Thermodynamic Effects of Mesoscale Convective Systems on the Environment over the Eastern Atlantic

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Abstract

Distributions of composited convective heating and drying vary substantially during the life cycle of six cloud clusters identified by Frank (1978) in Phase III of GATE. Convective heating ($Q_1 - Q_R$) and drying (Q_2) begin in the lower troposphere. As cloud clusters mature, intensification of upper level convective heating increases; while below 600 mb drying accompanies decreases in convective heating. The upper level convective heating reaches its peak, when the upper level cloud cover is largest; whereas the Q_2 maximum at 850 mb coincides with the peak radar echo intensity. The depletion of moist static energy ($Q_1 - Q_2 - Q_R$) in the lower troposphere begins in the growing stage; whereas the upper level heating due to vertical eddy fluxes is most significant in later stages, when deep clouds are prominent.

1. Introduction

Numerical integrations in fluid dynamical equations are often performed over volumes with grid spacing small enough to resolve the phenomena of interest (grid-scale processes). Effects on grid-scale flow due to small scale motions that have been truncated must be expressed in terms of grid-scale variables. Deep convection, generally organized on the mesoscale (~ 100 km) cannot be fully resolved by large-scale models. Incorporation of the effects of deep convection on the large-scale (grid scale) flow in numerical models is a major problem in numerical weather prediction. The most important elements of a cumulus parameterization scheme are the prediction of the rainfall rate (Ogura and Cho, 1973; Yanai *et al.*, 1973; Thompson *et al.*, 1979; Krishnamurti *et al.*, 1980; Lord, 1982; and others) and the determination of the convective heating and drying profiles (Soong and Tao, 1980; Lord, 1982; Song and Frank, 1983; Krishnamurti *et al.*, 1983; Kuo and Anthes, 1984) in terms of large-scale variables.

Kuo (1965, 1974) assumed that rainfall is

proportional to the vertically integrated moisture convergence. Using Kuo's scheme, Krishnamurti *et al.* (1980) found a close correlation between the observed and predicted precipitation rates. Song and Frank (1983) compared the day-to-day observed and predicted convective heating profiles during the entire period of GATE (GARP¹ Atlantic Tropical Experiment). They found that the observed convective heating profiles vary more than those predicted by Kuo's scheme which tended to give maximum heating in the midtroposphere. Semiprognostic tests of the Arakawa and Shubert (1974) cumulus parameterization scheme (Lord and Arakawa, 1980; Lord, 1982) suggested that the cloud-work function quasi-equilibrium is a good approximation; the calculated instantaneous precipitation agrees well with radar rainfall estimates. The time-averaged predicted and observed vertical profiles of heating and drying are similar except for slightly more warming and drying in the lower troposphere. Lord (1982) suggested that discrepancies between the predicted and observed heating and drying may be due to the neglect of cumulus-

scale downdrafts and mesoscale circulations associated with stratiform clouds.

GATE studies revealed that precipitation over the eastern Atlantic was primarily produced by cloud clusters. These were defined (see Tollerud and Esbensen, 1985) as a group of cumulonimbus joined in their mature and dissipating stages by a common cirrus shield about several hundred to one thousand kilometers wide. Some of these cloud clusters consisted of several mesoscale precipitation features (Leary and Houze, 1979a). During the life cycle of cloud clusters, large scale vertical motion was characterized by: (1) low-level convergence or its enhancement prior to development; (2) intensification of upward motion at upper levels during development; and (3) decay usually starting at lower levels (Frank, 1978; Ogura *et al.*, 1979). It appears that convective heating and drying profiles depend on the "age" of cloud clusters since both the change and horizontal advection terms in the heat and moisture budgets are small compared to the vertical advection terms (Soong and Tao, 1980).

This paper will demonstrate that convective heating and drying vary substantially during the cloud cluster life cycle, suggesting that effects of the cloud cluster life cycle should be considered in parameterizing moist convection in large scale models with resolvable time scales ≥ 12 h or spatial scale ≥ 100 km. The vertical distributions of convective heating and drying for all six cloud clusters identified by Frank (1978) in Phase III of GATE were stratified according to stages of the cloud cluster life cycle. A composite analysis revealed similarities in the evolution of convective heating and drying for all cases.

2. Data

Thermodynamic data from Phase III of GATE (30 August–18 September 1974) described by Chen and Ogura (1982) and wind data provided by Dr. K. V. Ooyama (see Esbensen *et al.*, 1982) were used. Figure 1 shows the distribution of upper air stations in the A/B (outer) and B (inner) hexagons during Phase III. Hourly radiation and satellite cloud cover data for ten vertical levels from 1000 mb to 100 mb on a $0.5 \times 0.5^\circ$ latitude-longitude grid over the GATE A/B-scale ship array have been obtained from Cox and Griffith (1979). The satellite cloud cover was

Fig. 1. A/B and B-scale ship arrays for Phase III.

determined from IR cloud-top temperatures and radiosonde temperature profiles. Rainfall rates over the B-scale area estimated from radar data by Hudlow (1979) were also used.

3. Budget equations

Denoting the grid point value by an overbar, and the deviation of the true value from the grid point value by a prime, the large-scale heat and moisture equations are:

$$\begin{aligned} Q_1 - Q_R &= \frac{\partial \bar{s}}{\partial t} + \nabla \cdot (\bar{V} \bar{s}) + \frac{\partial \bar{\omega} \bar{s}}{\partial p} - Q_R \\ &= L(\bar{c} - \bar{d} + \bar{d}e - \bar{s}u) \\ &\quad + L_f(\bar{d}e - \bar{s}u + \bar{f} - \bar{m}) - \frac{\partial \bar{s} \bar{\omega}}{\partial p} - \nabla \cdot (\bar{s}' \bar{V}'), \end{aligned} \quad (1)$$

$$\begin{aligned} Q_2 &= -L \left[\frac{\partial \bar{q}}{\partial t} + \nabla \cdot (\bar{V} \bar{q}) + \frac{\partial \bar{\omega} \bar{q}}{\partial p} \right] \\ &= L(\bar{c} - \bar{e} + \bar{d}e - \bar{s}u) \\ &\quad + L \frac{\partial \bar{q}' \bar{\omega}'}{\partial p} + L \nabla \cdot (\bar{q}' \bar{V}'), \end{aligned} \quad (2)$$

$$\begin{aligned} Q_1 - Q_2 - Q_R &= \frac{\partial \bar{h}}{\partial p} + \nabla \cdot (\bar{V} \bar{h}) + \frac{\partial \bar{\omega} \bar{h}}{\partial p} - Q_R \\ &= L_f(\bar{d}e - \bar{s}u + \bar{f} - \bar{m}) \\ &\quad - \frac{\partial \bar{h}' \bar{\omega}'}{\partial p} - \nabla \cdot (\bar{h}' \bar{V}'), \end{aligned} \quad (3)$$

where $s = CpT + gZ$ is the dry static energy, $h = CpT + gZ + Lq$ the moist static energy, q the water vapor mixing ratio, L the latent heat of condensation, L_f the latent heat of freezing, Q_R the radiation heating rate, c the rate of condensation, e the rate of evaporation of the liquid water, de the rate of deposition, su the rate of sublimation, f the rate of freezing, and m the rate of melting. The horizontal wind velocity and the vertical p -velocity are denoted by V and ω ; Q_1 represents the apparent heat source and Q_2 the apparent moisture sink (Yanai *et al.*, 1973).

The budget equation for hydrometeors, including condensed water and ice particles, in the vertically integrated form can be expressed as:

$$\begin{aligned} & \frac{1}{g} \int_{p_s}^{p_T} \left(\frac{\partial \bar{I}}{\partial t} \right) dp + \frac{1}{g} \int_{p_s}^{p_T} \bar{V} \cdot (\bar{V} \bar{I}) dp \\ & + \frac{1}{g} \int_{p_s}^{p_T} \bar{V} \cdot (\bar{I}' \bar{V}') dp + \frac{1}{g} \int_{p_s}^{p_T} \bar{V} \cdot (\bar{q}' \bar{V}') dp \\ & + (P_0 - E_0) = \frac{1}{g} \int_{p_s}^{p_T} Q_2 dp, \end{aligned} \quad (4)$$

where P_s , P_T are pressure levels at the surface and tropopause, respectively; $\bar{I}$ represents the total hydrometeor content; E_0 is the evaporation from the ocean surface, and P_0 is the estimated rainfall rate.

Since the scale of analysis depends on station separation rather than grid spacing, phenomena with sizes smaller or comparable to the B -scale ship array such as cumulus clouds or mesoscale circulations associated with stratiform clouds within the cloud clusters cannot be fully resolved by the B -scale analyses and are considered as sub-grid scale processes. Latent heat due to phase changes involving the ice phase is included in the budget equations since analyses of radar reflectivity data suggested the presence of ice particles in convective cells (Szoke and Zipser, 1986) as well as in stratiform clouds (Leary and Houze, 1979b). However, GATE observations within cloud clusters were insufficient to resolve the contributions of various cloud-scale and mesoscale processes to the large-scale convective heating and drying over the life cycle. Although aircraft data gave the best airflow information within GATE cloud clusters (*e.g.*, Houze and Rappaport, 1984), they have been limited to a

few flight levels per observational time period. These limited data require a diagnostic model for quantitative interpretation of the evolution of large-scale convective heating and drying in terms of physical processes within cloud clusters. Horizontal eddy fluxes are retained in the budget equations. Since the B -scale array is about the same size as cloud clusters, the detailed airflow within cloud clusters was not fully resolved by the analysis (Esbensen *et al.*, 1982). Also, much heat and moisture detrained from cloud clusters at high levels may be transported outside the B -scale array by unresolvable horizontal eddies (Chen, 1985a).

4. Methods of analysis

a. Budget calculations

Using cubic spline under tension, the radiation data and A/B scale and B-scale thermodynamic data were interpolated into 38 levels same as those of the wind data. Horizontal distributions of thermodynamic data were obtained using the same procedures described by Chen and Ogura (1982). Convective heating and drying at 3-h intervals were evaluated from the large scale terms, *i.e.*, from the left-hand sides of Eqs. (1)–(3), at every grid point with 0.5° grid spacing. Under a steady state assumption, Gamache and Houze (1982) used a radiosonde compositing technique to construct three-dimensional kinematic fields associated with a squall line. The spatial resolution is increased because data from several time periods were incorporated into the analysis. A similar procedure was used for a mid-latitude squall line by Ogura and Liou (1980). In this study since the primary interest is on the evolution of vertical distributions of convective heating and drying during the life cycle of cloud clusters, area-averaged heating and drying at 3-h intervals were obtained by averaging grid point values within 2° of the center of the A/B ship array.

Frank (1980) discussed systematic errors in upper tropospheric temperature measurements due to solar heating. These introduced spurious time changes of dry static energy. Since the geopotential height was calculated from the hydrostatic equation, errors would be accumulated in the upper troposphere. Above the 400 mb level, relatively large temperature variations with am-

plitudes of $0.4\text{--}0.6^\circ\text{C}$ occurred with morning minima and afternoon maxima (Albright *et al.*, 1981). Frank (1980) suggested that the true amplitude of net tropospheric temperature change in the B-scale network is about two-thirds of the observed amplitude. Systematic errors in the dry static energy tendency in the upper troposphere were evaluated from the $Q_1-Q_2-Q_R$ profiles during the periods when deep convection was not vigorous. $Q_1-Q_2-Q_R$ should be small in the upper levels when the deep convection was weak. Frank (1978) identified six major cloud clusters (Day 245, 247, 248, 255, 256, 259) in Phase III. In the A/B scale region diurnal variations of $Q_1-Q_2-Q_R$ for days lacking major cloud clusters were composited (Fig. 2). Above the 400 mb level, systematic positive values in the composited $Q_1-Q_2-Q_R$ in the morning accompanied negative values in the late evening. Since deep convection is an important source of $Q_1-Q_2-Q_R$ in the upper troposphere (Riehl and Malkus, 1958), the change in $Q_1-Q_2-Q_R$ from positive in the morning to negative appears to be caused by instrumentation errors due to solar heating. To estimate instrumentation errors, the composited $Q_1-Q_2-Q_R$ was first decomposed into time mean and deviations from it. Then a three point running mean was applied to the deviations of the composited $Q_1-Q_2-Q_R$ to remove small scale fluctuations. The smoothed values above the 400 mb level are considered as diurnal errors in the dry static energy tendency estimates due to solar heating (Table 1). To compensate for these errors, 80 percent of these values were subtracted from dry static energy tendency for every diurnal cycle. These corrections modified the life cycle composites of Q_1-Q_R for cloud clusters only slightly.

b. Composite analysis

Over the eastern Atlantic, cloud clusters are categorized as squall or nonsquall. In satellite imagery, squall clusters grow explosively; and are oval, very bright and fast moving (Martin, 1975). Three of the six identified by Frank (1978) in Phase III were squall clusters (Day 247, 255, 259) as revealed by radar reflectivity data (Leary and Houze, 1979b). After low level convergence triggers convection, isolated convective cells start to grow. During intensification, convective cells

Fig. 2. Diurnal variations of $Q_1-Q_2-Q_R$ in units of $^\circ\text{C}$ per day excluding days when major cloud clusters were present in Phase III.

Table 1. Three-point running mean of the deviations of $Q_1-Q_2-Q_R$ from the day mean in units of $^\circ\text{C}$ per day excluding days when major cloud clusters were present in Phase III.

	GMT (Hour)							
P(mb)	00	03	06	09	12	15	18	21
160	-0.7	1.0	1.9	2.2	1.2	-0.5	-2.0	-1.6
175	-0.6	1.2	1.9	2.1	1.2	-1.2	-2.2	-1.7
191	-0.6	0.6	1.6	2.1	1.2	-0.8	-1.4	-1.8
208	-0.8	0.2	1.2	1.9	1.4	-0.4	-1.8	-1.7
227	-0.7	0.2	1.0	1.7	1.3	-0.3	-1.6	-1.6
247	-1.0	0.4	1.4	2.1	1.2	-0.6	-2.1	-2.0
269	-0.9	0.1	0.9	1.8	1.4	-0.2	-1.5	-1.6
292	-1.9	0.1	0.7	1.6	1.3	-0.1	-1.3	-1.4
317	-0.6	0.1	0.6	1.3	1.1	-0.1	-1.2	-1.2
343	-0.3	0.2	0.4	0.9	0.7	0.0	-0.8	-0.5
371	0.3	0.5	0.2	0.4	0.1	-0.4	-0.8	-0.3

grow and merge with new cells which develop between and ahead of existing cells. As clusters mature, these systems comprise convective cells and extensive uniform precipitation associated with upper level anvil-type cirrus. During dissipation, convective cells weaken but horizontally uniform precipitation persists for several hours. Over the life cycle of cloud clusters, the evolution of radar reflectivity is consistent with larger scale vertical motions computed by Frank (1978) and Ogura *et al.* (1979). Evidence of mesoscale downdrafts below the anvil-type clouds was found in nonsquall (Zipser *et al.*, 1981) as well as in squall clusters (Zipser, 1977; Houze, 1977).

Houze and Betts (1981) and Ogura (1985) discussed structure and evolution of squall and nonsquall clud clusters.

During squall line occurrences, Frank (1978) found a strong low-level vertical wind shear over the GATE B array. Chen (1985b) showed that the lower troposphere easterly jets observed for all squall clusters were along the leading and southern edges of Saharan air outbreaks (Carlson and Prospero, 1971). Although profiles of zonal wind, relative vorticity and vorticity budget residual differed considerably between squall and nonsquall clusters (Sui and Yanai, 1986), the evolutions of the divergence and vertical motion fields during different stages of the life cycle for squall and nonsquall clusters were remarkably similar (Frank, 1978; Ogura *et al.*, 1979). Similar evolutions in the divergence and vertical motion fields were found for an intense Oklahoma squall line despite greatly differing synoptic-scale settings (Ogura and Chen, 1977). These results suggest a close link between these fields and mesoscale processes after the development of cloud clusters (Frank, 1978; Houze 1982; Tollerud and Esbensen, 1985). Since ver-

tical advection terms dominate the left-hand sides of budget equations (1)–(3) compared to the change and horizontal advection terms (Soong and Tao, 1980), there are apparently no qualitative differences in Q_1 and Q_2 profiles between squall and nonsquall clusters. In fact, time-averaged Q_1 , Q_2 profiles for three squall and three nonsquall clusters identified by Frank during GATE Phase III were found to be similar (not shown). In this study, these six cloud clusters were used in developing life cycle composites of the vertical distributions of convective heating and drying. Frank's classification scheme based on digitized radar data (Table 2), and Frank's periods used in each stage composite (Table 3) were followed.

Some of these cloud clusters moved away from the center of B-scale array during their life cycle (for example, Day 247). In budget calculations, Kuo and Anthes (1984) and Esbensen and Wang (1984) used quasi-Lagrangian coordinates moving with cloud clusters. However, in this paper the analysis domain is fixed in space. Although the partitioning between the tendency and advection terms for fixed coordinates is different from that for the quasi-Lagrangian coordinates, the convective heating and drying profiles do not depend on the coordinate system chosen. For an individual case, time changes of convective heating and drying profiles in a fixed domain may be partially related to the propagation of clusters, since propagation may produce changes in fractional area coverages both by convective and stratiform clouds over the B-scale area. However, if more cases are used in the life cycle com-

Table 2. Cloud cluster classification (after Frank, 1978)

Stage	Convection	Convection tendency (next 3 h)
1	weak	increases
2	moderate	increases
3	strong	increases
4	strong	steady
5	strong	weakens
6	moderate	weakens

Table 3. Classification of time periods (GMT) for clusters (after Frank, 1978)

System	Day	Stage					
		1	2	3	4	5	6
1	244	21					
	245	00	03	09, 12	15	18, 21	
	246						00
2	247		09	12, 15		18, 21	
3	248		06	09	12	15, 18	21
4	255	06	09	12	15	18	21
5	256	09	12	15	18, 21		
6	258	21					
	259		00	03, 06	09, 12, 15, 18, 21		
	260					00	03

posite, mean fractional area coverages for both convective and stratiform clouds over a fixed domain for each stage of the life cycle would be more representative. Among cloud clusters, fundamental similarities in the evolution of vertical distributions of convective heating and drying would emerge from the time composite procedures. Random errors in the analysis would be reduced.

5. Results

Early in cloud cluster life, convective heating ($Q_1 - Q_R$) and drying (Q_2) profiles are greatest near the 850 mb and 950 mb levels, respectively (Figs. 3 and 5). As cloud clusters intensify, peaks in $Q_1 - Q_R$ and Q_2 profiles shift upward and increase. Later in the life cycle, both convective heating and drying peak at the 430 mb level in agreement with Esbensen and Wang (1984), suggesting the development of an upper level stratiform cloud deck. Apparently, the net condensation within stratiform clouds occurs primarily in the 400–600 mb layer. The shift of maximum convective heating from the lower troposphere to anvil level as cloud clusters mature is consistent with the evolution of vertical motion found by Frank (1978) and Tollerud and Esbensen (1985), and the life cycle aspects of cloud clusters dis-

cussed by Nitta (1978, 1979) and Albright *et al.* (1981). During the growth, the maximum vertical motion near 800 mb with primary divergence at middle levels suggests development of cumulus congestus with the top reaching 500 mb (Fig. 4). In stages five and six, midlevel divergence is replaced by convergence, and this contributes to the large-scale upward motion that maintains the

Fig. 3. Convective heating ($Q_1 - Q_R$) as a function of stages of cloud cluster life cycle in units of $^{\circ}\text{C}$ per day. Stages after Frank (1978).

Fig. 4. Same as Figure 3, but for vertical motion in units of microbars per second.

Fig. 5. Same as Figure 3, but for apparent moisture sink (Q_2) in units of $^{\circ}\text{C}$ per day.

stratiform anvil and weakens upward motion in the lower troposphere. Late stage increases in upper level heating ($Q_1 - Q_R$) and drying (Q_2) are accompanied by decreases in lower levels due to the reduction in cumulus cloud populations (Leary, 1984), and the presence of evaporative cooling within the unresolved regions of mesoscale downdraft beneath the stratiform clouds (Houze, 1977; Zipser, 1977). Cooling near the surface, from stages one to five, may be related to the injection of cold cumulus downdraft air to the lowest levels beneath the convective cloud base, and evaporation cooling of the convective rainfall.

In the composited upper level cloud cover averaged over the 2° radius of the A/B array center, the deep cloud populations increase during the growing stages, consistent with increase in the upper level convective heating (Fig. 6). Upper level cloudiness is greatest at stage five, coincident with maximum heating (and maximum vertical motion) at the anvil level. The precipitation from convective cells appears to reach its peak in stage four, when the radar echo intensity becomes steady and weakens in stage five, according to Frank's classification of cloud cluster life cycles. Upper level cloud cover and convective heating increase rapidly with very little change in the area-averaged radar observed rainfall rate between stages four and five (Fig. 6), suggesting that the stratiform precipitation grad-

ually becomes predominant as cloud clusters mature. These results agree with Nitta's (1979) finding that IR brightness has its peak a few hours after the peak radar observed precipitation rate. Although the phase mean convective heating and drying peak at 550 mb and 850 mb, respectively (Thompson *et al.*, 1979), the Q_2 maximum at 850 mb and the upper level $Q_1 - Q_R$ maximum do not coincide in time. The upper level $Q_1 - Q_R$ and cloudiness both are greatest in stage five; whereas the Q_2 maximum at 850 mb occurs in stage four, when the radar echo intensity is at its peak. Johnson (1984) showed that in cloud clusters, both the convective heating and drying profiles of cumulus clouds differ from those of stratiform clouds. He suggested that area-averaged convective heating and drying profiles depend on the fractional area coverages of both cumulus and stratiform clouds. During the early stage of cloud clusters, effects on the large scale are primarily due to cumulus clouds in the convective region. However, as cloud clusters mature, the area of stratiform clouds increases. The convective heating and drying due to mesoscale processes associated with stratiform clouds, such as: condensation in mesoscale updrafts above the cloud base, evaporation in mesoscale downdrafts at low levels, and melting at the bright band below 0°C then become important (Houze, 1982). The Q_2 maximum at low levels during the early and growing stages (stages one to four) of cloud clusters with divergence in the middle levels are consistent with the observed weak updrafts within convective cells, $<3\text{--}5\text{ ms}^{-1}$ (LeMone and Zipser, 1980), and the radar reflectivity profiles reported by Szoke and Zipser (1986). They found modest reflectivities at low levels in these cells, decreasing rapidly with height above the freezing level.

The imbalance in the moist static energy budget ($Q_1 - Q_2 - Q_R$) contains contributions from both latent heat of fusion, $L_f(de - su + f - m)$, and eddy fluxes [right-hand side of Eq. (3)]. If we consider a quantity, h_f , which is defined as:

$$h_f = h + L_f(q + l\omega),$$

where h is moist static energy, q the mixing ratio, $l\omega$ the cloud liquid water content; then h_f within a parcel is conserved for phase changes involving ice phase. The imbalance in the grid scale h_f

Fig. 6. Same as Figure 3, but for the percentage of cloud populations with tops higher than 400 mb (—); vertically integrated Q_2 in units of mmh^{-1} (---); radar derived rain rate (P) minus surface evaporation (E_0) in units of mmh^{-1} (-.-).

budget at the anvil level is due to eddy fluxes only. Within the upper level clouds, $l\omega$ is of the order of 0.5 g/kg (Tao and Simpson, 1984). It appears that $h \approx h_f$ in the upper levels, since L_f is considerably smaller than L and both q and $l\omega$ are relatively small. Therefore, the residuals of the h budget are close to those of the h_f budget in the upper levels. This suggests that eddy fluxes contribute significantly to the imbalance in the h budget in the upper levels. The $Q_1 - Q_2 - Q_R$ source in the upper troposphere is generally confined to growing and mature stages (stages three to five) of cloud clusters (Fig. 7). Since horizontal eddies are important energy sinks in the upper levels (Chen, 1985a), the $Q_1 - Q_2 - Q_R$ source there, apparently stems from vertical eddy fluxes. Most moist static energy in the upper levels is deposited in stage five when upper level cloudiness is greatest, indicating the important role played by deep convection. Although these upper level stratiform clouds are based at the middle levels where the moist static energy is least, the high moist static energy air in the lower troposphere is transported upward by the convective updrafts and advected to stratiform clouds in the higher levels (Lo *et al.*, 1982). Gamache and Houze (1983) suggested that mesoscale upward motion in the stratiform cloud of a squall cluster accounts for only 25–40% of the condensate making up the stratiform cloud;

while the remaining 60–75% is supplied by horizontal transfer of condensate generated in cumulus clouds to the stratiform region. Convective cells usually last about 1 hour. After their decay, the remnants of convective cells associated with cloud clusters frequently become merged in the anvil clouds (Szoke and Zipser, 1986). The lag between the low-level maximum in $Q_1 - Q_2 - Q_R$ sink and the upper level maximum in $Q_1 - Q_2 - Q_R$ source is much greater than the typical lifetime of convective cells. This indicates that mesoscale circulations, associated with cloud clusters, play an important role in the vertical redistribution of moist static energy in the troposphere.

Vertically integrated Q_2 [the right-hand side of Eq. (4)] agrees with the composite of the area-averaged hourly radar-derived rainfall (Hudlow, 1979) minus surface evaporation ($P - E_0$), estimated by the bulk aerodynamic method (Chen and Ogura, 1982), throughout most of the life cycle (Fig. 6) except stage six. The time lag between the vertically integrated Q_2 and the radar-observed precipitation peaks found by Frank (1979) is not evident, in agreement with Ruprecht's (1982) results. The discrepancy between the vertically integrated Q_2 and radar-derived rain rate at stage six may result from the neglect of grid-scale hydrometeor fluxes and contributions of horizontal eddies, as upper level stratiform clouds dissipate.

6. Conclusion

The vertical distributions of convective heating and drying undergo substantial variations during the life cycle of cloud clusters. At first, convective heating and drying are greatest in the lower troposphere, and shift upward as cloud clusters mature. Toward the end of the life cycle, both convective heating ($Q_1 - Q_R$) and drying (Q_2) peak at 430 mb, responding to development of upper level stratiform cloud decks and condensation within them. Decreases in $Q_1 - Q_R$ and Q_2 in the lower troposphere as upper level $Q_1 - Q_R$ and Q_2 increase and reach their peaks, indicate the presence of evaporative cooling in the mesoscale downdrafts. The upper level $Q_1 - Q_R$ maximum occurs in stage five, when upper level cloudiness is greatest; whereas the 850 mb level Q_2 maximum occurs in stage four, when the

Fig. 7. Same as Figure 3, but for $Q_1 - Q_2 - Q_R$ in units of $^{\circ}\text{C}$ per day.

radar echo intensity reaches its peak. The vertical eddy transports of moist static energy to the upper levels occur primarily during the growing and mature stages; and are most significant when upper level cloudiness reaches its peak in stage five.

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東大西洋上における中規模対流系が周囲に及ぼす熱力学的効果

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GATE の Phase III 期間中の六つのクラウド・クラスターについて Frank (1978) による分類に基づくライフ・サイクルの合成結果は、積雲による加熱と乾燥化が 1 サイクルの間に大きく変化することを示す。積雲による加熱 ($Q_1 - Q_R$) および乾燥化 (Q_2) は下部対流圏において始まる。クラウド・クラスターが成熟するにつれ上部対流圏の加熱は増大し、一方 600 mb 面以下では乾燥化と積雲による加熱の減少がみられる。上層の積雲加熱の最大は上層雲量の最大時にみられ、 Q_2 の値の最大はレーダ・エコー強度の最大時にみられる。湿潤静力学エネルギー ($Q_1 - Q_2 - Q_R$) の下部対流圏における減少は積雲系の成長期に始まる。一方上層においては背の高い積雲が支配的となるより後の段階で、鉛直方向の渦輸送による加熱が重要な要素となる。