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Effects of climate change on extreme precipitation events in the western US

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1. Introduction

How the climate change induced by increased CO_2 affects daily hydrologic extremes is an important concern as it is directly related to the frequency of natural disasters such as flooding (IPCC 1995). Existing projections suggest that increases in the atmospheric CO_2 are likely to alter substantially the characteristics of the hydrologic cycle in the western US (Giorgi et al. 1994; Leung and Ghan 1999; Kim 2001; Kim et al. 2002). Even though the quantitative changes in these projections vary with the general circulation models (GCMs) and regional climate models (RCMs) employed, they tend to agree in several important aspects including increased cold season precipitation, reduced snow cover at the end of winter, and a large decrease of spring runoff in high elevations, especially in the Sierra Nevada.

Observational studies indicate that recent changes in extreme hydrologic events and diurnal cycle of the low level temperature are statistically significant. Groisman and Easterling (1994) and Elliott et al. (1995) show increases in precipitation and precipitable water in the western United States. Increases in precipitation and precipitable water have important implications on the occurrence of extreme hydrologic events. Analyses by Groisman et al. (2001) show that the trends of increased heavy precipitation and high stream flow events in the US during the second half of the 20-th century is significant. Iwashima and Yamamoto (1993) show similar trends in Japan and the US. The changes in the low level temperature, most notably in the range of diurnal temperature variations as well as warming (IPCC 1995) have large impacts on the cold season snow budget and snowmelt driven runoff during spring and early summer. The recent temperature trend is suspected to be the main cause of early snowmelt in the western US (Dettinger and Cayan 1995) and increases in the number of frost-free days (Cooter et al. 1995).

The projected changes may affect hydrologic extremes in the western US in which steep terrain often causes extreme precipitation and flooding through orographic lifting and rapid stream flow response to local heavy rainfall in mountain watersheds (Goodridge 1994; Soong and Kim 1996; Kim et al. 1998). Some observational studies (Groisman and Easterling 1994; Groisman et al. 2001; Elliott et al. 1995) suggest that recent changes in hydrologic extremes are statistically significant and may be related to recent warming trends.

A regional projection of the effects of climate change induced by increased CO_2 on hydrologic extremes in the western US is investigated using a nested modeling method in which an RCM is nested within GCM-projected global data. Note that this study is based on downscaling one scenario from a GCM, and the projected signals are qualitative. An outline of the experiment is presented below. It is followed by analyses of the projected climate change signals in the daily hydrologic characteristics in the western US and in major Sierra Nevada basins.

2. Experimental design

To examine the effects of increased CO_2 on the hdyroclimate of the western US, a regional climate model is nested within two GCM projections from HadCM2 (Mitchell et al 1995), which represent states of future climate under two different CO_2 concentrations. The control run (CNTL) represents the climate of a 10-year period of 2040-2049 under an assumption that the atmospheric greenhouse gas (GHG) concentration stays at the same level as the late 20^{th} century. The transient run (TRAN) represents the climate of the same period under an assumption that the equivalent concentration of the GHG increases at a 1 %/year rate from the year 1990. Details of the GCM and RCM simulations below are presented by Mitchell et al. (1995) and Kim et al. (2002), respectively.

The RCM employed in this study is the coupled Mesoscale Atmospheric Simulation (MAS) and Soil-Plant-Snow (SPS) model (hereafter MAS-SPS) which has been employed for regional climate and extended range forecast studies for the western US. with good results. Details of MAS-SPS are presented in Kim and Ek (1995), Kim and Soong (1996), and Soong and Kim (1996), and will not be repeated. The regional climate simulations cover the western US at a $36x36km^2$ resolution in the

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horizontal, with 18 atmospheric and two soil layers in the vertical. For more details of the regional climate simulations, readers are referred to Kim (2001) and Kim et al. (2002).

3. Daily precipitation characteristics

Previous papers by Kim (2001) and Kim et al. (2002) report that the regional climate change signals projected in the simulations suggest large increases in cold season precipitation, especially in the mountainous regions along the Pacific Ocean. In this follow up study, the effects of the climate change on daily precipitation intensity, especially the occurrence of heavy events, in major California basins during the cold season are examined. Here, the cold season is defined as the 6-month period from October to March of the following year, the first half of a water year.

First, the number of wet days during the cold season is examined. The wet days are defined with a threshold value of 0.5mm/day. Variations of the projected cold season signals for elevation ranges and north-south locations are examined below. Overall, it was projected that the number of wet days would increase in the western US during the cold season in increased CO_2 climate. Hence, the projected increase of cold season precipitation in the region under increased CO_2 (Kim 2001, Kim et al. 2002) is partially due to increases in the number of wet days.

Precipitation characteristics vary widely as a function of elevation in the Sierra Nevada region. The occurrence of wet days increases in all elevation ranges (Table 1). Similar increases in wet days are projected for the basins in low and mid elevation ranges, i.e., below 2.5km, while the projected increase of wet days in the high elevation basins are slightly larger than the two lower elevation ranges.

Table 1. Percent-change ($100 \cdot (tran - cntl)/cntl$) of wet days averaged over the Sierra-Nevada basins in low, mid, and high elevation ranges.

Elevation (km)	z<1.5	1.5<z<2.5	z>2.5
% change	33	32	37

The basins in the southern Sierra Nevada show consistently larger increases in the number of wet days under increased CO_2 conditions (Table 2). The southern and northern basins are selected with respect to the parallel at 38N. The southern basins include the Kings, Merced, Tuolumne, and Stanislaus Rivers and the northern basins include the Feather, Yuba, and American Rivers. Note that all of the northern basins are located below 2.5km while three of four southern basins, the Kings, Merced, and Tuolumne Rivers, are partially located above the 2.5km level. The importance of the elevation difference between the southern and northern basins in the projected differences in the wet day signals are not clear as the signals in the southern basins are consistently larger than in the northern basins. The signals range from 30% to 34% for the northern basins and from 35% to 39% for the southern basins. Hence, the projected differences in the number of wet days between the northern and southern Sierra Nevada basins appear to be related to the large-scale moisture signal projected by HadCM2 (Kim et al. 2002).

Table 2. Percent-change ($100 \cdot (tran - cntl)/cntl$) of wet days averaged over southern and northern Sierra-Nevada basins.

Basin locations	Southern	Northern
% change	37	32

Next, the climate change signals in the frequency of precipitation intensity are examined. For all basins, the frequency of light precipitation events remains unchanged or decreases slightly, but the frequency of heavy precipitation events increases notably under increased CO_2 conditions. These changes, combined with a large increase of rainfall in the transient simulation (Kim 2001, Kim et al. 2002), suggest that extreme hydrologic events are likely to increase under increased CO_2 conditions.

Figure 1 compares the frequency distribution of the cold season precipitation intensity in four selected basins projected in the control (light gray bar) and the transient (dark bar) simulations. The signals in the Feather River basin show notable increases in precipitation intensities exceeding 40mm/day (class 9 and 10) under increased CO_2 conditions. The substantial increases in the strongest class, representing events exceeding 45mm/day, from less than 0.1% to over 1% is of a special concern for the frequency of flooding. Another notable changes in Fig. 1 are that light events tends to decrease slightly in all basins. In the Kings River basin, the changes are similar, but less dramatic since there are already a large number of heavy precipitation events in the control climate. Despite the less dramatic changes, increases in the heavy precipitation occurrence from 1% to 3% suggests a substantial increase in flooding, especially there are quite a few events exceeding 100mm/day in the transient run. Unlike the differences between the Feather River and the Kings River that represent northern and southern Sierra Nevada basins, the frequency distribution is similar in different elevation ranges within a basin.

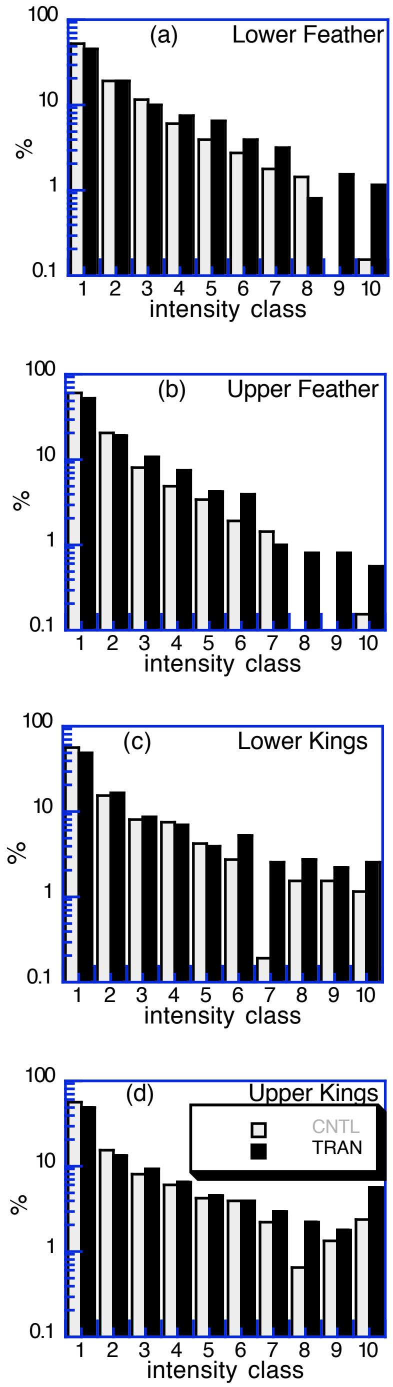

Fig. 1 The frequency of daily precipitation intensity in four basins. The intensity class are, in mm/day: 1: 0.5-5; 2: 5-10; 3: 10-15; 4: 15-20; 5: 20-25; 6: 25-30; 7: 30-35; 8: 35-40; 9: 40-45; 10: >45.

4. Discussions

The projected climate change signals in this study suggest that daily precipitation characteristics in California basins may be altered substantially as a result of increased atmospheric CO2. The most notable changes in daily precipitation are increases in the number of wet days, and more importantly, a large increase in heavy precipitation events.

Compared to the control climate, both the number of wet days and the frequency of heavy precipitation events increase under increased CO2 conditions. The climate change signals in the number of wet days and the frequency of heavy precipitation show notable variations in the north-south directions. The variations due to elevation differences are, however, small within the same basin. Note that the signals in precipitation type and snow budget show much larger elevation dependences than meridional dependences (Kim 2001).

The number of wet days in the Sierra Nevada basins shows larger increases in the south of the 38N than in the north of it. This is associated with the global model signals, which projected that the positive water vapor signals decrease to the north.

The frequency of heavy precipitation increases notably for the Sierra Nevada basins north of the 38N in the transient run. Despite the smaller signal, the frequency of heavy precipitation is larger in the southern basins than in the northern basins. The results suggest that the frequency of flooding is likely to increase substantially in northern Sierra Nevada basins.

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