Partitioning Tropical Heat and Moisture Budgets into Cumulus and Mesoscale Components: Implications for Cumulus Parameterization

RICHARD H. JOHNSON

Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523

(Manuscript received 26 November 1983, in final form 11 May 1984)

ABSTRACT

Results from recent heat and moisture budget studies of tropical mesoscale convective systems have been used to partition the total heating in tropical disturbances into cumulus and mesoscale components. The mesoscale component refers to that part of tropical cloud systems which contains mesoscale anvil circulations, viz., a mesoscale updraft in an upper-tropospheric cloud shield extending from near the 0°C level to near the tropopause and a mesoscale downdraft in the lower troposphere. The cumulus component, which is determined as a residual, consists of contributions from cumulus elements of all sizes, ranging from deep cumulonimbus to shallow cumulus; however, deep cumulus effects predominate in the tropical disturbances studied here. The method of partitioning requires an estimate of the fraction f of the total rainfall in tropical disturbances produced by mesoscale anvil systems.

The total apparent heat source Q_1 and moisture sink Q_2 of Yanai and others and the mesoscale anvil Q_1 and Q_2 profiles of Johnson and Young form the basis for the partitioning. For realistic estimates of f, the total heating, which has a peak near 450 mb (6 km), is found to be a consequence of two distinctly different circulation features: 1) the mesoscale anvil, which has a heating peak near 350 mb (8 km) and a cooling peak below near 700 mb (3 km) and 2) the cumulus, which produces a heating peak centered near 600 mb (4 km).

The partitioning of the apparent moisture sink Q_2 produces qualitatively similar results. The mesoscale anvils give a drying peak in the upper troposphere near 350 mb (8 km) and a moistening peak (through evaporation) near 800 mb (2 km). However, the effects of the cumulus in this case (which dry the lower troposphere through removal of water vapor by net condensation) are such that the cumulus drying has a peak somewhat lower in the troposphere (near 750 mb or 2.5 km). Thus, the double-peak structure in Q_2 often seen in tropical budget composite studies is a consequence of the combined, but vertically-separated drying effects of two distinct convective phenomena: mesoscale anvils and deep cumulus.

The results of this study have implications for cumulus parameterization schemes in general, but particularly for those that assign vertical distributions to the convective heating. It has been shown that the cumulus and mesoscale heating distributions are considerably different. Schemes that use an assigned vertical distribution of convective heating chosen to match those obtained from large-scale tropical budget studies should consider carefully the different contributions to total convective heating by the separate cumulus and mesoscale components. Possible errors may result if the proportion of cumulus versus mesoscale-produced rainfall in the region of model application is different from that in the region where the assigned distribution was derived. The results of this study suggest that cumulus parameterization schemes that permit vertical heating distributions to evolve in a realistic way during the course of model integrations are preferred, at least on a physical basis, over those that prescribe the distributions.

1. Introduction

One of the remaining central problems for large-scale numerical weather prediction is the realistic treatment in models of subgrid or unresolved (or partially resolved) moist convective processes. The methods of treatment, often referred to as cumulus parameterization schemes, vary widely in scope and complexity (Haltiner and Williams, 1980; Anthes, 1983; Frank, 1983). The objective is to represent the collective effects of moist convection occurring on the unresolved scales in terms of large-scale (resolvable) properties of the flow. In convectively disturbed situations these effects, as they impact on the large-scale fields of mass, heat, moisture and momentum, can be rather significant, as numerous studies have shown. The need to parameterize cumulus convection for *large-scale* models is clearly realized. As one proceeds downward in model horizontal scale, the question of which convective features need parameterization and which do not is an open one, largely dependent on specific model applications (Anthes, 1983; Frank, 1983).

The emergence of an improved understanding of mesoscale (~100 km) convective systems in the tropics, particularly stemming from the GARP Atlantic Tropical Experiment (GATE) of 1974 (see reviews by Houze and Betts, 1981; Houze and Hobbs, 1982), has focused attention on certain approximations traditionally made in schemes developed for cumulus parameterization. Specifically, a major simplifying assumption often proposed, namely, that the bulk of the convective transports takes place in cumulus towers, has come under question as a result of studies of tropical cloud clusters containing mesoscale precipitation features (Houze, 1977; Zipser, 1977; Brown, 1979; Leary and Houze, 1979; Johnson, 1980; Leary and Houze, 1980; Houze and Cheng, 1981; Gamache and Houze, 1982 and 1983; Houze and Rappaport, 1984). These studies have shown that convection organized on the mesoscale more often than not contains mesoscale, precipitating stratiform cloud structures, hereafter referred to as *mesoscale anvils* (after Brown, 1979), which extend from near the 0°C level to the upper troposphere. Observational studies have provided convincing evidence that mesoscale anvils contain a mesoscale updraft, below which there exists an evaporatively-driven mesoscale downdraft (Zipser, 1977; Gamache and Houze, 1982; Johnson, 1982). While the vertical velocities associated with mesoscale anvils are small ($\sim$10 cm s^{-1}), their area is large enough for them to contribute importantly to the heat and moisture budgets of large-scale tropical disturbances (Johnson, 1980; Leary and Houze, 1980).

Cheng and Houze (1979) have estimated that approximately 40% of the precipitation in GATE was from mesoscale anvil cloud systems. If their results can be generalized, even to some degree, to the entire tropics, the implications for parameterization are significant. Early parameterization efforts (Ooyama, 1971; Arakawa and Schubert, 1974) and diagnostic studies (Yanai *et al.*, 1973) anticipated the impact of such complications. For parameterizations that include cloud models to represent the important vertical transports associated with moist convection, some account should be reasonably given to mesoscale convective motions if, indeed, diagnostic studies that show them to be important (Johnson, 1980; Leary and Houze, 1980; Houze and Cheng, 1981) are correct. Of course, for models on relatively smaller scales, e.g., hurricane models, successful simulations may be achieved by actually resolving the mesoscale convection (Yamasaki, 1977; Rosenthal, 1978).

We may best focus on the primary objective of this paper by referring to specific parameterization schemes. For the sake of discussion, we consider one class of parameterization schemes, namely those patterned after Kuo (1965, 1974). Kuo's scheme and modified-Kuo schemes (Krishnamurti *et al.*, 1976, 1980; Anthes, 1977a and others) have been used successfully in modeling hurricanes (Rosenthal, 1970; Mathur, 1974; Anthes, 1977b) as well as in regional scale modeling (Krishnamurti *et al.*, 1976; Carr and Bosart, 1978; Anthes and Keyser, 1979; Anthes *et al.*, 1982). It is important to note that in many applications the vertical distribution of convective heating is specified (e.g., Anthes *et al.*, 1982) using heating profiles established from tropical diagnostic studies (e.g., Yanai *et al.*, 1973). These and other well-known vertical distributions of convective heating based on data from tropical rawinsonde observations (e.g., Reed and Recker, 1971; Thompson *et al.*, 1979) are, however, determined for tropical disturbances containing *both* cumulus and mesoscale convective components. Importantly, it is now becoming evident that the convective heating by the mesoscale components of tropical disturbances is considerably different from the vertical distribution of heating by their cumulus components (Houze, 1982; Johnson and Young, 1983). Houze (1982) has shown that mesoscale anvils contribute to a peak in the convective heating in the upper troposphere, whereas the heating peak due to deep cumulus is in the mid- to lower troposphere. Thus, in applications of the Kuo or modified-Kuo schemes, the use of an assigned vertical distribution of convective heating chosen to match distributions given by Yanai *et al.* (1973) or others which reflect contributions of *cumulus and mesoscale* convection in particular tropical regions may lead to errors if the proportion of cumulus versus mesoscale-produced rainfall in the region of model application is different from that in the region where the assigned distribution was derived. For this reason, as well as others, a partitioning of total convective heating (such as that given by Yanai *et al.*, 1973; Reed and Recker, 1971; Nitta, 1972; Thompson *et al.*, 1979) into cumulus and mesoscale components appears to be a worthy objective and, indeed, is a goal of this study.

The need to further understand the physical processes contributing to observed vertical distributions of convective heating has been highlighted by recent large-scale modeling studies that show a marked sensitivity of simulation results to the specified vertical heating distributions (Tracton, 1973; Anthes and Keyser, 1979; Gyakum, 1983; Anthes, 1982; Hartmann *et al.*, 1984). Bearing importantly on this problem is the increasing recognition that mesoscale convective systems at midlatitudes (e.g., Maddox, 1980; Fritsch and Maddox, 1981) have many structural characteristics similar to those observed in the tropics (Houze and Hobbs, 1982); therefore, many of the conclusions on heating distributions drawn from tropical studies can be applied to midlatitudes.

The methodology of this study will be to partition the "apparent heat source" Q_1 and "apparent moisture sink" Q_2 of Yanai *et al.* (1973) into cumulus and mesoscale components using the mesoscale anvil vertical heating and moistening distributions given in Johnson and Young (1983). The vertical distributions of cumulus heating and moistening will be solved as residuals. In order to accomplish the decomposition, estimates are made of the fraction of total rainfall in tropical disturbances produced by mesoscale anvil cloud systems. This fraction is not known for the globe as a whole and, therefore, the sensitivity of results to the estimates made will be presented.

2. Data and analysis procedures

a. Budget studies

This study draws primarily on published heat and moisture budget results from the earlier works of Reed and Recker (1971), Yanai *et al.* (1973), Johnson (1976), Thompson *et al.* (1979) and Johnson and Young (1983), papers that will be hereafter referred to as RR, Y, J, T and JY respectively. They represent a selection of investigations from a large number of diagnostic budget studies that are based on large-scale rawinsonde observations in the tropics. These diagnostic studies span the tropical latitudes from the Winter MONEX (Monsoon Experiment, December 1978) region of the South China Sea (JY) to the western Pacific Marshall Islands (RR, Y) to Florida (J) to the eastern Atlantic GATE region (T) (Fig. 1). The rawinsonde observations are from land (J), island (RR, Y) and ship (T, JY) stations whose positions describe polygons of large-scale dimension ($\sim 10^5$–10^6 km^2 area).

The emphasis of this study is on heat and moisture budgets. We will work with profiles of Q_1, the "apparent heat source" (Nitta, 1972; Yanai *et al.*, 1973) and Q_2, the "apparent moisture sink" defined by

$$Q_1 \equiv \frac{\partial \bar{s}}{\partial t} + \bar{\mathbf{v}} \cdot \nabla \bar{s} + \bar{\omega} \frac{\partial \bar{s}}{\partial p}$$

$$= -\frac{\partial}{\partial p} \overline{\omega' s'} + \bar{Q}_s + \bar{Q}_R, \qquad (1)$$

$$Q_2 \equiv -L\left(\frac{\partial \bar{q}}{\partial t} + \bar{\mathbf{v}} \cdot \nabla \bar{q} + \bar{\omega} \frac{\partial \bar{q}}{\partial p}\right)$$

$$= L \frac{\partial}{\partial p} \overline{\omega' q'} - L\bar{Q}_q, \qquad (2)$$

where $s = c_pT + gz$ is the dry static energy, q the specific humidity, Q_R the net radiative heating rate, Q_s and Q_q the sources of heat and water vapor, respectively, due to water phase changes and L is the latent heat of vaporization. In (1) and (2) the overbars refer to an average over a large-scale area defined by the domain of the stations. These areas are large enough to contain many cumulus clouds at any one instant, but perhaps only a few of the mesoscale anvil cloud systems. Due to problems in sampling convection representatively at individual observation times, as well as limitations in data and analysis procedures, averaged or composite budgets for many convective episodes are presented in the above studies. All of the composites include occurrences of deep convective activity for at least part of the time during the compositing interval. A summary of the key elements of the composites is given in Table 1.

The studies of RR, Y, J and T all examine tropical disturbances containing both cumulus and mesoscale convective components (easterly waves, ITCZ disturbances and a tropical depression; see Table 1). The vertical heating and moistening distributions presented contain the effects of both scales (and the various types) of convection. The number of observation times in each composite varies greatly. Primary reference will be made to Y, since it includes the most cases and, moreover, is widely referred to. The analysis methods vary between studies; however, one of the most crucial factors in the analysis—the balancing of ω to zero near the tropopause (the height has some variation from one region to the next, Johnson and Kriete, 1982)—was carried out in all cases and a level close to 100 mb uniformly selected. Also included in Table 1 is the average rainfall rate estimate for each composite. This information is later used to normalize the heating and moistening rates.

As stated earlier, JY and Y will be the primary studies employed in a partitioning of the heating and moistening distributions into cumulus and mesoscale components. Johnson and Young (1983) is used along with Y because data from the Marshall Islands region alone do not exist to enable a partitioning to be done. Fortunately, the regions of these studies are

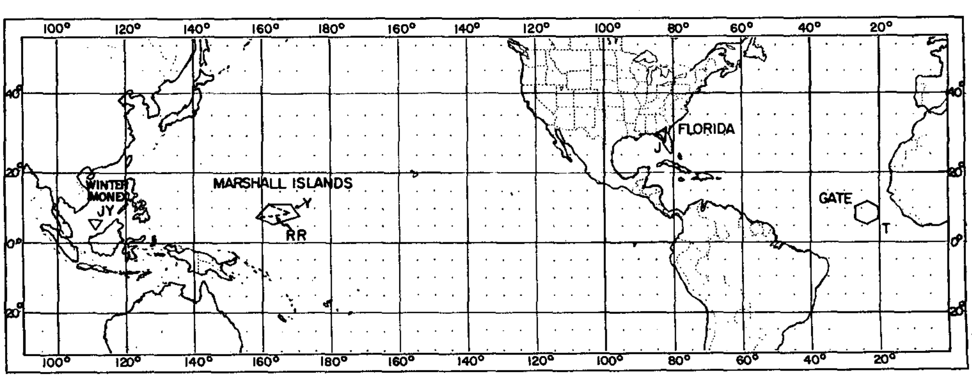

FIG. 1. Locations of observation networks referred to in this study. Polygons are formed from rawinsonde sites in the different regions. The studies referred to are: RR (Reed and Recker, 1971), Y (Yanai *et al.*, 1973), J (Johnson, 1976), T (Thompson *et al.*, 1979) and JY (Johnson and Young, 1983).

TABLE 1. Composite heat and moisture budget studies from which heating and moistening distributions are taken for use in this paper.

Authors of study	Location of budget study (No. of stations)	Disturbance composites	No. of observation times in composite	Method of analysis	Top level of $\omega = 0$ (mb)	Composite rainfall rate (cm d^{-1})
Reed and Recker (1971)	Marshall Islands (3)	Easterly wave trough	24	Linear interpolation	80	1.61 ± 0.55
Yanai *et al.* (1973)	Marshall Islands (5)	Easterly waves, ITCZ	390	Quadratic surface fit	100	1.4*
Johnson (1976)	Florida (3)	Tropical depression	4	Linear interpolation	100	5.71
Thompson *et al.* (1979)	Eastern Atlantic, GATE (15)	Easterly waves	160	Quadratic surface fit	100	1.25
Johnson and Young (1983)	South China Sea near Borneo (3)	Mesoscale anvils	7	Linear interpolation	85	1.2

* Mean of the station measurement average (1.0 cm d^{-1}) and the computed moisture budget average (1.8 cm d^{-1}).

in relatively close proximity, so that variations in mean environments and tropopause heights between the two are not significant (Johnson and Kriete, 1982). The use of JY for the South China Sea region near Borneo to represent the mesoscale component of the budgets in the Marshall Islands region, while not proven to be valid, is argued to be justified on physical grounds based on the reported existence of very similar mesoscale anvil cloud systems virtually everywhere throughout the tropics (Houze and Betts, 1981; Houze and Hobbs, 1982). The use of the JY profile for mesoscale anvils in the Marshall Islands region is supported by the qualitative agreement found between the heating profiles determined for mesoscale anvils in the Borneo region and those for an idealized model computed by Houze (1982) as reported in Johnson and Young (1983, Fig. 9). It should be kept in mind that the observations in Y and JY are taken in different seasons (Y: April–July; JY: December). Reid and Gage (1981) report a tropopause variation at these locations over this time period of ~1 km. Such a variation may have a slight influence on the levels of the convective heating maxima, but the resulting effects on the conclusions of this study are expected to be minimal.

b. Partitioning methodology

The composite budget analyses (except JY) include cumulus clouds (whose lifetimes are short, ≤1 h) and mesoscale convective systems (whose lifetimes are longer, ~10 h) at various stages of their life cycles. As shown by Nitta (1977), Frank (1978), Betts (1978), Houze (1982) and others, the large-scale vertical motion computed over a domain containing a tropical cloud cluster (with an approximate lifetime of 12–24 h) exhibits significant variation throughout its life cycle. Thus, the vertical distributions of heating and moistening reported in the composite studies represent both a mixture of disturbance types (easterly waves, ITCZ disturbances, etc.) and stages in the life cycle of the convective systems. Unfortunately, due to limited observations, an accurate partitioning of the composite budget heating and moistening distributions as proposed is simply not possible. Only in situations where radar data are available to separate the convective elements into distinct types by radar signature (as done by Gamache and Houze, 1982), can a relatively precise partitioning be done.

Since detailed information on the structure of the convective systems in the budget studies is limited, a procedure is adopted that draws on more-detailed findings regarding precipitation characteristics that are derived from other works. In particular, reference will be made to the GATE study of Cheng and Houze (1979) that contains information on the relative contributions of cumulus and mesoscale precipitation to the total precipitation in tropical disturbances.

Let us assume that a fraction f of the total accumulated rainfall can be ascribed to the mesoscale anvil component. The area-averaged precipitation rate P_0 can be written as

$$P_0 = \sigma_m P_m + \sigma_c P_c, \tag{3}$$

where $\sigma_m \equiv A_m/A$ and $\sigma_c \equiv A_c/A$ are the fractions of the total area A covered by mesoscale anvil and cumulus clouds (individually occupying areas A_m and A_c), respectively, and P_m and P_c are the average mesoscale anvil and cumulus precipitation rates. Assuming, for simplicity, that P_m and P_c are constant, the accumulated mesoscale and cumulus rainfall amounts (R_m and R_c) in time Δt are

$$R_m = A_m P_m \Delta t, \tag{4}$$

$$R_c = A_c P_c \Delta t, \tag{5}$$

and the total rainfall is

$$R_0 = R_m + R_c = AP_0\Delta t. \quad (6)$$

From our definition of $f \equiv R_m/R_0$, we find, using (3)–(6),

$$f = \sigma_m \frac{P_m}{P_0} = 1 - \sigma_c \frac{P_c}{P_0}, \quad (7)$$

or, alternatively,

$$\sigma_m = f\frac{P_0}{P_m}, \quad (8)$$

$$\sigma_c = (1-f)\frac{P_0}{P_c}. \quad (9)$$

The apparent heat source Q_1 can be written as

$$Q_1 = \sigma_m Q_{1m} + \sigma_c Q_{1c} + (1 - \sigma_m - \sigma_c)Q_{1e}, \quad (10)$$

where Q_{1m} is the heating due to mesoscale anvil clouds, Q_{1c} is the cumulus (both shallow and deep) heating and Q_{1e} is Q_1 in the environment of the convective clouds. This partitioning of the heating can be formally shown to be valid by writing $\overline{\omega' s'}$ in (1) terms of cloud mass fluxes and static energies as done in Houze (1982). From (8)–(10) we see that

$$\frac{Q_1}{P_0} = f\frac{Q_{1m}}{P_m} + (1-f)\frac{Q_{1c}}{P_c} + (1 - \sigma_m - \sigma_c)\frac{Q_{1e}}{P_0}. \quad (11)$$

It is helpful at this point to estimate the sizes of some of the terms in (11). For $f = 0.4$ (say, from Cheng and Houze, 1979), $P_0 = 1.4$ cm d^{-1} (from Y and Table 1 of this paper), $P_m = 7.2$ cm d^{-1} (from JY) and an estimate of P_c of 50 cm d^{-1},

$$\sigma_m \approx 0.08,$$

$$\sigma_c \approx 0.02.$$

These estimates, which certainly may vary by a factor of 2 or more under different situations, suggest that mesoscale anvil and cumulus clouds occupy ~10 and ~1%, respectively, of the total area of tropical disturbances. If nonprecipitating cloud overhang associated with mesoscale anvils is also considered, the *total* cloud area fraction may be several times greater than σ_m (e.g., Houze, 1982). This larger cloud fraction may have significance for cloud radiative parameterizations. Acknowledging the limitations of these estimates and assuming that $Q_{1e} \approx Q_{Re}$, where Q_{Re} is the radiative heating rate in the environment of the convective clouds, then (11) may be written in simplified form as

$$\hat{Q}_1 \approx f\hat{Q}_{1m} + (1-f)\hat{Q}_{1c} + (Q_{Re}/P_0), \quad (12)$$

where the carat refers to values of Q_1 normalized by rainfall rate.

For Q_2 the expression analogous to (12) is

$$\hat{Q}_2 = f\hat{Q}_{2m} + (1-f)\hat{Q}_{2c}. \quad (13)$$

In (13) no approximation is involved since radiation does not play a role in the moisture budget.

The procedure used in this study is as follows:

1) Use Y to determine the normalized heating and moistening rates $\hat{Q}_1$ and $\hat{Q}_2$.
2) Use JY to determine the normalized mesoscale anvil heating and drying rates $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$.
3) Assign a value to f.
4) Using an assumed vertical profile of Q_{Re}, compute the normalized vertical distribution of cumulus heating $\hat{Q}_{1c}$ as a residual from (12).
5) Compute the normalized vertical distribution of cumulus drying $\hat{Q}_{2c}$ as a residual from (13).

In the above procedure we have interpreted the residuals in (12) and (13) as cumulus heating effects. However, this interpretation may be complicated by two factors, in addition to those discussed earlier, when we use the heating and moistening rates for mesoscale anvils taken from JY. First, we note that since these rates (from JY) are considered to be representative of the mature phase of these systems, part of the computed residual may be associated with the transitional phases (growth or decay) of mesoscale anvils. This conclusion is based on a consideration of the long record of observations in the Y composite, wherein sampling of mesoscale anvils at various stages in their life cycles must have occurred. The heating and moistening distributions may be slightly modified during the transitional phases (Houze, 1982).

Secondly, a small contribution to the $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$ profiles in the lower troposphere (the lowest 3 km) in the JY composite may exist due to shallow cumulus on the periphery of the mesoscale anvils (Warner, 1982; Churchill and Houze, 1984).

Though these complications exist, they are not considered important enough to qualitatively alter the conclusions of this study. In the first case, we observe that studies have shown in the mature phase of mesoscale anvils to be the longest in duration (Leary and Houze, 1979, 1980), so that errors incurred by using mature mesoscale anvil $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$ profiles should be small. In the second case, a relatively small fraction of the observational network area in the JY study was covered by scattered shallow cumulus (<30%), so that the net effect on the $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$ profiles should be small. Based on the trade wind cumulus budget study of Nitta and Esbensen (1974), it is estimated that errors in $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$ in the lowest 2 km due to shallow cumulus effects should be less than 10 and 20%, respectively.

3. Comparison of budget study heating and moistening distributions

For the budget studies of RR, Y, J and T the normalized apparent heat source $\hat{Q}_1$ ($\equiv Q_1/P_0$) and moisture sink $\hat{Q}_2$ ($\equiv Q_2/P_0$) have been computed using data from these papers and the precipitation rates in Table 1. A comparison of $\hat{Q}_1$ from these studies is shown in Fig. 2. The profiles from the west Pacific (RR and Y) are in close agreement with a $\hat{Q}_1$ peak evident near 450 mb or 6.5 km. The peak for the Florida heavy rain case is also near this level (500 mb or 6 km). A striking difference is noted, however, in the eastern Atlantic where the $\hat{Q}_1$ maximum is much lower, near 600 mb or 4 km. This lower level of maximum heating in the eastern Atlantic GATE region has been attributed by T to the existence of a greater population of shallow, low-level detraining convective clouds there than in the Pacific region. Although this argument seems plausible, a detailed comparison of cloud population characteristics between the two regions is not available to substantiate this claim.

Note from Fig. 2 that, to a reasonable approximation, the areas enclosed by the $\hat{Q}_1$ profiles are nearly the same. This near equality should be expected since the integral of Q_1 through the depth of the troposphere is

$$\frac{1}{g}\int_{p_T}^{p_s} Q_1 dp = \frac{1}{g}\int_{p_T}^{p_s} \bar{Q}_R dp + LP_0 + S_0, \quad (14)$$

where S_0 is the surface sensible heat flux, p_s the surface pressure and p_T the tropopause pressure and, therefore,

$$\frac{1}{g}\int_{p_T}^{p_s} \hat{Q}_1 dp = L + \frac{1}{gP_0}\int_{p_T}^{p_s} \bar{Q}_R dp + \frac{S_0}{P_0} \approx L. \quad (15)$$

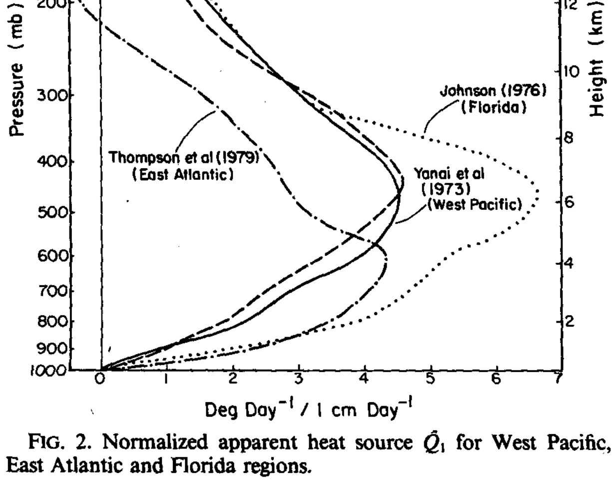

FIG. 2. Normalized apparent heat source $\hat{Q}_1$ for West Pacific, East Atlantic and Florida regions.

The approximation (15) is good to within 10% based on an average 1°C d^{-1} cooling in the troposphere (Cox and Griffith, 1979), $P_0 \sim 1$ cm d^{-1} and $S_0 \sim 10$ W m^{-2} (T). As is evident from (15), visual comparison of areas determined by $\hat{Q}_1$ profiles should strictly only be done on plots linear in p. Hereafter, areas will refer to those obtained on graphs with the ordinate linear in p. The slight differences in integrated $\hat{Q}_1$ are a consequence of observation errors (in sounding and precipitation data), analysis errors and differences in $\bar{Q}_R$ and S_0 between the regions.

The profiles of $\hat{Q}_2$ for the four studies are shown in Fig. 3. A characteristic of these profiles that makes them distinct from those of $\hat{Q}_1$ is the double peak structure (except for T). Mid- and lower-tropospheric maxima in $\hat{Q}_2$ exist near 500 and 800 mb for RR, Y and J. This characteristic structure has been discussed by Y and J although no satisfactory explanation has yet been given for its appearance in tropical budget studies. An explanation for this feature will be proposed in Section 4 based on the findings of this study.

The areas under the $\hat{Q}_2$ curves (at least for RR, Y and T) should again be approximately equivalent since

$$\frac{1}{g}\int_{p_T}^{p_s} Q_2 dp = P_0 - E_0, \quad (16)$$

where E_0 is the surface evaporation, or

$$\frac{1}{g}\int_{p_T}^{p_s} \hat{Q}_2 dp = 1 - \frac{E_0}{P_0}. \quad (17)$$

For the studies of RR, Y and T, $E_0 \sim 0.3$ cm d^{-1} and $P_0 \sim 1.3$–1.6 cm d^{-1}. Indeed, inspection of Fig. 3 shows that the areas of these three cases are nearly the same. The case of J, on the other hand, has a considerably larger P_0 (~5 times) with nearly the same E_0 so that from (17) the area should be about 25% larger. Visual inspection of Fig. 3 (considering changing the vertical scale to linear in p) suggests qualitative agreement with this conclusion.

The east Atlantic GATE region is again an anomaly with only a single peak in $\hat{Q}_2$ near 850 mb. The reasons for the differences in the eastern Atlantic are not clear, but again the explanation is probably linked to the considerably different population of cumulus clouds in this region.

4. Partitioning of budget results of Yanai *et al.* (1973)

a. Normalized heating and moistening rates

As stated earlier, we will partition the western Pacific heat and moisture budget results of Y into cumulus and mesoscale components using findings for mesoscale anvils from the nearby Winter MONEX region (JY). First, however, we must establish the normalized mesoscale anvil heating and moistening rates $\hat{Q}_{1m}$ and $\hat{Q}_{2m}$.

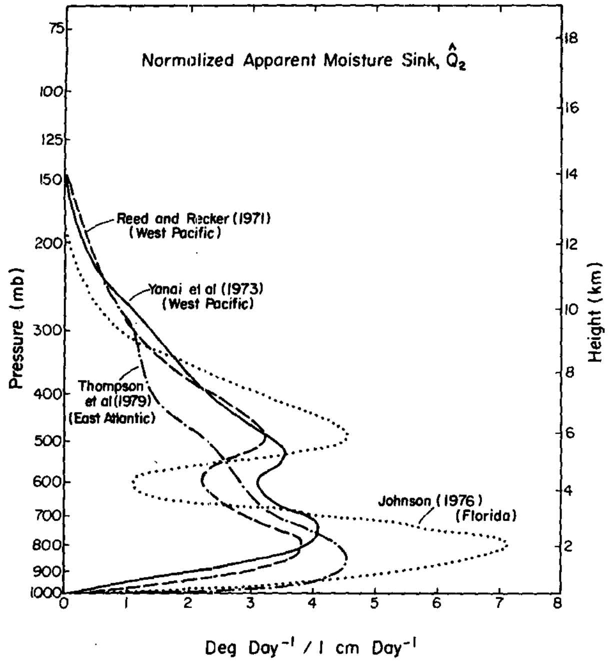

FIG. 3. Normalized apparent moisture sink $\hat{Q}_2$ for West Pacific, East Atlantic and Florida regions.

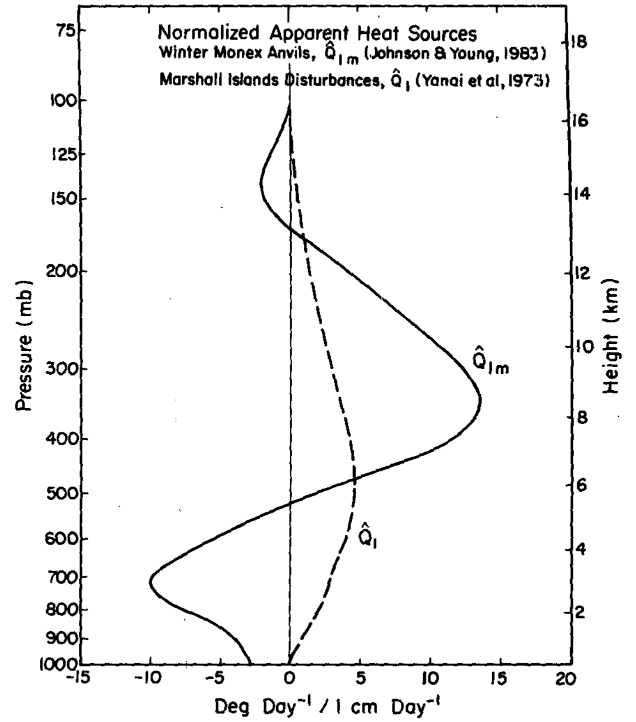

FIG. 4. Normalized apparent heat source $\hat{Q}_1$ from Yanai *et al.* (1973) and mesoscale anvil apparent heat source $\hat{Q}_{1m}$ from Johnson and Young (1983).

The normalized $\hat{Q}_{1m}$ is taken from JY (their Fig. 6) using the estimated rainfall rate of 1.2 cm d^{-1} reported in that paper for the large-scale area defined by the Winter MONEX ship positions. The result along with $\hat{Q}_1$ is shown in Fig. 4. As discussed in JY and Houze (1982), the profile of $\hat{Q}_{1m}$ shows a heating maximum in the upper troposphere near 350 mb associated with condensation and freezing in the mesoscale anvil, and a cooling peak in the lower troposphere near 700 mb associated with melting and evaporation beneath the mesoscale anvil cloud. While the amplitude of $\hat{Q}_{1m}$ is considerably greater than that of $\hat{Q}_1$, the areas under the two curves are nearly equivalent, as they should be, since they represent normalized heating rates [see Eq. (15)].

The mesoscale-anvil normalized-apparent moisture sinks $\hat{Q}_{2m}$ and $\hat{Q}_2$ are shown in Fig. 5. Again, there is a considerable difference in the amplitudes of the two profiles. The poorer agreement between the vertical integral of the profiles in this case can probably be attributed [see Eq. (17)] to the greater surface evaporation in the Winter MONEX region where surface wind speeds in the northeast monsoon flow are considerably greater ($\sim$10 m s^{-1}, Johnson and Priegnitz, 1981) than those in the Marshall Islands region ($\leqslant$5 m s^{-1}, Reed and Recker, 1971). In fact, the $\hat{Q}_{2m}$ profile suggests evaporation slightly exceeds precipitation in the Winter MONEX area of study. Here we may also be seeing some (though small) moistening effects on the lower troposphere of shallow cumulus on the periphery of the mesoscale anvils (as discussed earlier).

b. Partitioned budgets

Although Cheng and Houze (1979) estimate 40% of the total GATE rainfall was from mesoscale anvil

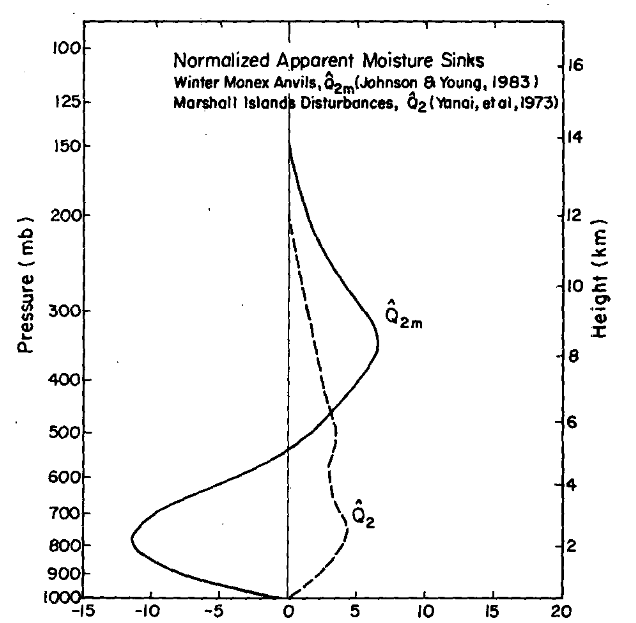

FIG. 5. Normalized apparent moisture sink $\hat{Q}_2$ from Yanai *et al.* (1973) and mesoscale anvil apparent moisture sink $\hat{Q}_{2m}$ from Johnson and Young (1983).

systems, corresponding estimates for other areas of the tropics have not been made. A fraction this large obviously implies that a significant portion of the total heating can be attributed to mesoscale anvil convection. It should be kept in mind, however, that part of the precipitation that actually falls from the mesoscale anvil systems is produced in cumulus updrafts and is transferred over to the anvil by the storm circulation (Leary and Houze, 1980; Gamache and Houze, 1983). For a GATE tropical squall line this transferred portion has been estimated by Gamache and Houze (1983) to be between 60 and 75%. Therefore, the 40% estimate by Cheng and Houze (1979), when referred to the actual heating by mesoscale anvil motions, is probably an upper limit. The Gamache and Houze (1983) study of a tropical squall line suggests a value of f in the range of 0.1–0.2; however, the extent to which their squall line results apply to the more numerous nonsquall tropical mesoscale anvils is not well known. The fraction of precipitation transferred over from cumulus updrafts in the less-well-organized nonsquall cluster may be less than that occurring in squall lines. Based on these considerations, $f = 0.2$ is selected for illustration of most of the results and an indication of the sensitivity to this choice will be given.

The partitioning of $\hat{Q}_1$ into mesoscale and convective-scale components for $f = 0.2$ is shown in Fig. 6. The convective-scale heating is solved for as a residual by (a) assuming $Q_{Re} = 0$ and (b) using Q_{Re} determined for mean Phase III GATE B-scale array conditions by Cox and Griffith (1979). The choice of an appropriate Q_{Re} profile is difficult considering the lack of knowledge concerning the nonconvective cloud types that may exist in the environment of the convective clouds. However, for realistic estimates to Q_{Re}, it will be seen that the sensitivity to the assumed profile is not great.

From Fig. 6 several conclusions can be drawn:

1) The single $\hat{Q}_1$ peak of Yanai *et al.* (1973) near 400–500 mb is a reflection of the contribution of different vertical heating distributions associated with two different convective phenomena. Specifically, the convective-scale or cumulus heating has a peak in the lower troposphere near 600 mb (4 km) and the mesoscale anvil heating has a peak near 350 mb (8 km); it is the superposition of the two that gives a peak near 400–500 mb (6 km). These findings are qualitatively consistent with those reported by Houze (1982).

2) The positive total heating $\hat{Q}_1$ in the lower

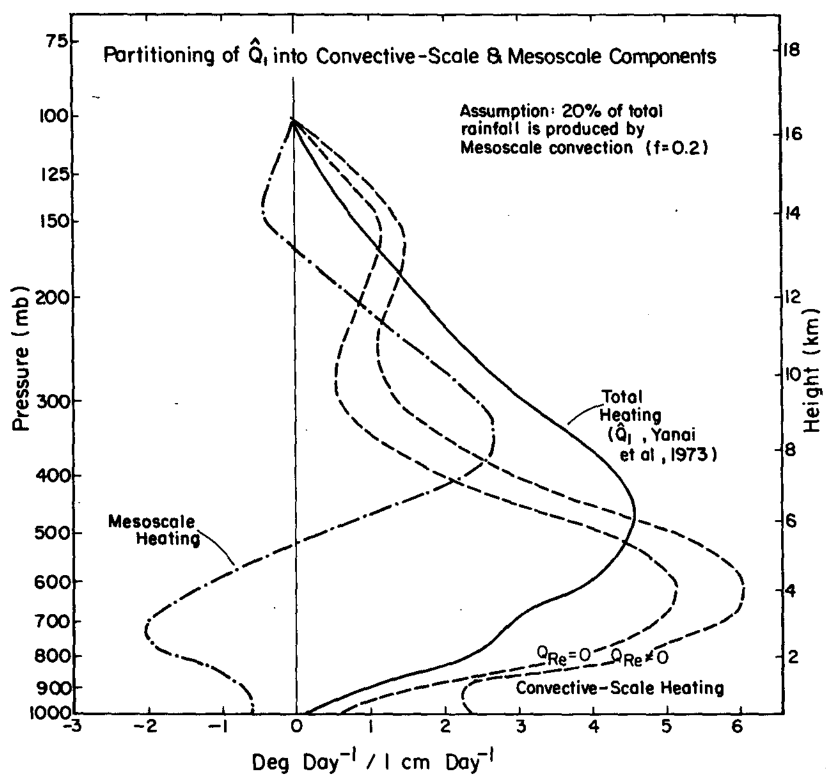

FIG. 6. Partitioning of the normalized apparent heat source $\hat{Q}_1$ into convective-scale (cumulus) and mesoscale components for $f = 0.2$; f is the fraction of the total rainfall produced by mesoscale anvils. Curve marked $Q_{Re} \neq 0$ is result for assumed radiative heating profile in the environment of the convective clouds (Q_{Re}) equivalent to that given by Cox and Griffith (1979) for mean Phase III conditions.

troposphere is a consequence of the large low-level cumulus heating which outweighs the cooling beneath mesoscale anvil clouds.

3) The partitioning of the heat budgets and their interpretation are not qualitatively sensitive to assumptions pertaining to radiative heating.

4) As a minor point, the large values of convective-scale heating in the boundary layer diagnosed as a residual for $Q_{Re} \neq 0$ are a reflection of the sensible heat flux convergence caused by dry convective processes occurring there.

The qualitative picture of partitioning shown in Fig. 6 does not change for f in the range of 0.1–0.3. The normalized convective-scale heating rate for f = 0.1, 0.2 and 0.3 [using the Cox and Griffith (1979) Q_{Re} profile] is shown in Fig. 7. If f is as large as 0.4, then the mesoscale heating in the upper troposphere (near 200–300 mb) exceeds $\hat{Q}_1$ so that the diagnosed cumulus heating actually becomes negative at this level, a situation which is considered unrealistic. Therefore, the partitioning exercise here has actually helped to put some bounds on f (at least for tropical disturbances in this region of the tropics); however, its precise value in any region is not well-known and, in general, it is difficult to determine (e.g., Cheng and Houze, 1979). The level of maximum cumulus heating descends from 450 mb or 6 km for $f = 0$ (marked by an × in Fig. 7) to 650 mb or 3.5 km for $f = 0.3$. Thus, there is a sensitivity in the level of maximum cumulus heating to f; however, based on the best

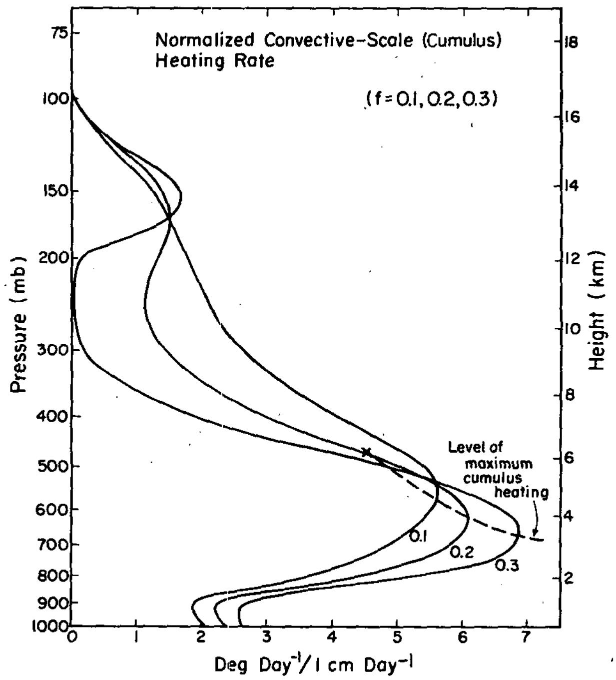

FIG. 7. Sensitivity of normalized convective-scale (cumulus) heating rate to f. Dashed line marks level of maximum heating for different values of f: × marks this level for $f = 0$ (no mesoscale anvils).

estimates contained in this study, it probably lies in the 500–600 mb or 4–5 km range.

The partitioning of total drying $\hat{Q}_2$ is shown in Fig. 8. As in the case of the $\hat{Q}_1$ partitioning, the diagnosed convective-scale component has a peak in the lower troposphere; in this case, however, radiative heating does not play a role [Eq. (13)]. Unlike $\hat{Q}_1$, however, $\hat{Q}_2$ has a double-peak structure. It is seen that this feature is a consequence of the widely separated peaks in drying from two different physical entities: mesoscale anvils (with a peak near 350 mb) and cumulus clouds (with a peak near 750 mb). These peaks occur at the levels of maximum removal of water vapor by net condensation in the two cloud systems.

The reason that these separate peaks result in a double heating structure in the case of $\hat{Q}_2$ and not for $\hat{Q}_1$ is that the cumulus drying is proportional to $M_c\partial\bar{q}/\partial p$ [where M_c is the cumulus mass flux, (Y)], and with $\bar{q}$ having an exponential (in p) structure in the lower troposphere, the cumulus drying effect (through environmental subsidence) yields a low-level peak near 750 mb. The cumulus heating, on the other hand, is proportional to $-M_c\partial\bar{s}/\partial p$, where $\bar{s}$ is roughly linear with p, and yields (for the same M_c) a peak at a higher level (near 600 mb). Thus, while in the case of the heat budget the two separate heating processes combine to give a single $\hat{Q}_1$ peak, the effects of each on the moisture budget are widely separated enough in the vertical to lead to a double-peak structure in $\hat{Q}_2$.

The sensitivity of the partitioning of $\hat{Q}_2$ to f is qualitatively the same as that for $\hat{Q}_1$. The lower tropospheric drying peak is shifted downward as f increases.

5. Implications for cumulus parameterization

In the application of some cumulus parameterization schemes [e.g., Kuo (1965) or modified-Kuo types], the vertical distribution of convective heating is specified (e.g., Anthes *et al.*, 1982) using heating profiles established from tropical diagnostic studies (e.g., Yanai *et al.*, 1973). As we have discussed, however, these profiles are determined for tropical disturbances containing *both* cumulus and mesoscale convective components. The partitioning that has been done in this study (and by Houze, 1982) has demonstrated that the vertical distribution of total heating (e.g., Yanai *et al.*, 1973) is quite different from that given by the separate cumulus and mesoscale components. Therefore, the application of a cumulus parameterization scheme of this type to a convective region that does not have proportions of cumulus and mesoscale anvil-produced rainfall similar to those in the region from which the heating profile was derived, could lead to model simulation errors. Errors could arise from at least two factors: 1) the fraction f of mesoscale anvil rainfall may vary considerably in a time-averaged sense from one region to

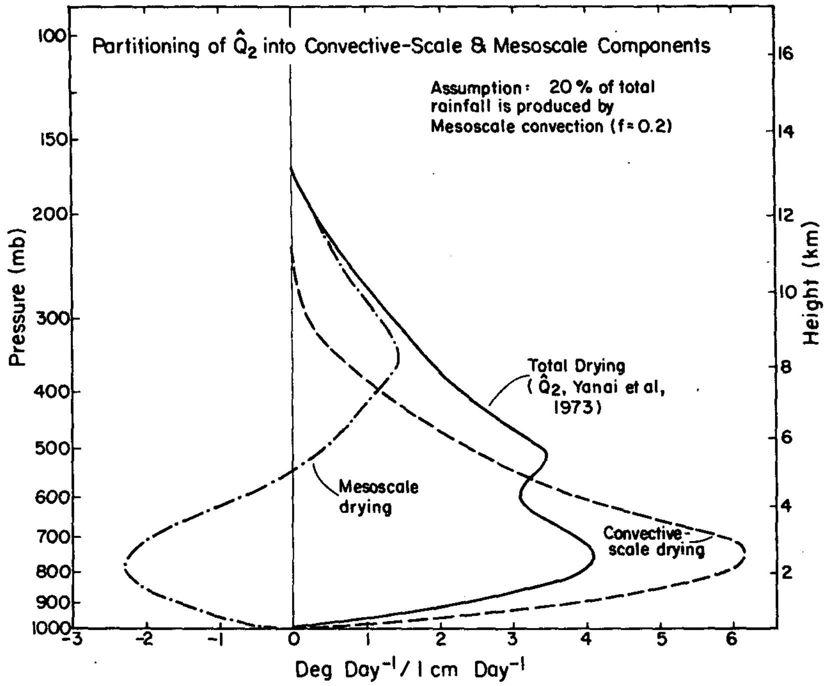

FIG. 8. Partitioning of the normalized apparent moisture sink $\hat{Q}_2$ into convective-scale (cumulus) and mesoscale components for $f = 0.2$. Note that double-peak $\hat{Q}_2$ structure is a consequence of the widely-separated drying peaks associated with mesoscale anvils and cumulus.

the next and 2) f may change with time as disturbances progress through their life cycle. The latter complication may be more important for regional, shorter-period similations, since $\bar{\omega}$ and Q_1 profiles change considerably in mesoscale convective systems during their life cycle (Nitta, 1977; Frank, 1978; Houze, 1982), than it is for longer-term predictions (e.g., global general circulation models), where the integrated effect of many convective systems over their life cycles is important to the large-scale circulation.

This study suggests that improvements to the Kuo or modified-Kuo schemes may be possible if the proportions of cumulus and mesoscale rainfall can be determined and, accordingly, the total heating be appropriately assigned in different convective situations.[1] At this stage, however, only an empirical approach is suggested with some bounds on f given for guidance. The heating distributions may have considerable variations, say, from one extreme, where mesoscale anvil cloud systems are quite prevalent (such as in the winter monsoon region near Borneo, Houze *et al.*, 1981), to another extreme where deep cumulus convection predominates (such as in rapidly-developing tropical and extratropical cyclones, e.g., Gyakum, 1983). For example, a dominance of cumulus over mesoscale anvil heating in the intensifying stage of very strong extratropical cyclones ("bombs," Sanders and Gyakum, 1980) is suggested by this work (refer to the cumulus heating profiles in Fig. 7) and that of Gyakum (1983) and Anthes *et al.* (1983) who found the best model representation of the intensification rate for the 1978 *Queen Elizabeth II* storm over the western Atlantic with a lower tropospheric peak in the convective heating rate.

6. Summary and conclusions

The apparent heat source Q_1 and apparent moisture sink Q_2 of Yanai *et al.* (1973) have been partitioned into individual cumulus and mesoscale contributions using the mesoscale anvil vertical heating and moistening distributions reported in Johnson and Young (1983). The vertical distributions of cumulus heating and moistening have been solved for as residuals. In order to accomplish the decomposition, estimates have been made of the fraction f of total rainfall in tropical disturbances produced by mesoscale anvil cloud systems. These estimates are based on the GATE studies of Cheng and Houze (1979) and Gamache and Houze (1983).

The solution for cumulus heating as a residual depends only in a minor way on assumptions pertaining to the vertical profile of radiative heating, and results with and without the radiative term in the heat budget equation are qualitatively the same.

For realistic estimates of f (between 0.1 and 0.2),

[1] This idea first was suggested by Robert Houze at a 1982 conference on cumulus parameterization at Florida State University.

the total heating of Yanai *et al.* (1973), which has a peak near 450 mb (6 km), is found to be a consequence of two distinctly different circulation features: 1) the mesoscale anvil, which has a heating peak near 350 mb (8 km) and a cooling peak below near 700 mb (3 km) and 2) the cumulus, which produces a heating peak centered near 600 mb (4 km). These findings are in qualitative agreement with those of Houze (1982), although the maximum in cumulus heating found in his study is at a level somewhat higher (5–6 km) than that reported in this work. The difference is due to the fact that Houze's estimates of cumulus heating are for deep clouds whereas, in this study, because of the procedure used to determine the cumulus heating as a residual, the effects of both deep and shallow cumulus are included. The heating effects of many shallow precipitating clouds in tropical disturbances (perhaps, in part, during the growing phase of deep cumulus) is apparently sufficient to help shift the total cumulus heating to lower levels.

The partitioning of the apparent moisture sink Q_2 produces qualitatively similar results. The mesoscale anvils give a drying peak in the upper troposphere near 350 mb (8 km) and a moistening peak (through evaporation) near 800 mb (2 km). However, the effects of the cumulus in this case (which dry the lower troposphere through removal of water vapor by net condensation) are such that the cumulus drying has a peak somewhat lower in the troposphere (near 750 mb or 2.5 km). Thus, the double-peak structure in Q_2 often seen in tropical budget studies is a consequence of the combined, but vertically-separated drying effects of two distinct convective phenomena: mesoscale anvils and deep cumulus.

The results of this study have implications for cumulus parameterization schemes in general, but particularly for those that assign vertical distributions to the convective heating. It has been shown that the cumulus and mesoscale heating distributions are considerably different. Schemes that use an assigned vertical distribution of convective heating chosen to match those obtained from large-scale tropical budget studies should consider carefully the different contributions to total convective heating by the separate cumulus and mesoscale components. Possible errors may result if the proportion of cumulus versus mesoscale-produced rainfall in the region of model application is different from that in the region where the assigned distribution was derived. The results of this study suggest that cumulus parameterization schemes that permit vertical heating distributions to evolve during the course of model integrations (e.g., Arakawa and Schubert, 1974) are preferred, at least on a physical basis, over those that prescribe the distributions.

It has not been the purpose of this paper to propose a new cumulus parameterization theory. Rather, the goal has been to bring attention to the important contribution of mesoscale processes to the total convective heating and moistening distributions. Whether or not cumulus parameterization schemes should include, for example, a mesoscale anvil component depends on the particular model's horizontal resolution and application. Global general circulation models clearly cannot resolve the mesoscale anvil structures and, therefore, must somehow parameterize them, whereas regional models may actually resolve the mesoscale anvil circulations and, consequently, need only parameterize the cumulus component. Further discussion of this subject has been recently given by Anthes (1983) and Frank (1983).

Of course, accurate partitioning of the total heating is a complex problem and requires information on cloud water budgets, rainfall rates, characteristic precipitation echo distributions and so on. The partitioning done here is sensitive to a number of assumptions, as pointed out. This study should be considered a preliminary effort to draw attention to this problem and further work in this direction is clearly needed.

Acknowledgments. The author appreciates comments on this manuscript provided by Robert Houze, Steven Esbensen and two anonymous reviewers. Thanks are extended to Machel Sandfort for typing and Judy Sorbie for drafting the figures. This work has been supported by the Atmospheric Sciences Division (GARP Program) of the National Science Foundation under Grant No. ATM-8206808.

REFERENCES

Anthes, R. A., 1977a: A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.*, **105**, 270–286.

——, 1977b: Hurricane model experiments with a new cumulus parameterization scheme. *Mon. Wea. Rev.*, **105**, 287–300.

——, 1982: *Tropical Cyclones—Their Evolution, Structure, and Effects. Meteor. Monogr.*, No. 41, Amer. Meteor. Soc., 208 pp.

——, 1983: Regional models of the atmosphere in middle latitudes. *Mon. Wea. Rev.*, **111**, 1306–1335.

——, and D. Keyser, 1979: Tests of a fine-mesh model over Europe and the United States. *Mon. Wea. Rev.*, **107**, 963–984.

——, Y.-H. Kuo, S. G. Benjamin and Y.-F. Li, 1982: The evolution of the mesoscale environment of severe local storms: Preliminary modeling results. *Mon. Wea. Rev.*, **110**, 1187–1213.

——, Y.-H. Kuo and J. R. Gyakum, 1983: Numerical simulations of a case of explosive marine cyclogenesis. *Mon. Wea. Rev.*, **111**, 1174–1188.

Arakawa, A., and W. H. Schubert, 1974: Interaction of a cumulus cloud ensemble with the large-scale environment: Part I. *J. Atmos. Sci.*, **31**, 674–701.

Betts, A. K., 1978: Convection in the tropics. *Meteorology Over the Tropical Oceans.* Roy. Meteor. Soc., 105–132.

Brown, J. M., 1979: Mesoscale unsaturated downdrafts driven by rainfall evaporation: A numerical study. *J. Atmos. Sci.*, **36**, 313–338.

Carr, F. H., and L. F. Bosart, 1978: A diagnostic evaluation of rainfall predictability for Tropical Storm Agnes, June 1972. *Mon. Wea. Rev.*, **106**, 363–374.

Cheng, C.-P., and R. A. Houze, Jr., 1979: The distribution of convective and mesoscale precipitation in GATE radar echo patterns. *Mon. Wea. Rev.*, **107**, 1370–1381.

Churchill, D. D., and R. A. Houze, Jr., 1984: Development and structure of winter monsoon cloud clusters on 10 December 1978. *J. Atmos. Sci.*, **41**, 933–960.

Cox, S. K., and K. T. Griffith, 1979: Estimates of radiative divergence during Phase III of the GARP Atlantic Tropical Experiment: Part II. Analysis of the Phase III results. *J. Atmos. Sci.*, **36**, 586–601.

Frank, W. M., 1978: The life cycles of GATE convective systems. *J. Atmos. Sci.*, **35**, 1256–1264.

——, 1983: The cumulus parameterization problem. *Mon. Wea. Rev.*, **111**, 1859–1871.

Fritsch, J. M., and R. A. Maddox, 1981: Convectively driven mesoscale weather systems aloft. Part I. Observations. *J. Appl. Meteor.*, **20**, 9–19.

Gamache, J. F., and R. A. Houze, Jr., 1982: Mesoscale air motions associated with a tropical squall line. *Mon. Wea. Rev.*, **110**, 118–135.

——, and ——, 1983: Water budget of a mesoscale convective system in the tropics. *J. Atmos. Sci.*, **40**, 1835–1850.

Gyakum, J. R., 1983: On the evolution of the *QE II* storm. II: Dynamic and thermodynamic structure. *Mon. Wea. Rev.*, **111**, 1156–1173.

Haltiner, G. J., and R. T. Williams, 1980: *Numerical Prediction and Dynamic Meteorology.* Wiley and Sons, 477 pp.

Hartmann, D. L., H. H. Hendon and R. A. Houze, Jr., 1984: Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate. *J. Atmos. Sci.*, **41**, 113–121.

Houze, R. A., Jr., 1977: Structure and dynamics of a tropical squall-line system observed during GATE. *Mon. Wea. Rev.*, **105**, 1540–1567.

——, 1982: Cloud clusters and large-scale vertical motions in the tropics. *J. Meteor. Soc. Japan*, **60**, 396–410.

——, and A. K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541–576.

——, and C.-P. Cheng, 1981: Inclusion of mesoscale updrafts and downdrafts in computations of vertical fluxes by ensembles of tropical clouds. *J. Atmos. Sci.*, **38**, 1751–1770.

——, and P. V. Hobbs, 1982: Organization and structure of precipitating cloud systems. *Advances in Geophysics*, Vol. 24, Academic Press, 225–315.

——, and E. N. Rappaport, 1984: Air motions and precipitation structure of an early summer squall line over the eastern tropical Atlantic. *J. Atmos. Sci.*, **41**, 553–574.

——, S. G. Geotis, F. D. Marks, Jr. and A. K. West, 1981: Winter monsoon convection in the vicinity of North Borneo. Part I: Structure and time variation of the clouds and precipitation. *Mon. Wea. Rev.*, **109**, 1595–1614.

Johnson, R. H., 1976: The role of convective-scale precipitation downdrafts in cumulus and synoptic scale interactions. *J. Atmos. Sci.*, **33**, 1890–1910.

——, 1980: Diagnosis of convective and mesoscale motions during Phase III of GATE. *J. Atmos. Sci.*, **37**, 733–753.

——, 1982: Vertical motion in near-equatorial winter monsoon convection. *J. Meteor. Soc. Japan*, **60**, 682–690.

——, and D. L. Priegnitz, 1981: Winter monsoon convection in the vicinity of North Borneo. Part II: Effects on large-scale fields. *Mon. Wea. Rev.*, **109**, 1615–1628.

——, and D. C. Kriete, 1982: Thermodynamic and circulation characteristics of winter monsoon tropical mesoscale convection. *Mon. Wea. Rev.*, **110**, 1898–1911.

——, and G. S. Young, 1983: Heat and moisture budgets of tropical mesoscale anvil clouds. *J. Atmos. Sci.*, **40**, 2138–2147.

Krishnamurti, T. N., M. Kanamitsu, R. Godbole, C. B. Chang, F. Carr and J. H. Chow, 1976: Study of monsoon depression II, dynamical structure. *J. Meteor. Soc. Japan*, **54**, 208–226.

——, Y. Ramanathan, H.-L. Pan, R. J. Pasch and J. Molinari, 1980: Cumulus parameterization and rainfall rates I. *Mon. Wea. Rev.*, **108**, 465–472.

Kuo, H. L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, **22**, 40–63.

——, 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.*, **31**, 1232–1240.

Leary, C. A., and R. A. Houze, Jr., 1979: The structure and evolution of convection in a tropical cloud cluster. *J. Atmos. Sci.*, **36**, 437–457.

——, and ——, 1980: The contribution of mesoscale motions to the mass and heat fluxes of an intense tropical convective system. *J. Atmos. Sci.*, **37**, 784–796.

Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374–1387.

Mathur, M. B., 1974: A multiple-grid primitive equation model to simulate the development of an asymmetric hurricane (Isbell, 1964). *J. Atmos. Sci.*, **31**, 371–393.

Nitta, T., 1972: Energy budget of wave disturbances over the Marshall Islands during the years of 1956 and 1958. *J. Meteor. Soc. Japan*, **50**, 71–84.

——, 1977: Response of cumulus updraft and downdraft to GATE A/B-scale motion systems. *J. Atmos. Sci.*, **34**, 1163–1186.

——, and S. Esbensen, 1974: Heat and moisture budgets using BOMEX data. *Mon. Wea. Rev.*, **102**, 17–28.

Ooyama, K., 1971: A theory of parameterization of cumulus convection. *J. Meteor. Soc. Japan*, **49**, 744–756.

Reed, R. J., and E. E. Recker, 1971: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.*, **28**, 1117–1133.

Reid, G. C., and K. S. Gage, 1981: On the annual variation in the height of the tropical tropopause. *J. Atmos. Sci.*, **38**, 1928–1938.

Rosenthal, S. L., 1970: A circularly symmetric primitive equation model of tropical cyclone development containing an explicit water vapor cycle. *Mon. Wea. Rev.*, **98**, 643–663.

——, 1978: Numerical simulation of tropical cyclone development with latent heat by the resolvable scales. I: Model description and preliminary results. *J. Atmos. Sci.*, **35**, 258–271.

Sanders, F., and J. R. Gyakum, 1980: Synoptic-dynamic climatology of the "bomb." *Mon. Wea. Rev.*, **108**, 1589–1606.

Thompson, R. M., Jr., S. W. Payne, E. E. Recker and R. J. Reed, 1979: Structure and properties of synoptic-scale disturbances in the intertropical convergence zone of the eastern Atlantic. *J. Atmos. Sci.*, **36**, 53–72.

Tracton, M. S., 1973: The role of cumulus convection in the development of extratropical cyclones. *Mon. Wea. Rev.*, **101**, 573–593.

Warner, C., 1982: Mesoscale features and cloud organization on 10–12 December 1978 over the South China Sea. *J. Atmos. Sci.*, **39**, 1619–1641.

Yamasaki, M., 1977: A preliminary experiment of the tropical cyclone without parameterizing the effects of cumulus convection. *J. Meteor. Soc. Japan*, **55**, 11–30.

Yanai, M., S. Esbensen and J. H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611–627.

Zipser, E. J., 1977: Mesoscale and convective-scale downdrafts as distinct components of squall line structure. *Mon. Wea. Rev.*, **105**, 1568–1589.