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ESTIMATES OF INCOMING SHORTWAVE RADIATION AND NET RADIATION FROM STANDARD METEOROLOGICAL DATA

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Abstract

This report deals with estimates of hourly averages of incoming shortwave (solar) radiation and net radiation from standard meteorological observations. It is shown that incoming shortwave radiation can be estimated relatively accurate from solar elevation and total cloud cover only. Furthermore, from incoming shortwave radiation, albedo, total cloud cover and screentemperature the net radiation can be estimated by day, with a fair accuracy. In the night the net radiation can be estimated, but not very accurately, from the observed windspeed and total cloud cover.

Contents

1. Introduction

An important input parameter in boundary layer models and air pollution dispersion models is the surface heat flux. For practical applications of these models simple estimates of the heat flux from routine synoptic data are useful.

Such estimates, in principle, can be obtained from surface energy budget considerations. The first step in this approach is to estimate the net radiation. This can be done from measured incoming shortwave radiation, screentemperature and cloud cover. When no shortwave radiation is measured it can be estimated from solar elevation and cloud cover.

Estimation schemes are tested with hourly data obtained at Cabauw and De Bilt in 1973. Hours with rain or fog are excluded because in these cases the measurements are unreliable. This is not a serious problem because in these conditions the surface heat flux is small.

In section 2 we discuss the incoming shortwave radiation. Section 3 deals with the net radiation. Section 4 contains the conclusions of this investigation.

2. Estimates of shortwave radiation

2.1. Clear skies

For the estimation of hourly averages of incoming shortwave (solar) radiation (K_o^+) at ground level from clear skies, several models are given in literature. We take the following representation (Lumb, 1964; Collier and Lockwood, 1974, 1975):

$$K_o^+ = I + D \qquad (2.1)$$

Here I is the direct shortwave radiation given by:

$$I = S\, t(\gamma) \sin\gamma \qquad (2.2)$$

with S the solar constant (1353 Wm^{-2}), $t(\gamma)$ the transmissivity of the atmosphere and γ the solar elevation. D represents the diffuse shortwave radiation:

$$D = D_o \sin\gamma \qquad (2.3)$$

where D_o is assumed constant for clear skies. For the transmission function $t(\gamma)$ we write:

$$t(\gamma) = a' + b \sin\gamma \qquad (2.4)$$

where a' and b are constants.

Combining the relations (2.1), (2.2), (2.3) and (2.4) we obtain:

$$K_o^{+} = S \sin \gamma \ (a + b \sin \gamma) \qquad (2.5)$$

where a is identical to a' + D_o/S.

Table 1 gives values of a and b found in literature and for De Bilt in 1973 for clear skies. Our constants a and b were obtained from a regression model: Y = a + bX, where Y = K_o^{+} measured $(S \sin \gamma)^{-1}$ and X = $\sin \gamma$. Only hours with total cloud cover (N_t) less than or equal to one octa observed 10 minutes before and at the end of the hour were taken into account.

The solar elevation (γ) was estimated with a simple procedure, with an average accuracy of 0.3 degrees (see Appendix). The hourly averages of the shortwave radiation (K_o^{+}) were obtained from measurements with a Moll-Gorczynski-pyranometer with a sampling period of 10 minutes.

The differences in a and b shown in table 1 are probably caused by variations in the attenuation of the solar beam by aerosol in the atmosphere. The differences in the constants are causing a decrease of the shortwave radiation with about 10% for De Bilt in comparison with open ocean. This percentage was also found by an investigation at the Rijnmond industrial area in the Netherlands (Frantzen and Raaff, 1978).

No account has been taken of the varying solar distance. This would involve a correction to K_o^{+} of not more than 3 percent, which is less than the estimated accuracy of the measurements (about 5 percent).

Figure 1a shows a diagram of a random sample of observed values of incoming shortwave radiation and of values calculated with equation (2.5) with a and b found in De Bilt. For hourly averages at clear sky conditions (triangles) the agreement is good (SE = 39 Wm^{-2}, r = 0.98).

2.2. Cloudy skies

In general the incoming shortwave radiation is reduced by presence of clouds. The ratio between the shortwave radiation by overcast to the value at clear skies is given by Haurwitz (1948), for different types of clouds. For middle latitudes he found that high clouds cut off about 20 percent of shortwave radiation, middle clouds about 50 to 60 percent, and low clouds 65 to more than 80 percent.

In the case of a sky with cloud covers N_i of types i, the incoming shortwave radiation can be evaluated from the product of individual cloud layer transmissivities:

$$K^{+} = K_o^{+} \cdot \prod_{i=1}^{n} \{1 - (1 - t_i) \cdot N_i\} \qquad (2.6)$$

where t_i is the transmittancy for the cloud type i (Davies and Uboegbulam, 1979).

A problem with the use of equation (2.6) for every type separately, is the possible overlap of different types of clouds and the position of the clouds, with respect to the direct solar beam. Davies and Uboegbulam (1979) propose a procedure which accounts for the first effect, by expressing middle and high cloud amounts as fractions of the visible sky at the respective levels. The procedure needs total and low cloud amount and the types of cloud present at each level. These data can be obtained from synoptic weather reports.

With synoptic data and measured shortwave radiation at cloudy skies in De Bilt (1973), we made comparisons between observations and several methods for estimating hourly averages of shortwave radiation. The shortwave radiation was measured with a Moll-Gorczynski-pyranometer. Table 2 gives statistical information for four methods.

Method 1 is based on the equations (2.5) and (2.6), the procedure from Davies and Uboegbulam and values of t_i obtained from Haurwitz (1948). Here we take for the transmittancy t_i (i = 1, 2, 3): t_1 = .3 (low clouds), t_2 = .45 (middle clouds) and t_3 = .8 (high clouds).

The other methods are based on:

$$K^{+} = K_o^{+} F(N_t) \quad (2.7)$$

with K_o^+ estimated from equation (2.5) and F(N) is a function of total cloud cover (N_t) only. The coefficients in $F(N_t)$ were estimated from Haurwitz (1948), Kasten (1977) and our data. Method 2 uses:

$$F(N_t) = 1 - c\, N_t \quad (2.8)$$

where c = 0.65. The methods 3a and 3b make use of:

$$F(N_t) = 1 - c\, N_t^2 \quad (2.9)$$

where c = 0.7. In case of method 3b the data were restricted to hours with solar elevation γ is 10 degrees or more and changes of total cloud cover (N_t) less or equal 2 octas in a hour.

Method 4 makes use of:

$$F(N_t) = 1 + c_1\, N_t^2 + c_2\, N_t \quad (2.10)$$

where c_1 = -1.12, c_2 = 0.42. This method was also applied on the restricted data.

As we see from table 2, methods 3 and 4 give somewhat better results than the methods 1 and 2. However, the coefficients in (2.8), (2.9) and (2.10) are partly based on our data. So there could be some bias. Nevertheless, it seems reasonable to conclude from table 2 that the simple schemes of method 3 and 4 show a performance comparable with the more complicated scheme of method 1.

The function (2.10) for the effect of clouds, that we used in method 4, deserves a brief discussion. This function has a maximum, at a cloud cover of 1 octa to 2 octas. This implies that on the average the incoming shortwave radiation (K^+) at these cloud covers, is about 5% larger than the clear sky value (K_o^+). This has also been found by Kasten (1977).

A possible explanation for this phenomenon is that often a partial cloud cover is observed on the verge of the sky. In such cases the interception of the direct solar radiation is small (except for clouds in the east and the west, when the solar elevation is low). On the other hand, reflection of solar radiation by the clouds will contribute to the diffuse shortwave radiation. Apparently this contribution is greater, on the average, than the decrease of direct solar radiation for a partial cloud cover.

We may note that the above phenomenon is present because the observation of the cloud cover and the measurement of the shortwave radiation are made in one point. When horizontal averages of cloud cover and shortwave radiation are compared, this feature would not be present. In these cases the shortwave radiation should decrease monotonically with cloud cover. For such applications method 3 is probably preferable, allthough the difference with method 4 is not large (within 10 percent).

Figure 1 shows a diagram of a random sample of observed and estimated hourly averages of shortwave radiation (K^+), at cloudy and at clear skies. The hourly averages of K^+ were calculated with (2.5), (2.7) and method 4 with an averaged value of total cloud cover (N_t), between the observations of N_t at the beginning and the end of the considered hour.

In general the agreement is good (SE = 64 Wm^{-2} , r = 0.95). However, cases with mainly higher clouds and with cumulonimbi show the greatest deviations from the model of method 4. It is usefull to average total cloud cover (N_t) with cloud fraction (N_h) from lower clouds, in cases with mainly higher clouds, to avoid underestimates of the shortwave radiation in these conditions.

An explanation that in a statistical sense total cloud cover (N_t) gives satisfactory estimates of shortwave radiation, is found in the "U-shaped"-frequency distribution of total cloud cover (Paltridge and Platt, 1976).

3. Estimates of net radiation

3.1. Daytime

The net radiation (Q^*) at ground level at daytime is the sum of the net shortwave radiation (K^*) and of the net longwave radiation (L^*):

$$Q^* = K^* + L^* \tag{3.1}$$

with

$$K^* = (1 - \alpha) \cdot K^+ \tag{3.2}$$

where α is the albedo, and:

$$L^* = L^+ - L^- \tag{3.3}$$

In (3.3) L^+ is the downward atmospheric radiation and L^- is the upward longwave radiation from the earth's surface. The shortwave radiation (K^+) can be estimated with the models listed in the preceding chapter. We further need estimates of α, L^+ and L^-.

For the albedo (α) we use an average value $\alpha = 0.23$, measured at Cabauw (Slob, 1980).

For the downward atmospheric radiation (L^+) we use an empirical function due to Swinbank (1963), Paltridge (1970) and Paltridge and Platt (1976):

$$L^+ = L_o^+ + 60\ N_t \tag{3.4}$$

where N_t is the total cloud cover and:

$$L_o^+ = 5.31 . 10^{-13}\ T^6 - 20 \tag{3.5}$$

is the clear sky value. T is the airtemperature at screenheight (2 m).

The outgoing longwave radiation is:

$$L^- = \varepsilon \sigma T_s^{\ 4} \tag{3.6}$$

where ε is the emissivity of the earth's surface, σ is the Stefan-Boltzmann constant and T_s is the surface temperature. The surface temperature T_s is, however, not a routine synoptic datum. Therefore we need an estimate for L^- from other routine data.

By day the surface temperature exceeds the airtemperature, due to heating of the surface by the net solar radiation. So the use of the airtemperature T instead of T_s in equation (3.6) leads to an underestimate of L^-.

For not too large differences $(T_s - T)$ we may write equation (3.6) as:

$$L^- = \varepsilon\,\sigma\,T^4 + 4\,\varepsilon\,\sigma\,T^3\,(T_s - T) \qquad (3.7)$$

We assume the correction term $4\,\varepsilon\,\sigma\,T^3\,(T_s - T)$ to be proportional to the net solar radiation K^*. With this approximation it follows from (3.7):

$$L^- = \sigma T^4 + \beta K^* \qquad (3.8)$$

where the emissivity ε is taken 1 and β is an empirical dimensionless constant.

One may expect that the temperature difference $(T_s - T)$ and so the net radiation may be influenced by the wind speed. However, from our data it followed that the wind speed plays not a significant rule in daytime conditions to estimate net radiation.

From our data we found $\beta = 0.09$ for clear sky conditions, by comparing computed and measured values of net radiation. From (3.7) and (3.8) it follows:

$$T_s - T = \frac{\beta\,K^*}{4\sigma T^3} \qquad (3.9)$$

This equation yields realistic values for the air-surface temperature difference $(T_s - T)$ e.g. for $K^* = 600\ Wm^{-2}$, $T = 300$ K, which are high values, we find: $T_s - T = 8.8$ K.

We assume that the equations (3.8) and (3.9) can be applied to cloudy skies. Now net radiation can be calculated from the equations (3.1), (3.2), (3.3), (3.4), (3.5) and (3.8) with measured or estimated values of shortwave radiation (K^+), albedo (α), airtemperature (T) and total cloud cover (N_t) and with $\beta = 0.09$.

Figure 2 shows a random sample of calculated hourly averages of net radiation (Q^*) versus measured values of Q^* with a "Suomi" net pyrradiometer at Cabauw. Because cloudiness is not observed at Cabauw the average was taken of the observations at 4 synoptic stations around Cabauw, for both the preceding and the considered hour.

We used the shortwave radiation K^+ measured at Cabauw for the calculation of Q^*. Only cases with solar elevation (γ) greater than or equal to 15 degrees are included in figure 2, for reasons given hereafter.

In general figure 2 illustrates the satisfactory agreement (SE = 30 Wm^{-2}, r = 0.97) between measured and calculated values of Q^*. When the shortwave radiation, calculated with method 4 from section 2.2 is used, instead of the measured value, the scatter increases somewhat (SE = 45 Wm^{-1}, r = 0.93).

Figure 3 shows our model of net radiation as a function of sin γ for different values of total cloudiness N_t. We used an fixed value for the temperature T = 288 K. With this value of T it follows from (3.1), (3.3), (3.4), (3.5) and (3.8):

$$Q^* = K^* + 60\ N_t - 107 - \beta K^* \qquad (3.10)$$

We estimated K^* from (2.5), (2.7) and (3.2):

$$K^* = (1 - \alpha)\ S \sin\gamma\ (a + b \sin\gamma)\ .\ F(N_t) \qquad (3.11)$$

In figure 3 we used: a = 0.48, b = 0.29, S = 1353 Wm^{-2}, α = 0.23, β = 0.09 and $F(N_t)$ according to method 4 of section 2.2. When no temperature is available we can use (3.10) for a crude estimate of Q^*. However, in daytime conditions the temperature contains in general significant information to estimate the net radiation (Q^*).

It appears that the net radiation is affected very little by cloud cover as long as the amount N_t is 4/8 or less. This can be explained by the diffuse radiation and the longwave radiation, which tend to compensate for the reduction in the direct solar radiation as cloud increases. But in cases with a cloud amount N_t is 6 octas or more, the net radiation significantly drops.

From figure 3 it follows that we can expect in general positive values of Q^* for solar elevations (γ) of about 15 degrees or more (sin γ = 0.26). In transition hours ($0 < \gamma < 15$) we recommend a lineair interpolation in γ between the net longwave radiation part of our model in daytime conditions and a model at night. The model at night shall be considered in the next section. The net radiation in transition hours may also be calculated from:

$$Q^* = (1 - \alpha)\ K^+ + (1 - \frac{\gamma}{15})\ L_{night} + (\gamma/15).\ L_{day} \qquad (3.12)$$

By comparisson data and calculations with (3.12) we found a standard error SE = 20 Wm^{-2} (r = 0.70).

3.2. Net radiation at night

At night ($\gamma < 0$), shortwave radiation vanishes and net radiation (Q^*) is identical to the net longwave radiation (L^*), so it follows from (3.3) and (3.7):

$$Q^* = L^+ - \varepsilon\sigma T^4 - 4\varepsilon\sigma T^3\ .\ (T_s - T) \qquad (3.13)$$

At night net radiation (Q^*) is negative and the surface temperature T_s is lower than the airtemperature T.

It is a well known fact that at night, the temperature difference ($T - T_s$) decreases with increasing wind speed and increases with decreasing net radiation. Therefore we propose to scale the correctionterm $4\varepsilon\sigma T^3(T_s - T)$ crudely as:

$$4\varepsilon\sigma T^3(T_s - T) = B \frac{gh}{u_{10}^2} \quad Q^* \tag{3.14}$$

Here B is an empirical constant, g the accelaration of gravity, h the measuring height of the wind speed u_{10} (h = 10 m). The right hand side of (3.14) resembles a bulk Richardsonnumber.

With (3.14) we obtain from (3.13):

$$Q^* = \frac{L^+ - \varepsilon\sigma T^4}{1 + \frac{Bgh}{u_{10}^2}} \tag{3.15}$$

Because the temperature difference ($T - T_s$) cannot increase indefinitely with decreasing wind speed we put a lower limit $u_{10} = 2\ ms^{-1}$ to the use of (3.14) and (3.15). For $u_{10} < 2\ ms^{-1}$ we use the value obtained with $u_{10} = 2\ ms^{-1}$.

We may have a brief look at the behaviour of the numerator of (3.15) as a function of the airtemperature T. It appears that $L^+ - \varepsilon\sigma T^4$ varies very little at clear skies in the range of nighttime temperatures, commonly occuring in the Netherlands. Furthermore the measured data of Q^* show a very poor correlation with measured temperature. So we may as well take: $L^+ - \varepsilon\sigma T^4 = A$, where A is a clear sky constant.

On the other hand the correlation with wind speed is significant. From our data we found: $Bgh = 4\ m^2s^{-2}$ and $A = -90\ Wm^{-2}$. To calculate hourly values of net radiation by night at clear skies we propose therefore:

$$Q^*_o = \frac{-90}{1 + \frac{4}{u_{10}^2}} \quad \text{for } u_{10} \geqslant 2\ ms^{-1} \tag{3.16}$$

and

$$Q^*_o = -45\ Wm^{-2} \text{ for } u_{10} < 2\ ms^{-1} \tag{3.17}$$

The inclusion of a wind speed factor accounts for a variation of Q^*_o between $-45\ Wm^{-2}$ and $-90\ Wm^{-2}$, as is observed for clear skies.

An estimate for the temperature difference ($T_s - T$) can be obtained from (3.14). $Q^*_o = -60\ Wm^{-2}$, $u_{10} = 3\ ms^{-1}$, T = 280 K and $\varepsilon = 1$ yields $T_s - T = -5.4$ K. This is a realistic value.

Figure 4 shows a diagram with calculated and observed values of Q^* from a random sample at night. We used the windspeed (u_{10}) obtained from the Cabauw mast in the second half of the hour. A distinction is made between cases with u_{10} = 2 ms^{-1} orless and cases with u_{10} greater than 2 ms^{-1} and between cases with total cloud cover N_t = 2/8 or less and more cloudy conditions. The values of Q^* in a cloudy atmosphere were obtained from:

$$Q^* = Q^*_o (1 - cN_t^2) \qquad (3.18)$$

where N_t is total cloud cover and c = .9 (Sellers, 1965). Q^*_o were estimated from (3.16) or (3.17). Equation (3.18) provides better results in combination with (3.13) and (3.14) than a lineair form in N_t:

$$Q^* = Q^*_o (1 - cN_t) \qquad (3.19)$$

with c = .9.

We see from figure 4 and equation (3.16) that the windspeed u_{10} explains much of the observed variation in hourly averages of net radiation at clear skies (triangles). The remaining scatter is still relatively large. For clear skies we found: SE = 8 Wm^{-2} (r = 0.69), and on the whole sample (clear skies and cloudy skies): SE = 15 Wm^{-2} (r = 0.79).

We also tried the Brunt-formulae to estimate Q^*_o during nighttime:

$$Q^*_o = L^*_o = \sigma T^4(a + b\sqrt{E} - 1) \qquad (3.20)$$

where E is the humidity at screenheight. The coefficients a and b were taken from Wartena et al (1973). They found for the Netherlands: a = .678 and b = .041 $mb^{-\frac{1}{2}}$ (average values). Comparison of (3.17) with observations show a much poorer agreement (SE = 13 Wm^{-2}, r = 0.30) than our estimate shown in figure 3 for clear skies (SE = 8 Wm^{-2}, r = 0.69).

This conclusion is also valid for the Swinbank type formula, found for the Netherlands by Wartena et al (1973):

$$Q^*_o = aT^6 + b - \sigma T^4 \qquad (3.21)$$

with a = 4.99 10^{-13} $Wm^{-2}K^{-6}$ and b = 39,5 Wm^{-2}. Here we found a standard error SE = 11 Wm^{-2} and a correlationcoefficient r = 0.15, between measured and calculated values at clear skies.

To estimate hourly averages of net radiation at clear skies by night it is thus worthwhile to account for the effect of windspeed on the temperature difference between the earth's surface and the airtemperature at screenheight. On the other hand variations in temperature and humidity do not seem to be important.

4. Conclusions

The incoming shortwave radiation at ground level from clear skies can be estimated with fair accuracy from solar elevation. Cloudiness causes in general a non lineair decrease of shortwave radiation. This can be modelled with a simple procedure, which uses total cloud cover only.

Net radiation by day can be estimated from airtemperature at screenheight, total cloud cover and estimated or measured incoming shortwave radiation. For hourly averages of net radiation it is useful to account for the temperature difference between the surface and screenheight. We estimate this temperature difference using net shortwave radiation.

We obtained an acceptable estimate of net radiation for clear nights, taking into account the effect of windspeed on the temperature difference between surface and screenheight. It seems that temperature and humidity are not relevant. Our model yields better results for hourly averages than the Brunt and Swinbank formulae. The effect of cloudiness at night can be satisfactory described by a simple quadratic function of total cloud cover.

Our results show that it is possible to obtain realistic hourly averages of incoming shortwave radiation and net radiation from standard meteorological data.

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APPENDIX

The calculation of the solar elevation (γ).

The solar elevation for a given time and location (γ) may be calculated by simplifying well-known astronomical formulae. For a given day with daynumber d (0 is 1 January and so on) the solars longitude (L) can be evaluated from:

$$L = 279.1 + d + 1.9 \sin d \qquad (A1)$$

The declination δ follows from:

$$\delta = \arcsin (0.398 \sin L) \qquad (A2)$$

With L, δ and d we can compute the hour angle (τ) from:

$$\tau = - \lambda + 2.47 \sin 2L - 1.9 \sin d + 15\ t + 180 \text{ (degrees)} \qquad (A3)$$

where $\lambda\lambda$is the Western longitude and t is the universal time in hours. Solar elevation follows from the above relations by applying:

$$\sin \gamma = \sin \delta \sin \phi - \cos \delta \cos \phi \cos (\tau - 180) \qquad (A4)$$

where ϕ is latitude.

In our estimates for shortwave radiation we use (A4). The accuracy is within 0.3 degrees, if we use a crude estimate for the daynumber d:

$$d = 30\ (M - 1) + D \qquad (A5)$$

where M is the number of the actual month (1 - 12) and D is the number of the day in the month (1 - 31).

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Notation

I	: The direct shortwave radiation (solar beam) at ground level (Wm^{-2}).
D	: The diffuse shortwave radiation at ground level (Wm^{-2}).
D_o	: Constant component of D.
K^{+}	: The incoming shortwave radiation at ground level (Wm^{-2}).
K^{*}	: Net shortwave radiation at ground level (Wm^{-2}).
L^{+}	: The downward longwave (atmospheric) radiation at ground level (Wm^{-2}).
L^{-}	: The upward radiation at ground level (Wm^{-2}).
L^{*}	: Net longwave radiation at ground level (Wm^{-2}).
Q^{*}	: Net radiation (shortwave and longwave) at ground level (Wm^{-2}).
$_o$	: Subscript, indication for clear skies.
S	: Solar constant (Wm^{-2}).
N_i	: Cloud cover of type i (0/8-8/8).
N_t	: Total cloud cover.
N_h	: Cloud cover of lower clouds only.
$F(N_t)$	: Some function of total cloud cover.
T	: Airtemperature at screenheight (K).
T_s	: Temperature of the earth's surface (K).
ε	: Emissivity.
σ	: The Stefan-Boltzmann constant ($5.66910^{-8} Wm^{-2}K^{-4}$).
g	: The acceleration of gravity (ms^{-2}).
t_i	: The transmittancy for cloud type i.
$t(\gamma)$	: The transmission function for shortwave radiation in the atmosphere.
h	: Measuring height of the wind speed (m).
E	: The humidity at screenheight (mb).
α	: Albedo of the earth's surface.
γ	: The solar elevation (degrees).
r	: Correlationcoefficient.
n	: Number of pairs (X_i, Y_i) in a sample.

SE : Standard error of estimate of a variable X_i with a model Y_i defined as:

$$SE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (Y_i - X_i)^2} .$$

SL : Slope of the lineair relationship Y = SL.X with SL defined as:

$SL = \Sigma XY / \Sigma X^2$.

$\overline{X}$: Mean value of X.

σ_X : Standard deviation of X.

Table 1

Values for the constants a and b of equation (2.5). See section 2.1.

	1	2	3
a	0.61	0.49	0.48
b	0.20	0.37	0.29

1 According to Lumb (1964), found for the ocean weather station "Juliett" ($52^{o}30'$N, 20^{o}W).

2 According to Collier and Lockwood (1975) found in a small catchment in Yorkshire (Great Brittan).

3 Our results for De Bilt in 1973, found from 496 measurements with total cloud cover N_t is 1/8 or less and solar elevation γ is 10 degrees or more.

Table 2

Comparison of observations (X) and several models (Y) to estimate the shortwave radiation (K^{+}). See section 2.2.

Method	1	2	3a	3b	4
n	4308	4308	4308	3229	3229
$\overline{X}$	235	235	235	283	283
$\overline{Y}$	207	215	226	267	288
σ_X	216	216	216	213	213
σ_Y	177	178	192	187	204
SE	82	78	69	78	72
SE/$\overline{X}$	0.35	0.33	0.29	0.28	0.25
SL	0.83	0.86	0.91	0.90	0.98
r	0.94	0.94	0.95	0.94	0.94

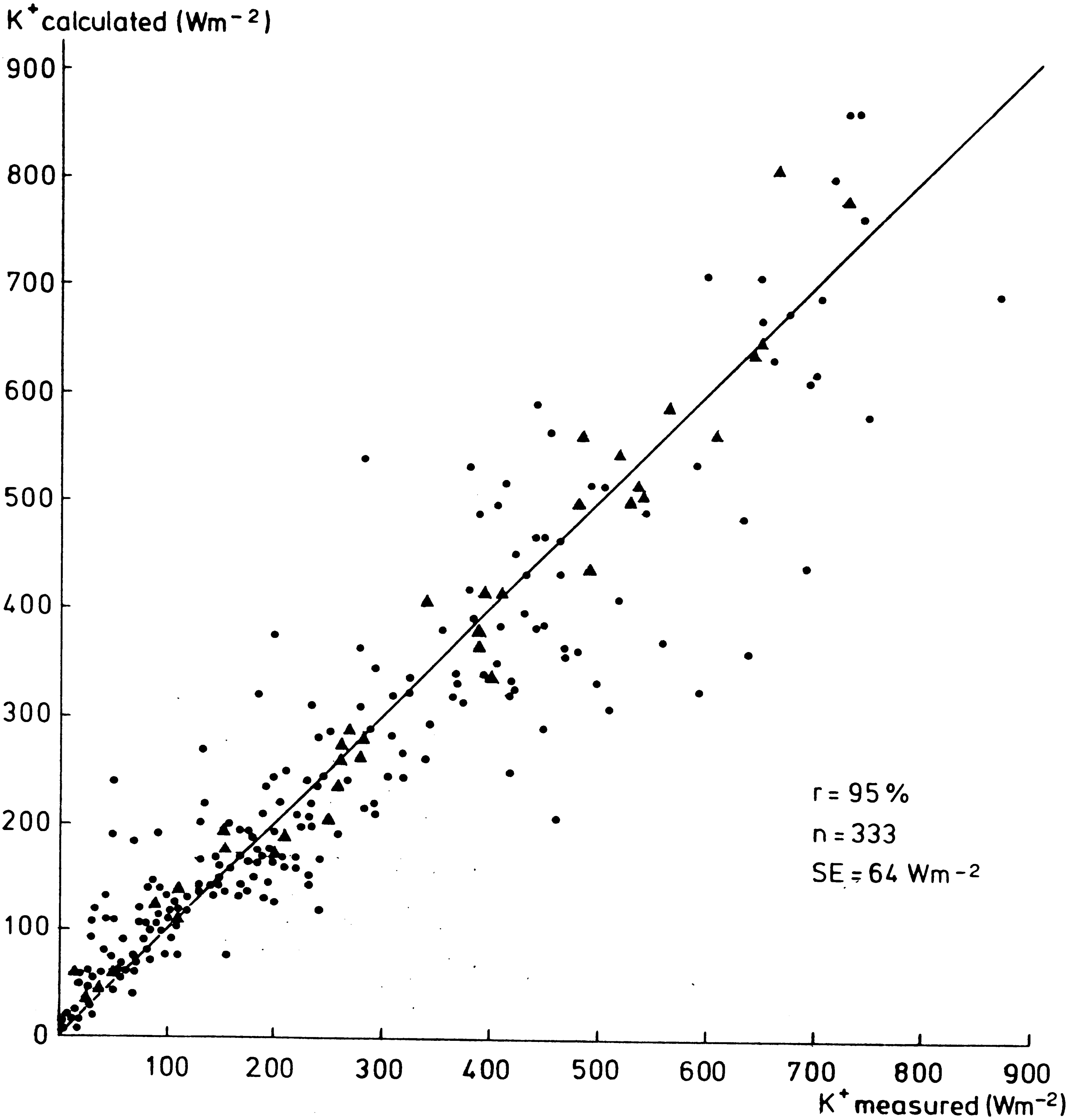

Figure 1. Diagram of calculated and measured hourly averages of shortwave radiation (K^{+}). Triangles represent cases with total cloud cover N_t = 2/8 or less and dots represent more cloudy conditions. The data are a random sample over the year 1973.

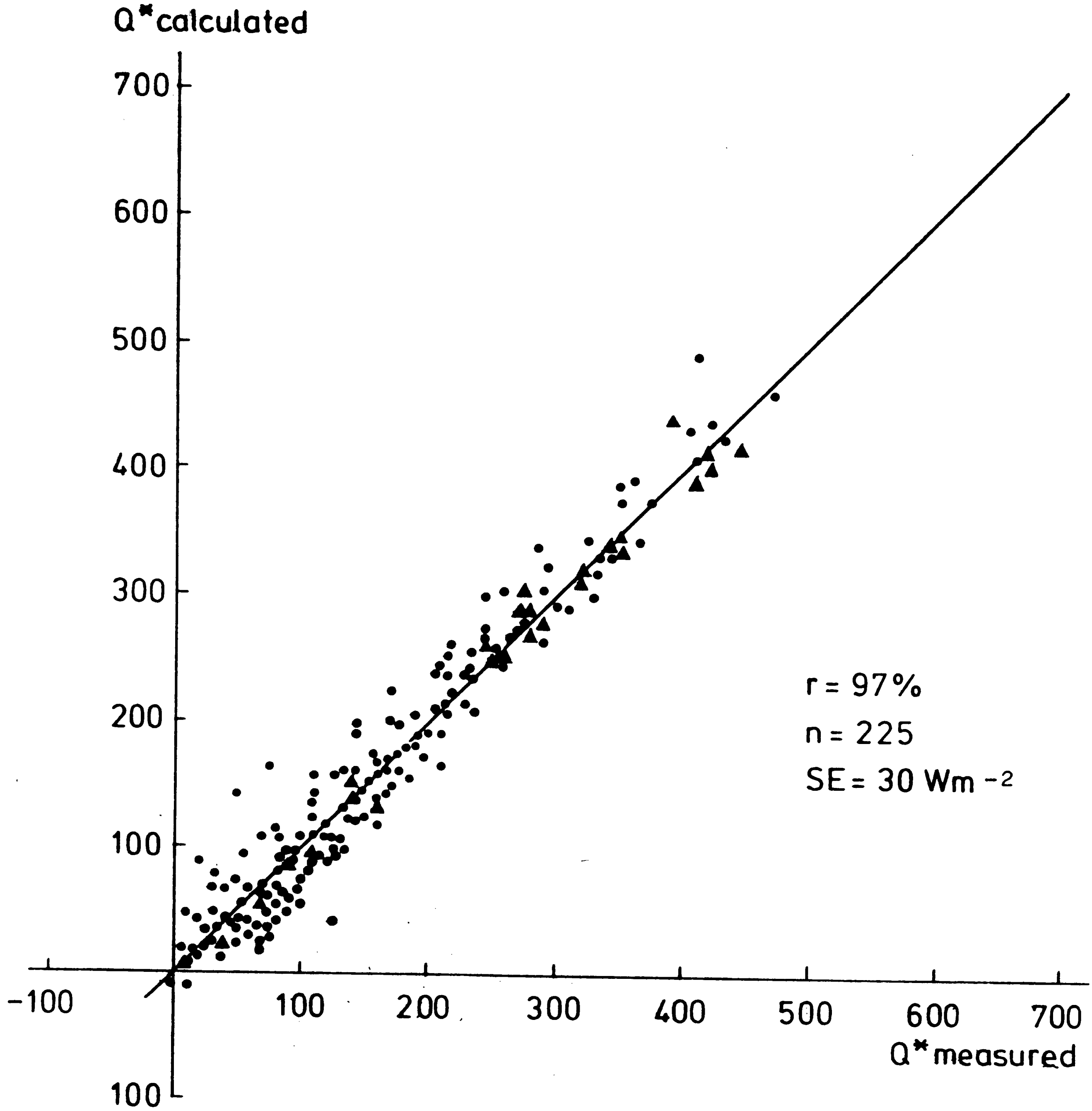

Figure 2. Diagram of calculated and measured hourly averages of net radiation (Q^*) for solar elevation γ = 15 degrees or more. Triangles represent cases with total cloud cover N_t = 2/8 or less and dots represent more cloudy conditions. The data are a random sample over the year 1973.

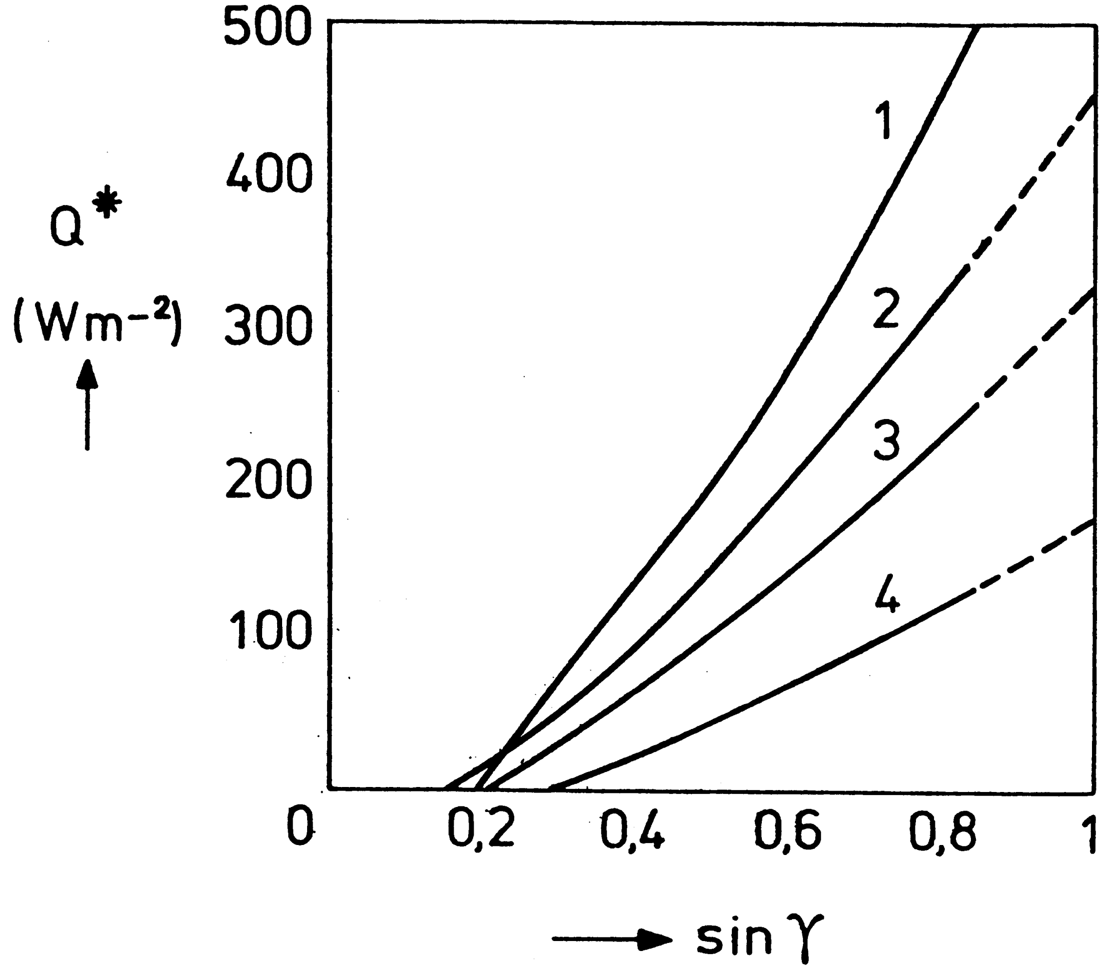

Figure 3. Plot of modelled net radiation at a fixed temperature T = 288 K versus the sine of the solar elevation (γ) for different values of the total cloud cover (N_t):

1 : N_t = 0 - 4/8

2 : N_t = 6/8

3 : N_t = 7/8

4 : N_t = 8/8

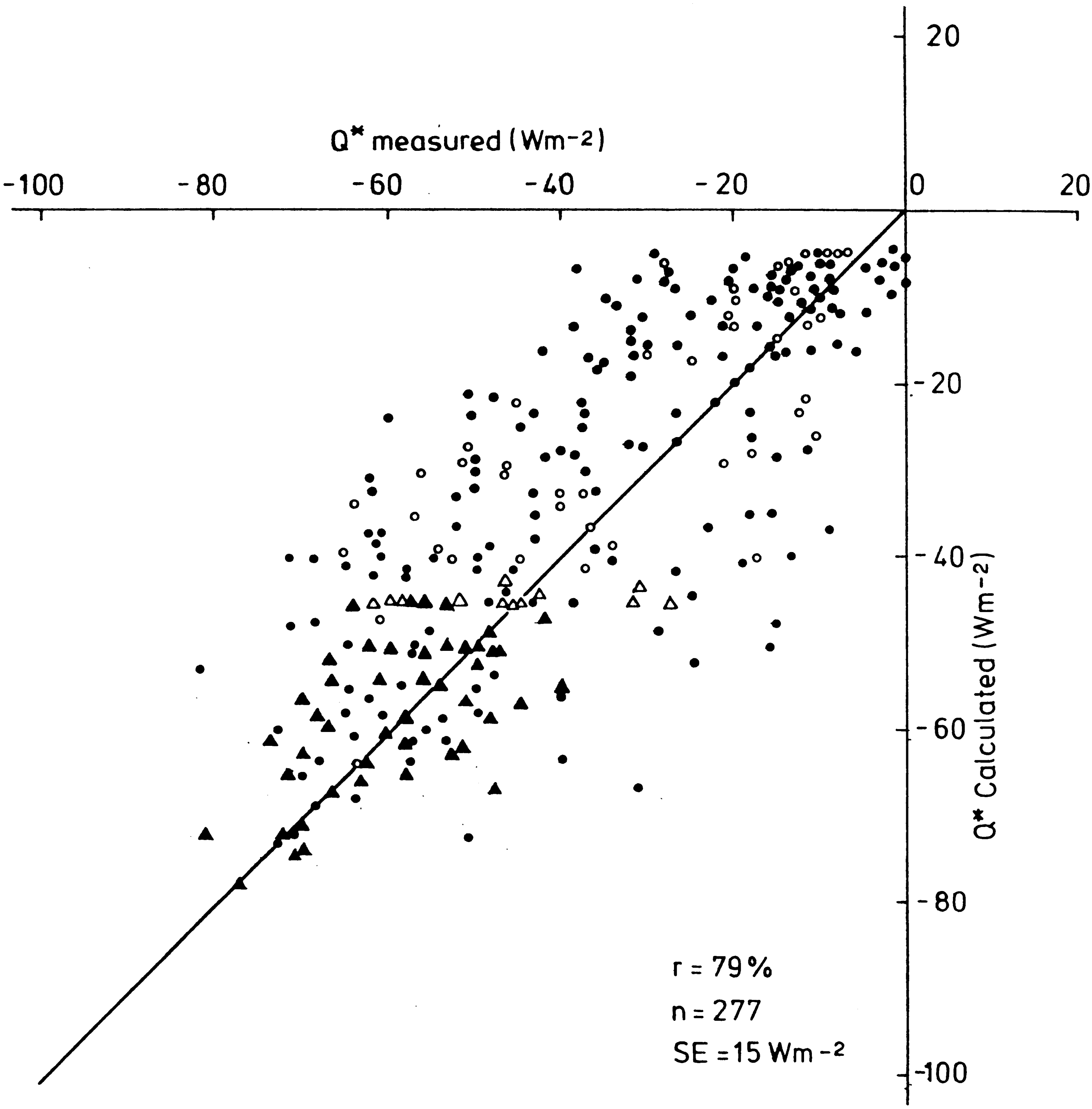

Figure 4. Diagram of calculated and measured hourly averages of net radiation by night. Triangles represent cases with total cloud cover N_t = 2/8 or less and dots represent more cloudy conditions. Open triangles or dots refering to windspeed u_{10} = 2 ms^{-1} or less and full triangles or dots refering to cases with windspeed u_{10} more than 2 ms^{-1}. The data are a random sample over the year 1973.