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Hydrological changes in the U.S. Northeast using the Connecticut River Basin as a case study: Part 2. Projections of the future

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ABSTRACT

The focus of this study is on whether the recent warming-induced hydrologic changes in the U.S. Northeast will continue in the future (2046–2065) and how future changes of precipitation characteristics may influence other hydrological processes in the Connecticut River Basin (CRB). Our previous study (Parr and Wang 2014) examines the impact of climate changes during 1950–2011 on hydrological processes in the Northeast using the CRB as a case study. Our results showed a clear increase of precipitation intensity and suggested that the basin is entering a wetter regime more subject to meteorological flood conditions than to drought conditions. For this future analysis, three North American Regional Climate Change Assessment Program (NARCCAP) models are used to derive the meteorological forcing for the Variable Infiltration Capacity (VIC) hydrological model, using both present day and the future projected A1B scenario climate. Our future projections indicate wetter winters including significantly greater precipitation, runoff, and soil moisture, decreases to spring runoff, and enhanced ET for all four seasons. We also find a shift toward earlier and faster snow melting and an earlier date of peak discharge. Future precipitation extremes show a decreased amount compared to the early 21st Century, but increased when compared to our entire historic period or the late 20th Century, as well as a consistently increasing mean intensity throughout the past and future. Analyses of extreme hydrologic events reveals changing characteristics of flooding involving increasing duration but decreasing frequency of flood events as well as a reduction of drought risk.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC)'s 4th Assessment Report (AR4), warming of the climate is unequivocal and long term temperature changes have been observed at all spatial scales. Increasing temperatures have major effects on the hydrologic cycle and the surface energy budget. One such possible impact to the hydrological cycle is an increase in precipitation intensity. More specifically, atmospheric moisture holding capacity increases exponentially with temperature which can lead to more intense heavy precipitation (Trenberth, 1999; Allen and Soden, 2008; Shaw et al., 2011). The warming-induced changes to evapotranspiration (ET), characteristics of precipitation, and the seasonality of snow melt and stream flow peaks could all substantially increase flood and drought risks (e.g., Sheffield and Wood, 2007). Climate models project a warmer future world characterized by heavier rain and snow, increased heat waves, droughts, and floods (Tebaldi et al., 2006). Extreme events like droughts and floods account for a large proportion of climate-related damages.

Due to the substantial spatial variability of climate, there is a high degree of regional dependence of responses to climate change. This study focuses on the U.S. Northeast, a region where a strong increase of precipitation extremes has been observed in the past several decades. Based on NOAA's National Climatic Data Center (NCDC) station data archives, Groisman et al. (2005) analyzed the increases of the amount of precipitation in the top 1% of extreme events from 1958 to 2007, and found that within the U.S. these increases range from 9% in the Southwest to 67% in the Northeast. The U.S. Northeast is therefore a critical place to investigate extremes (Karl et al., 2009). In studying climate changes impact on hydrological processes in the Connecticut River Basin (CRB) of the U.S. Northeast during the period 1950–2011, Parr and Wang (2014) found significant increases in simple daily intensity of precipitation and the number of days with 10 mm or more of precipitation. They also found that the total amount of precipitation from the upper 1% of daily precipitation increased by 240% during 1950–2011 in CRB, and the weight of extreme precipitation is the greatest after the turn of the century, with extreme precipitation accounting for about 10.6% of total precipitation in the 1950s to 30.4% in the 2000s.

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It has been shown previously that runoff and stream flow have been increasing in the greater Northeast region of New England (Groisman et al., 2004; Collins, 2009), and peak discharges are on the rise in the entire Northeast (Collins, 2009). Wake and Markham (2005) and Hayhoe et al. (2006) documented greater winter discharge and an earlier shift of peak flows. Part 1 of this study (Parr and Wang, 2014) found that the hydrological cycle has changed toward greater discharge and runoff ratios, primarily as a result of increasing mean precipitation and increasing precipitation intensities combined. Increases to precipitation are almost entirely accounted for by increases to runoff, with a negligible trend in ET despite a strong warming trend. However, Parr and Wang (2014) found no discernable earlier shift in the timing of peak discharges and snowmelt season, and no increase of winter discharge. It was suggested that the basin is entering a wetter regime more subject to meteorological flood conditions than to drought conditions. This current study focuses on how the hydrologic cycle might be affected by continued warming in the future and whether the responses and trends found in the historical period will continue in the future.

Many studies have examined future hydrological changes of which several have focused on the Northeast. A number of studies have noted that as temperature increases, the increase of the atmospheric moisture holding capacity enhances the atmosphere's evaporative demand and therefore the global average of evapotranspiration (Trenberth, 1999; Huntington, 2006). Huntington (2003) suggested that increasing temperatures could lead to an ET-driven runoff reduction of 11–13%, especially in April and May, the wettest months in New England. Using the VIC model driven with future climate projections, Hayhoe et al. (2006) found increases in winter runoff but decreases in spring runoff with an earlier shift of peaks for the Northeast for the period 2000–2099. Hayhoe's simulation also showed reduced probability of winter low flows (10th percentile) and increased probability of high flows (90th percentile) with significantly higher flows across much of the northern part of the Northeast as well as projections of drier, hotter summers and more frequent short and medium-term droughts. Similar to these prior results, another study using the SWAT model in the Connecticut Watershed found annual surface runoff decreases of 12–22% (depending on CO2 emission scenarios) for the period 2060–2100, and these decreases take place primarily during the early spring to fall seasons (Marshall and Randhir, 2008). Higher temperatures could lead to a smaller proportion of winter precipitation falling as snow, which could lead to greater winter discharges and earlier peak discharges in the spring.

Sheffield and Wood (2008a, 2008b) stated that although increasing precipitation may lead to positive soil moisture trends in many parts of North America, increasing temperatures present the potential for enhanced drought in the 21st Century. Warming has major effects on the surface energy budget, and influences evapotranspiration (Teuling et al., 2009). The focus of this part of our study is on whether the recent warming-induced changes in precipitation characteristics will continue in the future and how future changes of precipitation characteristics may influence other hydrological processes in the CRB. In the following, Section 2 provides a description of the data sets and methods of analysis used, including the use of the Variable Infiltration Capacity (VIC) hydrological model. Section 3 describes the results of the study in regard to future changes, including mean hydrological changes, extreme precipitation, snow pack and discharge seasonality changes, and an in depth analysis of changing flood risk and drought risk respectively. Section 4 presents conclusions and discussion.

2. Data and methods

2.1. VIC model and data

The VIC hydrological model was calibrated based on observational river discharge on the Connecticut River during Part 1 of this study. The same model parameters are used here, including land cover data from University of Maryland's Global Land Cover Facility and soil data (type, texture, porosity, and bulk density) from Reynolds et al. (1990) made available by the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center (NGDC). The same soil layers are used at depths of 0–10 cm, 10–40 cm, and 40–150 cm. To simulate the future hydrological conditions in the Connecticut River Basin, both present-day (1971–1995) and projected A1B scenario future (2046–2065) climate from the North American Regional Climate Change Assessment Program (NARCCAP) models are used to derive the meteorological forcing for the VIC model, including daily precipitation, surface air temperature, and wind speed. Note that VIC can be run in two different modes of operation, with the “water balance mode” requiring daily meteorological forcing and the “water and energy balance mode” requiring hourly forcing (Gao et al., 2009). Here the “water balance mode” is utilized for consistency with the availability of downscaled and bias-corrected future driving forcing for VIC.

To account for inter-model variability of future projections, data from three NARCCAP RCMs are used, including the Regional Climate Model version 3 (RegCM3; Giorgi et al., 1993a,b; Pal et al., 2000, 2007) driven with lateral boundary conditions (LBCs) from the Canadian Climate Centre Coupled General Circulation Model version 3 (CGCM3; Scinocca and McFarlane, 2004; Flato, 2012) (REGCM–CGCM), RegCM3 driven with LBCs from the Geophysical Fluid Dynamics Laboratory Climate Model (GFDL; GFDL Global Atmospheric Model Development Team, 2004) (REGCM–GFDL), and the Canadian RCM (CRCM; Caya and LaPrise, 1999) driven with LBCs from CGCM3 (CRCM–CGCM). The future daily meteorological forcing from each RCM–GCM combination was first downscaled to 1/8 degree resolution and bias-corrected using the methodology of Ahmed et al. (2013). Specifically, parameters for a quantile mapping methodology were derived by comparing the present-day climate from each model with the present-day observational data, and were then applied to the future climate projection from the same model to correct the model bias. The resulting downscaled and bias-corrected meteorological forcing data is then used to drive VIC for future hydrological projections.

Although data from additional NARCCAP models exist, they have been shown to predict very similar future changes (Ahmed et al., 2013). In addition, in terms of hydrological variables and indicators, downscaling and bias correction was shown to produce very similar hydrological results between different models in past studies (Wood et al., 2002, 2004). Within this study, the three different GCM–RCM combinations produce extremely similar mean and variability of stream flow and concur in signal for almost every hydrological analysis conducted. Among the ten RCMs and GCMs for which output were downscaled and bias-corrected for the domain of this study (Ahmed et al., 2013), the projected precipitation changes by the three models used in this study are within one standard deviation from the multi-model ensemble mean in most of the months, and none of the models stands out as an outlier. More importantly, in any specific month, of the three models used, some are above the ensemble mean and some are below. Therefore, results from our study should be representative of the larger ensemble behavior and should not contain systematic biases. We therefore consider the three combinations used here sufficient for studying changes in hydrological processes. Although the NARCCAP models have been shown to underestimate extreme precipitation in the U.S. East (Mishra et al., 2012), the quantile mapping approach corrects both mean and variability based on the Cumulative Distribution Functions (CDF), and thus has been shown to adjust for more frequent heavy precipitation events in this region (Ahmed et al., 2013), potentially correcting these underestimations.