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Sensitivity of greenhouse summer dryness to changes in plant rooting characteristics

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Abstract. A possible consequence of increased concentrations of greenhouse gases in Earth's atmosphere is "summer dryness," a decrease of summer plant-available soil water in middle latitudes, caused by increased availability of energy to drive evapotranspiration. Results from a numerical climate model indicate that summer dryness and related changes of land-surface water balances are highly sensitive to possible concomitant changes of plant-available water-holding capacity of soil, which depends on plant rooting depth and density. The model suggests that a 14% decrease of the soil volume whose water is accessible to plant roots would generate the same summer dryness, by one measure, as an equilibrium doubling of atmospheric carbon dioxide. Conversely, a 14% increase of that soil volume would be sufficient to offset the summer dryness associated with carbon-dioxide doubling. Global and regional changes in rooting depth and density may result from (1) plant and plant-community responses to greenhouse warming, to carbon-dioxide fertilization, and to associated changes in the water balance and (2) anthropogenic deforestation and desertification. Given their apparently critical role, heretofore ignored, in global hydroclimatic change, such changes of rooting characteristics should be carefully evaluated using ecosystem observations, theory, and models.

Introduction

A possible consequence of increased concentrations of greenhouse gases in Earth's atmosphere is "summer dryness," a decrease of summer plant-available soil water in middle latitudes (Manabe et al., 1981, 1992; Manabe and Wetherald, 1987; Wetherald and Manabe, 1995; Kattenberg et al., 1996). Summer dryness occurs in climate model experiments when the radiatively-induced increase of summer evaporative demand outstrips any corresponding increases in soil-water supply.

Various biospheric feedbacks, neglected in models until recently, may significantly affect the sensitivity of global and regional water balances to changes of radiative forcing. The focus of recent attention has been on above-ground plant biomass. At the leaf scale, non-water-stressed plant transpiration may be suppressed if stomata decrease in number or close (Woodward, 1987; Henderson-Sellers et al., 1995; Sellers et al., 1996) in response to increased atmospheric CO_2, potentially counteracting the tendency toward summer dryness (Henderson-Sellers et al., 1995). At the plant or community scale, however, possible increases in total foliar area might have the opposite effect of promoting an increase of evapotranspiration (Martin et al., 1989).

Ultimately, water availability limits evapotranspiration in ecosystems that experience water stress. Water availability is determined by climate, soil, and plant-root systems (*i.e.*, below-ground biomass); plant-available water-holding capacity of soil (w_0, a parameter in some climate models) is proportional to the volume of soil whose water is accessible to plant root systems. The latter is strongly affected by plant rooting characteristics. An increase of w_0 in a climate model induced hydrologic changes (Milly and Dunne, 1994) similar, but opposite in sign, to some of those associated with increased atmospheric CO_2 (Manabe et al., 1987). The objectives of this letter are to identify and explain the sensitivity of summer dryness to changes of w_0 in one climate model and to note the implied relevance of root-system changes for studies of global hydroclimatic changes.

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Numerical Experiments

Numerical experiments were performed using a three-dimensional, time-dependent numerical model of the radiation balance, thermodynamics, general circulation, and water cycle of the atmosphere, coupled to a mixed-layer representation of the ocean; the model is similar to one used in a recent study of summer dryness (Wetherald and Manabe, 1995). Ocean-surface temperatures were computed by an energy balance on a surface mixed layer of 50-m thickness, neglecting horizontal oceanic heat transport and heat exchange with the deeper ocean. Cloud was generated when relative humidity exceeded 99%. For simplicity of interpretation, all simulations had alternating 60°-wide continents and oceans, with no mountains. To examine summer dryness unrelated to changes in snowfall and snowpack (and associated surface albedo), water was not allowed to freeze.

The plant-available soil-water storage (w) was tracked for each land gridpoint (at a resolution of approximately 4.5° latitude by 7.5° longitude) by an accounting of precipitation (P), evapotranspiration (E), and runoff. E was the product of potential evapotranspiration (E_p), which is determined by energy availability at the land surface (Milly, 1992), and a simple water-availability function (Manabe, 1969):

$$E = E_p min\left(\frac{w}{0.75w_0}, 1\right) \tag{1}$$

Runoff (Y) was allowed to occur when necessary to prevent w from exceeding w_0. Physically, this corresponds to an assumptions that all precipitation can infiltrate the soil, and that root-zone storage in excess of capacity drains rapidly from the soil under the force of gravity, accounting for all runoff; furthermore, upward flow to the root zone during dry periods is neglected.

Four model runs were performed. The first, denoted "1x150", was run with an atmospheric CO_2 concentration of 300 ppm and w_0 equal 150 mm. Simulations "4x100", "4x150" and "4x200" had quadrupled (1200 ppm) CO_2, and w_0 equal 100 mm, 150 mm and 200 mm, respectively. The 150-mm value is standard for this model; the 100-mm and 200-mm values, arbitrarily chosen, permitted analysis of the effects of root-characteristic changes. All results reported here are based on 10 years of model output, following 20 years of spinup from initial conditions.

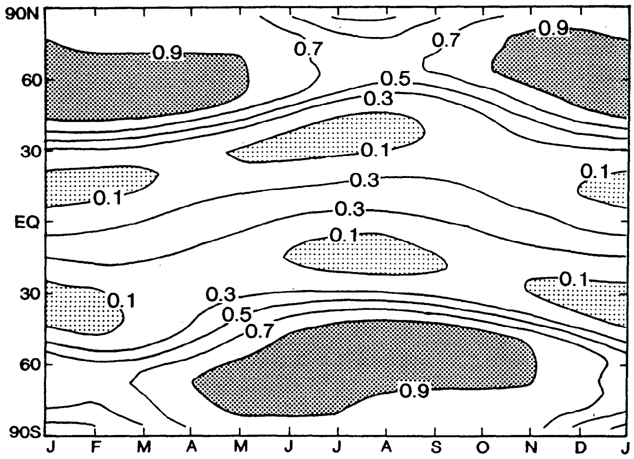

Figure 1. Zonal-mean soil-water storage (w), expressed as a fraction of plant-available water-holding capacity (w_0 =150 mm), as function of latitude and month of year in simulation 1x150. In this figure and Figure 2, the symmetry (with 6-month lag) between northern and southern hemispheres is indicative of the statistical robustness of the simulations.

Results

The seasonal cycle of w varied with latitude in run 1x150 (Figure 1); the pattern was similar in 4x100, 4x150 and 4x200. In the middle latitudes, w had a strong seasonal cycle. Storage was near saturation in winter, when P exceeded E_p; winter E was limited by E_p (Eqn 1). Storage was depleted during summer, when E_p exceeded P; summer E was water-limited, and approximately equal to the sum of summer P and the winter-summer decrease of w; the latter could not exceed w_0.

Under CO_2-quadrupling, with fixed w_0, annual totals of P and E_p increased 15% and 30%, respectively, over 45°-60° latitude (Table 1). The increases of P and E_p were concentrated in winter and summer, respectively (Table 2). Because winter soil water was already near saturation in 1x150, the additional P in 4x150 was mostly forced to run off. In summer, the water-limited E could not increase in proportion to E_p from 1x150 to 4x150; the resultant decrease of summer E/E_p led, via (1), to reduction of summer w/w_0 (Figure 2). (In this model, seasonal mean w is much more a result of the water balance than a determinant of it (Milly, 1992).) These seasonal changes of water balance largely explain the annual changes (Table 1); increase of annual E (7%) was proportionately less than that of P, while increase of annual Y (28%) was much greater.

Table 1. Modeled Mid-Latitude Water Balances of Land

Simulation	P	E_p	E	Y	Y/P	w_S/w_0
1x150	944	1299	593	352	0.373	0.495
4x100	1014	2023	553	461	0.455	0.348
4x150	1084	1691	635	450	0.415	0.429
4x200	1121	1467	693	429	0.383	0.507

P (precipitation), E_p (potential evapotranspiration), E (evapotranspiration), and Y (runoff) are annual totals, expressed as mm of liquid water. w_S is time-average plant-available soil water during summer half-year (May-October in northern hemisphere, November-April in southern hemisphere). All variables are areal means over land 45° S-60° S and 45° N-60° N.

Table 2. Differences (4x150 minus 1x150) of P, E_p and E over Midlatitude Land

Period	P	E_p	E	Y
summer	22 (5%)	366 (33%)	18 (4%)	-1 (-2%)
winter	118 (24%)	25 (14%)	24 (14%)	100 (35%)
annual	140 (15%)	391 (30%)	42 (7%)	98 (28%)

Differences (4x150 minus 1x150) of annual and seasonal P (precipitation), E_p (potential evapotranspiration), and E (evapotranspiration), expressed as mm of liquid water. These differences represent the computed changes associated with quadrupling of atmospheric carbon dioxide, with plant-available water-holding capacity of soil being held constant. Seasons and averaging areas are defined in Table 1.

The 50-mm decrease (increase) of w_0 was more than sufficient to double (negate) the reduction in summer w/w_0 induced by CO_2 quadrupling (Table 1; see also Figure 2). These changes came about because the smaller (larger) values of w_0 permitted less (more) conservation of the winter water excess for use in summer E, leading, via (1), to lower (higher) summer w/w_0.

Dependences of summer w/w_0 and annual runoff ratio Y/P on w_0 were nearly linear (Table 1). Linear interpolation with respect to w_0 suggests that a 28% decrease (increase) of w_0 would be just enough to double (negate) the summer dryness (measured by change of summer-half-year w/w_0, 45°-60° latitude) induced by a quadrupling of CO_2. Given the logarithmic dependence of climatic variables on atmospheric CO_2 (Wigley, 1987), a ±14 % change of w_0 would reverse or double the drying associated with a doubling of CO_2. (And a ±19 % change would reverse or double the related change of Y/P.)

Discussion

In assessing these sensitivities, limitations of the study should be kept in mind. The model did not represent the real distribution of land and sea on earth, and it had no mountains. Water was not permitted to freeze. Land-surface hydrology was represented in a very simple manner. Analysis of model results was based only on large-scale averages. Nevertheless, the main features of the climatic sensitivity to w_0 seen here are supported by a more detailed study, free from most of these restrictions (Milly and Dunne, 1994). Furthermore, on the basis of the mechanisms identified herein, it appears quite likely that similar conclusions would have been reached if the experiments had been conducted using an explicit model of root distribution.

The model did not include a representation of surface resistance to evaporation under non-water-stressed conditions, and so could not include the sensitivity of that resistance to atmospheric CO_2 concentration. Hence, the model did not predict the relative summer moistening noted by Henderson-Sellers et al. (1995), nor could it predict the possible compensating effect of any potential increase of total leaf area. To first order, however, such effects are presumably additive with the effect that has been described here. Future studies could address this issue.

The high sensitivity of summer dryness and related annual water balances to changes of plant-available water-holding capacity implies the importance of evaluating changes in plant rooting characteristics. Root distributions may change when ecosystems respond to "greenhouse" warming, carbon-dioxide fertilization (Rogers et al., 1994), and related changes in soil-water availability (Weaver, 1968; Kozlowski, 1971; Milly, 1994). Responses may

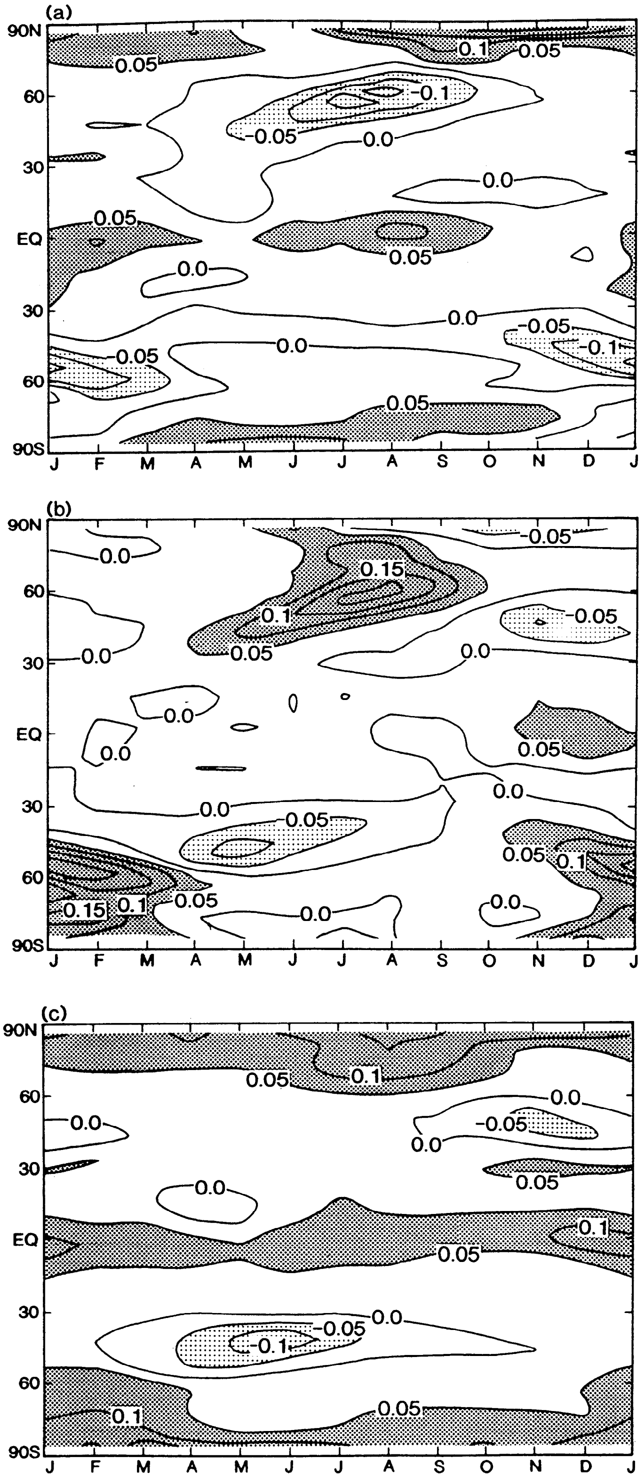

Figure 2. Difference in zonal-mean soil-water storage (w/w_0), as function of latitude and month of year. a. 4x150-1x150, showing midlatitude summer dryness due to increased CO_2; b. 4x200-4x150, showing mid-latitude summer moistening due to increased w_0; c. 4x200-1x150, showing superposition of effects shown in a. and b. Stippling indicates regions in which absolute value of storage difference is more than 5% of capacity.

be constrained by nutrient availability and depth of soil development. Anthropogenic deforestation and desertification could disturb rooting characteristics regionally. Speculation as to the net change in volume of soil accessible to roots can easily run in either direction. Credible estimates of future root-distribution changes might result from observational, theoretical and modeling studies, using a coupled ecological/climatological perspective, with attention also to land-use changes.

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