On the Measurement of In-Cloud and Wet-Bulb Temperatures from an Aircraft

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ABSTRACT

Measurements of air temperature with an immersion thermometer from an aircraft are invariably affected by the increased temperature of the decelerated air in the vicinity of the element. For dry air and a dry thermometer this effect is well known and usually taken into account. However, the evaporation of water from an element which has been wetted either intentionally (as in a wet-bulb thermometer) or unintentionally (by cloud or rain droplets) reduces this temperature increase. The psychrometric equation generalized for high-speed flow is used to calculate the aerodynamic correction factor for a wet temperature sensor. As an example of the magnitude of the evaporation effect, the temperature difference between a wet and a dry thermometer in a saturated airstream moving at 70 m sec^{-1} is $>$1C.

Aircraft measurements in clouds from 3 different temperature sensors are discussed. The temperature differences between an exposed and a protected thermometer are found to be as large as 1C in conditions where the exposed thermometer is wet and the protected thermometer is dry. More importantly, the outputs of the two sensors are well correlated in clear air but are uncorrelated in cloud. Humidity measured with a wet-bulb depression sensor is found to compare very well with the output of a dewpoint hygrometer in clear air. This sensor is also a good cloud indicator since the wet-bulb depression is $\sim$0 only when the dry-bulb thermometer is completely wet.

1. Introduction

The direct measurement of air temperature invariably involves the insertion of a temperature-sensitive element into the airstream. If the velocity of the airstream is small ($<$10–15 m sec^{-1}), and if the exchange of heat between the element and its environment by radiation, phase change, conduction or convection is negligible, the temperature of the element will be the same as the temperature of the airstream. On an aircraft the deceleration of the air in the vicinity of the element causes the temperature of the air to increase. Because of this, the sensing element on an aircraft comes to thermal equilibrium at a temperature higher than the ambient air temperature (the dry recovery temperature). If the sensing element is wet, either because of liquid water in the airstream or through the internal transport of water to the surface of the element by means of a wick (as in a wet-bulb thermometer), the evaporation of water results in a reduction of the temperature of the element to a value below the dry recovery temperature.

This effect is important not only for the measurement of wet-bulb temperature from aircraft, but also for cloud temperature measurement where it is possible for the sensing element to become wet. In the next section equations are derived for calculating the absolute humidity from wet- and dry-bulb temperatures and for calculating the difference in temperature between a wet and dry thermometer that include the heating effect of the airstream deceleration. If this difference is not taken into account in measuring cloud temperature, for example, a significant error can result. In practice, it is very difficult to ensure that any element remains completely dry in all clouds. In fact, it seems reasonable to assume that in some type of cloud condition (depending on housing design) any immersion thermometer will eventually become totally or partially wet. If this happens, even though the cloud air is saturated, the aerodynamically heated air in the immediate vicinity of the sensing element may not be saturated. Thus, water will evaporate from the sensor and it will approach the wet-bulb temperature of this heated air.

2. Wet-bulb temperature equation

One of the oldest and most widely used methods for measuring atmospheric humidity is by psychrometry, which is a measurement of the cooling of a wet thermometer. The relationship between the wet- and dry-bulb temperatures and water vapor pressure can be predicted from theory, but in practical applications the

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usual procedure is to use an empirical relationship under the conditions specified for psychrometric observation. This is the basis for the psychrometric reduction technique outlined in List (1963). Arnold (1933) has pointed out that the difficulty in theoretically justifying this reduction technique is that radiation from the surrounding environment tends to increase the wet-bulb temperature. If this is taken into account, the empirical relationship can be theoretically predicted. Monteith (1954) has derived an equation for reduction of psychrometric data for a wet-bulb thermocouple small enough and a ventilation rate large enough that radiation can be neglected. In all these analyses, however, the ventilation rate is considered to be small enough that dynamic temperature changes are negligible (<10–15 m sec^{-1}). If the wet bulb temperature is measured from an airplane, however, the aerodynamic heating of the thermometer must be considered in evaluating the psychrometric data.

In deriving an expression for wet-bulb temperature we assume that (a) the temperature sensing element stays completely wet; (b) the effects of conduction of heat through the sensor supporting structure are negligible; and (c) the effects of radiation exchange between the sensor and its environment are negligible.

The heat lost from a wet thermometer by evaporation is $\dot{m}L$, where $\dot{m}$ is the mass flow rate and L is the heat of vaporization of water vapor. This quantity is equal to the heat gained by the element due to forced convection. For a sufficiently low ventilation rate, the convective heat transfer rate is proportional to $(T_\infty - T_0)$ where the subscript "∞" refers to conditions in the undisturbed air and "0" to conditions at the sensor surface. For high speed flow, Eckert and Drake (1959) show that the same relationship for heat flow across a temperature difference is valid except that the recovery temperature, T_r, is substituted for T_∞. T_r is the temperature of the element in the airstream assuming no heat transfer across the surface of the element. If the air is adiabatically decelerated to zero velocity, the resulting temperature increase is equal to $\frac{1}{2}U^2/c_p$, where U is the free airstream velocity and c_p is the specific heat of air at constant pressure. In practice, most elements measure some temperature between T_∞ and $T_\infty + \frac{1}{2}U^2/c_p$. The difference between the temperature of the element and the ambient air normalized by $\frac{1}{2}U^2/c_p$ is called the recovery factor, r. Therefore,

$$T_r - T_\infty = \tfrac{1}{2} r U^2/c_p. \qquad (1)$$

For a cylindrical element with its axis normal to the flow, r has been measured to be somewhere between 0.6 and 0.7; the recovery factor of a spherical element has been measured to be about 0.75 (Jakob, 1957; Moffat, 1962). The energy budget of a wet thermometer can now be written as

$$\dot{m}L = hS(T_r - T_0) \qquad (2)$$

where S is the surface area of the wet thermometer and h is the convective heat transfer coefficient.

The transport of water vapor per unit area at the air-water interface is composed of two terms—a molecular diffusion term and a mean transport term due to the transpiration velocity of the water vapor at the liquid-air interface; i.e.,

$$\dot{m}/S = -\rho_0\left[\mathfrak{D}\left(\frac{\partial q}{\partial y}\right)_0 - q_0 V_0\right], \qquad (3)$$

where ρ_0 is the density of the moist air, $\mathfrak{D}$ is the water vapor-air diffusion coefficient, q is the specific humidity (i.e., the ratio of the water vapor density to the density of moist air) and V_0 is the transpiration velocity. The direction of the coordinate "y" is perpendicular to the sensor surface. Since the mass flux of air normal to the sensor, $\dot{m}_a$, must be zero at the liquid-air interface, we may write

$$\dot{m}_a/S = -\rho_0\left[\mathfrak{D}\left(\frac{\partial \rho_a/\rho_0}{\partial y}\right)_0 - \frac{\rho_a}{\rho_0}V_0\right] = 0, \qquad (4)$$

where ρ_a is the density of dry air.

Since

$$\rho_a/\rho + q = 1, \qquad (5)$$

(4) can be solved for V_0. Thus

$$V_0 = -\frac{1}{(1-q_0)}\mathfrak{D}\left(\frac{\partial q}{\partial y}\right)_0. \qquad (6)$$

Substituting (6) into (3) yields

$$\dot{m}/S = -\rho_0\mathfrak{D}\left(\frac{\partial q}{\partial y}\right)_0\left(1 + \frac{q_0}{1-q_0}\right). \qquad (7)$$

A mass transfer coefficient, h_w, may be defined in such a way that

$$\frac{h_w}{\bar{\rho}}(q_0 - q_\infty) = -\mathfrak{D}\left(\frac{\partial q}{\partial y}\right)_0 \qquad (8)$$

where $\bar{\rho}$ is the mean density of the moist air in the vicinity of the element. If we limit ourselves to cases where the airstream velocity is considerably less than the speed of sound, $\bar{\rho} \cong \rho_0$. Then (8) and (7) may be combined to give

$$\dot{m}/S = \frac{h_w(q_0 - q_\infty)}{1 - q_0}. \qquad (9)$$

Using the equation of state to express density in terms of pressure and temperature we have

$$\frac{\dot{m}}{S} = \frac{h_w \epsilon}{P_0}\left(e_0 - \frac{T_r}{T_\infty}e_\infty\right)\frac{1}{1 - e_0/P_0}, \qquad (10)$$

where ϵ is the ratio of the molecular weight of water vapor to dry air, R is the gas constant for dry air, P is the moist air pressure and e is the water vapor pressure.

Inserting (10) into (2) we have

$$h/h_w=\frac{L\epsilon}{(T_r-T_0)P_0}\left(e_0-\frac{T_r}{T_\infty}e_\infty\right)\frac{1}{1-e_0/P_0}. \quad (11)$$

We note that since the element is wet, e_0 is the saturation vapor pressure at the temperature T_0; thus $e_0=e_s(T_0)$.

Chilton and Colburn (1934) proposed an empirical relationship between the heat transfer coefficient and the mass transfer coefficient that has proved useful for a variety of flow situations. This includes flow parallel to a flat plate, transverse flow around a cylinder and also flow around a sphere for Reynolds number, Re, $\gg 2$. The relation is

$$\frac{h}{\rho c_p U}\,\mathrm{Pr}^{\frac{2}{3}}=\frac{h_w}{\rho U}\,\mathrm{Sc}^{\frac{2}{3}}, \quad (12)$$

where Pr is the Prandtl number (the ratio of kinematic viscosity to the thermal diffusivity) and Sc is the Schmidt number (the ratio of kinematic viscosity to the diffusion coefficient). Rearranging (12),

$$h/h_w=c_p\left(\frac{\mathrm{Sc}}{\mathrm{Pr}}\right)^{\frac{2}{3}}. \quad (13)$$

More recent measurements by Bedingfield and Drew (1950) of the sublimation of substances with various values of Sc indicate that for transverse flow around a cylinder the relation

$$h/h_w=c_p\left(\frac{\mathrm{Sc}}{\mathrm{Pr}}\right)^{0.56} \quad (14)$$

is more nearly correct. Monteith (1954) obtained a value of 0.53 for the exponent in (14) by assuming the mechanism for heat and mass transfer are identical and using Hilpert's (1933) results for heat transfer from a cylinder in transverse flow for $40<\mathrm{Re}<4000$.

Setting (14) equal to (11) and solving for the water vapor pressure of the ambient airstream,

$$e_\infty=\frac{T_\infty}{T_r}[e_s(T_0)-AP_0\Delta T_{wb}], \quad (15)$$

where $\Delta T_{wb}=T_r-T_0$ is the measured wet-bulb depression and

$$A=\frac{c_p}{\epsilon L}\left(\frac{\mathrm{Sc}}{\mathrm{Pr}}\right)^{0.56}\left(1-\frac{e_s(T_0)}{P_0}\right) \quad (16)$$

is the psychrometric parameter for a cylindrical sensor at right angles to the airstream direction. Using values for the constants in (16) from List (1963), we have $A=0.000586(1-0.00094\cdot T)^{-1}$, where T (in celsius) is approximately the average of T_r and T_0. (The water vapor pressure dependency of A indicated in (16) is very nearly cancelled by the pressure dependency of c_p.) The value given by List (1963) for use with standard mercury thermometers at ventilation rates $4<U<10$ m sec^{-1} is $A=0.000660\ (1+0.00115T_0)$; the 13% difference is due mainly to a significant radiative transfer rate from the environment to the wet-bulb thermometer. Eq. (15) can be used directly to calculate the water vapor pressure measured from an aircraft. However, in order to show the effect of aerodynamic heating on the wet-bulb measurement, we derive an expression for correcting the wet-bulb temperature for the heating effect of the airstream.

At low ventilation rates the wet-bulb depression is $\Delta T'_{wb}=T_\infty-T_0'$, where T_0' is the equilibrium temperature of a wet element in an airstream of negligible aerodynamic heating. Under this condition, (15) becomes

$$e_\infty=e_s(T_0')-AP_0\Delta T'_{wb}. \quad (17)$$

Introducing (1), ΔT_{wb} may be written as

$$\Delta T_{wb}=\Delta T'_{wb}-(T_0-T_0')+\frac{r_dU^2}{2c_p}, \quad (18)$$

where r_d is the recovery factor of the dry element.

The difference in saturation vapor pressure between T_0 and T_0' can be estimated from a finite-difference approximation to the Clausius-Clapyron equation, $de_s/dT=Le_s(T)/(R_wT^2)$; i.e.,

$$e_s(T_0)-e_s(T_0')=\frac{Le_s(\bar{T}_0)}{R_w\bar{T}_0^2}(T_0-T_0') \quad (19)$$

where $\bar{T}_0^2=(T_0T_0')$ and R_w is the gas constant for water vapor. For a temperature difference of <10C, the error of this approximation in calculating the water vapor pressure difference is <0.2 mb. Solving (15) for $e_s(T_0)$, introducing (1) and inserting this into (19) we have,

$$T_0-T_0'=\frac{R_w\bar{T}_0^2}{Le_s(\bar{T}_0)}\left[e_\infty-e_s(T_0')+\frac{r_wU^2}{2c_p}\frac{e_\infty}{T_\infty}+AP_0\left(T_\infty-T_0+\frac{r_wU^2}{2c_p}\right)\right], \quad (20)$$

where r_w is the recovery factor of the wet element. Using (17), (20) can be rewritten as

$$T_0-T_0'=\frac{r_wU^2}{2c_p}\cdot\frac{1+\dfrac{e_\infty}{AP_0T_\infty}}{1+\dfrac{Le_s(\bar{T}_0)}{R_w\bar{T}_0^2AP_0}}. \quad (21)$$

Solving (18) for $\Delta T_{wb}'$ and using (21) we have

$$\Delta T'_{wb}=\Delta T_{wb}-\frac{U^2}{2c_p}\left[r_d-r_w\cdot\frac{1+\dfrac{e_\infty}{AP_0T_\infty}}{1+\dfrac{Le_s(T_0)}{R_wT_0^2AP_0}}\right]. \quad (22)$$

If $r_d=r_w=r$,

$$\Delta T'_{wb}=\Delta T_{wb}-\frac{rU^2}{2c_p}\cdot\left[\frac{D-\dfrac{e_\infty}{AP_0T}}{D+1}\right], \quad (23)$$

where $D=Le_s(\bar{T}_0)/(R_wA\bar{T}_0^2P_0)$. Since for any reasonable temperature, $e_\infty/(AP_0T_\infty)<0.06D$,

$$\Delta T'_{wb}\cong\Delta T_{wb}-\frac{rU^2}{2c_p}\frac{D}{1+D}. \quad (24)$$

Any of the last three equations can be used to calculate the difference in wet-bulb depression between a measurement made at low speed and a measurement that includes significant aerodynamic heating. The water vapor pressure can also be determined by inserting the calculated value of $\Delta T'_{wb}$ into (17).

It is interesting to note that even when the ambient air is saturated ($\Delta T'_{wb}=0$) the measured wet-bulb depression is not zero if the airstream velocity is large enough to cause significant heating of the sensing element. For example, at a temperature of 15C and a pressure of 1000 mb, $D=1.889$. If the ambient air is saturated, from (24), $\Delta T_{wb}=0.66\ rU^2/2c_p$. At an airplane velocity of 70 m sec^{-1} and a recovery factor of unity, $\Delta T_{wb}=1.6$C.

3. Cloud temperature measurement from an aircraft

a. *Equilibrium temperature*

The equations that describe the behavior of a wet-bulb thermometer can also be applied to the problem of cloud temperature measurement from an aircraft. If (1) is applied to cloud temperature measurements we make two implicit assumptions: (a) the sensor never becomes wet and (b) liquid water in the airstream does not change the probe recovery factor (i.e., there is no evaporation of the liquid water in the airstream before it reaches the sensing element). In practice, it may be impossible to determine whether the temperature sensing element remains completely dry as the probe passes through clouds.

If a sensor becomes completely wet during a cloud penetration, it behaves as a wet-bulb thermometer. In this case, the error in temperature measurement can be obtained from (23) by setting $\Delta T'_{wb}=0$; i.e., assuming that $e_\infty=e_s(T_\infty)$, which yields

$$T_r-T_0=\frac{rU^2}{2c_p}\cdot\frac{D-\dfrac{e_s(T_\infty)}{AP_0T}}{D+1}\cong\frac{rU^2}{2c_p}\cdot\frac{D}{D+1}, \quad (25)$$

where $D=Le_s(\bar{T})/(R_w\bar{T}^2AP_0)$ and $\bar{T}=(T_\infty T_0)$. As in the previous example, at a temperature of 15C, a static pressure of 1000 mb, a recovery factor of unity and an airspeed of 70 m sec^{-1}, $T_r-T_0=1.6$C. Thus, for the conditions of this example, an error of up to 1.6C in measured air temperature can occur in cloud if the sensing element unknowingly becomes wet.

In order to evaluate the effects of liquid water evaporation on the probe recovery factor, a simplified model of mixed phase flow through a temperature housing was constructed. In the model relative motion between the droplets and the air was neglected, and it was assumed that upon entering the housing the airstream undergoes an instantaneous adiabatic deceleration to a very low Mach number. The model shows, not suprisingly, that the effects of evaporation are strongly dependent upon the liquid water content, the mean drop diameter and the probe ventilation time (the time between the air deceleration and its contact with the element). For probes with short ventilation times and for airspeeds <100 m sec^{-1}, the temperature error is less than 0.1C. At this airspeed, ventilation times on the order of several tenths of a second would be required before evaporation effects could be considered important.

b. *Response time*

The total amount of heat transferred to a wet thermometer is the difference between the heat gained by convection and conduction from the surrounding air [right-hand side of (2)] and the heat lost by evaporation from the surface of the thermometer [Eq. (10)]. If a sudden change in temperature, humidity, or both, occurs, the heat energy equation is (using the finite difference approximation to the Clausius-Clapyron equation and neglecting compressibility)

$$C\frac{dT_0}{dt}\cong hS(T_r-T_0)-hSD(T_0-T_{d\infty}) \quad (26)$$

where C is the specific heat of the thermometer (cal °C^{-1}), and the temperature used to calculate D defined by (23) is the geometric mean of T_0 and the dew point of the undisturbed air, $T_{d\infty}$. Rearranging terms,

$$\frac{dT_0}{dt}+\frac{hS}{C}(1+D)T_0=\frac{hS}{C}(T_r+DT_{d\infty}). \quad (27)$$

Thus the time constant for a step function change in T_r or $T_{d\infty}$ is $(1+D)^{-1}$ times less for the same thermometer when it is wet than when it is dry [i.e., $hSD(T_0$

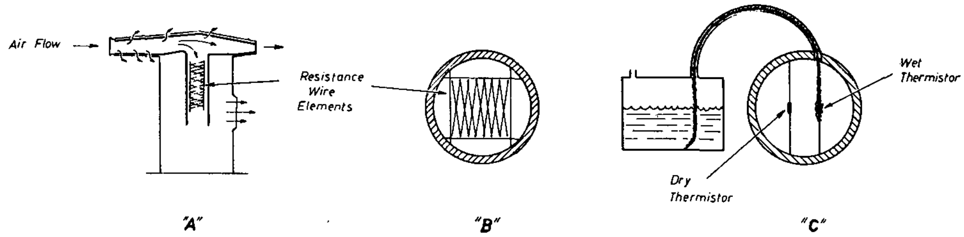

FIG. 1. Schematic drawings of the temperature probes which were mounted on the aircraft nose boom. Sensor "A" is a total air temperature probe; sensor "B" is a resistance wire probe directly exposed to the airstream, and is designed for fast response; sensor "C" is a wet-bulb depression sensor, mounted in the same tube as "B", with a wick leading from a water reservoir alongside the tube to the wet thermistor.

$-T_{d\infty})=0]$, neglecting the contribution of the water to the specific heat of the thermometer. For the example given in the previous section, this factor is about 0.34; that is, the time constant for a wet thermometer is 0.34 times the time constant for a dry thermometer of the same specific heat, shape and surface area.

In the case of a normally dry thermometer that has become wet by being flown through a cloud, after leaving the cloud the thermometer first approaches the wet-bulb temperature outside the cloud until the thermometer becomes dry. This may take a considerably longer time than the thermometer time constant. The total mass of water evaporated from a wet thermometer is, from the second term on the right-hand side of (26),

$$\int_m^0 dm = -\frac{hS}{L}\int_0^t D(T_0-T_{d\infty})dt. \tag{28}$$

Assuming the temperature of the thermometer is constant, neglecting the contribution of the water to the specific heat, solving for t and dividing by the time constant of the dry thermometer,

$$t/\tau = \frac{mL}{CD(T_0-T_{d\infty})}. \tag{29}$$

The specific heat of the thermometer is equal to the mass, m_t, times the specific heat per unit mass of the thermometer, c_t. Therefore, in order for t/τ to be less than 1, i.e., in order to avoid a significant discrepancy between the time constant of the thermometer leaving a cloud and the same thermometer entering a cloud, $m/m_t < 0.002(T_0-T_{d\infty})$.

4. Aircraft temperature measurements

The theory developed in the previous section is applied to measurements that were obtained from sensors mounted on a boom about 1.5 m in front of the nose of a Beechcraft Queen Air aircraft. The flights were conducted in June within and immediately outside of the commonly-occuring stratus clouds off the coast of central California. The data was recorded digitally on magnetic tape at 8 samples per sec, then averaged over 1 sec intervals and smoothed with a 3-point running mean before being plotted.

The sensors are drawn schematically in Fig. 1. Sensor "A" is a total air temperature probe (manufactured by Rosemount Engineering, Minneapolis, Minn., Model No. 102E2AL) that is designed to have a recovery factor very close to unity. The 0.025-mm diameter platinum resistance wire sensing element is protected to some extent from water droplets by a 90° bend in the housing. For flights through relatively dry clouds with few very small droplets, the sensing element may stay dry. However, small droplets may be able to turn the corner and impinge on the element. Furthermore, water may accumulate in the housing during a cloud penetration. Thus, flying through clouds or rain may cause unknown errors in temperature measurement because of not knowing whether part or all of the sensing wire is wet or whether a significant temperature change due to evaporative cooling is taking place inside the housing.

Sensor "B" contains a 0.025-mm diameter 1-m long tungsten wire wound around a nylon monofilament grid attached to the inside of a 5-cm ID tube. The wire is directly exposed transversely to the airstream, and therefore immediately becomes wet when the aircraft encounters liquid water. Conversely, since the element is suspended well away from the walls of the housing, it drys out rapidly when the source of water disappears.

Lenschow (1972) has compared the time constant of sensor "B" with the total temperature probe in dry air. He found that the total temperature probe has a delayed total response to a temperature change because of heat conduction between the element and the housing. The total temperature sensing element is better protected by its housing than the directly exposed sensor, but at the same time, it is in better thermal contact with the housing, which has a much larger thermal mass than the element.

Sensor "C" contains two 0.2-mm diameter uncoated bead thermistors, one wet and one dry, mounted inside the 5-cm tube downstream from the exposed wire thermometer. The wet thermistor is kept wet by a cotton wick which extends from a reservoir alongside the sensor housing to the thermistor. The thermistor and adjacent sections of the lead wire are covered with individual fibers of cotton unwound from a thread. The reservoir has a port exposed to the ram air pressure of the aircraft to increase the water flow rate during flight. The two

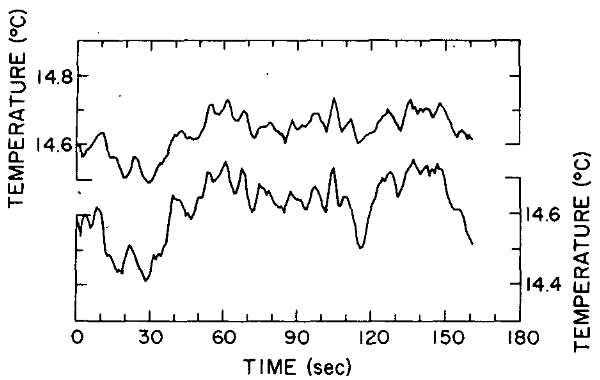

FIG. 2. A comparison of the ambient temperature obtained from the output of the total temperature probe (top) and the exposed wire sensor (bottom) in clear air.

thermistors are on opposite arms of a wheatstone bridge. Therefore, a difference in temperature between the thermistors causes a corresponding difference in voltage in the output of the bridge. Thus, the thermistor bridge output is a monotonic function of the wet-bulb depression. This unit has been tested in a wind tunnel as well as on the aircraft and was observed to remain wet at aircraft flight speeds even at depressions >10C. The dry-bulb temperature is obtained from the corrected output of the total air temperature probe.

Fig. 2 shows a comparison between the ambient air temperature measured by the total temperature probe and the exposed wire sensor in clear air. Eq. (1) has been used to correct for the temperature increase due to the dynamic heating of the sensors. The two temperatures follow each other very closely, with a correlation coefficient (after removing the trend) of 0.84. As expected, the major difference is the somewhat greater amplitude of response to high-frequency temperature fluctuations of the exposed wire sensor. This is reflected by the difference in standard deviation of the two sensor outputs; 0.093C and 0.062C for the exposed wire and total temperature probes, respectively.

Fig. 3 is an example of the sensor outputs when the aircraft is flown through tenuous intermittent stratus clouds. The presence of clouds is best indicated by the wet-bulb depression. Since both the thermistors and the exposed wire sensor are mounted inside the same tube and directly exposed to the same airstream, it is very likely that when the dry-bulb thermistor is wet the exposed wire sensor is also wet. When the depression rises above about −0.1C, the dry-bulb thermistor is not completely wet, indicating that the sensor is encountering regions of little or no liquid water.

The −0.1C offset may be due to either measurement inaccuracies or to a difference in the recovery factors of the two thermistors. The wet thermistor can probably be modeled most closely by a transverse cylinder, because of the wick surrounding both the thermistor and the lead wires. However, since the dry thermistor bead diameter is approximately 8 times the lead wire diameter, it is more closely represented by a sphere. As was pointed out earlier, a sphere has a somewhat larger recovery factor than a cylinder. A 0.1C difference at this airspeed (64 m sec^{-1}) is equivalent to a recovery factor difference of only 0.04.

From (25), the calculated difference in temperature in the output of the exposed wire when dry minus when it is wet is 0.84C. ($T_\infty=13.2$C, $P_0=983.7$ mb, $e_s=15.17$ mb, $U=64.3$ m sec^{-1}, and $r=0.65$.) This is very close to the difference observed in Fig. 3 between the dry-bulb ambient temperature [calculated by means of Eq. (1)] obtained from the output of the total temperature probe, and that obtained from the exposed wire sensor when the dry-bulb thermistor appears to be wet. Consequently, for this particular case it appears that the total temperature probe was little affected by the liquid water. DeLeo and Werner (1960), however, have shown that water droplets can affect the temperature measured

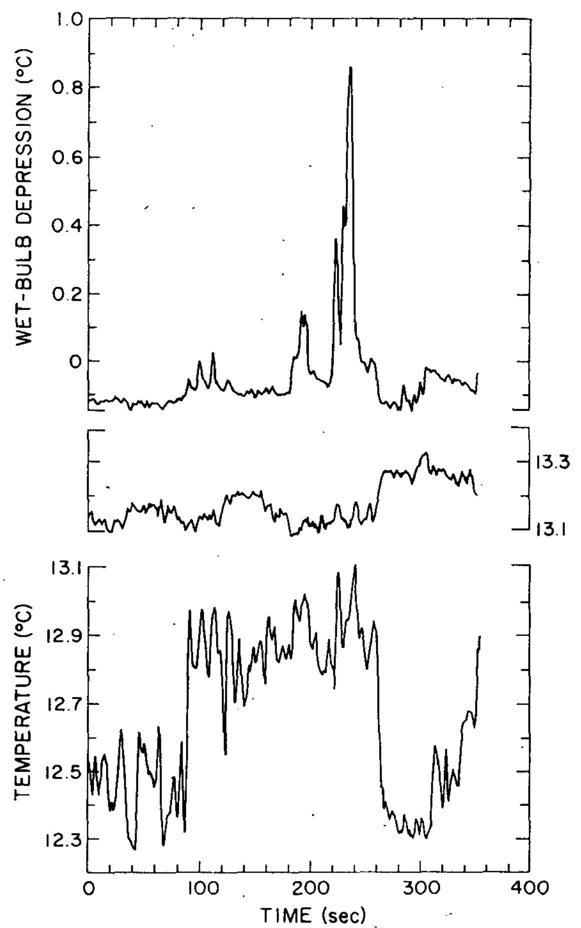

FIG. 3. A comparison of the ambient temperature obtained from the output of the total temperature probe (middle) and the exposed wire sensor (bottom) in intermittent clouds. The fluctuations in the wet-bulb depression (top) indicate that the "dry" thermistor (which becomes wet in cloud) is occasionally partially drying out as the probe passes through regions of little or no liquid water. The average airplane velocity was 64.3 m sec^{-1}; therefore, 100 sec corresponds to a distance of 6.4 km.

by the total temperature probe. They injected a water spray into a closed system to simulate cloud and rain and mounted the probe on a rotating arm. At a Mach number of 0.5, they measured an effective recovery factor of 0.89, equivalent to a temperature error of −1.5C.

Fluctuations of up to 0.5C, which can be seen in the output of the exposed wire but not in the output of the total temperature probe in Fig, 3, are very likely the result of partial drying of the exposed wire. As a result, the two temperatures have no obvious similarity. This is a graphic demonstration of the importance of knowing whether an element is wet or dry. It also points out the usefulness of a wet-bulb depression measurement in indicating the presence of liquid water.

This is demonstrated even more noticeably in Fig. 4, which shows the wet-bulb depression as the probe flies through another region of intermittent clouds well below the top of the cloud-capping inversion off the California coast. From (24), the calculated wet-bulb depression in saturated air is 0.90C, which agrees reasonably well with the magnitude of the observed fluctuations of wet-bulb depression. These fluctuations are not present in the output of the total temperature probe.

Fig. 5 is a comparison of dew-point temperature measured directly with a dew point hygrometer and calculated from the measured wet-bulb depression (also shown in Fig. 5). Eq. (24) is used to calculate $\Delta T'_{wb}$ (the wet-bulb depression with no aerodynamic heating). The water vapor pressure is then calculated from (17) and the dew-point temperature from Tetan's equation (Berry, Bollay, and Beers, 1945). The measurement was taken at a height of 763 mb, in the relatively dry air above the stratus clouds off the California coast.

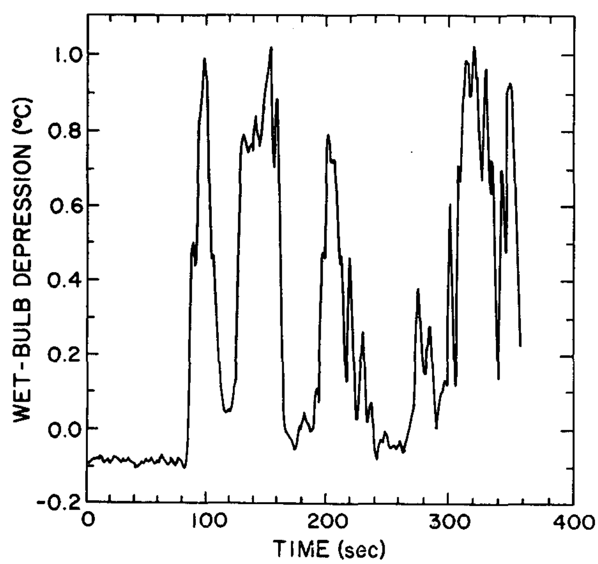

FIG. 4. Wet-bulb depression measured in a region of intermittent cloud. The first 80 sec is in solid cloud; the remainder is in intermittent clouds well below the top of the cloud-capping inversion off the coast of central California.

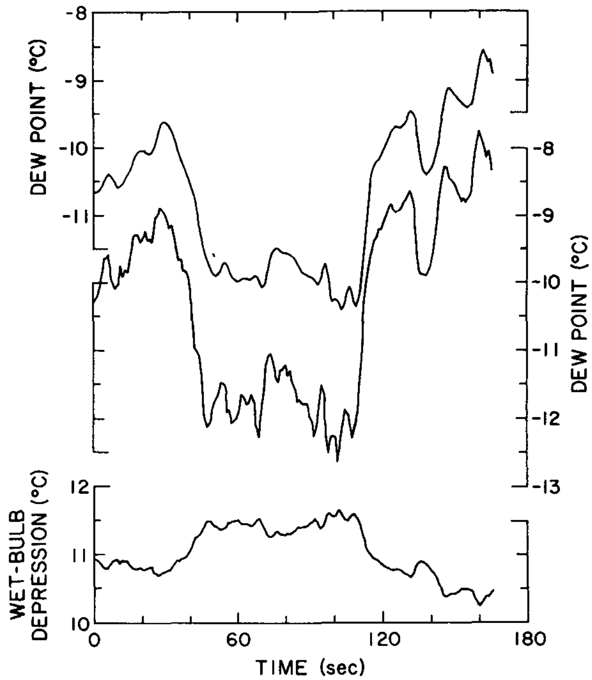

FIG. 5. A comparison of dew point temperature measured directly with a dew-point hygrometer (top) and calculated dew point temperature (middle) obtained from the measured wet-bulb depression (bottom). The measurements were made at 763 mb, above the low-level stratus clouds off the California coast.

The mean values of the two dew-point temperature measurements are within 1C of each other almost everywhere, except when the dew point is changing rapidly. When this occurs, it is evident that the wet-bulb sensor is responding more rapidly and is capable of delineating smaller scale structure than the dew-point hygrometer.

5. Conclusions

Measuring air temperature from an aircraft in clouds with an immersion thermometer is at best a risky procedure. Errors of ~1C can occur at aircraft speeds of ~70 m sec^{-1} if the thermometer unknowingly becomes wet. For temperatures above freezing, the use of a wet-bulb thermometer may be a better approach. Telford and Warner (1962) have shown that a wet-bulb thermometer, with the appropriate correction for aerodynamic heating, measures cloud temperature to within about 0.1C providing the measurement is not made in a violent downdraft or the cloud is not primarily drizzle drops. Ultimately, an even better solution may prove to be an indirect sensing technique such as an infra-red radiometer.

The dew point temperature measured directly with a dew point hygrometer compares very well with that calculated from the wet- and dry-bulb temperatures. In addition, the wet-bulb depression responds somewhat faster than the dew-point hygrometer. Consequently, wet-bulb depression measurements may, under appropriate conditions, be a useful adjunct to other humidity measurements.

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