The Life Cycles of GATE Convective Systems

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ABSTRACT

The life cycles of GATE squall lines and loosely organized cloud clusters are analyzed and documented using radar and composited rawinsonde data. Time variations of the temperature, moisture, wind and vertical motion fields are presented for both types of systems. The convective systems are usually triggered by the approach of a middle-level trough in the easterlies. Low-level convergence increases prior to intensification of convection, possibly by several hours. Once the convection begins, the systems largely cause the changes in their upper and lower level divergence profiles through cumulus-induced and radiational heating. Squall line and cluster systems are found to be essentially similar except for their propagation speeds and their vertical wind shears.

1. Introduction

Since the early satellite days it has been known that the predominant tropical weather systems are cloud-covered convective areas about 4°–8° latitude in diameter. These systems, known as cloud clusters, usually contain one or more mesoscale areas of deep cumulonimbus (Cb) convection of about 50–100 km diameter with accompanying cirrus. They may be highly organized around squall lines or exist as loosely organized clusters. Cloud clusters typically exist anywhere from a few hours to many days. Due to limited time and space resolution of conventional tropical data networks, it has been difficult to obtain quantitative analyses of these systems except for large data composites of satellite-observed cirrus-covered regions or easterly wave troughs (Williams and Gray, 1973; Ruprecht and Gray, 1976; Reed and Recker, 1971). The composite clusters have usually been assumed to be in steady state, a tenuous assumption in view of their relatively short and variable lifetimes.

GATE has provided the first data set with sufficient time and space resolution to analyze the life cycles of tropical convective systems. This study uses GATE rawinsonde and radar data to perform composite analyses of both loosely organized cloud clusters and squall lines and to study the various stages of their evolution. Also discussed are the interactions between the convection and larger scale easterly waves. Nitta (1977) has previously compared the growth stages of two GATE clusters with the decay stage of one of the clusters.

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2. Method

a. Data set and analysis technique

Rawinsonde data from the GATE B scale and A/B scale arrays (Fig. 1) are analyzed. The GATE processed and validated data tapes from the National Weather Records Center at Asheville, NC, are used, and the systems are classified using radar data as discussed later.

There are significant persistent differences between height, moisture and temperature data recorded by different ships (Ooyama and Esbensen, 1977). Many of these result from instrumental problems. Instrumentation and measurement techniques differed between nations, and changes were made at several ships between phases. To reduce these intership biases, phase mean values of each of the above parameters were composited for each ship. Deviations of a given sounding from the ship's phase mean were computed as in Eq. (1), i.e.,

$$\Delta T = T - \bar{T}, \qquad (1)$$

where ΔT is the deviation temperature, T the temperature observation and $\bar{T}$ the phase mean temperature for that ship. The use of deviations from phase means as analysis variables eliminates persistent instrumental differences. Since the use of deviation fields obscures real mean gradients between ship locations, the actual observed height, temperature and moisture fields were analyzed as well. In most cases, however, the composited deviations yielded much smoother results.

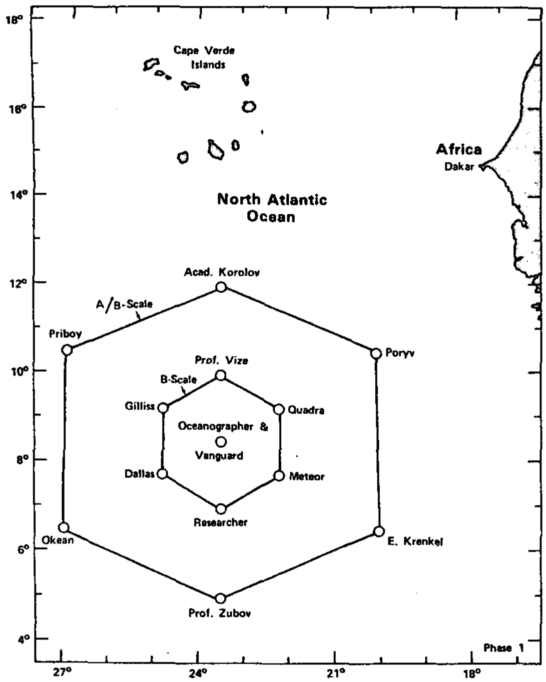


FIG. 1. A/B and B scale ship arrays for Phase 1 of GATE.

b. Classification of systems

Twelve deep convective systems which developed within the B array were chosen for analysis. Four of these mesoscale systems consisted of squall lines, defined here as lines of cumulonimbus aligned generally north-south and propagating westward as fast or faster than the winds at any level. The remaining eight systems were more loosely organized and are hereafter referred to as clusters. The clusters often showed east-west line structure, but the motion of the echoes was usually much slower than in the squall lines. The systems were classified into eight convective stages based on convective intensity and observed changes in intensity during the next 3 h. The classification scheme is shown in Table 1. Systems which

TABLE 1. Convective system classification.

Stage	Convection	Convection tendency (next 3 h)	Remarks
00	—	—	All soundings 3 h before stage 0
0	Weak	Steady	
1	Weak	Increases	
2	Moderate	Increases	
3	Strong	Increases	
4*	Strong	Steady	
5*	Strong	Weakens	
6	Moderate	Weakens	

* Maximum convection/rainfall occur during stages 4 and 5.

TABLE 2. Classification of time periods (GMT) for clusters.

System	Day	Stage 00	0	1	2	3	4	5	6
1	180				12	15	18, 21		
	181							00	
2	183				09	12	15, 18	21	
	184								00
3	187	18	21						
	188			00	03		06, 09 15	18, 21	
4	189	00	03	06	09	12	15, 18	21	
	190								00
5	223	15	18	21					
	224				00, 03	06	09, 12	15	18
6	244	15	18	21					
	245			00	03	09, 12	15	18, 21	
	246								00
7	248				06	09	12	15, 18	21
8	256	03	06	09	12	15	18, 21		

advected into the B-array radar coverage were not included in the growing stage composites (stages 1–3) and systems which advected out of the B-array were excluded from decaying stage (5–6) composites.

The systems were classified using digitized radar pictures from the *Oceanographer* and *Researcher* and mean radar-determined rainfall rates over the visible field for these ships and for the *Gillis* for Phase III (supplied by Hudlow, personal communication). The time periods used in each stage are shown in Table 2 and 3. Fig. 2 shows examples of digitized radar photographs for stages 1–6 of day 189. Nitta's (1977) study of two GATE systems classified the systems as growing or decaying based on satellite photographs. Since cloud cover lags echo development, his stages are not directly comparable to stages in this study.

Few of the individual systems went through all of the observed stages in seven consecutive 3 h steps. Many followed different time scales, developed from existing moderate disturbances, etc. In addition, very few time periods had data for all 12 ships in the two arrays, and many soundings were cut off before reaching the upper troposphere. To obtain meaningful analyses of all the life-cycle stages it was thus necessary to combine the cases into composites. Squall lines and clusters were composited separately. For each type of system eight composites were constructed—one for each stage. The average time step

TABLE 3. Classification of time periods (GMT) for squall lines.

System	Day	Stage 00	0	1	2	3	4	5	6
1	179				03, 06	09	12	15, 18	21
2	247				09	12, 15		18, 21	
3	255	00	03	06	09	12	15	18	21
4	258	15	18	21					
	259				00	03, 06	09, 12 15, 18 21		
	260							00	03

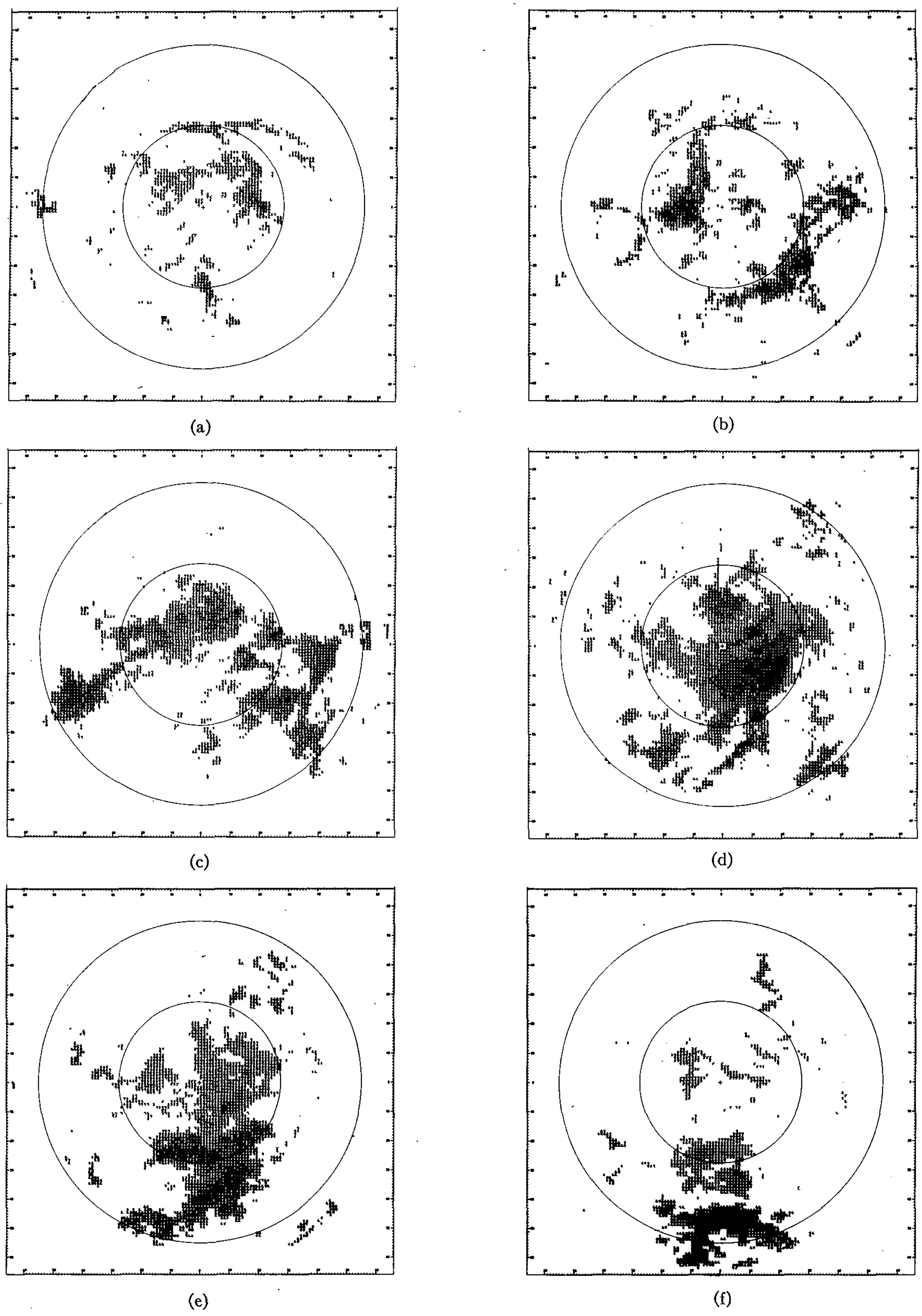


FIG. 2. Digitized radar pictures at various convective stages of day 189. Radar is at center of B array, circles are at 110 km intervals. (a) 0600 GMT, stage 1. This is near the maximum amount of convection allowed for Stage 1. Other pictures are more typical of their stages: (b) 0900 GMT, stage 2; (c) 1200 GMT, stage 3; (d) 1800 GMT, stage 4; (e) 2100 GMT, stage 5; (f) 0000 GMT day 190, stage 6.

between stages is about 3 h (4 h between stages 3–4 and 4–5). Thermodynamic and wind data were analyzed for both the B and A/B arrays, but only A/B divergence and vorticity data were used due to rather large noise observed in the B-array winds. Mean divergence within the A/B array was computed from

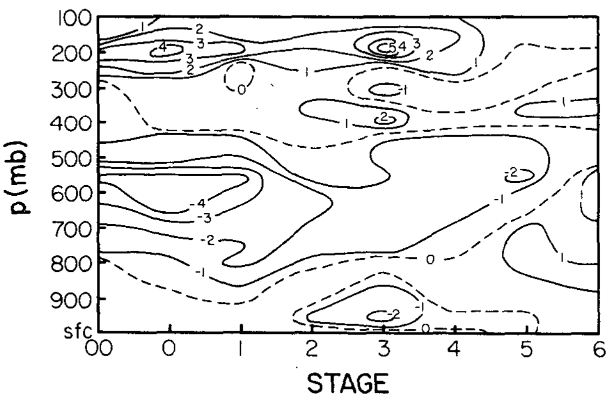
$$\overline{\nabla \cdot \mathbf{V}} = 2\bar{V}_r/r, \qquad (2)$$

using the mean A/B scale radial wind ($\bar{V}_r$). Vorticity was computed similarly. All wind data flagged as suspicious by the Center for Experiment Design and Data Analysis (CEDDA) were removed.

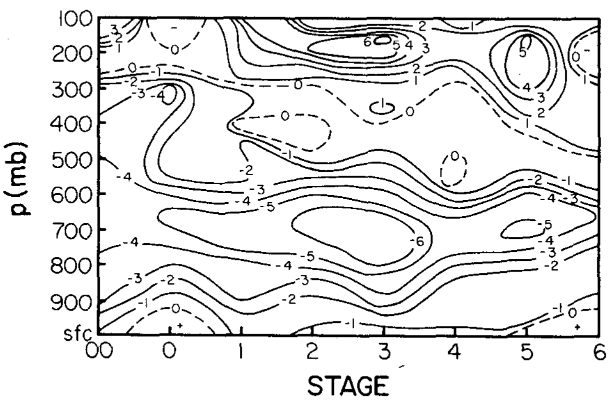
3. Results

a. Observed life cycles

The B-scale meridional wind components ($\bar{v}$) are shown in Fig. 3 and the A/B scale vorticities are depicted in Fig. 4. The clusters form near the northerly wind maxima preceding 700 mb easterly wave troughs as noted by Reed *et al.* (1977) and Payne and McGarry (1977). The squall lines tend to occur at or near easterly wave troughs as well, although this is harder to tell from Fig. 3b. The squall lines show stronger vertical shears of the meridional wind and higher 700 mb vorticities than do the clusters. Both systems exhibit slight strengthening of the upper level anticyclone during the deep convective stages (3–5). This is a direct result of increased upper level divergence (shown later) which accompanies the development of deep convection.

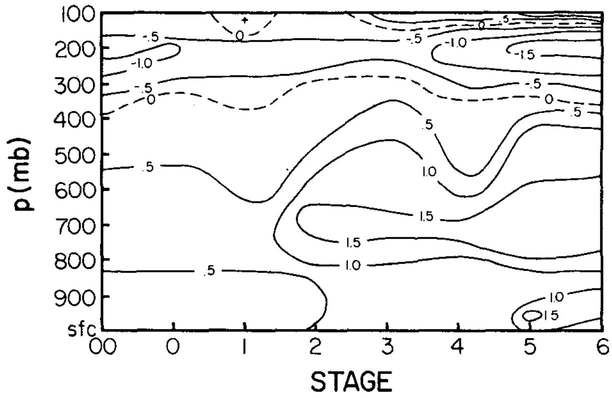


(a)

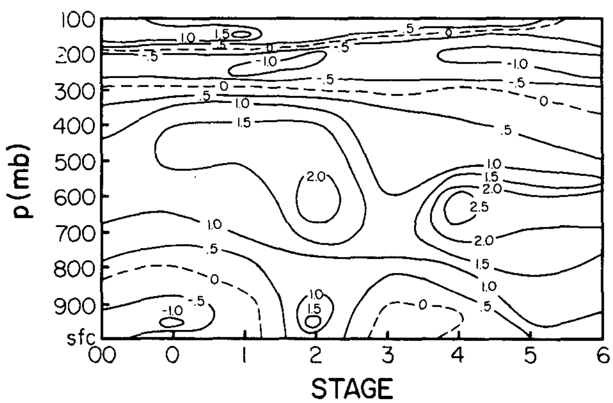


(b)

FIG. 3. Mean B-array meridional winds for the eight life cycle stages for clusters (a) and squall lines (b). Contours are in m s^{-1}.



(a)



(b)

FIG. 4. Mean A/B-array vorticities for clusters (a) and squall lines (b). Contours are in 10^{-5} s^{-1}.

b. Divergence and vertical motion

The A/B scale divergence patterns of squall lines are very similar to those of clusters (Fig. 5). Initially the systems show weak low-level convergence balanced primarily by divergence near 600 mb. Inflow peaks at 400 mb and some outflow near 250 mb is also observed. The first noticeable increase in convection occurs between stages 1 and 2. However, low-level convergence increases well prior to any observed increase in convection indicating a lag time between the dynamic boundary layer forcing and the formation of significant clouds. This is discussed later. Note that the low-level convergence is generally

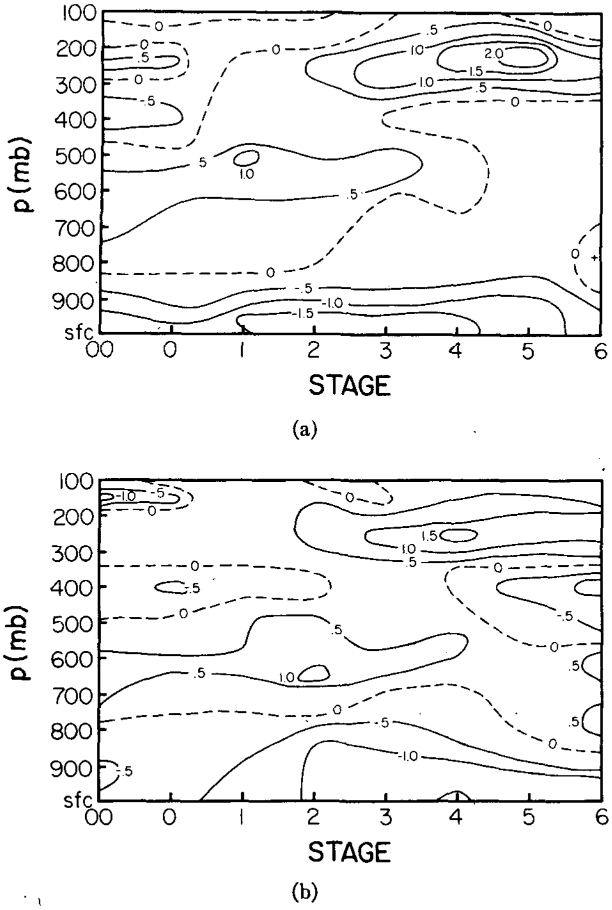


FIG. 5. As in Fig. 4 except for divergence.

greater than the low-level vorticity indicating that frictional convergence is relatively unimportant.

As the convection increases, strong divergence peaks near 250 mb develop, and the middle-level divergence changes to weak inflow by stage 5. Significant middle-level convergence is typical of mature western Pacific and West Indies weather systems (Williams and Gray, 1973; Ruprecht and Gray, 1976; Reed and Recker, 1971; Yanai *et al.*, 1973; Frank, 1977).

Vertical motions are computed from Eq. (3) after the divergence profiles are adjusted linearly to achieve $\bar{\omega}=0$ at 100 mb:

$$\bar{\omega}(p)=\int_{P_0}^{P}\overline{\nabla\cdot\mathbf{V}}dp. \tag{3}$$

Fig. 6 shows the development of low-level maxima in upward vertical motion during the early growth stages. Deep upward motion and upper level maxima occur during the mature convection and early decaying stages (4 and 5). Mean upward motion decreases rapidly as the systems decay (stage 6). Both systems show weak upper level subsidence prior to the onset of low-level convergence and convection.

The evolutions of the divergence and vertical motion fields of these systems are remarkably similar to those observed in a midlatitude continental squall line by Ogura and Chen (1977) despite quite different environmental conditions. The reader is referred to that paper for an excellent case study of the life cycle of an individual squall line.

c. Temperature and moisture

Clusters and squall lines both evolve from an initial stage where they are colder than normal above about 450 mb and warmer below (Fig. 7). As the systems develop, they warm rapidly in the upper troposphere. Since horizontal temperature advection is small, the warming is due to a combination of cumulus and radiational heating. The upper level temperature maxima near 300 mb agree well with previous estimates of maximum cumulus heating from 300–400 mb in deep convective tropical systems (Yanai, 1963). Absorption of solar radiation by cirrus clouds should be maximum near 200 mb (Gray and Jacobson, 1977). The lower troposphere cools with time. This may result from increasing evaporation of liquid water accompanying the increasing convection. The systems

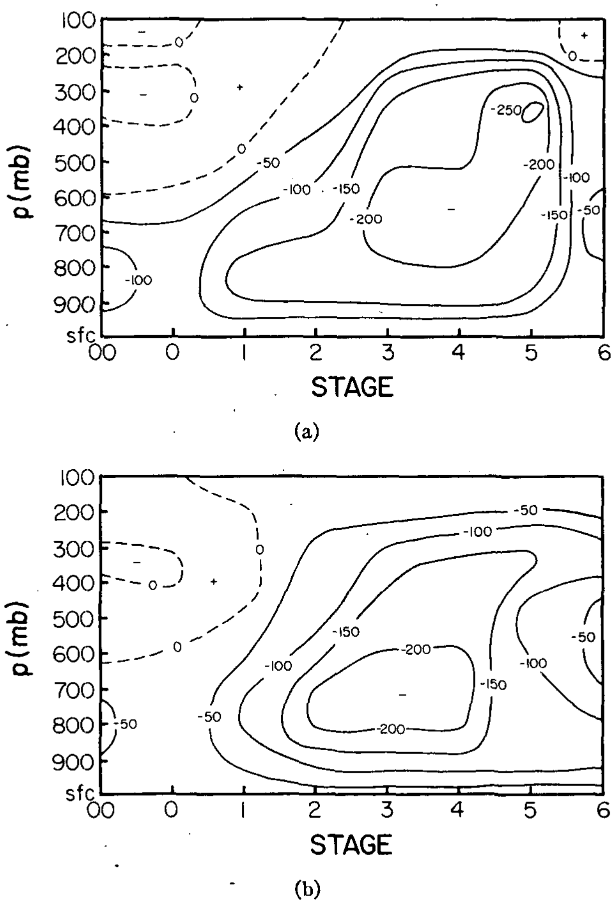


FIG. 6. As in Fig. 4 except for vertical motion ($\bar{\omega}$). Contours are in mb day^{-1}.

become colder than normal in the low levels during their latter stages. The lower tropospheric cold core structure of easterly wave troughs and cloud clusters has been noted by Riehl (1948, 1969) and Yanai (1961, 1964). The net temperature and thickness changes integrated through the entire troposphere are very small.

Estimation of the relative magnitudes of the upper level cumulus and radiational warming is complicated by the fact that both types of system show a strong diurnal phasing. GATE A/B area clusters and squall lines tend to develop in the late evening/early morning and reach their maximum intensities in the afternoon (see Tables 2 and 3) (Weickmann *et al.*, 1977). Therefore, the time of maximum observed upper level temperature corresponds statistically with strong afternoon absorption of solar radiation by the cirrus deck and other upper level layer clouds (Gray and Jacobson, 1977). Gray and Jacobson have demonstrated that radiative processes are significant in the energetics of tropical weather systems. The temperature increase cannot be partitioned between cumulus-induced and radiational warming without detailed

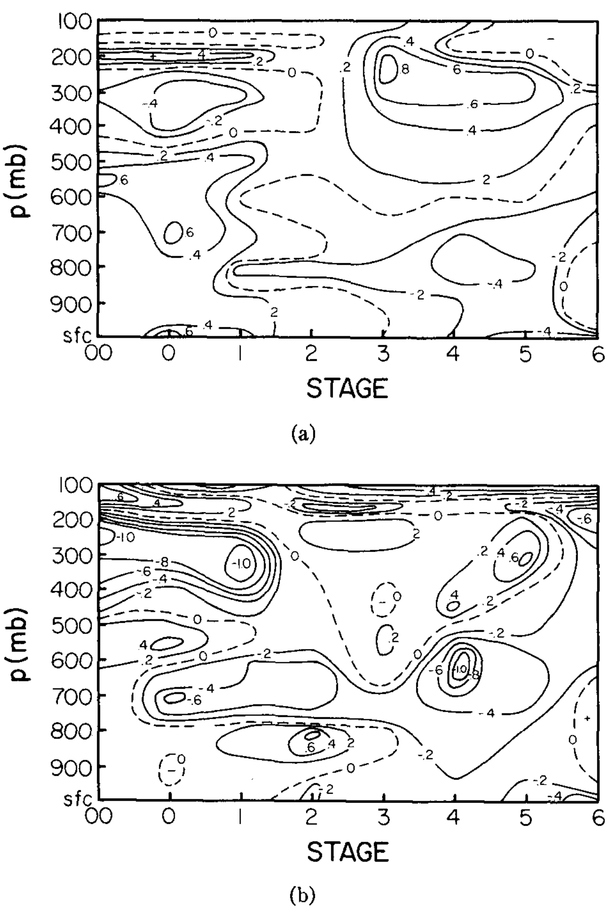


FIG. 7. Mean B-array temperature deviations (°C) from phase mean temperatures for clusters (a) and squall lines (b).

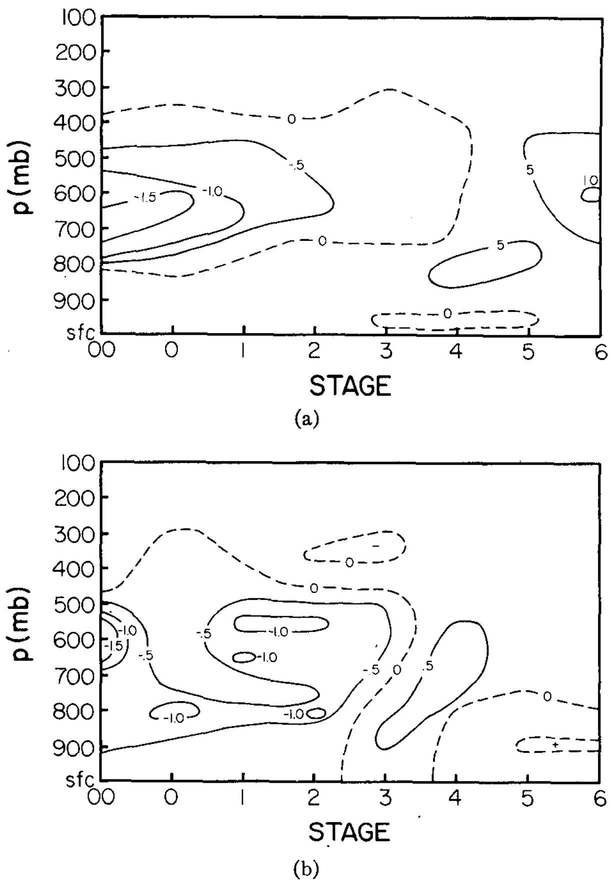


FIG. 8. As in Fig. 7 except for specific humidity deviations (g kg^{-1}) from phase mean humidities.

knowledge of the cloud populations, so it must be viewed as the result of the sum of these terms.

As expected both types of system undergo continuous moistening of the middle troposphere throughout their lifetimes (Fig. 8). The boundary layers dry slightly with increasing convection indicating the presence of precipitation-induced downdrafts. This drying, coupled with the low level cooling shown in Fig. 7 results in lower θ_E values in the boundary layer and acts to stabilize the lower troposphere. Convectively induced lowering of boundary layer θ_E values has been observed in tropical squall lines by Betts *et al.* (1976) and Zipser (1969).

d. Comparison of clusters and squall lines

Figs. 3–8 show the life cycles of GATE clusters and squall lines to be remarkably similar. Their divergence, vorticity, vertical motion, temperature and moisture fields go through nearly identical life cycles. The most significant differences between the systems are in the vertical wind shears. In Figs. 3 and 9 it can be seen that the squall lines have more meridional shear between the surface and 600–700 mb than the clusters. They also have more meridional

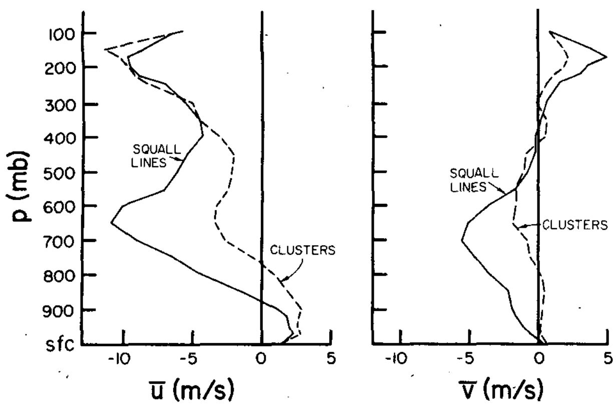


FIG. 9. Mean B-array zonal and meridional winds averaged over stages 00-6. Contours are in m s^{-1}.

shear of opposite sign between 600–700 mb and 200 mb. Far more striking are the differences in the zonal shear (Fig. 9). The squall lines exhibit more than twice as much surface to 650 mb easterly shear as the cluster regions. Since the upper level zonal winds are similar, the clusters exhibit stronger 650–200 mb easterly shears than do the squall lines. Vertical momentum transports are strongly dependent on vertical wind shear, so the effects of these transports must also differ.

The conditions required for squall line generation may be generalized as conditional instability (including substantial low level moisture), strong winds throughout the troposphere, and some sort of triggering mechanism (Aspliden *et al.*, 1976; Newton, 1963). In the GATE region the conditional instability, relatively strong winds and triggering mechanisms (easterly wave troughs) are present and similar for both clusters and squall lines. Strong low-level vertical shear appears to be the critical factor which results in convection organizing into rapidly propagating squall line configurations. It is not possible to define a threshold value of zonal shear for the development of squall lines from such a small data source. It should be noted, however, that a mean (stages 00–6) B-scale easterly shear of 6 m s^{-1} between 950 and 650 mb was observed in the cluster cases, while the mean shear for the squall lines was 13 m s^{-1}.

As was shown in Figs. 7 and 8, both clusters and squall lines tend to stabilize the lower troposphere on the B scale slightly by cooling and drying the boundary layer. It is of interest to cumulus parameterization theory as to whether the two systems differ with respect to the magnitude of this effect on the larger (A/B) scale. Fig. 10 shows the surface to 950 mb average temperature and moisture deviations for each stage for all ships in the combined B and A/B arrays. Although the data are somewhat noisy, no obvious differences between clusters and squall lines are seen in the cooling of the boundary layer. The clusters dry the A/B scale boundary layer slightly more than do the squall lines. There is some indication that the cluster boundary layer returns to normal faster (see stage 6) after the death of the system.

One obvious difference between squall lines and clusters is in their propagation speeds. GATE A/B area clusters generally moved west-southwest at average speeds of 8–10 m s^{-1}, and the mesoscale convective areas and echoes embedded within clusters often moved much more slowly and in various directions (Burpee and Dugdale, 1975). The squall lines tended to propagate faster and moved westward faster than the winds at any level (Aspliden *et al.*, 1976). From a parameterization viewpoint this may be their only significant difference. Time-space relationships of cumulus heating to the large scale may thus depend on the magnitude of the low-level shear. The effects of vertical shear on squall line dynamics and propagation have been modeled by Moncrieff and Green (1972) and Moncrieff and Miller (1976).

e. Lag of convection to large-scale forcing

The results of this study indicate that increases in convection lag increases in low-level convergence. Although the data are of limited time resolution, the lag is on the order of a few hours. It has been suggested that a buildup of middle-level moisture may be required before deeper convection can exist due to entrainment-drying considerations. Alternatively, there may be a characteristic time required for large-scale low-level convergence to become dynamically organized into updraft regions of sufficient size to result in deep convection. It is hypothesized that the latter process is dominant. The GATE A/B region has relatively large amounts of middle-level moisture most of the time. The variations in middle level humidities seen in Fig. 8 seem too small to have significant effects on the growth of convection. However, Lopez (1976, 1977) has speculated that large convective cells may result from stochastic formation or growth processes

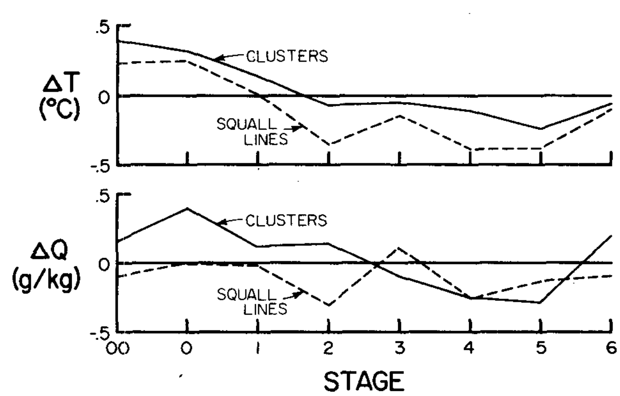


FIG. 10. Surface to 950 mb mean temperature deviations (°C) from phase mean temperatures (top) and specific humidity deviations (g kg^{-1}, bottom), averaged for all B and A/B array ships.

which follow the law of proportionate effects. That is, a cloud's change in size at any time would be a random proportion of its previous size, i.e.,

$$A_t - A_{t-1} = \epsilon A_{t-1}, \quad (4)$$

where A_t is the cloud updraft area at time t and ϵ is a random number. If cloud growth is indeed governed by this or some similar type of process, then a lag between large-scale forcing and the formation of large updrafts would be expected. Investigation into the causes of this lag time should be pursued further.

f. Wind/pressure-gradient relationships

In the deep tropics the winds often blow down the pressure gradient. Mesosynoptic scale height gradients are largely controlled by cloud-induced warming and vary on rapid time scales relative to wind adjustment times. The result is that whenever there is a height gradient perturbation from a quasi-balanced state of even one or two meters, the wind accelerates rapidly downgradient. Since the Coriolis deflection adjustment is much slower than the downgradient acceleration, whenever a net inward/outward height gradient is established, downgradient flow occurs. This results in diabatically induced convergence/divergence. In this manner a mesoscale convective system can produce its own divergence life cycle superimposed on the large-scale wind field.

g. Relationships of convective systems to easterly waves

Composites of easterly waves over Africa and the GATE network indicate upper and lower tropospheric structures in the northerly wind-maximum-to-trough region [phases 2–4 of the Reed and Recker (1971) classification scheme] which are remarkably similar to the composites of convective system life cycles presented here (Reed *et al.*, 1977; Burpee, 1974). These waves are generated and driven by instabilities of the 600–700 mb jet which occurs over Africa and the eastern Atlantic during the late summer (Burpee, 1972).

In the GATE region the easterly flow at ~600 mb is moving much faster than the trough axis. This leads to divergence to the west of the trough at the jet level (Riehl, 1954; Reed *et al.*, 1977; Rennick, 1976). Fig. 5 does show rather strong divergence in the middle levels prior to the onset of convection. Rennick's (1976) model of West African waves shows convergence in the lower troposphere preceding the trough with resulting upward motions of 10–20 mb day^{-1} at 800 mb. It is assumed that this rather weak large-scale forcing is sufficient to trigger the development of mesoscale convective systems in the convectively unstable region south of the jet. The clusters/squall lines amplify their own circulations resulting in the observed upward motions of more than 200 mb day^{-1} averaged over the A/B array (400 mb day^{-1} for the B array).

The observed convergence/divergence patterns in the lower to upper troposphere result largely from cumulus and radiation-induced heating and resultant height gradient changes as previously discussed. In this way the convective systems may be thought of as a link between the mid-tropospheric wave and the upper and lower levels. The similarity of the observed changes in the divergence and vertical motion fields to those found in a Great Plains squall line with much different synoptic conditions (Ogura and Chen, 1977) lends support to the hypothesis that these are largely governed by mesoscale processes. Since the locations of the convective systems are highly correlated with wave phase, a composite of easterly waves yields a structure very similar to a composite of the weather systems.

4. Conclusions

Squall lines and loosely organized clusters which occurred during GATE have been analyzed at various stages of their life cycles. Time variations of these systems have been documented. Both types of systems undergo similar evolutionary changes. As the convection develops, the systems progressively warm in the upper troposphere and cool in the lower levels. Moistening of the lower and middle troposphere occurs throughout the life cycles.

Low-level convergence increases are observed prior to any observed increase in convection. It is hypothesized that this lag results from inherent updraft formation/growth properties as suggested by Lopez (1976, 1977). Since the low-level convergence is generally larger than the vorticity, it is not primarily driven by frictional forcing.

The only significant observed differences between squall lines and cloud clusters are their vertical wind shears and propagation speeds. In parameterization schemes sensitive to mesoscale movements of convective systems, the movement of squall lines and clusters might have to be specified in terms of low-level vertical wind shears.

The modulation of convection by easterly waves and the resultant strong correlation between deep convection and wave troughs (Reed *et al.*, 1977; Burpee, 1974) result in many observed similarities between composite easterly wave structure and composite convective system structure. Upper and lower level wave structure are strongly dependent upon the abilities of the middle-level wave to trigger low-level convergence and of the troposphere to sustain deep convection. Although the waves trigger the convective systems, the structural changes observed during the life cycles appear to be forced primarily by mesoscale dynamic processes.

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