1-2006

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Recommended Citation

Maurer, E.P., S. Gibbard, and P.B. Duffy, 2006, Amplification of streamflow impacts of El Niño by increased atmospheric greenhouse gases, Geophysical Research Letters, Vol. 33, No. 2, L02707 10.1029/2005GL025100

GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L02707, doi:10.1029/2005GL025100, 2006

Amplification of streamflow impacts of El Niño by increased atmospheric greenhouse gases

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Received 31 October 2005; revised 15 December 2005; accepted 20 December 2005; published 27 January 2006.

[1] Some El Niño events produce unusually large precipitation amounts in Northern and Central California. We use a high-resolution global model of the atmosphere coupled to a physically-based model of surface hydrology to investigate effects of increased atmospheric CO_2 and this type of El Niño, both individually and in combination, on monthly river flows in California. Increased CO_2 changes the seasonal timing of river flows and increases their variability. SST anomalies typical of a strong El Niño SST increase monthly-mean flows. The two perturbations together result in increased mean flows and increased variability, raising the possibility of both increased flood risk and water shortages. The river flow response to this strong El Niño in an increased CO_2 climate is significantly different from the sum of the responses to the individual perturbations. **Citation:** Maurer, E. P., S. Gibbard, and P. B. Duffy (2006), Amplification of streamflow impacts of El Niño by increased atmospheric greenhouse gases, *Geophys. Res. Lett.*, *33*, L02707, doi:10.1029/2005GL025100.

1. Introduction

[2] One anticipated effect of a warming climate is the acceleration of the hydrologic cycle, with its concomitant increase in the frequency of extreme events, such as floods and droughts [*Cubasch and Meehl*, 2001; *Trenberth*, 1999; *Yang et al.*, 2003]. Some studies have already observed increases in extreme event occurrence [*Groisman et al.*, 2001; *Trenberth et al.*, 2003]. In snow-dominated areas such as California, warmer winter temperatures also produce more precipitation falling as rain instead of snow, which increases the risk of wintertime flooding. [*Dettinger et al.*, 2004; *Stewart et al.*, 2005; *Vanrheenen et al.*, 2004]

[3] El Niño conditions (warm sea surface temperature anomalies in the equatorial Pacific Ocean) [*Trenberth*, 1997] often (but not always) produce above-average precipitation (P) and thus streamflow in California. For example, in the 1997–1998 El Niño season, P was 250% of normal in San Francisco, and similarly high elsewhere in Northern California[*Ross et al.*, 1998]. Other recent El Niños, such as that in 1991–1992, produced normal or even below-average P in this region. In this paper we investigate river flows in a hypothetical scenario in which an El Niño similar to that of 1997–1998 occurs in a greenhouse-warmed climate. We emphasize that the 1997–1998 El Niño had unusually large SST and regional P anomalies compared to other recent El Niños. Thus, the scenario we are studying is not necessarily typical of future-climate El Niños. Whether it is or not depends on if and how SST anomalies associated with El Niño evolve as anthropogenic climate change proceeds. Climate modeling studies are divided on this question [*Cubasch and Meehl*, 2001; *van Oldenborgh et al.*, 2005].

2. Methods

[4] The general approach used here is to simulate monthly river flows using a surface hydrology model driven by meteorology from a global-domain, high-resolution atmospheric climate model. This model in turn was driven by prescribed SSTs and sea-ice extents corresponding to four climate scenarios:

[5] 1) A baseline present-day climate (clim_control), simulated using climatological monthly mean SSTs for 1979–2001. Because SSTs are the same in each year, any inter-ensemble variability results from processes internal to the atmosphere and land surface. This simulation used a constant CO_2 concentration of 355 ppm.

[6] 2) The 1997–1998 winter season (9798Niño), which experienced a major El Niño event. Here the climate model was forced with observed SSTs for 1997–1998. To assess chaotic variability, we performed an ensemble of 11 simulations all using the same SSTs but starting from different atmospheric and land-surface initial conditions; these were taken from August 1 of successive years of the clim_control simulation. These simulations also used a CO_2 concentration of 355 ppm.

[7] 3) A doubled-CO_2 climate (clim+$CO_{2,}$), simulated using SSTs consisting of 1979–2001 climatological mean SSTs plus an anomaly corresponding to doubled CO_2. This anomaly was taken from a simulation performed with the CCSM3 coupled ocean-atmosphere GCM [*Collins et al.*, 2006]. This simulation used a CO_2 concentration of 710 ppm and spanned 10 simulated years.

[8] 4) A hypothetical future-climate El Niño winter (9798Niño+CO_2). Here we performed an ensemble of 11 simulations using SSTs consisting of observed climatological means plus the above model-based 2xCO_2 SST anomaly, plus observed 1997–1998 SST anomalies. The maximum tropical SST anomaly including both effects is 8.4°C. This compares to a maximum observed 1997–1998 SST anomaly of 5.3 C. These SSTs represent a future-climate El Niño, similar (in the sense of having the same SST anomalies) to the 1997–1998 El Niño. Initial conditions for each simulation were taken from August 1 of successive years of the clim+ CO_2 simulation. These simulations used a CO_2 concentration of 710 ppm.

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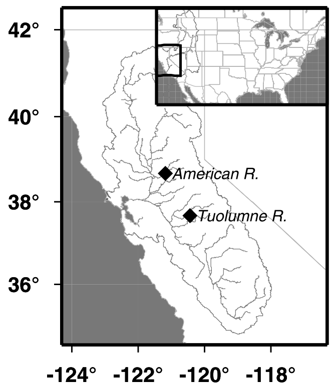

Figure 1. Locations of the two sites included for detailed analysis of hydrologic impacts.

[9] We configured the National Aeronautics and Space Administration atmospheric finite volume global climate model (FVGCM) [*Lin*, 1997; *Lin and Rood*, 1996, 1997] at a spatial resolution of 0.5 deg. by 0.625 deg. (about 50 km in California). This resolution is similar to that used in regional climate models nested within coarse-resolution global models to simulate California [*Kim*, 2005; *Snyder et al.*, 2004].

[10] Monthly P and near-surface temperature from each FVGCM simulation were extracted, and for the clim_control scenario an ensemble average field was computed. For the other three implementations, for each ensemble member the difference from the clim_control simulation was computed as a fraction for P and as a shift for temperature. These changes were interpolated to a 1/8 degree grid and applied to the observed, historical average climate of 1979–2001, using the observationally based data set of *Maurer et al.* [2002]. The resulting meteorology was used to drive the variable infiltration capacity (VIC) model [*Liang et al.*, 1994], a physically based, spatially distributed land surface hydrology model that has been used extensively in studies of the interaction of climate change and hydrology [*Christensen et al.*, 2004; *Hayhoe et al.*, 2004; *Maurer and Duffy*, 2005; *Payne et al.*, 2004; *Wood et al.*, 2004]. VIC model parameterization is identical to *Vanrheenen et al.* [2004], with calibration performed for monthly streamflow at major basins as shown by *Maurer et al.* [2002], transferring calibrated parameters to uncalibrated areas.

[11] Two locations that drain the western slopes of the Sierra Nevada Mountains in California (Figure 1) were selected for this study. The majority of the managed water in the State originates from the Sierra Nevada, and the changes in peak flows or hydrograph timing have important implications for reservoir management [*Brekke et al.*, 2004; *Vanrheenen et al.*, 2004]. The basin upstream from the American River at Folsom Dam measures 4850 km^2 with a basin average elevation of 1335 meters. For the Tuolumne River at New Don Pedro Reservoir the contributing area is 3970 km^2 and the basin is higher at 1755 meters, and hence is more snow dominated.

3. Results and Discussion

[12] Figure 2 shows for two stream locations the flow, basin average P, temperature, and snow pack (as snow water equivalent). All results shown are multi-year means. Comparing clim_control and clim+CO_2 the typical effect of a warming climate on mountain basin hydrology where snow plays a role is evident. For example, for the Tuolumne River an increase in winter stream flow and a decrease in late spring flow result from less winter P falling as snow (JFM temperatures in this basin are on average about 1.4°C warmer), and earlier melt driven by higher spring temperatures (1.9°C warmer for AMJ). For the Tuolumne the MAM flow increases over 60% due to doubling of CO_2. The increase in February flow illustrates the increased proportion of rain falling in winter. Figure 2 shows that the increase in winter streamflow during simulated 97–98 El Niño conditions is due to increased winter P, since temperature on average is nearly identical to clim_control.

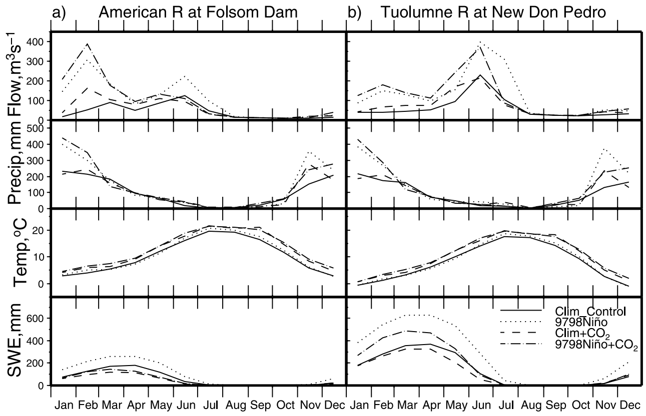

Figure 2. Monthly streamflow, precipitation, surface air temperature, and snow water equivalent (SWE) for each of the four scenarios included in the study for (a) the American River upstream of Folsom Dam and (b) the Tuolumne River at New Don Pedro Reservoir. Note that clim_control is the hydrograph from the VIC hydrologic model driven by climatological average precipitation and temperature, which is not expected to produce climatological streamflow due to nonlinearity in processes governing streamflow.

[13] Figure 2 illustrates that in the higher CO_2 environment, temperatures increase for both basins, and the increase is nearly identical for both El Niño and non-El Niño conditions. The changes in winter P and streamflow due to the presence of a wet El Niño event are much larger than the effects of the CO_2 increase. Under clim+CO_2, P is slightly higher on average than under clim_control, also contrib-

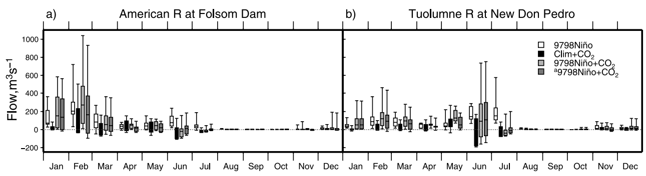

Figure 3. Differences in monthly streamflow from the clim_control simulation mean for the two sites. Median is indicated by horizontal line in the box, bottom and top of the box are the 25 and 75 percentiles, lower and upper whiskers are the minimum and maximum. The rightmost bar is similar to the others except that it shows the difference between 9798Niño+CO_2 and clim+CO2 monthly average conditions.

uting to higher winter flows. For example, the January flow increase for the American River for 9798Niño+CO_2 (320 m^3/s) exceeds the sum of the increases due to increased CO_2 (60 m^3/s) and El Niño (240 m^3/s) alone, indicating that the increased CO_2 may have an amplifying effect on streamflows during wet El Niño conditions.

[14] Figure 3 illustrates these changes and their variability (variability in this study refers to inter-ensemble variability within one of the four scenarios). The three leftmost bars for each month show the streamflow difference from clim_control for these two sites in the clim+CO_2, 9798Niño and 9798Niño+CO_2 simulations. Median winter flows increase under El Niño, climate warming, and the combination of the two. Figure 3 also shows a marked increase in variability in El Niño river flows in an increased CO_2 environment. This results from an increase in variability in P simulated by the FVGCM model under increased CO_2 conditions. This phenomenon has been seen in other climate models as well [*Giorgi and Bi*, 2005]. While extreme low flows are rare during El Niño events (changes are typically above zero in Figure 3), more extreme high values occur under 9798Niño+CO_2. For the American River, with a higher influence of rain compared to the highly-snow dominated Tuolumne, the increased variability in stream flow is most evident in the high P months of January and February. For the Tuolumne River, while some increase in streamflow variability is seen in January and February (the high P months for this basin), the effects on flow are delayed until June when the majority of snow melt occurs. Where under 9798Niño the highest streamflow variability is in July, with increased temperatures under 9798Niño+CO_2 the variability increases markedly and shifts to June.

[15] To further examine these changes in flow, the rightmost bar for each month in Figure 3 is the change in streamflow in a warmer climate due to the presence of El Niño conditions; i.e., the difference between 9798Niño+CO_2 and clim+CO_2 monthly means. For January for the American River median for the rightmost bar exceeds the median for the leftmost bar, suggesting the median flows experienced during 9798Niño may be somewhat amplified in January with increased CO_2. For both January and December for both rivers, and in June for the Tuolumne a marked increase in variability of the flow changes during El Niño is seen under increased atmospheric CO_2 conditions.

[16] The combined effect of El Niño and doubled CO_2 on river flows qualitatively differs from the sum of the El Niño effect and the doubled CO_2 effect. This is illustrated in Figure 4, which summarizes the changes in flow from clim_control for the 9798Niño+CO_2 simulation and a composite consisting of the sum of the individual effects of El Niño and doubled CO_2. For each month, the composite change from clim_control mean is defined as:

$$\Delta\overline{Q}_{\text{composite}} = \Delta\overline{Q}_{\text{9798Niño}} + \Delta\overline{Q}_{\text{clim\_CO}_2} \quad (1)$$

The two variables on the right side of equation (1) are calculated as $\Delta\overline{Q}_{\text{scenario}} = \frac{1}{n}\sum_{i=1}^{n}(Q_{\text{scenario}} - \overline{Q}_{\text{clim\_control}})$ for n ensemble members, where the overbar indicates a mean across ensembles. The composite standard deviation, $\sigma_{\Delta\overline{Q}[\text{composite}]}$, is the square root of the sum of $\sigma^2_{\Delta\overline{Q}}$ for

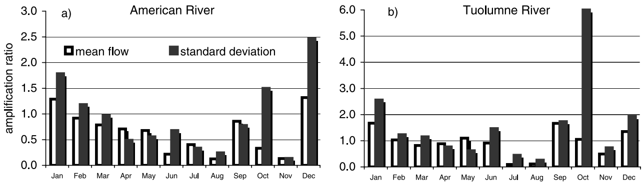

Figure 4. Amplification ratios for the two streamflow sites. See text for description.

9798Niño and Clim+CO_2. The amplification ratios for the mean and standard deviation are then calculated as $\Delta\overline{Q}_{\text{9798Niiño+CO}_2}/\Delta\overline{Q}_{\text{composite}}$ and $\sigma_{\Delta\overline{Q}[\text{9798Niño+CO}_2]}/\sigma_{\Delta\overline{Q}[\text{composite}]}$, respectively.

[17] Figure 4 shows the change in mean flow for 9798Niño+CO_2 is larger than the composite (amplification ratio > 1) for December and January, with January mean flow increase for 9798Niño+CO_2 being 29% and 67% greater than the composite response for the American and Tuolumne Rivers, respectively. January is the month with the highest P under El Niño conditions, suggesting the apparent amplification of mean flow response in January during El Niño under doubled CO_2 is driven by P. Amplification of variability is more striking, with the standard deviation for 9798Niño+CO_2 exceeding that for the composite in December–February for both basins, and for June in the Tuolumne, including high flow months for basins. For these months, the standard deviation for 9798Niño+CO_2 flow increase is between 120–250% of the composite. The high amplification of October streamflow is of less importance due to much lower fall flows in these basins.

[18] When amplification of both mean and variability exceeds one, the potential for increased extreme flows is highest. For example for the American River in January, if the warming and El Niño effects were simply additive, flows would exceed 230 m^3/s in 25% of El Niño years. We find that under the coupled 9798Niño+CO_2 simulation that the flow would exceed 375 m^3/s in 25% of the El Niño years, while currently flow exceeds this value in fewer than 10% of El Niño years. In February, however, the variability amplification is largely offset by the amplification of the mean being less than one.

4. Conclusions

[19] This study evaluated the combined impact of a wet El Niño and doubled atmospheric CO_2 on streamflow in two California rivers. As in the present climate, regional precipitation associated with El Niño will likely vary from one event to another; thus, the results presented here may not be typical of future-climate El Niños.

[20] We find that increasing CO_2 and rising temperatures cause a greater proportion of winter precipitation to fall as rain causing the typical shift in streamflow timing, as well as increased variability. A wet El Niño increases winter precipitation and snow accumulation with dramatic flow increases. The combination of a wet El Niño and increased CO_2 shows all these effects; the striking result, however, is that the combined effects of a wet El Niño and warming are not additive. There is a clear amplification in winter months of mean flows and variability when climate warming is assumed on top of a wet El Niño. This suggests that the risk

of winter floods and late-season water shortages may be increased due to the combined effects of El Niño conditions and climate warming.

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