Natural Climate Variability on Decade-to-Century Time Scales
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On the Initiation and Persistence of the Sahel Drought

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ABSTRACT

On the basis of analysis of data collected over the Sahel, India, and China, it is conjectured that the occurrence of above-normal rainfall over the Sahel during the decade of the 1950s and below-normal rainfall during the decades of the 1970s and 1980s is a manifestation of natural variations in the planetary-scale coupled ocean-land-atmosphere climate system. In the light of the results of general-circulation model sensitivity experiments, and the fact that the Sahel region is particularly susceptible to changes in land-surface conditions, it is concluded that strong local atmosphere-land interactions over the Sahel region have contributed toward further reduction of rainfall. Both natural climate variability and human activities degrade the land surface in a way that exacerbates the ongoing drought, and therefore there is no guarantee that natural variability can reverse the present trend.

INTRODUCTION

The West African famine during the late 1960s and the 1970s focused the world's attention on the Sahel. The Sahel is a 200- to 500-km wide band across the southern reaches of the Sahara desert. It is ecologically fragile, though it supports nomads, herders, and sedentary farmers; it has a mean rainfall of 300 to 500 mm per year, which is extremely variable. During the past 25 years, rainfall over the Sahel has been significantly lower than the long-term mean. In the recorded meteorological data for the past 100 years, there is no other region on the globe of this size for which spatially and seasonally averaged climatic anomalies have shown such persistence. (See the paper by Nicholson in this section.)

In this paper we shall attempt to address the following questions concerning the Sahel drought:

1. What are the causes of the onset of the drought? In particular, what significant roles did the natural variability of the global climate system and of human activities play in the initiation of the drought?
2. What mechanisms are responsible for the persistence of the Sahel drought?
3. What are the prospects for reversal of the current trend? In particular, what roles might the natural variability of the global climate system and human intervention play in reversing the current trend?

It is of course difficult, if not impossible, to give precise

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answers to these questions. We will attempt to address them by interpreting past observational data and the results of controlled sensitivity experiments made with general-circulation models (GCMs).

ONSET OF THE SAHEL DROUGHT

Figure 1 shows the 10-year running-mean seasonal rainfall anomalies over Sahel, India, and China. The Chinese rainfall data are available for only a 30-year period (1951-1980); therefore, the Indian and the Sahel rainfall data have also been shown for that period.

We interpret these data to suggest that the occurrence of above-normal rainfall during the decade of the 1950s and the early 1960s, and below-normal rainfall during the late 1960s and the 1970s, is a feature common to the vast areas of African-Asian monsoon, not one confined to the Sahel region. We do not know why rainfall over such a large geographic region, covering two continents, was above normal during the 1950s. We also do not know why the transition from above-normal to below-normal rainfall that took place during the late 1960s occurred over the entire African-Asian monsoon region. However, on the basis of comprehensive GCM sensitivity studies (Folland et al., 1986; Rowell et al., 1992; Xue and Shukla, 1993), it is now generally accepted that the rainfall anomalies, especially over the Sahel, are consistent with, and can be simulated using, the global sea surface temperature (SST) anomalies during these periods.

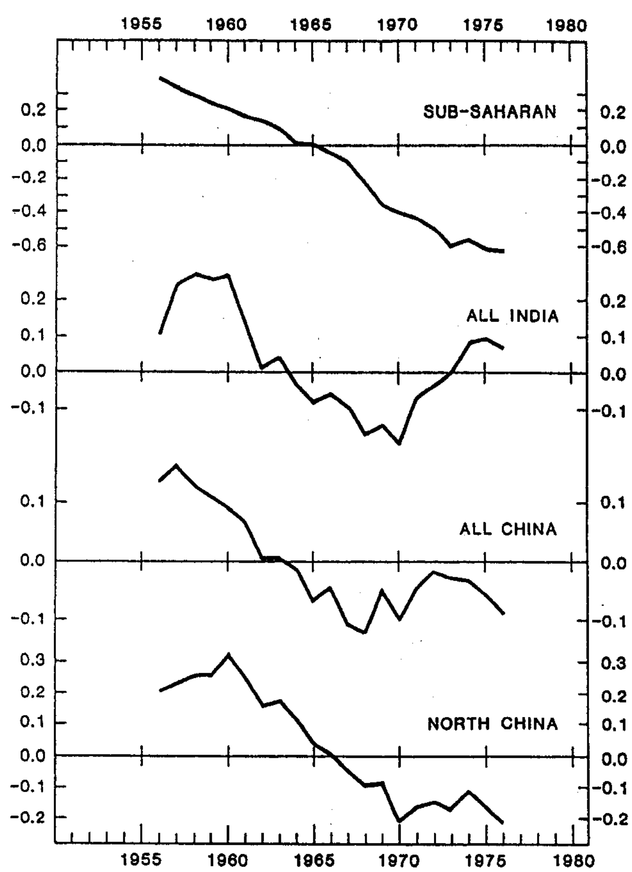

FIGURE 1 Ten-year running mean of normalized rainfall anomalies averaged for all the stations over the sub-Saharan region (10°-25°N, 18°W-25°E), India, and China. North China refers to the area to the north of 35°N.

On the basis of the GCM sensitivity experiments and observations shown in Figure 1, we conjecture that the onset of the Sahel's rainfall deficit in the late 1960s, along with the above-normal rainfall in the 1950s, should be explained as a regional manifestation of the planetary-scale variability of the global coupled ocean-land-atmosphere climate system. Considering the large spatial and temporal extent of these rainfall anomalies, we cannot conceive of any possible mechanism by which local human-induced changes could initiate such major droughts over two continents. We therefore reject the notion, often mentioned in popular literature, that the Sahel drought was initiated by human activities.

We believe that the pertinent question about the Sahel drought is not what initiated the drought (we conjecture it was natural variability) but why the drought has persisted for 25 years.

PERSISTENCE OF THE SAHEL DROUGHT

We further propose that strong interaction between atmospheric and land-surface processes is one of the primary causes of the drought's persistence: A reduction in rainfall (due to natural variability of the climate system) would change the land surface characteristics (increase in albedo and decrease in vegetation), which in turn would cause further reduction in rainfall. The basic mechanisms of atmosphere-land coupling have the potential to perpetuate an initial drought (or an initial excessive-rainfall) regime until they are reversed by an opposite forcing, which could be produced by natural variability.

The extent to which changes in the land-surface properties can influence the local climate depends on the spatial scale of the changes in the land-surface characteristics and the geographic location of the region. We submit that the Sahel region is particularly sensitive to atmosphere-land coupling processes. The Sahel region is geographically unique in that it is adjacent to the largest desert on the earth's surface, and it represents the largest contiguous land surface without extensive mountain terrains. The absence of large-scale topographic forcing in the region is perhaps one of the main reasons for the lack of zonal asymmetry in the rainfall pattern there. As Charney (1975) pointed out in his seminal paper on the dynamics of Sahel drought, climate in the subtropical margins of the deserts is particularly vulnerable to changes in the land-surface properties.

During the past 20 years there have been a large number of GCM sensitivity studies (Mintz, 1984; Dirmeyer and Shukla, 1993) that show that increases in albedo and decreases in vegetation cover and soil moisture tend to further reduce rainfall over the Sahel. We do not know of any GCM sensitivity study challenging this basic result. We present here the results of a recent GCM sensitivity study (Xue and Shukla, 1993 and an unpublished manuscript) in which the Center for Ocean-Land-Atmosphere Interactions (COLA) model was integrated with two sets of land-surface conditions over the region south of the Sahara desert. In one set of integrations, referred to as the "desertification" experiment, it was assumed that the area approximately between 10° and 20°N and 15° and 40°E was covered by shrubs above bare soil. In the other set of integrations, referred to as the "reforestation" experiment, the area approximately between 15° and 40°E was covered by broadleaf trees above ground cover. The first set of surface conditions (desertification) was considered to represent the exaggerated state of current conditions. The second set of surface conditions (reforestation) represented a hypothetical situation in which vegetation was maintained in the margins of the Sahara Desert. It was an exaggeration of the conditions during the 1950s, when rainfall over the Sahel was above normal, and the latitude of the 200 mm isoline of seasonal rainfall in the western Sahel was at about 18°N. The model was integrated with identical global SST patterns for each change in the land-surface conditions.

Figure 2a shows the difference between the observed rainfall averaged for 1950 plus 1958 and 1983 plus 1984. Figure 2b shows the difference between the desertification and reforestation experiments for seasonal mean rainfall. The similarity between Figures 2a and 2b is remarkable. Both show negative rainfall departures between 10° and 20°N and a positive rainfall departure to the south of the negative departures. The dipole nature of both the observed and the model rainfall anomalies suggests a southward displacement of the mean rainfall pattern.

Since the only changes in these integrations were those in land-surface conditions, it is reasonable to conjecture that if the natural variability of the global climate system were to produce an initial drought, the strong atmosphere-land interaction over the Sahel region could contribute toward the persistence of that drought.

We further propose that since natural changes in the Sahel rainfall have led to large-scale changes in human activities in the region, it is quite likely that the degradation of the land surface was exacerbated by human activities (overgrazing, deforestation, soil desiccation, etc.), thereby producing further reduction in the Sahel rainfall. The exacerbating effects of human activities could have been especially large during the past 30 years because the population density has been much higher than at the beginning of the century.

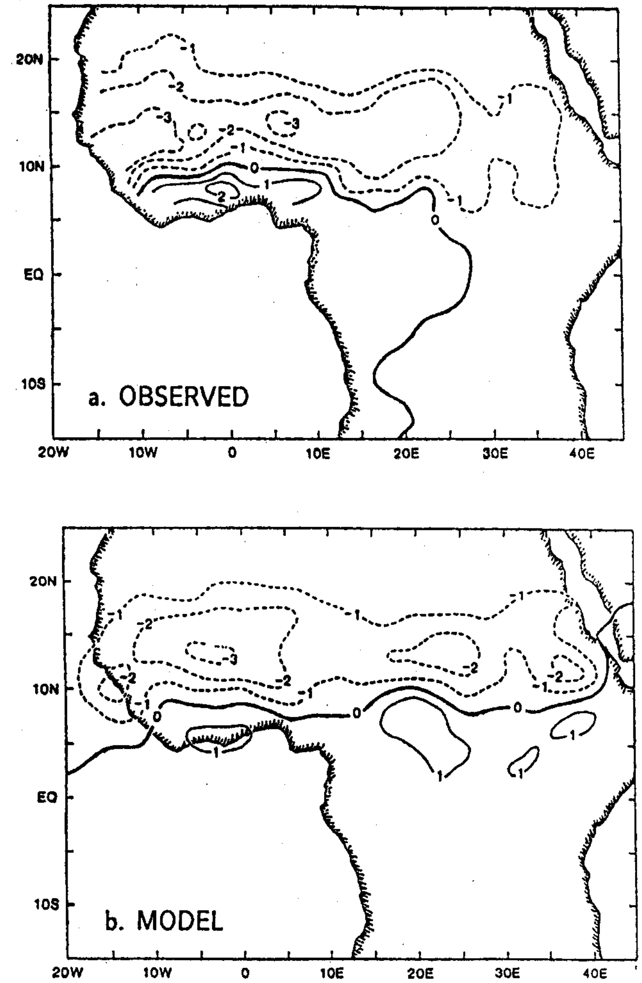

FIGURE 2 (a) Observed summer (June, July, August, September) rainfall difference, in millimeters per day, for the average of 1983 and 1984 minus the average of 1950 and 1958. (b) Rainfall difference between desertification and reforestation GCM experiments.

The various conjectures put forward in this paper so far have been synthesized in a schematic diagram shown in Figure 3. It is seen that the atmosphere-land interaction has a positive feedback mechanism, so that initial drought caused by the natural variability of the climate system is perpetuated by increases in albedo and decreases in vegetation, soil moisture, and surface roughness. In addition, the human-induced effects also produce an increase in albedo and a decrease in vegetation, soil moisture, and surface roughness. Thus, both the planetary-scale effects and the human-induced effects are mutually reinforcing the dry conditions, which has led to an unprecedentedly long and severe drought over the Sahel.

THE FUTURE

If we accept the premise presented in the beginning of this paper, that the Sahel drought was initiated by natural

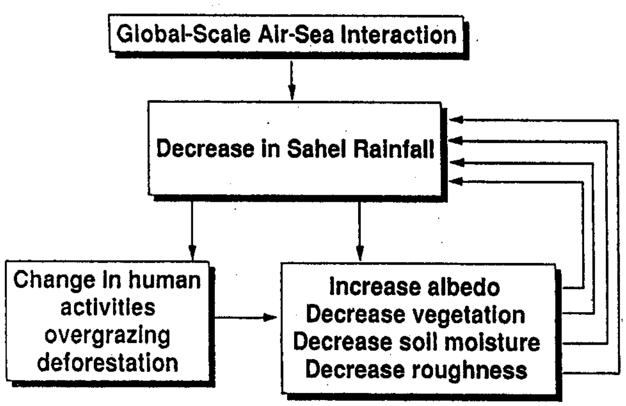

FIGURE 3 Schematic representation of the mechanisms affecting Sahel rainfall. Both the natural variability and the human-induced changes are contributing to the reduction in Sahel rainfall.

variability of the global climate system, it is reasonable to assume that at some unpredictable future time the natural variability (global SST patterns, for example) is likely to produce excessive rainfall over the Sahel and thus reverse the current drought. However, it is unclear whether the changes in the land-surface characteristics can also be reversed. Therefore, even if the global circulation shifts in such a way as to be favorable for reversing the current drought, the global natural changes will have to be stronger than before, and more favorable, to overcome the opposing effects of local atmosphere-land interactions. In fact, it is entirely possible that the Sahel drought will continue indefinitely, because the natural variability effects may never be large enough to counteract the persistent effects of the local land-surface changes.

In a hypothetical GCM sensitivity experiment, Xue and Shukla (unpublished manuscript) have shown that rainfall over the Sahel can be increased by replacing the broadleaf shrubs over ground cover and the shrubs over bare soil by broadleaf trees over ground cover over a large region that includes the Sahel. This suggests that although human effects were not responsible for the initiation of the Sahel drought, a suitable combination of large-scale natural variability and human intervention might contribute toward reversing the current drought. Modification of surface albedo, evapotranspiration, or surface roughness would all be of assistance, though of course it would be extremely difficult to sustain vegetation on a scale sufficiently large to halt the spread of the desert.

Discussion

DESER: Do you think local forcing applies to the string of wet years in the 1950s and 1960s too?

NICHOLSON: Absolutely. What I feel is the critical factor involved in the forcing is the fluxes to the atmosphere, including dust. The land surface forcing should be reversible, or symmetric, for the wet and dry periods.

RIND: How successful have people been in quantifying the albedo change between the wet and dry periods, as far as the land surface is concerned?

NICHOLSON: One study made 10 or 15 years ago took the available satellite data and reconstructed the albedo over about 8 years. The small changes found were not consistent with rainfall fluctuations, and I think basically showed that albedo is not one of the major forcing factors. More recently, Vivian Gornitz searched historical archives for material on land-surface changes, and constructed a beautiful map of West Africa showing changes due to human activities. Again, in terms of absolute values of albedo, it's a very small change, and sometimes in the wrong direction for the Charney mechanism. So I think that not albedo but something coupled to soil moisture, vegetation, and dust will be the major factor.

DIAZ: To what degree do you think that time differences in the frequency of the westward-propagating tropical disturbances affect the variability you're seeing?

NICHOLSON: I think they're key to understanding the region. This may be the one place on the globe where the land-surface forcing per se has a major impact on the overall large-scale dynamics. The jet stream at the mid-levels here, which is critical in disturbance development, is due to nothing other than the temperature gradient across the land surface down to the ocean.

Some of the models done years ago, during the GATE days, showed that if you change the relationship between baroclinic and barotropic instability you can change the characteristics of the disturbances. The difference between the wet 1950s and the dry 1970s can be explained by one or two disturbances a month that produce, say, 150 mm of precipitation a day, where the dry periods have nothing over 50. I think the large-scale circulation is clearly coupled to the land surface there. Incidentally, the dust in that region is right at the level of the African easterly jet, about 650-700 mb, which is another reason I think it is so important.

CANE: I can see that the land-surface processes can affect what's happening, but I'd like to hear what you see as the feedback mechanism for very-long-period changes. How would you cycle in and out, and what would the trigger be?

NICHOLSON: Well, if you assume some large-scale trigger in the general atmospheric circulation, maybe a major change in SST, you could get a continental-scale pattern like the wet 1950s all over Africa. But in other areas the rainfall goes back to normal, whereas in the Sahel the anomalies persist for 10 or even 20 years. There has to be some other smaller-scale forcing that reinforces the existing conditions until it's overridden by some larger trigger in the atmosphere-ocean circulation.

COLE: Ropelewski and Halpert's analysis of global rainfall suggests that the ENSO teleconnection with African rainfall is strongest in the east. Do you see a strong ENSO signal in the variability in the area you've been looking at?

NICHOLSON: There's a small one in the coastal region, but nothing in the central Sahel.

RIND: Shukla, your hypothesis suggests two questions to me. The first is, can it be documented—through satellite observations, for instance—that the vegetation really changed so extremely in those 10° latitude belts? And the second is, did those British experiments in which SST anomalies related so well to the Sahel changes, also produce the drying conditions in China and India between the 1950s and 1980s?

SHUKLA: We have exaggerated the extent of land degradation in our experiments. But there is a very clear shift in the rainfall between the 1950s and the 1980s, and Tucker and his colleagues have shown from the vegetation data that there is a very clear relationship between the two. If you look at the latitude of an isoline, it is definitely going down; the 200-mm isoline has dropped by 2° or 2.5°. So there are changes at the boundary, albeit of less magnitude than what I have chosen for this experiment.

BERGMAN: Sharon, when I was at the Climate Analysis Center, we found amazing discontinuities in precipitation time series in Western Africa that suggested that the station sites for some locations must have been moved, although there was no record of a change. Did you find this, and were you able to correct for it?

NICHOLSON: There were only a couple of stations in my network that had to be thrown out because of that sort of discontinuity, though we did find differences at the same station because of varied sources. Our approach has been to take aerial averages and hope that the outliers get factored out. But let me make a pitch here for the need to put together an archive of some of the old, forgotten data sources, such as pilot balloon data, to help us understand decadal and longer-scale variability.

RASMUSSON: It is still not clear to me that we are seeing the effect of human intervention. The vegetation seems to move north again in wetter years. Can you see an underlying southward trend?

NICHOLSON: Shukla and I differ somewhat in our views here. I think that so far human intervention has very little to do with it. Many of the papers on desertification are essentially inferring continent-wide desertification from two data points in West Africa. But I don't think that the vegetation's recovery changes any of the ideas about the relation between low-frequency forcing and land surface.

One other thing I'd like to mention with respect to Shukla's argument is that I think one variable has been left out: dust. If I had to put money on any of those land-surface variables, I'd pick dust. It responds to both rainfall and land-surface factors, it has the best memory in the system, and it has shown the most consistent relationship over time with rainfall fluctuations.

SHUKLA: That is certainly a point that ought to be discussed further, if we had time. I'd like to think a little more before I put my money on dust. But let me add just a couple of things. The population pressure has been higher than ever before in the past 20 or 30 years, and that period coincides with the most severe drought in the 100 or so years for which we have reliable instrumental data. Proxy-data evidence of persistent droughts by no means rules out a human role in the current situation. It is also possible that human intervention, such as large-scale agriculture and afforestation, has the potential for reversing the present tendency, whatever its origin.