Model for Sensible Heat flux estimation over an heterogeneous surface during The Hapex Sahel Experiment

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ABSTRACT

In order to model surface-atmosphere water and heat flux exchanges properly, it is important to realistically include all the surface components that interact with the atmosphere. This is specially true for sparsely vegetated surfaces where neither the soil nor the canopy totally dominate the exchanges. A mixed two-layer, two-compartment model has been developed to estimate sensible heat flux over a mixed shrubs-grass surface. The surface is represented by three components: Shrubs, grass under the shrubs and open grass. The contributions of each component to sensible heat flux were parameterized. The model is based upon the assumption that both shrubs and grass under the shrubs are at the same temperature. This leads to a simple formulation of sensible heat flux that requires only measurements of radiometric surface temperature, which are available from remote sensing. Data collected at the Hapex Sahel International Experiment, carried out in southern Niger in the summer of 1992, were used to validate the model. The results show that the model provides reasonably good estimates of sensible heat flux. It is therefore an important step towards an operational model for monitoring surface-atmosphere exchanges in arid and semi-arid regions.

INTRODUCTION

Recently, increased emphasis has been placed on understanding the interaction between regional climate and the hydrological cycle in arid and semi-arid regions (Kerr and Sorooshian, 1989; Kustas et al., 1991; Goutorbe et al., 1993). Reliable predictions of general weather patterns depend on our ability to properly represent the interaction of integrated land-surface processes and the Atmospheric Boundary Layer (ABL). Accurate partitioning of available energy ‘into sensible and latent heat flux is crucial to the understanding of surface-atmosphere interaction. However, this is very difficult in arid and semi-arid regions because the relative contributions to total sensible and latent heat flux from the soil and plant components may vary through a day and throughout a season. Several models have been developed that attempt to estimate surface fluxes from sparsely vegetated areas (Shuttleworth and Wallace, 1985; Choudhury and Monteith, 1988; Shuttleworth and Gurney, 1990). These models, based on generalizations of the single-source approach, seemed to be appropriate for sparse and uniform vegetation. However this may not be the case for natural surfaces in arid and semi-arid regions where the vegetation is generally non-uniform (Nichols, 1992). On the other hand, classical two layer models retie on measurements of surface components temperature, which are not routinely available from remote sensing. This may be a major handicap in using these models for operational purposes, Alternative solutions to this problem have been recently proposed in the literature. Kustas et al. (1 989, 1990) suggested that adding a new resistance, K_b, to heat transfer in a one layer model may correct the increase in sensible heat flux that occurrs when the soil is dry and becomes the major source of sensible heat. This resistance was empirically related to wind speed and the air-surface temperature gradient. Using data from the Hapex Sahel Experiment and a conceptual two layer model, Lhomme et al. (1993b) developed a new expression for sensible heat flux. This flux was formulated as a function of the temperature gradient between the surface and the air, and the temperature difference between the soil and the vegetation. The soil-vegetation temperature difference was then expressed as a linear function of air-surface temperature difference. The model seemed to perform quiet well in estimating sensible heat flux over fallow savannah. However, it may not be possible to generalize this empirical relation as well as the Kb relation to other surfaces with different vegetation types. Another major concern about these two-component model concepts is related to the fact that they are based upon the assumption that the distribution of the vegetation within the surface is uniform, and thus the sensible heat flux enters or leaves the atmosphere only via the canopy. However in natural arid and semi-arid regions, the vegetation distribution is typically non-uniform since it grow only in areas of shallow ground water. Therefore, heat and mass transfer between the soil and the atmosphere may take place without interaction with the canopy. Thus, the surface may be better represented by a model which assumes a small compartment of vegetation adjacent to a large compartment bare soil.

The objective of this study is to present a conceptual model for sensible heat flux estimation over Sahelian sallow savannah. The surface was represented by three components Shrubs, grass-under-shrubs, and free "open" grass. The contribution of each component to sensible heat flux was parametrized, The model, based upon the assumption that the first two components are at the same temperature, leads to a simple expression for sensible Heat flux that requires only remotely sensed radiometric surface temperature.

MODELING APPROACH

Model theory

It is know recognized that all exchanges between the surface and the atmosphere have a surface resistance (Vidal and Perrier, 1990). Therefore, sensible heat flux for an heterogeneous surface can be expressed as :

$$H = \rho Cp (T_E - T_a) / (R_E + R_a) \qquad (1)$$

where p is the air density (Kg m^{-3}), Cp the specific heat of air at constant pressure (J/kg/K), R_a the aerodynamic resistance across the surface-atmosphere interface and T_a is the air temperature at a reference height. T_E and R_E are respectively the equivalent surface temperature and surface resistance to sensible heat flux.

The surface is represented by three components : shrubs (s), grass under the shrubs (gs) and open grass (g). These components are respectively, characterized by three temperatures (T_s, T_gs ,T_g) and three resistances (r_s, r_{gs}, r_g). The exchange between the atmosphere and the compartment representing the shrubs and the underlying grass can be described with a conceptual two-layer model. Following Lhomme et al. (1993a,b), the equivalent resistance R_e and temperature T_e of this compartment can be obtained by adopting the Ohm's law analogy. Considering the total sensible heat flux emanating from this compartment is the sum of the contribution of each component, Te and Re are then respectively expressed as :

$$T_e = (r_{gs} T_s + r_s T_{gs}) / (r_s + r_{gs}) \quad (2)$$

$$R_e = r_{gs} \, r_s / (r_s + r_{gs}) \quad (3)$$

The second compartment which represents the free grass part of the surface is characterized by the grass temperature Tg and the grass resistance to sensible heat flux rg.

If the entire surface is now represented by these two adjacent compartments, the equivalent surface temperature can be represented by area weighted mean of the two compartment temperatures as :

$$T_E = (1 - f) T_e + f T_g \quad (4)$$

Where f is the percent shrubs cover. The equivalent surface resistance is conceptually more complicated to define. Koster and Suares (1992) have discussed different network strategies for representing resistances for heterogeneous surfaces. They reported that the real world situation is in some sense intermediate between the homogeneous mixture and mosaic representations. Raupach (1991) has investigated the effects of surface horizontal heterogeneity on surface-atmosphere exchanges. He suggested that the average or the equivalent resistance for an heterogeneous surface can be represented by an area-weighted parallel sum of all the equivalent resistances of individual patches/compartments. Therefore, the equivalent resistance for the current surface can be then expressed as :

$$1 / R_E = (1 - f)/R_e + f/r_g \quad (5)$$

In order to compute Sensible heat flux from Equation 1, the grass-under-shrubs temperature is required. The measurement of this temperature is not really especially at large scale since it depends on the shadow cast by the shrubs, which varies throughout the day and throughout the season. During a single day this temperature is most likely to oscillate between air temperature and canopy temperature. However, Humes et al., 1992, showed that in arid and semi-arid area, canopy temperature is more often close to the shaded part of the surface temperature. One possibility to derive grass-under-shrubs temperature, is to assume that this temperature can be expressed as an average of air and shrubs temperatures:

$$T_{gs} = (T_s + T_a) / 2 \quad (6)$$

The other possibility is to assume that the grass under the shrubs temperature is similar to the shrubs one's. Using this assumption and combining equations

(2) and (3), leads to the conclusion that the equivalent temperature of the first compartment can be considered approximately equal to the shrubs temperature.

$$Te = Ts \qquad (7)$$

By combining equation (4) and (7), the equivalent surface temperature T_E can expressed as a composite temperature (area-weighted mean of shrubs and grass temperature), which is similar to the radiative surface temperature T_r measured by an inverted Infrared Radiometer looking at the nadir (Choudhury, 1986; Kalma and Jupp, 1990; Lhomme et al., 1993a, b). This assumption ignores the fact that some part of the surface is shaded. However, considering the sparseness of the shrubs, we believe that that the shadow effect is not very significant, In this case, the final expression of sensible heat flux is then written as only a function of the air-surface temperature gradient without any additional temperature measurement requirement, so that:

$$H = p \, Cp(Tr - Ta)/(RE + Ra) \qquad (8)$$

In the following analysis, sensible heat flux will be computed using both expressions of Tgs.

RESISTANCE EXPRESSIONS

Surface resistances .

The present model uses the Choudhury and Monteith (1 988) formulations with minor modification, to compute the shrubs and the grass under the shrubs bulk resistances (Lhomme et al. 1993b). The bulk boundary-layer resistance of the shrubs was defined as :

$$r_s = A_n[w/U(h_s)]^5/[2A_0(1 - \exp(-A_n/2))]/2LAI \qquad (9)$$

where $U(h_s)$ is the wind speed at the top of the shrubs, LAI is the leaf area index assumed to be uniform over the shrubs height, w is the shrubs mean leaf width (0.02 m), An is the attenuation coefficient for wind speed (dimensionless), A_0 is an empirical parameter of 0.005 m/s^2. The grass-under-shrubs resistance, rgs, which represents the resistance between the grass source height $(d_g + z0g)$ and the sink of momentum in the shrubs $(d_s + ZOS)$

is defined from the standard relation between the turbulent transfer coefficient, friction velocity and height as :

$$r_{gs} = h_s \exp(A_w)[\exp(-A_w(d_g+z0_g)/h_s) - \exp(-A_w(d_s+z0_s)/h_s]/[A_w K(h_s)] \quad (10)$$

where d_g and $z0g$ are, respectively, the displacement height and roughness length for grass, defined as a functions of grass height in the same way as for the shrubs, $K(h_s)$ is the eddy diffusivity at shrubs height obtained from K(z) by assuming an exponential extinction with respect to the height (Brutsaert, 1982). A_w is the attenuation coefficient for eddy diffusivity (dimensionless). Different values of A_w and An have been reported in the literature. Choudhury and Monteith (1988) use, respectively, values of 2 and 3. Lhomme et al. (1993b) use respectively values of 2.5 and 2.5 for these parameters. Working with data from central Nevada, Nichols (1992) determined a value of 3.8 and 0.6 for A_w and An. The values of 2.5 and 2.5 were respectively used In this study, but we will explore the extent to which model predictions of sensible heat is affected by the choice of these parameters.

The last surface resistance term that needs to be defined is the bulk resistance for open grass rg. This resistance was formulated as a function of wind speed and aerodynamic characteristics of the grass (i.e. roughness length and the displacement height) as :

$$r_g = [\log(z-d_g)/z0_g] [\exp(k/U]/(k h_g) \quad (11)$$

Aerodynamic Resistance

The equations given by Mahrt and Ek (1984) were adapted and used to formulate an expression bulk aerodynamic resistance. Ra was expressed under stable condition (i. e., $T_r - T_a < 0$) as :

$$R_a = [Ln[(z-D+Z_0)/Z_0]/k][Ln((z-D+Z_0)/Z_0)+Kb)/1(] (1+15Ri)(1+5Ri)^{0.5}/U \quad (12)$$

and for the unstable conditions (i. e., $T_r - T_a > 0$) as :

$$Ra = [Ln[(z-D+Z_0)/Z_0]/k][Ln((z-D+Z_0)/Z_0)+Kb)/1(] [1 - 15Ri/(1+C(-Ri)^{-0.5})]^{-1}/U \quad (13)$$

Ri and C are respectively, the bulk Richardson number and a stability correction factor, and are defined as:

$$C = 75 k^2 [(z-D+Z_0)/Z_0]/k]^5 / Ln[(z-D+Z_0)/Z_0]^2 \quad (14)$$

$R_i = g(T_a - T_E) / (T_a U^2)$ (15)

where U is wind speed measured at height z , k is von karman's constant (0.4), T_E is the equivalent surface temperature, D and Z_O are, respectively, the effective displacement height and roughness length representing the whole surface. They were assumed here to be similar to the value of shrubs (d_s, z_{os}) and were expressed as a function of shrubs height hs as: D = ds = 0.65 hs , and Z_0 = zos = 0.1 h_s . Kb is an added resistance to take into account the fact that roughness lenght for heat and momentum can be different (Chamberlain, 1968). Brutsaert (1 982) reviews both theoretical and experimental evidence that suggests the magnitude of Kb can vary from order 2 to 10. Kustas (1 989) developed an empirical expression of Kb as function of wind speed and air-surface temperature gradient as:

Kb=.17 U (Tr-Ta) (16)

For this study the value of 4 for Kb was used. However the value of 2 and 8 will be tested in the following paragraph.

DATA USED

The International Hydrologic and Atmospheric Pilot Experiment in the Sahel (Hapex-Sahel) was held during the Monsoon season of 1992 in the South West of Niger. One of the scientific objectives of the experiment (see Goutorbe et al. 1993 for more details) was to investigate the effects of changing soil moisture and vegetation conditions on surface radiation balance, the hydrological cycle, and the feedbacks to the atmosphere in arid and Semi-arid regions. The study area was about 100 x 100 km2 , and was devided into three “ super sites “. The soil was mostly sandy, the vegetation was very heterogeneous, and included millet, grass and shrubs.

In this study, data from fallow savannah sub-site in the “Central East site” were used (Lhomme et al. 1993b), The shrubs have a crown height about 3.2 m and cover about 17 % of the surface, the rest of the surface is covered by a sparse herbaceous canopy made up of a mixture of different grass species. The Leaf Area index of the shrubs was about 0,5 and the mean grass height varied from about 0.2 m at the beginning of September to about 0.6 in mid-October (Table 1) ,

Bowen ratio-energy budget data were collected from September to October. Vapour pressure and air temperature were measured at two heights above the surface (4.5 and 9m), net radiation was measured at 12 m above the surface and four heat flux plates buried 3 cm below the surface were used to estimate soil heat flux. Shrubs and grass temperatures were measured separately using infrared thermometers. The quality of the data collected was only fair; numerous technical problems were encountered during the course of the field experiment, data from several days were useless.

SENSITIVITY ANALYSIS

Radiometric and eauivalent surface temperature

During the 7 weeks of the experiment POI (Periode d'Observation Intensive), equivalent surface temperature TE, was computed using grass-under-shrubs temperature T_gs from both Equations (6) and (7). The mean daily difference between the two temperatures was less than ,005 degree Celsuis. This is mainly due to the fact that temperature of transpiring vegetation is more often close to the air temperature. Of course there is no direct relationship between this fact and grass-under-shrubs temperature. However, it confirmed what it has been observed during MONSOON'90 experiment. It is certainly possible to develop, an argument based on the energy partitioning between shrubs and underlying grass using some extinction formula, to discuss the relationship between the temperatures of each component. However we believe that the assumption in Equation (7) is realistic for arid and semi arid regions. Therefore, sensible heat flux can be expressed using Equation (8). This equation will be used in the following analysis.

Model sensitivity to canopy parameters

Data from weeks 37 and *41* were used to test the sensitivity of the model to the choice of A_w, An parameters. The data for these two weeks represented two extreme cases for the partitioning of surface energy balance. Week 37 was at about the beginning of the rainy season, when the latent heat flux was the most important term in the energy balance. This was reversed for week 41 which was near the end of the rainy season and sensible heat flux dominated, Three combinations of the A_w and An parameters corresponding to a typical values reported in the literature were used to perform the sensitivity analysis (Table 2). Figure 1 (respect., Figure 2) represents the surface equivalent resistance (RE) behavior with wind speed for week 37 (respect., week 41), using three combinations A_w and An parameters (Table 2). It can be seen in theses figures shows that, R_E is not very sensitive to Aw and An parameters. This is not true with component 'resistances (r_{gs} and r_s). As an example for week 41, rgs (respect., rs) varied from 75 (respect, 51) to 178 (respect., 34) s/m, when case 1 or case 3 associated parameters are used. The mean difference between sensible heat flux simulation for the three different cases did not exceed 10 W/m2. This shows a lack of sensitivity to canopy parameters which are usually unknown when we only have remote sensing data. The case 1 parameters were chosen in this study to be able to make consistent comparison with Lhomme (93b) model.

Model Sensitivity to Kb value

Figure 3, presents aerodynamic resistance mean value as function of three different values of Kb (2, 4 and 8), for week 37 and week 41. As expected, Ra increases linearly with increasing Kb values, for both weeks. The mean simulated sensible heat flux value variation with Kb is presented in Figure 4. This figures shows that model predictions is very sensitive to Kb values. The value of 4 for Kb was chosen as standard in this study because the values of sensible heat flux produced are the most consistent with the data. However additional theoretical as well as experimental studies are needed to understand the dependence of Kb parameter on surface types and conditions.

MODEL PREDICTION

Figure 5 (5a through 5g) presents comparisons between predicted and measured sensible heat flux using the Bowen ratio energy balance method. The model underestimated sensible heat flux for some days during week 37 (Figure 5b) and week 38 (Figure SC). A slight overestimation is also observed during few days in week 39 (Figure 5d) and week 42 (Figure 5g). The model estimations are well correlated to observations during week 36 (Figure 5a), week 40 (Figure 5e) and week 41 (Figure 5f). This model generally performed better under clear sky condition that under cloudy sky. Considering the fair quality of the data associated with the technical limitations of the Bowen ratio method for measuring surface fluxes in heterogeneous terrain,' the agreement of the model simulations with the field data is generally satisfactory. Additional investigations are needed. In particular, a more sophisticated formulation of surface resistances may improve the model predictions. We may speculate that varying Kb value with the vegetation status (LAI, height, % Cover) may yield more satisfactory results.

In order to compare the performance of this model with the results of other models, we have run Lhomme's model (1 993b) using the same data set. Figure 6 gives the corresponding root mean square error (RMSE) for two models. The model developed in the present study yields solutions similar to those of the model of Lhomme (1 993b) with modest improvement of the RMSE. However, the present model needs only one radiometric surface temperature that can be obtained from any thermal remote sensing system.

DISCUSSIONS

Although this study has emphasized the estimation of sensible heat flux for heterogeneous surface. The model described in this paper gives very satisfactory results, the average RMSE for the seven weeks of the Experiment was about 46 W/m2. It can, of course, be said that some steps of the model development are not totally physically based. Especially how grass-under-shrubs temperature was derived. But, our objective here was to develop an operational model and thus, the formulation chosen was an compromise between the physics and. the feasibility. However, this model can be improved by using surface aerodynamic resistance formulation developed by Paulson (1 970), which takes into account atmospheric stability in more physically based way. More sophisticated formulation of surface resistances may also improve the model results. Additional experimental as well as theoretical work is need to understand the relationship between the Kb values and surface features. This model, however, has a great potential to be readily used as a land-surface parameterization for several adjacent compartments used in GCM Models.

SUMMARY AND CONCLUSIONS

Accurate estimation of sensible heat flux is a key factor in monitoring surface energy using remotely sensed surface temperature in arid and semi-arid regions. A model based on the generalization of a single compartment approach was developed to estimate sensible heat flux over heterogeneous surface during the Hapex-Sahel Experiment, The surface was represented by two adjacent compartments. The first compartment contained a layer of grass under a layer of shrubs, the second compartment contained a layer of open grass. The model, “ based upon the assumption that the shrubs and the grass under the shrubs are at the same temperature, leads to a simple expression for sensible heat that requires only a radiometric surface temperature and not the temperatures of the scene components as is the case for the other two-layer models. The model sensible heat flux predictions seemed to fit the observed flux better than other existing models. However, additional studies are needed to asses the performance of this representation when applied to other vegetation types. Thus, we believe an additional step toward the monitoring surface energy balance in arid and semi-arid regions has been accomplished.

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Table-1 : Grass height during the Field Experiment

Week Number	Calendar dates	Grass height
36	30/08- 06/09	0.2m
37	07/09- 13/09	0.2m
38	14/09- 20/09	0.3m
39	21/09- 27/09	0.3m
40	28/09-03/10	0.4m
41	04/10-11/10	0.5m
42	12/10-18/10	0.6m

Table-2 : Model Coefficients

Case 1	Case 2	Case 3
Lhomme (93)	Choudh (88)	Nichols (92)
An=2.5	An=3	An=0.6
Aw = 2.5	Aw=2	Aw=3.8

Figure captions

Figure 1: Surface equivalent resistance variation with wind speed, for three combination of An and Aw parameters (week 37)

Figure 2: Surface equivalent resistance variation with wind speed, for three combination of An and Aw parameters (week 41)

Figure 3: Aerodynamic resistance variation with Kb value for week 37 and week 41

Figure 4 Predicted Sensible heat flux variation with Kb value for week 37 and week

Figure 5a: Comparison between simulated and measured sensible Heat flux (week 36)

Figure 5b: Comparison between simulated and measured sensible Heat flux (week 37)

Figure SC: Comparison between simulated and measured sensible Heat flux (week 38)

Figure 5e: Comparison between simulated and measured sensible Heat flux (week 39)

Figure 5f: Comparison between simulated and measured sensible Heat flux (week 40)

Figure 5g: Comparison between simulated and measured sensible Heat flux (week 41)

Figure 5h: Comparison between simulated and measured sensible Heat flux (week 42)

Figure 6 RMSE comparison between the current model and Lhomme (93b) model .

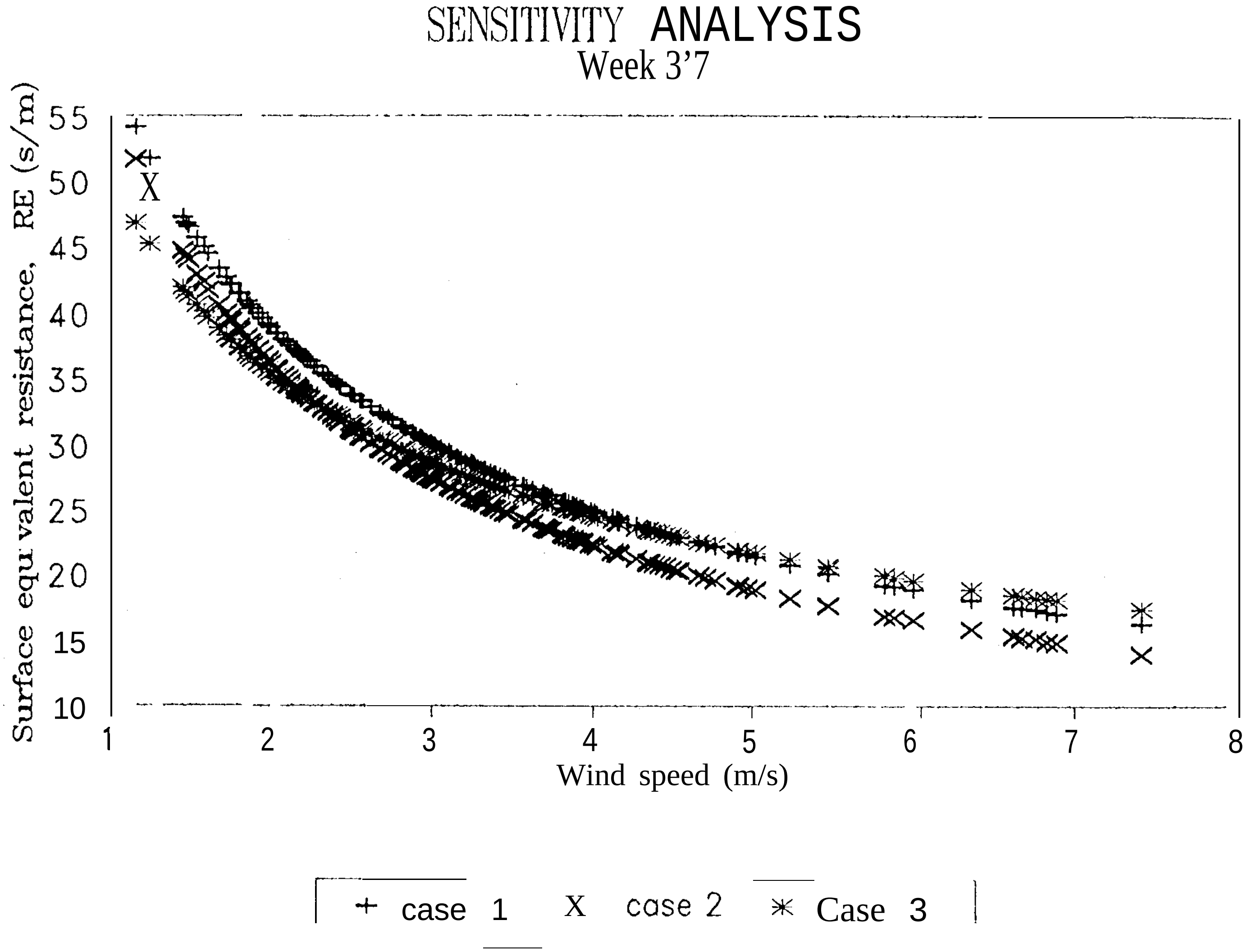

SENSITIVITY ANALYSIS
Week 3’7
Surface equ valent resistance, RE (s/m)
55
50
45
40
35
30
25
20
15
10
1
2
3
4
5
6
7
8
Wind speed (m/s)
+ case 1
X case 2
✳ Case 3

Fig4.

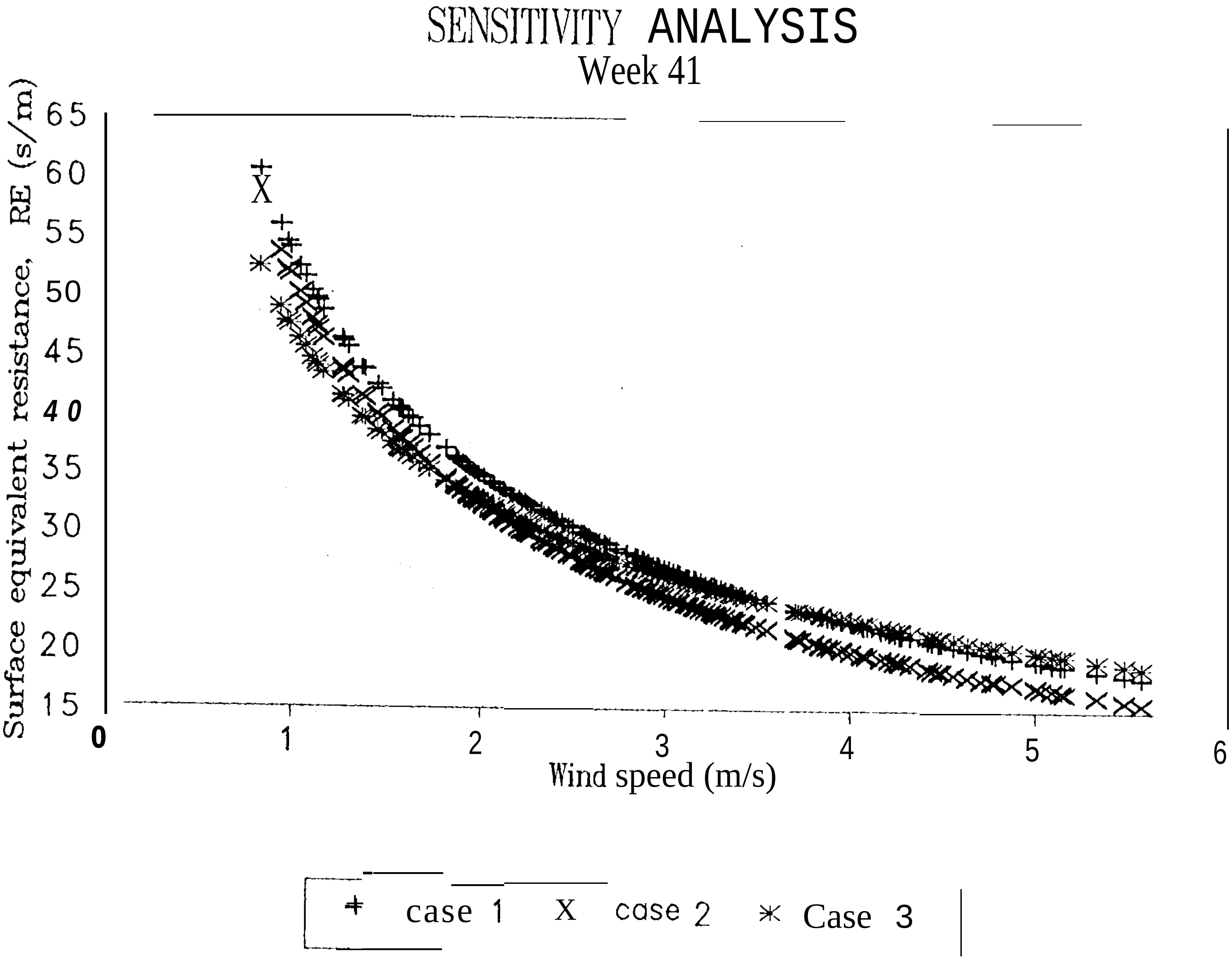
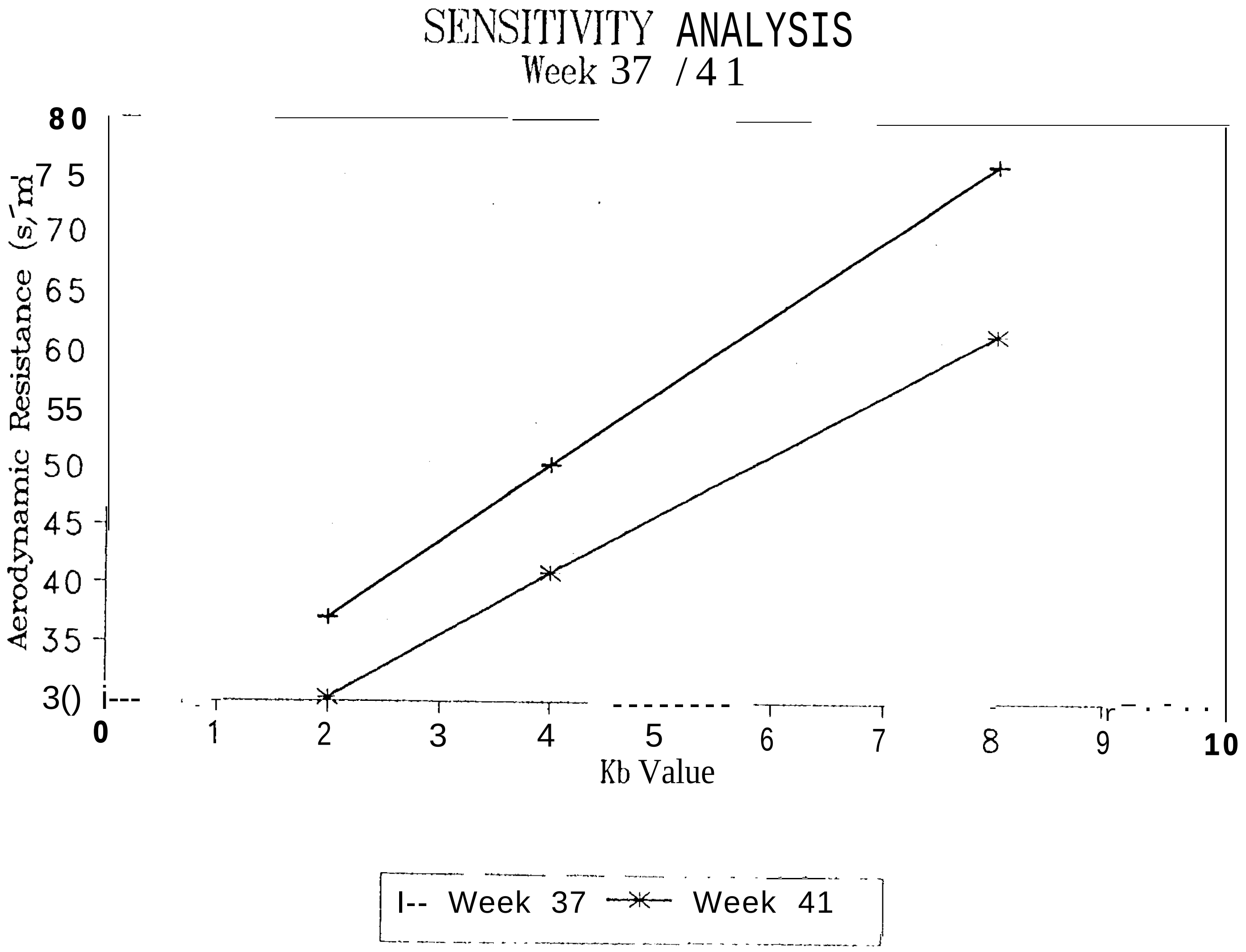

SENSITIVITY ANALYSIS
Week 41
Surface equivalent resistance, RE (s/m)
65
60
55
50
45
40
35
30
25
20
15
0
1
2
3
4
5
6
Wind speed (m/s)
+ case 1
X case 2
* Case 3

Fig 2



SENSITIVITY ANALYSIS
Week 37 / 41
Aerodynamic Resistance (s/m)
80
75
70
65
60
55
50
45
40
35
30
0
1
2
3
4
5
6
7
8
9
10
Kb Value
Week 37
Week 41

Fig 3

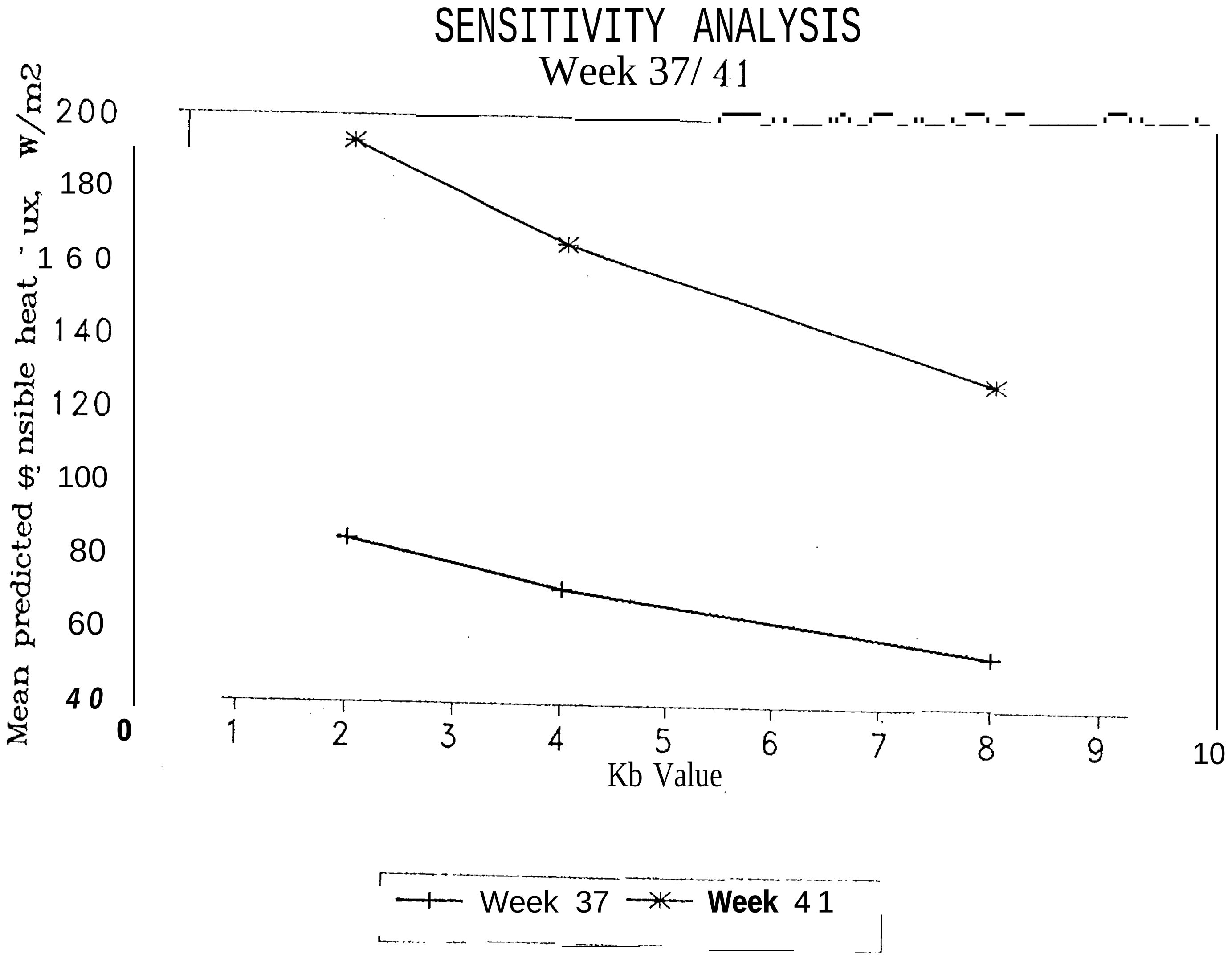
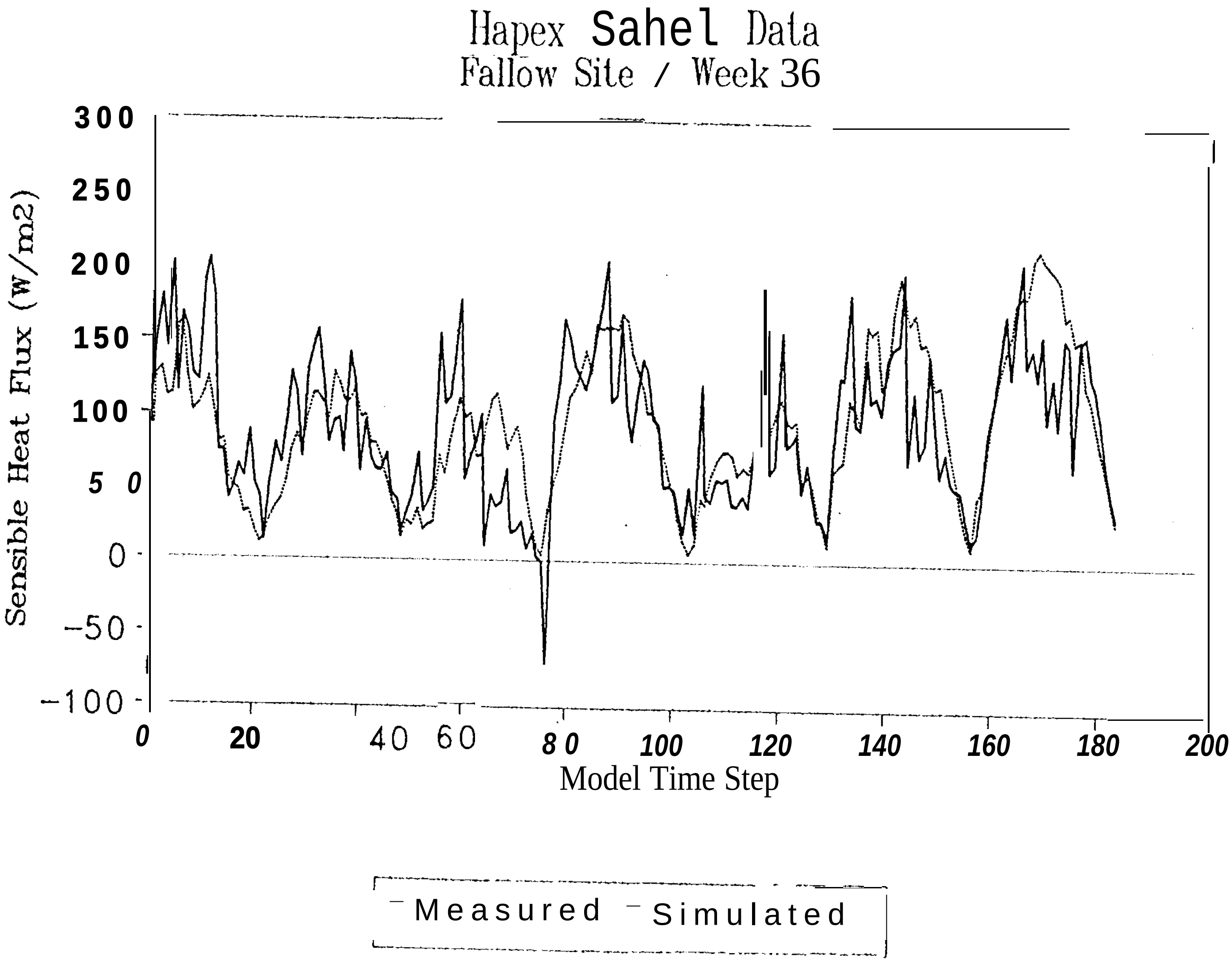

SENSITIVITY ANALYSIS
Week 37/ 41
Mean predicted sensible heat flux, W/m2
200
180
160
140
120
100
80
60
40
0
1
2
3
4
5
6
7
8
9
10
Kb Value
Week 37
Week 41

Fig 4



Hapex Sahel Data
Fallow Site / Week 36
Sensible Heat Flux (W/m2)
300
250
200
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
160
180
200
Model Time Step
Measured
Simulated

Fig 5a

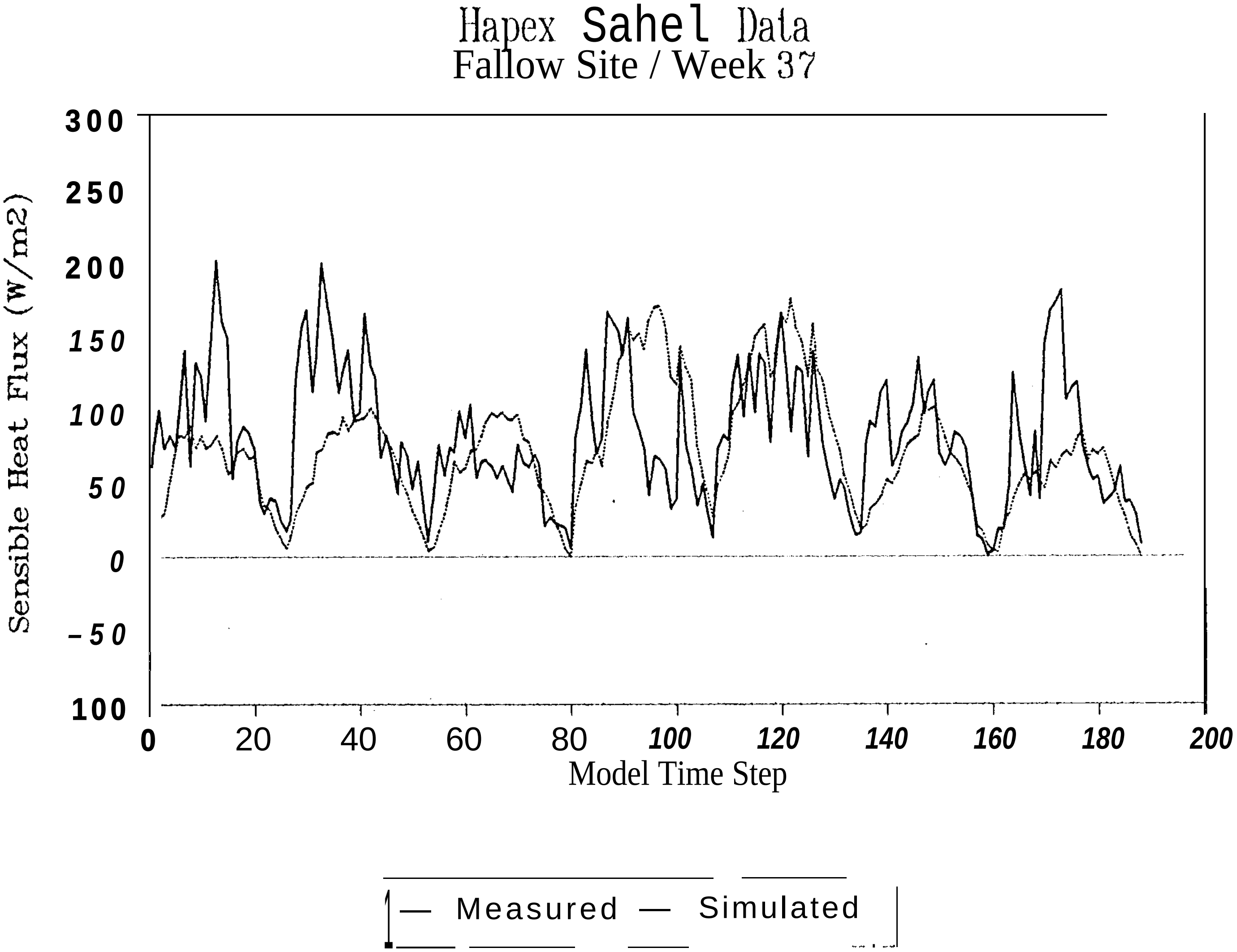

Hapex Sahel Data
Fallow Site / Week 37
Sensible Heat Flux (W/m2)
300
250
200
150
100
50
0
-50
100
0
20
40
60
80
100
120
140
160
180
200
Model Time Step
— Measured — Simulated

Fig 5b

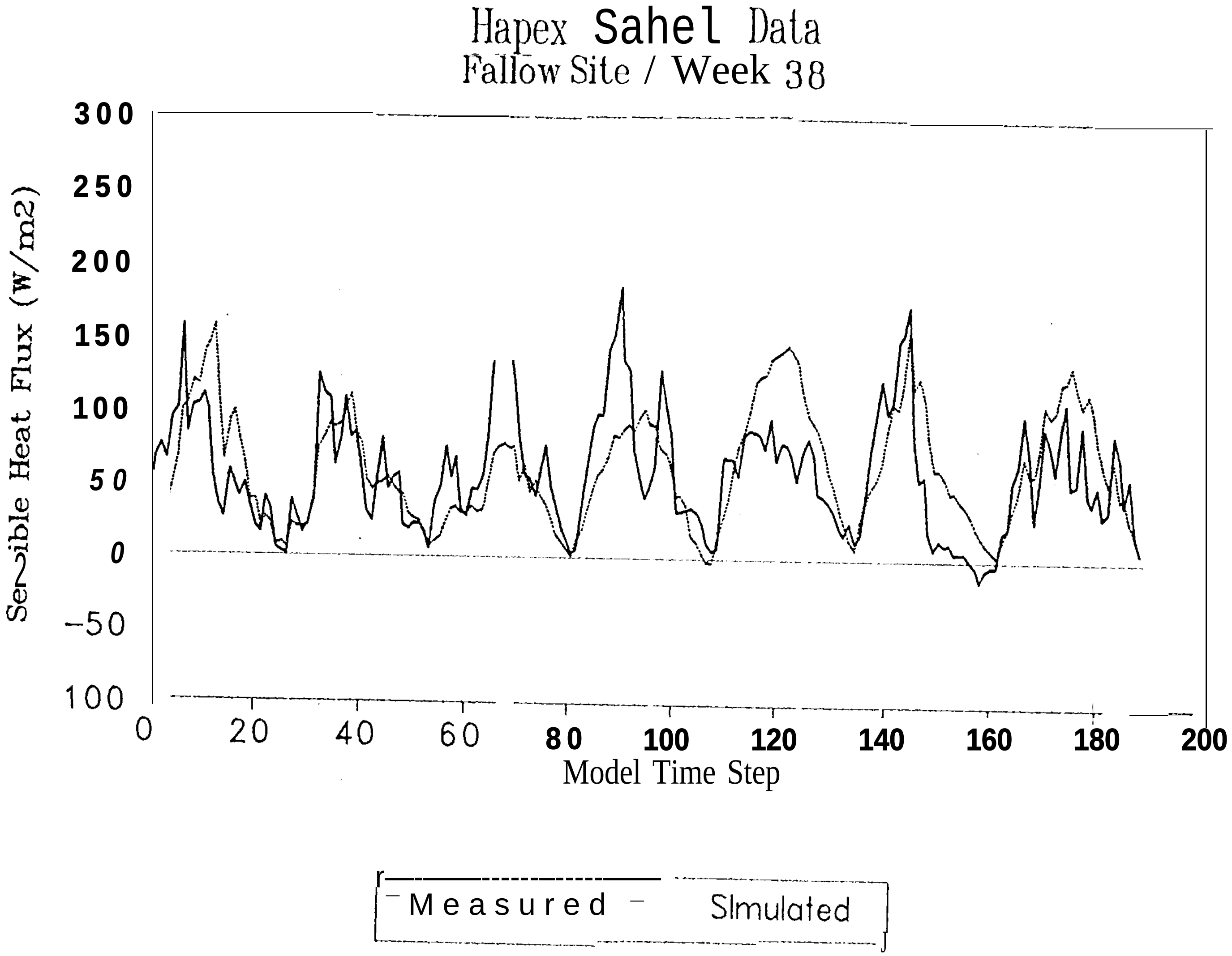

Hapex Sahel Data
Fallow Site / Week 38
Sensible Heat Flux (W/m2)
300
250
200
150
100
50
0
-50
100
0
20
40
60
80
100
120
140
160
180
200
Model Time Step
Measured
Simulated

Fig 5c.

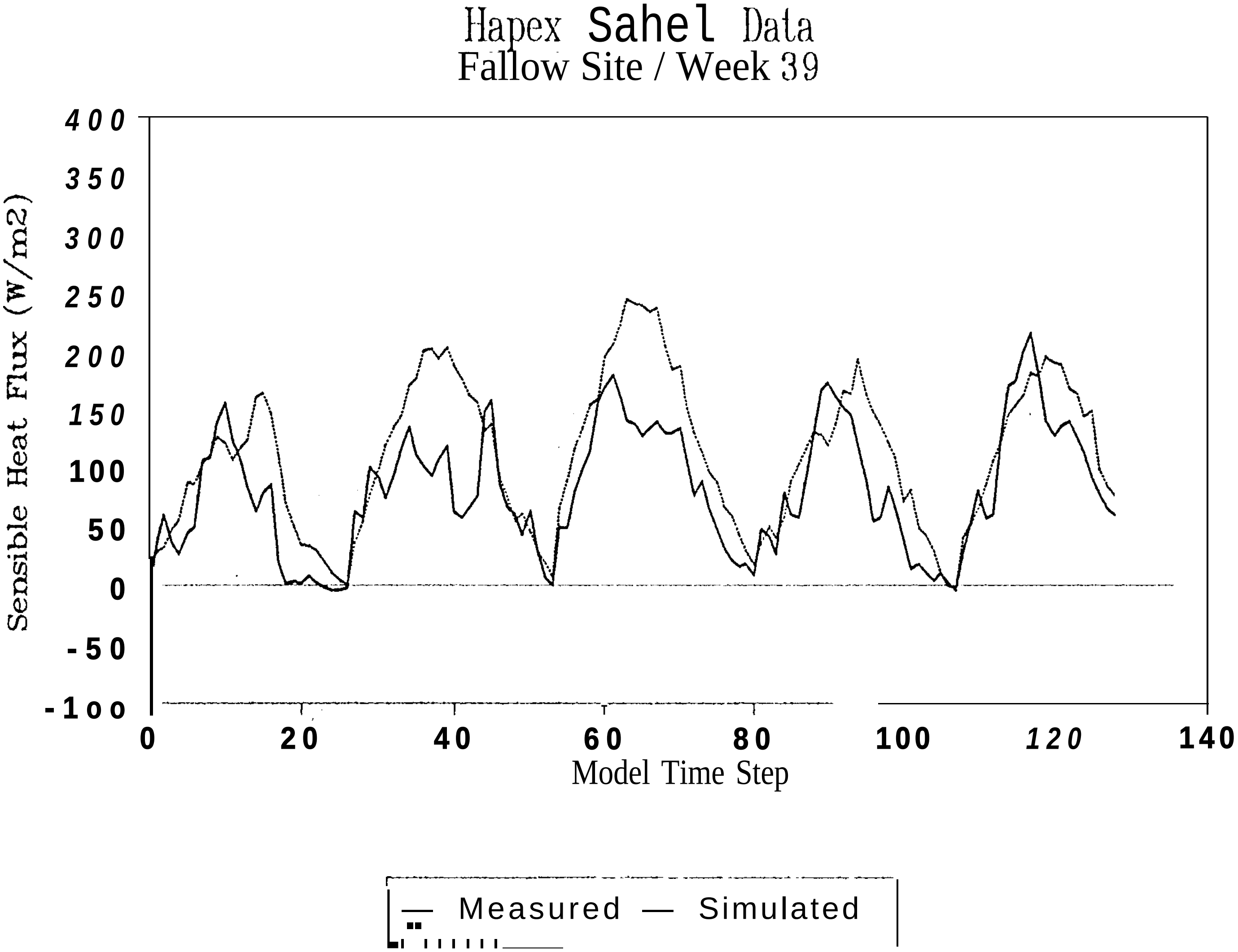

Hapex Sahel Data
Fallow Site / Week 39
Sensible Heat Flux (W/m2)
400
350
300
250
200
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
Model Time Step
— Measured — Simulated

Fig 5d

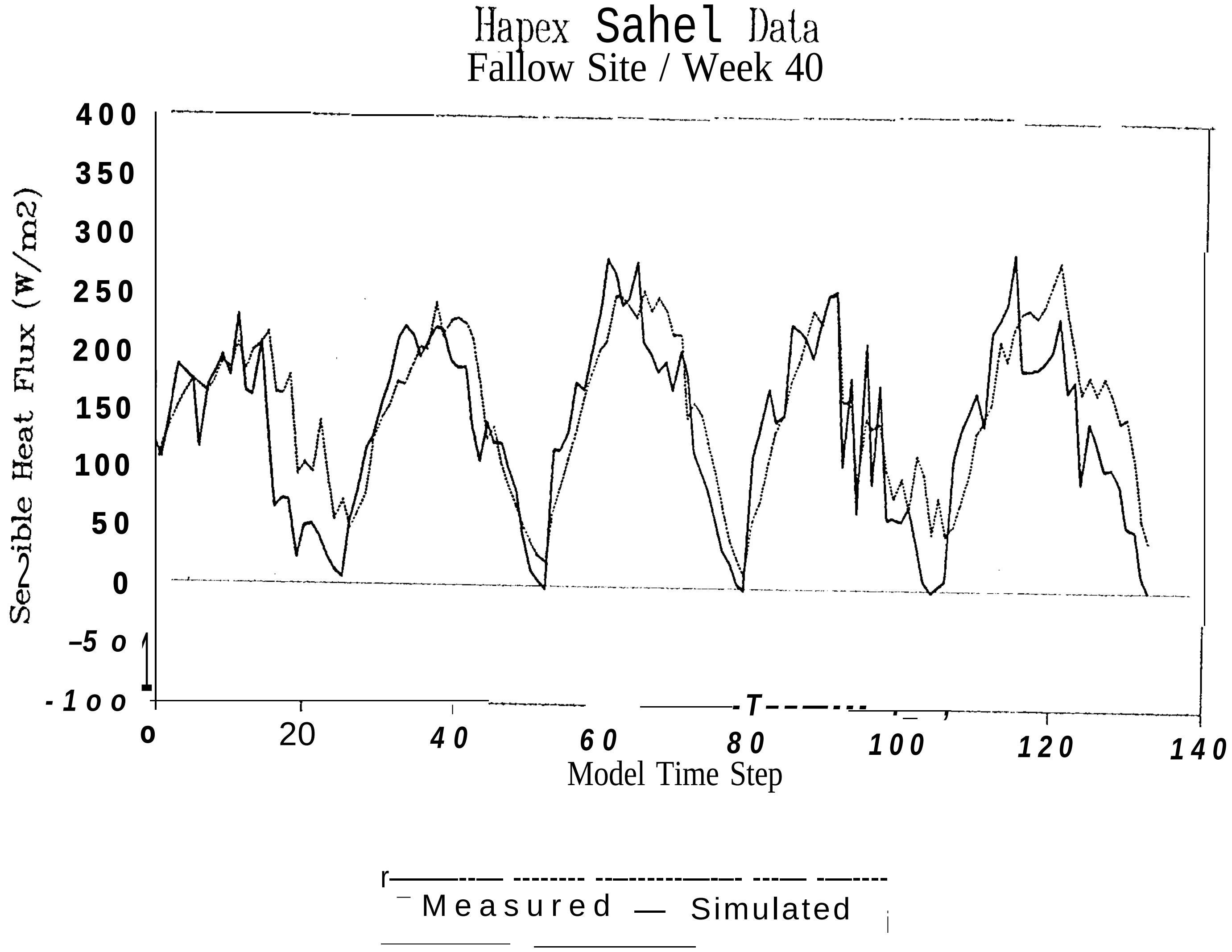

Hapex Sahel Data
Fallow Site / Week 40
Sensible Heat Flux (W/m2)
400
350
300
250
200
150
100
50
0
-50
-100
0
20
40
60
80
100
120
140
Model Time Step
Measured
Simulated

Fig.5 e

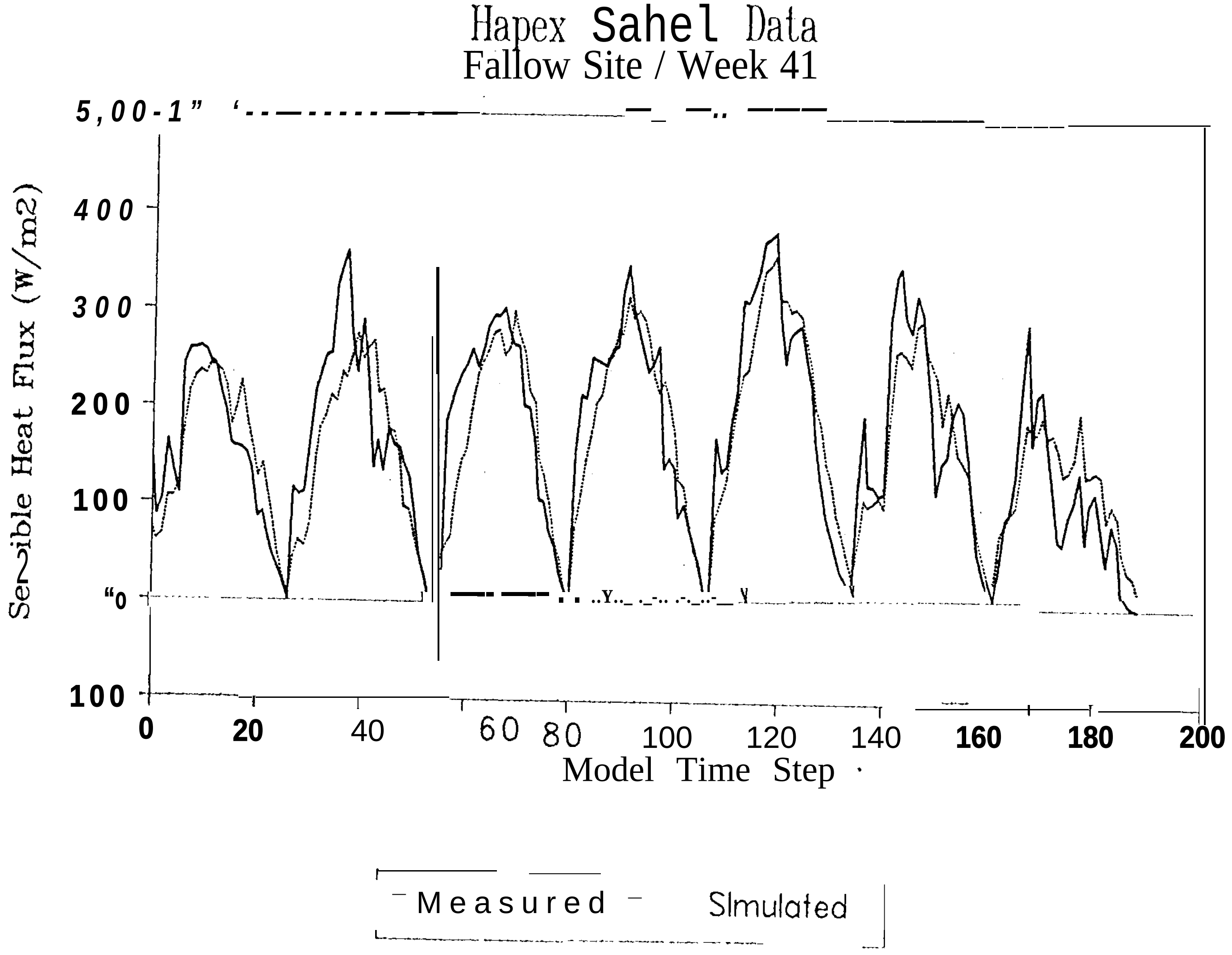
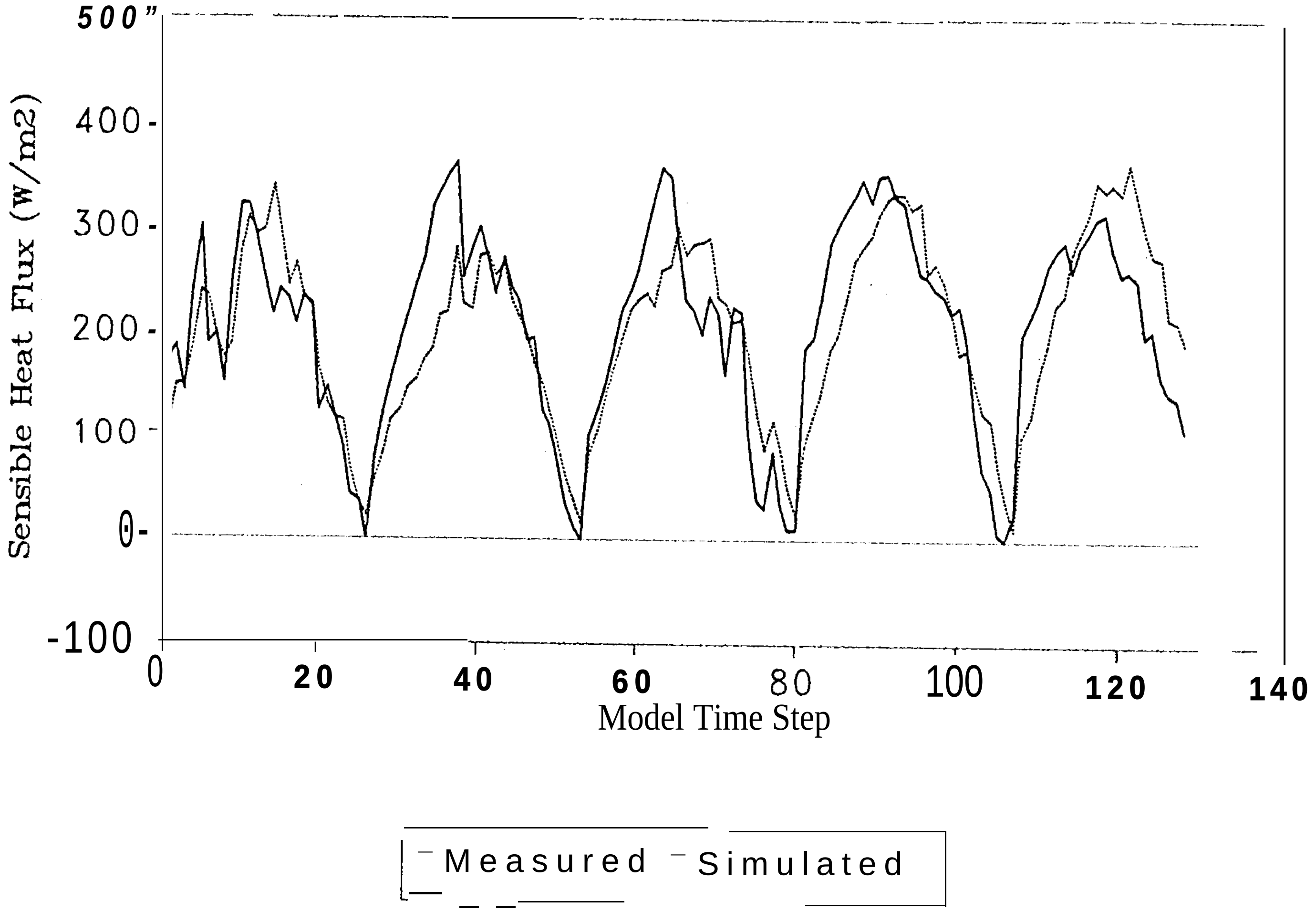

Hapex Sahel Data
Fallow Site / Week 41
Sensible Heat Flux (W/m2)
500
400
300
200
100
0
100
0
20
40
60
80
100
120
140
160
180
200
Model Time Step
Measured
Simulated

Fig 5f



Hapex Sahel Data
Fallow Site / Week 42

Fig 5g

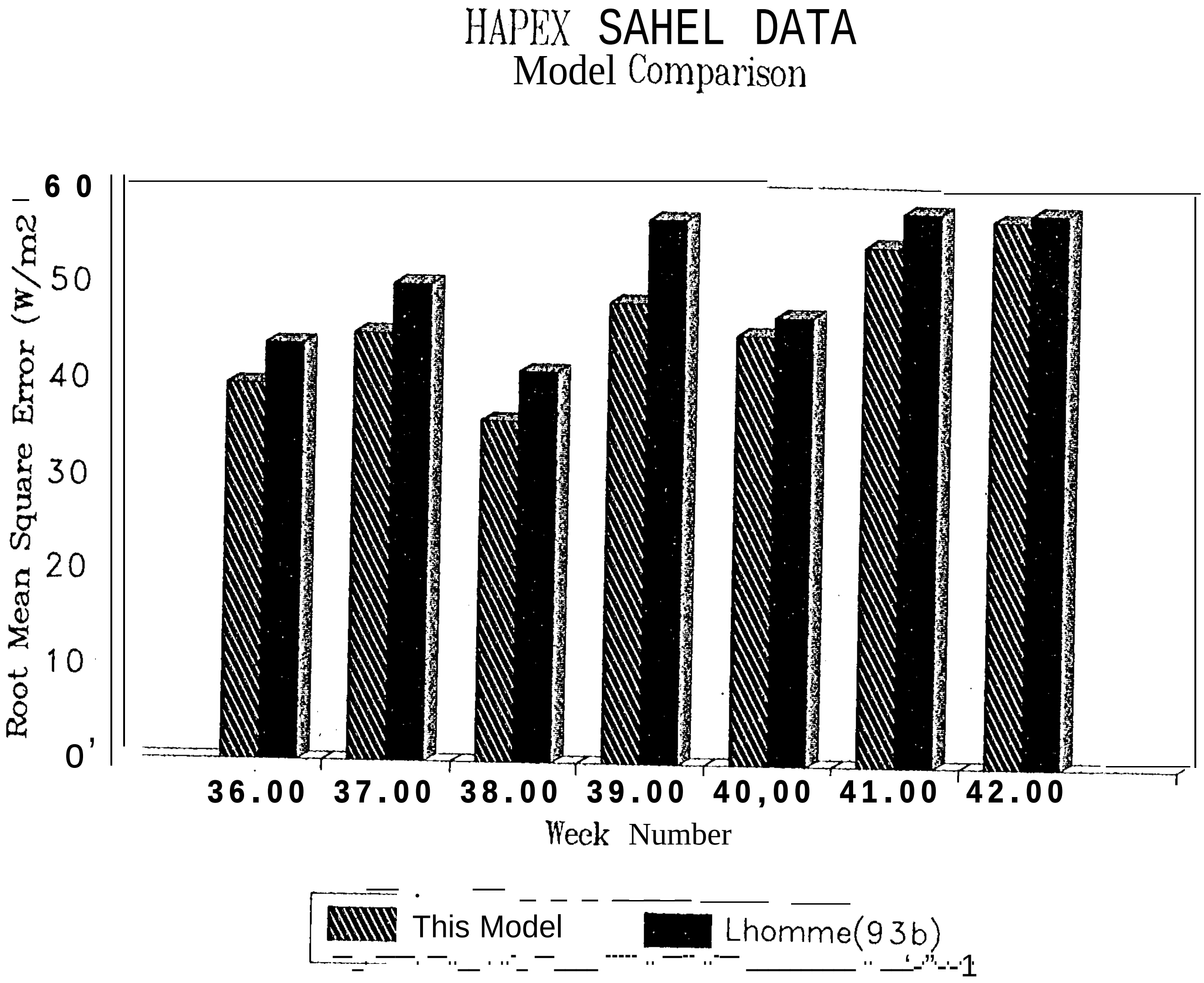

HAPEX SAHEL DATA
Model Comparison
Root Mean Square Error (W/m2)
60
50
40
30
20
10
0
36.00
37.00
38.00
39.00
40,00
41.00
42.00
Week Number
This Model
Lhomme(93b)

Fig6