ESTIMATION OF REAL EVAPOTRANSPIRATION USING REMOTELY SENSED DATA

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ABSTRACT

Remotely sensed surface temperatures (i.e. radiative surface temperatures) have been widely used in estimating spatially distributed energy balance equation components. The general approach consists of estimating the sensible heat flux and available energy from micrometeorological and optical/thermal infrared remotely sensed data. Real Evapotranspiration is then derived as the residual term of the one-dimensional energy balance equation. The problem however is that remotely sensed variables do not exactly correspond to the variables needed by the energy balance model. One operational solution is to relate empirically remotely sensed parameters to those needed by the model, such as, radiative surface temperature to aerodynamic surface temperature; vegetation index to leaf area index and canopy height. This solution is limited by the fact that it is site specific. The objective of this study is to test the performance of method using data taken over a semi-arid site in Arizona. Comparisons between measured and remotely sensed surface energy fluxes is presented. Finally, a principle of new and robust approach of using remotely sensed data will be outlined.

1- INTRODUCTION

Recently, increased emphasis has been placed on understanding the interaction between regional climate and the hydrological cycle in arid and semi-arid regions (Kustas et al., 1991; Goutorbe et al., 1993). 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 neither the soil nor the vegetation totally dominates the exchange of water and heat with the atmosphere. The relative contributions to total sensible and latent heat flux from the soil and plant components may vary throughout the day and throughout the season.

Thermal infrared remotely sensed surface are increasingly being used in operational models to evaluate the spatial variation in the energy balance components. While this approach has been found to be successful over surfaces with near full vegetation cover, its performance has been questioned over sparsely vegetated surface. The problem has been that over partial cover conditions, the assumption that consists on assimilating aerodynamic surface temperature to remotely sensed surface temperature is not valid. Over such surfaces the difference between radiative and aerodynamic temperatures can reach 10 to 15 °C.

The objective of this analysis is to investigate the extend to which remotely sensed data in the visible, near-infrared, and thermal infrared in conjunction with ancillary meteorological data and one dimensional energy balance model for surface fluxes estimation in arid and semi-arid area. Data collected during Monsoon'90 experiment have been used. The advantage and limitations of this approach are investigated. Finally, a principle of new and robust approach of using remotely sensed data will be outlined.

2- MODELING

2-1 Available Energy

Net radiation (R_n) , which represents the balance of short and long wave radiation reaching and leaving the surface can be expressed as :

$$R_n = (1-\alpha)R_s + \varepsilon_s\sigma(\varepsilon_a T_a^4 - Tr^4)$$

where Rs is the incoming short-wave radiation, σ is the Stephan-Boltzmann constant (W m^{-2} K^{-4}), and ε_e is the surface emissivity; ε_a is the sky emissivity defined as: $\varepsilon_a = 1.24(e_a/T_a)^{1/7}$, where ea and Ta are air vapor pressure and air temperature respectively. α is the surface albedo which was obtained from red and NIR surface reflectances (see Kustas et al., 1994 for a review) as :

$$\alpha = 0.526 red + 0.474 NIR$$

where red is the surface reflectance in the red band and NIR is the surface reflectance in the near - infrared band.

The soil heat flux (G) is a significant component of net radiation in arid and semi-arid region. Field observations provide real evidence for a direct relation between R_n and G. It has been found that for bare soil, the relationship between R_n and G depends on the surface soil moisture, while for vegetated surface, the ratio G/R_n can be obtained from visible and near-infrared reflectances. In this analysis G was formulated in terms of the Modified Soil Vegetation index (MSAVI) as:

$$\frac{G}{R_n} = 0.50\exp(-2.13 MSAVI)$$

where MSAVI (Qi et al., 1994) is defined as:

$$MSAVI = \frac{red - NIR}{red + NIR + A}(1 + A)$$

where A is a self adjusting factor defined to adapt the soil noise correction to the proportion of soil seen by the sensor. A is given by the expression :

$$A = 1 - 2\frac{NIR - red}{NIR + red}(red - 1.06 NIR)$$

In this study we have considered MSAVI as the vegetation index to use since it was found to be less sensitive to soil brightness variations including shadows than other spectral vegetation indices (Chehbouni et al., 1994). This is of importance since the contribution of bare soil to scene reflectance is very significant for partially covered surfaces.

2-2 Sensible and Latent heat flux

From theoretical view point, sensible heat flux should be expressed in terms of aerodynamic surface temperature since it is aerodynamic temperature which determines the loss of sensible heat flux from a surface. Aerodynamic surface temperature is defined as the extrapolation of air temperature profile down to an effective height within the canopy at which the vegetation components of sensible and latent heat flux arise, say ($d + z_o'$), where z_o' is the roughness length for heat, and d is the zero-plane displacement height assumed to be the same for heat and for momentum (Kalma and Jubb, 1990). The problem is that the estimation of the roughness length for heat (z_o') is not trivial over sparsely vegetated surfaces. To overcome this difficulty, it has been suggested that one can was to consider that the exchange of heat and moisture between the surface and the atmosphere takes place at an effective level located at the same height as the effective sink of momentum i.e. level $d+z_o$, which corresponds to the level where the logarithmic profile takes its surface value (zero). Then a new aerodynamic surface temperature can be defined as the extrapolation of air temperature profile down to this level. Sensible heat flux can be then formulated as:

$$H = \rho C_p \frac{T_o - T_a}{r_a}$$

where ρ is the air density (kg m^{-2}), c_p the specific heat of air at constant pressure ($J\, kg^{-1} K^{-1}$), r_a (sm^{-1}) is the aerodynamic resistance, calculated between the level of the apparent sink for momentum and the reference height. T_a (°C) is the air temperature at a reference height (z) above the surface, and T_o (°C) is the aerodynamic surface temperature defined above.

Since aerodynamic temperature cannot be directly measured, it is often replaced by radiative temperature (Tr) in the formulation of sensible heat flux. The problem is that the derivation of exchange coefficient from Monin-Obukhov similarity theory does not apply when the surface radiative temperature is used instead of aerodynamic temperature in the surface heat flux formulation. Under dense canopy, the difference between aerodynamic and radiative surface temperatures is very small, which leads to small errors in heat flux prediction. Over sparsely vegetated surfaces, however, the difference can exceed 10 °C, as a result sensible can be largely overestimated.

The approach suggested by Chehbouni et al. (1995a-b) consists of formulating a relationship between aerodynamic and radiative surface temperature, and They then defined the coefficient β as:

$$\beta = \frac{T_o - T_a}{T_r - T_a}$$

Numerical simulations (Chehbouni et al., 1995a) have shown that the multitemporal behavior of the coefficient β through the growing season is compared to the variation of Leaf Area Index, which lead to a parameterization of the coefficient β with respect to LAI as:

$$\beta = \frac{1}{\exp(L/(L - LAI)) - 1}$$

where L is an empirical factor that was set by least squares regression to a value of 1.5 (Chehbouni et al., 1995a). Previous studies have indicated that a modified Beer's law expression can accurately describe the general relationship between vegetation index and LAI (Asrar et al., 1984). In this analysis, an exponential type relationship was used to obtain LAI from remotely sensed MSAVI as:

$$MSAVI = 0.88 - 0.78 \exp(-0.6 LAI)$$

By combining the last three equations, sensible heat flux can be expressed in terms of one remotely sensed surface temperature, MSAVI , and air temperature .

Finally latent heat flux can be formulated as the residual term of the energy balance equation as :

$$LE = Rn - G - H$$

For the remaining of the paper surface fluxes estimated as described above will be called remotely sensed surface fluxes.

3- EXPERIMENTAL DATA

3-1 Location and site description

The Monsoon '90 multidisciplinary field campaign was conducted over the U.S. Department of Agriculture's Agricultural Research Service Walnut Gulch experimental watershed in southeastern Arizona (31° 43'N, 110°W) during the summer of 1990 (see Kustas et al., 1991, and Kustas et Goodrich., 1994). The main objective of the experiment was to investigate the potential of using multispectral remotely sensed data in conjunction with hydrological models to quantify spatial and temporal variability of surface energy and water fluxes in Arid and semi-Arid regions. The study sites were located in an area comprising the upper 150 km^2 of the Walnut Gulch drainage basin and situated about 1300 m above mean sea level..

The annual precipitation in this region ranged from 250 to 500 mm/yr., with approximately two thirds of the rainfall occurring in the monsoon season (July-August).
The surface soil texture was mainly sandy loam with high fraction of rocks. The vegetation in the western half of the watershed was shrubs dominated, while the eastern half is grass dominated. The analysis in this paper is limited to the shrub dominated site (Lucky Hills), where spatial heterogeneity between shrub clumps and adjacent bare soil was higher (Kustas and Goodrich, 1994). The shrubs was about 0.6 m height and covering about 0.26 % of the surface (see Weltz et al., 1994). The surface leaf area index was about 0.3-0.4 which implies that the clump leaf area index of the shrubs ranged between 1.15 and 1.54.

3-2 Surface measurements

The four components of the energy balance equation used in this study were measured using a 2 m tall roving eddy correlation tripod : ROVEC. Net radiation was measured with a REBS Q6 net radiometer at a height of 1.6-1.7 m. The soil heat flux was measured using a soil heat flux plates (MELCOR, CP 1.4-71-06-L). Latent and Sensible heat flux were measured with the eddy correlation method, using a single axis sonic anemometer, a krypton hygrometer, and a 12.7 mm-diameter thermocouple, all manufactured by Campbell Scientific, Inc. Measurements of wind, humidity and temperature fluctuations at 2 m height were made at 10 Hz, and 10 mn means were used to compute covariances.

In addition to those measurements, the four components of the radiation budget were taken with Eppley Precision Spectral Pyranometers (PSP) and Precision Infrared Radiometers (PIR). The PIR's were equipped with thermistors to measure dome and case temperatures so that the measured long-wave radiation could be corrected for temperature gradients between the dome and case. Vapor pressure gradients were determined by measuring dew-point temperature at two heights using Campbell Scientific, Inc. single-cooled-mirror hygrometer. The measuring heights were 1.25 m and 2.25 meters above the soil surface. Air is alternately drawn through intakes at each height and routed to the cooled mirror; a single pump aspirates the system. Air temperature was measured at the same two, heights, using 76 mm diameter unshielded non-aspirated chromel-constantan thermocouples. In addition to these measurements, soil surface temperature was measured using an Everest Interscience (IR) sensor, model 4000 with a 15° filed of view, mounted 2 m above the soil surface. At this height the sensor viewed an area of bare soil about 0.45 m in diameter. Canopy temperature was measured with an Everest Interscience IR sensor model 110 or model 4000 with a 3° field of view. It was mounted about 30 cm above the top of the canopy. Since no measurement of the shaded soil temperature was made, it was assumed for this analysis that shaded soil temperature is the average of the temperatures of the unshaded soil and the canopy. However other formulations for deriving soil under the shrubs temperature were also tested. Wind speed was measured at 1.25 and 2.25 m above the soil surface using photo-chopper anemometers with a threshold of 0.2 ms^{-1}. These sensors were samples at 10 seconds intervals and the data averaged over 20 minute periods. For this study, all the data were averaged over one hour periods.

Additionally, ground-based surface reflectances were measured from a height of 2 m above the ground surface, using yoke-based radiometers (Exotech with spectral filters covering bleu, green, red and NIR) and a calibrated reflectance panel (See Moran et al., 1994a,b). These data were taken over a ground target of approximately 120 m by 120 m in size, during several day of the experiment. For this study red and NIR reflectances were used to compute short wave albedo, and the vegetation index .

4- RESULTS

Data described above has been used to estimate surface energy balance components during 13 days (DOY 209 to DOY 221). Comparison between observed and remotely sensed net radiation is presented in Figure 1. In general, net radiation estimation compared well with the observations (RMSE of about 50 Wm^{-2}). However, there is a slight discrepancy which may be due to the limitation of the expression used to estimate incoming long wave radiation under cloudy sky conditions (Brutsaert, 1975). Figure 2, is a comparison of the data-derived and the model- derived soil heat flux. The RMSE was about 40 Wm^{-2} for values ranged between 0 and 250 Wm^{-2}. It must be emphasized however that the expression between Rn and G used here is developed for clear sky conditions only. Furthermore, this expression does not take into account the time lag between G and Rn (Moran et al., 1994). additionally, it may be possible that the relationship between net radiation and soil heat flux does not depend only surface type (bare versus vegetated surface) but also depends on the distribution of the vegetation within the surface (Chehbouni et al., 1995c). These reasons may explain the scatter between measured and remotely sensed soil heat flux.

In Figure 3, eddy correlation based sensible heat flux is compared to that estimated using remotely sensed surface temperature and vegetation index. The model tends to underestimate H when measured values ranged from 50 to 150 Wm^{-2}. This may be due to the error associated with the formulation of β coefficient or to that associated with the estimation of LAI from MSAVI which does not take into account the effect of solar angle variation. However, the root mean square error (RMSE) between observed and simulated sensible heat was about 44 Wm^{-2} for measured values ranged between 0 to 300 Wm^{-2}. Additional studies are needed to test the universality of β parameterization, and to investigate how the L parameter changes with vegetation type and structure.

Figure 4 presents a comparison between measured latent heat flux and that obtained as the residual term of the energy balance equation. The model estimates of latent heat flux are reasonable, the RMSE is about 54 Wm^{-2} .

5- CONCLUSION

It can argued that the simplicity of this approach combined with the availability of remotely data, makes this approach very attractive for operational monitoring of surface fluxes in arid and semi-arid areas. The major problem with this approach is that the relationship between remotely sensed variables and those needed for process formulation are empirical. In this regard, such relationships are site specific. This represents a major handicap for generalizing such approach. Furthermore, if one always needs to redo calibration for each individual site, one can legitimately challenge the effectiveness of this approach. One alternative approach of using remotely sensed data for quantitative purposes could be to combine SVAT type model with radiative transfer model. The principle of this method is to use the SVAT output such as surface temperature and soil moisture as input to radiative transfer models. The radiative transfer models will simulate in a given waveband the spectral signature of the surface as it can be observed by a remote sensor. By minimizing the differences between measured and simulated remote sensing variable, on can assume that the resulting surface fluxes are correct. This approach is certainly more robust, but it needs accurate SVAT and radiative transfer models, which are not readily available at this time.

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FIGURE CAPTIONS

Figure 1: Comparison between measured and remotely sensed net radiation

Figure 2: Comparison between measured and remotely sensed soil heat flux

Figure 3 : Comparison between measured and remotely sensed sensible heat flux

Figure 4 : Comparison between measured and remotely sensed latent heat flux

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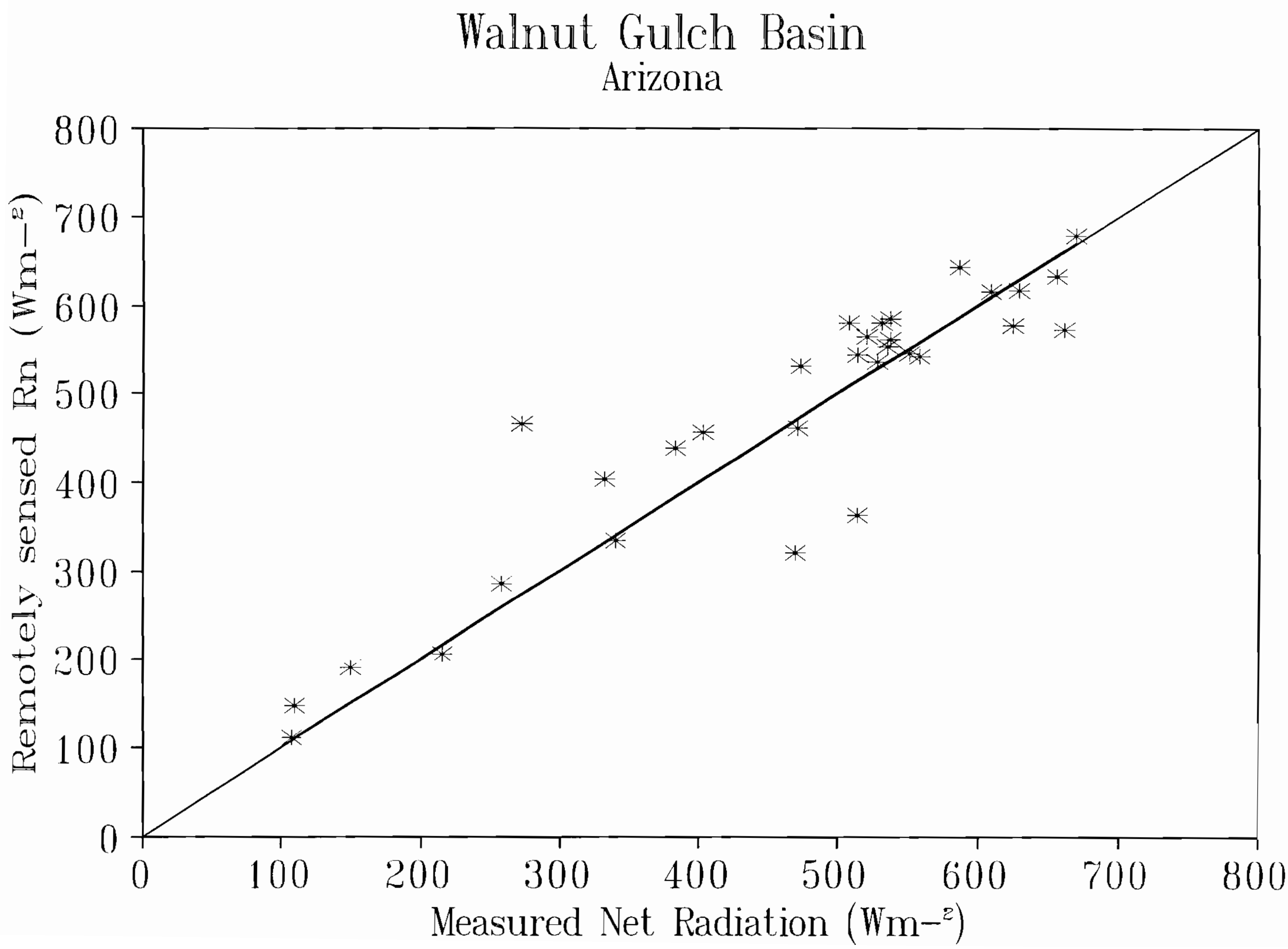
FIG. 1



Walnut Gulch Basin
Arizona
Remotely sensed Rn (Wm⁻²)
Measured Net Radiation (Wm⁻²)
0
100
200
300
400
500
600
700
800

FIG. 2

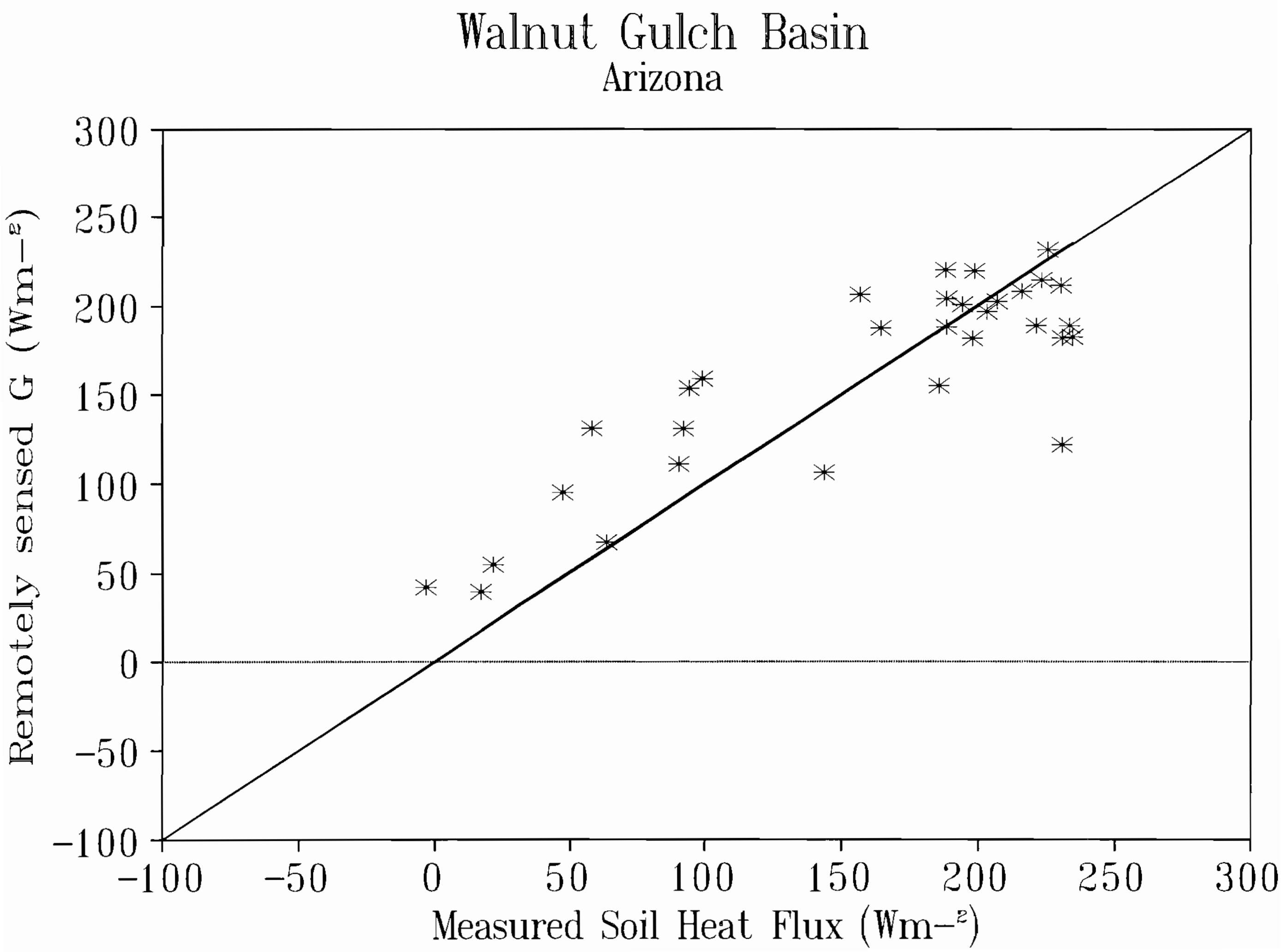

Walnut Gulch Basin
Arizona
300
250
200
150
100
50
0
−50
−100
Remotely sensed G (Wm^{-2})
−100
−50
0
50
100
150
200
250
300
Measured Soil Heat Flux (Wm^{-2})

FIG. 3

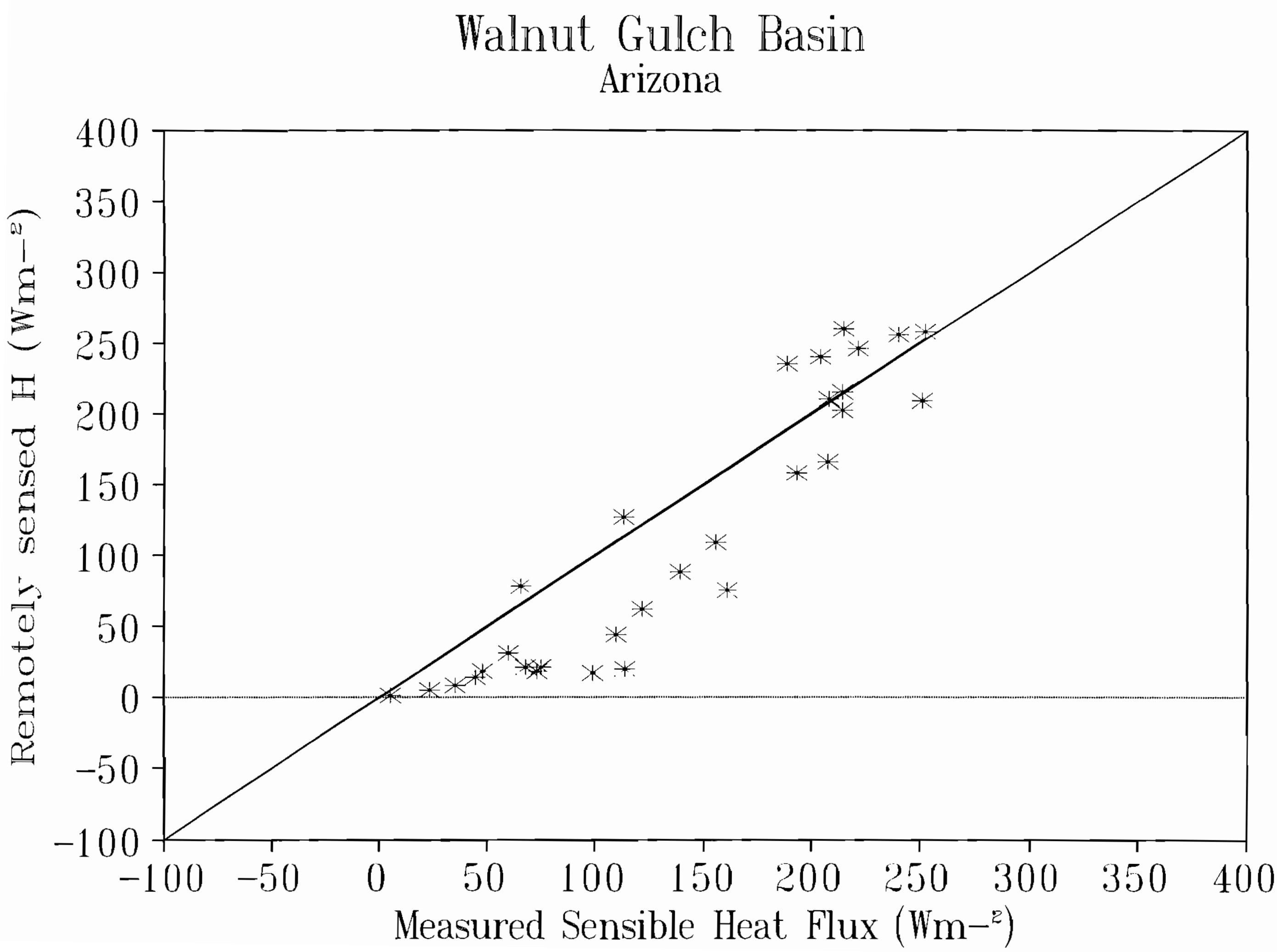
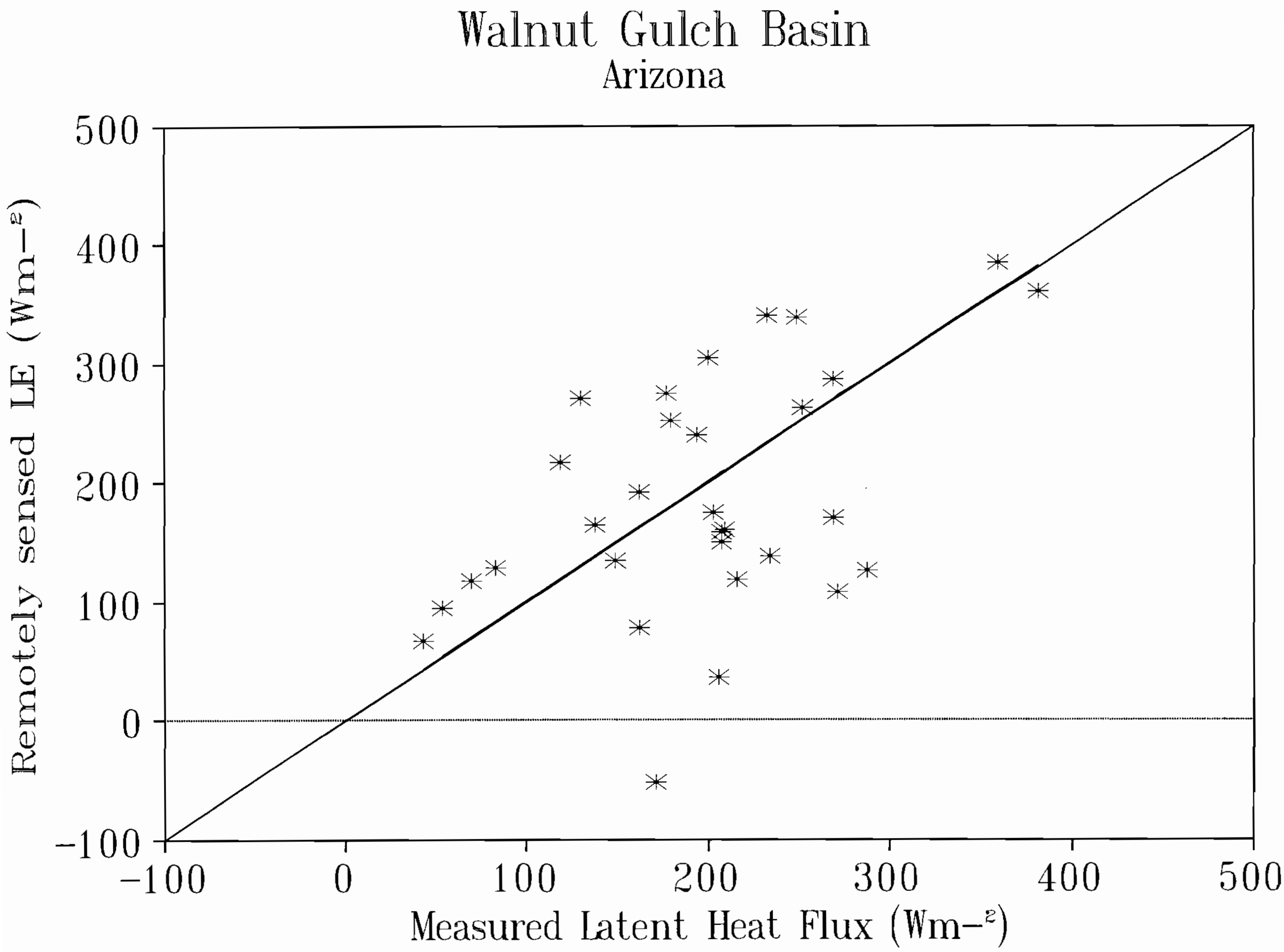

Walnut Gulch Basin
Arizona
400
350
300
250
200
150
100
50
0
−50
−100
−100
−50
0
50
100
150
200
250
300
350
400
Remotely sensed H (Wm−²)
Measured Sensible Heat Flux (Wm−²)

FIG 4


Walnut Gulch Basin
Arizona
Remotely sensed LE (Wm−2)
Measured Latent Heat Flux (Wm−2)
500
400
300
200
100
0
−100
−100
0
100
200
300
400
500