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Abstract

Atmospheric general circulation models (GCMs) used to project climate responses to increased CO_2 generally omit irrigation of agricultural land. Using the NCAR CAM3 GCM coupled to a slab-ocean model, we find that inclusion of an extreme irrigation scenario has a small effect on the simulated temperature and precipitation response to doubled CO_2 in most regions, but reduced warming by as much as 1^{o} C in some agricultural regions, such as Europe and India. This interaction between CO_2 and irrigation occurs in cases where agriculture is a major fraction of the land surface and where, in the absence of irrigation, soil moisture declines are projected to provide a positive feedback to temperature change. The reduction of warming is less than 25% of the temperature increase modeled for doubled CO_2 in most regions; thus greenhouse warming will still be dominant. However, the results indicate that land use interactions may be an important component of climate change uncertainty in some agricultural regions. While irrigated lands comprise only ~2% of the land surface, they contribute over 40% of global food production. Climate changes in these regions are therefore particularly important to society despite their relatively small contribution to average global climate.

Introduction

The value of models that project societal impacts of climate change depend largely on the ability to make clear and accurate statements about the uncertainties associated with such projections. One impact of great interest is the effect of climate change on regional or global crop production, and the associated changes in food security. Uncertainties for these impacts depend largely on uncertainties associated with climate model projections over agricultural regions [*Parry, et al.*, 2005].Therefore, a clear understanding of climate uncertainty over agricultural regions is important for evaluating climate change mitigation and adaptation strategies. Irrigated systems are particularly relevant, as they provide roughly 40% of global food production [*FAO*, 2002] despite covering just 2% of global land surface area [*FAO*, 2004].

Quantification of climate uncertainty is commonly achieved by comparing outputs from several different general circulation models (GCMs) [*IPCC*, 2001; *Palmer, et al.*, 2005]. However, this approach can only capture uncertainties due to processes that are represented differently in different models. As most GCMs were designed primarily to study global scale climate changes, they often treat very simply or entirely omit processes that are important in agricultural regions. For example, according to the documentation for the 22 models used for projection of future climate for the next Intergovernmental Panel on Climate Change (IPCC) report (available at www.pcmdi-llnl.gov), only eight include some representation of land use, and none include irrigation.

Previous work has shown that changes in irrigation extent can have substantial effects on local climate [*Adegoke, et al.*, 2003; *Lobell, et al.*, 2006]. Thus, climate projections in areas with expansion or retraction of irrigation are subject to uncertainties related to the magnitude of, and climatic response to, this land use change. However, if the effect of irrigation is independent of other climate forcings, then estimates of irrigation's impact on climate can simply be added to projections based on other forcings, such as greenhouse gas increases. This study investigates whether the effects of irrigation and CO_2 on climate are indeed independent or, instead, interacting. If the latter is true, then estimates of CO_2 induced warming over irrigated regions may be biased in the current suite of GCMs that ignore irrigation.

One reason to expect an interaction is that GCMs often simulate a reduction of soil moisture in future climate [*Manabe, et al.*, 1981; *Wetherald and Manabe*, 1995; *Manabe, et al.*, 2004; *Wang*, 2005], in particular for the summer months in middle latitudes where much of agricultural activity occurs. Moisture decreases are driven largely by the nonlinear increase in atmospheric saturation vapor pressure, and thus evaporation rates, with higher temperatures [*Wetherald and Manabe*, 1995]. These moisture decreases subsequently lead to an increase in the fraction of incident radiation partitioned to sensible heat flux, which provides a positive feedback to temperature change as more energy is used to heat the land surface rather than evaporate water. Irrigation eliminates the potential for this feedback because soil moisture is maintained via human activity (assuming that irrigation water availability is unaffected by climate change). At issue here is whether the presence of irrigation has the potential to significantly modify the response of climate to CO_2 over agricultural regions, and if so where these interactions are most likely to be important.

Model and Experiment Design

We used the Community Atmosphere Model version 3.0 (CAM) [*Collins, et al.*, 2004] coupled to version 3.0 of the Community Land Model (CLM) [*Oleson, et al.*, 2004]. CAM has 26 levels in the vertical dimension and was run using 2.0° latitude x 2.5° longitude resolution using the Finite Volume (FV) dymanical core. We used a version of CAM that was coupled to a slab-ocean / thermodynamic sea-ice mode to allow interaction between atmosphere, ocean and sea ice. The horizontal ocean heat transport and mixed layer depth for the oceanic surface mixed layer were prescribed to ensure realistic sea surface temperatures and ice distributions for the present climate.

The CLM model, described in detail by Bonan et al. [2002], includes up to four different plant function types (PFT's) within each 2.0° x 2.5° grid cell, with a single PFT used to represent croplands. Multiple soil columns are simulated for grid cells with croplands, with cropland soils treated separately from natural vegetation. The percent of each grid cell with cropland (Figure 1a) is defined in CLM from satellite-based land cover maps [*Loveland, et al.*, 2000]. Monthly values of LAI for each PFT in CLM are prescribed based on satellite measurements from 1992-1993 [*Bonan, et al.*, 2002], and thus do not respond to CO_2 changes. However, the physiological effects of CO_2 on canopy photosynthesis and stomatal conductance are modeled within CLM [*Oleson, et al.*, 2004].

Four 50-year simulations were performed, with the first 20 years of each simulation treated as spin-up and the last 30 years used for analysis. The first two runs included the default land surface in CLM, which does not include irrigation, and atmospheric CO_2 levels of 355 ppm (CLM default) and 710 ppm, respectively. The difference between these two runs provided an estimate of the climate response to doubled CO_2 in the absence of irrigation. These experiments were then repeated, but with soil moisture in all agricultural soil columns maintained at soil saturation percentage throughout the simulation. This extreme irrigation scenario was not intended to represent reality, where many regions are not irrigated and even irrigated soils are usually below saturation. Instead, the experiments provide a simple measure of the sensitivity of greenhouse warming to irrigation practices. Figure 1b shows a recent estimate of the percent of actual land surface that is irrigated [*Doll and Siebert*, 2000], for comparison with the modeled distribution (Figure 1a).

Results and Discussion

Doubling of CO_2 in the absence of irrigation resulted in increases of global mean temperature by 2.2 °C and precipitation by 4 %. Consistent with nearly all GCMs, the simulated warming was greatest at high latitudes (Figure 2a) because of decreases in sea ice and snow extents [*Dai, et al.*, 2001; *IPCC*, 2001]. Soil moisture exhibited significant changes in many regions (Figure 2b) with notable reductions in Europe, southern India, Southeast Asia, western United States, and northern South America. Increases in soil moisture were simulated in northeast Africa, Saudi Arabia, and western South America. Reductions in soil moisture corresponded to increases in the ratio of sensible to latent heat fluxes (not shown), which thus provided a positive feedback to temperature changes in these regions.

In the presence of irrigation, doubling of CO_2 resulted in global mean increases of temperature by 2.1 °C and precipitation by 4 %. Thus, even an extreme scenario of irrigating all agricultural soils to saturation had little effect on the global climate sensitivity to CO_2. In many agricultural regions, such as the corn belt of the U.S. or most of South America and China, irrigation had negligible effects on the climate response to CO_2 (Figure 2c). However, temperature changes differed significantly in several regions, in particular those with a positive soil moisture feedback in Figure 2b. Compared to the simulations without irrigation, the annual mean temperature response to doubled CO_2 was roughly 0.5°C lower in southern India and Southeast Asia in the presence of irrigation, and 1.0 °C lower throughout much of Europe. While significant, these temperature differences represented less than 25% of the simulated warming from doubled CO_2 in most regions (Figure 2d).

Another way irrigation could modify CO_2 response is through the addition of extra water vapor, a strong greenhouse gas, to the atmosphere in response to elevated CO_2. However, if water vapor feedbacks were important one would expect to see interactions over all irrigated regions, which was not observed. This agrees with Boucher et al. [2004], who found that direct radiative effects of water vapor from irrigation were much smaller than temperature effects of increased surface latent heat flux.

The results presented here suggest that simulated climate changes in some agricultural regions may be biased if current models anticipate feedbacks from soil moisture that, in reality, will not occur because of irrigation. In the present model, irrigation tended to mitigate the simulated temperature response to doubled CO_2. It is also possible, at least in principle, that irrigation could amplify the simulated response, if an agricultural region is located within an area simulated to have a strong negative soil moisture feedback.

A recent inter-comparison of 15 GCMs found that modeled soil moisture changes for an A1b emission scenario were consistently negative in the summertime for southern Europe, southwestern U.S., Australia, and northern and southern Africa [*Wang*, 2005]. Southeast Asia also exhibited significant declines in moisture content for most models, while changes in India were inconsistent among models. No regions were found to have a consistent increase in summer soil moisture. Thus, the results presented here for Europe appear more robust than those for South and Southeast Asia. In addition, it appears unlikely that including irrigation would ever increase projected warming, given a lack of agricultural regions with a negative soil moisture feedback.

The use of extreme irrigation scenarios in this study was useful for bracketing the potential impact of irrigation on GCM simulations of greenhouse gas responses. For example, it appears that irrigation is relatively unimportant for simulating temperature or precipitation responses at the global scale, given the limited intersection of agricultural land and regions of strong simulated soil moisture feedbacks. At the regional scale, the presence of irrigation may significantly mitigate greenhouse warming but is unlikely to aggravate it. Simulations of more realistic distributions of irrigation (e.g., Figure 1b) would be useful for assessing the actual impact of irrigation on future regional climates.

While this study focused on the interaction between irrigation and CO_2, a comparison of temperature changes for doubled CO_2 with those for irrigation are also of interest and readily evaluated from the experiments. Table 1 shows that cooling from an extreme irrigation scenario was ~0.5º C larger in magnitude, on average, than warming from doubled CO_2 over cropland regions in summer months. Conversely, irrigation-induced cooling was lower than CO_2-induced warming in winter. Table 1 also reveals that the modification of CO_2 warming by irrigation, which was ~0.3º C in summer and ~0.2º C in winter, was roughly one-tenth the magnitude of the direct cooling influence of irrigation.

Thus, accounting for changes in irrigation are likely more important than the interaction between irrigation and CO_2 when projecting climate change in regions with substantial land use change. However, these results depend on how irrigation was represented in the model and should be compared with other models. The results are also potentially sensitive to the lack of LAI response in CLM to irrigation or CO_2, and the modeled response of stomatal conductance to CO_2 [*Betts, et al.*, 1997].

Conclusions

GCM's are nearly universal in their simulation of summertime soil drying in response to increased atmospheric CO_2 in many important agricultural regions, such as Europe and southern North America. Thus, modeled temperature changes over these regions due to historical or future CO_2 changes likely include, to some extent, a positive feedback between moisture change and near-surface air temperatures. The results presented here indicate that irrigation can significantly modify (i.e. interact with) greenhouse warming by eliminating this moisture feedback. Inclusion of irrigation in GCMs would thus likely reduce simulated warming in some agricultural regions, although the effect on global mean temperature is likely to be small relative to the consequences of the enhanced greenhouse effect by increased greenhouse gas concentrations. Given that a disproportionate amount of food production originates in irrigated regions, however, it is possible that the interaction of irrigation and CO_2 is an important source of overall uncertainty for projecting societal impacts of climate change. Thus, future work to better understand and reduce this source of climate uncertainty in heavily irrigated regions appears warranted.

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Table 1. Average temperature change (°C) over land in response to extreme irrigation[a] (first 2 rows) or doubled CO_2 (last two rows).

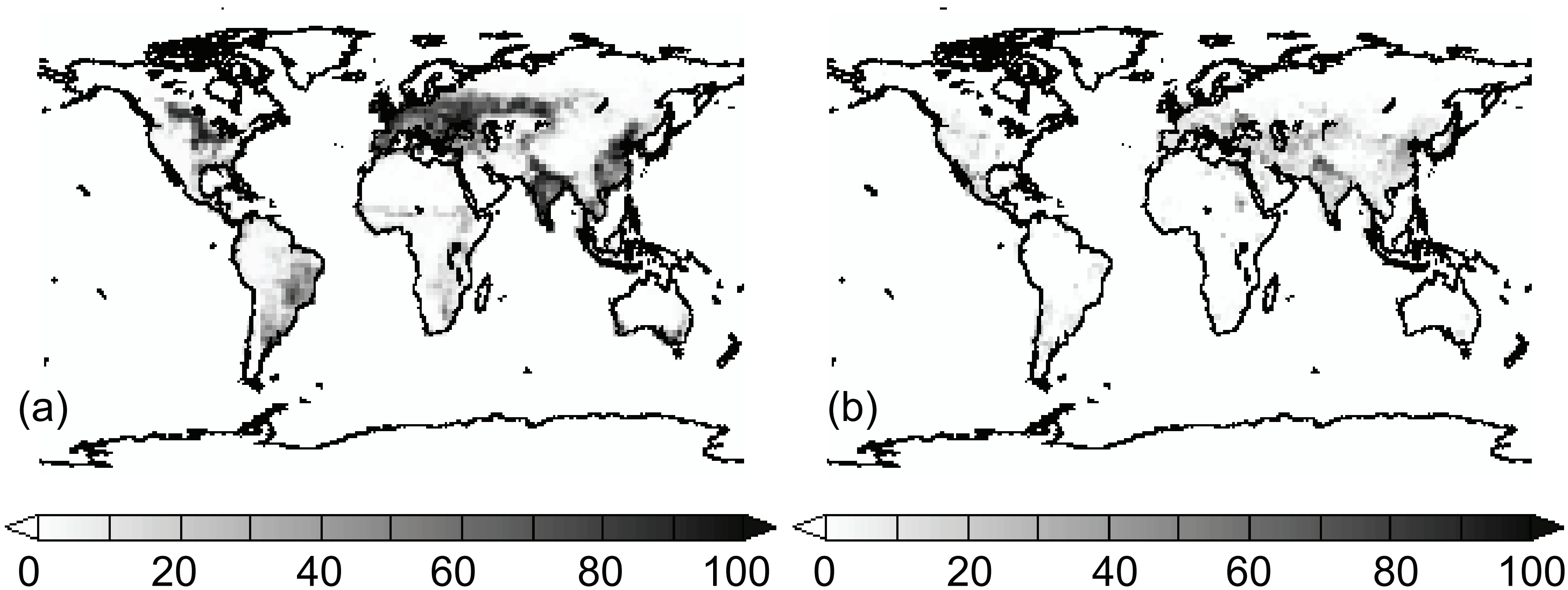
	JJA		DJF	
Model Experiments	All land	Cropland only	All land	Cropland only
$1xCO2_{irr} - 1xCO2_{no-irr}$	-1.8	-2.7	-0.9	-1.4
$2xCO2_{irr} - 2xCO2_{no-irr}$	-2.1	-3.0	-1.1	-1.6
$2xCO2_{no-irr} - 1xCO2_{no-irr}$	2.7	2.2	2.6	2.1
$2xCO2_{irr} - 1xCO2_{irr}$	2.4	1.9	2.4	1.9

[a]Irrigation corresponds to all cropland grid cells being maintained at soil saturation.
JJA = June-July-August; DJF = December-January-Februrary.

Figure Legends:

1) (a) The percentage of each 2.0° x 2.5° grid cell defined as cropland within CAM3. (b) The estimated percentage of each 2.0° x 2.5° equipped for irrigation [*Doll and Siebert*, 2000]

2) Annual average surface (a) temperature (°C) and (b) soil moisture (%) changes for doubled CO_2 in the absence of irrigation, $[2xCO_2 – 1xCO_2]_{no-irr}$. (c) Difference in temperature response to doubled CO_2 with and without irrigation, $[2xCO_2 – 1xCO_2]_{irr}$ – $[2xCO_2 – 1xCO_2]_{no-irr}$. (d) Ratio (%) of same responses, $[2xCO_2 – 1xCO_2]_{irr}$ / $[2xCO_2 – 1xCO_2]_{no-irr}$. Gray cells are not significant at $p = 0.05$.


(a)
(b)
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40
60
80
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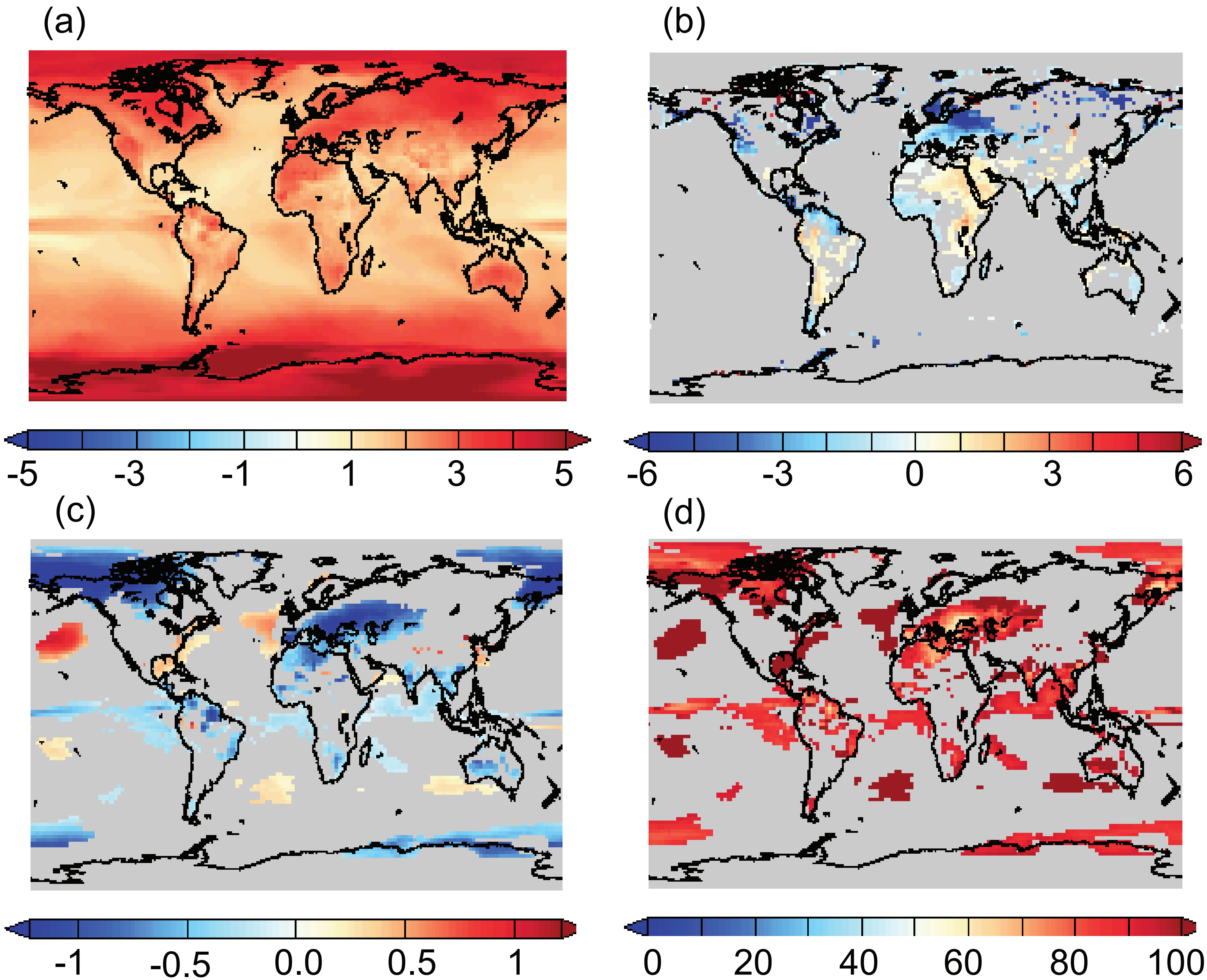
60
80
100


(a)
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(b)
-6
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6
(c)
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(d)
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80
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