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The Effect of Temperature on the Tension of Water in the Soil

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THE EFFECT OF TEMPERATURE ON THE TENSION

OF WATER IN THE SOIL

by

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of

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The tenacity with which water is held in the soil is an important factor in determining the availability of water to plants. It is this attraction for water by the soil particle which is the basic phenomenon of soil moisture tension. Soil moisture tension may be defined as the pressure difference that must be maintained across the wall of a porous cup in order to attain a zero transfer rate between water in the soil, which is subject to surface-force action, and water in the cup, which is not subject to surface force action.

Tensiometers are devices used to measure the tension with which water is held in the soil. Because of their wide use in research it is important that the experimenter get the best information possible from their use. Previous experimenters (11, 14, 20, 27, 32 and 33) have observed large fluctuations in tensiometer readings as a result of temperature changes, and some have indicated that temperature corrections for moisture tension data might be of significant magnitude.

The purpose of the study reported herein was to obtain information on the effect of temperature on soil moisture tension with 2 specific objectives in mind: first, to see if temperature has a significant effect on moisture tension and if the effect is of significant magnitude to apply corrections to field data. The second purpose was to see if soil moisture thermodynamic relations, such as those given by Edlefsen and Anderson (13), can be used to show this effect.

Two experiments were carried out, one in the laboratory and one in the field. A laboratory experiment was conducted to find the effect of

temperature on soil moisture tension. A field experiment was conducted to study diurnal fluctuations of tensiometers and to see if temperature relations found in the laboratory will explain observed fluctuations of tensiometers in the field.

REVIEW OF LITERATURE

Soil moisture energy relations

Many workers (1, 3, 7, 10, 12, 13, 15, 17, 35, 36, 38, 39, 40 and 43) have used the free energy concept for expressing soil moisture energy relationships. Using free energy to describe the behavior of water in the soil makes it possible to evaluate the effect of temperature on the energy relations of soil moisture.

The difference in free energy between that of a datum and that of the water in soil will be referred to as the free energy of soil moisture. The free energy of free, pure water will be taken as the datum and will have the same temperature as the water in the soil whose free energy is to be determined. The free energy of the datum resulting from its position in a gravitational field is arbitrarily taken as zero, and the free energy of soil moisture, which will also be in a gravitational field, will be measured with respect to the datum. The datum is assumed to be free of all extraneous fields. The total free energy of soil moisture can be found from vapor pressure measurements by employing the formula given by Edlefsen and Anderson (13)

$$\Delta F = \frac{RT}{m} \ln \frac{P}{P_o} \tag{1}$$

where ΔF is the total free energy at temperature T and R is the universal gas constant. m is the molecular weight of water. P denotes the vapor pressure of the soil moisture when the vapor is in equilibrium with the water in the soil. P_o is the vapor pressure of the datum when in equilibrium with the free water surface.

It is known from thermodynamics that the specific free energy

decreases for spontaneous changes. When considering a body of pure, free water, where the free energy is taken equal to zero, in contact with an unsaturated soil, whose free energy is not zero, water will flow spontaneously from free water into the unsaturated soil. The free energy change between the datum and the water in the unsaturated soil will therefore be negative. Moisture also flows spontaneously from wet to dry soil. Therefore, the drier the soil the larger the negative value of the free energy.

Edlefsen (12) and Edlefsen and Anderson (13) have suggested various thermodynamic functions that are important in describing the behavior of water in the soil. There are various factors affecting the free energy of soil moisture as the temperature is changed. Edlefsen and Anderson (13) give the following equation to represent the components of the free energy of soil moisture and show how each component depends on temperature.

$$\Delta F_{ST} = RT \ln \frac{P}{P_0} = \Delta F_{\sigma} + \Delta F_{P} + \Delta F_{O} + \Delta F_{f} \qquad (2)$$

ΔF_{ST} is the total free energy of soil moisture at temperature T. R, P and P_0 have the same meaning as previously given. ΔF_{σ} denotes the component of the free energy caused by surface tension and radius of curvature of the air-water interface; ΔF_{P} represents the free energy that the water has resulting from the hydrostatic pressure it is under; ΔF_{O} is that component of the free energy contributed by osmotic pressure of the dissolved material, and ΔF_{f} is the free energy possessed by water by virtue of its position in the adsorptive field surrounding the particle as well as in the earth's gravitational field.

They suggest the 2 component free energies ΔF_{f} and ΔF_{P} arising from the adsorptive field surrounding the soil particle are

constants independent of temperature. Therefore, $\Delta F_f + \Delta F_p = K_1$ where K_1 is a constant independent of temperature. They give the equation $\Delta F_o = k_2 T$ to show that the free energy caused by osmotic pressure is a function of temperature. In showing the dependence of ΔF_σ to temperature, they employ the Kelvin equation as discussed by Glasstone (16). They make the assumptions that the soil moisture system meets the requirements for applying the Kelvin equation. In employing this equation they assume the vapor to behave as an ideal gas and that the radius of the pores in the soil behave as spherical drops.

The Kelvin equation $\Delta F = RT \ln \frac{P}{P_o} = \frac{2V\sigma}{r}$ relates the free energy ΔF and vapor pressure P of the water in the soil to the molar volume V and the surface tension σ of water and the radius of curvature r of the air-water interface. P_o is the vapor pressure of a free water surface at temperature T, and R the gas constant. In employing this equation they further assume the moisture content is kept constant as the temperature is varied.

The component of the total free energy of soil moisture caused by the surface tension of water and radius of curvature of the air-water interface at temperature T is given by

$$\Delta F_{\sigma_T} = \frac{2V\sigma_T}{r} \tag{3}$$

The radius of curvature r of the air-water interface of soil moisture is hard to determine directly; therefore it is eliminated from the equation by the following procedure. The molar volume V and the radius of curvature r are considered constant and independent of temperature for moist soils. Thus,

$$\frac{2V}{r} = \frac{\Delta F_{\sigma_T}}{\sigma_T} = \frac{\Delta F_{\sigma_{T_1}}}{\sigma_{T_1}} \quad \text{or} \quad \Delta F_{\sigma_T} = \frac{\left(\Delta F_{\sigma_{T_1}}\right)\left(\sigma_T\right)}{\sigma_{T_1}} \tag{4}$$

In order to express ΔF_{σ_T} in terms of the temperature T, the surface tension must be expressed in terms of T. For the temperature range concerned with in this report the surface tension of water will be assumed to be a linear function of temperature. Therefore, $\Delta F_{\sigma_T} = K_3 + K_4 T$. The equation $\sigma = 117 - 0.152\ T$ is used to get the surface tension of water in terms of temperature.

A single resultant equation expressing the dependence of the total free energy of soil moisture on soil temperature can be obtained by adding the effect of temperature on each individual component.

Since $\Delta F_f + \Delta F_p = K_1$, $\Delta F_o = K_2 T$, and $\Delta F_{\sigma_T} = K_3 + K_4 T$, equation 2 becomes

$$\Delta F_{ST} = K_1 + K_2 T + K_3 + K_4 T \tag{5}$$

Combining constants gives

$$\Delta F_{ST} = C_1 + C_2 T \tag{6}$$

In order to determine the constants C_1 and C_2 requires the determination of the total free energy at 2 different temperatures. Hence

$$\Delta F_{ST_1} = C_1 + C_2 T_1 \qquad \text{and} \qquad \Delta F_{ST_2} = C_1 + C_2 T_2$$

Solving the 2 equations simultaneously gives

$$C_1 = \frac{T_1\ \Delta F_{ST_2} - T_2\ \Delta F_{ST_1}}{T_1 - T_2} \tag{7}$$

and

$$C_2 = \frac{\Delta F_{ST_1} - \Delta F_{ST_2}}{T_1 - T_2} \tag{8}$$

Inserting equations 7 and 8 into equation 6 gives

$$\Delta F_{ST} = \frac{T_1\ \Delta F_{ST_2} - T_2\ \Delta F_{ST_1}}{T_1 - T_2} + \frac{\Delta F_{ST_1} - \Delta F_{ST_2}}{T_1 - T_2} \tag{9}$$

Edlefsen and Anderson have derived equations 4 and 9 to show how

temperature influences ΔF_σ and ΔF_{ST}. In order to employ equation 4,

$\Delta F_{\sigma_{T_1}}$ must first be determined at some temperature T_1 from which

ΔF_{σ_T} can be determined at any other temperature T. Equation 9 requires

the determination of the total free energy of soil moisture at 2

different temperatures, from which it can be determined at any other

temperature.

Babcock and Overstreet (1) include one more term than is customary

for expressions for the chemical potential. They add a moisture content

term which was not included in the equation of Edlefsen and Anderson.

They give the expression $du = Vdp + \dfrac{\partial u}{\partial P_W} d_{TW}$ where u is the chemical

potential, P the pressure, V the partial molar volume, and P_W the mois-

ture content. $\dfrac{\partial u}{\partial P_W}$ shows the rate of change of the chemical potential

with moisture content. Edlefsen and Anderson do not include a term to

show how the free energy function changes with moisture content, but

assume that the pressure variable adequately explains it. Babcock and

Overstreet feel that the pressure variable is needed to describe the

total pressure exerted by the surroundings on the soil system. By

defining the pressure term in this manner it is inferred that the P_W

term includes the changes in pressure that result from changes in radius

of curvature of the air-water interface.

Schofield (38) proposed the pF as a free energy scale. The symbol

p indicates a logarithm, while the symbol F suggests free energy.

Therefore, pF can be defined as the logarithm of the free energy of

soil moisture. He suggests that the osmotic component of the total free

energy of soil moisture is often not given proper considerations. He

suggests that accurate vapor pressure data is hard to determine above pF

values of 4.15 (RH = 99 percent). Freezing point measurements are possible between pF 4.4 and 3.0 and for pF values below 3, direct suction measurements are possible. He also shows a definite relationship between soil moisture tension and relative humidity.

Campbell (8) used freezing point depressions to measure soil moisture tension. He found close similarities between moisture content-moisture tension curves obtained from pressure membranes and those using freezing point data.

Bodman and Day (3) have shown success using freezing point depressions to determine free energy. Free energy determinations from freezing point depression measurements have also been made with some success by Schofield and Botelho da Costa (39). They say there is very little effect of salts on pF if the concentrations are less than 500 ppm.

Richards and Weaver (35) also suggest we often exclude osmotic effects when considering the free energy of soil moisture. They suggest the soil moisture tension at a moisture percentage equal to the moisture equivalent may account for less than one-half the free energy value.

Robins (36) studied 3 thermodynamic properties, the specific free energy, the specific heat content, and the specific entropy. By using the equation $\Delta F = \frac{RT}{m} \ln \frac{P}{P_o}$ and measuring the vapor pressures by using 14 different H_2SO_4 solutions, he found the specific free energy increased numerically with increasing temperature. He states: "For the wetted samples, it appears that the specific free energy increases numerically with increase in temperature. The change appears to be, to a first approximation directly proportional to the ratio of the absolute temperature."

Mooney, Keenan, and Wood (25) ran desorption isotherms at 0 and 20° C. for sodium montmorillonite. Their results showed the 0° C. isotherm

to be above the 20° C. when water content was plotted on the abscissa and relative pressure on the ordinate. Results also showed the heat of desorption to decrease as the moisture content increased. At higher moisture contents the decrease in heat of desorption appeared to be small.

Temperature effect on the amount of water absorbed by soil

Many workers have reported on the effect of temperatures on the amount of water absorbed by soils. Puri, Crowther, and Keen (29) report that water absorption at definite relative humidities is almost independent of temperature over the range of 20 to 40° C. for high relative humidities but decreases markedly with increasing temperature for lower relative humidities.

Baver and Winterkorn (2) report a work similar to that of Puri, Crowther, and Keen. They report that the water-absorption capacity of modified soil materials in a constantly maintained humidity of 94 percent decreases rapidly as the temperature is increased.

On the other hand Veihmeyer, Oserkowsky, and Tester (43) show that the moisture equivalent is increased by an increase in temperature during the period of saturation.

Wadsworth (44) determines a relative humidity versus moisture content curve for 3 temperatures, 40° C., Room temperature, and 8° C. His results showed the 40° C. curve to be above the room temperature curve which in turn is above the 8° C. curve. His results were similar for both wetting and drying curves.

Wadsworth (45) suggests that water in an unsaturated soil is held by 2 disimilar processes.

1. Water held tightly by surface activity of the colloid surface. He calls this chemosorption.

2. Water condensed in the fine pores is called capillary condensation. This water is loosely held and the amount depends on the curved water interface.

He predicts that in the chemosorption region temperature would have more effect on the amount of water absorbed at constant relative humidity than in the capillary condensation region. If his hypothesis is true, differences in temperature should effect more significantly the amount of water absorbed at low moisture contents than at higher moisture contents. Results showed that at low relative humidities, the moisture held at a given value is consistently less in the cold series than in the hot series, the difference becoming less apparent and perhaps insignificant at higher humidities.

Richards and Weaver (35) show that the amount of moisture a soil will retain for a given tension depends somewhat on the time allowed for wetting the air-dried sample. For sandy soils results showed no increase in moisture retention for wetting times beyond 15 minutes, whereas fine textured soils may require 18 to 24 hours. They also reported the effect of temperature on the moisture percentage at one-half atmosphere and 15 atmospheres tension for a group of soils. Results showed a slight decrease in moisture retained as the temperature increased.

Diurnal fluctuations of tensiometers

Several possible causes of fluctuations have been given. Richards (32) suggests fluctuations result from the changes in volume of the water within the tensiometers. He suggests that this undesirable effect be minimized by reducing the water capacity of the tensiometer. Richards, Russell, and Neal (34) in a later work conducted an experiment to show fluctuations of tensiometers in the field. They suggested the observed diurnal fluctuations were caused from temperature fluctuations

of the soil and suggested the fluctuations were caused from the thermal expansion of the tensiometer water. A refinement in the design of the tensiometer was made by restricting the water capacity. Coleman, Hanawalt, and Burch (11) also attempt to reduce fluctuation in manometer readings caused by temperature induced volume changes in the water.

Haise and Kelley (20) studied the diurnal fluctuations of tensiometers. They found minimum tension values occurred at 6 to 8 a.m. and maximum at 7 to 9 p.m. They also found fluctuations to depths of 48 inches and the magnitude of variation decreasing with depth. Daily variations of 350 to 400 cm. of water were common for the 6-inch depth. They explained these fluctuations as being primarily caused by temperature gradients between the porous cup and the soil. When the cup is warmer than the surrounding soil water will evaporate from the cup, resulting in a higher manometer reading. When the cup is colder than the soil water will condense on it, causing a lower manometer reading.

These reports have concluded that the observed fluctuations of tensiometers were caused entirely by the instrumental behavior of the tensiometer. They have not considered the direct effect of temperature on the soil moisture tension.

Moore (26, 27) conducted an experiment to show the relation of temperature to soil moisture pressure potential, retention, and infiltration rate. Porous clay tensiometer cups, attached to mercury manometers, were inserted in a container containing soil and were placed in a water bath where the temperature was varied from 0 to 40° C. He found the variation of pressure potential with temperature was relatively small at the higher soil moisture contents and increased with decreasing soil moisture. However his results were not consistent in showing the effect of temperature on pressure potential. He concluded that

temperature may be of minor importance in determining pressure potential.

Gardner (14) found that in 3 soils at constant moisture content the tension tended to decrease at approximately 0.008 atmospheres per degree rise in temperature within the range of 0 to 50° C. He also reported that no matter what the moisture percentage during the experiment the slopes of the moisture tension vs. temperature curves were all approximately the same. Most of his curves tended towards a curvilinear rather than a straight line relationship. He suggests that theoretically moisture tension should not be independent of the temperature, but he gives no theoretical means for checking the temperature effect on soil moisture tension.

Variation of soil temperature with depth and moisture content

Kazahov (24) studied the density of stand of perennial herbage on the temperature and moisture of the soil. The summer surface temperature of the light chestnut soil was about 5° C. lower under a dense (87 percent) herbage cover than under a lighter (75 percent) one. The temperature difference leveled at about a 10 cm. depth. Irrigation lowered the soil temperature during the summer months by 10 to 11° C. and often as much as 20° C. He attributed the lower temperature not only to the higher moisture content of the soil, but also to the dense covering of plants on the irrigated soil. Jakobsen, Sorenson, Middelboe, et al. (22) also observed that dry soil was warmer than wet soil. They found a maximum difference of 30° C. and an average difference of 10° C. The difference was greater in the top 5 cm. of soil. The difference was also greater at noon than at other times of the day. They stated that under lucerne the temperature difference between wet and dry soil was generally small and rather erratic.

Hysteresis

Hysteresis in moisture tension-water content curves have been observed by many investigators. They have generally regarded hysteresis as being associated with the delay in refilling of empty parts of the pore space upon wetting.

Richards (30) ran uptake and removal curves over one atmosphere. He noted that curves resulting from cyclic changes in tension forms loops instead of single curves. His results showed the uptake curves are steeper than removal curves.

Salvody, Roa, and Roa (13) also show a hysteresis loop and conclude that a soil retains more water during removal than during uptake.

Holmes (21) also shows a hysteresis effect between soil moisture tension and water content. He explains that hysteresis was not caused entirely by delay in refilling empty parts of the pore space on rewetting, but the readjustments of clay particles relative to their neighbors also made a contribution.

Movement of moisture under thermal gradients

Breazeale, McGeorge, and Breazeale (5) reported that to all depths to 5 feet below a 4-inch black-asphalt aerodrome runway the soil moisture content was 3 times greater than the surrounding Arizona desert. Vapor movement appeared to be the most logical source of moisture accumulation under the runway.

Brawand and Kohnke (4) estimate the annual moisture gains from vapor transfer from the subsoil to the surface soil, not including evaporational losses, is 1.34 inches of water on bare ground and 0.77 inches on meadow. From March to October the vapor transfer from the subsoil was confined to night hours but during the day there was a 2-directional moisture loss from the surface.

Gurr, Marshall, and Hutton (19) observed that in all except the
wettest and driest columns of soil there was a transfer of water towards
the colder end of the soil column. They found that movement of water in
the liquid phase occurred at a water content of pressure potential of
-0.8 x 10^7 ergs/gm. ($\rho F = 3.9$).

Cavazza (9) and Taylor and Cavazza (42) studied the influence of
temperature gradients on soil moisture flow. By using an air gap tech-
nique they show that moisture flow from warm to cold soil is largely in
the vapor phase. The amount of water transfer was found to be influenced
by the thickness of the air gap. Movement of moisture from the warm to
the cold soil results in an induced potential gradient which at equi-
librium causes liquid flow equal to and opposite that of vapor flow.
Thus they report moisture movement takes place in 2 directions under a
thermal gradient.

Rollins (37) also observes movement of moisture under a temperature
gradient. Results indicate that the main mechanism of moisture migra-
tion under a thermal gradient is associated with vapor movement.

Brooks and Rhoads (6) observed that diurnal magnitudes of heat flow
were more than twice as great in watered plots as in unsaturated plots.

Conclusions from the literature reviewed

The literature indicates the following:

1. The free energy functions seem to be a suitable treatment of
soil moisture problems from the energy point of view. However, conveni-
ent and accurate methods of measuring the free energy of soil moisture
over the range of moisture for plant growth are limiting. Vapor pres-
sure methods and freezing point depression measurements have shown some
success in measuring the free energy of soil moisture. Tensiometers
have shown success for measurements of free energy in the absences of

salt and when the moisture content is high (soil moisture tensions less than about 0.3 atmospheres).

2. Previous experiments indicate that the free energy of soil moisture increases as the temperature is increased.

3. Evidence is given which indicates that temperature may markedly modify the shape and position of the moisture content-surface force curve.

4. Unsaturated soil at a given potential holds less water at a higher temperature than at a lower temperature. Therefore, samples of a given soil at a specified moisture percentage will have equal moisture potentials only when their temperatures are equal.

5. Large diurnal fluctuations in tensiometer readings in the field which seem to be associated with temperature variations have been observed.

6. Fluctuations in moisture tension and moisture contents may be erroneously attributed to causes other than temperature.

7. Soils contain more water during a removal cycle, at a fixed tension, than during an uptake cycle.

8. Movement of moisture in the vapor phase is from warm to cold soil under a thermal gradient. When the soil moisture system is in a state of equilibrium the amount of moisture flow in the liquid phase is equal to the amount in the vapor phase and is opposite in direction.

EXPERIMENTAL METHODS

The tensiometer is widely used in measuring soil moisture tension in the high moisture range. The moisture potential is based upon a suction force of soil for water. When the porous cup of the tensiometer is placed in contact with unsaturated soil, water will leave the cup and enter the soil and thus cause the mercury to rise in the manometer. As the soil becomes wet, and the tension of the water in the soil is less than that in the cup, water enters the cup which causes the mercury in the manometer to fall. When moisture in the soil is in equilibrium with the water in the cup, the potential of soil at that given moisture content is equal to the potential read on the manometer.

Laboratory investigation

A laboratory experiment was conducted to show the effect of temperature on soil moisture tension. An attempt was made in designing this experiment to reduce the effect of temperature on the instrumental behaviors of tensiometers as much as possible. The tensiometers used in this study were built according to the specifications of Richards (31, 32). However, the tensiometers used in the laboratory experiment had no metal supports. Elimination of these metal supports reduces the temperature gradient effect as reported by Haise and Kelley (20). Since the design of tensiometers for measuring soil moisture, improvements have been made. Some workers (11, 32, 33) have indicated a thermometer effect in tensiometers, which is caused by changes in volume of tensiometer water, as a result of temperature changes. These workers have

suggested ways for improving troublesome characteristics of tensiometers.
One of the improvements suggested was to restrict the water capacity of
the tensiometer. In this experiment the water capacity was decreased
considerably by decreasing the length of both the three-quarter inch
copper and glass tubing.

For convenience of reading the tension the mercury manometers were
connected to a common panel board. The manometer scale was calibrated
to read directly in centimeters of water.

Four 2-liter electrolytic beakers were used as soil containers.
About 1 inch of soil was placed in the bottom of each beaker. A
porous cup was then placed in the center of each beaker and soil packed
around it to get a good soil-cup contact. The porous cup was surrounded
by soil and the beaker was packed with soil to within about one-half
inch of the top. A thin sheet of cotton was placed over the soil and
then hot paraffin was poured over the cotton. This eliminated evapora-
tion from soil surface, thus keeping the moisture content approximately
constant throughout the experiment. In order to maintain atmospheric
pressure a small pin hole was kept open between the atmosphere and the
soil surface.

A Millville loam soil of varying moisture content, within the
range of tensiometers, was used. Soils were brought to arbitrary
moisture percentages by moistening the soil with an atomizer and stir-
ring or by mixing moist and dry soil. The soil moisture percentages
studied varied between 21 and 10 percent moisture by weight on a dry
weight basis.

The constant temperature bath was a kerosene oil bath with a con-
tinuous stirrer, a heating coil, and a cooling unit. A thermocap relay
as proposed by Taylor (41) was used to control temperature. The

temperature was controlled to within about ± 0.05° C. Throughout the experiment the temperature was varied from 2 to 45° C. The beaker containing the porous cup was lowered into the oil bath until all but about 1 inch was surrounded by oil. Time was allowed at each temperature for a tension reading to become constant. A variable amount of time was required at each temperature. For higher temperatures 4 hours was sufficient time to reach approximate equilibrium whereas at lower temperatures about 12 hours was allowed. It was assumed that equilibrium was reached when the mercury manometer readings became constant. Temperature gradients are set up in the soil when the temperature of the bath is changed. Thermometers with scale divisions of 0.1° C. magnitude were used to indicate when no temperature gradient exists in the soil. One thermometer was placed in the soil about one-half inch from the porous cup. Another was used to read the temperature of the bath.

After a series of soil moisture tension and corresponding temperature readings were made the tensiometers were removed from the soil. Two samples of moist soil were taken from each beaker and the average percentage of the 2 samples was recorded as the moisture content for the particular beaker. The moisture content was determined by measuring the loss in weight upon drying 24 hours in an oven at 110° C. and dividing by the dry weight of the sample. The moisture content is the average for the particular beaker and probably closely approximates rather than represents the condition of the soil in contact with the tensiometer cup.

Figure 1 is a cut away diagram of the apparatus used in the laboratory to study the effect of temperature on soil moisture tension.

Field investigation

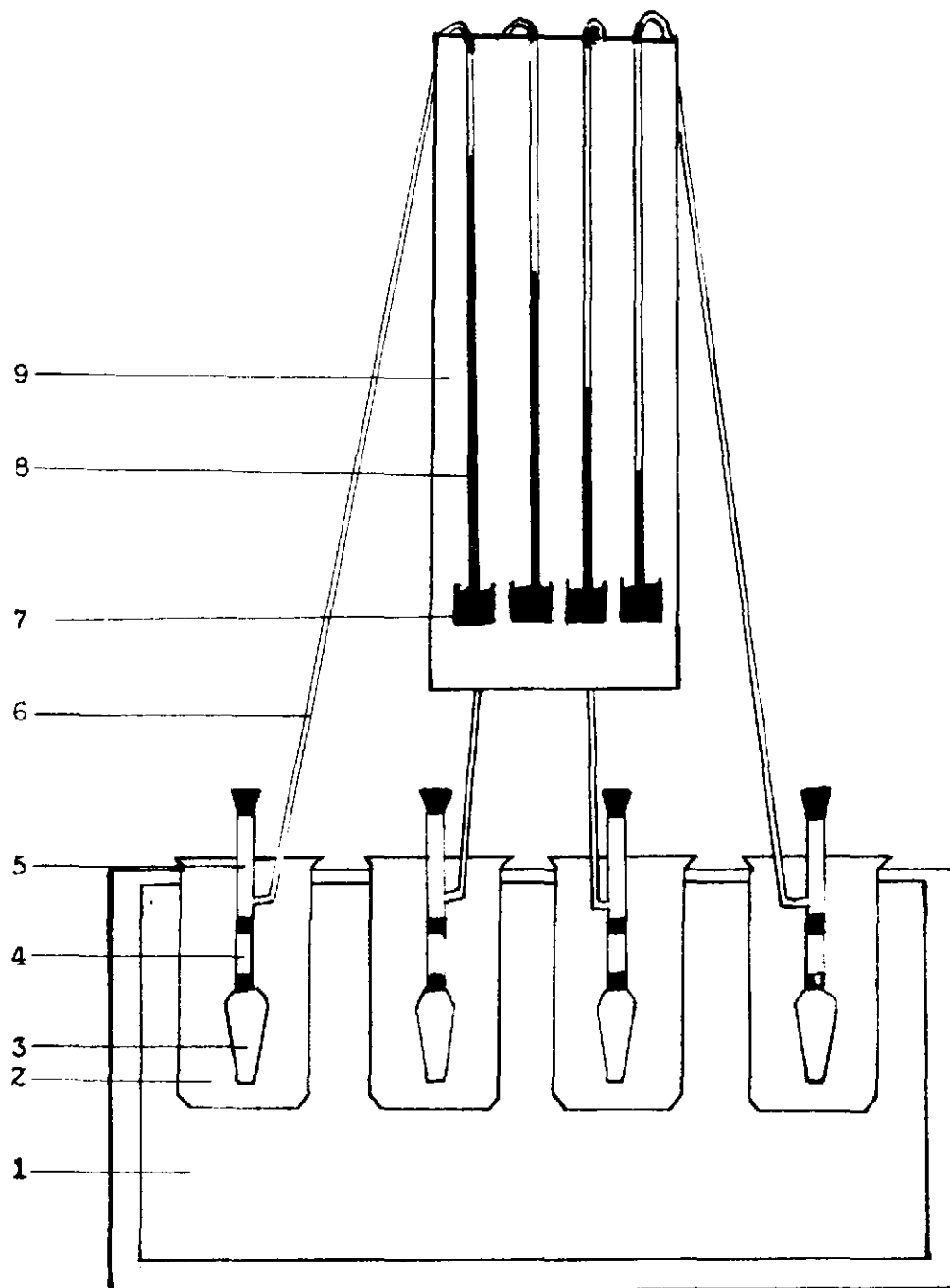A field experiment was conducted to determine the magnitude of

Figure 1. Cutaway diagram of apparatus used to study the effect of
temperature on soil moisture tension. 1. Oil temperature
bath. 2. Two-liter beaker containing moist soil. 3. Porous
cup. 4. Three-fourths inch copper tube. 5. Three-fourths
inch glass air trap. 6. One-eighth inch copper tube. 7.
Mercury well. 8. Manometer. 9. Panel board.

diurnal fluctuations of tensiometers used in the field.

The tensiometers used in the field to measure moisture tension were the same as those used in the laboratory study except they have metal supports and their water capacity is greater at the deeper depths because of the increased length of the three-quarter inch copper and glass tubing. Therefore, the tensiometers used in the field were more subject to instrumental influences.

Tensiometers were installed at 6-, 12-, 18-, and 24-inch depths in sugar beets. They were used to measure tension in 2 moisture ranges, one "high" moisture level where the tension in the root zone is kept below 0.2 atmospheres and another level somewhat lower where the tension is held below 0.5 atmospheres. Tension readings were taken twice a day, once about 30 minutes before sunrise and once about 15 minutes after the sun goes down in the evening.

Previously calibrated thermistors were used to measure the temperature of the soil in the field. Thermistors were calibrated by observing the change in resistance corresponding to a change in temperature. Calibration of the thermistors was done in the laboratory by placing them in a beaker of moist soil and the beaker placed in the oil temperature bath. The temperature of the bath was varied from 2 to 40° C. The resistance was read using a wheatstone bridge and galvonometer. A calibration curve for each thermistor was made by plotting ohms resistance against the temperature of the soil. A calibrated thermistor was placed adjacent to and at the same depth as each tensiometer in the field. A Bouyoucos wheatstone bridge adjusted to read the same resistance as the galvanometer was used to measure the ohms resistance of the thermistors in the field. From the previously determined calibration

curves it was possible to get the temperature of the soil from the measured resistance.

RESULTS

Laboratory investigation

Experimental effect of temperature on moisture tension. In conducting the laboratory experiment there were 3 variables: soil moisture content, soil moisture tension, and soil temperature. Soil moisture content was held constant and temperature varied. Curves with soil moisture tension as a function of temperature are shown in figures 2 and 3. In the drier soils these curves tend towards a curvilinear, rather than a straight line relationship as predicted by the Edlefsen and Anderson equation. However, as the moisture content increases, the curves tend to approach a linear relationship. There is also an observed hysteresis effect; the cooling curves do not follow the same path as the heating curves.

These curves show that temperature has a significant effect on soil moisture tension, the magnitude depending on the moisture content. As a first approximation, the effect of temperature on moisture tension was found to be approximately 0.0015 atmosphere per centigrade degree change in temperature at a moisture percentage of 20.42; 0.003 atmospheres per degree centigrade when the moisture content was 17.59; 0.007 atmospheres per degree centigrade when the moisture content was 13.52; and 0.009 atmospheres per degree centigrade when the moisture content was 12.09.

The relationship between soil moisture tension and temperature has been demonstrated in figures 2 and 3. The magnitude of the interdependence varies with moisture content. Therefore, if temperature corrections for moisture tensions are to be made the relationship between the soil moisture percentage and moisture tension must be known.
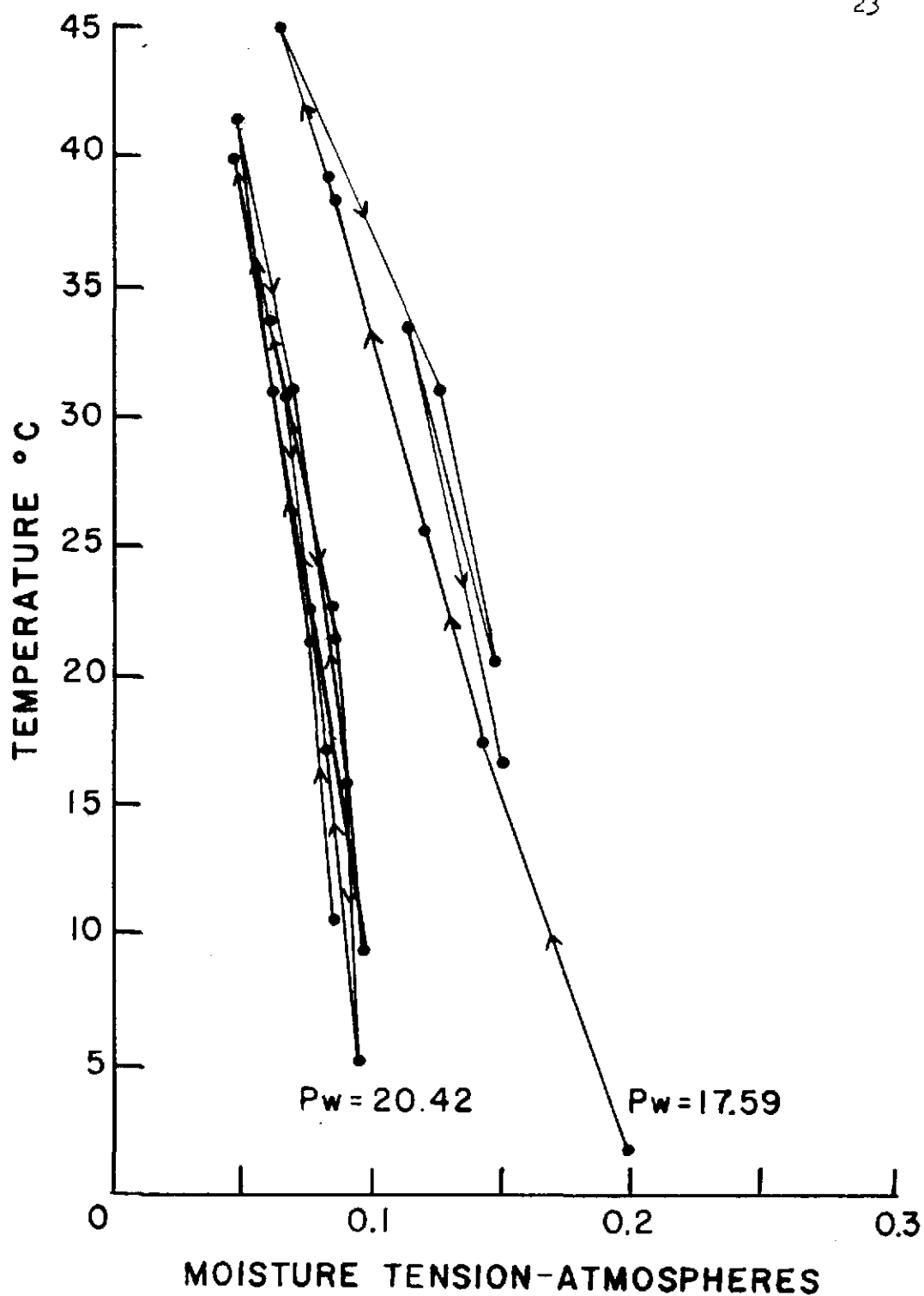
Figure 2. Moisture tension as a function of temperature with moisture content held constant
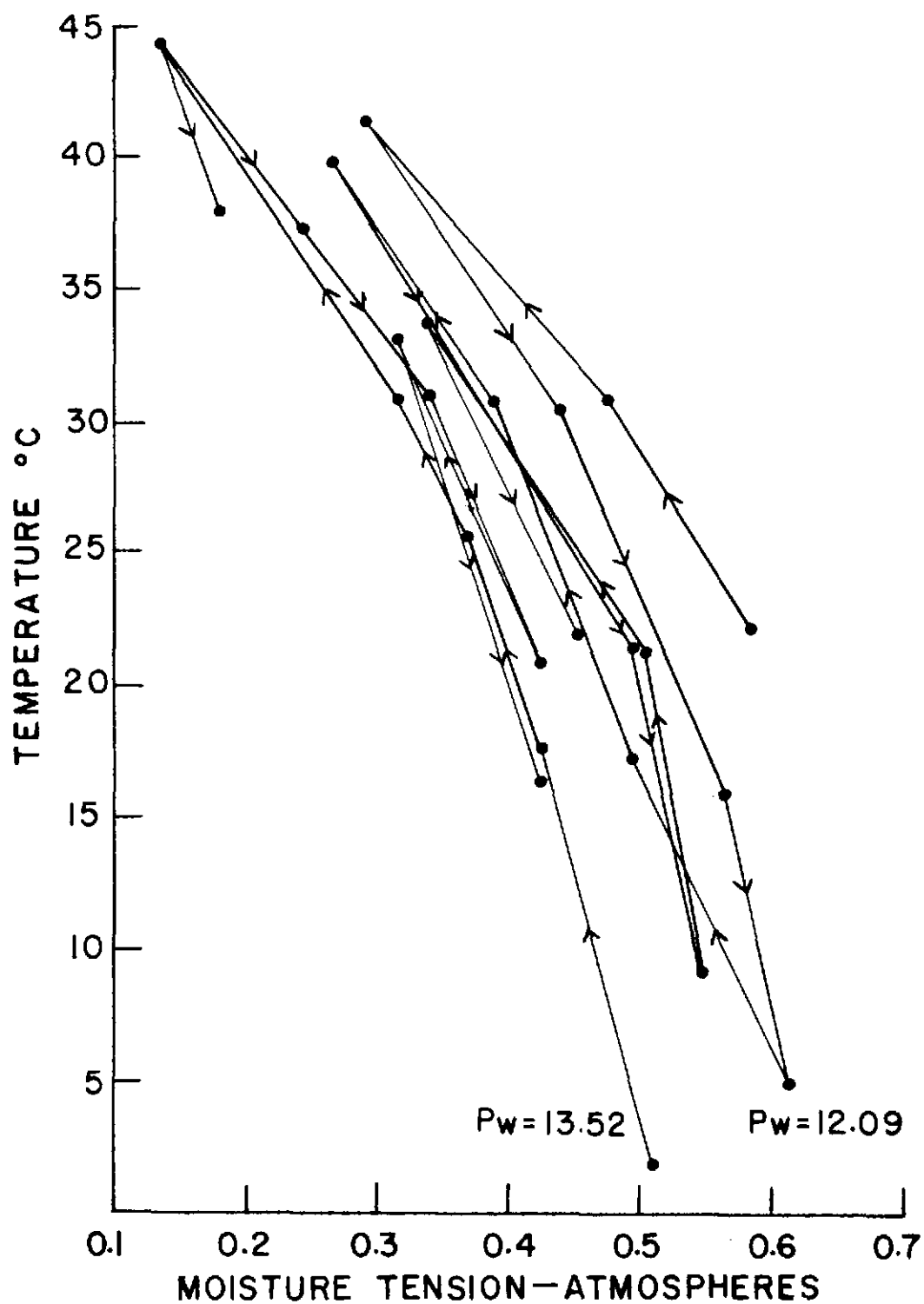
Figure 3. Moisture tension as a function of temperature with moisture content held constant

It was found (figure 7) that for the summer months studied the maximum temperature of the soil for the 6-inch depth was about 25° C. and a minimum temperature of about 1° C. was recorded for the same depth. For this temperature range the curves in figures 2 and 3 are approximately linear. Assuming a linear relationship between temperature and tension an approximate average equation for these curves was determined from linear regression within this temperature range. Plotting the moisture content against moisture tension with temperature held constant gives the isotherms illustrated in figure 4.

Using the isotherms in figure 4, table 1 was made. This table may be used to make temperature corrections for tension data. The table is made to correct tensions to a temperature of 20° C. If tension measurements are made when the soil temperature is below 20° C. and table 1 used to correct this tension to 20° C., an appropriate correction value will be subtracted from the measured tension. If the soil temperature is greater than 20° C. the correction value will be added.

Predicted effect of temperature on tension. For a relative moist soil the effect of the adsorptive force field surrounding the soil particle on the air-water interface is small. If the adsorptive field is assumed to be negligible for a moist soil the tensiometer can be used to measure the capillary potential which is practically synonymous with the free energy. Tensiometers do not measure osmotic potentials caused by dissolved materials. However, the effect of temperature on this component of the total free energy of the soil moisture was not important in this experiment because salt free soil was used. For moist soils the tensiometer will give an approximate measure of the free energy resulting from surface tension and radius of curvature of the air-water interface. For drier soils the tensiometer will also measure adsorptive forces. The
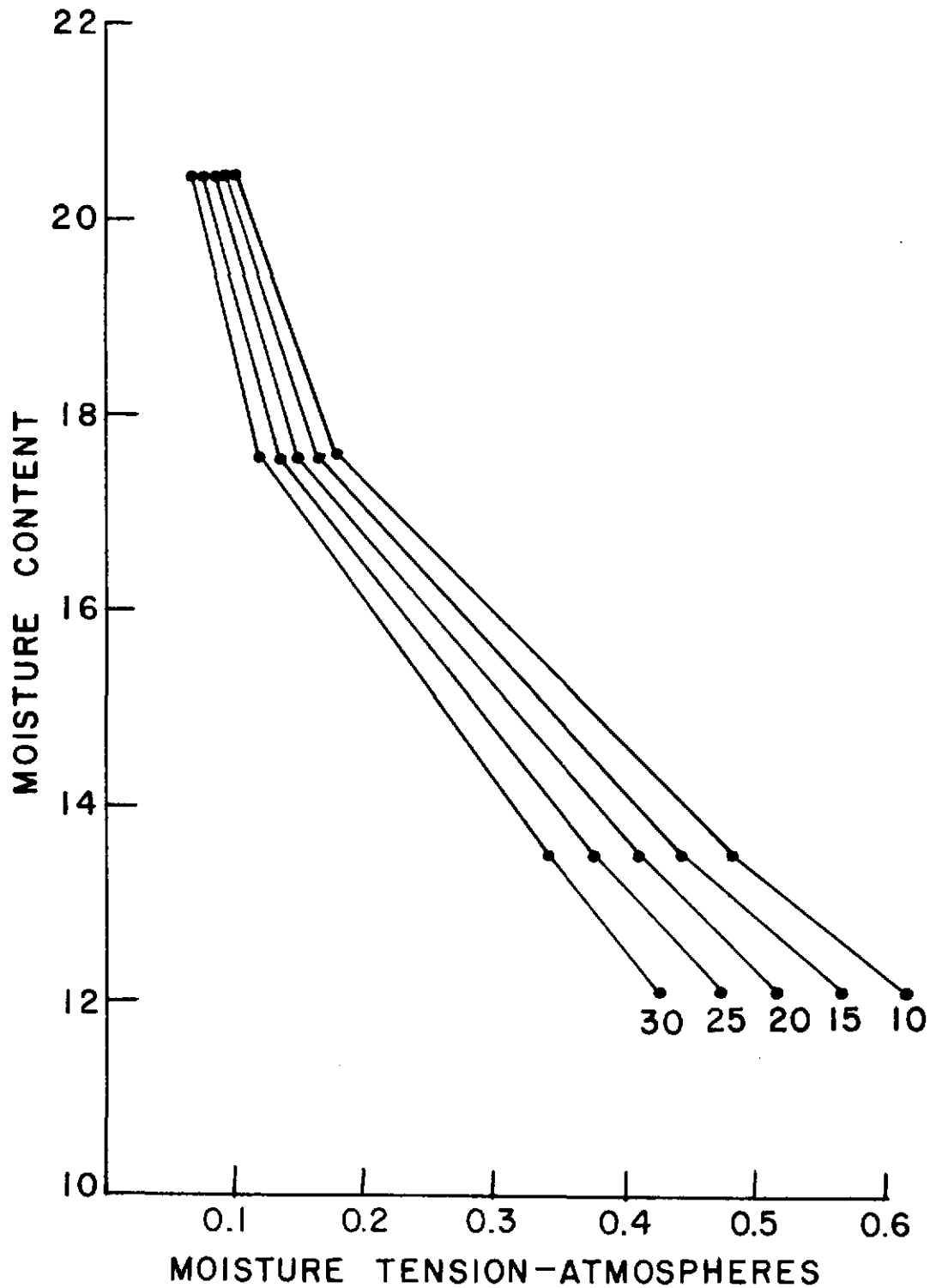
Figure 4. Moisture tension as a function of moisture content at different temperatures. The number below each curve is the temperature in degrees centigrade.

Table 1. Correction values used to correct moisture tension to 20° C.

Soil moisture tension	Soil temperature deviation from 20° C.								
cm. water	2	4	6	8	10	12	14	16	18
> 600	22	44	66	88	110	132	154	176	198
550–600	20	40	60	80	100	120	140	160	180
515–550	18	36	54	72	90	108	126	144	162
465–515	16	32	48	64	80	96	112	128	144
400–465	14	28	42	56	70	84	98	112	126
330–400	12	24	36	48	60	72	84	96	108
250–330	10	20	30	40	50	60	70	80	90
170–250	8	16	24	32	40	48	56	64	72
110–170	6	12	18	24	30	36	42	48	54
75–110	4	8	12	16	20	24	28	32	36
< 75	2	4	6	8	10	12	14	16	18

equation presented by Edlefsen and Anderson will be used to show how they predict soil moisture tension will vary with temperature. In applying this equation it will be assumed that the soil moisture tension h_T is a close approximation of ΔF_{σ_T} and h_{T_1} is an approximation of $\Delta F_{\sigma_{T_1}}$.

Then

$$\Delta F_{\sigma_T} = \frac{(\Delta F_{\sigma_{T_1}})}{(\sigma_{T_1})}\ \sigma_T \quad \text{or} \quad h_T = \frac{h_{T_1}}{\sigma_{T_1}}\ (117 - 0.152\ T) \tag{5}$$

Twenty degrees C. was taken as the reference temperature T_1 and the tension h_{T_1} corresponding to that temperature was taken as the reference tension.

To show, as a first approximation, the effect of temperature on soil moisture tension, a straight line was determined from linear regression for each curve in figures 2 and 3. The experimental and the predicted dependence of soil moisture tension on temperature are shown in figure 5. A statistical analysis was used to determine the significance of the difference between the slopes of the experimental and predicted curves. Employing the t-test (25) indicated a highly significant difference, at the 1 percent level, between the slopes of each set of curves. The data and statistical analysis are given in tables 3 and 4 of the Appendix.

The surface tension of water at different temperatures is given in table 2. It also shows for each moisture content the predicted soil moisture tension at different temperatures.

Field investigation

Temperature measurements were made in the field for the purpose of correcting tensiometer readings for temperature changes that occur in the soil.
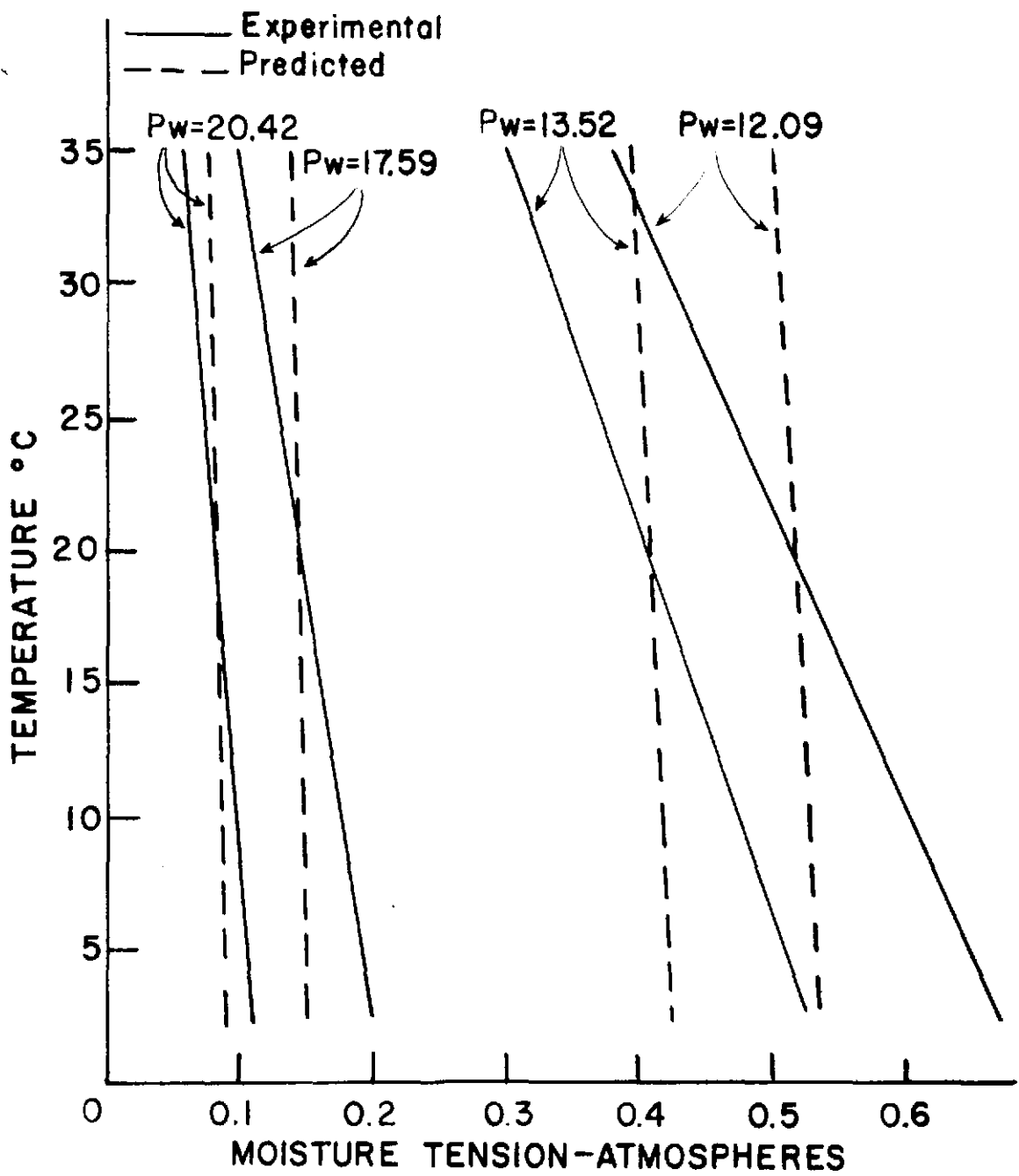
Figure 5. Experimental and predicted effect of temperature on soil
moisture tension at different moisture contents

Table 2. Surface tension of water and soil moisture tension as functions of temperature

Temperature °C. T	Surface tension water σ_T	Predicted moisture tension			
		$P_W=2?.42$ $h_{T_1}=0.??$	$P_W=17.59$ $h_{T_1}=0.145$	$P_W=13.52$ $h_{T_1}=0.406$	$P_W=12.09$ $h_{T_1}=0.516$
0	75.60	0.083	0.151	0.422	0.536
5	74.90	0.082	0.149	0.418	0.531
10	74.22	0.082	0.148	0.414	0.526
15	73.49	0.081	0.146	0.410	0.521
20	72.75	0.080	0.145	0.406	0.516
25	71.97	0.079	0.143	0.402	0.510
30	71.18	0.078	0.142	0.398	0.505
35	70.73 /0.37/	0.077	0.141	0.392	0.499
40	69.56	0.077	0.139	0.389	0.494

There is a significant temperature difference between a.m. and p.m. measurements for the 6-inch depth as shown in figure 6. The top curve shows the change in temperature for the p.m. measurements from day 200 to 280. The bottom curve is for a.m. temperature measurements for the same depth and time interval. The wide maximum range between morning and evening temperatures indicates that if tensions are measured more than once a day, at the 6-inch depth, it might be desirable to apply temperature corrections.

The p.m. and a.m. temperature measurements for the 12-inch depth are shown in figure 7. The maximum temperature difference is about 2° C., therefore temperature corrections for this depth are small. Temperatures for the 18- and 24-inch depths are not shown because there was very little difference in temperature between p.m. and a.m. measurements.

Uncorrected tensiometer readings taken in the evening and morning during irrigation intervals are shown in figures 8, 9, and 10. Figure 8 is for the 6-inch depth when there is considerable tension and temperature changes between irrigation intervals. The tensiometer readings went up fast during the day whereas they might actually drop during the night.

Similar results are shown in figure 9 for the 12-inch depth; however, the rate of tension change is much less than for the 6-inch depth. For the 18-inch depth the rate of tension change is slightly greater during the day than at night as shown in figure 10. For the 24-inch depth the rate of tension change during the day is about the same as at night. It can be seen that the magnitude of fluctuations decrease with depth.

It was previously noted that soil temperature fluctuations between a.m. and p.m. measurements were about 6° C. for the 6-inch depth and as
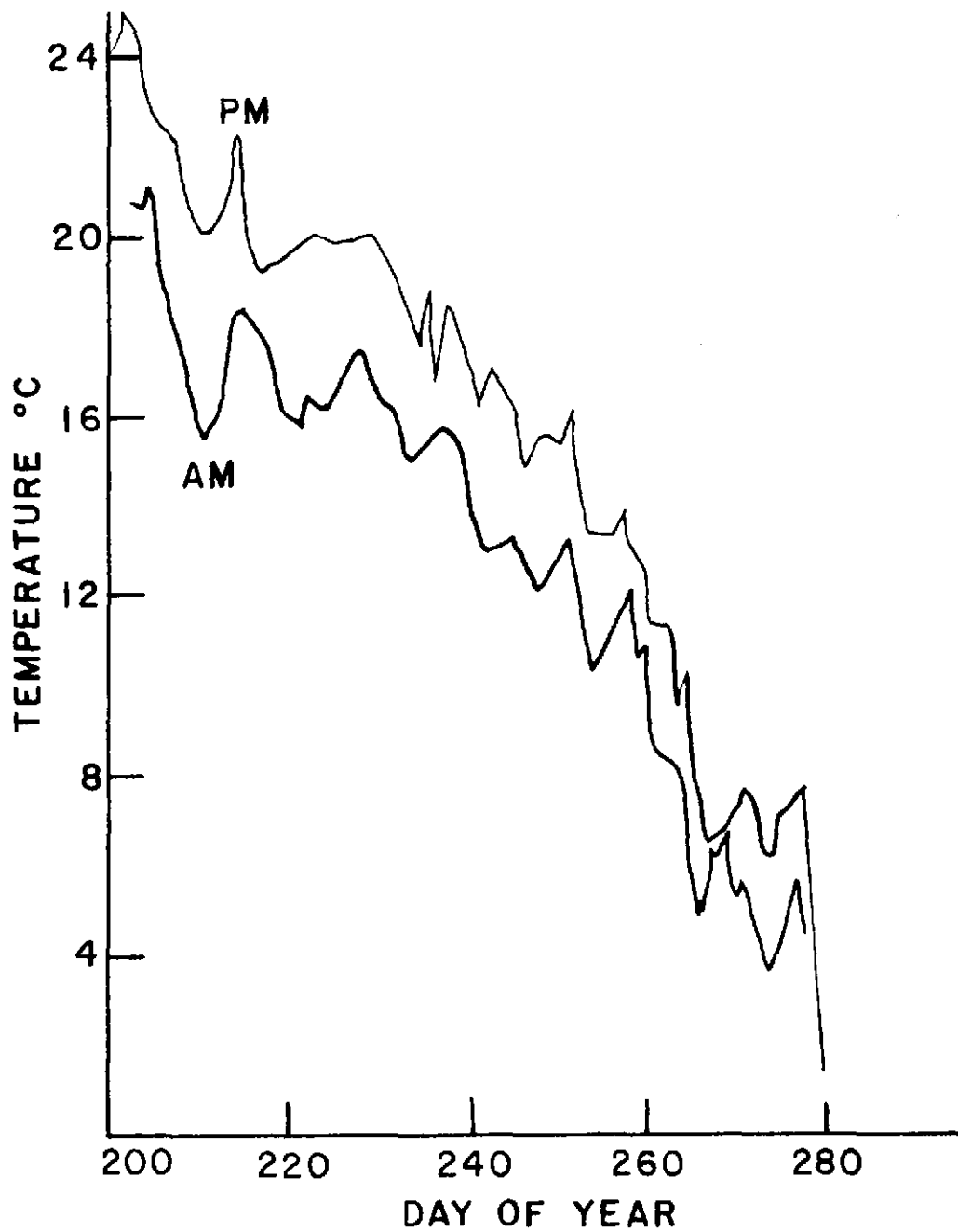
Figure 6. Temperature of the soil at 6 inches for morning (AM) and evening (PM) measurements
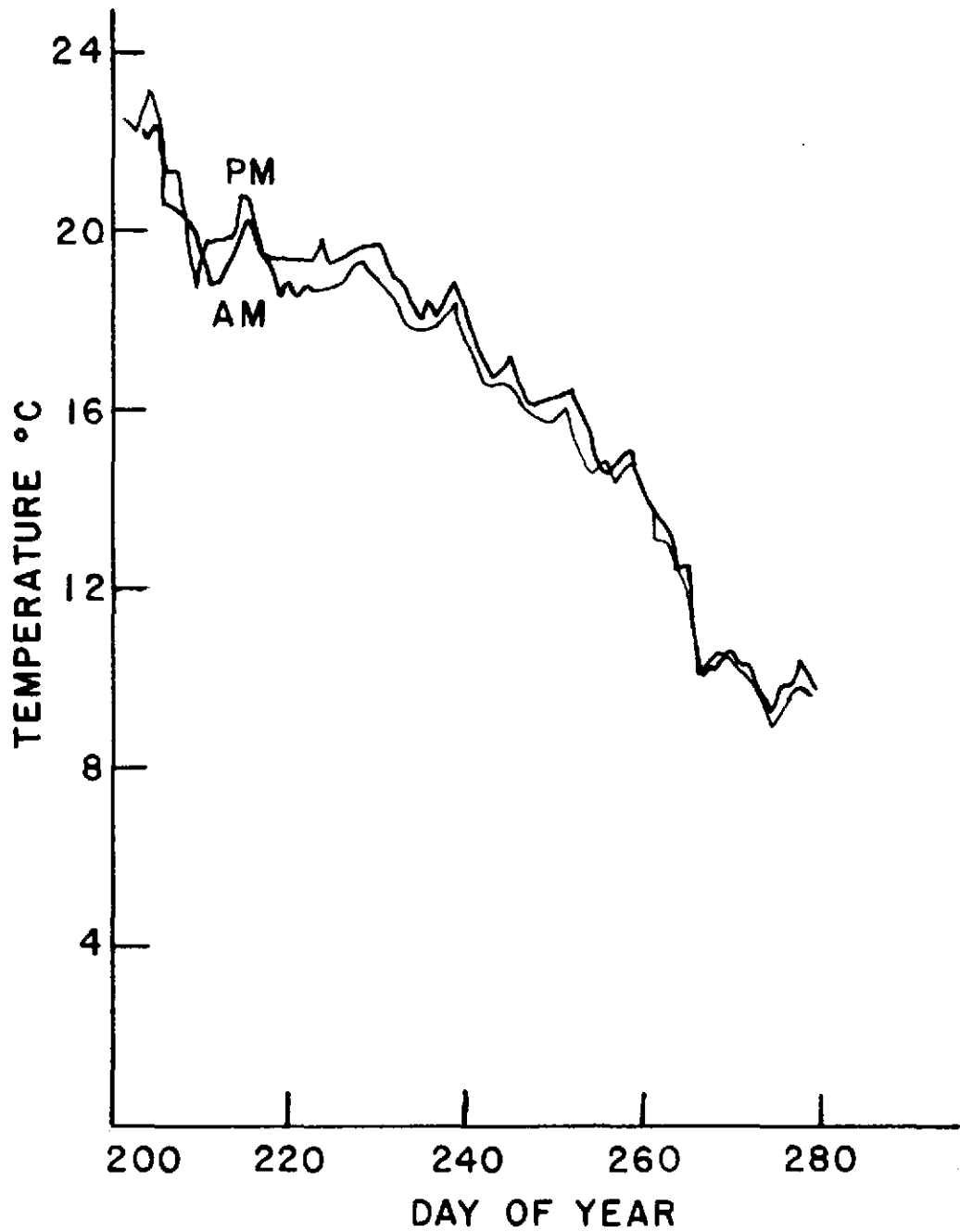
Figure showing temperature (°C) versus day of year, with PM and AM curves.
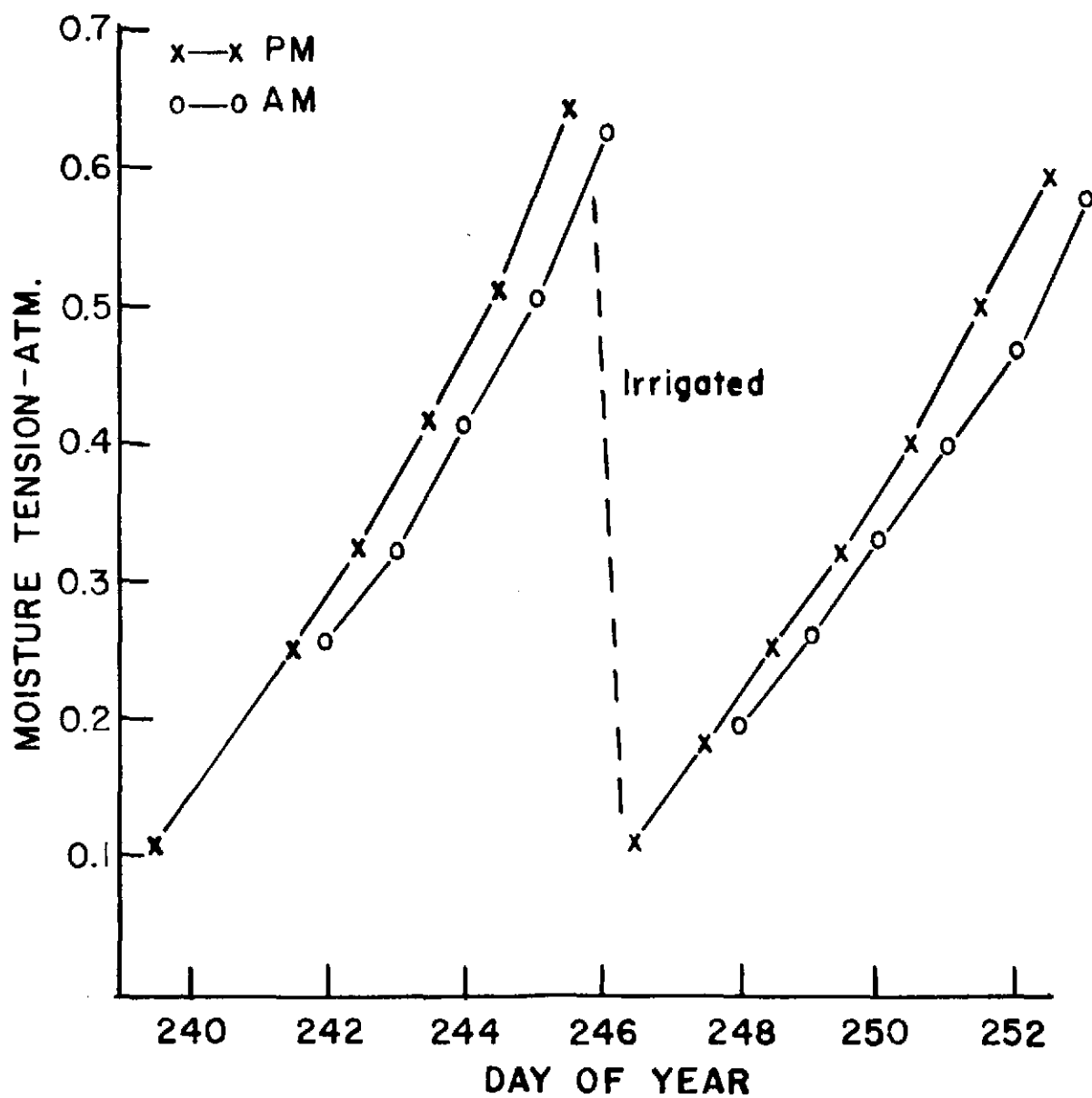
Figure 8. Six-inch tensiometer readings before applying temperature corrections
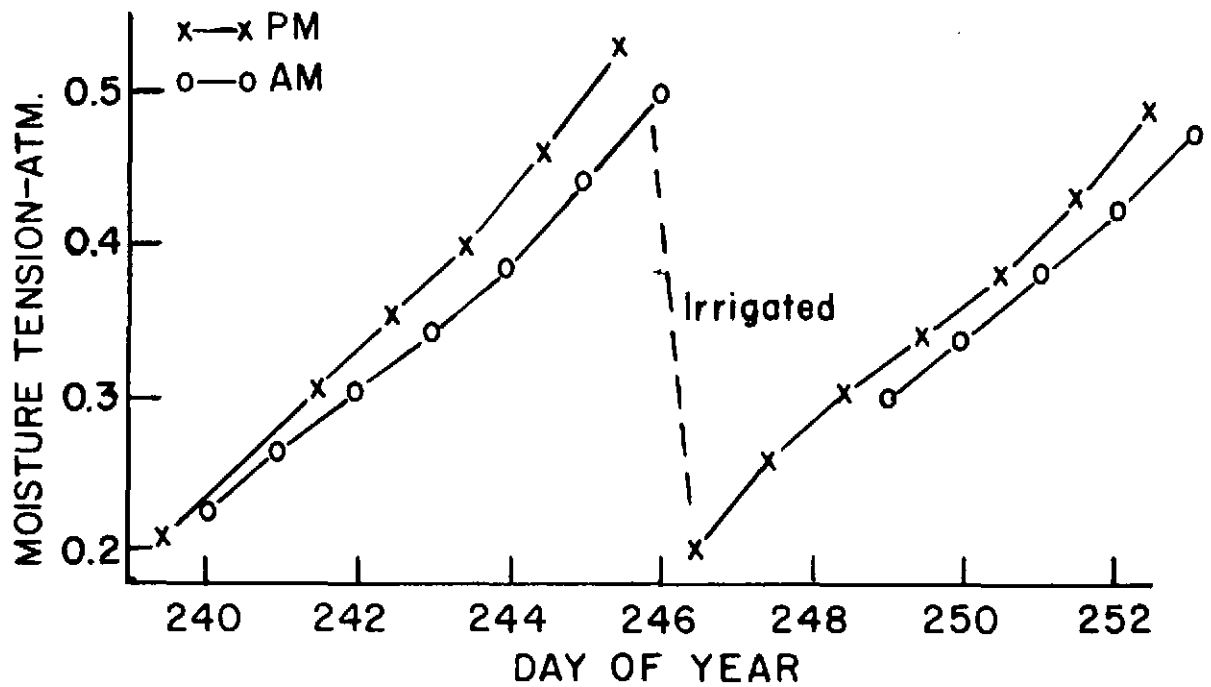
Figure 9. Twelve-inch tensiometer readings before applying temperature corrections
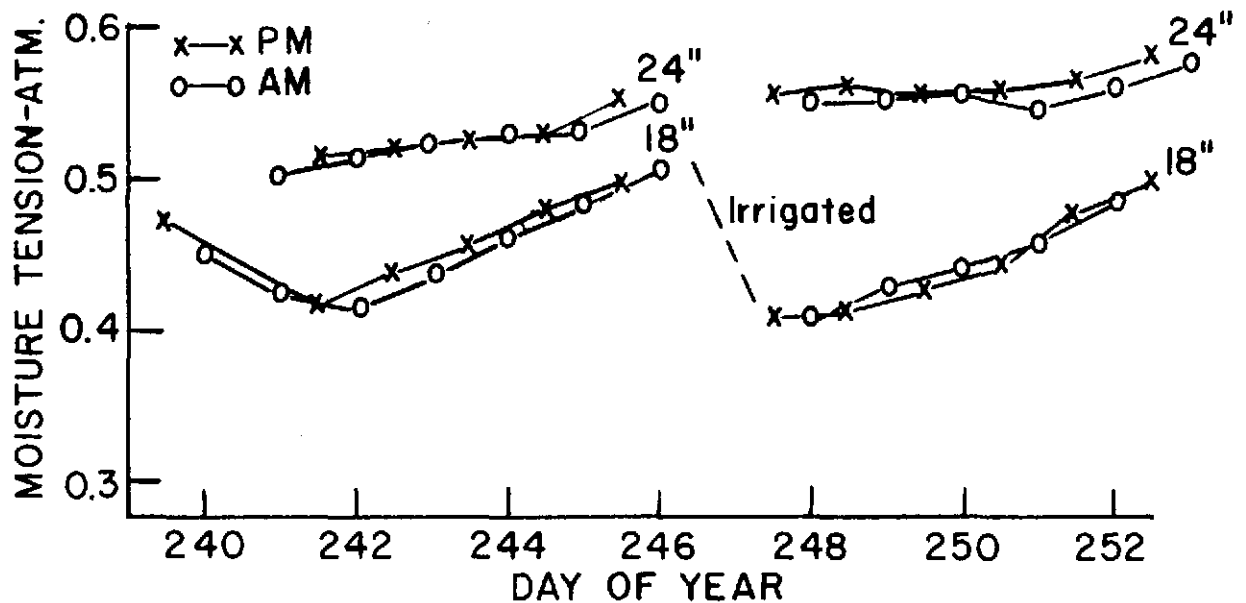
Figure 10. Eighteen- and 24-inch tensiometer readings before applying temperature corrections

much as 2° C. for the 12-inch depth. Using table 1 tension readings at these depths were adjusted to a 20° C. standard.

The results after temperature corrections were applied are shown in figures 11 and 12. For this interval of time (day 238 to 255) the temperature of the soil was always below 20° C., as shown in Apendix table 5; therefore, in applying temperature corrections a correction value was always subtracted from the measured tension. Appendix table 5 shows the corrected and uncorrected tensiometer readings. Since soil is colder in the morning than it is at night a larger correction was applied to the a.m. than the p.m. tension measurements. Applying temperature corrections brought the 2 curves farther apart.
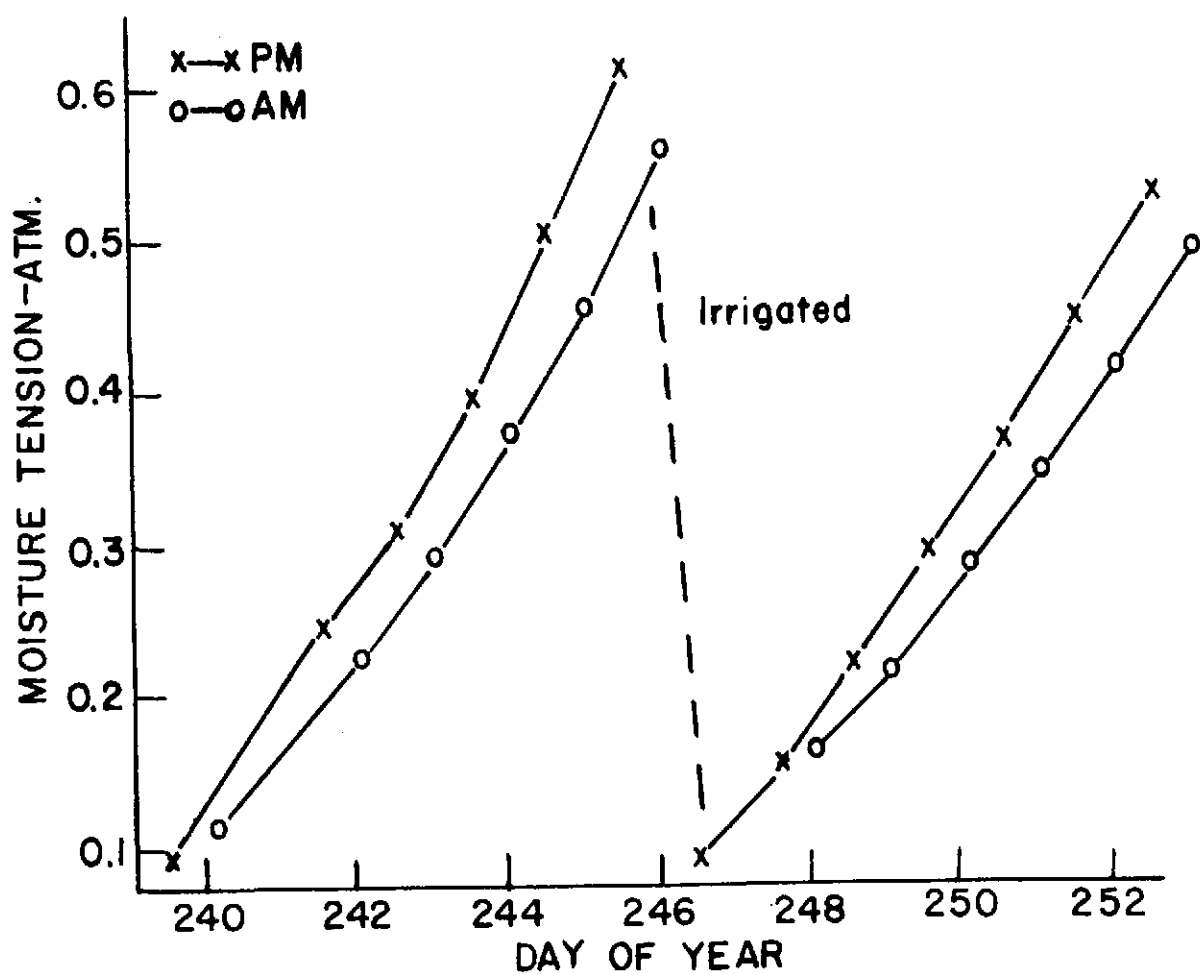
Figure 11. Six-inch tensiometer readings after applying temperature corrections
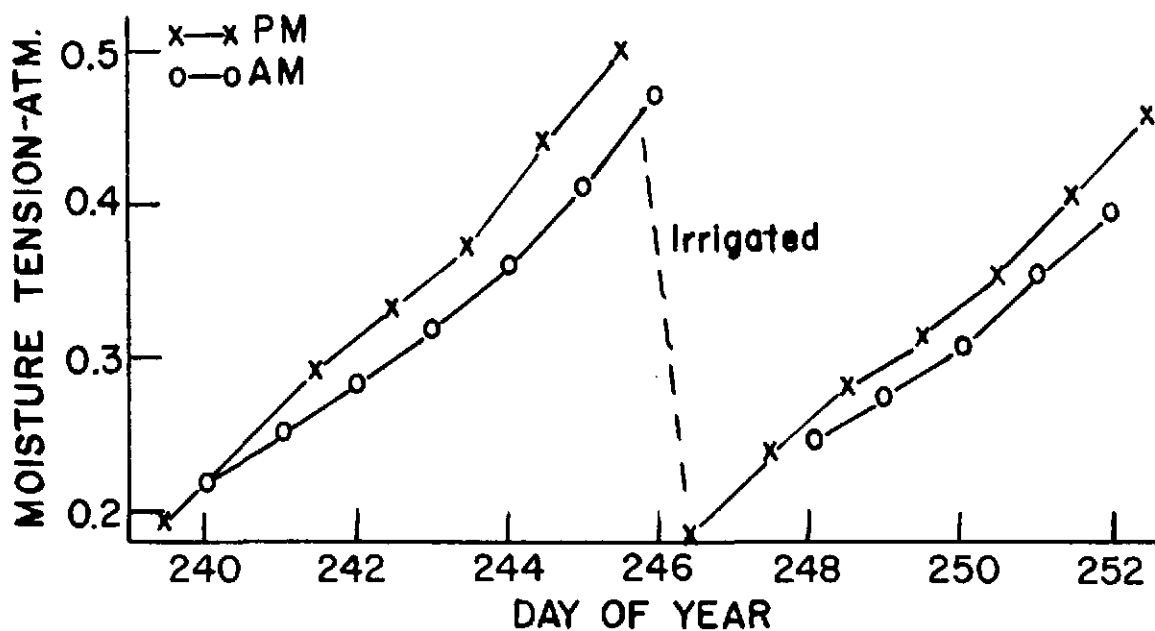
Figure 12. Twelve-inch tensiometer readings after applying temperature corrections

DISCUSSION AND CONCLUSIONS

Laboratory

It is evident that temperature variations may influence the accuracy of many types of soil moisture studies. Fluctuations of these soil moisture properties may be erroneously attributed to causes other than temperature unless it is known how each varies with temperature. If variations with temperature are known it will be possible to make corrections for temperature changes.

One purpose of the laboratory study reported herein was to determine the effect of temperature on moisture tension and to make temperature corrections for field data. Laboratory results showed that temperature had a significant effect on soil moisture tension. The magnitude of the temperature effect depends on the moisture content. At high moisture contents the effect was small whereas at the low moisture contents the effect becomes more significant. Using this information a table was constructed so that temperature corrections could be applied to field data.

The interdependence between moisture tension and temperature that was predicted by Edlefsen and Anderson was much smaller than was found experimentally. Edlefsen and Anderson included only the effect of temperature on the surface tension of water in the soil. It is apparent from the laboratory investigation that the temperature influence on this component of the total free energy is not the only factor involved in showing how moisture tension varies with temperature.

Edlefsen and Anderson assumed that the adsorptive forces are not a function of temperature, and they did not adequately account for the

fact that the kinetic energy of adsorbed water increases with temperature. Their treatment would indicate that the amount of water adsorbed is independent of temperature. On the other hand, work of Mooney, Keenan, and Wood (25) shows that at a given relative vapor pressure the amount of water adsorbed increases as the temperature is decreased. The temperature effect becomes less significant at higher relative vapor pressures. This is in accordance with laboratory results reported herein in showing temperature to have a greater effect at low moisture contents.

The Kelvin equation ($\Delta F = RT \ln \frac{P}{P_o} = \frac{2V\sigma}{r}$) was employed in deriving the Edlefsen and Anderson expression to show the dependence of free energy on temperature. Certain assumptions were made in employing this equation. They first assumed water vapor to behave as an ideal gas and that the radius of the pores in the soil behave as spherical drops. These 2 assumptions might result in error when applied to the soil moisture system. The radius of curvature of the air-water interface is hard to determine directly; therefore, they eliminate it from their equation by assuming it to be constant, independent of temperature. The thermal expansion of water is much greater than that of the solid phase and therefore an increase in temperature would increase the radius of curvature of the air-water interface. The radius of curvature is, therefore, a function of temperature and would introduce error when assuming it to be independent of temperature.

In applying the Edlefsen and Anderson equation the variation of the surface tension of water with temperature had to be known. They assumed the effect of temperature on the surface tension of soil moisture, which is in an adsorptive field, to be approximately equal to that of pure water, which is not in an adsorptive field. Water under the influence

of adsorptive forces is likely to be affected differently by temperature than pure free water which is not influenced by adsorptive fields.

Another source of error might have resulted by using the tensiometer to measure the component of the free energy caused by capillary forces. Edlefsen and Anderson suggest that the porous bulb method can be employed to measure the capillary potential. They also suggest that for a relatively moist soil the capillary potential is synonymous with free energy and the adsorptive field is negligible, and has no influence on the air-water interface. Drier soils result in larger adsorptive forces and, therefore, influence the air-water interface. The component of the free energy involved in the Edlefsen and Anderson equation does not include adsorptive forces. Tensiometers measure capillary forces as well as adsorptive forces; therefore, if adsorptive forces are not negligible, tensiometers will not give an accurate measure of the capillary potential.

One error inherent in the design of the tensiometer which tends to erroneously magnify the moisture tension-temperature relationship would be caused by the thermal expansion of the tensiometer water. When the temperature is increased there is an increase in volume of the tensiometer water which causes a lower tension reading. Conversely, a decrease in temperature decreases the volume of water which causes a higher manometer reading. The magnitude of this error is not known but is considered to be small because of improvements in the design of tensiometers.

The experimental data presented in this thesis is believed to be a reasonably accurate measure of the effect of temperature on soil moisture tension. Strong evidence is given by the laboratory results which indicate that the Edlefsen and Anderson expression did not include all of the factors that influence the effect of temperature on soil moisture

adsorption. A few possible explanations why the Edlefsen and Anderson expression did not fit the experimental data have been suggested. However, it is not known how each will influence the effect of temperature on soil moisture tension. This indicates that more work needs to be done in showing theoretically how temperature will influence soil moisture tension.

Field

It is apparent from the field investigation that the diurnal fluctuations of tensiometers are probably associated with temperature variations. However, when making tension measurements in the field it was found that temperature had an opposite effect on tensiometer readings than was indicated by the laboratory experiment. Laboratory results showed that the soil moisture tension decreased with an increase in temperature whereas field results showed that as the temperature increases the tensiometer readings also increase. It is evident that other factors are influencing tensiometer readings in the field other than the direct effect of temperature on soil moisture tension.

In the field there are considerable temperature and moisture gradients throughout the soil profile. Because of these gradients the soil moisture system is not in equilibrium when making tension measurements. Therefore, using field data it is impossible to make a correct evaluation of the temperature effect on moisture tension. However, from the field data it is possible to make suggestions that will increase the accuracy of tension measurements using tensiometers.

Several possible explanations for causes resulting in large diurnal fluctuations of tensiometers in the field can be given. One possible explanation would be that during the sunshine hours the evaporation rate

can exceed the upward flow of water from the wet soil below. This results in a net drying of the surface soil and a corresponding rise in tension. After sundown the upward rate of water movement may exceed the evaporation rate which results in a lowering of the tension. After the sun goes down the surface soil cools at a greater rate than the soil at lower depths. Water would tend to move under a thermal gradient from the warmer soil below to the cooler soil above.

Another possible explanation is that during the hours of sunlight the transpiration rate of plants is much greater than during the hours of darkness. The quantity of water removed from the soil by plants during the daytime is, therefore, much greater than during the night. Hence, the soil moisture tension should increase at a much greater rate during the daytime than during the night. Sometimes it was observed that the tension may decrease during the night. This would indicate water is moving from the wet soil below to dry soil above.

A third possible explanation is given by Haise and Kelly (20) who report that fluctuations may be caused by the effect of air temperature changes in creating a temperature gradient between the porous cup and the surrounding soil. The metal portion of the tensiometer is above ground and exposed to changes in air temperature. Radiation of heat from the metal would occur more rapidly than in the soil. This would result in a temperature gradient between the porous cup and the soil. When the cup is cooler than the surrounding soil, water will move from the soil in the vapor phase and condense on the tensiometer system. Water condensing on the cup enters it because the water in the tensiometer system is under tension. This situation occurs in cool evenings when the air temperature is less than that of the soil. Water entering the tensiometer system results in a decrease in the manometer reading.

The reverse situation would occur when the soil is cooler than the tensiometer cup. This usually happens during the daytime when the air temperatures are high. Water will leave the warmer cup surface in the vapor phase and condense on the cooler surrounding soil. This results in an increase of the manometer reading.

These effects would all tend to increase the manometer reading as the temperature is increased and conversely as the temperature is decreased the manometer reading would decrease.

The fluctuations caused by volume changes of the water in the tensiometer would be opposite in direction to the actual changes observed in the field. The change in volume of the tension water caused by thermal expansion would tend to minimize the other effects.

SUMMARY

1. The purpose of this investigation was to determine the effect of temperature on soil moisture tension.

2. At a constant moisture content an increase in temperature results in a lower moisture tension. The significance of the temperature effect increases as the moisture content decreases. For low moisture contents the tension was found to decrease at approximately 0.009 atmospheres per degree rise in temperature. For moisture contents near saturation the temperature effect appeared negligible.

3. For the temperature range between 0 and 30° C. the effect of temperature on soil moisture tension, as a first approximation, appeared to be linear.

4. Moisture tension was plotted as a function of moisture content for different temperatures. Knowing the equation of the isotherms, a table was prepared so that tensions could be corrected to a 20° C. standard.

5. The magnitude of temperature influence on soil moisture tension predicted by Edlefsen and Anderson was much less than laboratory results indicated.

6. The field experiment indicated that there may be considerable fluctuations of tensiometers in the field. Tensiometer readings were sometimes found to be greater at night than they were the next morning. For this reason it is important to read tensiometers the same time each day.

7. Fluctuations of the tensiometers in the field as a result of temperature changes were opposite to those predicted from laboratory results.

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APPENDIX

Table 3. Soil moisture tension as a function of temperature

Temp. °C.	P_W=12.09 atm. tension	Temp. °C.	P_W=13.52 atm. tension	P_W=17.59	Temp. °C.	P_W=20.42 atm. tension
22.4	0.582	2.0	0.510	0.194	10.6	0.082
31.0	0.474	17.6	0.424	0.140	22.4	0.072
41.4	0.290	25.7	0.370	0.120	31.0	0.064
30.8	0.435	31.0	0.315	0.100	41.4	0.044
16.0	0.562	44.3	0.132	0.062	30.8	0.068
5.0	0.610	37.7	0.170	0.085	16.0	0.090
17.2	0.484	31.0	0.336	0.126	5.0	0.092
30.8	0.382	20.7	0.422	0.146	17.2	0.080
39.8	0.262	33.5	0.310	0.112	30.8	0.064
21.4	0.494	16.4	0.424	0.143	39.8	0.047
9.2	0.544				21.4	0.084
21.3	0.500				9.2	0.093
33.8	0.334				21.3	0.062
21.8	0.448				33.8	0.058
					21.8	0.086

Table 4. Statistical analysis

P_W	Equation of regression line — Experimental	Equation of regression line — Predicted	Calculated T value $T = \dfrac{b - B}{S_b}$
12.09	$\hat{Y} = 65.9 - 90.6\ X$	$\hat{Y} = 510.5 - 952\ X$	41.80
13.52	$\hat{Y} = 80.6 - 149.2\ X$	$\hat{Y} = 511.5 - 1212\ X$	97.16
17.59	$\hat{Y} = 65.9 - 321.0\ X$	$\hat{Y} = 503.3 - 3333\ X$	54.17
20.42	$\hat{Y} = 75.5 - 699.8\ X$	$\hat{Y} = 553.3 - 6666\ X$	56.02

* All values are highly significant at the 1 percent level.

Table 5. Corrected and uncorrected tensiometer readings for the 6-,
12-, 18-, and 24-inch depths. No correction was applied to
the 18- and 24-inch depths.

Depth	Day of year	a.m. measurements			p.m. measurements		
		Temp.	Atmospheres tension		Temp.	Atmospheres tension	
in.		°C.	before correction	after correction	°C.	before correction	after correction
6	238	15.7	0.466	0.436	18.4	0.570	0.538
12		18.1	0.440	0.426	16.8	0.520	0.506
18		18.0	0.450	–	18.4	0.464	–
24		17.8	0.384	–	17.8	0.478	–
6	239	15.7	0.472	0.444	17.8	0.106	0.100
12		18.4	0.474	0.462	18.1	0.102	0.194
18		18.0	0.466	–	17.8	0.476	–
24		17.8	0.482	–	17.4	0.440	–
6	240	14.3	0.132	0.117	–	–	–
12		17.5	0.222	0.214	–	–	–
18		17.6	0.450	–	–	–	–
24		17.4	0.480	–	–	–	–
6	241	13.3	0.296	0.276	17.1	0.252	0.247
12		16.6	0.264	0.250	17.2	0.304	0.289
18		17.3	0.422	–	16.9	0.420	–
24		17.0	0.502	–	17.0	0.512	–
6	242	13.0	0.258	0.228	16.3	0.335	0.311
12		16.6	0.300	0.285	16.8	0.350	0.329
18		17.3	0.418	–	16.6	0.435	–
24		17.0	0.514	–	16.6	0.518	–
6	243	13.0	0.330	0.294	17.0	0.424	0.400
12		16.5	0.340	0.320	16.8	0.398	0.373
18		17.3	0.440	–	16.8	0.454	–
24		17.0	0.524	–	16.6	0.524	–
6	244	13.3	0.416	0.376	16.6	0.546	0.515
12		16.5	0.382	0.362	17.2	0.466	0.439
18		17.0	0.462	–	16.7	0.476	–
24		16.7	0.532	–	16.6	0.526	–
6	245	13.3	0.522	0.467	16.2	0.648	0.604
12		16.6	0.438	0.413	16.8	0.528	0.498
18		17.0	0.484	–	16.7	0.492	–
24		16.7	0.530	–	16.7	0.552	–

Table 5. Continued

Depth	Day of year	a.m. measurements			p.m. measurements		
		Temp.	Atmospheres tension		Temp.	Atmospheres tension	
in.		°C.	before correction	after correction	°C.	before correction	after correction
6	246	12.5	0.638	0.563	14.8	0.104	0.91
12		16.3	0.498	0.470	16.1	0.196	0.176
18		16.7	0.504	–	16.7	0.492	–
24		16.7	0.550	–	16.1	0.508	–
6	247	–	–	–	15.1	0.178	0.158
12		–	–	–	16.1	0.260	0.240
18		–	–	–	16.1	0.412	–
24		–	–	–	16.1	0.556	–
6	248	12.0	0.194	0.164	15.6	0.246	0.218
12		15.8	0.264	0.244	16.2	0.300	0.280
18		16.1	0.410	–	16.1	0.414	–
24		16.1	0.552	–	16.1	0.558	–
6	249	12.4	0.252	0.217	15.5	0.316	0.293
12		15.9	0.300	0.280	16.2	0.336	0.312
18		16.4	0.428	–	16.1	0.426	–
24		16.1	0.552	–	16.1	0.552	–
6	250	12.6	0.324	0.290	15.4	0.370	0.363
12		15.8	0.338	0.312	16.3	0.378	0.354
18		16.4	0.436	–	16.2	0.446	–
24		16.1	0.556	–	16.1	0.556	–
6	251	13.2	0.406	0.364	16.2	0.482	0.450
12		16.1	0.480	0.358	16.4	0.430	0.402
18		16.4	0.458	–	16.2	0.470	–
24		16.1	0.546	–	16.0	0.568	–
6	252	12.8	0.428	0.382	14.7	0.580	0.530
12		16.1	0.422	0.396	16.1	0.490	0.458
18		16.4	0.482	–	16.1	0.496	–
24		16.1	0.510	–	16.1	0.578	–
6	253	13.6	0.572	0.498	–	–	–
12		15.8	0.474	0.420	–	–	–
18		15.5	0.308	–	–	–	–
24		15.6	0.376	–	–	–	–