Journal of Hydrology 541 (2016) 1003–1019

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Effects of different regional climate model resolution and forcing scales on projected hydrologic changes

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ARTICLE INFO

Article history:
Received 17 April 2016
Received in revised form 13 July 2016
Accepted 7 August 2016
Available online 8 August 2016
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief

Keywords:
Climate change
Regional climate model
Spatial aggregation
Horizontal resolution
Hydrologic model structure

ABSTRACT

We examine the effects of regional climate model (RCM) horizontal resolution and forcing scaling (i.e., spatial aggregation of meteorological datasets) on the portrayal of climate change impacts. Specifically, we assess how the above decisions affect: (i) historical simulation of signature measures of hydrologic behavior, and (ii) projected changes in terms of annual water balance and hydrologic signature measures. To this end, we conduct our study in three catchments located in the headwaters of the Colorado River basin. Meteorological forcings for current and a future climate projection are obtained at three spatial resolutions (4-, 12- and 36-km) from dynamical downscaling with the Weather Research and Forecasting (WRF) regional climate model, and hydrologic changes are computed using four different hydrologic model structures. These projected changes are compared to those obtained from running hydrologic simulations with current and future 4-km WRF climate outputs re-scaled to 12- and 36-km.

The results show that the horizontal resolution of WRF simulations heavily affects basin-averaged precipitation amounts, propagating into large differences in simulated signature measures across model structures. The implications of re-scaled forcing datasets on historical performance were primarily observed on simulated runoff seasonality. We also found that the effects of WRF grid resolution on projected changes in mean annual runoff and evapotranspiration may be larger than the effects of hydrologic model choice, which surpasses the effects from re-scaled forcings. Scaling effects on projected variations in hydrologic signature measures were found to be generally smaller than those coming from WRF resolution; however, forcing aggregation in many cases reversed the direction of projected changes in hydrologic behavior.

1. Introduction

Although global climate models (GCMs) are widely used for generating information on future climate scenarios, their native grid size (~100 to 200 km on a side) is a serious limitation for characterizing climate projections at the basin scale, where features such as elevation and aspect become relevant. To reconcile differences between coarse resolution GCM outputs and regional or local scale climate processes, Regional Climate Models (RCMs) are run with lateral boundary conditions from GCMs to force fine-scale climate simulations, a process typically referred to as dynamical downscaling (Xu, 1999; Fowler et al., 2007). Teutschbein and Seibert (2010) presented a detailed review of approaches that make use of RCMs for quantifying climate change impacts on hydrologic processes, and a plethora of additional example applications can be found in the literature (e.g., Wood et al., 2004; Steele-Dunne et al., 2008; Suklitsch et al., 2008; Kay et al., 2009; Prudhomme and Davies, 2009; Gao et al., 2011; Vicuña et al., 2011; Majone et al., 2012; Wi et al., 2012; Lauer et al., 2013; Velázquez et al., 2013).

However, a key aspect rarely explored is the choice of RCM horizontal resolution, which determines how precipitation – in particular snowfall – and other hydrologic variables are

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http://dx.doi.org/10.1016/j.jhydrol.2016.08.010
0022-1694/

represented in highly heterogeneous regions (Rasmussen et al., 2011). For example, Kleinn et al. (2005) compared hydrologic model simulations forced with 14-km and 56-km RCM outputs in the Rhine basin in Central Europe, finding that although the finer resolution provided more realistic precipitation fields, improvements in streamflow simulation skill were small. Contrarily, Dankers et al. (2007) showed that 12-km simulations conducted with the HIRHAM RCM provided a better representation of orographic patterns and extreme precipitation events in the Upper Danube basin in Central Europe, and better simulations of hydrologic extreme events at the sub-basin scale in comparison to coarser (50-km) RCM outputs. Graham et al. (2007) concluded that a 25-km resolution provided more systematic and less spatially variable biases in RCM precipitation and temperature fields when compared to 50-km resolution. Van Roosmalen et al. (2010) evaluated the implications of choosing different RCM resolutions (12-, 25- and 50-km) on delta change factors (e.g., additive perturbation for temperature, multiplier for precipitation) – from a control and future climate scenario – computed at a monthly basis for Denmark, finding that the added value of increasing resolution was almost negligible. A set of studies conducted in the Colorado Headwaters Region (Ikeda et al., 2010; Rasmussen et al., 2011, 2014) explored the effects of horizontal resolution using the Weather Research and Forecasting (WRF) regional climate model (Skamarock et al., 2008). Specifically, they showed that the use of horizontal resolution of 6 km or less in RCMs allowed accurate estimations of vertical motions driven by topography without the need to include a convective parameterization scheme, improving the representation of seasonal snowfall and snowpack. Along these lines, Prein et al. (2013) compared the effects of different horizontal resolutions (4-, 12- and 36-km) on daily heavy precipitation events simulated by WRF over the same domain, finding that only the 4-km simulation was able to reproduce heavy summertime events, and that both 4-km and 12-km outputs were comparable and superior to the 36-km simulation when looking at winter events. More recently, Olsson et al. (2015) obtained similar findings – i.e., better simulation of summer extremes and summer wet spells – when moving from 50-km to 6-km horizontal grids.

The choice of the RCM resolution is typically determined by climate modelers to optimize some constraints including available computer (i.e., time to compute the solution) and the need to represent selected important atmospheric processes as explicitly as possible, but the domains of these solutions are nearly always rectilinear for the Eulerian grid. However, hydrologic modelers choose any shaped spatial element named Hydrologic Response Unit (HRU) at which the hydrologic model is run. The HRUs can be the entire catchment, a grid box, or hydrologically similar areas (e.g., similar soil-vegetation areas) and those are at different scale than RCM resolution. Accordingly, scaling or spatial aggregation of RCM outputs is nearly always required to obtain HRU averaged meteorological forcing. Several studies have examined the hydrologic implications of spatially aggregating meteorological fields from finer scales (e.g., Finnerty et al., 1997; Koren et al., 1999; Bell and Moore, 2000; Arnaud et al., 2002; Liang et al., 2004; Shrestha et al., 2006, 2007; Tramblay et al., 2011; Rasmussen et al., 2012), showing mixed conclusions. Lobligeois et al. (2014) conducted a detailed review of previous efforts, and analyzed the benefits of using high-resolution rainfall fields for flood simulation, including a large sample of flood events (3620) in a large number of catchments (181). Although they concluded that these effects are "scale-dependent and event-specific-dependent", they also found that regions with high spatial rainfall variability obtained the greatest benefits from high-resolution precipitation inputs. Importantly, none of the above studies assessed the sensitivity of hydrologic changes to the spatial scale at which historical and future climate datasets are used.

Given the evidence showing that RCM resolution affects climate outputs, a natural question that arises is how the effects of RCM horizontal resolution on hydrologic portrayals of climate change compare to those of scaled RCM at the same horizontal resolution. This paper examines how the grid spacing adopted in a RCM for dynamical downscaling affects hydrologic change estimates. In particular, we aim to characterize these effects on: (i) historical simulation of signature measures of hydrologic behavior (e.g., runoff ratio, seasonality, log-term baseflow), and (ii) projected hydrologic change in terms of annual water balance and hydrologic signature measures. Further, we compare the implications of choosing different horizontal grid sizes to those associated with spatial aggregation of high resolution RCM output. Given the increasing awareness of the importance of hydrologic model structural uncertainty to climate change impact studies (e.g., Boorman and Sefton, 1997; Jones et al., 2006; Jiang et al., 2007; Kay et al., 2009; Ludwig et al., 2009; Bae et al., 2011; Bastola et al., 2011; Najafi et al., 2011; Poulin et al., 2011; Miller et al., 2012; Vano et al., 2012; Surfleet et al., 2012; Addor et al., 2014; Mendoza et al., 2015, 2016; Mizukami et al., 2016), we include four different hydrologic/land surface models for two reasons: to examine the robustness of RCM resolution and forcing aggregation effects, and to obtain insights on the relative importance of forcing-related decisions versus hydrologic model choice.

The remainder of this paper is organized as follows. Section 2 provides a description of the study domain. Section 3 describes the meteorological forcing data, hydrologic models and the experimental design adopted in this study. Section 4 illustrates how the choice of RCM horizontal resolution and forcing aggregation affect hydrologic portrayals – obtained from different hydrologic models – under historical and modified climatic conditions. Finally, Section 5 summarizes our main findings.

2. Study area

The Colorado River basin (CRB) is one of the major water sources for consumption, irrigation and hydropower in the western United States, draining parts of seven states and Mexico, and covering the needs of more than 30 million people. Given its strategic relevance, several studies have been conducted to quantify the potential effects of changes in precipitation and temperature on the hydrology of this area (e.g., Milly et al., 2005; Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; Ray et al., 2008; Rasmussen et al., 2011, 2014; Miller et al., 2011, 2012; Bureau of Reclamation, 2012; Vano et al., 2012; Vano and Lettenmaier, 2014). Much of the water for this region comes from the high-elevation area – the Colorado Headwaters – that acts as a natural reservoir during the winter, storing precipitation as snowpack. Hence, we select three basins in the Colorado Headwaters with outlets at streamflow stations managed by the United States Geological Survey (USGS) – Yampa River at Steamboat Springs, East River at Almont and Animas River at Durango – whose location and elevation ranges are shown in Fig. 1.

Table 1 summarizes the main hydroclimatic characteristics of the three basins for which historical data are available, over an 8-year period (October/2000 - September/2008). Mean basin precipitation ranges between 700 mm/year and 900 mm/year, while mean basin elevation is above 2500 m.a.s.l. Among these basins, the East River at Almont has the largest runoff ratio (0.42), and the Yampa at Steamboat Springs has the lowest runoff ratio (0.32, with the lowest runoff and precipitation amounts). The land surface of the Yampa and Animas River basins is predominantly covered by deciduous forests (26% at Yampa and 23% at Animas) and evergreen forests (37% at Yampa and 39% at Animas), while