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Comparison of Three Sensible Heat Flux Schemes

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A.E. Galinski and D.J. Thomson

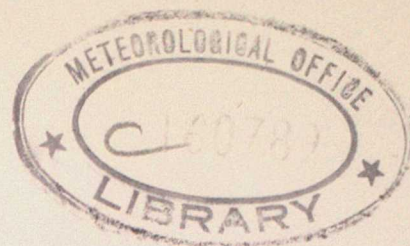
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8th December 1992

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Comparison of Three Sensible Heat Flux Schemes

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Abstract

This paper compares three schemes which use standard meteorological observations to estimate hourly values of the daytime or night-time sensible heat flux. All three schemes have been designed to be applicable to mid-latitude, grass covered surfaces. The estimates from the schemes, made using data from RAE Bedford and from the Meteorological Office Research Unit (MORU) at Cardington Bedfordshire, are compared with heat flux data measured by a sonic anemometer situated at Cardington. The daytime heat flux schemes each include parametrizations of net radiation which are compared with net radiation values measured at Cardington. Consideration is also given to the problem of predicting the surface sensible heat flux when cloud information is not available, as is the case for automatic weather stations. Provided incoming solar radiation is available, the predictions are not substantially worse.

1 Introduction

Dispersion in the Planetary Boundary Layer is affected by two predominating factors; the surface pressure field, which governs the large scale advection of air in the atmosphere, and the surface sensible heat flux, which determines the stability and convection in the boundary layer. In recent years a number of schemes have been developed to estimate the sensible heat flux from standard hourly meteorological data. Here three such schemes, by Smith, 1990, Holtslag and Van Ulden, 1982 and 1983, and Berkowicz and Prahm, 1982, are compared with observed sensible heat flux values. During the daytime these schemes are based on the surface energy balance which can be characterized by the following relationship

$$R_n = H + LE + G \quad (1)$$

where R_n is the net incoming radiation, which balances G , the ground, LE , the latent, and H , the sensible heat fluxes (this and other notation is summarised in appendix A). Net radiation is determined by the balance between the incoming and outgoing short and long wave radiation fluxes

$$R_n = K^+ - K^- + L^+ - L^- \quad (2)$$

where $K^{+/-}$ represents the incoming/outgoing short wave radiation and $L^{+/-}$ represents the incoming/outgoing long wave radiation. Short wave radiation is predominately dependent on the solar elevation (Appendix B) and cloud cover, while long wave radiation is mostly dependent on temperature and cloud cover. Each of the three schemes considered here is based on a parametrization of the net radiation and the ground heat flux together with the Penman-Monteith approach for the modelling the partition of $R_n - G$ between the sensible and latent heat fluxes. The Penman-Monteith or 'resistance' method (see e.g. Monteith and Unsworth, 1990) expresses the latent heat flux in terms of 'aerodynamic' and 'surface' (or 'stomatal') resistances to heat and moisture transfer. Excluding the Berkowicz and Prahm scheme, parametrization of the nocturnal sensible heat flux is approached more simply. With no solar radiation present, the heat flux is estimated directly, without reference to the surface energy balance (eqn. (1)), from cloud cover and wind speed (or friction velocity). The scheme designed by Berkowicz and Prahm uses the same formulation for day and night.

The schemes' estimates of net radiation and sensible heat flux are compared with values measured at the Meteorological Office Research Unit, Cardington. Where possible, measured values of net radiation and incoming solar radiation are also used in place of estimated values in the schemes for further comparison. Where there are separate day and night heat flux schemes, daytime estimates of the sensible heat flux are made using both the daytime and nocturnal heat flux schemes, and the higher of these estimates is used. This procedure is invoked to account for the development of stable surface conditions near dawn and dusk and is intended to help ensure a smooth transition between the day and night-time schemes. In appendix C the feasibility of estimating H in the absence of cloud observations is investigated.

2 Observational Data

The Meteorological Office Research Unit (MORU) site at Cardington is situated in an open field surrounded by a flat terrain of agricultural fields. The site has a roughness length z_0 of about 0.01m (Grant, personnel communication, 1992) with an albedo of 0.26 (determined from the ratio of outgoing to incoming solar radiation measured at the site over the data period). The heat flux, wind speed and friction velocity data used in this study were measured by a Kaijo Denki sonic anemometer and cover 33 months of data between 01/02/1988 to 31/10/1990, excluding several short periods and the whole of the following months: May 1988, February 1989 and March 1990. Over the initial 7 month period of data collection the anemometer was mounted at a height of 18m, and at 21m for the remaining period (in analysing the data a constant height of 20m was assumed for convenience, and the height is referred to as 20m throughout this paper). The sonic anemometer was changed on 4/10/89, a Kaijo Denki TR61A being used up to that date and a TR61B thereafter. The data were recorded at 1Hz and, from these data, hourly means of the wind velocity components, temperatures and de-trended fluxes were calculated. The sensible heat flux was estimated from the temperature and vertical velocity covariance and, for the TR61A, a correction factor was applied to account for the effect of the wind on the transmit time of the sound pulse (Schotanus et al, 1983). For the TR61B the appropriate correction factor depends on wind direction and no attempt

at a correction was made. The sonic anemometer measurements were made on a 24 hour basis at Cardington and values were omitted when observed heat flux values were outside the range -150Wm^{-2} and 350Wm^{-2} (this range includes the range of values normally encountered in this country and values outside the range are probably incorrect), when consecutive heat flux values changed by more than 150Wm^{-2} (again such changes are considered unlikely to be real), or during precipitation events as the vertical velocity and temperature readings are adversely affected by precipitation (precipitation was not measured at Cardington but was assumed to occur if it was recorded at Bedford or if the temperature variance from the sonic anemometer was abnormally large). Data were also excluded when the sonic anemometer's fine-scale temperature value departed by more than 5°C from its (adjustable) zero value, as the fine-scale temperature measurements, and hence also the heat flux values, can be in error in such cases. The radiation data were measured using a Middleton net radiometer and a Kipp and Zonen solarimeter. These data cover a period of 19 months from 01/04/89 to 31/10/90. For the comparisons for which incoming solar radiation was used, occasions when K^+ was outside the range 0 to 1000Wm^{-2} were excluded. When net radiation was used, values less than -100Wm^{-2} which occurred during the daytime were excluded. Such values of K^+ and R_n seem likely to be due to measurement errors. Comparisons within this paper will be made for both the 33 month period and the 19 month period depending whether the radiation data is required.

The standard meteorological observations used by the schemes were measured at RAF Bedford, which is situated 10km from the site at Cardington and at an elevation 10m higher. Observations at Bedford are made on weekdays only. The observations used are current weather code, cloud amount, dew point and dry bulb temperature and ground state (as these are not systematically recorded at Cardington). The distance between sites potentially introduces a source of error into the comparison. However, as the sites are not too distant geographically or different topographically we hope that this is a relatively minor source of error. The observations of ground state were used to exclude any occasions when snow covered the ground from the comparisons. Occasions when fog was recorded were also excluded. The temperature measurements used in the schemes were the Bedford observations (and not the Cardington sonic anemometer temperatures).

Although data is measured and recorded on hourly basis at both the MORU, Cardington and at RAF Bedford, only around 40% of the maximum possible amount of hourly data was available for comparison. This is due to the quality control procedures and periods when some of the instruments were not operating or were being adjusted.

3 The Smith Heat Flux Scheme.

This heat flux scheme was developed by Smith (1990) and uses ideas from the work of Wang (1984) and Smith and Blackall (1979). The scheme was developed using data also measured at the MORU, Cardington, between March 1976 and March 1977. We will consider first daytime conditions (defined by $\phi > 0$, where ϕ is the solar elevation).

3.1 Net Radiation

The net radiation is calculated from the following equation and uses the total medium/low cloud cover

$$R_n = \begin{cases} -172.1s^3 + 742.2s^2 + 102.5s - 45.0 & \text{if cloud} < 7 \text{ oktas} \\ 99.6s^3 + 155.9s^2 + 41.6s + 6.2 & \text{cloud} \geq 7 \text{ oktas} \end{cases} \quad (3)$$

where s is the sine of solar elevation (see Appendix B). This estimate of net radiation was obtained by Wang (1984) using observations at Cardington.

Values of net radiation calculated using this method were compared with the radiation data measured at Cardington. The results are given in table 1 and a scatter plot of observed and predicted values of net radiation is given in figure 1. From the results it can be seen that there is a useful degree of correlation between estimated and observed values, although the tendency of the scheme to underestimate when R_n is small and to overestimate when R_n is large is a little surprising in view of the use of cubic polynomials to relate R_n and s .

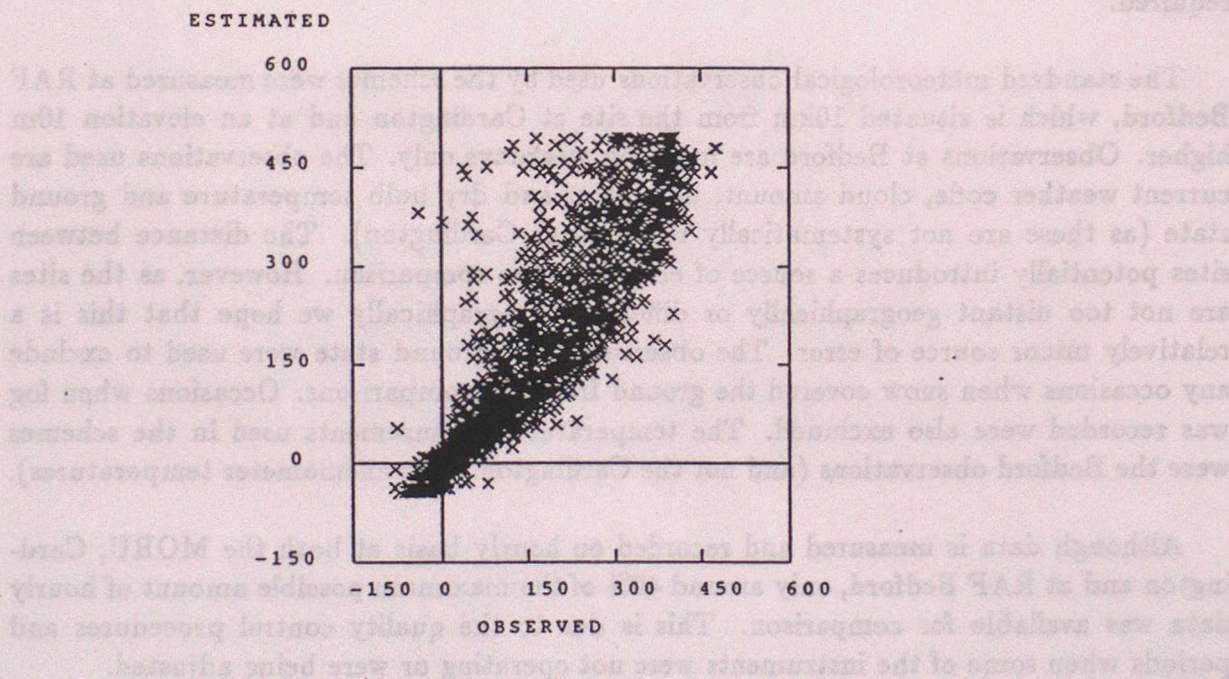


Fig. 1 Scatter plot of predicted and observed values of net radiation from the Smith net radiation scheme.

Smith Net Radiation Scheme Statistics	
n	2066
\bar{x}	158.82
\bar{y}	169.80
s_x	135.90
s_y	158.19
$\bar{y} - \bar{x}$	10.98
σ	70.22
r	0.90

Table 1: Smith net radiation scheme results, where n = no. of values, \bar{x} = mean observed value, \bar{y} = mean estimated value, s_x = standard deviation of the observed value, s_y = standard deviation of the estimated value, $\bar{y} - \bar{x}$ = mean error in the estimated value, σ = root mean square (rms) error and r = correlation coefficient.

3.2 Surface Energy Budget

The amount of radiation available for the sensible and latent heat fluxes is the net radiation less the amount taken up by the ground heat flux. This is parametrized by

$$R_a = R_n - G = (1.2 - 0.4s/s_m)R_n \quad (4)$$

where s_m is the sine of the solar elevation at midday. With R_a determined, the sensible heat flux is calculated using the Penman-Monteith resistance method (see e.g. Monteith and Unsworth, 1990)

$$H = \frac{R_a(r_a + r_s) - \delta q \rho c_p / \gamma}{(1 + \Delta / \gamma)r_a + r_s} \quad (5)$$

Here δq is the humidity deficit $(1 - h/100)e_s(T)$ where h is the relative humidity (in percent) and $e_s(T)$ is the saturated vapour pressure at the screen level as a function of temperature (T). The terms r_a and r_s are the aerodynamic and surface resistances, γ is the psychrometric constant and $\Delta = de_s/dT$. In presenting his scheme, Smith follows the practice which is sometimes adopted in the Penman-Monteith method of writing the term $\delta q \rho c_p / \gamma$ in (5) as $r_i R_a$, where r_i is the 'climatological' resistance. Smith approximates $e_s(T)$, γ and ρc_p by $6.1 + 0.475T + 0.0095T^2 + 0.0005T^3$, $0.646 + 0.0006T$ and $1305 - 4.3T$ respectively, where T is expressed in $^{\circ}\text{C}$, and takes Δ to be the average of the values of de_s/dT at the screen and surface temperatures with the surface temperature T_0 estimated using

$$T_0 = \begin{cases} T + \frac{R_a}{\rho c_p} r_a (5.25(\frac{r_s}{1000}) - 6.25(\frac{r_s}{1000})^2) & \text{if } r_s < 400 \\ T + \frac{R_a}{\rho c_p} r_a & r_s \geq 400. \end{cases} \quad (6)$$

The aerodynamic resistance is determined from the following equation

$$r_a = \frac{c_z}{u_z} \quad (7)$$

where c_z is a height dependent parameter and u_z is the wind at a height z . For winds measured at a height of 3m, Smith proposes $c_{3m} = 188.9$. In applying equation (7) here using the 20m winds we use $c_{21m} = 251.7$ which is based on Smith's value for 3m winds

and the assumption of a logarithmic wind profile with a roughness length of 0.01m. The surface resistance is temperature dependent and is given by

$$r_s = \begin{cases} 65.0s & \text{if } T < 23^\circ\text{C}, \\ 65.0s + 234.0 & T \geq 23^\circ\text{C}. \end{cases} \quad (8)$$

If it is raining, r_s is set equal to zero and for 'winter' days ($80 > n > 230$, where n is the Julian day number) there is a default value of $r_s = 900\text{ms}^{-1}$. Note however that we are excluding occasions with rain from the comparisons.

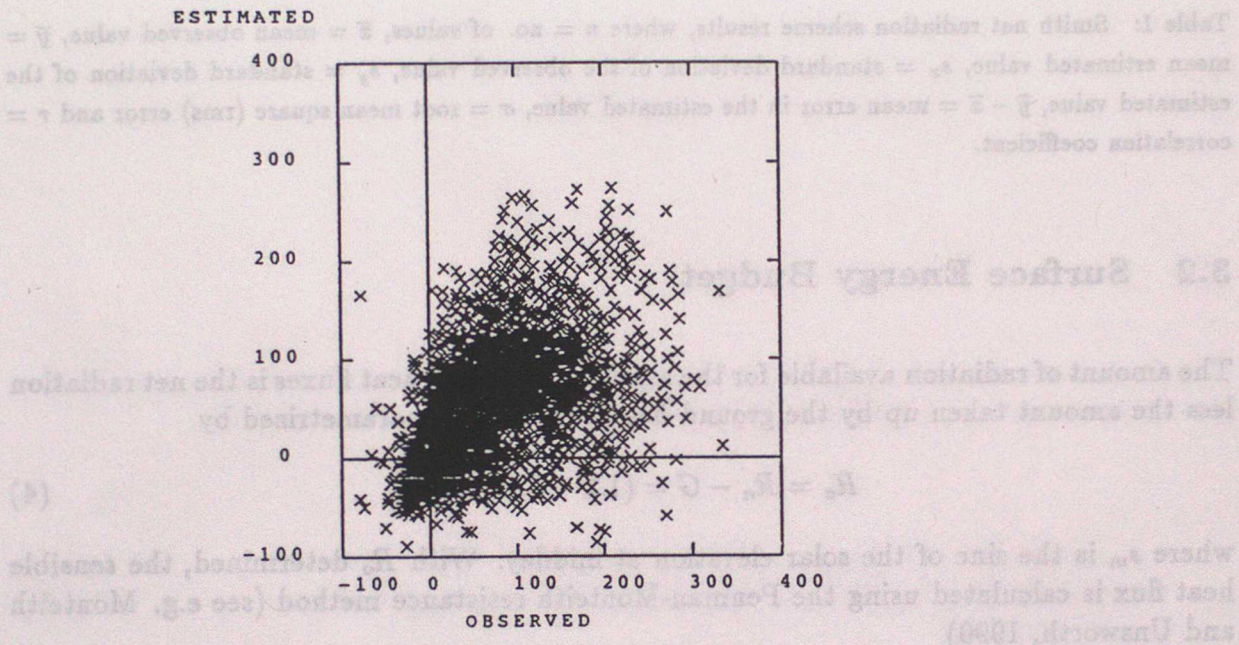


Fig. 2 Scatter plot of predicted and observed values of daytime sensible heat flux from the Smith heat flux scheme.

Smith Daytime Heat Flux Scheme Statistics			
	33 months data	19 months data	19 months data/real R_n
n	4057	2166	2166
\bar{x}	48.93	64.01	64.01
\bar{y}	40.80	43.33	43.63
s_x	64.72	71.58	71.58
s_y	55.41	58.13	61.28
$\bar{y} - \bar{x}$	-8.13	-20.67	-20.37
σ	57.38	66.86	73.99
r	0.56	0.54	0.44

Table 2: Smith daytime heat flux comparison statistics (see notes for table 1)

The data used in the development of this scheme are from Cardington and the data they are compared with are also from Cardington so we might expect the scheme to

perform better than it would at an arbitrary site. However the two sets of data cover different periods (Wang, 1984). A scatter plot of heat flux values from the Smith daytime scheme against observed values is given in figure 2 and statistics are given in table 2. Table 2 shows statistics for the 33 month period and statistics obtained using the observed values of net radiation (instead of equation (3)) for the 19 month period. Also shown for comparison purposes are statistics obtained over the 19 month period without using the net radiation observations. As indicated in the introduction, in order to account for stable conditions which occur after dawn and before dusk, estimates from both the daytime and night-time (see below) schemes were made. The value from the night-time scheme was used when $H_{night} > H_{day}$. From table 2 it can be seen that for the 33 month period there is a useful degree of correlation between observed and estimated daytime sensible heat fluxes with a tendency to slightly underestimate the sensible heat flux. However, for the 19 month period, the scheme tends to further underestimate the daytime heat flux. Also when the measured net radiation is used the scatter is, somewhat surprisingly, increased and there is a corresponding decrease in the correlation coefficient. It seems likely that a significant cause of the scatter in figure 2 and table 2 is the lack of any means to assess or account for the moisture content of the soil.

3.3 Nocturnal Heat Flux Scheme

The night-time scheme uses 3m wind speed and cloud amount for estimation of the nocturnal heat flux

$$H = -\frac{4}{7}(2Y + Y^2) \quad (9)$$

where $Y = u_3 + 2(1 - (N/8)^2)$ and N is the total low/medium cloud amount in oktas. Once a value of H has been determined then the Monin-Obukhov length L , can also be calculated using

$$L = -\frac{\rho c_p T u_*^3}{\kappa g H} \quad (10)$$

where T is now in Kelvin, κ is the von Karman constant and u_* is the friction velocity which can be estimated using

$$u_z = \frac{u_*}{\kappa} \left[\log\left(\frac{z}{z_0}\right) + c \frac{(z - z_0)}{L} \right] \quad (11)$$

Smith proposes taking κ to be 0.4, c to be 5.2 (Webb, 1970) and $\rho c_p T / \kappa g$ to be $94700 \text{ W m}^{-4} \text{ s}^3$. Values of u_* and L can be determined from the above equations by iteration. Whenever the sensible heat flux is less than

$$H_{crit} = \frac{-172.67 u_z^3}{(z - z_0)(\log(z/z_0))^2} \quad (12)$$

where z is the height of the wind measurement and z_0 is the site roughness length, these equations have no solution and the iteration process fails. If this is the case, Smith takes H equal to H_{crit} .

In this study the wind data used is measured at a height of 20m, while the scheme requires a 3m level wind. To determine a value of u at the 3m level from the 20m wind we use a modification of the iteration method suggested by Smith (1990). This is summarized by the following:

1. assume $1/L = 0$
2. estimate u_* using eqn. (11) with $z = 20$
3. estimate u_3 using eqn. (11) with $z = 3$
4. estimate H using eqn. (9)
5. revise estimate of L using eqn. (10)
6. repeat steps (2-5) until values have converged (i.e. until successive changes in H are less than 0.01 W m^{-2})

If the iteration does not converge after 30 iterations we assume there is no solution and the sensible heat flux is calculated from equation (12) using the 20m wind. However, in practice we found that the heat flux value failed to converge on only about 1% of occasions.

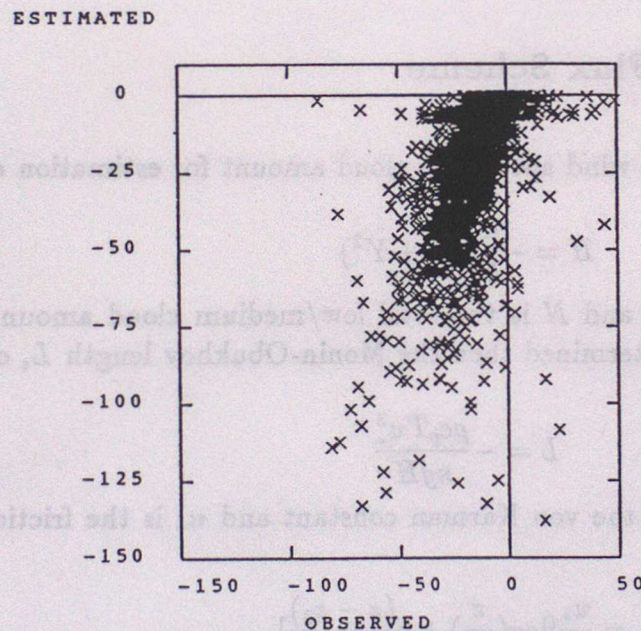


Fig. 3 Scatter plot of predicted and observed values of nighttime sensible heat flux from the Smith heat flux scheme.

Figure 3 shows a scatter plot of heat flux values from Smith's nocturnal scheme against observed heat flux values and the corresponding statistics are given in table 3. In comparison to the daytime scheme the nocturnal heat flux scheme has approximately the same degree of accuracy, i.e. the rms error is of the same magnitude as the standard deviation and the correlation coefficient is again of the same order as that for the daytime scheme. Proportionally the mean error is larger than in the corresponding daytime scheme results; here the scheme overestimates the magnitude of the nocturnal heat flux. A possible cause of error (which also applies in connection with the other schemes considered here) is the

occurrence of shallow boundary layers. In such cases H at 20m may be significantly less than the surface flux. This could account for some of the overestimation, but it is difficult to assess the overall significance of this effect..

Smith Nocturnal Heat Flux Scheme Statistics	
n	3562
\bar{x}	-10.91
\bar{y}	-15.71
s_x	14.30
s_y	18.42
$\bar{y} - \bar{x}$	-4.80
σ	16.58
r	0.55

Table 3: Smith nocturnal heat flux comparison statistics (see notes for table 1).

4 The Holtslag and Van Ulden Heat Flux Scheme.

The second heat flux scheme which we consider is a combination of schemes by Holtslag and Van Ulden (1983) for the daytime and by Holtslag and Van Ulden (1982) for the night. These schemes were developed using mainly data from Cabauw in the Netherlands. As for the Smith scheme, we consider daytime conditions first.

4.1 Net Radiation

In estimating the net radiation, R_n , Holtslag and Van Ulden evaluate the terms of the equation

$$R_n = (1 - r)K^+ + L^+ - L^- \quad (13)$$

where K^+ is the incoming solar radiation, L^+ and L^- are the incoming and outgoing long wave radiation, and r is the surface albedo. From measurements of surface albedo over short grass, Holtslag and Van Ulden found r to be 0.23 while the value at Cardington was found to be slightly higher at 0.26; both values agree well with other studies (Oke, 1978). In the comparison we opted to use the 'suggested' value of 0.23 as this may give a better impression of the accuracy of the scheme in the absence of any site specific tuning.

Incoming solar radiation depends on solar elevation, and for clear skies it is calculated by

$$K_0^+ = a_1 \sin \phi + a_2 \quad (14)$$

where a_1 and a_2 are empirical coefficients which describe the attenuation of solar radiation in the atmosphere by water vapour, trace gases and dust particles. In this study we used $a_1 = 990 \text{ Wm}^{-2}$ and $a_2 = -30 \text{ Wm}^{-2}$ which have been determined for a site near Harrogate (Collier and Lockwood, 1975) and which, as Holtslag and Van Ulden (1983) observe, give a fair average of observations at a number of sites. Other values of a_1 and a_2 , corresponding

to different sites (Holtslag and Van Ulden, 1983) were tested on the scheme, but the results showed little significant overall improvement or degradation to the estimated heat flux results over the 33 months of data.

When clouds are present, their effect on net incoming radiation must be accounted for; this can be done by applying a correction factor for cloud cover to equation (14):

$$K^+ = K_0^+(1 - b_1(N/8)^{b_2}). \quad (15)$$

Here N is total cloud cover (in oktas) and b_1 and b_2 are empirical coefficients which are taken to be 0.75 and 3.4 respectively.

Incoming long wave radiation is estimated using the relationship

$$L^+ = c_1 T^6 + c_2 (N/8) \quad (16)$$

where T is equal to the screen temperature (Kelvin) and c_1 and c_2 are empirical constants and taken to be $5.31 \times 10^{-13} \text{ W m}^{-2} \text{ K}^{-6}$ and 60 W m^{-2} respectively. For estimation of the outgoing long wave radiation, the surface is assumed to emit radiation as a black-body. Therefore, using the Stefan-Boltzmann law, outgoing long wave radiation is given by

$$L^- = \sigma T_0^4 \quad (17)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ and T_0 is the surface temperature. However, because T_0 is not easily determined, outgoing long wave radiation is approximated by

$$L^- = \sigma T^4 + c_3 R_n \quad (18)$$

where $c_3 = 0.12$. The last term is an empirical correction to allow for the difference between screen and surface temperature, with c_3 being a 'heating coefficient' for the surface. Net radiation is determined by combining the above equations (13-18) to give

$$R_n = \frac{(1 - \tau)K^+ + c_1 T^6 - \sigma T^4 + c_2 (N/8)}{1 + c_3} \quad (19)$$

Holtslag and Van Ulden Net Radiation Scheme Statistics		
	estimated K^+	measured K^+
n	2066	2066
\bar{x}	158.82	158.82
\bar{y}	186.07	164.01
s_x	135.90	135.90
s_y	150.83	144.90
$\bar{y} - \bar{x}$	27.25	5.19
σ	66.17	35.86
τ	0.92	0.97

Table 4: Holtslag and Van Ulden net radiation scheme results (see notes for table 1).

We applied the Holtslag and Van Ulden scheme to the observations at Cardington and Bedford in two ways – firstly as indicated above and secondly using observed values of K^+

in place of estimates from (14) and (15). Table 4 shows statistics of a comparison between the resulting values of net radiation and observations. The comparative accuracies of the two methods for determining net radiation can also be seen in figures 4 and 5. These show scatter plots of net radiation estimated in each of the two ways against observed net radiation. For both methods there is a high correlation between the predicted and observed values. In the original comparison the rms error and correlation coefficient are given as $\sigma=63.2\text{Wm}^{-2}$ and $r = 0.857$ when K^+ is estimated and as $\sigma=24.8\text{Wm}^{-2}$ and $r = 0.982$ when the measured K^+ is used. The values we obtain here are comparable when K^+ is estimated and slightly worse when the measured K^+ is used.

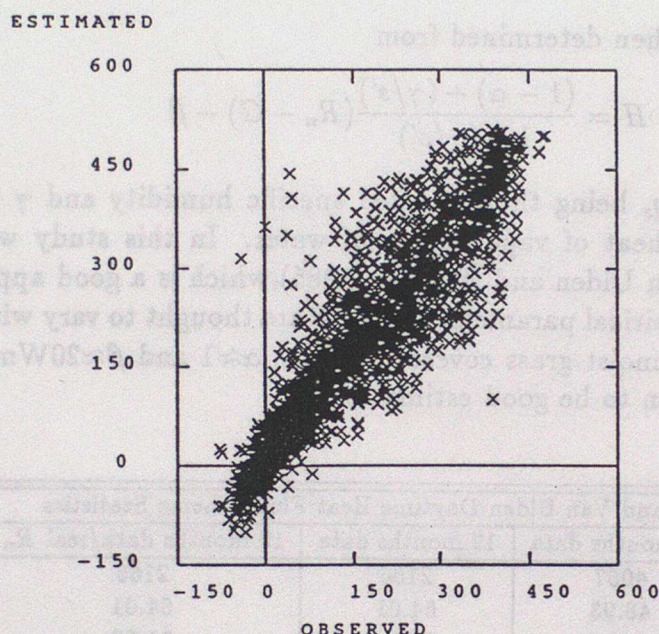


Fig. 4 Scatter plot of predicted and observed values of net radiation from the Holtslag and Van Ulden net radiation scheme using estimated values of K^+ .

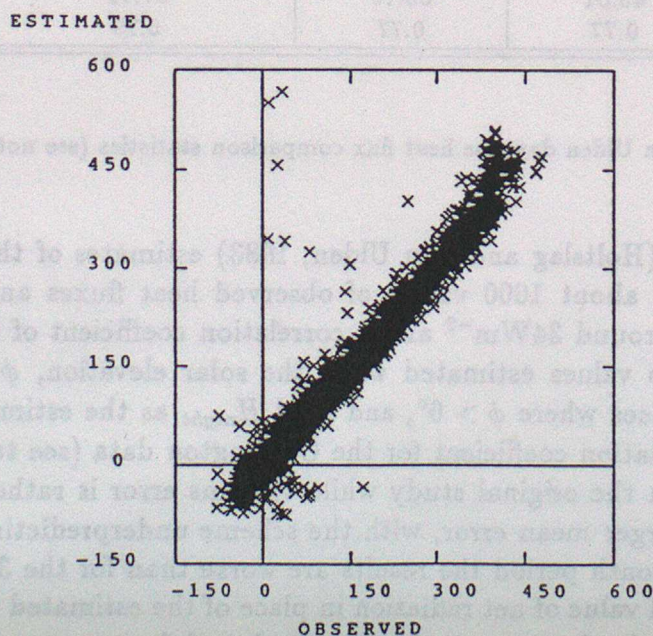


Fig. 5 Scatter plot of predicted and observed values of net radiation from the Holtslag and Van Ulden net radiation scheme using measured values of K^+ .

4.2 Surface Energy Budget

With the net radiation determined, the sensible heat flux is now calculated by estimating the soil heat flux and using an approximation to the Penman-Monteith resistance method, which parametrizes the division of available energy between the sensible and latent heat fluxes. During the daytime the soil heat flux is small and can be given as a fraction of the net radiation (De Bruin and Holtslag, 1982):

$$G = 0.1R_n. \quad (20)$$

The sensible heat flux is then determined from

$$H = \frac{(1 - \alpha) + (\gamma/s')}{1 + (\gamma/s')} (R_n - G) - \beta \quad (21)$$

where $s' = dq_s/dT$ with q_s being the saturated specific humidity and $\gamma = c_p/\lambda$ with λ being the specific latent heat of vaporization of water. In this study we used $\gamma/s' = \exp[-0.055(T - 279)]$ (Van Ulden and Holtslag, 1985) which is a good approximation for $270 < T < 310\text{K}$. The empirical parameters α and β are thought to vary with differing soil moisture conditions. For moist grass covered surfaces $\alpha \approx 1$ and $\beta \approx 20\text{Wm}^{-2}$ were found by Holtslag and Van Ulden to be good estimates.

Holtslag and Van Ulden Daytime Heat Flux Scheme Statistics			
	33 months data	19 months data	19 months data/real R_n
n	4057	2166	2166
\bar{x}	48.93	64.01	64.01
\bar{y}	32.27	38.84	31.29
s_x	64.72	71.58	71.58
s_y	39.75	41.56	38.29
$\bar{y} - \bar{x}$	-16.66	-25.17	-32.72
σ	45.51	53.70	57.79
r	0.77	0.77	0.79

Table 5: Holtslag and Van Ulden daytime heat flux comparison statistics (see notes for table 1).

In the original study (Holtslag and Van Ulden, 1983) estimates of the daytime heat flux were compared with about 1000 values of observed heat fluxes and they quote a rms (standard) error of around 34Wm^{-2} and a correlation coefficient of 0.64. They also limit their comparison to values estimated when the solar elevation, $\phi > 10^\circ$; in this study we compared all cases where $\phi > 0^\circ$, and used H_{night} as the estimate for H when $H_{\text{night}} > H_{\text{day}}$. The correlation coefficient for the Cardington data (see table 5) is rather better than that found in the original study while the rms error is rather worse, due in part to a substantially larger mean error, with the scheme underpredicting the heat flux on average. For the 19 month period the results are worse than for the 33 month period and the use of a measured value of net radiation in place of the estimated value has mixed results; when the measured value is used, the magnitudes of the rms error and mean error increase while the correlation coefficient improves. Figure 6 shows an apparent inability of the scheme to predict high values of sensible heat flux, with a 'cut-off' at about 150Wm^{-2} (which probably contributes to the negative mean error). The general shape of the

scatter plot is similar to that found by Holtslag and Van Ulden. The poor results obtained when the observed value of H is large seem almost certainly due to the inappropriateness of the value of α which should vary with soil moisture content.

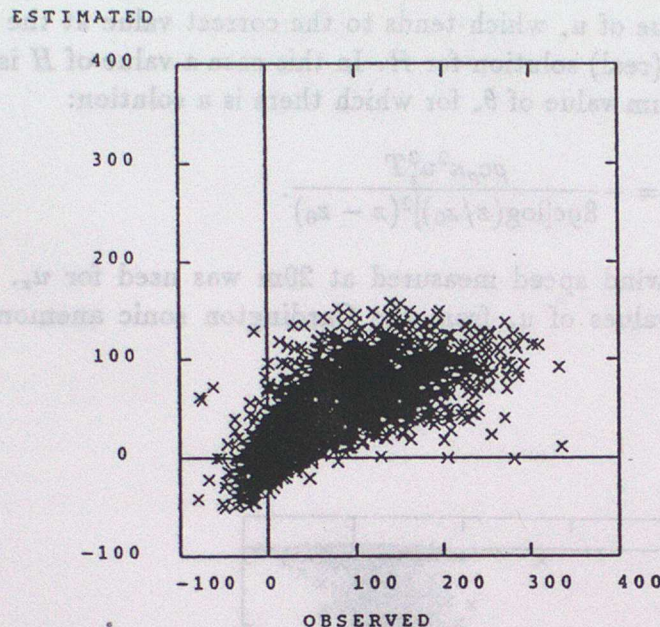


Fig. 6 Scatter plot of predicted and observed values of daytime sensible heat flux from the Holtslag and Van Ulden heat flux scheme.

4.3 Nocturnal Heat Flux Scheme

Holtslag and Van Ulden (1982) estimate the nocturnal sensible heat flux from friction velocity and the turbulent temperature scale, θ_* , which is determined from cloud cover. Holtslag and De Bruin (1988) recommend a more complicated method as a 'counterpart' to the daytime scheme proposed by Holtslag and Van Ulden (1983). However as the earlier scheme (Holtslag and Van Ulden, 1982) is much simpler and the conditions under which Holtslag and De Bruin's (1988) equations have unique solutions, no solutions or multiple solutions are unclear to us, we opted to use the earlier scheme to model the nocturnal sensible heat flux. In this scheme H is given by

$$H = -\rho c_p u_* \theta_* \quad (22)$$

where

$$\theta_* = 0.09[1 - 0.5(N/8)^2] \quad (23)$$

As u_* is not usually known, equation (11) and the equation (10) for the Monin-Obukhov length are substituted into equations (22) and (23) and solved for H . Here κ was taken here to be 0.4, $c = 5.2$, $\rho = 1.225 \text{ kg m}^{-3}$, $c_p = 1004.6 \text{ J kg}^{-1} \text{ K}^{-1}$ and $g = 9.81 \text{ m s}^{-2}$. The

solution of the quadratic equation gives a value of nocturnal sensible heat flux

$$H = -\frac{\rho c_p \kappa [u_z \pm (u_z^2 - 4 \log(z/z_0) g c \theta_* (z - z_0) / \kappa T)^{1/2}] \theta_*}{2 \log(z/z_0)} \quad (24)$$

Usually eqn. (24) gives two solutions for H . The solution with the larger magnitude is chosen as it corresponds to a value of u_* which tends to the correct value at the neutral limit. If u is too light there is no (real) solution for H . In this case a value of H is chosen which corresponds to the maximum value of θ_* for which there is a solution:

$$H_{crit} = -\frac{\rho c_p \kappa^2 u_z^3 T}{8 g c [\log(z/z_0)]^2 (z - z_0)} \quad (25)$$

In equations (24) and (25) the wind speed measured at 20m was used for u_z . H was also estimated using measured values of u_* from the Cardington sonic anemometer in equations (22) and (23).

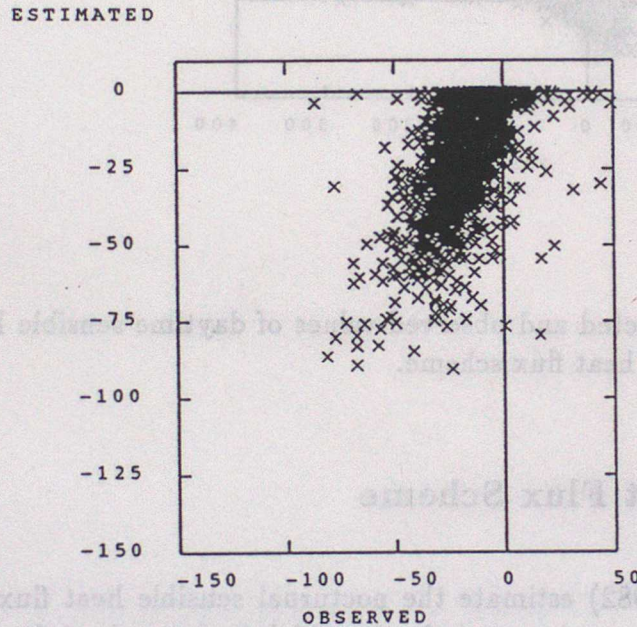


Fig. 7 Scatter plot of predicted and observed values of nighttime sensible heat flux from the Holtslag and Van Ulden heat flux scheme with u_* estimated from the 20m wind.

From table 6 it can be seen that there is a reasonable correlation between the scheme estimates and observed values of nocturnal sensible heat flux. Figure 7 shows a scatter plot of estimated and observed heat flux values. Using an observed value of friction velocity in place of an estimated value (i.e. using equations (22) and (23) directly without the need for equation (25)) had little significant effect on the nocturnal results, although the mean error is somewhat increased.

Holtslag and Van Ulden Nocturnal Heat Flux Scheme Statistics		
	estimated u_n	measured u_n
n	3562	2827
\bar{x}	-10.91	-13.85
\bar{y}	-13.55	-21.33
s_x	14.30	12.86
s_y	15.11	14.65
$\bar{y} - \bar{x}$	-2.64	-7.48
σ	13.12	13.47
r	0.62	0.68

Table 6: Holtslag and Van Ulden nocturnal heat flux comparison statistics (see notes for table 1).

5 The Berkowicz and Prahm Heat Flux Scheme.

The third scheme we consider uses the method of Berkowicz and Prahm (1982) to estimate sensible heat flux from R_n , which is itself estimated from a parametrization proposed by Nielsen et al (1981). This scheme requires more input parameters than the other schemes detailed here, although it is conceptually similar; incoming and net radiation are parametrized by estimation of solar elevation and the effect of cloud cover, while the partitioning of available energy between the fluxes of sensible and latent heat is estimated by the Penman-Monteith approach. This scheme can be used to estimate either the daytime or nocturnal heat flux. The scheme was developed using experimental data from three sites: Højbakkegaard in Denmark, Marsta in Sweden and Cabauw in Holland.

5.1 The Nielsen et al Net Radiation Scheme

Daytime Net Radiation from Measured Global Radiation and Cloud: Net radiation can be quite accurately determined if measurements of global radiation (i.e. incoming solar radiation) are available. Nielsen et al use a modified version of the Monteith and Szeicz (1961) formula in which the parameters vary with cloud amount instead being constant as in the original equation. They propose

$$R_n = \frac{(1 - \tau)}{(1 + \beta)} K^+ + L_n(N). \quad (26)$$

with both net L_n and $(1 - \tau)/(1 + \beta)$ given as functions of total cloud cover (Nielsen et al, 1981).

Daytime Net Radiation from Cloud Measurements: For cases when global radiation is not measured, Nielsen proposed an empirical formula derived from net radiation data measurements over a five year period at Højbakkegaard, Denmark (Nielsen et al, 1981). Solar elevation, ϕ , and a modified cloud cover N_m , are used to determine the net radiation. Modified cloud cover is determined by the height of the predominating cloud.

If the predominating cloud is high then N_m is determined from the total cloud amount N as follows:

$$\begin{aligned} N < 3 &\rightarrow N_m = N, \\ N = 3 &\rightarrow N_m = N - 1, \\ N > 3 &\rightarrow N_m = N - 2. \end{aligned}$$

However if the cloud is predominately low or medium cloud then $N_m = N$. This modification of total cloud amount is applied to account for the decreased 'shielding' effect of high cloud on incoming radiation. We make the assumption that the predominating cloud is high when $N > N_{low/medium} + 2$. Net radiation is then determined from the following relationship

$$R_n = a_0 + a_1 s + a_3 s^3 \quad (27)$$

where the regression coefficients a_n are functions of N_m (Nielsen et al, table VI). However if the nocturnal scheme (see below) gives a value of R_n greater than the daytime scheme, then the value from the nocturnal scheme is chosen in preference.

Nighttime Net Radiation from Cloud Measurements: For nocturnal cases, net radiation is primarily determined using the amount of cloud cover; for skies with $N < 4$ oktas Nielsen et al found a useful correlation between net radiation, wind speed, cloud amount and temperature

$$R_n = a_0 + a_1 u_{2m} + a_2 u_{2m}^2 + a_3 T^6, \quad (28)$$

where the regression coefficients a_n are functions of cloud amount (Nielsen et al, table III), u_{2m} is the 2m wind speed and T is the 2m air temperature (in Kelvin). Here we have assumed a log profile to give a 2m wind speed and assumed the screen temperature to be the same as a 2m temperature. For more overcast conditions the above relationship was found to give a poor correlation and Nielsen et al (table V) give mean values as a function of modified cloud amount for $N_m > 3$. In applying this scheme, we have used N_m throughout for simplicity instead of using N and N_m .

As for the Holtslag and Van Ulden scheme, we have done two comparisons of daytime net radiation, one using measured K^+ and cloud and one using cloud only. For daytime hours, table 7 shows the statistics of the comparison of predicted and observed net radiation values and figures 8 and 9 show the corresponding scatter plots. The difference in accuracy between the two types of scheme is readily seen from the graphs in figures 8 and 9 where the scheme which uses a measured value of K^+ has a very good correlation and relatively very low scatter between predicted and observed values. The mean errors for both these schemes are positive and indicate that the estimates tend to be higher than the observed values.

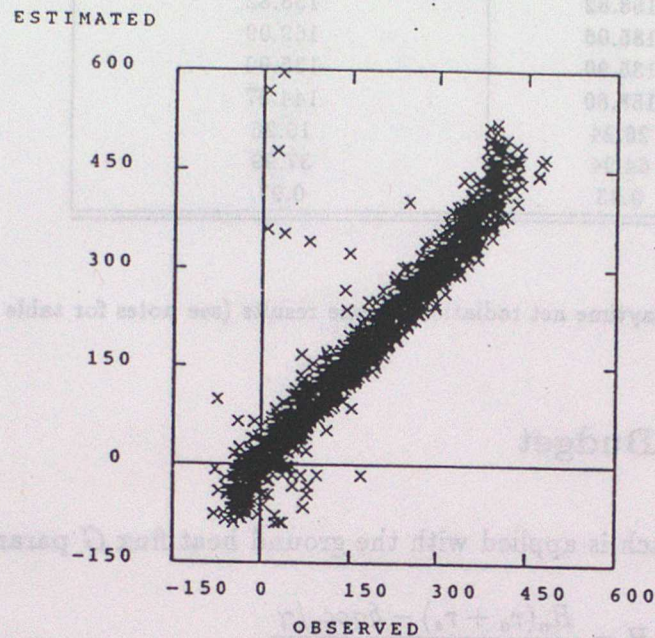


Fig. 8 Scatter plot of predicted and observed values of daytime net radiation from the Nielsen et al net radiation scheme using measured values of K^+ and cloud amount.

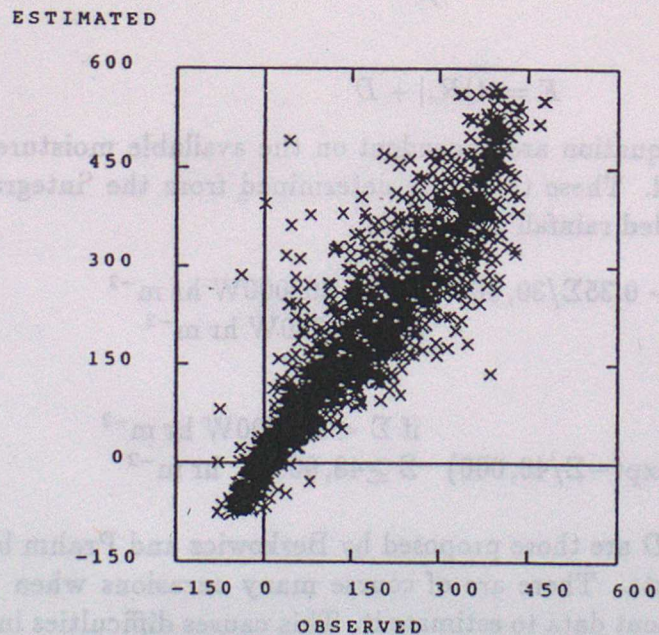


Fig. 9 Scatter plot of predicted and observed values of daytime net radiation from the Nielsen et al net radiation scheme using cloud measurements only.

Nielsen et al Net Radiation Scheme Statistics		
	cloud measurements	measured K^+ and cloud amount
n	2066	2066
\bar{x}	158.82	158.82
\bar{y}	185.06	169.09
s_x	135.90	135.90
s_y	158.80	144.97
$\bar{y} - \bar{x}$	26.24	10.26
σ	64.94	37.99
r	0.93	0.97

Table 7: Nielsen et al daytime net radiation scheme results (see notes for table 1)

5.2 Surface Energy Budget

The Penman-Monteith approach is applied with the ground heat flux G parametrized by $H/3$ giving

$$H = \frac{R_n(r_a + r_s) - \delta q \rho c_p / \gamma}{4/3 r_s + (4/3 + \Delta/\gamma) r_a} \quad (29)$$

Here we represent ρ , c_p , γ , e_s and Δ more simply than in Smith's scheme, taking $\rho = 1.225 \text{ kg m}^{-3}$, $c_p = 1004.6 \text{ J kg}^{-1} \text{ K}^{-1}$, $\gamma = 0.6634^1$, $e_s(T) = \exp[(1.8096 + 0.08006T)/(1 + 0.00412T)]$ with T the screen temperature in $^{\circ}\text{C}$ (Gill 1982), and we evaluate Δ at the screen temperature. Berkowicz and Prahm propose taking the surface resistance to be

$$r_s = \frac{\delta q \rho c_p}{\gamma F} \quad (30)$$

where

$$F = A|R_n| + D \quad (31)$$

The terms A and D in this equation are dependent on the available moisture for evaporation from the grass and soil. These terms are determined from the 'integrated hourly net radiation since last recorded rainfall', Σ , where

$$A = \begin{cases} 0.6 - 0.35\Sigma/30,000 & \text{if } \Sigma < 30,000 \text{ W hr m}^{-2} \\ 0.25 & \Sigma \geq 30,000 \text{ W hr m}^{-2} \end{cases}$$

and

$$D = \begin{cases} 33 & \text{if } \Sigma < 48,000 \text{ W hr m}^{-2} \\ 110\exp(-\Sigma/40,000) & \Sigma \geq 48,000 \text{ W hr m}^{-2} \end{cases}$$

These expressions for A and D are those proposed by Berkowicz and Prahm based on the data from Cabauw and Marsta. There are of course many occasions when R_n was not available or there was insufficient data to estimate it. This causes difficulties in calculating Σ . In such situations we have used average values. These averages were computed over the 33 months of data when considering predictions from the Nielsen scheme and over the 19 months of data when considering observed values. Separate averages for day and nighttime hours were used.

¹The value at U.S. standard atmosphere surface temperature and pressure.

The aerodynamic resistance used by Berkowicz and Prahm, which is based on the Monin-Obukhov similarity theory, is determined by iteration using the following equations

$$r_a = \frac{0.74}{\kappa u_*} [\log(z_T/z_0) - \psi_h(z_T/L) + \psi_h(z_0/L)] \quad (32)$$

with the friction velocity, u_* , given by

$$u_* = \kappa u_z / [\log(z/z_0) - \psi_m(z/L) + \psi_m(z_0/L)]. \quad (33)$$

Here z_T = height of temperature measurements (1.22m here) and the Monin-Obukhov length is given by equation (24). The ψ functions used in the iteration of equations (29)-(33) are given by

$$\psi_h(\xi) = \begin{cases} 2\log(1+y) & \text{when } \xi < 0 \\ -6.35\xi & \xi > 0 \end{cases} \quad (34)$$

and

$$\psi_m(\xi) = \begin{cases} \log[(1+x)^2(1+x^2)] - 2\tan^{-1}x & \text{when } \xi < 0 \\ -4.7\xi & \xi > 0 \end{cases} \quad (35)$$

where κ is taken to be 0.35, $x = (1 - 15\xi)^{1/4}$ and $y = (1 - 9\xi)^{1/2}$. The sensible heat flux is first estimated using $L = \infty$ (i.e. assuming neutral conditions) and then these equations were solved using the iteration technique described in Berkowicz and Prahm (1982), the iteration being repeated (to maximum of 30 times) until the change in estimated value of H is less than 0.01 W m^{-2} . In approximately 1% of all cases the iteration process failed. In these cases conditions the initial (neutral) estimate was assumed.

To investigate the effect of the ψ functions on the estimate of the sensible heat flux, the heat flux estimates were compared to estimates calculated without using the ψ functions (i.e. assuming logarithmic profiles). The effect on the estimate of the ψ functions can be seen in figure 10; in unstable conditions these functions have only a negligible effect while in stable conditions they tend to decrease the magnitude of the estimate of sensible heat flux.

In comparing the scheme estimates with observed heat flux values we have separated the data into day and night-time cases in order to compare the scheme results with the other schemes, despite the fact that the scheme is designed for both unstable or stable conditions. From the data in table 8 and figures 11 and 12 it can be seen that there is a good correlation between estimated and observed values of heat flux for daytime conditions. Over the full 33 month period the mean and rms errors are both quite low. For the 19 month period the results are not as good with larger rms errors and greater mean errors although the correlation is very slightly improved. Using an observed value of net radiation, although improving the correlation, had the effect of increasing the rms and mean errors. For nocturnal estimates of the sensible heat flux the correlation is poorer and the rms error is not as good considering the typical range of nocturnal sensible heat flux values. The mean error is also quite large.

The aerodynamic resistance used by Berkowicz and Prahm, which is based on the Monin-Obukhov similarity theory, is determined by iteration using the following equations

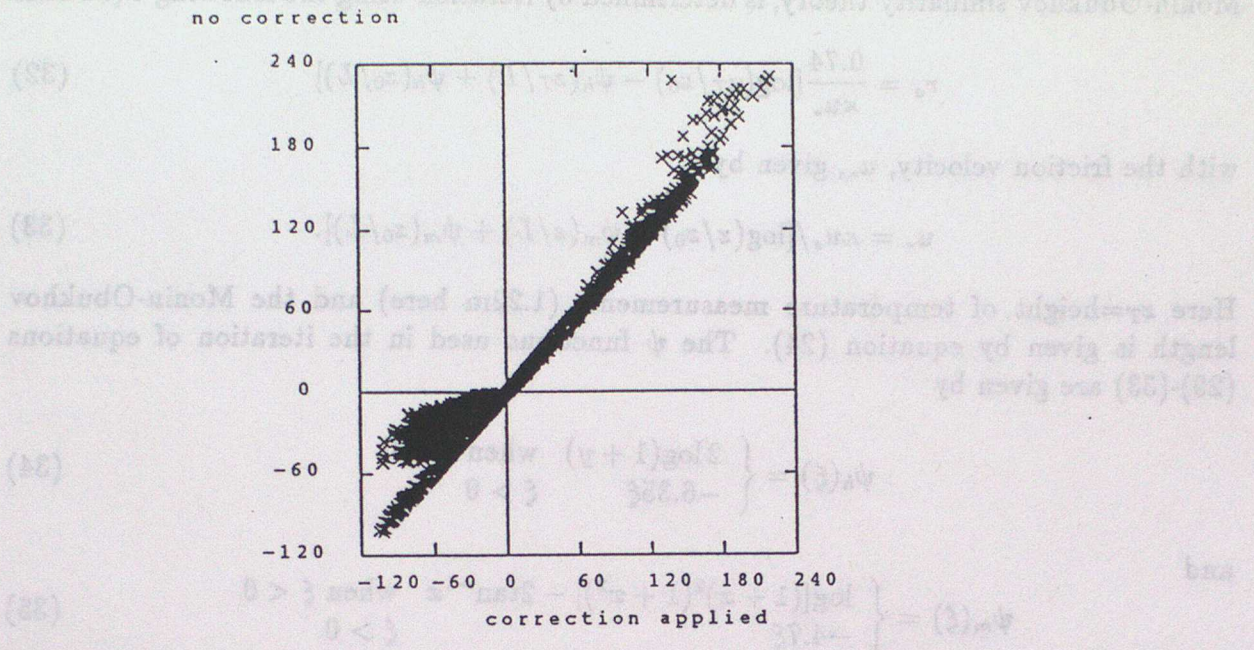


Fig. 10 Scatter plot of the Berkowicz and Prahm heat flux estimates with and without the stability correction iteration.

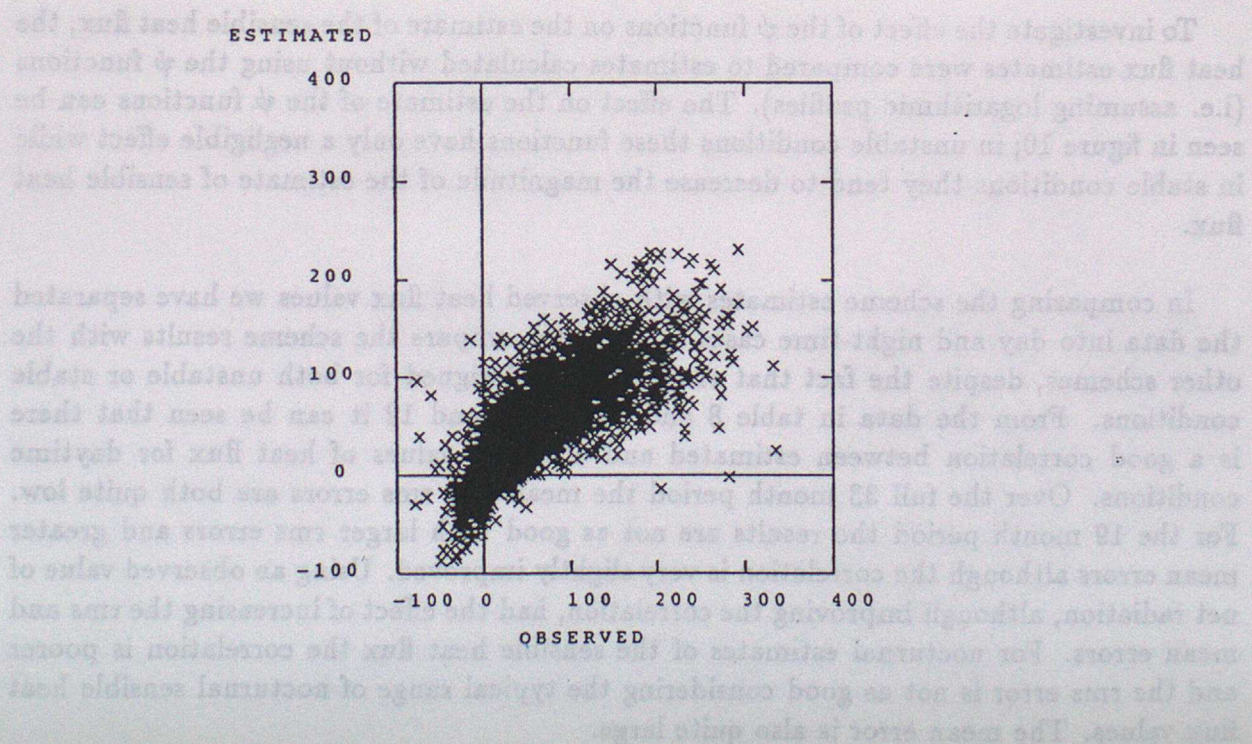


Fig. 11 Scatter plot of predicted and observed values of daytime sensible heat flux from the Berkowicz and Prahm heat flux scheme.

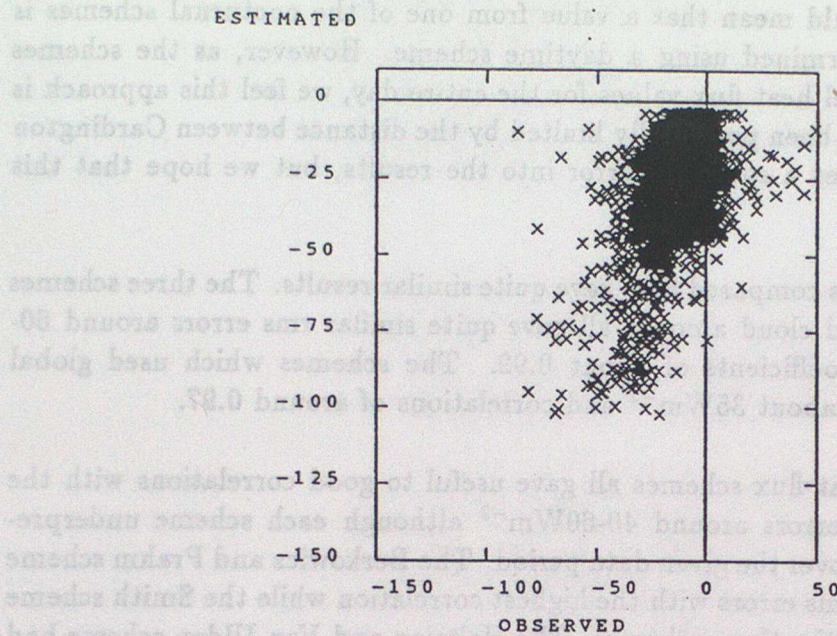


Fig. 12 Scatter plot of predicted and observed values of nighttime sensible heat flux from the Berkowicz and Prahm heat flux scheme.

Berkowicz and Prahm Heat Flux Scheme Statistics				
	daytime			night-time
	33 months data	19 months data	19 months data/real R_n	
n	4057	2166	2166	3562
\bar{x}	48.93	64.01	64.01	-10.91
\bar{y}	40.97	50.33	41.94	-25.74
s_x	64.72	71.58	71.58	14.30
s_y	50.44	55.08	47.76	16.91
$\bar{y} - \bar{x}$	-7.96	-13.68	-22.07	-14.83
σ	38.48	43.71	46.68	21.99
r	0.81	0.82	0.84	0.47

Table 8: Berkowicz and Prahm heat flux comparison statistics (see notes for table 1).

6 Discussion and Conclusion

The three net radiation and heat flux schemes have been compared statistically against observations using the following measures: means, standard deviations, mean errors (to give an estimate of the bias in each scheme) and root mean square (rms) errors and correlation coefficients (to give an estimate of accuracy). In carrying out the comparisons between the three schemes and observations some modifications to the schemes were

adopted. In particular, to account for cases when stable conditions occur during the daytime hours, an estimate of heat flux was obtained from the nocturnal heat flux scheme in addition to the daytime estimate, and the greater of these two estimated values was used. In some cases this could mean that a value from one of the nocturnal schemes is compared with a value determined using a daytime scheme. However, as the schemes are to be considered to model heat flux values for the entire day, we feel this approach is justified. This study has also been potentially limited by the distance between Cardington and Bedford which introduces a source of error into the results, but we hope that this error is small.

The net radiation schemes compared here gave quite similar results. The three schemes which use solar elevation and cloud amount all gave quite similar rms errors around $60\text{--}70\text{Wm}^{-2}$ with correlation coefficients of about 0.92. The schemes which used global radiation gave rms errors of about 35Wm^{-2} and correlations of around 0.97.

The daytime sensible heat flux schemes all gave useful to good correlations with the Cardington data with rms errors around $40\text{--}60\text{Wm}^{-2}$ although each scheme underpredicted the sensible heat flux over the given data period. The Berkowicz and Prahm scheme had the smallest mean and rms errors with the highest correlation while the Smith scheme had the largest rms error of the three schemes. The Holtslag and Van Ulden scheme had the largest mean error and displayed a marked tendency to underpredict higher values of the daytime sensible heat flux. The use of measured net radiation data made little difference to the results of all three schemes.

The nocturnal heat flux schemes proposed by Smith (1990) and Holtslag and Van Ulden (1982) are separate from the daytime heat flux schemes in that, without the effect of solar heating, H is determined from wind speed and cloud cover. Berkowicz and Prahm's (1982) estimate is determined by the same method of calculation by which the daytime estimate is made, although in stable conditions the iteration process (which accounts for the effect of stability on r_a) has a larger effect. Of the three nocturnal schemes, the Holtslag and Van Ulden scheme has the lowest rms and mean errors and the greatest correlation coefficient. Using measured values of the friction velocity in the Holtslag and Van Ulden scheme (instead of an estimated value) had the effect of increasing the mean error while improving the correlation.

Results have been presented for two periods, the first covering 33 months of data from February 1988 to October 1990 and the second 19 months from April 1989 to October 1990. For the second data period estimates of heat flux were made with observed and estimated values of net radiation and the results were compared to see the effect of using real net radiation values. However during the later 19 month period it was noted that the mean and rms errors were appreciably worse than over the entire 33 month period. The seasonal variability of the mean and rms errors can be seen in figures 13 and 14. In the case of the nighttime schemes there appears to be little clear evidence of seasonal variability. However the daytime schemes all seem to give large mean and rms errors in the summer months (peaking during August) and almost zero mean error and minimum rms error occurring during the winter months. By examining some specific hourly cases, the hours with the largest mean and rms errors seemed to coincide with occasions when the air humidity was quite low. In August the air and ground are at their driest in a typical English year. Figure 15 shows a graph of the monthly mean daytime humidities

measured at RAF Bedford and figure 16 shows the relation between monthly average daytime humidity and daytime rms error for the three schemes. These graphs seem to indicate a good correlation between low humidity and large errors from the daytime sensible heat flux schemes. The Berkowicz and Prahm scheme is the only one of the three schemes which attempts to account for the amount of water that is available for evapotranspiration, something which is a determining factor on the stomatal and, to a lesser extent, the ground resistances. The scheme does this by using the 'integrated hourly net radiation since last recorded rainfall' as an approximate way to gauge the soil moisture content. However the scheme is only a little better than the Holtslag and Van Ulden scheme in the summer months despite the additional complexity, suggesting that the method adopted by Berkowicz and Prahm does not fully represent such effects. As the amount of soil moisture decreases the plant stomata close up to prevent water loss by transpiration — therefore there is little water available for evaporation and so LE is very low in equation (1) and more energy is available for H . In the drier summer months the schemes would, as a result of low rates of evaporation from the soil and plants, over-predict the latent heat flux and so underpredict the sensible heat flux. This is also suggested by the scatter plots of the daytime sensible heat flux in figures 2, 6 and 11. In figure 6 and 11 the graphs exhibit a clear tendency to underpredict high values of heat flux and there is also a suggestion of this in figure 2.

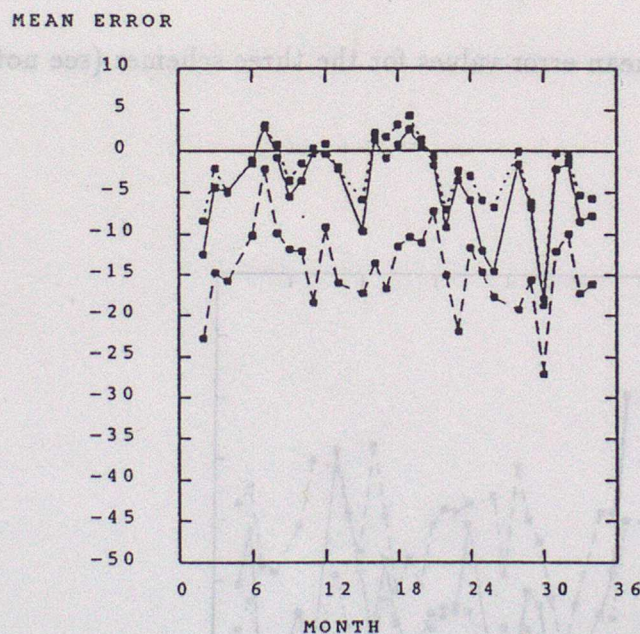


Fig. 13a Monthly nighttime mean error values for the three schemes (full line: Smith; dotted: Holtslag and Van Ulden; and dashed: Berkowicz and Prahm). Month 1 is January 1988 and month 36 is December 1990. No figures are plotted for months with no data.

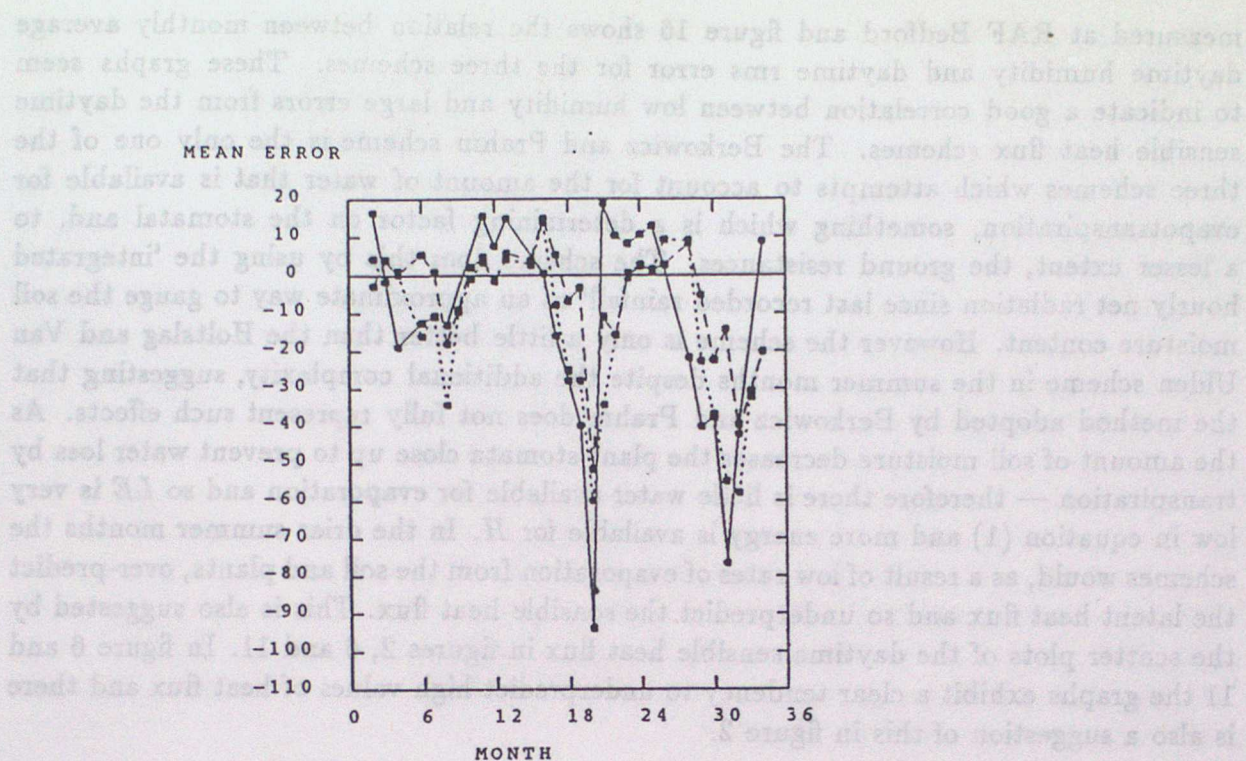


Fig. 13b Monthly daytime mean error values for the three schemes (see notes for figure 13a).

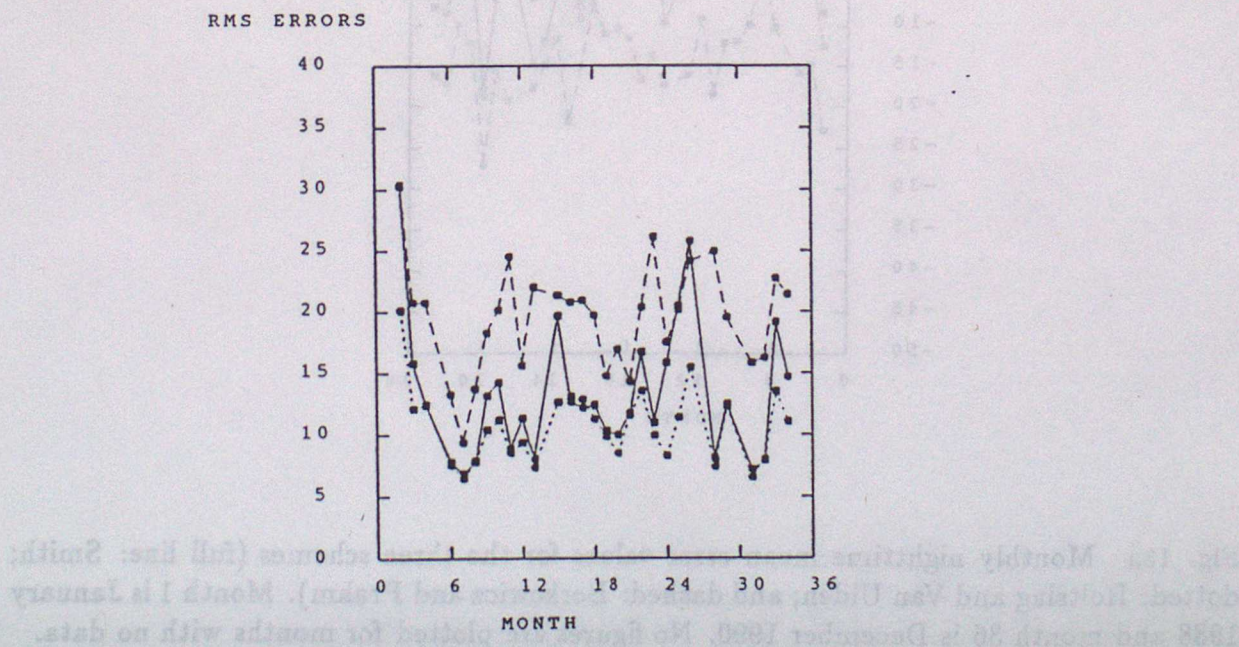


Fig. 14a Monthly nighttime rms error values for the three schemes (see notes for figure 13a).

RMS ERRORS

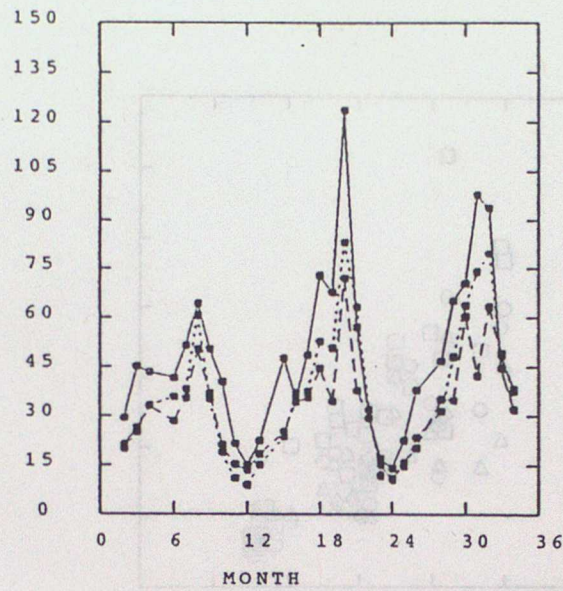


Fig. 14b Monthly daytime rms error values for the three schemes (see notes for figure 13a).

HUMIDITY (%)

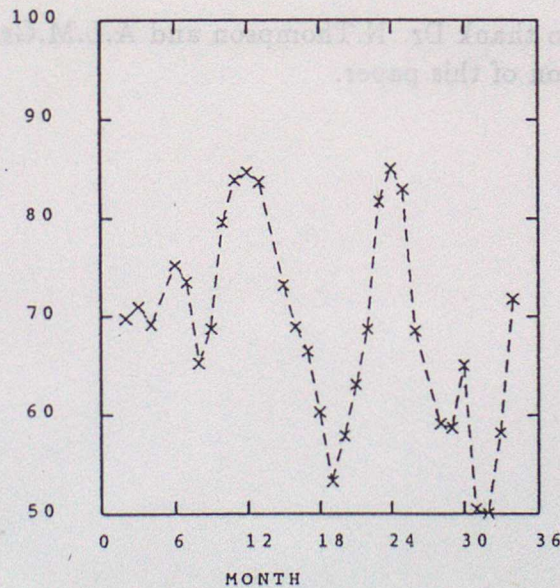


Fig. 15 Mean monthly daytime values of relative humidity (%) measured at RAF Bedford. Month 1 is January 1988 and month 36 is December 1990. No figures are plotted for months with no heat flux data.

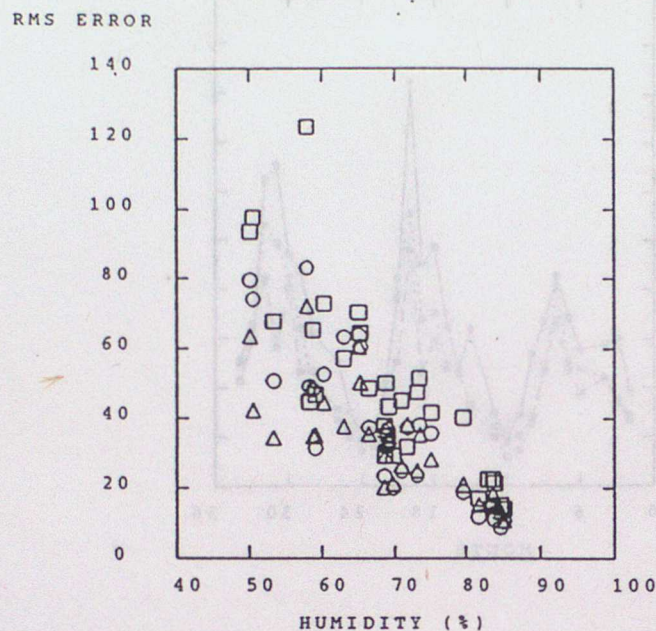


Fig. 16 Relationship between the rms errors of the three daytime schemes and monthly average daytime humidity (squares; Smith scheme, circles; Holtzlag and Van Ulden and triangles; Berkowicz and Prahm).

The authors would like to thank Dr. N.Thompson and A.L.M.Grant for their help in the discussion and preparation of this paper.

Appendix A: Nomenclature

A	solar declination
c_p	specific heat capacity of air
e_s	saturated vapour pressure
G	ground heat flux
g	gravitational acceleration
H	surface sensible heat flux
H_{crit}	critical value of sensible heat flux
H_{day}	estimate of sensible heat flux from one of the daytime schemes
H_{night}	estimate of sensible heat flux from one of the night-time schemes
h	relative humidity
K^+	incoming solar radiation
K_0^+	incoming solar radiation for clear skies
K^-	outgoing short wave radiation
L	Monin-Obukhov length
L^+	incoming long wave radiation
L^-	outgoing long wave radiation
LE	latent heat flux
N	cloud cover in oktas
N_m	modified cloud cover in oktas
n	Julian day number
q_s	saturated specific humidity
R_a	available energy ($R_n - G$)
R_n	net radiation
r	surface albedo
r_a	aerodynamic resistance
r_s	surface resistance
s	sine of the solar elevation
s_m	sine of the midday solar elevation
s'	dq_s/dT
T	screen temperature in kelvin (unless otherwise stated)
T_0	surface temperature
u_z	wind speed at height z
u_*	friction velocity
z_0	roughness length
z	height of wind measurement
z_T	height of temperature and humidity measurement
γ	psychrometric constant
Δ	de_s/dT
δq	humidity deficit $(1 - h/100)e_s$
θ	latitude
θ_*	surface layer temperature scale
κ	von Karman's constant
λ	specific latent heat of vaporization of water
ρ	density of air
Σ	integrated hourly net radiation since last recorded rainfall
ϕ	solar elevation

Appendix B: Solar Elevation

This appendix describes a scheme to calculate the solar elevation using Julian day number, latitude and local time. Smith, Holtslag and Van Ulden, and Berkowicz and Prahm each propose different schemes for calculating solar elevation, but for brevity Smith's method was used in all cases. These equations were proposed by Smith (1990) and have been estimated to give a maximum error equivalent to ± 15 minutes. Using the same method for determining solar elevation also ensures that the same input data is used in each of the schemes. Solar elevation, ϕ , is given by

$$s = \sin\theta\sin A + \cos\theta\cos A\cos(15(t - 12)) \quad (36)$$

where $s = \sin\phi$, θ is the latitude, A is the solar declination and t is the local time in hours. Solar declination is given by

$$A = 23.3\sin(0.9863(n - 81)) \quad (37)$$

where n is the Julian day number. In (36) and (37) the angles are expressed in degrees. Midday elevation (which is used in the Smith scheme) is given by

$$s_m = \sin\theta\sin A + \cos\theta\cos A \quad (38)$$

This algorithm gives s in the range -1 to 1 where nocturnal values are negative, zero for sunrise/sunset and 1 for (equatorial) midday. As Cardington has a longitude very close to 0° , no correction to convert Greenwich mean time to local time needed to be applied. The latitude of Cardington is about 52° and this value has been used in all the calculations.

Appendix C: Estimates of the sensible heat flux in the absence of cloud observations

Where routine observations of cloud amount are not available (as is the case for e.g. automatic weather stations), it may still be possible to obtain estimates of sensible heat flux. In daytime conditions some surrogate for cloud measurements is clearly required and incoming solar radiation is the obvious candidate as this is often measured by automatic weather stations. At night the situation is more difficult, but it should be noted that in the Holtslag and Van Ulden scheme (which had the best rms error and correlation of the three nocturnal schemes) the dependence on cloud amount is quite weak, and so the problem may not be as difficult as it at first seems. Here we investigate the possibility of applying the Holtslag and Van Ulden scheme (for day and night) in the absence of cloud information.

In daytime conditions with incoming solar radiation known, cloud has a relatively weak influence on the heat flux, appearing only in equation (16). As a result we investigate two approaches: (i) choosing the cloud amount to be some fixed value, and (ii) attempting to diagnose cloud amount from the incoming solar radiation using (14) and (15). For the latter approach we calculate cloud amount by solving $(N/8)^{b_2} = A$ where A is obtained from $[1 - K^+/(a_1 \sin \phi + a_2)]/b_1$ by limiting it to lie between 0 and 1. The results for approaches (i) and (ii) are shown in tables 9 and 10 respectively and show that there is not much to choose between the different methods of estimating cloud. Because the rms error is still improving at $N = 8$ we have given figures for $N = 10$ and 13 as well in table 9. The minimum rms error actually occurs at $N = 13$, this surprising result being at least partly a consequence of the reduction in the mean bias in the scheme achieved by taking N outside its natural range. The results are also comparable to those obtained when cloud data is available as shown in table 5 (note the figures should be compared with the '19 month' figures in table 5 since the radiation data needed for the comparison presented in tables 9 and 10 was only available for that period).

Holtslag and Van Ulden Daytime Heat Flux Scheme Statistics											
N	0	1	2	3	4	5	6	7	8	10	13
\bar{y}	26.33	28.07	29.85	31.67	33.52	35.41	37.34	39.32	41.37	45.81	54.52
s_y	40.77	41.13	41.47	41.77	42.06	42.31	42.53	42.71	42.81	42.64	40.27
$\bar{y} - \bar{x}$	-39.67	-37.92	-36.15	-34.33	-32.48	-30.59	-28.66	-26.68	-24.63	-20.19	-11.48
σ	61.80	60.63	59.49	58.38	57.31	56.30	55.33	54.42	53.58	52.12	51.19
r	0.79	0.79	0.79	0.79	0.78	0.78	0.78	0.78	0.77	0.77	0.75

Table 9: Holtslag and Van Ulden daytime heat flux comparison statistics obtained with the assumption of constant cloud amount in eqn. (16) and the use of measured K^+ (see notes for table 1). $n = 2024$, $\bar{x} = 66.00$ and $s_x = 72.30$.

Holtzlag and Van Ulden Daytime Heat Flux Scheme Statistics	
n	2024
\bar{x}	66.00
\bar{y}	36.55
s_x	72.30
s_y	40.68
$\bar{y} - \bar{x}$	-29.45
σ	55.55
r	0.79

Table 10: Holtzlag and Van Ulden daytime heat flux comparison statistics obtained with the use of measured K^+ and with cloud amount diagnosed from measured K^+ (see notes for table 1).

For nocturnal conditions, we looked at the effect of fixing the cloud amount at a constant value in the Holtzlag and Van Ulden scheme. The results for different values of N are shown in table 11. As the mean and rms errors appeared to be decreasing, values of cloud amount above 8 oktas were included to find the value corresponding to the minimum values of the mean and rms errors as for the daytime case. It can be seen that for a value of cloud cover around '8 oktas', which corresponds to $\theta_* \simeq 0.045K$, the scheme gives the best results, with a rms error of around $12Wm^{-2}$ and mean error close to zero. If this value for θ_* is assumed as a default, then the rms error values are (slightly) better than if cloud measurements are used, although the correlation is not quite as good. It should be stressed that this is a consequence of the weak effect of cloud and the tendency of the Holtzlag and Van Ulden scheme to overestimate the magnitude of the heat flux at Cardington; this latter aspect may not be true at other sites - for example it seems likely that the data on which the scheme was originally developed would suggest a value more towards the middle of the range 0 to 8. As a result it is probably more sensible to adopt an intermediate value in applying the scheme at an arbitrary site. A possible choice would be $N = 5$ or 6. Because θ_* depends non-linearly on N , this choice would correspond to a value of θ_* lying in the middle of the range implied by (23).

Holtzlag and Van Ulden Nocturnal Heat Flux Scheme Statistics											
N	0	1	2	3	4	5	6	7	8	9	10
\bar{y}	-16.51	-16.43	-16.19	-15.79	-15.20	-14.40	-13.34	-11.97	-10.22	-8.01	-5.16
s_y	19.29	19.15	18.73	18.01	17.00	15.68	14.03	12.05	9.72	7.04	4.07
$\bar{y} - \bar{x}$	-5.59	-5.51	-5.28	-4.87	-4.29	-3.49	-2.43	-1.06	0.69	2.91	5.75
σ	17.27	17.15	16.78	16.18	15.36	14.38	13.30	12.33	11.77	12.09	13.69
r	0.56	0.56	0.56	0.56	0.57	0.57	0.57	0.58	0.58	0.58	0.57

Table 11: Holtzlag and Van Ulden nocturnal heat flux comparison statistics obtained with the assumption of constant cloud amount in eqn. (23) (see notes for table 1). $n = 3562$, $\bar{x} = -10.91$ and $s_x = 14.30$.

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