Chapter A.5

The Sahelian Climate

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A.5.1 Introduction

The Sahel has experienced several drought periods in the past 500 years, however no available records show a drought as persistent and severe as the one that started in the 1960s (Nicholson 1978). Many thousands of people died and many more suffered severe disruption of their lives in the severe phases of this drought (e.g. in 1984). The human dramas and socio-economic consequences resulting from drought-induced famines in the Sahel region have presented a strong motivation for research into the causes of the drought. Ever since, the causes for this prolonged drought have been sought somewhere between two extreme views. One view considers land-surface degradation resulting from population pressure in excess of the region's carrying capacity as the main driver. This implies the existence of positive land-surface/atmosphere feedbacks mostly internal to the region, and in principle could incite the development of mitigation strategies to reverse the trend. The other view attributes the drought to unfavourable anomalous patterns in sea-surface temperature (SST) in the oceans. This implies the existence of a driver external to the region and by nature beyond human control, and requires the development of adaptation strategies to make the region's societies less vulnerable to droughts.

To position ourselves in this scientific debate, several important questions must be answered. We focus on the questions related to the first view, as it is still the more controversial of the two.

1. Can land-surface dynamics in principle lead to a drought of the magnitude witnessed over the last decades?
2. What is the role of soil moisture dynamics? Does soil degradation alter these dynamics?
3. What is the role of internal vegetation dynamics? Is vegetation a passive victim of the drought or an active modulator?

If the answer to the first question is positive, and with knowledge of issues raised in the other two, we can go a step further:

4. Are observed land-surface anomalies, if any, sufficiently strong to induce climate anomalies of the observed magnitude?
5. If so, do anthropogenic activities indeed form a significant driver in the observed land-surface dynamics?

Only with sufficient knowledge of all these issues may we be able to assess the relative importance of land surface *versus* SST forcing as the cause of droughts in the region, and may we hope to answer questions such as:

6. Is the current drought a temporary variation or a persistent and perhaps irreversible trend?

We will address aspects of all these questions in the next sections. First we will characterise the Sahelian region in ecological and climatological terms on one hand, and socio-political terms on the other. Then we will review the scientific efforts that have built the current understanding of land-surface/hydrology/climate interactions in the region, which includes discussion of the role of past and present field experiments in the region, and the results and evidence from modelling studies. Finally, after analysing the mechanisms, we will come back to the questions formulated above and assess where we stand.

A.5.1.1 Background

The Sahel is a tropical, semi-arid region (approximately 1.5×10^6 km^2) along the southern margin of the Sahara desert formed from large parts of six African countries and smaller parts of three more. The word "Sahel" was derived from the Arabic for a "shore", and this was presumably how the vegetation cover seemed to early traders who entered the region from the Sahara desert to the south. Today it is a bioclimatic zone of predominantly annual grasses with shrubs and trees, receiving a mean annual rainfall of between 150 and 600 mm y^{-1}. There is a steep gradient in climate, soils, vegetation, fauna, land use and human utilisation, from the almost lifeless Sahara desert in the north to savannas to the south. The similarity of climate and land cover in the

E-W direction contrasts dramatically with the strong N-S gradient. The uniformity of this geographical pattern is partly a result of an absence of rapid changes in topography but also because of the zonal nature of the climate with desert to the north and ocean or humid forests to the south. The geographical patterns of rainfall, vegetation cover, soils, human settlement and land use all share this zonal arrangement and are strongly correlated, so that cause and effect are hard to disentangle. The continental scale land mass and relative flat orography (excluding eastern Sahel) warrant that land-surface/atmosphere interactions play a major role in the regional climate and also allow such interactions to be detected relatively easily in model simulations. In fact, tropical northern Africa is the first region where continental scale land-surface/atmospheric interaction studies were conducted (Charney 1975).

The monsoon climate system increases further the potential for interaction between the lower atmosphere and the land surface. The Sahel summer climate is dominated by the West African monsoon system. The basic driver of the monsoon circulation is provided by thermal contrast between the continent and adjacent oceanic regions (Holton 1992). Any changes in the contrast may affect substantially the monsoon flow. Furthermore, the region is located in the tropics. In the tropics, the dynamical flow instabilities are relatively weak (compared to mid-latitudes). The boundary conditions modify the diabatic heating (latent and radiative heating) which in turn changes circulation and rainfall at seasonal and interannual time scales.

Soils in this region are dominated by a sand sheet of varying depth, usually resulting in unstructured, free-draining soils with low nutrient content and with a strong tendency to form an impervious "cap". This low soil nutrient content is sometimes considered a more serious constraint on rangeland quality and production than low rainfall (Breman and de Wit 1983). As a result of the crust formation, much rainfall runs off rather than infiltrating and is subsequently concentrated in local depressions.

These pools provide surface water for livestock allowing traditionally nomadic herdsmen to take their cattle, sheep, goats, camels and donkeys away from permanent water points such as boreholes, wells and rivers during the rainy season. As the people of the Sahel are dependent almost entirely on subsistence livestock production and agriculture they are therefore particularly vulnerable to the frequent droughts that occur in the region.

A.5.1.2 Climate Anomalies and Climate Change in the Sahel

Rainfall is the controlling factor in the life of the Sahel. A brief rainy season occurs, caused by the northward movement of the Intertropical Convergence Zone (ITCZ) in the northern summer, which causes humid air from the Gulf of Guinea to undercut the dry north-easterly air. West-moving squall lines and local convective activity cause mixing of the two air masses and results in short, torrential thunderstorms that increase in frequency and rainfall amount towards the south where the humid air mass is deeper. The rainy season varies in length from two to four months, but "rain days" can be separated by weeks of no rain.

Rainfall in the Sahel is characterised by high spatial and temporal variability, both within and between seasons, and by a high north-south gradient in the region. The climatological annual rainfall gradient over the Sahel is about 1 mm km^{-1} (Lebel et al. 1992). Not only is year to year variability high but also longer dryer or wetter periods may continue over a number of years.

Although the Sahel is usually defined with reference to a range of annual average rainfall, it is not always the amount of rainfall that is the most important characteristic, rather the spatial and temporal variation in rainfall, especially interannual variations, which determines much of the type and pattern of vegetation, fauna and human utilisation. Using satellite remote sensing the Sahel can be delimited by the zone of high interannual variations in vegetation activity. These characteristics have been discussed by a number of studies (e.g. Lamb 1978a,b; Nicholson and Palao 1993; Lebel et al. 1997).

Since the late 1960s, a persistent summer drought has lasted for more than 30 years. Although in the 1990s the rainfall was not as scarce as the 1980s, it was still below the climatological average (Fig. A.35). One of the important features of sub-Sahara drought is the displacement

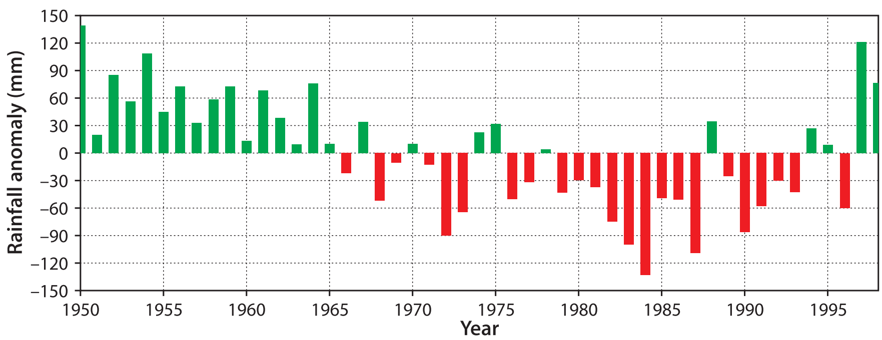


Fig. A.35. July-August-September rainfall anomalies for the Sahel region (10–20° N, 15° W to 40° E) of isohyets in the 1980s, retreating southward in the northern Sahel during dry years and also shifting slightly to the south in the southern Sahel. This redistribution reduces the rainfall in the Sahel and increases rainfall to the south of 10° N. Figure A.36b shows the zonal average rainfall over the African continent from Nicholson's observational data. It indicates that the maximum rainfall was not reduced very much and it was the shifting alone that gave rise to the rainfall deficiency in the Sahel.

At small scales the data, even though relatively scarce by standards of temperate countries, do allow for detailed statistical analysis of spatial and temporal dynamics in certain areas. Le Barbé and Lebel (1997) have shown that the drought in Niger is associated mostly with a decrease of the number of rain events at the height of the rainy season (July/August). The mean event rainfall and the length of the rainy season hardly contributed to the decrease in annual rainfall. The rainy season duration and timing between dry (1970–1990) and wet (1950–1970) periods are similar.

A number of studies has also shown that many rivers in the region exhibit substantial reduction in discharge between the 1950s through the 1980s (for example, Savenije 1995; Oki and Xue 1998) as a consequence of the reduced rainfall. Annual discharge declined to less than one-third at some stations during the 1980s. The discharge of the River Niger at Niamey was reduced from an annual average of 1 060 $m^3 s^{-1}$ over the period 1929–1968 to 700 $m^3 s^{-1}$ over the period 1969–1994, e.g. a decrease of 34%. At the same time the average discharge during the month of low water decreased from 64 $m^3 s^{-1}$ to 11 $m^3 s^{-1}$. Figure A.37 shows the river runoffs during 1950–1970 and 1971–1990 from the Koulikoro station based on the data from the Global Runoff Data Centre. This station, with a basin size of 12 104 km^2, is located in the upstream region of the River Niger, and represents the mean runoff from the south-western Sahel region. The figure shows that the river runoff is substantially reduced during 1971–1989, and this reduction occurs mainly during the summer monsoon season.

In addition, several investigations have found that the temperature has increased in the Sahel during dry years (Tanaka et al. 1975; Schupelius 1976; Kidson 1977). Tanaka et al. (1975) reported a surface air temperature increase of about 2 K. The observed temperature data, provided by the Oak Ridge National Laboratory (Vose et al. 1992), has also shown that the summer surface temperature over the Sahel region is greater by 1–2 °C during the summers of the 1980s compared with the 1950s (Xue 1997).

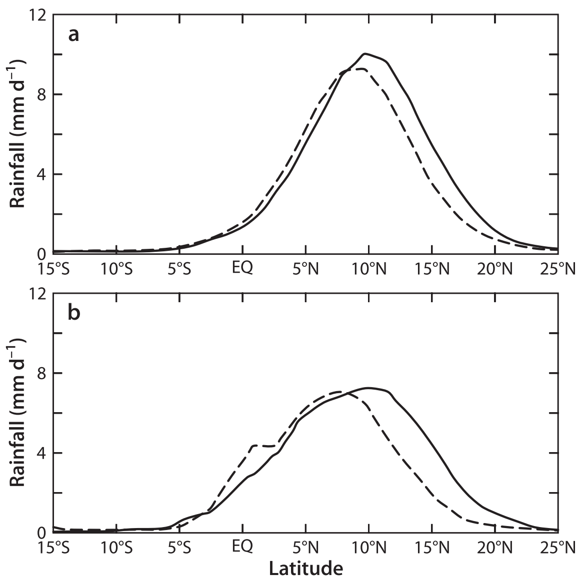


Fig. A.36. Zonally averaged rainfall distribution (mm d^{-1}). **a** Three-month mean for control run (*solid line*) and desertification run (*dashed line*); **b** *solid line* is the mean for 1950 and 1958, *dashed line* is for 1983 and 1984 (from Xue and Shukla 1993)

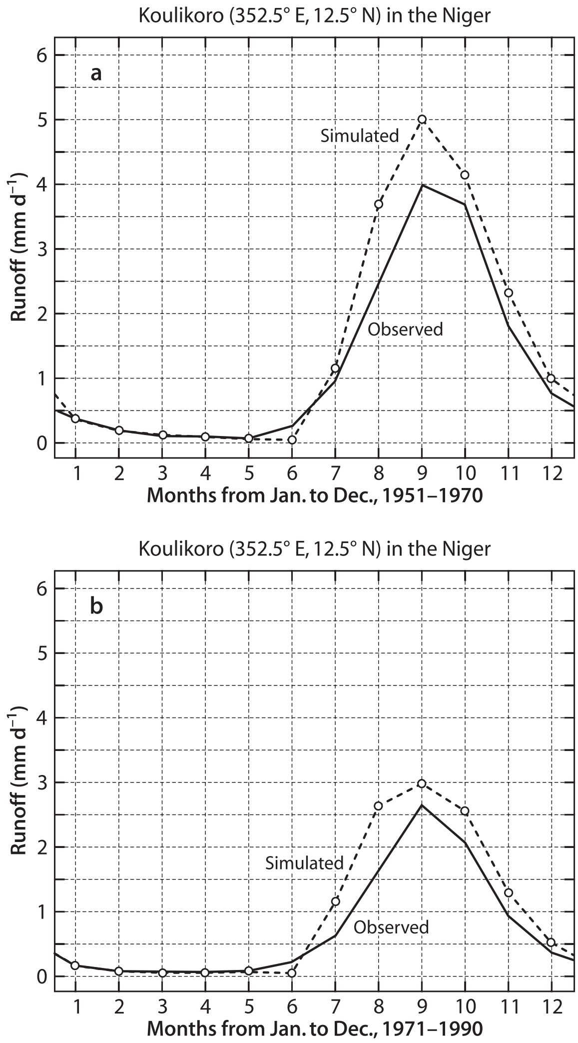


Fig. A.37. Comparison of simulated and observed runoff. **a** Control run and observed mean from 1951–1970; **b** desertification run and observed mean from 1971–1990 (after Oki and Xue 1998)

In prehistoric times, the Sahelian region had a much more dramatic desertification episode than that which persists today. The climate was humid in the early and mid-Holocene from 10 000 to *c.* 4 000 years B.P. (Alexandre et al. 1997; Claussen and Gayler 1997). During that period, swamp forest vegetation was established in the interdune depression in the Nigerian Sahel. The vegetation limit in the region reached at least 23° N. A dry phase during the late Holocene (between *c.* 4 000 and 1 200 years B.P.) followed and came to be replaced by wetter climate conditions from *c.* 1 000 years B.P. The modern shrubs and savanna were developed *c.* 700 years B.P. Subtle changes in the Earth's orbit, strongly amplified by regional and global climate-vegetation interactions, are currently believed to be the main causes for this change in the region's climate 4 000 years B.P. (Kutzbach et al. 1996a).

Historical data reveal several other drought periods from the 16th century in the Sahelian area (data from before the 16th century are very scare), but no records show a drought as persistent and severe as the one that started in the 1960s (Nicholson 1978). Only the drought during the 1840s might be as severe as the one in the 1980s.

A.5.1.3 The Complex Processes of Land-use Change in the Sahel

The Sahel region has a variety of land uses that generate goods and services for the population: fuelwood in natural vegetation areas, food for subsistence and market demands in croplands, livestock in the pastoral area. Pastoralism is particularly extensive. Biomass production relies on the natural productivity of grasslands. Burning is used in most rangelands to preserve savannas against woody invasion and to reduce weeds and pests. Production from shrubs and trees, and crop residues is also important for consumption by livestock. In extensive farming systems in African savannas, four years of cultivation is the usual time limit before the land is put into fallow.

The Sahelian region has undergone significant changes in land cover over the past decades. These changes result from interactions between short-term climate fluctuations and longer-term anthropogenic impacts, in particular, agricultural expansion, agricultural intensification, and rangeland modifications (Stephenne and Lambin 2001). Expansion of cultivation into previously uncultivated areas or migration into unsettled areas takes place with the help of newly developed technology. Agricultural expansion thus leads to deforestation and to a reduction in pastoral land. Pastoral land also expands into natural vegetation areas. Note that grazing livestock move into fallows and cropland during the dry season. Expansion of cropland and pastoral land is thus driven by changes in human and animal populations that increase the demand for food crops and forage, through variability in rainfall that modifies land productivity, and policy changes that modify the rules of access to resources and market changes. The rate and reversibility of change are, however, much higher for rainfall compared to demographic, institutional or economic changes.

Once specific land thresholds are reached, additional demand for food crops results in agricultural intensification. In Sahelian agriculture, intensification mostly takes place as a shortening of the fallow cycle, compensated by the use of labour, agricultural inputs (mainly natural fertilisers) and selection of seeds with, so far, only a minor use of mechanisation and irrigation (Diop 1992; Gray 1999). A shortening of the fallow cycle without input rapidly depletes soil fertility.

The increase in livestock population combined with shrinking pastoral land results in an increasingly sedentary society, where livestock relies more on crop residues for consumption. This puts increasing grazing pressure on pastoral land. Conflicts between pastoralists and sedentary farmers sometimes take place when land scarcity becomes acute.

State policies throughout sub-Saharan Africa are framed in the belief that rangelands are over-stocked by pastoralists, leading to rangeland degradation (Oba et al. 2000). The resulting management strategies aim to control, modify, and even obliterate traditional patterns of pastoralism (Ellis and Swift 1988). Rangelands are maintained by the interaction of human and biophysical drivers, and reducing or excluding the human use may trigger significant changes in these ecosystems. Indeed, reduced grazing is associated with a loss of species diversity, a decline in vegetation cover and reduced plant production. A weakened indigenous pastoral system may lead to economic decline or to urban migration with rural remittances.

There has been rapid population growth in the region over the past 50 years. For example, the population of five Sahelian countries (Senegal, Niger, Mali, Sudan and Chad) rose from 20 million in 1950 to 55 million in 1990 and is projected to rise to over 135 million by 2025 (World Resources Institute 1994). This rise in population, as well as political constraints on nomadism, will continue to cause extensive land-cover conversion. This population growth has occurred at a time of generally reduced rainfall but the proposition that this has led to widespread desertification is not fully established.

Desertification is a loosely defined concept but it is taken here to mean the degradation associated with increased soil erosion caused by wind and water, soil compaction and reduced water holding capacity, reduced infiltration of rainfall and vegetation production, and loss of palatable species, all leading to a decline in crop yields, livestock production, and fuel-wood supply (Le Houérou and Hoste 1977; Dregne 1983; Rapp 1987;

Le Houérou 1989; Goudie 1990; Barrow 1991; Verstraete and Schwartz 1991). Semi-arid rangelands are highly dynamic and resilient, moving through multiple vegetation states by shifting chaotically in response to human and biophysical drivers. This intrinsic variability of rangeland ecology makes it difficult to distinguish directional change (e.g. loss of biodiversity, soil degradation) from readily reversible fluctuations, such that interpretations of "degradation" and "desertification" must be viewed cautiously.

The distinction between desertification and degradation on the one hand, and drought on the other, is not always clearly drawn. Although there is consensus on local degradation in the Sahel (e.g. Lindqvist and Tengberg 1993; Mabbutt and Floret 1980), opinions on widespread degradation in the Sahel are quite controversial. A number of studies showed that overgrazing of the natural rangelands by livestock, northwards extension of cultivation and increased fuel-wood extraction, coupled with severe drought, are leading to widespread land degradation (Gornitz 1985; Dregne and Tucker 1988; Skoupy 1987; Lanly 1982; Dregne and Chou 1992; Akhtar-Schuster 1995; Benjaminsen 1993; Gray 1999). However, some studies, based on the satellite data from the late 1970s, have challenged views on large scale degradation (e.g. Watts 1987; Forse 1989; Tucker et al. 1991; UNCED 1992; Nicholson et al. 1998; Prince et al. 1998). Measuring rates of dryland degradation is thus a complex challenge and requires long time-series of rainfall data, remote sensing-based indicators of surface conditions and field observations of soil attributes, floristic composition, etc.

The issue is in urgent need of reconsideration with more appropriate data (Helldén 1991). The actual extent and severity of regional and subcontinental-scale degradation is an important issue that affects policy with respect to economic development strategies and aid programmes, and also the degree to which changes in the land cover need to be considered in the context of global climate change modelling (Rasmusson 1987; Schlesinger et al. 1990). Prince et al. (1998) have used the ratio of net primary production (NPP) to precipitation – the rain-use efficiency (RUE) – to map degradation. In the Sahel the results suggested that NPP was remarkably resilient, a fact that was reflected in only little variation in the RUE during the period of study. Thus, in much of the region, NPP seems to be in step with rainfall, recovering rapidly following drought and not supporting the fears of widespread, subcontinental scale desertification taking place in the nine-year period that is studied (Nicholson et al. 1998). In fact, the results show a small but systematic increase in RUE for the Sahel as a whole from 1982 to 1990, although some of the areas contained within the region did have persistently low values.

A.5.2 Observational Studies of Sahelian Land-surface/Atmosphere Interactions

To investigate interactions of land surfaces with the atmosphere and impact of land-cover change in the Sahel region, requires regional measurements of land-surface energy and water balances, and of boundary layer and free-atmosphere dynamics. They provide useful information about Sahelian surface hydro-meteorology and are essential to validate models.

Two large field campaigns were conducted during the late 1980s (Sahelian Energy Balance Experiment, SEBEX) and 1991–1992 (HAPEX-Sahel). Building on these, two additional studies are currently operational (SALT and CATCH). Most of these projects incorporate substantial remote sensing programmes. Figure A.38 shows the locations of these four field experiments. Table A.2 lists the web sites for these experiments.

A.5.2.1 The Sahelian Energy Balance Experiment (SEBEX)

This experiment was conducted by the U.K. Institute of Hydrology and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Center at two sites near Niamey, Niger, from 1988 through to 1991 (Wallace et al. 1992) and covering three contrasting Sahelian land types. One site was a fenced area of fallow sa-

Table A.2. Relevant websites relating to Sahelian studies

HAPEX-Sahel online database (Hydrological Atmospheric Pilot Experiment)	*http://www.orstom.fr/hapex/index.htm#1*
CATCH project (Couplage de l´atmosphère tropicale et du cycle hydrologique)	*http://www.lthe.hmg.inpg.fr/catch/welcomefr.html*
SALT project (Savannas in the Long Term)	*http://medias.obs-mip.fr/www/francais/lettre/10/Dossiers/pf2225/pf2225.htm*
WAMP project (West African Monsoon Project)	*http://www.met.rdg.ac.uk/~swsthcri/tropical.html*
CLD project (Climate and Land Degradation)	*http://www.nwl.ac.uk/ih/cld/*
Sahel standardised rainfall index (Mitchell)	*http://tao.atmos.washington.edu/data_sets/sahel/#values*
Sahel standardised rainfall index (Hulme)	*http://www.cru.uea.ac.uk/tiempo/floor2/data/sahel.htm*
El Niño impacts in Africa	*http://www.essc.psu.edu/~osei/west/westaf1.html*

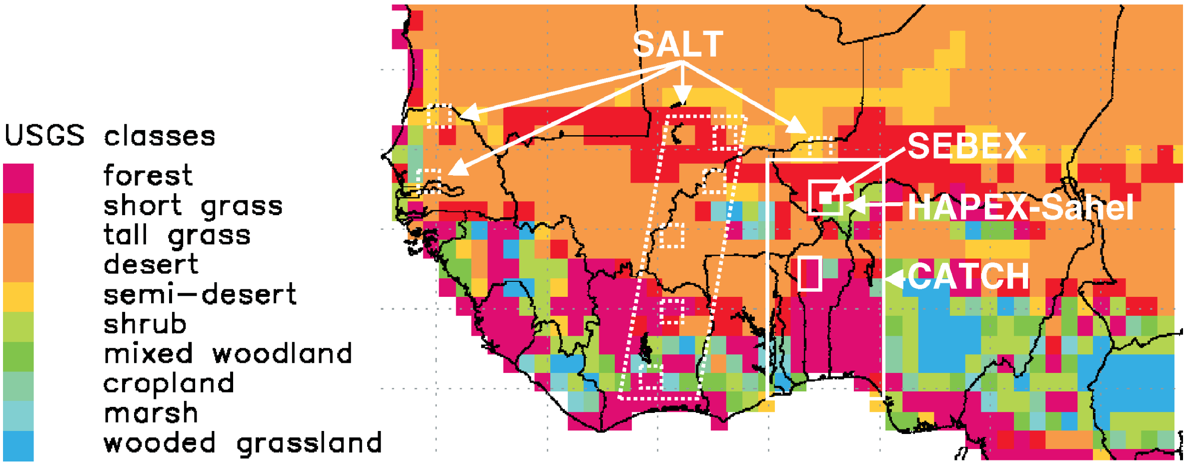


Fig. A.38. Location of past and present land-surface experiments in the Sahel region, projected on USGS land-cover classification. SEBEX comprised two sites near Niamey (Niger), HAPEX Sahel a 1° gridbox in the same area. CATCH includes the latter, while adding a catchment of similar area in Benin, both nested inside two larger regions. SALT includes eight 40 km² along two gradients

vanna, which supported a comparatively high density of natural vegetation, and a second was an area of degraded natural forest, which consisted of a mosaic of dense vegetation and large areas of bare soil. There was also agricultural land that was used for growing traditional crops such as millet. One major objective of the project was to obtain direct measurements of available energy, evaporation and sensible heat flux from different land surfaces, and to improve understanding of the impact of changes in vegetation on the energy and water balance. The measurements covered both the Sahelian dry and rainy seasons. Although there were minor differences among measured variables, all datasets include hourly evaporation rates, sensible heat flux, soil heat flux, friction velocity, short-wave and long-wave radiation flux, net radiation at surface, and meteorological data.

A.5.2.2 The Hydrological and Atmospheric Pilot Experiment in the Sahel (HAPEX-Sahel)

The HAPEX-Sahel experiment was executed in Niger, West Africa during 1991–1992 (Goutorbe et al. 1994, 1997a). The objective of this experiment was to improve the parameterisation of surface hydrological processes in semi-arid areas at scales consistent with general circulation models, and to develop methods for monitoring the surface hydrology at such large scales. With objectives similar to the SEBEX experiment, the experiment was carried out at a much larger scale, i.e. in a 1° square (2–3° E, 13–14° N) in Niger. The vegetation within the experimental area was typical of the southern Sahelian zone: arable crops, fallow savanna and sparse dryland forest. The observations included a period of intensive measurement during the transition period of the rainy to the dry season, complemented by a series of long-term measurements. Analyses of data from satellite remote sensing combined with ground measurements were carried out to estimate energy fluxes for the GCM grid scale.

Three super-sites were instrumented with a variety of hydrological and meteorological equipment to provide detailed information of surface energy exchange at the local scale. Two less heavily instrumented sites were also established. These were to extend the spatial coverage over the square. In addition to these sites, a network of automated weather stations was established over the full 1° square. They provided information on the regional-scale variability of the main climatic variables. Meanwhile, balloon and aircraft measurements were also carried out to provide information about the development of the atmospheric boundary layer.

The experiments in the Sahel were extensive and complex and the main experimental results are presented in a Special Issue of the Journal of Hydrology (Goutorbe et al. 1997a). The main contributions from these experiments of interest to the climate modelling community are:

- Measurements of the energy balance of the main cover types were made, including mean surface albedo, skin temperature and evaporation, for millet cropland and natural vegetation. Millet is the dominant crop grown by subsistence farmers, in areas cleared of natural savanna vegetation. The millet crop had a significantly higher surface albedo and skin temperature and lower evaporation rate (Table A.3; Gash et al. 1997), indicating some of the changes in land-surface properties were likely to have been a result of the extension of agriculture.

Table A.3. Mean surface albedo, surface skin temperature and evaporation at the HAPEX-Sahel Southern Super-Site, through August and September, 1992 and simulated differences between degraded and control experiments over the test area

Vegetation type	Surface albedo	Surface skin temperature (°C)	Evaporation (mm m^{-1})
Millet	0.27	29.5	77
Fallow savanna	0.19	28.4	115
Observed difference	0.08	1.1	–38
Simulated differences	0.08	0.8	–24

- Detailed measurements of the bare soil patches within the vegetation covers were made. The energy and water balance of the bare soil areas turned out to be crucial to the response of the overall landscape.
- The extensive raingauge network has yielded considerable insight into spatial rainfall and soil moisture patterns in the Sahel (see e.g. Lebel et al. 1997; Taylor and Lebel 1998). These data are beginning to be used to understand the aggregate description of the Sahelian landscape (e.g. Taylor and Blyth 2000).
- Extensive site and spatial datasets have been produced which are providing an invaluable resource for current and future Sahelian research.

A.5.2.3 Coupling Tropical Atmosphere and Hydrological Cycle (CATCH)

While HAPEX-Sahel produced key results, some important shortcomings made it difficult to place those results in a broad climatic context. First, the lack of appropriate atmospheric measurements at the regional scale prevented a link between the mesoscale and the large circulation. Second, intensive experiments for a limited time are not on their own sufficient to describe the interannual and decadal variabilities of the water cycle. Finally, the mechanisms that control the variability of West African climate and hydrology must be studied.

Therefore, CATCH addresses scales larger than those in HAPEX-Sahel. A nested approach encompasses the following:

- West Africa as a whole, to study the structure and the variability of large atmospheric entities (e.g. easterly waves);
- the so-called CATCH regional window (0–5° E; 6–15° N) will be used as a reference area to compare the outputs of various atmospheric models (global to mesoscale) with observations;
- two focus areas were selected for fine resolution measurements and process studies: the HAPEX-Sahel square (2–3° E; 13–14° N) and the upper Ouémé catchment (1.5–2.5° E; 9–10° N);
- super-sites, covering in the order of a hundred km^2, allow for small-scale studies, especially fluxes at the soil-atmosphere interface.

CATCH is organised around four themes:

1. an atmospheric theme addresses climatic variability related to east African waves and global teleconnections aiming at improving seasonal precipitation forecasts, and spatio-temporal dynamics of convective processes in relation to planetary boundary layer (PBL) dynamics;
2. a biospheric theme focusing on the role of small-scale spatial and structural (trees *v.* herbaceous vegetation) heterogeneity in evapotranspiration and carbon cycling;
3. a hydrospheric theme focusing on precipitation/runoff dynamics, as well as on non-saturated zone moisture dynamics at larger scales;
4. a land-atmosphere interaction theme focusing on an integrated (modelling) analysis of coupling of the other themes.

Recently, CATCH has evolved into a larger international project centered on the study of the whole West African monsoon system and of its links with the water cycle. This project, named AMMA, is endorsed by CLIVAR, GEMEX and GCOS.

A.5.2.4 Savannas in the Long Term (SALT)

While AMMA is a project rather strongly oriented towards atmospheric and hydrological processes, SALT addresses more ecological issues. Set up as a transect (and as such endorsed as an IGBP-GCTE Transect), its observational programme includes eight sites covering the two major eco-climatic gradients in the region: the south to north aridity gradient, and a west to east continentallity gradient. SALT's primary objective is to understand and predict current and future dynamics and changes in West African savanna ecosystems under climatic and anthropogenic pressures. It addresses savanna dynamics in terms of species composition and spatial structure in relation to the cycles of water, energy, carbon and nutrients. A special focus is on how these are affected by land degradation and erosion.

Apart from ground measurements, remote sensing plays an important role in SALT to scale up vegetation dynamics, to monitor fire dynamics and to study aerosol dynamics.

A.5.2.5 Satellite Data

Validation and calibration studies using the SEBEX and HAPEX-Sahel data have helped to improve the models' simulations in semi-arid areas and to understand the important features and mechanisms of land-surface/atmosphere interactions in the Sahel area (Goutorbe et al. 1997b; Kabat et al. 1997b; Xue et al. 1996a, 1998). However, considering the high spatial variability in land-surface conditions in the Sahel, and given that these two experiments cover relatively small areas and short periods of time, both the observed and derived land data from HAPEX-Sahel are not wholly representative of vegetation conditions over the entire Sahel area.

During the past two decades, new satellite data have brought the Earth systems science community to the brink of a new era for land-surface data information (Shuttleworth 1998). In the earlier stage, vegetation maps were the main products from satellite data (DeFries and Townshend 1994). Recently, vegetation parameters with more physical meaning, such as leaf area index (LAI) and biomass, and surface meteorological, ecological, and hydrological variables, such as surface temperature, albedo, soil moisture, can be derived with increasing accuracy from space (for example, Los et al. 2000; Goetz 1997; Goward et al. 1999), due to more optimised sensor characteristics, better atmospheric correction procedures and better algorithms. Such datasets will increasingly feed directly to models for land-atmosphere interaction studies.

During HAPEX-Sahel, a very wide range of aircraft and satellite measurements was made (Prince et al. 1995). Recently, a subset of a global biophysical land-surface dataset at 8 km spatial and 15-day temporal resolutions for 1982–1998 derived from AVHRR by NASA Goddard Space Flight Center (GSFC) has been introduced to Sahel studies by Kahan (2002). This dataset (hereafter referred to as Los data) is an extension of their previous 1° dataset (Los et al. 2000), and includes LAI and fraction of photosynthetically active radiation (FPAR) absorbed by vegetation. Using this dataset and vegetation cover information, other vegetation properties, such as green leaf fraction, surface roughness length, vegetation cover percentage, are obtained.

This dataset was used to specify the land-surface conditions over a 1° square area in the Sahel. With a forcing dataset from ISLSCP Initiative I CD-ROM (International Satellite Land Surface Climatology Project; Meeson et al. 1995), uniform over the one degree box, the off-line version of the Simplified Simple Biosphere Model (SSiB; Xue et al. 1991, 1996b) was integrated from 1 January 1987 through 31 December 1988 at every 8 km pixel. Figure A.39 shows the July, August, September (JAS) means for latent heat and surface air temperature for the both years 1987 and 1988 from this 1° area, respectively. The figures show that even with a uniform meteorological forcing in a 1° box, vegetation distribution (with 8 km resolution) alone can produce a north-south temperature gradient due to significant spatial variation in sensible and latent heat fluxes. Furthermore, using the same Los dataset, the model also simulated the interannual variations well. The year 1987 (a dry year) has higher surface temperature and lower latent heat flux than 1988 (a normal year).

A.5.3 Coupled Modelling of Sahelian Land-Atmosphere Interactions

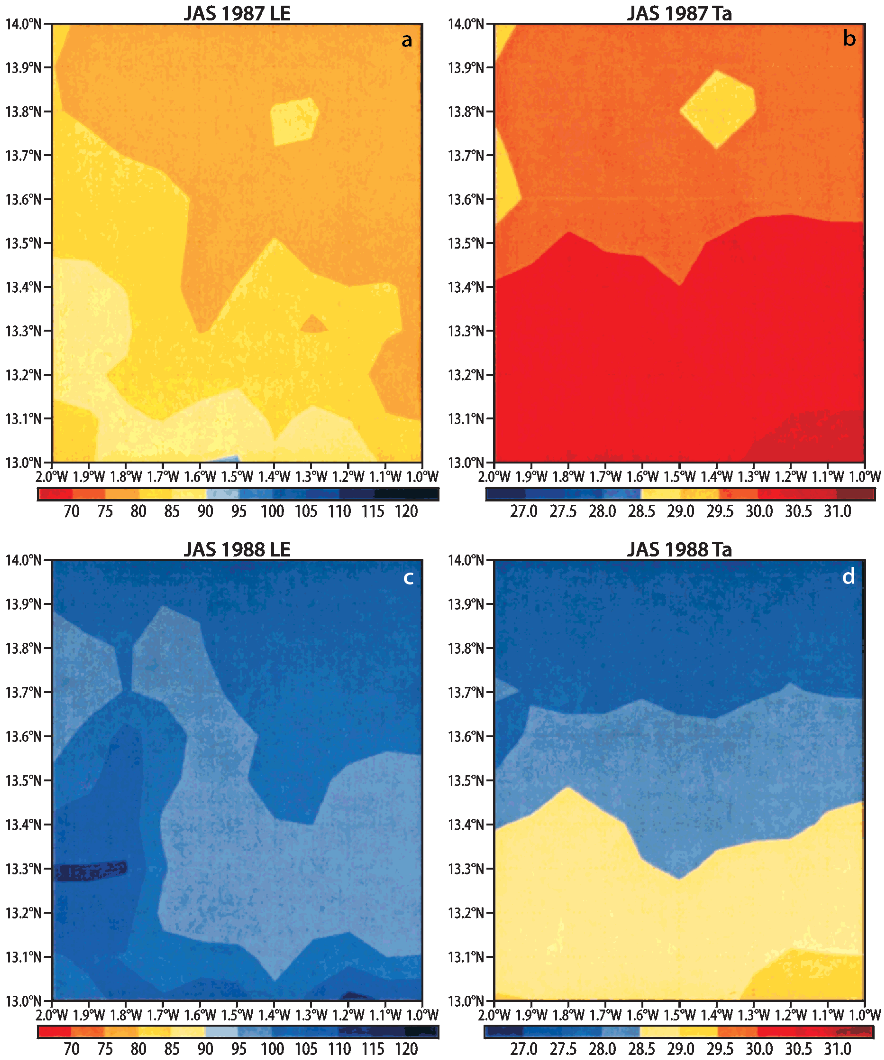
A.5.3.1 Brief Overview

A number of studies with different models have been conducted over the past 20 years to examine the role of biospheric feedbacks in the Sahel drought of the same period. In the pioneering work by Charney et al. (1977) on the effects of albedo on the climate, he found that increases in albedo caused a reduction in precipitation. This discovery has been confirmed by a number of studies with different models (for example, Chervin and Schneider 1976; Sud and Fennessy 1982; Laval and Picon 1986). The effects of soil moisture and evaporation have also been investigated (e.g. Walker and Rowntree 1977; Sud and Fennessy 1984). Most studies showed that less initial soil moisture leads to less precipitation. Furthermore, the combined effects of surface albedo and soil moisture have been studied (e.g. Sud and Molod 1988; Kitoh et al. 1988). Kitoh et al. (his Table 2) found that the combined effects almost equalled the sum of the albedo or soil moisture effects alone. Besides these two parameters, other factors have also been investigated (Cunnington and Rowntree 1986). These modelling studies consistently demonstrated that the land surface may have a significant impact on the Sahel climate.

In the studies that were carried out during the 1970s and 1980s, simple surface layer models of the bucket type were used for sensitivity studies. In most cases, only a single land-surface parameter was tested each time. The primary factors of the desertification under investigation were surface albedo and soil moisture. In most of these sensitivity studies, the area associated with land-surface changes and the extents of the changes in the surface characteristics, such as albedo and soil moisture, were somewhat arbitrary. Atmosphere-biosphere interactions are, however, much more complex in the real world and involve many more parameters and processes.

Therefore, sophisticated land-surface models are needed to assess realistically the impact of desertification on the Sahel drought. A proper evaluation of the surface feedback to climate can be obtained only when all comparable components of the energy and water balances are considered. A number of surface schemes that include a realistic representation of the vegetation

Fig. A.39.
1° × 1° fields of latent heat ($W\,m^{-2}$) and surface air temperature (°C) in the Sahel in two successive years (1987: dry; 1988: wet) as simulated by SSiB. The images show the impact of the land-surface variability obtained from satellite observations (at 8 km resolution). Climate forcings were uniform for the entire grid cell



responses have been applied to the Sahel (e.g. the Biosphere-Atmosphere Transfer Scheme, BATS, Dickinson et al. 1986; the Simplified Simple Biosphere Model, SSiB, Xue et al. 1991; the Meteorological Office Surface Energy Scheme, MOSES, Cox et al. 1998). They have been coupled with atmospheric models to conduct a number of Sahel drought studies (Xue et al. 1990; Xue and Shukla 1993; Xue 1997; Clark et al. 2001). Different from the studies in the early 1980s, some of these studies not only tested the sensitivity of the regional climate to land-surface processes but were also intended to link the land-surface processes to observed decadal climate anomalies and, therefore, explored the possible mechanisms involved more realistically.

Most recently, an additional level of complexity is being explored by the coupling of dynamic vegetation models to atmospheric models. Though still in its early development stage, this field of activity has already produced a number of interesting results regarding land-surface climate interactions in the Sahel. Some studies investigated the climate equilibrium states (e.g. Claussen and Gayler 1997; Wang and Eltahir 2000b). Using a GCM with an interactive vegetation model, Claussen and Gayler (1997) found multiple equilibrium states in climate/vegetation dynamics in northern Africa which could not be found in other parts of the world. This discovery was confirmed by Wang and Eltahir (2000a) with a coupled two-dimensional climate/dynamic vegetation model. In another study using a coupled atmosphere and dynamic vegetation model, Zeng et al. (1999) reproduced the decadal precipitation variability in Sahel, which could not be simulated if interactive vegetation processes were not included in their model.

Mesoscale models are also introduced to Sahel land-atmosphere interaction studies. Thermal anomalies in a landscape may trigger convection and lead to rainfall. The causes of these contrasts in surface energy partitioning can be attributed to contrasts in soil moisture (Taylor et al. 1997b) and/or to contrasts in vegetation density (Hutjes and Dolman 1999). Whilst models illustrate this possibility, it remains to be proven from observations that mesoscale heat flux gradients are strong enough to influence rainfall patterns by this mechanism.

In addition to land-surface effects, observational and model studies have revealed that SST anomalies are highly relevant to the seasonal and interannual rainfall variability in northern Africa (Lamb 1978a,b; Palmer 1986; Semazzi et al. 1988; Folland et al. 1991; Lamb and Peppler 1991; Shinoda and Kawamura 1994; Rowell et al. 1995; Xue and Shukla 1998). Some of the modelling studies on this subject will be briefly introduced in Sect. A.5.3.2 and A.5.3.4 for comparison.

A.5.3.2 Large Scale Force-Response Studies of the Sahelian Climate Anomaly: The Relative Importance of Land-surface Processes and Sea-surface Temperatures

Starting in the late 1980s, numerical experiments with coupled biosphere-atmosphere models have been conducted to derive a better understanding of the mechanisms of land-atmosphere interactions in northern Africa. More realistic simulations of climate anomalies have been achieved by using land-surface descriptions which can be changed to represent changes closer to the real world than was the case in the earlier experiments. In the following we will use the results obtained by Xue and collaborators to describe in detail the up-to-date achievement in simulating the climate anomalies and the most important pathways through which land-cover change affects Sahelian climate. Meanwhile, other recent Sahel studies with models of interactive vegetation and mesoscale models will also be presented.

To explore the impact of land degradation in the Sahel on seasonal climate variability and the water balance, the coupled Center for Ocean-Land-Atmosphere Study's GCM (COLA GCM, Kinter et al. 1988) and SSiB land-surface model (Xue et al. 1991, 1996b) was integrated using a "normal" vegetation map (control simulation) and several vegetation maps where savanna or shrubs with ground cover were changed to shrubs with bare soil in a specified area (degraded simulation). Climatological SSTs were used as the lower atmospheric boundary conditions over the oceans. Because of the internal variability in GCMs, the model in Xue's study (1997) was integrated from 1 June, 2 June, and 3 June for three years, respectively, and ensemble means were used to identify climate impacts.

The world vegetation map was read into the coupled surface-atmosphere model to provide the land-surface conditions required by SSiB. Twelve vegetation types are recognised by SSiB, including trees, short vegetation, arable crops and desert. Different vegetation and soil properties, including surface albedo, LAI, soil hydraulic conductivity and surface roughness length, are defined for each vegetation type. For land-surface degradation simulations, the normal vegetation types in the Sahel area were changed to the types that would result from land degradation, altering the prescribed vegetation and soil properties. Since there are no quantitative data available for the 1950s' land-cover information in the Sahel, the selections of the degradation areas were based on some available information (e.g. Dregne and Chou 1992) but do not necessarily represent the reality that occurred during the past 50 years. As a result, these simulations must be regarded as sensitivity studies.

The differences between the ensemble mean July-August-September (JAS) rainfall of the degraded and control simulations are shown in Fig. A.40b. The rainfall is reduced in the degraded area but increases slightly to the south. This dipole pattern is consistent with the observed pattern for dry climate anomalies in Fig. A.40a, which shows the JAS rainfall differences between the 1980s and the 1950s. The simulated rainfall in a test area (from 9° N to 17° N, and 15° W to 43° E), including most of the specified degraded area, is reduced by 39 mm month^{-1}, close to the 45 mm month^{-1} observed reduction.

At the beginning of the Sahelian dry season (October-November-December, OND), when the Intertropical Convergence Zone (ITCZ) moves to the south, little rainfall is observed or simulated in the Sahel. However, the areas of reduced rainfall related to land degradation shift to the south of the Sahel, with a positive anomaly over eastern Africa (Fig. A.40d), consistent with the observed OND rainfall anomaly (Fig. A.40c). Thus, the effect of land degradation is not limited to the summer rainy season within the Sahel but extends to the autumn and into East Africa.

The JAS surface air temperature is higher in the degraded simulation than the control, consistent with the observed JAS temperature difference between the 1980s and the 1950s. In the test area, the simulated surface air temperature increases by 0.8 K, close to the observed increase over the same area, 1.1 K, and consistent with the difference measured in the field (Table A.3).

The impact of land-surface degradation on river discharge variability in tropical northern Africa has also been investigated. The simulated soil moisture, surface runoff and subsurface drainage in degradation experiments decrease, consistent with the reduction in rainfall. To compare the runoff at grid points in GCM simulations with observed river discharge, a linear river routing scheme is applied. The lateral flow direction is taken from Total Runoff Integrating Pathways (TRIP; Oki and Sud 1998). The simulated river discharges from control and degradation experiments at the Koulikoro station, located at the top end of the River Niger, represent the mean runoff from south western Sahel region and are used to compare with the observed 1951–1970 mean and the 1971–1990 mean, respectively (Oki and Xue 1998). Some stations in the Sahel cannot be used because their

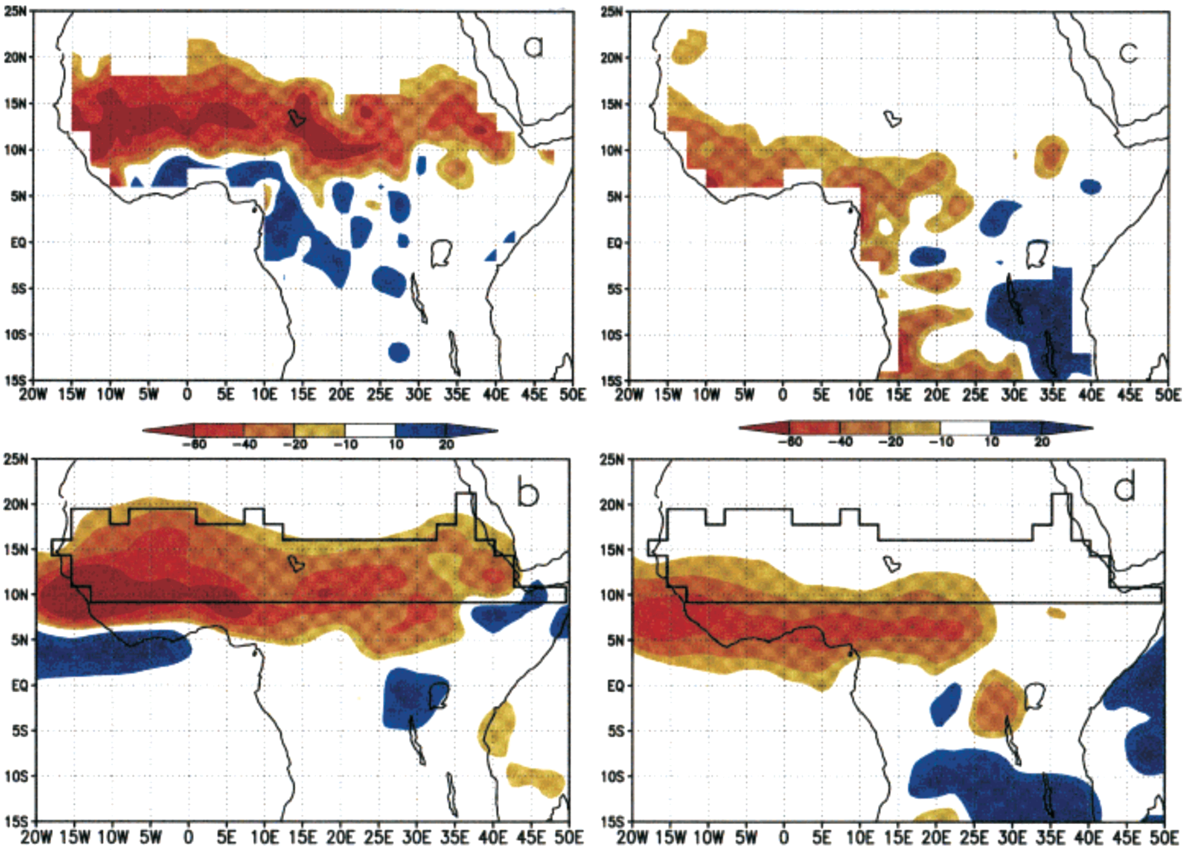


Fig. A.40. **a** Observed JAS rainfall difference (mm month^{-1}) between 1980s and 1950s; **b** JAS rainfall difference in ensemble mean, degraded minus control; **c** same as (**a**) but for OND; **d** same as (**b**) but for OND. In the degraded simulations the vegetation types in the *heavy lines* were changed to shrubs with bare soil (adapted from Xue 1997)

data are severely affected by irrigation. The mean monthly discharges are simulated fairly well and the contrast between control and degraded simulations corresponds to the observed difference between 1951–1970 and 1971–1990 (Fig. A.37).

Since we may never know the exact extent and degree of real land degradation in the last 50 years, another set of tests was designed to investigate how the extent of specified land-surface changes may affect the results. Five subregions were degraded in turn: northern Sahel, southern Sahel, West Africa, East Africa, and the coast area along the Gulf of Guinea (Clark et al. 2001). In general, degradation results in reduced rainfall over the changed surface. But considerable differences between the areas indicate that the location of the degraded area is important. Degradation in northern Sahel and West African Sahel results in the largest and most significant reductions of rainfall. In particular, degradation of northern Sahel causes widespread reduction of rainfall across tropical northern Africa, both within and outside the degraded area. Meanwhile, the deforestation in the coast area produces little rainfall variation.

The simulated climate anomalies are caused by the specified land degradation, which affects the atmosphere mainly through modulating the hydrological processes and energy balance at the surface. There are about 20 parameters in a biosphere model. To investigate the effects of each parameter in this degradation study, numerical degradation experiments have also been conducted, in which not the vegetation type but rather the individual parameter was changed in the degraded area (Xue et. al. 1997). The results show that surface albedo, surface aerodynamic resistance, stomatal resistance, LAI, and hydraulic conductivity of the soil have the largest impact on the simulation results. The surface albedo change caused by land degradation has a strong effect on the surface energy and water balances, so it must be specified realistically in Sahel studies. The albedo changes used in the Sahel study were reasonable (0.09–0.1) and close to the observed albedo difference between the cropland and natural vegetation in the Sahel (Table A.3). Despite the importance of albedo, changes in other vegetation and soil properties (such as LAI) also contribute significantly to rainfall and surface temperature anomalies.

Land degradation also manifests itself in the changes in large-scale circulation and easterly wave propagation. One of the important features of sub-Saharan drought is the displacement of isohyets in the dry years. The isohyets retreat southward in northern Sahel during dry years, which reflects the changes in ITCZ position. In southern Sahel, the isohyets also shift slightly to the south. This movement reduces the rainfall in the Sahel and increases rainfall to the south of 10° N. In the model simulations, both shifting and reduction of the maximum rainfall play roles in reducing the rainfall in the Sahel (Fig. A.36). Both the strength and the depth of the monsoon flow may change.

Reed (1986), based upon the observed data from 1967 to 1982, concluded that the sub-Saharan baroclinic zone and near equatorial rain belt jointly spawned about the same number of disturbances over Africa each year, but that fewer strong and/or highly convective disturbances occurred near the coast during periods of extended droughts. In the degraded experiments (Xue and Shukla 1993), the intensity of disturbances was greatly reduced but not the number of the disturbances. However, recently available observational data from Niger (Le Barbé and Lebel 1997) show that the drought in Niger is mostly associated with a decrease in the number of rain events in July and August. The mean event rainfall and the length in the rainy season hardly contributed at all to the decrease in annual rainfall.

At the continental scale, the oceans play an important role, and the relative strength of forcing of land surface *versus* SSTs has been a subject of some studies. In particular, the relationship between SST and seasonal to interannual rainfall variations in the Sahel region has long been an important scientific subject. The first comprehensive observational evidence for a possible relationship between the Atlantic SST anomalies and the Sahelian rainfall anomalies was presented by Lamb (1978a,b). Lamb showed that a relationship exists between displacements of Atlantic SST patterns and rainfall patterns. Tropical Atlantic SST patterns are known to accompany extreme sub-Saharan rainfall conditions, especially towards the west. This discovery was further confirmed, and extended by several subsequent studies (Hastenrath 1984, 1990; Druyan 1991; Lamb and Peppler 1991), to explain long-term changes. In addition, weaker but significant correlation was found between El Niño/Southern Oscillation indices and sub-Saharan rainfall especially towards eastern (horn of Africa) and southeastern Africa. But there is considerable disagreement in the literature on the ENSO signal in the Sahel (e.g. Wolter 1989; Nicholson and Kim 1997).

Several other observational and modelling studies suggested that the global SST anomalies also played an important role in producing rainfall anomalies over the Sahel and the adjoining regions (Folland et al. 1986; Palmer 1986; Folland et al. 1991; Palmer et al. 1992; Rowell et al. 1995). Folland et al. (1991) found that the relatively modest variations observed in the large-scale patterns of SST had a substantial impact on the variations of Sahel rainfall. Tropical oceans, on the whole, had considerably more influence than extra-tropical oceans. They also found that warmer SST in the Southern Hemisphere relative to that in the Northern Hemisphere had been associated with Sahel drought. Rowell et al. (1995), using realistic SST as the boundary condition for the UK Meteorological Office GCM, found that the model was able to simulate the interannual and decadal variations of Sahelian rainfall very well.

These results were not confirmed by the simulations by other modelling groups (Sud and Lau 1996). In an experiment with the COLA GCM and the same SSTs used by Folland et al. (1991), Xue and Shukla (1998) found that, although the results generally supported the conclusion of Folland et al., they were quite model-dependent. For example, in the 1958 case, the COLA GCM could not produce the observed rainfall anomaly pattern as did the U.K. Meteorological Office model. The simulated anomalies had relatively larger sensitivity to the initial conditions in this study than those in their desertification study (Xue and Shukla 1993). Furthermore, the simulated rainfall anomalies were smaller than observed ones. The results from the desertification experiments (Xue and Shukla 1993; Xue 1997) showed that despite the dramatic changes in prescribed land-surface conditions in the desertification experiment, the simulated rainfall anomaly was still smaller than observations. In the COLA GCM, neither SST nor land anomaly forcing alone could reproduce the observed rainfall anomalies. It is likely, therefore, that both SST and land-surface anomalies play a role in Sahelian rainfall.

The teleconnection between Sahel climate and other parts of the world is an important scientific subject. Observational evidence has shown a correlation between the rainfall anomalies in the Sahel and the rainfall anomalies in other tropical regions (e.g. India) and subtropical regions (e.g. Europe, Ward 1995). But thus far, there are few studies on this subject.

Xue's study (1997, Fig. A.40d) shows there may be a potential link between Sahelian and East African climate, and some impact of Sahel desertification on circulation in some tropical regions. Further study is necessary to investigate this issue. Another example of possible teleconnections influencing Sahelian rainfall comes from a palaeoclimate study in which vegetation changes associated with agricultural expansion and deforestation in Mediterranean Europe and North Africa toward the end of the Roman Classical Period (some 2 000 years ago) appear to contribute to long-term climate change in the Sahel. Reale and Dirmeyer (2000) and Reale and Shukla (2000) reconstructed the distribution of vegetation in lands surrounding the Mediterranean Sea from a variety of historical and palynological sources. The Mediterranean forests of southern Europe, the Middle East, and the mountains of North Africa and the Roman agricultural belt in North Africa were restored. That distribution was substituted for present-day vegetation in the COLA GCM and the model has been integrated for both cases. The most striking difference in the simulations is that rainfall over sub-Saharan Africa is greatly affected. There is a stronger northward propagation of the ITCZ and its associated rain into the Sahel during boreal summer in the Roman Classical Period case.

A.5.3.3 Mesoscale Interactions between Sahelian Precipitation and Land-surface Patterns

The heterogeneity of vegetation distribution within a GCM grid box has not been taken into account in previous GCM simulations. Observational evidence showed that spatial heterogeneity of surface types in the HAPEX-Sahel area was high (Prince et al. 1995), with a distinct north-south gradient. Taylor et al. (1997a) found soil moisture variations to be the important cause of variations in surface energy partitioning. Hutjes and Dolman (1999) also found variations in vegetation density to be more dominant in surface energy partitioning than soil moisture in certain cases. The later work also focused on issues of aggregation of surface characteristics. Based on a vegetation classification map with 30 m resolution (Prince et al. 1997), Arain et al. (1997) aggregated vegetation parameters to the model resolution of 2 km, using either those of the dominant class or averaging each parameter appropriately weighted by subgrid relative areas of each vegetation class. Either method produced similar domain-averaged heat fluxes but the variation in fluxes differed significantly. Moreover, only aggregated vegetation parameters could, at least qualitatively, reproduce observed rainfall, whereas using dominant class parameters at the land surface did not produce any rainfall at all.

Observational evidence suggests positive surface feedback leads to persistent rainfall gradients, which are much stronger and more localised than the large-scale average. Taylor and Lebel (1998) found strong positive correlation between daily and antecedent rainfall differences at a range of time scales. In semi-arid regions this mechanism may lead to preferred and seasonally persistent rainfall patterns. The influence of antecedent rainfall on storm development is particularly noticeable when intense large-scale storms passed over areas of marked gradients in evaporation. Preliminary 2D-simulations of a single storm with resolved convective processes by Taylor and co-workers (pers. comn.) could reproduce rainfall enhancement over wet soils surrounded by dry ones. In a similar 3D-study of two consecutive storms, Hutjes and co-workers found that (pers. comn.) rain did not fall over the area wetted by the first storm, but fell instead on the still dry land.

Both preliminary studies need to have a larger number of ensembles for statistical confidence favouring either mechanism. These are two forms of a land-surface/atmosphere feedback that occurs at a much smaller scale than in previous studies, and therefore needs to be included in future regional studies of climate and mesoscale change.

A.5.3.4 Climate System Interactions in the Sahel

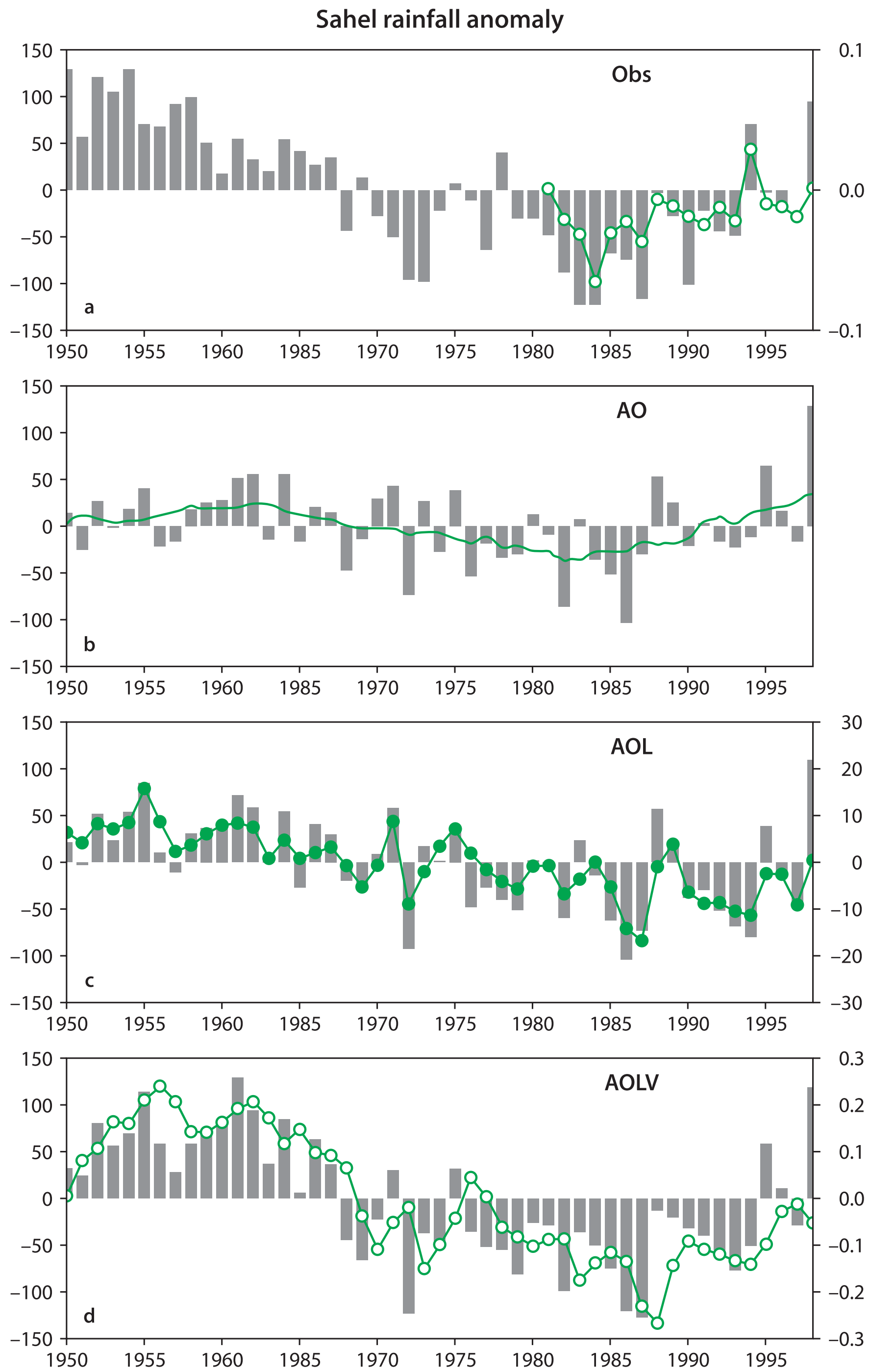
In all the studies described above, vegetation types were fixed during the period of model integration. This may be realistic for time periods of days up to a few years but obviously becomes less so for longer, decadal to centennial or even millennial scale studies, although we do not know yet how much the impact could be. The logical conclusion from the studies discussed above is that there is a need for a realistic representation of land-surface conditions in land-atmosphere models. At the same time it stresses the need to test the reverse link: responses of land-surface conditions to environmental changes.

In the past decade, a number of groups attempted to quantify the missing climate-vegetation feedbacks by coupling equilibrium biogeography models “asynchronously” to GCMs and regional models (for example, Prentice et al. 1992; Neilson and Marks 1994; Woodward et al. 1995). These vegetation models attempt to simulate global vegetation patterns and predict the potential change in vegetation distribution associated with changes in other components of the climate system. This kind of study involves an iterative procedure in which the GCM calculates a climate implied by a given land cover; and the vegetation model calculates the land cover implied by a given atmospheric-ocean condition. This process is repeated until a mutual climate-vegetation equilibrium is reached (for example, Claussen 1994).

In another type of model, the land cover is treated as an interactive element, by incorporating dynamic global vegetation models (DVGMs) within climate models in a physically consistent way (for example, Friend et al. 1993). During recent years, several studies were conducted to develop physically consistent biosphysical/biogeochemical models (for example, Sellers et al. 1996c; Dickinson et al. 1998). Attempts have also been made to develop dynamic biosphere models (Foley et al. 1998) and to use interactive vegetation models for regional climate prediction (for example, Pielke et al. 1999; Lu et al. 2001; Eastman et al. 2001a,b).

Claussen and Gayler (1997) used the first type of vegetation model developed by Prentice et al. (1992) cou-

Fig. A.41.
The role of the land surface in controlling precipitation variability in the Sahel, as inferred from the study of Zeng et al. (1999). *Top panel*: the observed anomalies in rainfall (*black bars*) and NDVI (*green dots*); *lower three panels*: modelled anomalies in rainfall (*black bars*) and vegetation (*green dots*) arising from ocean-atmosphere interactions ("*AO*"), ocean-atmosphere-land interactions ("*AOL*") and ocean-atmosphere-land-vegetation interactions ("*AOLV*")



pled to ECHAM (climate model based on the ECMWF model, version 3.2) to simulate climate evolution over the long time scales. As discussed in Sect. A.5.1.2, the climate in the Sahara during the early and middle Holocene was much wetter than today, and vegetation was found far north of the present desert border. Using an interactively coupled model, this shift in vegetation has been recaptured. On the other hand, when only an atmospheric model and present-day land-surface conditions are employed, the enhancement of simulated precipitation was insufficient to diagnose an encroachment of xerophytic woods/shrub into the Sahara north of approximately 20° N.

Using the coupled model, Claussen (1994, 1997, 1998) also found that, starting from different initial conditions, the system came to multiple equilibrium states in climate/vegetation dynamics in northern Africa. Under present-day conditions of the Earth's orbital parameters and SST, two stable equilibria of vegetation patterns were possible. One solution corresponds to present-day sparse vegetation in the Sahel and desert in the Sahara (desert equilibrium) while the second solution yielded savanna, which extended far into the western part of the Sahara (green equilibrium).

Wang and Eltahir (2000a,b) used a different modelling concept to show how different initial vegetation conditions may lead to different equilibrium climate patterns. They used a zonally symmetric two-dimensional regional model, synchronously coupled to the Integrated Biosphere Simulator (IBIS, Foley et al. 1996) biosphere model. Their surface conditions outside the tropics were fixed to NCEP (National Centers for Environmental Prediction) re-analysis climatology. IBIS is a DVM of the second type which models vegetation growth and competition explicitly. Using this model they found that the equilibrium climate pattern, as in Claussen (1994), was sensitive to the initial vegetation distribution. Starting with desert covering all of west Africa, the vegetation at equilibrium varied from tall grass near the coast to short grass and desert northward. In contrast, starting with forest all over west Africa, the equilibrium vegetation consisted mostly of forests covering most of west Africa, with a narrow grassland band in the north and a much higher productivity and rainfall than in the first case.

In addition, they showed that the new equilibrium states depended on the initial disturbances in model simulation. The system was able to recover completely in terms of vegetation distribution and rainfall when the grass biomass removal was less than 60% between 12.5 and 17.5° N. With 60–75% biomass removed, the system converged to a new equilibrium, about 40% drier and 65% less productive. When even more biomass was removed the system collapsed to a 60% drier and nearly 100% less productive equilibrium. These new drier equilibria were associated with both weaker large-scale circulation and suppressed local convection. The reason for this weakening/suppression was found to differ between wet and dry seasons. In the dry season, a degradation process that leads to higher albedo, reduced net radiation, and cooler land surface was the dominant process, while in the wet season reduced evaporation and warm land surface was the dominant process. Because the lack of the zonal wave disturbance in a 2-D model may have contributed to the existence of multiple equilibrium solutions, further studies with a 3-D model are necessary.

Recent work by Zeng and Neelin (2000) shows how interannual variability in forcing (SST) affects the multiplicity of stable climate patterns. Using a simple DVM, conceptually of the second type, they showed how in absence of SST variability (using the same SST climatology each year again) the equilibrium vegetation was sensitive to initial vegetation distribution, consistent with the findings of both Claussen and Wang. However, when real SSTs, exhibiting variability on various time scales, were used to force the model, the equilibrium climate pattern becomes nearly independent of initial conditions.

In another study, Zeng et al. (1999) also showed that the interaction between all three vegetation, soil and oceans components, best reproduces observed climate in terms of interannual precipitation variability over the Sahel. In a model run with soil moisture and vegetation fixed, precipitation showed little variability compared to the climatology of the last 50 years. Decadal variability is nearly absent and the amplitude of interannual variability is small. A run with soil moisture feedback, but with each year having the same imposed vegetation dynamics, improves precipitation variability somewhat in both respects (timescale and amplitude). Allowing vegetation to respond to precipitation/soil moisture reproduced the best-observed precipitation decadal variability and with an amplitude of the correct magnitude (Fig. A.41).

A.5.4 Understanding Mechanisms

All the experiments described above demonstrate the importance of land-surface processes in Sahel climate. Here, we analyse the mechanisms involved in the atmosphere/land-surface interactions and their relative importance for the Sahel region. The following discussion of the dominant physical mechanisms is outlined in Fig. A.42, with heavy lines representing the main processes. The major differences in the energy balance between degradation and control experiments are also listed in Table A.4 for comparison.

Vegetation degradation and soil drying increase the albedo. In the southern Sahel, when the albedo increases, more solar radiation would be reflected back into the atmosphere. However, there are fewer clouds as a result of less evaporation associated with the higher albedo. Therefore, a negative feedback occurs, and the solar radiation that reaches the ground is not significantly changed. In the northern Sahel, however, although a higher albedo increases the short-wave radiation that reflects into the atmosphere, it cannot reduce clouds any further because there are not many clouds in the first place. The values given in Table A.4 show that in the northern Sahel, where clouds are scarce, a cloud/radiation feedback is, therefore, not important and the increased albedo leads to reduced surface heating. In the southern Sahel, in contrast, the cloud/radiation interaction is particularly strong and the net short-wave radiation absorbed by the surface does not change. The net

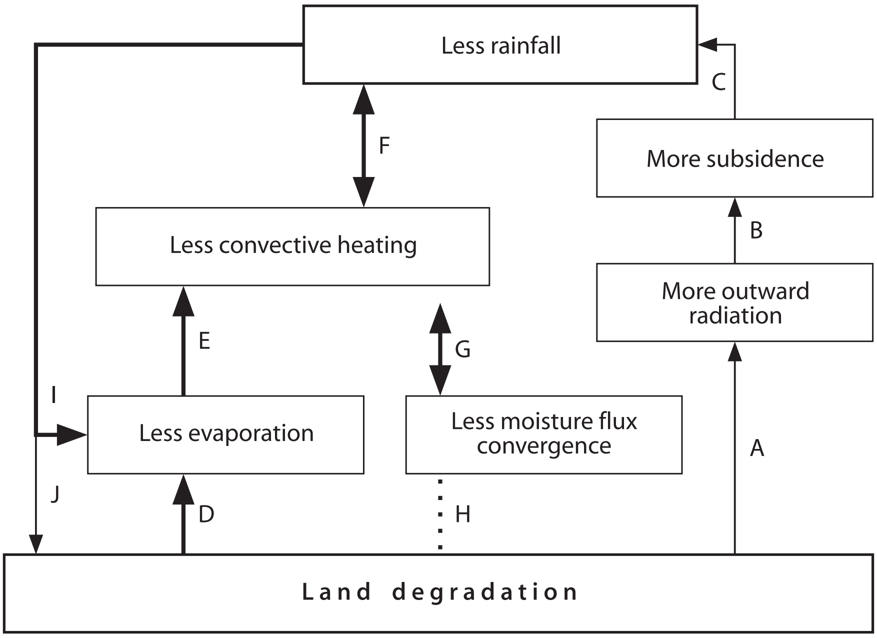


Fig. A.42.
Schematic diagram of land-surface degradation interactions and feedback processes. The *dark lines* represent the main process. The *dashed line* between the surface and MFC indicates the uncertainty of their interaction

long-wave radiation at the surface is reduced because the higher surface temperature increases outgoing long-wave radiation. The reduced cloud and water vapour in the degradation simulations also reduce the incoming long-wave radiation at the surface. However, this reduction is smaller compared with other energy components.

The changes in sensible heat flux are associated with the changes in short-wave radiation. The sensible heat flux is reduced when the short-wave radiation decreases substantially, such as in the northern Sahel. Otherwise, it increases to balance the reduction of latent heat flux in the surface budget such as in the southern Sahel. Evaporation in Table A.4 is substantially lower in both regions, correlating with the simulated rainfall reductions. Evaporation decreases partially because of the reduced net radiation, but more importantly because of lower LAI, surface roughness length, higher stomatal resistance, and changes in other vegetation and soil properties in the degradation simulations. The reduced evaporation is similar to that observed (Table A.3) when replacing the denser natural vegetation by thinner crops. Again, there is a difference between northern and southern Sahel. When there is more evaporation initially (southern Sahel), the effect is stronger.

Because of the large reduction in evaporation (see the letter E in Fig. A.42), less moisture is transferred to the atmosphere through the boundary layer. Table A.4 shows that this results in less convection and lower atmospheric latent heating rates at 500 mb, where the largest reduction occurs. (Fig. A.42, F). The lower convective latent heating rate is responsible for more than 70% of the re-

Table A.4.
Simulated ensemble mean differences between control and degradation experiments over different regions

Parameter	South Sahel[a] (JAS)[b]	North Sahel[c] (JAS)
Precipitation (mm month^{-1})	–56	–29
Latent heat flux / evaporation (W m^{-2} / mm month^{-1})	–23 / –26	–18 / –21
Sensible heat flux (W m^{-2})	10	–8
Net short-wave flux (W m^{-2})	–1	–16
Net long-wave flux (W m^{-2})	–12	–10
Total diabatic heating at 500 mb (K d^{-1})	–0.69	–0.59
Convective latent heating at 500 mb (K d^{-1})	–0.47	–0.41
Moisture flux convergence (mm month^{-1})	–29	–12
Surface temperature (K)	1.1	0.4
Albedo (W m^{-2})	0.10	0.09

[a] From 9 to 13° N and 15 to 43° E.
[b] *JAS:* July, August, September.
[c] From 13 to 17° N and 15 to 43° E.

duction in the total atmospheric diabatic heating rate in these experiments. The reduced total diabatic heating rate in the atmosphere is associated with relative subsidence, which in turn weakens the African monsoon flow, reduces moisture flux convergence (Fig. A.42, G), and lowers rainfall (Fig. A.42, F). How precisely monsoon flow and moisture convergence are affected depends on the geographical position of the land-surface anomaly as shown by Clark et al. (2001).

Early Sahel studies considered albedo as the major factor causing the long-term drought. But the dramatic albedo changes assigned in these studies and the cooling caused by high surface albedo are not supported by observations, and as a result the credibility of the land-surface effect has long been challenged (for example, Ripley 1976). In the experiments discussed above, the albedo changes were reasonable (close to the Nicholson et al. (1998) estimation). The dominant factor in diabatic cooling of the upper troposphere and enhanced subsidence appears to be the reduction of convective heating rates as a result of reduced latent heat flux and moisture flux convergence. The change in radiative heating rate was rather a secondary factor, although it may trigger other anomalous processes.

Once rainfall is affected additional feedbacks start playing a role. Reduced rainfall reduces evaporation producing a positive feedback (Fig. A.42). These feedbacks exhibit different temporal scales associated with different "memory time scales" of the processes involved. Very fast response time scales, such as hours or less, are normally associated with evaporation of moisture in the top soil layer and water intercepted by the vegetation. This process could be active during a storm (Taylor and Lebel 1998). Longer time scales, such as weeks to a season, are associated with plant transpiration, which reduce the deeper soil moisture. Yet longer time scales, such as seasons to years, are related to plant development. The study by Zeng et al. (1999) illustrates how the combination of multiple feedbacks, each with its own time constant, recreates a realistic interannual rainfall variability. When a drought is persistently long enough, the ecosystems may change or "move". This brings up issues such as ecosystem resilience as explored by Wang and Eltahir (2000b). At the longest time scales, such as centuries and longer, the additional interaction may result in "step changes" in response to gradually imposed forcings (Claussen et al. 1999).

In the above discussion, the surface evaporation is a dominant factor. However, in some cases, even surface temperature change alone could also produce a robust feedback process, such as in Charney's study (1975) and Wang and Eltahir's study (2000b). We shall not discuss this process further here since the hydrological processes are dominant in the desertification experiments presented in this chapter.

By and large, the above analysis shows that land degradation, and in particular vegetation degradation, modifies the water and energy balance as well as the partitioning of available energy over sensible or latent heat fluxes. These are first-order effects and their relative importance may vary spatially and temporally. In the atmosphere, differences in radiation, latent and sensible heat inputs lead to altered heat and moisture contents within the atmospheric boundary layer. This effect produces a feedback to the surface through atmospheric stability conditions and other environmental factors, which control stomatal behaviour of plants, thus creating a first potential loop. Meanwhile, the turbulence fluxes and thermal structure within the boundary layer also affect convective heating, total diabatic heating, subsidence, and moisture convergence. All these processes affect cloud formation, precipitation and the strength of the monsoon flow. Clouds strongly affect radiation flux transfer and create the second potential feedback loop. When precipitation is affected, additional feedback loops are activated through soil moisture storages, vegetation growth and phenology, and eventually ecosystem changes.

A.5.5 Conclusion

Research on Sahelian land-surface/atmosphere interactions has been continuing for several decades. It started with a very simple model with even no water in it (Charney 1975). During the early 1980s, a number of studies were conducted by simple bucket type of land models coupled with GCMs. The vegetation models were introduced from the late 1980s. All this research showed a consistent result: the Sahelian climate is sensitive to the local land-surface processes.

In the introduction, we have raised several issues related to land-surface/atmosphere interaction in the Sahel region. This Chapt. A.5, by reviewing the relevant research during the past two decades, has aimed at understanding and clarifying these issues. The answer to question one in the introduction is apparently positive. In principle, land-surface changes can result in rainfall reductions of the observed magnitude. The studies discussed in Sect. A.5.3.2 illustrate this. If changes in vegetation properties between the 1950s and the 1980s were comparable to the specified control/desertification differences in that study, the results indicate that the degradation could lead to regional climate changes of the order of the differences found between the 1950s and the 1980s, with increases in the surface air temperature, and reductions in the summer rainfall, runoff, and soil moisture over the Sahel region. The impact is not only limited to the specified desertification areas and the JAS period but it also affects the region south of this area and continues into the OND period in East Africa. All these results are in line with the observed climate anomalies, which suggest that the climate anomaly during the 1980s could be due to land-surface processes. While early studies attributed the drought primarily to a albedo/radiation driven process chain, we now realise that an evaporation/convection driven process chain is probably more important.

An apparent shortcoming in sensitivity studies was that the specified land-cover changes and simulated land-surface energy and water balances at the surface were not verified by observations. The SEBEX and HAPEX-Sahel field experiments provided very important information of land-surface processes in the Sahel region. These field measurements have led to a considerable increase in our understanding of the surface energy balance at the Sahelian land surface and in particular the interplay between the hydrological responses of soil and vegetation.

In general, these experiments have resulted in improved calibration and validation of the surface biosphere models. Our knowledge of physical and biological characteristics of soil and vegetation and energy and hydrological processes has improved significantly (e.g. Taylor and Blyth 2000; Xue et al. 1996a). These spatial analyses are leading to a strategy for the aggregate description of the landscape in these regions where both the rainfall and the vegetation have high spatial variability. However, since all these measurements were conducted in one region, it is difficult to apply the results to the continental scale. Therefore, new field measurements should cover much larger areas and should include more typical vegetation. In addition, long-term measurements, which include at least a few growing seasons, are necessary to understand the seasonal and interannual variability in the region. Both the SALT and CATCH projects seek to fill these needs.

Satellites have provided land-surface conditions since the late 1970s. The various results discussed before (Sect. A.5.2.5) demonstrate the great potential in applying the satellite dataset for Sahel studies. These data provide temporal and spatial variations of land-surface conditions over the entire globe and cannot be obtained from any other method. They can also be and have been used to specify land-surface conditions more realistically in model simulations, although more research is needed to develop and validate the methodology used to convert satellite signals to vegetation characteristics and other land-surface information. In addition, they provide useful information for potential validations of dynamic vegetation models, which we believe has not yet been attempted. The full potential of satellite measurements should be explored further.

Our knowledge of the role of vegetation dynamics in the Sahelian drought has also greatly improved recently by the use of dynamic vegetation models. Although such models are still at the preliminary stage, several studies with African climate as a prime subject have demonstrated their promising potential. Thus far, these studies focused on time scales of decades and centuries. Further development in coupled dynamic vegetation-atmosphere models and more realistic simulations at seasonal-interannual-decadal scales are necessary.

The field experiments, satellite data, off-line land-model validations, dynamic vegetation models and coupled models greatly help us to understand land-surface processes and the roles of soil and vegetation in these processes, and the influence and mechanisms of land-surface/atmosphere interactions (Questions 2 and 3 in the introduction).

As to the real land-cover change in the Sahel, we may never know the real scope of the changes that occurred during the past half century. However, it is undeniable that the human population in Sahel has increased substantially over the last 50 years. The rise in population and projected further increases have caused, and will continue to cause, extensive conversion of land from natural vegetation to agriculture, and increasing demand for fuelwood and grazing (Stephenne and Lambin 2001). Currently, work is under way to use this type of information to produce more realistic reconstructions of land-surface dynamics over the past 40 years and to make projections in to the future (Taylor pers. comn.). This line of research will eventually provide a better answer to the question of whether it is really population pressure leading to land degradation that leads to desertification. We now know it could; we may soon know whether it did, and what might happen in the future. This should partially answer the Questions 4 and 5.

At this stage, we still cannot decide whether the current drought is a temporary phenomenon, what is the exact role of humans in its cause, or what kind of possible remedy should be taken (Question 6). One area that remains unclear is how well the normal and degraded vegetation scenarios specified in the Sahel represent the real land-surface conditions in the 1950s and the 1980s, as reliable information is unavailable. With the dynamic vegetation models, we may be able to assess more realistically the role of SST, land-surface processes, and other processes in the long-term African drought.

However, we might come closer to answering this question by looking at other regions undergoing similar desertification trends, such as Inner Mongolia (see Chapt. A.8 and Xue 1996). To decide whether such droughts are "permanent", at least on human time scales, we may look back into the distant past that some groups have begun to explore (Claussen et al. 1999).

The present chapter demonstrates that changes in surface properties caused by intensification of land use may have had serious consequences for the regional climate. To avoid such consequences, the implementation of sustainable resource management policies must be a priority. Xue and Shukla (1996) demonstrated that widespread afforestation of the Sahel might reverse the regional climate changes caused by land degradation. In this chapter we mainly presented the biophysical process studies for the Sahel area. We believe other dimensions of the Sahelian droughts, e.g. water resources, food security issues, and human activity (socio-economic and political drivers of land-use change), should be much more tightly integrated with physical process studies. Thus new links in the process chains may be discovered, leading to better reconstruction of past and better predictions of future climate changes and anomalies in this sensitive region.