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The accuracy of aspiration thermometers

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Abstract.

The accuracy of an Assman-type thermometer is investigated as a function of wind speed and ventilation velocity. Errors originating from the outer radiation shield can attain values of about 10% of the temperature difference between the outer radiation shield and the unmodified air. These errors occur when the wind speed exceeds the ventilation velocity. They can be reduced by applying an insulating layer on the outer radiation shield. The temperature field around the meteorological mast at Cabauw, the Netherlands, was briefly investigated. Temperature errors of 0.1-0.2^{o}C were found at the leeward side of the tower on sunny days. A periodically heated thermometer was developed in order to detect errors due to moisture deposited on the thermometer (rain, fog, drizzle). The evaporation of the moisture on the thermometer can last several hours and the errors can reach values between 0^{o}C and -3^{o}C.

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1. Introduction.

Meteorologists usually measure temperature inside an unventilated screen of the Stevenson type (Sparks, 1970). It is wel known that these screens may reduce the radiation errors, but they introduce errors caused by the screen itself. These errors are largest at low wind speeds and decrease with increasing wind speeds. In order to overcome these difficulties Assmann (1892) constructed a thermometer with an artificial ventilation of 4 m/s and two concentric cylinders as radiation shields. He showed that this instrument measured the air temperature with small errors ($\simeq 0.01^{o}C$) at low wind speeds. This "Assmann" type of thermometer has become standard for air temperature measurement. It is generally assumed that the ventilation eliminates all possible errors, except maybe a small radiation error, provided the observation procedure is correct (Kramer et al., 1954). The few publications on the improvement of Assmann thermometry (for a review see Tanner (1963) and Sparks (1970)) deal chiefly with the optimal choice of dimensions and materials to eliminate radiation errors (see Fuchs, 1965), and with practical improvements of the electronics. Little or no attention has been given to advection errors originating from the shields.

For the instrumentation of the 215 m high meteorological mast at Cabauw (Wieringa, 1973 and Van Ulden et al., 1976) a temperature profile measurement system with an accuracy of $\pm$ 0.05^{o}C was required. An aspiration thermometer of the Assmann type was used with an outer radiation shield made of stainless steel, but its accuracy proved to be insufficient, although the ventilation velocity was 8.5 m/s. Investigations in a wind tunnel revealed that the circulation around the ventilation intake changed when the wind speeds became greater than the ventilation velocity and advection errors originating from the outer radiation shield could reach the sensing element. An insulating layer on the outside of the shield reduced the errors appreciably, and thermometers of this type (see Fig. 1) are at present used in the meteorological mast.

The first investigations on this subject were reported to W.M.O. (Slob, 1973). The present article describes in more detail the origin of the errors and their dependence on wind speed and ventilation velocity.

In section 3 the errors caused by nearby obstacles (booms and the mast itself) are discussed, and section 4 deals with the problems in humid conditions.

2. Advection errors.

Suppose we want to measure the undisturbed air temperature T_0 in a position x, but near a surface S with an average temperature $\overline{T}_S$. From S heat is transferred to the air causing in x a temperature error ΔT.

The heat flow Q_S from S is

$$Q_S = h_s \left[\overline{T}_S - T_0 \right] \cdot S \qquad \text{(Eq. 1)}$$

where h_S is the average heat transfer coefficient.

The temperature error $\Delta T(x)$ downestream is proportional to Q_S and some mixing function f_S that depends only on flow parameters and on the position of x.

For an Assmann thermometer, the surfaces S are the radiation shields, x is a position in the measuring section and the flow parameters are the wind speed u and the ventilation velocity v. The temperature error can be written as

$$\Delta T(x) = f_S(v,u,x) \left[\overline{T}_S - T_0 \right] . \qquad \text{(Eq. 2)}$$

This equation is used in the experiments. $\Delta T(x)$ and $\left[\overline{T}_S - T_0 \right]$ were measured and $f_S(v,u,x)$, a normalized error function, was calculated.

Experimental set-up.

The surface that must be considered first as a source of errors is the outer radiation shield.

The temperature of this shield can deviate considerably from the air temperature due to radiation or, when the shield is wet, due to evaporation of water. In most types of Assmann thermometers this shield is a metal cylinder. The temperature on the outside is nearly equal to the temperature on the inside of the cylinder because of the good thermal conductivity of metal. The result is that both surfaces can contribute to the error. When an insulating layer is put on the outside (see Fig. 2) of the shield the contribution of the inside to the error is effectively reduced.

The thermometer used for the experiments was the same as those used in the mast for routine measurements (see Fig. 2). The outside of the outer radiation shield S1 is a white-painted aluminium cylinder. A layer of 1 cm polyurethane foam separates S1 from the inside of the outer radiation shield S2, which is made of stainless steel.

The inner radiation shield S3 is made of brass. For the routine measurements a thermocouple is placed in position C only, but during the experiments several small thermocouples were installed (in Fig. 2 indicated by crosses). All these couples lie in a horizontal line parallel to the wind direction and 1 cm above the ventilation intake.

S1, S2 and S3 could be heated by heating coils made of thin wire, which were wound tightly around these surfaces. The temperature of the surfaces was measured at several locations and appeared to be rather uniform during the heating, with local deviations of $\approx 0.1\ (\overline{T}_S - T_0)$. The average temperature $\overline{T}_S$ was used in the calculation of f_S.

The experiments were carried out in an open wind tunnel. A reference thermocouple, placed 0.5 m upstream, was shielded from radiation by a cylinder (length 5 cm, diameter 2 cm). With the heating off there was no difference in temperature between the reference and the other thermocouples except for small dynamic errors at wind speeds $\approx$20 m/s and greater. When the heating was on, the insulating layer did not totally prevent heat transfer between S1 and S2. When one of them was heated, the other also contributed to the measured error. This contribution was neglected and the uncorrected functions f_{S1} and of f_{S2} were calculated. With the help of these functions the measured $\Delta T(x)$ were corrected. The corrections were always < 10%. Finally, the corrected functions f_{S1} en f_{S2} were calculated.

The ventilation air flow was measured with a gas-meter. The ventilation velocity was calculated as the ratio of the volume flux and the cross-section of the ventilation tube.

The average heat transfer coefficient $h_S(v,u)$ was calculated from (1). Through regression calculations h_S was expressed as a linear function of ventilation velocity and wind speed. The heat flow Q_S is equal to the energy dissipated in the heating coils. Here $\left[\bar{T}_S - T_0\right]$ is measured and S is known from the geometric dimensions.

Windtunnel results.

Fig. 3 shows $f_{S1}(v,u,x)$ as a function of the position x (see Fig. 2) with v = 4.8 m/s and several wind speeds.

For $u < v$ very small errors;

$u \approx v$ a steep error gradient with large values on the wind-side, small ones on the lee-side;

$u > v$ the error is spread more homogeneously, on the windward side becoming smaller, on the leeward side larger.

Fig. 3B shows $f_{S2}(v,u,x)$.

For $u < v$ the error is small;

$u \approx v$ the errors increase towards the windward side;

$u > v$ a steep error gradient is found, which is almost independent of wind speed.

Figures 4A, 4B and 4C show the normalized error function in position C, the normal position during measurements, as a function of wind speed.

Fig. 4A shows the normalized error function caused by the outside of the insulating layer S1.

For $u < v$ the error is small;

$u \approx v$ the error increases rapidly;

$u \approx 1.5\text{-}2\ v$ the error reaches a maximum;

$u > v$ the error seems to be exclusively a function of u.

Fig. 4B shows the normalized error function originating from the inside of the insulating layer S2.

For $u < v$ the error is small;

$u \approx 1\text{-}2\ v$ the error increases rapidly;

$u > 2v$ the error remains more or less constant.

Fig. 4C shows the normalized error function due to the inner radiation shield S3.

The calculations of the average heat transfer coefficients resulted in:

$h_{S1} = 22 + 8\ u$ Watt per $m^2\ {}^oC$ v and u in m per s

$h_{S2} = 37.8 + 4.1\ v + 3.5\ u$ Watt per $m^2\ {}^oC$

$h_{S3} = 46 + 6.5\ v + 3\ u$ Watt per $m^2\ {}^oC$

Error estimation for a standard Assmann thermometer.

To derive maximum temperature errors with the help of Fig. 4 and (2) we need the temperature differences between the shields and the undisturbed air $\left[\bar{T}_S - T_O\right]$.
In bright sunshine (sun's altitude 45°) $\left[T_{S1}(v,u) - T_O\right]$ can be estimated from Fig. 5. This fig. shows measurements of $\left[T_{S1} - T_O\right]$ for a standard Assmann thermometer made of polished stainless steel, without insulating layer. Because the shield has a good heat conductivity $(T_{S1} - T_O) \approx (T_{S2} - T_O)$, so that the maximum error ΔT in C can be estimated with:

$$\Delta T(v,u,C) = \left[f_{S1}(v,u,C) + f_{S2}(v,u,C)\right]\left[T_{S1}(v,u) - T_O\right] \qquad \text{(Eq. 3)}$$

With an insulating layer the error originating from S2 is reduced effectively and can be neglected.

In this case a good estimate of the maximum error ΔT in °C is

$$\Delta T(v,u,C) = f_{S1}(v,u,C)\left[T_{S1}(o,u) - T_O\right] \qquad \text{(Eq. 4)}$$

The contribution of the inner radiation shield S3 to the error is usually negligible because $\left[T_{S3} - T_O\right]$ is very small. In some weather conditions, however, $\left[T_{S3} - T_O\right]$ can increase. For instance, after fog or rain, when the inner radiation shield can still be wet and the sensing element is already dry, $\left[T_{S3} - T_O\right]$ can become quite large.

Also errors originating from S3 can be of some importance in a psychrometer where sections of the inner radiation shield can become wet.

It must be stressed here, that these estimations are valid only for this type of thermometer and for the position C. Another form of the ventilation intake for instance can change the maxima and the form of the functions f_{S1} and f_{S2} a little, but the similarity will subsist.

From experiments it was inferred that a fluted ventilation intake caused smaller errors than a simple cylindrical shape of the intake.

Evidently, a fluted intake more effectively prevents the modified air from the outside of the shield from reaching the measuring section.

3. Influence of the Cabauw mast on temperature measurements.

The Cabauw mast is a cylinder with a length of 215 m and a diameter of 2.0 m. It has, at 20 m intervals, 9 m booms in three directions (Fig. 6), with measuring instruments located at the end of each boom (Van Ulden et al. (1976)).

At the 20 m- and 200 m-levels the temperature differences, measured on the three different booms on sunny days between 10 and 16h GMT, were analyzed. The 10-minutes average temperature differences were calculated from seven observations. The lowest average at the level was taken as a reference. In this way two differences, with a positive sign were obtained for each level. In the Figures 7A, 7B and 7C these deviations are plotted as a function of wind direction for each boom. The largest deviations (in the order of 0.1 and 0.2 $^{\circ}$C) occur when the boom is on the leeward side of the mast, while the deviations in the other directions amount to about 0.03 $^{\circ}$C, a value related to the overall accuracy of the measurements.

The average weather conditions during the measurements were:

average wind speed	at 20 m	4.3 m/s ± 2.3 m/s
	at 200 m	5.5 m/s ± 3.3. m/s
average global radiation		689 Watt/m^2 ± 193 Watt/m^2

4. Humid conditions.

In humid conditions all parts of the sensor mentioned before, the sensitive element itself included, may become wet and approach the wet bulb temperature T_W. The resulting errors can be estimated with the help of (2):

$$\Delta T(v,u,C) = \left[f_{S1}(v,u,C) + f_{S2}(v,u,C) + f_{S3}(v,u,C)\right]\left[T_W - T_O\right] \quad \text{(Eq. 4)}$$

If the sensitive element itself is wet, the error equals $(T_W - T_O)$.

In the laboratory some experiments were performed to determine the time t_d needed to dry the sensitive element as a function of ventilation velocity. The wind speed was zero during these experiments and the thermometer was of the type we used for routine measurements at Cabauw (see Fig. 2). The thermometer was wetted by a spray of small droplets. In the laboratory $(T_O - T_W) \approx 9^oC$.

The evaporation is taken proportional to $(T_O - T_W)$ and therefore $\int_0^{t_d} (T_O-T_W)dt$ had to be computed. The variance in $\int_0^{t_d} (T_O-T_W)dt$ was large ($\approx$200%), and further experiments showed that this was mainly due to the variable amount of water on the tip of the sensitive element at the start. A drop of water might just have fallen, or not yet have fallen from the tip of the sensitive element. In later experiments the largest possible drop that just did not fall was brought on the tip of the element using a hypodermic needle. The variance in

$\int_0^{t_d} (T_O-T_W)dt$ decreased to $\approx$ 20% after these precautions.

Table I shows $\int_0^{t_d} (T_O-T_W)dt$ at various ventilation velocities.

The sudden decrease at v $\approx$10 m/s is due to aerodynamical forces by which the drops are sucked into the ventilation system.

From these experiments it may be concluded that the drying may last many hours when (T_0-T_W) is small. For $(T_0-T_W) \approx 1^{\circ}C$ $t_d \approx 10^4 s = 2.5$ hours was found. Experience in the mast confirms these experiments. Table 2 shows some averages and standard deviations based on 20 different observations in the mast, where the ventilation velocity is 8.5 m/s.

Table 1

ventilation air speed	$\int_0^{t_d} (T_O - T_W)\,dt$	number of observations
1.6 m/s	$10.2\ 10^3\ ^oC\ s$	4
4.5 m/s	$9.9\ 10^3\ ^oC\ s$	5
7.5 m/s	$12.0\ 10^3\ ^oC\ s$	6
8.5 m/s	$8.2\ 10^3\ ^oC\ s$	3
10 m/s	$2.8\ 10^3\ ^oC\ s$	11

Table 2

	average	standard deviation
Time t_d needed for drying	5450 s	2140 s
(T_O-T_W) when the element becomes dry	$1.23\ ^oC$	$0.47\ ^oC$
$\int_0^{t_d} (T_O - T_W)\,dt$	$3.8\ 10^3\ ^oC\ s$	$2.3\ 10^3\ ^oC\ s$
$\frac{d(T_O-T_W)}{dt}$	$0.825\ ^oC/hr$	$0.328\ ^oC/hr$

5. Control instrument for humid conditions.

In order to determine the reliability of temperature measurements on the mast in humid conditions, a control device was placed at heights of 2 and 215 m. This instrument consists of three thermometers, all of them provided with insulating radiation shields. The first is a standard thermometer to measure T_O, and the second measures the wet-bulb temperature T_W in the usual psychrometer fashion.

The third thermometer is periodically heated and measures T_H. The sensing element of this thermometer is a thermocouple mounted in a stainless steel capillary with a diameter of 1 mm. A heating coil is tightly wound around this capillary, and a thermal conductive adhesive layer (Delta Bond 152) binds them together. The final diameter of the element is ≈2 mm. The response time at a ventilation velocity of 8 m/s is ≈7 s. The measuring cycle has a duration of 168 s. The first part of this cycle consists of heating during 21 s, after which the element reaches a temperature of some 30°C above the air temperature. Then it cools down towards its equilibrium, and T_H is read three times, namely 63, 105 and 133 s after the heating has stopped.

The cooling curve of the element depends on its shape and dimensions and on the ventilation velocity, but is also affected by the presence of hygroscopic particles and by dust accumulating on the element by impact. At high relative humidities the cooling rate decreases slightly and this can be detected in the first measuring point of T_H, which may be some tenths of a degree higher than T_H measured after 105 and 133 s. This can be explained by a latent heat release, due to condensation on hygroscopic dust during the cooling. In order to reduce this effect, the element is wiped once a week.

Registrations of (T_H-T_O) and (T_O-T_W) were made on a Brown recorder. Figures 8A, 8B and 8C show in outline examples of the registration during fog, drizzle and rain respectively. For the interpretation the following criteria are used:

1) $(T_H-T_O) = 0$ and $(T_O-T_W) > 0$ In Fig. 8 before A and after D.

The relative humidity is < 100% and both T_O and T_H are correct.

2) $(T_H-T_O) = 0$ and $(T_O-T_W) = 0$. In Fig. 8 between B and C.

The relative humidity may be 100%; then T_O and T_H are correct, or the relative humidity is < 100% and both T_O and T_H are incorrect because of moisture. In the fog situation T_O and T_H are correct, because the relative humidity is 100%. In the drizzle and shower situation, however, both T_O and T_H are incorrect.

3) $(T_H-T_O) > 0$ and $(T_O-T_W) = 0$. In Fig. 8 between A and B and between C and D.

The relative humidity is < 100%. T_O is incorrect and T_H is correct. (T_H-T_O) is the actual wet-bulb depression.

The errors after fog dispersal last for several hours and can rise to ≈1.5 °C. This is in agreement with the investigations of George (1970), where about the same values were found in a screen. During drizzle the errors are ≈0.5 °C.

The errors during showers are in the order of some degrees Centigrade and the drying is more rapidly than during fog or drizzle because of the higher values of the wet-bulb depression.

Continuous measurements with this triple sensor were made in Cabauw at the levels 2 and 215 m.

Fig. 9 shows the monthly average percentage of time that at least on one level the temperature elements are wet or nearly wet as a function of season. In summer this percentage is about 25%, but in winter it may increase to 50% or more. In about 1/3 of the time that the sensors are wet there is fog or low clouds with a visibility of 500 m or less.

6. Conclusion.

An aspiration thermometer of the Assmann-type is accurate as long as the wind speed is lower than the ventilation velocity. It becomes less accurate at wind speeds in the order of the ventilation velocity. This in contrast to a thermometer screen, where the errors are largest when the wind speed is low. This difference in behaviour between the screen and the Assmann is probably the reason for the wide-spread misunderstanding that a ventilated thermometer under all circumstances has an accuracy of 0.01 °C.

Especially difficult are temperature measurements in humid or wet conditions. A periodically heated thermometer may be helpful in some of these conditions.

7. Acknowledgements.

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Legends to figures.

Fig. 1	The Assmann-type thermometer as used in the meteorological mast.
Fig. 2	The Assmann-type thermometer as used for the experiments.
Fig. 3A, 3B	Normalized error function caused by the outside (3A) and by the inside (3B) of the outer radiation shield, as a function of position within the shield.
Fig. 4A, 4B, 4C	Normalized error function in the centre caused by respectively the outside of the outer radiation shield (4A), the inside of the outer radiation shield (4B) and the inner radiation shield (4C), as a function of wind speed and ventilation velocity.
Fig. 5	Temperature difference between the air and the outer radiation shield of an Assmann thermometer, without insulating layer, as a function of wind speed and ventilation velocity, in bright sunshine.
Fig. 6	Section of the meteorological mast with booms in three directions.
Fig. 7A, 7B, 7C	Temperature errors on respectively the north boom (7A), the south-east boom (7B) and the south-west boom (7C), as a function of wind direction at the heights of 20 m and 200 m.
Fig. 8A, 8B, 8C	Registration of the control instrument during respectively fog (8A), drizzle (8B) and rain (8C).
Table 1	The integrated value of (T_0-T_W) over the drying time t_d, as a function of the ventilation velocity.
Table 2	Observed values in the meteorological mast with a ventilation velocity of 8.5 m/s.
Fig. 9	Percentage of the time that the temperature elements in the meteorological mast are wet.

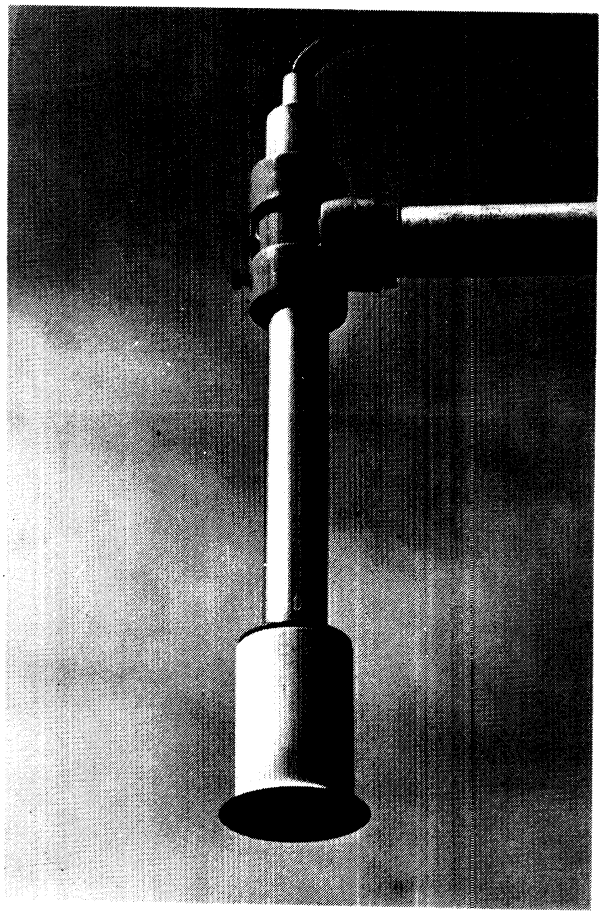


FIG. 1

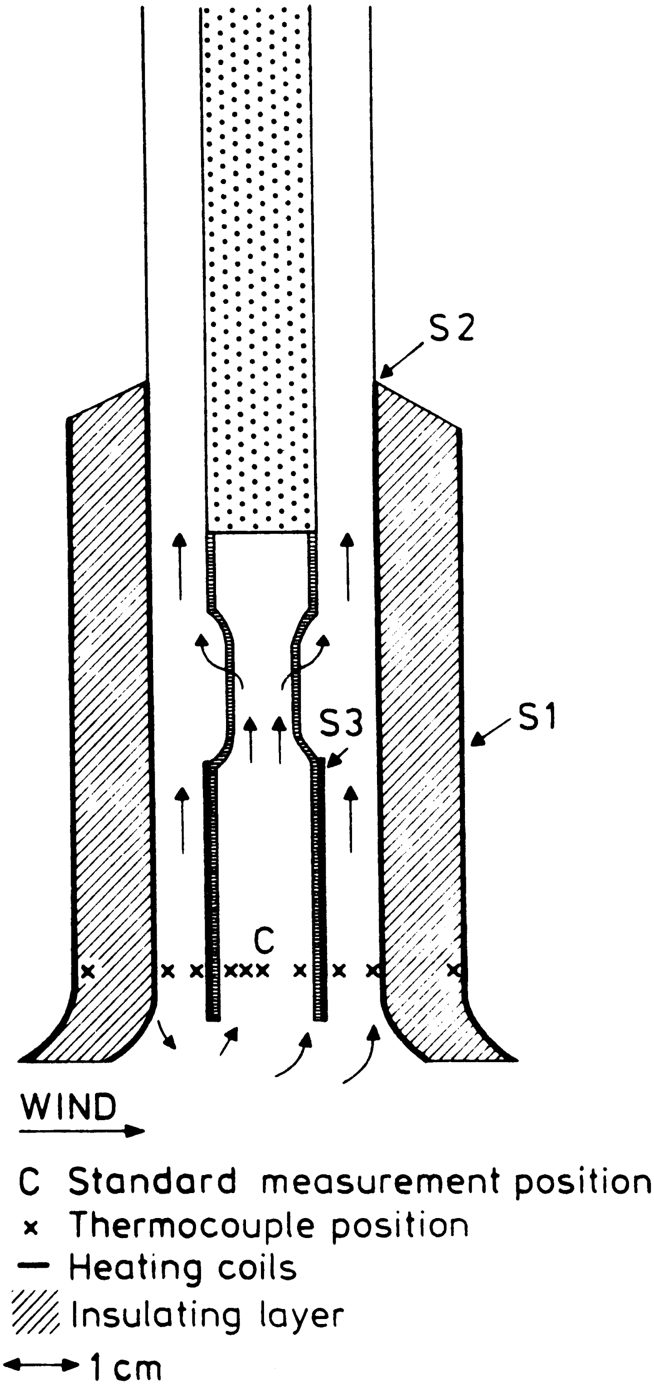
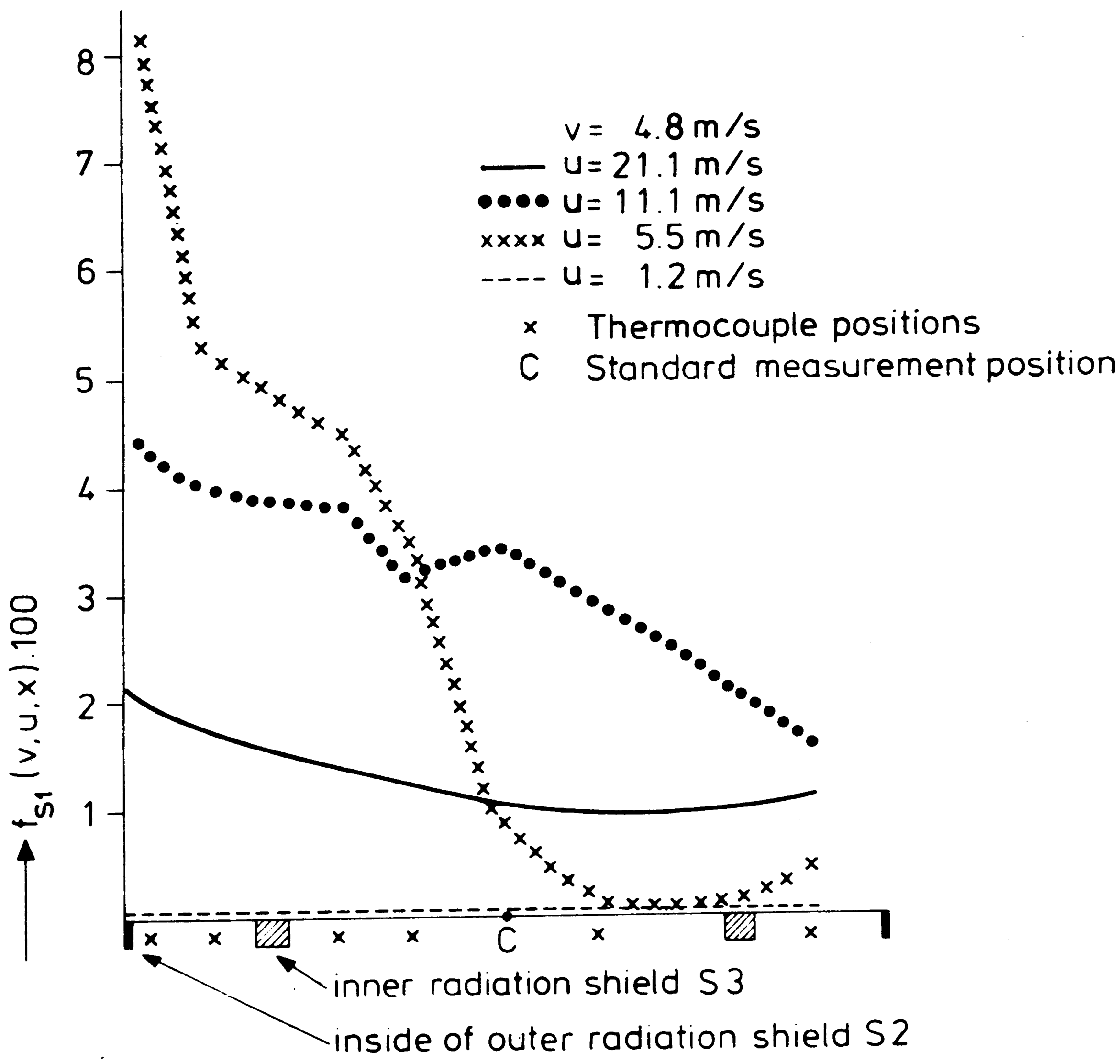

S2
S1
S3
C
WIND
C Standard measurement position
× Thermocouple position
— Heating coils
Insulating layer
1 cm

FIG. 2



fs1 (v,u,x).100
8
7
6
5
4
3
2
1
v = 4.8 m/s
u = 21.1 m/s
u = 11.1 m/s
u = 5.5 m/s
u = 1.2 m/s
Thermocouple positions
C Standard measurement position
C
inner radiation shield S3
inside of outer radiation shield S2

FIG. 3A

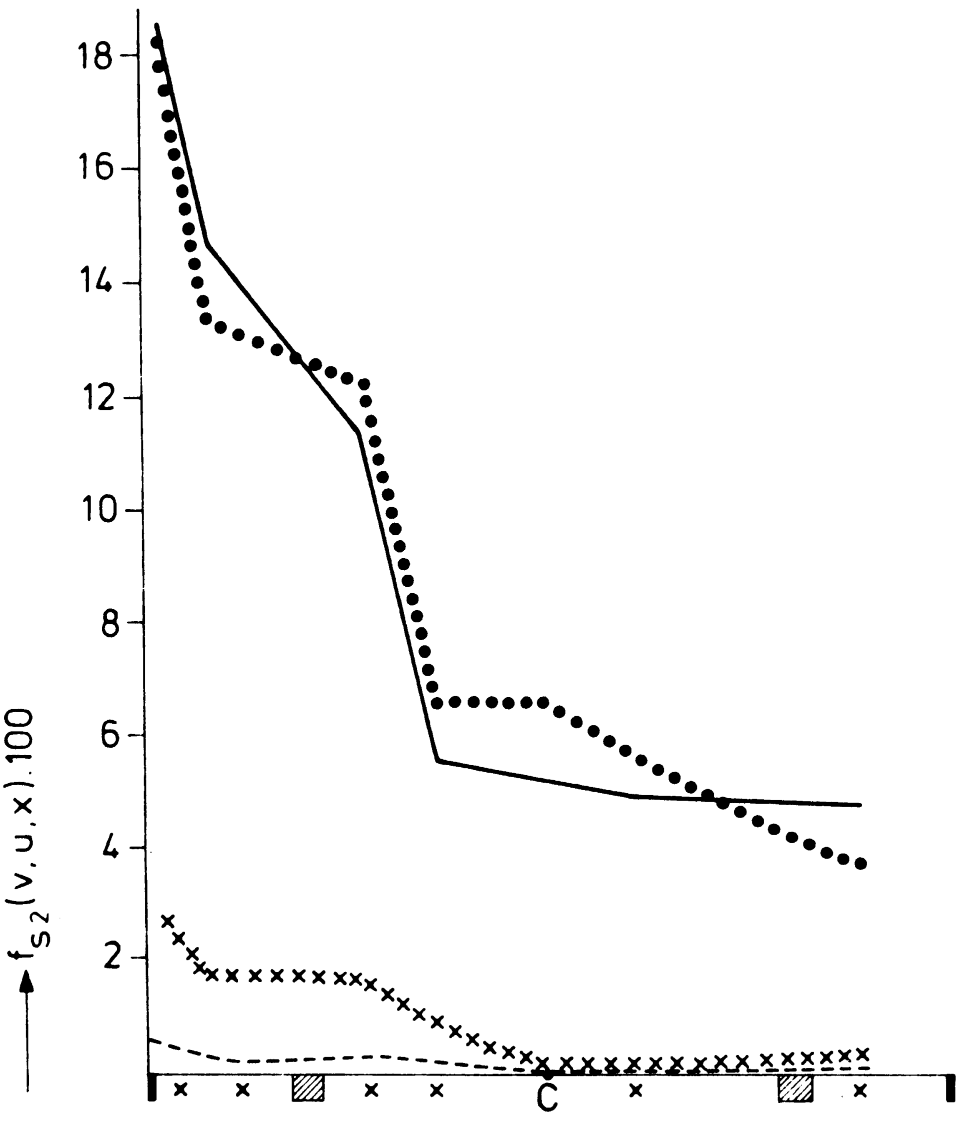
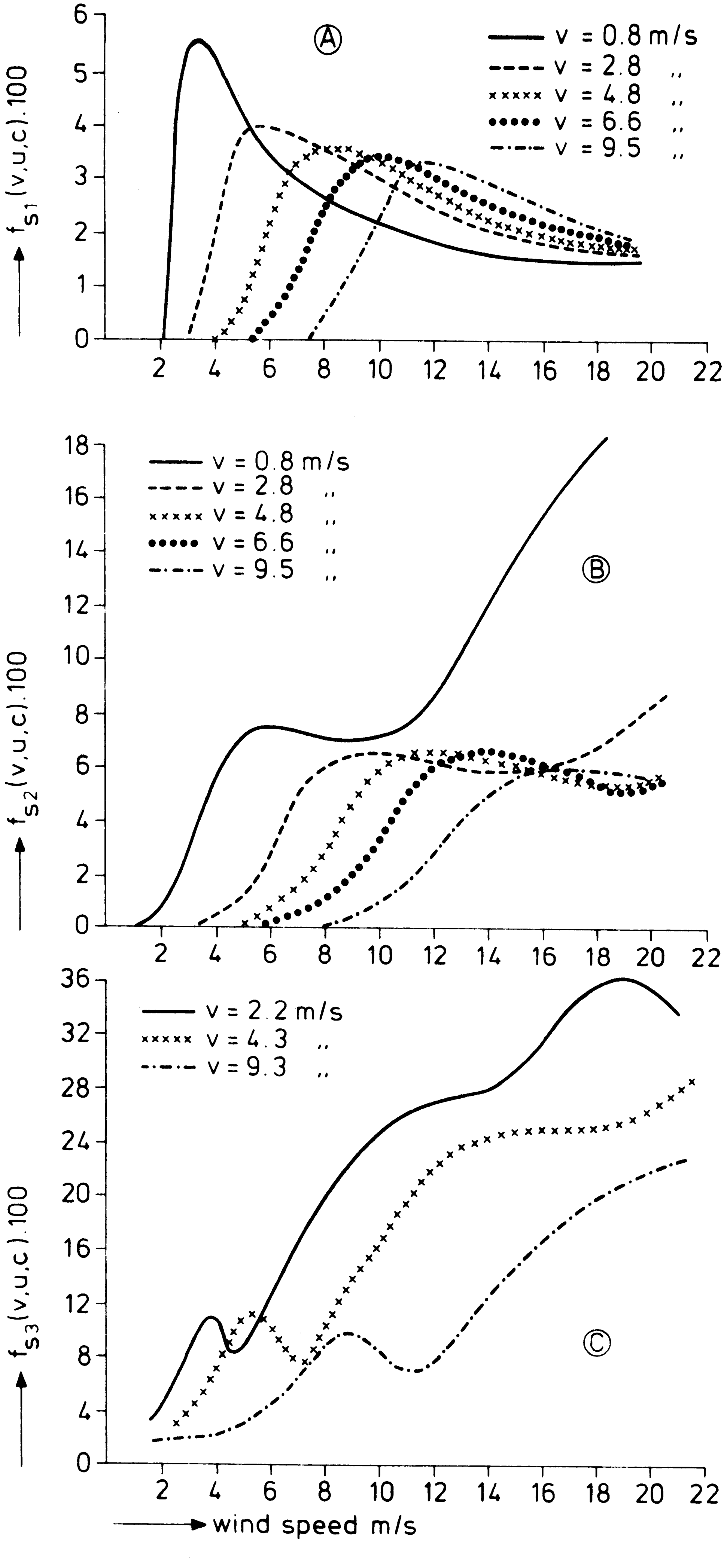
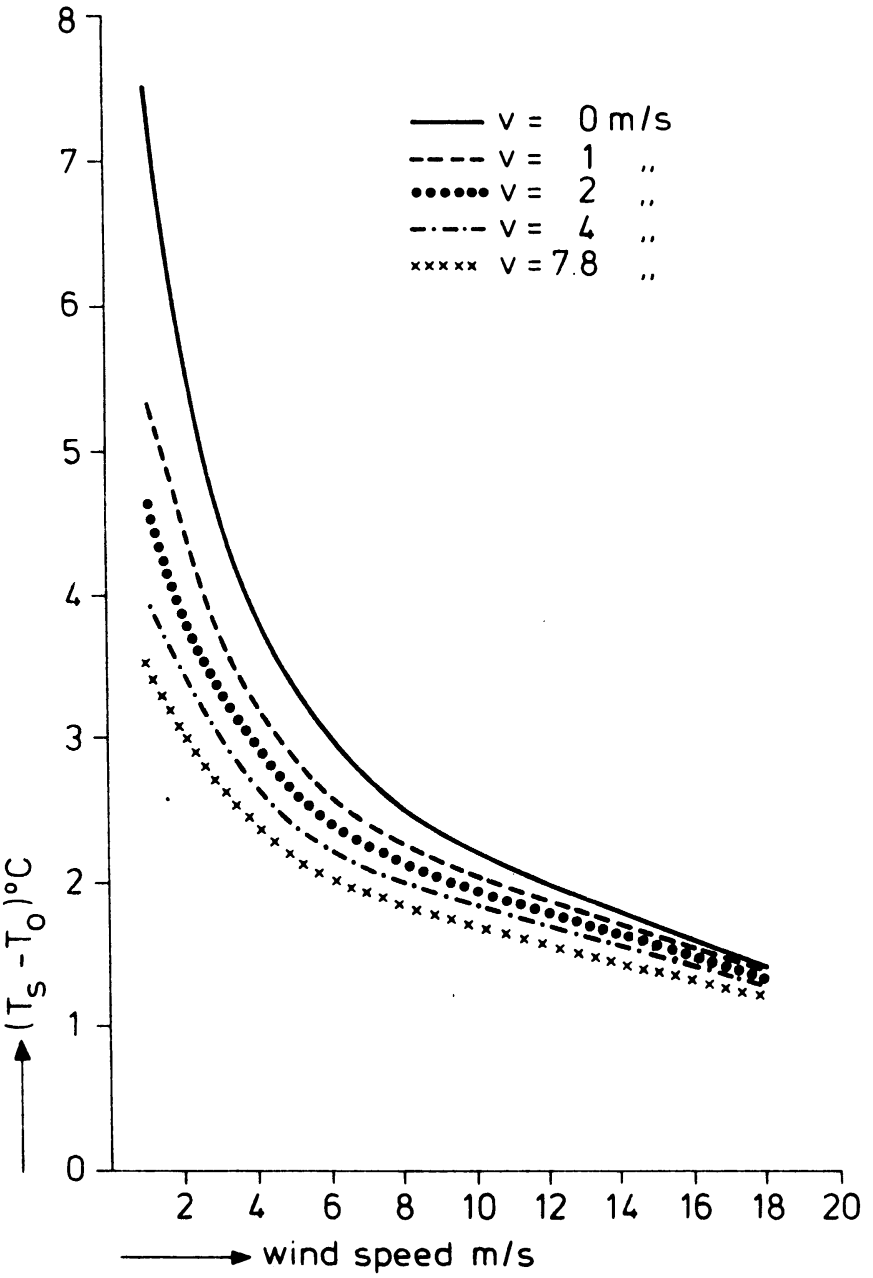


FIG. 3B



Ⓐ
v = 0.8 m/s
v = 2.8 ,,
v = 4.8 ,,
v = 6.6 ,,
v = 9.5 ,,
f_s1 (v,u,c).100
Ⓑ
v = 0.8 m/s
v = 2.8 ,,
v = 4.8 ,,
v = 6.6 ,,
v = 9.5 ,,
f_s2 (v,u,c).100
Ⓒ
v = 2.2 m/s
v = 4.3 ,,
v = 9.3 ,,
f_s3 (v,u,c).100
wind speed m/s

FIG. 4



v = 0 m/s
v = 1 ,,
v = 2 ,,
v = 4 ,,
v = 7.8 ,,
(Ts - To)°C
wind speed m/s
0
1
2
3
4
5
6
7
8
2
4
6
8
10
12
14
16
18
20

FIG. 5

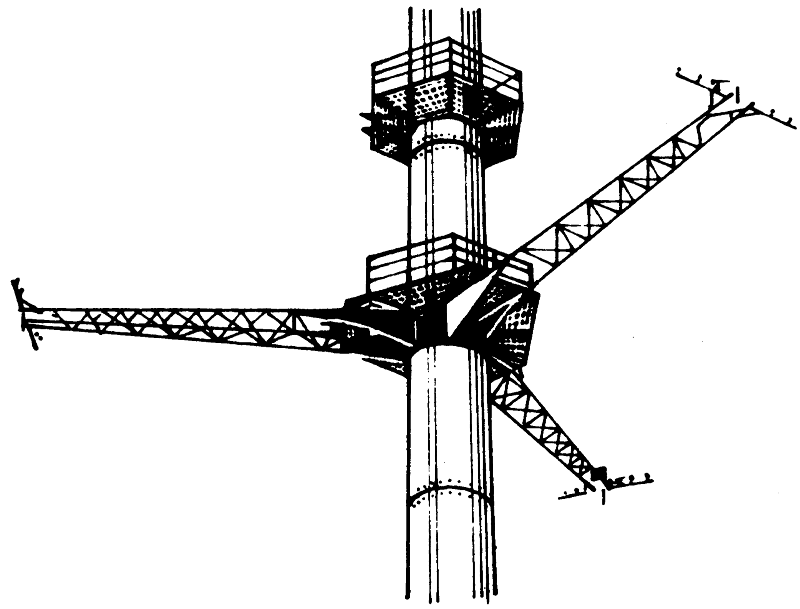


FIG. 6

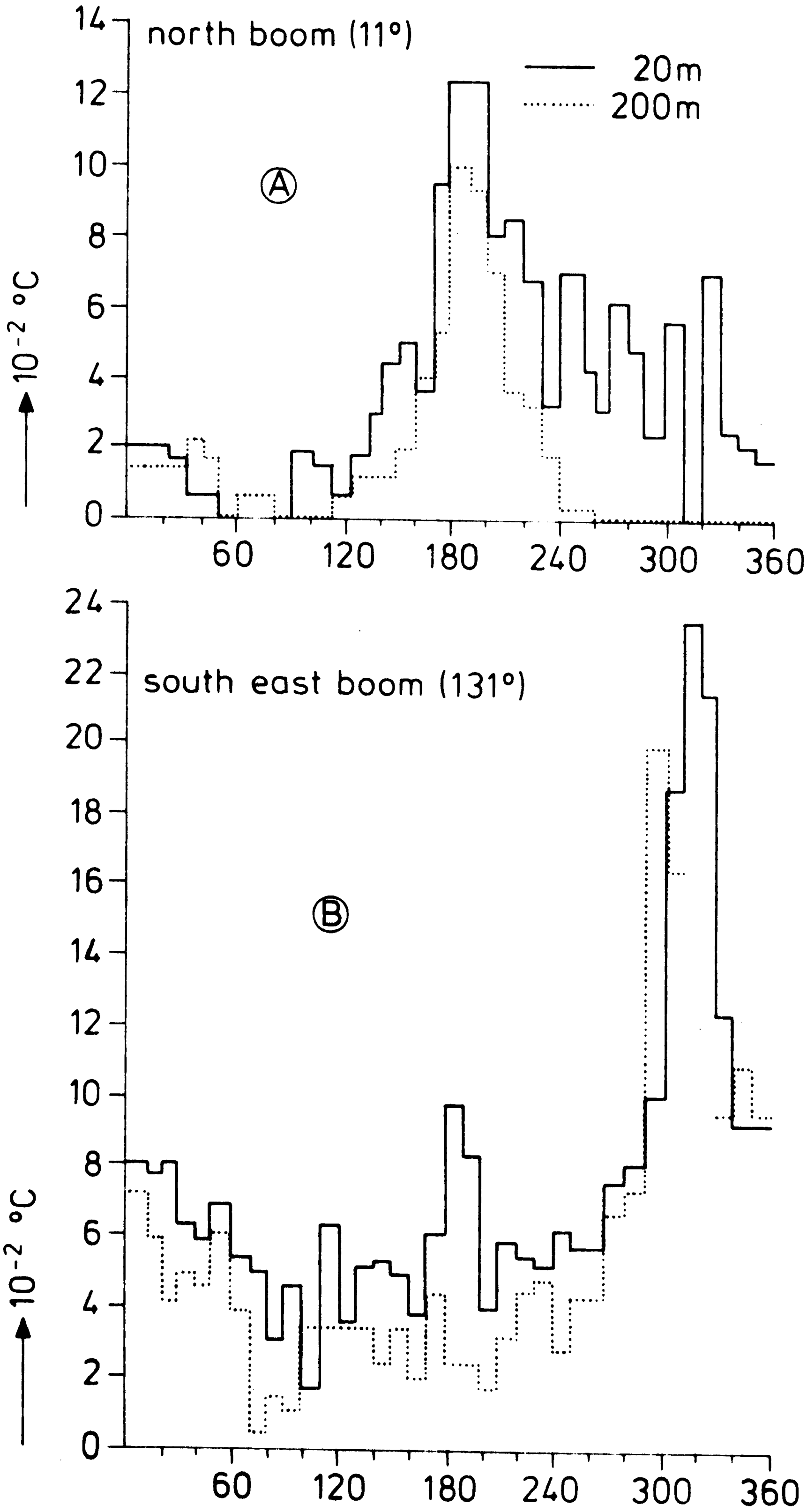
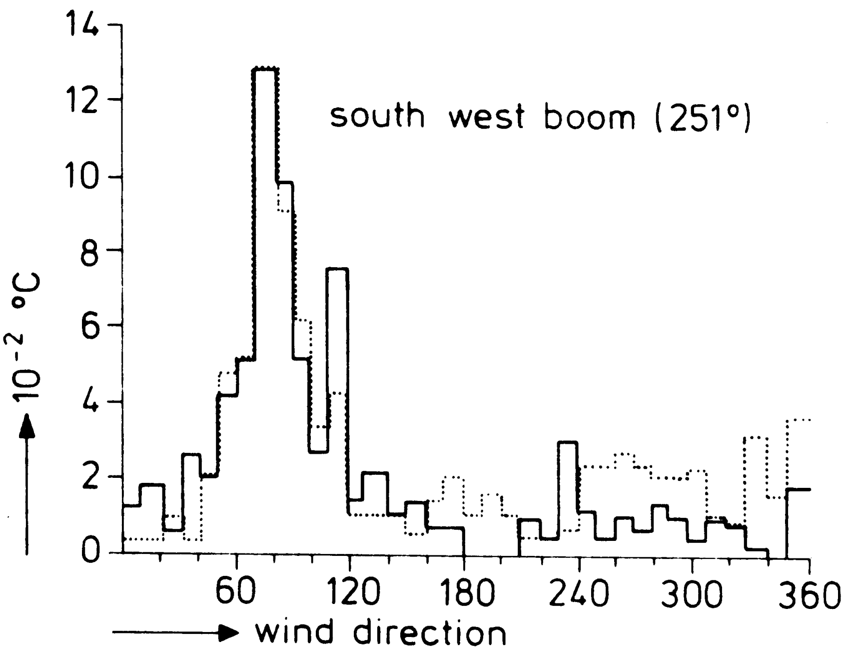
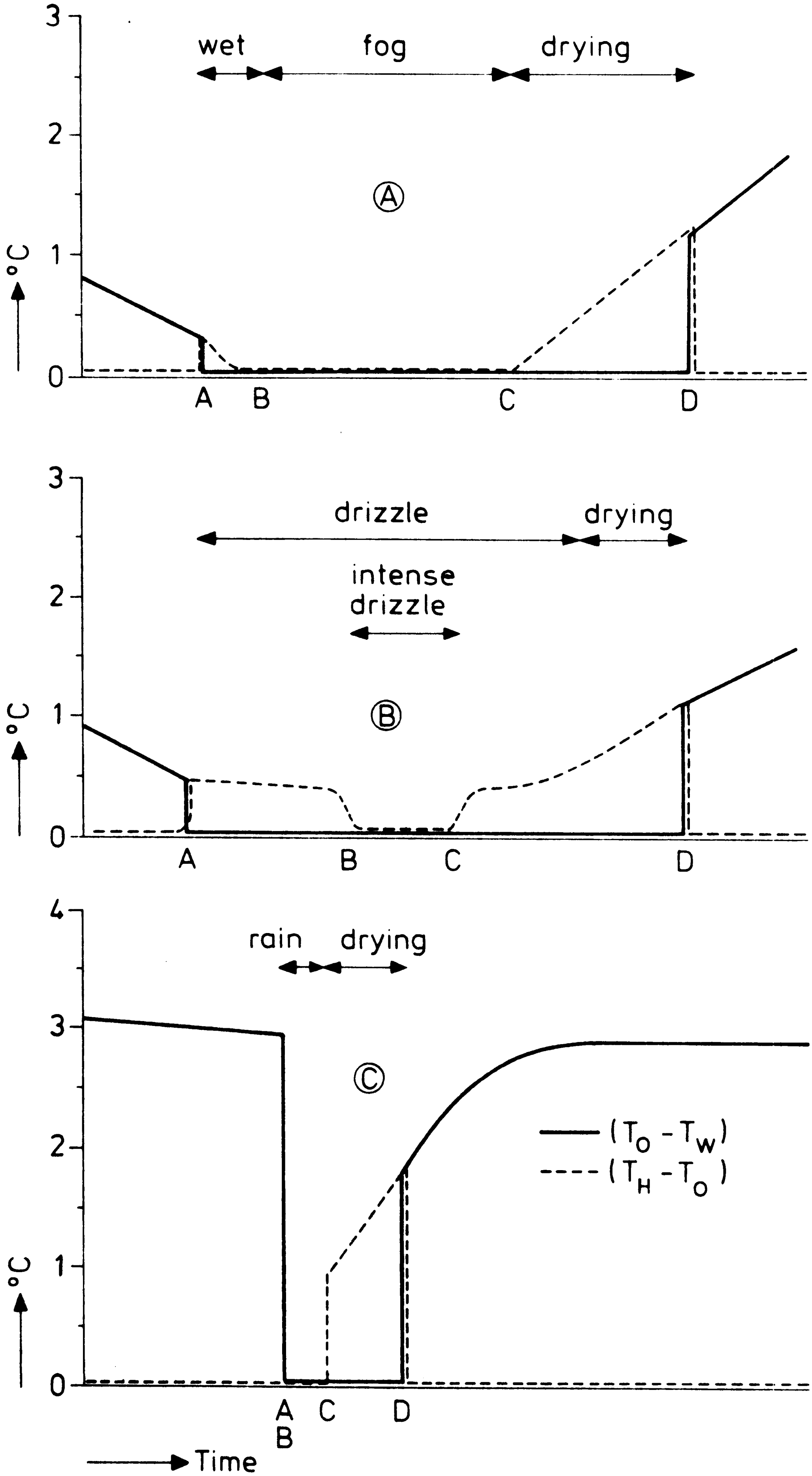


FIG. 7



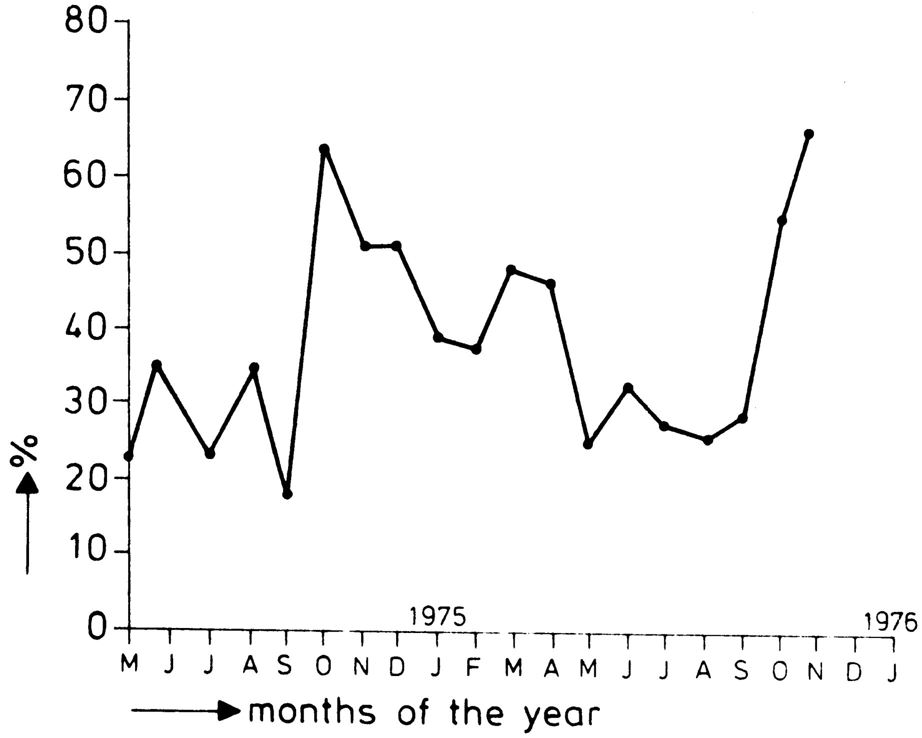
14
12
10
8
6
4
2
0
10⁻² °C
south west boom (251°)
60
120
180
240
300
360
wind direction

FIG. 7C



wet
fog
drying
Ⓐ
°C
3
2
1
0
A
B
C
D
drizzle
drying
intense drizzle
Ⓑ
°C
3
2
1
0
A
B
C
D
rain
drying
Ⓒ
4
3
2
1
0
°C
$(T_O - T_W)$
$(T_H - T_O)$
A
B
C
D
Time

FIG. 8



80
70
60
50
40
30
20
10
0
%
1975
1976
M J J A S O N D J F M A M J J A S O N D J
months of the year

FIG. 9