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Report on
Measurement of Temperatures
Near the Surface

by

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This report by Dr. D.R. Davis (USA), CAgM-VI Rapporteur on Application of Minimum Temperatures Near the Surface, was recommended by the President for circulation to members of CAgM. A copy of the report is therefore attached for information*. It should be noted that this report is not to be considered as an official publication of WMO.

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Measurement of Temperatures Near the Surface

S. E. Taylor and D. R. Davis[1]

1. Introduction

In a report to the President, Commission for Agricultural Meteorology, Davis, (1976), the WMO Rapporteur on Applications of Minimum Temperatures Near the Surface, noted that temperatures near the surface are not extensively measured for a number of reasons. The reasons he enumerated included:

(1) Most readily available instruments, normally used for weather shelter measurements, are not suitable for measurements near the surface.

(2) Shelters modify the microclimate near the surface making the use of shelters near the surface impractical.

(3) Aspirated sensors cannot be used near the surface to successfully measure temperature at one level.

(4) Exposed liquid-in-glass or liquid-in-metal sensors that are unsheltered or unshielded are subject to liquid separation or breakage on high insolation days.

(5) Finally, unshelterd and non-aspirated sensors register temperatures somewhere between the true air temperature at the level exposed and the radiation temperature of the back-ground environment.

There are many applications in agriculture for near-surface temperature data (Davis, 1976). A better understanding of the problems involved in making these measurements and some definitive recommendations on instruments, exposure, etc., is needed. The purpose of this report is to review

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instrumentation, examine the problems involved in near surface measurements and to suggest thermal sensors for the measurements. Recommendations on exposure are also included.

2. Problems of measuring temperatures near the surface

Many of the problems involved in accurately measuring air temperatures near the surface are inherent in the physical properties of thermal sensors. The term thermometer will be used to include thermal sensors of all types throughout this report. A thermometer designed to measure air temperature is affected by physical factors other than air temperature. It is crucial that a thermometer for measurements near the surface be designed so that it is much more sensitive to air temperature than to other sources and sinks of energy in the environment.

"The principal cause of error in the measurement of the temperature of any substance is the lack of similarity in the physical properties of the sensor and the substance being investigated" (Schwerdtfeger 1976 p 2). The primary sources of error in the measurement of the atmosphere's temperature are the thermometer's responses to the radiation of the background environment, convection, conduction, and the emissive characteristics of the sensor. It is necessary to understand the nature of energy exchange at the thermometer if one wishes to know the sources and magnitude of errors in temperature measurement.

2.1 Energy Exchange at a grass level thermometer

The response of a thermometer to the environment can be described by energy balance notation as:

$$0 = Hcv + Hcd + Re + Rae + Rai + Rbe + Rs + Rrt \qquad (1)$$

where Hcv is the convective heat transfer, Hcd is conduction, Re is the radiation loss of the thermometer to the environment, Rae is the long wave thermal radiation received from the environment from above the thermometer.

Rai is radiation received from other instruments or instrument parts and will usually be included in Rae or Rbe. Rbe is radiation from the environment below, Rs is solar radiation and Rrt is any other radiation factor such as radiofrequency emissions. If the thermometer is wet, there is also an evaporation term, E, that must be included in the energy balance expression. The role of the meteorological parameters together with those of the thermometer as they affect the observed temperatures can be assessed by examination of each element of equation (1).

2.1.1 Convection

The transfer of heat between the atmosphere and the thermometer is expressed by the convection term, Hcv, of equation (1). From a physical standpoint both convection and conduction are involved in this process. However, for the purpose intended herein, conduction refers only to conduction from the sensor to other solid objects or to other portions of the thermometer in solid or liquid contact with the sensor.

A change in air temperature will cause a change in the indicated temperature on the thermometer within a finite time. The time required for the thermometer to indicate the modified air temperature is controlled by the thermometer's heat capacity, and the exchange of energy with the free air through the boundary layer of unstirred air at the thermometer surface. A detailed analysis of thermometer time lag and resulting intergration of air temperature is given by Middleton and Spilhaus (1953).

The thickness of the boundary layer affects both the time required for the thermometer to indicate a changed temperature and, when radiant or latent sources or sinks of energy are significant, the actual temperature that the thermometer indicates. A thermometer in direct sunlight may be heated above the temperature of the air; however, if the boundary layer is very thin, heating will be less an error than when a thick boundary layer is present. The same principle applies to a thermometer which radiatively cools below the temperature of the air: the instrument with a thin boundary layer will exhibit a temperature very near that of the air.

The thickness of the boundary layer is dependent on air speed and on the characteristic dimension of the thermometer. This relationship is commonly expressed as the Reynolds relationship or "Reynolds Number":

$$R \ = VD/v \qquad (2)$$

where Re is the Reynolds Number, V is the air speed, D is the characteristic dimension and v is the kinematic viscosity of the air (often assumed 0.15 cm^2/sec).

The Reynolds Number gives an indication of whether the airflow is turbulent or laminar. Laminar flow generally exists where Re is less than 10^5 and turbulent at larger values. The exact value is affected by the shape and smoothness of the surface. It is not within the scope of this paper to review in depth the physics of convective processes and the reader is referred to general meteorological and biometeorological texts for complete discussion of equation development. For most thermometers, the convective transport at the thermometer is laminar and the thermometer itself is in an area of turbulent transfer especially if placed near the ground.

The characteristic dimension is the diameter of the thermometer, if cylindrically shaped, or the width of a flat surface measured in the direction of air flow. The term "characteristic" is needed to denote that the dimension used in the mathematical expression may not be the actual width or diameter as the direct measurement is only appropriate for smooth cylinders and flat smooth rectangular plates. Irregular shaped, rough, or variously curved surfaces have a characteristic dimension which is the dimension that a hypothetical, cylindrical, smooth surface must have to yield the same Reynolds number as the irregular object.

The rate of convective heat transfer to or from the thermometer is dependent upon the characteristic dimension of the thermometer, the air movement and the difference between air temperature and the actual temperature of the thermometer. The primary convective factors can be expressed as

$$Hcv = k\ (Ta-T)\quad (V/D)^{1/2} \tag{3}$$

for plate type thermometers and as

$$Hcv = k\ (Ta-T)\quad (V^{1/3}D^{-2/3}) \tag{3a}$$

for cylindrical thermometers where k is a proportionality coefficient for convective heat exchange taken to be, 6.17×10^{-3} (Gates, 1962). Ta is the air temperature, T is the temperature of the thermometer, V is the air speed (cms^{-1}) and D is the characteristic dimension of the thermometer (cm).

The convective transfer of heat becomes much larger as the size (D) of the thermometer decreases. Accordingly, a very thin thermometer will be very close to the temperature of the air. Increased air flow over the thermometer increases the convective transport and brings the thermometer to a temperature near that of the air assuming that the air flow is not great enough to cause significant direct frictional heating and compressive errors. A friction and compression term need seldom if ever, be considered as contributing significantly to errors in temperature measurements near the surface. Tanner (1963 p A-2) discussed ventilation velocity errors.

He stated:

> ".......as a rough rule-of-thumb ventilation
>
> at 100 m/sec. will develop about 1°C error."

Additional information regarding the frictional and compression error due to ventilation velocity is found in Middleton and Spilhaus (1953). When friction and compression is considered, it is included as an additional term of equation (1).

Artificial convection, or ventilation, is not practical for observations near the surface or for grass minimum thermometers since the draft may destroy the effect under observation. Schwerdtfeger (1976) suggests a thermometer of small dimension be used near the ground or near plants. The sensor of smallest dimension will be closest to air temperature. A long thin wire sensor approaches the ideal limit. However, the rapid response to transient temperatures is often a disadvantage when using small wire sensors.

2.1.2 Conduction

Conduction is the process by which heat is directly gained or lost by the thermometer through contact with other materials. Conduction as treated here does not include heat transfer through the unstirred air layer at the thermometer. Conduction to solid objects can be expressed as

$$Hcd = (2K' B/x)\ (Ts - T) \qquad (4)$$

Where K' is the thermal conductivity of the object in contact with the sensor (such as sensor lead wires in the case of electrical thermometers), B is the cross-sectional area of the object, x is its length, Ts is the temperature of the object and T is the temperature of the sensor.

Conduction can become a very significant consideration in the measurement of temperatures near the surface. The soil is a large heat reservoir that can supply considerable amounts of heat to the thermometer or conduct significant amounts of heat away. The low-level thermometer must be mounted such that contact with the soil heat reservoir is minimized. Contact between the soil and the thermometer can be minimized by lengthening the thermometer supports and by using small supports which have little heat capacity and are poor heat conductors.

2.1.3 Radiation

The thermometer immersed in air is in a radiation environment and although intended to measure only the temperature of the air there is always some affect of the radiating environment on the indicated temperature. The affects of the radiant environment can, however, be minimized by thermometer design, shielding, placement, and mounting of the thermometer. The thermometer is affected primarily by solar and thermal radiation, with other forms of electromagnetic radiation (Rrt) only rarely being significant. It must be noted, however, that thermometers at telemetering stations may be affected by radio-frequency emissions from telemetering transmitters. High precision electrical thermometers may be affected by emission from local radio stations.

a. Radiative Heating

The long wave thermal radiation received from the environment above the thermometer can be described by

$$Rae = \sigma \varepsilon T_{ae}^{4} \qquad (5)$$

where T_{ae} is the apparent radiation temperature of the background environment σ is the Stefan-Boltzmann constant and ε is the thermal emissivity of the thermometer. The emissivity of the background itself need not be defined since the measured apparent radiation temperature is a function of both the background temperature and its emissivity.

The amount of heat actually delivered to a thermometer from the areal environment depends both on the factors of equation (5) and on the total surface area of the thermometer.

The thermal radiation from beneath the thermometer is normally much greater than that from above. When the upper side is exposed to the sky the energy received will be very low unless clouds dominate the global environment. The lower half of the thermometer is always exposed to the comparatively warm terrestrial surface. The terrestrial radiation can account for considerable heating of the thermometer above the temperature of the air.

The longwave radiation absorbed by the lower half of the thermometer is calculated in the same manner as for the up-looking parts (eq 5) as follows:

$$Rbe = \sigma \varepsilon T_{be}^{4} \tag{6}$$

where T_{be} is apparent temperature of the environment below the thermometer. When the actual terrestrial surface temperature is known the equation is expressed as

$$Rbe = \sigma \varepsilon_b \varepsilon T_b^{4} \tag{7}$$

where ε_b is the emissivity of the emitting objects below the thermometer and T_b represents an actual temperature rather than an apparent radiation temperature as in (6). Equation 7 assumes that multiple reflection of radiation is not significant.

A thermometer at the surface is subject to direct solar heating during daylight hours. Direct solar heating is not a problem in the measurement of overnight minimum temperatures but is very important in the measurement of maximum temperatures. The effects of solar radiation on minimum temperature observations are secondary, resulting primarily from the diurnal heating of objects at the ground level. Effects on daytime measurements are primarily a result of direct heating at the thermometer. The daytime solar effects may be expressed as:

$$R_S = aI \tag{8}$$

where a is the absorptivity of the thermometer surface to solar radiation and I is the solar radiation incident on the thermometer. The value of "I" depends on the condition of the atmosphere (cloudy, clear, turbid, etc) and the incidence angle of the direct solar beam.

A more detailed treatment would divide the scattered radiation from the direct beam and consider the spectral composition of the radiation. There would be a value a' given for the absorptivity of the thermometer to each individual spectral component of the radiation (see Gates, 1962).

b. Radiative Cooling

The thermometer emits heat to the environment according to the fourth power of its absolute temperature. The actual amount of heat radiated depends on both the temperature of the thermometer surface and its radiative characteristic (thermal emissivity). A surface with a low emissivity will lose little heat by radiation and accordingly will seldom fall significantly below air temperature. Surfaces which have high thermal emissivity will lose heat readily and thereby attain an equilibrium temperature below the air temperature, especially when clear, calm, nighttime conditions prevail. The depressed temperature effect can be reduced in the case of a highly emissive surface by shielding, ventilation, or by decreasing thermometer size. The principle is illustrated by the equation for the heat radiated from the thermometer surface:

$$Re = A\sigma\varepsilon \quad T^4 \tag{9}$$

where A is the surface area of the thermometer (this term is dropped when calculations are made per unit area), and T is the temperature of the thermometer surface.

The heat lost by radiation is in some measure counterbalanced by heat gain from radiating objects in the background including the soil or vegetative surface and other objects including gases in the hemisphere above the thermometer.

c. Terrestrial radiation balance

The terrestrial surface temperature at night normally does not differ greatly from the air temperature within a few centimeters of the surface. Because the net radiation exchange between the thermometer and the surface is very low, the indicated temperature is little influenced by radiation exchange between the ground and the thermometer.

The atmospheric layer above the thermometer is quite transparent to thermal radiation from objects at terrestrial temperatures. When the atmosphere is clear of clouds, dust, and other particulates, a considerable amount of terrestrial radiation passes through the atmosphere to the void of space. Under clear air conditions very little energy is radiated toward the earth's surface from the atmospheric layer above. Therefore, the upper half of a thermometer or any other terrestrial object which is exposed to the low radiation of the cold cosmic environment is only slightly modified by the intervening air layer. The atmosphere, when clear, has a black body equivalent temperature of 0 degrees Celcius or less and although the radiation from a body at this temperature is significantly greater than zero it is generally low when compared to the terrestrial radiation available to down looking surfaces.

Radiation from objects exposed to the relatively cold sky can result in a significant lowering of temperature especially where air movement and other sources of energy to the thermometer are minimal. The undesirable effects of radiation cooling can be somewhat overcome by use of a thermometer with low emissivity upper surface. The low emissivity insures that little radiation is emitted and thereby cooling is minimized. Vegetation, however, does not have low emissivity.

The agricultural use of grass thermometers is intended to measure the environment at crop level more meaningfully than is done with the standard screen configuration. A strong argument can be presented for a thermometer with energy exchange characteristics similar to those of plants. The leaves of plants have high emissivity (Fuchs and Tanner 1966). A glass or a painted thermometer normally has a high thermal emissivity; however, a metalic surface may differ considerably in emissivity from that of vegetation. The heat capacity, conductivity and dimension of thermometers are additional physical characteristics that often differ greatly from crop characteristics and do affect the indicated temperature.

2.2 Air Temperature vs Radiation temperatures

Care must be exercised in the design, selection and use of the thermometer for measuring temperatures near the ground. The instrument will be influenced by the factors discussed in section 2.1. The magnitude of radiation errors in near the surface thermometry was described by equation (1).

The primary design considerations for measurement of air temperature near the surface are dimension, emissivity, absorptivity and the thermal inertia of the instrument. A large instrument with high emissivity in a poorly ventilated location will indicate a temperature determined in large measure by the radiation environment. Changing any of the above named parameters will make the thermometer more sensitive to air temperature.

The effects of ventilation, emissivity and dimension are such that an object having 0 emissivity (absorptivity) will be at air temperature. An object approaching 0 dimension will be at air temperature, regardless of the emissivity. Because all real objects have an emissivity greater than zero and have finite dimension, the actual temperature of the object will be between the air temperature and the background radiation temperature.

An exposed thermometer should have low emissivity to avoid excessive response to radiation temperature. It should be well ventilated but forced ventilation is not desirable for low level measurements because of disturbance to the micro environment. The instrument should be as small as practical. These considerations are important for accurate measurement of the air temperature.

There are limits on the dimension both from a structural standpoint and according to desired response. A very small sensor will respond quickly to changes in temperature of the air. The difference of response time between the thermometer and the subject of study can in itself be undesirable. A plant leaf, for example, may require 15 to 30 seconds to adjust to a sudden change in air temperature and be unaffected by variations in air temperature of one or two second duration. The thermometer need not, of course, record these very short term changes (2-3 seconds) and may be deceiving if it does so. Alternately a massive thermometer will effectively integrate short time temperature variations and conceivably not indicate the meaningful extremes of temperature.

2.3 Instrumentation

Thermometers used for near surface measurements can be divided into four general catagories. These include liquid-in-glass, bimetalic and liquid-in-metal, electrical, and remote sensing.

2.3.1 Liquid in glass

a. Six's thermometer - one of the most used grass thermometers was described by James Six in 1872 (Middleton 1966). Six's thermometer is a spirit instrument which indicates both the minimum and maximum temperature. Since both soil and grass have thermal emissivity similar to that of glass the thermometer is quite satisfactory for determination of minimum temperatures. The thermometer is not as well suited to measuring maximum temperature due to effects of conduction and solar radiation. However, where ether is used as the sensing liquid, the effects of solar radiation are reduced.

b. Grass minimum thermometer - Thermometers referred to as grass minimum thermometers are most often liquid-in-glass minimum thermometers mounted at grass level. The thermometer bore contains alcohol and a small glass index. The index is kept inside of the alcohol column by surface tension. The thermometer is placed in a horizontal position and the index is moved toward the bulb by decreasing temperature. When temperature increases the index remains in place until reset by temporarily elevating the bulb.

The observer must be alert to the development of beads of spirit in the high temperature end of the bore. The beads are caused either by small amounts of the spirit adhering to the glass when temperature decreases or by evaporation and condensation of the spirit solution. Usually the beads can be reunited with the spirit column by holding the thermometer almost vertical and gently tapping the bulb end on the palm of the hand. Breaks in the spirit column are also quite common and should be reunited by the same method. Sometimes immersion of the bulb in a "dry ice" environment is required to reunite a broken spirit column. Heating until spirit enters the expansion chamber at the high temperature end of the bore is a method of reuniting the spirit column if the separation is near the high temperature end of the column. The latter method is not recommended since overheating can result in thermometer breakage.

2.3.2 Bimetallic and liquid in metal thermometers

The bimetalic thermometer is normally bulky when compared with liquid in glass thermometers. Further, the thermal emissivity properites of metals are often very different from those of plants, soils, and of the atmosphere. Accordingly the bimetallic thermometer is subject to a wide range of errors resulting from radiation and conduction.

The recording-bimetallic thermograph has been used in some areas to collect grass level minimum temperatures. Whenever thermograph data are used, the user should be fully aware that radiation errors are inherent in using the instrument.

Liquid-in-metal thermometers also have the disadvantage of non-similarity to the substance being measured. The sensitive portion can, however, be painted or otherwise treated to approximate the emissive properties of vegetation. Some liquid-in-metal thermometers are physically quite small and accordingly avoid some of the problems associated with the bulkiness that plagues most bimetallic instruments.

2.3.3 Electrical thermal sensors

Electrical sensors of the non radiation type are in common use for temperature measurement. In several respects these sensors are well adapted for measuring temperatures near the surface where a voltage source is available. Some of the advantages include dimension, ease of exposure, accuracy and continuous recording. Some common types are resistance wire, thermisters, thermocouple, and crystal. For a detailed discussion of electrical sensing, the reader is referred to Measurements & Data (1969). Table 1 shows a comparison of these three electrical temperature techniques as summarized in Measurement & Data.

a. Resistance wire thermometers

Resistance thermometers operate on the principle of a change in resistance of conductors with temperature. The most often used thermometers employ resistance wire, usually platinum, copper, or nickel. Metallic wire increases in resistance as temperature increases.

Resistance thermometers in some systems require that some electrical current pass through the sensor. This results in some heat production in the sensing element. The heating, often termed "self heating", must be kept small or the sensor becomes sensitive to air movement. When a null balancing potentiometer is used, no current passes through the sensor and no self heating occurs.

TABLE 1. Comparison of electrical temperature sensors (adapted from Measurements and Data Course 16, 1969)

	Resistance Wire	Thermister	Thermocouple
accuracy	0.005 to 0.05°C	0.05 to 0.5°C	0.5 to 5°C
stability	less than 0.1°C drift in 5 yrs.	0.1°C drift per year	0.5°C drift per year
sensitivity	0.2 to 20 ohms per °C	100 to 1000 ohms per °C	10 to 100 μ volts per °C
usual output	1 to 6 volts	1 to 3 volts	0 to 50 millivolts
features	best stability and accuracy over wide temperature range.	Greatest sensitivity--good stability	Good economy if lead wires are short. Wide temperature range.

Most resistance wire thermometers are constructed from fine platinum wire. Because the wire may be very thin (e.g. 0.1 mm) sensors can be manufactured which have very little radiation error. However, in so doing, the time constants of the thermometer become so short that very short term temperature phenomena are detected, often on the order of parts of a second. The short time constant, as mentioned above, can be undesirable where maximum and minimum temperatures are sought since some very short lived warm parcels of air may cause a high reading for a brief moment but have little, if any, influence on most objects affected by air temperature.

To avoid a too rapid response and to increase the amount of resistance in the sensor, the wire may be coiled or wound onto a small frame and encased for protection. This coiling increases the thermal time lag sufficiently to avoid difficulties with transient temperatures. The sensor's response is quite linear over a large range of temperatures. Several may be connected in series or in series and parallel combinations to give average temperature over several points. Only a simple bridge system is required to produce a relatively high output compared to the output of thermocouples.

b. Thermistor resistance thermometers

Thermistors are semiconductor sensors which have a negative temperature coefficient. They are manufactured in many shapes, sizes, coatings, housing and for many temperature ranges with a wide selection of resistances. The resistance of the sensor can be chosen high enough that sensor lead wire resistance is negligible. Several manufacturers produce precision temperature sensing thermistors that may be interchanged without individual calibration for most meteorological applications.

The thermistor does not have a linear response to temperature change over wide ranges of temperature. Sensors must be chosen appropriate to the expected temperature range. The non-linearity is not a serious drawback for most temperature measurements but is a decided weakness if temperature differences are to be measured. At least one manufacturer (YSI) markets a thermolinear device consisting of a combination of thermistors and balancing resistance circuitry. The thermolinear sensors are accurate within 0.2°C over the range of -50°C to +50°C and are satisfactory for measuring temperature differences within the specified temperature range.

Thermistors have the advantages of low price, stability, small size, interchangeability and modest measuring circuitry requirements. Thermistors are resistance sensors and are subject to self heating, however, they may be operated with an output many times greater than a thermocouple of like dimension with negligible heating error.

c. Thermocouples.

Thermocouple thermometers are made by joining two conductors of unlike metals together. It is possible to measure temperature differences with such a device since a thermoelectric potential is produced when two junctions are at different temperatures. The principal is simple but problems arise from the fact that output per degree is very small, usually millivolts or microvolts.

Measurement of temperature requires that one junction be held at a known reference temperature, or that an electronic signal be provided to simulate a reference temperature. Usually an electrical/electronic reference junction is used to replace one thermocouple junction. The electronic units are usually more convenient than using an ice-water bath or other reference temperature, however, the reference itself becomes a source of some error. The low output, reference and accompanying electronics for signal amplification, together with variations from one thermocouple to another, limit the reliability and accuracy of these instruments. They are best applied to temperature difference measurement.

d. Crystal oscillators.

The frequency of oscillation of quartz (and other) crystals is temperature dependent. Some fine research thermometers with high accuracy and with precision to better than 0.001°C are available using crystal sensors. The expense and precision are both generally beyond the scope of micrometeorological requirements. The physical dimensions can be extremely small and they possess the same advantages of being easily shielded and protected from radiation. On the basis of accuracy and expense, however, they are not the most desirable for making measurements in the microclimate near the surface (Table 1).

2.3.4 Remote sensing thermometers

Remote sensing thermometers are normally passive devices which do not disturb the surface being measured nor cause appreciable disturbance to the environment in the immediate vicinity of the object being measured. The remote sensing thermometer operates by passively detecting the energy radiated from a surface. The instrument is sensitive to either the amount of energy radiated or to the frequency of emitted energy.

Remote sensing thermometers can be designed to measure the apparent temperature of a volume of air adjacent to the detector. Such instruments have found limited application in the measurement of air temperature. There are no great drawbacks to the use of the instrument. However they are not commercially available for routine air temperature measurements and accordingly have prohibitive cost for large scale observing networks.

Environmental satellites often contain one or more devices for measuring surface temperature or atmospheric temperature. Satellite data will become increasingly more valuable for determination of temperature at the earth's surface. Usually the actual temperature of the soil, plant or water surface is measured rather than air temperature. The measure of actual surface temperatures is potentially valuable in studies ranging from agrometeorology to planetary energy balance. However, the actual surface temperature may vary a few degrees from air temperature just a few centimeters above the surface at night and by many degrees when the surface is subject to insolation.

2.4 Instrument selection and exposure

The thermometers described above represent the most common or most available types. Many other methods of measurement are known but are not in general usage. Such instruments as diode and sonic thermometers are available and have been applied to grass level measurement. Some devices not now available may become practical in the near future with the development of inexpensive microelectronic field systems.

Regardless of the sensor chosen, the investigator should be aware of the limitations of the instrument and of the sources of error discussed above. Proper exposure requires that no artificial sources of heat be near the sensor. Such sources may locally modify the air temperature or may directly serve as heat radiators that influence the sensor. Sensors should have small dimension, low thermal emissivity and be carefully mounted to avoid thermal contact with heat reservoirs such as the soil, vegetation or the mounting brackets themselves. Natural ventilation should be as good as possible.

The authors recommend as a standard exposure that routine observations be made five (5) centimeters above the soil surface where sod is not maintained. Where sod is maintained the thermometer should be placed at grass height. Thermistor type sensors are recommended where practical. Otherwise a Six's type thermometer with an ether, or other transparent fluid, filled bulb may be used. The sensor bulbs should be shielded from direct daytime solar radiation with a simple shield which interfers little with air flow. The shield may be a light metal arch painted white on upper surface and either painted or unpainted lower side.

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