Qi, J., Chehbouni, A., Huete, A.R., Kerr, Y.H. and Sorooshian, S., 1994. A modified soil adjusted vegetation index. Remote Sens. Environ., 48: 119–126.

Rahman, H. and Dedieu, G., 1994. SMAC: a simplified method for atmospheric correction of satellite measurements in the solar spectrum. Int. J. Remote Sens., 15(1): 123–143.

Taupin, D., et al., 1993. EPSAT Niger, Campagne 1992, ORSTOM DMT, 64 pp.

Ulaby, F.T., Bradley, G.A. and Dobson, M.C., 1979. Microwave backscattering dependence on surface roughness, soil moisture, and soil texture: Part II—vegetation covered soil. IEEE Trans. Geosci. Electron., GE-17(2): 33–40.

Ulaby, F.T., Aslam, A. and Dobson, M.C., 1982a. Effects of vegetation cover on the radar sensitivity to soil moisture. IEEE Trans. Geosci. Remote Sens., GE-20(4): 476-481.

Ulaby, F.T., Moore, R.K. and Fung, A.K., 1982b. Microwave Remote Sensing, Vol. 2. Addison Wesley, Reading, MA.

Ulaby, F.T., Moore, R.K. and Fung, A.K., 1986. Microwave Remote Sensing, Vol. 3. Addison Wesley, Reading, MA.

Ulaby, F.T., Sarabandi, K., McDonald, K., Whitt, M. and Dobson, C., 1990. Michigan microwave canopy scattering model. Int. J. Remote Sens., 11(7): 1223–1253.

Van de Griend, A.A. and Owe, M., 1993. Determination of microwave vegetation optical depth and single scattering albedo from large scale soil moisture Nimbus/SMMR satellite observations. Int. J. Remote Sens., 14(10): 1875–1886.

Van Ovelen, P.J., Hoekman, D.H. and Vissers, M.A.M., 1992. Soil moisture and surface roughness measurements during HAPEX-Sahel 1992, ground data collection report. Rep. 38, Dept. of Water Resources, Wageningen Agricultural University, 27 pp.

Wiesmann, A., 1994. Remote sensing of land surfaces with the ERS-1 windscatterometer. Diploma Thesis, Institute of Applied Physics, University of Bern.

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The variability of evaporation during the HAPEX-Sahel Intensive Observation Period

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Abstract

The variation in evaporative fraction and actual evaporation is examined for three sample days in the HAPEX-Sahel Intensive Observation Period (IOP), including data from all the vegetation types and sites. The trends in evaporative fraction over the IOP are also presented for eight sites. The high rate of evaporation from bare soil in the days following rainfall produces a variability in evaporation which makes differences between sites difficult to interpret on a day-to-day basis, but over the whole IOP it is shown that the millet uses a smaller proportion of the available energy for evaporation than the tiger bush or fallow savannah. The combined effect of differences in the total energy used and its partitioning into evaporation and sensible heat flux is demonstrated from the trends in cumulative total energy use and evaporation at the three southern sites, where it is shown that there is systematically less evaporation from the millet than from the savannah or tiger bush sites.

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Table 1

A summary of the instrumentation used to make surface flux measurements by the participating institutions at the various sites

Institution	West Central				East Central		Southern			Danguey Gourou
	Millet	Fallow	Degraded fallow	Tiger bush	Millet	Fallow	Millet	Fallow	Tiger bush	Millet
CNRM					Solent[a] Krypton[b]	Solent[a] Krypton[b]				
INRA[c] Bioclimatologie						1D-sonic[d] Krypton[b]				
Institute of Hydrology							Hydra[e]	Hydra[e]	Hydra[e]	
ORSTOM					Bowen ratio	Bowen ratio				
University of Berlin			Solent[a] Krypton[b]							
University of Copenhagen	Solent[a] Li-Cor[f]									Solent[a] Li-Cor[f]
University of Edinburgh							Solent[a,g] Ohtaki[g,i]	Solent[a] Ohtaki[i]	Solent[a,h] Ohtaki[h,i]	
University of Reading								Solent[a]		
Wageningen Agricultural University		Solent[a] Li-Cor[f]								
Winand Staring Centre		Solent[a] Li-Cor[f] Krypton[b]		Bowen ratio Solent[a] (H only)						

[a] Solent three-dimensional ultrasonic anemometer (Gill Instruments, Southampton, UK).

[b] Krypton hygrometer KH20 (Campbell Scientific, Shepshed, UK).

[c] Days 227–245 only.

[d] One-dimensional sonic anemometer (Campbell Scientific, Shepshed, UK).

[e] Institute of Hydrology Mk II Hydra (Shuttleworth et al., 1988).

[f] H_2O–CO_2 IR gas analyser LI6262 (Li-Cor, Inc., Lincoln, Nebraska, USA).

[g] Days 230–257 only.

[h] Days 260–283 only.

[i] Open path gas analyser (Advanced Systems Inc., Okyama City, Japan).

1. Introduction

The principal objective of HAPEX-Sahel is to improve the parameterization of the energy fluxes from Sahelian-type vegetation in global circulation models (GCMs) (Goutorbe et al., 1994). The first requirement towards meeting this objective is to quantify the energy and water balance of the one-degree study area, an area comparable in size to a GCM grid square. Such a large area will inevitably contain a variety of vegetation, and, in a climate with spatially variable rainfall, a wide range of soil moisture conditions. The philosophy of the experiment has therefore been based on scaling up from field scale micrometeorological measurements to the larger, grid square scale using a combination of aircraft-measured fluxes, boundary-layer measurements, remote sensing and mesoscale modelling. The role of the micrometeorological measurements is to provide both continuity in time, to allow interpolation between infrequent satellite overpasses, aircraft flights, boundary-layer soundings or mesoscale model runs, and extrapolation in space, by providing accurate measurements at a limited number of representative sites. The sampling strategy for the micrometeorological measurements was based on a network of sites covering the three principal vegetation types of the region in three different locations or Super-Sites (see Monteny, 1993; Wallace et al., 1994; Kabat and Goutorbe, 1995; Kabat et al., 1996; Goutorbe et al., 1997). There is a south to north gradient in annual rainfall of about 1 mm km^{-1}, between the high-rainfall belt on the west African coast and the Sahara desert to the north. The Super-Sites were positioned so as to capture at least some of this expected gradient in rainfall. Evaporation was also measured at one additional smaller site in the north-east of the square, to extend the range of the measurements into drier conditions.

This paper analyses the variability of the micrometeorological evaporation fluxes measured during the Intensive Observation Period (IOP) of HAPEX-Sahel. The first objective is to assess the variation in space, as that sets the aggregation problem, both for the remote sensing and the meteorological modelling initiatives. Second, the variation in time is examined, as this defines the need to monitor the changes in the vegetation as the wet season progresses and the response of the vegetation to the meteorological conditions and soil moisture depletion. The influence of evaporation from the exposed soil immediately after rain storms is considered, as well as the variation in the energy available for evaporation. This will vary according to the surface temperature and the albedo—which is itself a dynamic parameter and will depend, for example, on leaf age and leaf area, as well as on the amount and type of soil exposed (Allen et al., 1994). The success of the scaling-up operation and the modelling of the overall energy balance of the HAPEX-Sahel square will depend on how well the remote sensing algorithms and the meteorological models' vegetation–atmosphere–soil transfer schemes cope with this variation.

2. Methods

A general overview of the instruments deployed to measure the surface fluxes in HAPEX-Sahel is given in Table 1. Detailed descriptions of the instrumental systems

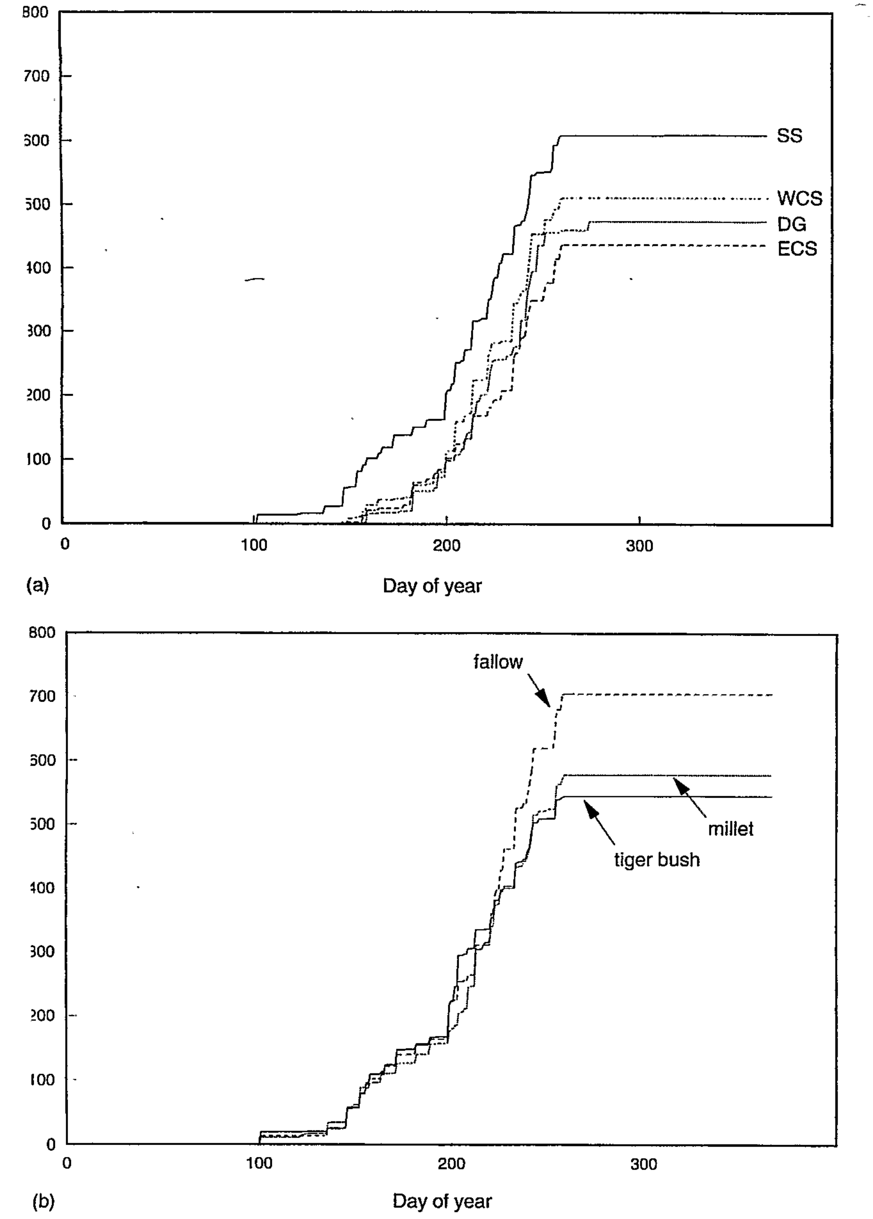

Fig. 1. Cumulative rainfall for 1992, taken from (a) the average of the EPSAT-Niger raingauges surrounding the Super-Sites and Danguey Gourou and (b) the raingauges at each of the Southern sub-sites.

used in the individual studies at each of the sites will be given in the separate publications describing the work at those sites. The eddy correlation technique was the main micrometeorological technique used. It was employed to measure the fluxes of evaporation and sensible heat flux at all but three of the sites, where the Bowen ratio method was used. The uncertainties in these instrument systems have been evaluated and discussed by Lloyd et al. (1997), and for the purposes of the present paper the differences of up to 20% that were typically observed to occur between instrument systems have been neglected. However, wherever possible, the results are presented as evaporative fraction, the evaporation normalized by the sum of evaporation and sensible heat flux. This practice avoids the effects of errors in measured net radiation and soil heat flux, when using the Bowen ratio method, and the effects of those errors in eddy correlation systems which appear as multiplicative factors, affecting both evaporation and sensible heat flux by the same percentage.

3. Rainfall during the IOP

Millet grown in the Sahel requires about 100 days between sowing and harvest, and adequate soil moisture conditions must be maintained throughout this period. The success of the millet harvest therefore depends not only on the amount, but also on the timing, of the rainfall, which is the critical meteorological variable in the Sahel (Sivakumar, 1990, Sivakumar, 1992). The variation in evaporation must also be expected to depend on the spatial and temporal distribution of rain. Fig. 1 shows the cumulative rainfall for the whole of 1992, taken from the average of the EPSAT-Niger raingauges surrounding each of the three HAPEX-Sahel Super-Sites and Danguey Gourou. It can be seen that there is most rain at the Southern Site (SS), which received 610 mm. The West Central Site (WCS) received 512 mm and Danguey Gourou (DG) 474 mm. The East Central Site (ECS) was the driest, receiving only 437 mm. Large differences in annual rainfall can still occur between sites which are relatively close together. For example, if the average data for the Southern Super-Site shown in Fig. 1(a) are shown as three separate southern sub-sites, it can be seen from Fig. 1(b) that during the last 4 weeks of the wet season the fallow site received systematically more rainfall than the other two sites, giving totals for the season of 704 mm, 576 mm and 544 mm for the fallow, millet and tiger bush sites, respectively. A detailed analysis of the rainfall during HAPEX-Sahel has been given by Lebel et al. (1997). A small storm of 14 mm was recorded at the Southern Site on day of the year 101 (10 April), but the wet season proper did not start until a fall of 10 mm was recorded at the Southern Site on Day 136 (15 May). The Southern Site millet was planted on 16 May (Wallace et al., 1994), but there was not sufficient rainfall to allow a successful planting until 30 June for the West and East Central sites. The development of the crops at these sites was therefore substantially behind that of the Southern Site throughout the IOP.

Fig. 2 shows the daily rainfall at each of the sites for the whole of the IOP. Rainfall in the Sahel is mostly generated by squall lines, which typically arrive at 3 day intervals throughout the rainy season. However, the storms within these squall lines are convective and thus the spatial distribution of the rainfall is highly variable. Although a typical squall line will produce some rain at all sites, the amount received at any particular site may vary

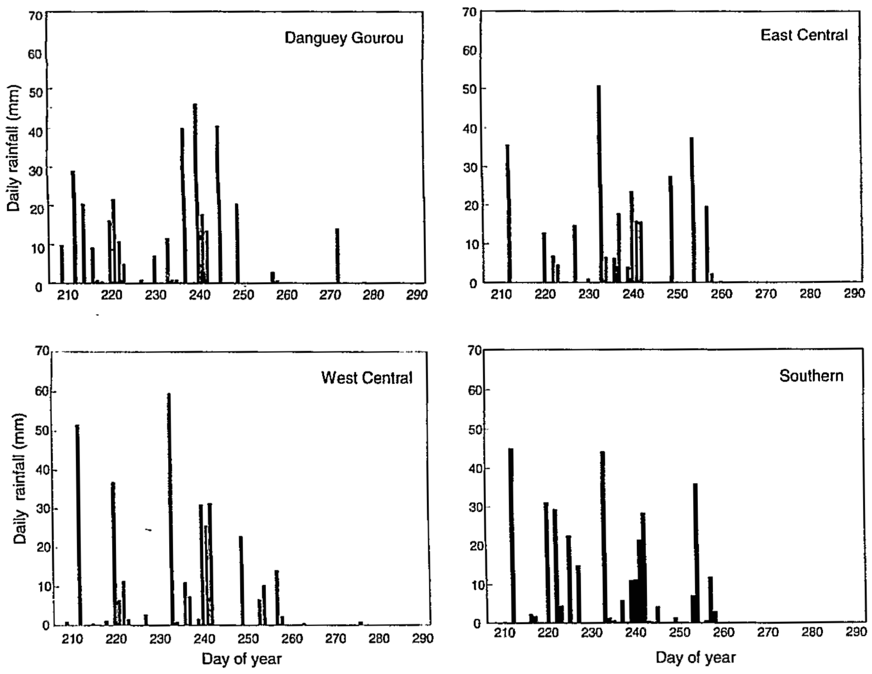

Fig. 2. The daily rainfall measured by the EPSAT-Niger raingauges surrounding the Super-Sites and Danguey Gourou, during the HAPEX-Sahel IOP.

from zero to 40 mm or more: for example, on Day 250 the West and East Central sites received 23 mm and 27 mm of rainfall, respectively, Danguey Gourou received 20 mm, but the Southern Site received only 1 mm. The rain during the IOP followed this pattern at each of the sites, with no long periods without rainfall being recorded, although at the end of the wet season there was a period of 22 days with only 5 mm of rainfall being recorded at Danguey Gourou. The rainfall on Days 254 and 255, which amounted to 43 mm, 17 mm and 37 mm at the Southern, and West and East Central sites, respectively, did not occur at Danguey Gourou; however, there was an unusually late storm of 14 mm on Day 273 which was not recorded at the other sites. During the IOP, the driest site (ECS) received some 240 mm over the 33 days before the last rain—an average of some 7 mm day^{-1}.

4. Results

4.1. Variation in evaporative fraction

Three example days have been selected to illustrate the spatial variability of evaporation under some of the different conditions enountered during the experiment. Day 233

Table 2
(a) The evaporative fraction and (b) the average evaporation (W m^{-2}), measured on Days 233, 261 and 282 for the millet, fallow and tiger bush at the Southern (S), West Central (WC) and East Central (EC) Super-Sites, and the millet at Danguey Gourou (DG)

(a)	Day 233				Day 261				Day 282			
	S	WC	EC	DG	S	WC	EC	DG	S	WC	EC	DG
Millet	0.64^{IH}	0.49^{Co}	0.63^{OR} 0.49^{CN}	0.49^{Co}	0.66^{IH}	0.63^{Co}	0.59^{OR} 0.78^{CN}	0.64^{Co}	0.55^{IH}	0.58^{Co}	0.38^{OR} 0.47^{CN}	0.41^{Co}
Fallow		0.49^{Wa}	0.59^{OR}		0.81^{IH}	0.75^{Be}	0.82^{OR} 0.77^{CN}		0.63^{IH}	0.58^{Wa} 0.46^{Be} 0.57^{SC}	0.38^{OR} 0.49^{CN}	
Tiger bush	0.53^{IH}	0.46^{SC}			0.75^{IH}	0.76^{SC}			0.44^{IH}	0.49^{SC}		
(b)	Day 233				Day 261				Day 282			
	S	WC	EC	DG	S	WC	EC	DG	S	WC	EC	DG
Millet	199^{IH}	119^{Co}	169^{OR} 161^{CN}	129^{Co}	182^{IH}	195^{Co}	243^{OR} 215^{CN}	207^{Co}	150^{IH}	181^{Co}	126^{OR} 121^{CN}	97^{Co}
Fallow		171^{Wa}	208^{OR}		331^{IH}	232^{Be}	385^{OR} 317^{CN}		215^{IH}	205^{Wa} 127^{Be} 204^{SC}	150^{OR} 157^{CN}	
Tiger bush	203^{IH}	183^{SC}			291^{IH}	357^{SC}			162^{IH}	172^{SC}		

Teams collecting the data: CN, Centre National de Recherches Météorologiques; IH, Institute of Hydrology; SC, Winand Staring Centre; OR, ORSTOM. Superscripts Be, Co, Ed and Wa refer to the universities of Berlin, Copenhagen, Edinburgh and Wageningen, respectively. (Note that the Berlin measurements were made in a degraded fallow site separate from the SC–Wa site.)

(20 August) was early in the IOP, when the vegetation at the Southern Site was already well developed. The millet leaf area index was close to its maximum (0.9) and the fallow site vegetation was also well developed (Wallace et al., 1994). In contrast, the vegetation at the other sites was relatively poorly developed, as a result of the later start to the wet season, with the millet at the central sites still being at the seedling stage. At the Southern and East Central sites this example day was preceded by 5 days without rain, but at the West Central Site there had been 1 mm, and at Danguey Gourou there had been 7 mm of rain, 2 days earlier. Day 261 (17 September) was selected as an example of a day with wet soil, there having been rain on both Days 258 and 259 at all sites. The third example, Day 282, was after the end of the wet season, and was chosen to represent dry conditions, there having been no rain at Danguey Gourou during the previous 10 days or at the three main sites during the previous 23 days.

Daytime evaporative fraction (total evaporation divided by the sum of total evaporation plus sensible heat flux) and the daytime average evaporation rate were calculated for 09:00–16:00 h GMT for each system operating on those days. The results are shown in Table 2. It can be seen that, when the data are presented as evaporative fraction, the variation between systems at the same site, and over the same vegetation type, is of the same size as the differences between sites and vegetation types. Any interpretation of differences between sites and vegetation types on a day-to-day time-scale must therefore be speculative. The picture that emerges is that on none of the days is there any great difference in evaporative fraction, although the millet sites are evaporating a smaller fraction of the available energy on Days 233 and 261 than the other vegetation types. As might be expected, the evaporative fraction on Day 261, the day with wet soil, is clearly higher than on the other 2 days. The actual evaporation indicates little difference between the three main sites, but shows larger differences between millet and fallow savannah.

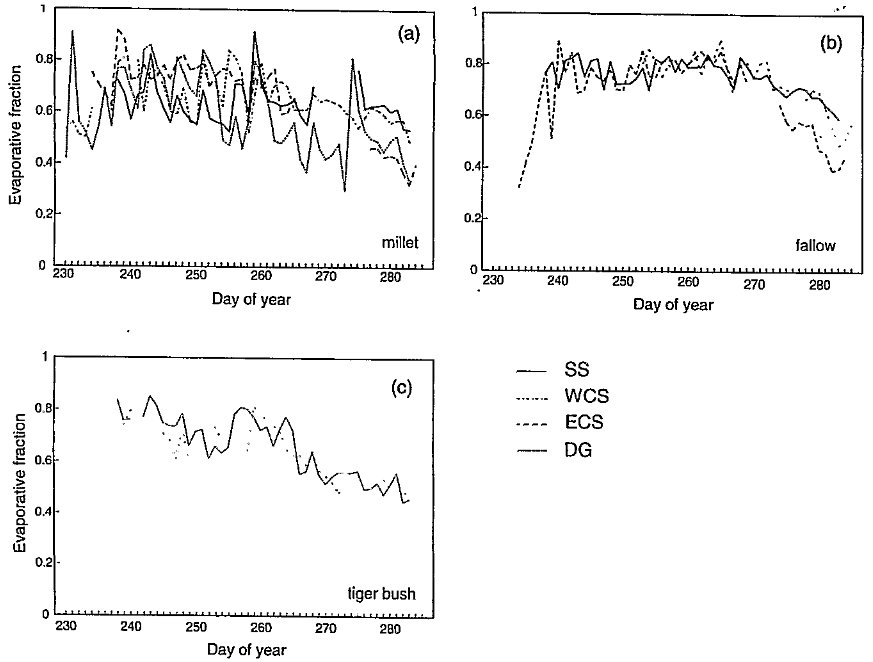

Fig. 3. The evolution of the evaporative fraction during the IOP for (a) the millet sites, (b) the fallow sites and (c) the tiger bush sites.

A clearer picture emerges if the data from the whole IOP are plotted as a time series. Fig. 3 shows daytime evaporative fraction for (a) the millet, (b) the fallow and (c) the tiger bush at each of the three sites. The Southern Site millet data have been interpolated between 25 and 30 September, when the data were missing. A striking feature of the time series is the saw-tooth pattern, which occurs because of the high evaporative fractions that follow immediately after rainfall but rapidly diminish in the subsequent days. The maximum evaporative fractions are similar (about 0.8–0.9) at all sites, but the minima are lower for the tiger bush (0.6–0.7) and for the millet (0.5–0.7), than for the fallow, which does not fall below 0.7 once the wet season is established at all sites. During the rainy period there is no long-term trend in the evaporative fraction, which is approximately constant, at between 0.7 and 0.8 for the fallow and tiger bush, and between 0.6 and 0.8 for the millet, indicating that a smaller proportion of the available energy is used for evaporation from the millet. However, after about Day 260 for the millet and tiger bush, and after about Day 270 for the fallow the evaporation diminishes. Kabat et al. (1997) have analysed this trend for the fallow savannah and tiger bush at the West Central Super-Site. They

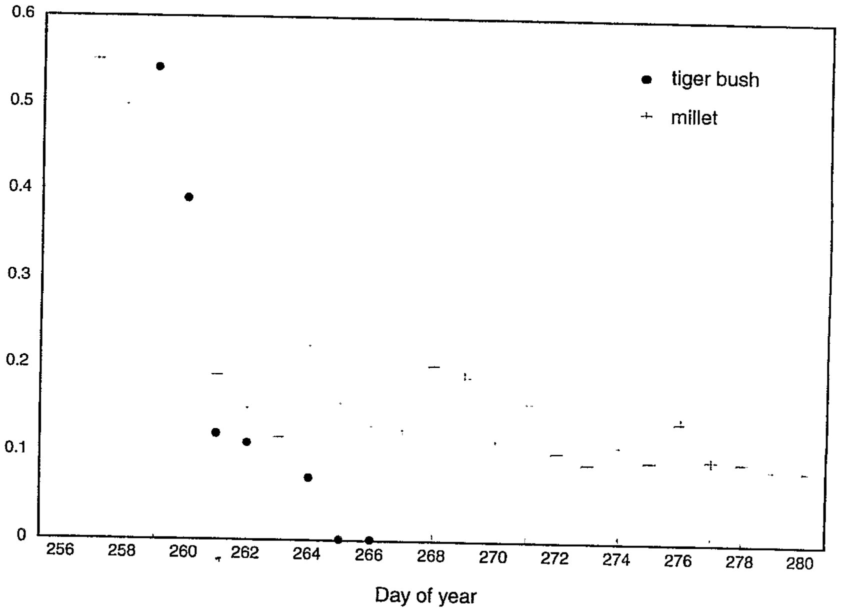

Fig. 4. The proportion of the evaporation from the soil to total evaporation for the West Central millet site and the Southern tiger bush site following the rain on Days 258 and 259.

concluded that the decline in evaporation from the tiger bush results from a strong response of the woodland canopy conductance to the increasing vapour pressure deficit; whereas for the the fallow savannah the decline in evaporation is caused by the reduction in evaporation from the shallow-rooted understorey as the top soil layer dries out. A similar trend was found for a different fallow savannah site by Gash et al. (1991).

4.2. Partitioning evaporation between different components

The partitioning of evaporation between soil and the different components of the vegetation has been presented in separate papers (Soegaard and Boegh, 1995; Wallace and Holwill, 1997; Monteny et al., 1997; Tuzet et al., 1997) and will not be discussed in great detail here. However, the results presented in Fig. 3 demonstrate the high rates of evaporation in the days following rainfall. This is confirmed by Fig. 4, which shows the fraction of the total evaporation coming directly from the soil for the dry period following the rain on Days 258 and 259. The data for two locations are shown: the millet at the West Central Site, where evaporation from the soil was derived from the difference between eddy correlation measurements of total evaporation and sap-flow measurements of transpiration (Soegaard and Boegh, 1995), and the tiger bush at the Southern Site, derived from Bowen ratio measurements made over a large expanse of bare soil and eddy correlation measurements of total evaporation (Wallace and Holwill, 1997). The figure demonstrates, at least for these two vegetation types, that the high rates of evaporation after rainfall are the result of the evaporation of near-surface soil moisture enhancing the overall evaporation. Immediately after rain the evaporation from the soil accounts for some 50% of the total evaporation, but within 2 days this has fallen, in both cases, to less than 20%.

4.3. Actual evaporation over the IOP

Although the energy partitioning is useful for assessing the behaviour of the vegetation type, it is essential to know how the actual evaporation varies. Differences in evaporation result from differences in available energy as well as evaporative fraction, and thus depend on the net radiation and soil heat flux. Net radiation in turn depends on the albedo and surface temperature, and soil heat flux on the amount of bare soil exposed. In Fig. 5 the sum of evaporation plus sensible heat flux is compared with the actual evaporation for the three Southern sub-sites. The sum of evaporation plus sensible heat flux has been used rather than the available energy to avoid the problem of the different vegetation samples of radiometers and micrometeorological fluxes in this heterogeneous vegetation (Lloyd, 1995). The measurements presented in Fig. 5 were made with identical instrument systems at each sub-site, so the effects of instrumental errors on differences between the vegetation types are minimized. The data are plotted as cumulative totals to remove random variations and errors, and to emphasize systematic trends. Despite the greater rainfall (shown in Fig. 1(b)) received during the later part of the IOP by the fallow site, compared with that received by the tiger bush site, it can be seen that the evaporation from the fallow and tiger bush are similar, but the millet evaporated systematically some 30% less. However, the total energy used for evaporation and sensible heat flux (i.e. the available

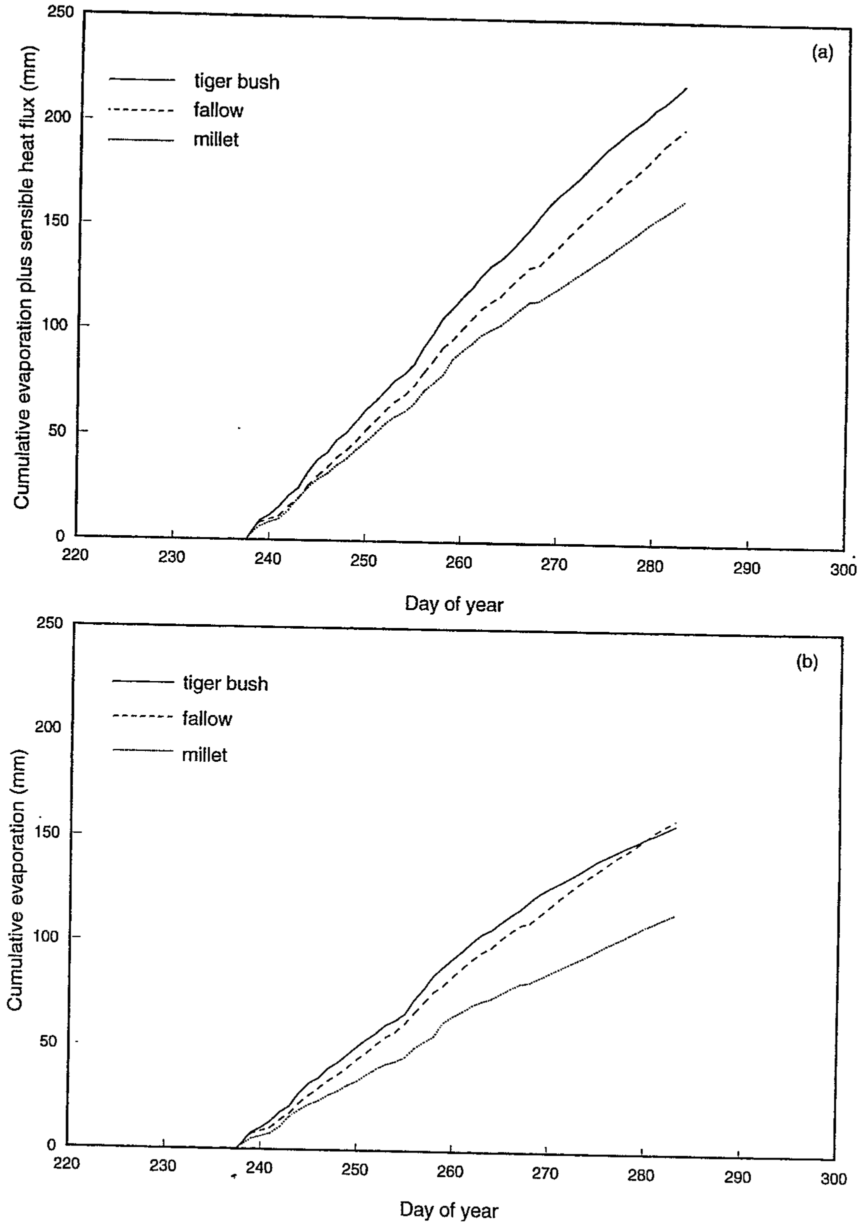

Fig. 5. (a) Cumulative evaporation plus sensible heat flux (expressed as equivalent of evaporated water, mm); (b) cumulative evaporation (mm) for the three southern sites.

energy) for the millet is only some 25% less than the total energy used for evaporation and sensible heat flux from the tiger bush, and 21% less than that from the fallow. This confirms the qualitative conclusion drawn previously from Fig. 3, and implies that the millet has a higher surface resistance. Likewise, the fallow has a similar evaporation to the tiger bush, but this is a larger fraction of the total energy used for evaporation and sensible heat flux; the surface resistance for the fallow must therefore be lower than for the tiger bush. The relative sizes of these bulk resistances have been confirmed by Blyth (1997), who calculated average wet season surface resistances of 98 s m^{-1}, 60 s m^{-1} and 154 s m^{-1} (conductance, 10 mm s^{-1}, 17 mm s^{-1} and 6 mm s^{-1}) for the Southern Super-Site tiger bush, fallow and millet, respectively. However, separating the canopy and soil resistances for the tiger bush and fallow savannah at the West Central sites (Kabat et al., 1997) showed that the higher bulk resistance of the tiger bush as a whole results from having a larger proportion of bare soil rather than greater canopy resistance for the vegetation. The resistance of the tiger bush vegetation is, in fact, lower than that for the savannah, with average wet season values of 40 s m^{-1} (conductance 25 mm s^{-1}) for tiger bush and 120 s m^{-1} (conductance 8.5 mm s^{-1}) for the savannah.

5. Concluding discussion

Once the wet season had become established over the whole domain the behaviour of particular vegetation types was similar at all sites, until the rain ceased on Day 260. The rainfall at all the sites was well distributed and, at an average of some 7 mm day^{-1}, was sufficiently in excess of both the energy available for evaporation (from Fig. 5(a)), some 3 mm day^{-1}, and the actual evaporation (from Fig. 5(b)), some 2.5 mm day^{-1}, for the vegetation not to suffer serious water stress. The primary factor determining the variability of the evaporation during the wet season was therefore the rainfall pattern, with the variation being the result of the fluctuation in the rate of evaporation coming directly from the soil. This occurs as a result of rapid evaporation from the soil surface following rainstorms and causes the evaporative fraction to fluctuate between about 0.6 and 0.8 for the millet and tiger bush, and about 0.7 and 0.8 for the savannah. Although this fluctuating rate of evaporation from the soil makes comparison between vegetation types difficult on a day-to-day time scale, the variation in the cumulative evaporation shows clear systematic similarities and differences between different vegetation types. Analysis of the Southern Site data shows that the slightly higher evaporative fraction from the savannah, coupled with a higher amount of energy being used for evaporation and sensible heat flux, produces a systematically higher rate of evaporation from savannah when compared with the millet which is grown on the same soils. In contrast, both the Southern Site data presented here and the West Central Site data analysed by Kabat et al. (1997) show that despite the tiger bush using a greater amount of energy for evaporation and sensible heat flux, its lower evaporative fraction results in its evaporating a similar amount to the savannah. However, the combinations of canopy and soil resistances which produce these evaporating rates are very different, both in the size and behaviour of the resistances, and in the extent of the canopy cover. Clearly, to produce a reliable estimate of the evaporation from the HAPEX-Sahel square it will be essential to have accurate estimates of the spatial distribution of available energy and multi-component (at least two-component) models of the land surface, which account for the different resistances to transpiration for each vegetation type, and the different evaporation rates from soil and vegetation.

In semi-arid areas with a seasonal rainfall the overall evaporation is limited by the rainfall. The lack of variation in evaporation between sites which was observed once the wet season was established should not be interpreted as a lack of dependence of the overall evaporation on rainfall. This dependence should become apparent when the data described here are applied, in combination with the longer records from the rainfall, soil moisture and synoptic weather station networks, to modelling the complete water balance of the HAPEX-Sahel domain. The motivation behind HAPEX-Sahel was to improve understanding of why the rainfall in the Sahel has been systematically low over the past two decades, and to improve the ability of climate models to predict how Sahelian rainfall might respond to the combination of global climate change and changing land surface cover in the region. In this respect, the surface energy balance will only be able to affect rainfall during the wet season, when the large-scale circulation makes rainfall possible. At the end of the wet season the Inter-Tropical Convergence Zone moves south, the surface wind changes direction and blows from the Sahara desert rather than from the coast, and there is descending air over the Sahel. Under these circumstances, there will be no rainfall.

There are clear systematic differences between the energy balances at the sub-sites, with systematically less evaporation from the millet compared with the savannah and tiger bush. From the data in Fig. 5 it can be calculated that the wet season evaporation from the millet is 22% less than that from the savannah, but the sensible heat flux is 41% greater. One of the land use changes that has been progressively taking place over the past two decades is the conversion of Sahelian savannah to agricultural millet production; this is expected to continue in response to population pressure in the region. Population pressure is also resulting in the greater exploitation of the remaining fallow areas and the tiger bush for grazing and the extraction of fuel wood. This removal of vegetation must be expected to lead to increasing heat flux, and decreased evaporation. A major question now is whether the changes in the energy and water balances which result from these land use changes could feed back through the boundary-layer, mesoscale and large-scale meteorology to affect the rainfall. The analyses of Dolman et al. (1997), Taylor et al. (1997) and Wai et al. (1997) have started the use of HAPEX-Sahel data to study the behaviour of the atmosphere at the larger scale. Subsequent studies must address the issue of why the Sahelian rainfall has declined. For example, a broad explanation may lie in the large-scale rainfall recycling discussed by Monteny (1986), Monteny and Casenave (1989) and Savenije (1995). Their hypothesis is that any reduction in evaporation as air moves north from the Guinea Coast causes a reduction in the atmospheric water content, and a subsequent reduction in the rainfall downwind. If the deforestation which has been carried out in the west African coastal zone over the past two decades results, as expected, in a reduction in wet season evaporation, this could in turn result in less rainfall further north. However, as the conversion of Sahelian savannah to agricultural millet production has also been taking place over this period, millet agriculture evaporating less water than savannah would exacerbate this reduction. The evidence of Fig. 5 is consistent with this argument.

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References

Allen, S.J., Wallace, J.S., Gash, J.H.C. and Sivakumar, M.V.K., 1994. Measurements of albedo variation over natural vegetation in the Sahel. Int. J. Climatol., 14: 625–636.

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

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., Wallace, J.S., Lloyd, C.R., Dolman, A.J., Sivakumar, M.V.K. and Renard, C., 1991. Measurements of evaporation from fallow Sahelian savannah at the start of the dry season. Q. J. R. Meteorol. Soc., 117: 749–760.

Goutorbe, J.P., Lebel, T., Tinga, A., Bessemoulin, P., Brouwer, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoeppfner, M., Kabat, P., Kerr, Y., Monteny, B., Prince, S., Saïd, F., Sellers, P. and Wallace, J.S., 1994. HAPEX-Sahel: a large scale study of land–atmosphere interactions in the semi-arid tropics. Ann. Geophys., 12: 53–64.

Goutorbe, J.P., Lebel, T., Dolman, A.J., Gash, J.H.C., Kabat, P., Kerr, Y.H., Monteny, B., Prince, S.D., Stricker, J.N.M., Tinga, A. and Wallace, J.S., 1997. An overview of HAPEX-Sahel: a study in climate and desertification. J. Hydrol., this issue.

Kabat, P. and Goutorbe, J.P., 1995. HAPEX II-Sahel/Phase I. Final report on EC Contract EPOCH CT90-0024C. DG XII, EPOCH/ENVIRONMENT, Brussels.

Kabat, P., Prince, S.D. and Prihodko, L., (Editors), 1996. HAPEX-Sahel West Central Supersite: Methods, Measurements and Selected Results. Report 130, DLO Winand Staring Centre, Wageningen.

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

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

Lloyd, C.R., 1995. The effect of heterogeneous terrain on micrometeorological flux measurements: a case study from HAPEX-Sahel. Agric. For. Meteorol., 73: 209–216.

Lloyd, C.R., Bessemoulin, P., Cropley, F., Culf, A.D., Dolman, A.J., Elbers, J.A., Heusinkveld, B., Moncrieff, J.B., Monteny, B. and Verhoef, A., 1997. An intercomparison of surface flux measurements 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 Clim. Satellitaire, 12: 39–51.

Monteny, B.A., 1993. HAPEX-Sahel 1992, Super-site central-est, campagne de mesure. Rapport ORSTOM, Montpellier, 230 pp.

Monteny, B.A. and Casenave, A., 1989. The forest contribution to the hydrological budget in tropical West Africa. Ann. Geophys., 7: 427–436.

Monteny, B.A., Lhomme, J.P., Chehbouni, A., Troufleau, D., Amadou, M., Sicot, M., Galle, S., Saïd, F., Verhoef, A. 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.

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.

Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., McNeil, D.D., Moore, C.J. and Wallace, J.S., 1988. An integrated micrometeorological system for evaporation measurement. Agric. For. Meteorol., 43: 295–317.

Sivakumar, M.V.K., 1990. Exploiting rainy season potential from the onset of rains in the Sahelian zone of West Africa. Agric. For. Meteorol., 51: 321–332.

Sivakumar, M.V.K., 1992. Climate change and implications for agriculture in Niger. Agric. For. Meteorol., 20: 297–312.

Soegaard, H. and Boegh, E., 1995. Estimation of evapotranspiration from a millet crop in the Sahel combining sap flow, leaf area index and eddy correlation technique. J. Hydrol., 166: 265–282.

Taylor, C.M., Harding, R.J., Thorpe, A., et al., 1997. A mesoscale simulation of land surface heterogeneity from HAPEX-Sahel. J. Hydrol., this issue.

Tuzet, A., Castell, A., Perrier, A. and Zurfluh, O., 1997. Transfer characteristics in a sparse canopy: the fallow savanna. 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. J. Hydrol., this issue.

Wallace, J.S., Brouwer, J., Allen, S.J., Banthorpe, D., Blyth, E.M., Blyth, K., Bromley, J., Buerkert, A.C., Cantwell, M., Cooper, J.D., Cropley, F.D., Culf, A.D., Dolman, A.J., Dugdale, G., Gash, J.H.C., Gaze, S.R., Harding, R.J., Harrison, R.G., Holwill, C.J., Jarvis, P.G., Levy, P.E., Lloyd, C.R., Malhi, Y.S., Massheder, J.M., Moncrieff, J.B., Pearson, D., Settle, J.J., Sewell, I.J., Sivakumar, M.V.K., Sudlow, J.D., Taylor, C.M. and Wilson, A.K., 1994. HAPEX-Sahel Southern Super-Site report: an overview of the site and the experimental programme during the intensive observation period in 1992. Institute of Hydrology, Wallingford, UK, 55 pp.