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from routine weather data.

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A.A.M. Holtslag and A.P. van Ulden

Abstract

This report deals with hourly estimates of the surface fluxes of heat and momentum from routine weather data during nighttime. For this purpose one year of measured profiles of wind and temperature are analysed. With the measured profiles the friction velocity (u_*) and the temperature scale (θ_*) are computed using the flux-profile relations of Dyer (1974). It appears that θ_* decreases for very high and low windspeeds. But in an intermediate region of u_* it follows that θ_* decreases mainly with increasing total cloud cover (N). These results are consistent with the analysis by Venkatram (1980), which is based on the Prairie Grass, Kansas and Minnesota data. The behaviour of θ_* with u_* and N is described. This implies that the surface fluxes can be obtained from a single windspeed, the surface roughness length, total cloud cover and the air temperature. The required procedures are fairly simple and are described in the paper. It is shown that the proposed scheme can furnish good estimates for the flux of sensible heat, the flux of momentum in terms of the friction velocity and the Obukhov stability parameter. With the scheme a satisfactory description can be given of the nocturnal surface layer.

1. Introduction.

The surface fluxes of heat and momentum are important parameters in the description of the atmospheric boundary layer. The fluxes determine the turbulent state and the stability of the surface layer. The fluxes are used in boundary layer models, air pollution models and for the description of profiles near the ground of wind and temperature.

In principle the fluxes can be measured. However, such measurements are difficult and in practice usually only standard meteorological data are available. So there is a need to relate the fluxes to routine weather data. It is the aim of this paper to establish such relations in stable conditions. For unstable conditions such relations are given by Holtslag and Van Ulden (1982), based on a parameterization of the surface energy budget.

The surface energy budget relates the flux of sensible heat H to the net radiation Q^*, the soil heat flux G and the flux of latent heat λE. It reads (Sellers, 1965):

$$H + \lambda E + G = Q^* \ . \qquad (1)$$

During nighttime Q^* is negative and it is mainly fed by H and G, because in the night evaporation is usually small for a vegetated surface. The soil heat flux G is a large fraction of Q^* and it is depending on the solar heating of the surface in the preceding day. Further Q^* is affected by windspeed and cloud cover (Holtslag and Van Ulden, 1980; Nielsen et al., 1981). In the following it is shown that also H is affected by windspeed. So modelling of the surface energy budget during nighttime is rather complicated.

Instead of trying to model H with the aid of the surface energy budget we may consider the temperature scale θ_* and the friction velocity u_*. These quantities are related to H by

$$H = -\rho \ c_p \ u_* \ \theta_* \ , \qquad (2)$$

where ρ is the density of air and c_p is the specific heat of air at constant pressure. The friction velocity is related to the flux of momentum τ by:

$$\tau = \rho \ u_*^2 \ . \qquad (3)$$

The friction velocity u_* and the temperature scale θ_* can be obtained from observed temperature and wind profiles (see section 2). However, normally the required data is not available and u_* and θ_* have to be obtained in an other way.

In this report θ_* is related to cloud cover and u_* (section 3). Consequently from θ_* , a surface roughness length and a single windspeed the friction velocity u_* is determined (section 4). Then the Obukhov stability parameter L, defined by

$$L = \frac{u_*^2}{k \frac{g}{T} \theta_*} \tag{4}$$

can be calculated. In (4) k is the Von Kårmån constant, g the accelaration of gravity and T the air temperature. The quantities of the scheme will be compared with the "observed" quantities of wind and temperature profiles (section 2).

2. Observation of the fluxes

The surface fluxes of heat and momentum can be obtained from the profiles of temperature and wind applying Monin-Obukhov similarity theory.
The semi-empirical flux-profile relations of Dyer and Webb (see Dyer, 1974) read in their integral form:

$$u_* = k\ u_z\ \left[\ln\left(\frac{z}{z_o}\right) + \beta\ \frac{z}{L}\right]^{-1} , \tag{5}$$

and

$$\theta_* = k\ \Delta\theta\ \left[\ln\left(\frac{z_2}{z_1}\right) + \frac{\beta(z_2-z_1)}{L}\ \right]^{-1} . \tag{6}$$

Here L is given by (4), z_o is the surface roughness length, U_z the windspeed at a height z and $\Delta\theta$ is a temperature difference between the two heights z_2 and z_1. Further k is the von Kårmån constant ($k = 0.41$) and β is an empirical contant ($\beta = 5.2$).

Using (4), (5) and (6) we can obtain u_*, θ_* and L from a single wind speed U_z, a temperature difference $\Delta\theta$, the air temperature T and the surface roughness length z_o. We use the following procedure. The surface roughness length is obtained from a method by Wieringa (1976, 1980), using routine wind measurements. Table 1 gives a crude estimate of z_o for eight classes of surface roughness lengths.

The calculation starts with L = 5 in (5) and (6). Then u_* and θ_* are obtained and L is calculated with (4). With this value for L the calculation of u_* and θ_* is repeated until successive values of L are within 1 percent. It follows that usually not more than 3 iterations are needed to achieve the required accuracy in L. Finally the surface fluxes H and τ are obtained with (2) and (3).

From one year of data at Cabauw (1 March 1977 - 1 March 1978) we have used 30 minute averages of the observed temperature difference between z_2 = 10 m and z_1 = 0.6 m, the air temperature at screenheight (2 m) and the 10 m windspeed. Only hours are taken into account with no rain or fog and with 10 m windspeed $U_{10} > 1\ ms^{-1}$. The results of this calculation are in agreement with the method of Nieuwstadt (1978), except in very stable conditions.

With Nieuwstadt's method u_* and θ_* are obtained applying least square techniques with weight factors to the observed wind and temperature profiles. We prefer to use the above method because the fluxes of Nieuwstadt's method are rather sensitive for the weight factors in very stable conditions. This problem does not occur in the above method. Besides of this the above method is less time consuming and it is more easy to handle.

3. Modelling of the temperature scale θ_*.

During stable conditions in the atmospheric surface layer the sensible heat flux H is negative and the turbulent temperature scale θ_* is positive (see (2)). In section 2 we have seen that a temperature difference $\Delta\theta$ is needed to obtain θ_*. However, normally $\Delta\theta$ is not available and θ_* must be obtained in an other way.

Venkatram (1980) suggests that θ_* is nearly constant in stable conditions. According to data of the Prairie Grass, Kansas and Minnesota experiments

$$\theta_* = 0.08 \text{ (K)} . \qquad (7)$$

This estimate is based mainly on observations made during clear nights in homogeneous conditions. We will extend (7) to cloudy conditions and we will investigate a possible dependence of θ_* on the friction velocity u_*.

Fig. 1 shows a plot of θ_* versus u_* for two classes of total cloud cover (N) during nighttime. Each point is an average of at least 15 observations of θ_* . In the figure lines are drawed for which the Obukhov stability parameter L = 10 m and the sensible heat flux H = -60 Wm^{-2}.

In Fig. 1 it is seen that between the two lines θ_* is almost independent from u_* but clearly a function of cloud cover.
From our data we found that:

$$\theta_* = 0.09\ (1 - 0.5\ N^2)\ , \tag{8}$$

yields satisfactory estimates of θ_* (in K) for L > 10 m and H < -60 Wm^{-2}. For 1643 (30 minute) averages of θ_* we found a root mean square error σ = 0.026 K and a correlation coefficient r = 0.5 between (8) and θ_* observed from profiles (section 2). The total cloud cover was interpolated from four synoptic stations around Cabauw (within 40 km). The estimate of (8) is consistent with (7), because (7) is based mainly on measurements made in clear nights.

For very stable conditions (L < 10) we see from Fig. 1 that θ_* decreases with u_*. A simple empirical solution to obtain the fluxes in these conditions is dicussed in section 4. At extremely high windspeed we obtain with (2) and (8) that the sensible heat flux increases indefinitely. We may expect that in these cases the surface radiation budget puts a limit on H. From our data it follows that H = -60 Wm^{-2} is an appropriate limit for H (see Fig. 1).

Our estimate (8) applies when the sun is below the horizon. When the sun is above the horizon the atmosphere becomes less stable until at a certain solar elevation ϕ_o the atmosphere becomes unstable. The latter occurs for $\phi_o \simeq 13$ degrees for N < 0.75 up to $\phi_o = 23$ degrees for N = 1 (Holtslag and Van Ulden, 1982).

When the heat flux is negative and the sun above the horizon the solar elevation ϕ enters the scheme for θ_*. We propose:

$$\theta_*^t = \theta_*^n\ \{1 - (\frac{\phi}{\phi_o})^2\} \tag{9}$$

for $0 < \phi < \phi_o$.

Here θ_*^n is the estimate of (8), θ_*^t is the estimate in transition hours and ϕ_o is the solar elevation for which a zero heat flux occurs. The latter quantity can be obtained from the daytime scheme of Holtslag and Van Ulden (1982). Here also a scheme is given for ϕ which uses geographical position and time. It appears that the estimate of (9) provides a comparable fit to data for transition hours as (8) does for night data.

4. Estimation of the fluxes from a modelled θ_*.

In this section we will derive the friction velocity u_* with our estimates for the temperature scale θ_* of the preceding section. Then the fluxes and the Obukhov stability parameter are obtained with (2), (3) and (4).

We may substitute (4) into (5) to obtain a quadratic equation in u_* for a given θ_*, U_z, z_o and T. The solution for u_* reads:

$$u_* = \tfrac{1}{2} \{u_{*N} + D_{u_*}^{\frac{1}{2}}\} , \qquad (10)$$

where D_{u_*} is given by:

$$D_{u_*} = u_{*N}^2 - \frac{4 \beta k g z \theta_*}{T \ln z/z_o} . \qquad (11)$$

Further u_{*N} is the value of u_* without stability correction ($L = \infty$ in (5)) given by

$$u_{*N} = \frac{k U_z}{\ln z/z_o} . \qquad (12)$$

The value of θ_* is given by (8) or (9) and z_o can be obtained from a method by Wieringa (1976, 1980) or table 1. Then it is seen that u_{*N}, D_{u_*} and thus u_* can be caluclated with U_z and T, but we have to require that $D_{u_*} > 0$.

The requirement $D_{u_*} > 0$ may reduce the practical use of (10). Let us compute for z = 10 m the values for the friction velocity u_{*o} and the Obukhov stability parameter L_o which occur at $D_{u_*} = 0$. Then it follows with (4), (10) and (11):

$$u_{*o} = \tfrac{1}{2} u_{*N} \qquad (13)$$

and

$$L_o = \frac{10\ \beta}{\ln \frac{10}{z_n}} . \tag{14}$$

With β = 5.2 and z_o = 0.15 (average value at Cabauw) we obtain with (14) L_o = 12.4 m. Then the 10 m windspeed U_{10} is U_{10} = 2.6 ms^{-1} at clear skies and U_{10} = 1.8 ms^{-1} at total overcast. Here we have taken T = 280 K in (11). It follows that $D_{u_*} < 0$ occurs at low windspeed and very stable conditions. These conditions correspond to the small values of θ_* and u_* in Fig. 1.

From Fig. 1 it is seen that for the very stable conditions (L < 10) u_* and θ_* both tend to zero. To obtain the fluxes in these conditions we propose a linear interpolation between $\theta_* = u_* = 0$ and θ_* estimated with (8) or (9) and u_* obtained with (13). Then it follows

$$\theta_* = 2\ \theta_{*s} \frac{u_*}{u_{*N}} , \tag{15}$$

where θ_{*s} is the value of (8) or (9) and u_{*N} is given by (12). With (15) u_* and L can be obtained in the very stable conditions using (4), (5) and (12). It reads for u_*:

$$u_* = \frac{k\ U_{10}}{\ln \frac{10}{z_o}} - \frac{20\ \beta\ g\ \theta_{*s}}{T\ U_{10}} , \tag{16}$$

where we have used the 10 m windspeed (U_{10}).
With (16) it follows that u_* = 0 for U_{10} = 1.8 ms^{-1} at clear skies decreasing to U_{10} = 1.3 ms^{-1} at total overcast. Beneath these small values of U_{10} the scheme gives $u_* = \theta_* = L = 0$.

With the above equations we can make estimates for θ_* and u_*. Then H, τ and L are given by (2), (3) and (4). We made a comparison of u_*, H and L of the scheme with corresponding values obtained from profiles (see section 2). We have used the 10 m windspeed, the air temperature at 2 m and total cloud cover interpolated from four synoptic stations around Cabauw (within 40 km). In 2 % of the cases H of the scheme H < -60 Wm^{-2}. Then we putted H = -60 Wm^{-2} and $u_* = u_{*N}$ given by (12). The latter estimate is within a few percent at these high windspeed cases. Results are shown in Figs. 2, 3 and 4 for nighttime hours. A distinction is made between cases with $D_{u_*} > 0$ and $D_{u_*} < 0$.

From the figures it is seen that rather good estimates for u_*, H and L can be obtained using our scheme. As expected the very stable cases show the largest deviations. However, on average of course the estimates of (15) and (16) are acceptable. These estimates are necessary in 10 % of the cases because then $D_{u_*} < 0$.

In the comparisons there is a bias because the same windspeed data has been used in the calculated and observed quantities. Nevertheless, our scheme will give reliable estimates for u_*, H and L in practice, because the fluxes from profiles compare reasonable with those from turbulence measurements (Nieuwstadt, 1978).

5. Summary and conclusions

In this report a simple scheme is presented which relates the surface fluxes of heat and momentum to routine weather variables. The required input weather data are the air temperature at screenheight (2 m), the 10 m windspeed and the total cloud cover. Further the surface roughness length is needed. As such the scheme can serve as an alternative for the traditional Pasquill stability classification (Pasquill, 1974).

From one year of measured windspeed and temperature profiles it appears that the turbulent temperature scale (θ_*) can be described as a function of the friction velocity (u_*) and the total cloud cover (N). It follows that θ_* decreases with increasing cloud cover. Further it follows that θ_* also decreases for very high and low windspeeds. The results are consistent with the analysis by Venkatram (1980).

With the described relation between θ_*, u_* and N it is shown that the scheme provides good estimates for the friction velocity, the flux of sensible heat and the Obukhov stability parameter. Because of this and its simplicity we conclude that the scheme is useful for many applications in boundary layer meteorology.

At present the scheme is applied in the Dutch boundary-layer/trajectory model for short range weather forecasting (Reiff et al., 1982) and in the KNMI mesoscale air pollution transport model (Van Dop et al., 1982).

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Table 1

Terrain classification by Wieringa (1980) in terms of aerodynamical roughness length z_0.

Class	Short terrain description	z_0 (m)
1	Open sea, fetch at least 5 km	0.0002
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, $x/h > 20$	0.10
5	High crops; scattered obstacles, $15 < x/h < 20$	0.25
6	Parkland, bushes; numerous obstacles, $x/h \sim 10$	0.5
7	Regular large obstacle coverage (suburb, forest)	(1.0)
8	City center with high- and low-rise buildings	?-?

Notes: Here x is typical upwind obstacle distance and h the height of the corresponding major obstacles. Class 8 is theoretically intractable within the framework of boundary layer meteorology and can better be modelled in a wind tunnel. For simple modelling applications it may be sufficient to use only classes 1, 3, 5, 7 and perhaps 8.

Figure captions

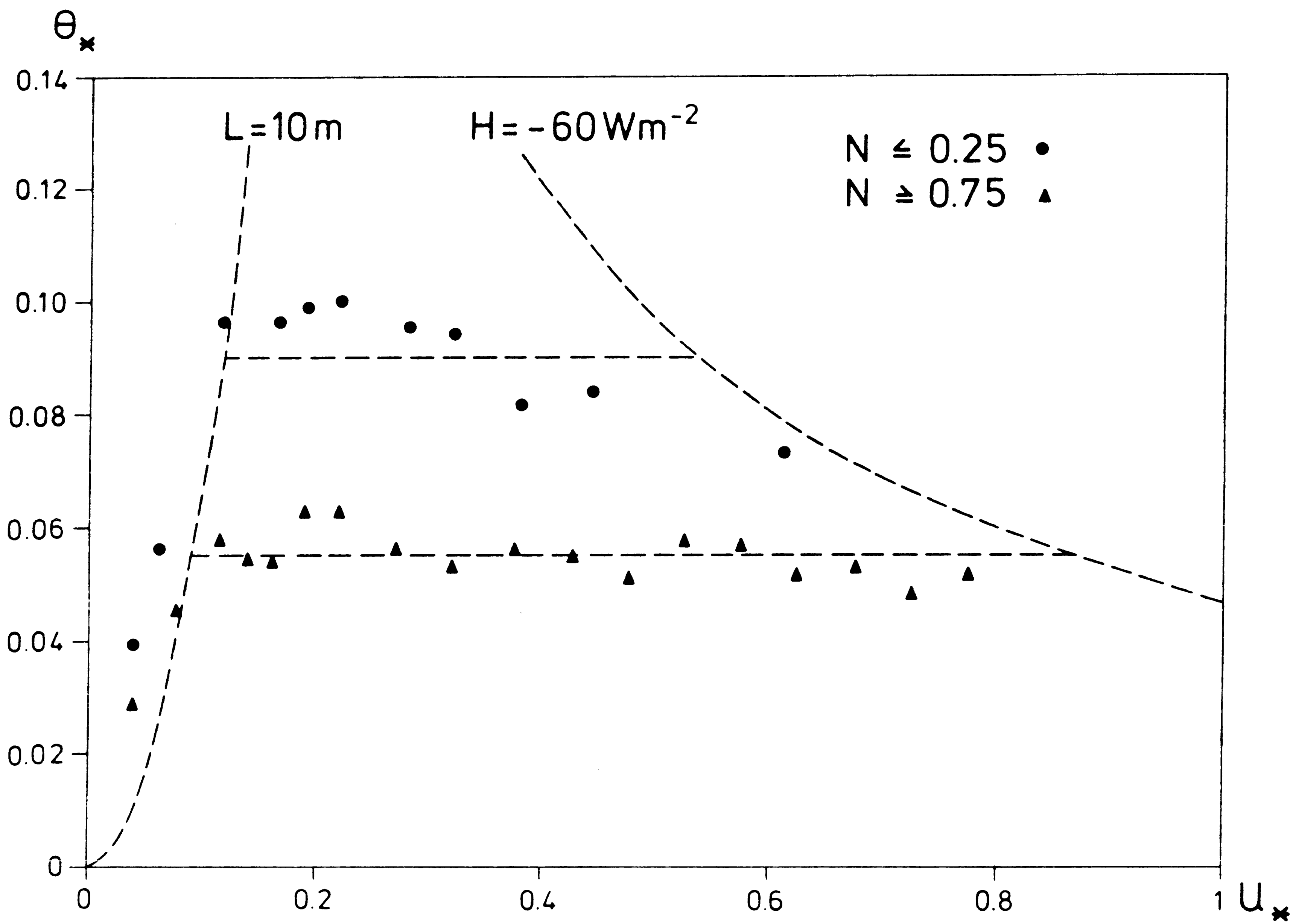
Fig. 1. The variation of the temperature scale θ_* (in K) with friction velocity u_* (in ms^{-1}) for clear skies (dots) and cloudy skies (triangles). In the figure N is total cloud cover, L is Obukhov stability parameter and H is the sensible heat flux.

Fig. 2. Comparison of 30 minute averages of the friction velocity u_* (in 0.01 ms^{-1}) obtained with profiles of wind and temperature with calculated values of the scheme. (σ = 0.03 ms^{-1}, r = 0.99).

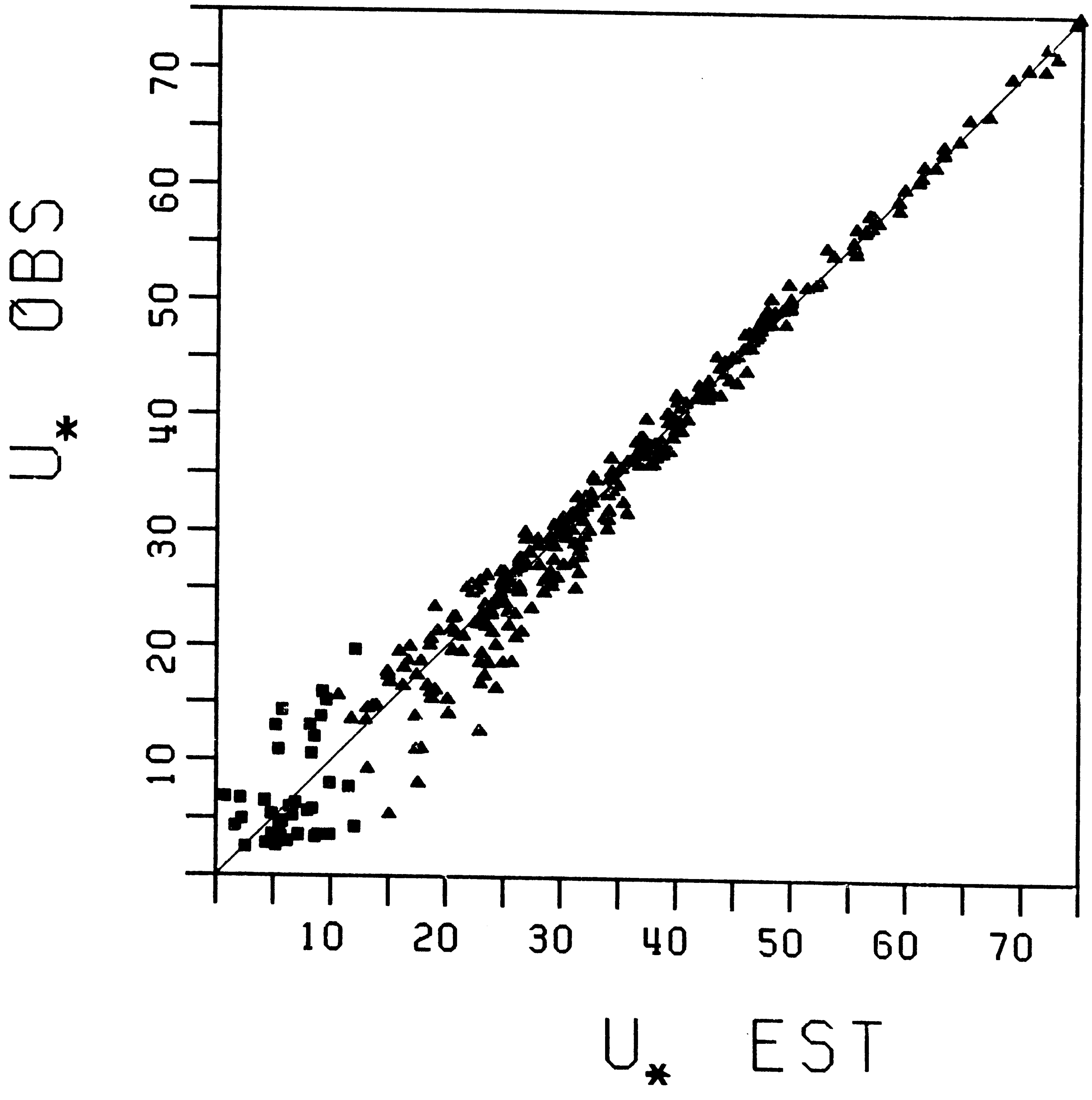
Notes: In the figure a selection of the whole data set is given. Triangles refer to stable conditions with $D_{u_*} > 0$ and squares refer to conditions with $D_{u_*} < 0$ (see (11)). The root mean square error σ and the correlation coefficient r are calculated for the whole data set of 1643 hours during nighttime. The additions OBS and EST along the axes of the figure refer to quantities observed profiles and those estimated with the present scheme, respectively.

Fig. 3. Comparison of observed and calculated 30 minute averages of the sensible heat flux H (in Wm^{-2}) (σ = 9.5 Wm^{-2}, r = 0.79). See notes of Fig. 2.

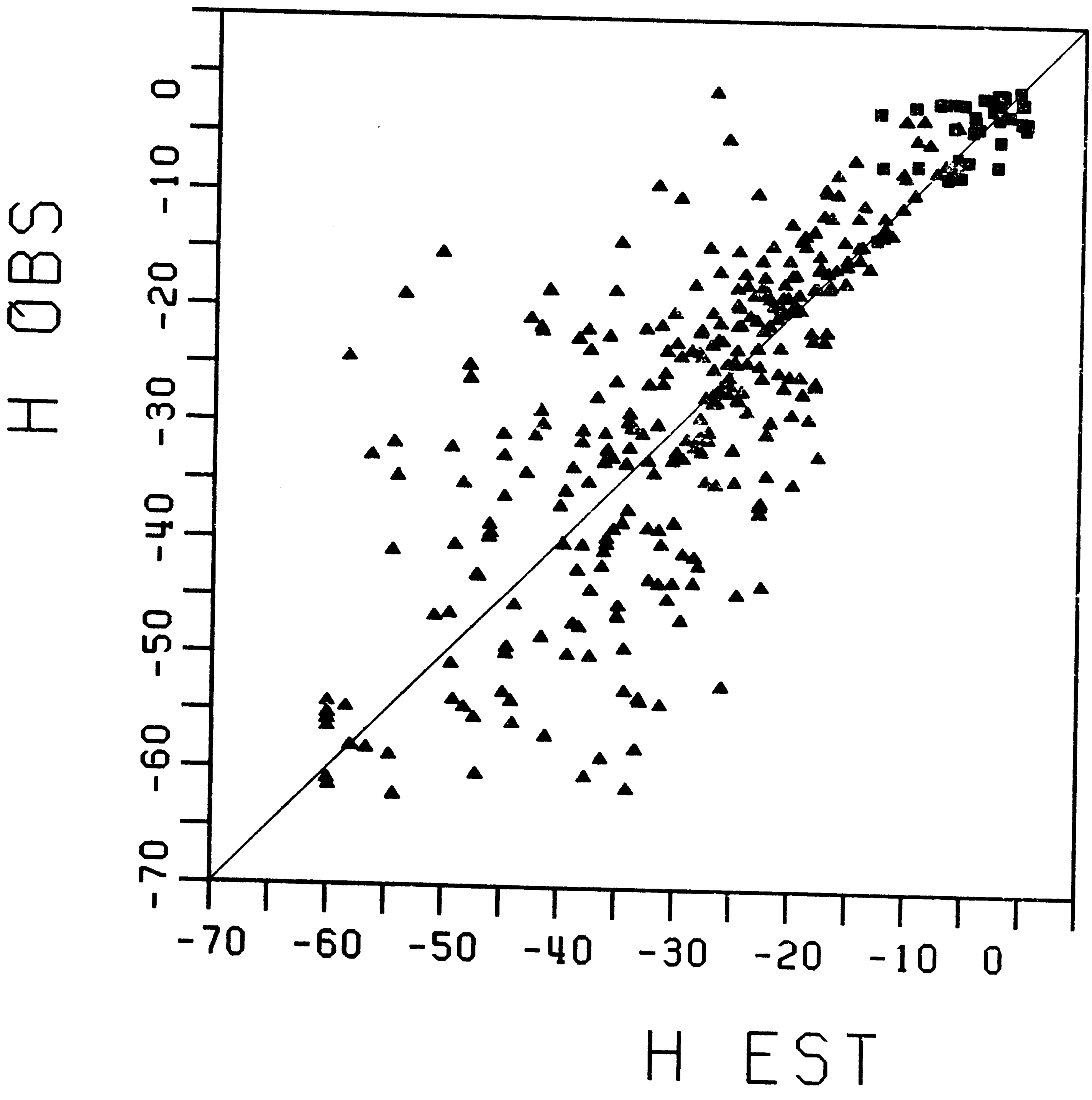
Fig. 4. Comparison of observed and calculated 30 minute averages of the Obukhov stability parameter L (in m) (σ = 50 m, r = 0.85). See notes of Fig. 2.



θ*
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.2
0.4
0.6
0.8
1
U*
L=10m
H=-60Wm-2
N ≤ 0.25
N ≥ 0.75



U* ØBS
U* EST
10
20
30
40
50
60
70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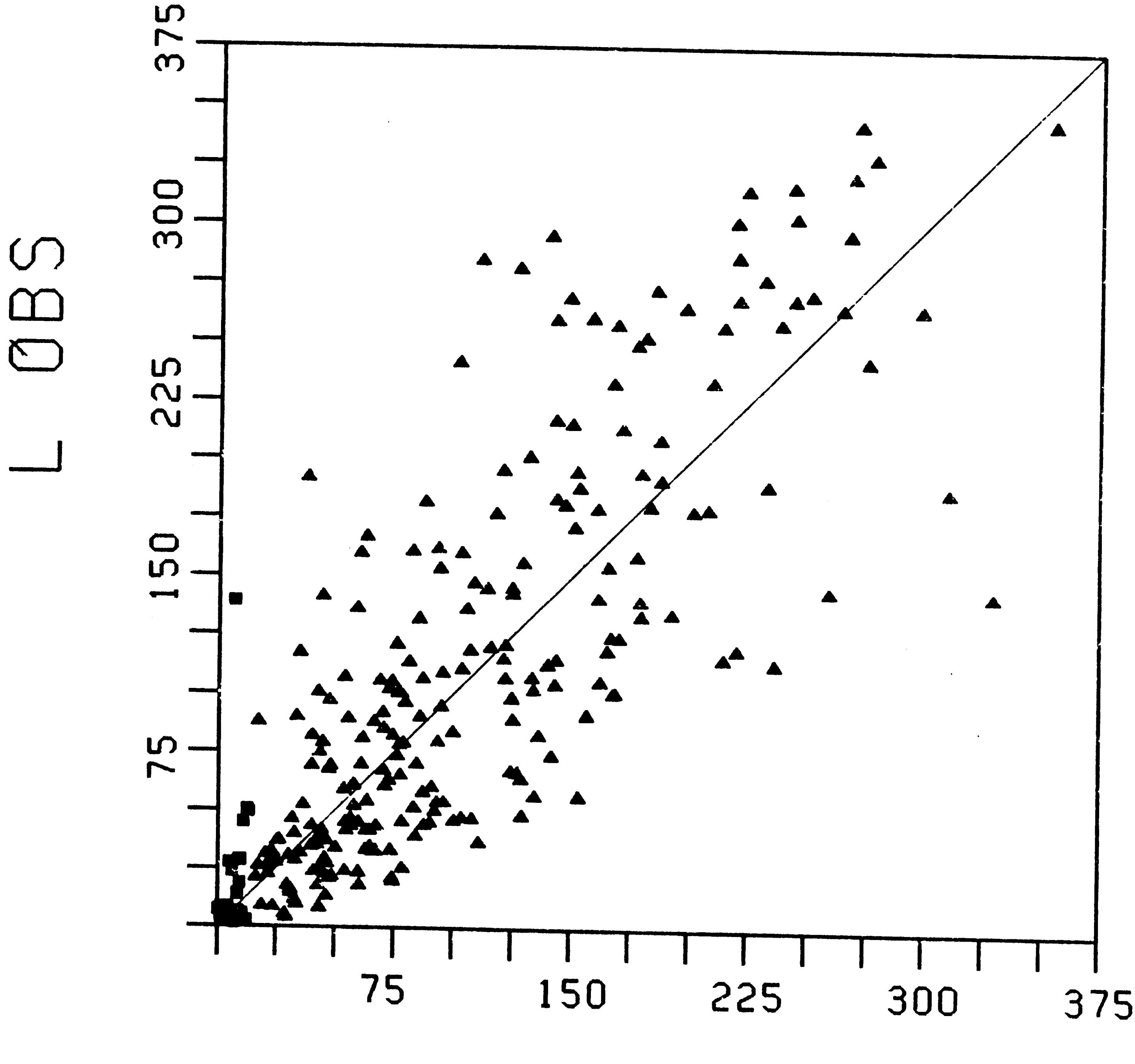
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300
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