Museum (Natural History), London, 1954], p. 34.
29. A. Lacasa Ruiz, *Revista Ilerda, Lleida* **46**, 227 (1985).
30. J. A. Talent, P. M. Duncan, P. L. Handby, *Emu* **66**, 81 (1966); M. Waldman, *Condor* **72**, 377 (1970).
31. G. R. de Beer, Archaeopteryx lithographica, *a Study Based upon the British Museum Specimen* [British Museum (Natural History), London, 1954], p. 37.
32. G. R. de Beer, *ibid.*, p. 2.
33. R. Owen, *Proc. R. Soc. London* **12**, 272 (1863).
34. We thank D. Claugher of the Electron Microscope Unit, L. Cornish of the Palaeontological Laboratory, G. C. Jones of the Mineralogy Department, T. W. Parmenter and P. V. York of the Photographic Unit and S. A. Runyard of the Press Office. Many other members of the Museum staff contributed useful assistance, advice, and discussion, in particular S. D. Chapman; likewise members of staff of the research laboratories in the British Museum in Bloomsbury and the National Gallery. We thank also Sir Fred Hoyle and N. C. Wickramasinghe for patiently clarifying various points in their papers.

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Reduction in Summer Soil Wetness Induced by an Increase in Atmospheric Carbon Dioxide

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The geographical distribution of the change in soil wetness in response to an increase in atmospheric carbon dioxide was investigated by using a mathematical model of climate. Responding to the increase in carbon dioxide, soil moisture in the model would be reduced in summer over extensive regions of the middle and high latitudes, such as the North American Great Plains, western Europe, northern Canada, and Siberia. These results were obtained from the model with predicted cloud cover and are qualitatively similar to the results from several numerical experiments conducted earlier with prescribed cloud cover.

In assessments of the possible change in climate due to the increasing CO_2 in the atmosphere, major emphasis has been placed on estimating the change in atmospheric temperature. However, for agricultural planning, the change in soil wetness may be just as important. In the study reported here, which is a continuation of earlier studies (*1, 2*), CO_2-induced changes in soil wetness were investigated by means of a mathematical model of climate in which cloud amount is a predicted variable. Because of the large temporal variability of the model hydrology, it has been difficult to distinguish the CO_2-induced change from the natural variability of soil wetness. Therefore, the earlier reports discussed mainly the zonal mean rather than the geographical distribution of soil wetness. To overcome this difficulty, it is necessary to obtain soil wetness of the model averaged over a very long period. The present study represents an attempt to extract the geographical distribution of soil wetness by substantially extending the averaging period.

The mathematical model of climate used for this research is an atmospheric general circulation model coupled with a static mixed-layer ocean model (*3*). The model has a global computational domain, realistic geography, and seasonally varying insolation.

Precipitation is computed whenever supersaturation is indicated by the prognostic equation for water vapor (*4*). It is identified as snowfall when the air temperature near the surface falls below freezing; otherwise it is identified as rain. The moist convective processes are parameterized by a moist convective adjustment scheme (*4*). Cloud cover is predicted whenever the relative humidity exceeds a certain critical value, which is 99 percent in this case. The distribution of cloud cover thus determined is used for the computation of solar and terrestrial radiation (*5*).

A change in snow depth is computed as a net contribution from snowfall, sublimation, and snowmelt that is determined from the requirement of surface heat balance (*6*). The budget of soil moisture is computed by the so-called bucket method (*6*). For simplicity it is assumed that soil can hold 15 cm of liquid water (*7*). When soil is not saturated with water, the change in soil moisture is predicted as a net contribution of rainfall, evaporation, and snowmelt. If the bucket is full, the excess water is regarded as runoff. The rate of evaporation from the soil surface is determined as a function of the water content of the "bucket" and potential evaporation (*8*).

The mixed-layer model of the ocean is idealized as a 50-m-thick, vertically isothermal layer of water with predicted sea ice (*3*). The effects of horizontal heat transport by ocean currents and heat exchange between the mixed layer and the deeper layer of the ocean are neglected.

Two separate experiments were performed: one with the normal atmospheric concentration of CO_2 (300 ppm) and the other with twice the normal value (600 ppm). By comparing the results from the two experiments, the CO_2-induced change in hydrology could be determined. In each experiment a numerical 40-year integration of the model was conducted starting from an isothermal initial condition. Toward the end of this period, the temporal variation of the global mean sea-surface temperature of the model no longer had a systematic trend, indicating that the model attained an equilibrium climate. To distinguish the CO_2-induced change from the natural variability of the model hydrology, the results were averaged over a sufficiently long period, the last 10 years of the 40-year integration. It is encouraging that, in the experiment with the normal CO_2 concentration, the model successfully reproduced the broad scale features in the geographical distributions of precipitation and annual mean runoff.

The geographical distribution of the CO_2-induced change in soil moisture during June to August is illustrated in Fig. 1A. In summer the soil becomes drier over the mid-continental region of North America, western Europe, and Siberia in response to the doubling of atmospheric CO_2.

The reduction in soil moisture over North America, western Europe, and Siberia is statistically significant at the 10 percent level (Fig. 1B) (*9*). In other words, the probability of falsely rejecting the null hypothesis of no change in soil moisture is 10 percent or less in these regions.

To demonstrate the practical implication of the CO_2-induced summer dryness identified above, the change in soil moisture was expressed as a percentage of the soil moisture from the normal CO_2 experiment (Fig. 1C). This result suggests that the CO_2-induced reduction in soil moisture over the mid-continental regions of North America, Siberia, and western Europe amounts to a substantial fraction of the soil moisture present in the standard CO_2 case.

In general, the soil moisture over the model continents in middle and high latitudes is reduced from the peak level in spring to the summer minimum. In high latitudes, this spring-to-summer reduction in moisture is caused by intense evaporation in late spring, when the continental surface absorbs a large amount of solar energy because of strong insolation and the disap-

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pearance of snow cover with high albedo. In middle latitudes, a similar mechanism also operates over the model continents. In addition, the reduction in soil moisture from spring to summer in middle latitudes is also due to the termination of the rainy period in spring that results from the poleward shift of the rain belt.

According to the comparison of the surface water budget between the normal and high CO_2 experiments, the CO_2-induced reduction in soil moisture in summer over Siberia and northern Canada results from the earlier disappearance of snow cover in the warmer climate. Since the snow cover has a high surface albedo, its disappearance increases the surface absorption of solar energy and accordingly the rate of potential evaporation (*8*). Thus the earlier termination of the snowmelt season results in the earlier commencement of the spring-to-summer reduction in soil moisture, causing the CO_2-induced reduction in soil moisture in summer.

Over the Great Plains, the earlier termination of the snowmelt season also contributes to the CO_2-induced summer reduction in soil moisture. Another factor responsible for the summer reduction is the change in the rate of precipitation in middle latitudes. The CO_2-induced warming in the lower troposphere in the model increases with increasing latitude. Therefore, in the high CO_2 atmosphere the warm, moisture-rich air penetrates into higher latitudes than in the normal CO_2 atmosphere. Thus the rate of precipitation increases markedly in the northern half of the middle latitude rain belt of the Northern Hemisphere, whereas it decreases in the southern half of the rain belt. Because of the poleward shift of the rain belt from winter to summer, a location in middle latitudes, which is situated at the northern half of the rain belt during winter, enters the southern half in summer. Therefore the CO_2-induced increase in precipitation rate at this location is rapidly reduced from spring to early summer, contributing to the reduction in soil moisture during this period.

Over western Europe the CO_2-induced reduction in soil moisture in summer occurs in a manner qualitatively similar to that over North America. However, the contribution of snowmelt is much smaller.

The summer dryness over North America and western Europe is further enhanced by the positive feedback process involving the change in cloud cover. When soil moisture is reduced, a larger fraction of radiative energy absorbed by the continental surface is ventilated through the upward flux of sensible heat rather than through evaporation. Accordingly, the temperature of the continental surface and the overlying layer increases, resulting in the general reduction in relative humidity and precipitation in the lower troposphere of the model. Accompanying the reduction in relative humidity is a reduction in total cloud amount, causing an increase in solar energy reaching the continental surface. Thus the radiation energy absorbed by the continental surface also increases, raising the rate of potential evaporation (*8*). Both the decrease in precipitation and the increase in potential evaporation mentioned above further reduce soil moisture during early summer and help to maintain it at a low level throughout the summer.

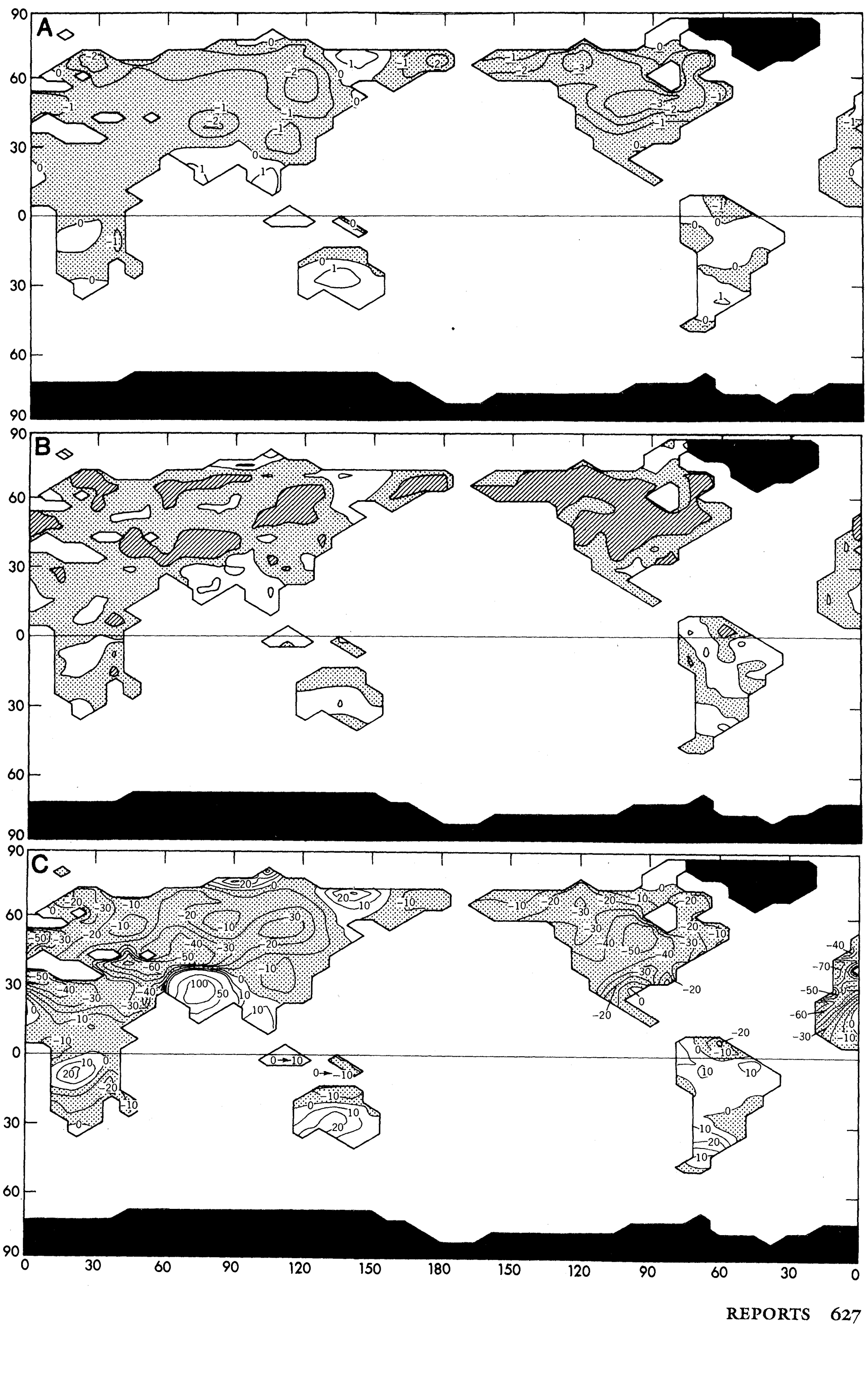

Fig. 1. (A) Geographical distribution of the change in soil moisture (centimeters) in response to a doubling of CO_2 for the period from June to August. Shading indicates regions where the CO_2-induced change is negative. (B) Statistical significance of the CO_2-induced change in soil moisture shown in (A). Areas shaded with lines are regions where the negative soil moisture change is statistically significant at the 10% level. (C) CO_2-induced change in soil moisture expressed as a percentage of soil moisture obtained from the normal CO_2 experiment.

Over the Great Plains in summer, total cloud cover is reduced and surface air temperature increases substantially in response to the doubling of the CO_2 concentration in the model atmosphere (Fig. 2). Qualitatively similar but smaller changes in cloud cover and temperature also occur over western Europe. In summary, the positive feedback process involving cloud cover enhances the CO_2-induced summer dryness over the Great Plains and western Europe.

The seasonal variation of the change in zonal mean soil moisture due to the CO_2 doubling is illustrated in Fig. 3. In middle and high latitudes, zonal mean soil moisture over the continents declines substantially during summer months and is consistent with the geographical distribution of soil moisture change discussed above.

In winter, when the middle latitude rain belt is displaced equatorward, soil wetness increases not only in high latitudes but also in middle latitudes. However, it is reduced at about 25°N, that is, in the southern half of the rain belt. Qualitatively similar changes of zonal mean soil moisture were obtained earlier (*1–3, 10*).

The results described above were obtained by using the model with predicted cloud cover. Similar experiments are also conducted by using another model with fixed cloud cover. A detailed analysis of these experiments also indicates the CO_2-induced reduction of soil moisture in summer, although the magnitude of the reduction is considerably smaller than that suggested here. These results suggest that the summer dryness in the mid-continental regions occurs despite the absence of the cloud feedback process. However, the cloud feedback process enhances the dryness.

Over the subtropical portion of the continents in the Northern Hemisphere (such as the northern coast of Africa, central Asia, India, and Southeast Asia), the geographical distribution of the CO_2-induced change in soil moisture varies greatly from one experiment to another. Furthermore, these changes are not always statistically significant, in part because of the large natural variability of the model hydrology. Therefore, one should not take too literally the changes in these regions pending further investigation. A similar caution applies to the geographical distribution of the CO_2-induced change in soil moisture over the continents of the model in the tropics and the Southern Hemisphere.

It is tempting to speculate that the Dust Bowl drought of the 1930's may have been induced by a warm climate anomaly. As noted by Vinnikov and Groisman (*11*), the seasonal and latitudinal profiles of the positive anomaly of surface air temperature during the 1930's resemble the CO_2-induced warming obtained from the present experiments.

In the model the CO_2-induced global mean increase in surface air temperature with predicted cloud cover is about 4°C and is 1.5 to 2 times larger than the corresponding warming with prescribed cloud cover (*3*). This indicates that the cloud feedback process can enhance the CO_2-induced increase in global mean surface air temperature, as suggested by Hansen *et al.* (*12*). However, a recent study by Somerville and Remer (*13*) suggests that the increase in the liquid water content of clouds in response to the warming of air may act as a negative feedback between temperature and cloud cover by increasing the planetary albedo, thereby reducing the sensitivity of climate. This effect is not considered in the model. In view of the primitive state of the art for the parameterization of cloud formation and other processes, the quantitative aspect of the present study should be interpreted with caution.

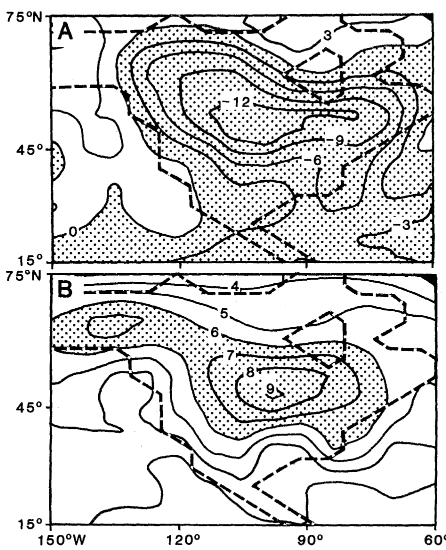

Fig. 2. Geographical distributions of the changes in (A) total cloud amount (%) and (B) surface air temperature (°C) in response to a doubling of CO_2 content for June to August. Only the distributions in the neighborhood of the North American continent are illustrated.

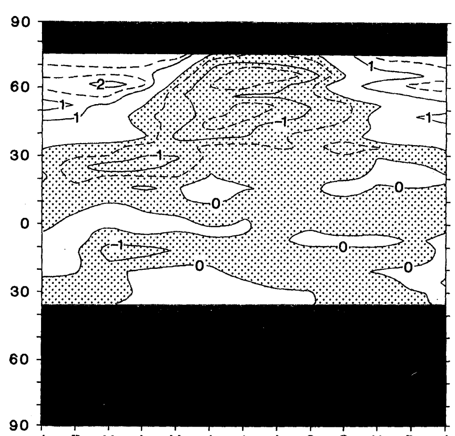

Fig. 3. Latitude-time distribution of the change in zonal mean soil moisture (centimeters) over the continents of the model in response to a doubling of CO_2.

Despite these uncertainties, it seems significant that all the experiments discussed in this report indicate CO_2-induced summer reduction and winter enhancement of soil wetness over extensive, mid-continental regions in middle and high latitudes. Furthermore, the analysis of the soil moisture budget suggests that these large-scale changes in soil wetness are determined by the latitudinal and seasonal profiles of the CO_2-induced warming and do not critically depend on the details of the warming. Therefore, it is likely that the basic conclusion is valid despite imperfections of the model.

REFERENCES AND NOTES

1. S. Manabe, R. T. Wetherald, R. J. Stouffer, *Clim. Change* **3**, 347 (1981).
2. S. Manabe and R. T. Wetherald, *Adv. Geophys.* **28** (part A), 131 (1985).
3. The thickness of the mixed-layer model of the oceans was chosen such that the amplitude of the observed seasonal variation of sea-surface temperature was approximately reproduced by the model. For further details, see S. Manabe and R. J. Stouffer, *J. Geophys. Res.* **85** (C10), 5529 (1980).
4. S. Manabe, J. Smagorinsky, R. F. Strickler, *Mon. Weather Rev.* **93**, 769 (1965).
5. R. T. Wetherald and S. Manabe, *J. Atmos. Sci.* **37**, 1485 (1980).
6. S. Manabe, *Mon. Weather Rev.* **97**, 739 (1969).
7. The moisture-holding capacity of soil is assumed to be constant everywhere in view of our ignorance of its geographical distribution. According to unpublished results from a recent numerical experiment, the simulated distribution of soil moisture expressed as a fraction of the moisture-holding capacity of soil is not very sensitive to the magnitude of the field capacity.
8. Potential evaporation is the evaporation that would occur were there an adequate soil moisture supply at all times. According to M. Budyko [*Climate and Life* (Academic Press, New York, 1974), pp. 335–339], potential evaporation is approximately equal to the total radiative energy absorbed by continental surfaces.
9. Student's *t* test was used. For this test, ten samples of summer soil moisture were obtained from the last 10-year periods of normal and above-normal CO_2 experiments conducted in this study. Because each sample represents an average of 90 daily soil moistures, it is likely that these samples are distributed approximately as Gaussian (as inferred from the central limit theorem), justifying the application of this test.
10. R. T. Wetherald and S. Manabe, *J. Geophys. Res.* **86** (C2), 1194 (1981).
11. K. Ya. Vinnikov and P. Ya. Groisman, *Izv. A.S. USSR Atmos. Ocean. Phys.* **18**, 1159 (1982).
12. J. E. Hansen, A. Lacis, D. Rind, G. Russell, *Climate Processes and Climate Sensitivity* (American Geophysical Union, Washington, DC, 1984).
13. R. C. J. Somerville and L.A. Remer, *J. Geophys. Res.* **89**, 9668 (1984).

14. We thank A. J. Broccoli and R. J. Stouffer, who gave excellent advice for the interpretation of the results from the numerical experiments conducted in the present study, and T. Delworth, N.-C. Lau, and H. Levy II for valuable comments on the manuscript.

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