Modulations of the Net Tropospheric Temperature during GATE

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ABSTRACT

The net vertically integrated temperature of the GATE B array is analyzed at each rawinsonde observation time for all three phases. Temperatures are adjusted to remove persistent intership biases and errors induced by solar heating of the rawinsondes. Modulation of the net temperature by direct solar heating, secondary circulation processes and latent heat release are explored.

Latent heat release does not warm the troposphere on the observed time (3–6 h) and space scales indicating that condensation heating is dispersed very rapidly from cloud-cluster-scale systems to larger circulations. The net temperature undergoes a regular diurnal temperature oscillation modulated primarily by direct radiational heating and indirect circulation. These processes are of comparable magnitudes.

1. Introduction

The GARP Atlantic Tropical Experiment (GATE) of the Global Atmospheric Research Program (GARP) has provided a tropical data set with sufficient complimentary data sources and resolution to permit detailed examination of temperatures and heat sources on the time and space scales of tropical weather systems. This study first examines the accuracy of GATE rawinsonde temperature measurements. Adjusted temperatures are then used to analyze time variations of the vertically integrated tropospheric temperature ($\overline{\Delta T}$) on the B scale. Variations of $\overline{\Delta T}$ associated with radiational heating and latent heat release are determined. The results indicate that radiation is the primary modulator of $\overline{\Delta T}$ on a diurnal time scale, but a large-scale diurnal circulation is also substantial. Latent heat release does not have a significant effect on net B scale temperatures implying that the dispersal of condensation heating to larger space scales occurs on a shorter time scale than can be resolved with the available 3–6 h resolution.

2. Data set

Rawinsonde data were taken from the GATE processed and validated data tapes from the National Weather Records Center at Asheville, North Carolina. Data flagged as suspicious by CEAS[1] were omitted. Temperature data from all A/B and B array ships (Fig. 1) were examined, but only B array temperatures were used in the final analysis. Wind data were taken from the seven Russian ships and the *Vanguard*. Winds from the remaining ships were not used due to the likely presence of systematic errors in winds from their Very Low Frequency (VLF) systems (Frank, 1979; Thompson *et al.*, 1979).

Radiation data for each time period of Phase III were taken from Cox and Griffith (1978; 1979). Although they found large level-by-level differences between radiation flux divergences (Q_R) in clear versus disturbed regimes, the vertically integrated net $\overline{Q_R}$ varied only slightly with the amount of convection (Fig. 2). The diurnal variations of $\overline{Q_R}$ were much larger than disturbed/undisturbed region differences, so the following simple method of estimating $\overline{Q_R}$ in Phases I and II was assumed adequate: For each time of day, Phase III time periods were classified as convective or suppressed according to total master array radar rainfall from Hudlow and Patterson (1978). Convective times were those with rainfall rates ≥ 1 g cm^{-2} day^{-1}. The GATE master array is a circle centered on the B ship array with a radius of ~200 km. Mean Phase III $\overline{Q_R}$ values for each time of day were computed for each rainfall group. These values were then applied to similar time periods in the first two phases based on radar rainfall.

Estimates of latent heat release were taken from the master array radar measurements of Hudlow and Patterson (1978) and from budget-derived condensation rates for the A/B scale area from Frank (1979). The latter study performed vertically integrated budgets of moisture (q) and dry static energy (s) solving for net condensation rates as residuals. The budgets were performed for the A/B area due to the previously mentioned problems with B array winds.

[1] Center for Environmental Assessment Services, formerly the Center for Experiment Design and Data Analysis.

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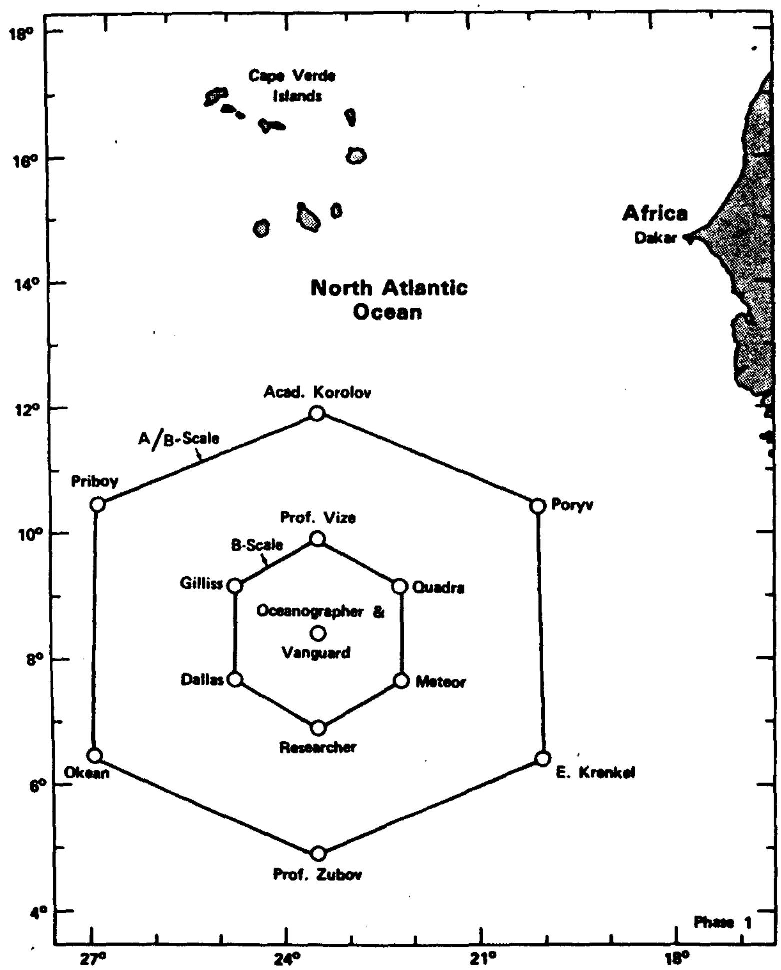

FIG. 1. GATE ship array during Phase I.

The radar precipitation estimate lagged budget condensation by an average of 4–6 h. Frank (1979) showed that much of this lag could be due to cloud-scale storage of liquid water, i.e., the budgets provide an estimate of condensation while the radar estimated precipitation. Both types of condensation estimate (budget and radar) were utilized independently in the present study.

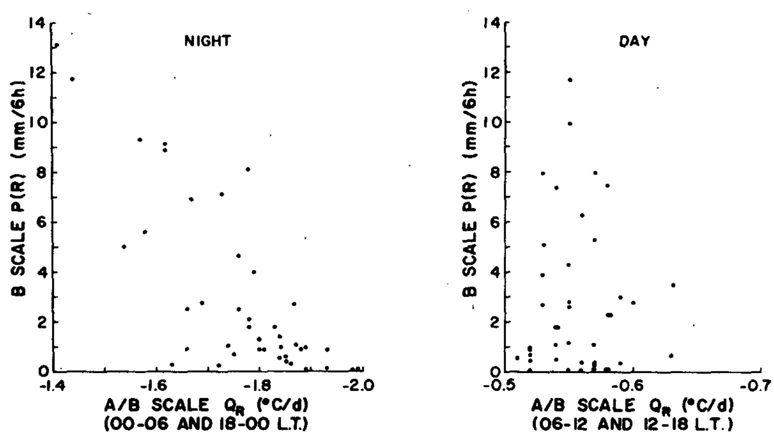

FIG. 2. Net night (1800–0600 LT) and day (0600–1800 LT) radiational cooling of the surface to 100 mb layer ($\overline{Q}_R$) versus B array radar rainfall estimates.

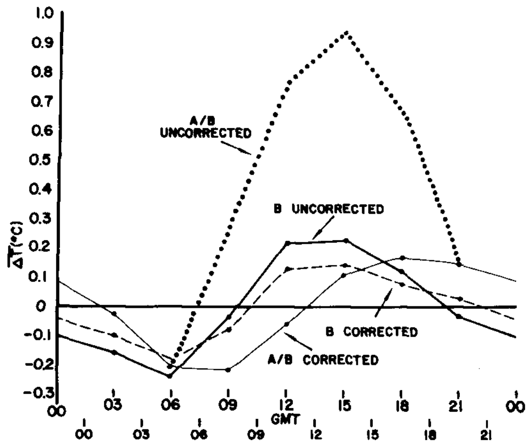

FIG. 3. Diurnal variations of the net tropospheric temperature ($\overline{\Delta T}$) for the A/B and B ship arrays. Values are shown with and without corrections for assumed solar heating errors.

3. Data quality and analysis

Temperatures were computed as deviations from phase mean values. An average temperature profile for each ship during each phase was constructed. At each level the phase mean temperature for a ship was subtracted from the observed value to give a deviation temperature

$$\Delta T = T - [T], \tag{1}$$

where ΔT is the deviation temperature, T the observed temperature and $[T]$ the phase mean temperature for that ship. This technique removed the very large persistent ship-to-ship biases in temperature measurements found by Ooyama and Esbensen (1977) and Reeves (1978). At each level and observation time an average deviation temperature was computed for each array (ΔT_B,ΔT_{AB}). The A/B array Russian ships were averaged separately from the B array ships (minus the *Vize*) since the former employed a large radiation correction factor. Temperatures were then integrated from the surface to 100 mb to give a mean tropospheric deviation temperature, e.g.,

$$\overline{\Delta T_B} = \frac{1}{p_{sfc} - 100} \int_{p_{sfc}}^{100} \Delta T_B(p) dp, \tag{2}$$

where $\overline{\Delta T_B}$ is the mean tropospheric temperature deviation for the B array at an individual time. Vertically integrated temperature is proportional to the total sensible heat ($c_p T$) content of the troposphere.

Daylight temperatures of Russian ships were adjusted at the time of the soundings to account for presumed errors due to solar radiation. The magnitudes of these corrections were very large (Fig. 3) and were applied without regard to cloud cover. The A/B corrections appear to be too large in the mean, but it is not known whether this is true at all individual time periods. Ooyama and Esbensen (1977) noted that the Russian ships showed a midnight temperature maximum in Phase III, while the current study and Dewart (1978) show maximum A/B array temperatures near 1800 GMT averaged over all three phases. The maximum $\overline{\Delta T_B}$ for the B array ships occurred near 1500 GMT (as did the uncorrected $\overline{\Delta T_{AB}}$) (Fig. 3). Since the A/B array radiation corrections were substantially larger than mean diurnal variations, they were considered unreliable for computation of mean temperatures during daylight hours.

TABLE 1. Assumed errors in $\overline{\Delta T}$ due to solar heating of the thermistor. (U.S. ship values are three-fourths of estimated maximum error. The reduction is to account for the shielding of the sondes by layer clouds.)

Time (LT) (GMT)	0730 0900	1030 1200	1330 1500	1630 1800
Corrections for assumed errors (°C)				
U.S. ships	0.10	0.15	0.15	0.10
Russian ships	0.50	0.83	0.83	0.50

There were undoubtedly some radiation-induced errors in the $\overline{\Delta T_B}$ measurements. Foltz and Gray (1979) surveyed various laboratory and observational studies of rawinsonde instrumentation and temperature measurements and concluded that the maximum error at any level below 300 mb is probably <0.2°C. National Weather Service laboratory and field tests of solar radiation effects on rawinsondes indicate a maximum error in $\overline{\Delta T_B}$ of ~0.2°C (Hodge).[2] The error would be largest at high levels due to decreasing ventilation of the thermistor. The maximum solar anomaly occurs at local noon with clear skies. It was not possible to derive an appropriate correction for each sounding. However, mean corrections of $\overline{\Delta T_B}$ for each time of day (Table 1) were estimated from Foltz and Gray (1979) and Hodge[2] and applied to the GATE average diurnal curve (Fig. 3). Since local noon was about 1330 GMT, the 1200 and 1500 GMT and the 0900 and 1800 GMT corrections should be symmetrical. The use of both the corrected and uncorrected diurnal temperature curves in subsequent analyses allowed estimation of sensitivity of results to possible radiation-induced errors.

Infrared (IR) radiation can also result in erroneous rawinsonde temperature errors. Harmantas and Hodge[3] have observed IR errors of at least 1.0°C in the upper troposphere. These effects are quite complex as they vary with height and distributions of cloud cover, temperature and moisture. It is as-

[2] M. W. Hodge, personal communication.

[3] C. Harmantas and M. W. Hodge, personal communication provided by Hodge.

TABLE 2. Temperature and condensation/precipitation estimates for 14 easterly wave troughs and ridges. Warming rates ($\partial\overline{\Delta T_B}/\partial t$) were calculated for the periods ±6 and ±24 h from the time of trough or ridge passage.

	Troughs	Ridges
$\overline{\Delta T_B}$ (°C)	0.05	0.09
$\frac{\partial\overline{\Delta T_B}}{\partial t}$ (°C day^{-1})		
±6 h	−0.3	0.0
±24 h	−0.1	0.0
s-budget condensation rate (°C day^{-1})	5.4	1.5
Radar precipitation rate (°C day^{-1})	5.4	0.9

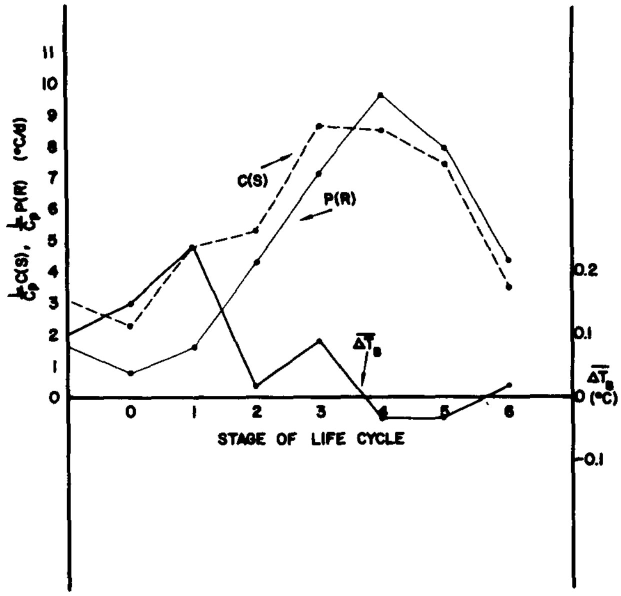

FIG. 4. *s*-budget condensation heating, radar rainfall estimated heating and net temperature during composite convective system life cycle. Stages are at ~3 h intervals.

sumed that IR errors are not correlated with time of day and hence do not bias long-term diurnal temperature variations, but there is insufficient quantitative knowledge of IR effects to assess fully the validity of this assumption.

4. Results

a. Effects of latent heat release

Numerous observational studies have indicated upper level warm cores of a few tenths of 1°C in association with deep convective systems (Reed and Recker, 1971; Williams and Gray, 1973; Ruprecht and Gray, 1976; Reed *et al.*, 1977; Frank, 1978a). Most of these studies also noted weak cold core structures through substantial portions of the lower troposphere. This temperature structure implies mean height gradient patterns which are consistent with observed divergence patterns (Gray and Jacobson, 1977; McBride and Gray, 1979). Since the upper and lower level temperature anomalies are of opposite sign, the effect of latent heat release on $\overline{\Delta T}$ must be smaller.

Reed *et al.*, (1977) showed that GATE rainfall was highly correlated with easterly wave phase, with maximum rainfall in or just ahead of the trough and minimum rain near the ridge. All three phases of GATE were examined for easterly wave passages. Fourteen (each) distinct troughs and ridges were classified according to B array vorticity and meridional wind values in the 600–700 mb layer. Condensation, precipitation and $\overline{\Delta T_B}$ were averaged ±6 h from the times of trough or ridge passage. Table 2 shows that the average $\overline{\Delta T_B}$ values were virtually indistinguishable despite major condensation differences. The waves did not accumulate net sensible heat in either region, and no net warming was observed with trough or ridge passage.

Frank (1978a) classified twelve convective systems according to stage of life cycle. The stages varied from 0 to 6 where stage 0 was at least 3 h prior to any observed increase in radar echo activity, stage 4 was the period of maximum radar rainfall and stage 6 was a late decaying stage. The stages were ~3 h apart. Fig. 4 shows $\overline{\Delta T_B}$ (diurnally filtered), condensation estimated from the dry static energy budgets, and radar rainfall at each stage of development. Despite large and rapid changes in condensation and rainfall, $\overline{\Delta T_B}$ remained very stable except for a small maximum during the earliest stages.

Correlation coefficients were computed to test relationships between the time rate of change $\overline{\Delta T_B}$ and rate of latent heat release at all individual time periods of Phase III. The third phase was chosen since it was the only one with large amounts of data at the odd-hour time periods and hence consistent 3 h resolution. Table 3 shows that $\overline{\Delta T_B}$ had small negative correlations with all three estimates of latent heat release. On the shortest observable time scale there were no significant relationships between

TABLE 3. Correlation coefficients (r) between the time rate of change of $\overline{\Delta T_B}$ (diurnally filtered) and three estimates of latent heat release: *s*-budget condensation [$c(s)$], *q*-budget condensation [$c(q)$] and radar precipitation (P). Phase III.

$$r\left[\frac{\partial\overline{\Delta T_B}}{\partial t}, c(s)\right] = -0.11$$

$$r\left[\frac{\partial\overline{\Delta T_B}}{\partial t}, c(q)\right] = -0.20$$

$$r\left[\frac{\partial\overline{\Delta T_B}}{\partial t}, P\right] = -0.14$$

Standard deviation for uncorrelated sample: $\sigma = 0.09$.

TABLE 4. Vertically averaged (sfc–100 mb) vertical motion $\bar{\omega}$ (mb day^{-1}) for all three phases. Odd time periods are adjusted to give the same daily mean as even time periods.

Time (GMT)							
0000	0300*	0600	0900*	1200	1500*	1800	2100*
−27	−20	−37	−65	−64	−70	−65	−37

* Adjusted.

net tropospheric temperature change and rate of latent heat release. Similar results for the total GATE period (including Phases I and II) were reported in Frank (1978b) although the time resolution in that study was often 6 h. The above results indicate that $\overline{\Delta T_B}$ was independent of the amount of latent heat release on the observable time scale of 3–6 h.

b. Lateral dispersal of condensation heating

Latent heat did not produce significant changes in the net tropospheric sensible heat content on the observed time (3–6 h) and space (300–400 km) scales. Since the rate of condensation heating of the ship array exceeded 15°C day^{-1} during major convective episodes, it is clear that the energy was dispersed rapidly to larger scales. This was accomplished primarily through a net export of dry static energy resulting from the typical low-level convergence/upper level divergence patterns associated with deep convection in the tropics (McBride and Gray, 1979).

The rapid lateral dispersal of condensation heating from a cluster-scale region raises an important question concerning scale interactions in convective weather systems: Does the regional-scale circulation (i.e., the ITCZ/monsoonal flow) vary in intensity on the same time scale as individual cloud clusters, or can it be treated as a closed system for periods of 3–12 h?

The GATE A/B array has an effective radius of ~400 km. During relatively undisturbed periods with a mean condensation rate for the array equivalent to about 1°C day^{-1}, the local area would be energetically balanced. The latent heat release plus the smaller surface sensible heat flux (~0.1°C day^{-1}) would balance the daily radiational cooling. However, during the growth phase of a strong cloud cluster the condensation rate can increase to over 15°C day^{-1} in <12 h (Frank, 1979; Hudlow and Patterson, 1978). At the time of maximum rainfall, the A/B array would be releasing enough latent heat to balance Q_R and S_0 over a region with 1500 km radius. Since no net warming occurs with this latent heat release, the growing system must be associated either with simultaneous decreases in convection over most of the rest of the northeast tropical Atlantic or with a rapid increase of large-scale sensible heat divergence. The former process would imply a steady large-scale circulation where a strong local buildup of convection in one area suppressed rainfall elsewhere. Total regional rainfall would be definable in terms of sea surface properties and slowly varying general circulation features. The location of a convective system within the region would be a more difficult problem since a growing cluser in one area might suppress development in an otherwise favorable region such as an easterly wave trough.

If the regional-scale circulation varies on the time scale of the cluster, the problem becomes very complex. The mesoscale circulations which develop in conjunction with thunderstorm/squall-line growth are thought to be strongly self-intensifying. Once triggered the systems proceed through a typical life cycle fueled by their own feedbacks to the larger scale. Ogura *et al.* (1979), Leary (1979), Thompson *et al.* (1979) and Frank (1978a) have shown that A/B scale upper level mass divergence of air with high static energy occurs after increases in low-level convergence and convection. It can thus be argued that once a cloud cluster begins to develop, its internally driven growth intensifies the vertical circulation of the entire ITCZ region. If true, this would have important implications for parameterization philosophies which consider the cloud populations as rapidly adjusting to a slowly varying large-scale circulation. The cloud population and the large-scale circulation would have to be viewed as a continually interacting system rather than as a system containing phenomena acting on separable time and space scales. More research is needed in this area.

c. Diurnal variations of parameters

Fig. 3 showed that $\overline{\Delta T_B}$ reached a maximum near 1500 GMT (1330 LT) and a minimum near 0600 GMT (0430 LT). This diurnal cycle was very regular. When 0000, 0600, 1200 and 1800 GMT temperatures were computed for each day, the 0600 GMT sounding showed the lowest $\overline{\Delta T_B}$ on 43 of 53 days. Dewart (1978) and Foltz and Gray (1979) have found similar diurnal temperature variations of deep tropospheric layers during GATE. The latter authors noted related variations in data from other tropical experiments and the Northern Hemisphere data tabulations.

There was also a strong diurnal variation of vertical motion. When the average A/B area vertical motion of the surface to 100 mb layer was computed, maximum upward motion was found at 1500 GMT with a minimum near 0300 (Table 4). These values were smoothed to remove a sampling bias. GATE soundings at 0000, 0600, 1200 and 1800 GMT were taken quite regularly, but the 0300, 0900, 1500 and 2100 soundings were usually restricted to days with active convection except during much of Phase III.

Therefore, the mean upward motion (and precipitation rates) for the odd-time periods exceeded the even-time values in all phases. To bring the values into agreement, the odd-time values were multiplied by the ratio of the even-time mean to the odd-time mean. Dewart (1978) and McBride and Gray (1979) have also found diurnal variations in GATE vertical motion patterns.

Precipitation was diurnally phased during GATE, but the time of maximum rainfall varied according to the measurement techniques as discussed by Frank (1979). Individual time period A/B scale budget analyses of moisture (q) and dry static energy (s) both showed maximum condensation rates in the late morning and minima near local midnight. The master array radar estimates showed a smaller amplitude with an afternoon maximum (Fig. 5d). Raingage measurements tended to agree with the radar estimate, although there was considerable noise. This paper will not address the relative accuracies of the various measurements, but it should be noted that solar heating of rawinsondes would slightly increase morning and decrease afternoon condensation in both s and q budgets due to the systematic effects of overestimates of T and underestimates of q (maximum near solar noon) on the storage terms. Unsampled cloud vapor storage in the moisture budgets tends to cause overestimates of condensation during the early stage of convective development (usually in the morning). All methods gave similar results for daily averaged rainfall.

d. Vertical process warming

The time rate of change of temperature at a level is given by

$$\frac{\partial T}{\partial t} = -\mathbf{v}\cdot\nabla T - -\omega\frac{\partial\theta}{\partial p} + Q_R + \frac{L}{c_p}(c-e), \quad (3)$$

where $\omega = dp/dt$, Q_R is the radiational heating, L the latent heat of condensation, c_p the specific heat at constant pressure, c the total condensation, and e evaporation. Since $\partial T/\partial t = \partial\Delta T/\partial t$, Eq. (3) was vertically integrated from the surface to 100 mb to give

$$\underset{\text{(a)}}{\frac{\partial\overline{\Delta T_B}}{\partial t}} + \underset{\text{(b)}}{\frac{1}{P_0-100}\int_{P_0}^{100}\mathbf{v}\cdot\nabla\Delta T_B dp} - \underset{\text{(c)}}{\overline{Q_R}}$$

$$= -\underset{\text{(d)}}{\frac{1}{P_0-100}\int_{P_0}^{100}\omega\frac{\partial\theta}{\partial p}dp} + \underset{\text{(e)}}{\overline{\frac{L}{c_p}(c-e)}}, \quad (4)$$

where $\overline{Q_R}$ and $\overline{(L/c_p)(c-e)}$ are the heating of the column due to radiation and net condensation, respectively. Terms (a) and (c) were observed/estimated by the previously described techniques. Term (b) was estimated by fitting the winds and deviation temperature gradients to a plane of least squares. The use of deviation temperatures obscured advection due to long-term mean temperature gradients, but these were considered small (Frank, 1979). The remaining terms (d and e) represent the total heating due to vertical advection on all scales and latent heat release. These terms tend to partially cancel when (e) is large. Although latent heat release (e) can be estimated from budgets and radar, term (d) is quite complex and difficult to interpret physically in a convective regime where vertical motions and variations in temperature gradients are dominated by convective-scale processes. Since (d) and (e) are integrally related in the tropics, it is convenient to refer to their sum as the vertical process heating (Q_V), i.e.,

$$Q_V = -\frac{1}{P_0-100}\int_{P_0}^{100}\left[\omega\frac{\partial\theta}{\partial p} - \frac{L}{c_p}(c-e)\right]dp. \quad (5)$$

Foltz and Gray (1979) defined a similar quantity which also contained term (b) and referred to it as the required warming (RW). This term is determined as a residual using Eq. (4).

Fig. 5 shows the diurnal variations of the components of the atmospheric temperature budget averaged for all three phases. Q_R follows a regular cycle in phase with solar elevation angle (Fig. 5a). Maximum values of $\overline{\Delta T_B}$ and $\overline{\Delta T_B(c)}$ ($=\overline{\Delta T_B}$ corrected for assumed solar errors) occurred after the time of solar heating maximum. The troposphere cooled at a nearly constant rate between 1500 and 0600 GMT. This was followed by strong warming from 0600–1200 GMT (Fig. 5b). Mean diurnal variations of horizontal temperature advection (not shown) were negligible.

The diurnal cycle of Q_V is shown in Fig. 5c. The mean value was $+1.15°\text{C day}^{-1}$, approximately balancing the average radiational cooling. Significant departures from the mean occurred between 0600–1200 GMT (maximum) and 1200–1800 GMT (minimum). The morning maximum indicates that the troposphere warmed (due to vertical processes) faster than could be explained by increased radiational heating alone. In the afternoon temperatures decreased despite continued solar heating above the daily average. Thus, Q_V was small between 1200–1800 local time.

It is tempting to try and relate the Q_V variations to the diurnal cycle in latent heat release (Fig. 5d) since budget-derived condensation showed a maximum in phase with the Q_V morning maximum. However, there are three problems. One is that day-to-day rainfall during GATE was erratic with respect to time while the $\overline{\Delta T_B}$ (and hence Q_V) cycles were much more regular as previously shown. In addition

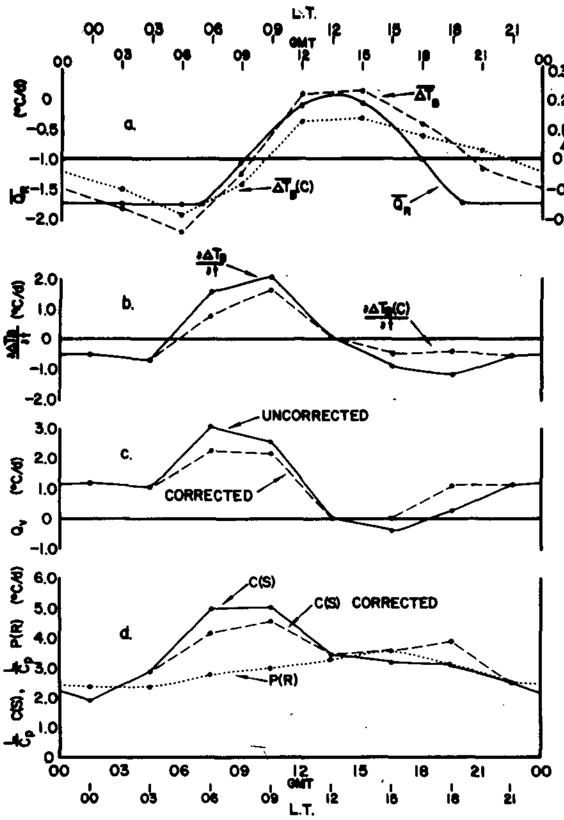

FIG. 5. Diurnal variations of (a) radiative heating ($\overline{Q_R}$), net tropospheric temperature ($\overline{\Delta T_B}$) and net temperature corrected for solar radiation-induced errors [$\overline{\Delta T_B}(c)$]; (b) time rates of change of $\overline{\Delta T_B}$ and $\overline{\Delta T_B}(c)$; (c) vertical process warming (Q_V) computed with $\overline{\Delta T_B}$ (uncorrected) and $\overline{\Delta T_B}(c)$ (corrected); (d) latent heat release due to s-budget condensation [$c(s)$], s-budget condensation computed using $\overline{\Delta T_B}(c)$ (corrected), and radar precipitation [$P(R)$].

Foltz and Gray (1979) showed that their "Required Warming" (analogous to Q_V) experienced similar diurnal variation patterns in different seasons and at various latitudes up to 85°N encompassing several regimes with afternoon or evening rainfall maxima. Finally, $\overline{\Delta T_B}$ was found to be almost completely independent of latent heat release on the time and space scales resolved in this study.

e. Effects of solar heating errors

The varied natures of the regimes with Q_V variations similar to Fig. 5c suggest that the cause must be either a global-scale phenomenon or a solar radiation-induced temperature error. From budget considerations Q_V nearly balances Q_R over long time periods particularly in the tropics where thermal advection is weak.

If it is hypothetically assumed that $Q_V = -\overline{Q_R} = 1.15$°C day^{-1} during GATE, where Q_V did not vary diurnally, then $\overline{\Delta T_B}$ would have varied with the diurnal cycle of Q_R shown in Fig. 6 [curve labeled $\overline{\Delta T_B}(Q_R)$]. Also shown are the differences between $\overline{\Delta T_B}$ and [$\overline{\Delta T_B}(c)$] and the Q_R-derived curve. These differences represent the amount of $\overline{\Delta T_B}/\overline{\Delta T_B}(c)$ which must be attributed to combinations of measurement error/additional error and time variations of Q_V. They are nearly symmetrical about 1200 GMT and quite steady over the 2100–0600 GMT period. A solar-radiation-induced error in $\overline{\Delta T_B}$ would be expected to be symmetrical about 1200 LT (1330 GMT) and restricted to daylight soundings (0900–1800 GMT for GATE). Since solar radiation errors are always positive, they would erroneously raise the phase mean temperature causing nighttime temperatures to appear colder than average and $\overline{\Delta T_B} - \overline{\Delta T}(Q_R)$ to be negative as in Fig. 6.

The shapes of the curves in Fig. 6 are consistent with a hypothesis of solar-induced measurement error. The near symmetry about 1200 GMT instead of 1330 GMT is probably not significant due to the following:

1) The curves in Fig. 6 are not quite symmetrical since afternoon temperatures are slightly warmer than corresponding morning values.

2) Rawinsondes are scheduled for release 15–30 min before observation time, but due to technical problems many were released at or well after that time. Since the balloons ascended at ~5 m s^{-1}, the average time of measurement was probably slightly after the indicated observation time.

3) Solar heating errors increase with elevation since ventilation of the thermistor decreases with decreasing air density and incident radiation increases. Therefore, the largest effects occur near the end of the balloon's ascent time.

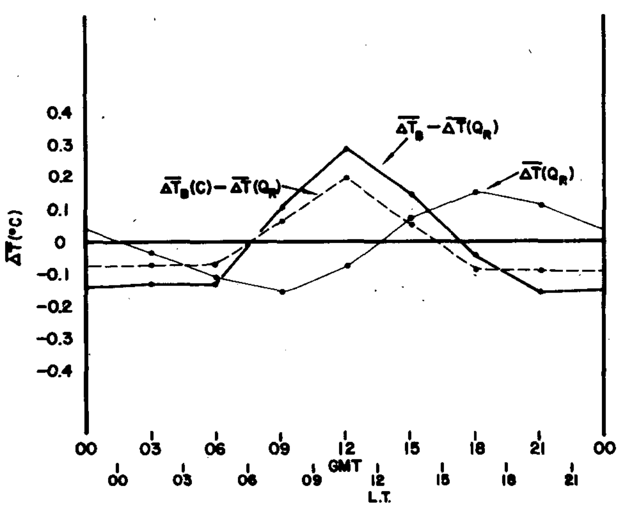

FIG. 6. Diurnal variation of $\overline{\Delta T}$ if Q_V = constant [$\overline{\Delta T}(Q_R)$, light solid line]. Differences between $\overline{\Delta T}(Q_R)$ and observed and solar-corrected values of $\overline{\Delta T_B}$ are shown by heavy solid and dashed lines, respectively.

4) There was a greater incidence of cirrus cloud over the GATE ship array during the afternoon hours than during morning hours. Cirrus clouds tend to reduce solar radiation incident on the sonde and their observed diurnal variation probably would have shifted the true solar error slightly toward the morning.

Thus, the question of a solar-error solution to the Q_V variations of Fig. 5 rests with assessment of the magnitudes of the curves in Fig. 6. If the mean $\overline{\Delta T_B}$ measurement error at 1200 GMT had been 0.42°C, that would have explained the variations. However, the previously discussed measurements of solar heating of thermistors indicate that the maximum error in $\overline{\Delta T_B}$ was probably <0.2°C. Mean errors should have been lower due to abundant GATE cloud cover and changes in incidence angle between the thermistor axis and the sun. It is felt that the solar correction factors of Table 1 are of the appropriate magnitude. Therefore, a substantial portion of the diurnal variation of Q_V must have resulted from a real physical process.

f. Large-scale diurnal circulation

The results of this and other referenced studies strongly indicate the presence of a regular large scale (perhaps global) circulation which acts to increase tropospheric warming in the morning and suppress it during the afternoon. The nature of this circulation cannot be discerned from a data network such as the GATE A/B ship array which spans only ~800 km, but the diurnal period and the regularity of this phenomenon suggest that it is a manifestation of an atmospheric tidal circulation.

Chapman and Lindzen (1970) and Lindzen (1978) have summarized the considerable research which has focussed on diurnal and semidiurnal atmospheric tides. The predominant forcing mechanism is solar heating, and theory adequately relates forcing mechanisms to the observed tropical semidiurnal pressure variation and both diurnal and semidiurnal variations in upper level winds. The present data and those of Foltz and Gray (1979) indicate that the solar tide or a related circulation also produces a diurnal warming of the troposphere which is out of phase with the direct solar heating cycle.

5. Conclusions

The total tropospheric sensible heat content (proportional to $\overline{\Delta T}$) did not vary with latent heat release on the observable time (3–6 h) and space (B–A/B ship array) scales. Therefore, a cloud-cluster-scale system must disperse energy to larger scale circulations on a time scale comparable to that of changes in area-averaged convection. An important topic for future research is to determine whether the regional ITCZ/monsoon circulation varies in intensity on a time scale comparable to that of convective system development.

The vertically integrated tropospheric temperature ($\overline{\Delta T_B}$) of the GATE B array underwent a very regular diurnal cycle during GATE. Maximum temperatures occurred near 1500 GMT and the daily minimum occurred at 0600 GMT. Only B array ship data were used in this analysis since the solar radiation errors and corrections of the A/B array ships were larger than the true diurnal variations of temperature. There also were diurnal variations of vertical motion and precipitation although there is some disagreement concerning the latter since budget analyses indicate a morning rainfall maximum while radar estimates show an afternoon maximum and a smaller amplitude.

The observed diurnal temperature cycle agreed in magnitude but not in phase with the cycle expected from direct radiative heating of the troposphere. There was a net increase in warming due to the sum of latent heat release plus vertical advective processes during the morning hours followed by a decrease to near zero in the afternoon. This cycle of vertical process (Q_V) warming was not a reflection of the diurnal rainfall variations. Some of the observed effect resulted from solar-radiation-induced measurement errors, but most of the diurnal modulation of Q_V appeared to be due to an atmospheric tidal circulation. This modulation of temperature was of approximately the same amplitude as the direct radiational warming cycle.

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