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Assessing the impacts of future climate change on the hydroclimatology of the Gediz Basin in Turkey by using dynamically downscaled CMIP5 projections

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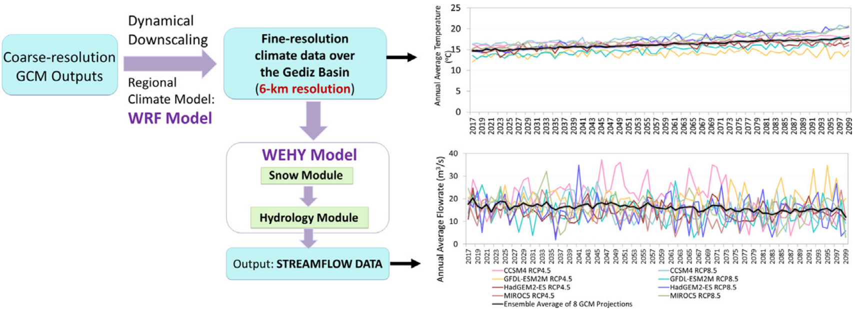
HIGHLIGHTS

- Dynamical downscaling of eight CMIP5 future climate projections
- Coupling of a regional climate model and a physically-based hydrology model
- Increasing trend in average annual temperature of the ensemble of all projections
- Decreasing trend in average annual inflows of the ensemble of all projections

GRAPHICAL ABSTRACT



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ABSTRACT

The Gediz Basin is a Mediterranean watershed along the Aegean coast of Turkey, in which the most important economic activity is agriculture. Over the last few decades, this basin has been experiencing water-related problems such as water scarcity and competing use of water. This study assesses the impact of future climate change on the availability of water resources in the Gediz Basin during the 21st century by investigating the inflows into the major reservoir in the basin, Demirkopru Reservoir, which is the major source of irrigation water to the basin. The analysis in this study involves setting up a coupled hydro-climate model over the Gediz Basin by coupling the Weather Research and Forecasting (WRF) model to the physically-based Watershed Environmental Hydrology (WEHY) model. First, the WRF model is used to reconstruct the historical climatic variables over the basin by dynamically downscaling the ERA-Interim reanalysis dataset. The calibrated and validated WRF model is then used to dynamically downscale eight different future climate projections over the Gediz Basin to a much finer resolution (6 km), which is more appropriate for the hydrologic modeling of the basin. These climate projections are from four Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Climate Models (GCMs), namely, CCSM4, GFDL-ESM2M, HadGEM2-ES, and MIROC5, under two IPCC (The Intergovernmental Panel on Climate Change) representative concentration pathway scenarios (RCP4.5 and RCP8.5). The outputs from the WRF model are then input into the WEHY model, which is calibrated and validated over the basin, to simulate the hydrological processes within the basin and to obtain the projected future inflows into the Demirkopru Reservoir. Results of the future analysis over the 21st century (2017–2100) are then compared to the historical values (1985–2012) to investigate the impacts of future climate change on the hydroclimatology of the Gediz Basin.

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1. Introduction

As much as the current climate is important to today's human activities, its future projections play an important role in alerting scientists and policy-makers to the expected impacts of future climate change. With such projections, the appropriate mitigation or adaptive measures can be accordingly planned for. Under a changing climate, increasing atmospheric concentrations of carbon dioxide and other trace gases released to the atmosphere due to a number of natural and anthropogenic processes bring about climatic alterations that have substantial impacts on the global hydrological system and water resources (Piao et al., 2007; Gerten et al., 2008). Moreover, the timing and magnitude of surface runoff and soil moisture, as well as the water availability are affected by these changes in the climate system (Gleick, 1989; Kundzewicz et al., 2008; Hidalgo et al., 2009). For this reason, hydrological impact analysis of future climate change has become a thriving area of research.

Over the last few decades, numerous studies have been carried out to investigate future climate change impacts on river flows and water resources at global (Arnell, 1999a, 2003; van Vliet et al., 2013), continental (Arnell, 1999b; Lehner et al., 2006), and regional scales (Nohara et al., 2006; Li et al., 2013; Bohner et al., 2014; Smiatek et al., 2014; Amin et al., 2017). Such studies are usually based on the climate projections of Global Climate Models (GCMs), which are also known as General Circulation Models. GCMs are the most powerful tools available today to understand the global climate system, and to project future climate change, which is associated with a variety of anthropogenic greenhouse gas emission scenarios (McGuffie and Henderson-Sellers, 2001). The capability of the GCMs in terms of how well they represent the physical climatic processes and reproduce the observed phenomena greatly affects the reliability of the projected changes in climate (ul Hasson et al., 2016). Several such GCMs were used by climate modeling groups from around the world to support the development of the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5) through a set of climate model experiments, known as the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). CMIP5 experiments were designed to enhance the understanding of the climate, and to help simulate the possible effects of future climate change under the scenarios known as the Representative Concentration Pathways (RCPs) (Moss et al., 2010). The RCPs focus on the 'concentrations' of greenhouse gas emissions, which will cause climate change, and they include 'pathways' that these concentrations will follow over time to reach a particular radiative forcing by the year 2100. Radiative forcing levels for the set of four RCPs, adopted by the IPCC, are 2.6, 4.5, 6.0 and 8.5 W/m^2 by the end of the 21st century for RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively (van Vuuren et al., 2011).

However, due to the GCMs' coarse spatial resolutions, which generally exceed 100 km, the GCMs are not able to account for the effect of regional- and watershed-scale land conditions on the climate, and thus they are not able to resolve cloud formation, soil moisture transfer or the mesoscale processes such as convection and orographic effects (McGuffie and Henderson-Sellers, 2001; Christensen and Christensen, 2003; Fowler et al., 2007; Jang et al., 2017). To overcome the scale incompatibility problem between the coarse-resolution GCM outputs (or reanalysis data) and the resolution required for regional- or watershed-scale impact assessment, a downscaling technique is required (Maraun et al., 2010). There are two fundamental downscaling techniques: (1) statistical downscaling, which is done by relating GCM-resolution climate variables and local observation data empirically with a statistical relationship (Wilby and Wigley, 1997; Wilby et al., 1998), and (2) dynamical downscaling, in which a fine-resolution regional climate model (RCM) is embedded within a GCM to obtain local weather variables by the explicit solution of the process-based physical dynamics of the system (Xu, 1999; Fowler et al., 2007; Spak et al., 2007). Both downscaling techniques have advantages and disadvantages, and their outputs could change based on the study area and various spatial and temporal scales (Jang and Kavvas, 2015). Although statistical downscaling requires less computational effort and is easier to apply than dynamical downscaling, it depends on the fundamental assumption of climate stationarity and it cannot incorporate the natural variability of the climate system (Fowler et al., 2007; Jang and Kavvas, 2015). Dynamical downscaling, on the other hand, is not restricted to such stationarity assumptions because it uses the same fundamental equations as a GCM to represent atmospheric dynamical and physical processes. As a result, dynamical downscaling has the advantage of being a physically based method that conserves the mass, momentum, and energy in the system, and that incorporates all topographical and natural factors into its downscaled atmospheric variables.

The downscaled atmospheric variables from GCMs are usually used as inputs into watershed hydrology models, thus making it possible to assess the impacts of climate change on a regional scale. These watershed hydrology models are used to represent the dynamic interactions occurring between the climate and the land surface hydrology. For instance, vegetation, snow cover, and permafrost active layer are all very susceptible to the changes in the lower boundary layer of the atmosphere. The hydrologic characteristics are affected significantly by the moisture and heat transfer between the land surface and atmosphere, which yield the lower boundary conditions for the climate modeling (Kavvas et al., 1998). Hence, using hydrologic models to assess the impacts of climate change has many attractive characteristics. First, the models are readily available to simulate various climatic conditions, and some are even established to run for different dominant hydrologic process representations and spatial scales. This provides flexibility in defining and selecting the most appropriate model for the evaluation of any particular watershed/region. Second, hydrologic models can be adjusted to run the characteristics of the available data. Since GCM-derived climate change scenarios, which are obtained from different levels of downscaling, can be used as hydrologic model inputs, a variety of hydrological responses to climate change scenarios can be simulated. Third, hydrologic models are relatively easier to tailor than GCMs. Fourth, hydrologic models can be used to assess the sensitivity of particular watersheds to climate change scenarios obtained from GCMs (Gleick, 1989; Schulze, 1997).

It is important to note, however, that uncertainties in the future simulations of both the hydrologic and climate models still exist, in spite of the improvements in their respective performances. The most significant source of uncertainty comes from the GCMs used (Wilby et al., 2006; Graham et al., 2007). Since different GCMs simulate atmospheric conditions and feedbacks by using different parameterizations and schemes, they differ widely in their projections, especially for precipitation (Wilby and Harris, 2006). Greenhouse gas emission scenarios, the conversion of emissions into atmospheric concentrations, and the associated radiative forcings also contribute to the uncertainty arising from GCM simulations (New and Hulme, 2000; Allen et al., 2001; Webster et al., 2003). Another source of uncertainty is the downscaling techniques, and this is due to the assumptions that are inherent in these techniques. As more assumptions are made with each modeling stage, uncertainties are naturally added to the computations (Trzaska and Schnarr, 2014). A third source of uncertainty arises from the selection of the hydrologic model. This is because hydrologic models use different sets of parameters and assumptions to simulate runoff at particular spatial and temporal scales (Praskievicz and Chang, 2009). Therefore, with all these uncertainties influencing the results of future simulations, an effective way to increase the reliability of long-term future projections would be through the use of an ensemble of model simulations. This is because predictions of climatic response to external forcings could be based on the statistical properties of these ensembles of simulations (Giorgi and Francisco, 2000; Raisanen and Palmer, 2001; Tebaldi and Knutti, 2007). Such an ensemble of simulations can be obtained by performing the required simulations for several of the GCM climate projections, thus providing the results for all these projections which would in turn help in understanding the expected future behavior through the study of their statistical properties.