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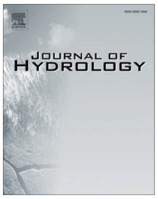

21st century increases in the likelihood of extreme hydrologic conditions for the mountainous basins of the Southwestern United States

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SUMMARY

Extreme hydrologic conditions, such as floods, droughts, and elevated stream temperatures, significantly impact the societal fabric and ecosystems, and there is rising concern about increases in the frequency of extreme conditions with projected climate changes. Here we ask what changes in the occurrence of extreme hydrologic conditions can be expected by the end of the century for the important water-generating, mountainous basins of the Southwestern United States, namely the Sierra Nevada and Upper Colorado River Basins. The extreme conditions considered are very high flows, low flows, and elevated stream temperature as derived from historic and future simulations using the Soil and Water Assessment Tool (SWAT) hydrologic model and downscaled output from a General Circulation Model ensemble. Results indicate noteworthy differences in the frequency changes of extremes based on geographic region, season, elevation, and stream size. We found wide-spread increases in the occurrence of stream flows exceeding 150% of historic monthly averages for winter by the end of the century, and extensive increases in the occurrence of both extreme low flows (representing <50% of historic monthly averages), and elevated stream temperatures (>3 °C of monthly averages) during the summer months, with some basins expecting extreme conditions 90–100% of the time by the end of the century. Understanding the differences in the changes of extreme conditions can identify climate-sensitive regions and assist in targeted planning for climate change adaptation and mitigation.

1. Introduction

Changes in the magnitude and frequency of extreme climatic events are thought to present some of the most serious challenges to society in adapting to climatic changes. Extreme climatic events such as heat waves, drought periods, and heavy precipitation events occur on multiple time and spatial scales, and have caused significant burdens on the social and economic fabric, public health, water resources, and the health of aquatic ecosystems (Beniston, 2004; FEMA, 2014; NCDC, 2014; Wernstedt and Hersh, 2001). With the global changes projected by the end of the century, there is significant evidence that an intensification of the hydrologic cycle will drive increases in the frequency and magnitude of extreme events thus magnifying societal and environmental vulnerabilities (Cooley, 2009; Forzieri et al., 2014; IPCC, 2013; Kao and Ganguly, 2011). Recent studies of temperature and precipitation extremes have focused on the validity of governing physical mechanisms between temperature and precipitation increases or advanced statistical analysis on their temporal and spatial distribution (i.e. Allan and Soden, 2008; Diffenbaugh et al., 2005; Kharin et al., 2007; Sugiyama et al., 2010). However, there is a need to better understand how the projected climatic extremes drive the probability of extreme hydrologic conditions in streams under a warming climate. A greater understanding of future changes in extreme hydrologic conditions is especially relevant for highly developed, water-limited regions, such as the Southwestern United States, where their impact will likely be largest.

Using probability arguments, climate scientists have argued that changes in climate can drive changes in the frequency of weather and climatic extremes (Cooley, 2009; Katz et al., 2002; Tohver et al., 2014; Wigley, 1988). This has been corroborated by observations over the past several decades, when average surface

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Abbreviations: SWAT, Soil and Water Assessment Tool; SW, Southwest; GCM, General Circulation Model; SN, Sierra Nevada; UCRB, Upper Colorado River Basin; ET, evapotranspiration; BCSD, bias correction and spatial disaggregation; DJF, December–February; MAM, March–May; SON, September–November; r, Pearson's correlation coefficient.

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temperatures have increased by approximately 0.8 °C globally, drastic reductions in snow, snowmelt and sea ice have occurred, and changes in extreme weather events have been widely documented (IPCC, 2013). Anthropogenic greenhouse gas emissions are expected to further raise mean global surface temperatures by 1–6 °C by the end of the century (Barnett et al., 2008; Seager and Vecchi, 2010) with an imminent shift towards low snow years across the Northern Hemisphere under even modest warming (Diffenbaugh et al., 2012), and an intensification of the hydrologic cycle (Kao and Ganguly, 2011). As a result, climate models project global increases in the frequency and intensity of extreme weather events (Kao and Ganguly, 2011), and increased aridity for most of the Americas, most of Africa, southern Europe, the Middle East, Australia, and Southeast Asia (Dai, 2011; MacDonald, 2010).

An evaluation of climatic extremes must be based on the particular climate in a region. Extreme events can be classified as (a) those that are extremes of the climatic pattern occurring every year at a given location, such as a very high daily summer temperature, or heavy monthly winter rainfall amount, and (b) more complex event-driven extremes, such as droughts and floods, which do not necessarily occur every year at a given location, but which often control the statistics in (a) (Easterling, 2000). Extreme climatic conditions, such as warmer surface air temperatures, droughts, and high precipitation events, drive the presence of extreme hydrologic conditions in streams on several time scales through changes in heat storage and alterations of the flow system, such as decreased snowmelt or increases in overland flow. Generally, higher temperatures and/or lower precipitation result in increased stream temperatures and less available surface water through lower inputs and higher evapotranspiration rates, while high precipitation events lead to higher flow or flooding conditions. The actual stream flow and stream temperature resulting from extreme and non-extreme weather and climatic events, though, is the result of the local climatic, geologic, and hydrologic conditions in both space and time (Chang and Psaris, 2013; Ficklin et al., 2013a; Mantua et al., 2010; van Vliet et al., 2011). Comparatively few works have evaluated changes in low flows (de Wit et al., 2007; Hurkmans et al., 2010; Majone et al., 2012).

Very high/low stream flow conditions and elevated stream temperatures are important metrics for water supply management, water quality, ecosystem health, and public safety. Thus it is of considerable concern that these effects have already been documented with the comparatively modest warming to date. For example, warmer stream temperatures and lower flows linked to anthropogenic climate change are currently hastening the population declines and restricted distributions of many freshwater fish species, especially native fish, in arid regions (Comte et al., 2013; Moyle et al., 2011). Native fish have greater vulnerability to climatic change than non-native species, with 82% of natives considered highly vulnerable. A systematic assessment of future changes in hydrologic extremes is still needed for many regions.

Average surface temperatures across the Southwestern U.S. (SW) have increased by approximately 1–2 °C over the last several decades (Fritze et al., 2011; Stewart et al., 2005), and the occurrence of cold years, experienced regularly before 1993, has been diminished (Cayan et al., 2010). By 2100, warmer temperatures of 3–10 °C (depending on emission scenario, model, and region) are projected (Ficklin et al., 2010). The higher temperatures are thought to drive higher potential evapotranspiration, as well as changes in the type and spatial and temporal patterns of precipitation (Ficklin et al., 2010). While future precipitation overall is expected to remain the same or decrease, as compared to historic volumes, both future local increases and decreases are possible. In the SW, slight decreases or no changes in precipitation coupled with warmer temperatures lead to less precipitation stored as snow, decreased snowpack, substantial declines in stream flow, less soil and groundwater storage, decreased runoff and subsurface flow, earlier snow melt, increased potential evapotranspiration, longer summer dry periods, and more frequent drought periods (Cayan et al., 2010; Christensen et al., 2004; Ficklin et al., 2010, 2012a; Fritze et al., 2011; Null et al., 2010; Stewart et al., 2005; Stewart, 2013; Weiss et al., 2012). Indicating the importance of assessments at the local scale, there are indications for increases in some water-generating areas such as the high-elevation northern-most regions of the Colorado River Basin (Cayan et al., 2008; Ficklin et al., 2010, 2013b; Karl et al., 2009; Smith and Mendelsohn, 2007; Mote and Salathé, 2010).

In light of the importance of extreme hydrologic conditions for water supplies and ecological functioning in water-limited regions, this study assesses the likely changes in their magnitude and/or frequency with projected climatic changes. We ask what type and magnitude of extreme hydrologic events will likely be occurring by the end of the century, if significant changes in their frequency of occurrence are likely, and how any changes in frequency extremes are connected to geographic region, season, elevation, and stream size. To this end, we compare monthly stream flow and stream temperature values projected from a hydrologic model driven by downscaled General Circulation Model (GCM) output to those for a 30 year historical reference period. Thus the flow extremes we consider, are extremes in the monthly water balance, and not short-term extremes. Our focus is on the mountainous, water-generating basins of the Sierra Nevada (SN) and Upper Colorado River Basins (UCRB) in the SW due to their importance for large urban and agricultural regions. However, results may be of interest for other water-limited, highly-seasonal settings. By contributing to the understanding of future hydrologic extremes in the Southwest we aim to further the development of targeted adaptation strategies for sub-basin management.

With the continued changes in the climatic system projected for the SW over the next few decades, a key question is whether those changes are likely to impact the frequency and magnitude of extreme hydrologic conditions in streams critical for water generation. Global change and drought periods in the SW are likely to manifest in similar ways, with warmer temperatures, higher evaporation rates, and less moisture availability (Ficklin et al., 2012a,b, 2013a; Woodhouse et al., 2010). Although there might be substantial differences in the amount of future drying or wetting across the region (Cayan et al., 2010), paleoclimatic evidence suggests that generally warmer temperatures further strengthen the severity of drought conditions, and drive increases in aridity across the SW (Cook et al., 2004; Woodhouse et al., 2010). In this context, reduced water supplies and impacts on ecological systems are primary concerns (Cayan et al., 2010; Serrat-Capdevila et al., 2013). In addition, warmer temperatures have been linked to increases in the frequency of atmospheric rivers, the length of the storm season, and the size and frequency of floods (Das et al., 2013; Dettinger, 2011; Hamlet and Lettenmaier, 2007).

2. Study area

The SW consisting of California, the Great Basin, and the Colorado River Basin, is a region where increases in climatic extremes could be particularly consequential. Here, the combined effects of general water scarcity resulting from arid and semi-arid climates, and climate variability, collide with the needs of rapidly growing populations and economies as well as those of nationally important agricultural operations (Ackerman and Stanton, 2011; Cayan et al., 2010; Konieczki and Heilman, 2004). Precipitation is highly seasonal and variable on multiannual timescales, indicating its sensitivity to large-scale atmospheric