TECHNICAL NOTE No. 20

THE CLIMATOLOGICAL INVESTIGATION
OF SOIL TEMPERATURE

MILTON L. BLANC

TECHNICAL NOTE No. 21

MEASUREMENT OF EVAPORATION,
HUMIDITY IN THE BIOSPHERE AND SOIL MOISTURE

(Report prepared by a working group of the Commission
for Instruments and Methods of Observation)

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THE CLIMATOLOGICAL INVESTIGATION
OF SOIL TEMPERATURE

MILTON L. BLANC
# The Climatological Investigation of Soil Temperature

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L'ÉTUDE CLIMATOLOGIQUE DE LA TEMPERATURE DU SOL

Résumé

Cette Note technique est basée sur un document (CC1-II/42) présenté à la Commission de climatologie lors de la discussion du point 16 de l'ordre du jour sur les recherches concernant la température terrestre.

La Note souligne l'importance que revêtent les mesures de la température du sol pour les recherches de base dans lesquelles intervient le bilan thermique de la terre et pour les applications pratiques telles que la prévision du gel. Elle cite des exemples de l'importance biologique des températures du sol. Une de ses parties est consacrée à l'étude de quelques relations entre la température et l'humidité du sol.

Elle examine les techniques d'observation, la profondeur et la fréquence auxquelles s'effectuent les observations, ainsi que les effets des caractéristiques physiques du sol et du couvert végétal ou autre. Elle passe en revue les divers types d'instruments et retrace leur évolution jusqu'à nos jours.

Cette Note a pour objet de définir la portée et l'importance que revêtent les investigations sur la température terrestre pour la climatologie et de stimuler la discussion et l'étude dans l'espoir qu'elles contribueront à l'établissement de normes permettant aux services climatologiques de mettre en œuvre un programme plus efficace d'observations de la température du sol.
КЛИМАТОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ ТЕМПЕРАТУРЫ ПОЧВЫ

Краткое изложение

В основу настоящей Технической Заметки взят документ 42/НКл-11, который был представлен Комиссией по климатологии для обсуждения в связи с рассмотрением пункта повестки дня 16 об исследованиях температуры земли.

В статье обсуждается важность измерений температуры почвы в больших научных исследований, связанных с тепловым балан- ком земли, а также их практическое применение в таких областях как прогнозирование заморозков и т.д. Один из разделов посвящен рассмотрению некоторых взаимосвязей существующих между температурой почвы и ее влажностью.

Здесь же рассматриваются методы и техника, глубина и час- тота наблюдений, влияние физической и вегетативной характери- ристики почвы или другого покрова, а также виды приборов и их историческое развитие.

Цель этой статьи заключается в том, чтобы подчеркнуть важность исследований температуры земли в климатологии и до- казать необходимость дальнейших дискуссий и изучений в над- дежде на то, что они помогут в разработке стандартов, которые в свою очередь приведут к созданию климатологическими служба- ми мира более рациональной программы наблюдений над темпера- турой почвы.
EL ESTUDIO CLIMATOLOGICO DE LA TEMPERATURA DEL SUELO

Resumen

Esta Nota Técnica está basada en el documento CCl-II/No. 42 presentado a la segunda reunión de la Comisión de Climatología, en relación con el punto 16 del orden del día: "Investigaciones relativas a la temperatura del suelo".

Se trata en ella de la importancia que presentan las medidas de la temperatura del suelo en las investigaciones teóricas sobre el balance calórico y en las aplicaciones prácticas tales como la predicción de heladas. Se dan ejemplos de la importancia biológica de la temperatura del suelo. Una sección está dedicada a examinar algunas de las relaciones entre la temperatura y la humedad del suelo.

Se analizan las diversas técnicas de observación, tomando en consideración la profundidad y la frecuencia de las observaciones y la influencia de las características físicas del suelo así como de la cubierta vegetal o de otra naturaleza. Se pasan en revista los tipos de instrumentos y su desarrollo histórico.

El propósito de este trabajo es señalar el alcance y la importancia de las investigaciones sobre temperatura del suelo en climatología así como también estimular nuevos estudios sobre la materia, con la esperanza de que puedan llegar a establecerse métodos y aparatos normalizados que permitan un programa más útil de observación de la temperatura del suelo a efectuar por los servicios climatológicos del mundo.
THE CLIMATOLOGICAL INVESTIGATION OF SOIL TEMPERATURE

1. **Introduction**

   Agenda item 16 of the second session of the Commission for Climatology, Washington, January 1957, was concerned with earth temperature investigations. The following Executive Committee Resolution 51 (EC-IV) was one of the reference citations:

   Considering that measurements of earth temperature at various depths are of value for many purposes, including agricultural meteorology, climatology, and the study of heat exchange between ground and atmosphere.

   **Decides to refer the general question of earth temperature investigations to the Commission for Agricultural Meteorology, the Commission for Instruments and Methods of Observation, and the Commission for Climatology for study and report.**

   This Technical Note, based on document CCI-11/42, examines in some detail the suggestions in Resolution 51 (EC-IV), giving particular attention to the relationship of soil temperatures to soil moisture. While workers in the several disciplines may consider it redundant to examine the value of earth temperature records, such a discussion should be of assistance to administrators of meteorological services in developing a program involving a substantial investment in equipment and personnel.

2. **Physical relationships**

   We may first look briefly at the role of earth temperatures in the study of heat exchange between the earth and atmosphere or the earth and space. Here we may be concerned with basic or pure research in the heat balance of the earth or in the general atmospheric circulation or we may be interested in more direct applications on a meso- or micro-scale, such as forecasting the occurrence of frost or fog or the relationship of "hot spots" to tornado genesis. The response of soil surface temperatures to radiation conditions is remarkably well pronounced, especially on clear days and nights. The amplitude of the temperature at the soil surface often greatly exceeds that of the air temperature a few feet above. At night it has the lowest value in the vertical profile, both up and down. In daytime it can become very warm, and certainly shows the maximum of the whole vertical temperature profile, Figure 1, showing data from the O'Neill, Nebraska study (1), demonstrates the nature of the diurnal range in temperature. Profiles of wind speed in the lower layers at corresponding times are also shown.

   This tendency toward extreme temperature ranges in the soil surface leads to some consequences of great importance for the lowest layer of the atmosphere, which we might call the bio-zone. Through conduction, convection, and
radiation in the daytime, part of the soil surface heat is imparted to the air and often a very steep lapse rate of temperature develops. This is a physically unstable condition. It contributes to turbulence, gustiness of the wind, and removal of moisture from the soil. It is this low level convection and turbulence which causes much of the interchange of gases in the soil and of spread of pollen and spores. At night, the cool soil surface also cools the air adjacent to it by conduction. This is often aided by gravity flow of cool air to lower levels in rolling or hilly terrain. The result is an inversion of temperature with warmer air aloft and colder air at the surface. This is a stable stratification which reduces turbulence and leads to lower and steadier winds. It also promotes surface condensation and conservation of moisture. Further, it may lead to accumulation and, indirectly, to fallout of pollutants, wherever these are produced or present.

Guild (2), carried out studies in the Arizona desert in a soil which he describes as "bare ... a fine, loose, sandy silt ... powdery dry". The diurnal fluctuation was very slight (on the order of one to two degrees C) at the 12-inch depth and practically zero at the 18-inch depth. At the surface the diurnal range was near 50°C.
He shows how calculation of the heat flux to or from the soil using soil temperature soundings gives a better understanding of the gain or loss of heat by the atmosphere at critical points during the diurnal exchange. Use of this information improves the calculation of minimum air temperatures for frost and fog forecasting.

A study by Kuhn et al. (3) indicates that local antecedent surface thermal patterns or "hot spots" are closely related to the position of occurrence of tornadoes. The dependence of the addition of sensible heat in the lower levels on soil and soil cover characteristics suggests the repeated development of hot spots within certain areas which may give rise to repeated outbreaks of severe convective activity within rather limited areas downstream producing "tornado alley".

Geiger (4), in his text on climate near the ground, devotes several chapters to a discussion of soil temperature in relation to micro-climate. He reports data from the University of Leipzig (after L. Herr) showing a surface diurnal range on a radiation day in summer of 26°C (14° to 40°) which is dampened to about 1°C (16° to 17°) at a depth of 35 cm. The average annual range observed over several years at Königsberg (after A. Schmidt and E. Leyst) was 19.5°C (-1° to 18.5°) at 3 cm (1 inch) depth and only 1.5°C (7.5° to 9°) at 753 cm (24 1/2 ft) depth.

One chapter of his book (Chapter 14) is devoted to a discussion of the influence of the type and condition of the soil. He says:

The supplementary heat supply from below is dependent upon the kind of soil, the amount of evaporation (water content of the ground) and (indirectly through the surface temperature) also the effective outgoing radiation ... the nocturnal thermal economy is - in principle - already determined by the three elements already mentioned. The kind of soil and the conditions of the ground are, therefore, more important for the danger of night-frost than the more or less intensive exchange within the air layers near the ground.

The temperatures of the ground consequently govern the climate near the ground to the greatest extent, this is valid not only for the night, as in the above mentioned example, but for any time.

The following table, taken from Thornthwaite (5), presents data from the O'Neill study (1) previously cited. These figures illustrate the changes in the proportion of energy used for evaporation and for heating the air and soil as the soil moisture changes:

(see next page)
Heat used for convection, evaporation, and storage in soil and soil moisture content on different days at O'Neil, Nebr., 1953

<table>
<thead>
<tr>
<th>Date</th>
<th>Heat used for convection (C) (cal/cm²)</th>
<th>Heat stored in soil (S) (cal/cm²)</th>
<th>Heat used for evaporation (E) (cal/cm²)</th>
<th>Total C+S+E (cal/cm²)</th>
<th>( \frac{E}{C+S+E} ) (%)</th>
<th>Soil moisture in 0-18&quot; profile (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug. 13, 14 ...</td>
<td>56.3</td>
<td>29.7</td>
<td>377.2</td>
<td>463.2</td>
<td>81</td>
<td>1.65</td>
</tr>
<tr>
<td>Aug. 18, 19 ...</td>
<td>59.1</td>
<td>-4.8</td>
<td>287.8</td>
<td>342.1</td>
<td>84</td>
<td>1.40</td>
</tr>
<tr>
<td>Aug. 22 .......</td>
<td>98.4</td>
<td>19.0</td>
<td>216.2</td>
<td>333.6</td>
<td>65</td>
<td>1.20</td>
</tr>
<tr>
<td>Aug. 25 .......</td>
<td>181.9</td>
<td>41.5</td>
<td>131.8</td>
<td>355.2</td>
<td>37</td>
<td>1.05</td>
</tr>
<tr>
<td>Aug. 31 .......</td>
<td>242.3</td>
<td>28.3</td>
<td>44.5</td>
<td>315.1</td>
<td>14</td>
<td>.75</td>
</tr>
<tr>
<td>Sept. 3, 4 ......</td>
<td>121.1</td>
<td>-47.5</td>
<td>136.5</td>
<td>210.1</td>
<td>65</td>
<td>1.20</td>
</tr>
</tbody>
</table>

Thus it can be seen that the moisture content of the soil can greatly affect the use of solar energy and, as a result, can influence both the air and soil temperatures. This is especially important during drought periods when the dry soil favors high soil and air temperatures, thus tending to augment the effects of the drought.

Sutton, in his text on micrometeorology (6), brings together the results of the work of many investigations in soil temperatures and related phenomena. He emphasizes the importance of soil temperatures in connexion with frost and fog occurrences as well as their contributions to an understanding of many other atmospheric processes. Methods for computing soil temperatures are shown and formulas for computing minimum temperatures are discussed. In commenting on the latter (but equally applicable to both) Sutton states:

The dependence on soil constants seriously limits the practical application of theoretical formulas of the type discussed above, since it is improbable that accurately determined values of soil density, specific heat, and conductivity will be available to the meteorologist on all occasions. Average values of the constants are of little use in this connexion because of the large changes in conductivity which are brought about by relatively small variations in water content, amount of vegetation, and so on.

Langbein (7), also describes a method for computing the soil temperature at a given depth as the result of changes in surface temperature. The cumulative effects of several such changes for various time periods can be shown. Thermal diffusivity of the soil layer must be known and any changes in diffusivity due to changes in soil moisture during the period will affect the results.

On a seasonal or annual basis, the logarithmic variation of extreme temperatures or temperature range at various depths is very well marked. Figure 2, from an unpublished paper by Collins after data from Miller (8), illustrates this feature. If we know this function from two measurements, we can extrapolate or interpolate for other depths. In practice this gives us the
opportunity, on a climatic basis, to determine the depth at which the annual temperature amplitude has diminished to any given specified value, including the depth at which it becomes insignificantly small. We can also determine the average depth of frost penetration. The extreme depth of frost penetration, based on soil climatic records for a location can also be readily derived.

Figure 2

Annual soil temperature range
Midland, Michigan

The stability of annual mean temperature with depth, as illustrated in Figure 2, was also shown by Potter (9) in a study in eastern North Dakota. He reports on two years of weekly readings at depths of 1 and 6 inches and 1, 2, 3, 4, 5 and 6 feet using thermocouples and portable potentiometers.

He describes a spring and fall reversal of temperature gradient with a 5-month summer period of progressive decreasing temperature with depth and a 7-month winter period with increasing temperature with depth.
He also points to the remarkable uniformity of annual mean temperatures at a given site at all depths.

Representative data under grass sod were:

<table>
<thead>
<tr>
<th>Depth</th>
<th>Yearly mean $T_0$ (two-year period)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&quot;</td>
<td>48.5</td>
</tr>
<tr>
<td>6&quot;</td>
<td>48.1</td>
</tr>
<tr>
<td>1'</td>
<td>48.5</td>
</tr>
<tr>
<td>2'</td>
<td>48.4</td>
</tr>
<tr>
<td>3'</td>
<td>48.5</td>
</tr>
<tr>
<td>4'</td>
<td>48.6</td>
</tr>
<tr>
<td>5'</td>
<td>48.7</td>
</tr>
<tr>
<td>6'</td>
<td>48.6</td>
</tr>
</tbody>
</table>

3. Biological relationships

In the introduction to his report on soil temperatures in the South Carolina Piedmont (10), Green states:

The temperature of the soil is important because it is one of the limiting factors to root growth. Plant growth has been found to be accelerated within certain ranges of soil temperature and inhibited or prevented beyond such boundaries. Consequently, knowledge of soil temperature may be useful in determining suitability of planting sites, length of growing season, and periods of most rapid growth.

In addition to presenting useful data not previously available, Green's report illustrates the difficulty of drawing valid conclusions from "once-a-day" soil temperature readings of upper layers. The effects of diurnal change may mask or exaggerate differences due to environment. It would be more desirable to obtain hourly readings or readings of maxima and minima.

There are many relationships in the field of agriculture in which soil temperatures are a critical or limiting factor. Seed germination, root elongation, salt accumulation, shoot-root ratio, and weed and disease control are but a few. The following quotations from Meyer and Anderson's text on plant physiology (11) illustrate some of these points:

The fact that salt accumulation by root cells is dependent upon respiration suggests that temperature may have a marked effect on the process, a supposition which has been confirmed experimentally ... the $Q_{10}$ of the process of ion accumulation is in the range of two to three (page 466).

The same authors (page 708) state:

In the absence of other limiting factors the seeds of any species will germinate within a certain range of temperatures, but at temperatures above or below this range no germination will occur. As a rule, the seeds of species indigenous to temperate regions germinate in a lower range of temperatures than seeds of species whose native habitat is in
tropical or sub-tropical regions. Wheat seeds, for example, germinate at temperatures only slightly above 0°C and at temperatures as high as 35°C, whereas the range of temperatures for germination of seeds of maize (a species of sub-tropical origin) lies between a lower value of 5°C - 10°C and an upper limit of about 45°C. The optimum temperature is usually about midway between the two extremes of temperature at which germination will occur.

Again, in discussing water absorption, Meyer and Anderson write:

Reduction in the absorption rate of water occurs in many kinds of plants at soil temperatures well above freezing, but the exact magnitude of this effect differs according to species. In general, plants native to warm climates undergo a greater reduction in rate of water intake when the soil is chilled than those which are habitants of cooler climates. For example, Kramer (1942) found that watermelon and cotton, warm season crops, absorbed only 20 per cent as much water at 10°C as at 25°C, while collards, a cool season crop, absorbed 75 per cent as much water at the lower of these two temperatures as at the higher.

In his reply to a questionnaire by the CAGM Working Group on observational requirements in agriculture in 1957, Dr. V.V. Sinelshikov, Moscow, reported the following soil temperatures (at seeding depth) at which sowing takes place:

<table>
<thead>
<tr>
<th>Crop</th>
<th>C0</th>
<th>C1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn, millet, sorghum, soya bean, cotton</td>
<td>10-12</td>
<td>50-53,6</td>
</tr>
<tr>
<td>Potatoes</td>
<td>8-10</td>
<td>46,4-50</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>6-7</td>
<td>42,8-44,6</td>
</tr>
<tr>
<td>Rice, buckwheat</td>
<td>14-15</td>
<td>57,2-59</td>
</tr>
<tr>
<td>Tobacco</td>
<td>14</td>
<td>57,2</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>14-16</td>
<td>57,2-60,8</td>
</tr>
</tbody>
</table>

4. Soil moisture relationships

Many meteorological services have a partial or complete responsibility for the hydrologic service of their country, including the estimation of water supplies and the forecasting of stream levels and stream flows. The moisture supply in the soil and its capacity for additional storage are both essential parameters in providing such services. Changes in moisture content of soils are primarily dependent upon several meteorological variables including precipitation, condensation, vapor pressure gradient, wind movement, and radiation. For these reasons, the meteorological services of the world, either voluntarily or through the pressure of requests from other sources, are giving increased attention to measuring and recording soil moisture as part of the climatology of their area. This requires that meteorologists have a knowledge of soil temperature - soil moisture relationships and that the services conduct adequate soil temperature investigations as part of their soil moisture program.

In his investigations in the relationship between soil temperature and water capacity, Haberland (12) found the following decreases in water holding capacity with increasing temperatures;
SOIL MOISTURE RELATIONSHIPS

Temperature      Water capacity per cent dry weight

15°C             53.1
20°C             52.6
30°C             51.3
50°C             47.7
100°C            46.2

He obtained similar but greater differences from another experiment with humus and clay soils:

<table>
<thead>
<tr>
<th>Soil</th>
<th>T°C</th>
<th>Water capacity</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Humus</td>
<td>15°C</td>
<td>65.6 %</td>
<td>18.4 %</td>
</tr>
<tr>
<td></td>
<td>60°C</td>
<td>47.2 %</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>15°C</td>
<td>46.4 %</td>
<td>12.6 %</td>
</tr>
<tr>
<td></td>
<td>60°C</td>
<td>33.9 %</td>
<td></td>
</tr>
</tbody>
</table>

Klenze (13) investigated the same relationship at lower temperatures, trying to keep the experiment closer to natural conditions. He found the following values:

<table>
<thead>
<tr>
<th>Type of soil</th>
<th>Particle Size mm</th>
<th>Mellow soils 5°C</th>
<th>Mellow soils 35°C</th>
<th>Dense soils 5°C</th>
<th>Dense soils 35°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>2.50-4.00</td>
<td>4.65 %</td>
<td>4.00 %</td>
<td>6.03 %</td>
<td>4.12 %</td>
</tr>
<tr>
<td>Quartz sand</td>
<td>1.18-2.50</td>
<td>12.42</td>
<td>7.82</td>
<td>14.25</td>
<td>12.26</td>
</tr>
<tr>
<td>2. medium</td>
<td>0.74-1.18</td>
<td>26.60</td>
<td>23.19</td>
<td>22.49</td>
<td>21.45</td>
</tr>
<tr>
<td>3. fine</td>
<td>0.30-0.74</td>
<td>28.08</td>
<td>26.63</td>
<td>24.01</td>
<td>23.77</td>
</tr>
<tr>
<td>4. very fine</td>
<td>0.30</td>
<td>28.91</td>
<td>26.88</td>
<td>26.34</td>
<td>26.28</td>
</tr>
<tr>
<td>Quartz dust</td>
<td>-</td>
<td>30.66</td>
<td>29.26</td>
<td>28.67</td>
<td>27.36</td>
</tr>
<tr>
<td>Peat</td>
<td>-</td>
<td>158.65</td>
<td>172.11</td>
<td>118.13</td>
<td>126.66</td>
</tr>
</tbody>
</table>

Ulrich (14) experimented with mineral soils, and obtained the following water holding capacities in per cent of dry weight:

<table>
<thead>
<tr>
<th>Soil</th>
<th>0°C</th>
<th>10°C</th>
<th>20°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>69.42</td>
<td>67.25</td>
<td>65.86</td>
<td>65.07</td>
</tr>
<tr>
<td>Clay with lime</td>
<td>41.06</td>
<td>39.93</td>
<td>39.53</td>
<td>39.03</td>
</tr>
<tr>
<td>Clay, fine grained</td>
<td>46.75</td>
<td>45.93</td>
<td>45.18</td>
<td>44.62</td>
</tr>
<tr>
<td>Lime sand, fine</td>
<td>25.15</td>
<td>24.65</td>
<td>23.94</td>
<td>23.34</td>
</tr>
<tr>
<td>Quartz sand</td>
<td>15.90</td>
<td>15.45</td>
<td>15.12</td>
<td>14.86</td>
</tr>
</tbody>
</table>

All three investigators found that the field capacity of mineral soils decreased with higher temperature. However, Klenze showed that peat has the converse relationship: with field capacity increasing as temperature increases. This was supported by the following figures obtained by Ulrich from experiments with organic soils:

<table>
<thead>
<tr>
<th>Soil</th>
<th>0°C</th>
<th>10°C</th>
<th>20°C</th>
<th>30°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chernozem (Tula)</td>
<td>47.46</td>
<td>43.80</td>
<td>49.80</td>
<td>50.23</td>
</tr>
<tr>
<td>(Tambov)</td>
<td>47.50</td>
<td>43.51</td>
<td>49.90</td>
<td>50.53</td>
</tr>
<tr>
<td>Peat (Shlesheim)</td>
<td>155.10</td>
<td>155.34</td>
<td>155.43</td>
<td>155.71</td>
</tr>
<tr>
<td>(Oldenburg)</td>
<td>593.00</td>
<td>604.50</td>
<td>615.50</td>
<td>620.00</td>
</tr>
</tbody>
</table>
In an investigation of pressure-membrane determinations of soil-moisture tensions, Richards (15) subjected 12 soils, covering a wide texture range, to 1/2 atmosphere and 15 atmosphere tensions at temperatures near 0, 12, 21, 30 and 37°C. He, also, found higher percentages of moisture retained at the lower temperatures, as might be expected from the increase in surface tension of water at lower temperatures. Quantitatively, the differences were of the same order of magnitude as the changes in surface tension with temperature.

Smith (16) confirms the work of Bouyoucos (17) showing transfer of significant amounts of moisture due to the application of temperature gradient with negligible amounts due to vapor transfer alone. Movement is described as almost entirely capillary due to changes in surface tension with the mechanism triggered by an original evaporation-condensation exchange. The amounts of moisture transfer found by Smith were considerably larger than those reported by Bouyoucos. Smith points to the masking effect of the large volumes of soil used by Bouyoucos which were not influenced by the temperature gradient which he imposed. Both found that moisture transfer was negligible in dry soil, increasing to a maximum in soil wet to about 50% of the moisture equivalent and reducing to negligible amounts at moisture equivalent. This is explained by the necessity of having some capillary moisture to move and also of having some free pore spaces in which to move.

Fragmented soil samples were found to show much larger amounts of moisture transfer than the same soils in a natural undisturbed condition. This supports the hypothesis that the availability of additional pore spaces facilitates movement under this mechanism.

The following table* contains a few of Smith's results. Moisture contents are in percent dry weight. They are given for the original sample and for samples from the warm and cold sides after thermal equilibrium was reached. Physical condition refers to fragmented (crushed and sieved) or monolith (undisturbed, natural) samples.

Perman (18), in examining records of temperatures in the surface one-half inch of soil in fallow plots, found a useful relationship between air temperature maxima and minima and corresponding soil temperature maxima and minima. He found he could estimate the maximum and minimum temperatures of the soil surface by dividing the year into two parts, one in which air temperature maxima average below 55°F and one in which they average above 55°F. In the colder period soil surface maximum and minimum temperatures (Tₛ) usually equal air temperature (Tₐ) while in the warmer period they follow the form Tₛ = 2Tₐ - 52. He found that this division also separated two recognizable regimes of soil water loss. During the colder period he found evaporation from fallow soil to nearly equal the evaporation from an open water surface. Using the temperature relationship above, he found that the amount of evaporation from fallow soil could be calculated from air temperatures. However, during the warmer period he found that evaporation from fallow soil during periods of the order of one month to be less than from an open water surface similarly

* See next page.
### Table

<table>
<thead>
<tr>
<th>Soil</th>
<th>Horizon</th>
<th>Physical cond.</th>
<th>Temp. grad. °C/cm</th>
<th>Moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernes loam</td>
<td>A</td>
<td>Frag.</td>
<td>5.5</td>
<td>5.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.9</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.5</td>
<td>8.9</td>
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<td></td>
<td></td>
<td></td>
<td>2.7</td>
<td>5.7</td>
</tr>
<tr>
<td>Miami s.c.l.</td>
<td>A₁</td>
<td>Mon.</td>
<td>2.1</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.2</td>
<td>8.5</td>
</tr>
<tr>
<td>Miami s.l.</td>
<td>A₁</td>
<td>Mon.</td>
<td>2.1</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.9</td>
<td>15.9</td>
</tr>
<tr>
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<td></td>
<td>2.3</td>
<td>10.6</td>
</tr>
<tr>
<td>Chester loam</td>
<td>A₂</td>
<td>Mon.</td>
<td>1.4</td>
<td>26.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.4</td>
<td>21.1</td>
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<td></td>
<td></td>
<td></td>
<td>2.3</td>
<td>12.4</td>
</tr>
<tr>
<td>Miami s.c.l.</td>
<td>A₁</td>
<td>Frag.</td>
<td>3.4</td>
<td>32.3</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>6.3</td>
<td>30.5</td>
</tr>
<tr>
<td>Miami s.l.</td>
<td>A₁</td>
<td>Frag.</td>
<td>2.8</td>
<td>14.7</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>5.7</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.0</td>
<td>22.4</td>
</tr>
<tr>
<td>Chester loam</td>
<td>A₂</td>
<td>Frag.</td>
<td>2.3</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.7</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.1</td>
<td>26.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25.6</td>
</tr>
</tbody>
</table>

Exposed. This is explained on the basis of an accelerated rate of evaporation from the surface for a short period, drying out a shallow layer. This dry layer reduces upward movement and net evaporation loss drops off rapidly to fall well below the rate from open water even though the temperature of the soil surface is substantially higher than the air temperature.

It is evident that soil temperature measurements are an important and an appropriate field of investigation for the climatologist. It remains to examine the manner in which such investigations can best be conducted.

5. **Observational techniques**

5.1 **Depth and frequency**

The Commission for Agricultural Meteorology recommended, in its draft Technical Regulations (Res. 2 (CAGM-I)), that both soil temperature and soil moisture should be observed at 10, 20, 50 and 100 cm depths. The Commission for Climatology, in its second session in Washington, January 1937, passed the following recommendation:
Rec. 7 (CC1-II) - EARTH TEMPERATURE MEASUREMENTS

THE COMMISSION FOR CLIMATOLOGY,

NOTING Resolution 51 (EC-IV) and Resolution 2 (CAgM-I); and

CONSIDERING,

(1) That measurements of earth temperature, soil moisture and soil texture, the radiation temperature of the earth's surface and of heat flow in the soil are of great importance for climatological as well as for agricultural purposes;

(2) That further study is needed on the methods of carrying out these measurements;

(3) That earth temperature and soil moisture are at present only observed at a relatively small number of stations in some countries;

RECOMMENDS,

(1) That members should arrange for:

(a) Observations of earth temperature at depths of 10, 20, 50, 100, 150 and 300 cm to be made at their agro-meteorological stations and at a selection of climatological stations;

(b) Studies to be carried out on the measurement of the radiation temperature of the earth's surface and of heat flow in the soil;

(2) That the Commission for Instruments and Methods of Observation should prepare further material for the Guide to International Meteorological Instrument and Observing Practice on the measurement of earth temperature, the radiation temperature of the earth's surface and heat flow in the soil.

Observations once a day are generally sufficient at depths where the diurnal fluctuation is smaller than the accuracy required in the data. Most investigators agree that at depths of one metre (three feet) the diurnal change is negligible. Even at 30 to 35 cm (about one foot) the diurnal range is of the order of one degree F and for most purposes a reading once a day would be adequate at 50 cm (20 inches) and deeper. At shallower depths continuous recordings would be most desirable. If this is not practicable then daily maximum and minimum readings or readings at fixed hours (preferably at intervals of not more than six hours) are suggested.

Several references follow showing data on the depths of diurnal and annual fluctuations and the ranges to be expected. Figures 1 and 2, presented earlier*, are also of interest in this regard.

Bouyoucos (19) found diurnal ranges in Michigan of about 10° F at 18" depth.

* See pages 2 and 5.
In their summary of an extensive collection of records of soil temperatures in the United States, Fitton and Brooks (20) report that a depth of three feet seems to be the extreme limit of diurnal fluctuation and that in one complete series of data at New Haven the daily range is reduced about one-half for each 3-inch increase in depth. From this relationship the amount of diurnal change is seen to diminish to less than 10°F at depths of 18 to 21 inches.

Annual ranges of as much as 10°F were measured at depths of 10 feet at Bozeman, Montana and were estimated to be measurable down to 30 or 40 feet.

Data presented by Smith (21) taken at 1/2, 3, 6, 12, 24 and 36 inch depths in bare unirrigated soil shows that the diurnal fluctuation reaches an almost negligible amount (about 10°F) at 12" and disappears at 24".

Data from MacDougal (22) taken at the New York Botanical Garden show a diurnal fluctuation at 30 cm (one foot) of the order of 1°C, exceeding this slightly during extreme summertime conditions and becoming more uniform during winters.

Brawand and Kohnke (23) found no significant diurnal fluctuation at the 20-inch depth.

Smith (24) concluded that averages of soil temperature readings taken at 15-minute intervals were more true than averages of hourly readings. However, the differences were small, not exceeding 10°F, and it can be concluded that such precision is not necessary for soil temperature observations.

5.2 Soil physical characteristics and cover

Published records of soil temperature should include information or references to soil series and type and to the nature of vegetative cover. Depth, duration and type of snow cover should also be reported. Crawford (25) cites a report showing noticeable effects on soil temperature measurements if the snow cover near the reporting area is trampled.

Johnson and Davies (26) investigated the effects of surface cover or material on temperatures near the surface of the soil. Their results clearly show the modifying effect of a grass cover and the extremely high maxima experienced under a black macadam cover.

De Vries (27), in reporting on equipment for determining thermal conductivity of soil in situ lists some of his results. He found that within a period of a week the values of thermal conductivity near the surface (4 cm) varied from 1.29 to 4.55 millicalories per centimetre per second per degree C. At a depth of 32 cm they ranged from 2.68 to 3.78. Moisture change due to precipitation during the period was thought to be the cause.

Several investigators (Richards (28), Sutton (6), Langbein (7)) have shown that temperatures and temperature changes at one depth can be calculated from temperatures and temperature changes at another depth in the same soil profile if certain physical properties of the soil (bulk density, moisture content, specific heat and thermal conductivity and diffusivity) are
known. From this it follows that temperature observations at two depths in the profile should be adequate and that temperatures at any other desired depths could be determined by establishing suitable formulas or tables.

This approach has appeal when the expense and difficulty of establishing a number of observing stations for all depths are considered. It may be possible to provide useful approximations of weekly or monthly averages for many depths with a minimum of expense and effort by selecting appropriate values of the physical constants as obtained in similar soils elsewhere. Richards (28) lists a good many with their source. Rider (29) provides generalized curves showing how thermal conductivity, thermal diffusivity, and heat capacity vary with the moisture content of the soil.

However, the practical realization of this method on a network basis has yet to be demonstrated. The difficulty and expense of determining the various physical constants for all layers in the soil and under all ranges of soil temperature and moisture are perhaps greater than those attending the establishment of a complete temperature observing net.

Lettau (30) discusses the failure of the classical theory of heat diffusion in a solid medium to explain soil temperature changes. He states that:

An obvious reason for such failure derives from the inhomogeneity of nature soil. Density, porosity, moisture content, and other factors are usually functions of depth. Recently, de Vries (27) has thoroughly discussed the available information in regard to dependency of heat conductivity and capacity of the soil on variations of the above factors, especially soil-moisture content. De Vries' theoretical and experimental results confirm the findings of various authors inasmuch as heat conductivity and capacity may vary up to one order of magnitude within soil layers of a few centimetres thickness.

He then shows that the non-homogeneous case of soil-heat conduction, that is when soil-heat conductivity and capacity are functions of depth, can be treated rigorously. A formula is derived which gives the thermal diffusivity of the soil as a function of depth, on the basis of Fourier coefficients of diurnal courses of soil temperature at a variety of depths. Employment of the new model of soil-heat diffusion avoids misleading results which are obtained when the classical model of heat-diffusion in a solid conductor is applied to natural soil indiscriminately. The case of depth-time varying thermal diffusivity can only be solved in approximate form. The practical application of the classical and the two new models are discussed with the aid of soil temperature data.

5.3 Instruments

Various types of instruments are available for use in measuring and recording soil temperatures. They are too well known to require description here but a few references to their development and use and to a few special forms may be helpful.

In 1894 the United States Weather Bureau issued Circular G (31) describing a specially constructed recording maximum and minimum soil thermometer
employing mercury and alcohol in glass. The bulb of the thermometer was six inches long and was inserted so that it was in contact with a layer of soil extending from three inches to nine inches below the surface. The temperatures reported were therefore an approximate average of the temperature of that layer.

Locations were selected to represent the soil in the area best suited to the principal crop of the area. Plots 20 feet square were laid off and the thermometer was inserted in the centre of the plot. The surface was in open sun light and was kept free of grass and other vegetation. Maximum and minimum readings were made once a day and the indexes were set to the current temperature.

Apparently the equipment was experimental in nature as it is not in present use and there are no published records of any extensive series of observations with this type.

Penman (18) describes a method of measuring surface temperatures by pressing a looped strip of brass, one-half inch wide, edgewise into the soil. The soil inside the loop was then removed and a mercury-in-glass thermometer, the bulb encased in soft copper gauze, was inserted in such a manner as to be in good thermal contact with the brass strip. Visual readings of the thermometer were taken as representing the mean temperature of the upper layer of soil one-half inch deep.

Rider (32) describes a convenient method of utilizing thermocouples inserted in brass plugs set at intervals in a heavy plastic tube. Good contact with the soil is maintained and the instrument may be moved from one location to another with a minimum of difficulty.

Smith (24) used thermohms (electrical resistance thermometers) at depths of 6, 12, 18 and 24 inches with automatic recordings on a Micromax recorder at 15-minute intervals.

Bouyoucos (33) in 1947 described two types of electrical resistance thermometers adapted to the resistance scale of the Wheatstone bridge used with soil moisture blocks. Type 1 has a range from about -20°F to 100°F and type 2 from about 32°F to 134°F. Resistance of the type 2 near 40°F increases about 50,000 ohms with a 1° drop in temperature. At 75°F the change is about 8,000 ohms per degree.

A short time later (1948) a somewhat different type of resistance thermometers became available. Their use in soils work was reported by Richards and Campbell (34). The resistance at 50°C is about 820 ohms, increasing to 2,000 ohms at 25°C and 5,700 ohms at 0°C. The rate of change is about 80 ohms per degree C at 25°C.

Bliss (35) used soil thermographs with bulbs buried at 3, 6 and 12-inch depths in bare unshaded soil which was frequently irrigated. The bulbs were inserted in niches in the side of a trench and soil from each niche was replaced and firmly packed. In this way each sensitive unit was in relatively undisturbed soil. For deeper readings (2, 3, 4, 6 and 8 feet) he lowered standard thermometers into bakelite tubes inserted in holes produced with a
soil sampling tube. The bulb of the thermometer was allowed to come in contact with the soil in the bottom of the pipe. This method seems open to considerable experimental error.

Richards (28) summarizes much of the literature and experience in soil temperature investigations in the United States. He emphasizes the need for uniformity and standardization and amply illustrates the present lack of both. In a section on instrumentation he describes the several methods most commonly employed. While no specific recommendations are made, his discussion seems to favor a recording instrument of the electrical resistance type.

6. Conclusion

A review of the physical and biological aspects of soil temperature, with emphasis on the relationship to soil moisture, clearly indicates an important and appropriate field of inquiry for the climatologist. This conclusion is verified by the action of the Commission for Climatology in its Recommendation 7 (CCl-II). However, there is a serious lack of uniformity or standardization in methods of observation. This lack extends to instrumentation, exposure, and depth and frequency of observation. The suggestions and literature references in this paper were first assembled to provide a basis for a discussion of the problems by members of the Commission for Climatology. They are reproduced now as a Technical Note in the hope that they may assist in the development of a more useful program of soil temperature investigation by the climatological services of the world.
LIST OF REFERENCES


   or:


12. Haberland, F. - Landwirtschaftliche Versuchsstationen. (Agricultural Experimental Stations) vol. 8. (German)
13. Klenze, H., 1877 - Landwirtschaftliche Jahrbücher. (Agricultural Yearbooks) N. 1, 1877 (German).
LIST OF REFERENCES


TECHNICAL NOTE No. 21

MEASUREMENT OF EVAPORATION,
HUMIDITY IN THE BIOSPHERE AND SOIL MOISTURE

Report of a working group of the Commission for Instruments and Methods of Observation, prepared by N.E. RIDER, Chairman
# MEASUREMENT OF EVAPORATION, HUMIDITY IN THE BIOSPHERE AND SOIL MOISTURE

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**Section 3 - Suitability of instruments for the measurement of soil moisture**

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MESURE DE L'EVAPORATION, DE L'ETAT HYGROMETRIQUE DE LA BIOSPHERE
ET DE L'HUMIDITE DU SOL

Résumé

En 1953, la Commission des instruments et des méthodes d'observation de l'O.M.M. créait un groupe de travail chargé d'examiner dans quelle mesure les méthodes et les instruments utilisés convenaient pour mesurer l'humidité du sol, l'évaporation et l'évapotranspiration, l'humidité de la biosphère, et la structure du vent dans les couches basses de l'atmosphère. Le texte principal du rapport, qui est reproduit ici, est consacré aux trois premiers points. Il traite d'abord de la question de l'évaporation, étant donné que l'évaporation ne peut pas être mesurée de la même manière que l'humidité par exemple. Le rapport passe en revue les méthodes principales permettant de mesurer l'évaporation et l'évapotranspiration réelle, ainsi que les instruments qui conviennent le mieux pour mesurer les facteurs connexes ou les indices nécessaires. Cette partie est complétée par un tableau indiquant les mesures nécessaires à l'application de chacune des méthodes envisagées et par un exposé des considérations qui ont abouti au choix du bac d'évaporation à utiliser pendant l'AGI. La partie suivante traite de la mesure de l'humidité dans la biosphère. Toutes les techniques connues sont exposées et pour chacune d'elles des exemples d'instruments sont donnés. Cette partie se termine par quelques suggestions destinées à faciliter le choix de l'instrument qui convient le mieux pour une application déterminée. La partie consacrée à la mesure de l'humidité du sol commence également par exposer toutes les méthodes ayant été utilisées jusqu'à présent, avec plus ou moins de succès. Elle conclut que le problème de la mesure de l'humidité du sol n'a pas encore été résolu et que les perspectives ne sont guère encourageantes dans ce domaine.

Le rapport se termine par une bibliographie représentative de 130 mémoires environ et par les observations formulées par certains membres du groupe de travail au sujet du rapport tel qu'il a été présenté au Président de la C.I.M.O. En général, ces observations ne reflètent pas de désaccord sur les conclusions auxquelles le groupe de travail a abouti, mais développent plutôt diverses parties du rapport.
ИЗМЕРЕНИЕ ИСПАРЕНИЯ, ВЛАЖНОСТИ ВОЗДУХА
БИОСФЕРЫ И ВЛАЖНОСТИ ПОЧВЫ

Краткое изложение

В 1953 году Комиссия по приборам и методам наблюдений (КПНН) Всемирной Метеорологической Организации (ВМО) создала рабочую группу для изучения степени пригодности приборов и методов, используемых для измерения влажности почвы, испарения с почвы и растительного покрова, содержания влажности в биосфере, а также структуры ветра в самых нижних слоях атмосферы. Воспроизводимый здесь текст доклада рабочей группы посвящен первым трем проблемам. Вопросы испарения вначале рассматриваются с учетом того, что измерение испарения не может быть произведено таким же образом, как скажем, влажность. В докладе рассматриваются основные методы измерения действительного испарения почвы и растительного покрова, а также дается общая оценка степени пригодности приборов для измерения факторов, связанных с определенными показателями. Этот раздел заканчивается таблицей, в которой приводятся измерения необходимые для применения каждого из рассматриваемых методов; здесь также даются соображения, которые привели к выбору испарительного бассейна для использования во время МГТ. Следующий раздел посвящен вопросам измерения влажности в биосфере. В этом разделе рассматриваются все новые методы, приводятся примеры приборов, которые подпадают под каждый вид. В конце раздела даются некоторые предложения, направленные на то, чтобы облегчить выбор отдельного прибора для определенной цели. Раздел измерения влажности почвы также рассматривает все методы, которые использовались до настоящего времени с большим или меньшим успехом. Этот раздел заканчивается выводом, что проблема измерения влажности почвы еще не разрешена и, что перспектива на ближайшее будущее не имеется.

В заключении доклада дается подробная библиография, насчитывающая 130 работ и заключительные замечания членов группы по докладу, в том виде в каком они были представлены Президенту КПНН. Эти заключительные замечания, как правило, носят пояснительный характер различных частей доклада и не расходятся с выводами, изложенными в нем.
MEDIDA DE LA EVAPORACION, DEL ESTADO HIGROMETRICO DE LA BIOSFERA
Y DE LA HUMEDAD DEL SUELO

Resumen

La Comisión de Instrumentos y Métodos de Observación (CIMO) de la OMM estableció en 1953 un grupo de trabajo encargado de examinar hasta que punto los instrumentos utilizados actualmente eran los más convenientes para medir la humedad del suelo, la evaporación y evapotranspiración, la humedad de la biosfera y la estructura del viento en las capas bajas de la atmósfera. La parte principal del informe del grupo, que constituye el contenido de esta Nota Técnica, está dedicada a los tres primeros puntos. Trata primero de la evaporación, puesto que ésta no puede medirse de la misma manera que la humedad, por ejemplo. El informe para revista a los métodos principales para la medida de la evaporación y la evapotranspiración efectivas, y también a los instrumentos mejor adaptados para medir los factores connexos y los índices necesarios. Esta parte se completa con un cuadro indicativo de las medidas necesarias para la aplicación de cada uno de los métodos considerados y con una exposición de las consideraciones que han llevado a la elección del tanque de evaporación que debe utilizarse durante el Año Geofísico Internacional. La parte siguiente trata de la medida de la humedad en la biosfera. Se hace una exposición de todas las técnicas conocidas y se dan ejemplos de instrumentos para cada una de ellas. Esta parte termina con algunos consejos destinados a facilitar la elección de los instrumentos más apropiados para una aplicación determinada. La parte destinada a la humedad del suelo empieza también con un resumen de todos los métodos que se han utilizado hasta ahora con más o menos éxito. Se llega a la conclusión que el problema de la medida de la humedad del suelo no está resuelto todavía y que hay pocas esperanzas de obtener una solución satisfactoria.

El informe termina con una bibliografía de unos 130 trabajos, y con los comentarios formulados por ciertos miembros del grupo sobre el informe, tal como ha sido presentado al Presidente de la CIMO. En general, estos comentarios no están en desacuerdo con las conclusiones del grupo de trabajo, sino que amplifican ciertas partes del informe.
MEASUREMENT OF EVAPORATION, HUMIDITY IN THE BIOSPHERE AND SOIL MOISTURE

INTRODUCTION

This is the substance of the report of the Working Group on the measurement of soil moisture, etc., which was set up by the president of the Commission for Instruments and Methods of Observation in accordance with Recommendation 3C (CIMO-I) and Recommendation 6 (CAgMI-I).

The membership of the group consisted of:

M.A. Kohler, Washington
F.D. White, Washington
O. de Pasquale, Messina
S.P. Venkiteshwaran, Poona
D.A. de Vries, Wageningen/Deniliquin
S. Suzuki, Tokyo
V.H. Guerrini, Limerick
J. Neumann, Tel Aviv
W. Friedrich, Coblenz

At the outset, the interpretation of the tasks of the group was considered by the members and it was decided that they should be formulated as follows:

(1) To consider the suitability of the instruments available for:
(a) The continuous recording of soil moisture;
(b) The measurement of real evaporation and evapotranspiration;
(c) The measurement of the humidity content of the biosphere;
(d) The investigation of the wind structure of the lowest layers of the atmosphere.

(2) To draft, for inclusion in the Guide to International Meteorological Instrument and Observing practice (Pub. WMO - No. 8, TP.3), paragraphs dealing with such instruments for the purposes listed at (1) above as are considered suitable.

(3) To communicate the results of our considerations and the drafts of paragraphs to the president of the Commission for Instruments and Methods of Observation.
The activities of the group were carried out entirely by correspondence although the chairman had the opportunity of discussing the group's activities with M.A. Kohler and D.A. de Vries in the early stages.

All the tasks set were not completed. In particular we were not able to give any consideration to item (1)(d), nor were we able to write instructions for inclusion in the Guide to International Meteorological Instrument and Observing Practice except that we attached to the report a copy of our recommendation on the choice and operation of an international standard evaporation tank which we thought should replace the present section of the Guide devoted to this subject. This recommendation was originally produced by the group in response to a request for guidance on the choice of an instrument for use in the International Geophysical Year programme. The variety of instruments available is large and it is doubtful if it is appropriate at this stage to attempt to make a general recommendation in favour of a particular type for the majority of the observational requirements considered here. In most cases the choice of an instrument must depend on the aim of the investigation in hand and on the facilities available to the investigator. We hoped that the report would at least serve to outline the choice available.

It will be appreciated that the terms of reference covered a wide field of meteorological instrumentation and, in fact, the instruments and techniques required for the measurement of evaporation and evapotranspiration can be largely covered under items (1)(a), (c) and (d). We therefore arranged our report so that a discussion of item (1)(b) is followed by sections on items (1)(a), the measurement of soil moisture, and (1)(c), the measurement of humidity.
SECTION 1

SUITABILITY OF INSTRUMENTS FOR DETERMINING EVAPORATION AND EVAPOTRANSPIRATION

1.1 Introduction

Studies of vapour transport from the earth's surface fall into one of three categories - evaporation from water bodies; actual evapotranspiration (the total water loss as the sum of evaporation and plant transpiration) from land areas; and potential evapotranspiration (that which would occur were there ample water supply). Although potential evapotranspiration is not mentioned in the working group's terms of reference, the concept has become so widely recognized that it could hardly be omitted in this discussion. It has important climatological significance in its own right; it is a good approximation to true evapotranspiration for irrigated areas and in humid regions; and its determination frequently constitutes a necessary first step in the actual computations and estimates of evapotranspiration.

The direct measurement of evaporation or evapotranspiration under field conditions is not feasible, at least not in the sense that one is able to measure temperature, humidity, wind, etc. As a consequence, a variety of techniques has been derived and developed for estimating the loss of water from water and land surfaces which utilize observations of related factors which may be determined by suitable instrumental techniques. Thus, a consideration of the suitability of instruments for measurement of evaporation and evapotranspiration becomes, in reality, a consideration of instruments for observing related or index factors.

The working group has been directed to consider the suitability of instruments available for the measurement of (a) soil moisture, (b) evaporation and evapotranspiration, (c) humidity of the biosphere, and (d) low-level wind structure. Although this report is organized to provide individual and specific treatment for each of these lettered items, with the exception of item (d) (see Introduction, paragraph (3)), the use of various indirect methods for deriving vapour transport data requires that all the other items be introduced in this section. Some repetition is inevitable under these circumstances, but every attempt has been made to avoid duplication wherever feasible. Thus, while the role of humidity, wind and soil moisture in vapour transport studies is discussed in this section, the suitability of available instruments for humidity and soil moisture determinations is discussed in the following sections.

From a theoretical viewpoint, there are three recognized approaches to vapour transport studies, namely the water budget approach, the energy budget approach and the turbulent transport approach. In addition, pans or evaporation tanks, atmometers, lysimeters and evapotranspirometers are used in an empirical, or index, manner. Any attempt to discuss instrumental requirements of the three basic approaches individually leads to some confusion
because specific studies reported in the literature frequently involve them in combination. Penman's (1, 2) method for the specification of potential evapotranspiration solves simultaneously the energy budget equation and an empirical turbulent transport equation derived from pan observations. Use of the energy budget approach requires an approximate water budget to evaluate advection and storage terms (3). Empirical techniques have been developed for using the energy budget in combination with a pan (4), and water budget in combination with turbulent transport equations (5). In addition, there are empirical techniques such as Thornthwaite's (6). Nevertheless, an attempt is made to segregate the basic approaches in the subsequent discussion of instrumental requirements.

In appraising the adequacy of the existing instruments, one must bear in mind the time factor considered. The requisite precision for some measurements varies inversely with the time period for which the final result is required. Thus changes in storage and soil moisture can often be neglected in annual or mean annual computations even when such a neglect would render the result of daily or weekly computations completely in error. Since it is impossible to cover all time aspects in a report of this type, all subsequent discussion should be considered to apply to practical applications, unless otherwise indicated. It is believed that determinations for periods of much less than a month are only required in experimental work.

A table has been prepared to illustrate the variety of observations required in applying the various approaches. In attempting to generalize, it will be noted that the observational requirements include all the elements needed in any one of the equations or techniques falling under the general heading. For example, surface temperature is listed as a required observation under the turbulent transport approach for evaluating evaporation even though it is not required in applying the Thornthwaite-Holzman equation (4).

1.2 The water budget approach

1.2.1 General

The water budget approach is exceedingly simple in theory, but application rarely produces reliable results. It is based on the assumption that storage and all items of inflow and outflow except evaporation can be measured, and that the volume of water required to balance the continuity equation represents the amount of evaporation. Thus all errors in measuring inflow, outflow and storage are reflected directly in the computed evaporation.

1.2.2 Lake evaporation

Of the factors required in computing lake evaporation by maintaining a water budget, seepage is usually the most difficult to evaluate since it, too, must be estimated indirectly from measurements of ground water levels, permeability, etc. If seepage from the lake approaches or exceeds in magnitude the corresponding loss by evaporation, reliable estimates of the latter are quite unlikely. However, there is reason to believe that simultaneous
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$E_1$ - Evaporation from lake or other free water surface  
$E_t$ - Actual evapotranspiration  
P.E. - Potential evapotranspiration  
* - Evapotranspirometer or lysimeter  
# - Including that artificially applied  
$\dagger$ - Approximate water budget required  
+ - For observing water-table elevation  
$\dag$ - Or solar radiation, percent sunshine etc.
solution of the water budget and empirical mass transfer equations can provide reliable evaporation and seepage estimates (5).

Determination of rainfall generally does not represent a major observational difficulty except possibly where the lake is surrounded by very rugged terrain, or where precipitation is relatively much greater than evaporation. Snowfall, on the other hand, quite apart from any difficulties there may be in measuring it, often renders the water budget totally unreliable since the lake tends to trap blowing snow and the quantity added to a small lake may be several times as great as that observed along the shore.

Water storage recorders are sufficiently precise for determining storage changes provided the stage area relationship is accurately established. Variations in bank storage are sometimes important sources of error in monthly computations but can usually be neglected in estimates of annual evaporation. Similarly, expansion or contraction of stored water with large temperature changes can readily introduce errors of up to 1 to 2 cm per month if not taken into account (page 34 of (7)).

Stream-flow measurements (inflow and outflow) are normally based on water stage recorder data and a stage discharge relationship derived from current metre observations. Notable deficiencies are primarily those of technique, rather than of an instrumental nature, brought about by insufficient current metre observations to adequately define the stage discharge relation throughout time. A related factor, often troublesome in water budget computations, is the determination of surface runoff entering the lake and by-passing all gauging points.

The relative effect of errors in the inflow and outflow terms vary considerably from lake to lake depending upon their magnitude with respect to the surface area. Determinations of stream flow to within 5 per cent are normally considered as 'excellent' and corresponding evaporation errors may be expected in off-channel lakes and reservoirs from which no water is released. If the quantity of water passing through a lake or reservoir is large compared with the evaporation losses, water budget results are of questionable accuracy, even though the most precise instrumental equipment is used.

1.2.3 Real and potential evapotranspiration

Water budget techniques for determining real and potential evapotranspiration are essentially identical. The distinction rests solely on the availability of water in the soil for the evapotranspiration process. Although there are notable exceptions (8), the determination of percolation normally presents a more formidable problem in maintaining a water budget for land areas than is the case for lakes because of the intermittent nature of ground water accretions. Moreover, an additional element is required for short period determinations, namely, change in soil moisture storage.

Soil moisture can be determined more or less directly by oven drying a sufficient number of samples taken over the area of interest. This method is undoubtedly the most reliable (particularly in even-textured soils free of gravel, stones, etc.), but it is extremely laborious and expensive when
applied on a routine basis. While such determinations are inevitable in a calibration process, endless effort has been devoted to the development of a reliable and inexpensive technique for in situ measurement of soil moisture. Such techniques are usually based on the relationship of moisture content to some other physical property of the soil such as capacitance (9, 10, 11) or resistance (12, 13, 14), thermal conductivity (15, 16, 17), vapour tension (18, 19, 20), and the scattering of radiation from radioactive sources (21).

It cannot be unequivocally stated that available soil moisture instruments are or are not satisfactory for water budget computations - views expressed in the literature are quite diverse (22, 16, 12, 23, 25, 26) in this respect. All methods have their deficiencies, advantages and disadvantages, but it can be said that there is at present no means available for the reliable determination of water stored in a rocky soil where direct sampling is not feasible.

Most indirect methods are subject to hysteresis effects during the wetting and drying cycles (23, 24) and the resistance type measurements are highly susceptible to variations in salt concentration (13, 24) brought about by the application of fertilizer and the leaching effects of heavy rains. Variation in soluble salts presents no obstacle in the heat conductivity technique, but equipment now in use is not believed to be particularly suited to routine, continuous field operation. Although the neutron scattering technique is free from both these deficiencies (hysteresis and variation with salt concentration) the required equipment is so expensive as to have precluded other than experimental use to the present time.

It must be pointed out that water budget computations require changes in moisture storage rather than the absolute values of soil moisture. In other words, only the slope of any calibration curve is important. If computations are made over periods for which the initial and final moisture conditions are indicated to be equivalent by any of the empirical measurements, the deficiencies described above should be of no great consequence. A more complete discussion of the suitability of soil moisture measuring instruments is presented in Section 4 of this report.

If one is interested only in normal annual evapotranspiration over a basin, storage changes become inconsequential and differences between rainfall and streamflow often provides a good estimate (2, 27, 28, 29). However, such computations normally consider that the area of ground water contribution corresponds to that of the surface runoff and this assumption can lead to appreciable error.

1.3 The energy budget approach

1.3.1 General

The energy budget approach, like the water budget method, employs a continuity equation which is solved for evaporation as the residual required to maintain the balance. Although the continuity equation in this instance
is one of energy, an approximate water budget is required as well, since inflow, outflow and storage of water represent corresponding energy values which must be considered in conjunction with the respective temperatures (3).

The transfer of sensible heat between the surface and the over-lying atmosphere is exceedingly difficult to measure and it has become customary to assume that the relation of this factor to evaporation to be proportional to the ratio of the temperature to the vapour pressure gradients, the Bowen ratio (30). Subsequent discussion assumes that this relation and the continuity equation are solved simultaneously to obtain the amount of energy associated with evaporation as distinct from the sum of this energy and that associated with air heating.

1.3.2 Lake evaporation

In estimating evaporation directly from the water budget, errors in measuring precipitation, inflow, or any other of the required elements are reflected in the results, undiminished in magnitude. In applying the energy budget, approximate values of inflow, outflow (including a rough estimate of evaporation) and storage changes are subjectively adjusted to obtain a water balance. The resultant effect of water measurement errors under these circumstances depends upon the temperature differences of the elements involved. For example, assume that the true inflow and outflow for a month were equivalent to 20 and 10 cm depth over the lake respectively; that inflow = outflow = 15 cm was used in the computations; that all other water measurements were correct as used; and that the average inflow and outflow temperatures differed by 5°C. It follows that the resultant error would be 5 (20 - 10) = 50 calories per cm², which is equivalent to less than a millimetre of evaporation. It is thus evident that the high value of the latent heat of vaporization obviates the need to maintain an accurate account of water volumes.

Similarly, temperatures of the inflowing and outflowing water need not be measured with precision. Changes in the energy storage in a deep lake, on the other hand, must be based on reliable temperature profile data for accurate monthly evaporation determinations. An average error of 0.1°C over a depth of 100 metres is equivalent to about 1.7 cm of evaporation. Even so, it is believed that the available water temperature equipment is fully adequate for energy, advection and storage computations.

Temperature and vapour pressure of the water surface and temperature and vapour pressure at one selected height, usually at about one to two metres, are required for computing Bowen's ratio. At Lake Hefner, Oklahoma, U.S.A. (7), monthly values of the ratio varied from minus one third in February to plus one forth in November, and the annual mean value was -0.03. Computed monthly evaporation is therefore appreciably affected by the value used for Bowen's ratio, but the instruments available for the determination of humidity necessary for the calculation of this ratio are considered to be adequate (see Section 2 of this report).

Net radiation in the period considered is undoubtedly the most important factor in the energy budget equation. It is the algebraic sum of the
incident and reflected sun and sky short-wave radiation, incident and reflected long-wave atmospheric radiation and long-wave radiation emitted by the water body. Most routine observations from established networks provide measurements of incident short-wave radiation only; but of recent years considerable effort has been devoted to the development of radiometers which measure either the total incoming or the net radiation (31, 32, 33). Some study has also been given to the computation of net radiation from records of short-wave incident radiation (34). The results of the Lake Hefner study (7) indicated an apparent discrepancy between the Eppley pyrheliometer and the radiometer in use, but it is believed that instruments with the required reliability are available. Suitability of the existing radiometers for continuous routine field use could be improved and perhaps further effort should be directed towards this objective.

Another approach to the determination of net radiation which has considerable merit involves the maintenance of an energy budget for an insulated pan, otherwise known as a Cummings' radiation integrator (7). The assumption is made that incident and reflected solar and long-wave radiation are the same for the pan as for the near-by lake. Having the sum of these items for the pan and the surface temperature of the lake (emitted long-wave radiation), net radiation for the lake can be determined. Whereas net radiation is an independent factor in computing lake evaporation, it is the dependent factor in the case of the pan, the pan evaporation being one of the observations made.

The Cummings integrator is, in reality, a cumbersome calorimeter with the water surface exposed to the atmosphere and the natural radiation exchange. A relatively small vacuum container should, if properly designed, provide equally reliable results with a large gain in convenience and economy. Further investigation and additional development work along these lines is recommended.

1.3.3 Real and potential evapotranspiration

There appears to be little need to discuss water budget items in this section other than to stress the relative unimportance of precise measurements when 'practical' periods are considered. Instead of being concerned with heat storage in a mass of water as in a lake, that stored in the soil profile must be determined. Specific heats of soils vary from about 0.2 to 0.8, depending firstly upon the moisture contents and secondly on the soil types, so one must know the specific heat as well as the temperature. An alternative approach is provided by the use of flux plates to measure the heat transfer through the surface layers of the soil. This is probably the less satisfactory method theoretically since it is subject to cumulative error, but practically it may well prove to be the most workable (35, 36). Barring frozen conditions, the extreme annual change in heat storage of the soil seldom exceeds the equivalent of 5 cm of evaporation and monthly changes are usually equivalent to something of the order of 1/2 cm. Available soil temperature equipment is considered to be sufficiently precise for the purpose (36, 37), but in situ measurements of soil moisture may be required to adequately account for the variations in specific heat. Both temperature and specific heat measurements can be avoided by the use of soil flux plates and some effort should be given to the development of reliable types.
In applying Bowen's ratio to a lake, temperature and vapour pressure at the water surface together with those at some convenient height are used. Measuring the vapour pressure at a land surface (particularly with a vegetation cover) presents a far more difficult problem, and it becomes necessary to measure the gradients between two specific levels above the surface. Instrumental requirements and suitability in this regard are discussed in Section 2 of this report.

As in applying the energy budget to a lake, net radiation is the most important factor in the computation of evapotranspiration. Net radiometers designed to provide the necessary measurements (31, 32, 33) are considered to be sufficiently precise but, as stated previously, further research should be directed towards the development of an instrument better suited to routine continuous field operation.

1.4 The turbulent transport approach

1.4.1 General

The theoretical development of the turbulent transport equations has followed two basic approaches, namely, the discontinuous or mixing length concept (40, 41, 42, 43) introduced by Prandtl (38) and Schmidt (39) and the continuous mixing concept introduced by Taylor (44). Recently a review of the available equations for the computation of evaporation has been given by Sutton (45) and a report (3) prepared in advance of the Lake Hefner (7) and Lake Mead (46) trials sets out the present state of development of the equations in some detail. A multitude of empirical mass transfer equations appear in the literature (47). While this is not the place for a discussion of these equations we must note that those based on the mixing length concept, with one important exception (41), are not suitable for application to land surfaces since they demand a knowledge of the surface temperature or vapour pressure. Some of these equations contain the dimensions of the evaporating surface, others do not. Equations based on the continuous mixing concept, perhaps the more satisfying fundamentally, are applicable to all surfaces. Penman (48) has given a short but useful discussion.

1.4.2 Lake evaporation

The available turbulent transport equations based on the mixing length concept were derived primarily for water surfaces. Basic observations required are the vapour pressure (or temperature) of the water surface, vapour pressure of the air, wind speed and, in some cases, air temperature. As indicated earlier in this section, available instrumental equipment for measuring surface water temperature is considered to be entirely satisfactory. Humidity instruments are discussed in a subsequent section of the report, but it can be said here that suitable instruments exist for all the necessary measurements. The equation based on the continuous mixing concept demands a knowledge of the instantaneous values of the vertical and horizontal fluctuations of wind speed and humidity (49) and the instruments used up to the present for this type of measurements must be regarded as research tools. They are definitely not suitable for routine use.
1.4.3 Real and potential evapotranspiration

Although applicable to free water surfaces, the Thornthwaite-Holzman equation (41) is particularly suited to evapotranspiration determinations and has been most widely used for this purpose (8, 50, 51, 52, 53, 54). Instrumental requirements are much more exacting than for the other turbulent transport equations since the wind and vapour pressure terms in the equation appear as differences; i.e. the difference between the observed values of these two elements at two levels near the surface under investigation. Computed evapotranspiration is proportional to the product of these two differences and, consequently, an error of say 10 per cent in either difference results in a corresponding error in the computed value of evapotranspiration. With care, existing instruments are capable of yielding the required accuracy of reading, but it is probably fair to say that the method will never be suitable for routine use; its main use being as a method by means of which other techniques may be tested. The remarks under the paragraph above concerning the application of the continuous mixing concept apply equally here.

1.5 Evaporation tanks and pans

1.5.1 General

The tank or pan is undoubtedly the most widely used evaporation instrument today and its application, particularly to lake evaporation estimates, is of long standing. Endless criticism has been leveled at the pan approach and perhaps justifiably so on theoretical grounds. Nevertheless, the ratio of annual lake to pan evaporation is quite consistent, year by year, and does not vary excessively from region to region. It has been demonstrated that more reliable estimates can be made of annual lake evaporation if adjustment is made for the heat transfer through the pan and for heat storage and advection with respect to the lake (4, 46). The same applies to monthly estimates. The pan also forms the basis of several techniques for estimating evapotranspiration (1, 55, 56, 57).

There are three types of exposure employed for pan installations - sunken, above ground, and floating. Divergent views persist as to the 'best' exposure and it is deemed inappropriate to attempt a resolution here, although a choice has to be made in specifying a suggested international standard tank (see appendix). Some of the more important advantages and disadvantages to be considered are listed below.

Floating pans - The evaporation from a pan floating in a lake more nearly approximates evaporation from the lake than does an on-shore pan exposed either above or below ground, although it does not completely account for heat storage. It follows that a pan is influenced by the particular lake in which it is immersed and therefore it is not necessarily a good 'climatic' indicator. Observational difficulties are the chief disadvantage of floating pans and splashing frequently renders the data unreliable.

Sunken pans - Burying the pan tends to eliminate objectionable boundary effects, such as radiation on the side-wall and heat exchange between the
atmosphere and the pan proper, but operational problems are thereby created. Sunken pans collect more trash; they are difficult to clean; leaks cannot easily be detected and rectified; and the height of vegetation adjacent to the pan is quite critical. Moreover, appreciable heat exchange does take place between the pan and the soil under circumstances which depend on many factors including soil type, moisture content and vegetation cover. Rather than attempt the necessary observations required to adjust for heat flow through the side-walls of the pan, it would appear advisable to use a large pan thus reducing its relative effect.

Surface pans - Pans exposed above ground experience greater evaporation than sunken pans, primarily because of the added radiant energy intercepted by the side-walls. Recent studies (4) indicate that this factor has no particularly adverse effect on the use of the pan as an index to lake evaporation, although heat transfer at the pan/air interface does introduce geographical (climatological) variations. Reasonable adjustment can be made for this transfer at the pan/air interface provided that supplementary observations of wind speed and air and water temperatures are available. Principle advantage of the above ground exposure lies in the ease of operation and maintenance. Adverse side-wall effects can be eliminated by an insulated pan, but this adds materially to the cost.

There is a great need for the standardization of pan evaporation stations throughout the world and it is to be hoped that the WMO can be instrumental in bringing this about as rapidly as possible. There are a multitude of pans in use today, varying in size, shape, construction and exposure. In the U.S.A. alone there are four types of pans in more or less general use, notwithstanding further inconsistencies resulting from floating, sunken and above ground exposures. National meteorological services might oppose wholesale instrumental or exposure changes because of the difficulty of interpreting the two types of data as a composite record. As an interim measure, the WMO might encourage a number of dual installations in each Member country, i.e. the establishment of international standard stations on the sites of existing equipment. The appendix containing a recommendation on the choice of an international standard evaporation tank or pan is attached to this section of the report.

1.5.2 lake evaporation

An evaporation pan which serves as a good climatic indicator (i.e. excluding floating pans) cannot reflect heat storage and advection in a body of water, since these factors are closely related to the geometry of the water body and dam operation practice. In a deep reservoir, changes in heat storage can produce wide month to month variations in the lake to pan ratio, and annual advection equivalent to as much as 20 to 30 cm of evaporation can take place (46). It follows that these two factors may require consideration in utilizing pan data to estimate lake evaporation. Available instrumentation is considered satisfactory for making the required measurements of lake stage, water temperature and stream flow.
It will be noted that the table indicates the need or desirability of numerous supplementary observations. Interpolation between pan stations is facilitated by humidity, air temperature, wind and radiation data; heat transfer through the pan can be estimated from air temperature and water temperature and wind movement; and the remaining indicated observations are involved in the computation of heat storage and advection in the lake under study. Suitability of available instrumentation for some of these supplementary observations are discussed earlier in this section or in subsequent appropriate sections of this report.

1.5.3 Real and potential evapotranspiration

Pan evaporation is governed primarily by solar radiation with air mass properties (wind speed, humidity and temperature) exercising a minor role by comparison, except in so far as they determine the radiation exchange. The same can be said of evapotranspiration provided there is an adequate moisture supply in the soil. In addition, the rate of evapotranspiration appears to be influenced to some extent by the type of vegetation cover and its stage of development (58). Notwithstanding, pan evaporation is an approximate index to evapotranspiration, particularly in humid regions, and has frequently been used in this capacity. Techniques have been developed for improving the results by introducing season-of-year and/or length-of-day factors (1, 55).

1.6 Atmometers

Although the word 'atmometer' is sometimes interpreted as a general term encompassing a whole range of evaporation instruments, it is used here to designate porous ceramic bodies, wet paper surfaces, and similar instruments, exclusively. Opinions are quite diverse as to the value of atmometer observations and on the relative merits of the different instruments falling into the general class. The Piche atmometer still finds a use in some countries while in others its use has been essentially abandoned. The fact that they are cheap and simple to operate has been one reason for their popularity. Their small size as compared with e.g. evaporation tanks has lead to their use when attempts have been made to measure evaporation in crops. The fact that they are easily transported has been another reason for adoption.

There appears to be no standard method of exposing these instruments, and the influence of differences in exposure on the indicated evaporation is often large (see e.g. (59)). There is also some evidence to suggest that the relative effects of differences in exposure vary from climate to climate. Recently a plea has been made (60) for the adoption of a Bellani or Piché instrument for the measurement of 'latent evaporation', but it seems that there are serious difficulties involved. These arise mainly as a result of the unlikelihood that the temperature of the atmometer would remain the same as that of the air. Until an atmometer which has all its working parts adequately screened from radiation is available the adoption of the suggested scheme might lead to difficulties and confusion. It does not appear that suitable screening would be easily achieved as witnessed by the difficulties encountered in designing screens for the accurate measurement of air temperature (110).
However atmometers are likely to remain useful instruments in small scale surveys.

1.7 Evapotranspirometers and lysimeters

The term evapotranspirometer usually signifies an instrument similar to that designed by Thornthwaite (62, 63) for observing potential evapotranspiration. It consists of a sunken tank (filled with soil and having the same vegetative cover as the adjacent area) with a drain and facilities for measuring the quantity of water entering or leaving the tank. The vegetation in the tank is either watered from below (constant-level water table) or sprinkled from above. Frequent overhead sprinkling is the preferred practice since it provides greater assurance of a healthy vegetative cover comparable to that around the tank.

A comprehensive report summarizing the results of evapotranspierometer observations at numerous points over the world was recently published by the Johns Hopkins University (63). Conclusions expressed in this report amply demonstrate the importance of standardization, both with respect to the instrumental equipment and operation procedure.

Lysimeters are multipurpose instruments (64) in that they are used to study several phases of the hydrologic cycle - infiltration, run-off, evapotranspiration, etc. They can be used for either potential or real evapotranspiration measurements, depending upon operational procedure, but their reliability for the latter type of observation is frequently questioned (65). Maintaining comparable vegetation cover within and without the lysimeter is extremely difficult and the unnatural boundary at the base of the lysimeter can render its moisture storage unrealistic with respect to natural soils.

Considerations regarding the choice of a standard evaporation tank for use in the IGY programme, together with a brief specification of the instrument recommended and instructions for its use

1. Choice of type of tank or pan

The evaporation tanks or pans in use may be divided into two types according to whether they are exposed with the whole of the tank and the evaporation surface at some small height above the ground or whether the main body of the tank is sunk below ground level, the evaporating water surface being at or near the level of the undisturbed ground surface. The instrument at present recommended in the Guide to International Meteorological Instrument and Observing Practice (Pub. WMO - No. 8.TP.3) is of the second type but in spite of this it appears that the majority of free water evaporimeters in use throughout the
world have an above ground exposure. Insulated tanks have been employed from
time to time but have never been in wide-spread use. The working group has
come to the conclusion that a non-insulated tank employing an above ground
exposure is desirable for the following main reasons:

(a) It is cheap to make and install;

(b) Any leakage which develops after installation is relatively easy to
detect and rectify;

(c) It stays cleaner than a sunken tank as dirt does not splash or blow
into the water from the surroundings to any large extent. Further
when cleaning becomes necessary it is more easily accomplished than
is the case for a sunken tank;

(d) Results from a number of sites using tanks with above ground exposures
are more likely to be comparable as the influence of differences in
heat exchange with the surrounding soil and of small differences in
surrounding soil cover (for example in grass length) will not influence
the performance of the instruments to the same extent as would be so
in a network of sunken tanks.

We have had in mind the one disadvantage of an above-ground exposure,
namely that heat transfer through such a tank is greater than that through a
sunken tank of the same size. However, since this can be eliminated from the
final results when an above ground exposure is used provided that air and
water temperatures, dew point and wind are also observed, and these observa-
tions with the exception of water temperature are likely to be made on the
same site, we consider that the operational and economic advantages of the
above ground exposure outweigh this objection. Moreover it must be remember-
ed that it is nearly always impossible to make a similar correction for a
sunken tank since this requires a knowledge of the soil temperature and mois-
ture profiles which are very much more difficult to obtain than the measure-
ments in the air and water which have already been mentioned.

2. Choice of the particular tank or pan

Having once decided the type of tank or pan which should be recommend-
ed it was obvious to us that there were overwhelming advantages in specify-
ing an evaporimeter which had been in use for some time and which had had its
performance and characteristics investigated in some detail. We have decided
to recommend the adoption of the American class 'A' pan since its performance
has been extensively studied under a range of climatic conditions within
quite wide limits of latitude and elevation. In particular it must be noted
that more reliable equations are available for the conversion of the class
'A' pan observations to lake evaporation than is so for any other type of
evaporimeter in use. Further it is possible to arrive at good estimates of
water loss from this evaporimeter from the climatic data, a consideration
which is of some importance when, for example, records are lost or freezing
temperatures persist for a considerable period of the year. Reference should
be made to Research Paper No. 38 'Evaporation from Pans and Lakes' by Kohler,
Nordenson and Fox, U.S. Weather Bureau, 1955, for detailed information on these aspects.

The working group does not recommend the wholesale replacement of existing evaporation tanks and pans by the class 'A' pan. Rather it is suggested that at stations where a new installation is to be made this evaporimeter should be employed and that in existing networks class 'A' pans should be set up alongside the existing evaporimeters at a few stations which differ as much as possible in latitude, elevation, etc.

3. Specification for the class 'A' evaporation pan and brief instructions for its installation and use

This section is based on information contained in Chapter 4 of 'Instructions for climatological observers', Circular B, tenth edition, issued by the U.S. Weather Bureau which should be consulted for detailed information and in particular for relevant drawings and figures.

The pan is of cylindrical design, 10 inches (25.4 cm) deep and 47 1/2 inches (120.65 cm) in diameter (inside dimensions). It is constructed of galvanized iron or an alloy similar to monel metal, preferably the latter in areas where the water contains large amounts of corrosive substances. The seams of the pan should be carefully made to prevent buckling of the bottom. The support should be made of 2 x 4 inches (5 x 10 cm) timber arranged in an open framework with seven lengths of wood covering the diameter of the pan one way and 4 lengths the other way. If it is intended to use a hook gauge for measuring the water level (see below), two white lines painted on the inside of the pan, 2 inches (5 cm) and 3 inches (7.5 cm) below the rim help in maintaining the correct water level. The pan should be installed on a fairly level site which is, as far as possible, free from obstruction. If an obstruction such as a tree is present, it should not be closer to the instrument than twice the height of the obstruction above the pan. The ground surface cover must be cut sufficiently frequently to keep grass, weeds, etc. below the level of the pan rim. The exposure of the pan must be such that no shadow of any obstruction falls across it. Close proximity to small areas of water should be avoided. On installation the ground should be filled sufficiently to level the support and keep the bottom of the pan above the level of surface water in rainy weather. The top of the earth fill should be 1 to 2 inches (2.5 to 5 cm) below the top of the wood supporting frame so that air may circulate under the pan and the base of the pan may be inspected without difficulty. Inspection should be carried out at least once a month, particular attention being paid to the detection of any leaks. The pan should be cleaned out as often as necessary to keep it free from litter, sediment, scum and oil films.

If it is intended to use a hook gauge for measuring the water level, it will be necessary to provide a still well with means for levelling. The still well may be made of brass or other non-corrosive material. The use of a fixed-point gauge is to be preferred to a hook gauge both from the point of view of cost and the maintenance of a consistent level of water in the pan. If a hook gauge is used the water level should be maintained between
the two white lines mentioned previously. The fixed-point gauge consists of a circular brass plate about 8 inches (20 cm) in diameter to which is attached a brass cylinder of 4 inches (10 cm) diameter, the cylinder being drilled radially with 3 holes 120° apart near the end which is attached to the plate. A brass rod with a pointed end is fitted to the centre of the plate along the axis of the cylinder so that its point is 7.5 inches (19 cm) from the base of the plate. This gauge is rested on the bottom of the pan and the water level is adjusted initially to coincide with the top of the pointed rod. It will be found convenient to use in conjunction with this gauge a measuring cylinder having a cross-sectional area one hundredth of that of the pan so that, for example, the addition of one inch of water from such a measuring cylinder to the pan will raise the water level in the pan by 0.01 inch. When such a measuring cylinder is not available an ordinary laboratory measuring cylinder may be used. With the fixed point gauge it is only necessary to add or remove water with the aid of such a graduated cylinder at each time of observation to bring the water level in the pan back to its original level as indicated by the height of the top of the pointed rod.
2.1 Introduction

2.1.1 The biosphere - Definition

It is first necessary to seek a definition of the biosphere. As far as we have been able to discover no hard and fast definition has been given either by the Commission for Instruments and Methods of Observation or the Commission for Agricultural Meteorology or any other body. However, the president of the Commission for Agricultural Meteorology, in his draft provisional Technical Regulations, has suggested the following:

It is considered from the agrometeorological point of view that the biosphere stretches from a 3 metre deep level in the soil to a 10 metre high level above the upper limit of the predominant vegetation.

This definition appears adequate to form a basis for the present report, but since a separate section (Section 3) is devoted to the methods available for the measurement of soil moisture, the present section will be confined to a consideration of the suitability of existing instruments for the determination of humidity of the air from ground level to a height of about 10 metres above the level of vegetation.

2.1.2 Conditions within the biosphere

The 'air section' of the biosphere is thus composed of two zones, namely that within the plant cover and that above it. Conditions in these two zones may and generally will differ very much and it might appear at first sight that two different measuring techniques might be required. For example, the specification of an air flow of 2.5 m per sec as a ventilation requirement for dry- and wet-bulb thermometers (CIMO draft provisional Technical Regulation 2.1.5.7.3) would appear to make the use of aspirated psychrometers unavoidable within a crop cover where the natural ventilation will, on the majority of occasions, be far less than this. Usually the humidity within the plant cover will be considerably higher than that above it, particularly in the case of fully transpiring plants in relatively dry air. Thus we must accept the possibility that because of differences in natural ventilation and humidity conditions and also because of differing requirements as to size, robustness, electrical insulation, etc., no single type of instrument may be adequate to cover all uses.

2.1.3 Modus operandi of the various humidity measuring devices

We may classify the available instruments into seven broad groups according to their respective methods of operation. These are:
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(a) Those operating on a thermodynamic basis, i.e. dry- and wet-bulb temperature measuring devices;
(b) Mechanical instruments;
(c) Chemical or absorption methods in which the change in weight of a substance which absorbs water vapour is measured;
(d) Electro-chemical instruments which utilize the change in resistance of films of certain materials when subjected to changes in humidity;
(e) Instruments of the Regnault type which indicate the dew point directly;
(f) Infra-red absorption instruments.

The remainder of this section of the report will deal with each of these types of instrument in turn.

2.2 Instruments operating on a thermodynamic basis

2.2.1 General

Included under this heading are the familiar dry- and wet-bulb mercury thermometers exposed in screens, both naturally and forced ventilated, the Assmann and sling psychrometers, and a multitude of psychrometers using dry and wet bulb temperature sensitive elements such as thermojunctions, resistance wires, and thermisters. A discussion of the thermodynamic basis of psychrometry forms no part of this report. It has been extensively treated in the literature and a history of its development with an analysis of the sources of error is given in document CIMO-I/83, Toronto 1953, which contains an exhaustive bibliography. We must note here that a glance at the psychrometric tables shows that the temperature difference between dry- and wet-bulb thermometers becomes inconveniently small for measurement at high humidities and low temperatures. Errors of 0.1°C in the temperature readings under these conditions will cause errors in the computed vapour pressure, dew point or relative humidity which may be outside the acceptable limits in micrometeorological work. This difficulty and likely source of error is common to all instruments in this class and will seriously handicap the accurate measurement of high humidity at temperatures below about 5°C, when the more common types of thermometers are used. However, by the use of, for example, sensitive galvanometers in combination with thermocouple thermometers this objection can be largely overcome although the instrumental requirements become more expensive and delicate. Another feature common to all psychrometers under conditions of fluctuating temperature and humidity is the different heat capacity of the two bulbs (66, 67) which is considerably greater for screened or aspirated psychrometers using mercury thermometers than for those using thermocouples or resistance wires of less thermal bulk.

2.2.2 Dry and wet-bulb mercury thermometers in screens

These are the accepted standard instruments in many surface synoptic networks. They may be naturally ventilated or force ventilated, and have been accepted as reliable indicators of the 'mean' condition of the layer of air
near the ground. They have also been used with success in crop covers, usually in screens of sub-standard size (68, 69, 70, 71) where the more or less rapid fluctuations of humidity are of no concern. Their main advantage lies in their cheapness, their ability to stand relatively rough handling, and the fact that skilled attention is not necessary for reading and maintenance. Their chief disadvantage arises from the size of the installation and the consequent possibility of damage to the crop cover in situ and the disturbance to the microclimate by the introduction of a large 'foreign' body which is adding water vapour to the environment and may be increasing the humidity to a measurable extent. Despite these drawbacks Grainger (69), Broadbent (71) and others have employed mercury-in-steel thermometers exposed in this way in potato crops with great success. Their experimental arrangements enabled reliable and trouble free recording of humidity to be made at some distance from the position of exposure. It is considered that while the field of application of such instruments is limited, they will continue to provide the means for taking the first step in investigations demanding a knowledge of the humidity within and above crops in all cases when the need for a knowledge of the fine structure of the region is not seen to be an absolute necessity at the outset.

2.2.3 The Assmann psychrometer and sling psychrometers

The Assmann psychrometer has been accepted as a standard instrument throughout the world as a result of its handy size and inherent accuracy and reliability, which is achieved by the use of good radiation shielding combined with a high aspiration rate. It suffers, like all instruments in this class, from the need to read temperatures to at least 0.1°C if the humidity is to be determined with any accuracy, and in its standard form it is not capable of providing a record remote from the position of exposure, although this has been achieved by the substitution of thermo-electric thermometers in place of the standard mercury-in-glass type. The high rate of ventilation (as much as 10 metres per second in the type with an electrically driven fan) stirs the air in the vicinity of the instrument and this must preclude its use in many micrometeorological situations where it is desired to measure the humidity at a particular position. Presumably it was this limitation that prompted the recommendation (CAGM draft provisional Technical Regulations, part II, 2.4.1.1) that this instrument should only be used at heights greater than 50 cm above bare soil or the top of plants. Modifications can be introduced to overcome this objection and at the same time provide for remote recording (72). In the micrometeorological laboratory under steady state conditions the Assmann psychrometer is a useful instrument for calibrating others.

The sling psychrometer cannot be considered as an instrument which is suitable for micrometeorological use. It will prove a reliable indication of the general condition of the biosphere, but the reasons for its rejection when a knowledge of the humidity structure of the biosphere is required are obvious.
2.2.4 Thermo-electric psychrometers

The thermodynamic principles underlying the use of the dry-and wet-bulb mercury thermometers apply with equal validity to any temperature sensing device. Of these, probably the greatest use has been made of thermocouples in all branches of meteorology, and particularly in micrometeorology. Among the advantages accruing from the use of thermocouples psychrometers are great sensitivity, the possibility of making the thermal inertia virtually negligible and rendering radiation error very small, great flexibility of application and the ease of making or recording observations over protracted periods of time from the convenience and comfort of a building. This latter feature is particularly helpful at night or when there is the likelihood that the presence of an observer near the point of measurement will vary the temperature and humidity conditions. In general copper-constantan thermocouples have been the most popular but other metals such as manganin, nichrome, bismuth and antimony have been employed from time to time, either in attempts to provide a more robust construction or to lessen the conduction of heat to or from the junction along the thermocouple wire. The potentials to be expected are of the order of 0.4 millivolts per 10°C and recording or reading to an accuracy of better than 0.1°C requires either D.C. electronic amplification or the use of a fairly sensitive galvanometer, if necessary in conjunction with a photographic recorder (53, 73). Perhaps the greatest advantage of the thermocouple psychrometer as compared with a similar instrument using mercury-in-glass thermometers is that it can be made so that it requires very much less ventilation. This has been demonstrated theoretically by Kettenacker (74) and verified experimentally by numerous workers. Thus Waterhouse (72) finds that 5 cm per second is an adequate ventilation rate for 0.008 cm copper-constantan thermocouples, and Powell (75) using wires of the same size in nichrome-constantan junctions found that the maximum 'wet-bulb' depression was attained in almost still air. A very sensitive instrument incorporating copper and constantan wires of about 0.003 cm diameter has been described by Swinbank (76). Naegele (85), Raschke (80) and Unger (86) all describe fine wire psychrometers which can be considered as typical of this type of instrument. These fine wire thermocouples avoid the necessity for providing forced ventilation and eradicate the difficulties associated with such draughts in disturbing the natural structure of the air. They also reduce to a minimum the likely radiation errors (77).

An ingenious device whereby relatively robust thermocouples can be used without aspiration as it is normally understood is described by de Wit (78). The dry-and wet-bulb thermocouples are vibrated mechanically at the end of a steel bar through an amplitude of about 1.5 cm at a frequency of about 40 cycles per second. This motion ensures that the full wet-bulb depression is reached owing to the relative motion of the bulbs to the air, the effective rate of aspiration being equal to that produced in the Assmann psychrometer without the interference with the ambient air caused by the latter.

Sufficiently small thermo-junctions, especially if silvered, require no radiation shielding. While the errors introduced in the temperature readings of the thermocouples by radiation will in general be of only secondary
importance when a pair of such couples are used as a psychrometer (79) it should be noted that even there small errors may be greatly reduced or even eliminated by the use of opposed thermocouples (80, 81, 82). If it is desired to avoid the complication of such circuits, radiation screening may be resorted to. Generally screens should be double with the outer surfaces silvered and the inner surfaces blackened, the desideratum being to provide the inner surface of the inner screen with a temperature equal to that of the thermocouple (or other sensing device) it surrounds, without introducing any impediment to the free ventilation. Such screens have been described and used by Pasquill (73), Rider (58), Rider and Robinson (83), Thornthwaite and Halstead (54), Bellaire and Anderson (84), and numerous others. The efficiency of screening is of particular importance when it is desired to compare conditions within and above a crop cover, since the radiation regime in the two positions will not be the same. It should be noted here that the use of fine thermocouples of very small thermal inertia sometimes introduces difficulties in the interpretation of the records or readings they provide, since these will follow the rapid temperature and humidity fluctuations quite faithfully unless some inertia is introduced in the recorders.

In all micrometeorological instruments using thermocouples great care must be exercised in the associated circuits to prevent the introduction of stray thermal e.m.f.'s. Even in the most carefully made instruments it is impossible to eradicate these completely (73) and in the most accurate work constant comparison between psychrometers of this type becomes a necessity.

A very simple device for the construction of fine thermocouples has recently been described (87), and alternative procedures are mentioned by Bellaire and Anderson (84).

The wetting of the wet 'bulb' is usually achieved by wrapping fine cotton thread around the thermocouple, and care must be exercised to see that absolute cleanliness is obtained. When the thermocouple wires are welded into copper bulbs it is possible to use the more normal sock and wick technique. Raschke (80) gives a discussion of the length of wick that must be provided to ensure that the wet bulb approaches its true depression.

The papers quoted constitute but a small fraction of the literature on the use of thermocouples in psychrometry but they should suffice to illustrate the great flexibility and usefulness of this device.

2.2.5 Resistance thermometers and thermistors

The dependence of the resistance of electric conductors or semi-conductors on temperature is used as a means of measuring temperature since resistance itself can be measured with great accuracy. Such a thermometer usually consists of a platinum wire or a thermistor: the latter is made of proprietary ceramic material with a very high temperature co-efficient of resistance, of the order of 4 per cent per degree C. They may be used in varying shapes, e.g. rods, discs, spheres, etc., and sizes, thus permitting great flexibility in application. The relative ease of recording changes in resistance of both resistance thermometers and thermistors may be expected to lead to their wide
use in micrometeorological work in the future. Suitable recorders are generally rather expensive.

It should be mentioned that thermistors and platinum resistance thermometers both enjoy the advantage that their readings are an absolute measure of temperature in the sense that they require no reference base or standard, compared to thermocouples which give differential readings requiring a standard bath, such as melting ice in water, which may be difficult to arrange or maintain for long periods of time in some situations. They are apparently very stable and hold calibration indefinitely.

For psychrometric work, a muslin sock can be drawn over one of the resistors exactly as in the case of mercury thermometers. Care must be taken to ensure that there is zero or very small current through the thermistor or resistance wire, as the ohmic heating can seriously affect its temperature (for other applications, e.g. anemometry, this does not apply). This can be readily achieved in resistance bridge networks.

A typical instrument using thermistors is described by Penman and Long (88). It consists of a combined thermometer, psychrometer and anemometer using thermistors whose resistance change in the range 0°C to 50°C was from 5600 to 800 ohms. The whole equipment consisted of a vertical stand 2 ft high and a small panel containing the variable resistances, switches, galvanometer and a two-volt cell. The sensitive elements are rather large and their use in tropical conditions gives results of doubtful accuracy (89).

Very small bead thermistors have been used in the U.S.A. for temperature and psychrometric measurements in low-level turbulence studies. It is believed that sufficiently small thermistors can be used without screening in consequence of their favourable surface-volume ratio. Silvering is not possible since it short circuits the bead; and attempts to provide an insulating layer between the bead surface and the silver coating have not been successful. Among the American workers have been Shaw and Waggoner (90), Hales (91) and Staley (92).

Platinum, nickel or copper resistance thermometers are used in exactly the same way as thermistors. Typical of this psychrometric device is the instrument described by Hesse (93) consisting of long (19.4 metres) fine (0.14 mm diameter) copper wires wound around two frames, one of the wires being kept wet by muslin. An accuracy of 0.01°C in temperature and 0.1 per cent in relative humidity is claimed, with practically zero lag, but the instrument is rather cumbersome; furthermore copper wire even though enamelled may be considered less than ideal for constant outdoor use. Several firms market versions of platinum resistance psychrometer, though all of these, in consequence of the length of wire used, tend to be rather large so that their indications refer to a large volume of air, compared to the thermocouple or thermistor which can be made to closely approximate to the ideal of a point. Much smaller resistance thermometers have been described recently by Long (94) and their use appears to be gaining favor. Apart from the lack of the need for a reference temperature they have no inherent advantage over thermocouples.
2.3 Electro-chemical instruments

Under this heading are discussed those instruments whose sensitive elements consist of a material whose electrical properties are changed by the chemical or physical changes consequent on varying humidity. The electrical property usually measured is resistance; a frequently used material is lithium chloride, which is spread as a solution on a plate of non-conducting material. The LiCl element suffers from drawbacks (slow response, temperature dependence, polarization) which make it unsuitable for use in micrometeorology: a recent variant (95) uses a film of carbon black mixed with certain other components. This material is sprayed on a polystyrene blank in several layers and gives an element of great stability and lag of about one second at room temperatures. Great care is necessary to eliminate impurities in the carbon and other components.

Koie (96) made use of the fact that the surface resistivity of glass wool, which absorbs water vapour, is dependent on atmospheric humidity, to construct a hygrometer suitable for micrometeorology; but this instrument has not so far established itself as the element is rather large, easily damaged and has a very high resistance, somewhat handicapping the measurement. Other models depending on resistance change use glass wool impregnated with a hygroscopic salt (96) and anodized aluminium (97).

An instrument measuring the resistance changes of a film of poly-acrylic acid consequent on exposure to changing atmospheric humidity has been developed for medical purposes by Verzar (98). It consists of a length of insulating material about 3 mm long, coated with a thin layer of poly-acrylic acid and placed between two electrodes. When dry, the resistance of the element is very high, but falls rapidly when exposed to moist air. Hitherto it has been used for measuring the humidity of the air in the mouth, pharynx and bronchial tubes. Though not fully tested, it appears to have a very fast response and in virtue of its small size, cheapness and ease of maintenance, should be nearly ideal for measurements in plant covers, and in all small volumes. Presumably, protection against wetting by liquid water would be necessary but since the sensitive film can be readily renewed, wetting would merely cause a short interruption. Resistance at room temperature changes from 2.5 megohms at 100 per cent relative humidity, to 70 megohms at 75 per cent, to 700 megohms at 40 per cent, the time for a change being of the order of 1 second.

Of similar type is the hygrometer developed by Edney (99). It consists of electrodes connected by a spiral of glass-fibre yarn impregnated with a 1 per cent solution of calcium chloride, the whole sensitive element measuring only 10 x 6 x 6 mm. An A.C. voltage is applied across the electrodes, and the current, measured on a microammeter, varies with varying humidity, due to the varying resistance of the electrolytic solution as water vapour is absorbed in it. The accuracy claimed is 1 per cent, but the lag of 5 to 10 minutes is too high for some microclimatic work: other disadvantages are the difficulty of standardizing the sensitive element, drift in calibration (which however is very slow after a three-week ageing), and the fact that contact with water drops disturbs the calibration by diluting the solution, so that it cannot be used safely in a saturated environment.
A somewhat faster responding instrument of a similar type is the so-called Foxboro 'Dewcel' (100). This was originally developed for air-conditioning measurements and has been modified for synoptic use. It consists of a tube about 18 cm long on which is wound a wick impregnated with lithium chloride crystals. On the wick are wound two parallel wires about 0.8 mm apart, between which an A.C. potential of 25 volts is maintained. If the salt solution is below moisture equilibrium with the surrounding air it will absorb water, which lowers the resistance between the electrodes so that the resulting current increase heats it up until equilibrium is reached. The temperature of the Dewcel is recorded by a remote recording thermograph. The equilibrium temperature corresponds to the water vapour pressure over the saturated salt solution; and the true dew point can be arrived at by an appropriate allowance for the difference between the dew point for the solution and that for pure water. The time lag is 2 minutes or more to take up 98 per cent of a sudden change and the accuracy claimed in the dew point determination is ± 3°F. The instrument is inexpensive, needs little servicing (apart from 're-doping' with LiCl every 90 days), and will withstand all kinds of weather. Thus the time lag and lack of accuracy are the chief objections which make this device unsuitable for micrometeorological observations: the slow response might be partly overcome by reducing the heat capacity of the tube and its wrappings. An improved form is described by MacDowall (101).

A variant (102) of the Foxboro Dewcel which has been adapted for radiosonde use indicates that the design is capable of extensive modification. In this version the lithium-chloride impregnated glass wool is wound on a tubular thermistor 4 ½ cm long and 3 mm in diameter. The thermistor fulfils the dual purpose of supporting the two fine silver wires and the humidity-sensitive glass wool, and of measuring the temperature of the assembly, from which the dew point is obtained.

2.4 Mechanical hygrometers

Mechanical hygrometers are those which utilize the effects of humidity in changing the structure (usually the crystalline of intermolecular structure) of materials such as hair or other animal fibres, goldbeaters' skin or paper; the response of these substances is to relative humidity. First among these is the familiar hair hygrometer widely used in synoptic meteorology. Because of its inaccuracy, lag, and need of frequent calibrations against dry- and wet-bulb psychrometers it is at a severe disadvantage and can hardly be recommended for micrometeorological work. Despite this it has been used in some studies on potato blight and other plant diseases and as it is the cheapest autographic instrument will doubtless continue to be used where speed of response and sustained accuracy are not of prime importance. The goldbeaters' skin hygrometer is similar to the hair model, but has the advantage of a quicker response.

Goillot (103) has described a mechanical instrument specially designed for micrometeorological purposes. It consists of thin strips of paper, metalized on one side, built up by successive strips to a thickness of about 0.2 mm; this element is bent into a spiral, one end of which is rigidly clamped.
The paper, on absorbing water vapour, increases in length producing a distortion of the element so that the free end turns. The element described has sufficient power to actuate a pointer which rotates over a dial indicating relative humidity. An accuracy of 1 per cent with practically zero lag is claimed: the calibration remains constant within practical limits for a year. Disadvantages are a slight hysteresis effect and a lack of sufficient power for incorporation into an autographic instrument. The author hopes to overcome these objections and if he does, he will have provided a cheap and reliable instrument; even without recording arrangements, the results so far attained offer encouragement for a detailed study of the prospects of further improvement and standardization.

2.5 Chemical methods

Chemical methods of determining atmospheric humidity depend on the use of a hygroscopic substance such as phosphorous pentoxide or calcium chloride to absorb the moisture, the substance being weighed before and after exposure. Obviously no instantaneous determination of humidity can be made in this way, and this is a great drawback for micrometeorological purposes. The method has been used in some experiments on turbulence (50) but even apart from the above-mentioned drawback, the difficulty of providing delicate balances to carry out the necessary weighings will often rule out the method.

A variant, proposed by Prudhomme (104), measures the heat of reaction produced when sulphuric acid combines with water vapour in the air bubble through it: this is also considered to be impracticable for the measurements under discussion here.

2.6 Instruments of the Regnault type

These instruments depend on the observation of the formation of a film of dew on a polished surface whose temperature is reduced until the dew point is reached. In Regnault's instrument the observation is visual and various commercial models are obtainable, some of which measure the surface temperature thermo-electrically; in modern instruments a photo-electric cell is used.

In its most recent versions, the instrument possesses the advantages of extreme sensitivity, rapidity of response, robustness, suitability for use in laboratory or field, and it can be made to record its observations. Somewhat disadvantageous are its expense and elaboration which demands skilled attention for operation and maintenance.

The first of the modern instruments was that of Thornthwaite and Owens (105). A small polished, photo-electrically observed mirror was cooled by a dry-ice-alcohol mixture; when the mirror cooled to the dew point the dew formation on it reduced the intensity of light reflected to the cell. The reduction of current in the latter triggered a relay in a heating circuit which heated the mirror to a temperature sufficient to clear the dew, when the photo-cell current again cut off the heat. This design has been improved on by Suomi (106), Brissman (107) and others and finally by Barrett and Herndon.
(108). The original Thornthwaite and Owens instrument suffered from a considerable lag and a tendency to generate oscillations in the mirror temperature. The latest models have eradicated these faults by the use of 'eddy' or radio-frequency induction heating of the mirror surface and improved circuitry, thereby producing an extremely sensitive instrument in which the mirror temperature oscillations above and below dew point are almost zero, the mirror condensate being in thermodynamic equilibrium with the surrounding water vapour. The lag, or time taken to change from one steady-state value to another, is stated to be 3 seconds for dew point increases, and 6 seconds for dew point decreases.

The instrument may be used directly in the field or in a shelter, air being drawn in to it from outside through plastic tubing. Screening is entirely dispensed with - a considerable advantage. It would appear to be a very good instrument for microclimatic humidity measurements, its only drawback being the necessity to provide a cold bath of CO₂ 'snow' and alcohol, Freon, or other refrigerant. Since microclimatic or agrometeorological work is usually done under conditions of relatively high temperature (i.e., above the freezing point of water), the provision of coolant for the mirror should not in general be a limiting factor in the use of this instrument. Melting ice, for example, contained in a Dewar flask would suffice for most field uses.

A further instrument of this type 'observes' the dew formation on the metallized surface of a piezo-electrically oscillating quartz crystal (109). The crystal is cut in such a way that its oscillation frequency is independent of temperature and is cooled by a coolant exactly as in the instrument described by Barrett and Herndon (108). The formation of dew on the crystal surface decreases the amplitude of its oscillation: this effect 'triggers' the heating (by eddy currents) which dissipates the layer of dew. Thus the crystal surface is maintained at dew-point temperature which can be measured thermo-electrically or otherwise. The paper quoted shows how quartz crystals can also be used to measure temperature and pressure. The electronic arrangements of this instrument are rather involved, and its maintenance might demand servicing facilities beyond the scope of the ordinary meteorological laboratory: the accuracy claimed for it is not adequate for micrometeorological work, i.e., + 3°C so the instrument hardly comes in question at the present time as a tool for this type of work. However, bearing in mind the extraordinary advances made in electronics in recent years, and the potentialities for further development of electronic devices, we might consider the idea behind this instrument as well worth bearing in mind.

2.7 Infra-red absorption

It is well known that water vapour absorbs infra-red light in a number of sharply defined absorption bands. If, therefore, one of these wavelengths can be isolated in a beam the intensity of the beam at a point away from its source will depend strongly on the water vapour content of the air it has passed through. A differential method using two beams of light, one in an absorption band, the other of wave-length close to but outside the absorption band, was proposed by Fowie (110). The method eliminates the disturbing effect of smoke, haze, etc., by affecting both beams similarly whereas changing
water vapour content in the air traversed affects only the absorbing wavelength. A complete description of a recent instrument based on this method, using band-pass filters to isolate the 1.37 μ (absorption) band and the 1.24 μ wavelength, and a lead sulphide photo-conductive cell to measure the intensity, is available (111). The length of path traversed by the infra-red light is one metre. The instrument is too cumbersome, expensive and complicated to be applicable to micrometeorology in growing plants or generally in the field, but its accuracy, speed of response and facility for registering at a distance might recommend it for laboratory use.

2.8 Conclusions

This review of the instruments available for the measurement of humidity in the biosphere may be considered as outlining the wide choice open to any investigator. While it cannot be claimed that the determination of humidity has been completely mastered, it will be agreed that instrumentalists have provided an impressive range of equipment for attacking this measurement. The selection of a particular type of instrument cannot be made without a consideration of the requirements of the particular investigation in mind; it must be made by the individual concerned and will always constitute a compromise between contending factors such as accuracy, cost, etc.

An intending investigator should seek answers to questions of the following kind before attempting to select a particular type of instrument:

(a) Over what period of time is a mean value of the humidity required?
(b) What degree of accuracy is required in the measurement?
(c) Is absolute accuracy necessary or will strictly comparable readings from a number of instruments suffice?
(d) What will be the period of exposure of the instruments?
(e) Is forced ventilation permissible?
(f) Is a power supply likely to be available?
(g) Is recording necessary, or will spot readings serve and if so how frequently should they be taken?

Mercury-in-glass or mercury-in-steel psychrometers still occupy an important place by virtue of their cheapness and ruggedness; several examples of their use have been mentioned above; the mercury-in-steel type will record automatically and is the cheapest and most easily maintained of all recording instruments.

For flexibility in use, combined with great speed where required, sensitivity and small interference with the environment, the thermo-electric psychrometer is unsurpassed; if constructed of sufficiently stout wires, it also proves quite robust, though sacrificing some of its speed. Where necessary the observations can be recorded with comparative ease, though the equipment for this may be expensive and delicate.
Resistance psychrometers in their latest types are strongly recommended. In the special form of thermistors they provide an instrument almost the equal of the thermocouple from any point of view, particularly where long exposure is likely and extreme accuracy in the humidity measurements is not required. Resistance thermometers have one definite advantage - they do not require a standard reference temperature.

The photo-electric dew-point meter appears to be one of the most accurate instruments at present available, especially in the version of Barrett and Herndon (108). It possesses the advantage of not interfering with its environment, and it will readily record its observations. As it is expensive and requires skilled maintenance, it will not represent a possible choice for most workers; further, since it only measures dew point, a thermometer of some sort will almost invariably be required to work in conjunction with it and the speed and accuracy of the dew-point meter demands a thermo-electric or thermistor measurement of temperature to match it, so that the user will usually find himself committed to need to use a sensitive thermometer as well. For these reasons, the dew-point meter will not readily find a place in field work, but for very accurate laboratory measurements it should prove of great use.

Among the electro-chemical instruments, there are several which operate with a film of material of moisture-conditioned electrical resistance. Those using lithium chloride have been found unsuitable as they lack durability and suffer from exposure to high humidities; the version using carbon black would appear to offer potentialities of development as it does not suffer from this drawback and also has a small hysteresis effect, a considerable advantage over other models. The Dewcel is also satisfactory as far as hysteresis is concerned but may be found wanting for speed and sensitivity. The Verzar instrument appears to meet all the requirements of micrometeorological measurements; but all of these electro-chemical instruments will require extensive testing under actual field conditions before an unqualified recommendation can be given.

The more elaborate instruments mentioned above, i.e. the infra-red absorption-hygrometer and the quartz crystal hygrometer would also seem to require much development and testing and, if possible, simplification, before they can be taken into use for routine micrometeorological measurements. In view of the great success achieved by electronic and optical measuring techniques, it is to be hoped that further study and development on these and similar devices will be continued, as their perfection would go far to solve the problems set by the measurement of humidity in the biosphere.
3.1 Introduction

The accurate quantitative measurement of soil moisture has been a major instrumental problem in agriculture, hydrology and meteorology for many years. Considerable effort and ingenuity have been devoted to this requirement but, as will become apparent, it cannot be claimed that anything like unqualified success has been achieved to date. This report attempts to set out very briefly the various methods that are in use, both recording and non-recording together with some discussion of their relative merits.

At the start it must be emphasized that each instrument or method measures one of two quite distinct quantities. These quantities are:

(a) The moisture content of the soil, usually expressed on a volume or dry weight basis; or

(b) The soil moisture tension, usually expressed in centimetres of water or millimetres of mercury.

The first of these is that which is normally of interest in meteorological problems, since the heat capacity of the soil is greatly influenced by its water content. It increased several times between 'dry' condition and the 'wet' condition (36) and the contribution of soil heat to the energy balance at the surface consequent upon changes in soil temperature will depend largely on the moisture condition. In hydrological problems also we wish to know the change in the water content of the soil over a defined period and again the first of the two quantities will be required. On the other hand agriculturists will be interested in the second quantity since it is this which determines the ease with which water is available to plants. A clay soil with a water content of 25 per cent might have less water available for plant use than a sandy soil with less than half this water content. Unfortunately there is no unique relationship between the moisture content and moisture tension in any soil, so that a determination of one will not permit the accurate specification of the other. In a moisture content-tension diagram the relation is presented by points which lie within or on a hysteresis loop, obtained by measuring the relation on a sample which is passed through a drying and rewetting cycle. The moisture content at a given tension is higher on the drying branch of the loop than on the wetting branch. It is hoped that this introduction will serve to show that it is of the utmost importance to understand which of the above two quantities is measured by any instrument.

A feature of all in situ methods which must be continually borne in mind is that their usefulness is limited by the fact that the moisture condition shown is appropriate to that of the soil in the immediate vicinity of the
measuring unit, and the figure obtained can be unrepresentative of the general condition of the soil under test. The likelihood of an unrepresentative result being obtained increases as the nature of the soil becomes more unhomogeneous. For example, a soil which contains a lot of stones will not readily lend itself to moisture determinations and further the moisture content in the vicinity of plant roots will probably differ markedly from that in soil some little way away.

3.2 Gravimetric methods

3.2.1 Oven_drying of soil samples

This is the most simple method available and it has the attraction that the answer, once it has been obtained, is completely unambiguous. It consists of extracting volume samples of the soil and determining their moisture contents by weighing before and after drying, usually at a temperature in the region of 105°C. The main difficulty lies in extracting the samples in an undisturbed state, and its application to a large number of samples (often necessary to get representative results) over a period of time is laborious and expensive. The method is always regarded as a standard for checking others. Obviously it cannot be made recording and it is not suitable for work on relatively small blocks of soil, e.g. in lysimeters.

3.2.2 The porous_block_method

In this method a porous block is brought into contact with the soil and its moisture content is determined by oven drying after moisture equilibrium is reached (113). Sometimes only part of the block is removed for weighing, this part being in the form of a plug which fits smoothly into the remainder of the block. Here moisture tension is measured, since this quantity controls the moisture equilibrium between the soil and the block, which constitutes a second porous medium. A deduction of moisture content from the results is hampered by the hysteresis effects in both the soil and the porous block and the method does not lend itself to recording.

3.3 The tensiometer method

The tensiometer provides a continuous indication of soil moisture tension directly (18, 19, 2C, 114). It consists of a porous cup filled with water which is buried in the soil at the point of interest. The cup, usually made of a ceramic or sintered glass, is attached to a pressure gauge such as a mercury manometer. The water in the cup is absorbed by the soil through the cup pores until the pressure deficiency in the instrument is equal to the suction pressure exerted by the soil. In practice tensiometers will measure changes in soil moisture tension up to suction values of pF 3* or 1

* The common logarithm of the soil moisture suction expressed in centimetres of water is equivalent to the pF value of the suction (116). This is analogous to the commonly used pH scale, the p indicating the use of logarithms and the F being a measure of the free energy of the water.
atmosphere. As vapour bubbles form when the absolute pressure in the water falls below the saturation vapour pressure* it cannot be used at higher tensions although theoretically water will withstand such tensions. The admission of air through joints in the apparatus can often be troublesome, and the readings are subject to variation with changes in ambient temperature (115). The tensiometer can be made to record comparatively easily but hysteresis effects are large in the tension range covered by the instrument, and this severely restricts its suitability for measuring moisture content.

3.4 Methods depending on the resistance of soil to mechanical force

These methods depend on the fact that the soil becomes more plastic as the moisture content increases. Two instruments falling into this category are the stabilimeter and the availameter (117). The former consists of a probe which is driven into the soil. The point of the probe is made of two steel plates set at right angles to one another and in use the operator, having driven the point to the required depth, fits a handle calibrated to measure torque to the shaft and then exerts enough force to just overcome the resistance of the soil to the rotation of the shaft and point. The torque applied can be interpreted in terms of the moisture content by means of prior calibration. The availameter consists of two pistons in a connecting cylinder to which is attached a pressure gauge. Two small diameter projections are attached to one of the pistons and the soil sample, after extraction by means of a special instrument, is fitted into the cylinder. The resistance in pounds offered by the soil to penetration by the standard sized projections to a depth of 0.2 inch is measured by the instrument, and by previous calibration this result can be interpreted in terms of soil moisture content. Neither of these methods may be made recording and they are apparently only suitable for use with heavy soils. They do not appear to offer a solution to our requirements.

3.5 Electrical methods

3.5.1 Dielectric methods

The capacitance of a block of soil, or a second porous material in moisture equilibrium with the soil, will provide a measure of soil moisture (9, 10, 11, 118). Changing electrolyte concentrations are troublesome and Childs (119) has raised some objections to the method which have not been answered. As far as the group is aware this method has not led to reliable results.

3.5.2 Resistance methods

The electrical resistance of a block of soil or of a porous material in moisture equilibrium with the soil can provide a measure of soil moisture.

* It must be remembered that the zero point on the tension scale is one atmosphere, as no suction is required to extract water having a pressure of one atmosphere from a saturated soil. At a suction value of, e.g. 0.3 atmospheres the absolute value of the pressure is 0.7 atmospheres.
In the earliest attempts to employ this principle, two electrodes were inserted into the soil but the results were generally unreliable on account of the variation in contact resistance between the electrodes and the soil. Attempts were made to overcome this difficulty by the use of four electrodes, but this has only been partially successful (120). According to Eastwell (121), this paper contains an extensive bibliography on the subject under discussion here) field trials of the latest four-electrode method of Kirkham and Taylor (122) have shown errors of ± 20 per cent of the correct moisture content. The method now appears to be regarded as outdated by the use of absorbent blocks, introduced by Bouyoucos and Nick in 1940 (123). These blocks are made of such materials as plaster of Paris, nylon and fibre glass (13, 124). The present state of development is given in (12). The electrodes are fixed in the block and the contact resistance remains constant, and once the block has been placed in the soil and has reached moisture equilibrium it follows further changes in the tension with a small time lag which is generally not a practical disadvantage. The electrical resistance in the block changes with temperature as well as with moisture content. The resistance must be measured with an A.C. bridge (usually 1000 cycles/second) since with direct current electrolysis and polarization occur. Gypsum has the advantage of a comparatively high ion concentration in the block, due to the ionization of the calcium sulphate, which makes the resistance to a large degree independent of the electrolyte concentration in the soil itself, but it has the disadvantage that it deteriorates on prolonged exposure as a consequence of its solubility. A nylon unit does not possess either this advantage or disadvantage, and it is superior to a gypsum block in that its resistance varies more rapidly with moisture content at the wet end of the moisture range. These blocks provide a measure of moisture tension and their most useful range of application lies above 1000 cm of water for gypsum blocks and above 100 cm of water for nylon blocks. The suitability for measuring moisture content is restricted by hysteresis effects and by the fact that calibration depends on the density of the soil and its temperature. The suitability of such blocks for obtaining quantitative results for application in water balance studies is doubtful, although there appears to be a wide divergence of opinion on this point (see 1,2,3). The method could be made recording without much difficulty.

3.6 Thermal methods

3.6.1 Thermal conductivity methods

The thermal conductivity of soil increases with its moisture content, and if the former is measured the latter may be obtained provided the relationship has been previously established in the laboratory (125). The relationship depends on soil density as well as moisture content and to a small degree on temperature as well. Soil density is difficult to assess in situ and the suitability of the method is therefore restricted to applications where this is known, e.g. in lysimeters. Two experimental arrangements have been used. In the first (126), a constant flow of heat is supplied to a copper wire wound on a glass tube which is buried in the ground. An estimate of the moisture content can be obtained from the final resistance of the wire
when the heat input balances the loss due to conduction in the soil. In the second (17), a known heat input is supplied to a body buried in the soil, e.g., a fine needle, and the rise in temperature near the heat source is measured with a thermocouple. The thermal conductivity is then derived from the temperature-time curve. The results obtained are invalid if good thermal contact is not obtained between the heat source and the soil and the application is therefore restricted to non-shrinking soils. The accuracy is low at the saturated end of the moisture range, but fairly high in the region between wilting point* and field capacity**. The moisture content of a rather small volume of soil close to the probe is measured. The method has no time lag as have those which rely on the establishment of moisture equilibrium between the soil and another medium. A recording apparatus has been described (125) and quantitative results were obtained in a Popoff cylinder which have been checked by weighing.

3.6.2 Heat capacity method

Albrecht (127) has suggested that it might be possible to determine simultaneously the thermal conductivity, \( \lambda \), and the thermal diffusivity, \( k \), by a method similar (128) to that described under 3.6.1 above. The heat capacity per unit volume, \( c \), can then be found from \( \rho c = \lambda / k \). As the heat capacity per unit volume is a linear function of the moisture content per unit volume, changes in this are directly proportional to changes in the moisture content as long as the dry density of the soil remains constant. As the diffusivity shows only a small variation over a wide range of moisture contents, a very high degree of accuracy would be required in the measurement of this quantity. So far no results of quantitative significance have been obtained as far as we are aware.

3.7 The neutron scattering method

The method is based on the scattering and slowing down of fast neutrons from a radioactive source, e.g. Po-Be, by hydrogen nuclei present in the soil. The scattered neutrons are detected close to the source by a slow neutron counter. The validity of the method is a consequence of the facts that (129, 21) (a) of all elements hydrogen is by far the most effective in slowing down fast neutrons and (b) most of the hydrogen nuclei present in soils are found in water molecules (with the exception of peat soils, which present a special

* It is supposed that plant roots cannot extract moisture from the soil when the water is held at a suction pressure greater than 16 atmospheres, and the moisture content at this suction is known as the wilting point.

** Field capacity has been defined as 'the amount of water held in the soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased'. At moisture contents below the field capacity the movement of moisture in the liquid phase is so slow that observable changes in the moisture content take a very long time.
problem). In this method the moisture content in a certain volume of soil, explored by the neutrons, is measured. The size of this volume is dependent on the moisture content of the soil, which is a disadvantage of the method. In some of the early experiments published (130), the volume is reported to be a sphere of approximately 12 inches diameter for high moisture content and 30 inches for low. These figures are only quoted to give some idea of the dimensions involved.

The source and counter are lowered into the soil through a hole and readings can be taken at any depth, but not too close to the surface. The calibration is to a large extent independent of the type or density of the soil (again excluding peat soils). A stainless steel or aluminium tube can be inserted in the hole without affecting the results. The method will lend itself to recording.

3.8 Conclusions

The problem of finding an accurate recording or non-recording quantitative method to measure soil moisture is unsolved and the development of a suitable apparatus looks remote at present.

The applicability of all existing methods is limited in one or more ways. The degree of accuracy obtainable in quantitative measurements of soil moisture content is insufficient for purposes of water and energy balance investigations.

The method employing electrical resistance blocks is in wide-spread use for a qualitative or semi-quantitative measurement of moisture tension and moisture content. The method is easy to apply and is inexpensive.

For tensions lower than about 500 cm of water the use of tensiometers for measuring moisture tension is to be preferred.

The thermal conductivity method can give results of quantitative significance for measuring the moisture content of non-shrinking soils of constant dry density. However, the method is laborious and requires skilled attention.

The neutron scattering method gives results of quantitative significance in the measurement of moisture content of a comparatively large volume of soil (linear dimensions of the order of 50 cm). It is easier to apply than the thermal conductivity method but it still requires rather complicated and expensive apparatus.

In accurate quantitative work, particularly where it is necessary to obtain a detailed soil moisture profile, there appears to be no substitute for the laborious task of oven drying numerous samples.
BIBLIOGRAPHY

This bibliography makes no claim to being complete in any way. The papers on the subjects dealt with in this report must be numbered in hundreds, and a selection has been made to illustrate the main lines of work and thought in the particular fields.


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5.1 W. Friedrich

Section 1, paragraph 1-2-3

The real evapotranspiration of a basin is a part of the water budget:

$$ P = R + E \Delta S $$

In this equation, $P$ represents the precipitation, $R$ the whole run-off, $E$ the real evapotranspiration, and $\Delta S$ the change in the water storage. Experience has shown that it is generally not possible to determine the water storage of a basin and its changes in an accurate manner. Only in those cases where the water storage is the same at the beginning and end of the period may the basin evapotranspiration be found by means of the water budget. If the water budget is established for a fairly long period of years, for which $\Delta S$ may be disregarded as against $R$ and $E$, the average annual evapotranspiration of a basin may be found as the difference between the corresponding averages of precipitation and run-off. In accordance with this procedure, frequently referred to as the 'hydrological method', the area evapotranspiration of a large number of basins of different sizes and in all kinds of climate has been ascertained. There should be no doubt about the fact that the average annual evapotranspiration, ascertained in this way, is the only reliable fact that is known about the numerical value of evapotranspiration.

Reference


5.2 J. Neumann

Section 1, paragraph 1-5-3

In our experiments at Lydda Airport, I find that, in the case of an irrigated crop, the transfer of sensible heat from the air may become an important factor which is not negligible in comparison with solar radiation. In the course of the growing cycle, on the whole, this transfer of sensible heat is from the air to the soil and vegetation rather than in the reverse direction (as assumed by some investigators).

As to pan evaporation as an approximate index of evapotranspiration, I would like to recall the results of our experiments which indicated that in the early stages of crop development pan evaporation rates were, indeed, close to evapotranspiration rates from the crop (alfalfa), but that when the crop reached its maximum development, the evapotranspiration rates from it
were nearly twice as great as the evaporation rates from the pan. In these experiments, the level of water in the pan was kept practically constant by the daily addition of water. Also, the pan was at some distance (c. 25 m) from the edge of the cropped area so that the evaporation from the pan could hardly have been retarded by the growing crop cover.

I have, of course, noted the statement in the report '... the rate of evapotranspiration appears to be influenced, etc.' but I feel that a stronger statement would be appropriate. This would be all the more desirable as much of the literature on methods of computing potential evapotranspiration is based on incorrect assumptions.

5.3 **S.P. Venkiteshwaran**

Section 1, appendix

(a) **Wire netting cover for the tank**

Birds and animals have a free access to the evaporimeter tank and they vitiate the exposure of water. This is particularly so in the tropical latitudes and arid or semi-arid regions. Though the tank may be protected from the animals with a suitable wire fence, it will be difficult to keep away birds. A suitable wire netting cover will be extremely useful. It seems to me that the working group may recommend a standard wire mesh cover. It may be possible to correlate evaporation from such a covered tank to that without any cover. The experiments at the Central Agricultural Meteorological Observatory at Poona have shown that when a G.I. wire mesh (22 s.w.g., hexagonal mesh 1½ inch between opposite sides) is used, the evaporation measured in this tank has to be multiplied by a factor 1.144 to obtain the evaporation in a standard tank without any cover. If this caution about animals and birds is not given, a lot of unreliable data may be collected.

(b) **Colour of tank**

The colour of the tank has an appreciable effect on the absorption of radiation on the sides of the tank. It is suggested that white paint be recommended for the outside of the tank only and the wooden support. The evaporation from an unpainted or black painted tank is approximately 10 to 15 percent more than that from a white painted tank.

**Section 3, paragraph 3.61**

A.U. Momin of the Central Agricultural Meteorological Observatory at Poona has devised a simple technique for measuring soil moisture. The instrument makes use of an ordinary soil thermometer. On half of the bulb of such a thermometer is wound an enamelled or silk covered constantan wire heating element. This heating element is electrically and to some extent thermally insulated from the soil by covering it with some insulating material. A 6 volt strong battery or a large capacity dry cell is used for supplying the heating current. The thermometer is buried in the soil with the bulb at the desired depth. The measurement is made by passing a fixed current through the heating
element and recording the time required for a 5° rise in temperature of the thermometer. The time is recorded in seconds with a stop watch. When the current is switched on, one half of the bulb is gaining heat at a rate depending on the current and resistance of the heating element, while the bare half of the bulb which is in good thermal contact with the soil is dissipating heat at a rate depending on the thermal conductivity of the soil. The combined effect of these two simultaneous processes is reflected in the rate of rise of the temperature of the thermometer. Thus, if the current is kept constant, it is possible to study the change in thermal conductivity of soil by observing the rate of rise of temperature of the thermometer. It was found that the time required to raise the temperature by 5° was very much larger when the soil was wet than when it was dry. A very high correlation was found to exist between the readings of this instrument and values of soil moisture as determined by the conventional method. Once a calibration curve for the above arrangement is drawn, it is only necessary to take a time reading of the instrument and the value of soil moisture can be immediately read off from the calibration curve.

Reference


5.4 D.A. de Vries

Section 1, paragraph 14

Substantial progress has recently been made by the CSIRO Division of Meteorological Physics in improving the method published by Swinbank (49) for measuring evaporation from natural surfaces. An automatic apparatus built on this principle was on display last month at the Exhibition of Scientific Instruments of the Institute of Physics held at Melbourne. Although this instrument is still delicate and complex it holds promise for enabling routine measurements of evaporation from natural surfaces to be made.

Section 1, paragraph 153

I object to the statement that 'pan evaporation is an approximate index to evapotranspiration'. This holds only for humid conditions and I think that it would be better (although rather trivial) to substitute potential evapotranspiration for evapotranspiration. Recent theoretical work on evaporation from bare soil has shown that when water is limiting there might even exist a negative correlation between solar radiation and actual evaporation.

Section 1, paragraph 16

An atmometer gives a measure of the evaporation from a wet surface (having the radiation characteristics of the particular surface employed) for the type of exposure given to this surface. It should be used as such. The evaporation from the atmometer can be calculated quantitatively from radiation, temperature, humidity and wind speed. This was demonstrated for the Piche evapori-
meter by de Vries and Venema. I have not seen the paper by Robertson (60) but I can see no necessity for nor special advantage in screening the atmometer.

Section 2, paragraph 2.2.5
According to my experience thermistors show a drift in calibration.

Section 2, paragraph 2.3
In this country one has a high opinion of the instrument developed by Mylie. It is now used as a standard at the National Standards Laboratory, Sydney. I have no personal experience with the method.

Section 3, paragraph 3.2
Combined gravimetric and 'chemical' methods

In these methods a soil sample is taken and weighed as before but the moisture content is not determined by oven drying. Instead it is obtained by boiling the sample with a second fluid (e.g. xylol or a non-volatile oil (78)) and measuring the distillate or by mixing the sample with calcium carbide and measuring the pressure of the developed acetylene.

Section 3, paragraph 3.7

Measurements near the surface cannot be made, since part of the neutrons are lost to the air. Attempts to extend the range to smaller depths by reflecting neutrons with a paraffin cover on the soil surface have not yet been successful. This restricts the applicability of the method for water balance investigations, as important changes in moisture storage usually occur in the upper 20 to 30 cm of soil.

References