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CORRECTION OF BOMEX RADIOSONDE HUMIDITY ERRORS

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Abstract. During the Barbados Oceanographic and Meteorological Experiment (BOMEX) in 1969, rawinsonde soundings indicated a large diurnal variation in relative humidity. Comparison with other measurement systems showed that values were as much as 25 percent too low at midday. The primary source of the error was found to lie in deficient design of the duct that housed the carbon-coated hygristor, which resulted in heating of the sensor by solar radiation. To correct this error, it was assumed that the daytime average ambient vapor pressure for a 7-day period was the same as the nighttime average. After application of the correction for radiation, and with the known lag properties of the hygristor taken into account, it was concluded that in most cases the corrected relative humidities should be within 5 percent or less of the actual value.

1. INTRODUCTION

During the Barbados Oceanographic and Meteorological Experiment (BOMEX), May to July 1969, approximately 2,500 rawinsonde flights were launched from five ships stationed at the corners and in the center of the 500-km by 500-km square array. These soundings, made at 1 1/2-hr intervals, showed a large spurious diurnal variation in relative humidity, with midday values being as much as 25 percent too low at some pressure levels in comparison with humidity measurements made by aircraft at various altitudes and by the Boundary Layer Instrument Package (BLIP) at a height of 300 m.

The measured relative humidity depends on both the water-vapor content of the air and the ambient temperature. In computing relative humidity, it is generally assumed that the humidity sensor has the same temperature as the ambient air. It was found, however, that the hygristor on the BOMEX sonde was subject to excessive heating by solar radiation, and the daytime temperature of the sensor was therefore usually higher than that of the ambient air. Also contributing to the error was the lag of the sensor's response to changing ambient temperature during ascent.

The problem of humidity error has been discussed in the literature by, among others, Morrissey and Brousaides (1970), Teweles (1970), and Ostapoff et al. (1970). In their evaluation of the error by comparative soundings, and by actual measurement of the hygristor temperature during ascent with an imbedded bead thermistor at Bedford, Mass., Morrissey and Brousaides provided much valuable information on the error distribution at that particular location. Ostapoff et al. (1970) used comparative soundings with a standard and modified sonde, as well as with German sondes having hair hygrometers, in order to evaluate humidity errors in data from the Atlantic Tradewind Experiment (ATEX) and to derive a correction procedure. They also did laboratory tests to determine the hygristor's relative ventilation rate, thermal lag constant, and excessive temperature caused by internal heating of the sonde package.

Since none of these studies provided a correction procedure that was specifically applicable to BOMEX, corrections had to be derived from the BOMEX data.

2. EXAMPLES AND SOURCES OF HUMIDITY ERRORS

In evaluating the humidity errors and deriving a correction for heating of the hygristor by solar radiation, a 7-day set of soundings from the four corner ships in the BOMEX array were used. The 7 days included a 5-day undisturbed period (June 22 to 26) and a 2-day disturbed period (June 28 to 30). The set consisted of data at 90-min intervals at 10-mb levels up to 500 mb, with values linearly interpolated in time for missing levels or observation times. The pressure used here is the p* coordinate system, where p* = sea-level pressure minus ambient pressure, i.e., $p^* = p_0 - p$.

Data for all 7 days from the four ships were averaged for each of the 16 daily observation times at 10-mb intervals for construction of a time vs. pressure array of mean temperature and relative humidity for the entire 7-day sample.

Figure 1 shows vertical profiles of the nighttime average (0000 to 0730 GMT) and midday average (1500 to 1630 GMT) relative humidities, after thermal lag correction of the former, as discussed in section 4. The humidity error in the moist layer at midday, as seen in this figure, is as large as 24 percent and approaches 20 percent at the level of p* = 500 mb. This spurious diurnal variation is more explicitly illustrated in figure 2, which shows the 7-day average specific humidity for 50 p* levels. The maximum deficit approaches 4 g/kg near the surface. The vertical gradient implied by the daytime difference between the manually recorded surface humidity and the rawinsonde value 10 mb above the surface is obviously totally unrealistic in a turbulently mixed marine layer. Further evidence that the diurnal variation is spurious was obtained by comparison of rawinsonde humidities with those derived from psychrometric data acquired with the Boundary Layer Instrument Package (BLIP) at 300 m. BLIP time-series data at 300 m and vertical profiles up to that height showed that any real diurnal variation of specific humidity is too small to be adequately defined by these data, and is certainly one order of magnitude smaller than indicated by the rawinsonde data. Study of aircraft observations at levels up to 7,000 ft yielded several similar results, and it was therefore safe to conclude that the diurnal variation reflected in the rawinsonde data was largely spurious.

One cause of the error was found to lie in deficiencies in the design of the duct in which the hygristor was mounted. The hygristor duct opening and the semitranslucent plastic cover permitted solar radiation to penetrate, internally reflect, and heat the carbon-coated hygristor. Also, the positioning of the duct opening and the shape of the duct reduced the airflow at the sensor to about 30 percent of the ascent rate, giving the hygristor a large thermal lag constant and causing its temperature to lag behind the ambient temperature during ascent by about 1°C, even at night.

The hygristor is assumed to correctly measure the relative humidity of an adjacent thin layer of air that has reached thermal equilibrium with the hygristor. Thus, with a given ambient vapor pressure, and a hygristor temperature that is higher than that of the ambient air, the measured relative humidity will be lower than the true relative humidity of the air sample. If, however, the temperature of the hygristor as well as the ambient temperature is known, the true ambient relative humidity can be determined.

In most of the daytime soundings, the hygristor was warmer than the ambient air at launch time because of solar radiation. If the atmosphere were isothermal, the hygristor would reach equilibrium with the ambient air within 2 or 3 min after release time, and the error in the relative humidity measurement would approach zero. However, except for the trade-inversion layer, the temperature normally decreases with height. The failure of the hygristor to respond quickly to the temperature change is a second source of temperature difference, which exists even when there is no temperature difference at launch time or no solar radiation for the rest of the flight.

A third cause for error is solar radiation which, in the absence of heavy cloud cover, provides a daytime source of heat.

3. ESTIMATING HYGRISTOR TEMPERATURE

The heat transfer properties of the hygristor itself are such that the boundary layer of air between the hygristor and the ambient atmosphere largely controls the heat-transfer process. Thus Newton's law of cooling, which states that the rate of cooling for the hygristor is proportional to the difference in temperature between the hygristor and atmosphere, is an accurate description of the total heat-transfer process between the hygristor and the ambient air. Values of temperature and relative humidity for BOMEX rawinsondes were obtained every 5 s. Making the assumption that radiational heating and the rate of change in ambient temperature are approximately constant during a 5-s interval, we can use the law of cooling in the form

$$
\begin{aligned}
[T_H(t+\Delta t) - T_A(t+\Delta t)] &= [T_H(t) - T_A(t)] * e^{-\Delta t/\tau(t)} \\
&\quad - \tau(t) * \frac{[T_A(t+\Delta t) - T_A(t)]}{\Delta t} * [1-e^{-\Delta t/\tau(t)}] \qquad (1) \\
&\quad + \Delta T_R(t) * [1-e^{-\Delta t/\tau(t)}] \quad ,
\end{aligned}
$$

where

t = time after launch (s),
$T_H(t)$ = hygristor temperature at time t (°C),
$T_A(t)$ = ambient air temperature at time t (°C),
Δt = time interval between sounding points (5 s for BOMEX),
$\tau(t)$ = thermal lag constant (s), and
$\Delta T_R(t)$ = portion of total temperature difference between hygristor and ambient air due to solar radiational heating (°C).

Equation (1) is used in an iterative fashion to find the hygristor temperature profile. Knowing $[T_H(t) - T_A(t)]$, $\tau(t)$, $\Delta T_R(t)$, and the ambient temperature at time t, we can calculate $[T_H(t+\Delta t) - T_A(t+\Delta t)]$ from eq. (1). Since $T_A(t+\Delta t)$ is known from thermistor measurements, we now obtain $T_H(t+\Delta t)$. The total hygristor-ambient air temperature difference at time $t+\Delta t$, $[T_H(t+\Delta t) - T_A(t+\Delta t)]$, is reinserted into eq. (1) to obtain the difference at time $t+2\Delta t$, etc.

4. EVALUATION OF INDIVIDUAL TERMS IN EQUATION (1)

The initial (deck level) values ($t = 0$) of temperature and relative humidity were obtained from manual shipboard observations. The hygristor temperature 5 s after release was inferred by observing that immediately after launch the rawinsonde would descend for a short time and then begin its ascent. At 5 s after launch it sampled approximately the same water-vapor content as the ship psychrometer. We therefore assumed that the specific humidity at the 5-s level was identical to the shipboard pyschrometric reading. Since the 5-s rawinsonde-measured relative humidity is known, the hygristor temperature at this level can be derived. The 5-s temperature difference averages about 6°C at midday and 2°C at night, based on evaluation of individual soundings.

The second term on the right of eq. (1) represents the lag of response to changing ambient temperature during ascent. Theory suggests that the thermal lag constant $\tau(t)$ is a function of ventilation rate and ambient air density. Using BOMEX data, we found that a reasonable expression for the lag constant in seconds is given by

$$\tau = 34.9\ (\rho V)^{-0.4} \quad ,$$

where

ρ = ambient air density (kg m^{-3}), and
V = ventilation rate of hygristor $\equiv 0.3 *$ ascent rate (m s^{-1}).

This gives values for the time constant on the order of 30 s near sea level, which is in good agreement with independent estimates (Teweles, 1970; Ostapoff et al., 1970). At ascent rates of 4 to 5 m s^{-1}, the lag constant is about 45 to 50 s at the p* = 500 mb level. The nighttime hygristor-ambient air difference stems mainly from this lag effect. For BOMEX data this difference is on the order of 1°C, and leads to relative humidity errors in the moist layer of 4 to 6 percent. Since this correction depends on knowledge of the ambient-temperature profile, it was also applied to individual soundings.

Radiation measurements for deriving correction methods were not available for individual ascents. The correction scheme was therefore based on an indirect method using 7-day average data. The aim was to obtain a simplified radiation correction term, $\Delta T_R(t)$, which depended only on p* level and time of day. The effects of varying cloudiness are ignored in this approach, and will be discussed further in section 6. Other heating effects, e.g., those due to the sonde electronics, were also included in the radiation correction term.

The 7-day average data were collected during BOMEX Observation Period III (June 19 to July 2). Since there was little variation of solar zenith angle during the other observation periods, the results are considered applicable to all BOMEX observations.

We made the assumption that the daytime ambient vapor pressure of the 7-day average array at each level was equal to the vapor pressure computed from the nighttime (0000-0730 GMT) soundings which had been corrected for the temperature lag of the hygristor. This can be written as

$$\overline{RH}_N * e_s\ (\overline{T}_N) = RH_D * e_s\ (T_D) \quad . \tag{2}$$

where

e_s = saturation vapor pressure (mb),
$\overline{RH}_N$ = average nighttime relative humidity (percent),
RH_D = daytime measured relative humidity (percent),
$\overline{T}_N$ = average nighttime ambient temperature (°C), and
T_D = daytime hygristor temperature (°C).

Since $\overline{RH}_N$, $\overline{T}_N$, and RH_D are known, T_D can be computed from eq. (2). The hygristor difference caused by radiation is then obtained by subtracting the ambient temperature from T_D.

The temperature difference array was then vertically averaged for each observation time in order to examine the average diurnal variation of ΔT_R. The result is shown in figure 3. The range of sunrise and sunset times at the four ships is shown by the vertical dashed lines. The average solar meridian passage (true solar noon) is at 1548 GMT. The vertically averaged diurnal data were closely fitted by the function $A * \sin^2(\theta)$, where $\theta = 10 *$ [Hour (GMT) - 6.5], covering the 18-hr period from 0630 GMT to 0300 GMT. We decided to use this same shape function at each level to find an amplitude term that depended on the p* level. The radiation term is expressed as

$$\Delta T_R(p^*, \theta) = A(p^*) * \sin^2(\theta) \quad . \tag{3}$$

Estimates of the amplitude at each 10-mb pressure level were obtained by dividing every ΔT_R by the appropriate $\sin^2(\theta)$ for each daytime observation and averaging at each level. The vertical profile of this average amplitude is shown in figure 4. We fitted this profile by the function

$$\begin{aligned} A(p^*) &= 3.8 & (0 \le p^* \le 320 \text{ mb}) \\ &= 3.8 + c * \log_e \frac{(1016-320)}{1016 - p^*} & (p^* > 320 \text{ mb}) \quad , \end{aligned}$$

where c = 13.03. The value 1016 was taken as a typical value of the sea-surface pressure in millibars.

We find ΔT_R from eq. (3) and substitute it in eq. (1) to obtain the hygristor temperature, T_H. Using our assumption that the air sampled by the hygristor has the same vapor pressure as the ambient air, we find the true relative humidity, RH_T, from the measured, RH_M, by the formula

$$RH_T = RH_M * \frac{e_s\ (T_H)}{e_s\ (T_A)} \quad . \tag{4}$$

5. ALTERNATE METHOD FOR CHECKING RADIATION CORRECTION

The method of using the daytime average relative humidity profiles for calculating a radiation correction is open to question. The averaging procedure may obscure important features, such as those caused by temperature inversions. Also, relative humidity is not a direct measure of water-vapor content, whereas specific humidity is. Since 70 percent of the water-vapor content during BOMEX was found beneath the trade-inversion layer, this fact should be weighted accordingly in the analysis.

In view of this, we checked our results by a method in which the specific humidity profiles of individual soundings are used. To fit the amplitude function, the following was done:

(a) An average, lag-corrected nighttime specific humidity profile was used as the true profile.

(b) Thirty-two individual, lag-corrected daytime soundings at 1500 GMT were used.

(c) An amplitude function of the form $A(p^*) = a + bp^*$ was assumed.

(d) The squared differences between individual q's and the night average for each level for all 32 soundings were summed, and the constants a and b chosen to minimize the sum.

The specific humidities act as a weighting factor. If q_i = fitted daytime specific humidities, $\overline{q}_i$ = nighttime average, and q_i^{MEAS} = measured daytime values, then the sum to be minimized can be written

$$\sum_i (q_i - \bar{q}_i)^2 = \sum_i (q_i - q_i^{MEAS})^2 - 2\sum_i w_i (q_i - q_i^{MEAS}) + \sum_i w_i^2 \quad ,$$

where $w_i \equiv \bar{q}_i - q_i^{MEAS}$. The weight term w_i is typically three to four times larger beneath the inversion layer than above it.

The results from the calculation show that the amplitude, A, is a slowly decreasing function of p*. Its mean value through the moist layer is within 5 percent of the value 3.8 obtained by the method in which average relative humidity was used. This provides additional support for the initial correction method and also shows that the amplitude function of eq. (3) will correct individual specific humidity values in the moist layer quite well.

6. EFFECTS OF CLOUDINESS AND RESULTS

For a preliminary check on the correction procedure we first applied it to the original 7-day mean set of observed specific humidities. Since we had assumed zero diurnal variation in specific humidity, the results show the effects of the simplified function that represents the radiation correction. They are shown in figure 5 and are a significant improvement over the uncorrected data in figure 2.

To find how well individual soundings made under differing cloud conditions are corrected by this procedure, we applied the mean correction separately to the mean data taken during the 5 undisturbed days and the 2 disturbed days. The uncorrected and corrected specific humidities averaged vertically through the 500-mb layer for the 5-day and 2-day periods are shown in figure 6. The averaged corrected daytime humidity is slightly lower than the nighttime average for the undisturbed period, and slightly higher for the disturbed. In general, the results appear quite satisfactory.

Additional tests were made by applying the corrections to 7 individual days for each of the four ships with conditions varying from clear to solid overcast with showers. The results indicate that the corrections are good for all but totally overcast conditions. Heavy showers and thunderstorms presented the most serious case of overcorrection, where the actual observational error was small, and the corrected relative humidities were as large as 130 percent. The rawinsonde processing program truncates these values to 100 percent and only a small overcorrection results for the near-saturated conditions.

The effect of cloudiness on the magnitude of the radiation correction was examined further by stratifying the data for the 7 days into three categories, based on visual surface observations:

(a) Clear - less than 50 percent; average, 38 percent.
(b) Partly cloudy - 50 to 75 percent; average, 63 percent.
(c) Cloudy - 75 to 100 percent; average, 87 percent.

In the total 7-day period, each category contained about 1/3 of the data.

To assess the role of cloud cover, the data from each category were analyzed to obtain ΔT_R. The amplitudes for the clear and partly cloudy categories were 12 percent greater than the amplitude for the whole 7-day period. The amplitude for the cloudy category was 30 percent less than the 7-day amplitude.

Based on the 7-day average, it appears that the procedure described may slightly undercorrect humidities on clear days, and slightly overcorrect humidities when total cloud cover exceeds 75 percent or precipitation is occurring. In a large majority of cases, however, the corrected relative humidities should be within 5 percent or less of the true value.

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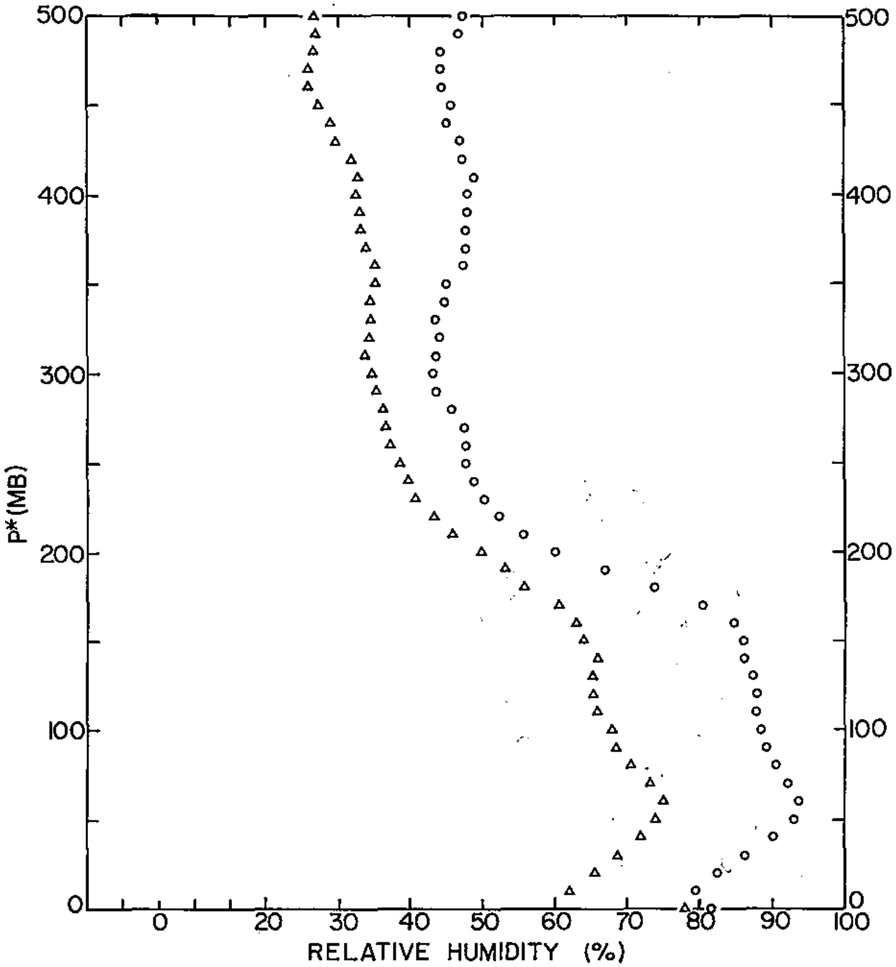

Figure 1.--Comparison of nighttime average (circles) and midday average (triangles) vertical profiles of relative humidity before correction scheme is applied.

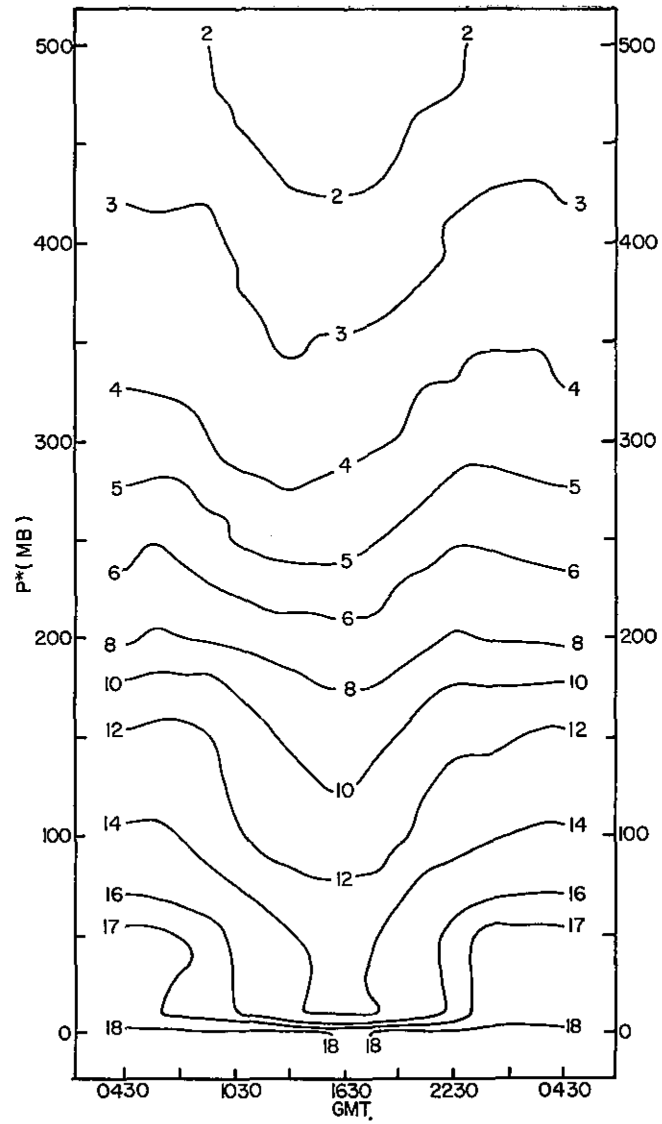

Figure 2.--Seven-day average values of specific humidity data before correction is applied.

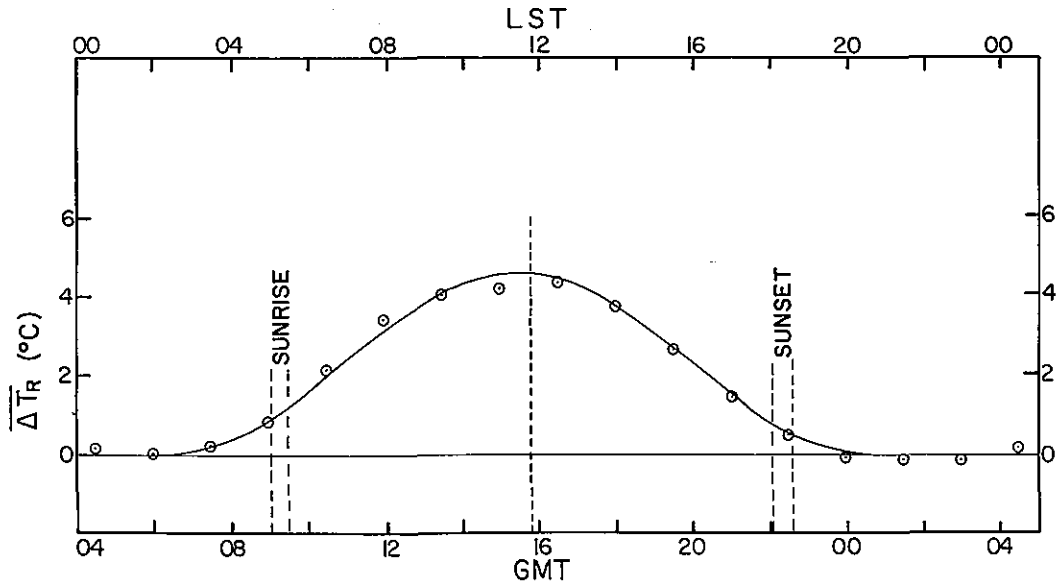

Figure 3.--Diurnal variation of 50-level average ΔT_R.

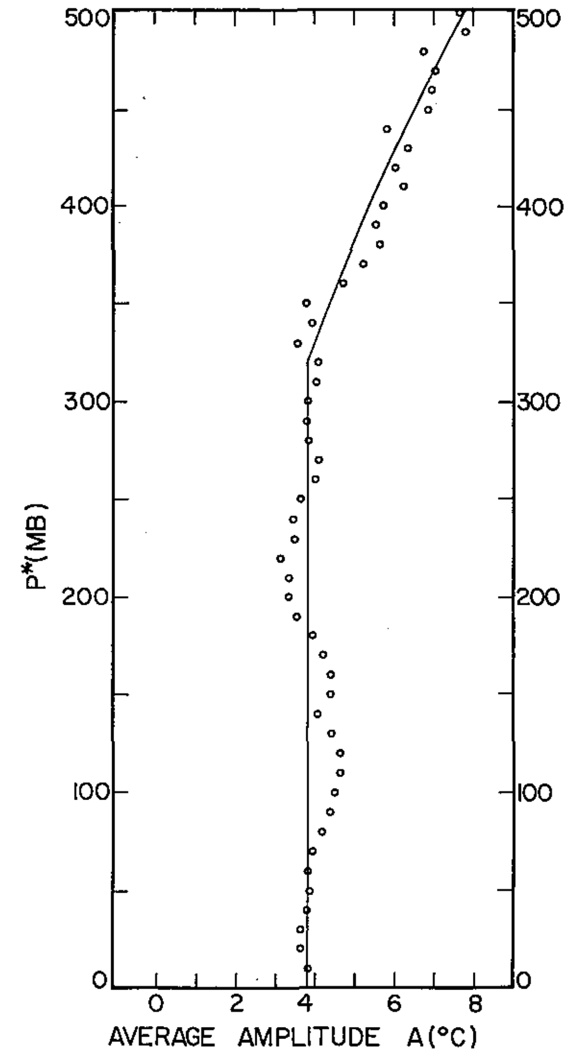

Figure 4.--Average amplitude A (°C) of radiation correction term.

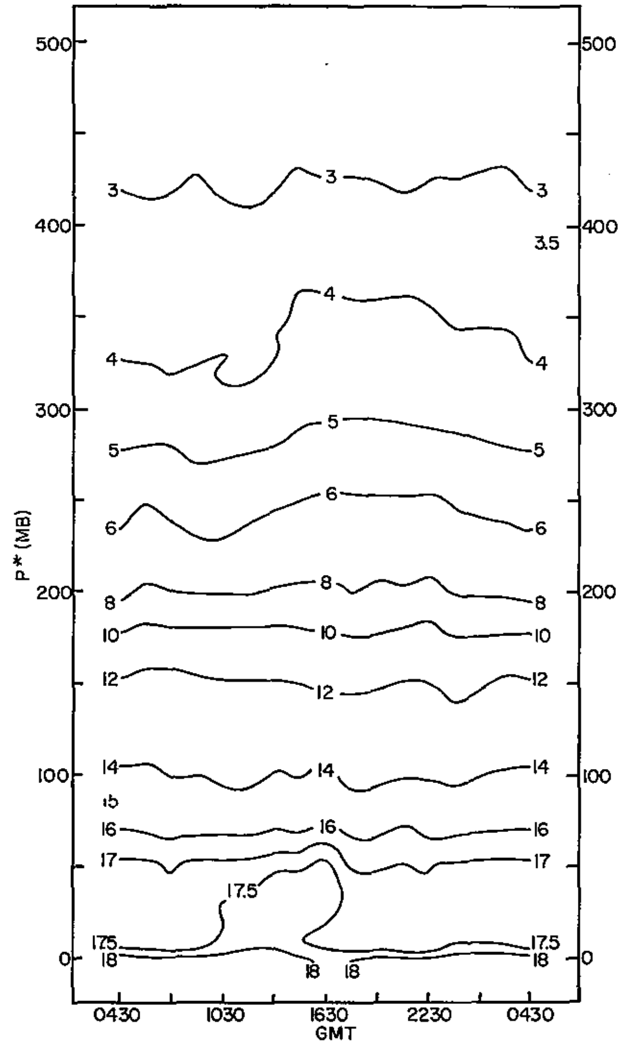

Figure 5.--Seven-day average values of specific humidity data after correction is applied.

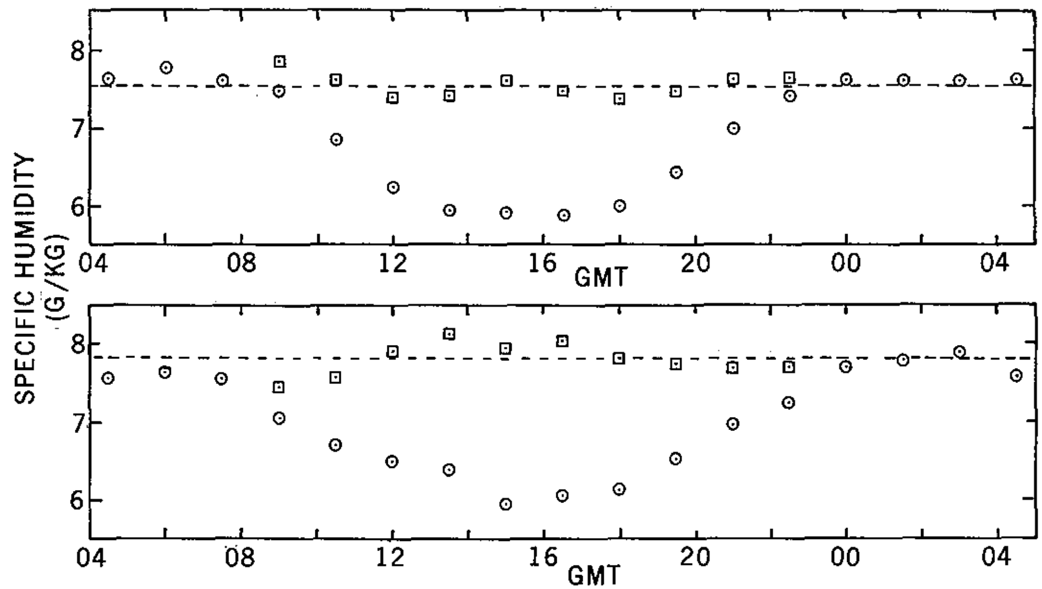

Figure 6.--Comparison of corrected daytime average specific humidities (squares) and the uncorrected average (circles) for the 5-day undisturbed period (June 22-26), shown in the top illustration, and the 2-day disturbed period (June 28-30), shown in the bottom illustration. The dashed line is the nighttime average.