DERIVATION OF RELEVANT SURFACE PARAMETERS FROM SATELLITE REMOTE SENSING

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1. INTRODUCTION

Despite the fact that the total land surface is far more smaller than the oceans, it has been demonstrated that a correct knowledge of the soil/plant/atmosphere energy and mass interaction is necessary if one wants to understand and model the atmospheric circulation. This relative importance is certainly due to the complex physical and biological behaviour of this system. At the opposite of the ocean surface, it experiences strong reactions to the daily as well as annual variations of the energetic and mass forcing from the sun and the atmosphere. The other fundamental characteristic of the land surface is its tremendous heterogeneity at small scale and the fact that, as the natural environment of human kind, it is very dependent on the human activities.

It is then clear that even if one has a perfect biophysical model of the land surface behaviour in relation to external atmospheric forcing, it would be necessary to reactualize the parameters describing the state of the surface at time intervals which may be as short as few days (modifications of the phenological state) or as long as few years (human activities). The heterogeneity of the surface is such that it is not imaginable to do this job by ground surveys or laboratory or field measurements. Very soon, the earth observation from space, which has an extraordinary development since the early seventy's, will be a good candidate for doing part of this job. But it must be pointed out that everything cannot be done using this type of techniques and that it will always be necessary to monitor a large number of parameters from ground measurements.

In this paper, it will be shown how one can use or imagine to use remotely sensed data in the land/atmosphere interaction models. This will be done with the help of one dimensional predictive model of the soil/plant/atmosphere continuum which has been designed to take into account as many remotely sensed data as possible (Taconet et al., 1986a, 1986b ; Taconet and Vidal-Madjar, 1988 ; Soares et al., 1988). In the first part, the model will be briefly described and its main functional parameters will be given, classified into those which describe the general biophysical state of the surface, those which concerned its radiative properties, those which are used to initiate a run of the model and finally those which are the boundary conditions.

In the second part, it will be shown how the various remote sensing observations can be used or may be used when they will be available on an operational basis. Here again, the applications will be divided into two categories : the ones leading almost directly to relevant parameters, and the ones which may be used together with the soil/plant model to derive some of those parameters.

2. DESCRIPTION OF THE SURFACE MODEL

As the number of measurable parameters from satellite remains limited, the present surface model assumes a simple, but still realistic parametrization, based on the formalism of Deardorff (1978) which allows the use of a small number of mesoscale soil/vegetation parameters. For a complete description of the model, the reader is referred to the paper of Taconet et al., 1986a.

2.1 Principle

The surface layer model consists of a single layer of vegetation, shielding more or less completely the soil which is represented as a two-layers system for thermal and hydraulic transfers (Fig. 1). The existing vegetation modifies the energy and mass transfers above bare soil, mainly in screening the incoming radiation, in changing the aerodynamic turbulence promoting the fluxes and in extracting by transpiration water from the deep soil layer. From Deardorff (1978), the general idea is to solve simultaneously the different thermal and hydraulic transfers at the ground level and at the canopy level by giving a realistic partition of the energy and momentum fluxes between the ground and the canopy.

Thus the first important parameter is the areal fraction occupied by the vegetation σf, tuning the incoming radiation between the ground and the canopy. σf is expressed as a function of the leaf area index LAI, depending of the type of the vegetation. The radiation balance for the soil/vegetation system is obtained using σf and the radiative properties of the 2 surface components in the visible and infrared bands (albedoes and emissivities). The foliage density is also used to express the partition of momentum controlling the turbulent exchanges at the foliage and ground surfaces.

Therefore the model needs a first category of parameters, describing the vegetation state which varies slowly with time : its type, leaf area index LAI, and height h.

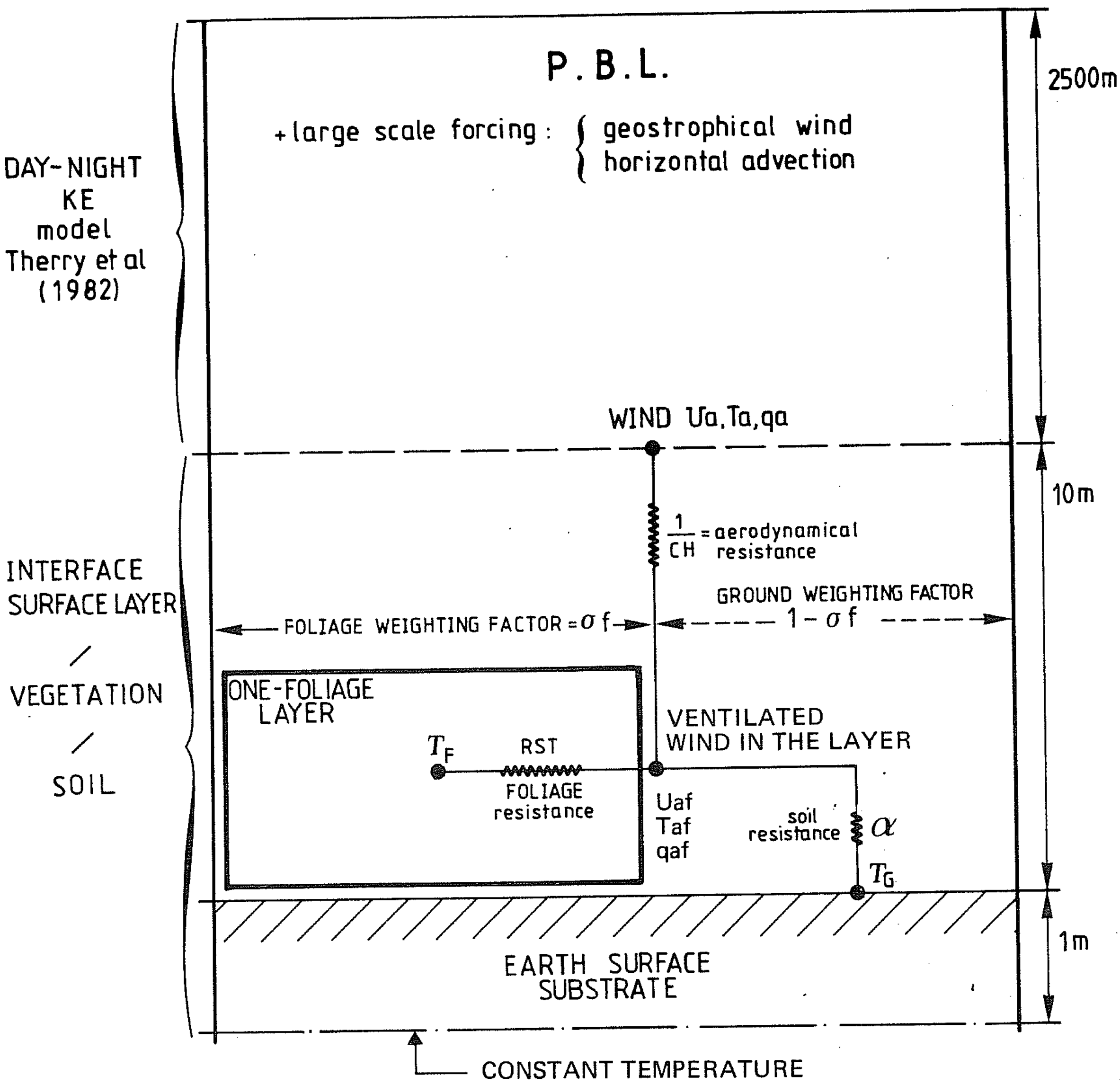

P.B.L.
+ large scale forcing : geostrophical wind
horizontal advection
2500m
DAY-NIGHT
KE
model
Therry et al
(1982)
WIND Ua,Ta,qa
10m
1/CH = aerodynamical resistance
INTERFACE
SURFACE LAYER
/
VEGETATION
/
SOIL
GROUND WEIGHTING FACTOR
FOLIAGE WEIGHTING FACTOR = σf
1 - σf
ONE-FOLIAGE
LAYER
VENTILATED
WIND IN THE LAYER
TF
RST
FOLIAGE
resistance
Uaf
Taf
qaf
soil
resistance
α
TG
1m
EARTH SURFACE
SUBSTRATE
CONSTANT TEMPERATURE

Fig. 1

2.2 Soil component

Having parametrized the available radiation and air turbulence at the ground surface, the soil is treated by the well-known formalism of the two-layers system (Fig. 2). The thermal transfers and temperature tendency are calculated from the force-restored method described by Blackadar (1976) and coupled with the resolution of the soil energy budget. The two functional parameters are, the thermal inertia P depending on the soil type and humidity content, and the evaporative diffusive conductance of the soil α. The diffusive conductance α is calculated using the concept of the limited evaporation Elim: the soil evaporation demand Epot is sustained so far as it does not exceed the maximum sustainable water flux of the soil when the skin surface is dessicated.As follows, $\alpha = \min(1, \mathrm{Elim} / \mathrm{Epot})$. The conductance α is a complex function of both the humidity content of the surface layer W_g and the near-surface soil properties (texture and mainly soil preparation), needing to the calibrated for use at mesoscale. Local empirical relationships of Elim are derived: for example,by Bernard et al. (1986) over Yolo light clay,

$$\mathrm{Elim} = a \exp(b\, Wg^2) \frac{Wg}{Wsat - Wg} \qquad (1)$$

where a,b,Wsat are soil related constants.

To solve the equations, the deep soil temperature T_2 has to be initialized, which is easily done from the seasonal evolution of the air temperature.

Again, following Deardorff (1977), the soil is described as a double layer, but where the exchange between the two layers is reformulated by a diffusivity type of "feeback" (Bernard et al., 1986). The flow equations are then :

$$\frac{\partial Wg}{\partial t} = -\frac{Eg}{d1} + C(W2)\,(W_2 - W_g) \qquad (2)$$

$$\frac{\partial W_2}{\partial t} = -\frac{Eg}{d_2} \qquad (3)$$

where, W_g, W_2 are the water content of surface (10 cm) and deep (1 m) layers, E_g is the soil evaporation flux and C is similar to the "pseudo-diffusivity" introduced by Bernard et al., (1986) depending mainly on W_2 and soil properties. The functional parameter accounting for the hydraulic temporal variation is the diffusivity $C(W_2)$, which needs also to be calibrated at regional scale. The two humidity contents (W_g, W_2) have to be initialized to solve the equations system.

With vegetation, the foliage transpiration E_{tr} contributing to the deep reservoir depletion is added, changing in Eq. 2 the term E_g by E_g+E_{tr}.

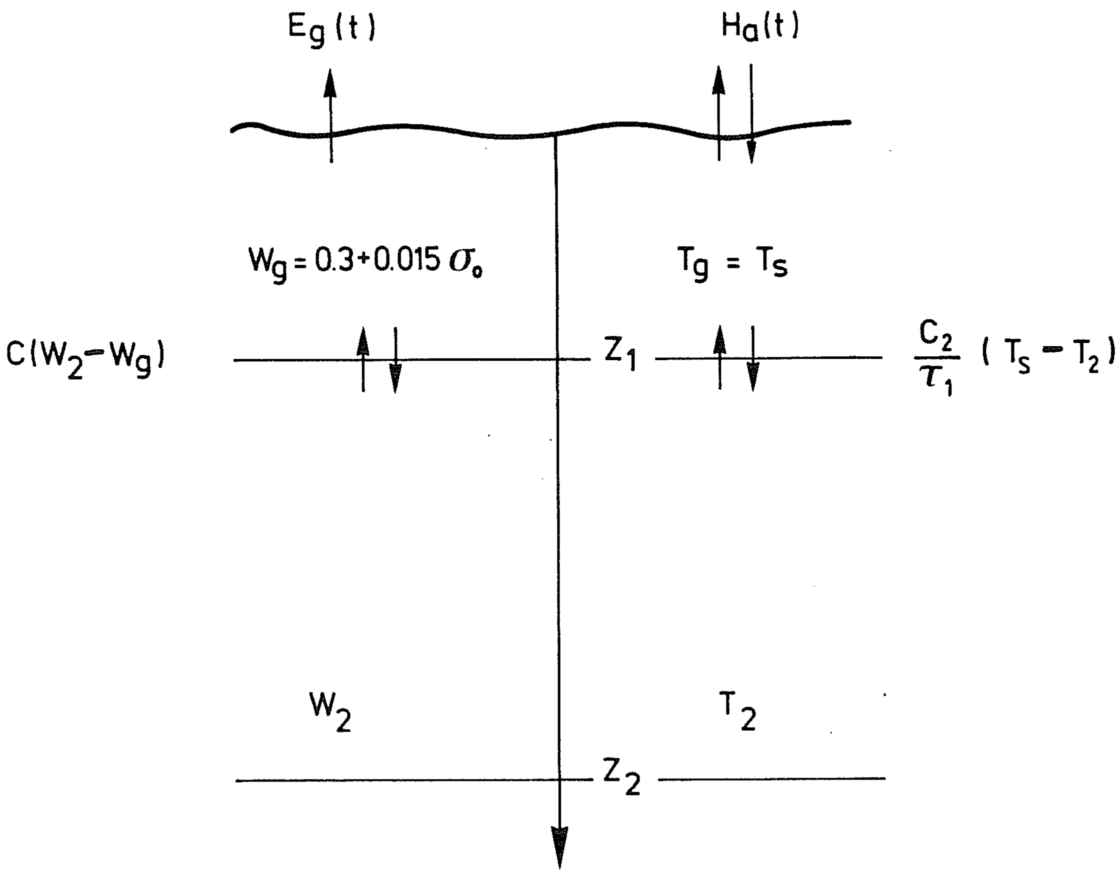


Fig. 2

2.3 Vegetation component

Assuming the vegetation to be a single layer of negligible heat capacity, only heat and mass (water) transfers have to be considered. The only functional parameter to be added is the factor R' accounting for resistance to evaporation, due either to stomatal resistance or to partial cover of dew or rain.

The latent heat transfer is :

$$LEf = \frac{\rho C_p}{\gamma} R' \, Cfh \, (q_{sat}(T_f) - q_{af}) \qquad (4)$$

where ρ, C_p, γ are the density, specific heat of the air and the psychrometric constant, Cfh the turbulent conductance, and $q_{sat}(T_f)$-q_{af}, the gradient between air water partial pressure and saturation one at the canopy level. For a dry canopy transpiring only through the leaves, with a stomatal resistance RST:

$$R' = \frac{1}{\beta + Cfh \, RST} \qquad (5)$$

Among the many physiological factors involved in the foliage resistance, RST varies under the control of the incoming solar radiation S, the water supply in root zone W_2 and the phenological state.

$$RST = Rst_{min} \times f_1 (S) \times f_2 (W_2) \qquad (6)$$

where Rst_{min} is the unstressed resistance depending of the phenological state.

Caution must be taken with the stressed function f_2 which has to be calibrated, depending of the culture type and soil pedological properties. Litterature values of the minimum resistance lead to consider two classes, over crops or meadows, Rst_{min} = 50 sm^{-1} ± 50 sm^{-1}, over forests Rst_{min} = 200 sm^{-1} ± 50 sm^{-1}, which seem sufficient due to the relative insensivity of the evaporation to the mentioned uncertainties of Rst_{min} (Pinty et Mascart, 1988). But this resistance may change significantly with the crop maturing, needing the knowledge of a phenological indicator.

Finally, the energy and mass equations of the soil/vegetation interface are solved, giving the solar and atmospherical forcing within the turbulent surface layer.

The main functional parameters are summed in the Table 1.

	State parameters	R.S.	Radiative parameters	R.S.	Functionnal parameters	R.S.	Initialization	R.S.
Vegetation	type	yes	albedo α_f	yes	Stomatal resistance RST	yes		
	height	no	emissivity ε_f	no				
	σ_f							
	phenological state							
Soil			albedo α_g	yes	thermal inertia P	yes	deep temperature T2	yes
			emissivity ε_g	no	pseudo diffusivity C(W2)	yes	deep reservoir W2	yes
					diffusive resistance	yes	surface humidity	yes

R.S. parameter measurable by remote sensing

TABLE 1

3. THE APPLICATIONS OF THE SATELLITE OBSERVATIONS

3.1 Nearly directly measurable relevant parameters

The existing satellite observations give informations about the general state of the surface at three different scales : the field scale (the Thematic Mapper of Landsat or the "Haute Resolution Visible" of SPOT), an intermediate scale from 1 to 5 km aside (the AVHRR of the NOAA satellites) and the regional or mesoscale (from 20 to 100 km) which is obtained by averaging the data taken at the two other scales. Information and details about the measurable parameters can be found in the special issue on AGRISTAR (IEEE Trans. GE-RS,1986).

At the field scale, it is now well known that the nature of the surface can be determined. Using the visible (0.65 µm) and near infrared (0.85 µm) radiances in one or more images, a distinction can be made between bare and vegetated soils. It is then possible to determine the dominant nature of the surface at regional scale. In particular, if a dominant crop exists, the value of the unstressed minimum stomatal resistance $R_{st\ min}$ may be roughly set. Further more a realistic relationship between the minimum stomatal resistance and the mean water content of the soil (W_2) may be determined by measurements within representative fields. Presently, there is no technique which can derive $R_{st\ min}$ from satellite observations.

At regional scale, the use of vegetation indices calculated from visible and near infrared channels leads, at the beginning of the growing season, to an evaluation of the Leaf Area Index (Fig. 3) which, in turn, is used to calculate the percentage of soil covered by the vegetation (σ_f). This is an operational use of the data. But there are two problems. The first one is the effect of the soil albedo on the indices which can lead to substantial errors on the LAI (Huete et al.,1985). As for as the soil albedo varies, in part, with the surface water content, this effect may be taken into account using the futur regional surface soil moisture which will be given by observations in the low frequency microwave range (see below). The second one is the saturation which occurs on the relation between vegetation indices and the LAI at high values of LAI. On that subjects, research is under way to overcome this difficulty with microwave observations.

When a medium infrared band (1.62 µm), which is dependent on foliar moisture content, is added, the phenological state of the crop may be determined. It may therefore be possible to monitor the phenological state at regional scale with a precision sufficiently good to allow the switching between the various function giving the stomatal resistance. Such a thing has never been done but may be considered as possible.

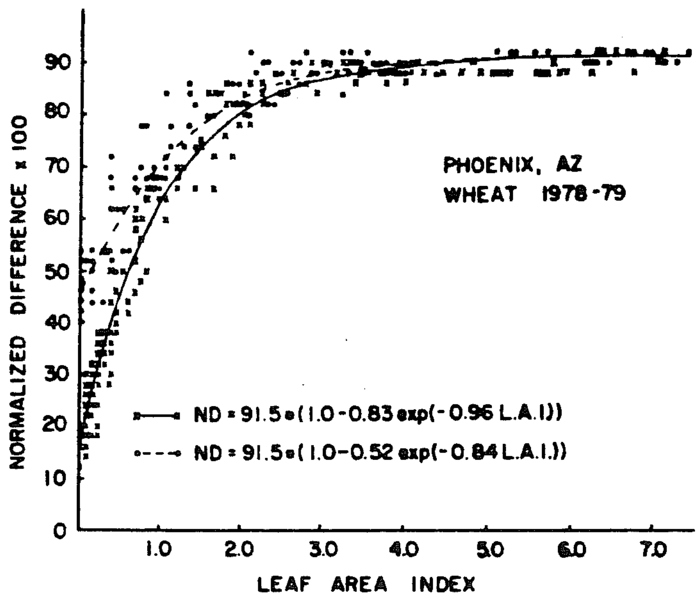


Fig. 3 Relation between normalized difference and green leaf area index for the growth (x——x) and scenescent (.-----.) periods of wheat.

Again at regional scale, the satellite radiances can be interpreted in terms of surface albedo (Gauthier, 1987). This is a nearly operational product of the geostationary satellites. By correcting the satellite data of the clear atmosphere effects and knowing the solar irradiance at the top of the atmosphere, several methods lead to the determination of the albedo with an error of about 15%.

This is not possible for the emissivity in the thermal infrared range. Obviously, the land surface must not be considered as a black body (this is an other important difference with the ocean) (Fig. 4) . Presently, the emissivity can not be measured at regional scale with reasonable precision (of the order of one percent). To set a value to the emissivity, one has to rely on laboratory or very local measurements (Nerry et al., 1988).

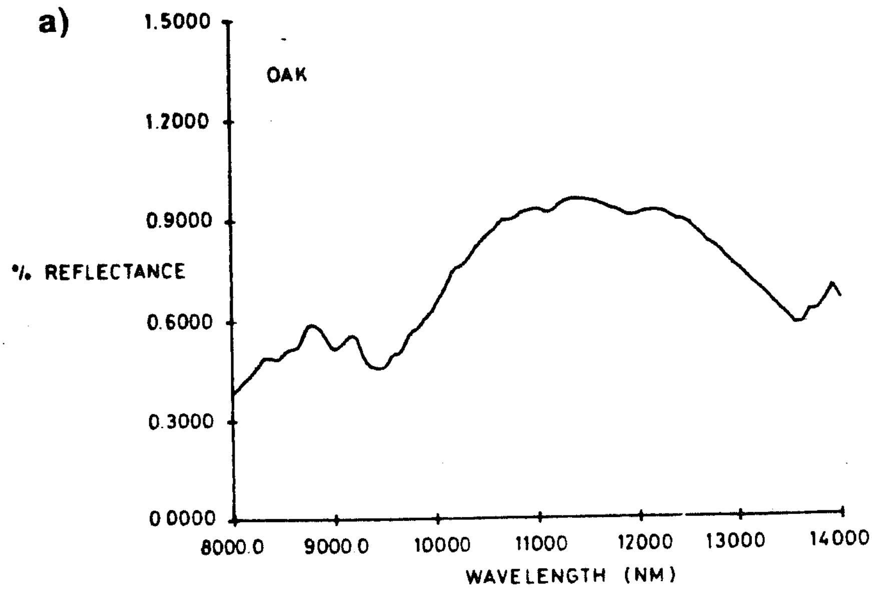
At last, but not least, it has been demonstrated at several occasions (see for example Soares et al., 1988) that active (radars) or passive (radiometers) microwaves give access to an estimation of the surface soil moisture (W_g) as is shown on figure 5. Which gives the experimental calibration of an airborne radar. Despite some problems (effect of vegetation and of the soil electromagnetic roughness), it is most likely that it will be possible to make such measurements before the year 2000 at regional scale on a global basis every 3 or 5 days. An other advantage of the low frequency microwaves is their total insensitiveness to clouds.

2.2 Indirect measurements of relevant parameters

Many of the functional parameters discussed in the first part of this paper have to be defined and estimated at regional scale. Some of them, like σ_f, do not present any conceptual difficulties and can be measured very easily. Others are difficult to define. It is the case of all the soil parameters or the plant resistance to evaporation. Conceptualy they have no mean as far as they come from very local definitions.

Obviously, by applying local relationships to regional behaviour, one makes the fundamental hypothesis that the field mechanisms are still valid at mesoscale. It remains the problem of the determination of the value of the functional parameters. They can not be deduced, at low price, from field measurements due to their spatial heterogeneity. Then one must find a way to determine them using regional measurements. Here, two examples will be given. The first shows the availability of coupling the infrared and microwave bands to infer over bare soil simultaneously the thermal and hydraulic functional parameters. The second concerns the application of thermal infrared data to evaluate regional plant resistance over dense canopies.

In the first example, during a drying period time series of remotely infrared and microwave sensed data are coupled to the soil component of the model to assign a value for the soil



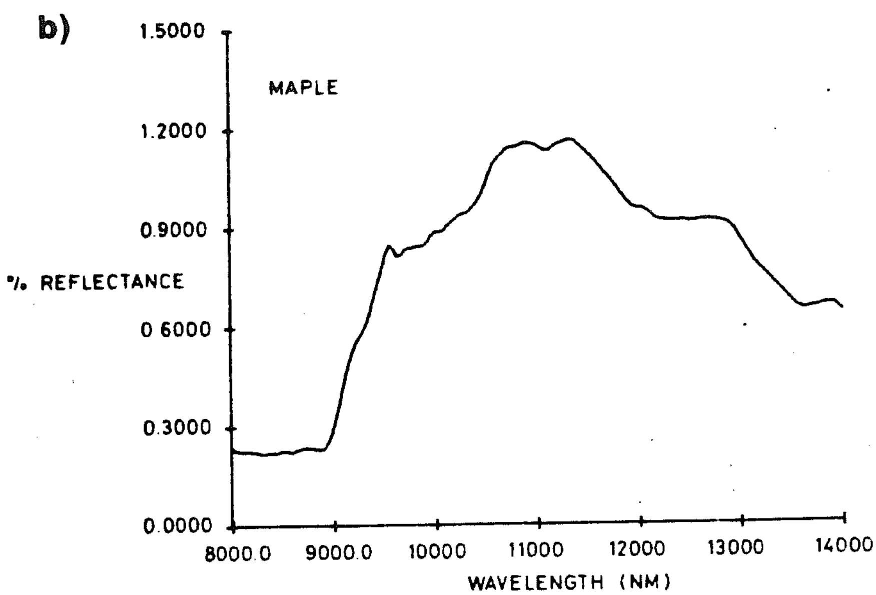


Fig. 4 Average reflectance spectra of a) black oak (Quercus velutina) and b) red maple (Acer rubrum) versus an aluminium mirror.

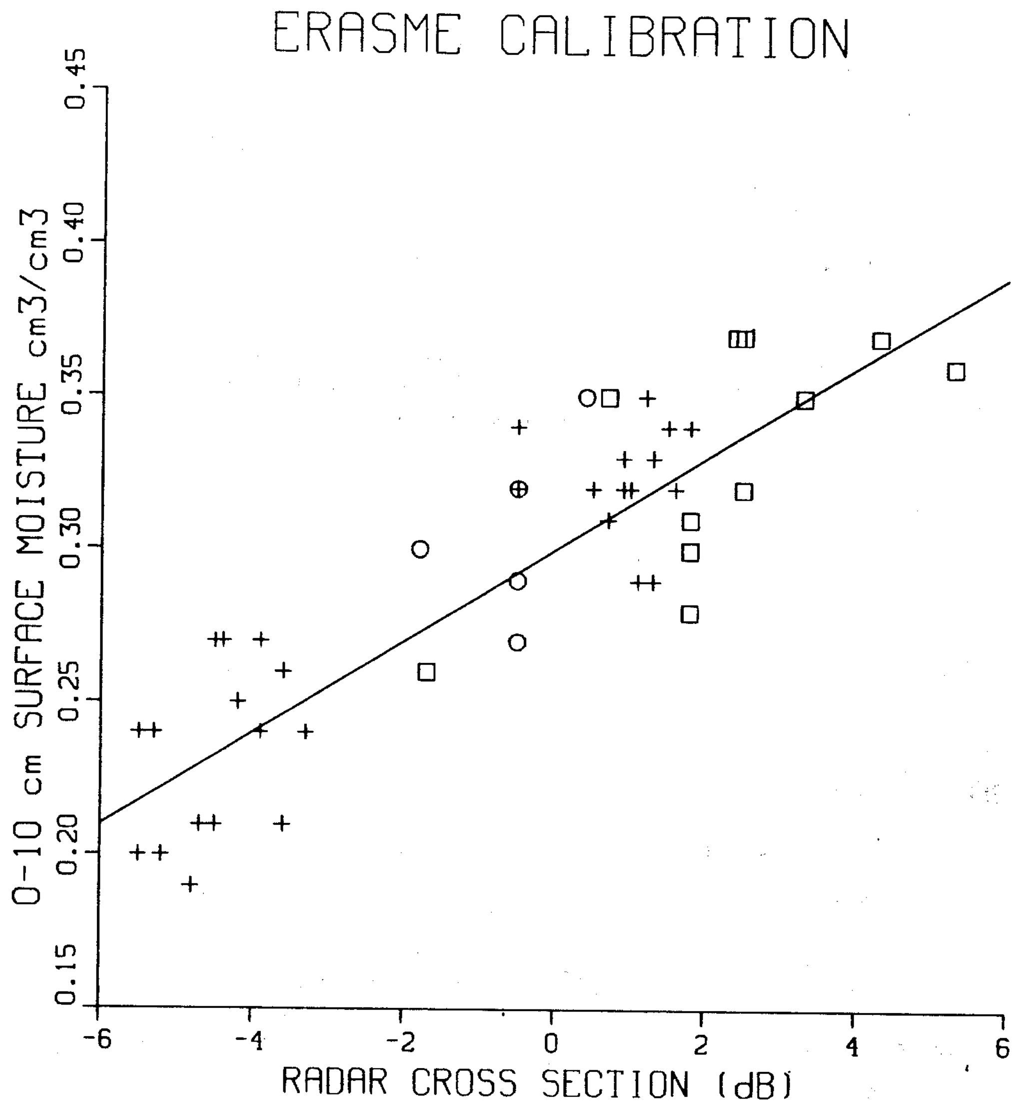

ERASME CALIBRATION
0-10 cm SURFACE MOISTURE cm3/cm3
0.15
0.20
0.25
0.30
0.35
0.40
0.45
-6
-4
-2
0
2
4
6
RADAR CROSS SECTION (dB)

Fig. 5

functional parameters (hydraulic and thermal). The principle is described on Fig.6. On that figure, the soil is bare and it is shown that the model, given the appropriate initial values of W_g, W_2 and T_2, is able to simulate the variations in time of the surface temperature T_s and the surface water content W_g in response to the atmospheric forcing represented by the net radiation flux R_n and the wind speed U_a, the air temperature T_a and the specific humidity q_a at a reference height within the surface layer. R_n, U_a, T_a and q_a may be given at the center of the region by classical meteorological measurements or by a mesoscale predictive boundary layer model coupled with the soil/vegetation one. It is not likely that they can be obtained in the future from space with a reasonable accuracy except for R_n (Gauthier, 1987). During the same period, remote sensing instruments have given T_s (thermal infrared radiometer assuming a value for the emissivity and a correct correction of the atmospheric effects) and W_g (passive or active microwaves). Briefly, we may recall that the infrared band is linked to the thermal and energetic properties. The only use of the daily infrared temperatures allows the determination over bare soil of the two thermal functional parameters, the thermal inertia P (with the nighttime temperature) and the diffusive conductance α (with the midday one) (Carlson,1985). On the other hand, the only measurement by microwave sensors of the soil humidity temporal evolution W_g,

$$\frac{\partial Wg}{\partial t} = -\frac{Eg}{d1} + C(W2)\,(W_2 - W_g) \qquad (2)$$

does not infer the hydraulic functions ($C(W_2)$ and W_2) without additional information on the evaporation. As evaporation is directly evaluated from the midday temperature, the coupling of infrared and microwave during a drying period is a way to initialize simultaneously at mesoscale the pseudo-diffusivity and the deep water reservoir, essential term for predicting long term evolution. The comparison between the predicted and the measured values of T_s and W_g may lead to determine W_2, P, α and C (T_2 is given as the mean preceding values of T_a). This has been done using data from airborne equipments during a period of 10 days in September 1983. The results are given on Fig. 7 and 8 which show, together with the comparison between the measured and predicted values of W_g and T_s, T_2 and W_2 calculated by the model. The best values for $W_2(0)$, P, a (in the Eq. 1 of α) and C were respectively 0.26 cm^3/cm^3, 1254 $J/(m^2\ {}^o k\ s^{1/2})$, 5 and $3.5 \times 10^{-6}\ s^{-1}$. Sensitivity analysis showed that it is W_2 which can be determined with the highest precision followed by P and α (which react only on the surface temperature). Fig.9 shows a comparison between the calculated sensible heat fluxes and regional fluxes from an acoustic Doppler Sodar on an hourly basis.

In the case of a dense canopy, it is possible from one estimated surface temperature T_s (from space borne thermal infrared radiometer assuming a value for the emissivity and a correct account of the atmospheric absorption) to estimate the regional stressed stomatal resistance. For doing so, one uses the soil/plant model together with the atmospheric forcing given in the

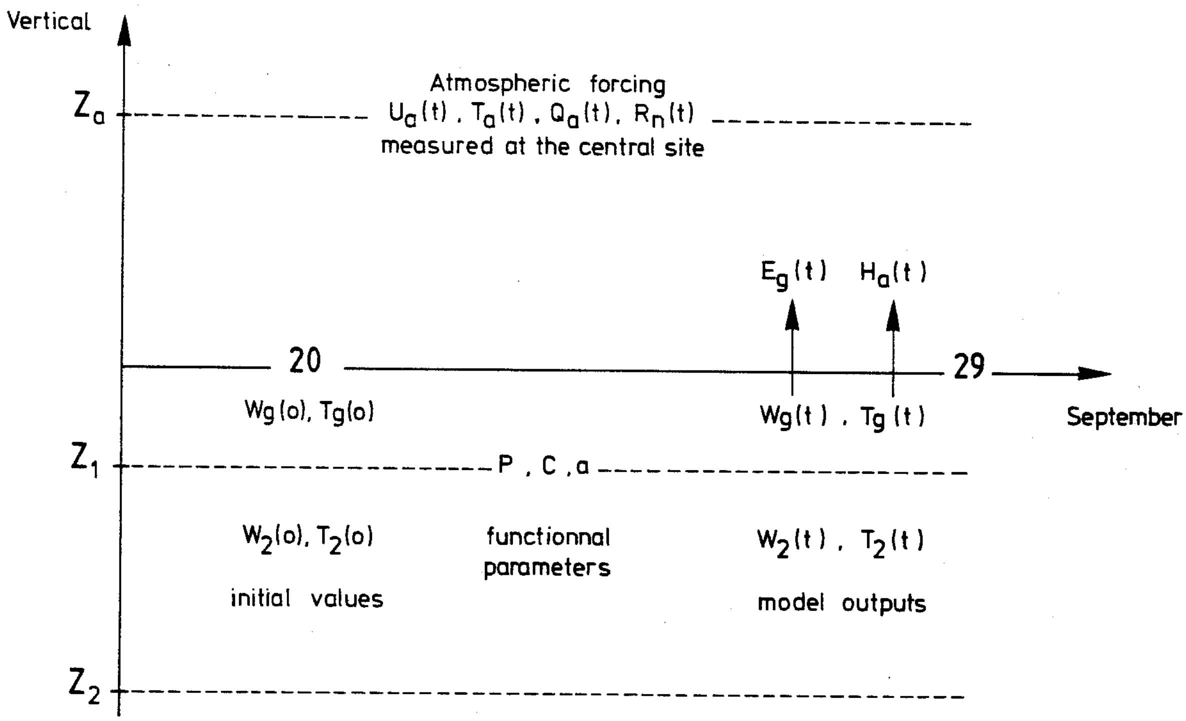

Vertical
Z_a
Atmospheric forcing
$U_a(t)$, $T_a(t)$, $Q_a(t)$, $R_n(t)$
measured at the central site
$E_g(t)$ $H_a(t)$
20
29
September
Wg(o), Tg(o)
Wg(t), Tg(t)
Z_1
P, C, a
$W_2(o)$, $T_2(o)$
initial values
functionnal
parameters
$W_2(t)$, $T_2(t)$
model outputs
Z_2

Fig. 6

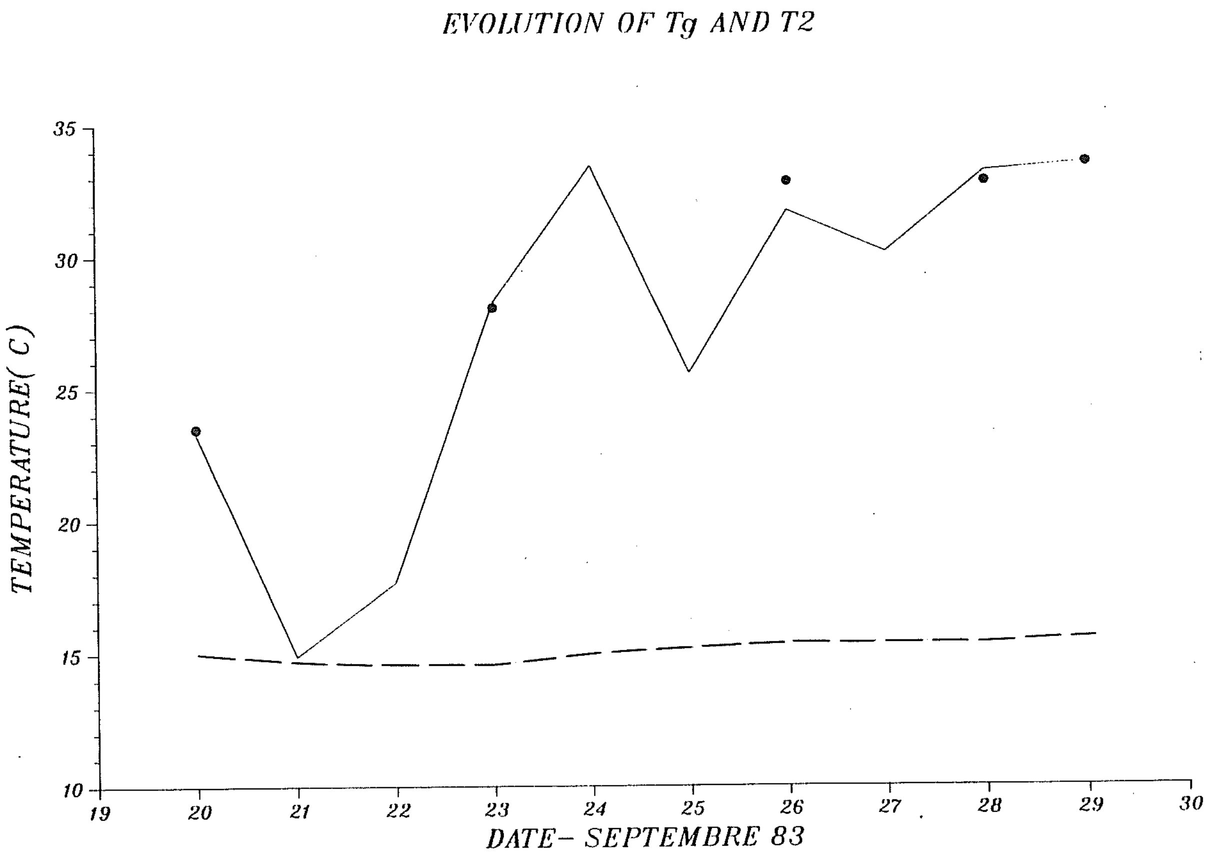
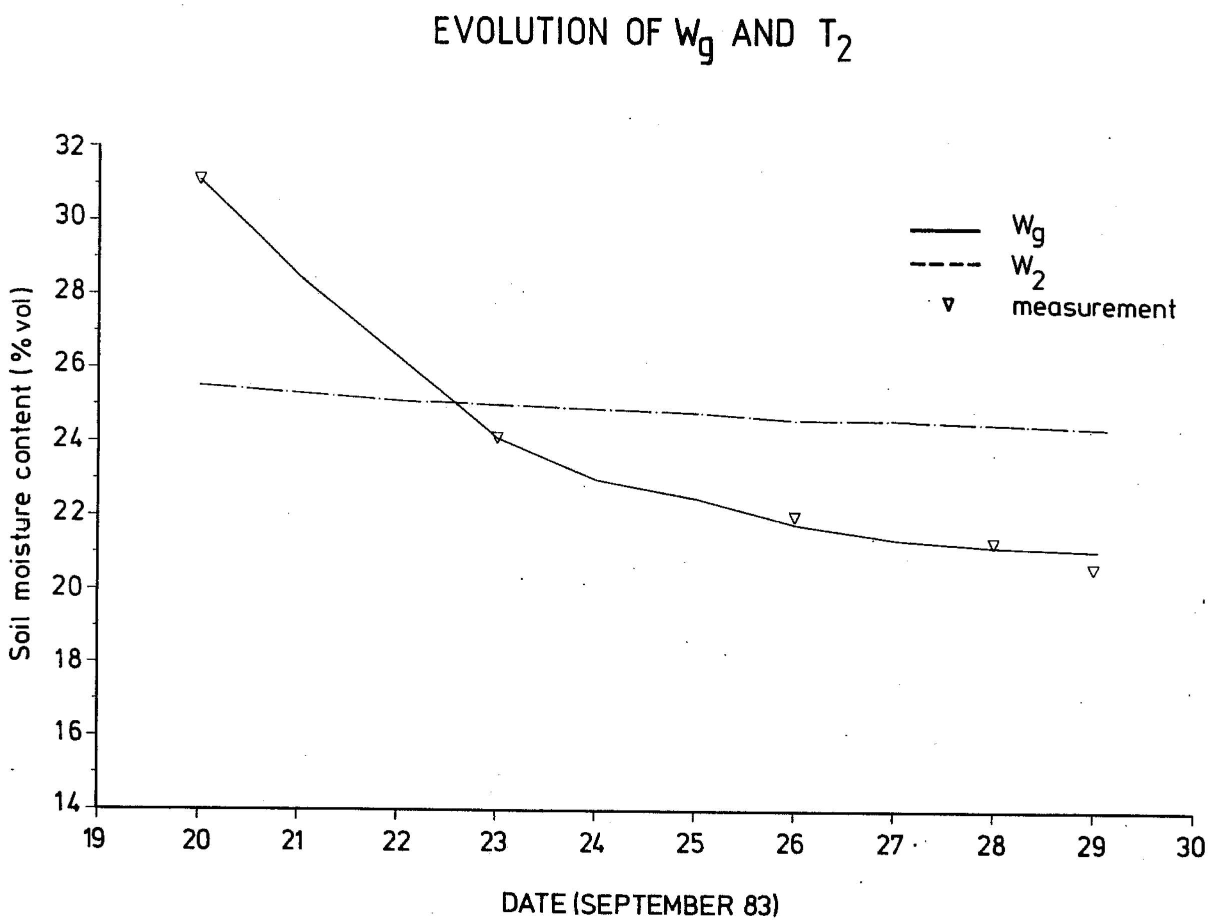

EVOLUTION OF Tg AND T2
TEMPERATURE(C)
35
30
25
20
15
10
19
20
21
22
23
24
25
26
27
28
29
30
DATE- SEPTEMBRE 83

Fig. 7



EVOLUTION OF W_g AND T_2
Soil moisture content (% vol)
32
30
28
26
24
22
20
18
16
14
19
20
21
22
23
24
25
26
27
28
29
30
DATE (SEPTEMBER 83)
W_g
W_2
measurement

Fig. 8

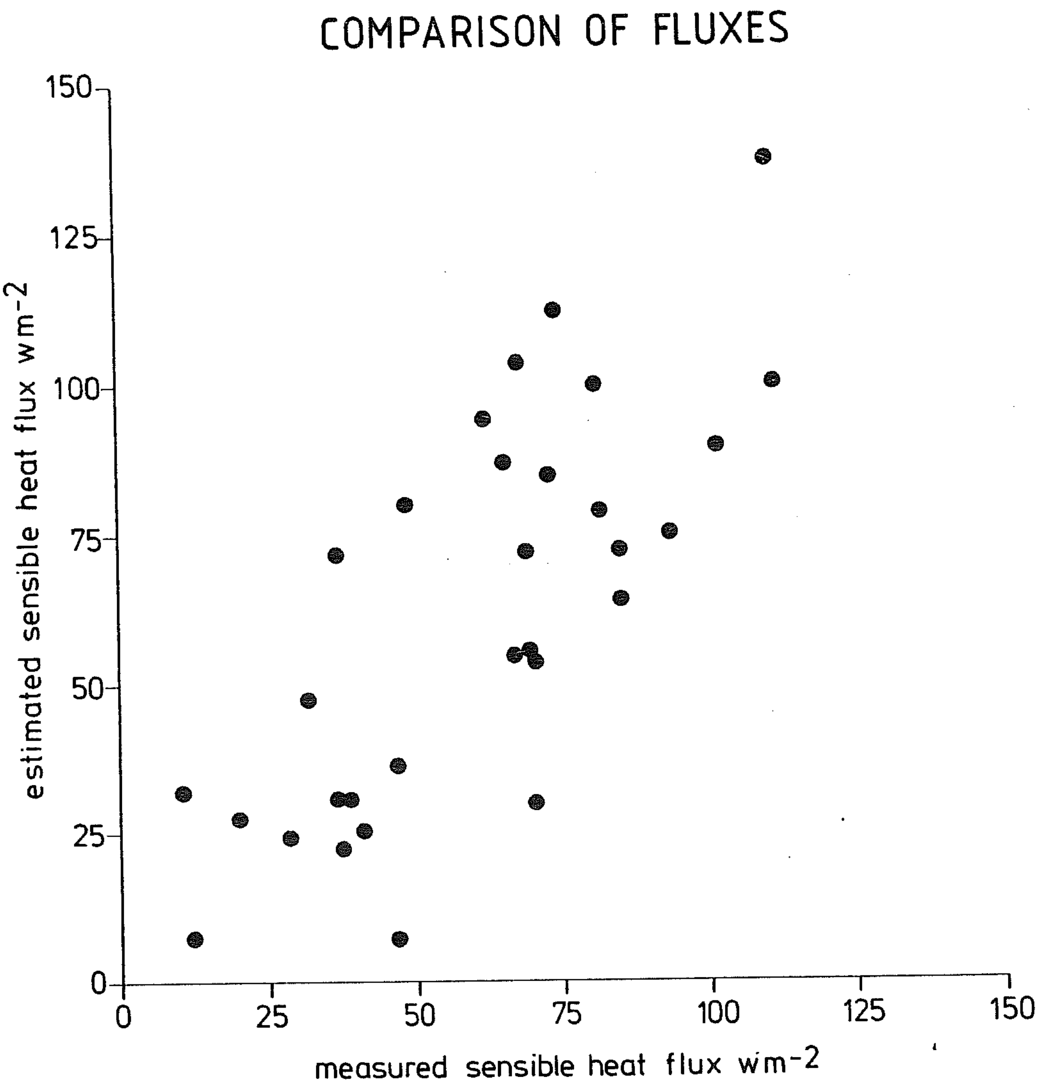

COMPARISON OF FLUXES
150
125
100
75
50
25
0
estimated sensible heat flux wm-2
0
25
50
75
100
125
150
measured sensible heat flux wm-2

Fig. 9

same way that for the bare soil procedure described above. The plant mean biological parameters may be determined for some of them (height, ...) by ground survey or for some others by satellite observations as discussed previously. The comparison between the measured and the predicted value of T_S gives the stomatal resistance RST. This has been done using data from NOAA-7 satellite during the beginning of July 1983 over a region essentially covered by wheat. If one assumes a relation between RST and W_2, it is then possible to estimate a regional value for W_2. Fig. 10 shows the evolution of this estimated regional W_2 compared with measurements within a field at the center of the region. Here again, the calculated values for RST are validated by a comparison of the sensible heat fluxes measured in the field and calculated by the predictive model (Fig. 11).

Other procedures to determine plant and soil parameters in the case of partial canopy have been proposed (see for example Wetzel et al., 1984), but they have never been used and compared with regional measurements. They are presently tested in the framework of HAPEX/MOBILHY experiment in 1986.

3. CONCLUSIONS

With the help of a soil/vegetation/atmosphere predictive model, a list of the fundamental parameters which have to be known, has been given (Table 1). The main characteristic of these parameters is that they are a generalization at regional scale of concepts defined at field scale. Therefore, there is a problem of definitions and of estimations. By its capability of mesoscale monitoring, the satellite observations of the land surface may be used to measure a little part of them (Table 1). Some are directly measurable from a proper analysis of the received radiation : nature of the surface, dominant crop, percentage of soil covered by the vegetation or the incoming solar radiation. For others, their estimations do not seem to be possible from space : unstressed minimum stomatal resistance, thermal infrared emissivity, etc... Another category of parameters has to be monitored indirectly using simultaneously time series of satellite observations and runs of the predictive model to tune the parameters to obtained a good simulation of the data. The model cannot run without the atmospheric forcing which, in turn, depends on the state of the surface. The atmospheric forcing may be given by classical meteorological network or coming from a predictive mesoscale boundary layer model. As these models cannot run without a realistic representation of the surface, they have to incorporate the same type of model as the one used in the interpretation of the remotely sensed data.

Before the end of the century, US, European countries and Japan will implement a system of satellites called EOS (Earth Observation System). EOS will benefit of all the past

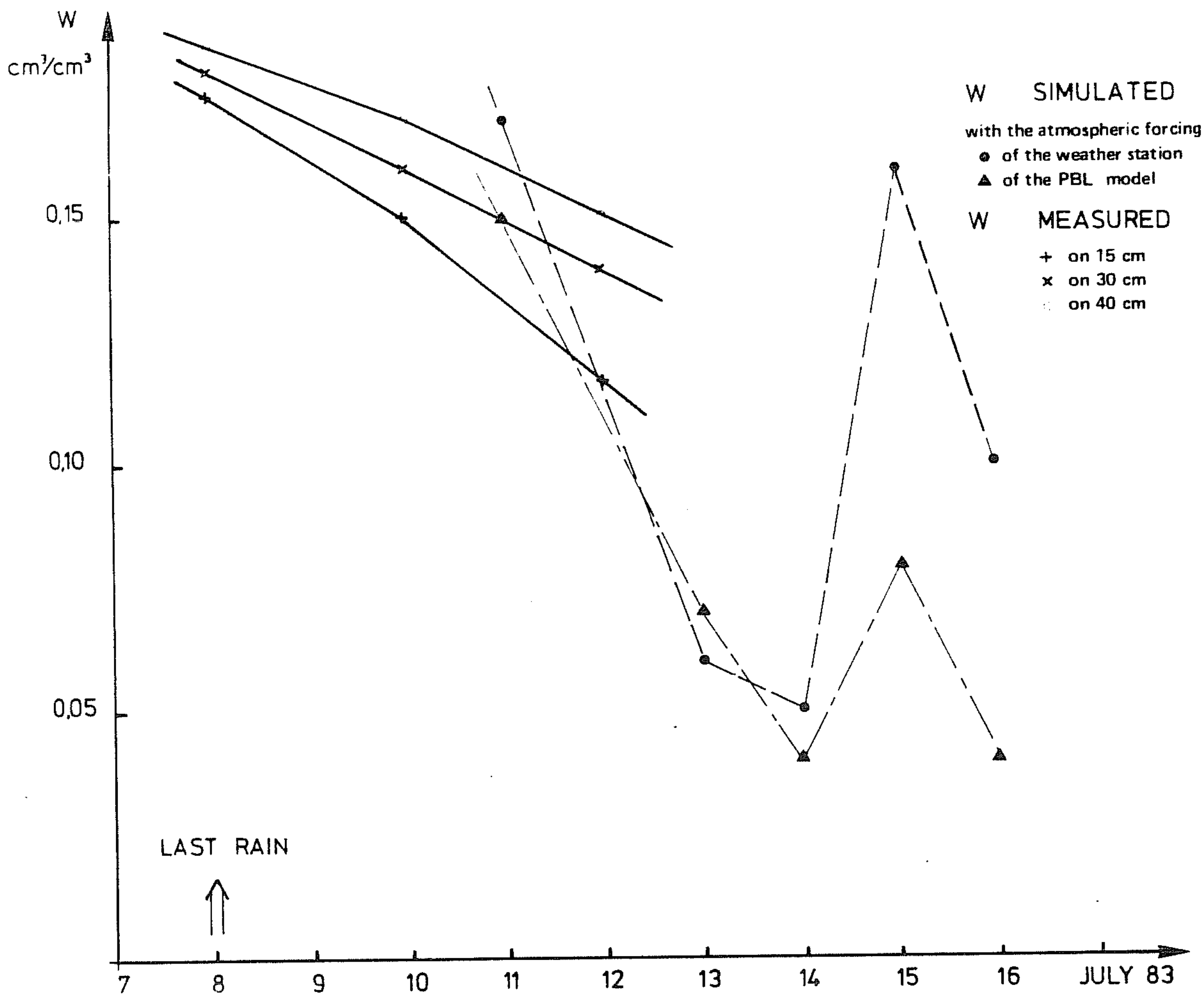

W
cm³/cm³
0,15
0,10
0,05
LAST RAIN
7
8
9
10
11
12
13
14
15
16
JULY 83
W SIMULATED
with the atmospheric forcing
of the weather station
of the PBL model
W MEASURED
on 15 cm
on 30 cm
on 40 cm

Fig. 10

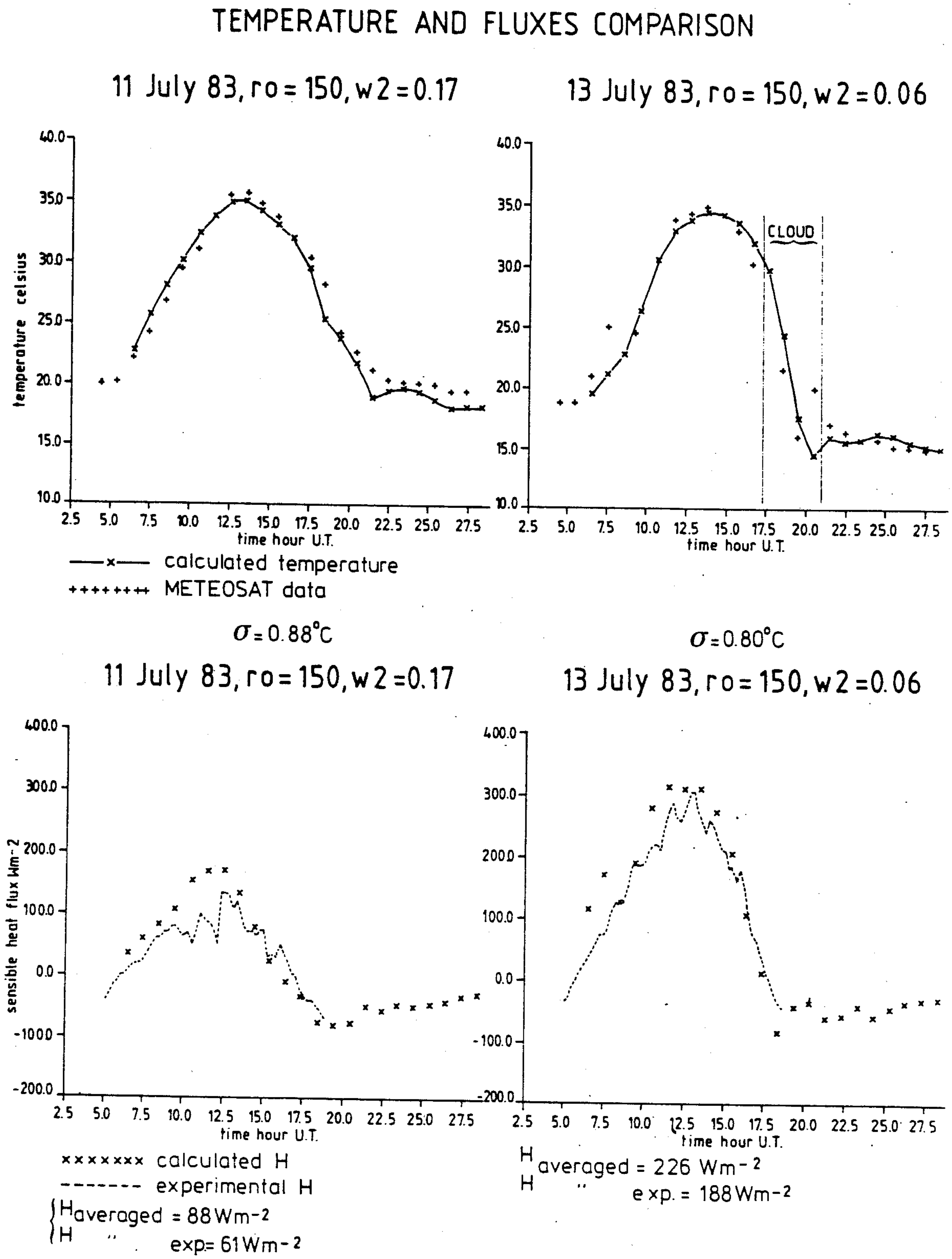

TEMPERATURE AND FLUXES COMPARISON
11 July 83, ro = 150, w2 = 0.17
13 July 83, ro = 150, w2 = 0.06
temperature celsius
time hour U.T.
CLOUD
calculated temperature
METEOSAT data
σ = 0.88°C
σ = 0.80°C
11 July 83, ro = 150, w2 = 0.17
13 July 83, ro = 150, w2 = 0.06
sensible heat flux Wm-2
time hour U.T.
calculated H
experimental H
H averaged = 88 Wm-2
H " exp = 61 Wm-2
H averaged = 226 Wm-2
H " exp. = 188 Wm-2

Fig. 11

experiences and so will have the necessary instruments to begin an operational use of the methodologies described in this paper.

To be reasonable, the first step must be to perform a test of them on several years over representative regions. This type of test, which has never been done until now, will give the opportunity to show the capability of satellite remote sensing to capture the climate interannual variability and the transformation of the land surface due to human activities. If these "satellite observatories" are decided, it will be necessary to implement on the test regions :

- a meteorological network to follow the atmospheric forcing ;
- a mesoscale tridimensional atmospheric model including a realistic soil/vegetation component similar to the one described here ;
- an archive of all the relevant remotely sensed data.

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