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J. Roodenburg

Forecasting minimum temperatures for an airport and a nearby urban site.

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Koninklijk Nederlands Meteorologisch Instituut,
Dynamisch Meteorologisch Onderzoek,
Postbus 201,
3730 AE De Bilt,
The Netherlands.

U.D.C.: 551.509.323:
551.509.314:
551.588.7

Abstract

For Zestienhoven Airport as well as for the nearby Rotterdam urban area regression equations have been derived as a tool for forecasting nocturnal minimum temperatures. Input to the equations are the sum of temperature and dewpoint, observed at 1500 GMT and an estimate of cloud cover and some wind parameters for 0300 GMT the following night. The performance of the equations on independent material is discussed. A few sections are devoted to nocturnal urban-rural temperature differences and their relation to various meteorological variables.

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1. Introduction

Many branches of economic activity take an interest in reliable forecasts of the nocturnal minimum temperature. Examples are energy-works, the petro-chemical industry, cargo-traffic, transhipment of temperature-sensitive goods like fruit, vegetables and flowers, horticulture, whether or not under glass and road-maintenance.

In many cases the weather forecasts issued by a Central Weather Office will suffice, in particular when there are strong winds and overcast skies. Under such circumstances minimum temperatures vary only slowly over large distances, if there is any variation at all. On clear, calm nights, however, very steep horizontal temperature gradients may develop locally. In such situations a general forecast, covering a large area and a timespan of 24 hours or more is of limited use.

It is on these occasions that regional weather-offices prove especially valuable. The forecasters know from experience where and when adjust the centrally issued forecast to the singularities of their surroundings. These adjustments, however, are often made in a subjective and qualitative way, since objective methods, giving quantative information, are lacking.

Zestienhoven-airport weather office is one of the Netherlands' regional offices. Although primarily intended for civil aviation, it also serves Rotterdam's roughly 175 square kilometers of residential, industrial and harbour area, inclusive Europoort. This is done by means of a tape-recorded telephonic weather broadcast that is updated six times a day.

It has been the aim of the present study to provide this office with an at the same time simple and reliable method for forecasting nocturnal minimum screen temperatures for the airport as well as for the urban area mentioned above. All minimum temperatures in this report refer to the period 1800-0600 GMT.

2. Geographical description of the sites

Zestienhoven is a small airport (fig. 1), situated in a flat grasscovered surroundings, a polder at about six meters below sea level. The area is strictly rural. The thermometer screen is very well exposed, the nearest obstacle being at least 200 meters away.

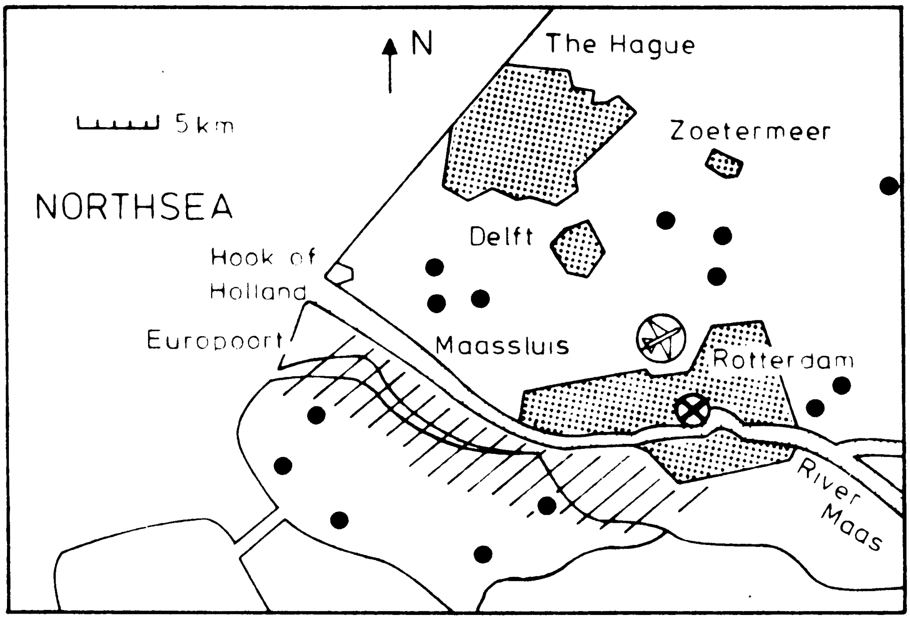


Figure 1. Plan of Zestienhoven airport (encircled) and surroundings.

Again referring to figure 1 it is observed that the airport is practically surrounded by a chain of towns of various sizes and at various, rather small, distances.

To the south is the centre of Rotterdam, a densely populated (1.000.000) residential area, the northernmost fringes of which reach to within 2 km from the airport. The harbour and the main industrial areas (for the greater part occupied by petro-chemical industries, inclusive oil refineries) stretch from the centre to the west along the river Maas. To the northwest of the airport is the conglomeration of the Hague and Delft at between six and ten km. Exactly to the north is Zoetermeer, a rapidly growing commuter town. Towards the northeast is an extensive lowlying agricultural area, relatively sparsely populated. Finally towards the east at two to four km Schiebroek and Hillegersberg, suburbs of Rotterdam, are situated.

It follows from this description that the airport is more or less enclosed by urban areas, which are generally warmer during the night (Oke, 1974, 1979).

Figure 2 shows a sketch of Rotterdam and its adjacent harbour and industrial areas. The thermometer screen is located in a garden of approximately 70 square meters. The garden is enclosed on three sides by buildings, the fourth (south) side facing the river Maas.

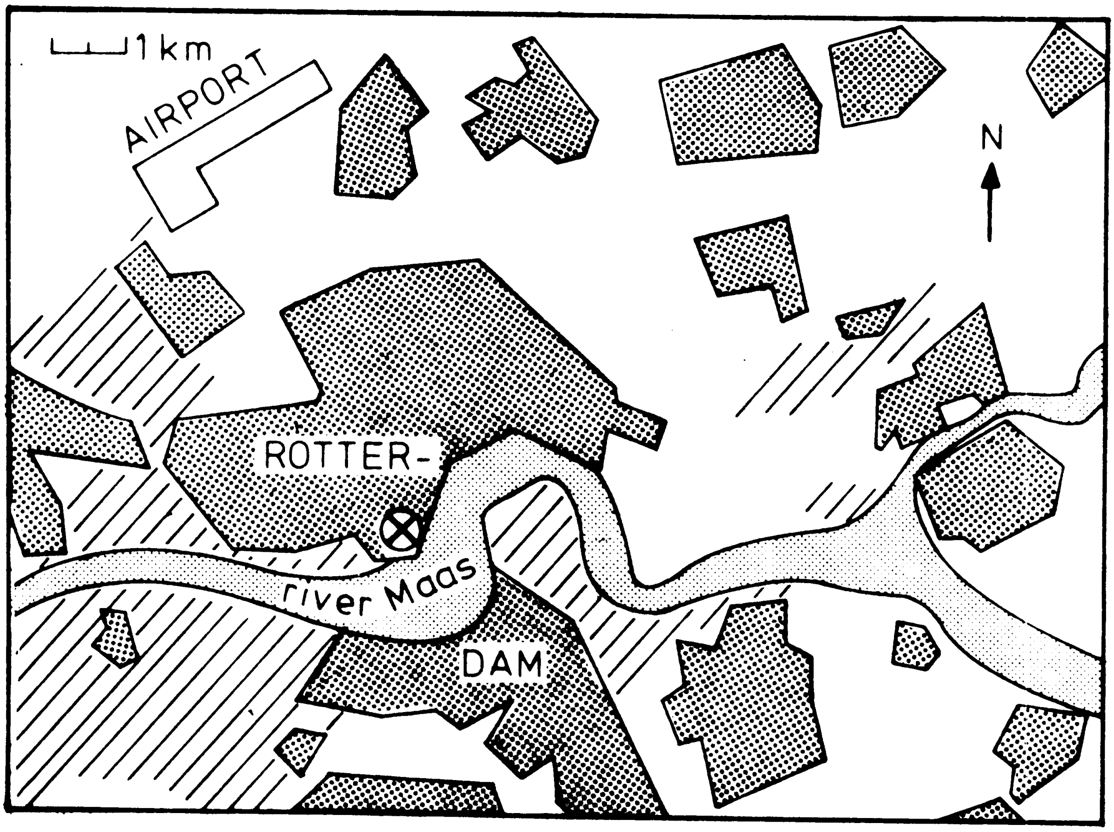


Figure 2. Plan of Rotterdam with urban site (encircled cross) and airport indicated.
Shaded : residential and business area.
Hatched: industrial and harbour area.

There is some doubt as to the representativeness of the temperature observations. Since no other data are available, representativeness had to be assumed.

3. Calculation of the minimum-temperature at Zestienhoven

3.1 Influence of temperature and humidity

Without clouds and without advection the minimum temperature would depend solely on the maximum temperature of the previous day, the amount of water vapour in the atmosphere and the length of the period of time available for cooling. The moisture content, in turn, strongly affects the cooling rate of the atmosphere. It seemed a sensible approach, therefore, to search for some combination of an afternoon temperature and a moisture parameter. This would at the same time reflect the length of the cooling period, as high afternoon temperatures and short nights go together.

In this study the sum of temperature and dewpoint of 1500 GMT was chosen on the following grounds:

- both temperatures are readily available;
- 1500 GMT is normally reasonably close to the time at which the maximumtemperature is reached (fig. 3);
- the dewpoint depression is an indicator of moisture deficit;
- if the sum is kept constant, various combinations of temperature and dewpoint resulting in the same sum will lead to approximately the same wet-bulb potential temperature, as is easily demonstrated on a thermodynamic diagram (it should be noted that the potential wet-bulb temperature is conservative for adiabatic processes and thus acts as an airmass identifier).

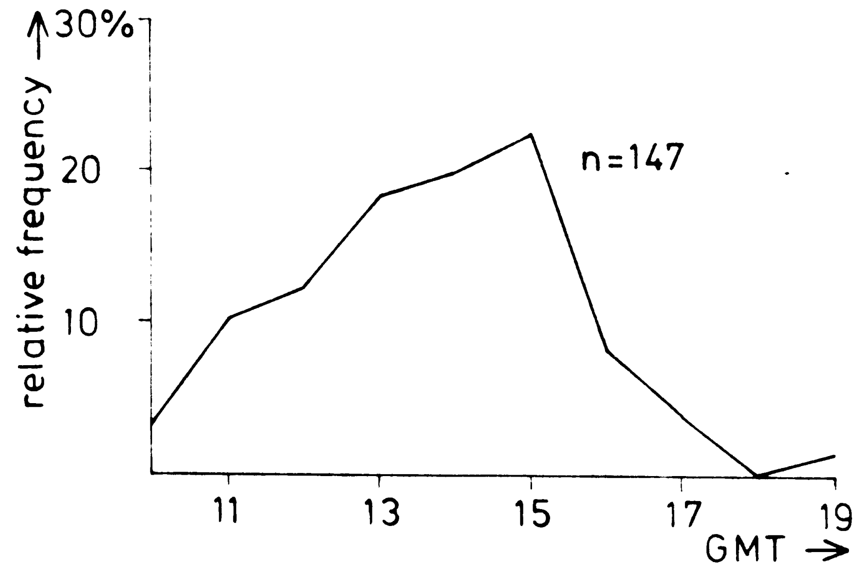


Figure 3. Relative frequencies of hours GMT at which the maximum temperature was reached (airport, Dec. 1979, Jan., Feb., June, July, Aug. 1980).

A similar approach was used in east England for forecasting minimum screen temperatures at Mildenhall (Gordon et al., 1969). They derived a regression equation, using temperature and dewpoint of 1200 GMT:

$$\hat{T}_r = 0.395(TT+T_dT_d)_{12} - 1.33 \qquad (1)$$

where the caret is used to indicate a calculated minimum temperature and r stands for rural. The other symbols have their usual meaning; temperatures are in °C. The correlation coefficient they obtained was 0.87, the root-mean-square error (rmse) was 2.34 °C. No allowance was made for cloudiness, wind velocity etc.

In the present study a regression equation of the same kind was derived between the sum of temperature and dewpoint of 1500 GMT and the subsequent minimum temperature. Data consisted of synoptic weather reports of Zestienhoven covering the period January 1974 up to December 1978 inclusive.

The result was:

$$\hat{T}_r = 0.42(TT+T_dT_d)_{15} - 1.47 \qquad (2)$$

($r = 0.89$, rmse 2.4 °C). There is very good agreement with Eq. (1) which illustrates the climatic similarity of east England and south-west Holland.

Application of Eq. (2) to independent material (1972, every three days) yielded figure 4. Scatter is considerable. Closer inspection of the data revealed that $\hat{T}_r$ was mostly too warm in typical radiation nights, whereas it was often too cold in overcast nights with moderate or strong southerly or southwesterly winds. Clearly more variables had to be taken into account.

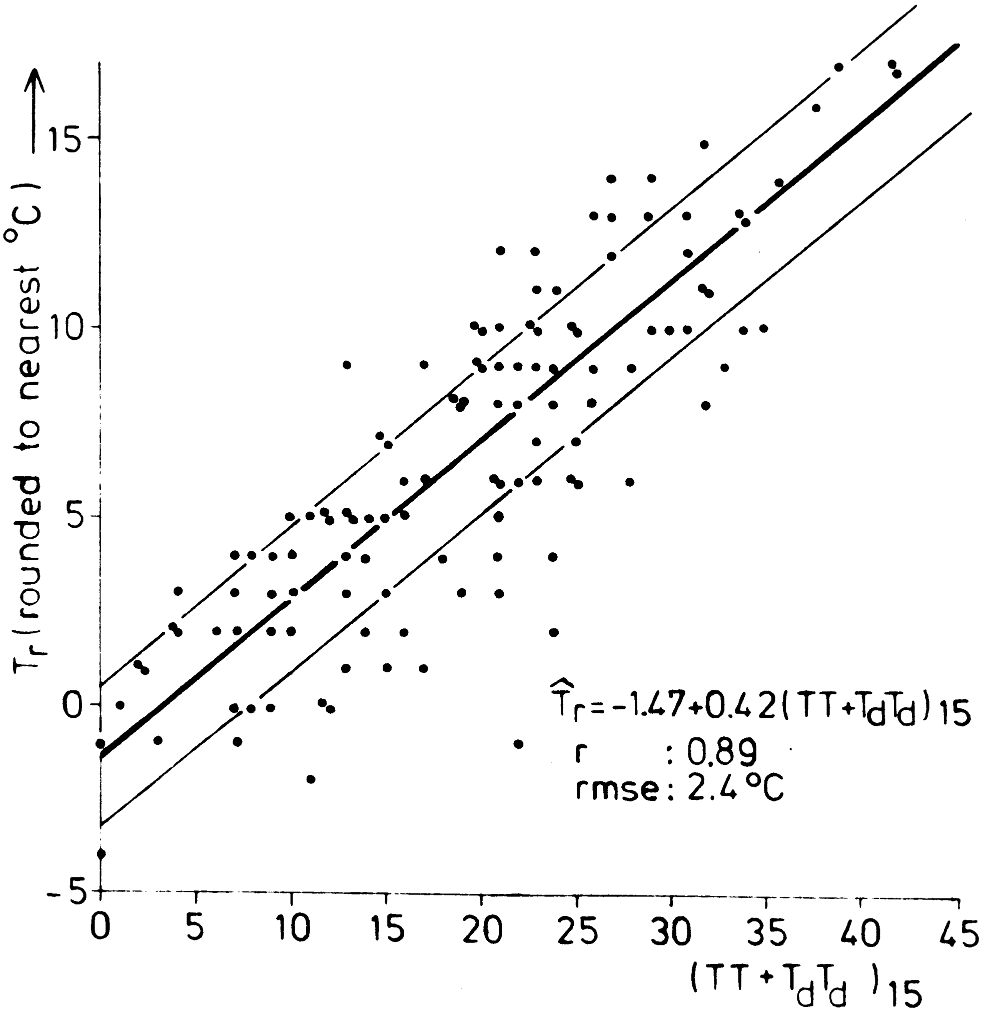


Figure 4. Eq. (2) applied to independent data.

3.2 The influence of cloud amount

To assess the influence of cloud amount, $\hat{T}_r$ and cloud amount N (oktas) observed at 0300 GMT at the airport, were submitted to a multiple regression analysis against T_r, the observed rural minimum temperature.

Since night-observation of cloud type is often difficult, total cloud cover was chosen instead, irrespective of type. A test, in which average cloud cover calculated from the observations of 2100, 0000, 0300 and 0600 GMT was compared with the 0300 GMT cloud amount, showed no significant differences between the two. For the sake of simplicity the 0300 GMT cloud amount was used.

The following regression equation resulted:

$$\hat{T}_r = -3.77 + 0.43(TT+T_dT_d)_{15} + 0.44N \qquad (3)$$

(r=0.91, rmse=2.2 °C).

Eq. (3) clearly shows that cloud amount substantially contributes to the ultimate minimum temperature.

3.3 Influence of wind speed

Using Eq. (2), relative cumulative frequencies were calculated of deviations from the observed minimum temperature for various wind speeds at 0300 GMT and cloud amount less than three oktas (fig. 5). The wind speeds were separated into classes in accordance with the Beaufort-scale, part of which, for the sake of convenience, is reproduced in table I. Wind speeds over 27 kts (a rare occurrence) were grouped under Bft 6, but since these winds were always accompanied by cloudy or overcast skies, they did not enter into the calculations.

Table I - Beaufort-scale

Bft	Wind speed (kts)
0	less than 1
1	1 - 3
2	4 - 6
3	7 -10
4	11-16
5	17-21
6	22 or more

From figure 5 it is readily seen that at nights with little wind in about 85% of the cases the calculated temperature is more than 2 °C too warm (average 4.0 °C, standard deviation 2.3 °C). With winds between 4 and 6 kts (Bft 2) this percentage drops to about 30 and for wind speeds of 7 to 10 kts the percentage is only 5.

On the other hand, with moderate winds (Bft 4) $\hat{T}_r$ is too cold in over 60% of the cases (average -0.7 °C, standard deviation 2.2 °C).

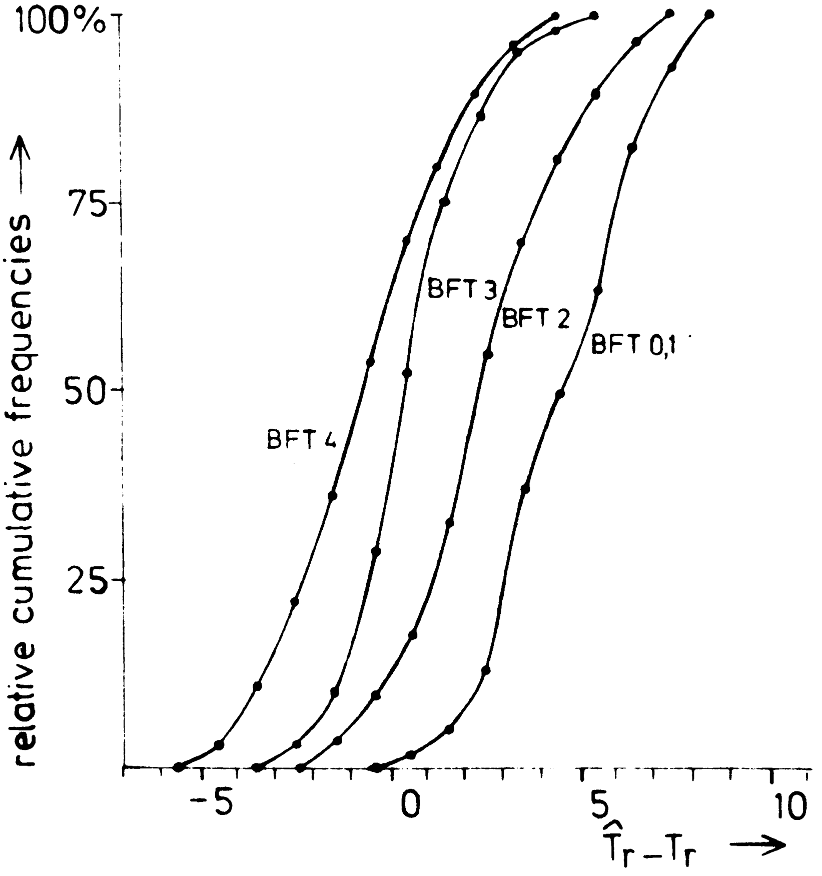


Figure 5. Relative cumulative frequencies of deviations from the observed minimum temperature for various wind speeds.

Evidently the largest departures occur in clear, calm nights. To further illustrate this, figure 6 depicts average deviations for various wind speeds in relation to cloud amount. In weak wind situations there is a strong dependence on cloud amount, the larger deviations occurring with the smaller cloud covers, whereas with moderate winds the calculated temperature is too cold irrespective of cloud cover.

If an average departure from the observed minimumtemperature of $\pm 2\ ^{o}$C would be acceptable (thin horizontal lines in fig. 6), a correction to $\hat{T}_r$ in the case of light winds would suffice.

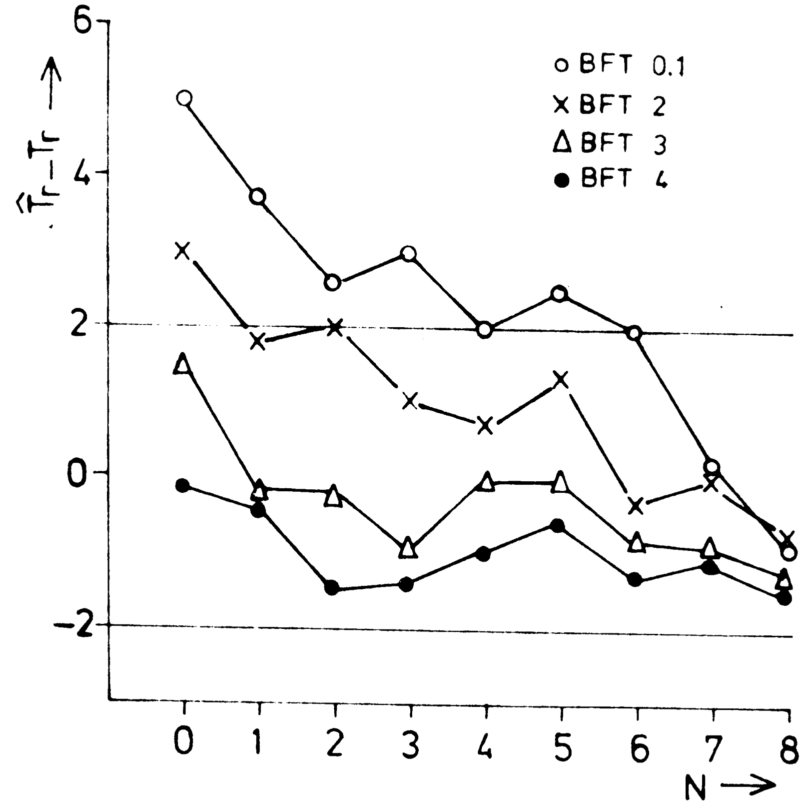


Figure 6. Average deviations in relation to cloud amount.

3.4 The influence of wind direction

A glance at figure 1 will at once make it clear that the direction of the wind during the night must have a noticeable influence on the minimum screen temperature at Zestienhoven. Many, in some directions extensive, sources of anthropogenic heat are present in the neighbourhood of the airfield. Downwind from these sources temperatures are apt to remain higher than elsewhere. (This is why Zestienhoven often can be diverted to when Amsterdam International airport is closed due to fog).

In order to gain some insight in the effect of wind direction on minimum temperatures, Eq. (3) was applied to data covering the years 1971 up to 1973 inclusive. This equation was chosen because it already contains a correction factor for cloud amount. The relative cumulative frequency distribution of differences between $\hat{T}_r$ and T_r exceeding 2 °C as a function of wind direction is shown in figure 7a (positive and negative values solid resp. broken lines).

The number of too warm forecasts grows most rapidly with wind directions between north and east. Too cold forecasts are most numerous with winds from between southeast and west (see again fig. 1).

With a view to these results and those of the preceeding section, four additional parameters were included in the multiple regression procedure. These were assigned a value of 0 or 1 according to the following scheme:

wind speed	≤ 3 kts	> 3 kts	> 3 kts	> 3 kts
direction (tens of dgs)	any	01-10	11-28	29-36
parameter				
X1	1	0	0	0
X2	0	1	0	0
X3	0	0	1	0
X4	0	0	0	1

Since these parameters are mutually exclusive, there are three degrees of freedom so only three parameters need enter into the regression procedure. In this study X1, X2 and X3 were chosen.

The resulting regression equation was:

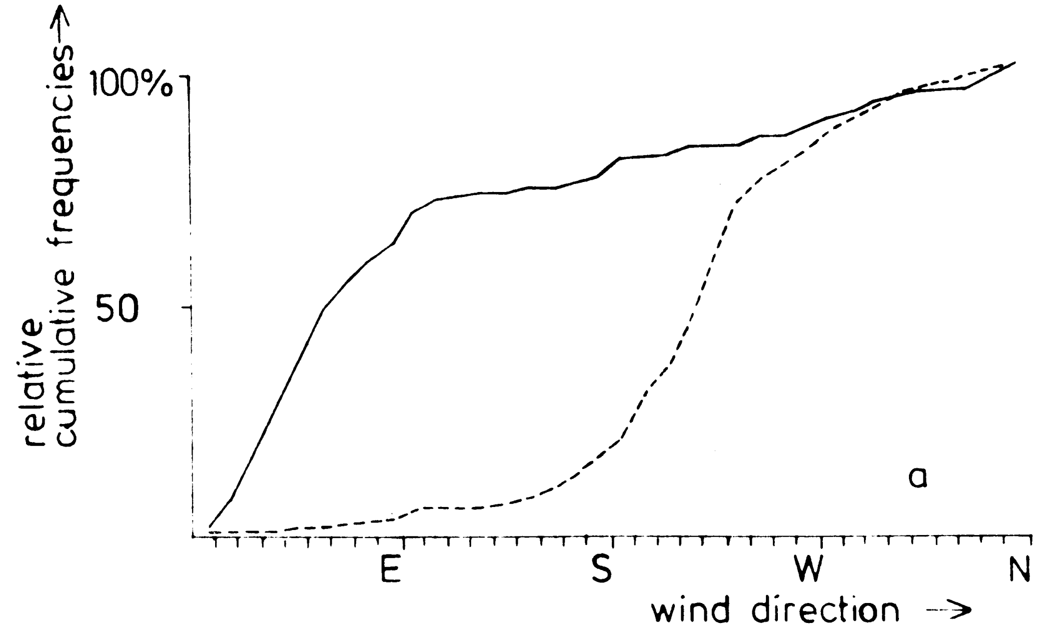
$$\hat{T}_r = -3.69 + 0.44(TT+T_dT_d)_{15} + 0.35N - 1.71X1 - 0.97X2 + 0.92X3 \quad (4)$$

The correlation coefficient was 0.93, the rmse 1.97 ^{o}C.

Eq. (4) was then applied to the same data. Again relative cumulative frequencies were calculated and plotted against wind direction (figure 7b). Although, admittedly, the points do not form a straight line (as they should, if all dependency on wind direction had been removed), the improvement of Eq. (4) over Eq. (3) is unmistakable.

It may be noted that forecasters in this formula have a tool to quantify the relative importance of the factors contributing to the minimum temperature. In figure 8 it has been applied to a set of 30 days chosen at random from the period 1971-1976.

Eq. (4) has been in use at Zestienhoven airport since the middle of June 1980. It's performance will be commented on in a later section.



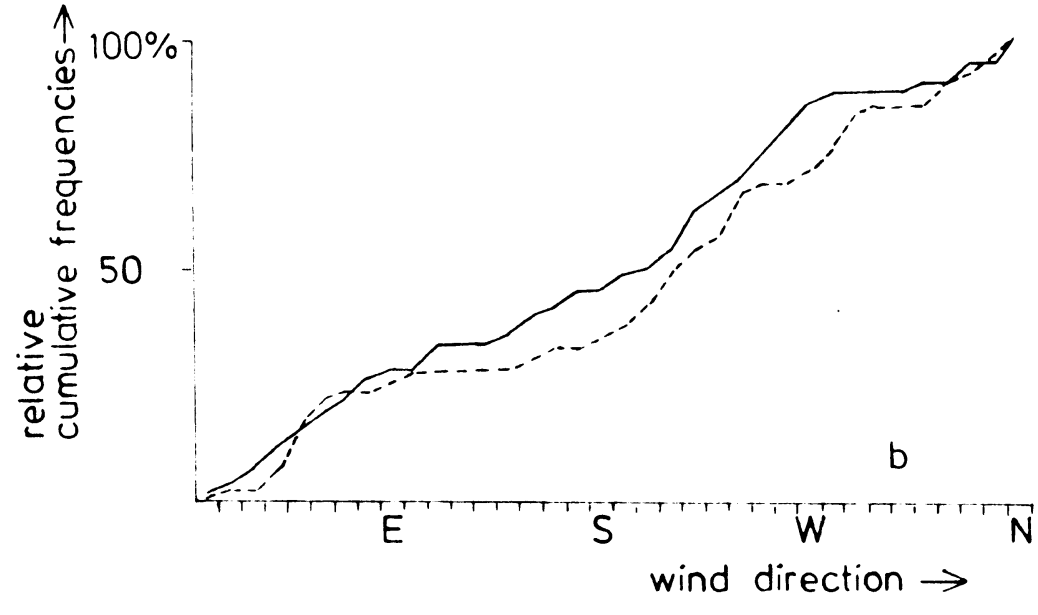


Figure 7a. Relative cumulative frequencies of deviations in excess of 2 degC in relation to wind direction. (solid line: $\hat{T}_r$ too warm), broken line: $\hat{T}_r$ too cold).

Figure 7b. As for 7a, after introduction of X_i ($i = 1,2,3$).

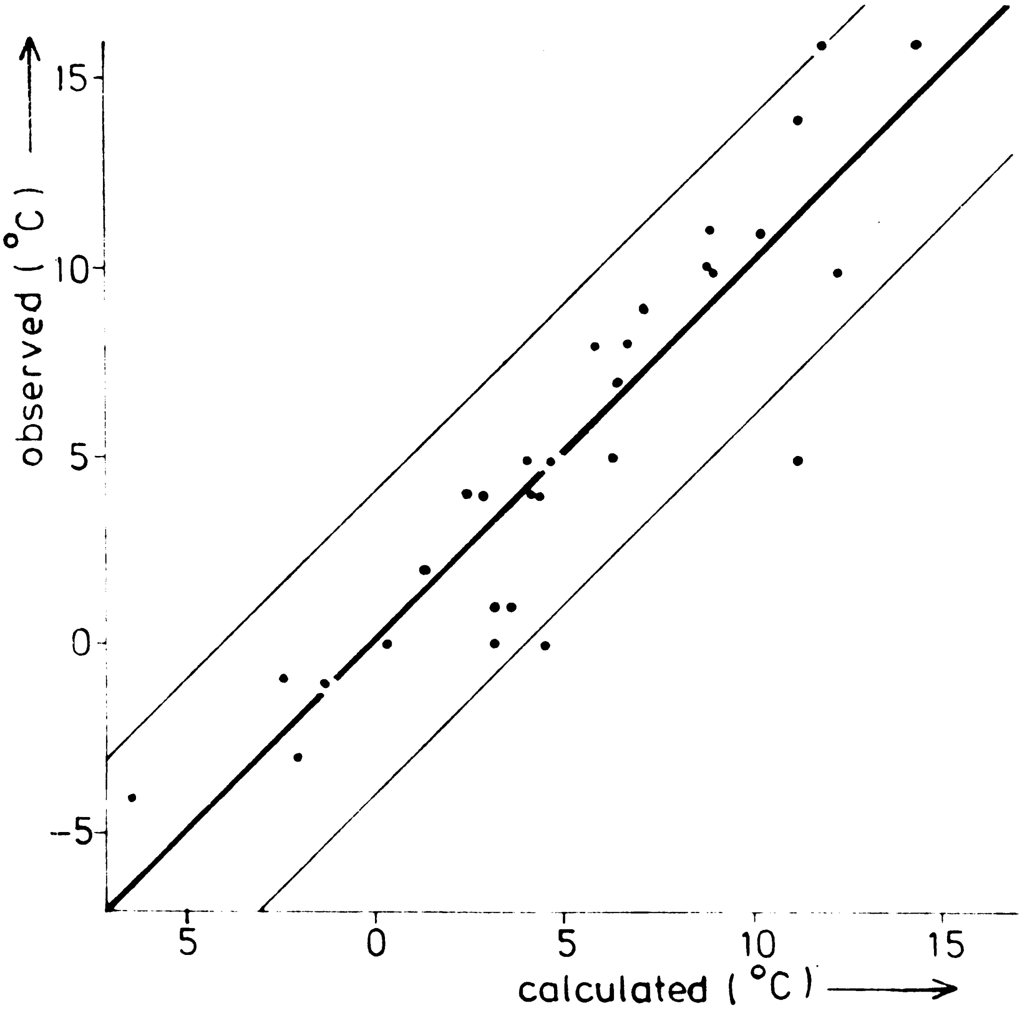


Figure 8. Eq. (4) applied to a random sample of 30 days (1971-1976). Thick line: ideal forecast, thin lines: deviations of 2 degC.

4. The minimum temperature of the urban area

4.1 The urban heat island

Literature on the urban heat island has amassed over the past decades. Since Oke (1974, 1979) gives extensive reviews, only a brief outline on the subject will be given here.

It is generally accepted that the urban heat island finds its origin mainly in:

- anthropogenic heat sources,
- trapping of short wave radiation between buildings, the 'canyon effect',
- decreased radiative cooling due to pollution,
- decreased net long wave radiation due to reduced sky view factor,
- convergence of sensible heat due to stagnation of airflow between larger urban roughness elements,
- decreased evaporation due to runoff of precipitation through sewer systems.

The great majority of authors have treated the subject from the climatologist's point of view. Mean monthly, seasonal and annual urban-rural temperature differences are known now for a great number of settlements (e.g. Sanderson et al., 1973, Eagleman, 1974). Little seems to be known, however, of the weather-related day-to-day variations of the heat island intensity of a particular town. Sundborg in Sweden (Sundborg, 1950) and Conrads in the Netherlands (Conrads, 1975) have attempted to forecast urban-rural minimum temperature differences by taking into account various meteorological parameters.

Sundborg, from automobile traverses through Uppsala and its surroundings derived the following regression equation:

$$D_{night} = 2.8 - 0.10N - 0.38U - 0.02\theta + 0.03e \qquad (5)$$

with

D_{night}: observed nocturnal urban-rural temperature difference,
N : cloud amount in the ten-degree scale,
U : wind speed (ms^{-1}),
θ : temperature (^{o}C),
e : absolute humidity (mbar).

The correlation coefficient was 0.66.

Conrads, employing a similar sampling technique at Utrecht arrived at an equation as follows:

$$\Delta T_{n_{0-12}} = 2.9 - 0.856 \ln v - 0.090 N \qquad (6)$$

with

$\Delta T_{n_{0-12}}$: difference in minimum temperature between city centre and rural area in the period 0 - 12 GMT,

v : mean daily wind speed (ms^{-1}) computed from hourly values at the Bilt, a rural station at 4 km to the northeast of Utrecht,

N : cloud amount in the ten-degree scale, observed at the Bilt at 0300 GMT.

The multiple correlation coefficient was 0.80. The standard deviation of calculated minus observed urban-rural differences amounted to 0.81 degC.

With a view to these not very promising results it seemed profitable to attempt to forecast the urban minimum temperature in a more direct manner. To pave the way, some climatological information on the Rotterdam heat island will be given first.

4.2 Climatology of the Rotterdam heat island

In figure 9 relative frequencies of heat island events are plotted against heat island intensity which, concurrent with literature, is indicated by:

$$T_{u-r} = T_u - T_r,$$

T_u and T_r being observed urban and rural minimum temperature respectively. Only nights with average wind speed less than 3 kts and average cloud amount less than 2 oktas were considered.

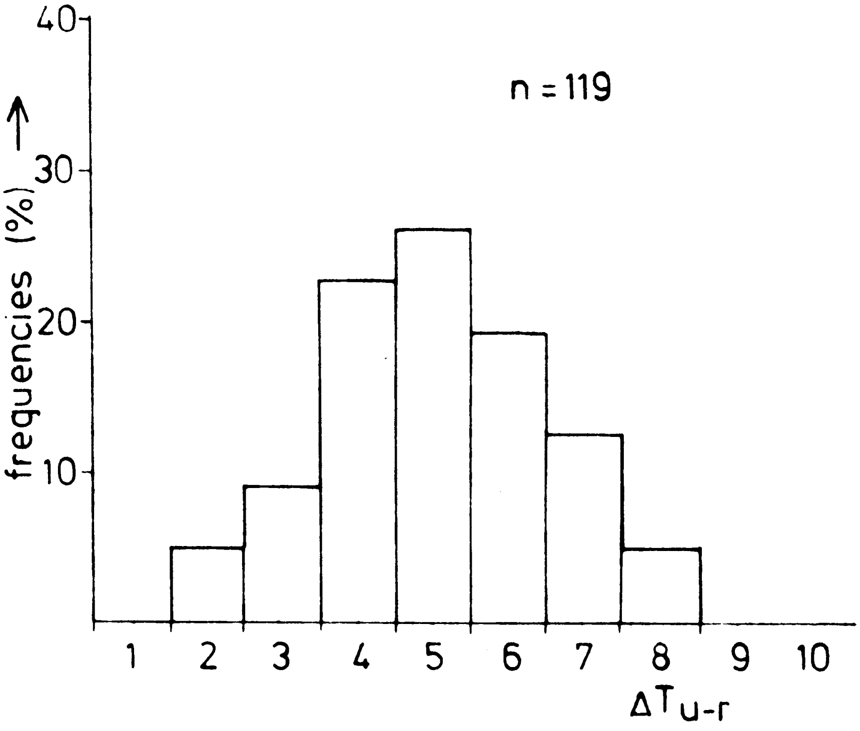


Figure 9. Relative frequencies of Rotterdam heat island events on clear, calm nights.

The maximum heat island intensity of a town is supposed to be closely related to its population (Oke, 1973). He derived a regression equation for European settlements (fig.10):

$$T_{u-r(max)} = 2.01 \log P - 4.06$$

with P for population. From figure 8 the maximum heat island intensity for the Rotterdam conglomeration is 8 °C. The overall population being approximately 1.000.000 (Statistical Yearbook 1979) this temperature fits remarkably well.

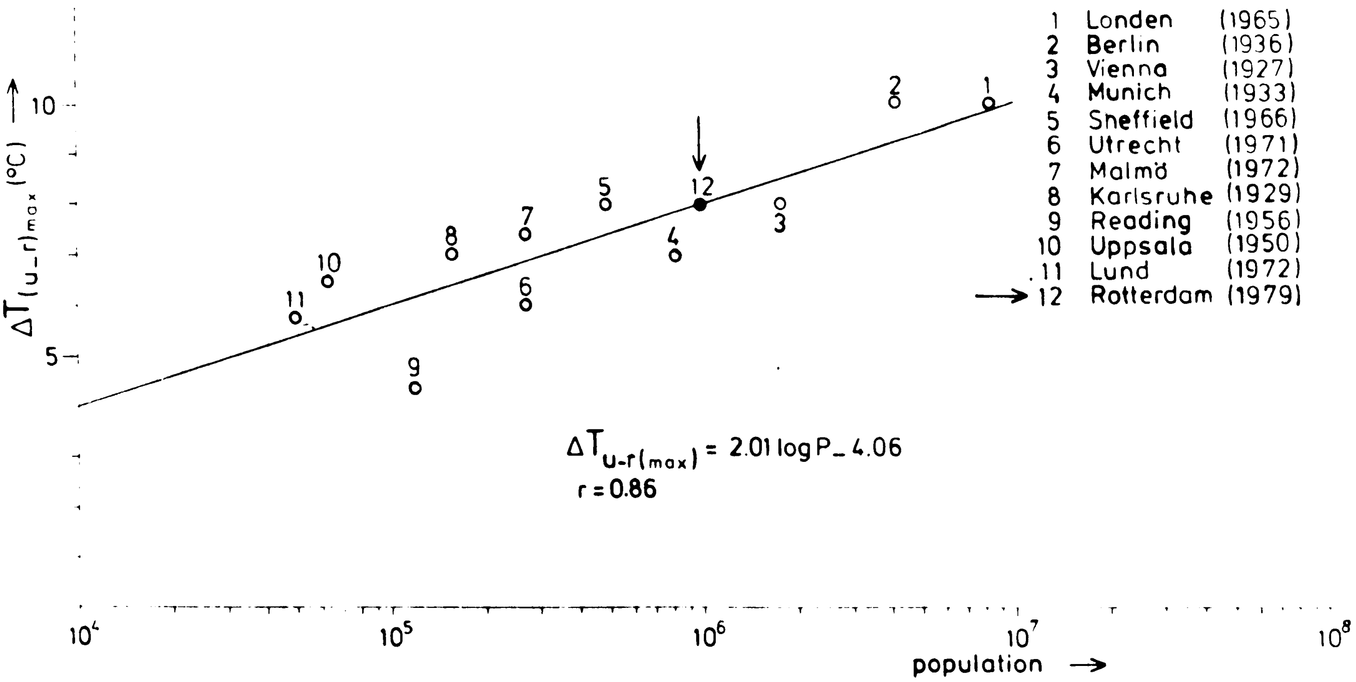


Figure 10. Dependence of maximum heat island intensity on population (adapted from Oke, 1973).

The mean heat island intensity on nights with weak winds and low cloud amounts during the entire period for which data were available (1971-1973, 1978) amounted to 5.0 °C with standard deviation 1.5 °C. For the various seasons the means (m) and standard deviations (s) are given in table II.

Table II. Average heat island intensities (°C) on calm, clear nights.

Season		m	s
Winter	December January February	4.3	1.2
Spring	March April May	4.9	1.5
Summer	June July August	4.5	1.3
Autumn	September October November	5.8	1.3
Year		5.0	1.5

Evidently the Rotterdam heat island is best developed in autumn and spring with a slightly greater variability in the latter season. A similar tendency was found in the Birmingham area in England (Unwin, 1980).

To gain an impression of the dependence of the heat island intensity on environmental wind speed, wind direction and cloud amount, table III was drawn up. Average nocturnal wind speeds, calculated from hourly observations at Zestienhoven, were separated as before according to the Beaufort-scale. Because the heat island is least intense with strong winds, average wind speeds exceeding 10 kts were left out.

Wind directions between north-west and north-east were labeled 'rural' (r), those between south-east and south-west 'urban' (u). Other directions did not enter into the calculations.

Average total cloud amounts, also calculated from hourly observations at Zestienhoven, were divided into three classes: scattered (sct, 0 - 2 oktas), broken (bkn, 3 - 6 oktas) and overcast (ovc, 7- 8 oktas)

Table III. Mean intensities (m) and standard deviations (s) of the Rotterdam heat island (degC) with 'rural' (r) and 'urban' (u) wind directions.

	Cloud amount											
	sct				bkn				ovc			
	r		u		r		u		r		u	
BFT	m	s	m	s	m	s	m	s	m	s	m	s
0	5.2	1.2	4.5	1.6	4.4	1.3	3.3	1.3	1.4	1.0	1.2	0.9
1	3.8	1.2	2.2	1.3	2.8	1.2	1.7	1.2	1.3	1.5	1.2	1.5
2	2.2	1.1	1.0	1.2	1.5	1.0	1.0	1.0	1.1	0.6	0.9	1.2
3	1.1	0.8	0.3	0.9	1.1	0.8	0.3	0.9	1.1	0.4	0.7	0.6

From table III it is seen that the heat-island intensity decreases with increasing cloud amount and increasing wind speed. Moreover the intensity is always greater with a 'rural' wind direction. This confirms the findings of earlier studies (e.g. Cech et al., 1976).

The Rotterdam heat island is also manifest in the reduced number of minimum temperatures below freezing as compared with Zestienhoven. In figure 11 frequencies are shown of freezing temperatures at both sites. The totals numbered 135 at the airport against 77 at Rotterdam. Table IV gives a summary.

Table IV. Freezing temperatures at Zestienhoven airport and at Rotterdam (1971-1973, 1978).

	Airport	Rotterdam
Number	135	77
Average temp.	-3.6	-3.0 °C
Standard dev.	2.7	2.3 °C

These results are comparable with figures for e.g. London, where night-time frost is about 50% less frequent than in adjacent rural areas (Chandler, 1965).

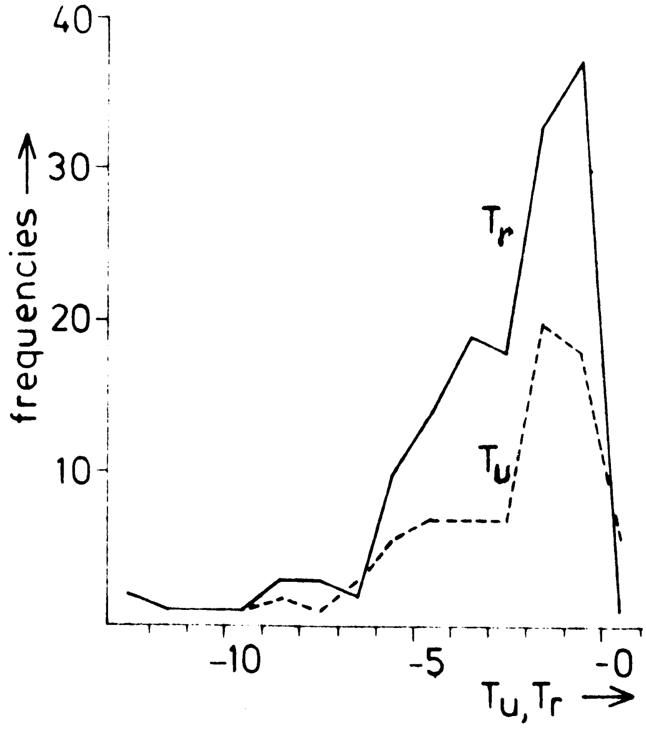


Figure 11. Frequencies of freezing temperatures at the rural and urban sites.

4.3 Calculation of the minimum temperature at Rotterdam

The step-wise procedure used before was adopted again to derive a regression equation for the urban area. With the same parameters as in Eq. (4) the result was:

$$\hat{T}_u = -0.93 + 0.44(TT+T_dT_d)_{15} + 0.14N - 1.71X1 - 1.09X2 + 0.15X3 \qquad (7)$$

(r = 0.95, rmse = 1.6 °C).

Eq. (7), however, proved to be systematically biased towards too warm forecasts in winter and towards too cold forecasts in summer. This feature was interesting in that it was not present when the rural equation (Eq. (4)) was tested on independent rural data.

In figures 12a-d frequency distributions are plotted of the average monthly mean minimum temperatures at the rural and urban sites. These pictures clearly show that the city only reluctantly disposes of its extra heat, especially after summer (fig. 12). This would explain the bias mentioned above: the urban heat surplus is not evenly distributed over the months, but has a distinct maximum in early autumn.

To compensate for this effect, without at the same time making computations too cumbersome (the equations are intended for routine-use) a very crude approximation was made by introducing a new parameter Q: Q was assigned the value 1 for the period June through November and 0 otherwise. After again submitting the entire set of parameters to multiple regression analysis finally emerged:

$$\hat{T}_u = -1.01 + 0.42(TT+T_dT_d)_{15} + 0.15N - 0.96X2 + 1.01Q \qquad (8)$$

(r = 0.96, rmse = 1.5 °C; parameters X1 and X3 were dropped from the equation because of their minor contributions).

Although the correlation coefficient increased only slightly, the bias was removed to a satisfactory degree.

Eq. (8) has been in use at Zestienhoven Met. Office since June 1980.

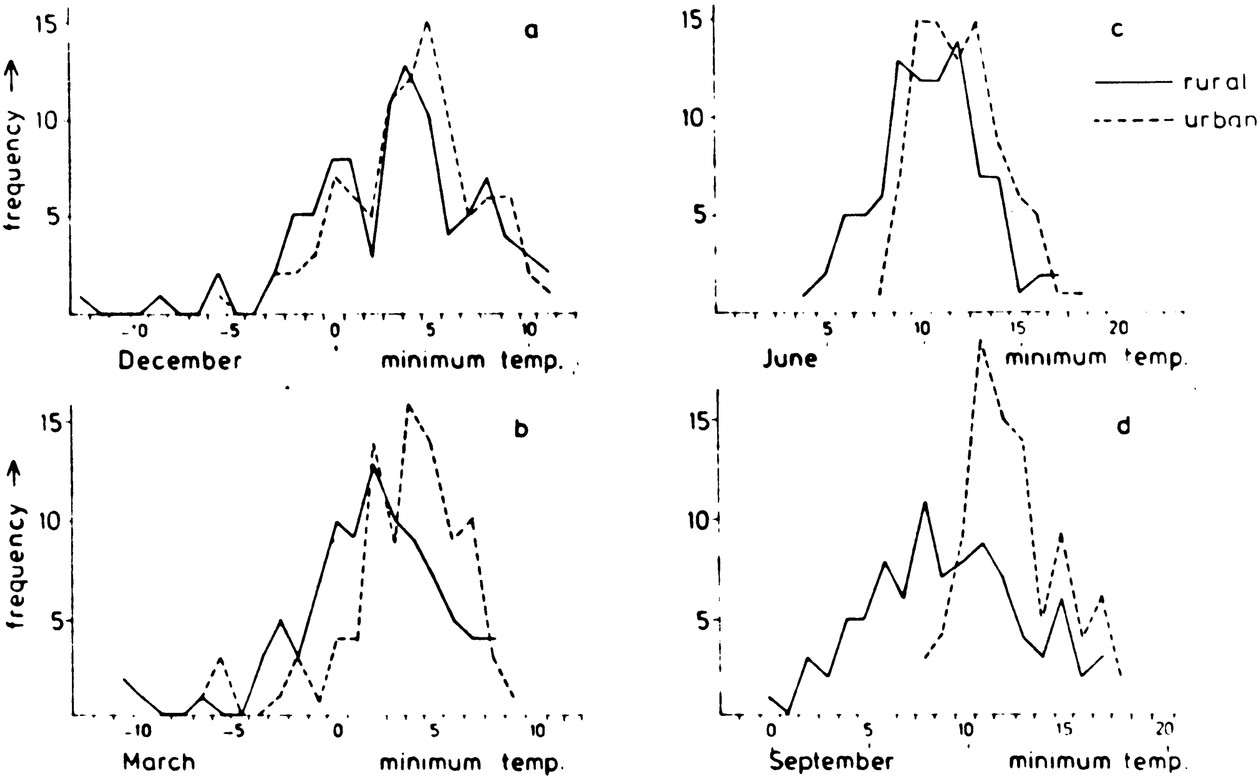


Figure 12. Frequencies of minimum temperatures at the urban and rural sites; a) December, b) March, c) June, d) September.

5. Discussion of the results

5.1 Performance of the equations

For the period June 1980 - March 1981 calculated minimum temperatures for the airport as well as for the urban area were verified. Table V gives a survey of the mean absolute errors (mae) and the root-mean-square errors. For comparison: the mae in the forecasts for the urban area before introduction of Eq. (8) was 2.3 °C; for the airport no data are available.

Table V. Mean absolute and root-mean-square errors of calculated minimumtemperatures June 1980 - March 1981.

	Airport		City	
	mae	rms	mae	rms
JUN	1.4	1.8	1.1	1.3
JUL	1.3	1.8	1.1	1.5
AUG	1.6	2.1	1.6	1.9
SEP	1.5	1.8	1.2	1.4
OCT	2.0	2.3	1.1	1.4
NOV	1.4	1.8	1.2	1.4
DEC	1.1	1.4	1.0	1.2
JAN	1.8	2.2	0.9	1.2
FEB	1.1	1.5	0.9	1.1
MAR	1.3	1.6	1.3	1.5
MEAN	1.4	1.8	1.1	1.4

The urban equation performs distinctly better than the rural one. This was to be expected for various reasons:

- rural minimum temperatures are much more variable (Böhm and Gabl, 1978), see also figure 12,
- cloud amount (which has to be estimated about 12 hours ahead) weighs heavier in Eq. (4) than in Eq. (8),
- this same argument applies to wind speed and direction.

5.2 Sources of errors

There are several sources of errors that affect the performance of both equations. Some are attributable to non-representativeness of the 1500 GMT temperature and dewpoint: a frontal passage during the evening associated with a sufficiently different new air mass is a common cause. The forecaster is sometimes able to correct for this effect by using as input temperature and dewpoint of the new air mass.

A less frequent cause of errors is pre-frontal advection of warmer and/or more humid air aloft. Without a simultaneous increase in cloud amount the calculated minima will be too low (Gall and Herman, 1980).

Afternoon showers may temporarily alter temperature and dewpoint considerably, thus leading to an erroneous outcome.

No mention has been made thus far of a possible influence of the surface temperatures of the river Maas and the Northsea (which is at approximately 25 km to the West) on the behaviour of the minimum temperatures. It is believed that errors due to neglect of these temperatures will generally be small. The river Maas is only about 500 m wide, so any influence will be noticeable with very weak winds only. Sea surface temperatures vary slowly throughout the year; their influence will be implicit in the weight assigned to the variable X3 and the constants in the equations. Extremely warm sea temperatures might, however, lead to an underestimation of the minimum temperature in case of southwesterly or westerly winds; the reverse would occur with extremely low temperatures.

6. Summary and conclusions

It has been shown that a strong relationship exists between the sum of the 1500 GMT temperature and dewpoint observed at Zestienhoven airport and the subsequent minimum temperature at the airport as well as in the nearby Rotterdam urban area. Further refinement was achieved by taking into account the influence of cloud cover, wind speed and direction and, for the urban area, the influence of the season. Simple lineair regression equations have been derived which, as has been demonstrated, perform satisfactorily and may be regarded as useful forecasting tools. The available data (over 1000 paired observations) also permitted the presentation of some statistics on the urban heat island intensity.

7. Acknowledgements

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