

Regime Shifts in the Sahara and Sahel: Interactions between Ecological and Climatic Systems in Northern Africa

Jonathan A. Foley,^{1*} Michael T. Coe,¹ Marten Scheffer,² and Guiling Wang³

¹Center for Sustainability and the Global Environment (SAGE), Gaylord Nelson Institute for Environmental Studies, University of Wisconsin, Madison, 1710 University Avenue, Madison, Wisconsin 53726, USA; ²Department of Aquatic Ecology and Water Quality Management, Wageningen University, P.O. Box 8080, NL-6700 DD Wageningen, The Netherlands; ³Department of Civil and Environmental Engineering, University of Connecticut, 261 Glenbrook Road, Storrs, Connecticut 06269, USA

ABSTRACT

The Sahara and Sahel regions of northern Africa have complex environmental histories punctuated by sudden and dramatic "regime shifts" in climate and ecological conditions. Here we review the current understanding of the causes and consequences of two environmental regime shifts in the Sahara and Sahel. The first regime shift is the sudden transition from vegetated to desert conditions in the Sahara about 5500 years ago. Geologic data show that wet environmental conditions in this region—giving rise to extensive vegetation, lakes, and wetlands—came to an abrupt end about 5500 years ago. Explanations for climatic changes in northern Africa during the Holocene have suggested that millennial-scale changes in the Earth's orbit could have caused the wet conditions that prevailed in the early Holocene and the dry conditions prevalent today. However, the orbital hypothesis, by itself, does not explain the sudden regime shift 5500 years ago. Several modeling studies have proposed that strong, nonlinear feedbacks between vegetation and the atmosphere could amplify the effects of orbital variations and create two alternative stable states (or "regimes") in the climate and ecosystems of the Sahara: a "green Sahara" and a "desert Sa-

hara." A recent coupled atmosphere-ocean-land model confirmed that there was a sudden shift from the "green Sahara" to the "desert Sahara" regime approximately 5500 years ago. The second regime shift is the onset of a major 30-year drought over the Sahel around 1969. Several lines of evidence have suggested that the interactions between atmosphere and vegetation act to reinforce either a "wet Sahel" or a "dry Sahel" climatic regime, which may persist for decades at a time. Recent modeling studies have indicated that the shift from a "wet Sahel" to a "dry Sahel" regime was caused by strong feedbacks between the climate and vegetation cover and may have been triggered by slow changes in either land degradation or sea-surface temperatures. Taken together, we conclude that the existence of alternative stable states (or regimes) in the climate and ecosystems of the Sahara and Sahel may be the result of strong, nonlinear interactions between vegetation and the atmosphere. Although the shifts between these regimes occur rapidly, they are made possible by slow, subtle changes in underlying environmental conditions, including slow changes in incoming solar radiation, sea-surface temperatures, or the degree of land degradation.

Key words: Sahel; Sahara; regime shifts; resilience; climate-vegetation interactions; drought; Holocene.

Received 12 August 2002; accepted 7 November 2002; published online 9 September 2003.

*Corresponding author; e-mail: jfoley@wisc.edu

INTRODUCTION

The behavior of environmental systems results from a complex interplay between their biotic and abiotic components. Over a large region, such as the Sahara or the Sahel, the coupled behavior of environmental systems are often expressed through strong biogeochemical, biophysical, and hydrological linkages among terrestrial ecosystems, aquatic ecosystems, and the atmosphere. These linkages can occur over a wide range of time and space scales, and may involve strong feedbacks among the components of the system.

Predicting the behavior of such a system is enormously challenging. Instead of following a simple linear path along existing trends, coupled environmental systems often exhibit highly nonlinear behavior. In fact, the behavior of environmental systems—especially those involving strong linkages and feedbacks between their component parts—may give rise to sudden, sometimes catastrophic changes (Scheffer and others 2001; Higgins and others 2002).

Such a sudden, large change in environmental conditions—called a “threshold response” or “regime shift” (following Scheffer and others 2001; see also Appendix)—often occurs without advance warning. In fact, predicting the exact timing, location, and pace of these regime shifts may be impossible. Regime shifts often appear to be caused by fairly small, stochastic events, such as an individual storm, drought, disease epidemic, or biological invasion. But these events are generally not the ultimate cause of the regime shift; rather, they are the “trigger” mechanism.

Instead of trying to predict the exact timing and location of all possible “triggers”, we can instead focus on the underlying conditions that may predispose a system to regime shifts. Typically, these underlying environmental conditions are changing very slowly and often go unnoticed. For example, Scheffer and others (2001) suggested that the loss of ecological resilience leads to a catastrophic regime shift in many environmental systems, even if a proximate “trigger” is never clearly identified. Other slow changes to the underlying environmental conditions—including changes from subtle astronomical, geological, ecological or human drivers—may also help predispose a system to a regime shift.

Here we consider two particular regions, the Sahara and Sahel of northern Africa, and examine how the behavior of these environmental systems may have given rise to important regime shifts in the past.

ENVIRONMENTAL CONDITIONS IN THE SAHARA AND SAHEL

Northern Africa is a land of extremes. To the north is the Sahara desert, the largest hot desert on the planet today. To the south, there is a sharp gradient of precipitation and vegetation cover ranging from open shrublands, through grasslands, to tropical savannas and forests. This transition zone is called the *Sahel*, which comes from an Arabic word for “shore” (Graetz 1991; Le Houerou 1980). For practical purposes, Nicholson (1994) suggested that the Sahel be defined as a region bounded between 15°W and 20°E longitude and 13°N and 20°N latitude (see Figure 1).

Many people think that the Sahel is losing ground—literally. There is a popular notion that the Sahara desert is slowly expanding, consuming the more productive ecosystems to the south. This process of “desertification”—the loss of perennial vegetation and topsoil and the associated decline in biological productivity—is often cited as one of the main ecological threats facing the semiarid regions of the world today (for example, see, Verstraete 1986; Mainguet 1991; Graetz 1991).

But recent analyses have indicated that the Sahel, although currently experiencing a persistent and serious drought, is not experiencing the slow, steady grind of desertification (Nicholson and others 1998; Helldén 1991; Thomas and Middleton 1994). In fact, evidence from long-term satellite records indicates that desertification has not been occurring along the Sahara/Sahel boundary during the last 20 years (Tucker and others 1991; Prince and others 1998; Tucker and Nicholson 1999). Instead, satellite and rainfall records indicate strong variations from year to year in rainfall and vegetation greenness since the late 1970s, but no systematic expansion of the deserts is seen.

Of course, this does not mean that the environments of the Sahara and Sahel are static and cannot change. Instead, we find that the environmental histories of the Sahara and Sahel are characterized by sudden, abrupt changes—including several dramatic regime shifts that occurred with no apparent warning. In the following sections, we review two major environmental regime shifts that occurred in the Sahara and Sahel during the last 6000 years.

REGIME SHIFT 1: SUDDEN ONSET OF DESERT CONDITIONS IN THE SAHARA ABOUT 5500 YEARS AGO

First we consider a dramatic regime shift that occurred in the Sahara and the neighboring Sahel

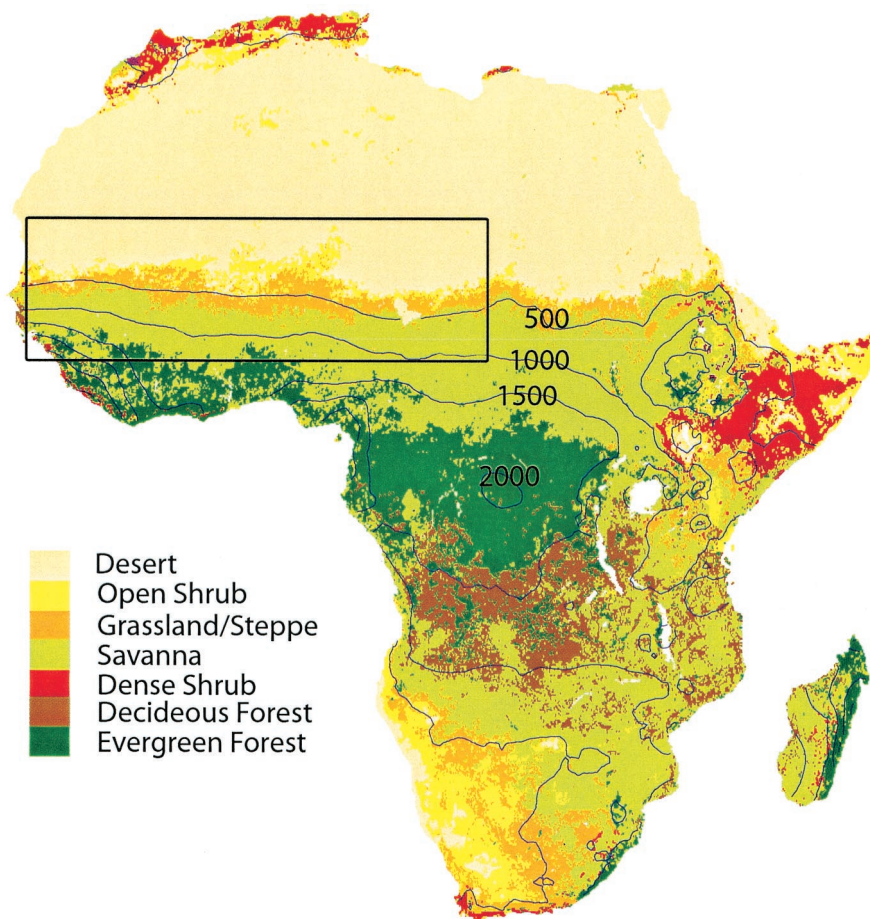


Figure 1. Vegetation cover and precipitation patterns of Africa. Patterns of precipitation (expressed as annual means, in units of mm/y) are tightly correlated with patterns of vegetation cover. Northern Africa is dominated by the Sahara, the largest hot desert on the planet today. The transition between the Sahara and the savannas to the south occurs in the Sahel zone (outlined in black).

approximately 5500 years ago. From the late Pleistocene until the middle Holocene era—roughly 14,500 to 5500 years ago (in terms of calibrated calendar dates, not raw radiocarbon dates)—the Sahara and Sahel were much wetter than today, with extensive vegetation cover, lakes, and wetlands; thriving animal communities; and numerous human settlements (McIntosh and McIntosh 1981; Ritchie and others 1985; COHMAP 1988; Street-Perrott and Perrott 1993; Petit-Maire and Guo 1996; Roberts 1998).

There are numerous geologic records left from this wet and productive environment, including fossil lakebeds and shorelines (Street and Grove 1979; Petit-Maire and Riser 1981; Fontes and others 1985; Street-Perrott and Harrison 1984; Gasse 1987; Haynes 1987; Pachur and Kröpelin 1987; Haynes and others 1989; Pachur and Hoelzmann 1991; Petit-Maire and others 1993; Yu and Harrison 1996), pollen from flourishing vegetation communities (Maley 1981, 1983; Ritchie and others 1985; Lézine 1991; Lézine and Casanova 1989; Lézine and others 1990; Schulz 1991; Street-Perrott and Perrott 1993), and the skeletal remains of grazing an-

imals (Pachur and Kröpelin 1987; McIntosh and McIntosh 1981; Petit-Maire and Guo 1996). In addition, there is abundant archaeological evidence of thriving human communities, including numerous cave paintings and rock carvings (Servant and Servant-Vildary 1980; McIntosh and McIntosh 1983, 1981).

Recent efforts have attempted to compile these geologic data to construct regional-scale descriptions of changing environmental conditions over the Sahara and Sahel (Petit-Maire and Guo 1996; Hoelzmann and others 1998; Jolly and others 1998; Prentice and others 2000). For example, Hoelzmann and others (1998) and Prentice and others (2000) presented maps of the Sahara and Sahel regions for the middle Holocene epoch (roughly 6000 years ago) showing that there was significantly less area of desert; instead, the region was dominated by grasslands and shrublands. Hoelzmann and others (1998) also showed that lakes and wetlands were much more abundant 6000 years ago, with large water bodies in the Chad basin (including Lake Megachad) and the Niger bend.

But these lush conditions did not last forever.

Sometime between 5000 and 6000 years ago, there was a switch to much more arid conditions extending throughout the Sahara and the Sahel (Street and Grove 1979; Street-Perrott and Harrison 1984; Pachur and Kröpelin 1987; Haynes and others 1989; Gasse and Van Campo 1994; Petit-Maine and Guo 1996; Pachur and Altmann 1997). Mesic vegetation communities disappeared rapidly (Lezine and others 1990; Lamb and others 1995) and lake levels declined dramatically (Street and Grove 1979; Street-Perrott and Harrison 1984). Archaeological evidence also shows that highly mobile pastoralist cultures started to dominate the region at this time, replacing the more sedentary lacustrine traditions (McIntosh and McIntosh 1981; Pachur and Kröpelin 1987; Petit-Maire and Guo 1996).

Compared to the long period of wet conditions (between roughly 14,500–5500 years ago), the drying of the Sahara and Sahel occurred rather abruptly. The terrestrial geologic records include a wide range of dates, but they generally indicate that the transition to desert conditions took place over a few centuries, sometime between 5000 to 6000 years ago, especially in West Africa. However, the climatic history of the eastern Sahara appears to be somewhat more complex; and may show a somewhat more gradual transition, punctuated by other fluctuations (Geyh and Jäkel 1974; Jäkel 1979; Pachur and Wünnemann 1996).

But it is extremely difficult to estimate the precise time of this switch to desert conditions using terrestrial records. Very few well-dated records can be found on land, since many of the sediment records from the early and middle Holocene epochs were eroded away in the last 5000 years. Perhaps the best evidence for an abrupt transition comes from a recent study by deMenocal and others (2000). They reported the results from a detailed and well-dated marine record of terrigenous (eolian) sediment from the Ocean Drilling Program Site 658C, which is located off the coast of Mauritania and presumably reflects conditions in the western Sahara. de Menocal and co-workers (2000) clearly show that there was an abrupt transition from wet to dry conditions in the western Sahara around 5500 years ago. Between 14,800 and 5500 (calendar) years ago, there was a period of low terrigenous sediment influx from the region, indicating wet conditions, extensive vegetation cover, and little loss of sediment from land. But starting 5500 years ago, an abrupt increase in the amount of terrigenous sediment was seen in the core, indicating a significant decline in vegetation cover and a significant increase in windborne sediments from the land. The increase is dramatic and occurs within a

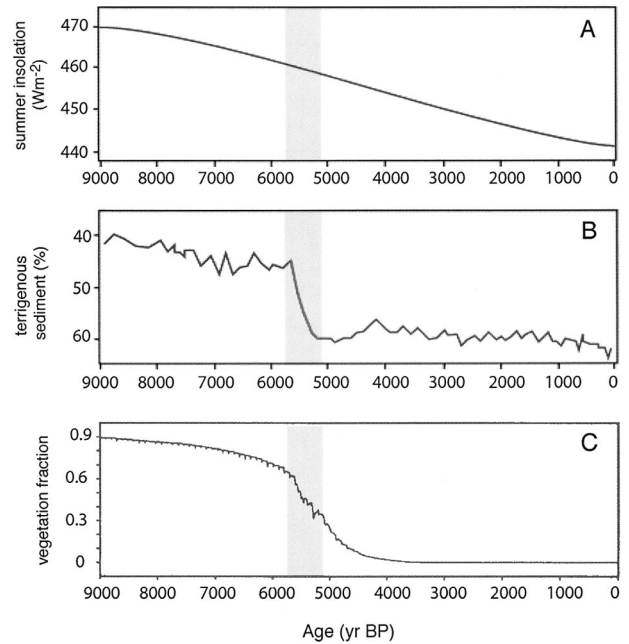


Figure 2. Orbital variations, sediment records, coupled model results. Many studies have suggested that gradual changes in the Earth's orbit and the amount of incoming solar radiation in summertime (A) are responsible for changes in climate during the Holocene. However, geologic records (including an ocean sediment record reported by deMenocal and others 1999) indicate that there was an abrupt change in the climate and vegetation cover over the Sahara roughly 5500 years ago (B). At this time, there was rapid change from the green Sahara to the desert Sahara condition. Claussen and others (1999) used a simple coupled atmosphere–ocean–vegetation model to demonstrate how a switch from a green Sahara to a desert Sahara could occur (C), even when the model was only forced by slow changes in incoming solar radiation (A). This is an excellent example of a regime shift. A and B were redrawn from deMenocal and others (2000) C was redrawn from Claussen and others (1999).

few decades or centuries (Figure 2). This increase in terrigenous sediment thus represents an abrupt regime shift—at least compared to the geologic time under consideration.

This sudden change in the climate, ecosystems, and lakes of the Sahara and Sahel has been difficult to explain. Conventional explanations of the wet climate during the late Pleistocene and early Holocene have suggested that changes in incoming solar radiation, caused by slow shifts in the Earth's orbit—the so-called Milankovitch variations, which include changes in tilt, eccentricity, and perihelion (see Berger 1978)—enhanced the strength of the summer monsoon rains (COHMAP 1988). Numerous climate model simulations, using atmospheric General Circulation Models (GCMs), have shown

how these changes in the Earth's orbit could have enhanced rainfall in the Sahel and Sahara region during the early and middle Holocene (Kutzbach and Otto-Bliesner 1982; Kutzbach and Street-Perrott 1985; Kutzbach and Guetter 1986; Street-Perrott and others 1990; deMenocal and Rind 1993). Comparisons of GCM paleoclimate simulations to geological data have shown general patterns of agreement over the Sahara/Sahel zone, suggesting that the Milankovitch hypothesis is correct (COHMAP 1988; Yu and Harrison 1996; Jolly and others 1998; Harrison and others 1998; Joussaume and others 1999).

However, the Milankovitch theory alone does not explain the regime shift in climate 5500 years ago; changes in the Earth's orbit produced very slow changes in the incoming solar radiation (Figure 2a), which by themselves would not be expected to cause such a sudden change in climate. To produce such a regime shift, there must have been a source of strong nonlinearity in the climate system—something that would enable a slow change in incoming solar radiation to cause a very large and sudden change in climate.

One hypothesis suggests that the interactions between the atmosphere and vegetation cover of the region may produce this nonlinear behavior. For example, several GCM-based studies have demonstrated how changes in the monsoon rains of northern Africa might have been amplified through feedbacks from the expanded vegetation cover (Street-Perrott and others 1990; Kutzbach and others 1996; Texier and others 1997, 2000; Claussen 1997, 1998; Claussen and Gayler 1997; Broström and others 1998; Pollard and others 1998; Braconnot and others 1999; Doherty and others 2000) and increased areas of lake and wetland cover (Coe and Bonan 1997; Broström and others 1998; Carrington and others 2001).

In this hypothesis, variations in the Earth's orbit initially lead to enhanced monsoon rains in the Sahara and Sahel regions, thereby increasing the extent of vegetation cover, lakes, and wetlands. The increased extent of vegetation and water bodies has two major effects on the land-surface water and energy balance: a significant reduction in surface albedo and an increased ability to recycle water back to the atmosphere through evapotranspiration. The lower albedo and increased ability to recycle water both help fuel the monsoon with additional energy and moisture, thereby increasing the summer rains and producing a positive feedback on the orbital variations (Figure 3). For a more detailed explanation of these vegetation–climate feedback

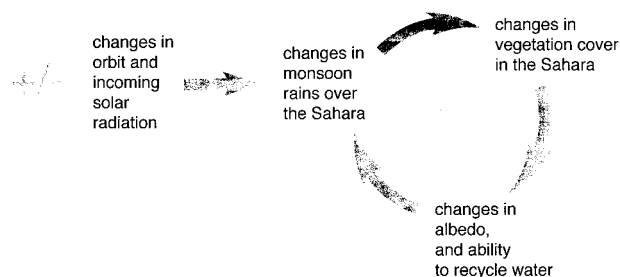


Figure 3. Feedbacks between vegetation and the atmosphere over the Sahara during the Middle Holocene. Claussen (1997) showed feedbacks between vegetation, and the atmosphere work to maintain two distinct climatic regimes over the Sahara—a green Sahara and a desert Sahara. This schematic illustrates the feedback loops among vegetation cover, albedo and evapotranspiration, and monsoon rainfall. The feedbacks can work in either direction—to maintain either green or desert conditions. Claussen and others (1999) further illustrated how changes in orbital forcing could have triggered the system to flip from a green Sahara to a desert Sahara approximately 5500 years ago.

mechanisms, see Eltahir (1996), Pielke and others (1998), and Claussen (1998).

Claussen (1998) went on to suggest that the feedbacks between climate and vegetation tend to reinforce two alternative stable states (or regimes) in northern Africa: a “green Sahara” regime, and a “desert Sahara” regime. Examining multiple simulations with a coupled climate–vegetation model, Claussen found that the climate–vegetation system could support only a green Sahara regime at 6000 years ago. However, for the modern climate, Claussen found that both a “green Sahara” and a “desert Sahara” were possible outcomes of the model, depending on the initial vegetation conditions stipulated in the model. This suggests that sometime between 6000 years ago and today, the Earth's orbital forcing caused the climate–vegetation system over the Sahara to change from a system with only one stable state (the “green Sahara”) to a system with two possible alternative stable states (a “green” or a “desert” Sahara).

But could climate–vegetation feedbacks (and the existence of alternative stable states in the atmosphere–biosphere system) have been responsible for the rapid switch between vegetated and desert conditions around 5500 years ago?

Using a coupled atmosphere–ocean–biosphere model of “intermediate complexity”, Claussen and others (1999) demonstrated how such an abrupt switch in climate could have occurred—even when the climate was being driven by slow changes in the Earth's orbit. Until recently, climate models could

not simulate the full climatic history of the Holocene era; traditional GCM-based climate models are too computationally expensive to perform repeated 10,000-year simulations. But the advent of new, computationally efficient climate models of "intermediate complexity" (for example, see, Ganopolski and others 1998; Claussen and others 1999) allow us to explore the feedbacks among atmosphere, biosphere, and oceans much more easily.

With their simplified climate model, Claussen and others (1999) were able to reproduce a major regime shift in climate and vegetation cover about 5500 years ago (5440 years ago, plus or minus 30 years) just by including the nonlinear coupling between vegetation and the atmosphere (Figure 3). In the model, a gradual reduction in monsoon precipitation (through slowly changing Milankovitch orbital forcing) continued until approximately 5500 years ago; thereafter, precipitation fell greatly in only a few centuries because of the effects of strong climate-vegetation feedbacks (Figure 2c).

The results reported by Claussen and others (1999) suggest that the climate-vegetation system crossed a "threshold" sometime around 5500 years ago, where gradual reductions in rainfall (caused by slow changes in the Earth's orbit) were suddenly amplified through land-surface feedback mechanisms. It appears that the climate-vegetation system maintained a "green Sahara" climatic regime as long as possible through the middle Holocene, and then suddenly made the transition to a "desert Sahara" regime when adequate rainfall could no longer be maintained in the Sahara zone.

According to Claussen and others (1999), the role of the oceans was relatively minor. In their simulations, the state of the oceans influenced the timing of the shift (producing a range between 5800 and 5300 years ago for the beginning of the desertification), but feedbacks from the oceans were not required to produce the climatic regime shift.

The model presented by Claussen and others (1999) provides a plausible explanation for the regime shift in the climate and ecosystems of the Sahara and Sahel around 5500 years ago. However, their results have not yet been confirmed by other modeling groups; much more work should be done to evaluate these climate feedback mechanisms. Additional evaluation of the paleoclimatic data is also needed. Specifically, more detailed comparisons between high-resolution, well-dated paleoclimatic records (for example, see deMenocal and others 2000) and new 10,000-year climate simulations (for example, Claussen and others 1999) should be performed.

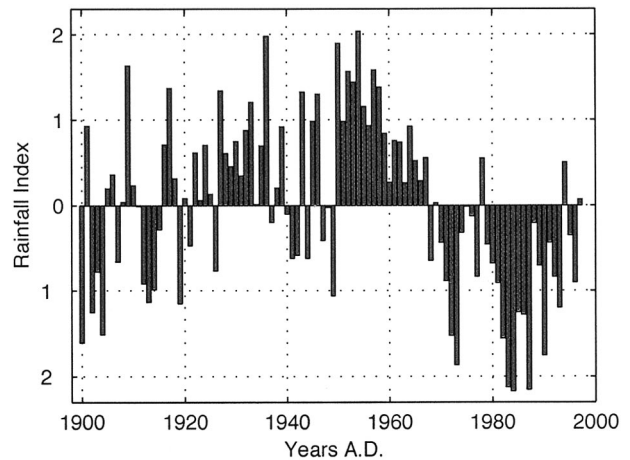


Figure 4. Precipitation record of the Sahel. Precipitation in the Sahel shows unusually strong persistence from year to year and decade to decade. In other regions of the world, runs of wet and dry years typically do not last more than a few years. The precipitation data are taken from Hulme and others (1998).

REGIME SHIFT 2: THE POST-1969 DROUGHT IN THE SAHEL

A second regime shift occurred around 1969 over the Sahel zone. Since then, the Sahel has experienced a devastating and prolonged drought.

The human impact of this drought captured worldwide attention. During the early 1970s; there were almost daily reports of the widespread human suffering caused by the drought. By the end of the decade, roughly half of the domestic livestock had died, nearly a million people had starved to death, and millions of people became refugees (Graetz 1991; Nicholson and others 1998).

Compared to the dramatic switch from the "green Sahara" to the "desert Sahara" around 5500 years ago, this change in climate has been relatively small and confined to a more limited region. Nevertheless, the drought has been one of the longest and most severe in recent history. Between 1968 and 1997, precipitation over the Sahel was 25%–40% lower than the standard climatological period of 1931–60 (Nicholson 2000). Furthermore, the drought has been unusually persistent: nearly every year since 1970 has been anomalously dry. In fact, looking back over the 20th century, we see that the persistence of both wet and dry conditions has been unusually long in the Sahel (see Figure 4); in other parts of the world, runs of wet or dry years typically do not exceed 2–5 years (Nicholson 2000).

Numerous hypotheses have been put forward to explain the Sahel drought. But each of these hypotheses must be tested against a variety of ques-

tions. First, is the hypothesized mechanism *sufficiently large* to trigger a drought of this magnitude? Furthermore, does this mechanism *maintain* such a persistent drought over a period of 3 decades—especially when the atmosphere should have no memory of the previous year? Finally, why did the mechanism cause a sudden “flip” between the two distinct modes—a “wet Sahel” (from the 1910s until the mid-1960s) and a “dry Sahel” (since 1969)—rather than slowly drifting through a series of intermediate conditions?

Over the last 25 years, there have been two leading explanations for the drought in the Sahel, one involving the land, the other the ocean. Both explanations provide a *one-way*, cause-and-effect explanation of the drought in the Sahel, considering how changes in land cover could affect the monsoon circulation, or how changes in the ocean could affect the monsoon. In neither case are *two-way* feedbacks among the atmosphere, ocean, and land considered. Here we will review both of these *one-way* explanations and describe why they are unlikely to provide a complete explanation for the magnitude and persistence of the post-1969 drought.

Land Degradation and “Desertification”

In a pioneering paper, Charney (1975) suggested that overgrazing and other human land-use pressures may be responsible for the Sahel drought, mainly through changes in the surface albedo (and the consequent changes in surface energy balance and atmospheric heating) and their impact on the West African monsoon. For a more detailed description of how changes in vegetation and the surface energy balance affect monsoon systems, see Eltahir (1996).

The specific mechanism of the original “Charney hypothesis”—land degradation causes a large increase in albedo, thereby affecting the surface energy budget and monsoon circulations (Charney and others 1977)—has now been largely discredited. Recent observations indicate that land degradation does not necessarily lead to a large increase in albedo (Fuller and Ottke 2002; Mortimore 1998). However, the Charney hypothesis has been expanded in scope to include other effects of land degradation on the surface energy and water budget, including changes in vegetation rooting depth, surface roughness, and leaf area.

Many studies have examined this “broader” Charney hypothesis using global climate models (for example, Xue and Shukla 1993; Xue 1997; Clark and others 2001). These studies have considered how human-induced changes in land cover in the

Sahel would change land-surface processes, atmospheric heating, monsoon circulations, and climate. These GCM sensitivity studies have generally concluded that anthropogenic land-cover change in the Sahel could cause a significant drought in the region. But it is important to note that these studies used idealized and highly unrealistic scenarios of land-cover change that greatly exaggerated the degree of land degradation in the Sahel region (Taylor and others 2002).

Taylor and others (2002) were the first to use a realistic history of land-cover change in the Sahel to drive a general circulation model. They concluded that land degradation in the Sahel could have led to drier conditions, but the drying simulated in their GCM was much smaller than the observed magnitude—casting serious doubt on the Charney hypothesis.

Furthermore, it is unlikely that human-induced land degradation, by itself, could have produced such a dramatic regime shift in climate in 1969. Before that time, there were several decades of wetter-than-normal conditions. After 1969, we have seen over 30 years of severe drought. How could gradual changes in land use, by themselves, have caused such an abrupt shift in climate? Again, the Charney hypothesis does not seem to provide an adequate explanation.

Changes in Ocean Temperatures

Other authors have suggested that the drought was caused by changes in the ocean—specifically, as a result of changes in sea-surface temperatures (SSTs) and their impact on atmospheric circulation patterns.

On a year-by-year basis, there are clear ties between SSTs and rainfall patterns in the Sahel (Folland and others 1991; Ward 1992; Fontaine and Janicot 1996; Rowell and others 1995). But on the decadal time scales of concern here, the picture is less clear. There are decadal-scale variations in SSTs that can be linked to rainfall in the Sahel (Ward 1998), but these variations are considerably smaller than those found on shorter time scales (Nicholson 2000), and are not as persistent as the precipitation changes over this time period. Nevertheless, Rowell and others (1995) were able to simulate some important aspects of the post-1969 Sahel drought in a climate model driven only by observed changes in SSTs. However, Sud and Lau (1996) were unable to duplicate this result with another climate model.

Nicholson (2000) has suggested that changes in ocean circulation and SSTs are potential contributors to the post-1969 drought, but other factors (possibly related to land-surface feedbacks) are also

likely to be involved. To back up this argument, Nicholson pointed out that the rainfall variability in the Sahel is correlated and in phase, with rainfall variations in Southern Africa on yearly and decadal time scales. This suggests that both precipitation regimes are affected by the same large-scale climatic controls, such as changes in ocean circulation and SSTs. However, Nicholson also indicated that the strong year-to-year persistence of rainfall anomalies does not occur in Southern Africa, suggesting that some other mechanism differentiates the two regions. Furthermore, she noted that the drastic "switch" from wet to dry conditions in the Sahel in 1969 did not occur in phase with changes in the large-scale atmospheric circulation over Africa.

Taken together, these arguments suggest that the SST hypothesis cannot completely explain the post-1969 drought in the Sahel. Ultimately, both of these one-way explanations for the Sahel drought have serious shortcomings. They fail to explain either the magnitude of the drought or the *strong persistence* over 3 decades. Neither hypothesis alone provides a totally satisfactory explanation of these two factors.

But a new set of simplified climate models that incorporate coupled representations of the atmosphere, oceans, and terrestrial ecosystems and the strong *two-way* feedbacks between them may begin to offer a plausible explanation for the magnitude and persistence of the post-1969 drought in the Sahel.

Zeng and others (1999) suggested that while the post-1969 drought could have been *initiated* by changes in SST patterns, its *magnitude* and *multidecadal persistence* are caused largely by nonlinear feedbacks between the natural vegetation cover and the atmosphere. Using a simplified model of the atmosphere, ocean, and terrestrial vegetation cover, Zeng and others (1999) showed how changes in the monsoon climate induced by forcing SSTs are greatly amplified by vegetation interactions.

Interestingly, the effect of these vegetation feedbacks appears to be strongest on decadal time scales. Zeng and others (1999) suggested that vegetation feedbacks amplify the interdecadal variation of the Sahel precipitation but act to reduce year-to-year variability. As a result, vegetation interactions allow for the decade-to-decade persistence of drought; without the memory of the vegetation cover, drought occurs sporadically as scattered events (Figure 5).

Using a different simplified climate model that links atmospheric and ecological processes, Wang and Eltahir (2000b) drew a similar conclusion. Without considering the impact of vegetation feedbacks, climate models may not reproduce the full

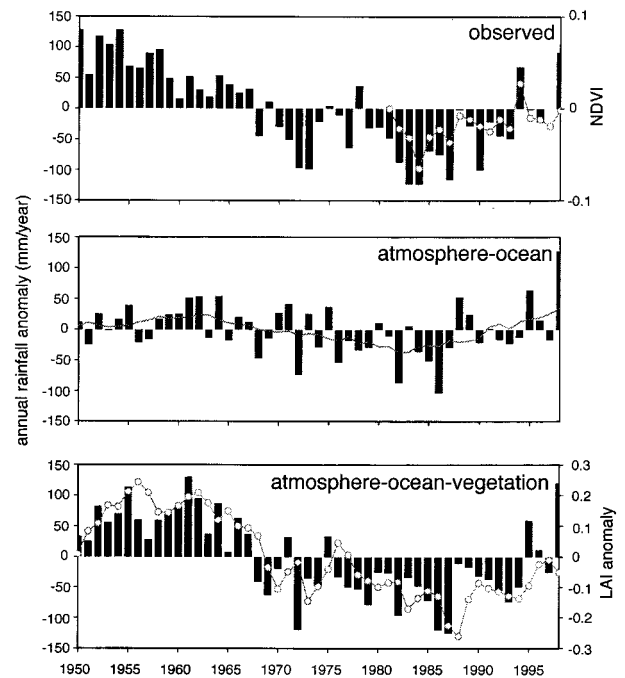


Figure 5. Observed and simulated precipitation histories over the Sahel. Zeng and others (1999) used a simplified coupled atmosphere–ocean–land model to investigate the mechanisms behind long-term climate variability in the Sahel region. They found that a model configured to represent only atmosphere–ocean coupling (B) did not match the observed record of precipitation (A). Only when vegetation dynamics and land-surface feedbacks were included in the model (C) did the model capture the long-term variations in rainfall observed in the Sahel. Figure redrawn from Zeng and others (1999).

spectrum of observed rainfall variability in the Sahel (Figure 6). According to Zeng and others (1999) and Wang and Eltahir (2000b), vegetation dynamics (that is, the growth, development, and death of vegetation over a few growing seasons) act as a sort of integrator to provide "memory" from one year to the next in this monsoon-dominated climate system. As a result, the vegetation allows there to be some influence from one summer monsoon season to the next; without the memory carried by vegetation (or, to some extent, the soil moisture content), the effect of last year's monsoon would have no significant impact on this year's monsoon.

A more complete explanation for the post-1969 drought was provided by Wang and Eltahir (2000a). Using their simplified climate model, they showed that the Sahel, through strong feedbacks between vegetation and the atmosphere, is predisposed toward having two distinct climatic regimes (or two alternative stable states): a "wet Sahel" and a "dry Sahel". (A similar feedback mechanism was

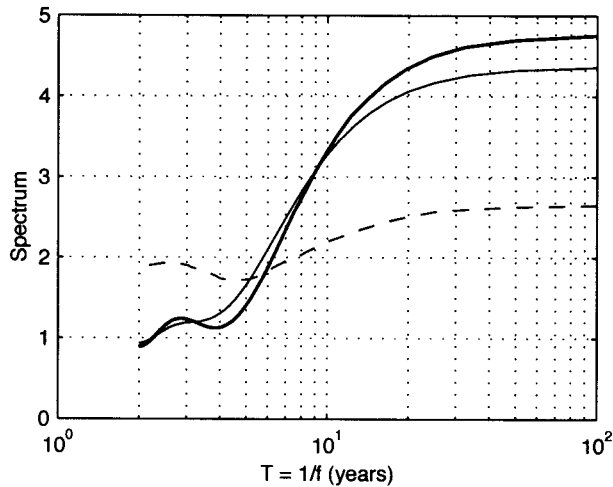


Figure 6. Observed and simulated spectra of precipitation variability in the Sahel. Wang and Eltahir (2000b) compared observed and simulated spectra of rainfall over the Sahel. The thick solid line shows the spectrum based on the observed rainfall time series in Figure 4; the thin solid and thin dashed lines show the spectrum of simulated precipitation with and without feedbacks from dynamic vegetation cover, respectively.

hypothesized by Claussen (1998) for the existence of the "green Sahara" and "desert Sahara" regimes. Wang and Eltahir further demonstrated that changes in SSTs or a small amount of land degradation in the 1960s could, through these vegetation–atmosphere feedbacks, have triggered the regional biosphere–atmosphere system to shift from the "wet Sahel" regime to the "dry Sahel" state within a relatively short time (Figure 7). Such a climate transition can take place abruptly once the coupled system reaches the attraction zone of the alternative regime (see Appendix), which helps explain the sudden onset of the severe post-1969 drought. In this case, changing SSTs or land degradation acts as the "trigger" for climate transition, while vegetation–atmosphere feedbacks reinforce the impact of the trigger during the transition process. Once the system settles into its new regime, these feedbacks then work to maintain the system in that regime for decades (Figure 8) before other triggering forcing pushes the system into the attraction zone of the alternative regime (see Appendix).

The hypothesis proposed by Zeng and others (1999) and Wang and Eltahir (2000a, 2000b) appears to provide a satisfactory explanation for the magnitude, duration, and sudden onset of the Sahel drought. However, the exact details of how the land surface and atmosphere are coupled may require additional consideration. For example, a recent study by Rosenfeld and others (2001) suggested

that increased amounts of desert dust in the atmosphere may suppress rainfall in the Sahel. Rosenfeld and others argue that clouds loaded with large amounts of dust have smaller water-droplet sizes, often below the 14- μ m radius needed for the onset of rainfall. If this hypothesis is correct, it could present a different positive feedback mechanism between the land surface and the atmosphere—whereby land degradation increases dust loading into the atmosphere, reduces rainfall, suppresses vegetation growth, and makes the land more susceptible to degradation. The effect of dust on the atmosphere is still a major topic of study (Ramanathan and others 2001; Nicholson 2000), and more research is needed to quantify the links among land cover, dust loading, and climate.

SUMMARY AND CONCLUSIONS

In this paper, we have described two major environmental regime shifts that occurred in the Sahel region during the last 6000 years.

For the first regime shift (mid-Holocene monsoon collapse), there is an abundance of geologic data to show how relatively wet environmental conditions—including extensive vegetation cover, lakes, and wetlands throughout the Sahara and Sahel—came to an abrupt end nearly 5500 years ago. Traditional explanations for the changes in climate during the Holocene era have suggested that slowly varying changes in the Earth's orbit could have caused wet conditions in the early Holocene and dry conditions today. But the orbital hypothesis, by itself, could not explain the sudden regime shift at 5500 years ago. A number of climate modeling studies suggest that strong nonlinear feedbacks between vegetation and the atmosphere can dramatically amplify the effects of orbital variations and create two alternative stable states (or regimes) in the climate and ecosystems of the Sahara—a "green Sahara" or a "desert Sahara". A recent coupled atmosphere–ocean–land modeling result from Claussen and others 1999 suggest that there was a shift from the "green Sahara" to the "desert Sahara" regime approximately 5500 years ago.

In the second regime shift (post-1969 drought), it appears that the 3-decade-long drought in the Sahel may be the result of complex interactions among the atmosphere, land, and ocean. Recent studies (Zeng and others 1999; Wang and Eltahir 2000a, 2000b) provide a plausible explanation for the drought, whereby dry conditions were initiated either through changes in SSTs or increases in degraded land cover. In each case, the strength and persistence of the drought results from the strong

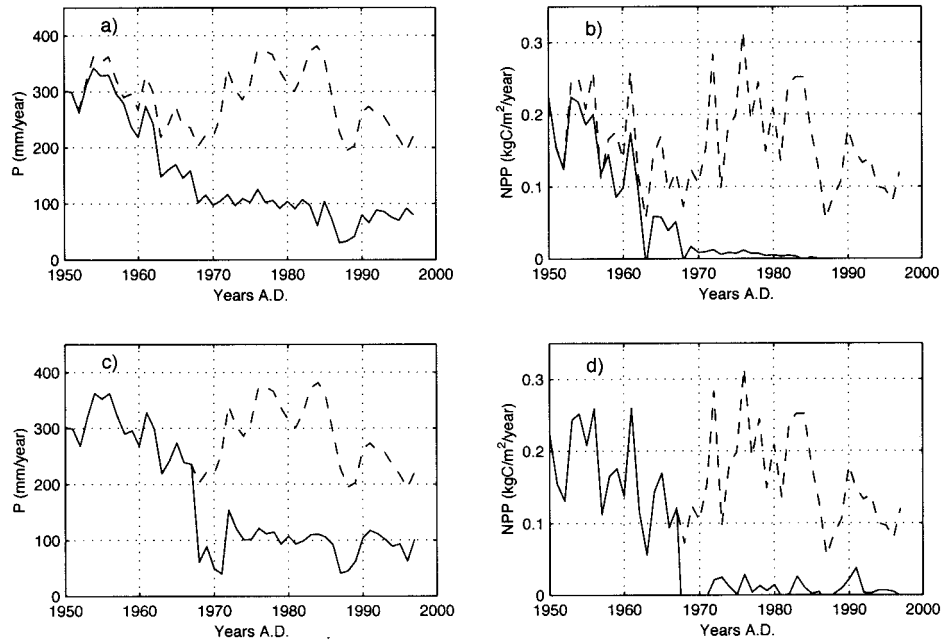


Figure 7. Simulated regime shifts in Sahel rainfall. Wang and Eltahir (2000a) used a simplified coupled atmosphere–ocean–land model to explore the dynamics of the Sahel climate. Their model results suggested that feedbacks between vegetation and the atmosphere create two distinct climatic regimes: a dry Sahel and a wet Sahel. Using this model, they showed that either changes in sea surface temperatures or slight increases in the amount of degraded land could have triggered a shift from the wet Sahel to the dry Sahel sometime in the late 1960s. This study provides the most complete explanation for the Sahel drought to date, including plausible mechanisms for the magnitude, duration, and rapid onset of the post-1969 drought. Changes in land degradation induce major reductions in precipitation (a) and vegetation productivity (b) in these simulations (*dashed lines* are for the control simulation; *solid lines* are where land degradation occurs). In addition, changes in sea surface temperatures can also cause an abrupt reduction in rainfall and vegetation productivity (c and d).

coupling between vegetation and monsoon circulations over the Sahel region. These conditions help to reinforce either a “wet Sahel” or a “dry Sahel” climatic regime, while the sudden onset of the drought may result from a transition of the climate system from its wet equilibrium to a drier one.

In both the Sahara and Sahel regions of northern Africa, it appears that environmental systems are predisposed toward having at least two alternative stable states (or regimes)—for example, the “wet Sahel”/“dry Sahel” or the “green Sahara”/“desert Sahara”. Strong feedbacks between vegetation and the atmosphere, operating through linkages between the surface energy and water balance and the West African monsoon circulation, appear to be responsible for the existence of these alternative steady-state conditions.

In these two examples, a switch from one regime to another is accomplished through slow, steady changes in underlying environmental conditions (for example, orbital variations over thousands of years, slowly changing patterns of ocean temperatures, or steady increases in land degradation),

combined with a stochastic triggering event (for example, a particularly wet or dry monsoon season). Under the right circumstances, a large enough perturbation to the coupled system can rapidly switch the Sahara or Sahel from one regime to another.

While the exact timing and circumstances of regime shifts may be unpredictable, the existence of the alternative stable states can be—and has been—predicted. We may therefore forecast the future of the Sahara and Sahel in terms of probabilistic assessments of wet *versus* dry or green *versus* desert conditions—but not the precise timing of the regime shifts.

The Sahara and Sahel present us with very good examples of regions with alternative stable states and dramatic regime shifts. The predisposition of these regions to regime shifts appears to result from the strong interactions between the vegetation cover and the atmosphere. We hypothesize that the unique geography of northern Africa, combined with the extremely sharp gradients in precipitation and vegetation cover across this region, may make

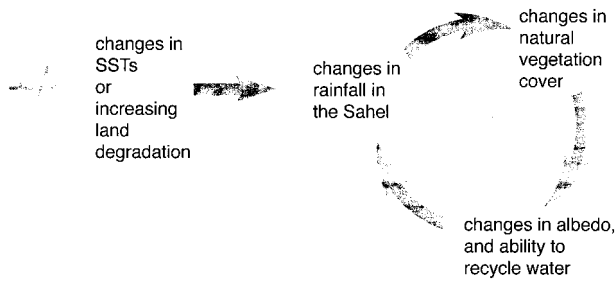


Figure 8. Feedbacks between vegetation and the atmosphere over the Sahel. Wang and Eltahir (2000a) showed how between vegetation feedbacks and the atmosphere work to maintain two distinct climatic regimes over the Sahel region—a dry Sahel and a wet Sahel. This schematic illustrates the feedback loops among vegetation cover, albedo and evapotranspiration, and monsoon rainfall. Note that the feedbacks can work in either direction, to maintain either wet or dry conditions. Wang and Eltahir further showed how changes in external conditions, including sea-surface temperatures or the extent of land degradation, can trigger the system to flip from one regime to the other.

the Sahara and Sahel such strong examples. However, other regions of the world may also be predisposed to such regime shifts.

Future research should examine the historical and geological data for evidence of large-scale environmental regime shifts in other regions of the world. By examining the underlying state of environmental systems and their degree of nonlinearity, we may be able to predict which regions of the world are susceptible to regime shifts and which are not. The results would provide us with important insights on the vulnerability and environmental sustainability of particular regions—and their possible response to human activities and global environmental change.

ACKNOWLEDGEMENTS

We thank Jim Reynolds for provoking the lead author to present an overview of abrupt environmental changes at a recent AGU meeting. We also thank Steve Carpenter for inviting us to submit this review paper to *Ecosystems*. We thank Eric Lambin and Chris Taylor for sharing their very interesting *Journal of Climate* manuscript while it was in press. Christine Delire, Mustapha El Maayar, and Navin Ramankutty provided helpful comments on a draft of this manuscript. Mary Sternitzsky and Ryah Nabelski helped to prepare the figures and references. Wolfgang Cramer, Martin Claussen, and an anonymous reviewer provided helpful comments on an earlier version of the manuscript. This work was supported by the National Science Foundation (Cli-

mate Dynamics Program) and the NASA Office of Earth Science (Interdisciplinary Science Earth Science Investigations). Some portions of this paper first appeared in a proposal to the J. S. McDonnell Foundation. We are grateful to the McDonnell Foundation for selecting this project for future support.

REFERENCES

- Berger A. 1978. Long-term variations of daily insolation and quaternary climatic changes. *J Atmos Sci* 35:2362–7.
- Braconnot P, Joussaume S, Marti O, de Noblet N. 1999. Synergistic feedbacks from ocean and vegetation on the African monsoon response to mid-Holocene insolation. *Geophys Res Lett* 26(16):2481–4.
- Broström A, Coe MT, Harrison SP, Gallimore R, Kutzbach JE, Foley J, Prentice IC, Behling P. 1998. Land surface feedbacks and palaeomonsoons in northern Africa. *Geophys Res Lett* 25(19):3615–8.
- Brovkin V, Claussen M, Petoukhov V, Ganopolski A. 1998. On the stability of the atmosphere–vegetation system in the Sahara/Sahel region. *J Geophys Res Atmos* 103:31613–24.
- Carrington DP, Gallimore RG, Kutzbach JE. 2001. Climate sensitivity to wetlands and wetland vegetation in mid-Holocene North Africa. *Clim Dynam* 17:151–7.
- Charney JG. 1975. The dynamics of deserts and droughts. *Q J R Meteorol Soc* 101:193–202.
- Charney JG, Quirk WJ, Chow SH, Kornfield J. 1977. A comparative study of the effects of albedo change on drought in semi-arid regions. *J Atmos Sci* 34:1366–85.
- Clark DB, Xue YK, Harding RJ, Valdes PJ. 2001. Modeling the impact of land surface degradation on the climate of tropical North Africa. *J Clim* 14:1809–22.
- Claussen M. 1997. Modeling biogeophysical feedback in the African and Indian monsoon region. *Clim Dynam* 14:883–90.
- Claussen M. 1998. On multiple solutions of the atmosphere–vegetation system in present-day climate. *Global Change Biol* 4:549–59.
- Claussen M, Gayler V. 1997. The greening of Sahara during the mid-Holocene: results of an interactive atmosphere–biome model. *Global Ecol Biogeog Lett* 6:369–77.
- Claussen M, Kubatzki C, Brovkin V, Ganopolski A, Hoelzmann P, Pachur H.-J. 1999. Simulation of an abrupt change in Sahara vegetation in the mid-Holocene. *Geophys Res Lett* 26(14):2037–40.
- Coe MT, Bonan G. 1997. Feedbacks between climate and surface water in northern Africa during the middle-Holocene. *J Geophys Res* 102(D10):11087–101.
- COHMAP. 1988. Climatic changes of the last 18,000 years: observations and model simulations. *Science* 241:1043–52.
- deMenocal P, Ortiz J, Guilderson T, Adkins J, Sarnthein M, Baker L, Yarusinsky M. 2000. Abrupt onset and termination of the African humid period: rapid climate responses to gradual insolation forcing. *Quart Sci Rev* 19:347–61.
- deMenocal P, Rind D. 1993. Sensitivity of Asian and African climate to variations in seasonal insolation, glacial ice cover sea-surface temperature, and Asian orography. *J Geophys Res* 98(4):7265–87.
- Doherty R, Kutzbach J, Foley JA, Pollard D. 2000. Fully coupled

- climate/dynamical vegetation model simulations over northern Africa during the mid-Holocene. *Clim Dynam* 16:561–73.
- Ellner S, Turchin P. 1995. Chaos in a noisy world: new methods and evidence from time-series analysis. *Am Nat* 145:343–75.
- Eltahir EAB. 1996. Role of vegetation in sustaining large-scale atmospheric circulations in the tropics. *J Geophys Res (Atmos)* 101:4255–68.
- Folland C, Owen J, Ward MN, Colman A. 1991. Prediction of seasonal rainfall in the Sahel region using empirical and dynamical models. *J Forecasting* 10:21–56.
- Fontaine B, Janicot S. 1996. Sea surface temperature fields associated with West African rainfall anomaly types. *J Clim* 9:2935–40.
- Fontes JC, Gasse F, Callot Y, Plaziat J-C, Carbonel P, Dupeuple PA, Kaczmarek I. 1985. Freshwater to marine-like environment from Holocene lakes in northern Sahara. *Nature* 317:608–10.
- Fuller DO, Ottke C. 2002. Land cover, rainfall and land-surface albedo in West Africa. *Clim Change* 54:181–204.
- Ganopolski A, Rahmstorf S, Claussen M, Brovkin V, Petoukhov V. 1998. Simulation of modern and glacial climates with a coupled global model of intermediate complexity. *Nature* 391:351–6.
- Gasse F. 1987. Diatoms for reconstructing paleoenvironments and paleohydrology in tropical semi arid zones—example of some lakes from Niger since 12000 BP. *Hydrobiologia* 154:127–63.
- Gasse F, Van Campo E. 1994. Abrupt post-glacial climate events in West Asia and North Africa monsoon domains. *Earth Plan Sci Lett* 126:435–56.
- Geyh MA, Jäkel D. 1974. The late glacial and Holocene climatic history of the Sahara desert derived from a statistical assay of ¹⁴C dates. *Palaeogeog Palaeoclimatol Palaeoecol* 15:205–8.
- Graetz RD. 1991. Desertification: a tale of two feedbacks. In: Mooney HA, and others, editors. *Ecosystem experiments*. New York: Wiley. p 59–87.
- Harrison SP, Jolly D, Laarif F, Abe-Ouchi A, Dong B, Herterich K, Hewitt C, Joussaume S, Kutzbach JE, Mitchell J, and others. 1998. Intercomparison of simulated global vegetation distributions in response to 6 kyr B.P. orbital forcing. *J Clim* 11:2721–42.
- Haynes CV Jr. 1987. Holocene migration rates of the Sudano-Sahelian wetting front, Arabian desert, eastern Sudan. In: Close AH, editor. *Prehistory of arid north Africa*. Southern Methodist University Press, Dallas, TX. p 69–84.
- Haynes J. Jr., Eyles CH, Pavlish LA, Ritchie JC, Rybak M. 1989. Holocene paleoecology of the eastern Sahara: Selima Oasis. *Quat Sci Rev* 8:109–36.
- Helldén U. 1991. Desertification—time for an assessment? *Ambio* 20:372–83.
- Higgins PAT, Mastrandrea MD, Schneider SH. 2002. Dynamics of climate and ecosystem coupling: abrupt changes and multiple equilibria. *Philos Trans R Soc London B* 357:647–55.
- Hoelzmann P, Jolly D, Harrison SP, Laarif F, Bonnefille R, Pachur H-J. 1998. Mid-Holocene land-surface conditions in northern Africa and the Arabian Peninsula: a data set for the analysis of biogeophysical feedbacks in the climate system. *Global Biogeochem Cycles* 12:35–52.
- Holling CS. 1973. Resilience and stability of ecological systems. *Annu Rev Ecol Syst* 4:1–23.
- Hulme M, Osborn TJ, Johns TC. 1998. Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations. *Geophys Res Lett* 25:3379–82.
- Jäkel D. 1979. Run-off and fluvial formation processes in the Tibesti mountains as indicators of climatic history in the central Sahara during the late Pleistocene and Holocene. *Palaeoecol Africa* 11:13–43.
- Jolly D, and others. 1998. Biome reconstruction from pollen and plant macrofossil data for Africa and the Arabian Peninsula at 0 and 6000 years. *J Biogeog* 25:1007–27.
- Jolly D, Harrison SP, Damnati B, Bonnefille R. 1998. Simulated climate and biomes of Africa during the Late Quaternary: comparison with pollen and lake status data. *Quat Sci Rev* 17:629–57.
- Joussaume S, Taylor KE, Braconnot P, Mitchell JFB, Kutzbach J, Harrison SP, Prentice IC, Broccoli AJ, Abe-Ouchi A, Bartlein PJ, and others. 1999. Monsoon changes for 6000 years ago: results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP). *Geophys Res Lett* 26:859–62.
- Kutzbach JE, Bonan G, Foley JA, Harrison SP. 1996. Vegetation and soil feedbacks on the response of the African monsoon to orbital forcing in the early to middle Holocene. *Nature* 384:623–6.
- Kutzbach JE, Guetter PJ. 1986. The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. *J Atmos Sci* 43:1726–59.
- Kutzbach JE, Otto-Bliesner B. 1982. The sensitivity of the African-Asian monsoon climate to orbital parameter changes for 9000 years B.P. in a low resolution general circulation model. *J Atmos Sci* 39:1177–88.
- Kutzbach JE, Street-Perrott FA. 1985. Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP. *Nature* 317:130–4.
- Lamb HF, Gasse F, Benkaddour A, El Hamouti N, van der Kaars S, Perkins WT, Pearce NJ, Roberts CN. 1995. Relation between century-scale Holocene arid intervals in tropical and temperate zones. *Nature* 373:134–7.
- Le Houerou HN. 1980. The rangelands of the Sahel. *J Rangel Manage* 33:41–6.
- Lézine A-M. 1991. West African paleoclimates during the last climatic cycle inferred from an Atlantic deep-sea pollen record. *Quat Res* 35:456–63.
- Lézine A-M, Casanova J. 1989. Pollen and hydrological evidence for the interpretation of past climates in tropical West Africa during the Holocene. *Quat Sci Rev* 8:45–55.
- Lézine A-M, Casanova J, Hillaire-Marcel C. 1990. Across an early Holocene humid phase in western Sahara: pollen and isotope stratigraphy. *Geology* 18:264–7.
- McIntosh SK, McIntosh RJ. 1981. West African prehistory. *Am Sci* 69:602–13.
- McIntosh SK, McIntosh RJ. 1983. Current directions in West African prehistory. *Annu Rev Anthropol* 12:215–58.
- Mainguet M. 1991. *Desertification: natural background and human mismanagement*. New York: Springer-Verlag.
- Maley J. 1981. *Etudes palynologiques dans le bassin du Tchad et paléoclimatologie de l'Afrique nord-tropicale de 30,000 ans à l'époque actuelle*. Technical Report 129. Paris: Inst. Fr. de Rech. Sci. pour le Dev. en Cooperation (ORSTOM).
- Maley J. 1983. Histoire de la végétation et du climat de l'Afrique nord-tropicale au Quaternaire récent. *Bothalia* 14:377–89.
- Mortimore M. 1998. *Roots in the African dust: sustaining the drylands*. Cambridge University Press, (UK): Cambridge University Press, pp 219

- Nicholson SE. 1994. Desertification. In: Schneider SH, Eds. Encyclopedia of climate and weather. New York: Oxford University Press. p 239–42.
- Nicholson SE, Tucker CJ, Ba MB. 1998. Desertification, drought, and surface vegetation: an example from the West African Sahel. *Bull Am Meteorol Soc* 79(5):815–29.
- Nicholson SE. 2000. Land surface processes and Sahel climate. *Rev Geophys* 38(1):117–39.
- Pachur H-J, Altmann N. 1997. The Quaternary (Holocene, ca. 8000a BP). In: Schandelmeier H, Reynolds P-O, Eds. Palaeographic-palaeotectonic atlas of north-eastern Africa, Arabia, and adjacent areas late Neo Rotterdam/Brookfield: Balkema. p 111–25.
- Pachur H-J, Hoelzmann P. 1991. Paleoclimatic implications of Late Quaternary lacustrine sediments in western Nubia, Sudan. *Quat Res* 36:257–76.
- Pachur H-J, Kröpelin S. 1987. Wadi Howar: Paleoclimatic evidence from an extinct river system in the southeastern Sahara. *Science* 237:298–300.
- Pachur H-J, Wünnemann 1996. Reconstruction of the palaeoclimate along 30°E in the eastern Sahara during the Pleistocene/Holocene transition. In: Heine K, editor. Palaeoecology of Africa and the surrounding islands. Rotterdam/Brookfield: Balkema. 27:1–32.
- Petit-Maire N, Guo Z. 1996. Mise en évidence de variations climatiques holocenes rapides, en phase dans les deserts actuels de Chine et du Nord de l’Afrique. *Sci Terre Planetes* 322: 847–51.
- Petit-Maire N, Page N, Marchand J. 1993. The Sahara in the Holocene. Map 1. Marseille: Laboratoire de Geologie du Quaternaire, Centre Nationale de la Recherches Scientifique.
- Petit-Maire N, Riser J. 1981. Holocene lake deposits and paleoenvironment in central Sahara, northeastern Mali. *Palaeogeog Palaeoclimatol Palaeoecol* 45:45–61.
- Pielke Ss RA, Avissar R, Raupach M, Dolman AJ, Zeng X, Denning AS. 1998. Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Global Change Biol* 4:461–75.
- Pollard D, Bergengren J, Stillwell-Soller LM, Feltzer B, Thompson SL. 1998. Climate simulations for 10,000 and 6,000 years BP using the GENESIS global climate model. *Palaeoclimates* 2:183–18.
- Prentice IC, Jolly D. 2000. Mid-Holocene and glacial-maximum vegetation geography of the northern continents and Africa. *J Biogeog* 27:507–19.
- Prince SD, Brown de Colstoun ., EKravitz LL. 1998. Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. *Global Change Biol* 4:359–74.
- Ramanathan V, Crutzen PJ, Kiehl JT, Rosenfeld D. 2001. Aerosols, climate, and the hydrological cycle. *Science* 294:2119–24.
- Ritchie JC, Eyles CH, Haynes CV. 1985. Sediment and pollen evidence for an early to mid-Holocene humid period in the eastern Sahara. *Nature* 314:352–5.
- Roberts N. 1998. The Holocene. Oxford: Blackwell, pp. 316.
- Rosenfeld D, Rudich Y, Lahav R. 2001. Desert dust suppressing precipitation: a possible desertification feedback loop. *Proc Nat Acad Sci* 98(11):5975–80.
- Rowell DP, Folland CK, Maskell K, Ward MN. 1995. Variability of summer rainfall over tropical North Africa (1906–92): observations and modeling. *Q J R Meteorol Soc* 121:669–704.
- Scheffer M, Carpenter SR, Foley JA, Folke C, Walker B. 2001. Catastrophic shifts in ecosystems. *Nature* 413:591–6.
- Schulz E. 1991. The Taoudenni-Agorgott pollen record and the Holocene vegetation history of the central Sahara. In: Petit-Maire N, Eds. Paléoenvironnements du Sahara. Lacs holocènes à Taoudenni (Mali). Paris: Centre Nationale de la Recherches Scientifique, p 143–62.
- Servant M, Servant-Vildary S. 1980. L’environnement quaternaire du bassin du Tchad. In: Martin A, Williams J, Faure H, Eds. The Sahara and the Nile: Quaternary environments and prehistoric occupation in northern Africa. Rotterdam: Balkema. p 133–62.
- Street FA, Grove AT. 1979. Global maps of lake-level fluctuations since 30,000 years BP. *Quat Res* 12:83–118.
- Street-Perrott FA, Harrison SA. 1984. Temporal variations in lake levels since 30,000 yr BP—an index of the global hydrological cycle. In: Hansen JE, Takahashi T, Eds. Climate processes and climate sensitivity. Washington (DC): American Geophysical Union. p 118–29.
- Street-Perrott FA, Mitchell JFB, Marchand DS, Brunner JS. 1990. Milankovitch and albedo forcing of the tropical monsoon: a comparison of geological evidence and numerical simulations for 9,000 yr BP. *Trans R Soc Edin (Earth Sci)*, 81:407–27.
- Street-Perrott FA, Perrott RA. 1993. Holocene vegetation, lake levels and climate of Africa. In: Wright HE Jr, and others, editors. Global climates since the last glacial maximum. Minneapolis (MN): University of Minnesota Press. p 318–56.
- Sud YC, Lau WM. 1996. Variability of summer rainfall over tropical North Africa (1906–92): observations and modeling. *Q J R Meteorol Soc* 122:1001–6.
- Taylor CM, Lambin EF, Stephenne N, Harding RJ, Essery RLH. 2002. The influence of land use change on climate in the Sahel. *J Clim* 15:3615–29.
- Texier D, de Noblet N, Braconnet P. 2000. Sensitivity of the African and Asian monsoons to mid-Holocene insolation and data-inferred surface changes. *J Clim* 13(1):164–81.
- Texier D, de Noblet N, Harrison SP, Haxeltine A, Jolly D, Jousaume S, Laarif F, Prentice IC, Tarasov P. 1997. Quantifying the role of biosphere–atmosphere feedbacks in climate change: coupled model simulations for 6,000 years BP and comparison with palaeodata for northern Eurasia and Africa. *Clim Dynam* 13:865–82.
- Thomas DSG, Middleton NJ. 1994. Desertification: exploding the myth. London: Wiley, pp. 194.
- Tucker CJ, Dregne HE, Newcomb WW. 1991. Expansion and contraction of the Sahara desert from 1980 to 1990. *Science* 253:299–301.
- Tucker CJ, Nicholson SE. 1999. Variations in the size of the Sahara desert from 1980 and 1997. *Ambio* 28(7):587–91.
- Verstraete MM. 1986. Defining desertification: a review. *Clim Change* 9:5–18.
- Wang G, Eltahir EAB. 2000a. Ecosystem dynamics and the Sahel drought. *Geophys Res Letter* 27:95–98.
- Wang G, Eltahir EAB. 2000b. Role of vegetation dynamics in enhancing the low-frequency variability of the Sahel rainfall. *Water Resources Res* 36(4):1013–21.
- Ward MN. 1992. Provisionally corrected surface wind data, world-wide ocean–atmosphere surface fields, and Sahelian rainfall variability. *J Clim* 5:454–75.
- Ward MN. 1998. Diagnosis and short-lead time prediction of

summer rainfall in tropical North Africa at interannual and multi-decadal timescales. *J Clim* 11:3167–91.

Xue Y. 1997. Biosphere feedback on regional climate in tropical North Africa. *Q J R Meteorol Soc* 123:1483–515.

Xue Y, Shukla J. 1993. The influence of land surface properties on Sahel climate. Part I: desertification. *J Clim* 6:2232–44.

Yu G, Harrison SP. 1996. An evaluation of the simulated water balance of Eurasia and northern Africa at 6000 y BP using lake status data. *Clim Dynam* 12:723–35.

Zeng N, Neelin JD, Lau KM, Tucker CJ. 1999. Enhancement of interdecadal climate variability in the Sahel by vegetation interaction. *Science* 286:1537–40.

Appendix: A Conceptual Model of "Regime Shifts"

In this paper, we have documented two "regime shifts" that occurred in the Sahara and Sahel during the last 6000 years. Such regime shifts may be linked to the existence of alternative stable states (or regimes) in an environmental system, which in turn are usually explained through strong positive feedbacks among the component parts of the system. Here we have suggested that strong feedbacks between vegetation and the atmosphere give rise to alternative stable states in the climate and ecosystems of northern Africa, thereby leading to a predisposition to regime shifts. In this Appendix, we briefly elaborate on these ideas and discuss some common misconceptions.

Positive feedbacks occur at various levels in many complex systems. For instance, as discussed in this review, vegetation cover may have a positive effect on local precipitation patterns. Furthermore, increases in local rainfall will, in turn, stimulate vegetation growth (Figure A1). One can easily imagine that such a feedback between precipitation and vegetation cover could lead to two alternative stable states: If there is no vegetation, water availability is too low for vegetation growth and plants cannot colonize; however, once vegetation cover is present, it may enhance water availability enough to ensure persistence of the vegetation.

To obtain a better intuitive feeling for the properties of a system with alternative stable states, imagine a situation in which large-scale, external climate drivers (for example, the Earth's orbital forcing, atmospheric carbon dioxide concentration) control precipitation over a dry region, but local precipitation is higher in the presence of vegetation than over desert (Figure A2). In the hypothetical case that vegetation dies and disappears at a critical precipitation level, this gives rise to alternative stable states of the coupled climate–vegetation system over a range of external climate drivers. (Obviously, the assumption that vegetation disappears com-

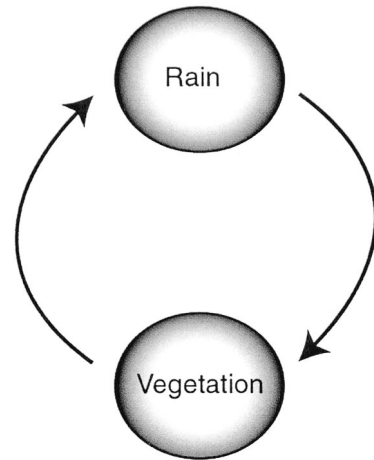


Figure A1. Vegetation–climate feedbacks. In dry areas of the world, a positive effect of vegetation cover on local precipitation may cause a feedback between vegetation and climate.

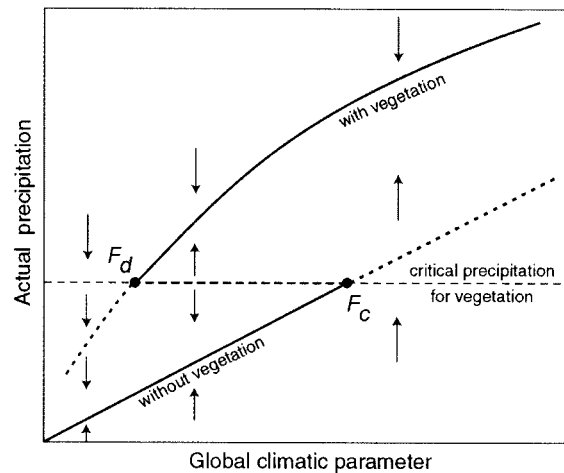


Figure A2. Alternative stable states in a coupled vegetation–climate system. This conceptual model is based on three assumptions: (a) Precipitation in the absence of vegetation is driven by the external climatic parameters (for example, solar radiation, carbon dioxide concentrations); (b) vegetation has a positive effect on local rainfall; and (c) vegetation disappears when precipitation falls below a certain critical level. Above a critical precipitation level, vegetation will be present. In this case, the upper equilibrium line is the relevant one; below this precipitation level, the lower equilibrium curve applies. Over a range of intermediate climatic situations, two alternative stable states exist: one with vegetation and one as a desert, separated by a (dashed) unstable equilibrium. The arrows indicate the direction of change if the system is not on one of the equilibrium lines. It can be seen from these arrows that the dashed middle line is unstable, since a small deviation from the line will make the system move further away to one of the (solid) stable equilibrium lines.

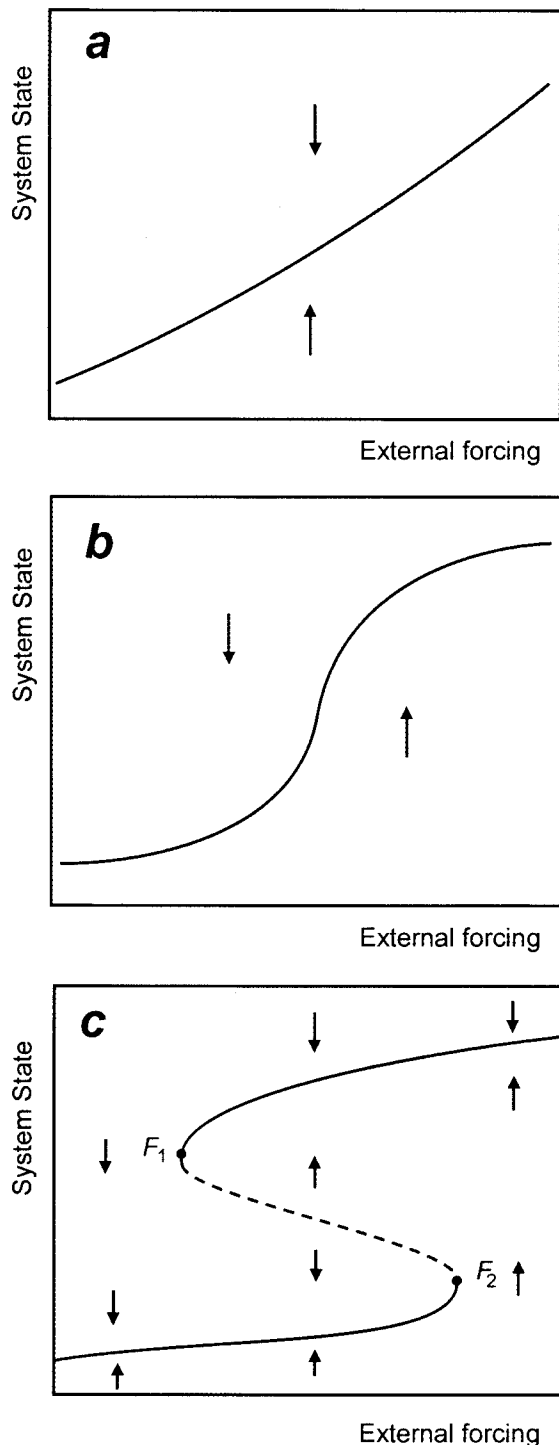


Figure A3. Ways in which ecosystem equilibrium states can vary with environmental conditions. A variety of different models confirm that alternative stable states may arise in environmental systems with strong positive feedbacks among components, but this is only one on a continuum of possibilities (Scheffer and others 2001). First, the state of some ecosystems may respond in a smooth, continuous way to environmental change (a). Another system may be quite inert over certain ranges of conditions, responding more strongly when conditions

pletely from a region at a critical precipitation level is a crude oversimplification. Some sites will always be more suitable than others, leading to a more gradual response of vegetation cover to precipitation).

More realistic models confirm that alternative stable states may arise in environmental systems with strong positive feedbacks among components, and that this is part of a continuum of possibilities (Scheffer and others 2001). For example, some ecosystems may respond in a smooth, continuous way to environmental change (Figure A3a). But another system may be quite inert over certain ranges of conditions, responding more strongly when conditions approach a certain critical level (Figure A3b). Finally, if positive feedbacks are of overriding importance, the ecosystem response curve is “folded” backward (Figure A3c). This final example corresponds to our simple graphical model (Figure A2), implying that for certain environmental conditions the ecosystem has two alternative stable states, separated by an unstable equilibrium that marks the border between the basins of attraction of the alternative stable states.

A system with alternative stable states typically responds in a discontinuous way to external forcing, making the exact timing of regime shifts difficult, if not impossible, to forecast. For example, in our simple model (Figure A2), when conditions are wet and vegetation cover is present, the state of the system lies on the upper branch of the diagram. However, if external climatic drivers gradually change and precipitation slowly decreases, the vegetation cover will remain present until the threshold (F_d) is passed and a sudden shift to a low-rainfall/desert state occurs. It is important to note that there is very little change in the state of the system before the regime shift. As a result, there is little or no early warning of the impending regime shift before it occurs.

Regime shifts can also be difficult to reverse. In our conceptual model, it is interesting to observe that returning the system back to the original state (F_d) does not occur easily. Simply restoring the external climate driving parameters back to their original values is not sufficient to induce a switch

approaches a certain critical level (b). Finally, if positive feedbacks are of overriding importance, the ecosystem response curve is folded backward (c). Only if the equilibrium curve is folded backward (c) will alternative stable states exist for a given condition. Modified after Scheffer and others (2001).

back to the upper branch. Instead, the climate needs to move beyond the other switch point (F_c) before the system can be restored to the original state. In dynamical systems theory, this phenomenon—where the forward and the backward switches occur at different conditions—is known as *hysteresis*. (Note that this is a more strict definition of hysteresis than the general meaning of “a tendency to remain constant in spite of external forcing changes.”)

The reader should note that a sudden shift in environmental conditions does not necessarily imply that there are alternative stable states in the system. Systems that have no alternative stable states may also respond in a discontinuous way to environmental change (for example, Figure A3b), although they will show no hysteresis. In practice, one cannot divide systems simply into those that have multiple attractors and those that have not. Also, in models, there is usually a gradual range of possibilities between strong hysteresis and merely a relatively steep response around a certain threshold which can vary depending on parameter settings (Brovkin and others 1998; Claussen and others 1999).

Another important aspect of systems with alternative equilibria is that stochastic events, such as extreme weather episodes, can bring the system into the basin of attraction of another state (Figure A4). If the valley of attraction (*resilience* from Holling 1973) around the current state of the system is small, a minor perturbation may be enough to cause a shift to the alternative stable state. Thus, even if in our example global climatic change may seem to have little effect on the state of the systems, the resilience may shrink, making the system more fragile in the sense that it can be easily tipped into a contrasting state by an adverse event.

Please note that these conceptual models of environmental systems are oversimplifications of reality. For instance, no states are truly “stable” in the sense that they could persist forever. Also, these states are certainly never stable in the sense that they are perfectly constant. Rather they are dynamic *regimes* in which random variation in weather and other conditions interact with the in-

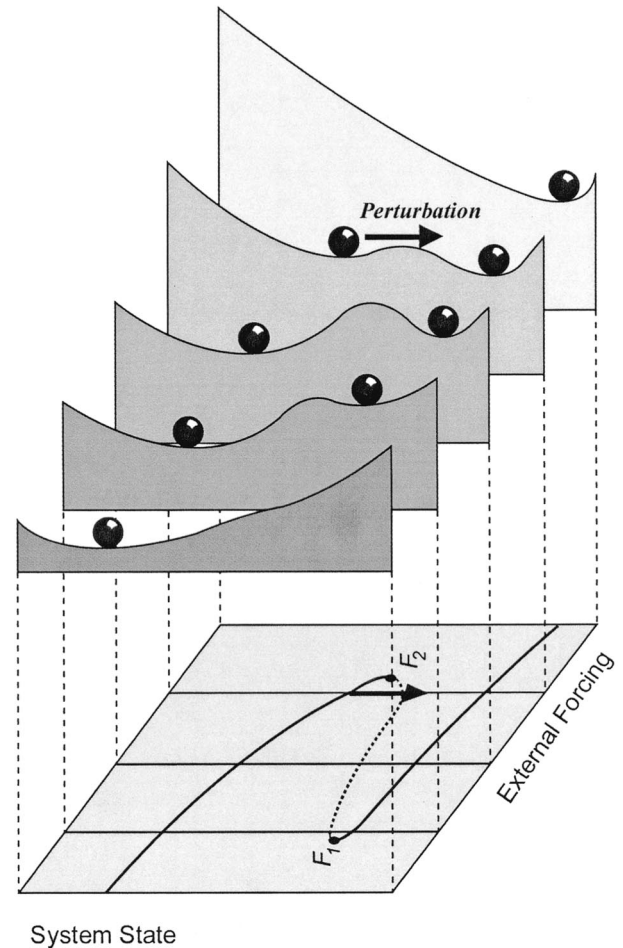


Figure A4. Stability landscapes. Stability landscapes illustrate how environmental conditions may affect the resilience of multistable ecosystems to perturbations. The bottom plane shows the equilibrium curve as in Figure A1. Each landscape depicts the equilibria and their basins of attraction for a range of different environmental conditions. Stable equilibria correspond to valleys; the unstable middle section of the folded equilibrium curve corresponds to hilltops. Close to a bifurcation (F_2), the size of the attraction basin is small, and perturbation may easily bring the system into the alternative basin of attraction. Modified after Scheffer and others (2001).

ternal dynamics of the system to produce erratic fluctuations (Ellner and Turchin 1995). This makes *regime shifts* a rather appropriate term to describe the changes we refer to in this paper.