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

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Abstract

This paper summarizes the results of HAPEX-Sahel presented in this Special Issue to produce a broad picture of the role land surface processes play in determining Sahelian climate. It highlights key achievements in the field of rainfall analysis, surface hydrology, surface energy and carbon balance, and large-scale meteorology and remote sensing. It discusses further research needed to understand the role of the land surface in the Sahel and makes some suggestions as to how to approach this problem through further modelling and data analysis, making use of the increased understanding produced by HAPEX-Sahel.

1. Introduction

It is more than 20 years since Charney (1975) wrote "One can speculate about bio-meteorological feedback cycles, but one needs more numerical experimentation and, above all, more data on physical changes in the region during pluvial and drought periods. Also hydrological information and data on evapo-transpiration in plants will be needed for

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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 HAPEX-Sahel data have also been published elsewhere.

2. Key results from HAPEX-Sahel

2.1. Precipitation and its redistribution on the surface

GCM studies so far (e.g. Xue and Shukla, 1993) have focused on the total reduction in rainfall following desertification. Similarly, analyses of the time series of rainfall

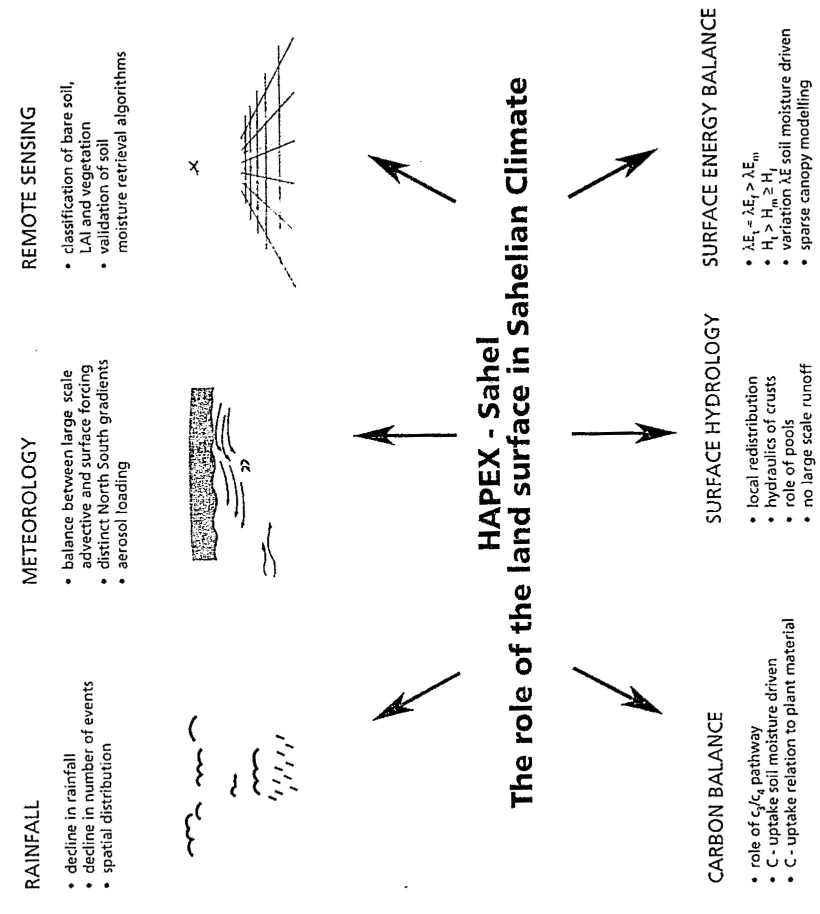

Fig. 1. Schematic representation of the key results of HAPEX-Sahel.

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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 produces a surface and subsurface hydrology which is highly spatially varying and which makes conventional hydrological modelling problematical. Peugeot et al. (1997) and Desconnets et al. (1997) illustrate the complexities of rainfall–runoff patterns in the Sahel. Peugeot et al. (1997) find no effect of vegetation on locally produced runoff for natural vegetation such as tiger bush and fallow savannah. Locally the runoff is strongly influenced by the spatial distribution of crusts, the hydraulic properties of which tend to increase runoff in crusted areas, and concentrate infiltration in non-crusted areas. At the field scale the measurement of runoff thus reflects this small-scale redistribution of rainfall. For hydrological modelling at field scale the correct specification of crusted and non-crusted areas is thus very important (Braud et al., 1997).

At a larger scale the spatially discontinuous surface flows tend to produce irregular flow patterns and finally form pools. At subcatchment scale, pools are the only reliable hydrological integrators controlling infiltration and recharge, and at this scale local effects dominate the water balance. The consequence of this high degree of irregularity is that at catchment scale no reliable estimates of the water balance can be given unless local characteristics are taken into account. At the much larger scales than the pools, say the 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 sparse canopies (Jacobs and Verhoef, 1997; Wallace and Holwill, 1997; Braud et al., 1997; Gash et al., 1997; Kabat et al., 1997; Lhomme et al., 1997; Troufleau et al., 1997; Tuzet et al., 1997). Generally these papers present observational and modelling evidence related to the interaction of bare exposed soil and the overlying canopy or vegetation. Gash et al. (1997) and Kabat et al. (1997) present observational evidence showing that the variability in evaporation rates on a diurnal basis is primarily determined by fluctuating rates of soil evaporation during the wet season. For the tiger bush, the contribution from soil evaporation may reach 28% of the annual rainfall (Wallace and Holwill, 1997).

Although tiger bush and fallow savannah are structurally quite different, results from HAPEX-Sahel (Gash et al., 1997; Kabat et al., 1997) have shown that over the length of the rainy season they have similar evaporation rates. However, this similarity hides a number of important differences between the two vegetation types. Despite the fact that the larger albedo and higher surface temperature of the tiger bush bare soil produce a lower available energy, the amount of bare soil gives rise to higher rates of sensible heat loss from the tiger bush as compared to fallow savannah. Part of this heat is used to boost transpiration rates by the vegetated part (e.g. Kabat et al., 1997), but a considerable amount is released to the atmosphere, where it will influence the temperature of the boundary layer.

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 demand and rainfall, structurally different vegetation types with similar leaf area indices may evolve in a particular environment, depending on local soil conditions (Thierry et al., 1995). This additional complexity is not represented in simple climate-dependent biome models (Woodward, 1987). These vegetation types can also have different energy balances, which may exert a different feedback on the climate.

2.3. Carbon exchange

That rainfall is a key driver of local surface differences is also apparent from the carbon studies. HAPEX-Sahel was the first international experiment where continuous flux measurements of CO_2 were successfully undertaken for an extended period covering the 2 months of the IOP (Moncrieff et al., 1997a). Eddy-covariance systems comprising 3-D sonic anemometers and closed path infrared gas analysers were deployed at several of the vegetation subsites in HAPEX-Sahel. It appeared from these measurements that the magnitude of the CO_2 flux depended strongly on the timing of vegetation growth and senescence (Moncrieff et al., 1997b). This was also found from harvest measurements (Hanan et al., 1997), who noted that net production was primarily driven by the amount of photosynthetically active plant material.

The relative proportion of C3 and C4 plants in a canopy is another important factor in determining both the behaviour of the surface conductance and CO_2 flux (Hanan and Prince, 1997; Kabat et al., 1997; Moncrieff et al., 1997b). Due to different pathways of CO_2 fixation C3 and C4 plants show different responses to environmental conditions, as is apparent from their different water use efficiency. Towards the end of the IOP this effect became visible in the decline of the evaporation and CO_2 flux of the fallow savannah vegetation. As the grasses, which comprise most of the active vegetation mass in the fallow savannah, began to experience soil moisture deficits due to their shallow rooting, the evaporation flux declined rapidly, while the CO_2 flux remained at relatively high levels. Monteny et al. (1997) show how this effect results in a measurable increase in CO_2 concentration in the atmospheric boundary and surface layers. It is uncertain if such an increase results in a noticeable effect on the water and energy cycles in the Sahel.

The implications of these observations for modelling water, energy and carbon exchange are profound. Not only will models have to differentiate between bare soil and vegetation, but also the carbon fixation pathways of plants need to be taken into account. As land degradation progresses, it is likely that this will be through a progressive increase in the amount of bare soil relative to the vegetation mass which may change the albedo and aerodynamic characteristics of the land surface cover. Predicting the likely effects of this change on the hydrology, ecology and climate of the area, will rely heavily on the ability of the current generation of land surface models to model the interaction between exposed bare soil and vegetation. Xue et al. (1996) recently used HAPEX-Sahel data and investigated the sensitivity of both GCM and stand alone land surface models to changes in groups of its parameters for the Sahel. They conclude that albedo changes were 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 C3 and C4 plant behaviour into account in land surface models. Land surface models increasingly incorporate submodels of carbon fixation and photosynthesis and link these to surface conductance and leaf area growth. Hanan et al. (1997) have compared simplified photosynthesis models that depend on light limitation and carbon diffusion pathways to the HAPEX-Sahel results. Although agricultural models have taken this interaction into account for a number of years, the climate modelling community has been relatively slow to recognize the importance of the linkage between the carbon, and water and energy cycles at the diurnal and seasonal timescales. The data set generated in HAPEX-Sahel has not only shown the close linkages between carbon and water (e.g. Moncrieff et al., 1996), but also provides an excellent opportunity to test the new models for both natural and agricultural vegetation in the Sahel. Ultimately these models will be used in studies of reciprocal vegetation–atmosphere interaction in which vegetation is allowed to respond dynamically to changes in ambient CO_2 and climate.

2.4. Meteorological feedbacks

HAPEX-Sahel was designed not only to look at the local fluxes of energy, water and carbon, but also at the larger (meso) scale meteorology. Due to the inherent complexity of the problem, a combined modelling and experimental programme was put in place. Dolman et al. (1997) and Wai et al. (1997) analysed the radiosonde data obtained in HAPEX-Sahel, whilst Saïd et al. (1997) used aircraft data to study the spatial variation in surface fluxes. Using a mesoscale model as an integration tool, Taylor et al. (1996) looked at the evolution of the boundary layer over the HAPEX-Sahel grid. Goutorbe et al. (1997) applied one-dimensional modelling techniques to understand the evolution of the boundary layer in the Sahel.

Rainfall also appears to be a key determinant in boundary layer behaviour. Differences in boundary layer growth, temperature and moisture content were observed between the Southern and Central sites during the latter part of the IOP (Dolman et al., 1997). During the wet period the differences were small. Aircraft observations (Saïd et al., 1997) corroborate this picture, with the existence of a clear gradient with humidity and temperature declining along a north–south gradient. The sensible heat flux shows a similar gradient, but the latent heat flux, which is more directly related to antecedent rainfall (Gash et al., 1997) shows a more random pattern over the square. These measurements show that the climatic effects of rainfall at the larger scale follow the generally observed north–south gradient in rainfall, but that these effects are modified at the smaller scale by local variations in rainfall.

All studies point to the complicated balance between surface driven variation and large-scale flow patterns. During the IOP the ITCZ (Inter Tropical Convergence Zone) was moving southwards, and associated with it was a low level south-westerly monsoon, bringing cold, humid air into the area. Overlying this was a dry north-easterly flow from the Sahara (see Wai et al., 1997). This flow situation created a complicated pattern 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 boundary layer. Goutorbe et al. (1997) point to the importance of the radiation divergence as a result of the high aerosol loading of the Sahelian atmosphere in determining the growth of the boundary layer.

Any variation in surface vegetation characteristics which could potentially induce variation in boundary layer properties appears to be masked by the overriding influence of the large-scale synoptic flow pattern (Taylor et al., 1996). Although the Taylor et al. (1996) mesoscale model study was performed for a single day, the analyses by Wai et al. (1997), Dolman et al. (1997) and Saïd et al. (1997) basically support the view that vegetation driven changes in boundary layer response may not always be visible. This is the result of the masking effect of large-scale advection. More detailed analysis of the synoptic data and future modelling studies using HAPEX-Sahel data may help to clarify this problem.

2.5. Aggregation and remote sensing

Modelling the land surface heterogeneity in the Sahel requires careful mapping of land surface parameters, rainfall and soil moisture for model initialization. Although HAPEX-Sahel was designed to answer the basic questions regarding aggregation, relatively few modelling studies in this Special Issue have been using HAPEX-Sahel data for that purpose. This is partly a result of recently increased understanding of how to aggregate small-scale land surface variability and partly due to the fact that aggregation modelling studies require several complex data sets to be ready at the same time. Recent studies (Blyth et al., 1993; Dolman and Blyth, 1997; Noilhan et al., 1997) have shown that for situations with small variability in land surface characteristics simple averaging rules may work well. This is confirmed for aggregation of the main vegetation types in the Southern supersite by Blyth (1997) who shows that by applying linear averaging of conductances, average evaporation can be estimated to within 5%. However, the current theoretically based aggregation rules for both vegetation and soil (Kabat et al., 1997) still need further testing and development against the real observations of HAPEX-Sahel.

To arrive at a useful area average parameter value, it is essential to know the distribution of parameter values in a particular (model) domain. Remote sensing may come to its full potential here. The remote sensing studies in HAPEX-Sahel can be divided into those dealing with microwave remote sensing and those dealing with optical wavebands. The use of the PBMR (Push Broom Microwave Radiometer) and the PORTOS instruments has for the first time made it possible to estimate the regional distribution of (surface) soil moisture (Chanzy et al., 1997; Teng et al., 1997). Such information is particularly valuable in the initialization of soil moisture fields for mesoscale models. In their study Taylor et al. (1996) had to produce large-scale estimates of soil moisture by applying a simple distributed water balance model using both surface and remotely sensed rainfall data as input. At the larger scale Magagi and Kerr (1997) retrieved soil moisture from the ERS-1 wind scatterometer.

The classification of vegetation, or the derivation of spatially distributed parameter

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 plant and soil spectral signatures (van Leeuwen et al., 1997). They were successful in deriving LAI (leaf area index) and fAPAR (fraction Absorber Photosynthetically Active Radiation) from remotely sensed images for the HAPEX-Sahel square. Barnsley et al. (1997) report the successful retrieval of BRDFs (Bidirectional Reflectance Distribution Function) from remotely sensed imagery, but also mention that routine application of the retrieval algorithms of these parameters from large-scale images is as yet problematical.

Other studies looked at the possibility of deriving physically or physiologically meaningful parameters from remote sensing. Hanan et al. (1997) investigated the use of IPAR (Intercepted Photosynthetically Active Radiation) estimation methods in estimating canopy photosynthesis and primary production, whilst Chehbouni et al. (1997) applied more conventional methods to derive sensible heat flux from remotely sensed surface temperature. Especially for the latter studies, the interaction between bare soil and canopy still presents major problems (Lhomme et al., 1997; Troufleau et al., 1997)

3. A perspective on future research needs

The ability of simple correlation models of sea surface temperature and rainfall to predict Sahelian rainfall, and the results of GCM studies showing the influence of the land surface on Sahelian rainfall (Xue and Shukla, 1993), have been a source of conflicting arguments about the role of the land surface in rainfall generation in the Sahel (Rowell et al., 1995). The results of HAPEX-Sahel may point to the answer that rainfall generation in the Sahel is a rather complex interplay between large-scale mechanisms operating at continental scale and mesoscale mechanisms influencing rainfall regionally (e.g. Xue and Shukla, 1993; Taylor et al., 1996).

Rainfall in the Sahel is associated with the movement of the ITCZ and organized westward travelling disturbances, the squall lines. Polcher (1995) recently demonstrated that changes in rainfall following changes in the land surface in GCMs, can be interpreted by classifying convection through differences in potential energy divergence. His analysis provides a useful framework to understand the recent changes in Sahelian rainfall and the role of the land surface therein. It also suggests new research paths which may lead to a better understanding of the Sahelian drought. Polcher identified three classes of tropical convective events, of which two are relevant for the Sahel: weak convective events and strong convective events. These can be differentiated by their potential energy. In this context it is important to distinguish between a change in rainfall due to a change in the number of events, and a change in the rainfall rate and length of the event: the characteristic precipitation (Polcher, 1995).

Le Barbé and Lebel (1997) have concluded that the interannual variation in rainfall in Niger can be largely explained by a decrease in the number of events, rather than a change in characteristic precipitation. This observed decrease in the number of convective events is consistent with the original Charney (1975) hypothesis, as recently reformulated by Polcher (1995), whereby a decrease in sensible heat flux through an increase in albedo 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.

How does this arguably simple, but appealing picture relate to HAPEX-Sahel results? The observations during HAPEX-Sahel suggest that a large-scale transformation of fallow savannah into arable crops like millet, may lead to a decrease in evaporation (Gash et al., 1997). This could have two effects: it could decrease the availability of moisture and act to reduce the characteristic rainfall, while at the same time generating more sensible heat which would act to increase precipitation. It is interesting to note that land degradation usually leads to more exposed bare soil. This would tend to increase the sensible heat flux (e.g. Gash et al., 1997; Kabat et al., 1997) and would counterbalance a potential decrease of rainfall through increased albedos. HAPEX-Sahel observations thus do not a provide straightforward answer to the questions of rainfall generation in relation to land surface change, but point rather to the complexity of the issue and the need to tackle these with land surface models which take account of the complex interactions in semi-arid vegetation.

It is interesting to compare this picture of land surface atmosphere interaction with more simple theories of rainfall generation through recycling (e.g. Monteny, 1986; Savenije, 1995). According to Polcher (1995) recycling relates primarily to changing the size of the characteristic event. In conditions of weak convection surface evaporation contributes relatively strongly to the potential energy of a convective event (Polcher, 1995), but this is not the case in conditions of high convective activity where the source terms are dominated by large-scale moisture convergence and internal energy conversion. Weak convective events play a role at the onset and end of the rainy season, while strong convective events are associated with the peak of the rainy period and the ITCZ. Le Barbé and Lebel (1997) further substantiate this hypothesis of a reduced number of events by showing that the mean event rainfall is rather constant during the core period of the rainy season, but fluctuates more at the beginning and end. This suggests that the role of surface evaporation is relatively small at the peak of the rainy season, but may become important at the beginning and end of the rainy season. However, Xue and Shukla (1993) report that the number of events in the form of squall lines remains similar when, in their GCM, shrub was replaced by desert. Clearly further large-scale modelling work is needed here to elucidate the precise mechanisms involved, but a consistent picture appears to be emerging of mesoscale processes interacting with larger scale phenomena to generate a complex pattern of space and time variability of rainfall in the Sahel.

This modelling work should not only look at large-scale mechanisms of rainfall generation, but also at processes which may affect is regional redistribution. It is important to note that at this scale rainfall is primarily a mesoscale process, where local-scale features may be important drivers in producing regional variability. The HAPEX-Sahel experiment 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 mesoscale 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 timing of rainfall critically determines the productivity of arable crops and of natural vegetation used for grazing. This is also evident from the results of the carbon work in HAPEX-Sahel: carbon fluxes (photosynthesis) are strongly dependent on the amount of photosynthetically active plant material, the growth of which is primarily determined by the rainfall pattern (Moncrieff et al., 1997b). The data and early insights obtained in the HAPEX-Sahel programme can now be used to perform more realistic impact studies of changing climate on agricultural production and net primary production from natural vegetation. Such studies are needed to develop sustainable management plans for the region. They are urgent because the population increase in the Sahel appears to be leading to a situation where traditional farming methods are no longer sufficient to sustain the demand for food. The land degradation aspects of these changes will need to be fully understood. HAPEX-Sahel data on hydrology, plant water use and growth is now available as a primary source of knowledge for developing management plans for the area.

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References

Barnsley, M.J., Lewis, P., Sutherland, M. and Muller, J.P., 1997. Estimating land surface albedo in the HAPEX-Sahel Southern Super-site: inversion of two BRDF models against multiple ASAS images. J. Hydrol., this issue.

Blyth, E.M., 1997. Representing heterogeneity at the Southern Super site with average surface parameters. J. Hydrol., this issue.

Blyth, E.M., Dolman, A.J. and Wood, N., 1993. Effective resistance to sensible- and latent-heat flux in heterogeneous terrain. Q.J.R. Meteorol. Soc., 119: 423–442.

Braud, I., Bessemoulin, P., Monteny, B., Sicot, M., Vandervaere, J.P. and Vauclin, M., 1997. Unidimensional modelling of a fallow savannah during the HAPEX-Sahel experiment using the SiSPAT model. J. Hydrol., this issue.

Chanzy, A., Schmugge, T.J., Calvet, J.-C., Kerr, Y., van Oevelen, P., Grosjean, O. and Wang, J.R., 1997. Airborne microwave radiometery on a semi-arid area during HAPEX-Sahel. J. Hydrol., this issue.

Charney, J.G., 1975. The dynamics of deserts and droughts. Q.J.R. Meteorol. Soc., 101: 193–202.

Chehbouni, A., Lo Seen, D., Njoku, E.G., Lhomme, J.-P., Monteny, B. and Kerr, Y.H., 1997. Estimation of sensible heat flux over sparsely vegetated surfaces. J. Hydrol., this issue.

Cuenca, R.H., Brouwer, J., Chanzy, A., Droogers, P., Galle, S., Gaze, S.R., Sicot, M., Stricker, J., Angulo-Jaramillo, R., Boyle, S.A., Bromley, J., Chebouni, A.G., Cooper, J.D., Dixon, A.J., Fies, J.C., Gandah, M., Gaudu, J.C., Laguerre, L., Lecocq, J., Soet, M., Steward, H.J., Vandervaere, J.P. and Vauclin, M., 1997. Soil measurements during HAPEX-Sahel intensive observation period. J. Hydrol., this issue.

d'Herbès, J.M. and Valentin, C., 1997. Land surface conditions of the Niamey region: ecological and hydrological implications. J. Hydrol., this issue.

Desconnets, J.C., Taupin, J.D., Lebel, T. and Leduc, C., 1997. Hydrology of the HAPEX-Sahel central Super-Site: surface water drainage and aquifer recharge through the pool systems. J. Hydrol., this issue.

Dolman, A.J. and Blyth, E.M., 1997. Patch scale aggregation of heterogeneous land surface cover for mesoscale meteorological models. J. Hydrol., in press.

Dolman, A.J., Culf, A.D. and Bessemoulin, P., 1997. Observations of boundary layer development during the HAPEX-Sahel intensive observation period. J. Hydrol., this issue.

Gash, J.H.C., Kabat, P., Monteny, B.A., Amadou, M., Bessemoulin, P., Billing, H., Blyth, E.M., deBruin, H.A.R., Elbers, J.A., Friborg, T., Harrison, G., Holwill, C.J., Lloyd, C.R., Lhomme, J.-P., Moncrieff, J.B., Puech, D., S ögaard, H., Taupin, J.D., Tuzet, A. and Verhoef, A., 1997. The variability of evaporation during the HAPEX-Sahel intensive observation period. J. Hydrol., this issue.

Gaze, S.R., Simmonds, L.P., Brouwer, J. and Bouma, J., 1997. Measurements of surface redistribution of rainfall and modelling its effect on water balance calculations for a millet field on sandy soil in Niger. J. Hydrol., this issue.

Goutorbe, J.P., Noilhan, J., Lacarrere, P. and Braud, I., 1997. Modelling of the atmospheric column over the Central sites during HAPEX-Sahel. J. Hydrol., this issue.

Hanan, N.P. and Prince, S.D., 1997. Stomatal conductance of West Central Supersite vegetation in HAPEX-Sahel: measurements and empirical models. J. Hydrol., this issue.

Hanan, N.P., Prince, S.D. and Bégué, A., 1997. Modelling vegetation primary production during HAPEX-Sahel using production efficiency and canopy conductance model formulations. J. Hydrol., this issue.

Jacobs, A.F.G. and Verhoef, A., 1997. Soil evaporation from sparse natural vegetation estimated from Sherwood numbers. J. Hydrol., this issue.

Kabat, P., Dolman, A.J. and Elbers, J.A., 1997. Evaporation, sensible heat and surface conductance of fallow savanna and patterned woodland in the Sahel. J. Hydrol., this issue.

Laval, K. and Picon, L., 1986. Effects of a change in the surface albedo on the Sahel on climate. J. Atmos. Sci., 43: 2418–2429.

Le Barbé, L. and Lebel, T., 1997. Rainfall climatology of the HAPEX-Sahel region during the years 1950–1990. J. Hydrol., this issue.

Lebel, T., Le Barbé, L. and D'Amato, N., 1997. Rainfall monitoring during HAPEX-Sahel. 1. General rainfall conditions and climatology. J. Hydrol., this issue.

Leduc, C., Bromley, J. and Schroeter, P., 1997. Water table fluctuation and recharge in semi-arid climate: some results of the HAPEX-Sahel hydrodynamic survey (Niger). J. Hydrol., this issue.

Lhomme, J.P., Troufleau, D., Monteny, B., Chebouni, A. and Baudin, S., 1997. Sensible heat flux and radiometric surface temperature over sparse Sahelian vegetation. II. A model for the kB^{-1} parameter. J. Hydrol., this issue.

Magagi, R.D. and Kerr, Y.H., 1997. Retrieval of soil moisture and vegetation characteristics by use of ERS-1 wind scatterometer over arid and semi-arid areas. J. Hydrol., this issue.

Moncrieff, J.B., Massheder, J.M., De Bruin, H., Elbers, J., Friborg, T., Huesinkveld, B., Kabat, P., Scott, S., Soegaard, H. and Verhoef, A., 1997a. A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. J. Hydrol., this issue.

Moncrieff, J.B., Monteny, B., Verhoef, A., Friborg, T., Elbers, J., Kabat, P., de Bruin, H., Soegaard, H., Jarvis, P.G. and Taupin, J.D., 1997b. Spatial and temporal variations in net carbon flux during HAPEX-Sahel. J. Hydrol., this issue.

Monteny, B.A., 1986. Forêt équatoriale, relais de l'océan comme source de vapeur d'eau pour l'atmosphère. Vielle Climatique Satellitaire, 12: 39–51.

Monteny, B.A., Lhomme, J.P., Chehbouni, A., Troufleau, D., Amadou, M., Sicot, M., Verhoef, A., Galle, S., Said, F. and Lloyd, C.R., 1997. The role of the Sahelian biosphere in the water and CO_2 cycle during the HAPEX-Sahel experiment. J. Hydrol., this issue.

Noilhan, J., Lacarrère, P., Dolman, A.J. and Blyth, E.M., 1997. Defining area-average parameters in meteorological models for landsurfaces with mesoscale heterogeneity. J. Hydrol., in press.

Peugeot, C., Esteves, M., Galle, S., Rajot, J.L. and Vandervaere, J.P., 1997. Runoff generation processes: results and analysis of field data collected at the East Central supersite of the HAPEX-Sahel Experiment. J. Hydrol., this issue.

Polcher, J., 1995. Sensitivity of tropical convection to land surface processes. J. Atmos. Sci., 52: 3143–3161.

Rowell, D.P., Folland, C.K., Maskell, K. and Ward, M.N., 1995. Variability of summer rainfall over tropical north Africa (1906–1992): observations and modelling. Q.J.R. Meteorol. Soc., 121: 669–704.

Saïd, F., Attié, J.L., Bénech, B., Druilhet, A., Durand, P., Marciniak, M.H. and Monteny, B., 1997. Spatial variability in airborne surface flux measurements during HAPEX-Sahel. J. Hydrol., this issue.

Savenije, H.H.G., 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. J. Hydrol., 167: 57–78.

Taylor, C.M., Harding, R.J., Thorpe, A.J. and Bessemoulin, P., 1996. A mesoscale simulation of land surface heterogeneity from HAPEX-Sahel. J. Hydrol., this issue.

Teng, W.L., Choudrury, B.J. and Wang, J.R., 1997. The effect of laterite and associated terrain components on the PBMR response in HAPEX-Sahel. J. Hydrol., this issue.

Thierry, J.M., d'Herbes, J.-M. and Valentin, C., 1995. A model simulating the genesis of banded vegetation patterns in Niger. J. Ecol., 83: 497–507.

Troufleau, D., Lhomme, J.P., Monteny, B. and Vidal, A., 1997. Sensible heat flux and radiometric surface temperature over sparse Sahelian vegetation. I. An experimental analysis of the kB^{-1} parameter. J. Hydrol., this issue.

Tuzet, A., Castell, J.F., Perrier, A. and Zurfluh, O., 1997. Flux heterogeneity and evapotranspiration partitioning in a sparse canopy: the fallow savanna. J. Hydrol., this issue.

van Leeuwen, W.J.D., Huete, A.R., Walthall, C.L., Prince, S.D., Bégué, A. and Roujean, J.L., 1997. Deconvolution of remotely sensed spectral mixtures for retrieval of LAI, fAPAR and soil brightness. J. Hydrol., this issue.

Wai, M.M.-K., Smith, E.A., Bessemoulin, P., Culf, A.D., Dolman, A.J. and Lebel, T., 1997. Variability in boundary layer structure during HAPEX-Sahel wet–dry season transition. J. Hydrol., this issue.

Wallace, J.S. and Holwill, C.J., 1997. Soil evaporation from tiger bush in South-West Niger. J. Hydrol., this issue.

Woodward, F.I., 1987. Climate and Plant Distribution. Cambridge University Press, 174 pp.

Xue, Y. and Shukla, J., 1993. The influence of land surface properties on Sahel climate. Part I: Desertification. J. Clim., 5: 2232–2245.

Xue, Y., Elbers, J., Zeng, F.J. and Dolman, A.J., 1996. GCM parameterization for Sahelian land surface processes. In: P. Kabat, S.D. Prince and L. Prihodko (Editors), HAPEX-Sahel West Central Supersite: Methods, Measurements and Selected Results. SC-DLO, Wageningen, UMCP University of Maryland, in press.