

## On the Difficulty of Measuring Temperature and Humidity in Cloud: Comments on "Shallow Convection on Day 261 of GATE: Mesoscale Arcs"

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### 1. Introduction

Warner *et al.* (1979) quote several sets of temperature and humidity measurements made in cloud. First, in Fig. 11, they show time series plots of temperature and dew points for the NCAR L-188

and the NOAA DC-6, along with shading to indicate when the aircraft were in cloud. Second, they show in Fig. 15 a time series from the DC-6 gust probe, remarking that "all cloudy updrafts penetrated by the DC-6 were negatively buoyant." They further comment that "penetrated clouds were small; therefore, effects of sensor wetting are neglected," but do not justify the statement.

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Buoyancy is directly proportional to the deviation of the virtual temperature from its environment. The virtual temperature is a function of temperature  $T$  and specific humidity  $q$ , given by

$$T_v = T(1 + 0.61q). \quad (1)$$

The temperature measurements taken from the DC-6 gust probe were gathered using a  $1.25 \times 10^{-4}$  m diameter thermistor directly exposed to the airstream (Bean *et al.*, 1976)<sup>2</sup>, while Rosemount (Model 102E2AL) sensors were used for the L-188 and DC-6 temperatures shown in Fig. 11. The humidity shown in Fig. 15 was from a microwave refractometer (*ibid.*), while the dewpoint measurements in Fig. 11 were from Cambridge dewpointers (Model CSI 137), according to GATE data documentation. We shall show below why none of the above instruments should be considered reliable in cloud, and hence why both the  $T$  and  $q$  measurements of Warner *et al.* (1979) should be held in question.

## 2. Temperature

We show below that the DC-6 thermistor should remain wet in the type of clouds intercepted during GATE, and that the resulting cooling should be close to that shown in Fig. 15 of Warner *et al.* (1979). We shall see that the rate of wetting due to interception of cloud droplets is larger than the rate of drying. It is assumed that drying due to shedding of water does not overwhelm that due to evaporation. If the sensor remains wet, then the cooling which results from evaporation can be estimated from Eq. (24) of Lenschow and Pennell (1974).

The number of cloud droplets reaching the sensor is the same as the environmental number, since they do not have time to evaporate as the air decelerates and consequently heats up near the sensor. The deceleration time for a droplet as it impinges the sensor is given approximately by the ratio of the sensor diameter to the true airspeed,  $d/U \approx 10^{-6}$  s. The time required for drops of the size intercepted in GATE to evaporate (Twomey, 1977) can be obtained from

$$\frac{dr}{dt} = \frac{SG}{r} f_v, \quad (2)$$

where  $dr/dt$  is the time rate of change of the drop radius;  $S$  the supersaturation, given by  $(q - q_s)/q_s$ , where  $q$  and  $q_s$  are respectively the specific humidity and saturation specific humidity;  $r$  the drop radius

( $5-50 \times 10^{-6}$  m for tropical cumulus, according to Fletcher, 1966);  $f_v$  is a ventilation factor, which is of order unity for the smaller (faster-evaporating) droplets considered here; and  $G \approx 1.2 \times 10^{-10}$  m<sup>2</sup> s<sup>-1</sup> (Twomey, 1977). From (2), the evaporation time for  $5 \times 10^{-6}$  m drops intercepting a dry sensor traveling at  $100$  m s<sup>-1</sup> through a cloud of temperature  $20^\circ\text{C}$  at  $950$  mb is  $\sim 0.5$  s.

For the range of droplets intercepted in the GATE clouds, the collision cross section of a  $1.25 \times 10^{-4}$  m sensor is close to the geometric cross section (Langmuir, 1948). Hence, we can calculate the amount of water intercepted by the thermistor per unit time from

$$\frac{dm}{dt} = m_0 \pi r^2 U \quad (3)$$

From above,  $m_0$  is the environmental concentration of liquid water. The characteristic concentrations for tropical cumulus are  $45$  drops cm<sup>-3</sup> (Squires, 1968) or  $0.5$  gm m<sup>-3</sup> [Fletcher (1966); also measured in comparable conditions in GATE], giving about  $100$  drops, or  $6 \times 10^{-7}$  gm, intercepted each second by the sensor. Thus, some wetting occurs by the time the sensor has penetrated a few meters inside the cloud. This is not necessarily true for the aircraft windshield, however. Because of the large radius of the aircraft nose, cloud droplets can be accelerated around it. Thus, it is dangerous to infer that the sensor is dry from watching the aircraft windshield.

The evaporative drying rate for a spherical sensor can be approximated by (2), if we adjust the ventilation factor to account for the sensor size,  $d = 2r$ . Pruppacher and Klett (1978) and Woo and Hamielec (1971) give an average  $f_v$  of about 5 for a Reynolds number  $Re = Ud/D = 100$ , where  $D$  is the water vapor diffusivity ( $10^{-4}$  m<sup>2</sup> s<sup>-1</sup>).

Since  $dm/dt = 4\pi r^2 \rho_w dr/dt$ , where  $\rho_w$  is the density of liquid water ( $1$  gm cm<sup>-3</sup>), we can rewrite (3) and form the ratio of the wetting and evaporation rates, i.e.,

$$\frac{\left(\frac{dr}{dt}\right)_w}{\left(\frac{dr}{dt}\right)_{d,e}} = \frac{m_0 U r}{4SG f_v \rho_w} \approx 5 \quad (4)$$

for the largest possible (dry-sensor) supersaturation of  $-0.28$  for a sensor traveling at  $100$  m s<sup>-1</sup>. Therefore, the sensor remains wet unless it sheds a large fraction of the impinging water drops.

We calculate the expected temperature error in a saturated (cloud) environment using Eq. (24) from Lenschow and Pennell (1974), which assumes a thoroughly wetted sensor. The resulting value,  $-3$  K, is about the in-cloud temperature depression in Fig. 15. This strongly suggests the sensor was

<sup>2</sup> Bean, B. R., R. O. Gilmer, R. F. Hartmann, R. E. McGavin and R. F. Reinking, 1976: Airborne measurement of vertical boundary layer fluxes of water vapor, sensible heat, and momentum, during GATE. NOAA Tech. Memo. ERL WMPO-35, 83 pp. [NOAA/ERL Weather Modification Program Office, Boulder, CO 80303].

wet. [Note that putting in the corresponding supersaturation ( $-0.11$ ) in (4) results in a larger ratio of about 12.]

The Rosemount thermometer has a smaller but still significant chance of wetting. It is designed to force the airstream to pass through a  $90^\circ$  angle before impinging on the sensor. Since the drops in the air cannot make the turn because of their inertia, the sensor should remain dry. However, smaller drops, either naturally occurring or formed by drop breakup around the aircraft, can hit the sensor. Lenschow and Pennell (1974) report that their airborne Rosemount thermometer remained dry much of the time during penetration of California marine stratus, but from an examination of a brief segment of the same data, Albrecht *et al.* (1979) concluded that the Rosemount readings were unreliable. Comparing heat flux<sup>3</sup> measurements from a PRT-6 radiometer and the Rosemount, they found that flux from the Rosemount data was a factor of 4 lower than that from the radiometer. The latter compared favorably with estimates of virtual heat flux produced by a stratocumulus-topped boundary layer model of Schubert *et al.* (1979), when the authors applied the mean conditions under which the measurements were taken. They related the low flux to an "extra" negative correlation between liquid water and temperature, probably a result of the evaporative cooling discussed above. Further, Heymsfield *et al.* (1978) document wetting of the Rosemount sensor in continental cumulus congestus.

The three-dimensional numerical model of Sommeria (1976) generates positive heat flux in the lower cloud layer, lending further doubt to the "cool" clouds of Fig. 15. (In GATE conditions, a  $q$  excess of  $16 \text{ g kg}^{-1}$  would be needed to make clouds 3 K cooler than the environment neutrally buoyant). Two simulations of tropical cumulus-topped boundary layers by Sommeria (1976) and Sommeria and LeMone (1978) indicate that the clouds generate positive buoyancy through the lower half of their depth. From the length of time spent in a typical cloud (30 s) the time series in Fig. 15 is probably in the lower half of the cloud. A more recent simulation by Nicholls *et al.* (1980) using essentially the same model gives the same result for a fair weather day in GATE.

### 3. Humidity

The Cambridge dew point sensor registers a dew point temperature as the temperature of a warming mirror just as evaporation frees the mirror of tiny

<sup>3</sup> Heat flux is here the average product  $\overline{w'T'}$ ,  $T'$  and  $w'$  being the temperature and vertical velocity departure from their respective averages  $\bar{T}$  and  $\bar{w}$ . The overbar represents an average over a straight and level flight leg.

droplets. If the mirror is wetted by cloud droplets, than the mirror must be warmed further, leading to erroneously high readings. Since air is drawn into the instrument from a hole in the fuselage, it is somewhat shielded from drops in the same way as the Rosemount. However, its response on the Electra (30 s) is so slow that its use in small clouds is limited, even with no wetting. The response time on the UK C-130 and the DC-6 ( $\sim 5$  s) is faster, but still marginal.

The humidity reading from the refractometer suffers from a dual problem. First, the presence of water droplets within the cavity or the wetting of its surface degrades the reading of the atmospheric refractive index. Second, the humidity is calculated from an equation involving the pressure and the temperature.

Again, the problem usually gets considerably worse with wetter clouds or rain, but the refractometer is sufficiently sensitive to cloud water that the refractometer humidity has been used as a "cloud indicator" in the analysis of GATE data.

### 4. Summary

In summary, both temperature and humidity measurements by the instruments cited in Warner *et al.* should be held in suspicion. First, there are physical reasons why they do not operate properly when wetted. Second, for all the instruments, wetting is possible in cloud; and for some (i.e., the refractometer and the thermistor) it is almost certain. This is substantiated both by the work of Lenschow and Pennell (1974) and the comparison of direct to radiometric temperature measurements by Albrecht *et al.* (1979).

Further, model results do not support the universal "negatively buoyant" cloud readings. Both theory (Schubert *et al.*, 1979) and three-dimensional numerical simulations suggest positive buoyancies in the cloud layer.

Accurate measurement of temperature and humidity in cloud should be viewed as an important goal.

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