Radiosonde Humidity Retrieval by Simultaneous Radiation Measurements[1]

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ABSTRACT

A radiometric method for the retrieval of moisture data at altitudes above the radiosonde hygristor cutoff region or in situations where a malfunction of the hygristor occurs is described. The method was applied to BOMEX radiation soundings. Regardless of the exact moisture profile, the method is designed to radiometrically infer the average decrease of moisture through the entire atmospheric column through a solution of the radiative transfer equation. This enables recovery of the total mass of atmospheric water vapor.

In at least 25% of all BOMEX radiometersonde ascents, humidity retrieval did produce a more realistic moisture profile and total mass of precipitable water vapor. In these cases, the radiosonde hygristor humidity deficiencies averaged from −45% at 800 mb to −30% at 600 mb. For such pressure levels, the optical mass of water vapor retrieved for the soundings discussed averaged 1.68 gm cm^{-2}. This represents 56% of the hygristor-measured optical mass. Above 400 mb the optical mass recovered averaged 0.7 gm cm^{-2} for all BOMEX radiometer soundings. It is suggested that a simple radiometer could be used to improve moisture measurements for soundings requiring the best possible water vapor data.

1. Introduction

It is known that the standard U. S. radiosonde and the U. S. military AMT-4 and AMT-12 radiosondes employing the carbon sensor hygristor do not correctly indicate atmospheric moisture at levels above mid-troposphere (approximately 400 mb in the tropics and 450 mb in mid-latitudes). This is due, among other causes, to the low humidities and low temperatures at such levels. There is also evidence to be presented that on occasion the hygristor may not indicate correct humidities at levels well below 400 mb. For some meteorological applications this humidity discrepancy is not important. For others it is a critical but unavoidable shortcoming. Among the latter are infrared (IR) radiative transfer calculations. In fact, it was as a result of radiative transfer calculations and comparisons with BOMEX (Kuettner and Holland, 1969) radiometersonde radiation measurements that one estimate of the hygristor discrepancy at high altitudes and, on occasion, at low altitudes became evident. The purpose of this research is to develop a radiometric method for retrieval of moisture data above the hygristor cutoff region or in regions where the hygristor malfunctions. Regardless of the exact moisture profile, the method is designed to radiometrically infer the average decrease of moisture through the entire atmospheric column. This, in turn, will recover the total mass of atmospheric water vapor.

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The magnitude of the humidity discrepancies between those measured by the hygristor and those radiometrically inferred by the technique to be described were found in some cases to be as large as 45% at 800 mb, 24% at 700 mb and 36% at 600 mb. The humidity differences for these lower tropospheric levels correspond, respectively, to 20.0, 7.0, and 17.0C dew point temperature differences. At mid-tropospheric levels the humidity differences for 300 and 200 mb were frequently 50–85% lower for the hygristor than the radiometrically inferred humidities. These differences correspond to 18.0 and 7.0C dew point temperature differences, respectively.

The radiation measurements that are proposed as a control for the humidity measurements have been made for several years with the balloonborne radiometersonde described by Suomi and Kuhn (1958) and Suomi *et al.* (1958). This instrument, attached to the standard radiosonde, was employed in some 300 BOMEX ascents. It is a simple but accurate hemispheric IR radiometer with upward and downward facing shielded and blackened sensing surfaces. It responds to incident power over the spectral range 0.40–50.0 μm, operating with the radiosonde through a self-contained multiplexer but in no way degrading the sonde data. Its basic design and critical dimensions have not changed since the earliest model.[2] This insures a long record of some 7000 comparative radiometric ascents. In principal, the radiometersonde provides

[2] Radiation Measuring Device, U. S. Patent Office No. 3098380.

separate measurements of upward and downward radiant power by furnishing a direct method of assessing the magnitude of the vertical flux of thermal power through its structure. Convective power transfer is totally suppressed by the unique layered construction.

The rms instrument error of the radiometersonde was evaluated by Bushnell and Suomi (1961). The error for a single measurement is 0.0035 cal cm^{-2} min^{-1}, approximately 2.5 W m^{-2}. This corresponds to an average water vapor mixing ratio error of 0.20 gm kg^{-1} at a level where the mixing ratio is 15.0 gm kg^{-1}, 0.15 gm kg^{-1} at 10.0 gm kg^{-1}, 0.10 gm kg^{-1} at 1.50 gm kg^{-1}, and 0.05 gm kg^{-1} at 0.30 gm kg^{-1}. Thus, even at low mixing ratio levels, the radiometersonde accuracy is adequate to retrieve a more realistic moisture profile in many instances than the hygristor.

2. Design of the moisture retrieval method

Basically the technique involves simultaneous radiometersonde measurements and iterative calculations of the downward IR radiant emittance. The calculations are moisture-adjusted to achieve agreement between measured and calculated radiation by insertion of a modified humidity profile into the radiative transfer equation (RTE). Downward radiative power calculations are preferred to upward because they are more sensitive to water vapor changes. This occurs because downward calculations are made against a zero radiation background transmission.

Upper level moisture, for tropical (this study) or mid-latitude regions (after Mastenbrook, 1968, and Kuhn and Cox, 1967) are entered for all calculations. However, between approximately 180 mb and the measured hygristor-moisture cutoff or discontinuity, as indicated by the profile of the first radiation calculation employing the hygristor-measured moisture, a humidity profile (after Smith, 1966) is inserted in the RTE. His power-law relationship between total precipitable water vapor and surface or reference-level mixing ratio is employed to provide the second iteration moisture profile. Subsequent iterative solutions of the downward power are made, after changing the mixing ratio, only to improve agreement between calculated and measured radiant power. A convergence criterion between measured and calculated radiant power was established for cloudy conditions ($\geqslant 8/10$ reported total sky cover), broken sky conditions (4/10 to 8/10 cover), scattered sky conditions (2/10 to 4/10), and cloudless ($\leqslant 2/10$). Both the power-law estimate of the moisture profile and the convergence criterion are further discussed in the succeeding sections.

The atmospheric saturation mixing ratio profile establishes the theoretical maximum of total precipitable water vapor which may exist. This control profile results from our prior knowledge of the temperature sounding. In each radiometric inference of the moisture profile, a calculation of the downward radiant power is made assuming saturated conditions. This calculated radiometric profile then establishes the *limiting value* of radiant power that can exist due to emission from water vapor, carbon dioxide and ozone. In fact, the "saturated" profile equaled or slightly exceeded the measured downward power in less than 25% of the soundings. This ever-present excess of measured over computed radiation is due primarily to clouds and atmospheric particulates. However, one cannot rule out the possibility that the absorption coefficients for water vapor, carbon dioxide and ozone that are employed in this and other RTE models may be in error to some degree.

It is interesting to note in the succeeding figures, which are typical of the bulk of the 300 soundings, that the particulate structure evidenced by the relatively sharp increase in the gradient with increasing pressure of the downwelling radiation, generally occurs from 850 mb downward. However, on days when Harmattan haze reaches the BOMEX area, the radiation soundings exhibit this gradient increase at a higher level, ~675 mb. The main criterion we have chosen for a properly inferred moisture profile is agreement between calculated and measured radiant power.

3. Radiation calculations

The downward radiant emittance (cal cm^{-2} min^{-1}) was evaluated by a particular numerical solution of the RTE. The mathematical representation of the calculated radiance (cal cm^{-2} min^{-1} sr^{-1}), viewed at zenith angle θ, is

$$I(\theta)=-\int_0^\infty \int_{\tau=1.0}^{\tau} B(\nu,T)d\tau(u_{H_2O})d\nu - \int_0^\infty \int_{\tau=1.0}^{\tau} B(\nu,T)d\tau(u_{CO_2})d\nu. \quad (1)$$

The radiant emittance follows from Eq. (1) and may be written as

$$N\downarrow = 2\pi \int_0^{\pi/2} I(\theta)\downarrow \sin\theta \cos\theta d\theta, \quad (2)$$

where τ is the transmissivity, B the Planck function, ν the wavenumber (cm^{-1}), T the absolute temperature, and u the pressure-corrected optical mass (gm cm^{-2}). Pressure-broadening effects on the optical mass of water vapor were determined from

$$u=U(p/p_0)^{\gamma(p)}, \quad (3)$$

where U is the measured or inferred optical mass, and γ is a function of the pressure p (Kuhn, 1963). For carbon dioxide and ozone, $\gamma(p)$ is replaced by 0.6.

The RTE model employed has a spectral density of 10 cm^{-1} and employs the water vapor absorption coefficients of Möller and Raschke (1964), continuum (atmospheric window) transmission coefficients of Saiedy

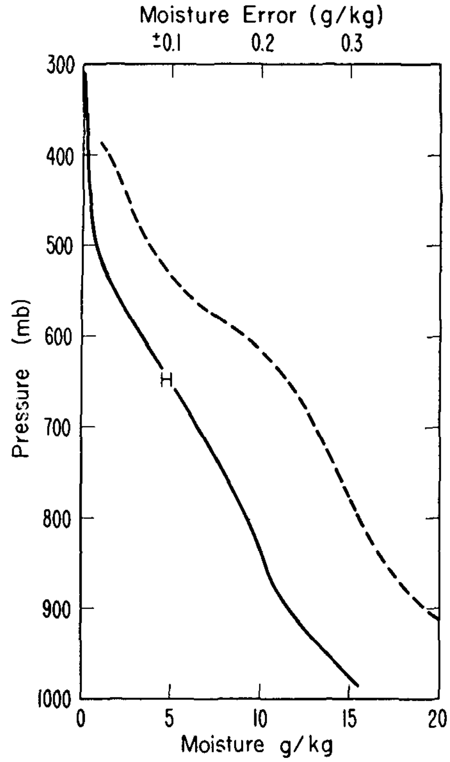

FIG. 1. Average mixing ratio profile for BOMEX radiometersonde ascents (solid curve) and mixing ratio error profile (dashed curves) due to the rms radiometersonde radiation error for the average curve.

and Hilleary (1967), and the carbon dioxide transmission data of Smith (1969). Computations can be made for any number of atmospheric levels and for any spectral interval (in this case, 0–2280 cm^{-1}).

The iterative solution method employing the RTE to infer the water vapor amount is possible since the emission due to CO_2 is a function of the atmospheric temperature and the total atmospheric centimeters (gm cm^{-2}) of CO_2 above any level in the atmosphere. Both quantities are known, leaving only the transmissivity of water vapor, $\tau(u_{H_2O})$, as a variable in Eq. (1). We have disregarded the small contribution of O_3 to the downward radiance, $I(\theta)$, in Eq. (1). It is thus possible to iterate through solutions of Eq. (2) until required convergence of measured minus calculated radiant power is achieved. This is done by employing and adjusting the moisture profile representation described by Smith (1969).

Smith has shown that regardless of the exact moisture profile, with the proper choice of the power λ for a given atmospheric situation, the average decrease of moisture through the entire atmospheric column may be described by a power law

$$w = w_0(p/p_0)^{\gamma}. \quad (4)$$

Here, w is the mixing ratio at any pressure level p, w_0 the mixing ratio at the earth's surface or at a reference level, and p_0 the corresponding pressure. For the BOMEX area during summer, Smith gives a value of 3.0 for λ.

4. Application of the method to typical soundings

We have applied the humidity retrieval method described to approximately 40 BOMEX radiometersonde ascents. This did not exhaust the number of ascents that could possibly be moisture-adjusted. It did serve, however, to demonstrate that this procedure could improve the humidity profiles and total atmospheric optical mass of water vapor for many soundings.

From this group of 40 radiometersonde ascents we chose four typical soundings to illustrate the results. Cloud conditions for the four runs ranged from 0.3 to 0.8 cumulus, typical for the Barbados region. One of the four ascents required no humidity adjustment and appears as a standard.

In applying the radiometric humidity retrieval method to a sounding judged by inspection to be well below the average seasonal moisture profile for the Barbados (or any other) region, we adopted the following computational procedure:

1) Computer-calculate downward radiant emittance with the actual hygristor-measured humidity.

2) Compare these RTE-calculated results with the radiometersonde-measured downward radiant emittances either graphically (CRT output) or numerically.

3) If agreement does not meet the radiant emittance profile convergence criterion, apply Smith's moisture profile as a "first guess" for the first RTE iteration. Convergence of the RTE-calculated and measured-downward radiation profiles at levels generally above 850 mb is defined by that condition in which

$$\sum |(N_0\downarrow - N_c\downarrow)_i|/N_0 \leqslant 0.0035 \text{ cal cm}^{-2}\text{ min}^{-1} + \epsilon, \quad (5)$$

where ϵ is the cloud factor and i the pressure-level index.

The value 0.0035 ly min^{-1}, the rms error of an individual radiometersonde measurement, was the obvious choice for a convergence criterion. How much this error affects the mixing ratio is shown in Fig. 1. This is a plot of the average mixing ratio profile for the BOMEX radiometersonde ascents together with the mixing ratio error profile for a 0.0035 ly min^{-1} radiometersonde rms error. RTE-calculated radiant power throughout the sounding cannot reach the measured power since the RTE calculations do not take into account clouds, aerosols and haze. Fig. 2, illustrating a sounding not requiring humidity adjustment, typifies the mean discrepancy between RTE-calculated and measured radiant power. The discrepancy is due, primarily, to the 8/10 cumulus cloud cover and lower level particulates. The difference of 0.07 ly min^{-1} is average for cloudy BOMEX ascents. By examining the average radiation profiles for cloud covers $\geqslant$8/10, 4/10 to 8/10, and

<4/10, the values for ϵ [Eq. (5)] were set at 0.06, 0.04 and 0.02 ly min^{-1}, respectively. Below 800–900 mb, the discrepancy between measured and calculated radiant power becomes considerably larger due to the inability of the RTE to handle particulates and haze as well as sea spray. Again, this is evident in Fig. 2 from an examination of the calculated downward radiant emittance (CDE) and the measured downward radiant emittance (MDE).

4) Using Smith's method successive moisture profile approximations are then entered in the RTE until convergence is reached.

5) The radiometrically inferred water vapor mixing ratio profile must not exceed saturation.

6) Moisture profile approximations are initiated from that pressure level where there is an evident moisture discontinuity or clear departure from a power-law lapse of moisture with height.

Fig. 2 illustrates a radiometersonde sounding under almost overcast cumulus conditions where the hygristor evidently functioned properly throughout the ascent. This was concluded from a RTE calculation of the CDE

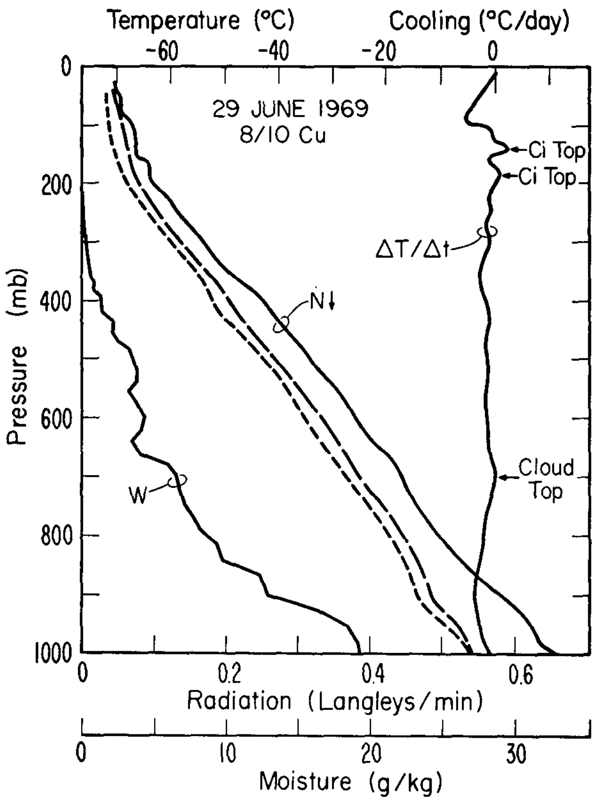

FIG. 2. A Barbados radiometersonde showing the mixing ratio profile (solid curve W), the RTE-calculated downward radiant emittance (CDE) based on hygristor moisture (short dashed curve), and the downward radiant emittance for saturation conditions (long dashed curve). The solid curve labelled $N\downarrow$ is measured downward radiant emittance (MDE). The solid curve labeled $\Delta T/\Delta t$ is the layer atmospheric cooling due to divergence of the net radiation. This is a sounding not requiring humidity adjustment.

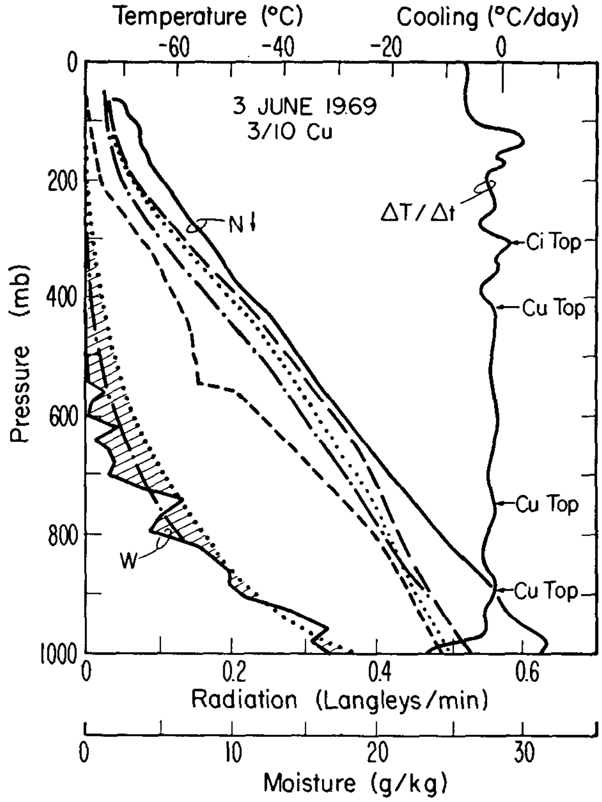

FIG. 3. A Barbados radiometersonde with labelled curves identified as in Fig. 2. The dot-dashed curve through the cross-hatched area is the Smith water-vapor profile for the first radiation iteration, while the dotted curve bounding the cross-hatched area is the Smith water-vapor profile for the second radiation iteration. The short dash curve is the CDE, the dot-dash curve the first radiation iteration and the dotted curve the final iteration. The long-dashed curve is the downward radiation for saturation. The figure illustrates the normal humidity adjustment procedure.

and a comparison of this profile with the MDE. Other than the overall average MDE-CDE discrepancy, no significant differences appear. The CDE curve for saturated conditions is illustrated for reference. The first tops of a rather deep cumulus system occur at ~700 mb from the increase in the radiational cooling rate. Another top is at 425 mb with cirrus-layer tops at 190 and 145 mb.

Fig. 3, illustrating a Barbados radiometersonde ascent, allows us to examine the results of the humidity retrieval procedure for typical BOMEX weather conditions. The CDE employing hygristor-measured moisture diverges widely from the MDE profile. The large MDE-CDE difference from 800 mb upward and the absences of any indicated moisture above approximately 550 mb shows the presence of water vapor not measured by the hygristor. Two radiation iterations employing the Smith power-law determination of the water vapor mixing ratio moved the CDE to within the convergence criterion from 700 mb upward.

Below 700 mb the presence of heavy Harmattan haze, reported by independent island observers, pro-

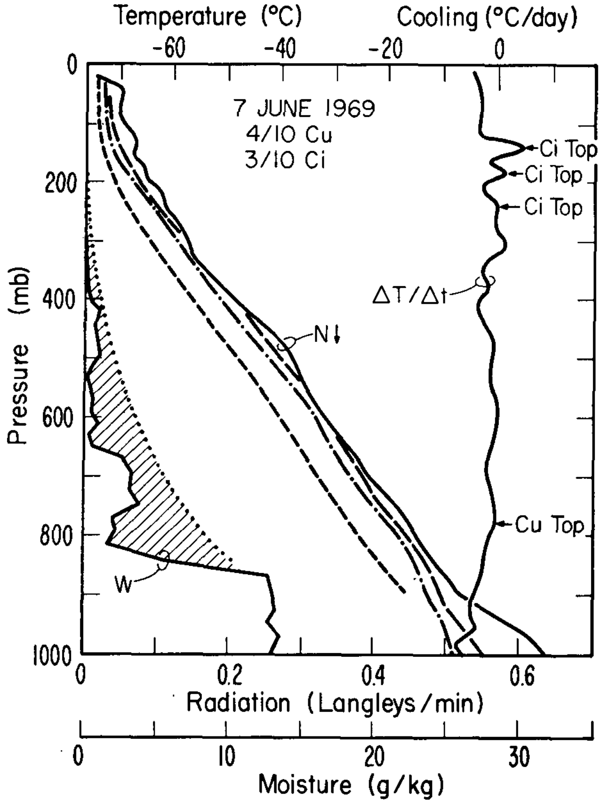

FIG. 4. A Barbados radiometer with labelled curves identified as in Fig. 2, with all other curves being identified in Fig. 3. The situation is one occurring in nearly 25% of all BOMEX soundings, where there was very low hygristor indicated above the 850–750 mb level and more above 550 mb.

duces sharp divergence between MDE and CDE profiles. The presence of haze up to 10,000 ft sweeping off Africa in easterly waves in the trades was verified in July 1969 from direct radiometric and visual observations from NASA's Convair-990.

Again, note that the final CDE does not reach the saturation CDE. The actual optical mass of water vapor retrieved by radiometric inference for this sounding was 1.57 gm cm^{-2}. In a sense, it is represented by the cross-hatched area of Fig. 3.

The water vapor profile retrieved by radiometric inference (Fig. 4) illustrates a situation that occurred in nearly 25% of all BOMEX radiometersonde (and, presumably, radiosonde) soundings. It is that of very low hygristor-indicated moisture above approximately 850–750 mb with virtually no water vapor indicated above 550 mb. To achieve agreement between MDE and CDE, it was only necessary to apply the Smith power-law water vapor profile to our CDE once. The moisture adjustment is quite large, represented by the cross-hatched area, and amounts to an increase of 1.52 gm cm^{-2}, total optical mass, over that indicated by the hygristor. Three rather distinct cirrus sheet tops at 250, 190 and 140 mb appear distinctly.

Fig. 5 displays another situation quite similar to that of Fig. 4 except that the retrieved optical mass of water vapor is 1.60 gm cm^{-2}, indicating a partial failure of the hygristor above 890 mb and the usual failure above approximately 550 mb. Two iterations employing the Smith water vapor profile first from the surface and then from 890 mb achieved convergence between MDE and CDE. The CDE employing the saturation water vapor mixing ratio profile as a control is quite close to the MDE. In both Figs. 4 and 5, the haze layer reaches only to about 900 mb; the level is indicated by the sharp divergence in the MDE and CDE profiles.

The computer solution of the radiometrically inferred moisture is extremely swift, requiring only some 3—4 sec (CDC-3800 computer type).

5. Conclusions

It appears evident that humidity retrieval by radiometric inference can, in at least 25% of all BOMEX radiometersonde ascents, produce a more realistic moisture profile and total mass water vapor above ~800 mb. Generally, above 550 mb, virtually all of

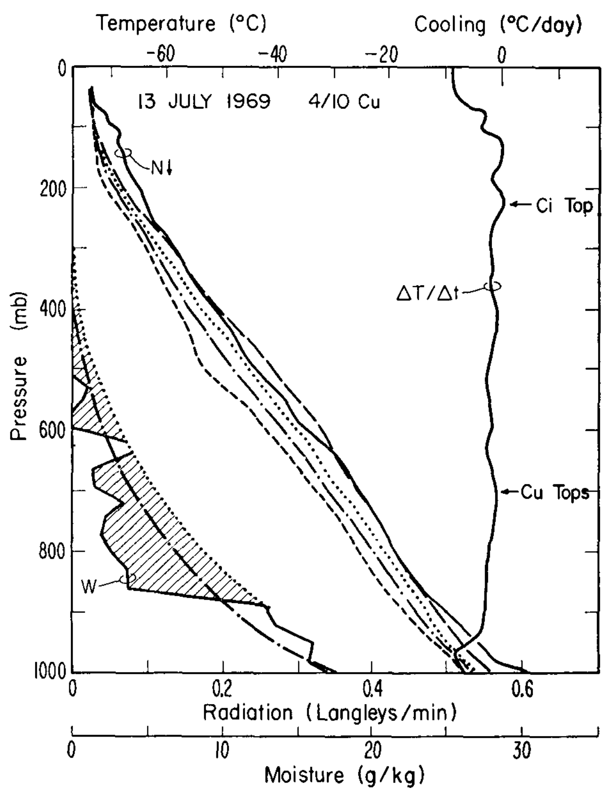

FIG. 5. A Discover radiometersonde with labelled curves identified as in Fig. 2 with all other curves being identified in Fig. 3. The situation is similar to that of Fig. 4 except for a retrieved optical mass of water vapor of 1.60 gm cm^{-2}, indicating a partial failure of the hygristor above 890 mb and the usual failure above ~550 mb.

the BOMEX radiometersonde ascents require humidity adjustment.

This apparent shortcoming in the radiosonde hygristor is well known at higher levels with low temperatures and low humidities, but perhaps is not as well recognized between 550 and approximately 800 mb and could affect BOMEX "core" experiments on the total energy and water vapor budgets. Presumably they should be considered and some adjustments made. Admittedly this is difficult post facto but can be considered for the future.

The comparison of calculated downward radiant emittance and the radiometersonde-measured downward radiant emittance and the recognition of discrepancies between the two profiles suggests a future alternative. The attaching of a simple, single thermistor, miniaturized Suomi-Kuhn radiometer to the radiosonde and keying it into the radiosonde-blocking oscillator and transmitter in place of the hygristor below a chosen pressure level could provide more accurate high-level moisture measurements.

Additional circuit modifications to the radiosonde could provide hygristor and radiation measurements resulting in comparative moisture observations (hygristor and radiometric inference) at higher pressures (lower levels). A simple version of this "humidity radiometer" was recently flown successfully as part of a standard radiosonde ascent. After several additional flights, the results will be reported.

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