REGIONAL SURFACE FLUXES FROM SATELLITE-DERIVED SURFACE TEMPERATURES (AVHRR) AND RADIOSONDE PROFILES

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Abstract. Radiometric surface temperatures, derived from measurements by the AVHRR instrument aboard the NOAA-9 and the NOAA-11 polar orbiting satellites, were used in combination with wind velocity and temperature profiles measured by radiosondes, to calculate surface fluxes of sensible heat. The measurements were made during FIFE, the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment, in a hilly tall grass prairie area of northeastern Kansas. The method of calculation was based on turbulent similarity formulations for the atmospheric boundary layer. Good agreement ($r = 0.7$) was obtained with reference values of sensible heat flux, taken as arithmetic means of measurements with the Bowen ratio method at six ground stations. The values of evaporation (latent heat fluxes), derived from these sensible heat fluxes by means of the energy budget, were also in good agreement ($r = 0.94$) with the corresponding reference values from the ground stations.

1. Introduction

The use of land surface temperature, measured from satellite platforms, in conjunction with standard meteorological data for the estimation of surface transport phenomena, is not without difficulties. One problem results from the discrepancy in scales: standard meteorological variables are measured only a few meters above the ground, so that they represent local conditions over upwind distances of the order of a few 100 m at most; satellite observations with such systems as NOAA-AVHRR or GOES-VISSR are made over pixels with characteristic dimensions of the order of 1 to 10 km on a side. A second difficulty is that the difference between the surface temperature measured from the satellite and the standard air temperature measured near the ground is often so small that it becomes lost in the noise in these measurements; this is especially troublesome in applications related to turbulent heat transfer and the corresponding evaporation.

A possible way to avoid or alleviate these difficulties is to use satellite-derived data in conjunction with measurements higher up in the atmospheric boundary layer (ABL), rather than with the standard measurements near the ground. Indeed, it is known that profiles of wind speed, temperature, humidity, etc., in the ABL between, say 100 and 1000 m, reflect surface conditions over upwind distances or fetches of the order of 1 to 10 km. These are of the same order of magnitude as typical pixel scales, and hence more compatible. In addition, at least

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in the case of an ABL under unstable conditions, the difference between the radiometric surface temperature and the temperature of the air aloft is normally larger and thus less susceptible to error than if the air temperature is measured at 10 m.

This idea is tested in this paper. First, a brief review is given of two formulations to determine regional surface heat flux, which are based on similarity principles for the unstable ABL. These methods are then implemented with radiometric surface temperatures measured by satellite together with temperatures and wind speeds in the unstable ABL measured by radiosondes. Finally, the regional evaporation is determined from the surface heat flux by means of the surface energy budget. The study focuses on unstable conditions because the surface fluxes are then largest. The data were recorded during FIFE, the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment. The measuring system for radiometric surface temperature was the Advanced Very High Resolution Radiometer (AVHRR) of NOAA-9 and NOAA-11. The main objective of the study is to illustrate the suitability of the two methods with these types of data.

2. Flux Formulations

2.1. Surface-Layer Formulation

This first method to determine the sensible heat flux is based on the well-known Monin–Obukhov similarity theory. When the surface temperature is measured by infrared thermometry, the mean (in the turbulence sense) potential temperature profile $\theta(z)$ in the surface layer of the ABL can be written as

$$\theta = \theta_{s,r} - \frac{H}{k\, u_*\, \rho\, c_p}\left[\ln\left(\frac{z - d_0}{z_{oh,r}}\right) - \Psi_h\left(\frac{z - d_0}{L}\right)\right] \tag{1}$$

where $\theta_{s,r}$ is the radiometric potential temperature of the surface, H the sensible heat flux, $k(=0.4)$ von Karman's constant, u_* the friction velocity, ρ the density of the air, c_p the specific heat of the air at constant pressure, d_0 the displacement height, and $z_{oh,r}$ the radiometric scalar roughness; the friction velocity u_* can be deduced from the profile of the mean wind speed. The symbol $\Psi_h(\ )$ is an integral of the Monin–Obukhov function for temperature. It represents the effect of atmospheric stability on the temperature profile; in the present study, the Businger–Dyer formulation was used to represent this function. The variable L is the Obukhov length, defined by

$$L = -\frac{u_*^3}{k(g/T_a)(H_v/\rho c_p)} \tag{2}$$

in which g is the acceleration of gravity, T_a the air temperature near the ground in K, $H_v = (H + 0.61 T_a c_p E)$ the virtual sensible heat flux at the surface,

$E(=LE/L_e)$ the rate of evaporation, LE the latent heat flux and L_e the latent heat of vaporization. Further details on the application of (1) with radiometric surface temperatures $\theta_{s,r}$ have been presented by Sugita and Brutsaert (1990b). In an earlier study by Brutsaert and Sugita (1990), the height range of the validity of (1) was determined to be $45(\pm 31) \leqslant (z - d_0)/z_0 \leqslant 104(\pm 54)$, in which z_0 is the surface roughness.

2.2. ABL Bulk Formulation

The second method used in this study is the ABL bulk similarity approach. In this formulation, the sensible heat flux is determined by means of the following

$$H = ku_*\rho c_p(\theta_{s,r} - \theta_{am})/\left[\ln\left(\frac{h_i - d_0}{z_{oh,r}}\right) - C\left(\frac{h_i - d_0}{L}\right)\right] \quad (3)$$

where θ_{am} is the mean potential temperature averaged over the outer region or mixed layer of the unstable ABL and h_i is the height of the mixed layer, i.e., the height of the bottom of the overlying inversion. The symbol $C(\ )$ is the bulk similarity function for sensible heat. Further details on the application of (3) with radiometric surface temperatures and on the functional form of $C(\ )$ have been presented by Brutsaert and Sugita (1991). The functional form of $C[(h_i - d_0)/L]$ used herein is

$$C = 1.01 \ln[1 - (h_i - d_0)/L] + 1.90\,. \quad (4)$$

The mixed layer may be assumed to cover the range between the top of the surface layer, at $(z - d_0)/z_0 = 104$, and its upper boundary at $z = h_i$.

3. Data Base

3.1. Experiment

The data used in this study were recorded during FIFE in the summer and fall of 1987 and in the late summer of 1989. This experiment took place in a strongly dissected, tall grass prairie section of the Flint Hills in northeastern Kansas. General descriptions of the scope of FIFE have been published by Sellers *et al.* (1988) and Hall *et al.* (1989).

3.2. AVHRR Data

The radiometric surface temperature data were obtained by the thermal infrared channel 4 of the Advanced Very High Resolution Radiometer (AVHRR) of NOAA-9 in 1987 and NOAA-11 in 1989. These are satellites with nearly polar, sun-synchronous orbits which passed over the experimental site daily around 1430 local solar time (1600 CDST). The uncorrected temperature values were derived by means of the Planck function from average radiances over the 15 × 15 km FIFE experimental area; these averages had been obtained from the radiances of pixels of around 1 km by the FIFE Information System team, but they had been calculated only for days on which the FIFE site was still visible and not obscured by heavy cloudiness.

These temperature values were then corrected for atmospheric effects. Both the linearized profile method (Price, 1983) and the split-window technique (Price, 1984) were used. In an earlier comparison with ground truth surface temperatures by Sugita and Brutsaert (1991), it had been found that the latter procedure gave the best results; as seen below, this is confirmed herein, and therefore mainly the results obtained with the split-window technique (channel 4 corrected with channel 5) are presented.

The resulting surface temperature values $T_{s,r}$ were finally converted to potential temperature $\theta_{s,r}$ by reduction from the pressure at 395 m above sea level, which is the mean ground surface elevation of the area, down to 1000 hPa. The pressure at 395 m was deduced from the measurements at the radiosonde launch site at 340 m ASL, by assuming a constant decrease rate of 0.1 hPa/m (Sugita and Brutsaert, 1990b).

For the present study, the radiometric surface temperature data were selected on the basis of the following criteria. (i) They were measured at times for which radiosonde profiles were available within a few hours. (ii) The wind was from the general southerly direction, covering the range between east and southwest. (iii) The stratification of the atmosphere was unstable; thus H was positive and θ_s measured by the satellite was larger than θ in the surface sublayer, as measured by the radiosonde (see below). (iv) The low and middle cloudiness was less than 0.5. This selection process yielded 8 passages in 1987 and 3 in 1989. The dates and times of these satellite passages are listed in Table I together with the values of $\theta_{s,r}$ obtained after application of the split-window technique for atmospheric correction.

3.3. Radiosonde profiles

During FIFE in 1987 and 1989, some 450 radiosondes were released measuring the necessary variables to derive profiles of wind velocity, temperature and specific humidity. The launch point was situated close to the northern edge of the experimental area to ensure that the measured profiles reflect surface conditions over the region in the general direction of the prevailing southerly winds. The vertical resolution of these profiles was typically around 15 to 20 m. The radiosonde system and the data processing procedures have been described by Sugita and Brutsaert (1990a) and Brutsaert *et al.* (1990).

The times of the radiosonde flights did not coincide exactly with those of the satellite overpasses. Therefore, the θ-profiles needed for (1) and (3) were obtained by linear interpolation between the available radiosonde profile just prior to, and that just after the time of a satellite overflight.

For the surface-layer formulation, this was done as follows. Because it is not easy to interpolate between two noisy $\theta(z)$ curves, (1) was applied with a characteristic

TABLE I

Some data and results

Date	Time of satellite (CDST)	$\theta_{s,r}$ (K) (Corrected w/split Window)	Flight No. of nearest radiosoundings (time)	h_i (m)	θ_{am} (K)	u_* (m/s)	H (W/m^2)	LE (W/m^2)	Sky conditions
87/6/27	1610	313.0	88 (1457) 89 (1635)	1251	302.2	0.71	139	368	Clear
87/7/02	1657	311.0	112 (1635) 113 (1759)	1261	303.5	0.36	52	390	0.1 Ci
87/8/07	1530	316.7	189 (1506) 190 (1633)	1787	309.9	1.17	137	400	Clear
87/8/10	1639	317.5	211 (1636) 212 (1756)	1915	305.8	0.73	155	224	0.2 small Cu
87/8/11	1628	321.6	218 (1509) 219 (1704)	1993	309.1	0.42	101	335	0.2 small Cu
87/8/15	1545	315.6	239 (1505) 240 (1630)	785	310.0	1.05	101	426	Clear
87/8/17	1704	313.2	257 (1639) 258 (1751)	1643	307.0	0.69	76	316	Clear
87/10/14	1641	303.0	316 (1603) 317 (1708)	870	299.1	1.02	71	74	0.8 Ci plus 0.3 Cs
89/7/27	1510	315.8	375 (1432) 376 (1627)	1646	306.0	0.66	121	291	Cu 0.4
89/7/28	1500	318.1	381 (1430) 382 (1632)	1413	306.2	0.93	199	180	Cu 0.3–0.4
89/8/04	1528	318.0	408 (1427) 409 (1625)	759	310.9	0.75	95	324	Clear

temperature within the surface sublayer, which was taken as the arithmetic mean θ_{as}, at its elevation z_{as} or

$$H = ku_*\rho c_p(\theta_{s,r} - \theta_{as})/\left[\ln\left(\frac{z_{as} - d_0}{z_{oh,r}}\right) - \Psi_h\left(\frac{z_{as} - d_0}{L}\right)\right]. \qquad (1')$$

Thus, first the arithmetic mean was taken for each radiosonde profile over the surface sublayer range of the ABL; in the case of the FIFE experimental area (see Brutsaert and Sugita, 1990) this range is between 74 and 136 m above the ground. The value of θ_{as} was obtained by linear interpolation between these mean θ-values for the radiosonde profile just prior to and just after the time of the satellite overflight. As a first approximation, it was assumed that θ_{as} can be assigned a height of $z = z_{as} = 100$ m, which is the log mean of 74 and 136 m. In the light of (1), this assumption is not correct; however, in a sensitivity test, it was found that the exact choice of z_{as} (e.g., 95 or 105 m), to be assigned to θ_{as} does not materially affect the results.

For the ABL bulk formulation (3), the value of θ_{am} represents the average taken over the mixed layer, that is between $z = 136$ m and $z = h_i$. Again, the values of θ_{am} at the time of the satellite overflight were obtained by linear interpolation between those for the radiosonde flights just before and just after the passage of the satellite. These interpolated values of θ_{am} are listed in Table I.

The values of u_* needed in both (1') and (3) were obtained by the same kind of linear interpolation between u_*-values calculated from the two wind speed profiles in the surface sublayer measured by the two radiosoundings closest to each of the satellite overpass times. The method of calculation from unstable wind speed profiles measured during FIFE has been presented by Brutsaert and Sugita (1990). In brief, for a given profile, u_* was calculated by linear regression through the origin of V versus Y (over the range $74 \leqslant z \leqslant 136$ m), viz.,

$$V = \frac{u_*}{k} Y \tag{5}$$

where V is the wind speed at a height z above the ground and $Y = [\ln((z - d_0)/z_0) - \Psi_m((z - d_0)/L)]$; the symbol $\Psi_m(\ )$ is an integral of the Monin–Obukhov function for momentum which can be represented by the Businger–Dyer function; for the FIFE experimental area, the roughness length was taken to be $z_0 = 1.05$ m and the displacement height $d_0 = 26.9$ m (Sugita and Brutsaert, 1990a). For each wind speed profile, (5) was applied in an iterative manner as follows. An initial value $L = \infty$ is assumed, which permits a first estimate of u_*; this in turn, with the reference fluxes H_s and LE_s at the time of the sounding (see Section 3.4), produces a new value of L by means of (2), and so on; the process converges rapidly. The present procedure, which was adopted for simplicity, is not the only possible way; actually when no reference fluxes H_s and LE_s are available, u_*, H and LE must be obtained by simultaneous solution of (1') or (3), with (2), (5) and the energy budget (6); however, several test calculations showed that the results are essentially the same. The values of u_* interpolated to the overpass times of the satellite are listed in Table I.

The values of the height of the mixed layer h_i, needed in (3), were obtained from the h_i values of the radiosonde θ-profiles, by simple linear interpolation to the overpass times of the satellite. Around 1430 local time, h_i usually remained fairly constant. For each profile, the value of h_i was taken as the height z, where $d\theta/dz \geqslant 6.0$ K/km, which was then confirmed by visual inspection to avoid spurious values resulting from small oscillations in the profile. These h_i values are also listed in Table I.

In (1) and (3), the Obukhov length L is required. The values of L were calculated by means of (2), making use of the interpolated values of u_*, discussed above, and the interpolated values of H_v measured at the reference flux stations, discussed below.

3.4. Reference flux stations

The accuracy of the surface fluxes calculated by means of (1) and (3) is assessed by comparison with reference values. For 1987, these reference values, denoted by H_s and LE_s, were derived from arithmetic means of values measured over 30 min periods by means of the Bowen ratio method at six ground stations spread over the FIFE experimental area; the stations were operated by a team directed by L. J. Fritschen of the University of Washington (e.g., Brutsaert *et al.*, 1990; Sugita and Brutsaert, 1990b). The values of H_s and LE_s, used herein, were obtained by interpolation of these 30 min mean values to the time of the satellite overpass.

During FIFE-87, soil moisture conditions were relatively uniform over the experimental area; therefore, the means of the 6 stations could be considered as representative at the regional scale of the 15×15 km experimental area. In contrast during FIFE-89, soil moisture conditions were non-uniform, and it was not clear how the regional flux values could be derived from local measurements at an array of stations (see Brutsaert and Sugita, 1992). For the present study, the 1989 reference values were simply taken as the averages of the measurements at all 12 flux stations deployed over the experimental area, for which data were available. However, because it is unknown how representative these average values are, in what follows the 1989 data are treated separately from those measured in 1987.

4. Implementation and Results

4.1. Surface-layer formulation with 1987 data

The application of (1) to calculate H still requires a knowledge of the scalar roughness $z_{oh,r}$. For this parameter, several theoretical expressions are available that are applicable to special uniform surfaces (e.g., Brutsaert, 1982, pp. 122–124). However, as is the case with z_0 for momentum, for natural surfaces it is best determined by calibration with experimental data. This is all the more so, because the surface temperature is often ill-defined for an irregular surface; this temperature depends on the definition of the surface and on the method and scale of its measurement. In the present study $z_{oh,r}$ was determined by trial and error. Thus for a trial value of $z_{oh,r}$, H was calculated by means of (1′) for each of the 8 satellite overflights. The ratio of the mean fluxes, H_s/H, or the slope of the regression through the origin was then determined. The value of $z_{oh,r}$ was changed and adjusted until the slope was found equal to 1.0.

With the $\theta_{s,r}$ values obtained by means of the split-window atmospheric correction, the result of this process was $z_{oh,r} = 5.86 \times 10^{-10}$ m. The values of H, calculated by means of (1′) and this value of $z_{oh,r}$, are compared in Figure 1 with the reference values measured at the ground stations. The correlation coefficient is

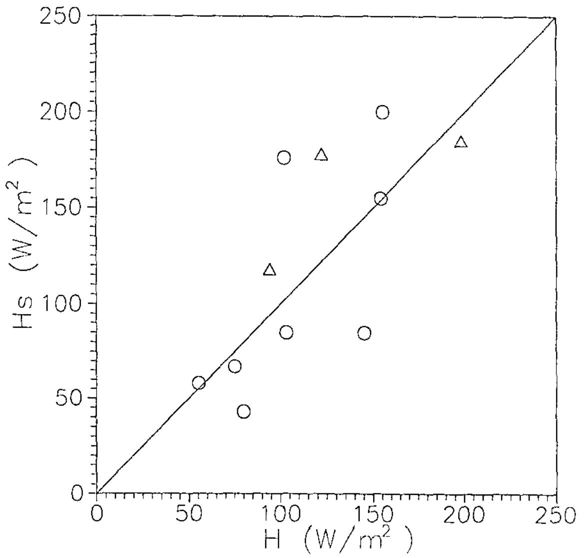

Fig. 1. Comparison between H values calculated with (1′) for the surface sublayer, and the mean reference values H_s measured independently at the ground stations. The correlation coefficient for the 1987 data (circles) is $r = 0.695$ and the ratio of the mean fluxes $H_s/H = 1.00$. The 1989 data are shown as triangles.

$r = 0.695$. The values of LE calculated from these H values by means of the energy budget

$$LE = R_n - G - H \tag{6}$$

(in which R_n is the net radiation and G the ground heat flux), are compared in Figure 2 with the LE_s values measured at the reference flux stations. The correlation is $r = 0.935$ and the ratio of the means $LE_s/LE = 1.00$.

The same procedure was also attempted with the $\theta_{s,r}$ values which were left uncorrected for the atmospheric effect, and with those corrected by means of the linearized profile method. In the case of AVHRR channel 4, only 6 uncorrected $\theta_{s,r}$ values could be used, because 2 of the 8 were lower than θ_{as}. (For channel 5, only 2 points were available, so they were not considered for analysis). For these 6 data points, the correlation between the resulting H values and the corresponding H_s became significantly smaller, namely $r = 0.46$. The reason for the deterioration is probably that the uncorrected $\theta_{s,r}$ were markedly smaller than the values corrected by the split-window technique. Typically, $(\theta_{s,r} - \theta_{as})$ for the corrected surface temperature was of the order of 10 K, while for the uncorrected values it was only of the order of 1–3 K, which is not very different from the error to be expected in this type of measurement. The correlation between the H values calculated with the $\theta_{s,r}$ corrected by means of the linearized profile method, and H_s from the reference stations was even worse, namely $r = 0.10$. The reason for this is not clear; however, it is perhaps due to the fact that while this correction

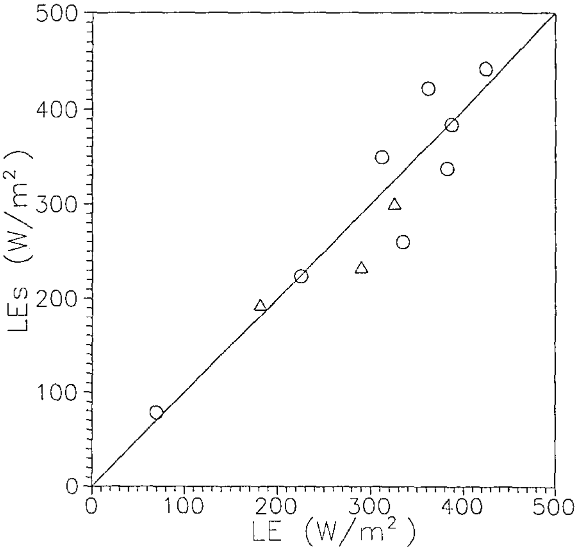

Fig. 2. Comparison between LE values, obtained by the energy budget (6) from the H values shown in Figure 1, and the mean reference values LE_s measured at the ground stations. The statistics on the 1987 data are $r = 0.935$ and $LE_s/LE = 1.00$. (Same symbols as in Figure 1.)

method produces better estimates of surface temperature, on average it also introduces additional error and thus noise in the calculated result.

These results show that flux calculations by means of (1) or (3) are sensitive to the atmospheric correction method used to obtain $\theta_{s,r}$. With the present data, the split-window technique appears to be best suited for this purpose.

The latent heat flux LE is usually well correlated with the available energy flux $(R_n - G)$; specifically, the coefficient is $r = 0.885$ for the present data. However, this is smaller than $r = 0.935$. Thus, while the estimation of H with (1) involves uncertainty, the use of (6) with these H values to estimate LE is still preferable over a simple regression of the type $LE = a(R_n - G) + b$.

4.2. ABL BULK FORMULATION WITH 1987 DATA

The results of the calculation of H by means of (3), with $z_{oh,r} = 5.86 \times 10^{-10}$ m (as determined above by inversion of (1′)), are listed in Table I. These results are compared with the corresponding H_s in Figure 3; the correlation coefficient is $r = 0.669$ and the ratio of the means, $H_s/H = 1.04$. The LE values calculated by means of (6) from these Hs are also listed in Table I, and they are compared with the reference values LE_s in Figure 4; the correlation is $r = 0.931$ and the ratio $LE_s/LE = 0.985$, on average.

4.3. RESULTS WITH 1989 DATA

The data recorded during the three satellite passages in 1989 were treated in the same way as the 1987 data. The resulting surface fluxes H and LE calculated by

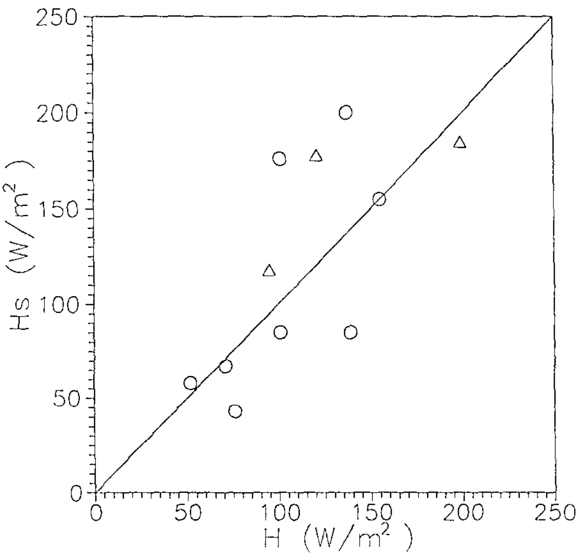

Fig. 3. Comparison between H values calculated with (3) of the Bulk Similarity Approach, and the mean reference values H_s measured independently at the ground stations. The statistics for the 1987 data are $r = 0.669$ and $H_s/H = 1.04$. (Same symbols as in Figure 1.)

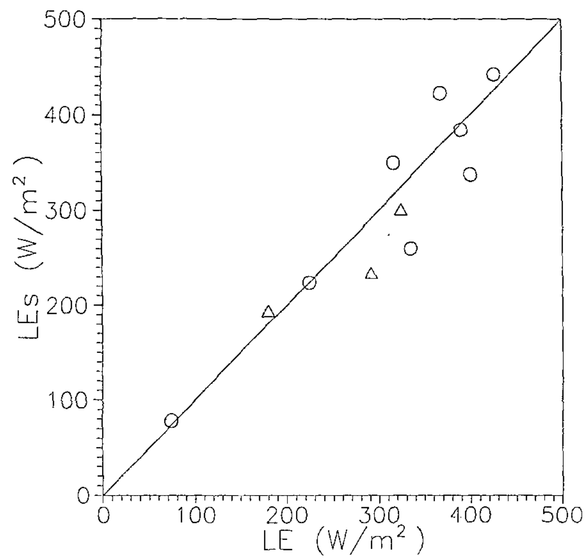

Fig. 4. Comparison between LE values, obtained by the energy budget (6) from the H values shown in Figure 3, and the mean reference values LE_s, measured at ground stations. The statistics for the 1987 data are $r = 0.931$ and $LE_s/LE = 0.985$. (Same symbols as in Figure 1.)

means of (1′) and (3) with the same value of $z_{oh,r}$ are compared in Figures 1–4 with the respective reference fluxes H_s and LE_s; the fluxes calculated by means of the bulk similarity method with (3) are also listed in Table I. While the reliability of the 1989 reference fluxes is unknown (see Brutsaert and Sugita, 1992), the results shown in Figures 1–4 appear to confirm the results obtained with the 1987 data.

5. Conclusions

Surface temperatures measured from a satellite can be used successfully ($r = 0.7$) in combination with temperature and wind speed measurements aloft in the ABL, in order to calculate surface flux values of sensible heat at the regional scale. The methods of calculation, applied for this purpose are based on turbulence similarity. The satellite measurements were made by the AVHRR instrument aboard the NOAA-9 and NOAA-11 polar orbiting satellites; the boundary-layer measurements were made with radiosondes. The sensible heat flux values, thus calculated, could be used in the surface energy budget equation to obtain reliable estimates ($r = 0.94$) of regional evaporation. The procedure is more reliable than simple regression with the available surface energy flux (R_n − G).

The value of the scalar roughness obtained by inversion of (1′) with the present data is $z_{oh,r} = 5.86 \times 10^{-10}$ m. This is somewhat smaller than the values obtained earlier (Sugita and Brutsaert, 1990b; Figures 2 and 3) for the same region, on the basis of $\theta_{s,r}$ measurements by means of infrared thermometers near the ground. This difference appears to be due to the fact that, in this case at least, the satellite surface radiometric temperature, as processed for FIFE, and as corrected by the split-window technique, tends to be larger than the median of the local ground-based measurements.

The 'regional' scale dealt with in this study is of the order of the size of the surface temperature scenes and of the characteristic fetch of the ABL, namely around 10 km.

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