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Climate model performance and change projection for freshwater fluxes: Comparison for irrigated areas in Central and South Asia

Shilpa M. Asokan[a], Peter Rogberg[a], Arvid Bring[a,b], Jerker Jarsjö[a], Georgia Destouni[a,*]

[a] Department of Physical Geography, and Bolin Centre for Climate Research, Stockholm University, Sweden
[b] Water Systems Analysis Group, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, USA

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ABSTRACT

Study region: The large semi-arid Aral Region in Central Asia and the smaller tropical Mahanadi River Basin (MRB) in India.

Study focus: Few studies have so far evaluated the performance of the latest generation of global climate models on hydrological basin scales. We here investigate the performance and projections of the global climate models in the Coupled Model Intercomparison Project, Phase 5 (CMIP5) for freshwater fluxes and their changes in two regional hydrological basins, which are both irrigated but of different scale and with different climate.

New hydrological insights for the region: For precipitation in both regions, model accuracy relative to observations has remained the same or decreased in successive climate model generations until and including CMIP5. No single climate model out-performs other models across all key freshwater variables in any of the investigated basins. Scale effects are not evident from global model application directly to freshwater assessment for the two basins of widely different size. Overall, model results are less accurate and more uncertain for freshwater fluxes than for temperature, and particularly so for model-implied water storage changes. Also, the monsoon-driven runoff seasonality in MRB is not accurately reproduced. Model projections agree on evapotranspiration increase in both regions until the climatic period 2070–2099. This increase is fed by precipitation increase in MRB and by runoff water (thereby decreasing runoff) in the Aral Region.

1. Introduction

To study climate-driven change in local-regional freshwater systems, downscaled climate model data are often used, from either statistical or dynamical downscaling methods, and subsequently processed through hydrological modeling. This approach provides a higher-resolved local-regional view of climate and hydrology than direct hydro-climatic output of global climate models. However, both the downscaled climate data and the hydrological model that uses them still depend fundamentally on the climate forcing and boundary conditions provided as output from global climate models. The driving

* Corresponding author at: Department of Physical Geography, Stockholm University, SE-106 91 Stockholm, Sweden.
E-mail address: georgia.destouni@natgeo.su.se (G. Destouni).

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global climate model may thus have greater impact on hydrological projection uncertainty than the hydrological modeling (Raje and Krishnan, 2012).

Furthermore, climate models are now used for multi-decadal predictions of climate change, in addition to the previous main focus on projecting differences between hypothetical future scenarios (Trenberth, 2010). Direct climate model output is also used outside the climate science community, e.g., for understanding of and adaptation to climate-driven freshwater changes (Arnell, 1999; Gleick and Chalecki, 1999; Lettenmaier et al., 1999; Kundzewicz and Stakhiv, 2010; Törnqvist et al., 2014). Global climate models thus influence the downscaled climate forcing used in hydrological modeling, multi-decadal predictions of hydro-climate, and direct freshwater assessments based on global climate model output. It is therefore important to study and inform the hydrological science community and other users about how the global climate models represent observations and agree among them with regard to freshwater conditions and changes.

Simulations and projections of Earth's past and future climate, including hydro-climate, are provided by the Coupled Model Intercomparison Project (CMIP), which is coordinated by the World Climate Research Programme and supports the assessment reports of the Intergovernmental Panel on Climate Change (IPCC). The global climate models in Phase 5 of the project (CMIP5; Taylor et al., 2012) are developed on their predecessors, the CMIP3 models (Meehl et al., 2007), with more complete representations of external forcing and with increased resolution. One of the earliest evaluations of CMIP5 datasets by Knutti and Sedláček (2013) showed similar model spread in CMIP3 and CMIP5 projections on global scale. Furthermore, a recent study by Mueller and Seneviratne (2014) indicated shortcomings in the CMIP5 climate model simulations of evapotranspiration and precipitation on regional scale.

However, few studies have so far evaluated CMIP5 model performance on hydrological basin scales. For planning and sustainable management of freshwater resources under both global and local-regional changes, hydrological drainage basins are recommended or even mandated as relevant spatial units (Pahl-Wostl, 2007; UNECE, 2009). Therefore, also climate model results for freshwater conditions and changes, as required in management, planning and adaptation for freshwater security and sustainability, need to be evaluated on hydrological basin scales. Moreover, hydrological basins offer a substantial modeling advantage of water and constituent balance closure by their topographic integration of both water fluxes (Karlsson et al., 2012; Destouni et al., 2013; Van der Velde et al., 2013; Törnqvist et al., 2014; Jaramillo and Destouni, 2014) and waterborne mass fluxes (Jarsjö and Destouni, 2004; Darracq et al., 2005; Shibuo et al., 2006; Destouni and Darracq, 2009; Törnqvist et al., 2011; Visser et al., 2012). Törnqvist et al. (2014) is one recent study that has applied a hydrological basin perspective for observation-based evaluation of CMIP5 performance with regard to freshwater fluxes, their resulting net water balance, and their changes in the Lake Baikal drainage basin. Other CMIP5 performance studies with focus on freshwater changes have not considered the aspect of basin-scale water balance (Deng et al., 2013; Siam et al., 2013), have not accounted for the historic water-use alterations within the basins (Ibrahim et al., 2015; Wambura et al., 2015; Yan et al., 2015), or have mostly discussed anthropogenic influences on the global scale (Alkama et al., 2013).

Furthermore, freshwater changes do not only depend on atmospheric climate change but also on direct change drivers in the landscape (Foley et al., 2005; Shibuo et al., 2007; Weiskel et al., 2007; Wisser et al., 2010; Asokan et al., 2010; Destouni et al., 2013). A recent worldwide study shows that landscape drivers are needed to explain observed historic freshwater changes in 74% of investigated hydrological basins over all continents (Jaramillo and Destouni, 2014); only in 26% of the studied basins worldwide can the observed atmospheric climate changes alone explain the observed freshwater changes. Adequate assessment of freshwater changes hence require account of both atmospheric climate change and changes in the landscape (Milly et al., 2002; Seneviratne et al., 2006; Piao et al., 2007; Destouni et al., 2010; Asokan and Destouni, 2014), which poses an even greater quantification challenge than just atmospheric-driven water changes (Milly et al., 2005; Groves et al., 2008; Bengtsson, 2010; Jarsjö et al., 2012).

Main human pressures that alter freshwater fluxes across the world include expansion of irrigated and non-irrigated agriculture, deforestation, and other human-driven land-use and water-use changes in the landscape (Gordon et al., 2005; Destouni et al., 2013; Törnqvist et al., 2015). In densely populated areas, such as many regions of Asia, water diversions and extractions for human uses amount to a considerable fraction of the original freshwater flows in hydrological basins (Shibuo et al., 2007; Destouni et al., 2010; Jarsjö et al., 2012; Törnqvist and Jarsjö, 2012; Asokan and Destouni, 2014; Karthe et al., 2015); as such, these diversions and extractions can greatly influence water fluxes and water availability in the landscape, in addition to such influences of atmospheric climate change.

In the present study, we investigate the performance of CMIP5 climate models in two Central and South Asian hydrological basins with previously well-investigated and compared freshwater changes, driven by direct human changes in the landscape (primarily irrigation developments in both regions) in addition to atmospheric climate change (Destouni et al., 2013; Asokan and Destouni, 2014). The two basins are: the Aral Sea drainage basin in Central Asia (1,888,810 km^2, including also the terminal Aral Sea itself and referred to as the Aral Region in the following) (Shibuo et al., 2007; Destouni et al., 2010), and the Mahanadi River Basin in India (135,084 km^2, referred to as MRB) (Asokan et al., 2010). In this study, we investigate and compare the CMIP5 model ability to reproduce observed historic conditions and project future changes in freshwater fluxes and their resulting net water balance in these two Asian basins. We further compare the CMIP5 model performance with that of the predecessor CMIP3 model generation (Solomon et al., 2007); the latter has also previously been analyzed for the Aral Region (Jarsjö et al., 2012). For future projections, we evaluate the consistency among individual CMIP5 model implications for future water fluxes and their changes.

The two investigated Asian basins are similar with regard to the primary direct human drivers of historic freshwater changes over the last century; irrigation developments in the basins have over this time period driven evapotranspiration