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Increases in flood magnitudes in California under warming climates

Tapash Das [a,b,*], Edwin P. Maurer [c], David W. Pierce [b], Michael D. Dettinger [d,b], Daniel R. Cayan [b,d]

[a] CH2M HILL, Inc., San Diego, CA, USA
[b] Division of Climate, Atmospheric Sciences, and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, CA, USA
[c] Santa Clara University, CA, USA
[d] United States Geological Survey, La Jolla, CA, USA

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SUMMARY

Downscaled and hydrologically modeled projections from an ensemble of 16 Global Climate Models suggest that flooding may become more intense on the western slopes of the Sierra Nevada mountains, the primary source for California's managed water system. By the end of the 21st century, all 16 climate projections for the high greenhouse-gas emission SRES A2 scenario yield larger floods with return periods ranging 2–50 years for both the Northern Sierra Nevada and Southern Sierra Nevada, regardless of the direction of change in mean precipitation. By end of century, discharges from the Northern Sierra Nevada with 50-year return periods increase by 30–90% depending on climate model, compared to historical values. Corresponding flood flows from the Southern Sierra increase by 50–100%. The increases in simulated 50 year flood flows are larger (at 95% confidence level) than would be expected due to natural variability by as early as 2035 for the SRES A2 scenario.

1. Introduction

Hydrometeorological extremes often have major impacts on human activities, water resources, agricultural activities, urban infrastructure and ecosystems. Floods in particular damage human infrastructure, take many lives globally and are one of the costliest types of natural disaster in economic and human terms (Bouwer and Vellinga, 2003). California, our focus here, has suffered many severe floods historically (Kelley, 1998) with annual damages averaging over $350 million (Pielke et al., 2002). California is highly vulnerable to floods because its dense communities and infrastructure in low lying areas (Lund, 2012).

California is characterized by a Mediterranean seasonal climate with precipitation falling almost entirely in the Winter (December–February) and Spring (March–May) (Cayan et al., 1998). Floods in California are typically associated with specific winter-spring atmospheric circulations (Cayan and Riddle, 1992), and recent research suggests relationships of atmospheric rivers with the largest floods in California (Ralph et al., 2006; Neiman et al., 2007; Dettinger and Ingram, 2013). In response to continuing increases in global greenhouse-gas emissions, California at the end of the twenty-first century is projected to experience warming by 1.5–4.5 °C (Cayan et al., 2008a,b). There are uncertainties about future changes in long-term average precipitation rates in California (e.g., Dettinger, 2005; Cayan et al., 2008a,b). At the seasonal level, the ensemble mean projected changes in precipitation for the mid-late 21st century have been shown to favor wetter winters and drier springs (Pierce et al., 2013a). These winter precipitation increases are largely driven by increases in daily precipitation intensity more so than the number of days with precipitation (Pierce et al., 2013b). It is projected that even though the overall frequency of precipitation events may decrease in many areas of California, there may be increases in the largest precipitation events (Easterling et al., 2000; Pierce et al., 2013a, 2013b).

With more water vapor and heat in the atmosphere, it is anticipated that storms will yield greater peak precipitation rates, and thus floods may become more intense in many areas (e.g., Trenberth, 1999; Milly et al., 2002; Kunkel et al., 2013). Indeed, there is already observational evidence that precipitation extremes have increased in many parts of the world (Groisman et al., 2005) and in some cases these increases have been attributed to human driven greenhouse gas increases (Min et al., 2011). However, as the polar regions are expected to warm more quickly than the lower latitudes, the equator-to-pole temperature differences would decline (Jain et al., 1999) which generally is expected to weaken

* Corresponding author at: CH2M HILL, Inc., San Diego, CA, USA. Tel.: +1 (619) 272 7272; fax: +1 (619) 687 0111.
E-mail address: tapash.das@ch2m.com (T. Das).

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mid latitude storm tracks of the sort that brings California dangerous storms.

The combination of these two conflicting tendencies (more moisture in the atmosphere yielding larger peak precipitation rates and weakened storm tracks reducing the power and opportunities for large storms) has left the future of flooding in California uncertain. Several studies have projected possibilities of more floods in California under climate change (e.g., Miller et al., 2003; Dettinger et al., 2004, 2009; Anderson et al., 2006; Raff et al., 2009; Das et al., 2011) but a more exhaustive evaluation of possible climatic futures has been lacking.

We describe here, for two primary catchments in California, potential changes in annual maximum 3-day flood discharges under a wide range of projected climate changes provided by a large ensemble of climate projections.

The 3-day peak flow is a widely used measure for flood planning purposes in California, and one that has been used in prior climate change impacts studies (CA DWR, 2006; Chung et al., 2009; Das et al., 2011). Das et al. (2011) found a robust increase in 21st century 3-day peak flow magnitudes based on output from three Global Climate Models (GCMs) using a single greenhouse gas emission scenario and output from three GCMs. In this study we expand this analysis to include two emissions scenarios, one with high (SRES A2, as in Das et al., 2011) and one with lower atmospheric concentrations of greenhouse gases (SRES B1) through the 21st century, and an ensemble of 16 GCMs (Table 1) from the World Climate Research Program's (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3), a number adequate to account for the effects of the natural internal climate variability and most model-to-model scatter among the GCMs. The study also performs a broader evaluation of how flood changes track changes in annual streamflows and precipitation. This evaluation is critical given continuing uncertainties in projected annual precipitation in the study area. Using this ensemble we are able to identify robust projections in flood magnitudes for different return periods. This analysis will help quantify the changes in these floods in ways that are informative to policymakers as they contemplate design recommendations for increases in the magnitudes of design floods (e.g., CA DWR, 2008) or changes in the design recurrence interval (Mailhot and Duchesne, 2010) as adaptation responses to increased flood risk.

2. Data, models and methods

2.1. Study area and data

The study area consists of the western slopes of the Northern and Southern Sierra Nevada mountains (Fig. 1). The Sierra Nevada are the primary sources of inflows to California's Central Valley, with about 40% of the State's total flows deriving from the range (Morandi, 1998). Flows from the Sierra Nevada provide about one-third of the water supplies serving about 25 million people across the entire length of the State and irrigation supplies for at least $36 billion/year in agriculture (Service, 2007; USDA, 2011). However, in addition to being the largest water supply source for the State, rivers from the Sierra Nevada have also, throughout history and prehistory, been the sources for devastating floods in the Central Valley (Dettinger and Ingram, 2013). The management of flows from the range have always been challenged by the tension between their value as water supplies and the risks they pose as major flood generators, a tension that may be greatly aggravated if flood risks increase with the changing climate.

The Northern Sierra catchment includes the drainage areas of the Sacramento River at Bend Bridge, the Feather River at Oroville and the Yuba River at Smartville. Streamflows from the Northern Sierra feed into Sacramento River. The Southern Sierra catchment is defined here to consist of the tributary drainages of the San Joaquin River: the Stanislaus at New Melones Dam, the Tuolumne River at New Don Pedro, the Merced at Lake McClure, and the San Joaquin at Millerton Lake.

We used observed, gridded fields of daily maximum and minimum temperature (T_{min}, T_{max}) and precipitation (P) from the Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu). The data have a spatial resolution of 1/8° (approximately 12 km per grid cell) and are derived from two different sources: Maurer et al. (2002) and Hamlet and Lettenmaier (2005). Both the Maurer et al. (2002) and Hamlet and Lettenmaier (2005) datasets used US National Oceanic and Atmospheric Administration (NOAA) Cooperative Observer (Co-op) stations. However, the Hamlet and Lettenmaier (2005) dataset focused more on the Historical Climatology Network (HCN) (Easterling et al., 1996) subset of Co-op stations. HCN

Table 1
GCM modeling group, GCM name and GCM abbreviation used in this study.

GCM Modeling Group, Country	WCRP CMIP3 I.D.	GCM abbreviation used in this study
Bjerknes Centre for Climate Research, Norway	BCCR-BCM2.0	bccr-bcm2.0.1
Canadian Centre for Climate Modeling & Analysis, Canada	CGCM3.1 (T47)	cccma-cgcm3.1.1
Meteo-France/Centre National de Recherches Meteorologiques, France	CNRM-CM3	cnrm-cm3.1
CSIRO Atmospheric Research, Australia	CSIRO-Mk3.0	csiro-mk3.0.1
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, United States	GFDL-CM2.0	gfdl-cm2.0.1
US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, United States	GFDL-CM2.1	gfdl-cm2.1.1
NASA/Goddard Institute for Space Studies, United States	GISS-ER	giss-model-e.r.1
Institute for Numerical Mathematics, Russia	INM-CM3.0	inmcm3.0.1
Institut Pierre Simon Laplace, France	IPSL-CM4	ipsl-cm4.1
Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan	MIROC3.2 (medres)	miroc3.2-medres.1
Meteorological Institute of the University of Bonn, Germany and Institute of Korea Meteorological Administration, Korea	ECHO-G	miub-echo-g.1
Max Planck Institute for Meteorology, Germany	ECHAM5/ MPI-OM	mpi-echam5.1
Meteorological Research Institute, Japan	MRI-CGCM2.3.2	mri-cgcm2.3.2a.1
National Center for Atmospheric Research, United States	CCSM3	ncar-ccsm3.0.1
National Center for Atmospheric Research, United States	PCM	ncar-pcm1.1
Hadley Centre for Climate Prediction and Research/Met Office, United Kingdom	UKMO-HadCM3	ukmo-hadcm3.1