A SURVEY OF MAJOR LAND-SURFACE EXPERIMENTS AND A REVIEW OF THEIR MAIN FINDINGS

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Summary : This paper is aimed at surveying results obtained during field programmes organized over the past ten years or so. After a brief description of the experimental strategy underlying most of these in situ experiments, one recalls what have been their main findings either at the local scale (remote-sensing, long-term hydrological budget,...) or at the meso-scale (coupling with hydrology, atmospheric modelling,...). One concludes by discussing the presently available methodology to up-scale, i.e. area-average, land-surface properties and their parameterization within larger-scale models.

1. INTRODUCTION AND MOTIVATION

Over a period of almost ten years we have seen a number of major land-surface experiments taking place in different parts of the world : HAPEX, FIFE, EFEDA, ... are names and acronyms known to a large number of meteorologists and climate modellers. They have been defined and organized under the auspices of the World Climate Research Programme (WCRP, 1983), later on relayed by the "Biospheric Aspects of the Hydrological Cycle" programme (BAHC, 1993), a core project of the IGBP (International Geosphere Biosphere Programme). Before reviewing their main findings it may be useful to recall what their scientific motivation and specific objectives are.

Land-surface processes play an important role in weather prediction (see, e.g., Beljaars et al., 1993) as well as in climate dynamics (see, e.g., André 1992). More details can also be found in Rowntree (1994). Besides controlling the exchange of heat and momentum with the atmosphere, they also, and maybe more critically, determine how much water is stored into the ground for later use by the vegetation and evapotranspiration back into the atmosphere. These processes, which control the partition of available radiative energy at the surface (R_n) into sensible (H) and latent (LE) heat fluxes, are the results of an interplay between the atmospheric water demand and the soil-moisture availability. Biospheric resistances, depending upon possible hydric and/or thermal stress acting on the vegetation, do modulate not only the Bowen ratio ($B=H/LE$) but also the exchange of carbon through respiration and photosynthesis (but we shall not discuss further this last point here, as it would need a full paper to be correctly described). Land-surface experiments are then, on the first hand, aimed at documenting and quantifying the individual physical processes at work.

Numerical weather and climate models do make use of spatial resolutions ranging from a few tens to a few hundreds of kilometers. In all cases, land-surface processes and parameters, which exhibit a very small-scale spatial variability linked to heterogeneities in soil properties and land cover, cannot be considered as being constant throughout any grid box of the model. As many processes do exhibit non-linear behavior, spatial aggregation and up-scaling has to be given a lot of attention. Land-surface experiments are then, on the second hand, aimed at providing methods to derive "effective", i.e. area-averaged, parameterizations of land-surface processes for implementation within numerical models.

A third objective of land-surface experiments, which will not be developed here but is reviewed in André et al.(1989b), is to provide the ground-truth for developing, calibrating and validating remote-sensing of land-surface properties, as satellite observation is the only feasible possibility to derive land-surface parameters for the entire globe.

2. MAIN FEATURES OF LAND-SURFACE EXPERIMENTS

Almost all of the past and next-to-come land-surface experiments are organized in such a way that both the surface energy and upper-soil-moisture budgets are carefully, and as much as possible redundantly, measured :

$$R_n = H + LE - G \qquad (1)$$

where G is the heat flux into the ground, and

$$dm/dt = P - E - Y \qquad (2)$$

where the time-variation dm/dt of the upper-soil moisture content m is due to precipitation P, evapo(transpi)ration E, and surface and deep run-off Y.

Figure 1 shows a typical sketch of the experimental strategy, encompassing observation both at local scales (the so-called "scale 1, ca. 1-10 km), mostly aimed at documenting physical processes in all necessary details, and at the meso-scale (the so-called "scale 2", typically the size of a numerical grid box, ca. 100 km), mainly for upscaling purposes.

Table 1 recalls the names, main biome conditions and timing of the major land-surface experiments developed under WCRP and IGBP/BAHC. As can be seen, only temperate and arid conditions have been under scrutinity up-to-now. Boreal and rain forests are next on the agenda, while it will remain necessary to organize experiments to deal with the toundra on the one hand, and with hilly or mountainous terrain on the other hand, during the second half of the decade (WCRP, 1990 ; BAHC, 1993).

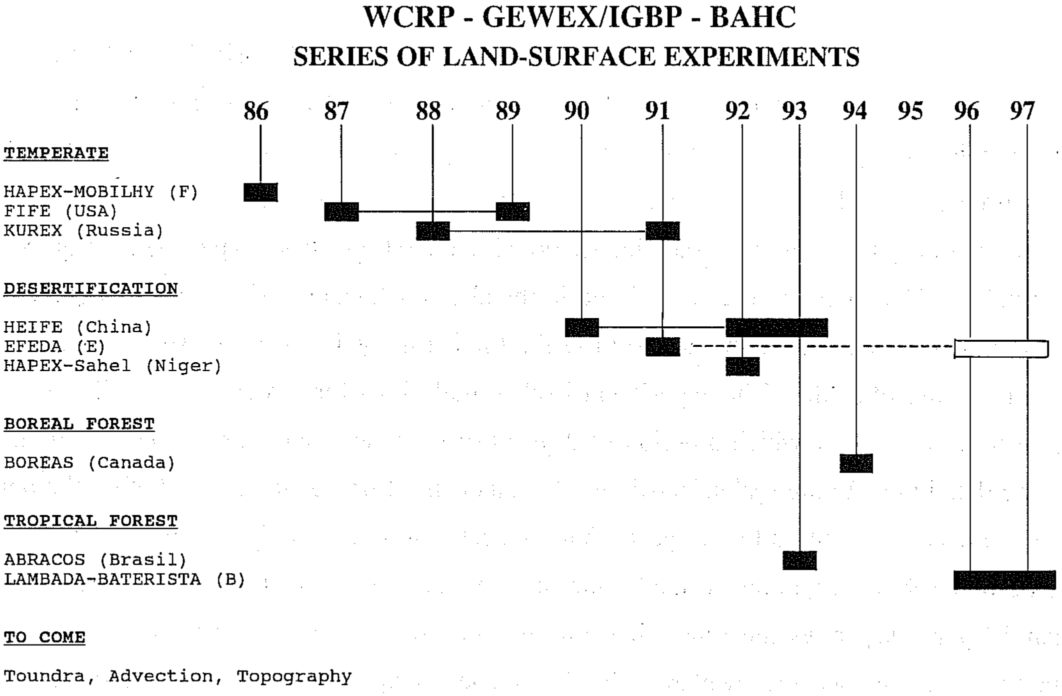

Table 1 The series of major land-surface experiments as recommended by WCRP/GEWEX and IGBP/BAHC.

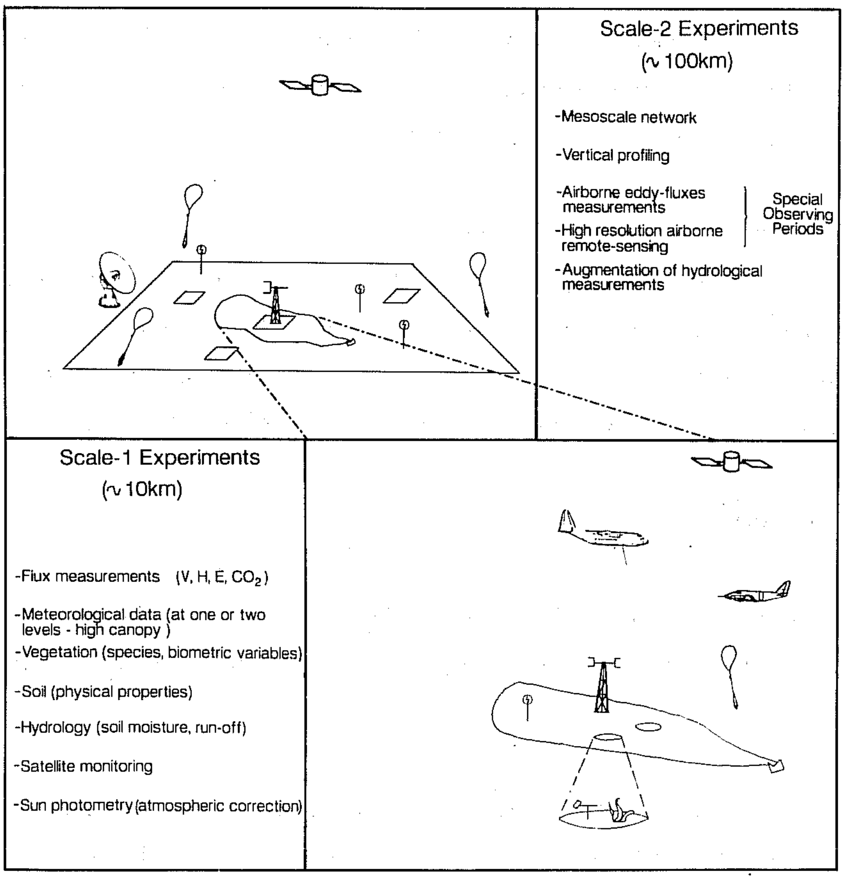

Fig. 1 Schematic view of major, mesoscale land-surface experiments (see, e.g., WCRP, 1990).

Before going into the main body of the present paper and discussing the principal outcomes of these experiments, it may be of interest to recall what their timing and duration are. Between the time when a scientist or a group of scientists proposes to organize an experiment, aimed at studying a particular process, and the time the experiment is effectively done, one usually has to spend 3 years or so in order to organize the necessary international cooperation (these experiments require indeed a large number of facilities, on the ground and in the air, which cannot be met by a single laboratory or agency, nor by a single country) and to raise the funds (the typical price of such an experiment is indeed of the order of 5 M$). The experiment itself usually lasts for a few months , if not a year or more (see Section 3), after which a period of 2 years or so is necessary for processing the data and feeding the data base. As the real scientific work cannot, most of the time, start before the data base is fully completed, it is only after six years that the scientific interpretative studies can be launched, the results themselves becoming available one or two years later ! Alltogether, a period of barely less than 10 years separates the time when one has the idea for the experiment and the time the corresponding results become available. In this respect major land-surface experiments share a number of features with satellite developments, although they are (much !) cheaper !

3. THE LOCAL SCALE AND THE DOCUMENTATION OF INDIVIDUAL PROCESSES

As this lecture is mostly intended for people involved in numerical weather forecasting, we shall not develop here about the interactions between the vegetation and the atmosphere, which are mostly to be felt for rather long time-scales relevant for climate dynamics.

We shall neither discuss in depth the question of remotely sensing the land-surface properties, as this also would deserve a full presentation. Let us just mention here the difficulties in this field, as, e.g., examplified by the strong overestimation of surface heat fluxes which is obtained if one uses remotely-sensed radiometric surface temperature T_{rad} instead of the aerodynamically-defined surface temperature T_s in the bulk formula for the surface sensible heat flux H

$$H = - \rho \, C_{Dh} \left| \underset{\sim}{V} \right| (T_{air} - T_s) \qquad (3)$$

Figure 2 (taken from Hall et al., 1992) shows indeed in the case of the FIFE-87 experiment the comparison between measured heat fluxes H_{meas} and heat fluxes H_{calc} estimated from Eq. (3) where T_{rad} substitutes for T_s .

Turning now to topics more directly relevant to numerical weather prediction (NWP), Figure 3 shows the type of already well-known local results which have steadily been produced by past land-surface experiments. Diurnal cycle of the surface energy budget (see (Eq.(1)) has been documented for a number of biomes and meteorological conditions, and the data have been used to calibrate and

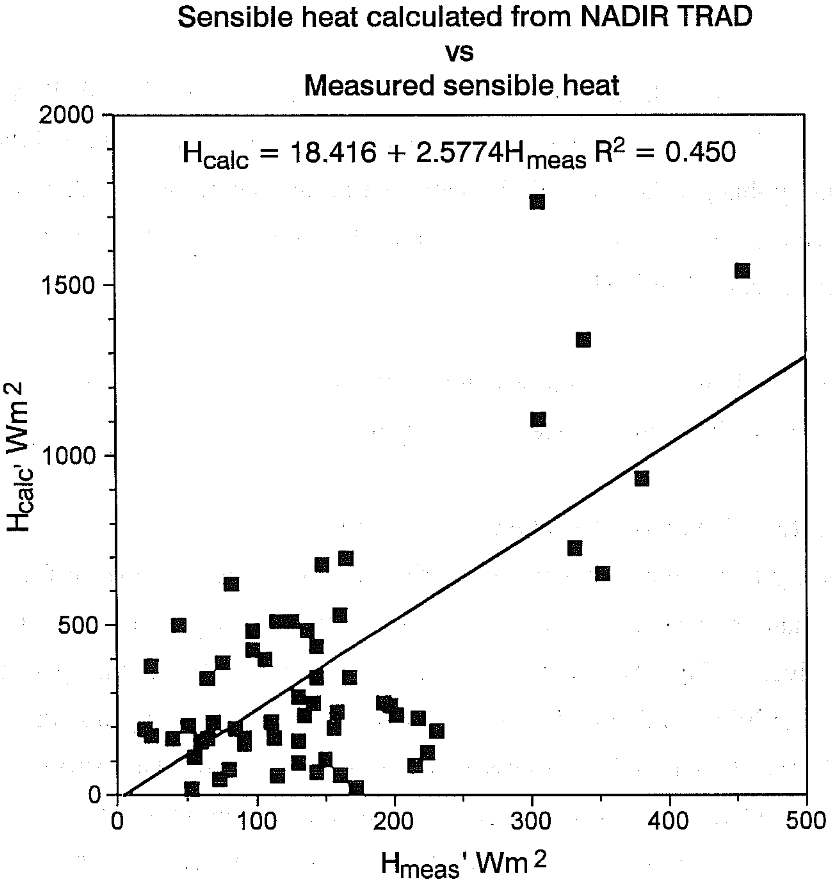

Fig. 2 Comparison between measured values of heat fluxes and their estimates using a bulk aerodynamic formula where the skin radiative temperature is used as the surface temperature (for the FIFE experiment, see Hall et al., 1992).

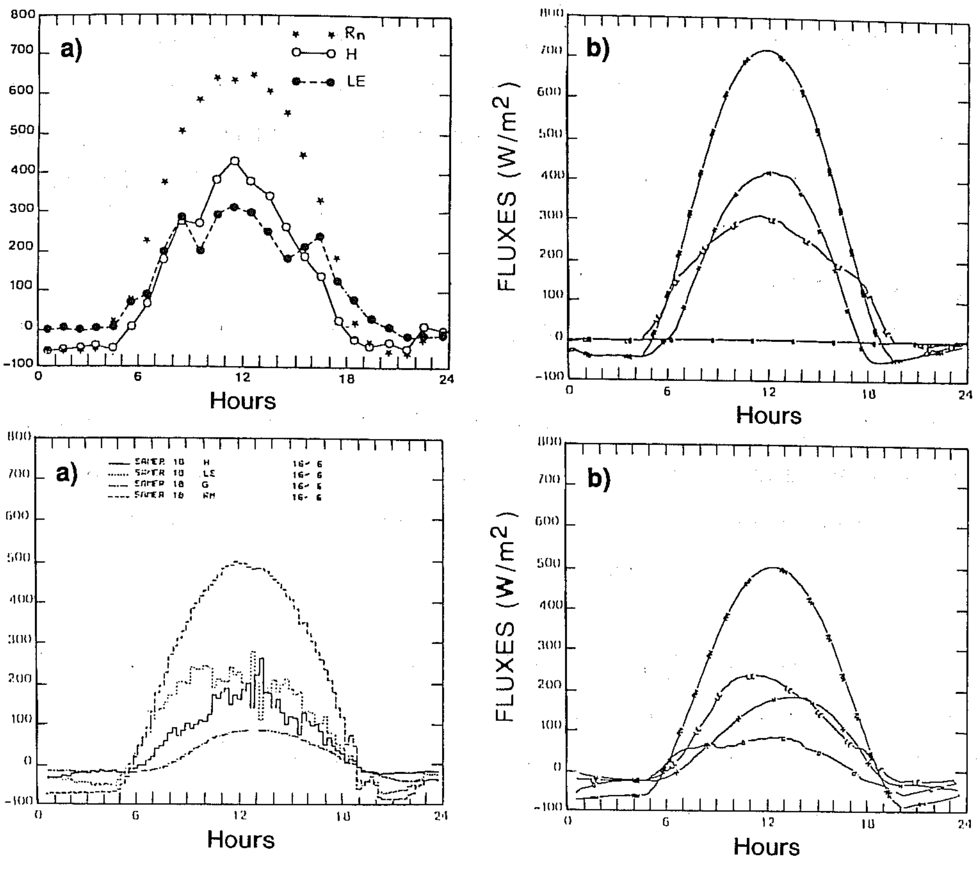

Fig. 3 Comparison between measured and modelled components of a given-day surface-energy-budget (for the HAPEX-MOBILHY experiment, see Noilhan and Lacarrère, 1994).

validate parameterization schemes for land-surface processes used in NWP models (see, e.g., Bougeault, 1991). Not to say that parameterization schemes should not be validated against such local surface-energy-budget data, as this is really the basic features which should be accounted for by theses schemes, but is seems fair to say that nowadays the priority for developing parameterization schemes is elsewhere !

Two such important issues are discussed here : the longer-term behavior of the surface energy budget, and the relationhip with surface hydrology and soil-moisture storage.

3.1 Long-term behavior of surface energy budget

It is now necessary to produce from field experiments time series of surface fluxes which make it possible to validate parameterization schemes for a variety of conditions. Examples of such validations are given in Figures 4 (the Noilhan and Planton (1989) scheme against the FIFE data ; see Noilhan et al.,1992) and 5 (the NCAR community climate model against the ARME data ; see Shuttleworth, 1991). This is indeed necessary as "snapshots" of the land-surface processes are not enough to really validate parameterization schemes, and as a large number of experimental data are indeed necessary to identify and trace back difficulties in parameterization related to, for example, stable and highly convective conditions (Fig. 4) and cloudiness (Fig. 5).

3.2 Local monthly budget of the upper-soil moisture

As we shall look at it more carefully in the next pages, it is of outmost importance to control the evapo(transpi)ration fluxes into the atmosphere through soil-moisture budget (Eq.2). Evapo(transpi)ration retrieved as a residual of this budget is indeed completely independant of estimates derived from the more usual bulk formula using mostly atmospheric information :

$$E = -\rho C_{Dq} |\underset{\sim}{V}| (q_{air} - q_s) \qquad (4)$$

where q_{air} [resp. q_s] is the humidity of the air just above the surface [resp. the surface humidity].

Figure 6 shows the type of agreement which can be obtained when one compares accumulated evaporation as estimated from atmospheric measurements and as computed from a model describing the upper-soil moisture budget. The same figure also shows the accuracy of such a model as far as the moisture content of the top soil meter is concerned.

It becomes then clear that correctly measuring and modelling Eq.(2) in the upper-soil layer (typically the root zone) is of crucial importance for determining independantly the evapo(transpi)ration. Such studies have been undertaken at the occasion of some of the major past land-surface experiments, an example of which being given in Figures 7 and 8.

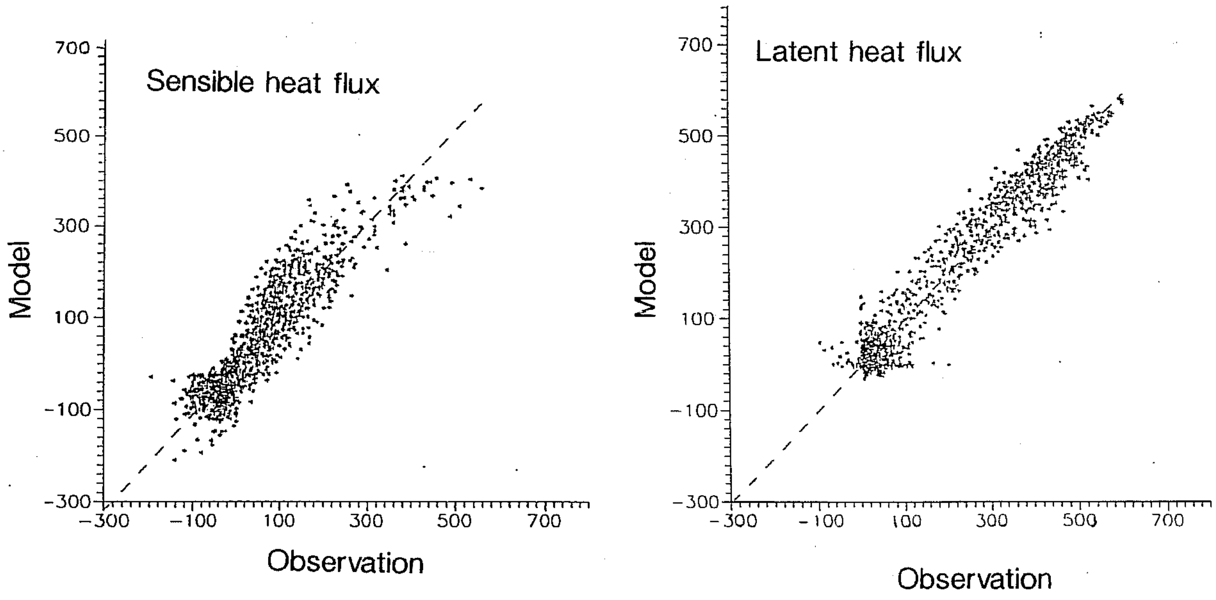

Fig. 4 Scatter diagram between measured and modelled values of sensible and latent heat fluxes (for the FIFE experiment, see Noilhan et al., 1992).

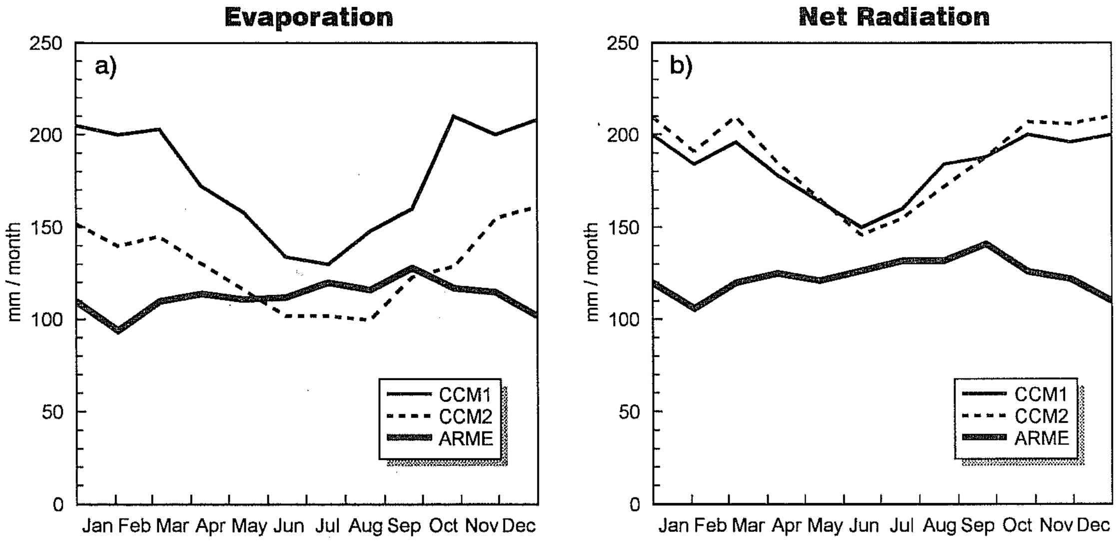

Fig. 5 Comparison between monthly average (a) evaporation and (b) evaporation equivalent of net radiation and that modelled using two versions of the NCAR community climate model (for the ARME experiment, see Shuttleworth, 1991).

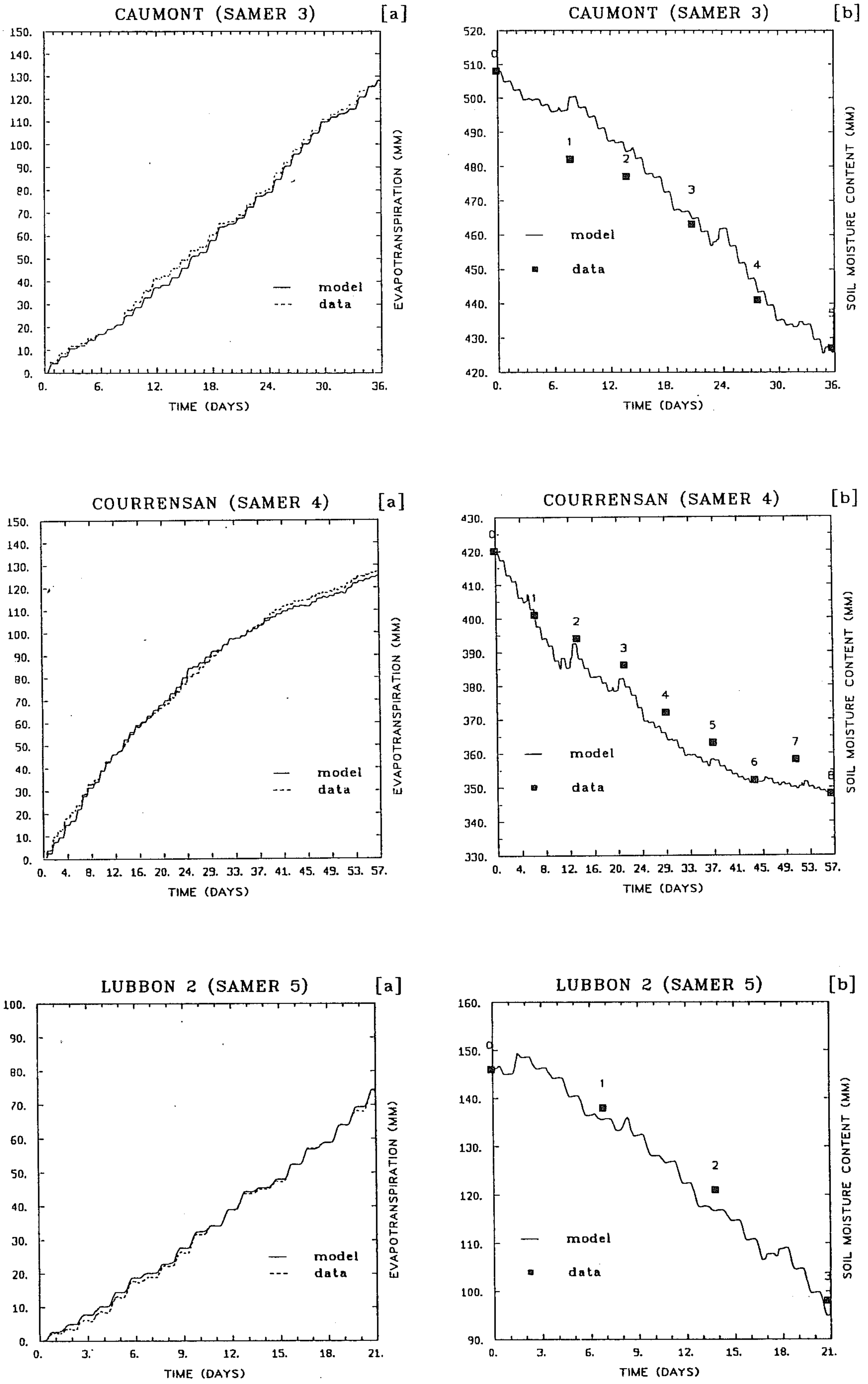

Fig. 6 Time evolution of accumulated evaporation (left) and soil moisture content (right) observed (dashed line) and modelled (solid line) (for the HAPEX-MOBILHY experiment, see Noilhan et al., 1992).

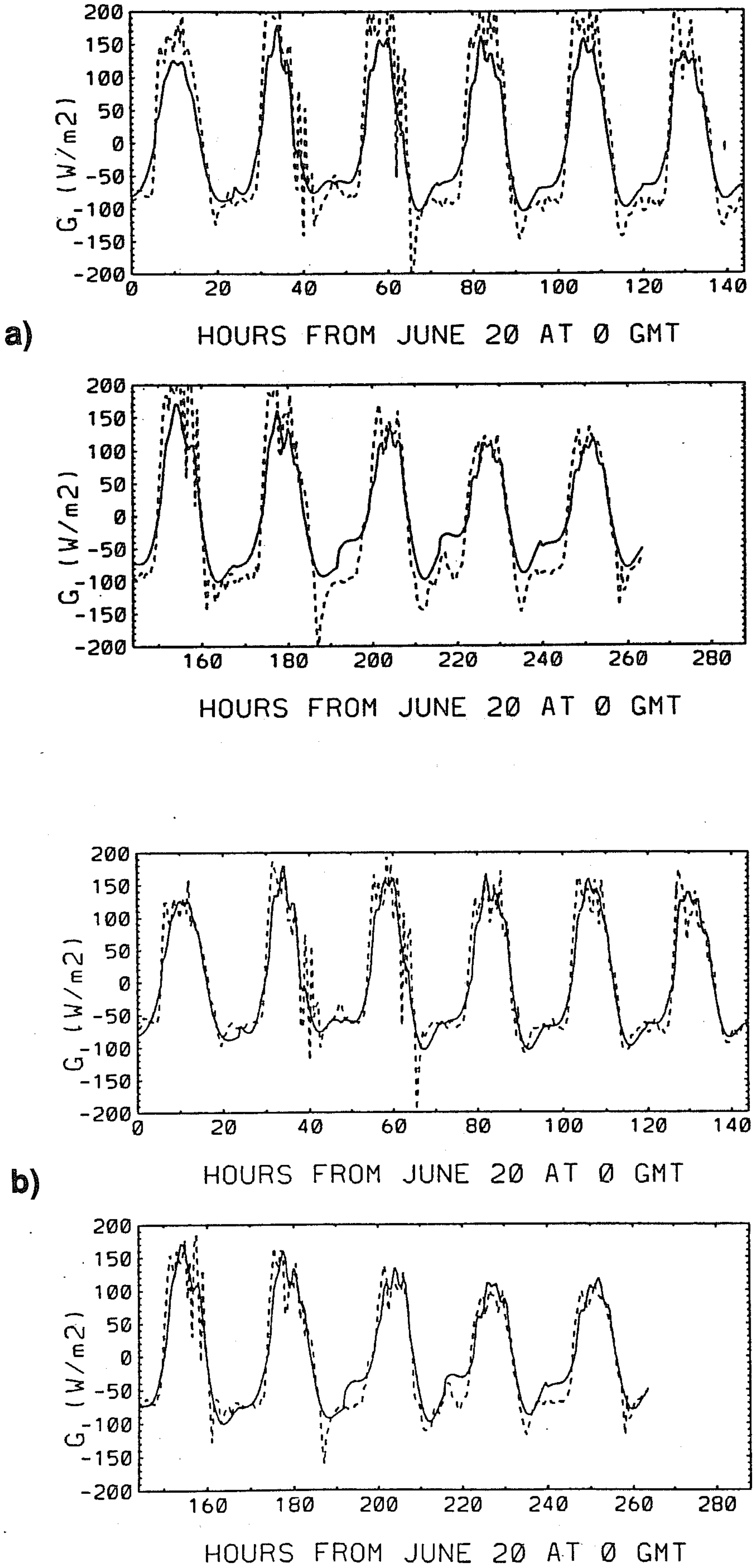

Fig. 7 Comparison between observations of the soil heat flux time-evolution (solid line) and prediction by the Braud et al.'s (1993) model (dotted line) when (a) the thermal properties are derived from the soil type and (h) the measured thermal properties are used (for the EFEDA experiment, see Braud et al., 1993).

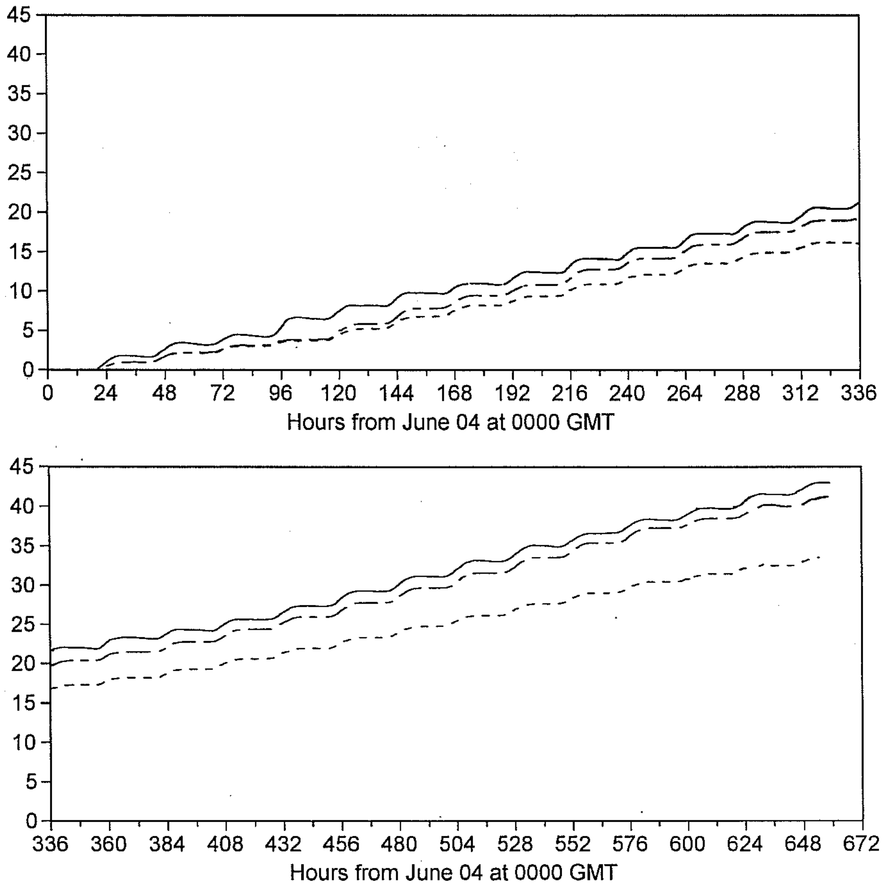

Fig. 8 Comparison between accumulated evapo(transpi)ration as measured (solid line) and modelled using two versions of the ISBA transfer scheme, the first one being the standard one (dotted line), and the second one being improved by taking into account, among others, different roughness length for heat and momentum and vapour phase transfer in the soil (for the EFEDA experiment, see Noilhan et al.. 1992).

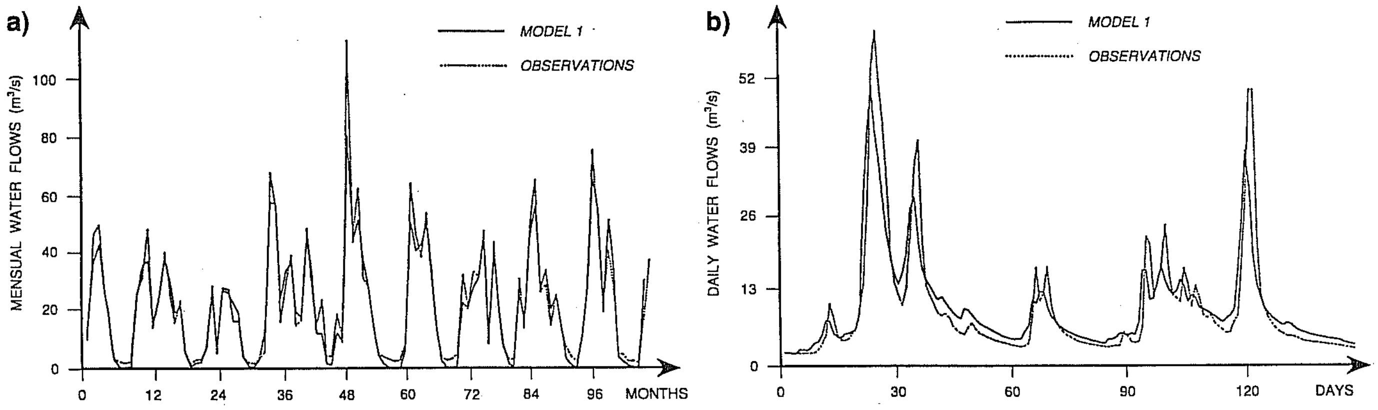

Fig. 9 (a) Monthly water flows over the Luy de France river basin and (b) daily water flows over the Adour river basin, as modelled by Ottlé and Vidal-Madjar (1994) and measured at the occasion of the HAPEX-MOBILHY experiment.

It can be seen there that long-term (i.e., at least decadal) measurements
- of soil heat flux G allows for the improvement of models of the local soil moisture content, e.g., through a better determination of soil thermal properties ;
- of accumulated evaporation allows for further improvement of these models by showing the necessity to include new processes such as, e.g., vapour-phase transfer.

For more detail interested readers are referred to Noilhan et al. (1992) and Braud et al. (1993).

4. THE MESO-SCALE AND THE UP-SCALING PROBLEM

4.1 Regional hydrology and land-surface fluxes

Following the idea that surface hydrology does indeed give a way to control evapo(transpi)ration fluxes into the atmosphere, it is of interest to try this approach at the meso-scale, i.e. the catchment-scale for hydrological processes as well as, at the same time, the grid box-scale of atmospheric modelling.

Using observations of the various terms entering Eq.(2) taken during HAPEX-MOBILHY experiment (André et al., 1988), it is possible to develop and calibrate distributed meso-scale hydrological models (Ottlé and Vidal-Madjar, 1994) which do reproduce correctly the surface flow (Figs. 9a and 9b) as well as the upper-soil-moisture storage (Fig.10). These models do in turn lead to an estimation of evapo(transpi)ration within the experimental domain, which can be used as a control for the other means of measuring this same quantity (see Fig.11).

Almost reciprocally, information such as the temperature and humidity of the air at screen level has ben shown by Bouttier et al. (1993) to allow for an efficient determination of upper-soil-moisture storage using optimum interpolation techniques, land-surface experiments providing the necessary soil-moisture data against which to test these assimilation techniques.

4.2 Up-scaling the surface fluxes through boundary-layer budgets

Land-surface experiments such as HAPEX-MOBILHY and FIFE have shown that frequent (ca. hourly) sounding of the atmospheric boundary layer may be used to retrieve area-averaged sensible and latent heat fluxes through vertical integration of the corresponding conservation equations for temperature T and humidity q :

$$\partial/\partial t \int_0^h (T,q)\, dz + \text{horizontal advection} = (H,LE) - (\overline{w'T'}_h, \overline{w'q'}_h) \qquad (5)$$

where h is the depth of the atmospheric boundary layer, and where horizontal and vertical (last term in the l.h.s.) advection terms may be estimated from weather analysis charts or numerical atmospheric mesoscale modelling. Such a procedure has been pioneered during HAPEX-MOBILHY

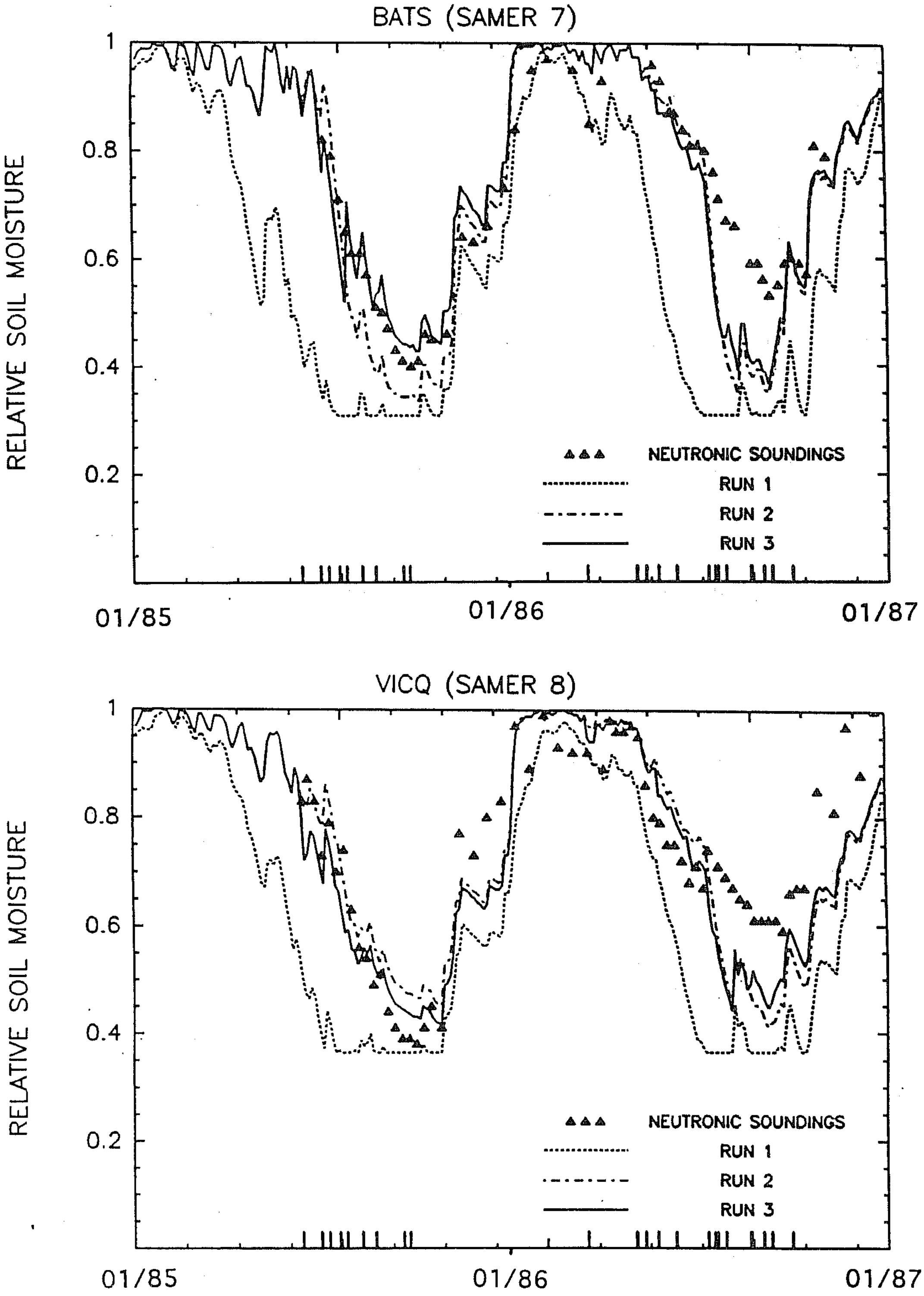

Fig. 10 Comparison between modelled (Ottlé and Vidal-Madjar, 1994) and measured values of the upper-soil moisture content at two sites during the HAPEX-MOBILHY experiment.

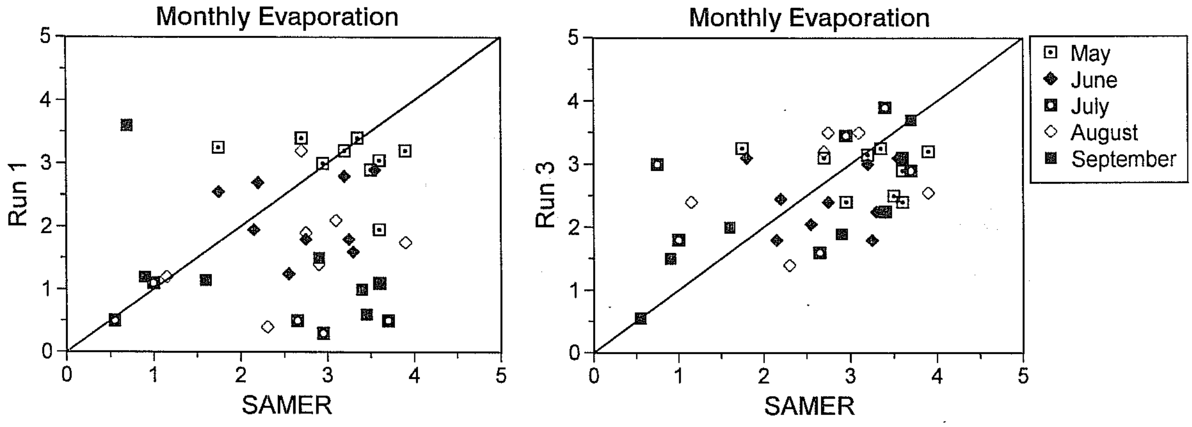

Fig. 11 Scatter diagram between measured and hydrologically modelled values of monthly accumulated evapo(transpi)ration (for the HAPEX-MOBILHY experiment, see Ottlé and Vidal-Madjar, 1994).

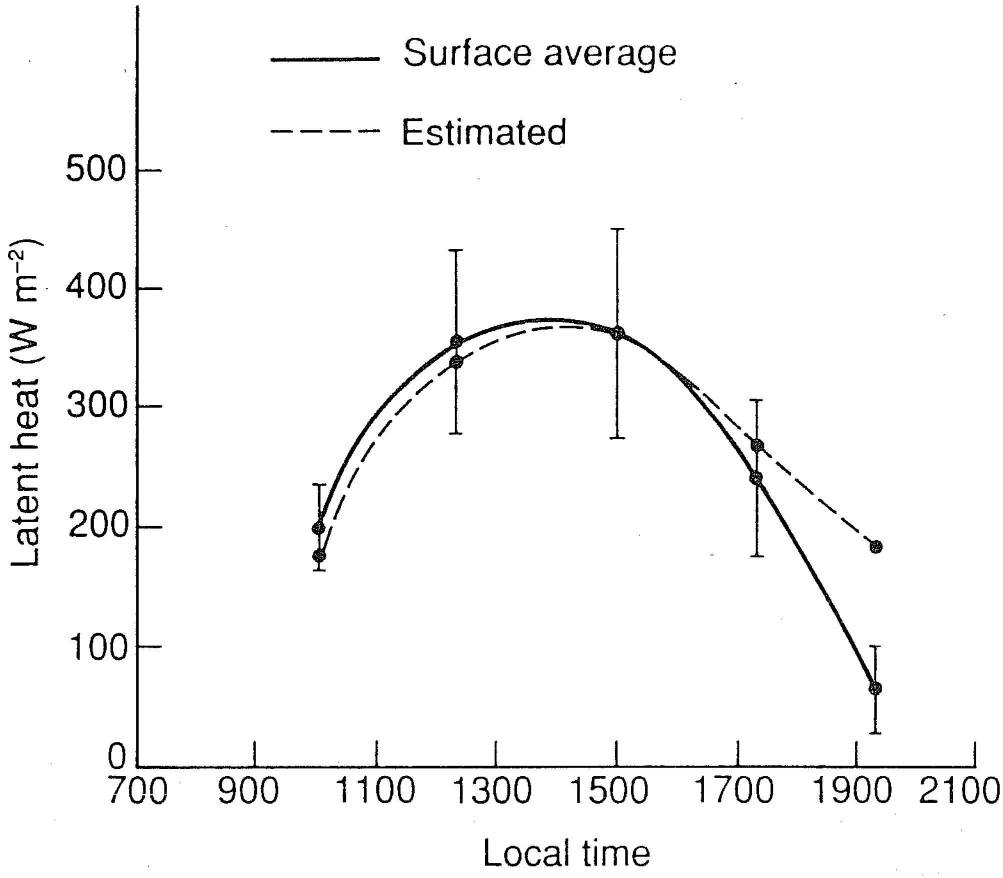

Fig. 12 Area-averaged latent heat flux derived from a moisture conservation model of the boundary layer, as compared with that measured at the surface (for the FIFE experiment, see Murley and Hipps, 1990).

(see André et al., 1988) and also applied during FIFE, see Fig. 12 (from Munley and Hipps, 1990 ; see also Shuttleworth, 1991).

4.3 The use of high-resolution atmospheric meso-scale modelling

Since the early proposal by André and Bougeault (1988), many modellers have indeed tried to simulate at high spatial resolution the boundary-layer and meso-scale processes in order to derive ways to area-average surface heat, moisture and humidity fluxes. One must here distinguish between two types of approaches which, although they may look quite alike due to their similar use of atmospheric mesoscale modelling, are quite different in essence.

In the first one, one tries to address very extreme, and consequently physically unrealistic situations, in which for example a patch of pure desert (i.e. completely dried-out soil) lies in the middle of a swamp (i.e. fully satured soil), or the other way around. Such irrealistic numerical studies show indeed that quite intense meso-scale circulations may develop in the boundary layer, although it is not clear if these circulations modify even slightly the atmospheric water demand and hence the surface evaporation flux. Such examples can be found in Taylor et al. (1994).

In the second one, one only addresses situations which are physically realistic. They may concern an idealized transition between two different types of surface cover (e.g., André et al., 1989) or more interestingly a real patchwork of land-surface conditions. In these cases, following André and Bougeault's (1988) methodology, the three-dimensional meso-scale model is implemented by prescribing surface conditions from satellite observations and describing the land-surface exchange through a transfer scheme previously validated against surface energy-budget measurements (see, e.g., André et al., 1990, or Noilhan and Lacarrère, 1994). In a way the high-resolution mesoscale model is then "simply" used as a tool to realistically interpolate between points measurements taken during the corresponding field experiment. Validity and accuracy of these model outputs can be checked by comparing with independant experimental information, namely boundary-layer fluxes as measured from instrumented aircraft. An example of such a comparison is shown in Fig. 13 in the case of the HAPEX-MOBILHY experiment (see Noilhan and Lacarrère, 1994), but similar results have been obtained for other field programmes.

With the experimental situation being fully known and controlled from the field results on the one hand, and from the model "interpolation" on the other hand, it is then easy to test any method for deriving area-averaged, or "effective", values for the land-surface parameters at the meso-scale. Noilhan and Lacarrère (1994) have indeed shown that mean properties constructed by linearly-averaging parameters entering linearly the equations (albedo, leaf-area-index (LAI), vegetation cover) and by logarithmically -(resp. harmonically-) averaging parameters entering non-linearly the equations (roughness length or, resp. stomatal resistances) do allow for a quite accurate

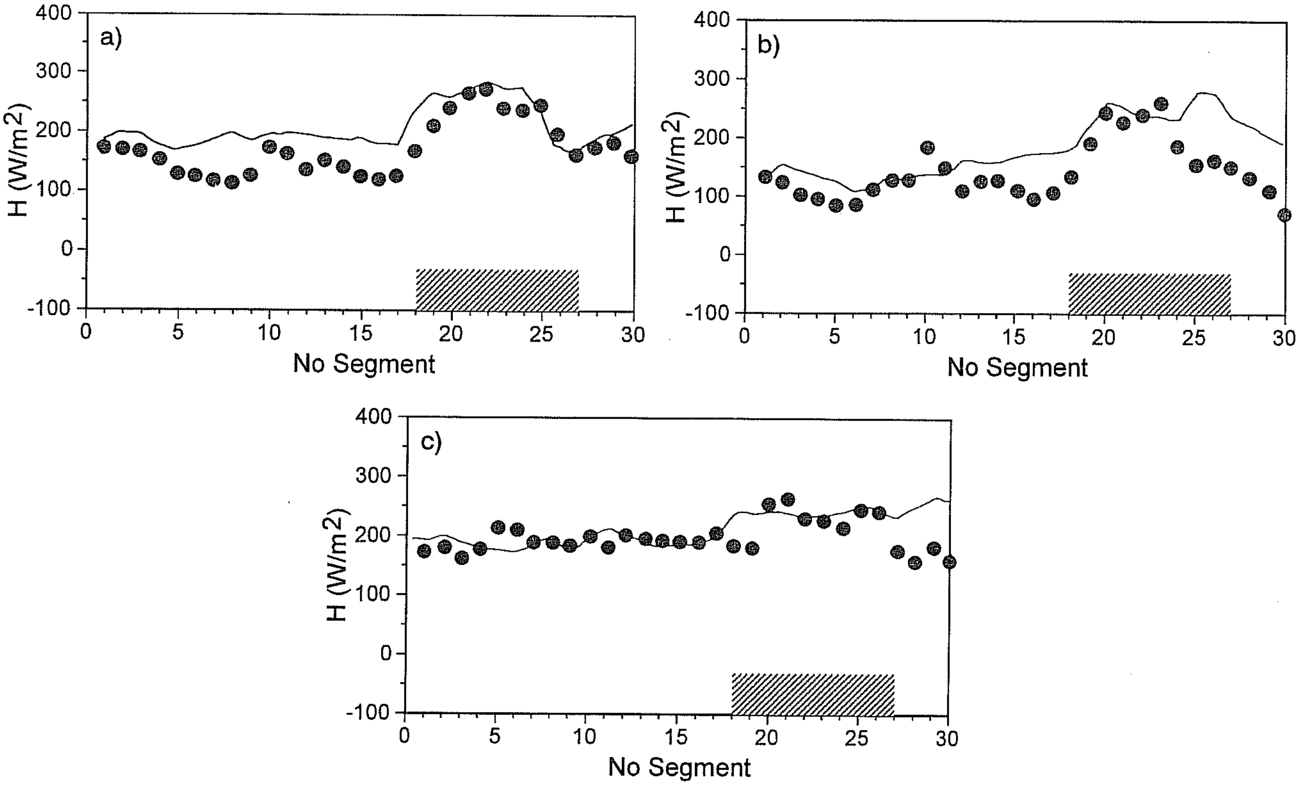

Fig. 13 Comparison between sensible heat flux as estimated from eddy-correlation airborne measurements and as modelled using a three-dimensional atmospheric mesoscale model {for the HAPEX-MOBILHY experiment, see Noilhan and Lacarrère, 1994).

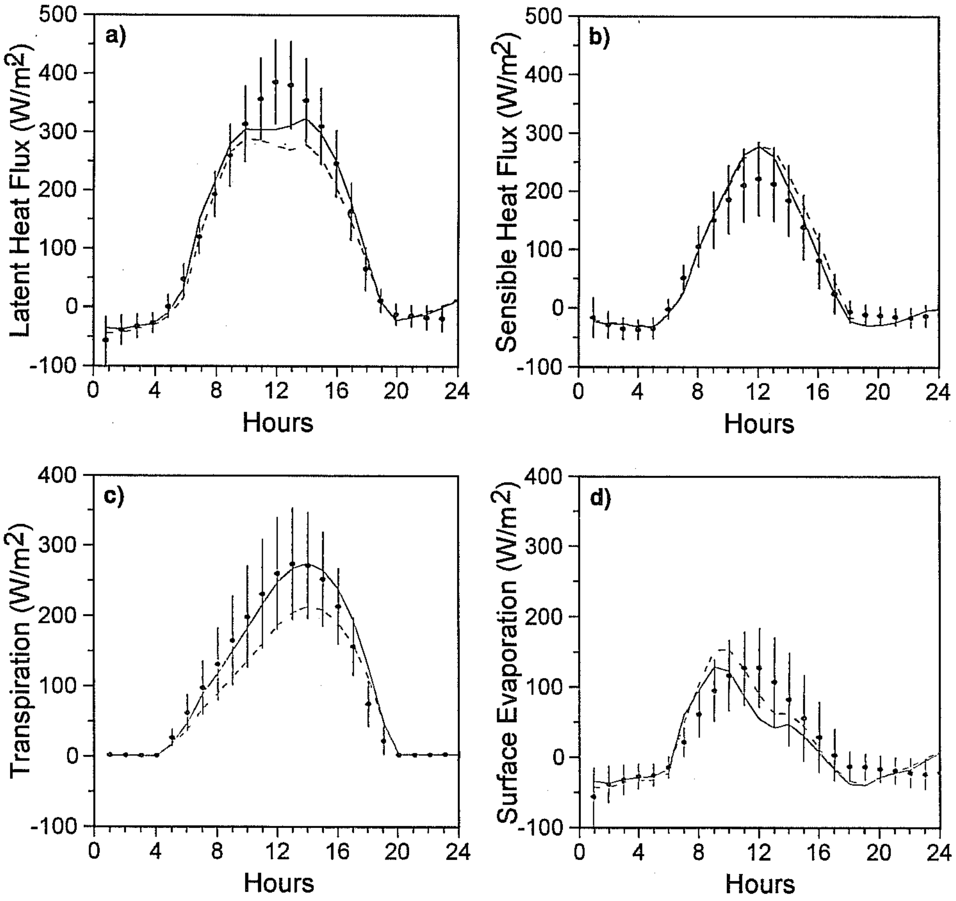

Fig. 14 Comparison between area-averaged values of the diurnal values of (a) latent heat flux (b) sensible heat flux (c) net radiation and (d) heat flux into the ground as "measured" from experimental field data interpolated through atmospheric mesoscale modelling (points and vertical bars, showing sub-grid-scale variability), and as estimated from a one-dimensional transfer scheme using either dominant (dotted line) or "effective" (solid line) surface properties (for the HAPEX-MOBILHY experiment, see Noilhan and Lacarrère, 1994).

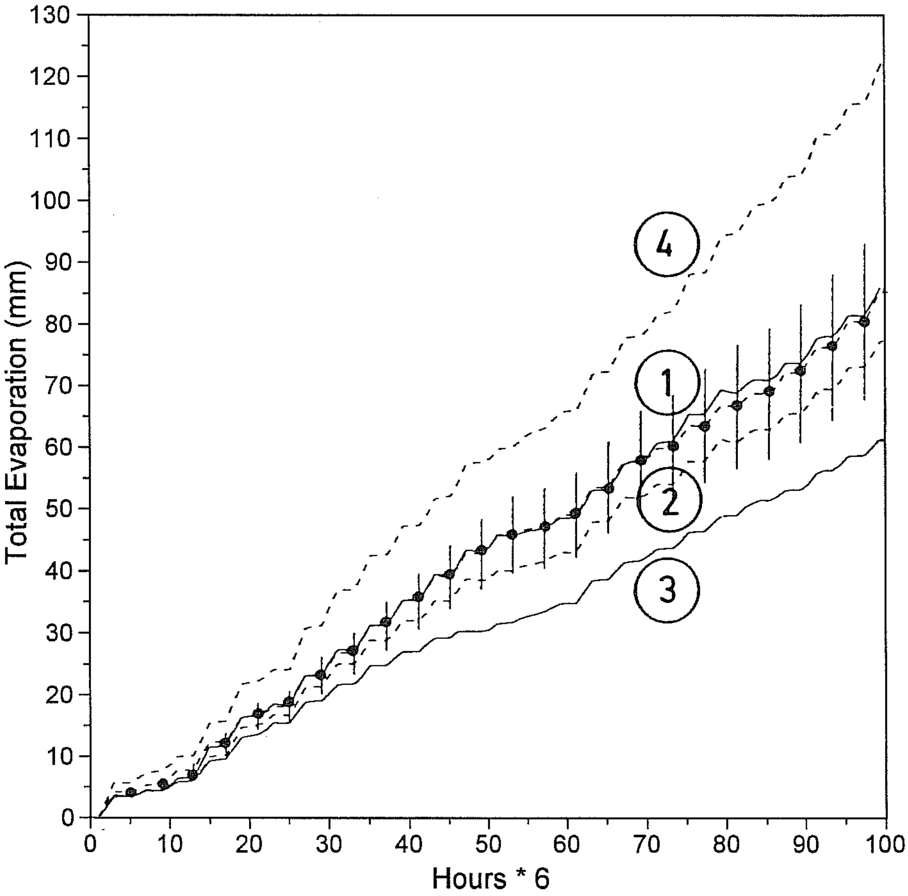

Fig. 15 Comparison between values of area-averaged accumulated evapo(transpi)ration as measured (points and vertical bars, showing sub-grid scale variability) and modelled using a one-dimensional transfer scheme fed by either dominant (solid line, curve 3) or "effective" (solid line, curve 1) surface properties (for the HAPEX-MOBILHY experiment, see Noilhan and Lacarrère, 1994).

representation of the area-averaged surface fluxes as compared to the value obtained by compositing the flux values at the pixel scale. An example is shown in Fig. 14 in the case of the HAPEX-MOBILHY experiment (Noilhan and Lacarrère, 1994). Such a determination of "effective" surface properties at the meso-scale is of crucial importance for a proper balancing of both the surface energy and soil-moisture budgets (see, e.g., Fig.15). It further indicates that non-linear effects possibly related to a modulation of the atmospheric demand by induced meso-scale circulations are quite small in all the realistic situations which have been under study up-to-now

5. PERSPECTIVES

It seems that the major land-surface experiments organized up-to-now, or to be organized within the next to or three years (i.e. before 1997-98), have brought a wealth of results which need now to be fully exploited in the framework of large-scale (NWP and climate) modelling. We indeed have now validated strategies for up-scaling and we do or will soon have physical information for the major biomes in the world : agricultural landscape, semi-arid regions, temperate, boreal and tropical forests.

One is then looking mainly for additional insight about some physical and physiological processes corresponding to particular ecosystems, which can be achieved by organizing much smaller-scale field studies.

The pressure for going back in the fields to organize major in situ programmes will nevertheless be possibly felt when new sensors on board the next generation of satellites, or new pieces of yet unknown research, will have stimulated new ideas... and this for sure will happen !

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References

André, J.C., 1992 : "Les processus de surface continentale et le cycle de l'eau". Proc. "Africa and Global Change", IGBP Report 29, Stockholm.

André, J.C., and Ph. Bougeault, 1988 : "On the use of the HAPEX-MOBILHY data for the validation and development of parameterization schemes of surface fluxes". WCP 126, B1-18, Geneva.

André, J.C., Ph. Bougeault and J.P. Goutorbe, 1990 : "Regional estimates of heat and evaporation fluxes over non-homogeneous terrain. Examples from the HAPEX-MOBILHY programme". Bound. Layer Meteorol., 50, 77-108.

André, J.C., Ph. Bougeault, J.F. Mahfouf, P. Mascart, J. Noilhan and J.P. Pinty, 1989 : "Impact of forests on mesoscale meteorology". Phil. Trans. R. Soc. Lond., B 324, 407-422.

André, J.C., J.P. Goutorbe, A. Perrier et al., 1988 :"Evaporation over land-surfaces. First results from the HAPEX-MOBILHY special observing period". Annales Geophysicae, 6, 477-492.

André, J.C., J.P. Goutorbe, Th. Schmugge and A. Perrier, 1989b : "HAPEX-MOBILHY : Results from a large scale field experiment". IAHS Pub. 186, 13-20.

Beljaars, A.C.M., P. Viterbo, M.J. Miller, A.K. Betts and J.H. Ball, 1993 : "A new surface boundary-layer formulation at ECMWF and experimental continental precipitation forecasts (July 1993)". GEWEX News, 3, 1-9.

BAHC (Biospheric Aspects of the Hydrological Cycle), 1993 : "The operational plan". IGBP Report 27, Stockholm.

Bougeault, Ph., 1991 :"Parameterization schemes of land-surface processes for mesoscale atmospheric models". Land-surface evaporation, measurement and parameterization, Th. Schmugge and J.C. André. Eds., Springer-Verlag, 55-92.

Bouttier, F., J.F. Mahfouf and J. Noilhan, 1993 :"Sequential assimilation of soil moisture from atmospheric low-level parameters". J. Appl. Meteor., 32, 1335-1364.

Braud, I., J. Noilhan, P. Bessemoulin, P. Mascart, R. Haverkamp and M. Vauclin, 1993. "Bare-ground heat and water exchanges under dry conditions : Observations and parameterization". Bound. Layer Meteor., 66, 173-200.

Hall, F.G., K.F. Huemmrich, S.J. Goetz, P.J. Sellers and J.E. Nickeson, 1992 : "Satellite remote-sensing of surface energy balance : Success, failures and unresolved issues in FIFE". J. Geophys. Res., 97, 19.061-19.089.

Munley, W.G., and L.E. Hipps, 1990 : "Estimation of regional evaporation for a tallgrass prairie from measurements of properties from the atmospheric boundary layer". Water Ressources Res., 27, 225-230.

Noilhan, J., and P. Lacarrère, 1994 : "GCM grid-scale evaporation from mesoscale modelling". J. Climate, in press.

Noilhan, J., J.F. Mahfouf, A. Manzi and S. Planton, 1992 : "Validation of land-surface parameterizations : Developments and experiment at the French weather service". ECMWF Proc. "Validation of models over Europe", Vol II, 125-158.

Noilhan, J., and S. Planton, 1989 : "A simple parameterization of land-surface processes for meteorological models". Mon. Wea. Rev., 117, 536-549.

Ottlé, C., and D. Vidal-Madjar, 1994 : "Assimilation of soil moisture inferred from infrared remote-sensing in a hydrological model of the HAPEX-MOBILHY region". J. Hydrol., 158, 241-264.

Rowntree, P., 1994 : "The significance of land-surface processes and their role in the atmospheric general circulation". ECMWF, these proceedings.

Shuttleworth, J.W., 1991 : "The modellion concept". Rev. Geophys., 29, 585-606.

Taylor, Ch., R. Harding and A. Thorpe, 1944 : "Mesoscale modelling of surface heterogeneity in the Sahel". European Conference on GEWEX, London, July 1994.

WCRP (World Climate Research Programme), 1983 : "Report of the meeting of experts on the design of a pilot atmospheric hydrological experiment for the WCRP". WCP 76, Geneva.

WCRP (World Climate Research Programme), 1990 : "Report of the first session of the WCRP-GEWEX/IGBP-CP3 joint working group on land-surface experiments". WCRP 38, Geneva.