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# Modeling Feedbacks between Water and Vegetation in the Climate System

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## Abstract

Not only is water essential for life on earth, but life itself affects the global hydrologic cycle and consequently the climate of the planet. Whether the global feedbacks between life and the hydrologic cycle tend to stabilize the climate system about some equilibrium level is difficult to assess. We use a global climate model to examine how the presence of vegetation can affect the hydrologic cycle in a particular region. A control for the present climate is compared with a model experiment in which the Sahara Desert is replaced by vegetation in the form of trees and shrubs common to the Sahel region. A second model experiment is designed to identify the separate roles of two different effects of vegetation, namely the modified albedo and the presence of roots that can extract moisture from deeper soil layers. The results show that the presence of vegetation leads to increases in precipitation and soil moisture in western Sahara. In eastern Sahara, the changes are less clear. The increase in soil moisture is greater when the desert albedo is replaced by the vegetation albedo than when both the vegetation albedo and roots are added. The effect of roots is to withdraw water from deeper layers during the dry season. One implication of this study is that the insertion of vegetation into the Sahara modifies the hydrologic cycle so that the vegetation is more likely to persist than initially.

1.Introduction

The relationship between water and vegetation within the context of the climate system is complex. A number of modeling studies have addressed various aspects of this issue. At the global scale, Shukla and Mintz (1982) examined the differences in the climate system depending on whether the surface is saturated or dry. They found that there was a positive feedback when surface water was present because it leads to more precipitation and maintains the high water content in the soil. Kleidon et al. (2000) did a similar study but instead of using wet and dry surfaces, imposed fully vegetated or fully desert conditions. They found that the hydrologic cycle intensified substantially for the fully vegetated case. Bonan (1995) compared two climate model experiments, one with and one without inland water grid points, and found that the presence of water led to summer cooling and increased latent heat flux. Claussen (1998) combined a climate model and biome model to investigate whether feedbacks between vegetation and climate tend to favor the presence of the existing vegetation

There have also been modeling studies of the regional relationships between vegetation and the hydrologic cycle. Among the first was that of Charney (1975) who modeled the impacts of human activity on desertification in the Sahel region of Africa. He suggested that increases in surface albedo would lead to increased atmospheric stability and less rainfall. There have also been studies of the effects of Amazon deforestation on both regional and global climate (Dickinson and Henderson-Sellers, 1988; Henderson-Sellers et al., 1993). Bonan et al. (1992) have examined the effects of boreal forest vegetation on global climate. Many of these earlier studies were restricted to examining only the impacts of changes in surface albedo. Kleidon and Heimann (1998) examined the effects of plant roots and found that the rooting depth of vegetation can have a significant impact on model simulations. A recent study by Sud et al. (2001) used a single column model to show that an increase in solar absorption and surface evaporation help to increase local rainfall. The above studies are based on models. The recent study of Bonan (2001) uses observations to show that the conversion of forest to grassland in the central U.S. has increased the albedo there and led to cooling.

Northern Africa is a generally arid region, and there have been a number of studies of the relationships between vegetation and climate in both the Sahel region (e.g., Charney, 1975), and to a lesser extent in the Sahara Desert. Eltahir (1998) examined a soil moisture feedback mechanism and Zheng and Eltahir (1998) considered the role of vegetation in the dynamics of west African monsoons. Sud and Molod (1988) and Cunnington and Rowntree (1986) did model experiments in which albedo and soil moisture were modified in the Sahara Desert. Bonfils et al. (2001) modified Saharan albedo to try to better represent climate conditions 6000 years ago. These studies support the conclusion that decreased albedo in the Sahara Desert would enhance convection and increase rainfall. The purpose of this study is to extend these studies to examine the role of vegetation on the local water budget of the Sahara Desert and to determine whether the replacement of desert by vegetation changes the local water budget. If so, would it change in a way that favors the existence of vegetation?

## 2. The climate model

The model used in this study is the atmospheric component of the global coupled model described by Russell et al. [1995]. This model includes nonlinear dynamics, advection, a full radiation scheme, parameterizations of moist convection and surface interaction, and treatments of subsurface reservoirs except for the ocean. The ocean surface temperature and sea-ice cover are specified from monthly climatology. The resolution of the model is 4 degrees in latitude, 5 degrees in longitude, and 9 vertical layers for mass and momentum. Heat and humidity have finer resolution because both means and prognostic directional gradients are defined within each grid cell. Moist convection, for example, is performed on 2 by 2.5 degree horizontal resolution.

The ground hydrology scheme [Abramopoulos et al., 1988] handles snow, bare soil and vegetation, a canopy layer, six ground layers (depths are 0.1, 0.173, 0.298, 0.514, 0.886, 1.529 m), and surface and underground runoff. In a grid cell, the bare soil and vegetated fractions are treated separately with separate variables. Over the bare soil fraction or dormant vegetation, water that infiltrates below the surface layer has difficulty returning to the surface, but continues to penetrate downward through the six layers until it becomes underground flow and is added to the grid cell's rivers and lakes. Over nondormant vegetation, roots can remove water from the lower soil layers and transpire directly from the canopy.

3. Formulation of model experiments

The control is a model simulation for the present climate. It includes ground and vegetation characteristics of the present-day Sahara Desert (85% desert and 15% shrubs and small trees). The first experiment replaces these characteristics in the region shown in Figure 1 (Sahara Desert: 15W-35E, 16N-36N, western Sahara: 15W-0, 16N-28N, eastern Sahara: 20E-35E 20N-32N) by the same vegetation found in the Sahel region to the south of the Sahara. Because there are asymmetries in the model response to these changes between eastern Sahara and western Sahara, these two regions are examined in greater detail in the analysis. The replacement of desert by vegetation changes the seasonally varying surface albedo and adds roots that allow water to be extracted from deeper soil layers. Vegetation also affects the model's surface roughness, although in this study, it is not modified so that we can focus on the roles of roots and albedo.

Table 1 shows that the average albedo for the control for the entire region is about 32% with little change between summer and winter. Tables 1-3 show that the surface albedo is reduced to 15-16% when the desert albedo is replaced by vegetation having the same characteristics that are presently native to the surrounding region. A second experiment replaces only the albedo in the control with that used in the vegetation experiment just described. This experiment allows us to sort out the changes to the hydrologic cycle that are caused by roots from those that are caused by albedo changes. The two experiments were run for 22 years and are referred to as the vegetation and albedo experiments.

4. Impact of vegetation on the hydrologic cycle in the Sahara Desert

In this section, the geographic patterns of the hydrologic impacts caused by replacing desert with vegetation are examined, both within and outside the study region. Figure 2 compares the control's seasonal variation of precipitation for western Sahara and eastern Sahara with the observed climatology of Shea (1986). The model's annual cycle for western Sahara is similar to the observed with little rainfall except in the summer. The model's maximum precipitation occurs one month too late and is about twice the observed value. In eastern Sahara there is little rainfall in any season for both the model and the observations.

In the remainder of this section we use the second decade of the model experiments to examine the spatial changes that occur in three components of the hydrologic cycle (precipitation, evaporation, and soil moisture) when desert is replaced by vegetation in the Sahara. Figure 2 and Tables 1-3 show that precipitation increases significantly in summer with the largest increase (from 2 mm/day in September to 5.35 mm/day in August) occurring in western Sahara. In eastern Sahara, there is little change in precipitation except for the large increases between August and October.

The spatial distribution of changes in precipitation is shown in Figure 3. It shows that there is little change anywhere in the region in January and that there are increases in most of the region in July. There is an east-west gradient in the change with a generally increasing change moving from east to west. Figure 3 also shows that there are precipitation changes in other areas away from the Sahara. This potential downstream effect will be discussed later.

Tables 1-3 show that there are significant changes in evaporation, too, with the largest changes again occurring in summer. The evaporation increases in February throughout much of the region and increases significantly in western Sahara in summer. Greater increases in evaporation over precipitation in February are possible because more water is stored from prior months.The east-west gradient in the increased evaporation is consistent with that for precipitation.

For the vegetation experiment, the average soil moisture for the entire study region is higher in February and August than it is in the control (Table 1). However, as Tables 2 and 3 show, there are significant differences between eastern and western Sahara. The largest increases occur in western Sahara and are much larger in summer than in winter. In fact, the largest increases in the west occur just south of the study region. Table 3 shows that there is almost no change in soil moisture in eastern Sahara in summer or winter. The average increases in soil moisture for the entire region are dominated by the increases in western Sahara.

## 5. Role of albedo and roots in vegetation feedbacks on the hydrologic cycle

Changes in the hydrologic cycle induced by insertion of vegetation into the Sahara region are generally caused by the combined effects of changes in albedo, surface roughness, or extraction of water from deeper soil layers by roots. To sort out the effects of one of these, only the surface albedo is changed from the control. The albedo is specified according to the seasonally varying albedo of the vegetation in the Sahel region to the south of the Sahara Desert (Tables 1-3). In the vegetation experiment, both the albedo changes and the effects of roots are included. Both experiments use the same value for surface roughness as the control.

Figure 4 shows the second decade of the monthly precipitation for the control, vegetation, and albedo experiments. The February and August averages for the second decade of the experiments are shown in Tables 1-3. There is a significant change in the annual cycle of precipitation with the greatest change occurring in summer where the maximum precipitation occurs a month sooner and is much larger than for the control as shown previously in Figure 2. The summer maximum in precipitation is usually larger in the albedo experiment than it is in the vegetation experiment.

In western Sahara (Fig. 4a), there is considerable interannual variability in the maximum summer precipitation in the control. Figure 2 showed that the model's maximum summer precipitation there for the present climate is about twice as high as the observed. Much of that can be accounted for by the model's high interannual variability and specifically the 3 highest summer precipitation months during the 22-year record. In almost all years, the albedo experiment has greater precipitation than does the vegetation experiment, which in turn, has much greater precipitation than the control. For the vegetation and albedo experiments, the relative magnitude of the interannual variability is significantly reduced from that of the control.

In eastern Sahara (Fig. 4b), the changes are more irregular. One of the interesting differences between eastern and western Sahara is that the interannual variability of the control is large in the west and small in the east. However, for the vegetation and albedo experiments, this is reversed (i.e., higher interannual variability in the east and smaller in the west). The increase in the maximum precipitation in the albedo experiment is also much higher than in the vegetation experiment, although in three of the ten years shown, the vegetation experiment's maximum is higher.

Among the most interesting changes are those that occur in the soil moisture budget. Figure 5 shows that for the control in western Sahara there is a small annual cycle in soil moisture with the maximum occurring in summer after the maximum precipitation. When compared with Figure 4, one can see that the larger peaks in soil moisture are associated with peaks in precipitation as expected. For western Sahara, the soil moisture tends to go back down after the large peaks although in the eastern Sahara, it tends to remain high after the maximum precipitation. The soil moisture then decreases until the following rainy season. When vegetation is inserted into the region, the magnitude of the annual cycle for western Sahara increases as does the mean soil water content which increases from 45 cm to 73 cm in August. In the albedo case, there is an even larger increase in soil moisture to 92 cm in August. Why are the changes in soil moisture so different between the vegetation and albedo cases? Consider first the albedo experiment, the lower surface albedo leads to the absorption of more solar radiation during clear days, which leads to increases in upward sensible heat, which warms the surface air, which rises, drawing moist air into the region at low altitudes. There will only be increased evaporation if there is sufficient water to evaporate, which there is due to the significantly enhanced precipitation. Although the winter drawdown of water is much higher than in the control, it starts at a much higher value, and therefore the minimum monthly soil moisture is still higher than in the control.

Why does the above picture change when the full effects of vegetation are included, and not just the albedo? The difference is that vegetation has roots. The analysis given above for the albedo case still holds but now the drawdown of water in the dry season is larger because there are roots that can extract water from all six soil layers instead of only the surface layer in the albedo case.

This drawdown causes the minimum soil moisture to approach that of the control. The conclusion is that the effect of the vegetation's albedo leads to a much larger increase in soil moisture than when the other effects of vegetation are also included. This is because the roots of the vegetation can remove water from deeper layers than they can when only the albedo is modified. The case for eastern Sahara is of considerable interest because the soil moisture in the vegetation experiment is actually lower than in the control for some months. As before the albedo experiment leads to higher soil moisture.

## 6. Discussion and conclusions

This study is focussed on regional changes in the hydrologic cycle due to modifying the land surface by inserting vegetation into the Sahara Desert. For the present climate, the model's representation of monthly precipitation in western and eastern Sahara is in reasonably good agreement with observations; there is low precipitation in winter and higher precipitation in summer. When desert is replaced by vegetation, there is little change in precipitation during the winter dry season, but there is a significant increase in precipitation and soil moisture in the summer when the precipitation is maximum.

In the previous sections we examined changes in the components of the water budget. These changes also have implications for other variables within the climate system, such as the surface heat budget and surface air temperature. Figure 6 and Tables 1-3 show that the surface air temperature in summer has cooled in western Sahara but has increased in eastern Sahara. The cooling in the west is due to increased cloud cover. In winter, the temperature is higher throughout the region.

There is evidence in the spatial changes in precipitation in the vegetation experiment that there are downstream effects over the ocean, and there is reason to believe that these effects are real and related to changes in the Hadley circulation. Can the surface modification also lead to global changes? One way to examine that possibility would be to determine whether there is any change in the intensity of the Hadley circulation. An analysis of the latitude of maximum intensity of the Hadley circulation shows little change between the control and the vegetation case. In both cases the maximum upward motion in January occurs at 8 N and is 188 for the control and 180 for the vegetation experiment (note that units are in 10^9 kg/s). The Ferrell cell is maximum at 36 N and is 26 in the control and 29 with vegetation. In July the maximum Hadley circulation is at 8 S and is 217 for the control and 215 with vegetation. The maximum for the Ferrell cell occurs at 20 N and is 35 for both cases. Although there is no significant change globally, the regional changes may still be important because increases in the Hadley circulation over the Sahara Desert must be accompanied by increased downward motion elsewhere. This is consistent with other studies.

One of the principal findings of this paper is that one should be careful when looking at previous studies that only modified the albedo when looking at vegetation experiments. Our results here support the idea that albedo-only experiments tend to enhance the amplitude of the seasonal cycle of precipitation. When the effects of roots are added, the effect is reduced because the roots extract water from deeper layers in the summer.

In the context of the Gaia hypothesis, the results here support the idea that the addition of vegetation to a desert region would modify the climate in such a way as to encourage the existence of vegetation. The results support the hypothesis that there is a positive feedback between vegetation and soil moisture. The next step in examining these relationships should be to do the experiment with a fully dynamic vegetation model coupled to the GCM.

Figure captions.

Figure 1. Shaded area represents region where desert is replaced with vegetation. Darker shaded areas are used to identify two sub-regions of the study area referred to as western Sahara and eastern Sahara.

Figure 2. Annual cycle of precipitation for the control, vegetation experiment, albedo experiment, and observations for (a) western Sahara and (b) eastern Sahara. Observations are based on Legates and Willmott (1990) and model is based on second decade of simulations.

Figure 3. Changes in precipitation in the vegetation experiment (vegetation experiment minus control) based on second decade of model simulations.

Figure 4. Monthly time series of precipitation for the second decade of the control and vegetation and albedo experiments for (a) western Sahara and (b) eastern Sahara.

Figure 5. Monthly time series of soil moisture for the control and vegetation and albedo experiments for (a) western Sahara and (b) eastern Sahara.

Figure 6. Annual cycle of surface air temperature for the control, vegetation experiment, albedo experiment and observations for (a) western Sahara and (b) eastern Sahara. Observations are based on Shea (1986) and model is based on second decade of simulations.

Table captions

Table 1. February and August averages of model variables for control, vegetation experiment and albedo experiment for entire study region based on second decade of model simulations.

Table 2. Same as Table 1 but for western Sahara.

Table 3. Same as Table 1 but for eastern Sahara.

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Table 1. Model variables averaged over the entire Sahara Desert for years 11 to 20.

| | Control | | Vegetation | | Albedo | |
|---|---|---|---|---|---|---|
| | Feb | Aug | Feb | Aug | Feb | Aug |
| Cloud Cover | 13.2 | 13.9 | 9.8 | 43.0 | 11.2 | 48.3 |
| Inc.Solar Rad.Surf. | 237.4 | 310.8 | 233.8 | 264.3 | 231.6 | 258.2 |
| Abs.Solar Rad.Surf. | 160.8 | 209.2 | 198.9 | 221.1 | 197.1 | 216.0 |
| Surface Albedo | 32.0 | 32.6 | 14.9 | 16.3 | 14.9 | 16.4 |
| Surf.Air Temp. | 20.2 | 32.6 | 22.4 | 29.7 | 22.5 | 28.8 |
| Soil Moisture | 49.4 | 47.6 | 56.9 | 58.9 | 78.8 | 81.5 |
| Precipitation | 0.16 | 0.41 | 0.10 | 3.00 | 0.11 | 3.64 |
| Evaporation | 0.20 | 0.39 | 0.43 | 1.61 | 0.30 | 2.46 |

Table 2. Model variables averaged over the western Sahara Desert for years 11 to 20.

| | Control | | Vegetation | | Albedo | |
|---|---|---|---|---|---|---|
| | Feb | Aug | Feb | Aug | Feb | Aug |
| Cloud Cover | 9.1 | 25.4 | 3.2 | 67.1 | 7.9 | 76.3 |
| Inc.Solar Rad.Surf. | 250.1 | 305.4 | 247.8 | 246.1 | 242.5 | 237.6 |
| Abs.Solar Rad.Surf. | 168.8 | 205.5 | 211.0 | 205.7 | 206.5 | 198.6 |
| Surface Albedo | 32.5 | 32.7 | 14.8 | 16.4 | 14.8 | 16.4 |
| Surf.Air Temp. | 24.5 | 33.4 | 26.1 | 27.8 | 27.6 | 26.3 |
| Soil Moisture | 46.0 | 44.9 | 56.2 | 73.4 | 76.8 | 91.8 |
| Precipitation | 0.01 | 0.85 | 0.01 | 5.35 | 0.01 | 6.43 |
| Evaporation | 0.07 | 0.75 | 0.58 | 2.57 | 0.24 | 4.07 |

Table 3. Model variables averaged over the eastern Sahara Desert for years 11 to 20.

| | Control | | Vegetation | | Albedo | |
|---|---|---|---|---|---|---|
| | Feb | Aug | Feb | Aug | Feb | Aug |
| Cloud Cover | 15.3 | 2.5 | 12.9 | 13.3 | 12.2 | 14.1 |
| Inc.Solar Rad.Surf. | 231.3 | 318.9 | 225.4 | 294.5 | 225.9 | 293.2 |
| Abs.Solar Rad.Surf. | 153.5 | 210.7 | 192.0 | 247.2 | 192.4 | 246.0 |
| Surface Albedo | 33.3 | 33.9 | 14.9 | 16.1 | 14.9 | 16.1 |
| Surf.Air Temp. | 18.1 | 32.6 | 21.1 | 34.1 | 20.2 | 34.1 |
| Soil Moisture | 40.9 | 40.2 | 42.5 | 39.2 | 70.1 | 67.4 |
| Precipitation | 0.19 | 0.01 | 0.09 | 0.45 | 0.10 | 0.54 |
| Evaporation | 0.22 | 0.05 | 0.20 | 0.36 | 0.22 | 0.44 |

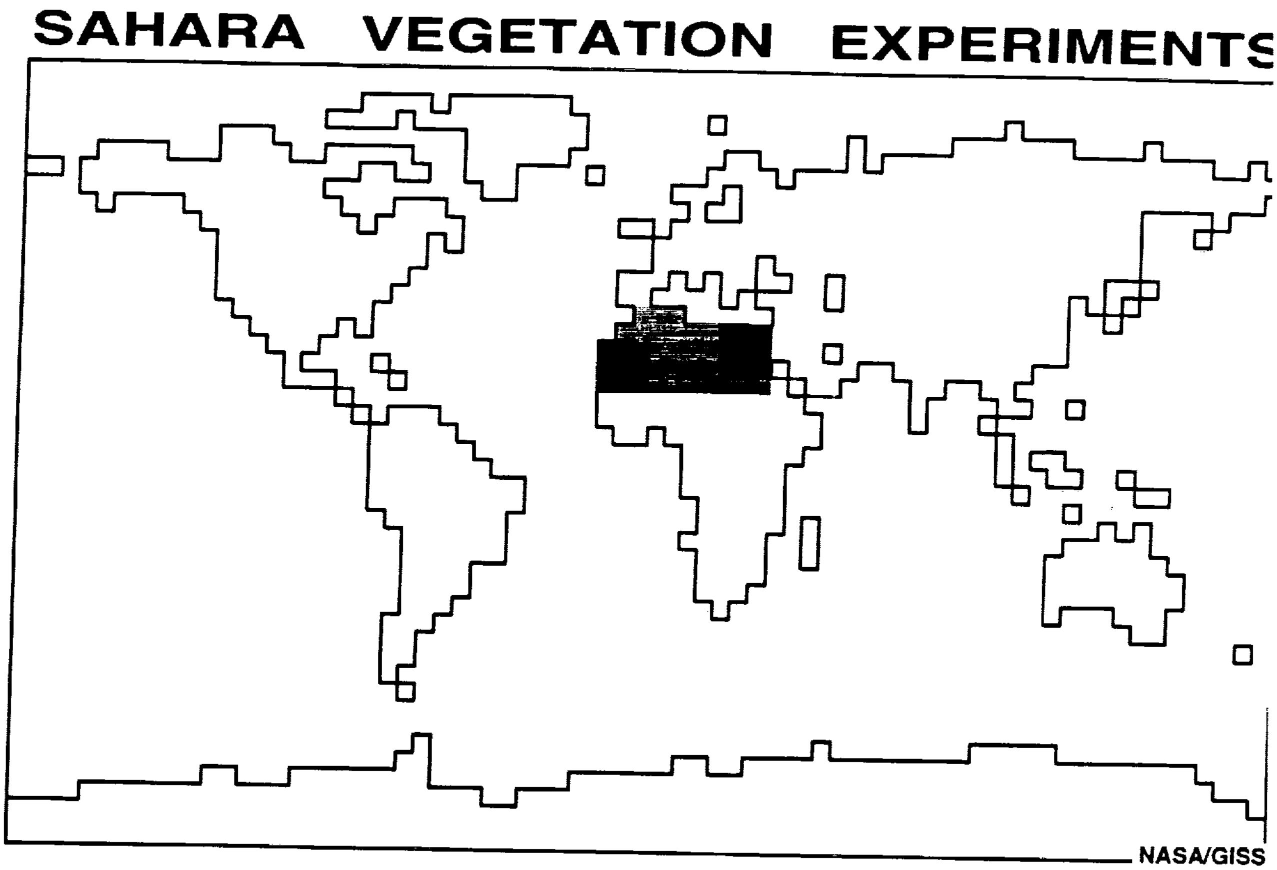
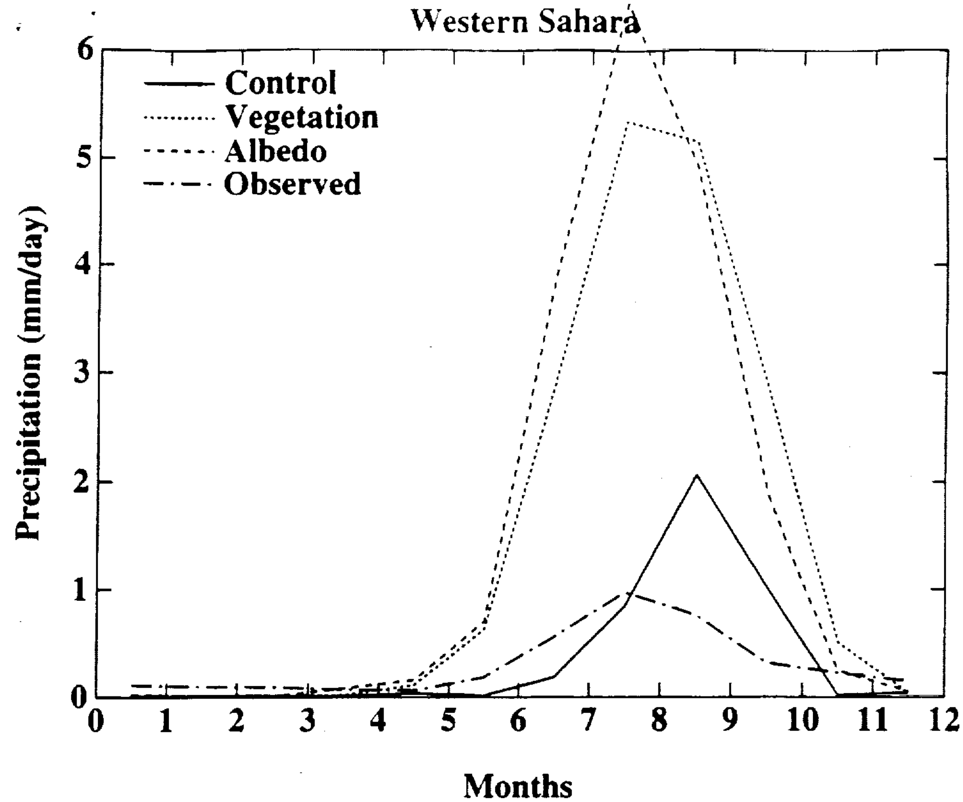



Figure 1


Western Sahara
Control
Vegetation
Albedo
Observed
Precipitation (mm/day)
Months

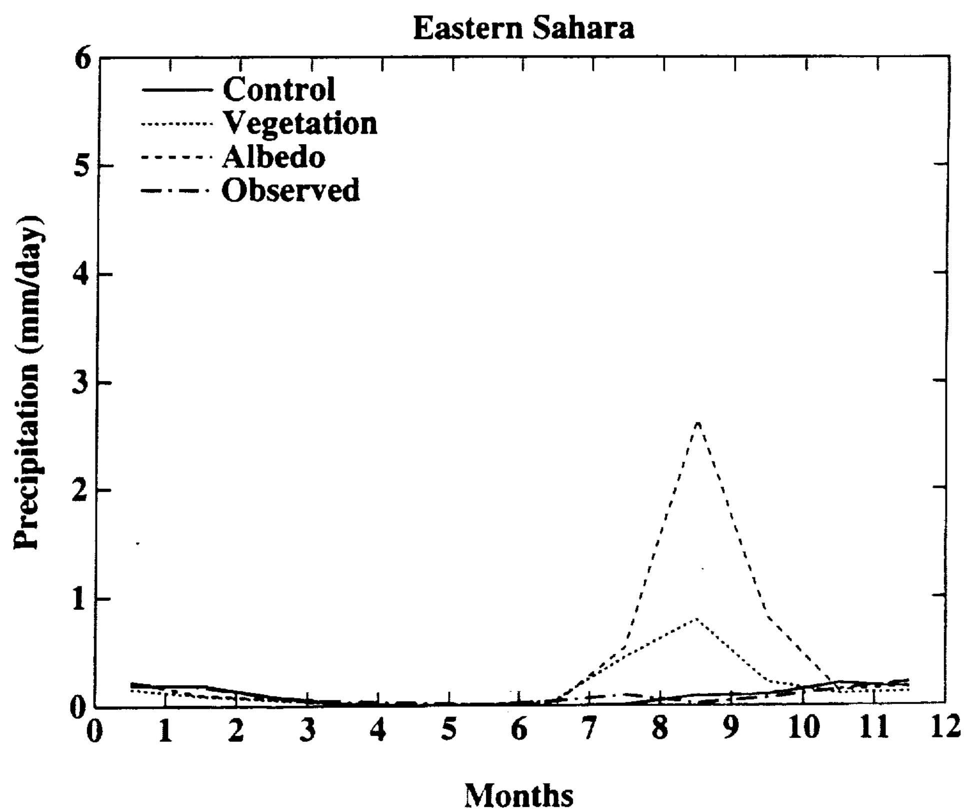
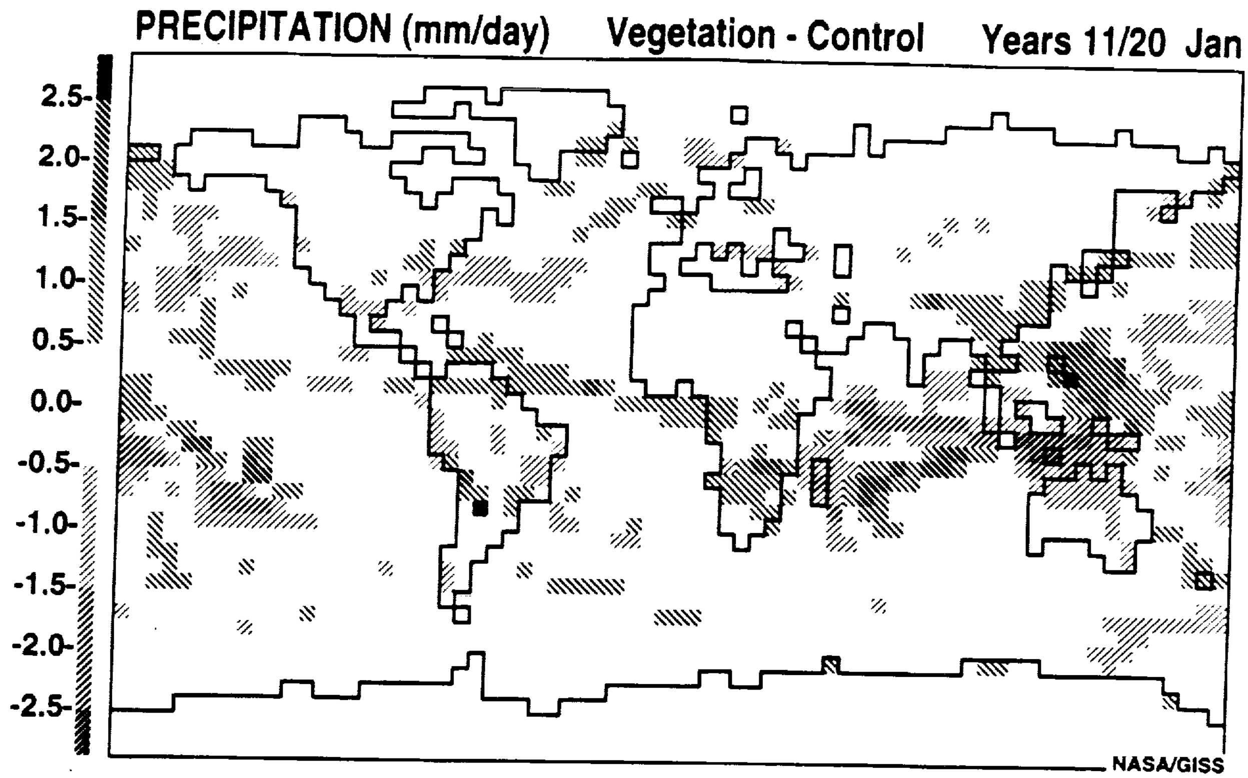

Eastern Sahara
Control
Vegetation
Albedo
Observed
Precipitation (mm/day)
Months

Figure 2


PRECIPITATION (mm/day)
Vegetation - Control
Years 11/20 Jan
2.5-
2.0-
1.5-
1.0-
0.5-
0.0-
-0.5-
-1.0-
-1.5-
-2.0-
-2.5-
NASA/GISS

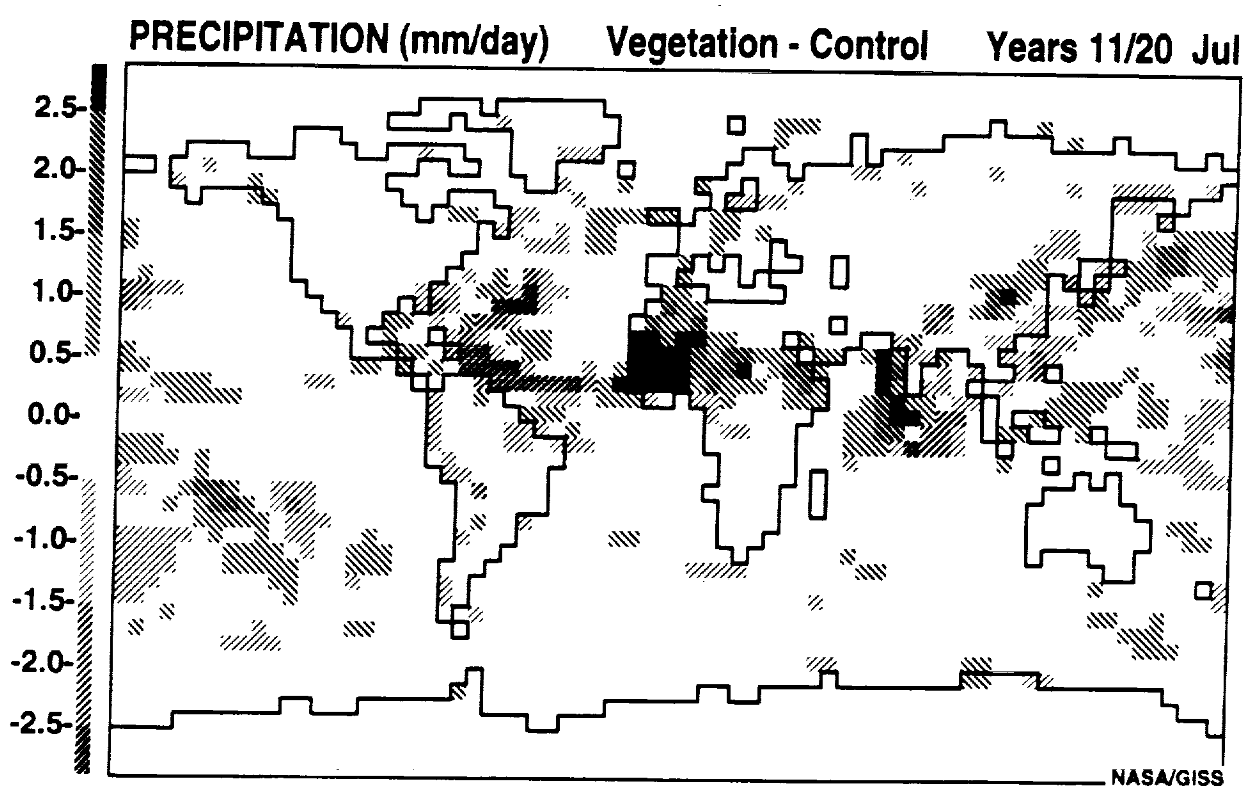
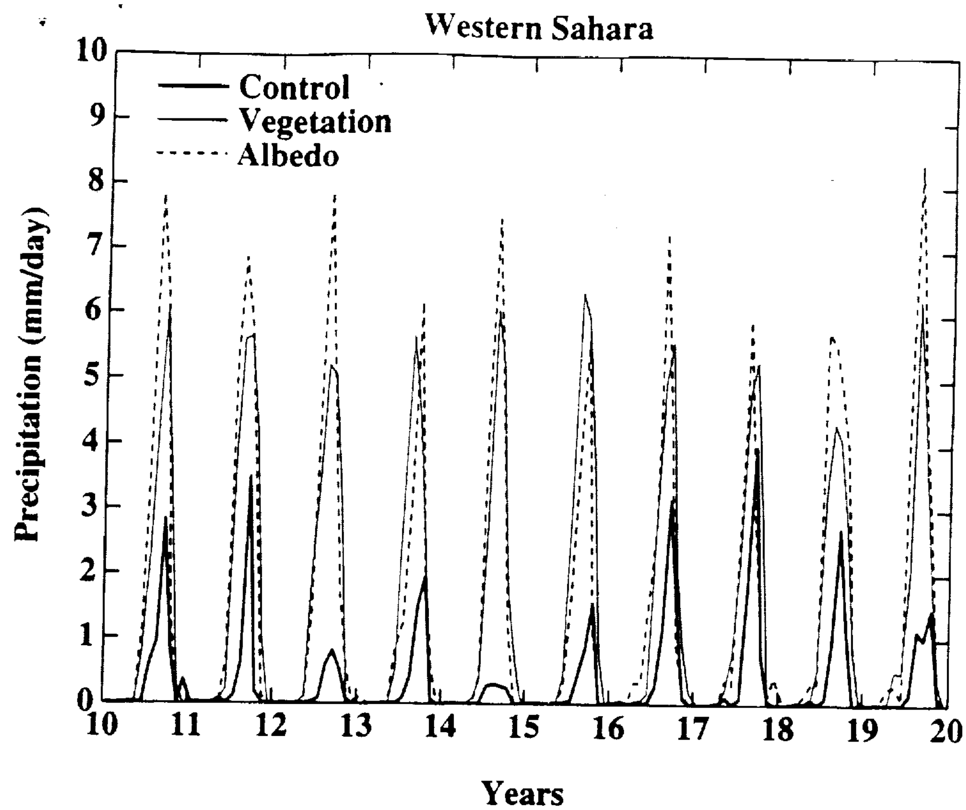

PRECIPITATION (mm/day)
Vegetation - Control
Years 11/20 Jul
2.5-
2.0-
1.5-
1.0-
0.5-
0.0-
-0.5-
-1.0-
-1.5-
-2.0-
-2.5-
NASA/GISS

Figure 3


Western Sahara
Control
Vegetation
Albedo
Precipitation (mm/day)
0
1
2
3
4
5
6
7
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9
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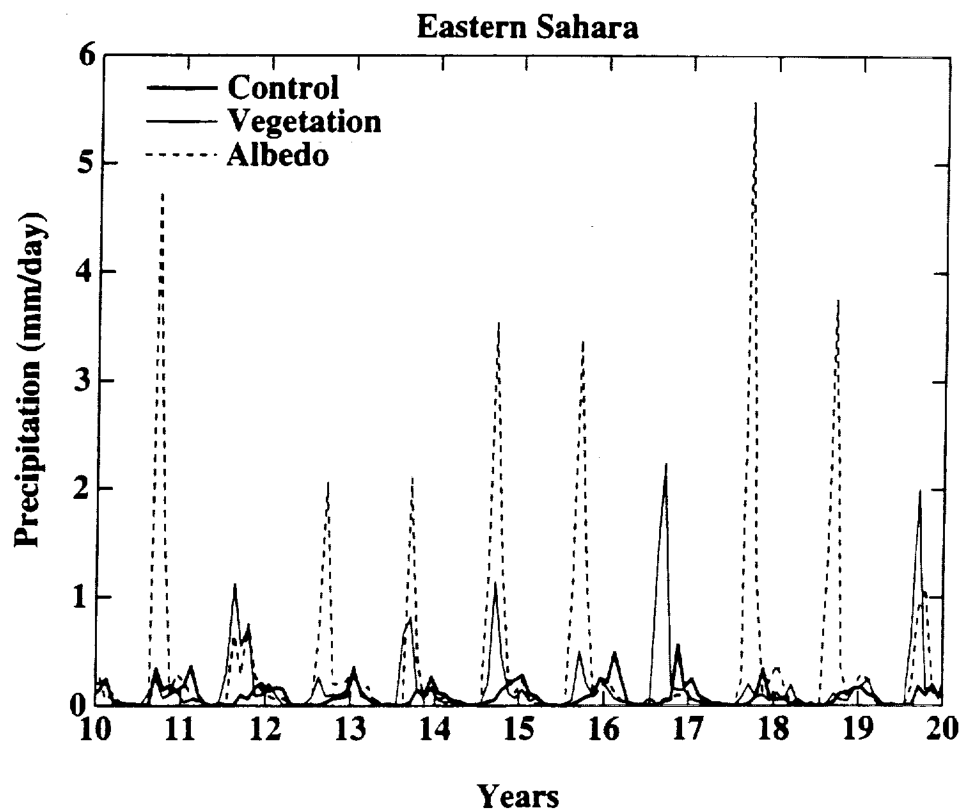
10
11
12
13
14
15
16
17
18
19
20
Years


Eastern Sahara
Control
Vegetation
Albedo
Precipitation (mm/day)
0
1
2
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4
5
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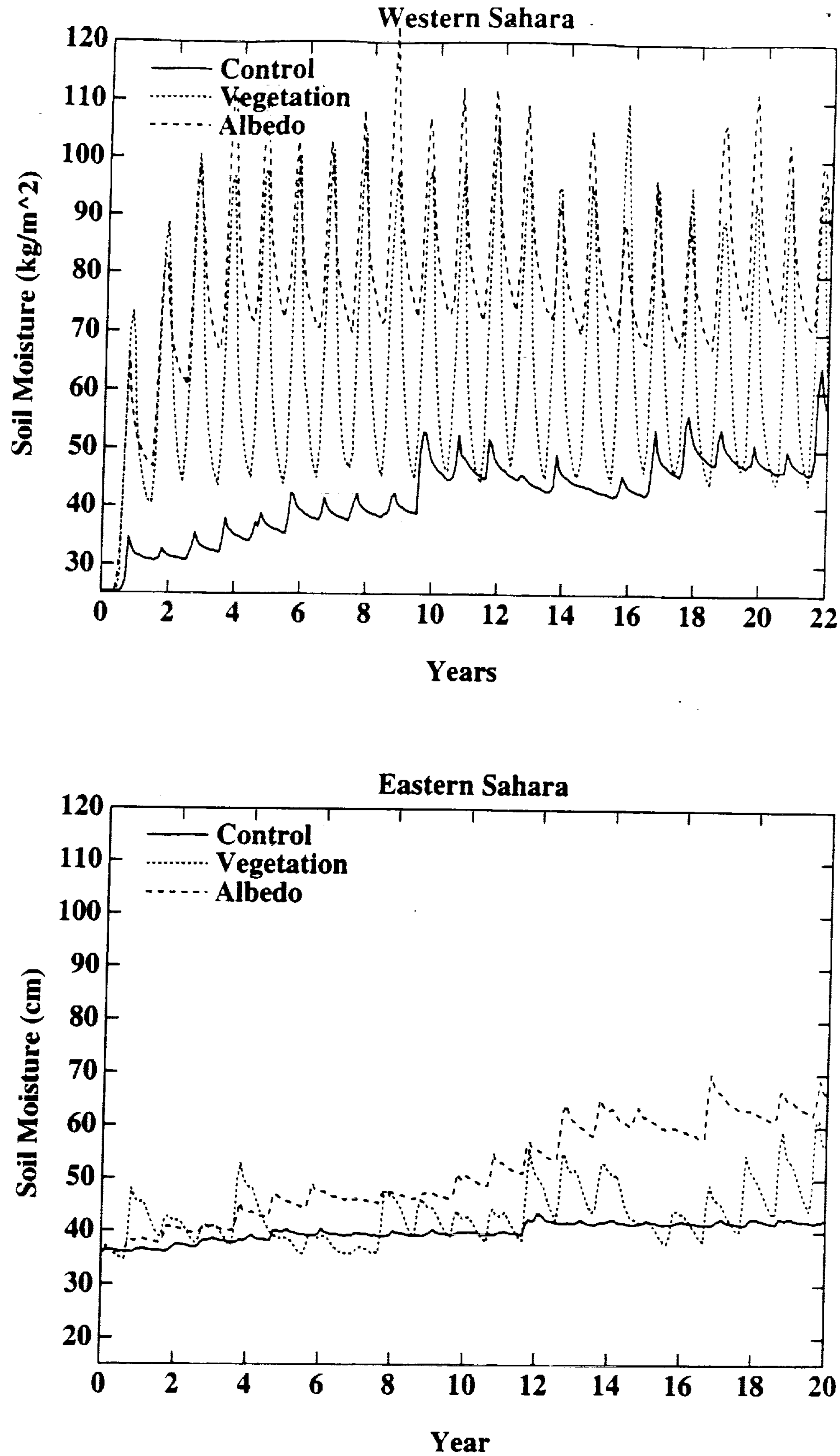
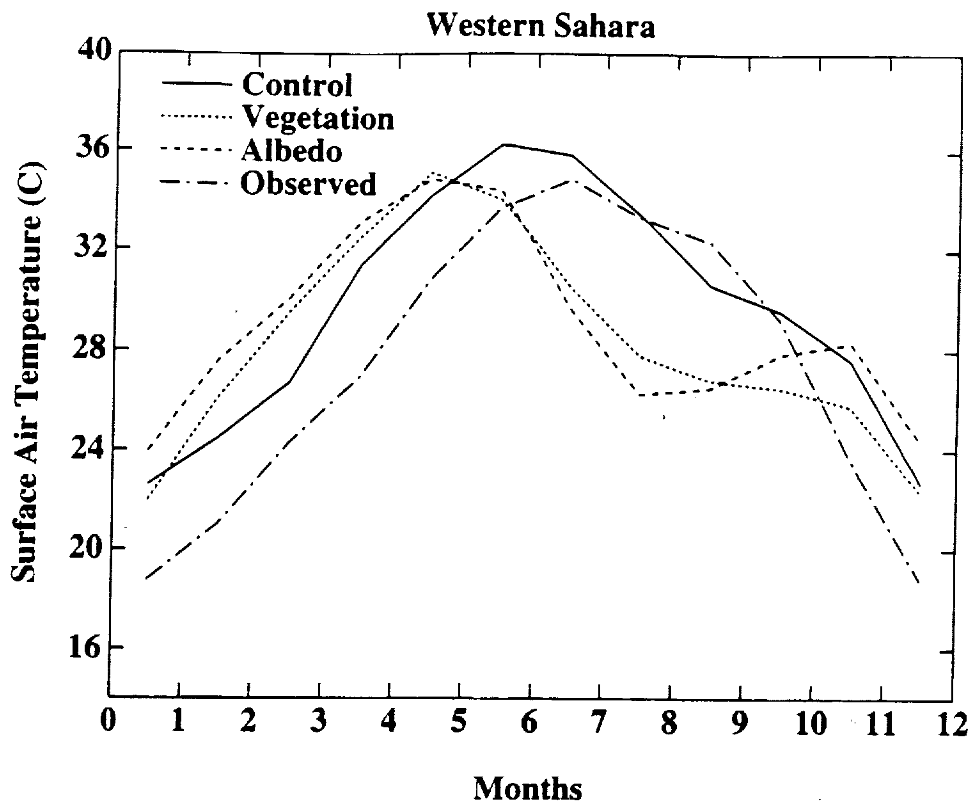
20
Years

Figure 4



Western Sahara
Control
Vegetation
Albedo
Soil Moisture (kg/m^2)
Years
Eastern Sahara
Control
Vegetation
Albedo
Soil Moisture (cm)
Year


Figure 5


Western Sahara
Control
Vegetation
Albedo
Observed
Surface Air Temperature (C)
40
36
32
28
24
20
16
0 1 2 3 4 5 6 7 8 9 10 11 12
Months

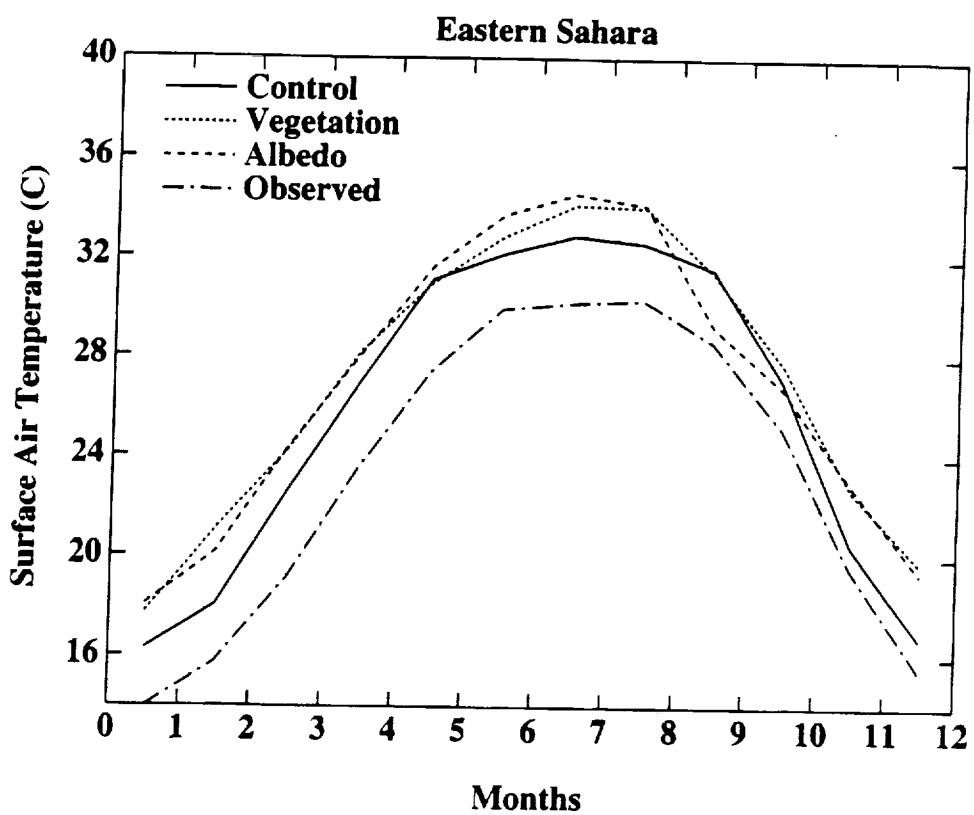

Eastern Sahara
Control
Vegetation
Albedo
Observed
Surface Air Temperature (C)
40
36
32
28
24
20
16
0 1 2 3 4 5 6 7 8 9 10 11 12
Months

Figure 6