Institute of
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Overseas Development Report

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Natural Environment Research Council

REMOTE SENSING OF SEMI-ARID REGIONS

Final Report on ODA Project T06055B1

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Executive summary

Land degradation of semi-arid areas is thought to be a result of over exploitation due to population pressure, as well as climate fluctuations/change. To prove this hypothesis General Circulation Models (GCMs) are used, however recent research has shown that these models need improving and validation of their estimation of the surface fluxes of evaporation and sensible heat. Only remote sensing has the potential to provide measurements of these fluxes at the scale of GCMs i.e. hundreds of kilometres. Improved predictions of climate change by GCMs would help aid agencies in planning new hydrological and agricultural schemes.

Previous research has shown that estimates of sensible heat flux using remotely sensed data from semi-arid areas of sparse vegetation with classical formulation of the transfer coefficient are significantly over-estimated. Previous research had suggested a theoretical basis for an excess resistance in this classical formulation. The current research analysed data from Niger to determine the excess resistance to correct for this bias. Introduction of this excess resistance reduced the transfer coefficient by a factor of four. To check whether this value of the excess resistance was typical of semi-arid rangeland areas, collaboration was set up with 4 groups in USA and 1 in the Netherlands. The resulting analysis of data from another 6 sites gave the same answer. To check how successful this excess resistance was in estimating sensible heat flux and evaporation from sparse prairie grass, data from the FIFE project in Kansas, USA was analysed. Without including the excess resistance the sensible heat flux was over-estimated by factor of 2, whereas inclusion of the excess resistance resulted in only an under-estimate of 18% in the sensible heat flux and an over-estimate 5% in evaporation. On the basis of these encouraging results this revised relationship could be used to determine sensible heat flux and evaporation for other semi-arid areas if satellite measurements of radiometric surface temperature are available. Besides providing data for validation of GCMs, this information should lead to improved assessment of water resources for these areas.

Report on ODA funded project 'Remote Sensing of Semi-arid Regions' for 1992/93 and 1993/94

1. Goal

Vegetation and land degradation are widespread in arid areas and constitute a major global environmental problem. Large parts of the dryland areas which cover over one third of the earth's land surface are being degraded, with serious effects on the environment, food production and the lives of hundreds of millions of people. Although current estimates of global dryland degradation vary widely, the extent of the problem is vast and most severe in Africa and Asia. Large scale changes in vegetation cover in semi-arid areas may produce changes in climate. Changes in climate resulting from changes in vegetation cover can only be predicted using mathematical models of the atmosphere and its interaction with the land surface - these models are commonly known as General Circulation Models (GCMs).

To have confidence in the predictions of climate change from GCMs, the output from these models needs validation. The primary method of validation has been to compare model temperatures and pressure patterns at different levels in the atmosphere with measured values. It has now been recognised that a major limitation of current GCMs is their simplistic parameterisation of exchange processes at the land - atmosphere interface. This parameterisation determines the magnitude of the turbulent fluxes - evaporation and sensible heat flux - from the surface. Therefore a stringent test of the land surface parameterisation would be a comparison between modelled and measured surface fluxes. However because of their complexity GCMs can only run on current computers with very low spatial resolution i.e. typically the distance between grid points is hundreds of kilometres; therefore conventional ground based measurements of surface fluxes, which are representative of areas of less than 1 km across, cannot provide appropriate data. Only satellite remote sensing data has the potential to provide measurements at the relevant scale.

On the World scale improved prediction of climate change will enable Governments to make rational decisions about their policies which effect the production of carbon dioxide. At the regional scale it will help aid organisations in planning new hydrological and agricultural schemes to cope with changing rainfall patterns.

2. Previous results using remote sensing

Physically the sensible heat flux - energy in the form of heat which is transferred by turbulence from the earth's surface into the atmosphere - is related to the difference between the surface temperature and the air temperature. The radiometric surface temperature can be derived from satellite measurements in the thermal infra-red band if the effects of the atmosphere can be corrected for. Then sensible heat flux can be derived if the near surface air temperature and the transfer coefficient can be determined. The near surface air temperature can be derived by interpolating between ground-based measurements or from models. In contrast there is much more uncertainty about the appropriate transfer coefficient to use. Classical micrometeorological theory relates the transfer coefficient to wind speed and the aerodynamic roughness of the surface. However a number of previous studies (Choudhury *et al*, 1986; Kustas *et al*, 1987; Stewart *et al*, 1989; Hall *et al*, 1992) have shown that large systematic errors can be caused by using classical theory to derive the sensible heat flux from radiometric surface temperature, particularly when the measurements are made over sparse vegetation.

3. Purpose

The purpose of this analysis was to overcome these systematic errors found in the turbulent fluxes derived from remotely sensed radiometric surface temperatures measured over sparse vegetation. Based on previous research (Owen and Thompson, 1963; Chamberlain, 1966) it was proposed to introduce an excess resistance into the calculation of the transfer coefficient. The objective of this analysis was to determine the average value of the excess resistance and test whether this value was typical of other semi-arid rangeland areas.

4. Data used for analysis

To remove the additional problems of using satellite data, i.e. the effect of intervening atmosphere and the uncertainty in geographical location; data from tower mounted instruments was used for this analysis instead. Another advantage of ground based measurements is the complete coverage of the diurnal cycle rather than at a single time of day, as provided by sensors on polar-orbiting satellites. The radiometric surface temperatures were measured by infra-red thermometers (IRT) mounted over the vegetation and soil at two of the sites studied as part of the SEBEX project (Wallace *et al*, 1992) in Niger, West Africa.

The SEBEX project provided the other essential measurements - near surface air temperature and wind speed, sensible heat flux and determination of the aerodynamic roughness of the surface. One site was in an area of open natural forest, known locally as Tiger Bush. The other was an area which had been used for growing millet and had been left fallow for 7 years and the natural savannah had regenerated.

5. Results

Analysis of 1142 daylight hours from the Tiger Bush site and of 507 daylight hours from the Fallow/Savannah site gave values of 48 and 38 s m^{-1} respectively for the excess resistance. The total resistance which is the sum of the classical aerodynamic resistance and the excess resistance and is the reciprocal of the transfer coefficient, was 60 and 55 s m^{-1} respectively. Therefore the transfer coefficient is reduced by factors of 5.0 and 3.2 respectively. Details of the analysis are given in the Appendix 1. In meteorological theory the excess resistance is described in terms of the quantity kB^{-1}. For these two sites the values of kB^{-1} are 8.3 and 5.8 respectively. To use these results for other areas of sparse vegetation the values of kB^{-1} were averaged giving a value of 7.1.

To test whether this value of kB^{-1} is generally representative of semi-arid rangeland vegetation, collaboration with three groups in USA and one in the Netherlands was set up. Each of these groups had similar data to that obtained in Niger. After discussion the same analysis procedure was applied to all the data sets. These four groups between them had data from another 6 sites which gave an average value for kB^{-1} of 7.1 - identical to the value obtained from the two sites in Niger. However it needs stressing that this agreement is probably fortuitous, since the values for the individual sites varied widely. Details of the analysis are given in Appendix 2.

To test the accuracy of the estimates of the sensible heat flux using an excess resistance derived from the average value of kB^{-1}, data obtained by the Institute of Hydrology as part of their participation in the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) was used. This project was run by NASA in the tall grass prairie area of Kansas. Without incorporating an excess resistance term, the sensible heat flux was over-estimated by 214 per cent, incorporation of the average excess resistance resulted in an under-estimate of 18 per cent - a greatly improved result. The evaporation determined using these values of sensible heat flux in the energy budget gave an average over-estimate of 5%. Details of the analysis are given in Appendix 3.

6. Dissemination of results

As a result of the funding of this project the analysis has been reported at the following meetings:

American Geophysical Union Spring Meeting, Baltimore, Maryland, USA. 24-27 May 1993.

Thermal Infrared Workshop, La Londe les Maures, France. 20-24 September 1993.

FIFE Follow-on Workshop, Manhattan, Kansas, USA. 13-14 October 1993.

Horticultural Research Institute meeting, Kerikeri, New Zealand. 1-2 December 1993.

Also the following papers have been written:

Stewart, J.B., Kustas, W.P., Humes, K.S., Nichols, W.D., Moran, M.S. and de Bruin, H.A.R. Sensible heat flux - radiometric surface temperature relationship for 8 semi-arid areas. Submitted to Journal of Applied Meteorology.

Stewart, J.B. Turbulent surface fluxes derived from radiometric surface temperature of sparse prairie grass. Submitted to Journal of Geophysical Research.

7. Future work

It is to be hoped that further tests of the accuracy of the excess resistance derived from the data for the 8 semi-arid rangelands sites will be undertaken by other groups after the papers by Stewart *et al*, (1994) and Stewart (1994) have been published. The results from the current analysis looks sufficiently promising that the method should be used to estimate regional scale sensible heat flux from satellite data for semi-arid areas such as Southern Africa. If the other components of the energy budget can be assessed then the evaporation can be determined as the residual term. Since our current knowledge and methods of estimation of evaporation in these semi-arid regions is very poor, these satellite based estimates will be a great improvement in our understanding and modelling of the hydrological cycle of these regions.

Acknowledgements

The measurements from the SEBEX project and their interpretation could not have been made except for the major contributions from John Gash, Jim Wallace, Simon Allen, Ken Blyth, Cathy Holwill, Colin Lloyd and Ivan Wright of the Institute of Hydrology and M V K Sivakumar of the ICRISAT Sahelian Center.

The efforts of Jim Shuttleworth, Ken Blyth, Colin Lloyd, Cathy Holwill, David McNeil and Mike Stroud in collecting the FIFE data is gratefully acknowledged.

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Appendix 1

Analysis of data from Fallow/Savannah and Tiger Bush sites in Niger

1. Introduction

Previous studies (Choudhury *et al.*, 1986; Kustas *et al.*, 1987; Stewart *et al.*, 1989) have shown that measurements of the difference between radiometric surface temperature and air temperature systematically over-estimate the sensible heat flux when the classical aerodynamic resistance is used. In this analysis an empirical excess resistance is determined for each hour and then averaged for each site, using data collected under the ODA funded Sahelian Energy Budget Experiment (SEBEX) with additional measurements of the radiometric surface temperature.

2. Site characteristics

As part of SEBEX measurements were made over two of major vegetation types in this region of Niger in West Africa - savannah which had regenerated after an area used for growing millet had been left fallow for 7 years and natural open forest, known locally as Tiger Bush. Table 1 gives the location, vegetation classification and average annual precipitation for both sites. Table 2 gives the proportions of the surface cover and their aerodynamic characteristics. Values of z_{om} and d_o had been derived from eddy correlation measurements of the friction velocity, u_* (Lloyd *et al.*, 1992). At the fallow/savannah site the grasses were up to 0.3 tall and the shrubs up to 2.5 m tall. At the Tiger Bush site the trees were 3 to 5 m tall.

3. Measurements

In the SEBEX project the surface temperature was measured by infra-red thermometers (model 4000) manufactured by Everest Interscience Inc. They had a field of view of 15°. To obtain an areal average the measurements were replicated. The number used and the height of the mountings is given in Table 2. The sensors were positioned so that they sampled the various components of the land cover. The individual measurements were weighted by the average proportion of the vegetation over the area. The air temperature was measured by an automatic weather station manufactured by Campbell Scientific Inc. and the data integrated over an hour. The hourly measurements of the sensible heat flux were made by the Institute of Hydrology Mk2 Hydra, an eddy correlation system using a vertical sonic anemometer and fine wire thermocouple (Shuttleworth *et al.*, 1988).

4. Methodology

The turbulent transfer of sensible heat from a surface can be parameterized by a resistance type formulation using the difference between the radiometric surface temperature T_S^R and air temperature T_a, typically measured several meters above the surface:

$$H = \rho c_p \left(T_S^R - T_a\right) / r_h \tag{1}$$

Where r_h is the resistance to heat transfer from a surface at T_S^R, ρ is the density and c_p is the specific heat of air at constant pressure. This is analogous to the equation involving the aerodynamic surface temperature, T_S^A, which replaces T_S^R in (1) and the resistance is defined by the classical aerodynamic resistance to heat transfer, r_{ah},

$$r_{ah} = \left\{ \ln\left[\frac{z_r - d_o}{z_{om}}\right] + \ln\left[\frac{z_{om}}{z_{oh}}\right] - \Psi_h\left[\frac{z_r - d_o}{L}\right] \right\} / k u_* \tag{2}$$

where u_* is the friction velocity defined by

$$u_* = ku \Big/ \left\{ ln\left[\frac{z_r - d_o}{z_{om}}\right] - \Psi_m\left[\frac{z_r - d_o}{L}\right] \right\} \tag{3}$$

The symbol d_o is the displacement height, z_{om} is the momentum roughness length, z_{oh} is the roughness length for heat, z_r is the level above the surface where windspeed, u, and T_a are measured, k is von Karman's constant (~0.4) and Ψ_h and Ψ_m are stability correction functions for heat and momentum, respectively, as a function of L, the Monin-Obukhov length. See Brutsaert (1982) for details concerning the stability correction functions of wind speed and temperature in the surface layer. Mathematically, r_{ah} is the resistance from a height $z_{oh} + d_o$ having an aerodynamic temperature T_S^A, to the height z_r in the lower atmosphere.

Under unstable conditions the value of T_S^R is frequently higher than T_S^A, and as a result, this requires that $r_h > r_{ah}$. This can be represented algebraically by adding an excess resistance to r_{ah}, namely,

$$r_h = r_{ah} + r_r \qquad (4)$$

where r_r is the excess resistance required in order to satisfy equation (1) given an estimate of r_{ah} computed from equations (2) and (3). Since the roughness length for momentum has been related to mean obstacle height and density (Brutsaert, 1982), it can be estimated from land use information. However, the roughness length for heat over different surfaces is not well known. Therefore, the term involving z_{oh} in eqn (2) is often neglected when r_{ah} is calculated. When this is done, the excess resistance r_r in eqn (4) also includes differences between z_{om} and z_{oh}.

Previous work has shown that momentum and heat transfer from vegetation and rigid obstacles are significantly different and has been quantified by the quantity B^{-1} ($=k^{-1}\ln(z_{om}/z_{oh})$) proposed by Owen and Thompson (1963) and Chamberlain (1966). It can be shown (e.g., Verma, 1989) that B^{-1} is related to r_r by the following relationship:

$$r_r = B^{-1}/u_* \qquad (5)$$

The value more often reported in the literature is kB^{-1} (Brutsaert, 1982), which is the $\ln(z_{om}/z_{oh})$ term in (2), and is the quantity calculated here from each set of hourly measurements used in equation (1) for both sites.

The wind speed and air temperature data were extrapolated to z_r = 10 meters for both sites using the Businger-Dyer surface-layer stability correction formulations for unstable conditions (Brutsaert, 1982). This was performed in order to have consistency in the calculation of resistances among the sites. The height z_r = 10 m is the measurement height for wind speed recommended by the World Meteorological Organization.

5. Results

Values of kB^{-1} were derived from eqn (1), (2) and (3) using measurements of H, T_S^R, and u. For both sites the average and standard deviation of kB^{-1} derived from all the hours of measurements is presented in Table 4 with the number of hours used. There is a considerable difference in the values of kB^{-1}; however, the values of the total resistance r_h (the sum of the aerodynamic and excess resistances) are similar. Note that the "excess resistance", r_r is typically larger than r_{ah}.

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Table 1 Location, dominant vegetation type and mean annual precipitation for both sites

Location	Latitude	Longitude	Altitude (m)	Vegetation	Precipitation (mm)
Niger	13°15'N	2°18'E	240	Savannah	564
Niger	13°12'N	2°15'E	260	Open forest	564

Table 2 Proportions of the components of the surface cover and the aerodynamic characteristics - roughness length, z_{om}, zero plane displacement, d_o - for both sites

Site	Surface cover (%)			Aerodynamic characteristics (m)	
	Bare Soil	Grass Forbes	Shrubs Trees	z_{om}	d_o
Savannah	3	78	19	0.17	0.93
Open forest	67		33	0.4	2.0

Table 3 Number of infrared thermometers and height of sensible heat flux, wind speed, surface and air temperature sensors

Project/Site	Period	Surface temperature (Number) Height (m)		Height (m) of		
		Grass/soil	Shrubs	Wind speed	Air temperature	Sensible heat flux
Fallow/Savannah	7/10/89-4/12/89	(3) 3.5	(3) 3.5	10.3	10.3	12.3
	11/5/90-7/6/90	(2) 6.0	(4) 3.5	10.3	10.3	12.3
Natural open forest	7/10/89-30/9/90	(3) 3.5	(3) 9.5	12.1	12.1	15.9

Table 4 *The average (avg) and standard deviation (std) of the quantity kB^{1} and the average resistances computed by Eqs. (1), (2) and (5) derived from the measurements of the sensible heat flux, radiometric surface - air temperature difference and wind speed for both sites*

Surface	**No of hours of observation**	**kB^{-1} (avg)**	**kB^{-1} (std)**	**r_{ah}**	**r_r**	**r_h**
Savannah	507	5.8	2.9	17	38	55
Open forest	1142	8.3	3.3	12	48	60
Average		7.1				

Appendix 2

Analysis of data from 6 semi-arid rangeland sites

1. Introduction

To investigate the generality of the empirical excess resistance determined for the two sites in Niger, collaboration was set up with other groups who had access to data for similar semi-arid areas in other countries. As a result K S Humes, W P Kustas, M S Moran and W D Nichols in USA and H A R de Bruin in the Netherlands analysed their data in the same way as had been done with the Niger data to determine an empirical excess resistance for each of their sites.

The excess resistances for the individual sites were averaged and then used to estimate the mean sensible heat flux for each site to compare with the mean measured sensible heat flux.

2. Site characteristics

During the last few years a number of multi-disciplinary projects have taken place. Their general aim has been to quantify and understand the fluxes from areas of sparse natural vegetation. Additionally these projects collected data to enable development and validation of remote sensing algorithms. The data from six of these projects is used in this analysis. The projects were La Crau, Monsoon 90, Owens Valley, Smith Creek Valley and Smoke Creek Desert. During some of these projects, measurements were made over more than one type of vegetation. Table 1 gives the location, vegetation classification and the average annual precipitation for each of the sites. Details of the sites are given by Kohsiek *et al.*, (1993), Kustas *et al.*, (1991), Kustas *et al.*, (1989), Nichols (1992), respectively.

Table 2 gives the proportions of the surface cover and the aerodynamic characteristics for each site. Values of z_{om} and d_o for each site had been derived from eddy correlation measurements of u_* (Kohsiek *et al.*, 1993), or estimated from empirical formulas that use canopy height and density (Kustas *et. al.*, 1989; Nichols, 1992), or determined by applying surface similarity theory to vertical velocity fluctuations (Kustas *et al.*, 1994). At these sites typically the height of the grass was 0.1 to 0.3 m tall, and shrubs being 0.5 to 2.5 m tall.

3. Measurements

In the Monsoon 90 project carried out in the Walnut Gulch catchment, the sensible heat flux was estimated using both eddy correlation and temperature variance techniques. The variance technique is described in Wesely (1988) while the eddy correlation methods used at these sites are described in Blanford and Stannard (1991) and Stannard *et al* (1994). Comparison of sensible heat fluxes by the eddy correlation and variance technique were satisfactory (Kustas *et al.*, 1991; Kustas *et al.*, 1994). Since the variance data allowed for a nearly continuous set of local sensible heat flux estimates at both sites, these fluxes were used in the current study. Measurements of wind speed and direction and air temperature were made by an RM Young Wind Sentry (model 3001-5) and Campbell Scientific Inc. fine-wire chromel constantan thermocouple. Twenty minute averages were recorded. For more details about the field sites and measurements, see Kustas *et al.*, (1991) and Kustas and Goodrich, (1994).

Continuous thermal-infrared observations were made at the two Walnut Gulch sites using Everest Interscience Inc (model 110) infrared thermometers having a 3° field of view. One sensor viewed the soil surface while the other viewed the vegetation. Sensors were positioned 2 m above the soil surface at the Lucky Hills site and 1 m above the soil surface at the Kendall site. Periodically ground-based transects with a nadir viewing thermal-IR sensor mounted on a yoke apparatus were collected near the flux stations. The composite surface temperature from these ground-based transects were in close agreement with low altitude aircraft observations having a much larger sensor footprint (Moran *et al.*, 1991). Therefore reliable estimates of the composite surface temperature with the continuous thermal-infrared observations was obtained by a least squares regression. The one sensor viewing the soil and the other viewing the vegetation were the independent variables and the composite temperatures from the yoke transects was the dependent variable. For the Lucky Hills and Kendall site the root mean square error between predicted and actual composite temperature was about 0.9°C and 1.1°C, respectively.

In Owens Valley, measurements of the surface energy balance were made by the Bowen ratio energy balance approach and eddy correlation method. For a description of the Bowen ratio systems see Gay (1988) and Stannard (1985) and for the eddy correlation systems see Tanner *et al.*, (1985). In general, the agreement between the two techniques was satisfactory (Weaver, 1992). Estimates of the surface energy balance components were adopted for the analysis from Kustas *et al.*, (1989). Wind speed and air temperature were measured by a portable meteorological station nearby the flux sites. Wind speed was measured by a RM Young 3-cup anemometer (model 12002) and air temperature was measured with a shielded and aspirated copper constantan thermocouple manufactured by the USDA-ARS, US Water Conservation Laboratory.

Remote sensing data were collected over Owens Valley using an Exotech four-band radiometer and an Everest Interscience (model 110) infrared thermometer mounted on an aircraft platform. Observations were made for several clear days in the late morning and early afternoon. The aircraft flew at an altitude of 150 m above ground level. The nadir looking instrument had a nominal 15° field of view, which resulted in a 40 m diameter footprint at the surface. For further details concerning the micrometeorological and remote sensing measurements see Kustas *et al.*, (1989) and Wilson *et al.*, (1992).

Sensible heat fluxes at Smith Creek Valley and Smoke Creek desert were evaluated with the

Bowen ratio-energy balance approach. Gradients of temperature and vapour pressure above the canopy were determined by measurements at two heights of air and dewpoint temperatures. The air temperatures were measured using fine wire thermocouples and dew point temperatures were measured with a single cooled mirror hygrometer. The Bowen ratio system was designed and manufactured by Campbell Scientific Inc. (Tanner *et al.*, 1987).

Continuous thermal infrared observations of bare soil temperatures were made at both sites using an Everest Interscience (model 4000) infrared thermometer with a 15° field of view mounted approximately 2 m above the soil surface. Canopy temperatures were measured with an Everest Interscience (model 110) with a 3° field of view mounted 2 m above the soil surface. Wind speeds were measured with R. M. young photo-chopper anemometers with a threshold of 0.2 m^{-1}. For more details concerning the micrometeorological and remote sensing measurements see Nichols (1992).

Measurements for the La Crau experiment were made in June 1987 in a region called 'La Crau' (S. France), a dry flat area of about 150 km^2 covered with pebbles and stones up to 15 cm high and a very sparse vegetation cover of grasses and herbs. Apart from synoptic observations (wind, temperature, humidity, pressure, precipitation and radiation), profile measurements (wind, temperature and humidity) the vertical fluxes of sensible heat, momentum and water vapour were measured with the eddy correlation method (3-D sonic anemometer, fast response thermometer and hygrometer). Also, surface temperature measurements were made with an Hermann KT24 infrared thermometer, which was looking South with an angle of 45°. To adjust for this view angle a correction has been applied of 0.001 times the incoming solar radiation (in W m^{-2}). For more detailed information on the site and measurements see Kohsiek *et al.*, (1993).

All the infrared thermometers operated in the 8 to 14 μm band. Since the surface emissivity of most of the sites was not determined and reliable estimates of the atmospheric longwave radiation were not available, the radiometric surface temperatures were derived from the infrared thermometer measurements assuming an emissivity of unity.

4. Methodology

The turbulent transfer of sensible heat from a surface can be parameterized by a resistance type formulation using the difference between the radiometric surface temperature T_S^R and air temperature T_a, typically measured several meters above the surface:

$$H = \rho c_p \left(T_S^R - T_a\right)/r_h \qquad (1)$$

Where r_h is the resistance to heat transfer from a surface at T_S^R, ρ is the density and c_p is the specific heat of air at constant pressure. This is analogous to the equation involving the aerodynamic surface temperature, T_S^A, which replaces T_S^R in (1) and the resistance is defined by the classical aerodynamic resistance to heat transfer, r_{ah},

$$r_{ah} = \left\{ \ln \left[\frac{z_r - d_o}{z_{om}} \right] + \ln \left[\frac{z_{om}}{z_{oh}} \right] - \Psi_h \left[\frac{z_r - d_o}{L} \right] \right\} / k u_* \qquad (2)$$

where u_* is the friction velocity defined by

$$u_* = ku \Big/ \left\{ ln \left[\frac{z_r - d_o}{z_{om}} \right] - \Psi_m \left[\frac{z_r - d_o}{L} \right] \right\} \qquad (3)$$

The symbol d_o is the displacement height, z_{om} is the momentum roughness length, z_{oh} is the roughness length for heat, z_r is the level above the surface where windspeed, u, and T_a are measured, k is von Karman's constant (~ 0.4) and Ψ_h and Ψ_m are stability correction functions for heat and momentum, respectively, as a function of L, the Monin-Obukhov length. See Brutsaert (1982) for details concerning the stability correction functions of wind speed and temperature in the surface layer. Mathematically, r_{ah} is the resistance from a height $z_{oh} + d_o$ having an aerodynamic temperature T_S^A, to the height z_r in the lower atmosphere.

Under unstable conditions the value of T_S^R is frequently higher than T_S^A, and as a result, this requires that $r_h > r_{ah}$. This can be represented algebraically by adding an excess resistance to r_{ah}, namely,

$$r_h = r_{ah} + r_r \qquad (4)$$

where r_r is the excess resistance required in order to satisfy equation (1) given an estimate of r_{ah} computed from equations (2) and (3). Since the roughness length for momentum has been related to mean obstacle height and density (Brutsaert, 1982), it can be estimated from land use information. However, the roughness length for heat over different surfaces is not well known. Therefore, the term involving z_{oh} in eqn (2) is often neglected when r_{ah} is calculated. When this is done, the excess resistance r_r is eqn (4) also includes differences between z_{om} and z_{oh}.

Previous work has shown that momentum and heat transfer from vegetation and rigid obstacles are significantly different and has been quantified by the quantity B^{-1} ($= k^{-1}\ln(z_{om}/z_{oh})$) proposed by Owen and Thompson (1963) and Chamberlain (1966). It can be shown (e.g., Verma, 1989) that B^{-1} is related to r_r by the following relationship:

$$r_r = B^{-1} / u_* \qquad (5)$$

The value more often reported in the literature is kB^{-1} (Brutsaert, 1982), which is the $\ln(z_{om}/z_{oh})$ term in (2), and is the quantity calculated here from each set of hourly measurements used in equation (1) for the 6 sites.

The wind speed and air temperature data were extrapolated to z_r = 10 meters for all sites using the Businger-Dyer surface-layer stability correction formulations for unstable conditions (Brutsaert, 1982). This was performed in order to have consistency in the calculation of resistances among the sites. The height z_r = 10 m is the measurement height for wind speed recommended by the World Meteorological Organization.

5. Results

Values of kB^{-1} were derived from eqn (1), (2) and (3) using measurements of H, T_S^R, and u. For each site the average and standard deviation of kB^{-1} derived from all the hours of measurements is presented in Table 4 with the number of hours used. For most sites, the standard deviation is relatively high with the coefficient of variation being greater than or equal to 0.5. There is a range in kB^{-1} for the different sites of over three to one; however, the range in the total resistance r_b (the sum of the aerodynamic and excess resistances) is considerably smaller. In addition the "excess resistance", r_r is typically larger than r_{ab}.

Averaging the mean values of kB^{-1} for the six sites gives a value of 7.1 which is identical to the value for the two sites in Niger. It must be stressed that this degree of agreement must be fortuitous, bearing in mind the variability of the values for the individual sites.

As a preliminary assessment of the improvement due to using an excess resistance, sensible heat fluxes for the individual sites were determined from measurements of T_S^R using a value of kB^{-1} derived by averaging all the values of kB^{-1}, yielding a value of 7. For comparison, the sensible heat fluxes were also determined without the use of an excess resistance that is $kB^{-1}=0$. Table 5 lists the estimate of the sensible heat flux, averaged over all hours, using the average kB^{-1} for all sites ($\overline{H}_e$) and using no excess resistance ($\overline{H}_o$) compared to the average measured value ($\overline{H}_m$) for each site. The Table also gives the differences between the estimated and measured fluxes. It is immediately obvious that the omission of an excess resistance results in gross over-estimates of the sensible heat fluxes for these semi-arid sites. In contrast, the use of an average value of kB^{-1} to calculate the excess resistance significantly reduced the differences in the average sensible heat flux measured and modelled. The percentage difference between $\overline{H}_e$ and $\overline{H}_m$ varied between 10% and 40% with an average for all the sites of about 20%.

6. Concluding remarks

The present analysis has confirmed that the data from these sites show large differences between radiometric and aerodynamic surface temperatures. Therefore the use of standard aerodynamic formula to determine sensible heat fluxes from radiometric surface - air temperature differences results in large overestimates of the fluxes. On the other hand, this preliminary study supports the use of a resistance type formulation for the estimation of sensible heat flux over semi-arid areas as long as one accounts for the significant "excess" resistance term.

In future analyses, practical methods for determining the appropriate magnitude of kB^{-1} or r_r will be explored. This will involve developing techniques that make use of meteorological and remotely-sensed data that are readily available on a regional scale. For example, global maps of vegetation index are available from NOAA-AVHRR data (Ohring *et al.*, 1989). Vegetation indices have been related to vegetation cover (Ormsby *et al.*, 1987), and surface temperature (Price, 1990). These relationships may provide operational methods for estimating regional values of kB^{-1}.

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Table 1 Location, dominant vegetation type and mean annual precipitation for the 6 sites

Project	Location	Latitude	Longitude	Altitude (m)	Vegetation	Precipitation (mm)
Monsoon '90	USA Arizona	33°44'N	110°3'W	1526	Grass	241
Monsoon '90	USA Arizona	33°45'N	109°56'W	1371	Shrubs	241
Owens Valley	USA California	37°15'N	118°15'W	1220	Shrubs	125
Smith Creek Valley	USA Nevada	39°19'N	117°30'W	1850	Shrubs	250
Smoke Creek Desert	USA Nevada	40°32'N	119°49'W	1192	Shrubs	155
La Crau	France	43°34'N	4°51'E	13	Stones/Grass	350

Table 2 Proportions of the components of the surface cover and the aerodynamic characteristics - roughness length, z_{om}, zero plane displacement, d_o - for the 6 sites

Project	Surface	Surface cover (%)			Aerodynamic characteristics (m)	
		Bare Soil	Grass Forbes	Shrubs Trees	z_{om}	d_o
Monsoon '90	Grass	60	36	4	0.01	0.3
Monsoon '90	Shrubs	74		26	0.04	0.5
Owens Valley	Shrubs	70		30	0.1	0.7
Smith Creek Valley	Shrubs	75	2	23	0.06	0.375
Smoke Creek Desert	Shrubs	70		30	0.04	0.25
La Crau	Grass	95	5		0.013	

Table 3 Number of infrared thermometers and height of sensible heat flux, wind speed, surface and air temperature sensors.

Project/Site	Period	Surface temperature (Number) Height (m)		Height (m) of		
		Grass/soil	Shrubs	Wind speed	Air temperature	Sensible heat flux
Monsoon '90 Shrub	28/7/90-10/8/90	(1) 2	(1) 2	4.3	4.0	4.0
Monsoon '90 Grass	28/7/90-10/8/90	(1) 1	(1) 1	4.3	4.0	4.0
Owens Valley	2/6/86-5/6/86	(1) 150*	(1) 150*	2.0	2.0	2.0
Smith Creek Valley	23/7/89-3/8/89	(1) 2	(1) 2	2.25	2.25	1.75

* Composite temperature obtained from an aircraft platform (see text)

Table 4 The average (avg) and standard deviation (std) of the quantity kB^{1} and the average resistances computed by Eqs. (1), (2) and (5) derived from the measurements of the sensible heat flux, radiometric surface - air temperature difference and wind speed for each site

Project	Surface	No of hours of observation	kB^{-1} (avg)	kB^{-1} (std)	r_{ah}	r_r	r_b
Monsoon '90	Grass	95	3.8	2.8	44	31	75
Monsoon '90	Shrubs	98	5.6	2.8	30	38	68
Owens Valley	Shrubs	22	8.0	3.8	22	55	77
Smith Creek Valley	Shrubs	69	12.4	5.9	24	73	97
Smoke Creek Desert	Shrubs	79	8.4	4.9	31	69	100
La Crau	Grass	40	4.5	2.1	31	22	53
Average			7.1				

Table 5 Mean sensible heat flux of all observations at each site estimated without an excess resistance ($\bar{H}_o$), estimated using the average value of kB^{-1} to compute the excess resistance ($\bar{H}_e$), measured ($\bar{H}_m$) and differences between estimated and measured values.

Project/site	$\bar{H}_m$ (W m^{-2})	$\bar{H}_o$ (W m^{-2})	**Difference** (W m^{-2})	$\bar{H}_e$ (W m^{-2})	**Difference** (W m^{-2})
Monsoon '90 Shrub	147	474	327	128	-19
Monsoon '90 Grass	139	291	152	103	-36
Owens Valley Shrub	239	1966	1727	264	25
Smith Creek Valley Shrub	146	960	814	203	57
Smoke Creek Desert Shrub	203	1214	1011	225	22
La Crau Stones/grass	211	426	215	153	-58

Appendix 3

Analysis of data for sparse prairie grass in Kansas, USA

1. Introduction

To assess the success of the average excess resistance determined from the analysis of 8 semi-arid rangeland sites, it was used with an independent data set for sparse grass prairie in Kansas, USA. Besides estimating the sensible heat flux from the difference between the radiometric surface temperature and the air temperature, the sensible heat flux was used with measurements of the energy budget to determine the latent heat flux (the total evaporation). This data set was obtained as part of the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment which was carried out in 1987 and 1989 under the management of NASA.

2. Theory

The relationship between sensible heat flux, H and the aerodynamic surface temperature, T_s^A is given by:

$$H = \rho c_p \frac{(T_s^A - T)}{r_{ah}} \qquad (1)$$

where ρ and c_p are the density and specific heat of air
T is the air temperature at the reference height, z_r
r_{ah} is the aerodynamic resistance to the transfer of heat from the surface to z_r given by:

$$r_{ah} = \left\{ \ln\left[\frac{z_r - d_o}{z_{om}}\right] + \ln\frac{z_{om}}{z_{oh}} - \psi_h + \psi_m \right\} \Big/ ku. \qquad (2)$$

where d_o is the displacement height
z_{om}, z_{oh} are the roughness lengths for momentum and heat respectively

ψ_h, ψ_m are the stability corrections for heat and momentum, respectively, which are functions of the Monin-Obukhov stability length, L
k is von Karman constant (=0.4)
u_* is the friction velocity
T_S^A is the aerodynamic surface temperature defined by equation (1).

An analogous relationship between sensible heat flux and radiometric surface temperature can be proposed:

$$H = \rho c_p \frac{(T_S^R - T)}{r_h} \tag{3}$$

where r_h is an aerodynamic resistance which is defined by equation (3).

Previous studies have shown that r_h is equal to or larger than r_{ah} and Stewart *et al.* (1993) proposed that:

$$r_h = r_{ah} + r_r \tag{4}$$

$$r_r = B^{-1}/u_* \tag{5}$$

where r_r is an excess resistance, which Stewart *et al.* (1993) determined empirically using equations (3) ad (4).
B^{-1} is the quantity proposed by Owen and Thomson (1963) and Chamberlain (1966).

Under neutral stability conditions z_{om} can be derived from measurements of u_* ie.

$$z_{om} = (z_r - d_o)/e^{kK} \tag{6}$$

where K is the slope of the linear regression of u against u_* passing through the origin.
r_r also accounts for the second term on the right hand side of equation (2) involving z_{oh}

The latent heat flux, λE, can be obtained from measurements of the sensible heat flux and the available energy, A given by

$$A = H + \lambda E = R_n - G \tag{7}$$

where R_n is the net all-wave radiation
G is the soil heat flux

Then $\lambda E = A - H$ (8)

3. Site and data

The site of the measurements (designated 26(8739-ECB) in 1987 and 926(8739-ECB) in 1989) was situated on a plateau within a commercial farm (lat. 38°59'N, long. 96°33'W, alt. 440 m). There was a uniform fetch of 200 to 500 m depending on the wind direction. The vegetation, dominated by a mixture of C_3 grasses and forbes, was heavily grazed resulting in a low leaf area index (LAI) - between mid May and mid October 1987 LAI averaged 0.5, of which about 55% was forbes - and up to 25% bare soil.

The turbulent surface fluxes were measured using the eddy correlation technique. The system designed and built at the Institute of Hydrology is known as Hydra and has been described by Shuttleworth *et al.* (1988). The Hydra is mounted at 2.5 m and uses a one dimensional sonic anemometer to measure the fluctuations in the vertical component of the wind speed, an infrared hygrometer for the humidity fluctuations and thermocouple for the temperature fluctuations. A light weight fast response cup anemometer measures the scalar wind speed, from which the friction velocity is derived. The fluxes were calculated over hourly periods. The radiometric surface temperature was measured by 8 Everest Interscience model 4000 infrared thermometers (IRT). Each IRT was mounted on a tripod at a height of 3.5 m so that the 15° field of view of the instrument sees an area of 0.7 m^2. The individual areas were distributed randomly up to 12 m apart and about 40 m from the Hydra. After checking the output from the IRTs the surface temperature was calculated by averaging the individual measurements from the serviceable instruments (6 to 8) assuming an emissivity of 1.0. Other meteorological data, temperature and humidity, were measured by an automatic weather stations (designated 21(8639) in 1987 and 921(8639) in 1989) mounted 20 m from the Hydra.

4. Analysis and results

In 1987 there were 4 Intensive Field Campaigns (IFC) and one in 1989. For each IFC the zero plane displacement, d_o was calculated as 64% of the vegetation height, h_v. For neutral stability conditions given by $-0.02 < (z_r - d_o)/L < 0.02$, the regression of wind speed, u, against the friction velocity, u_* was determined. The relationship was used in equation (6) to determine the roughness length z_{om}. Table 1 presents the values of z_{om}, h_v and surface cover for each IFC.

The average value of kB^{-1} of 7.0 obtained by Stewart *et al.* (1993) was used to calculate the excess resistance using equation (5), before calculating r_b for each hour during the day. The sensible heat flux was calculated for each hour when $L < -1.0$, $T_s^R - T > 2.0°C$ and $U > 1.0$ m s^{-1}. These restrictions were imposed to remove results which were effected by instrumental or other errors.

The latent heat flux was determined using equation (8) with the available energy obtained by summing the measured sensible and latent heat fluxes.

For each IFC, Table 2 presents the values of the three components that make up the total resistance r_h used in equation (3). For each period the excess resistance is the largest component, representing on average 62% of the total resistance. Figure 1 shows hourly values of sensible heat flux estimated by equation (1) ie. without using an excess resistance term. It can be seen that the sensible heat flux is greatly overestimated. Figure 2 shows the sensible heat flux estimated using equation (2) with the excess resistance derived from the 8 semi-arid rangeland sites. It can be seen that the relationship between estimated and measured sensible heat flux is not much below the 1:1 line, though there is considerable scatter for individual hours. Figure 3 shows the latent heat flux estimated using equation (8) with the sensible heat flux derived using the average value of kB^{-1}. It can be seen that the results are close to the 1:1 line and without much scatter. For each IFC, Table 3 presents the estimated and measured mean fluxes - the sensible heat flux was estimated neglecting the excess resistance as well as using the average value of kB^{-1} to estimate the excess resistance. For the combined data set the mean sensible heat flux derived using the classical formulation of the aerodynamic resistance overestimates measured mean sensible heat flux by 141 W m^{-2}. The introduction of the excess resistance term results in an underestimate of just 21 W m^{-2}. Table 3 also presents the difference between the estimated and measured mean sensible heat fluxes and the root mean square errors for the linear regressions forced through the origin of estimated against measured sensible and latent heat fluxes. Neglecting the excess resistance term in equation (3) besides causing a large bias in the mean estimate, also more than doubles the root mean square error ie. for the combined data set the root mean square error is 63 W m^{-2} compared to 26 W m^{-2} when the average value of kB^{-1} is used to estimate the excess resistance. Table 4 presents the linear regressions for the three cases.

5. Discussion

Hall *et al.* (1992) found that radiometric surface temperature measured by the helicopter mounted MMR overestimated the aerodynamic surface temperature calculated from the FIFE flux site measurements. These measurements of radiometric surface temperature when used in equation (1) led to large overestimates of the sensible heat flux. Hall *et al.* (1991) suggested that the overestimation of radiometric surface temperature could be reduced by making the measurements off-nadir. Vining and Blad (1992) made radiometric surface temperature measurements at 20°, 40° and 60° off nadir as well as at nadir and calculated the sensible heat flux using equation (1). They found that there was no single optimum view angle - it depended on the time of day and on the wind speed.

This paper demonstrates that the use of an excess resistance when estimating sensible heat flux from measurements of radiometric surface temperature greatly reduces the difference between estimated and measured average sensible heat fluxes. The excess resistance used here was derived from measurements made at 8 semi-arid rangeland sites with vegetation ranging in height from 0.5 to 5 m. The FIFE area cannot be considered as semi-arid rangeland so it is particularly encouraging that the excess resistance derived for these other sites worked so well.

The percentage bias in the estimates of latent heat flux were even smaller, since it is dominated by the available energy rather than by the sensible heat flux - for much of the IFCs in 1987 and 1989, there was a good supply of soil moisture for the prairie and the Bowen ratio was less than 0.5.

6. Concluding remarks

Use of an independently derived excess resistance, reduces the difference between the estimated and measured average sensible heat flux from 141 to −21 W m^{-2}. The current estimates used measured values of z_{om} and d_o to calculated the standard aerodynamic resistance which was corrected for stability effects. Future studies will investigate the sensitivity of the results to uncertainties in the values of z_{om} and d_o.

This method should enable useful estimates of the areal average fluxes to be derived from the aircraft measurements in the thermal infrared band over the FIFE area.

From their analysis of the FIFE data Hall *et al.* (1992) stated that as long as the classical formulation of the aerodynamic resistance (equations (1) and (2)) was used, there appeared to be no consistent way to use T_S^R as a reliable measure of T_S^A. The present analysis shows that the introduction of an excess resistance derived from a constant value of kB^{-1} can overcome most of the problem encountered previously in the use of T_S^R. To determine the range of conditions that this simple correction is applicable for, further experimental studies will be required.

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Table 1 The proportion of soil and grass, roughness length z_o and vegetation height h_v for 5 Intensive Field Campaigns (IFC)

Period	IFC	Proportions of soil (%)	Proportions of grass (%)	z_o (m)	h_v (m)
28/05-06/06/87	1	~25	~75	0.014	0.30
25/06-10/07/87	2	~20	~80	0.012	0.37
17/08-23/08/87	3	~25	~75	0.011	0.25
06/10-16/10/87	4	~30	~70	0.010	0.16
21/07-14/08/89	5	~25	~75	0.018	0.24

Table 2 The three components of resistance used in the formula to estimate sensible heat flux from radiometric surface temperature - the aerodynamic resistance for neutral conditions r_{am}, the stability correction r_{as} and the excess resistance r_b derived using $kB^{-1}=7.0$ for the five periods

Period	IFC	r_{am} (s m^{-1})	r_{as} (s m^{-1})	r_r (s m^{-1})
28/05-06/06/87	1	36.0	−3.9	49.3
25/06-10/07/87	2	40.6	−6.1	54.2
17/08-23/08/87	3	33.1	−3.4	43.2
06/10-16/10/87	4	39.1	−5.1	50.0
21/07-14/08/89	5	38.6	−5.8	55.46
28/05-14/08/89	all	38.3	−5.4	53.0

Table 3 Estimated and measured sensible heat fluxes (H_e and H_m), root mean square error (RMSE) and difference (δ) and estimated and measured latent heat fluxes (λE_e and λE_m) and root mean square error (RMSE) for each IFC

IFC	no of hours	H_m (W m^{-2})	H_e $kB^{-1}=0$ (W m^{-2})	RMSE (W m^{-2})	H_e $kB^{-1}=7.0$ (W m^{-2})	RMSE (W m^{-2})	λE_m (W m^{-2})	λE_e $kB^{-1}=7.0$ (W m^{-2})	RMSE (W m^{-2})
1	44	70	219	73	88	31	310	300	28
2	52	96	186	67	75	30	340	361	34
3	21	107	216	31	90	15	275	292	16
4	48	140	241	40	100	19	84	84	24
5	179	141	312	50	117	22	184	209	27
combined	344	124	265	63	103	26	210	231	34

Table 4 Regressions of estimated sensible and latent heat fluxes (H_e and λE_e) against measured fluxes for the combined data set of 344 hours between 28 May 1987 and 14 August 1989

	Intercept	Slope	R^2
H_e using $kB^{-1}=0$	0.8 ± 8.4	2.130 ± 0.062	77.5%
H_e using $kB^{-1}=0$ forced through origin		2.136 ± 0.025	77.5%
H_e using $kB^{-1}=7.0$	6.7 ± 3.4	0.776 ± 0.025	73.2%
H_e using $kB^{-1}=7.0$ forced through origin		0.821 ± 0.010	72.7%
λE_e using $kB^{-1}=7.0$	41.5 ± 2.8	0.903 ± 0.011	94.9%
λE_e using $kB^{-1}=7.0$ forced through origin		1.050 ± 0.007	91.5%

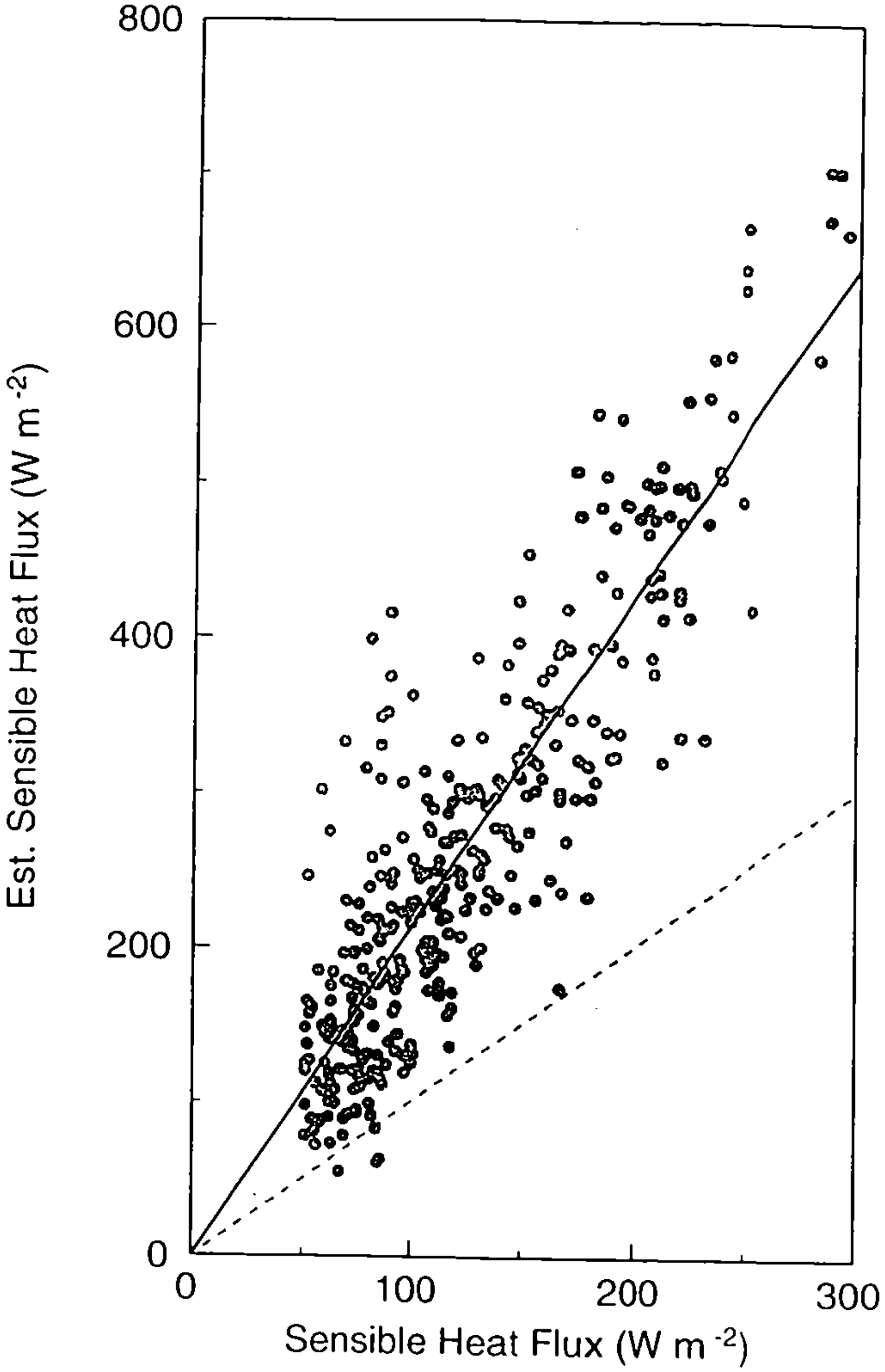

Figure 1 *Hourly sensible heat flux estimated using the standard formula with radiometric surface temperature plotted against measured sensible heat flux. Data for site 26 and 926 from 4 intensive field campaigns in 1987 and one in 1989. The full line represents the linear regression and the dashed line the 1:1 relationship.*

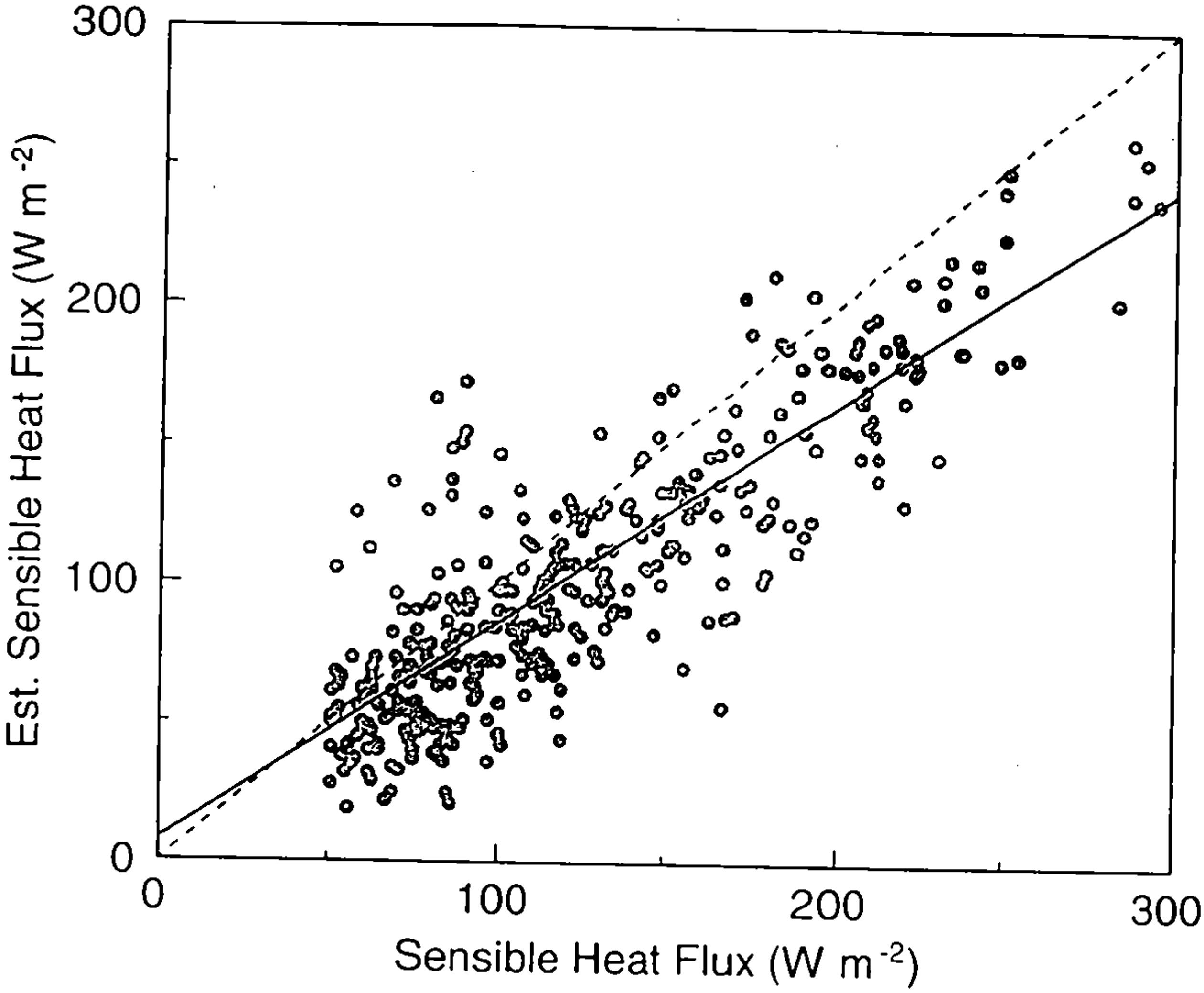

Figure 2 *Same data but hourly sensible heat flux estimated using a formula with an excess resistance derived from 8 independent semi-arid rangeland experiments. The full line represents the linear regression and the dashed line the 1:1 relationship.*

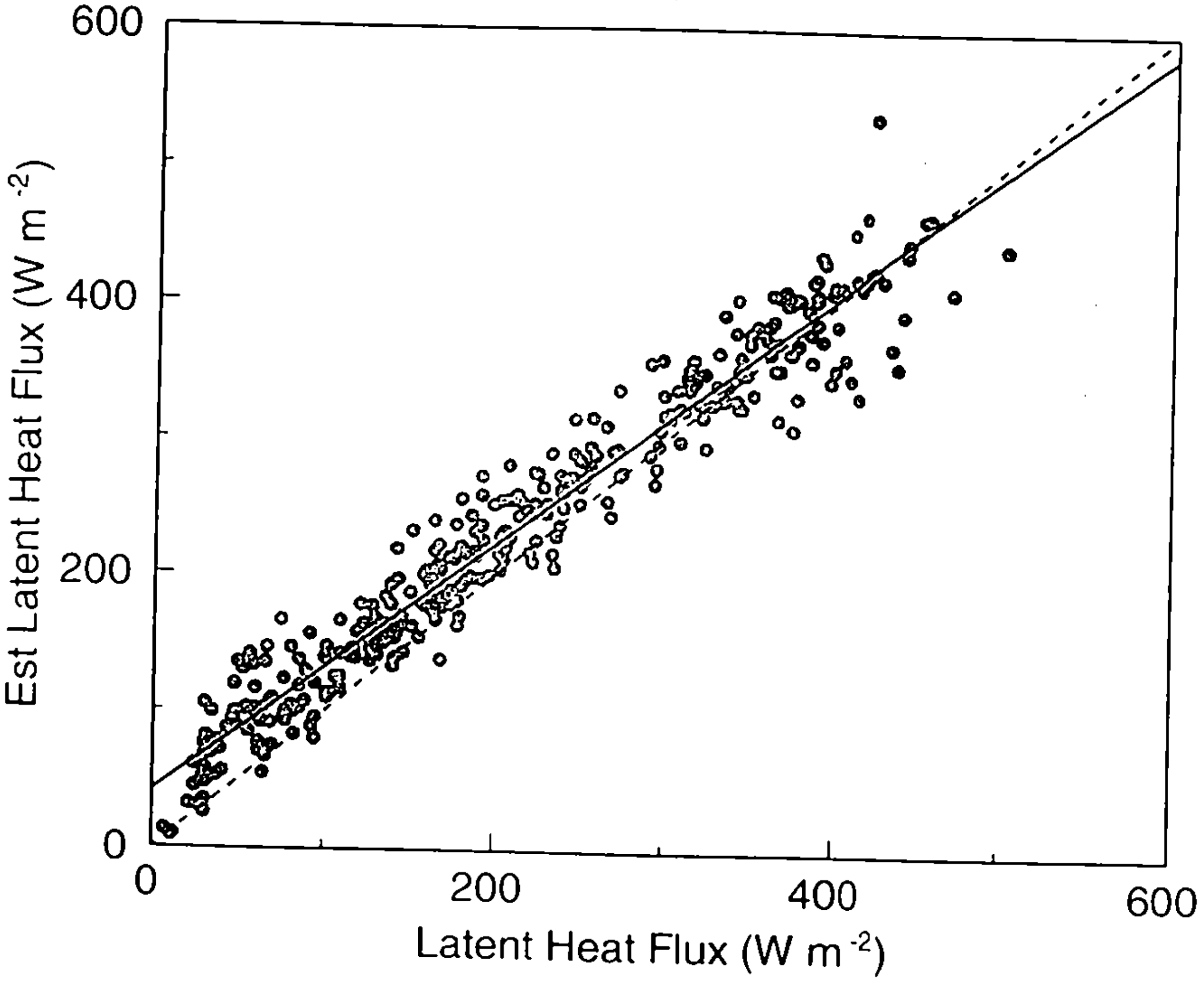

Figure 3 *Hourly latent heat flux plotted against measured latent heat flux. The latent heat flux estimated from the energy budget using an excess resistance to estimate the sensible heat flux for site 26 and 926 from 4 intensive field campaigns in 1987 and one in 1989. The full line represents the linear regression and the dashed line the 1:1 relationship.*