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ON THE MEASUREMENT OF TEMPERATURE, HUMIDITY AND WIND VELOCITY VERY NEAR THE GROUND

by

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Abstract

The average vertical distribution of temperature, humidity and wind velocity near the ground is described by means of basic equations and some observational results. The common errors of measurement, as placement error and situational error and their importance, are discussed. The operation principles of electric thermometers, psychrometers and anemometers, main sources of errors and correction methods are then explained with special reference to conditions near the ground.

1. *The average vertical distribution of temperature, humidity and wind velocity near the ground*

a) Temperature

In the free atmosphere the temperature gradient of the tropospheric region is, in normal cases, negative. Its extent cannot be appreciably greater than the dry-adiabatic lapse rate which may be stated with fair accuracy as 1°/100 m. Near the ground, however, the situation is essentially different. The sign of the temperature gradient now depends greatly on the radiation balance of the surface. A negative gradient in daytime under incoming radiation and a positive gradient at night under outgoing radiation may be considered typical.

BROCKS [7, 8] has, on the basis of very extensive and representative observations, made a statistical study of the general properties of the temperature gradient from near the ground up to a height of 300 m. According to his research an unstable atmospheric lower layer is observed near the ground when incoming radiation prevails. The height of this layer is at midday about 20 m, taken as an annual mean. At night, correspondingly, an inversion layer is found whose height at midnight is about 20 m. In these layers the temperature gradient may be represented by the equation:

$$\frac{dt}{dz} = az^b, \tag{1}$$

wherein: t = temperature
z = height from the ground
a, b = experimental constants.

The constants a and b are positive at night and negative in daytime. During inversion b varies from 0.05 to 0.2, whereas in daytime its value is fairly exactly -1, in which case (1) takes the form:

$$\frac{dt}{dz} = \frac{a}{z}. \tag{2}$$

The integration gives

$$t_z = t_1 + a \ln z \tag{3}$$

indicating that the temperature drops in the unstable atmospheric lower layer, when rising upwards, proportionately to the logarithm of height.

In examining the above equations as regards the conditions at the ground, the results seem to depend greatly on the quality and height of the surface cover. If the vegetation is sufficiently dense the main part of the incoming radiation is absorbed by the vegetation. Thus, under the prevalence of incoming radiation, the warmest layer is produced at a certain height from the ground, and the logarithmic law is valid only above the active surface. Correspondingly, the strongest outgoing radiation at night is found some distance above the ground, where the coldest layer is found.

If the ground, on the other hand, is bare and even, the logarithmic law presented in equation (1) may be valid very near the ground. By taking the logarithm out of equation (1) we have:

$$\log \frac{dt}{dz} = \log a + b \log z. \tag{4}$$

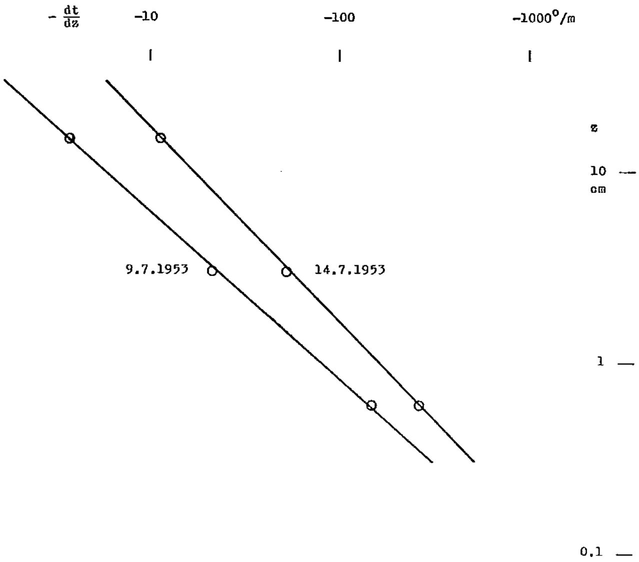

Fig. 1. Logarithmic vertical temperature distribution very near the ground at 12 o'clock noon.

If on a diagram paper, on which the scale is logarithmic in the direction of both axes, the temperature gradient and the height from the ground are chosen for variables, the pair of values realising the logarithmic law will coincide to the same straight line. Fig. 1 shows the results of two series of experiments made by the writer in the summer of 1953 at the Viiki Research Station near Helsinki. The measurements were made at a height of 2 mm, 1 cm, 5 cm, and 25 cm from the ground which was covered by smoothed out fine sand. As instruments of measurement 0.06 mm copper constantane thermocouples were used and as instruments for reading 2 spotlight galvanometers. The position of the spots was recorded by a film camera at intervals of one second for a period of two minutes. Each of the points shown in Fig. 1 thus contains 120 observations. The temperature gradient values have been reduced in the manner introduced by Brocks [7], and the result shows the logarithmic temperature distribution very near the ground.

b) Humidity

Determination of the vertical distribution of humidity is technically more difficult than the measurement of the temperature gradient.

Accurate studies dealing with the humidity gradient have remained rather few in number, and they have often been affected by incidental humidity conditions in the area of measurement. The most accurate measurements of the humidity gradient, therefore, have been made above water or snow surfaces.

SHEPPARD [34] has made a summary of the most important studies dealing with the vertical distribution of humidity. As a general feature it is observed that, in the case of incoming radiation, the vapour pressure diminishes upwards. This is the case also when the ground seems to be dry. During night inversion the vapour pressure gradient often changes to positive, especially when dew occurs. If the air, on the other hand, is sufficiently dry, a weak negative gradient may persist throughout the night. SHEPPARD has shown also that above the sea surface or ground of even humidity, e.g. a lawn, the vertical changes in the vapour pressure are proportional to the logarithm of height. In an area covered with leafy vegetation rules for the vertical distribution of humidity cannot be applied from the ground upwards, but first from a certain height at which evaporation may take place freely.

c) Wind Velocity

Wind velocity as a function of height is, as a rule, represented by means of exponent or logarithm function. Of these methods, that based on the exponent equation is older and has become known especially through the studies of HELLMANN [14]. This dependence may be written in the simple form:

$$u_z = u_1 z^a , \tag{5}$$

wherein

u_z = wind speed at a height z from the ground
u_1 = » » » » » 1 » » »
a = experimental constant.

The average value of the constant a has been calculated by HELLMANN as 0.27; he arrived at this result on the basis of an extensive series of observations. The measuring heights in his observation series were from 5 to 200 cm from the ground. HEYWOOD [15], again, from a series of measurements carried out at heights from 13 to 90 m, obtained the result $a = 0.26$, which is well compatible with HELLMANN's value. PAESCHKE [27] found variations, on an average, between 0.2 and 0.33.

In immediate vicinity of the ground, however, the simple dependence shown by equation (5) is not correct, as a rule, since owing to the varying roughness of the ground the abatement of the wind varies essentially in the neighbourhood of different surfaces. On the basis of equation (5) a correct picture of the abatement of the wind over a comparatively smooth surface, e.g. snow or even bare earth, is obtained. A very rough surface, e.g. long grass or corn, reduces the wind velocity till it is quite negligible even at some distance above the ground.

On the basis of observations made in hydrodynamics, PRANDTL [29] has evolved a method which takes into account also the roughness of the ground. The equation used as the starting point in that case is

$$u(z) = a \log z + b\,, \tag{6}$$

wherein

$u(z)$ = wind speed as the function of height z
$a,\ b$ = empirical constants.

According to PRANDTL's mixing length hypothesis the horizontal shearing stress T_0, during a turbulent flow, may be shown by the equation:

$$T_0 = \varrho\left(l\frac{du}{dz}\right)^2 \tag{7}$$

wherein:

ϱ = air density
l = mixing length.

According to KÁRMÁN [29] $l = kz$, wherein $k \sim 0.4$, from which follows:

$$\frac{du}{dz} = \frac{1}{kz}\sqrt{\frac{T_0}{\varrho}}\,. \tag{8}$$

We write $\sqrt{\frac{T_0}{\varrho}} = u^*$. The concept of friction velocity thus defined is almost independent of height when near the ground. By integrating (8) one arrives, substituting $\frac{u^*}{k} = a$, at

$$u(z) = a\,(\ln z + C)\,, \tag{9}$$

which is a way to present the vertical distribution of the wind, corresponding to equation (6). In order to define the constant C it is presumed that every rough surface affects the abatement of the wind near the ground in a certain way. This may be shown by a constant length z_0

which is called the roughness length. By writing $C = -\ln z_0$ equation (9) may be put into the form

$$u(z) = a \ln \frac{z}{z_0}, \tag{10}$$

which represents logarithmic velocity profile in an entirely rough flow. The roughness length z_0 is of the magnitude of 1 cm on an even ground or snow surface, and 5 cm in a hay or corn field, as shown by PAESCKHE's measurements [27]. Near the ground it is usually necessary, in order to achieve the correct result, to perform also what is called the zero-plane displacement. In this the ground is theoretically raised to the height d which corresponds to the average height of the roughness of the ground, as represented by vegetation or clods of earth. A perfect equation for rough flow near the ground is thus arrived at:

$$u = a \ln \frac{z-d}{z_0}. \tag{11}$$

Numerous measurements have shown the advantage of using equation (11) when describing wind conditions over natural ground. According to the more recent studies by SHEPPARD [32], both KÁRMÁN's constant and the roughness length seem to vary to some extent, depending on the equilibrium of the lowest atmospheric layers.

d) Summary

As regards the vertical distribution of temperature, humidity and wind velocity near the ground, the following common features may be observed on the basis of the above results:

1. The distribution may be represented, as a rule, by means of logarithm function near the ground.
2. In the immediate vicinity of the ground there occurs irregularity in the vertical distribution of each climatic factor. This may be taken as due to roughness of ground and height of vegetation covering the ground.

Starting from these results, BJÖRGUM [4] has worked out a formally coherent scheme for temperature, humidity, and wind profiles near the ground. By assuming that the basic factors of exchange may be determined by means of the first and second differential coefficients of the mean potential temperature Θ, the mean humidity F (specific humidity, mixing ratio, or vapour pressure), and the mean wind velocity U, the following equations may be valid to a height of about 25 m from the ground:

$$\frac{U}{U_*} = \frac{1}{k} \ln \frac{z-d}{a}, \tag{12}$$

$$\frac{\Theta-\Theta_0}{\Theta_*} = \frac{1}{l} \ln \frac{z-d}{b}, \tag{13}$$

$$\frac{F-F_0}{F_*} = \frac{1}{m} \ln \frac{z-d}{c}, \tag{14}$$

wherein:

Θ_0 = value of potential temperature at the ground
F_0 = value of humidity at the ground
U_* = friction velocity
Θ_* = the corresponding quantity for temperature
F_* = » » » » humidity
k, l, m, a, b, c = the parameters depending on roughness of ground and stability of air
d = zero-plane displacement.

By means of these equations also the vertical distribution of temperature and humidity has been brought into conformity with equation (11). Furthermore, BJÖRGUM has found, on the basis of the temperature observations made by BEST and the humidity observations made by SVERDRUP, that the form of presentation and the observations are in agreement.

2. *Fluctuations of climatic factors near the ground*

If various climatic factors are measured near the ground by means of sensitive measuring instruments, the results will in most cases show irregular fluctuation whose amplitude depends, apart from the sensitivity of the measuring instrument, primarily on the strength of turbulence and the horizontal and vertical distribution of the climatic factor in question. These shortperiod changes are called fluctuations of climatic factors and it is characteristic of them that their time integral is negligible provided the integration is extended to cover a sufficiently long interval of time. In this case the interval of time in question is generally a few minutes at the most, and thus the changes taking place evenly and slowly, which are caused e.g. by air mass advection or normal diurnal variations, cannot be included in fluctuations.

Let us indicate the mean of a climatic factor at a certain interval of time by letter $\bar{s}$. The momentary value of the said factor may be expressed by the following equation:

$$s = \bar{s} + s' , \tag{15}$$

wherein s' stands for the momentary additional therm caused by fluctuations. It is in accordance with the character of fluctuations that:

$$\int_{\tau - \frac{\Delta\tau}{2}}^{\tau + \frac{\Delta\tau}{2}} s' d\,\tau = 0 \tag{16}$$

if a sufficiently long interval of time ($\Delta\tau$) has been selected. This definition is identical with the definition of turbulence, if $\bar{s}$ indicates the mean wind velocity and s' the turbulent component of the wind.

According to Prandtl's [29] fundamental mixing length hypothesis:

$$\bar{s}' = l \left| \frac{d\bar{s}}{dz} \right| , \tag{17}$$

wherein l indicates the average mixing length, $\left| \frac{d\bar{s}}{dz} \right|$ the absolute value of the vertical gradient of the climatic factor in question, and $\bar{s}'$ the average extent of the fluctuations, or

$$\bar{s}' = \frac{1}{\Delta\tau} \int_{\tau - \frac{\Delta\tau}{2}}^{\tau + \frac{\Delta\tau}{2}} |s'|\, d\tau . \tag{18}$$

In the following we shall deal in greater detail with the measurements of temperature fluctuations carried out at the Viiki Research Station. Fig. 2 shows the results of the experiments made by the author on July 14, 1953, at about 12 o'clock noon. The method and instruments of measurement are described at Fig. 1. The upper curves in Fig. 2 represent the course of the temperature over an even sandy surface at heights of 2 and 10 mm, respectively, as observed at one-second intervals in the course of 2 minutes. The lower curves, on the other hand, show the course of the temperature at the same heights in fairly thin Timothy grass (length approx. 50 cm).

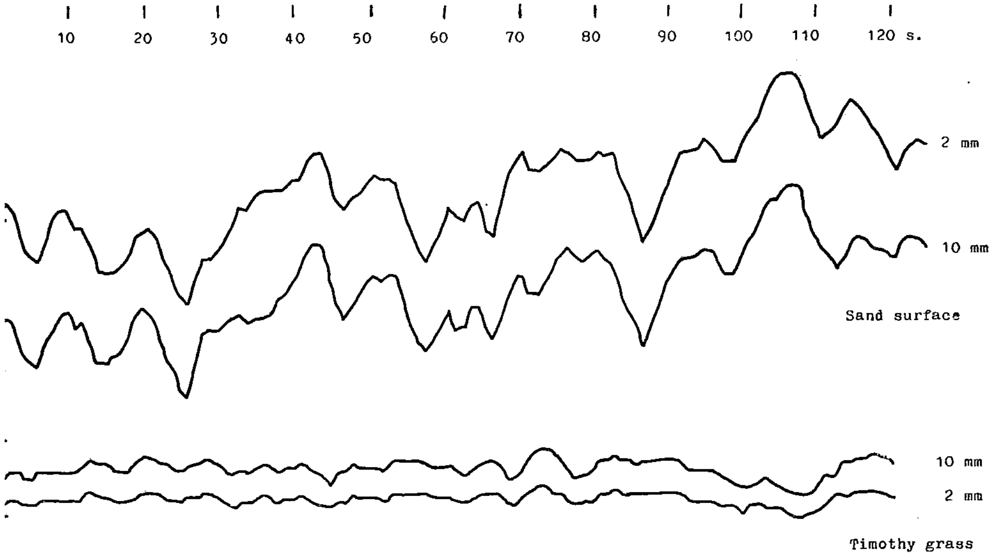

Fig. 2. Temperature fluctuations over an even sandy surface and in fairly thin Timothy grass.

Table 1 shows the values of temperature gradient and the relative amplitude of fluctuations over an even sandy surface, measured by the writer in Viiki on July 9, 1953, at noon. The temperature gradient values have been interpolated or extrapolated from Fig. 1. The relative amplitude of the fluctuations has been calculated from figures similar to Fig. 2.

Table 1.

Height (cm)	$\frac{dt}{dz}$	$\bar{t}'_{\mathrm{rel}}$
0.2	−540°/m	0.19°
1.0	− 82	0.23
5.0	− 13	0.23
25.0	− 2.0	0.20

According to SHEPPARD [34, p. 58] the average mixing length near the ground, under prevalence of incoming radiation, may be found from the equation

$$l = 0.25\ z^{1.15}\,. \tag{19}$$

Then the following average mixing lengths correspond to the heights found in Table 1:

z (cm)	l (cm)
0.2	0.04
1.0	0.25
5.0	1.6
25.0	10

On the basis of these values and the values given in Table 1, product $l\left|\frac{d\bar{t}}{dz}\right|$ may be formed and compared with the amplitude of relative fluctuations, in which case the coefficient of proportion k in Table 2 is the constant by which $\bar{t}'_{\mathrm{rel}}$ should be multiplied in order to find out the real average amplitude $\bar{t}'$ of fluctuations. The following values are derived from the results in Table 1:

Table 2

Height (cm)	$\bar{t}'_{\mathrm{rel}}$	$l\left\|\frac{d\bar{t}}{dz}\right\|$	$k = \frac{l\left\|\frac{d\bar{t}}{dz}\right\|}{\bar{t}'_{\mathrm{rel}}}$
0.2	0.19	0.22	1.2
1.0	0.23	0.20	0.9
5.0	0.23	0.21	0.9
25.0	0.20	0.20	1.0

The result, that k remains fairly constant over the whole course of measurement, indicates that PRANDTL's and SHEPPARD's equations (17) and (19) are valid.

Advective factors probably have no important effect on the short-period fluctuations of the temperature on summer days. HAUDE's [12] measurements in the Gobi Desert as well as the writer's measurements during the summer of 1953 show that the period of fluctuations remains the same in two objects for measurement placed above each other, although the distance between them varies. The effect of local advection, on the other hand, takes the form of gusts of wind, during which the mean temperature in a short time may change by several degrees. Typical long-period fluctuations of the temperature are caused by cumuli which, by preventing direct solar radiation, cause sudden and large changes of temperature, which in turn cause gusts of wind near the ground. Fig. 3

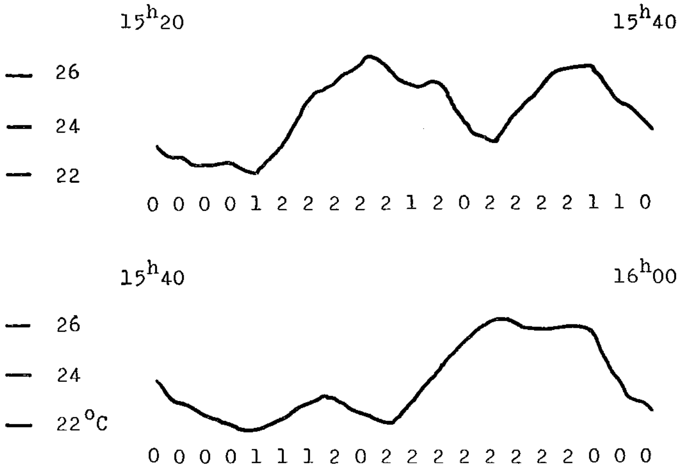

Fig. 3. Long-period temperature fluctuations caused by tower-like cumuli.

shows observations carried out by the writer in Viiki on July 13, 1953. During the observation tower-like cumuli covered about half the sky. The measurements of temperature were made at a height of about 3 cm from the ground at intervals of 30 seconds. As the instrument for measurement, a radiation-protected thermocouple was used whose lag coefficient was about 20 s. Fig. 3 also shows relative intensity of sunshine; 0 indicates that the sun is not visible, 1 shows that the sun is dimly seen behind the cloud, and 2 stands for bright sunshine. Koch [20] has published a result that he obtained on the basis of pilot balloon tests and according to which, in a case resembling that shown in Fig. 3, a cooling near the ground is followed by a warming aloft. Thus, a cumulus passing the site causes a powerful and rapid mixing to a height of at least 100 m. When the sun is visible again, a normal logarithmic distribution of temperature will be formed in a few minutes.

Measurement of short-period humidity fluctuations is technically more difficult, as described later in Chapter 5 c. On the basis of equation (17) it is to be expected that humidity fluctuations will be of the same type as those of temperature. Both generally conform to logarithmic distribution vertically, and the mixing length hypothesis is presumed to be valid in each case [34]. Fig. 4 shows Swinbank's [36] results, obtained by means of a thermocouple psychrometer made of 0.025 mm-wire. The figure shows that the temperature and vapour pressure fluctuations have practically speaking the same period and the same relative amplitude.

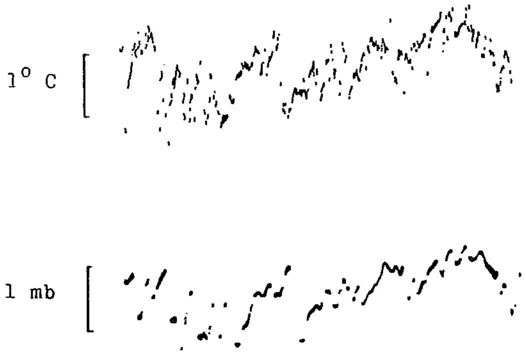

Fig. 4. Records of temperature and vapour pressure fluctuations during clear afternoon of 19 April, at level open site near Melbourne. (After SWINBANK [36]).

3. *Common errors of measurement*

In planning microclimatological measurements special attention should be paid to common errors in measurement. The inaccurate or inadequate results caused by said errors are similar in character, regardless of whether the climatic factor to be measured is temperature, humidity or wind velocity. Of these common measuring errors, the placement error and the situational error are dealt with in greater detail on the next few pages.

a) Placement error

If the measuring instrument is placed where it interferes with the natural progress of the climatic factor to be measured or where it gives an incidental or faulty picture of climatic conditions on the site studied, the error thus arising may be called placement error.

The interfering effect of the measuring instrument is usually caused by the size of the instrument or its auxiliary accessories, e.g. radiation shields, ventilation appliances or mounting appliances. These may hinder the exchange, mix atmospheric layers of different properties or act as disturbing sources of radiation. Natural conditions will also be interfered with if, in order to set up the measuring instrument, it is necessary to make a clearing in even vegetation or if the observer, when attending to the instrument, breaks the surface covering in the immediate proximity of the instrument. Especially obvious are the deviations caused by the said factors in areas covered by dense vegetation and in the immediate vicinity of the ground.

If the site of measurement is very variable in character and inhomogenous, a measuring instrument that has been placed at random usually gives a very incidental picture of the course of the climatic factor to be measured in the area in question. In planning microclimatological measurements it is advantageous to make a preliminary study of the values of the climatic factor to be observed in the area at a known height and in extreme conditions. If great differences then occur between different objects, a result representative of the conditions in the entire area may be obtained by one of the following procedures:

1. For measurements one chooses a site where the value of the climatic factor in question proves to be close to the mean obtained from the observations made in the entire area.
2. One connects in series several electric measuring instruments and places the instruments in the area to be studied at regular intervals. The system then shows the mean of the indications of the several instruments.
3. Line measurements are carried out in the area by means of a reliable measuring instrument and the mean of the results thus obtained is calculated.

Very great care should be observed in placing the measuring instrument in surroundings where the value of climatic factors varies greatly at short distances. This applies especially to the measurement of vertical distribution in immediate vicinity to the ground. As an example let us take the temperature distribution over a smooth even surface at incoming radiation:

$$\frac{dt}{dz} = \frac{a}{z} \tag{2}$$

It may be seen from the equation immediately that, when measuring the temperature gradient, the relative accuracy of the measurement of height should be the same at different heights. If, at a height of 1 metre, the measuring instrument is adjusted to the height required at an accuracy of 1 cm, the corresponding accuracy at a height of 1 cm should be 0.1 mm. Since the ground is always somewhat rough, fulfilling this condition is generally very difficult. In fact, measurements to be carried out in immediate nearness to the ground generally require artificial smoothing of the surface. In addition, very small-size measuring instruments have to be used.

The logarithmic vertical distribution of temperature, humidity and wind velocity makes it advantageous to choose the logarithmic altitute scale when choosing measuring heights. For practical reasons, however, it is advisable to use round figures, in which case the following altitude scale is quite suitable:

1, 2, 5, 10, 20, 50, 100, 200, 500 cm, etc.

If the site of measurement is very rough, e.g. a corn field or a patch of root crops, in which case in accordance with equations (12)—(14) it is necessary to make a zero-plane displacement proportional to the height of the vegetation, the most suitable choice is the evenly spaced scale in vegetation and the logarithmic scale above it. Furthermore one should try to find the location of the new zero plane, starting from which the logarithmic distribution is valid and, if possible, place instruments near to it spaced more closely than in normal cases.

b) Situational error

If microclimatological measurements are made under such meteorological conditions that the results of measurements give a misleading or incidental picture of the climatic factor under research, and no account is given of the course of other climatic factors affecting the case, the error thus arising may be called a situational error.

A typical situational error will arise when, on the basis of a short series of observations, during which accurate notes have been made of one climatic factor only, deductions are made of the general course of this climatic factor, or the results ranked in the same category with corresponding measurements made elsewhere. In this case, of course, the part played by other climatic factors leading to the said result cannot be estimated, and it is often the case that results and conclusions arrived at prove rather incidental. Brooks and Kelly [9] have dealt extensively with various points that should be taken into account when taking microclimatological measurements, and have drafted suggestions regarding observation equipment required by microclimatological stations. According to their proposal, all research concerning the effect of microclimate on the welfare of animals or plants should take into account at least the following climatic factors:

1. Air temperature
2. Air humidity
3. Radiation and cooling power
4. Soil temperature

5. Wind velocity
6. Evaporation
7. Precipitation.

In addition, one must be able to determine the general state of the weather, in view of which observations of at least the following factors are to be made: the quantity and quality of clouds, air mass and its stability, fog and rain. Brooks and Kelly have, on the basis of the interrelation between climatic factors, classified 9 different types of weather on the North-American continent. When sufficient material has been obtained by observation, this may now be classified according to the type of weather prevailing on each day of observation. In this way an idea may be gained of the average course of any climatic factor in a certain type of weather.

In estimating the effect of the situational error it is advisable to bear in mind the aim of the measuring task in hand. If the object is to find out only the variation limits of a certain climatic factor, the most extreme conditions chosen on the basis of experience may be taken as appropriate for measurement. Such extreme conditions, e.g. regarding diurnal temperature, may be provided by a completely cloudy and windy or, on the other hand, a completely clear and calm day. In contrast, research which aims at finding out the effect of a climatic factor on vegetation or fauna presupposes climatic observations as complete as possible and continuous, prolonged measurements irrespective of weather.

4. *Electric thermometers*

a) Electric methods of measurement and their sources of error

Electric thermometers may be divided into two principal groups:

α) Resistance thermometers

β) Thermocouples

The sensitive element of a resistance thermometer is made either of metal wire (Pt, Ni, W) or semiconductor, which is mainly an alloy of metal oxides. Resistance thermometers may be divided on this basis into resistance wire meters and thermistors. It is characteristic of the former that the resistance of the sensitive element increases as the temperature rises, whereas the thermistors' resistance strongly decreases as the temperature rises. The most notable sources of error of resistance thermometers are:

1. Heating of sensitive element due to measuring current
2. Dependence of result on measuring voltage

3. Phenomena of aging taking place in the system
4. Changes in transition resistance and resistance of connection cables.

The measuring current through a resistance thermometer heats all resistances in the connected circuit. As a rule, the hampering effect caused thereby makes itself felt in the sensitive element only, as the other resistances of the circuit are of coiled wire, the changes in whose resistance as a function of temperature are as slight as possible. Although certain measuring current heats the sensitive element with an approximately constant energy, the difference in temperature between the sensitive element and the surrounding medium will depend on the properties of the medium. If, for instance, the instrument is calibrated in water but used in air, too powerful a measuring current will produce too high temperature readings in the air, whose cooling effect under normal wind velocity conditions is considerably weaker than the cooling caused by water. For this reason, the measuring current has to be kept so low that the rise of temperature caused by it in the sensitive element remains within the limits required for accuracy in all conditions occurring in the course of measurement. RIBAUD [24] has produced a simple test for studying this error. It is advisable to make the test in air as calm as possible, since the cooling effect of air on the sensitive element is then at its smallest.

The result of measurement depends on the voltage when using general out-of-balance methods. The simplest connections, in which the sensitive element is connected in parallel or in series with the instrument, are not used in resistance thermometers as a rule, since part of the instrument's range remains unutilized. The connections most commonly used are variations of the Wheatstone bridge. In the out-of-balance method, a constant resistance coupled in place of the sensitive element is generally used as an aid; the current passing through the resistance being adjusted to correspond to a specified reading of the zero galvanometer scale. If the adjustment is made often enough, the error resulting from changes of voltage remains within the limits of accuracy required by measurement. As this error, in addition, is proportional to the deviation calculated from the zero point of the galvanometer, it is advantageous for certain series of measurements to connect the galvanometer zero point to correspond to the expected average temperature.

Symptoms of aging in the measuring system may be prevented by using for resistances wire that has been pre-aged by annealing, and the symptoms are detected by making regular comparative observations with standard thermometers. The effect of changing transition resistances depends essentially on the resistance values of the connection. When using small-ohmic sensitive elements the part played by the transition resistanees and the varying resistance of the connection cables may become considerable. In this case the elimination of transition resistances may be carried out by means of mercury contacts, and the variation of the connection cable's resistance compensated by means of a three or four lead circuit system [18].

As the thermistors' relative resistance variation per temperature unit is approximately ten times the corresponding variation of resistance wires, or roughly 5%/C°, it is not necessary, when using thermistors in normal cases, to pay special attention to transition resistances and the resistance of the connection cables. Thermistor manufacturers also generally indicate the heating value of the element in air, as affected by a given energy, so that the greatest permissible measuring current may be calculated in advance. These advantages in connection with thermistors have led to a great increase in the use of thermistors in resistance thermometers. A drawback is the fact that, especially in manufacturing small-size thermistors, it is necessary to compromise in the tolerance of the resistance values, so that the replacement of a broken thermistor with a new element identical to the old one is not possible, as a rule; each element must be calibrated separately.

In using thermocouples it is advantageous if the couples intended for field measurements are constructed of metals, the thermoelectric power between which is as great as possible, and which are obtainable in different thicknesses at reasonable price. The thermocouples most commonly used in meteorology are copper constantan or iron constantan couples. When using thermocouples, attention must be paid to the following sources of error:

1. Errors caused by passive connections
2. Leakage currents occurring in connection circuit
3. Symptoms of aging.

In order to eliminate the errors caused by passive connections it is necessary at these points to use metals whose thermoelectric properties are similar to those of the active conductor connected with them. As the conductors of the thermocouple intended for recording and registration apparatus usually have several passive connections, such as coupling screws, resistances or switches, particular care is required in connecting them, and both ends of the passive connections should if possible be brought to the same temperature. Also the voltage produced by thermocouples is so slight that even small leakage currents caused by a nearby direct current circuit or a galvanic element from thermocouple conductors may have a considerable effect on results. The part played by both passive connections and leakage currents is most clearly revealed by placing the active connections of the thermocouple in exactly the same temperature, e.g. in melting ice. When the passive connections are heated in different ways, the deviations of the reading apparatus indicate the magnitude of errors possibly caused by these connections. Similarly the part played by leakage currents may be made clear in principle. Their extent, however, may be varied incidentally by, for instance, variations of humidity, so that the best means of eliminating leakage currents is careful insulation. The artificial aging of thermocouples is effected in the same way as that of resistance thermometers, i.e. by annealing the wires of the element before use.

The accuracy of both resistance thermometers and thermocouples depends in addition on the recording, visual or automatic, apparatus used. Among the most common sources of error found in these are friction of the indicator mechanism and differences of interpretation, together with insufficient temperature compensation. The magnitude of errors in instruments of different type is quite individual, but differences of interpretation and temperature compensation may easily be checked by taking a series of observations at different temperatures but using a constant voltage. For the recording of the readings of resistance thermometers, tracing apparatuses may be generally used; most suitable in conjunction with thermocouples are spotlight galvanometers which record on sentized paper.

b) Temperature equation for thermometer

The temperature equation for a thermometer may be written in the form:

$$\frac{dQ}{d\tau} + F(t_0 - t) \cdot f(v, \varrho) - M\frac{dt}{d\tau} = 0, \tag{20}$$

wherein:

$\frac{dQ}{d\tau}$ = radiation balance of sensitive element of thermometer
F = surface area » » » » »
t_0 = air temperature
t = temperature shown by thermometer

v = ventilation received by thermometer
ϱ = air density
M = heat capacity of sensitive element of thermometer
τ = time.

The so-called ventilation function $f(v,\varrho)$ may be written in the form:

$$f(v,\varrho) = \sqrt{v} \cdot \varphi(\varrho) \tag{21}$$

or, since near ground we may assume ϱ = constant:

$$f(v,\varrho) = k\sqrt{v}\,, \tag{22}$$

in which k is an experimental constant.

By solving (20) we obtain as error of thermometer reading:

$$t - t_0 = \frac{\dfrac{dQ}{d\tau}}{kF\sqrt{v}} - \frac{M\dfrac{dt}{d\tau}}{kF\sqrt{v}}\,, \tag{23}$$

in which the first term of the right side is radiation error and the second lag error.

c) Radiation error

By equation (23) the magnitude of the radiation error depends on the radiation balance and surface area of the sensitive element of the thermometer and on the ventilation. In order to eliminate the radiation error of an electric thermometer we may use three principally different methods:

1. The sensitive element may be placed within a special radiation shield, or its reflection power may be increased.

2. The size of the sensitive element may be reduced or the thermometer may be supplied with artificial ventilation.

3. Radiation error may be reduced by aid of a suitably chosen electric coupling.

The purpose of the methods mentioned in 1. is to prevent changes in the radiation balance which arise from variations in the radiation coming into the sensitive element or going out from it. The best-known radiation shield is the Budig shield, which is a convex sheet of bright plate. When placed on top of the thermometer it quite effectively prevents the action of direct solar radiation upon the sensitive element. On the other hand radiation reflected from a surface below may affect the thermometer. In addition, the plate-like Budig shield at a time of weak exchange may form a boundary surface under which accumulated air may in extreme temperatures be appreciably warmer or colder than the surrounding air. Cylindrical radiation shields are inherently better. In the cylinder placed obliquely air can circulate freely and the radiation error can be eliminated fairly precisely without the use of ventilation as demonstrated by BAUER and BUSCHNER [3]. The effect of reflected radiation can be greatly reduced by blackening the inner surface of the radiation shield, as RÖSSLER [31] among others have shown. The reflecting power of the thermometer may be raised over 90% by aid of silvering or the method developed by BRASEFIELD [6]. The basis of this method is that the sensitive element is covered with special reflecting paint, which is protected against variations of weather by a waterproof coating.

The methods in 2. aim at strengthening the phenomena of temperature transition between thermometer and surrounding air. By equation (23), the magnitude of the radiation error is inversely proportional to the square root of the wind velocity. With the aid of ventilation the radiation error may thus be considerably reduced. Since artificial ventilation intermixes the surrounding atmospheric layers, this method cannot be used in observations where the temperature gradient varies significantly on different sides of the thermometer. Such is the case near ground level and, as a rule, in places where a stratified distribution of temperature exists. FRANSSILA [11] has shown that an Assmann psychrometer with artificial ventilation speed of 2 m $\sec^{-1}$ gives faulty temperature readings in the air layer stretching to a height of at least 20 cm from ground level both by night and day in summer, radiation being as normal for clear weather. When there is no danger of mixing, however, it is always advantageous to use artificial ventilation for removing air heated or cooled on account of radiation caused by the measuring instrument.

ALBRECHT [1] shows the relation between size of resistance wire thermometer and magnitude of radiation error by the equation:

$$Sd = a\Delta t, \qquad (24)$$

in which:

S = radiation intensity
d = diameter of resistance wire
Δt = magnitude of radiation error
a = constant to be determined experimentally, its magnitude depending on wind velocity.

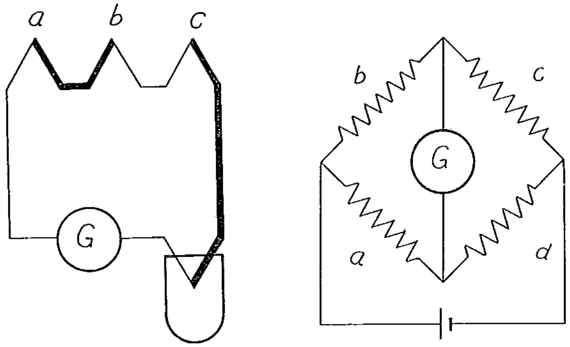

Fig. 5. Removal of radiation error by compensation. (After Höhne [17]).

With radiation intensity 1.5 cal cm^{-2} min^{-1} Albrecht obtained as radiation error for platinum wire of thickness 0.025 mm in calm weather, with assumed reflecting power 65%:

$$\Delta t = 0.14°$$

Kassander [22] has studied the magnitude of radiation error in a thermistor whose sensitive element is almost spherical with diameter 0.33 mm. In conditions corresponding to summer day radiation the error rose in calm weather to a maximum of about 0.7° and in wind of 2 m sec^{-1} to about 0.3°. At the Viiki Research Station in July 1955 the author, working with a spherical thermistor of 0.25 mm diameter on a clear summer day in wind of 2 m sec^{-1}, obtained as average radiation error:

$$\Delta t = 0.15°$$

These figures show that only the very smallest electric thermometers are practically speaking without radiation error when extreme radiation conditions and weak winds are present and no radiation shields are used.

Höhne [17] has shown simple methods of compensating the radiation error of electric thermometers. The radiation error of thermocouples is compensated by using at a measuring point exposed to radiation three successive active connections (Fig. 5). In the central of these, the radiation error is adjusted by experiment until it is equal to the sum of the radiation errors of the extreme connections *a* and *c*. This may be carried out by three different methods:

1. The absorption coefficient of central connection *b* is increased e.g. by blackening.

2. The absorption coefficient of connections *a* and *c* is reduced e.g. by reflecting paint or silvering.

3. *b* is made larger than *a* and *c*.

In resistance thermometers compensation of radiation error is achieved by arms *a*, *b* and *c* of the Wheatstone bridge (Fig. 5) being resistances affected by temperature and susceptible to radiation, whereas *d* is unaffected by temperature. The bridge is so adjusted that at the compensation temperature all the above resistances are of the same value and *b* is of wire twice as thick as *a* and *c*. According to (24) the radiation error of *b* is twice that of *a* and *c* provided all have the same absorption coefficient. HÖHNE has shown that if the original radiation error is 3° and the foregoing conditions for compensation are fulfilled, the radiation error from the secondary terms after compensation is about 0.02° in copper constantan thermocouples, whereas in platinum resistance thermometers the error may rise to 0.6°, if the measuring temperature deviates from the compensation temperature 25°. Removal of radiation error by compensation is thus very advantageous if thermocouples are used.

d) Lag error

The reading of a termometer which is moved from temperature t_1 to temperature t_0 may be obtained from the equation:

$$\frac{dt}{d\tau} = -\frac{1}{\lambda}(t-t_0) \tag{25}$$

in which:

t = momentary thermometer reading

λ = lag coefficient of thermometer.

If this equation is integrated by taking t_0 as constant, we obtain:

$$t-t_0 = (t_1-t_0)e^{-\frac{1}{\lambda}t} \tag{26}$$

and proceed by taking the logarithm from both sides of the equation:

$$\ln(t-t_0) = \ln(t_1-t_0) - \frac{1}{\lambda}\tau, \tag{27}$$

which is equation of a straight line, the angle coefficient being $-\frac{1}{\lambda}$. The lag coefficient λ of thermometer means the time $\Delta\tau$, after which $t-t_0 = \frac{1}{e}$

$(t_1 - t_0)$. The lag coefficient may easily be determined either on this basis or graphically by the use of equation (27).

From equations (23) and (25) we obtain, putting the radiation error zero:

$$\lambda = \frac{M}{kF\sqrt{v}} \tag{28}$$

i.e. the lag coefficient is dependent on the mass, specific heat and surface area of the sensitive element, and on ventilation. According to MIDDLETON and others [23] the dependence of the lag coefficient on ventilation speed v can be shown by the equation:

$$\lambda = kv^n, \tag{29}$$

in which k and n are constants and we may assume approximately $n = -\frac{1}{2}$. According to the researches of KASSANDER [22] equation (29) also is valid when a very fast instrument is used ($\lambda < 1$ sec) if $v > \frac{1}{2}$ m sec^{-1}.

The lag error of a thermometer may be considered in two different senses:

1. The lag coefficient is so great that the thermometer is unable to follow the rapid fluctuations of temperature which it is desired to measure.

2. The lag coefficient is so small that an individual observation may give an incidental picture of the average temperature to be measured.

The error as in 1. may be dealt with in measuring the fluctuations of temperature. Reduction of the lag coefficient is attained in the first place by reducing the size of the sensitive element. KASSANDER has obtained 0.7 sec as the lag coefficient of a thermistor of diameter 0.33 mm in calm weather, whereas the author obtained 0.3 sec as the lag coefficient of a thermistor of diameter 0.25 mm in calm weather, the determination being performed in the laboratory of the Institute of Meteorology, University of Helsinki. In both cases the lag was determined by aid of an oscilloscope, wherefore the lag of the reading apparatus may be left outside closer examination. With tracing apparatus and galvanometers their lag must be determined separately, which substantially complicates the procedure.

Fig. 6 shows lag coefficient of a thermistor as determined by the author with the aid of an oscilloscope. Determinations were made by taking temperature readings corresponding to known vertical deviations of the oscilloscope and the corresponding times, which were obtained from the speed of a Kipp oscillator or the exposure time of a camera.

In order to eliminate lag error we may also use electrical compensation of lag, in which case we proceed from equation (25) and obtain:

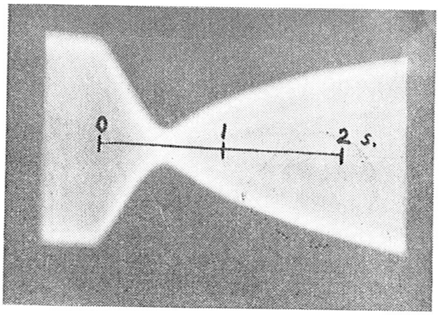

Fig. 6. Lag coefficient of Stantel F 22 thermistor, determined by aid of an oscilloscope.

$$t_0 = t + \lambda \frac{dt}{d\tau} \tag{25'}$$

in which t_0 thus represents true and t observed temperature. Compensation is made in principle as follows: the change of the electric temperature signal occurring in the time unit is multiplied by the lag coefficient and added to the basic reading. All these stages may be carried out electrically, but there is the difficulty that the lag coefficient is dependent on the wind velocity. This may largely be solved by using the value of λ corresponding to average wind velocity or by regulating the signal of λ by electric anemometer. It may be proved [22] that in the above manner mean compensated temperature agrees with mean true temperature if observation time is sufficiently long.

Too small a lag coefficient has an adverse effect on measurements based on a few observations which aim at giving a picture of the horizontal and vertical distribution of temperature in the observation area. The view of MIDDLETON [24, p. 66] is that the lag coefficient of a thermometer used for such measurements must not be smaller than 30 sec. Since an increased size of thermometer is not advisable because of radiation error, two methods must immediately be considered. The thermometer may be covered with a thin heat-insulating coating, e.g. rubber or plastic coating, or an instrument of greatly reduced indication speed may be used for registration.

5. *Electric psychrometers*

a) Psychrometer equation

The electric psychrometer is made up of a pair of electric thermometers, one of whose sensitive elements is coated with a suitably moistened covering material. From the readings of the dry bulb and wet bulb thermometer the vapour pressure in the air is obtained by aid of the psychrometer formula, which is:

$$e = E' - ap(t-t'), \tag{30}$$

in which:

e = vapour pressure prevailing in air,
E' = saturation pressure of vapour corresponding to reading of wet bulb thermometer,
a = psychrometer constant,
p = prevailing atmospheric pressure,
t = reading of dry bulb thermometer,
t' = » » wet » » .

The accuracy of the results given by formula (30) depends practically speaking on the accuracy of the thermometers and on how well the effect of various factors on psychrometer constant a is known. In estimating sources of psychrometer errors account must first be taken of all errors in the electric thermometers. In addition note must be taken especially of ventilation error, whose magnitude depends on the amount of ventilation to which the thermometer is exposed and on the size of the sensitive element.

b) Ventilation error

The effect of ventilation on the psychrometer constant has been studied since last century. SPRUNG [5] established so early as in 1888 that when the wind speed is 2 m sec^{-1} the following equation, the so-called Sprung formula, may be used for the Assmann psychrometer:

$$e = E' - C(t-t')\frac{p}{755} \tag{31}$$

in which constant $C=0.5$ (according to formula (30) $C=755\,a$). In later experiments MOLLWO [25] and YAMAMOTO [37] have determined the dependence of the Assmann psychrometer constant on ventilation speed (Fig. 7).

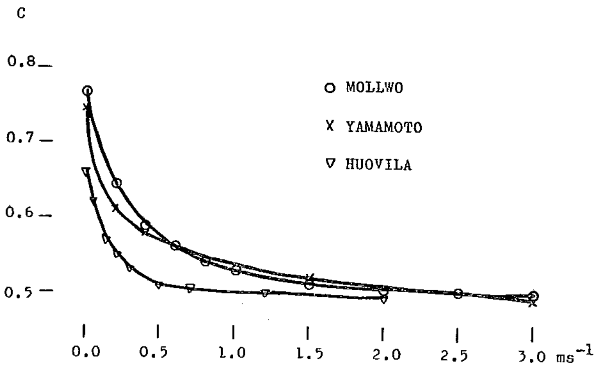

Fig. 7. Dependence on ventilation speed of the psychrometer constant in Stantel F 22 thermistor, determined by the author, and in Assmann-type thermometer, determined by MOLLWO [25] and YAMAMOTO [37].

KETTENACKER [19] has shown theoretically that the smaller the wet bulb of the psychrometer is, the smaller is the ventilation speed required to make the value of the psychrometer constant practically speaking permanent. The same result has been reached in experiments by, among others, KOCH [21], DIEM [10] and POWELL [28], according to whose studies very small thermocouple psychrometers give results which are almost independent of ventilation speed. If through evaporation in the moistening sock the air surrounding the wet bulb thermometer cools and descends, the psychrometer actually will not work in completely calm air unless the air is saturated with water-vapour. For this reason the dependence on wind speed of the constant of very small electric psychrometers probably cannot be exactly determined, because clearly discernible changes occur within the range of speed at which the effect of the descending current and other weak air currents have a bearing on results.

Fig. 7 shows result of an experiment made by the author in the laboratory of the Institute of Meteorology, University of Helsinki. In this may be seen the dependence on ventilation speed of the psychrometer constant in a Stantel F 22 type thermistor used for measurements of humidity. The thermistor in question is fused on to the tip of a glass tube 3.2 mm thick under a thin glazing. The ventilation being over 1 m sec^{-1}, observations were taken in a wind channel in which the speed of flow was measured by a fan anemometer and the air humidity by an Assmann psychrometer. Lesser wind speeds were produced in a box made of hardboard in which the thermistor psychrometer was revolved at a known speed about a vertical axle. At the time of the experiments the relative humidity of the laboratory was below 15%, so that psychrometer difference could be measured with great relative accuracy. Inserted in Fig. 7 for comparison are the experiments of MOLLWO and YAMAMOTO with the Assmann psychrometer thermometers. Results show that when using an F 22 thermistor equation (31) may be applied with a wind speed over 0.6 m sec^{-1}.

BONGARDS [5], on the basis of various studies has obtained for the relation between psychrometer constant and ventilation speed the form:

$$a = a_{\infty}\left(1 + \frac{k}{\sqrt[4]{v^3}}\right) \tag{32}$$

in which:

a_{∞} = value of psychrometer constant when ventilation speed is infinite.
k = constant depending on size of psychrometer.
v = ventilation speed.

If this equation is compared with the results previously mentioned, the conclusion may be drawn that with an infinitely small psychrometer $k = 0$. On the basis of BONGARDS' results it appears that k is roughly proportional to the diameter of the sensitive element of the instrument.

The ventilation error of electric psychrometers may be eliminated by three different methods:

1. The psychrometer is provided with a permanent ventilation, sufficient to give the psychrometer constant a permanent value. This method may be used when ventilation does not disturb the natural distribution of temperature and humidity.
2. The psychrometer is made from very thin conductors, so that the psychrometer constant has practically speaking a permanent value already in conditions of very weak wind.
3. The dependence of the psychrometer constant on ventilation speed and the psychrometer observations are integrated on the basis of simultaneous wind speed observations.

c) Lag error

In addition to the suggestions already made concerning lag error of thermometer (4 d), it should be aimed at if possible that dry bulb and wet bulb thermometers have the same lag coefficient when the lag error of a psychrometer is estimated. If the thermometers are of identical size, the lag coefficient of the wet bulb instrument is smaller than that of the dry. This fact, which at first sight seems paradoxical, has been proved correct both practically and theoretically by, among others, RÖSSLER [30], HECKERT [13] and SKEIB [33].

The observations carried out by HECKERT make it quite clear that the lag coefficient of the wet bulb thermometer decreases with a rising temperature faster than the lag coefficient of the dry bulb thermometer. On this account the lag error of the psychrometer cannot be fully compensated except in a known temperature range, for whose central point it is best to choose the expected average reading of the wet bulb thermometer. The compensation is best made by covering the sensitive element of the wet bulb thermometer with a thin insulating film, or, with a very fast thermometer, by reducing the indication speed of the reading apparatus to such an extent that the lag of this apparatus determines the lag of the system.

Lag error is an extremely harmful factor in measuring the fluctuations of humidity. In principle the method of electrical compensation for lag error may of course be applied, but because of many factors concerned in the matter its effect remains questionable.

d) Other errors

The sensitive element of the wet bulb instrument of the psychrometer is often many degrees colder than the surrounding air. Heat therefore flows to the element along the conductor attached to it and the intensity of the heat flow is proportional to psychrometer difference, cross section of conductor and thermal conductivity of conductor. This so-called conductivity error may easily be eliminated by the following methods:

1. The moistening sock is stretched amply over the sensitive element, at a distance from the sensitive element, according to experience, of at least 50—100 times the diameter of the conductor.
2. The conductor joined directly to the sensitive element is made of the thinnest possible wire, or of wire with poor heat-conductivity.

In small psychrometers the selection of a suitable moistening sock is difficult. Most generally used is porous cotton thread or thin muslin. Great care is needed for the even moistening and fixing of the sock, so that the use of such psychrometer for continuous registration is very questionable. The quality, thickness and cleanness of the moistening sock affect the lag coefficient and, in the opinion of some investigators, e.g.

EKHOLM [35], also the psychrometer constant, so that for accurate measurements it is necessary to use only socks of similar dimensions which have been fixed in a specified way.

Since the basic psychrometer equation in most general use, Sprung's formula (31) has been found not wholly reliable by later research (e.g. BONGARDS [5] pp. 167—172), an absolute error of 1—2% in the values of relative humidity may appear in psychrometer measurements carefully performed. The relative accuracy of measurements in favourable conditions may therefore prove greater than the absolute accuracy.

6. *Electric anemometers*

Electric anemometers are concerned with the electric measurement of the particular cooling effect produced by moving air in an object heated in a certain way. This heated object may be a resistance wire, a thermistor or a thermocouple, and electric anemometers are thus known as hot wire anemometers or thermocouple anemometers.

a) Equation for hot wire anemometer

If a round metal wire is heated with a given power, a certain correlation operates, while balance is maintained, between heating power, diameter of wire, wind velocity and temperature of wire. This can be shown by KING's equation:

$$Ri^2 = \frac{a}{d} + b\sqrt{\frac{v}{d}}\,(t - t_a) \qquad (33)$$

in which:

R = resistance of wire at temperature t
i = heating current
d = diameter of wire
v = wind velocity
t = temperature of heated wire
t_a = temperature of surrounding air
a, b = constants depending on temperature and properties of air.

It is seen from King's equation that the hot wire anemometer may in principle be connected in two different manners: either i may be taken as invariable and the value of R measured (constant current method), or R or the temperature of the resistance wire may be taken as invariable and i measured (constant resistance method). From the equation it is also seen that with both methods the sensitivity of the measuring apparatus increases as the wind velocity lessens. This feature makes the hot wire anemometer eminently serviceable especially in wind of slight force, where other types of anemometer cease functioning.

b) Convection error

When electric anemometers are used to measure the speed of a very weak wind, 1—10 cm $\sec^{-1}$, it is noticed, as OWER [26] first demonstrated, that the instrument usually indicates a small irregularity arising from the convection current around the sensitive element caused by heating. The speed of the convention current depends on the power of heating used and the placement of the instrument. In free air, where convection may occur without hindrance, the electric anemometer thus cannot show the speed of still air or the zero point of the velocity scale. On this account the zero point of the electric anemometer is so determined that the sensitive element is placed within a metal protection where the convection current cannot develop powerfully and where conditions at the start of measurement are always as similar as possible.

The convection current causes this further drawback, that in a very weak wind the electric anemometer gives different results for horizontal and vertical flows, which are identical regarding speed. In aiming at an accurate result it is therefore advisable to calibrate the electric anemometer separately for horizontal and vertical winds. The effect of convection current may also be weakened by reducing the measuring current. If the relation of heating power to size of instrument is suitably chosen, the effect of convection currents may be kept within the desired limits of accuracy. Measurements performed by the author [16] with a thermocouple anemometer of 0.3 mm wire gave a convection error of about ± 1cm $\sec^{-1}$ for wind velocity 10 cm $\sec^{-1}$ and heating power used rising to 50 mW. In a wind of over 20 cm $\sec^{-1}$ the convection error was negligible.

c) Other errors

If the sensitive element of the electric anemometer is made of wire, as in hot wire anemometers, the reading given by the instrument depends on the position of the wire. If the instrument is calibrated with the wire at right angles to the direction of the wind and is used with the wire in the direction of the wind, an error of over 50% may arise, according to

ALBRECHT [2]. The instrument may be made fairly independent of wind direction by making the sensitive element spherical. Certain thermistor types fulfil this condition with fair accuracy.

According to PAESCHKE [27], variations of humidity may cause an error of the order of 10% in the hot wire anemometer readings, while in rain or fog experience shows electric anemometers to give such unreliable results that their use does not correspond to the purpose. In hot wire anemometers it is also frequently observed that dust adhering to the wire causes faulty results. Since the very thin resistance wires are easily broken in field work, they should be used in electric anemometers and in all electric thermometers only for the measurement of microscale fluctuations.

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