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Abstract

The PI has developed a method for estimating values of soil moisture based on measurements of infrared surface temperature. A central element in the method of producing the soil moisture values is a boundary layer model. Although it has been shown that soil moistures determined by this method using satellite measurements do correspond in a coarse fashion to the antecedent precipitation, the accuracy and exact physical interpretation (with regard to ground water amounts) are not well-known. This area of ignorance, which currently impedes the practical application of the method to problems in hydrology, meteorology and agriculture, is largely due to the absence of corresponding surface measurements.

Preliminary field measurements made over France have led to the development of a promising vegetation formulation by the French (Taconet et al., 1985), which has been incorporated in the model of the PI. It is necessary, however, to test the vegetation component, and indeed the entire method, over a wide variety of surface conditions and crop canopies.

1. Background

The relationship found between moisture availability derived from satellite measurements and the precipitation for regions over the middle west, (described in previous reports and in articles by Carlson (1984), Carlson et al. (1984), Flores and Carlson (1985)), has been an encouraging result, in view of the relatively large pixel size and imprecision of the GOES temperature measurements. Nevertheless, the question persists: what are we really measuring with the satellite thermal channel? In the past year we have had the opportunity for the first time of addressing this question by using AVHRR thermal infrared temperature measurements in conjunction with ground measurements of soil moisture and surface energy fluxes. These ground measurements were made during three field experiments over France. The first two were made during July and September 1983 over a region called the Beauce. The third and most elaborate experiment was carried out during September 1984 over a region of the southwest of France as part of a project called "meso-gers," named after the region of Gers in which the field program was conducted. The PI is currently taking a sabbatical from Penn State in France where he is working with various French scientists on the development of the infrared method for remote sensing of soil moisture using data gathered during these field experiments.

2. Summary of Investigation in Progress

The 1983 French field program consisted of a principal measurement site at Voves in the Beauce and a secondary site about 20 km away at Montigny. The Beauce is one of the primary agricultural regions in France. In the area of

Voves, the principal crop is wheat, although there is also some corn. Measurements were made by means of a sodar from which one can obtain the surface heat fluxes appropriate to horizontal scales of about 1 km (Weill et al., 1980). Surface heat fluxes were also determined from wind and temperature measurements made by means of instruments mounted on a frame at two levels near the ground (Itier, 1980).

In a review article Carlson (1984) stated that a possible serious weakness of existing ground-atmosphere models is the inadequate treatment of vegetation. Deardorff (1978) proposed a model for a vegetative canopy which has been used in various forms. Deardorff's model, however, is rather cumbersome to apply because it contains a complex structure based on a large number of empirical parameters drawn from different studies over different types of crop cultures. In practice, many of these parameters are difficult to determine, and those given by Deardorff rest largely untested. Nevetheless, the Deardorff formalism opened a highly fruitful approach to the problem of modeling vegetation.

While at the University of California at Davis, R. Bernard of the CNET/CRPE in France (private communication) developed a simplified version of the Deardorff model based on more current measurements made at Davis. Tests with the revised vegetation component combined with a one-dimensional atmosphere-substrate model based on one of Therry and LaCarrere (1983) have proven encouraging in light of the measurements made over the Beauce in 1983. In particular, Taconet et al. (1985; also private communication) were able to demonstrate that their model is capable of simulating the evolution of the daily heat flux profile measured over the Beauce during a 5-day period in July. Our adaptation of the vegetation model of Bernard in the CM has produced almost identical results.

The heat flux measurements for the three of the five days during the period 11-15 July 1983, are shown in Figs. 1-3. The remarkable aspect of these measurements is a rather dramatic increase in the surface sensible heat flux between the 11th and the 15th. In these figures we also present the distribution of surface sensible heat fluxes obtained with the version of the CM without vegetation parameterization. All the model simulations make use of one afternoon (~ 1400 GMT) NOAA-7 infrared satellite temperature corrected for attenuation by atmospheric water vapor and carbon dioxide.

Although one is tempted to dispute the rapid increase in the measured heat flux values between the 11th and the 15th, it is difficult to deny the consistency of the ground measurements with respect to time and the similarity between the sodar and tower heat flux measurements. Independent ground water measurements made in the general area show a steady decrease with time in the water content of the soil until mid-July, after which the soil water content remained at a very low level until harvest. This decrease in soil water occurred during both 1982 and 1983 and is probably a normal consequence of the fact that evaporation exceeds precipitation and runoff during the growing season. According to the model, there was a decrease in the value of w_g (the volumetric water content) (from 0.20 to 0.14 to 0.09) between the 11th and 15th of July (Figs. 1-3).

Although the phenological reasons for this rapid drying are not clear, one can in terms of the model equations explain the striking increase with time between the 11th and the 15th (shown in Figs. 1-3) of the sensible heat fluxes. The coefficient of transfer for latent heat flux (LE) from the foliage (c_v) is given in the following expression:

$$LE = c_v(q_s(T_f) - q_{af}) \quad (1)$$

where $q_s(T_f)$ is the specific humidity at saturation at the temperature of the foliage (T_f) and q_{af} is an interfoliage (airspace) specific humidity. Now Taconet et al. (1985) let

$$c_v = c_{fh}/(1 + c_{fh} \cdot RST) \quad (2)$$

where c_{fh} is the transfer coefficient for sensible heat between the foliage and the interfoliage air spaces. Thus, for vegetation RST represents a resistance and takes the place of the moisture availability parameter. RST appears explicitly in the foliage equation, instead of the moisture availability (M), which totally governs the surface mositure resistance in the non-vegetated version of the model. The resistance RST is the key to the greater response of the surface sensible heat flux in the case of the vegetation component. Taconet et al. define RST as

$$RST = RO\left[\frac{800}{1 + S} + \left(\frac{1.2w_o}{0.9w_2 + 0.1w_g}\right)^2\right] \frac{PS}{LAI} \quad (3)$$

Here S is the downward global solar radiation (expressed in w m^{-2}), w_o is a reference value of soil moisture (loosely equated to that at the wilting point for the vegetation) and w_g and w_2 are the shallow-soil (10 cm) and deep-soil volumetric water contents (Deardorff, 1978). PS is a shelter factor which is related to the leaf area index (LAI). RO is a seasonal stomatal factor which appears, according to measurements made by Perrier et al. (1980), to remain relatively constant with time over the growing season (except for a stepwise increase to a new plateau in June). RO is evidently related to the phenology of the crop and probably to the long-term water stress on the plants. The moisture availability (M) is defined explicitly only with respect to the evaporation from the ground surface underneath the plant canopy by the definition $M = \frac{w_g}{w_{max}}$, w_{max} being the value of w for a saturated soil (here taken as 0.35); the initial value of w_g is set equal to w_2. The value of RST effectively limits the plant evaporation (which dominates that from the ground in situations of dense vegetation, even in situations of ground water saturation. This restriction on plant evaporation even where M = 1.0 constitutes the most important difference between the old and new version of the CM.[1]

The heat fluxes calculated with the non-vegetation version of the CM also show a modest increase during the four-day period, from a maximum of about 95 w m^{-2} on the 11th to about 140 w m^{-2} on the 15th, corresponding to a decrease in the volumetric soil moisture content (w_g) from 0.16 to 0.09 (Figs. 1-3). This increase in the surface heat flux even with the non-vegetation version is a consequence of the fact that the measured surface temperatures from the satellite increased during the period (with respect to the model initial temperatures as given by the radiosonde data). The

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[1]Somewhat better agreement between model and measurements can be achieved by an adjustment of the transfer coefficient for heat in accordance with values recommended by Taconet, et al., 1985.

vegetation model, however, increased the sensitivity of the surface heat fluxes and soil moisture to the measured increase in reductive surface temperature.

At present we are performing detailed simulations with the new version of the CM and comparing the output to that from the model of Taconet et al. The results from the two models appear to be very similar. We anticipate making tests with both models using the data obtained during the 1984 field experiment. The 1984 (meso-gers) program was far more elaborate than those of 1983. Instead of two there was a network of six sodars located at the corners of triangles of differing dimensions. At two of these sites local measurements of heat flux (made as over the Beauce, from instrumented towers) and of soil moisture and radiative surface temperature were made. On clear days, there were flights by instrumented aircraft, including a helicopter capable of making microwave (radar) measurements of soil moisture. Though heavily cultivated, the region of Gers is much hillier than the Beauce and corn is the dominant crop in the region of the experiment.

3. A Plan for the Future

The problem of using the infrared method for determining the surface energy budget and the soil moisture divides into two areas of activity: model and measurement. With regard to the latter, the success of the vegetation model in capturing the increase with time of the surface sensible heat fluxes rests with the ability of the satellite to discriminate small changes in temperature over crop surfaces with an accuracy of no worse than about a degree centigrade. Without going into a detailed discussion of measurement errors, already presented by Carlson (1984), we would like to mention that without proper consideration of measurements, no model is usable. These errors fall into three categories: that due to the satellite sensor, that due to atmospheric attenuation, and that due to sampling of the surface. There is also the uncertainty introduced by temperature, wind and humidity errors in the initial radiosonde data used in the model.

Excluding the problem of measurement, there remain the nagging questions of (1) are the results obtained form one set of case studies in any way general, (2) how can one obtain routinely and with any degree of confidence the necessary model input parameters (the leaf area index, RO, w_2 and other "constants" expressed in equation (3)), (3) how do the model output values of w_g or M relate to the real soil moisture at various depths below the surface, (4) what form does the resistance equation take for completely different types of surfaces (for example, forests), (5) how do the surface fluxes measured of different scales by different instruments correspond to those generated by the model using satellite surface temperatures, and (6) what practical importance is the infrared method in providing parameters to meteorological, agricultural and hydrological interests?

In light of the imperatives posed by the questions in (2.1), a fruitful approach must concern itself with (1) data acquisition and interpretation of model reslts, (2) system and model development, and (3) interaction with scientists with allied interests and in adjacent disciplines.

4. Conclusion

The ISLSCP and MOBILHY programs offer promise for obtaining both satellite and ground measurements over various types of terrain and vegetation. The stated goals of ISLSCP, those of developing algorythms and exploiting satellite measurements, are in close accord with our objectives.

The first ISLSCP Field Experimeint (FIFE) is proposed for 1986/1987. Although it is too early now to foresee the exact outcome of this field program, we must assume that it will yield a considerable amount of useful information. Accordingly, we feel a sense of commitment to its aims and therefore to playing an active role in its execution.

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Figure Captions

Figure 1. Surface heat fluxes (w m^{-2}) as a function of time (GMT; approximately sun time) on 11 July 1983 obtained with the CM with vegetation component (solid curve) and without vegetation component (dashed curve). Measurements made locally of surface heat flux are represented by the dotted curve. Heat fluxes made from sodar measurements at Voves (crosses) and at Montigny (triangles) are indicated. The model fluxes correspond to surface temperatures measured over Montigny by the AVHRR of NOAA-7 at 1346 GMT. In the title, the symbol w and m, respectively, correspond to values of the substrate volumetric water content (w_g in equation (3)) and the surface moisture availability (M).

Figure 2. Same as Fig. 1 but for 13 July 1983 corresponding to an AVHRR surface temperature measured over Montigny at 1501 GMT. No sodar data was taken at Montigny.

Figure 3. Same as Fig. 1 but for 15 July 1983 corresponding to a surface temperature measured over Montigny; no sodar data was taken.

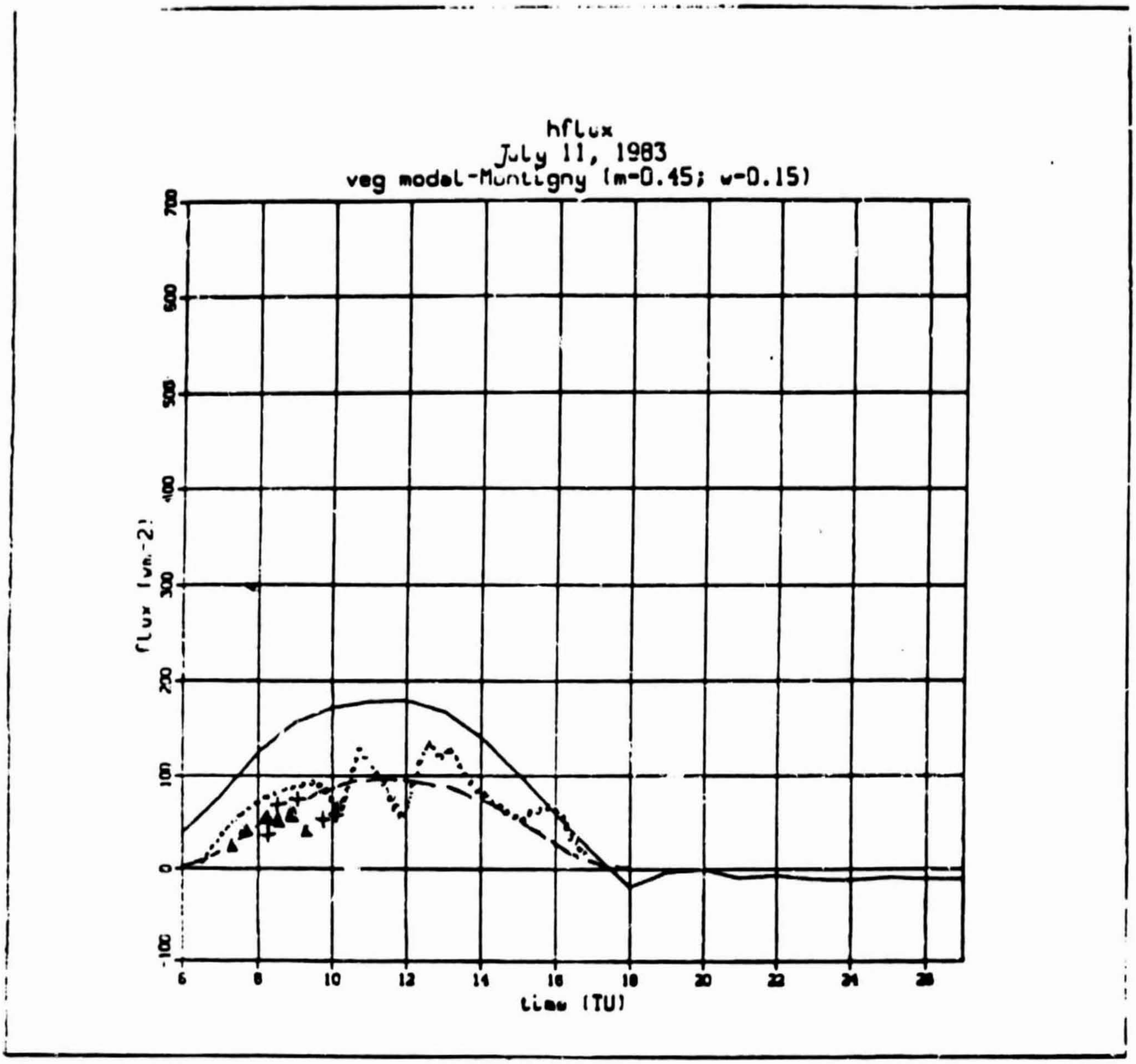
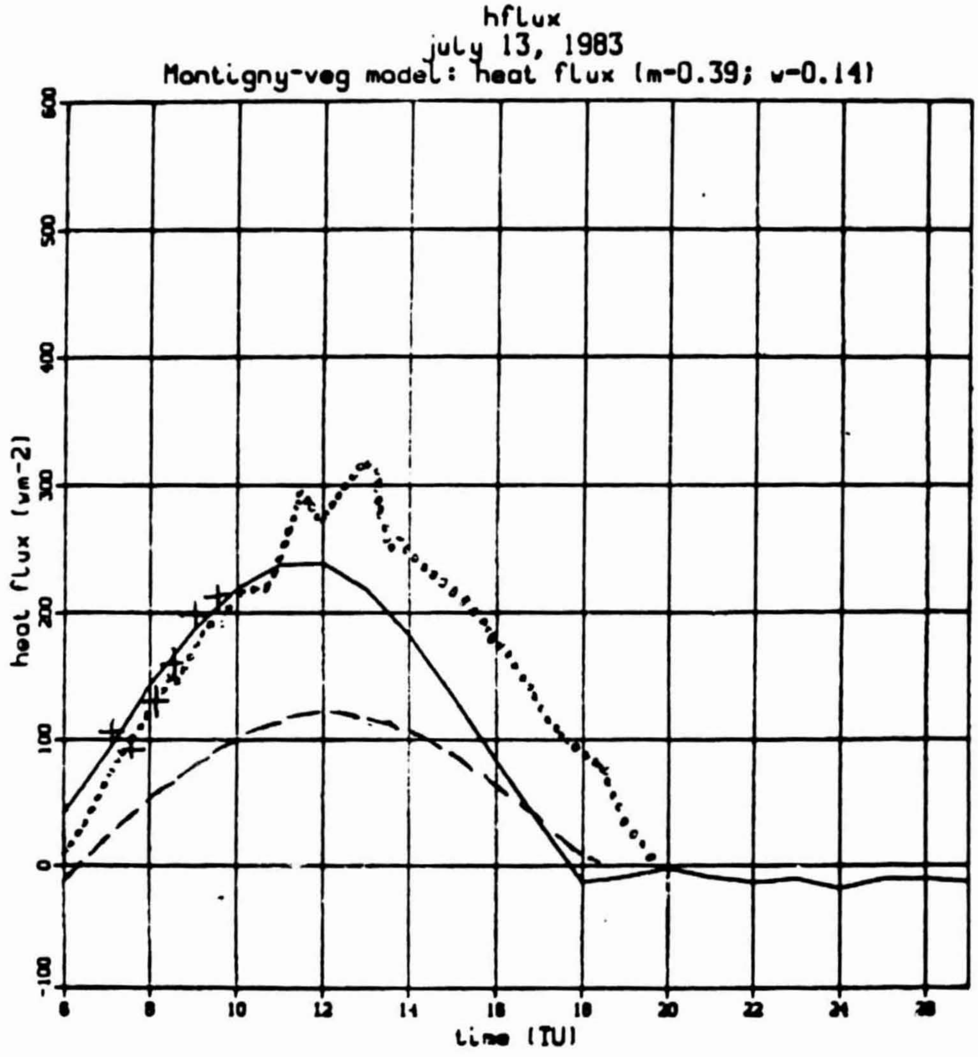
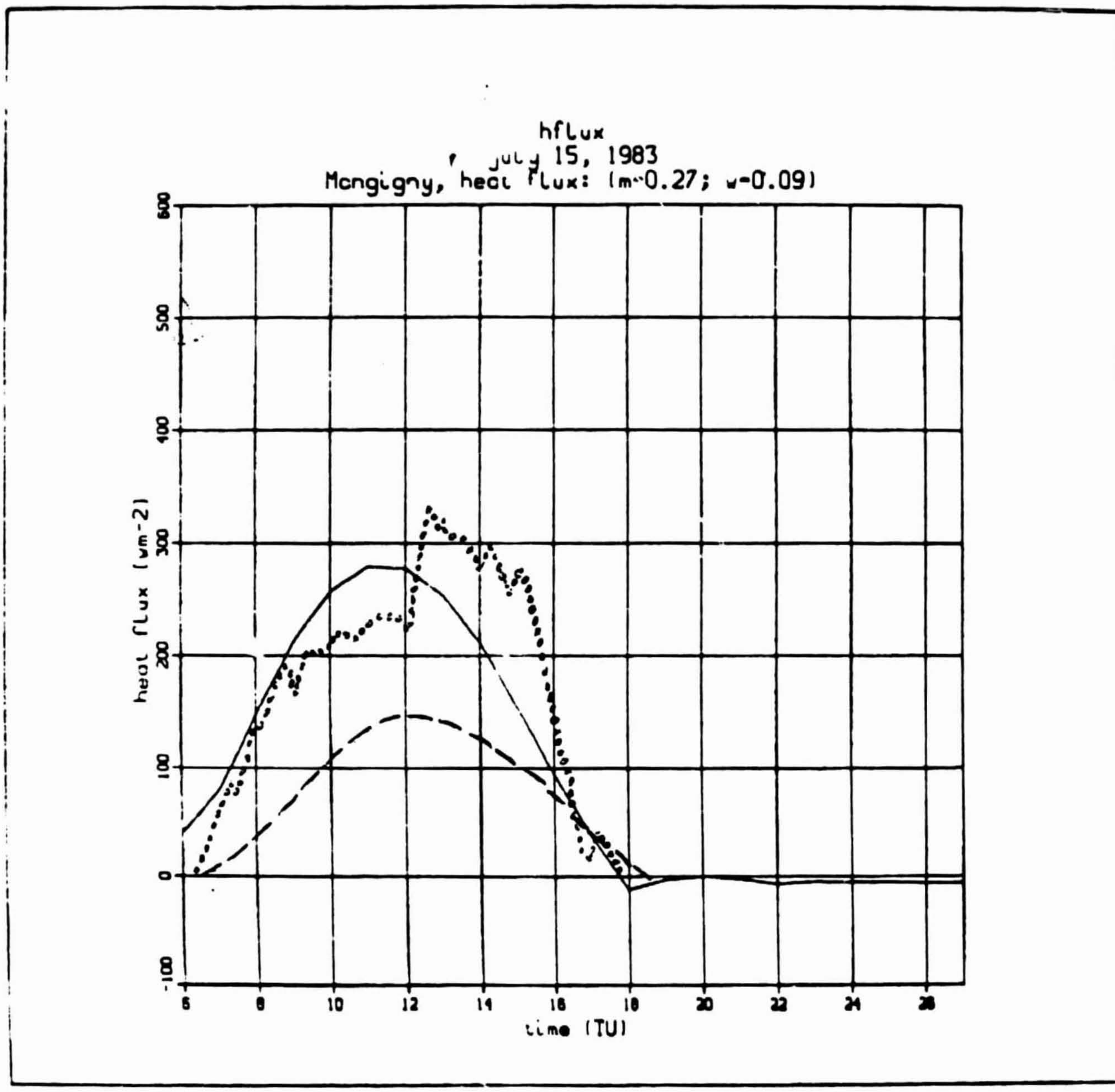

hflux
July 11, 1983
veg model-Montigny (m-0.45; w-0.15)
flux (wm-2)
time (TU)
700
600
500
400
300
200
100
0
-100
6
8
10
12
14
16
18
20
22
24
26

Fig 1



hflux
july 13, 1983
Montigny-veg model: heat flux (m-0.39; w-0.14)
heat flux (wm-2)
600
500
400
300
200
100
0
-100
6
8
10
12
14
16
18
20
22
24
26
time (TU)


hflux
july 15, 1983
Mongigny, heat flux: (m=0.27; w=0.09)
heat flux (wm-2)
time (TU)
600
500
400
300
200
100
0
-100
6
8
10
12
14
16
18
20
22
24
26

7