

Numerical Experiments on Land Surface Alterations with a Zonal Model Allowing for Interaction between the Geobotanic State and Climate

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ABSTRACT

A zonally-averaged steady-state hemispheric mean-annual climate model is used for conducting a series of experiments on land surface alterations: desertification, deforestation and irrigation. In each experiment a fixed perturbation of surface albedo and water availability is imposed in a single latitude belt (but a different perturbation is specified in each experiment). The desertification and deforestation experiments simulate modifications to the geobotanic state due to destruction of vegetation by overgrazing and excessive cultivation of the land in the semiarid and tropical zones, respectively. The irrigation experiment simulates the climatic impact of massive irrigation of the desert belt.

Results indicate that the effect of changes in evapotranspiration rather than in surface albedo is predominant in regulating the surface temperature. It is shown that the impact of biofeedback is strongest in the area adjacent to the perturbation zone. It is also concluded that the prescribed perturbations of the geobotanic state are not sufficient to modify climate to an extent that these perturbations would persist.

1. Introduction

Climate modification due to human modification of the Earth's surface has received growing attention from climate modelers. It has been suggested that human-induced processes such as desertification, deforestation, forestation, urbanization, irrigation, etc., may have a significant impact on local and global climate (Sagan *et al.*, 1979; Budyko, 1982).

In particular, the phenomena of drought and desertification have been the target of modeling efforts during the last decade. This was partially stimulated by the Sahel episode in the early 1970s when the southern margin of the Sahara (Sahel) experienced a persistent drought accompanied by famine and death on a continental scale. One of the first attempts to model the occurrence of these phenomena was made by Charney (1975). Using a simple zonal model with a frictionally controlled quasi-geostrophic circulation driven by the temperature contrasts, but with no hydrology, Charney showed that an increase in albedo (caused by overgrazing, for example) can produce sinking motion which would suppress cloud formation and rain. Independently, Otterman (1974) drew attention to the contrasts in reflectivity in the Sinai, the Gaza Strip and the Negev, and suggested that the baring of high albedo soils by overgrazing can cause ground surface temperature changes which may lead to appreciable regional climate effects. The ensuing major criticisms of these studies were directed at the neglect of the effect of vegetation on evapotranspiration (Ripley, 1976) and of the dependence of albedo

on ground wetness (Jackson and Idso, 1975). It was suggested that in the case of land covered by vegetation, denudation of the soil may have thermal and climatic effects which are the opposite of those postulated by Charney and Otterman. Additional testing and modeling have been performed by Berkofsky (1976) with a boundary-layer model, Ellsaesser *et al.* (1976) with a global zonal atmospheric model, Charney *et al.* (1975, 1977) with the GISS (Goddard Institute for Space Studies) general circulation model (GCM), and Chervin (1979) with the NCAR (National Center for Atmospheric Research) GCM.

Due to growing concern about climatic effects of the clearing of tropical forests in Amazonia and Africa, numerical simulations of these effects have been performed by, for example, Potter *et al.* (1975) and Lettau *et al.* (1979).

There have been many numerical experiments with GCMs simulating the climatic response to prescribed modifications of the water availability parameter (see the review by Mintz, 1982). Some of them (e.g., Shukla and Mintz, 1982) could be viewed as irrigation experiments.

Other possible intentional surface alterations such as melting of the arctic ice, "blackening" the desert belt, forestation or creation of "green belts," etc., theoretically realizable in the real world, have not yet been extensively investigated.

Although the ideal tool for the numerical simulation of a specific phenomenon would be a fully-resolved three-dimensional model, an efficient vehicle for obtaining some preliminary ideas of the climatic effects

is a simple climate model. Such a model is useful for experiments concerned with long-term climatic changes, and when a large number of experiments are to be carried out.

To our knowledge, very few tests concerning the climatic impact of surface alterations have been conducted with simple models. Among these, the major contribution has been made by numerical simulations performed with the two-dimensional statistical dynamic model of the Lawrence Livermore National Laboratory (LLNL) (Potter *et al.*, 1975, 1979; Ellsaesser *et al.*, 1976). Experiments with the LLNL model were designed to simulate climatic effects resulting from desertification due to overgrazing and from tropical deforestation, which have been hypothesized to be the principal causes of global albedo change (Sagan *et al.*, 1979). In these experiments, the geobotanic state changes were simulated by modifying the land surface albedo; the prescribed values of albedo were inserted over the land fraction of the latitude band centered at 20°N in the desertification experiment and 0° in the deforestation experiment. In the latter case, surface hydrological features were modified in addition to the albedo changes. Outside the prescribed region, surface albedo could vary only between its wet and dry values in response to changes in surface relative humidity. Geobotanic changes outside the prescribed zone were not considered in that study.

A surface characterization which allows for continuous variation of the geobotanic state (and, consequently, of albedo) with climate recently has been incorporated in the simple climate model of Gutman *et al.* (1984). This model enables geobotanic changes outside the prescribed zone to be taken into account in experiments such as those mentioned above.

Using this model, we have conducted a number of experiments simulating the climatic impact of changes at the Earth's surface. Here, we will present the results of experiments on three kinds of surface modification. Two of these experiments are similar to those conducted at LLNL and represent a simulation of inadvertent climate modification due to desertification in the semiarid zone and deforestation in the tropical zone. However, unlike the desertification test with the LLNL model (Ellsaesser *et al.*, 1976) and our previous sensitivity test on albedo changes (Gutman *et al.*, 1984), this time we associate the destruction of vegetation (e.g., savanna becoming desert) with changes in water availability, in addition to albedo changes. In a third experiment, we simulate irrigation in the desert zone, as an example of intentional climate modification.

Our goals are twofold: 1) To simulate the climatic response to the surface alterations, and 2) to investigate the impact of the biogeophysical feedback mechanism (biofeedback) incorporated in the model.

2. Brief description of the model

Here we present only a short summary of the model's main characteristics. A detailed description can be found in Gutman *et al.* (1984) and Ohring and Adler (1978).

This model is based on Ohring and Adler's (1978) zonally averaged annual steady-state hemispheric climate model. The governing equations are the zonally averaged quasi-geostrophic potential vorticity equations for two levels in the atmosphere (250 and 750 mb), the diagnostic equation for the thermal streamfunction at 500 mb, and the surface heat balance equation. The heating parameterization of the original model (Ohring and Adler, 1978) is modified so that precipitation and cloud amount are computed using the vertical velocity at 500 mb, which is calculated from the thermodynamic equation. Surface characterization involves making the surface state parameters, snow-free surface albedo α and water availability w , dependent upon the radiative index of dryness D which is dependent on the ratio of annual radiation balance R to annual precipitation P . Consequently, the geobotanic state, characterized by D , becomes interactive with the climate. The evapotranspiration E is parameterized to be consistent with the surface characterization.

3. The experiments

The experiments can be subdivided into the following groups: tests with and without biofeedback, where ice-feedback was not included, and then analogous tests including ice-feedback. The ice-feedback parameterization was taken from Ohring and Adler (1978), where it is described in detail. Qualitatively, ice-feedback did not introduce changes in our results except for the global albedo effect in the irrigation experiment which is outlined later. Therefore, we will discuss here the results obtained using the version of the model with no ice-feedback.

The climatic effects of the surface alterations are analyzed by comparing the equilibrium states obtained with the perturbed surface state parameters with the equilibrium state in the control experiment which was conducted by Gutman *et al.* (1984) to validate the model (simulation of the observed climate and geobotanic zones).

In each test, fixed perturbations of the snow-free land surface albedo α , and water availability w , were imposed in a single latitude belt (a different one in each test). In the runs without biofeedback, α and w were prescribed outside the perturbation belt using their distributions from the control experiment (see Gutman *et al.*, 1984). In the runs with biofeedback, α and w were prescribed only in the area of perturbation and could vary everywhere else.

The analysis of the climatic response to the surface

alterations is performed only for the runs with biofeedback (the impact of biofeedback is also discussed in the next section). The three experiments are briefly described below.

a. Desertification

One of the possible causes of this phenomenon is destruction of vegetation due to overgrazing or excessive cultivation. We simulate such a modification of the geobotanic state by prescribing fixed perturbations of w (from 0.56 to 0.31) and α (from 0.13 to 0.17) in the 10–20° belt. These values correspond to a change in the vegetational index D from 1.1 to 1.8, which can be interpreted as the conversion of a savanna zone into a desert zone. The “perturbed” values of α and w are consistent with the zonality of the system and, of course, differ greatly from the characteristic values of a “real” desert.

b. Deforestation

In order to simulate the conversion of the tropical forest zone into savanna, we prescribe an increase in α from 0.09 to 0.14 and a decrease in w from 0.72 to 0.52 in the latitude belt 0–10°. These changes correspond to an increase in D from 0.7 to 1.2.

c. Irrigation

In this test, the water availability is held equal to one in the latitude belt 20–30°. Thus, we assume that the desert zone is subjected to irrigation by an infinite supply of water so that evapotranspiration in this area would occur at its potential rate. Albedo in the perturbation zone was prescribed to be 0.07 (according to Budyko, 1982, the surface albedo can be lowered by 0.10 over irrigated zones).

4. Results

a. Desertification and deforestation

The model response to the prescribed perturbations is similar for the first and second experiments. Therefore, we will present their results together. The features common to both tests are: a radiation balance decrease due to the reduction in absorbed radiation (as a result of the albedo increase), a decrease in evapotranspiration induced by the decrease in both the water availability and the radiation balance; and a decrease in precipitation in the perturbation area with a concomitant increase in the adjacent regions.

Our results appear to be consistent with those of Potter *et al.* (1979), except for the temperature effect at the earth’s surface. In their model, the surface was cooled as a result of a decrease in absorbed radiation. Our experiments show that this effect can be less important than a reduction in evapotranspiration.

That is, the decrease in evaporative cooling of the surface overrides the effect of reduced absorbed radiation, thus resulting in a temperature *increase* as a net effect. This supports the important role of changes in evapotranspiration in the process of surface alterations (Shukla and Mintz, 1982) and agrees with Ripley’s (1976) arguments confirmed by data on grazed and ungrazed savanna. According to Ripley, overgrazing may lead to an increase in surface temperature due to the drastic reduction in evapotranspiration. This is also consistent with results of the NCAR GCM obtained by Chervin (1979).

Figures 1 and 2 show the changes (perturbed minus control) in radiation balance, surface temperature, precipitation and evapotranspiration, and 500 mb vertical velocities.

It is interesting to note the similarity between the model responses in the desertification and deforestation experiments. In both cases, the maximum changes occur in the respective perturbation zones: reduction in radiation balance, reduction in precipitation and evapotranspiration, etc. Such a similarity was outlined by Potter *et al.*, who emphasized, however, that “the location of the perturbation plays an important role in determining the response of the global circulation.” Indeed, the effect on the Hadley cell is different in the two experiments. Changes in ω (Fig. 2) correspond to a weakening of the Hadley circulation in the deforestation experiment and an intensification in the desertification experiment. The latter should probably be interpreted as a southward shift of the Hadley cell since subsidence was slightly suppressed between 20 and 35°.

Changes in 500 mb temperatures are not presented here because they were very small ($\leq 0.1^\circ\text{C}$) in both experiments. A slight cooling which occurred in the perturbation region was compensated by a slight increase in temperature south of the perturbation, so

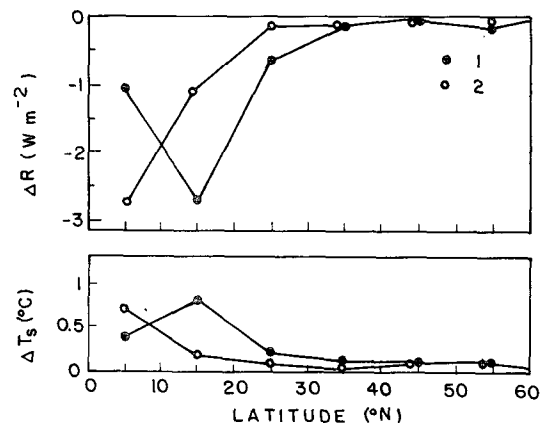


FIG. 1. Change (perturbed – control) in surface temperature ΔT_s and in radiation balance ΔR in the desertification (1) and deforestation (2) experiments.

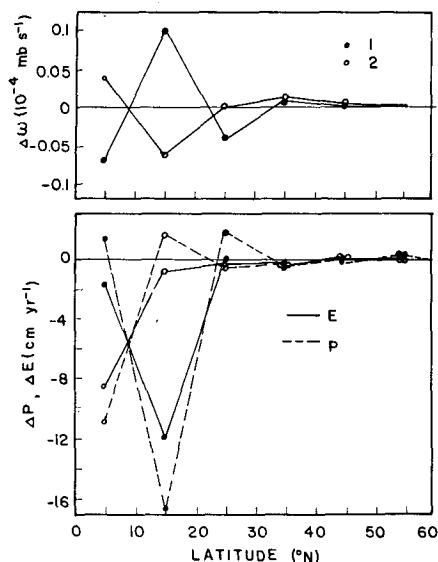


FIG. 2. Change (perturbed - control) in precipitation (dashed line), evapotranspiration (solid line, lower panel) and 500 mb vertical velocity ω in the desertification (1) and deforestation (2) experiments.

that the mean hemispheric 500 mb temperature did not change.

The precipitation changes in the deforestation experiment agree both in magnitude and sign with those reported by Potter *et al.* (1975) in their test of "complete deforestation." We obtained an increase in precipitation of 1.7 cm yr^{-1} in the $10\text{--}20^\circ$ latitude belt (adjacent to the perturbation). The mean hemispheric decrease was of the same magnitude (comprising 1.6% of the total hemispheric rainfall). Although these values are relatively small, it is unlikely that they represent merely a random error. Since the same results were obtained by two different zonal models, they probably have some physical significance.

The mean hemispheric albedo of the earth-atmosphere system increased by 6×10^{-4} in both the desertification and deforestation experiments. This can be compared with the estimates of global albedo changes over 25 years given by Sagan *et al.* (1979): 6×10^{-4} and 3.5×10^{-4} due to desertification and deforestation, respectively. Sagan *et al.*, as well as Potter *et al.* (1979), suggested that the above surface alterations produce a mean global surface cooling. Our results, however, indicate a slight increase in the hemispheric surface temperature: 0.2°C due to deforestation and 0.3°C due to desertification. Clearly, the overall effect of reduced evapotranspiration is greater than the effect of the mean hemispheric albedo increase.

Figure 3 shows changes (perturbed minus control) in the climatic index D . Note that while α and w were prescribed in the area of perturbation, D was a predicted variable (as R/LP) everywhere, including

this area. From Fig. 3, it can be seen that changes in D are very small. For both tests, the increase in D in the perturbation region corresponds to a drier climate, while in the adjacent regions a tendency toward a decrease in "aridity" is observed. Although in the perturbation regions the change in D is at its maximum, the predicted values of D are still much lower than those assumed for the vegetational modification: 1.2 compared to 1.8 in the desertification experiment and 0.74 compared to 1.2 in the deforestation case. This implies that if the perturbations at the surface were not fixed, the surface state would tend to return to its previous equilibrium with the climate, contrary to suggestions that a global climatic shift may become self-sustaining. The desertification mechanism could support itself if the computed equilibrium values of D were to become larger than those chosen for a perturbation of the surface state. However, this is not the case both in the desertification and the deforestation experiments. In other words, if there is a certain imposed alteration of the surface state which is finite in time, the climate will tend to return the surface to its initial state, in agreement with the results of Otterman (1974). Some factors such as soil erosion (e.g., see Budyko, 1982) can make the system quasi-irreversible. However, consideration of such effects cannot be included in a stationary model.

b. Irrigation

Figure 4 shows the changes (perturbed minus control) in radiation balance and surface temperature in the irrigation experiment. As would be expected, irrigation caused a radiation balance increase (with its maximum in the area of the perturbation). This is a result of the increased absorption of shortwave radiation (due to the reduction in albedo) and a decrease in the net longwave radiation (due to a lowering of the surface temperature). However, the

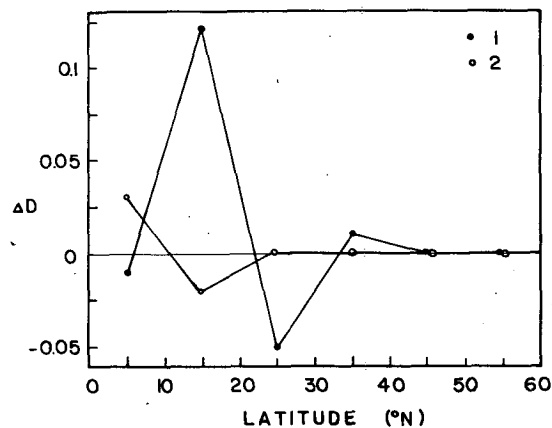


FIG. 3. Change (perturbed - control) in D in the desertification (1) and deforestation (2) experiments.

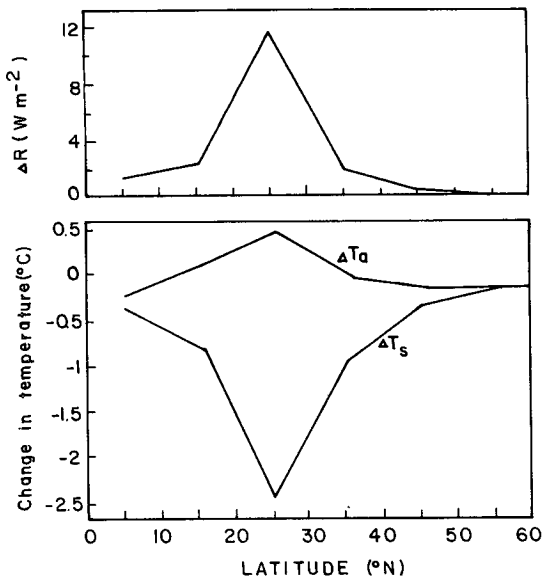


FIG. 4. Change (perturbed - control) in surface temperature ΔT_s , 500 mb temperature ΔT_a and radiation balance ΔR in the irrigation experiment.

increase in evapotranspiration substantially exceeded the reduction in the radiation balance, resulting in a decrease in sensible heating and surface temperature.

The mean hemispheric temperature decreased by 0.8°C ; this can be regarded as a significant overall effect of a local perturbation. Budyko (1982) has considered possible climatic changes due to irrigation of arid lands. He suggested, however, that because of decreased global albedo the mean surface air temperature would *increase*. Our model produced a relatively large hemispheric albedo decrease (0.0026), but the mean surface temperature was lowered nevertheless. Thus, we tentatively conclude that in regulating surface temperature changes, the effect of increased evapotranspiration due to irrigation in arid regions may be greater than that of reduced surface albedo in a regional as well as a global sense.

The 500 mb temperature increased by 0.5°C over the perturbation zone (mainly due to a large increase in latent heat release by condensation). However, the increase in the mean hemispheric 500 mb temperature was only 0.04°C , since outside the perturbation zone there was a compensating temperature decrease (see Fig. 4).

Figure 5 shows the latitudinal distribution of changes (perturbed minus control) in precipitation and evapotranspiration along with changes in the 500 mb vertical velocities. It can be seen that the largest changes in P and E are in the area with maximum evapotranspiration (i.e., the perturbation area). The evapotranspiration increase led to a 62% increase in precipitation (between 20 and 30°). This increase in P was partly induced by a reduction in the subsidence

rate. North of the region of perturbation, precipitation decreased in spite of a slight increase in evapotranspiration. On the other hand, south of 20° the precipitation increase is low in comparison with the increase in evapotranspiration. It is obvious, therefore, that there is a relatively large change in convergence of the water vapor flux. It can be seen from Fig. 5 that the increased subsidence and/or weakening of the upward motions are strong enough to suppress or even decrease (between 30 and 40°) precipitation in the regions adjacent to the perturbation. Over the perturbation zone, the decrease in subsidence contributed about 12% of the increase in precipitation. The mean hemispheric precipitation increased by 7%.

To illustrate the geobotanic changes, we present in Fig. 6 the changes (perturbed minus control) in D . It is seen that while D decreased sharply in the irrigated zone, the changes in D in the adjacent regions are relatively small. However, as a result of irrigation in the desert zone, the adjacent regions tend toward an increase in aridity. This can be explained by the fact that, together with the increase in the radiation balance (Fig. 4), precipitation decreased (or its increase was suppressed) due to the dynamical changes discussed earlier (Fig. 5).

The equilibrium value of D between 20 and 30° latitude changed to 1.2 (from 1.7 in the control experiment). This can be interpreted as a regional climatic shift from desert to grassland climate as a result of persistent irrigation.

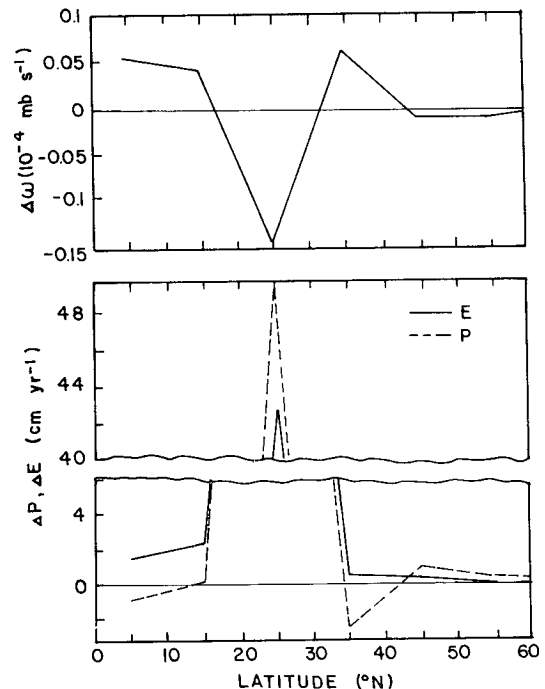


FIG. 5. As in Fig. 2 but for the irrigation experiment.

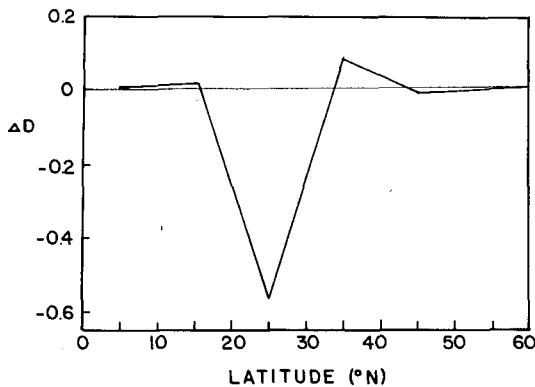


FIG. 6. As in Fig. 3 but for the irrigation experiment.

In conclusion, we note that in the ice-feedback version of the model, the surface temperature decrease was accompanied by a growth in ice/snow amount in northern latitudes. Hence, the reduction in mean albedo was compensated to a considerable extent. As a result, the mean hemispheric planetary albedo decreased by only 0.0006 (compared to 0.0026 in the no ice-feedback model), while the mean surface temperature decreased by 1°C. Note that such an effect would not be predicted in those studies where the mean surface temperature increases due to irrigation.

In nature, the albedo decrease may also be compensated by an albedo increase due to the salinization process, which is a serious problem in irrigation projects (see, e.g., Sagan *et al.*, 1979).

c. Impact of biofeedback

In order to illustrate the impact of biofeedback we will compare the changes (perturbed minus control) in precipitation obtained in the two runs (with and without biofeedback) which are given in Table 1. The results are shown only up to 50°N since in all three experiments the impact of biofeedback is noted mostly in the regions adjacent to the latitude belts with perturbations (denoted by X). We will associate the impact of biofeedback with the difference between the precipitation changes for the two runs.

Table 1 shows no biofeedback effect in the perturbation zones. Recall that in these zones the surface state parameters were fixed. It is clear that the impact of biofeedback could be "felt" only due to the meridional transport of momentum, heat and moisture from adjacent zones. Apparently, the differences in vertical velocities and temperatures between the two runs were not sufficient to produce any noticeable difference in precipitation changes over the perturbation zones. Note that the meridional transport of moisture could have led to such differences. However, the limitations of the model with respect to the description of humidity do not allow for this effect.

From Table 1, we see that the impact on precipi-

tation of biofeedback in the areas adjacent to the perturbed zones is on the same order as the changes induced by the modifications in the geobotanic state. Therefore, we believe that the simulated impact of biofeedback reflects the physics of the process, at least qualitatively. Note that these changes in precipitation seem to be small but it should be borne in mind that they were obtained with a zonally averaged mean-annual climate model. Obviously, a greater response can hardly be expected from such models.

As can be seen from Table 1, the precipitation changes have the same sign for both runs in each experiment. This implies that biofeedback does not modify the direction of changes; i.e., whether or not biofeedback is included, an increase (or decrease) in precipitation remains an increase (or decrease). Another regularity which can be noticed in Table 1 is that the biofeedback has an amplifying effect in the areas to the north of the perturbation zones and a moderating effect in the areas to the south.

Thus, our experiments allowed us to reach certain conclusions concerning the impact of biofeedback in tests on surface alterations. In summary, these are:

- 1) The impact of biofeedback is of a local nature and occurs mostly in regions adjacent to the perturbed zone.
- 2) Biofeedback can play an amplifying or moderating role, but it does not alter the sign the precipitation changes.

5. Conclusions

We have employed a simple climate model which incorporates a bio-geophysical feedback mechanism to simulate the climatic effects of three types of surface alteration: desertification, deforestation and irrigation.

It follows from our results that changes in evapotranspiration can play a dominant role in regulating surface temperature changes. That is, when the effect of changes in surface hydrology is considered, the mean surface temperature change may be opposite in sign to that given in studies which consider global albedo changes alone.

TABLE 1. Latitudinal distribution of changes (perturbed minus control) in precipitation for the two runs without biofeedback (1) and with biofeedback (2) in the three experiments.

Latitude (°N)	Deforestation		Desertification		Irrigation	
	1	2	1	2	1	2
0-10	-10.8	X -10.9	1.4	1.3	-0.9	-0.9
10-20	1.2	1.7	-16.7	X -16.7	0.7	0.2
20-30	-0.2	-0.3	0.7	1.8	49.3	X 49.3
30-40	-0.1	-0.2	-0.3	-0.5	-0.7	-2.3
40-50	0.0	0.0	-0.1	-0.1	0.9	1.1

Our experiments showed that the impact of bio-feedback was most pronounced in areas adjacent to the perturbation zones, while its effect could be either amplifying or moderating without influencing the sign of the precipitation change.

We stress that all of our conclusions refer to zonally-averaged climatic parameters. Land fraction has a relatively small weight in low latitudes when averaging over the entire latitudinal belt. Hence, the response of a zonal atmosphere to a perturbation of the land surface is "smoothed" to a considerable extent at these latitudes. In principle, a local atmospheric response could be much more pronounced, but a three-dimensional model should be used to simulate such local effects.

Concerning geobotanic changes, we concluded that the prescribed perturbations of the geobotanic state could not modify climate sufficiently to allow these perturbations to persist.

Note that since this model is stationary and has a unique steady-state solution, the perturbations in the surface state parameters had to be fixed for the duration of the experiment. This can occur in the real world through continuous destruction of vegetation (as in the first and second experiments) or persistent irrigation (as in the third), which can occur during some finite interval of time. Thus, in order to study the behavior of the geobotanic state following its perturbation and the concomitant climatic changes, a nonstationary model should be employed. Such work is currently underway.

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