MEASUREMENT OF RAIN TEMPERATURE

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ABSTRACT

A technique for measuring the temperature of rain at the ground and the methods for calibrating the equipment used for this purpose are described in this report. A preliminary analysis of the data indicates that significant differences between the rain and ambient air temperatures usually occur in the first portion of the thunderstorm rain period and that the differences in temperature between the ambient air and the rain falling from the latter portion of the storm are small.

1. Introduction

In studies of the thermodynamics of the thunderstorm it is recognized that falling raindrops cool the air underneath the clouds. In a previous paper [3] the senior author attributed the cooling to three factors: (*1*) the evaporation of water from the falling raindrops and wetted surface, (*2*) the bringing down from aloft of air having a potentially lower wet-bulb temperature, and (*3*) the melting of hailstones in a part of the air that is brought down. It was assumed that the raindrops, although falling downward toward continually higher wet-bulb tempeatures, would have their temperature increased so that they would not be colder than the wet bulb. This increase of temperature in the drops would come about not only through contact heating from the warmer air but also by heat from condensation on the drops which would take place as soon as they became appreciably colder than the ambient air. The heat exchange woud bring the air to its wet-bulb temperature and, according to the assumptions, the falling raindrops would have the same temperature as the air at this time.

The theory suffered from the fact that there was no proof that the rate of heat exchange to the raindrops was rapid enough to maintain temperature equilibrium. It therefore seemed necessary to make measurements of the rain temperatures. Meteorologists in Germany [1] and India [4] have described instruments for making such measurements, but no suitable instrument for this purpose was available.

A rain thermometer was therefore developed in the meteorological laboratories of the University of Chicago for use during the second observation season of the joint Air Force, Weather Bureau, NACA, and Navy Thunderstorm Project at Wilmington, Ohio in 1947 [6, 7]. It was placed in operation in time to obtain continuous simultaneous recordings of air and rain temperatures in several thunderstorms. The technique of rain-temperature measurement and an analysis of some of the data are presented in this paper.

2. Description of the instrument

Rain was collected in a thin aluminum funnel (A), mounted on a wooden stand three feet high (fig. 1). A small cylindrical ceramic resistor (B), $\frac{1}{2}$-inch long and $\frac{1}{32}$-inch in diameter, was mounted on a wire frame at the apex of the funnel; the aluminum cone (C) served as a protective shield. During moderate to heavy rain, water accumulated only up to the level of the overflow hole (D), which was about one-eighth of an inch above the temperature element. The hole (E) at the apex led to a capillary leak arrangement made from rubber tubing and an adjustable pinch clamp. The leakage outflow rate was set at approximately $\frac{1}{3}$ cm^3 per second, in order to measure the temperature of the water surrounding the thermistor element within ten seconds after it entered the funnel.

The ceramic resistor is much smaller in size than the temperature element of radiosondes presently used in this country, but is made of the same material. It has a large negative temperature coefficient, approximately 600 ohms per degree centigrade in the operating range, but the relation is sufficiently nonlinear to necessitate a careful calibration before using. Once calibrated, most resistors held their calibration to within 0.5C for weeks or even months.

Since the temperature element had to be continually immersed in water, it was necessary to completely insulate the resistor so that the parallel resistance path through the water from one lead to the other, or to ground, was at least 1 to 2 megohms. After trying a number of substances it was found that four or five applications of Glyptal[2] 1201 followed by baking at 125C for two hours after each coat provided satisfactory insulation. Before the first painting it was necessary to carefully eliminate all sharp edges, since insulation breakdowns occurred most frequently at

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[2] Manufactured by General Electric Company.

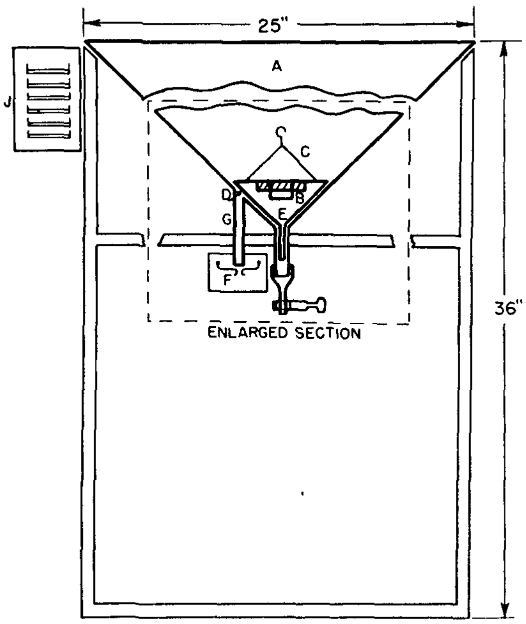

FIG. 1. Schematic diagram of rain-temperature equipment.

these points. Although four or five coats of Glyptal increased the lag of the ceramic resistor, the lag coefficient or time-lag constant [5] in water was still less than one second, more than sufficiently sensitive for the measurements to be made.

A small thermoscreen (J, fig. 1), housing a second thermal element, was mounted on the funnel stand. This element, also a ceramic resistor, measured the ambient air temperature; insulation was unnecessary because it remained dry. During runs the wind provided adequate ventilation.

The resistance and consequently the temperature of both thermal elements was measured by a vacuum-tube ohmmeter circuit [2] and recorded by a 0–5 milliampere Esterline–Angus Recorder used in place of the usual indicating milliammeter. A motor-driven switch alternated between the rain and air resistors approximately every 30 seconds. This vacuum-tube ohmmeter was previously used for air-temperature measurements by P-61C aircraft and only slight modifications were needed to adapt it for use here. The circuit diagram (fig. 2) shows that the basic element of the vacuum-tube ohmmeter is a bridge circuit. It may be seen that changes in the resistance of the temperature element varies the grid bias of V_1 and consequently causes a change in the plate-circuit current of this tube. The resulting change in potential across the bridge, from points A to B, is recorded on the Esterline–Angus Recorder. In the operating range the relation between the resistance of the temperature element and the meter current is approximately linear.

Before and after each set of measurements, the calibration of the ohmmeter was checked by substituting precision resistors for the temperature elements. Further calibration adjustment was obtained by varying resistors R_1, R_2, and R_3 which were used to correct for changes in the bias battery voltage, sensitivity, and zero-setting, respectively. The ohmmeter, however, was found to be very stable and little or no change occurred from day to day in the relationship between resistance and meter current.

Valid rain-temperature measurements are obtained only when the element is completely immersed in water and it is evident from fig. 1 that this must occur whenever water flows through the overflow tube, since the element would then be one-eighth inch below the water level in the apex of the cone. It is realized that on occasions when the rate of rainfall is just equal to the capillary outflow rate no water will pass through this tube even though the element is immersed. However, this will occur in only a few cases. An auxiliary apparatus was developed to indicate the immersion of the element by recording the passage of water through the overflow tube.

This apparatus consists of two wires (F, fig. 1), mounted just below the overflow tube (G). A drop of water falling from this tube makes contact with the wires, thereby lowering the resistance between them. The decrease in resistance causes a change in the current through a relay wired in place of the meter in a vacuum-tube ohmmeter circuit similar to the one shown in fig. 2. The flow of water through the overflow tube is recorded in the margin of the Esterline–Angus chart (fig. 3) by a chronograph pen controlled by the relay arrangements.

3. Sample record

As can be seen from the sample record (fig. 3), three types of information were recorded: (*1*) ambient air temperature is indicated on the left, near ordinate 36, (*2*) rain temperature is denoted near ordinate 52, and (*3*) the immersion of the rain-temperature element is shown by the pips in the right-hand margin. The chart speed was twelve inches per

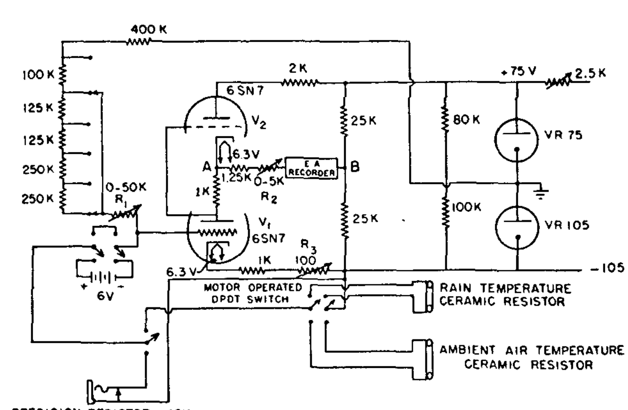

FIG. 2. Schematic diagram of vacuum-tube ohmmeter used for measuring rain and ambient air temperature.

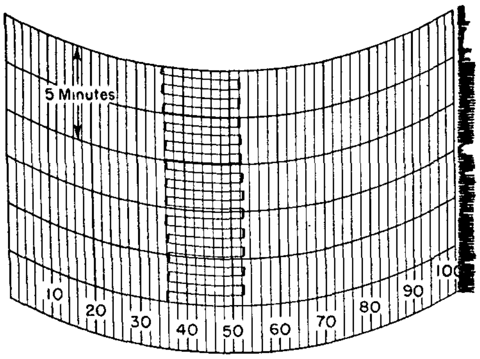

FIG. 3. Sample record showing rain and ambient air temperatures, and immersion pips.

hour, so that two and one-half minutes are represented by the interval between two arcs on the printed chart. A template relating temperature to the chart scale was used in evaluating the data; in general, one degree centigrade corresponds to one and one-half scale divisions.

4. Calibration of the equipment

Since rain falling through the atmosphere undergoes a change in temperature because of evaporational cooling and contact with the air, the temperature of the rain at any given time is a function of height. The rain temperatures discussed in this paper are those at the level of the funnel top, *i.e.*, 3 ft above the ground. It was necessary to determine by experiment the amount of change which occurred in the temperature of the rain from the time it entered the top of the funnel to the time of measurement. This change in temperature is essentially a function of the difference in temperature between the rain and the inner funnel surface. The temperature of the inner surface of the funnel is in turn determined by the ambient air temperature, the wet-bulb temperature, and the temperature and intensity of the rainfall. The effect of wind speed on the temperature of the wetted funnel surface was neglected since for the relative humidities and wind speeds present during the observations the corrections due to this effect would amount to a small fraction of a degree.

At the instant the rain starts, the funnel temperature is essentially equal to that of the air. During short rain periods, the relative humidity may remain below 100 per cent; in such cases the inner funnel surface tends to be cooled to the wet-bulb temperature but the outer surface is warmed by contact with the air. The presence of dry spots on the inner funnel surface further tends to keep the funnel from cooling to the wet-bulb temperature.

The result is that, in brief showers, even though the rain may reach moderate intensity, temperature gradients exist on the inner funnel surface and its mean temperature is somewhere between the ambient dry-bulb and wet-bulb temperatures. After rain has continued for some time or during heavy showers, the relative humidity rises to near 100 per cent, markedly reducing the funnel temperature gradients.

The temperature of the raindrops themselves influences the funnel temperature. This effect becomes very significant during heavy rain since the temperature of the inner funnel surface then approaches the rain temperature. When such is the case, the change in rain temperature from the time of entering the funnel top to the time of measurement becomes small.

A calibration chamber was constructed (fig. 4), in which it was possible to simulate rainfall conditions prevailing during summer thunderstorms in Ohio. The ambient air temperature, wet-bulb temperature or relative humidity, and the intensity and temperature of rainfall were measured and controlled in order to establish experimentally the effect of these variables on the amount of rain-temperature change from the funnel entrance to the measurement level. The following technique was used to control the rainfall.

Water of predetermined temperature was siphoned from container A (fig. 4) to the modified Erlenmeyer flask B. As a result of the overflow arrangement, the the water of flask B remained approximately at the level of the overflow arm and was independent of the pressure head of the water in container A. This maintained constant rainfall rates even though the amount of water in container A decreased. From the bottom outlet of flask B, the water passed through a spray unit (C) and thence to the funnel in droplets. A thermal element located at the perforated plate of the

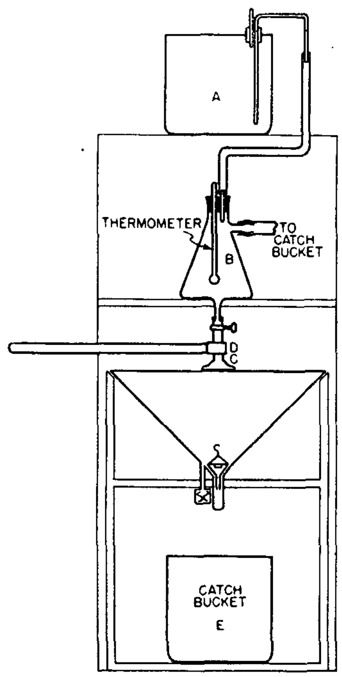

FIG. 4. Schematic diagram of rain-temperature calibration chamber.

spray unit measured the water temperature at approximately the level of the funnel top. The rate of simulated rainfall was controlled by a valve just below the flask outlet. During calibrations the spray unit was moved about by the agitator rod D, so that the water droplets usually hit the funnel before they reached the apex.

The relative humidity of the chamber was raised by placing dry ice into the catch bucket E containing

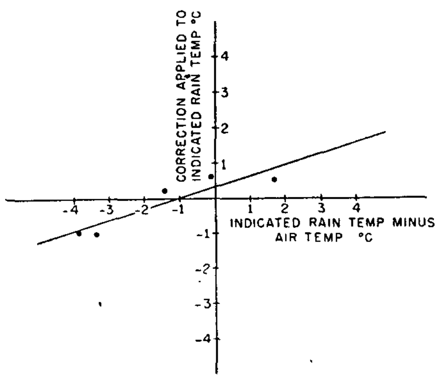

FIG. 5. Funnel calibration chart for rain-temperature measurements. Rainfall rate: heavy; relative humidity: over 90 per cent.

water and allowing bubbling to take place. By this method it was possible to raise the relative humidity to nearly 100 per cent in a few minutes. The rise in relative humidity was partly due to the lowering of the temperature and partly to the occlusion of water vapor in the carbon-dioxide bubbles. The air in the chamber was mixed by a motor-driven fan, and appeared to be thoroughly stirred since temperature measurements at three points in different parts of the chamber agreed to within a few tenths of a degree centigrade; also, humidity measurements by a wet- and dry-bulb psychrometer and a hair hygrometer at two separate locations agreed to within a few per cent, which is within the experimental error of such instruments. Adding silica gel or mixing the room air with that in the chamber served to lower the chamber humidity.

Calibration charts were constructed showing the correction for the influences on the rain-temperature occurring from the time the rain entered the funnel to the time of measurement. The curve of fig. 5 shows the corrections to be applied to the indicated rain temperature for various differences between the latter and the ambient air temperature under conditions of heavy rainfall and relative humidity over 90 per cent. Separate curves were drawn for other relative humidities and rates of rainfall.

5. A preliminary analysis of the rain temperature data

In analyzing the data, the rain temperature, ambient air temperature, wet-bulb temperature and rate of rainfall were plotted as functions of time (figs. 6–8). Seven storms were analyzed in this manner and several characteristic types of rain-temperature patterns were observed.

Type I.—A Type-I pattern is characterized by the decrease of the rain temperature to a minimum within a few minutes after the onset of rain and rising thereafter to within about 1C of the air temperature (fig. 6). In the meantime, the air temperature also lowers but at a slower rate so that the difference between the air and rain temperatures reaches a maximum within a few minutes after the rain begins. This characteristic drop in rain temperature associated with a lesser drop in air temperature has been termed the 'rain-temperature dip.' Such a pattern has been observed more frequently than the other types; the rain-temperature patterns of four of the seven storms considered in this report may be classed as Type I.

It is interesting to note that in the storm of 14 August 1947 (fig. 6) the time variation in the wet-bulb and rain temperatures are similar. This phenomenon is found during most rain periods and is not unique with the Type-I rain-temperature pattern.

The cold fast-moving downdraft associated with summer thunderstorms observed in Ohio causes the surface air temperature to drop from above 90F to approximately 70F in the course of about 20 to 25 minutes. The point at which the temperature begins to fall sharply has been termed the 'temperature break.' When rain first begins to fall from a young storm cell the 'temperature break' and the beginning of rain are separated by a few minutes in time so that the rain nearing the ground falls into an air layer which usually has a temperature in the eighties or upper seventies and is unsaturated. The temperature of the evaporating rain droplets then remains lower than that of the ambient air and tends toward the wet-bulb temperature. These are the conditions under which the Type-I rain-temperature pattern may be expected to occur.

Type II.—In Type II the rain temperature either drops very sharply shortly after the onset of rain or is initially considerably lower than the ambient air temperature—by as much as 10C (fig. 7). The chief differences between patterns I and II is one of degree, the differences between the rain and ambient air temperatures being considerably greater in Type II. This pattern appears to be associated with hail which either melts in the layers close to the earth or has actually reached the surface. Hail was reported near the instrument on two of the three occasions during which this pattern was observed. Only one of these storms, that of 14 July 1947, was used in this study.

Type III.—In this type of rain pattern there is no characteristic 'rain-temperature dip,' and the differ-

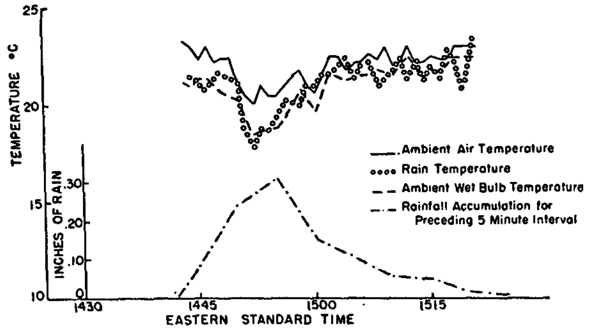

FIG. 6. Air–rain temperature relationships, Type I; 14 August 1947, Station B, Clinton County Air Force Base, Wilmington, Ohio.

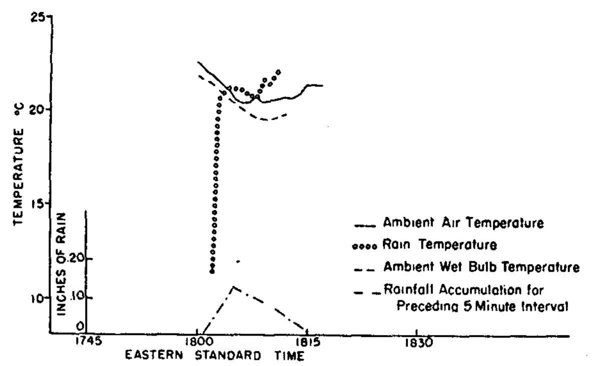

FIG. 7. Air–rain temperature relationships, Type II; 14 July 1947, Station B, Clinton County Air Force Base, Wilmington, Ohio.

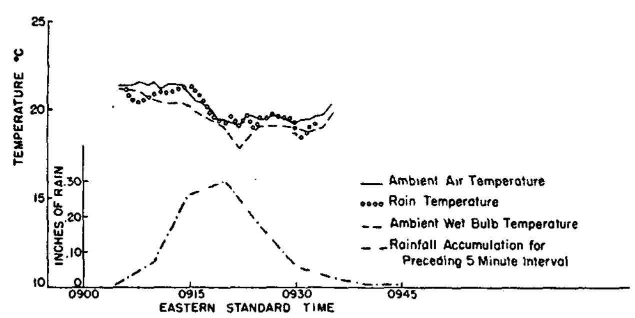

FIG. 8. Air–rain temperature relationships, Type III; 31 August 1947, Station B, Clinton County Air Force Base, Wilmington, Ohio.

ence between the air and rain temperature remains small throughout the entire storm (fig. 8).

The Type-III rain-temperature pattern occurs when the air near the ground has been previously cooled and is saturated. This condition is present in an aging storm when the cold moist air has moved out well ahead of the rain, and the rain falls into saturated air having a temperature in the lower seventies. The Type-III pattern may also be observed when a rain period, which has occurred one or two hours previously, has already cooled and saturated the surface air. An example of this type is found in the storm of 31 August 1947 when two periods of heavy rain occurred before the rain period considered in fig. 8. The first had occurred at 0550 EST and the second at 0700 EST.

An analysis has been made comparing the differences between the air and rain temperature in the periods of the 'temperature dip' and in the remaining portions. The data in this study were limited to periods where the rainfall rate was equal to or greater than 0.02 inches per 5 minutes, in order to minimize the funnel effect on the measurements. The 'temperature-dip' period in Types I and II was considered as beginning with the onset of the rain and ending when the rain temperature was within 0.2C of the air temperature. Fifty-seven of one hundred forty-five minutes of rain in the seven storms were considered to be in the 'dip' period. The average difference between the ambient air and rain temperatures in this period was 2.1C. In the 88 minutes of the 'non-dip' period, including the data from the Type-III storms, the average difference was 0.3C, the rain temperature being lower in both cases. It may be concluded that at the beginning of the rain period the rain can be several degrees colder than the ambient air. After the maximum rainfall rate has been reached, the rain–air temperature differences are usually less than 1C.

The instrument described in this paper measures the average temperature of the sample of raindrops collected in the funnel. A more complete picture would be obtained by an instrument measuring the mean temperature of an individual droplet. Since the droplets near the earth's surface vary in size, it is likely that they vary in temperature also. Larger droplets should be colder since they fall more rapidly and adjust to the environment more slowly due to their greater mass and smaller relative surface area. However, such an instrument awaits future development.

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