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The role of the land surface in Sahelian climate: HAPEX-Sahel results and future research needs

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refining the hydrological aspects of the climate circulation models.'' HAPEX-Sahel was designed to provide the data that Charney and many others since were calling for. This paper summarizes how the data have been used by the authors of this Special Issue and attempts to produce a broad picture of the role of land surface processes in determining the climate of the Sahel.

In the 5 years since HAPEX-Sahel was planned, the perception of the Sahelian problem has changed. Desertification is now no longer seen as a regional threat in which the whole of the Sahel is irreversibly being converted to desert. Rather it is recognized that a combination of local and external forces may, by reducing both vegetation and rainfall, lead to the degradation of the land surface, which may in extreme cases be permanent. Population pressure leads to the conversion of natural vegetation to arable agriculture, which in turn puts more pressure on the remaining natural vegetation both as grazing land, as a resource for fuel wood and as a fallow rotation. However, the central question that Charney, and many others since, posed remains: how does this vegetation influence the climate of the Sahel, and is the long-term decline in Sahelian rainfall connected to changes in vegetation?

Before HAPEX-Sahel, experiments with global circulation models (GCMs) predicted a sensitivity of the Sahelian climate to changes in roughness and albedo (e.g. Laval and Picon, 1986; see also Xue and Shukla, 1993). A change from savannah grassland to a smoother, more reflective, desert surface of bare soil was predicted to result in less rainfall. These early experiments were run with land surface schemes which were relatively simple compared with the more realistic soil–vegetation–atmosphere schemes (SVATS) which are in current use (e.g. Xue et al., 1996). Future GCM experiments will be carried out using the current generation of SVATS calibrated against HAPEX-Sahel data. New methods to derive the information needed to initialize large-scale models will be applied, as will new aggregate representations of the model parameters at the 1° grid square scale. This will make the GCM predictions more realistic and more credible. However, before these modelling experiments begin, it is timely to consider what has been learnt from HAPEX-Sahel in terms of how the region functions, so that model sensitivity experiments can be designed to test realistic future scenarios. In this paper the results presented in the HAPEX-Sahel Special Issue are drawn together to give a broad picture of current understanding of how the vegetation types that have been studied differ in their energy, water and carbon balances, how the hydrology interacts with the rainfall and the vegetation and how the boundary layer and mesoscale meteorology behave in response to different local and external forces. The results are graphically displayed in Fig. 1. This paper draws primarily on results presented in this Special Issue, although important results using

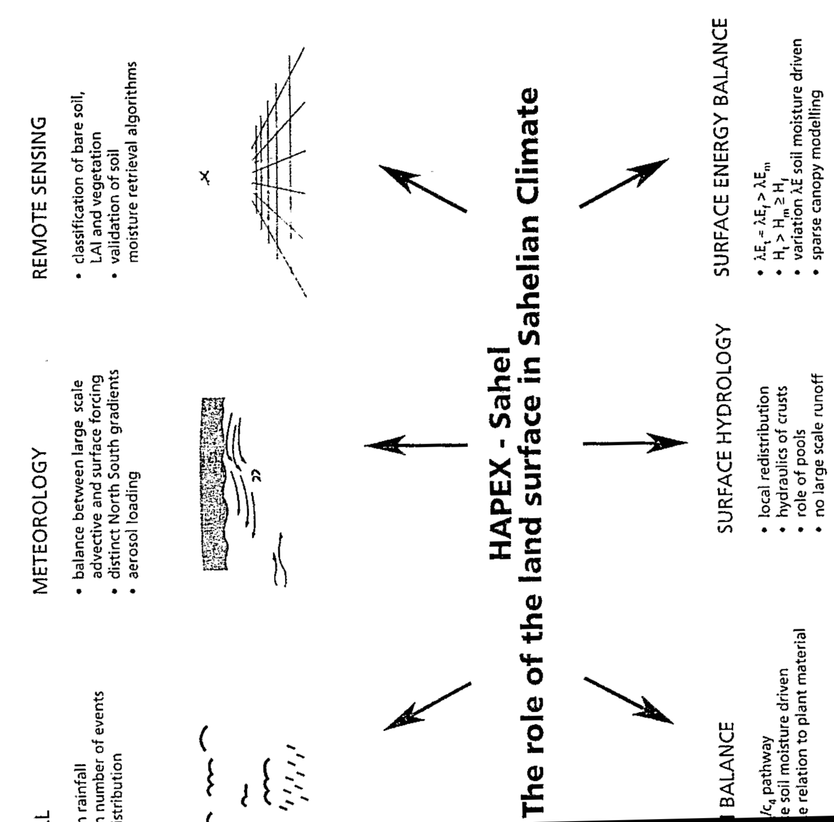

Fig. 1. Schematic representation of the key results of HAPEX-Sahel.

observations have focused on the anomaly in seasonal rainfall compared with the long-term average. Using the unique opportunity provided by the EPSAT-Niger network, Lebel et al. (1997) found that interannual variations in the observed rainfall are associated with a decrease in the number of events, rather than in the size of the event. Furthermore, they found that the length of the rainy season is not strongly correlated with its strength. Le Barbé and Lebel (1997) investigated the 1950 to 1990 rainfall records of Sahelian Niger and drew the same conclusion.

The long-term average rainfall declines along a south–north gradient and the vegetation gradient generally follows (d'Herbès and Valentin, 1997). During HAPEX-Sahel, the rainfall gradient was not strictly south–north but followed a more east–west orientation (Lebel et al., 1997). However, it is important to stress that the main feature of rainfall during HAPEX-Sahel was the patchy character and lack of a pronounced gradient in any direction. There was a large variation in the temporal (seasonal) and spatial distribution of rainfall between the supersites. This is reflected in the soil moisture content of the different soils under the three main vegetation types (Cuenca et al., 1997) and between the supersites.

Spatial analysis of EPSAT-Niger data (Lebel et al., 1997) has also generated insight in the parameterization of rainfall under convective conditions in current GCMs. Current GCMs attempt to take account of subgrid variability in rainfall patterns by concentrating rainfall into a fraction of the grid. The size of this fraction depends on whether the rainfall is of convective or frontal origin, but for convective rain, as is found in the Sahel, the figures are typically between 0.1 and 0.3. However, Lebel et al. (1997) find a 0.75 probability of any location having rain when there is a rainfall event within the HAPEX-Sahel gridsquare. These two figures are not directly comparable due to differences in the time-scales to which they refer, but clearly HAPEX-Sahel has generated a data set which allows testing of the important assumption in GCM parameterizations as to how to concentrate rainfall. The HAPEX-Sahel data set should also allow testing of some of the temporal assumptions in GCM convection schemes.

The spatial variation in rainfall ...

super site or the HAPEX-Sahel grid, the water balance becomes again mostly one-dimensional: runoff being virtually zero at this scale. Because of the non-linearities involved, it is important to parameterize subgrid runoff processes to arrive at a meaningful water balance for a GCM gridbox.

2.2. Surface energy balance and evaporation

At the scale of the HAPEX-Sahel grid square, aquifer recharge is thus determined by the balance between rainfall and evaporation. In this context the findings of Gash et al. (1997) suggest a direct mechanism by which the land surface potentially may influence both the climate and aquifer recharge. They find substantially less evaporation from millet than from the two natural vegetation types: fallow savannah and tiger bush. Less evaporation may imply under Sahelian conditions, increased aquifer recharge, although the infiltration at plot scale is small (see Gaze et al., 1997; Leduc et al., 1997). Less evaporation may also ultimately reduce the moisture content of the atmosphere, thereby decreasing the rainfall. This suggests that on a regional scale the evaporation may have been reduced as the area of millet has increased at the expense of the fallow areas. At present, an increase in infiltration under millet (Leduc et al., 1997) has been observed over the last 4 years, suggesting that the evaporation reduction is greater than the general reduction in rainfall. In the final section of this paper the nature of these feedbacks are discussed more extensively. In the future adequate monitoring of land use and the possible subsequent changes in hydrological properties (d'Herbès and Valentin, 1997) will be needed to produce stable and sustainable management plans for the area.

The major vegetation types of the study area all have incomplete canopy cover. Both millet and fallow have substantial amounts of exposed bare soil and the sparse canopy finds its ultimate expression in tiger bush. This has proven to be an important feature in modelling vegetation atmosphere interaction in HAPEX-Sahel. Several papers in this issue deal with different aspects of ...

It is tempting to use these results to speculate on the evolution of the different vegetation types in the Sahel. Assuming a leaf area of about 4 for the vegetated part of the tiger bush, the overall leaf area index of tiger bush would be in the range to 1 to 1.25, roughly similar to those of fallow savannah and mature millet. This suggests that given similar evaporative

most important, followed by roughness length, and that LAI had only a small direct effect on both simulations. HAPEX-Sahel has increased our understanding of these interactions and the data will hopefully continue to provide a testbed for future modelling efforts.

Similarly, the findings related to carbon uptake and respiration, point to the need to take of boundary layer response. In the wet period boundary layer growth appeared to be mainly driven by advection of moist air from the south and vertical flux divergence; whereas during the dry period subsidence increased the surface driven drying of the

maps, is important, not only for initializing mesoscale models, but also for identifying hydrologically active land surface areas (d'Herbès and Valentin, 1997). For instance, considerable progress has been made in applying linear mixture models to deconvolve causes a decrease in convective potential energy, which in turn limits the number of times convection is triggered. According to the Polcher hypothesis an increase in heat flux causes more potential energy to be generated, thus leading to an increase in the number of convective events and rainfall. The actual rainfall (moisture convergence) in this case is primarily sustained by features of the large-scale, global circulation, which in the case of the Sahel, supply moisture through the south-west monsoon. This mechanism can be modulated by evaporation which may alter the regional moisture availability, thereby changing some of the rainfall characteristics, such as the amount of rain and the length of the storm.

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has provided a wealth of data on land use and cover, surface fluxes, hydrology and boundary layer data, which can be used to initialize and test models. Sophisticated meso-scale models can take into account the variation in surface properties and thus investigate the opposing roles of the land surface and large-scale synoptic forcing. The data obtained in the boundary layer programme (Dolman et al., 1997; Wai et al., 1997) and in the modelling programme (Taylor et al., 1996) clearly indicate that such studies are needed to unravel the complex interactions taking place in the Sahel.

Rainfall is of course the prime driver of the 'conjoncture' in the Sahel. The amount and [illegible]

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