A modeling study of dynamic and thermodynamic mechanisms for summer drying in response to global warming

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[1] Past studies have suggested that increasing atmospheric CO_2 will lead to a significant reduction of soil moisture during summer in the extratropics. These studies showed an increase in wintertime rainfall over most mid-latitude continental regions when CO_2 is doubled, an earlier snowmelt season and onset of springtime evaporation, and a higher ratio of evaporation to precipitation in summer. These factors led to large-scale increases in soil moisture in winter and decreases in summer. We find that the above processes are important in simulated summer drying in a newly developed climate model. In addition to these thermodynamic processes, we find that changes in atmospheric circulation play an important role in regional hydroclimatic changes. Additional experiments show that the atmospheric circulation changes are forced by the CO_2-induced warming of the ocean, particularly the tropical ocean. These results highlight the importance of sea surface temperature changes for regional hydroclimatic changes.
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1. Introduction

[2] One of the most crucial issues in climate research is the need for a more thorough understanding of changes in continental hydrology on time scales of decades to centuries in response to increasing atmospheric greenhouse gases. A number of pioneering studies [e.g., *Manabe et al.*, 1981; *Manabe and Wetherald*, 1986; *Mitchell and Warrilow*, 1987; *Kellogg and Zhao*, 1988; *Meehl and Washington*, 1988; *Wetherald and Manabe*, 1995] have analyzed model projections of future climate, with particular emphasis on potential changes in summer continental hydrology in the extratropics. *Manabe and Wetherald* [1987] find that an increase of atmospheric CO_2 is likely to lead to increased summertime drying of soils in mid-latitude continental regions, particularly in North America and Asia. They explained this process, and the often-simulated wintertime wetting of soils in the same region, through the following mechanism: a greater fraction of wintertime precipitation occurs as rain instead of snow due to warmer temperatures; the warmer temperatures lead to an earlier start of the snowmelt season, as well as an earlier start of the spring and summer evapotranspiration season, thereby leading to a reduction of summer soil moisture. This mechanism primarily relies on thermodynamics, since the sequence of events is a consequence of a warmed overall climate, leading to greater oceanic evaporation and poleward moisture transport, coupled with warmer conditions in spring and summer leading to an earlier start of the snowmelt and evaporative season. Hence, this mechanism will be referred to as the "thermodynamic mechanism" for summer drying. The details and magnitude of this mechanism are sensitive to the precise model formulation, as demonstrated by *Mitchell and Warrilow* [1987], *Kellogg and Zhao* [1988], *Meehl and Washington* [1988], and *Milly* [1997]. *Robock et al.* [2005] provide some observational perspective, but are limited in the scope of their conclusion due to data limitations.

[3] Given the importance of this issue, in this paper we revisit this topic using a newly developed climate model. The model has been developed over the last several years at the Geophysical Fluid Dynamics Laboratory (GFDL), and expands upon earlier models in simulating climate variability and change. We analyze the results from an equilibrium doubled CO_2 experiment, and contrast those findings to previous model results. We find that the general conclusions about summer drying in a high CO_2 world are valid in this new model, but the important role of atmospheric circulation changes is emphasized.

2. Model and Experiments

[4] The model used is a newly developed atmospheric general circulation model (called AM2) coupled to a slab ocean model. The atmospheric resolution is 2.5° longitude by 2° latitude, with 24 vertical levels, and has both a seasonal and a diurnal cycle of insolation. The details of the atmospheric model are contained in a paper from *The GFDL Global Atmospheric Model Development Team* [2004] (hereinafter referred to as GAMDT04). GAMDT04 and *Milly and Shmakin* [2002] describe the bucket-style treatment of soil water used in this model: at each grid point, the bucket is intended to represent the plant root zone depth. Thus, the bucket sizes are dependent on vegetation and soil classifications. In the mid-latitudes, soil moisture buckets are typically between 10 and 15 cm deep, with exceptions in the northern-most regions where bucket depths are about 5 cm, and some regions with depths closer to 20 cm, the largest being the southeastern United States. GAMDT04 includes detailed comparisons of model output and observations for many fields. A comparison of soil moisture fields was not performed, given the absence of global observations of this field. However, we note that Northern Hemisphere precipitation is shown to closely match observations. Additional model documentation is available from the GFDL website at http://nomads.gfdl.noaa.gov.

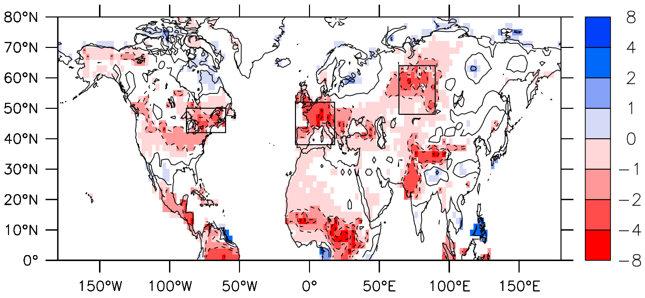

Figure 1. Map of difference in JJA root zone soil water (cm) between 2X experiment and control experiment. Differences were computed from 50-year time-means of each experiment. All differences are contoured (dashed lines for negative differences), but only areas with differences significant at the 90% level are shaded (white regions indicate insignificant differences). The three regions enclosed in boxes are highlighted in Figure 2.

[5] For the experiments described below, the atmospheric model is coupled to a 50-m-deep slab "mixed layer" model of the ocean. Atmosphere and ocean interact through exchanges of sensible, latent, and radiative heat. In addition, the temperature of the slab ocean is influenced by a heat-flux adjustment that serves as a simple way of accounting for the lack of ocean dynamics and other deficiencies in the model. The same heat flux adjustments are used in all the runs under the assumption that the horizontal heat transport by ocean currents does not change in these experiments. The ocean model is coupled to a dynamic/thermodynamic sea ice model [*Winton*, 2000].

[6] The primary pair of experiments conducted consisted of a 100 year control integration, with time-invariant concentrations of atmospheric greenhouse gases, and a 100 year perturbation experiment in which atmospheric CO_2 is instantaneously increased to twice its value in the control run (referred to as the "2X" experiment). The model takes several decades to come into equilibrium with the new forcing; therefore analyses are conducted on the last 50 years of the experiments. Additional experiments were also conducted (details below) to clarify the mechanisms of the differences between the 2X and control integrations.

3. Results

3.1. Simulated Hydrologic Changes in Response to a Doubling of Atmospheric CO_2

[7] In response to a doubling of CO_2 the annual mean surface air temperature of the model increases by 2.9K, with somewhat larger increases over continental regions than over oceanic regions. Wintertime changes in soil moisture (not shown) include increases throughout most of Asia, decreases in much of Europe, and generally insignificant changes throughout North America. The changes in Northern Hemisphere (NH) June–July–August (JJA) soil moisture simulated in response to the doubling of atmospheric CO_2 are shown in Figure 1. The focus in this study is on the NH extratropics during summer, although changes are also seen in other seasons and in other parts of the globe. Contours in Figure 1 indicate the magnitude of soil moisture differences between the 2X and the control run; these differences are shaded only where they are significant at the 90% level. A modified Student's *t*-test following the methodology of *Zwiers and von Storch* [1995] is used to test statistical significance. This modified test accounts for autocorrelation within the 50-year time series, and is therefore more stringent than a standard Student's *t*-test. Results are not highly sensitive to the significance level of the *t*-test.

[8] Figure 1 shows that large regions of decreased soil moisture span most of North America, southern Europe, and western and central Asia during JJA. The pattern of soil moisture changes is not uniform, however. There is a very clear spatial structure, which includes regions where soil moisture increases or does not change significantly, notably northeastern Europe and northeastern North America. (Note, however, that the area with significant increases does not exceed the 5% that is expected to pass the 90%-level significance test by chance.) It is difficult to explain such a pattern solely on the basis of the thermodynamic arguments summarized above from previous studies. As described below, the mechanisms summarized in previous studies do play a very important role in the changes seen in Figure 1, but are augmented by atmospheric circulation changes which influence the spatial pattern of the response.

[9] The seasonal cycle of soil moisture changes is shown in Figure 2 for the three mid-latitude regions with the most substantial summer drying: central Asia, southwestern Europe, and east of the Great Lakes, indicated by the boxes in Figure 1. The seasonal cycle of soil moisture from central Asia is consistent with the thermodynamic mechanism of summer drying. The model simulates increased soil wetness in winter in the 2X experiment, with a transition to reduced soil wetness in spring into summer in response to the earlier snowmelt season and more intense evaporative demand. In contrast, soil wetness is reduced in all seasons in southwestern Europe. Soils east of the Great Lakes are close to saturation during the winter in both the control and 2X runs, and are significantly lower in the 2X run during the summer.

[10] For the hydrologic changes over southwestern Europe and elsewhere, changes in atmospheric circulation are potentially important. Shown in Figure 3 are the differ-

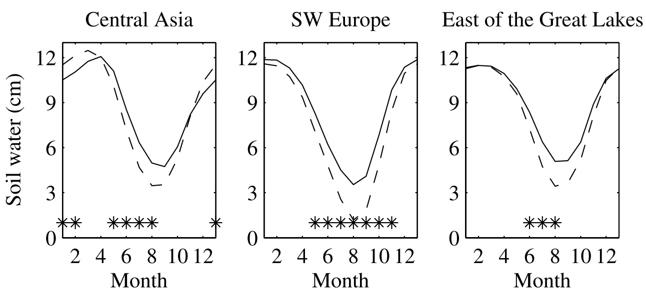

Figure 2. Fifty-year mean of the seasonal cycle of the areal average soil moisture for the regions indicated by the boxes in Figure 1. Central Asia is defined as 48°N to 64°N, 64°E to 90°E; Southwestern Europe is defined as 38°N to 52°N, 10°W to 18°E; and the region east of the Great Lakes is defined as 42°N to 50°N, 88°W to 60°W. Areal average maximum soil water for each region is 15.5 cm, 12.2 cm, and 11.6 cm, respectively. Differences in each region are significant at the 95% level in months with a star on the bottom of the plot.

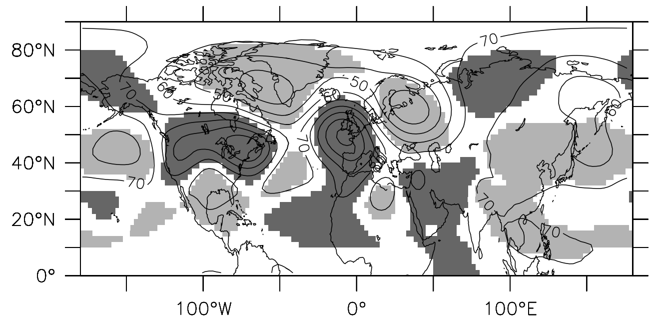

Figure 3. Map of difference in JJA 500 mb geopotential height (z_g, m) between 2X experiment and control experiment, indicated by the contours. Because of the large-scale warming of the atmosphere, contoured differences are positive and significant at all grid points. Shaded regions indicate where the differences are significant at the 90% level after the zonal means were removed. Dark shading is used for relative highs, light shading for relative lows. All differences were computed from 50-year time-means of each experiment. Contours are every 10 m.

ences in the northern summer (JJA) 500 mb geopotential height (z_g) between the 2X experiment and the control. The changes in geopotential height indicate substantial changes in tropospheric circulation, particularly over the western half of Eurasia and over much of North America. Note that the general warming of the atmosphere in a high CO_2 climate provides a global scale statistically significant background increase in geopotential heights. A uniform increase would not be associated with altered circulation patterns, but the regional minimums and maximums are. Shading is used in Figure 3 to indicate statistical significance of the difference between 500 mb z_g with zonal means removed. The circulation changes associated with the patterns in Figure 3 would tend to induce the soil wetness changes seen in Figure 1, with reductions over southwestern Europe and the region east of the Great Lakes associated with strong anomalous anticyclones (high z_g anomalies in Figure 3), and increases in soil wetness associated with the cyclonic anomalies centered over western Asia and the Baffin Bay (low z_g anomalies in Figure 3). The anticyclonic anomalies are also associated with a statistically significant reduction in summertime precipitation, particularly convective precipitation. Increased precipitation occurs in the northern portion of the cyclonic anomaly in western Asia and from the Hudson Bay eastward to Greenland. (A plot of precipitation differences is available as auxiliary material[1].)

3.2. Forcing of Atmospheric Circulation Change

[11] While these circulation changes are consistent with the pattern of soil wetness changes seen in Figure 1, it is unclear whether the circulation changes are a response to soil wetness changes, or whether they play some role in forcing the soil wetness changes. In order to address this issue, additional experiments were performed with the mixed layer model. In the first experiment, atmospheric CO_2 was fixed at the same level as the control integration, but soil wetness values were prescribed based upon a time series of daily soil wetness values archived from the 2X experiment. The intent of this experiment is to assess whether the soil wetness changes in the 2X experiment are capable of inducing the atmospheric circulation changes. This experiment will be referred to as the 2X_SOIL experiment. In the second experiment, atmospheric CO_2 was also prescribed to be the same as in the control integration, but sea surface temperatures (SSTs) from the 2X experiment were prescribed. (The annual average global SST difference between the 2X and the control experiments was 2.05°C. A plot of SST differences is available as auxiliary material.) The intent of this second experiment is to see whether global scale changes in SST are responsible for the simulated atmospheric circulation changes. This experiment will be referred to as the 2X_SST_GLOBAL experiment. A third experiment was also conducted in which SSTs from the 2X experiment were prescribed only in the tropics, while SSTs outside the tropics were prescribed using output from the control run. For the purposes of this study, the tropics were defined as 30°S to 30°N, and a weighted average of the two SST fields was used in 5° latitude transition zones between the extratropics and the tropics (e.g., from 27.5°S to 32.5°S). This third experiment will be referred to as 2X_SST_TROPICS.

[12] Note that the 2X_SST_GLOBAL and 2X_SST_TROPICS experiments will have warmer air temperatures than the Control experiment, despite having the same atmospheric CO_2 as the Control since the warm ocean will warm the atmosphere. Globally averaged JJA two-meter air temperature differences from the Control experiment are 2.8°C in $2xCO_2$, 2.6°C in 2X_SST_GLOBAL, and 1.5°C in 2X_SST_TROPICS. For the region north of 30°N, the differences are 2.8°C, 2.2°C, and 0.7°C, respectively.

[13] Maps of the differences in 500 mb geopotential height between the three new experiments and the control integration are shown in Figure 4. Figure 4a shows the results for the 2X_SOIL experiment, and Figure 4b shows the results for the 2X_SST_GLOBAL experiment. Comparison of these two plots with Figure 3 makes it clear that the circulation changes are forced predominantly by SST changes. The results from the 2X_SST_TROPICS experiment are shown in Figure 4c. The close correspondence between the middle and bottom panels of Figure 4 demonstrates that the circulation changes are predominantly forced from tropical SST changes. An additional experiment in which extratropical SST changes were prescribed from the 2X experiment shows little impact on the circulation (not shown), though those results and the larger magnitudes of Figure 4c compared to Figure 4b suggest that the extratropics may in fact modulate the changes forced by tropical SSTs. Nevertheless, Figure 4c makes it clear that atmospheric circulation changes driven from tropical SST changes may play a key role in future regional hydrologic changes in a world with elevated levels of atmospheric greenhouse gases. More detailed attribution of the tropical source regions for these changes is the subject of ongoing research.

4. Summary and Discussion

[14] Changes in continental scale hydrology could be of substantial societal relevance in the future. In this paper we have outlined some of the mechanisms by which continental

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023414.

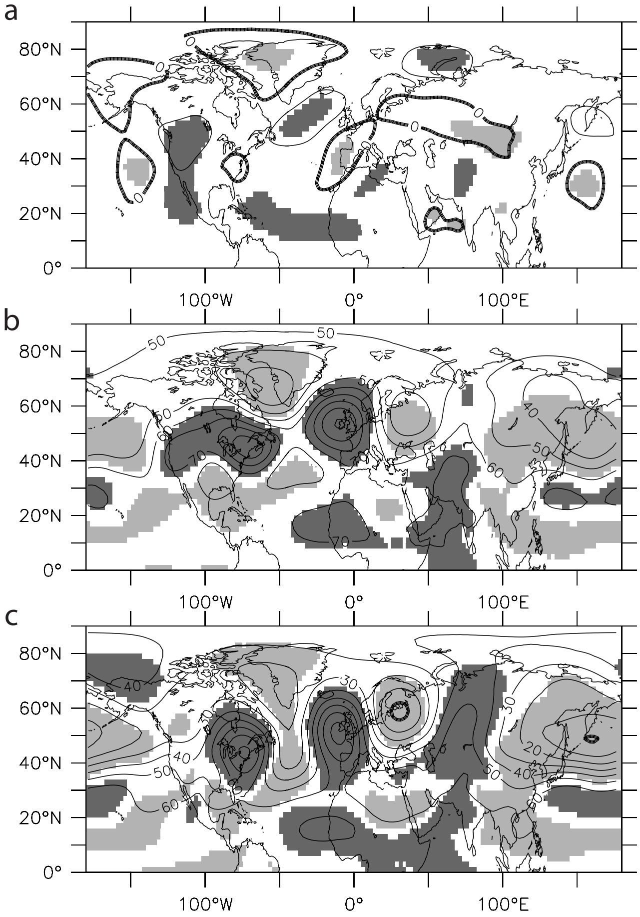

Figure 4. As in Figure 3, except differences are between (a) the 2X_SOIL experiment and the control; (b) the 2X_SST_GLOBAL experiment and the control; and (c) the 2X_SST_TROPICS experiment and the control.

hydrology may change as atmospheric greenhouse gases increase, and examined the output from a climate model which demonstrates such changes. We have focused on the Northern Hemisphere extratropics during the summer season.

[15] The results of this work suggest that changes in continental hydrology are driven by both thermodynamic and dynamic factors. Much previous work on the continental hydrologic response to increasing CO_2 has stressed the importance of thermodynamic changes, in which large scale changes in the energy budget impact the hydrologic cycle. In this paper we have affirmed that the thermodynamic mechanism is operating in GFDL's newly developed climate model. In addition, we have shown through model experiments that atmospheric circulation changes in a high CO_2 climate may also play a very important role in regional hydrologic changes. We have demonstrated that the circulation changes in this model are primarily driven by tropical SST changes in a high CO_2 world.

[16] The importance of tropical SST changes is in good agreement with model-based studies of recent climate changes [see, e.g., *Schubert et al.*, 2004; *Giannini et al.*, 2003; *Hoerling and Kumar*, 2003; *Hoerling et al.*, 2001], in which changes in tropical SST have induced global scale circulation changes with important consequences for regional hydrology. The precise pattern of circulation changes simulated in this study should not be taken as a literal prediction of future circulation changes; they were based upon results from a mixed layer model, in which ocean dynamics does not operate. In the real climate system changes in ocean dynamics, such as those associated with El Niño, could give rise to a different pattern of SST changes, and thus a different pattern of extratropical circulation changes. Additional experiments in which the same atmosphere was coupled to a dynamic ocean model and then subjected to elevated levels of atmospheric CO_2, show a slightly different pattern of extratropical circulation changes, but the general structure of the two anticyclone-cyclone pairs seen in Figure 3 is present. This is especially evident when atmospheric CO_2 levels are increased to four times the present-day levels. These results will be reported in a separate publication.

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