tion of specific substrates by enzymes —a procedure well known to biochemists for many years—may prove extremely useful in the analysis of other trace components of biological orgin in natural waters.

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## Drought in the Sahara: A Biogeophysical Feedback Mechanism

Abstract. *Two integrations of a global general circulation model, differing only in the prescribed surface albedo in the Sahara, show that an increase in albedo resulting from a decrease in plant cover causes a decrease in rainfall. Thus any tendency for plant cover to decrease would be reinforced by a decrease in rainfall, and could initiate or perpetuate a drought.*

In the Royal Meteorological Society's Symons Memorial Lecture for 1974 Charney (*1*) discussed a biogeophysical feedback mechanism which tends to produce changes in rainfall and plant cover. This mechanism operates because of the dependence of the surface albedo on plant cover. Ground covered by plants has an albedo in the range 10 to 25 percent, whereas ground with no vegetation frequently has a higher albedo, as high as 35 to 45 percent in the case of dry, light, sandy soil (*2*). Thus a decrease in plant cover may be accompanied by an increase in the surface albedo. This would lead to a decrease in the net incoming radiation and an increase in the radiative cooling of the air. As a consequence, the air would sink to maintain thermal equilibrium by adiabatic compression, and cumulus convection and its associated rainfall would be suppressed. The lower rainfall would in turn have an adverse effect on plants and tend to enhance the original decrease in plant cover. This positive feedback will be particularly important in regions such as the Sahara where (i) large-scale subsidence already occurs; (ii) most of the rainfall is from cumulus clouds; and (iii) transports of heat by the winds are particularly weak and inefficient at counteracting temperature changes due to albedo changes. This mechanism offers a possible explanation for past changes in the climate of the Sahara (*3*), and, in particular, for droughts in the Sahel (the southern region of the Sahara), where the process could be initiated by overgrazing.

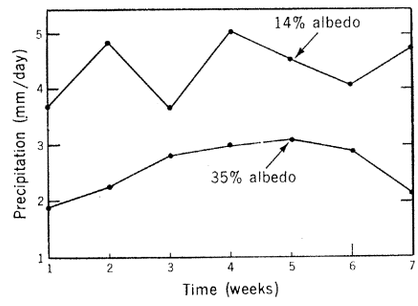


Fig. 1. Weekly mean rainfall rates in the Sahara during the 7 weeks of the experiments.

Otterman (*4*) has also drawn attention to the possible effects on rainfall of changes in the albedo due to overgrazing. He presents data showing actual albedo and temperature changes in the Sinai-Negev region and conjectures that similar changes on a far larger scale have occurred in the Sahel. His argument is that an increase in the albedo causes cooling of the ground and the development of a "thermal depression," the reverse of the "equivalent mountain" of Malkus and Stern (*5*), so that the air has to descend. The equivalent mountain effect of surface heating is essentially a gravity-wave phenomenon and applies only to small-scale heating. It might be relevant to the Sinai-Negev region, but in our opinion it is not applicable to the Sahel or to other large regions. Contrary to Otterman's assertion in his report, it is not in accordance with Charney's approach to the dynamics of subsidence in desert climates. In Charney's analysis an increase in the albedo in a large region causes enhanced sinking and drying only to the extent that the temperature departs further from radiative-convective equilibrium, and this departure depends on the efficiency of a frictionally controlled circulation which reduces the horizontal temperature gradients that would be established by radiation alone. However, both mechanisms fail to take into account the dynamical effect of the release of latent heat in precipitation and both ignore the effects of the global circulation. For example, they do not take into account the interaction of the desert circulation in the Sahara with the monsoon circulation to the south.

In order to assess the plausibility of Charney's mechanism, we need to calculate its effect together with the effect of all other mechanisms which operate simultaneously, and see if the net effect is appreciable. In the past decade computer models of the general circulation of the atmosphere have been developed which implicitly or explicitly include most atmospheric processes,

for example, winds, convection, clouds, rain, radiative absorption, and emission. We have used the general circulation model (GCM) developed at the Goddard Institute for Space Studies (*6*) to calculate the net effect of a change in surface albedo in the Sahara. We carried out two integrations, and for both we used the observed state of the atmosphere on 18 June 1973 as the initial condition. Both integrations were carried forward for 7 weeks of simulated time. The only difference between the two integrations was the prescribed surface albedo for the Sahara. Both integrations had boundary conditions, such as sea surface temperature and soil moisture, prescribed to correspond to climatological conditions for July (summer is the rainy season in the Sahara). In one integration the surface albedo in the Sahara was 14 percent, and in the other it was 35 percent. These albedos simulate, respectively, a Sahara covered with plants and a Sahara devoid of plant cover. The albedos in the two integrations differed at 46 grid points covering approximately the same region as the actual Sahara. (The model's resolution is 4° in latitude and 5° in longitude.)

Figure 1 shows the mean weekly precipitation averaged over the 46 grid points representing the Sahara, from both integrations. The rainfall in the high-albedo (35 percent) experiment was substantially smaller than that in the low-albedo (14 percent) experiment. The consistency in the difference in rainfall in each of the 7 weeks shows that the difference is real and not a result of statistical fluctuations in the GCM's behavior from one experiment to another. The mean rainfall over the Sahara during the calendar month of July was 4.4 mm/day in the low-albedo experiment and 2.5 mm/day in the high-albedo experiment, a decrease of 43 percent. The associated decrease in the zonal mean rainfall at the same latitudes was only 6 percent. There was also a decrease in cumulus cloud cover over the Sahara when the surface albedo was increased. The mean cumulus cloud cover during July was 26 percent in the low-albedo integration and 19 percent in the high-albedo integration.

Figure 2 shows the latitudinal distribution of the mean rainfall during July in the two experiments. From 18°N to 34°N the values plotted are the rainfall averaged over all the grid points

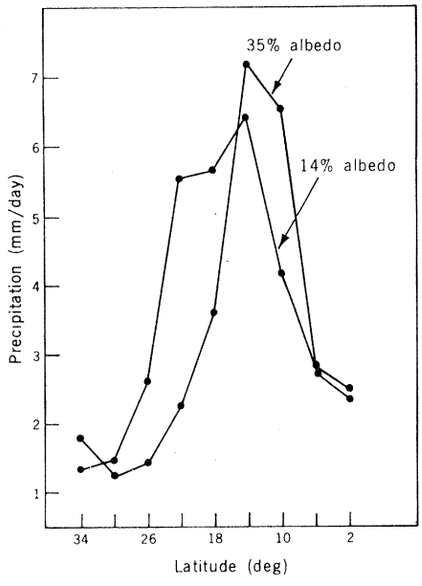


Fig. 2. Latitudinal distribution of mean rainfall during July in North Africa in the experiments.

in the Sahara at each latitude. South of 18°N where there were no Sahara grid points, the values plotted are averages over all grid points in the African continent at each latitude. Figure 2 illustrates that most of the rainfall over the Sahara actually occurs in the Sahel, near 18°N. The distribution of rainfall in the Sahara in the high-albedo experiment is quite close to the observed distribution in summer (*7*). Figure 2 also shows that the decrease in rainfall in the Sahara in the high-albedo experiment is compensated to some extent by an increase south of the Sahara. The shift in the rainfall distribution reflects a shift to the south of the Intertropical Convergence Zone (ITCZ) over Africa. The latitude of the mean low-level convergence over Africa during July was 22°N in the low-albedo experiment and 16°N in the high-albedo experiment. There was no such shift of the ITCZ over Asia in the two experiments. Here again, the high-albedo experiment is the more realistic one.

To determine how local the albedo change can be and still produce large changes in rainfall, we carried out a third numerical experiment. In this experiment the albedo was increased relative to the low-albedo experiment only in the Sahel, that is, only at the Sahara grid points located at 18°N. The initial condition for this integration was the same as that of the other two experiments, but this integration covered only 2 weeks of simulated time. Consequently the results do not have the statistical significance of the two experiments described above. However, they do show a similar effect on the rainfall. For example, during days 3 to 10 of the integration the mean rainfall at 18°N decreased by 75 percent. This result indicates that very local changes in albedo may be sufficient to produce droughts.

We conclude that surface albedos can have a substantial effect on climate in the Sahara, and that the biogeophysical feedback mechanism is a plausible one for causing such changes. We can envisage overgrazing in the Sahel leading to an increase in the surface albedo which causes the ITCZ to move south and the rainfall over the Sahel to decrease, perhaps by as much as 40 percent. Since the GCM we used does not include a model of the biosphere for calculating changes in albedo resulting from changes in rainfall, this 40 percent figure is, in effect, an upper bound on the amount that would occur if all links in the feedback mechanism were included. The need for a model of the biosphere emphasizes the complexity of climatic problems. Our results do show the importance of monitoring surface albedos from satellites.

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