, and also discusses results and implications from different modelling considerations; Section 5 presents the summary and conclusions.

## 2. Data and methods

In this study, the South Asia region refers to the domain between 5.25–38.00 °N and 65.25–93.75 °E. To facilitate presentation and discussion of results, nine sub-regions based on the freshwater ecoregion map of Abell et al. (2008) are used. The nine sub-regions, as shown in Fig. 1, are North-West region (NW), part of the Tibetan Plateau (TP), Indus River Basin (IND), Ganges-Brahmaputra River Basin (GA), part of the Arakan Coast (AC), Narmad-Tapti River Basin (NT), Deccan Plateau (DP), Ghats Coast (GH), and Sri Lanka Island (SL).

### 2.1. Baseline observations and CMIP5 database

The baseline period of 1976–2005 is used for this study ('baseline', 'present' and 'historical' are used interchangeably throughout the paper, they all refer to the period 1976–2005). The daily gridded climate data of precipitation, temperature, wind speed, air pressure and radiation are obtained from the Princeton Global Forcing (PGF) dataset with spatial resolution of $0.5^{\circ} \times 0.5^{\circ}$ (Sheffield et al., 2006). Fig. 1 shows the annual mean of precipitation, temperature, potential evaporation and aridity index for the baseline period across the South Asia region. The precipitation and temperature comes directly from the PGF dataset. Potential evaporation is estimated from the PGF climate variables using Morton's formulation of wet environment (or equilibrium or areal potential) evaporation (Morton, 1983; Chiew and McMahon, 1991). Aridity index is defined as mean annual potential evaporation divided by mean annual precipitation.

The future climate scenarios are derived from the CMIP5 database (http://cmip-pcmdi.llnl.gov/cmip5/), which archives transient climate experiments from more than 20 climate modelling groups around the world. All the ensemble runs of 42 CMIP5 GCMs with both historical and future outputs available on 15 March 2013 (the same date as that adopted by IPCC AR5) are used here. The results presented in this study are for a future period over 2046–2075 relative to the baseline period (1976–2005) for RCP8.5 (high representative greenhouse gas concentration pathway corresponding to radiative forcing of 8.5 $W/m^2$ by 2100 relative to pre-industrial value, see Moss et al., 2010; Taylor et al., 2012). It is worth noting that the discussions and results presented throughout this paper are applicable for any future global warming pathway or scenario, but the projected changes would be smaller for lower RCPs (like RCP4.5, RCP2.6 and RCP6.0).