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ON THE MEASUREMENT OF THE RADIANT TEMPERATURE OF VEGETATION SURFACES AND LEAVES

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INTRODUCTION

In a somewhat higher vegetation, e.g. a reed field or a wood it is possible to take micrometeorological measurements at different well defined heights. From these measurements it is possible to draw a characteristic profile, showing the conditions inside the vegetation in relation to the situation in free air (cf. STOUTJESDIJK, 1961).

The profiles obtained in this way are characteristic for the vegetation structure under consideration. They are well reproducible and essentially independent of the heights at which the measurements were made.

However, with very low vegetations of a few centimeters high, the irregularities of soil and vegetation surface are of the same order of magnitude as the height of the vegetation, i.e. the height inside the vegetation at which a measurement is made, is no longer sufficiently defined. Of course measurements inside a very low vegetation even with very small instruments, offer great practical difficulties as well.

Furthermore the strong patchiness of many vegetations made it very desirable to characterize the strong horizontal variation of microclimate by one single quantity which could be measured unambiguously.

We therefore tried to find such a factor that could be measured in a well-defined and reproducible way. It was expected that the mean surface temperature of the vegetation might be suitable in this respect, the more so as its relation to ambient temperature and radiation reflects the heat and water economy of the vegetation.

With a surface of so irregular a form the only practicable approach seems to derive the temperature of the surface from its heat radiation. When strong daylight does not interfere, a measurement of its heat radiation can be readily made by means of a suitably mounted thermopile or other radiation receptor. By day however, the amount of short-wave radiation emitted by vegetation can be as high as 0.2–0.3 cal/cm^2·min, while the heat radiation emitted increases only about 0.008 cal/cm^2·min for every degree centigrade the surface temperature increases. Therefore special precautions are needed to separate the effects of short-wave solar radiation from those of the long-wave heat radiation.

Recently filters have become available which transmit only the far infrared portion of the spectrum. However the performance of these filters does not seem to be altogether satisfactory. According to LORENZ (1960) they absorb and therefore re-emit a considerable part of the long-wave radiation. GATES (1963) shaded the surface of which the temperature was measured, indicating that strong short-wave radiation still interferes with the measurements inspite of the filters used. Therefore a radiation meter was constructed in which no infrared filter is used.

DESCRIPTION OF INSTRUMENT

In a copper block, $3 \times 6 \times 6$ cm, a bore is made with a diameter of 12 mm (Fig 1). A radiation receptor, size 1×1 cm, is inserted into this bore to a depth of 3.5 cm. The open end of the bore is closed with polyethylene foil with a thickness of 0.015 mm (cf. SCHULZE, 1962). Under the polyethylene cover, the opening can be closed by a glass shutter as well. When the shutter is opened it fits into a slit in the copper block. Close to this slit one junction of a thermocouple is inserted in the copper block. The block is isolated externally with a 3 mm layer of plastic foam, which is covered with aluminium foil.

When the shutter is open, the total radiation flux received by the thermopile can be split up as follows:

(1) reflected short-wave radiation.
(2) long-wave radiation from the walls of the bore.
(3) long-wave radiation from the surface at which the instrument is directed.

When the shutter is closed, (1) and (2) remain unchanged, but (3) is replaced by the long-wave radiation from the shutter. This has the temperature of the copper block, which is measured by the thermocouple.

The surface temperature to be measured is thus compared with that of a surface of known temperature. For this purpose often a separate black-body radiator, e.g. a block of metal with a cavity in it, is used. KOCH (1951) used a massive copper shutter. The next step was to use a glass shutter.

In the ideal case, only the long-wave radiation flux would be influenced by closing the shutter. A measurement with the shutter open and one with the shutter closed would make it possible to calculate the surface temperature, once the instrument is calibrated. However, the glass shutter causes losses by reflection and absorption i.e. when the shutter is closed the short-wave radiation decreases with about 10%. Partly for this reason it is important to make the thermopile as insensitive to short-wave radiation as possible. To achieve this, it was whitened with a mixture of magnesium oxide and titanium oxide, which reflects short-wave radiation strongly and is completely black for long wave radiation. The residual error is given by:

$$S(1-R)\ (1-T)$$

where S is the reflected short-wave radiation, R is the reflectivity of magnesium oxide in the short wavelengths, T is the transmission of the shutter in the short wavelengths. When either R or T is unity there is no residual error. T could be improved greatly by coating the glass surfaces with an anti-reflection layer. With a shutter of uncoated glass the residual error is under field conditions only a few tenths of degrees centigrade and a correction can be made for it.

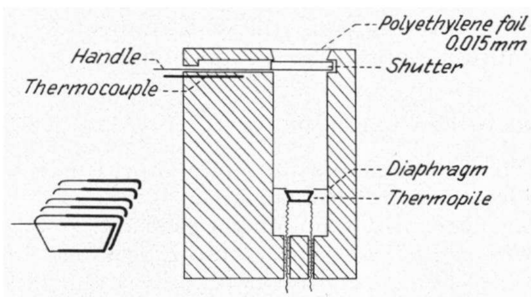

Fig. 1. Longitudinal section of radiometer. Detail of thermopile shows asymmetrical copper deposit, which allows for the higher heat conductivity of the copper-plated parts and improves sensitivity.

As a receptor, a thermopile of copper-plated constantane ribbon was used. A perspex rod, with a cross-section of 10×3 mm was wrapped with a layer of 0,015 mm polyethylene. Then the rod was wound with about 30 turns of constantane ribbon (0.25×0.015 mm) per cm. By plating each turn of ribbon partly with copper (Fig. 1), a series of differential thermocouples is made. The plating was done in an acidified bath of 2% copper sulphate, with a current of 1 mA. The layer of copper deposited was calculated to be about 0.0007 mm thick, i.e. the cross-section of the copper plating was about 10% of that of the constantane ribbon which makes the sensitivity of the thermopile virtually independent of its temperature (Höhne, 1962). After removing the perspex rod and the excess of cellulose cement covering the unplated parts, 1 cm length of the tubular thermopile thus obtained was painted white with a mixture of magnesiumoxide and titaniumoxide in a shellac solution.*)

The instrument was calibrated in the laboratory by means of a black radiator.

The following relation could be expected:

$$T_r^4 - T_s^4 = C\ (d_r - d_s) \qquad (1)$$

where T_r and T_s are the temperatures of the black radiator and the shutter, d_r and d_s are the deflections of the galvanometer when the shutter is opened and closed respectively and C is a proportionality factor dependent upon the sensitivity of the galvanometer. With differences between T_r and T_s of up to 25°C, this relation was found

*) The instrument is made now, in a small series, by the Landbouw Physisch-Technische Dienst, Wageningen.

to hold good with deviations not exceeding 0.2°C. This means that the fit was as good as could be expected with the experimental set-up used. The instrument was tested in the field on a surface of known temperature, i.e. melting ice. The absolute error did not exceed 0.5°C, with differences between T_r and T_s of up to 15°C.

The sensitivity of the thermopile is about 1 μ V for 0.00006 cal/cm^2. min received by the thermopile or, when mounted as described, 4.5 μV/°C for the surface temperature to be measured. The time of response of the pile is 15 seconds, its resistance is about 60 Ω.

For the calculation of results a simple slide rule was made using relation (1). On the temperature scale, the spacing is proportional to $T_r^4 - T_s^4$. On the moving scale, the scale units of the galvanometer are engraved with the appropriate proportionality factor.

Interpretation of measurements

For the interpretation of the radiant temperatures measured the following considerations are of importance.

After the law of Stefan-Boltzmann the heat radiation emitted by a surface is E 8.26 × $10^{-11} T^4$. The factor E is unity for a perfectly black surface only. For vegetation it may be about 0.98 (Falckenberg, 1928). The error thus introduced depends upon the temperature of the surroundings. When a surface emits 98% of the black-body radiation it reflects 2% of the radiation from the surroundings. With a good approximation the error introduced in the temperature measurements is then 2% of the difference surface temperature – surroundings temperature. For vegetation this surroundings temperature is the effective radiation temperature of the sky i.e. the temperature of a black body, emitting long-wave radiation with the same intensity as the sky. With a vegetation temperature of 30°C and an effective radiation temperature of the sky of —10°C, a common case, the vegetation temperature would be measured 0.8°C too low.

According to Gates (1963), leaves normally have an emissivity of 96% to 98%. When the temperature of the leaf is measured from the lower side the temperature of the surroundings rarely differs more than 10°C from that of the leaf and therefore the error will be usually below 0.3°C.

Vegetation temperatures

In Fig. 2, measurements of surface temperatures of dry grassland are plotted. Fig. 3 shows measurements, made simultaneously at a lower place with a lusher grass vegetation, mainly consisting of tussocks of *Calamagrostis epigeios*. The length of the vertical lines indicates the difference surface temperature-ambient temperature (called Δt afterwards).

The data clearly show how enormously varied a habitat like a few square metres of grassland can be in this respect.

The main cause for the great variation from point to point, doubtless

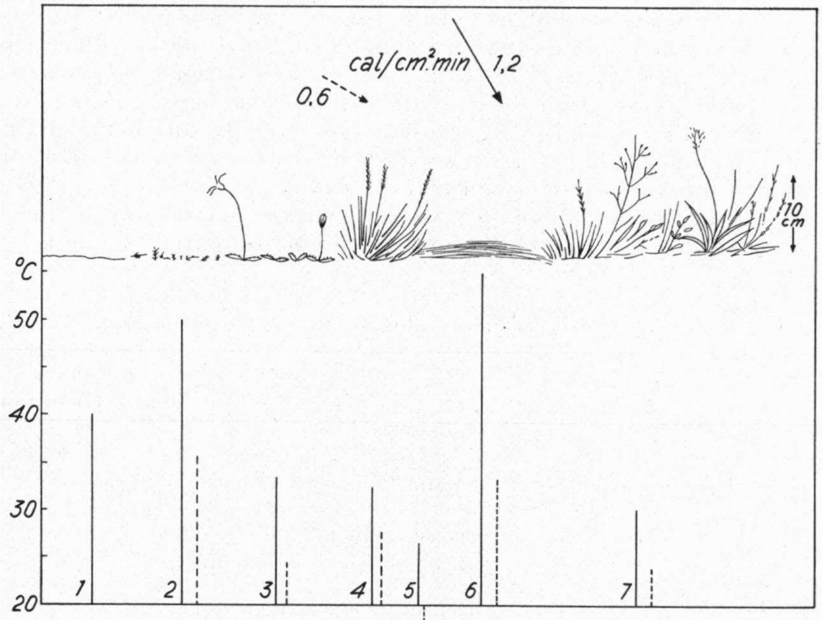

Fig. 2. Surface temperatures of dry grassland. The base line indicates ambient air temperature. The dotted lines refer to measurements taken with a low sun. The arrows indicate height, direction and intensity of solar radiation.

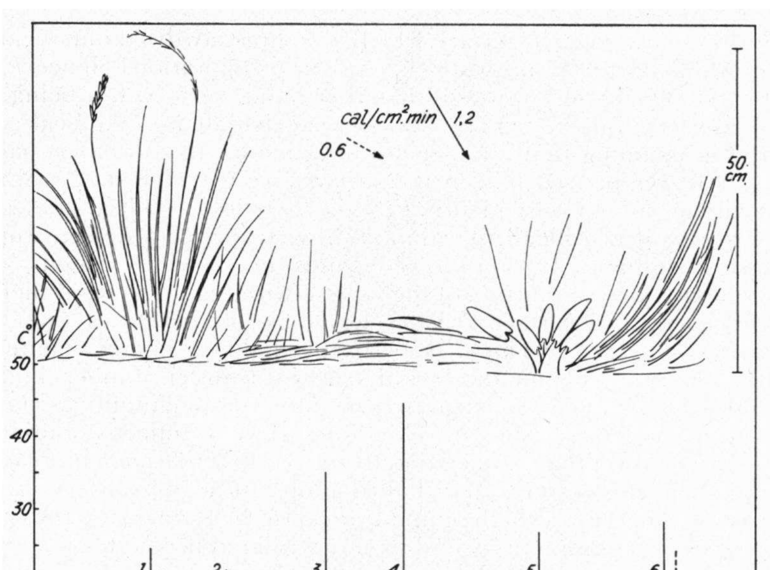

Fig. 3. Surface temperatures of high tussocky grass vegetation measured simultaneously with those of Fig. 2.

is the heat and water balance of the surface, which a priori could be expected to vary greatly. Where a patch of *Hieracium pilosella* (3 in the figure) breaks the surface cover of bone-dry *Politrichum piliferum* (2), this is reflected in the surface temperature. The moss, rooting in a completely dry topsoil, will transform practically all the available energy into heat. The *Hieracium* patch doubtless uses a considerable part of the available energy for transpiration.

For a more quantitative approach the energy balances of the moss-covered surface and that with *Hieracium* can be compared (Table 1).

TABLE 1

Energy balances of two vegetation surfaces. Energy fluxes in cal/cm²·min

INCOMING			OUTGOING Moss	OUTGOING Hieracium
Solar radiation	1.20	Reflected solar radiation	0.14	0.18
Long-wave radiation from the sky	0.44	Emitted long-wave radiation	0.90	0.72
		Taken up by the soil	0.01	0.01
		Heat used in evaporation (*E*), Heat given to the air (*H*)	0.59	0.73
Total	1.64		1.64	1.64

For the moss-covered surface which is completely dried out, we may assume that virtually no water is used for evaporation. Hence $E \simeq 0$ and $H \simeq 0.59$ cal/cm²·min. On the other hand, $H = \alpha . \Delta t$, α being the heat transfer number. For $\Delta t = 30°C$, we calculate $\alpha = 0.02$ cal/cm²·min·°C. Assuming that α has the same value for the *Hieracium* patch, with its leaves pressed flat on the surface, we get $H = 0.02 \times 13 = 0.26$ cal/cm²·min. Consequently $E = 0.73 - 0.26 = 0.47$ cal/cm²·min. At this time it is difficult to estimate to what degree α depends upon surface roughness. It doubtless depends upon wind velocity and consequently on the position of the surface with regard to wind shelter.

The bare sand surface reaches less high temperatures than the moss-covered surface. This may be partly due to a higher amount of heat taken up by the soil and to a higher heat transfer number. Finally the emissivity of a bare sand surface may not approach unity as closely as that of a vegetation surface. This could make the effective radiation temperature lower than the actual temperature. Dead *Festuca* (6) reaches even higher temperatures than Politrichum but dead *Calamagrostis* (4) does not attain quite as high temperatures. In the former case the cause may be a lower conductivity and a more sheltered position, i.e. a lower α. In the latter case, the loose structure of the dead patches causes a more gradual absorption of radiation.

Where green vegetation covers the ground, Δt is much lower but great differences exist, Δt varying between 13°C for *Hieracium* down to 4°C for *Calamagrostis* (1). In another series of measurements patches of Sedum acre had a Δt of 20°C with other vegetation temperatures virtually the same as those in the present series.

Combined with the measurements taken with a high sun, Figs. 2 and 3 contain measurements taken in September with approximately half the solar height and intensity. The measurements are again taken simultaneously. Air temperature was 18°C, but to make the measurements better comparable with those of the first series, all surface temperatures and the air temperature are plotted 2°C too high.

The reduction of Δt is in all cases about as much as could be expected with the reduced radiation intensity.

The effect of the shadows cast by the grass tussocks is much stronger now than with a high sun. Surface temperatures are up to 4°C below air temperature. This can be understood as the estimated net radiation was slightly negative in the shadow of the tussocks. The moss layer in such spots remains wet with dew all day in bright periods in September-October. Compared with the moss under a forest canopy it is in a greatly favoured position with regard to water and radiation, a low heat load being combined with a relatively high amount of photosynthetically active radiation. Under a forest canopy there is little photosynthetically active radiation and the moss is not wetted with dew in clear nights.

While Figs. 2 and 3 illustrated mainly the strong active part the vegetation has in micrometeorological differentiation, Fig. 4 shows a situation where differences in level and exposition play a considerable part in this respect.

The highest temperature is measured on the South-exposed slope of dry sand, which attains a temperature of 26°C above ambient air temperature.

On the weak slope between (5) and (8) there is a quite unexpected

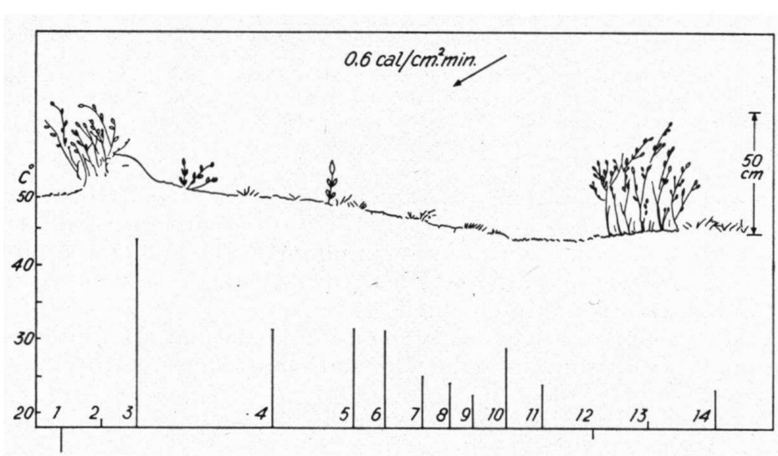

Fig. 4. Radiant temperatures of soil and vegetation surfaces in dune valley behind the coastal ridge.

sharp transition. Both (6) and (8) are bare spots, but (8) is somewhat damp, while (6) is completely dried out. Remarkable enough the difference exists as well where the surface is covered with a low vegetation of *Carex serotina* and *Agrostis stolonifera.*

In the shadow of the *Salix repens* patches the moss is wet and below air temperature as could be expected.

In general it can be said that vegetation temperatures are very stable. Short-time fluctuations are usually far below 1°C and measurements are well reproducible. The temperature of strongly overheated dry surfaces shows stronger fluctuations but still they are much smaller than those of the air immediately above the surface.

Leaf temperatures

The radiation method can be used to measure leaf temperatures when the leaves are big enough to fill the field of view of the instrument, a circle with a diameter of 25 mm at working distance. Of course it is often possible to press a temperature probe e.g. a thermocouple against the leaf. Often however, it is difficult to effectuate and maintain a good thermal contact between the leaf and the temperature probe.

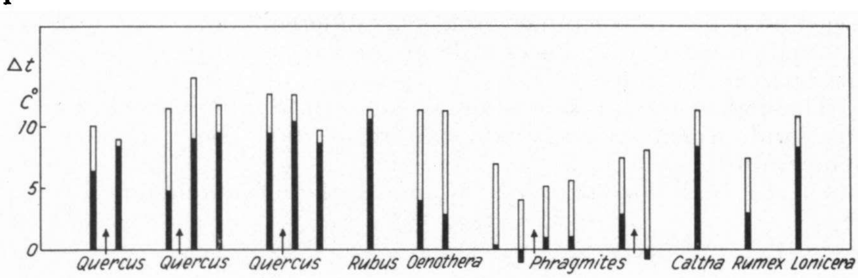

Fig. 5. Comparing temperature differences leaf-air of dry and fresh leaves. Black column: $\Delta\ t$ of fresh leaf. White column: Δt of dry leaf. Arrows indicate whether measurements were taken before or after noon. *Quercus* is *Q. robur, Oenothera* is *O. biennis, Rumex* is *R. hydrolapathum.*

Temperature measurements were made of leaves placed horizontally. The temperature was compared with the temperature of a dry leaf of the same species, measured simultaneously. The temperatures were measured at the lower side of the leaf, with the advantage that solar radiation was not intercepted.

In Fig. 5 representative measurements are collected. Measurements were made with strong sunlight with radiation intensities from 1.0 to 1.2 cal/cm^2·min.

It stands out clearly that often transpiring leaves have a temperature not very far below that of a dry leaf.

The temperatures of dry leaves can be up to 14°C higher than ambient air temperature. This temperature difference is small when compared with the dry moss or grass surfaces mentioned before. This must be due to the fact that the leaf has two surfaces to give off heat to the air and doubtless the heat transfer number is much higher for a small object placed free in the air than it is for the earth's surface.

From the temperature differences with the air of dry and fresh leaves and their energy balances, the transpiration rate can be calculated. For a dry leaf the relation exists (cf. Table 2, I):

$$R_{net} = H + E = H = \alpha\, \Delta t_{(dr)}.$$

TABLE 2

Energy balances in cal/cm²·min, of *Phragmites* leaves. I. Dry leaf. II. Transpiring leaf. III. Leaf transpiring at the calculated maximum rate

INCOMING			OUTGOING I	II	III
Short-wave rad. absorbed by leaf	0.94				
Long-wave radiation from the sky	0.52	Long-wave ra emitted by upper leaf surface	0.72	0.68	0.63
Long-wave rad. received by lower leaf surface	0.68	Long-wave rad. emitted by lower leaf surface	0.72	0.68	0.63
		Evaporation eney (*E*) / Heat given to air (*H*) } *R*net	0.70	0.78	0.88
Total	2.14		2.14	2.14	2.14

For a transpiring leaf (Table 2, II) we get:

$$H + E = R_{net(tr)} \quad H = \alpha\, \Delta t_{(tr)}$$

the suffix (tr) or (dr) indicates whether the leaf is transpiring or dry.

When we put: $R_{net(tr)} = R_{net(dr)}$

we get:

$$\frac{\Delta t_{(tr)}}{\Delta t_{(dr)}} = \frac{H}{H+E} \text{ and } 1 - \frac{H}{H+E} = \frac{E}{H+E}$$

for a transpiring leaf.

The error introduced is only small under normal conditions. This means that from a glance at the Δt's of dry and fresh leaves we can estimate immediately which fraction of the available energy, R_{net}, is used in transpiration. The measurements show, this fraction may vary considerably. The measurements marked *Quercus* (*robur*) were all made on one and the same leaf and even here there is a great amount of variation.

Apparently it is a common case that only a minor part of R_{net} is used in evaporation. *Oenothera* uses the bigger part of R_{net} for transpiration. *Phragmites* leaves may even have temperatures slightly below air temperature, indicating that R_{net} is transformed completely into transpiration energy and that even some energy is taken from the air.

While the temperature of a dry leaf provides us with an upper limit for leaf temperature in a given set of conditions, we can also ask the question what the lowest temperature is a transpiring leaf can have under the same conditions. LANGE (1959) has shown that leaves can have temperatures considerably below air temperature under desert conditions with strong radiation. The question imposes itself, to what degree this phenomenon is possible under temperate conditions.

RASCHKE (1956) has given a relation between leaf temperature, and net radiation, air temperature, heat transfer number and vapour pressure.

A somewhat different approach, yielding simpler results for the present purpose, is given below. The calculations are an adapted version of those that yield the well-known psychrometer formula (cf. VAN DER HELD, 1937).

It is assumed that a leaf is surrounded by a layer of still air of thickness d. When the leaf surface transpires like a free water surface, the outward flow of evaporation energy per cm² is expressed by:

$$\frac{(e_{leaf} - e_{air})\, DH}{d}.$$

The energy balance for a cm² of leaf can be written as:

$$\frac{2\,(e_{leaf} - e_{air})\, DH}{d} + \frac{2\,(t_{leaf} - t_{air})\, h_c}{d} - R_{net(tr)} = 0.$$

Where e_{leaf} and t_{leaf} are vapour pressure and temperature at the surface of the leaf, e_{air} and t_{air} refer to free air. D is the diffusion constant for water vapour, H is the evaporation energy for water h_c is the heat conductivity of still air.

When we replace $R_{net(tr)}$ by $R_{net(dr)}$, which is somewhat lower owing to the higher temperature, we can write:

$$R_{net(tr)} = R_{net(dr)} = \frac{2\,\Delta t}{d}\, h_c. \qquad (2)$$

Hence:

$$e_{leaf} - e_{air} + (t_{leaf} - t_{air})\,\frac{h_c}{DH} - \Delta t\,\frac{h_c}{DH} = 0. \qquad (3)$$

Now $\frac{h_c}{DH} = \gamma$ is the well-known psychrometer "constant". Under field conditions this factor varies between 0.42 and 0.44, dependent on temperature and barometric pressure (VAN DER HELD l.c.)

For a not irradiated surface we have the psychrometer relation

$$(e_{wet} - e_{air}) + (t_{wet} - t_{air})\,\gamma = 0. \tag{4}$$

Substracting (4) from (3) gives

$$e_{leaf} - e_{wet} + (t_{leaf} - t_{wet})\,\gamma - \Delta\, t\,\gamma = 0.$$

After PENMAN (1948) we write

$$e_{leaf} - e_{wet} = s\,(t_{leaf} - t_{wet})$$

s being the slope of the curve vapour pressure versus temperature. Then:

$$s\,(t_{leaf} - t_{wet}) + (t_{leaf} - t_{wet})\,\gamma = \Delta t\,\gamma$$

$$t_{leaf} - t_{wet} = \frac{\Delta\, t\,\gamma}{s+\gamma}. \tag{5}$$

Formula (5) gives the lowest temperature possible for a wet surface in relation to wet bulb temperature (t_{wet}) and $\Delta\, t$ of a dry surface. It also shows that the radiation error of a wet bulb thermometer is considerably smaller than that of a dry thermometer.

For a leaf which transpires on one side only we arrive along similar lines at the expression:

$$t_{leaf} = t_{wet} + \frac{2\,\Delta\, t + (t_{air} - t_{wet})}{s/\gamma + 2}. \tag{6}$$

The general expression is:

$$t_{leaf} = t_{wet} + \frac{n\,\Delta\, t + (n-1)\,(t_{air} - t_{wet})}{s/\gamma + n}.$$

where $1/n$ is a factor indicating how much the evaporation of a leaf is reduced as compared with a free water surface of the same temperature. This factor is called "Wasserbedeckungsfaktor" by RASCHKE (l.c.).

As an example, the lowest possible temperature of a *Phragmites* leaf is calculated.

Air temperature: 28.3°C. Wet bulb temperature: 20.6°C.

Temperature of dry leaf: 33.1°C. Measured temperature of transpiring leaf: 28.2°C. s: 1.36. γ: 0.43. Calculated temperature: 21.8°C.

As *Phragmites* has stomata on both sides of the leaf, equation (5) was used.

The error introduced by replacing $R_{net(tr)}$ of the maximal transpiring leaf by $R_{net(dr)}$ of the dry leaf can be estimated by comparing their heat balances (Table 2). For exact results $\Delta\, t$ in (5) should be replaced by:

$$\frac{0.88}{0.70}\,\Delta\, t = 5.9°\ \mathrm{C}.$$

The corrected value of the calculated leaf temperature is 22.0°C.

SUMMARY

The micrometeorological situation inside a higher vegetation can be characterized by profiles of the relevant meteorological elements. For principal and practical reasons this is impossible when the vegetation is very low. The mean temperature of the outer vegetation surface is considered a useful micrometeorological characteristic in this case. It can be calculated from the heat radiation emitted by the surface.

A radiometer is described, which permits measurements of thermal radiation even when high amounts of short-wave radiation are present. A glass shutter and a white thermopile are the characteristic features of the instrument.

The great differentiation of low patchy vegetation with respect to surface temperature is illustrated by examples.

The radiation method is suitable to measure leaf temperatures as well. Comparative measurements of dry and fresh leaves are given and the physical limits of transpiration cooling discussed.

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