Boundary-Layer Growth over the Tropical Ocean

DAVID R. FITZJARRALD[1] AND MICHAEL GARSTANG

Department of Environmental Sciences, University of Virginia, Charlottesville, 22903

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ABSTRACT

Results of a one-dimensional mixed-layer growth model are compared with thermodynamic observations made during the GARP Atlantic Tropical Experiment (GATE). Observed drying at low levels accompanying warming in the wake of a storm is hypothesized to be the result of rapid mixed-layer growth as well as of subsidence in the environment outside the storm. Sensitivity of the model solutions to changes in subsidence and stability above the mixed layer is shown. Model solutions show protracted recovery periods only when the wind speed near the surface is moderate (~3 m s^{-1}). Recovery of the mixed layer in the wake of the 12 September 1974 GATE squall line is simulated by the model.

1. Introduction

Over tropical oceans during undisturbed conditions, the atmospheric boundary layer consists of a nearly neutral mixed layer capped by a statically stable layer (Malkus, 1958). When the lower atmosphere is disturbed by precipitating clouds, downdrafts dilute the boundary layer and the mixed layer may shrink or disappear altogether (Seguin and Garstang, 1976; Gaynor and Ropelewski, 1979; Zipser, 1977; Betts, 1976). Barnes and Garstang (1981) describe three regions with characteristic boundary layer structure associated with a tropical oceanic system or cloud cluster: the *undisturbed* region ahead of the cloud cluster with the typical undisturbed mixed layer nearly uniform in temperature and moisture through a depth of some 500 m above the surface; the *disturbed* region of convective rain in which evaporative cooling and vertical mass exchanges associated with cloud-related updrafts and downdrafts are observed in the subcloud layer (Emmitt, 1978), and a *wake* region in which active low-level moist convection ceases, middle and upper level stratiform cloud types predominate, and the mixed layer, which may have disappeared in the region of precipitation, is growing back to its undisturbed depth.

In the wake region the reestablishment of a deep (500 m) mixed layer typical of undisturbed conditions may be slow [10–20 h, (Mandics and Hall, 1976)]. During this recovery, the shallow mixed layer is capped by a marked stable layer often quite distinct from a weaker transition layer lying just below convective cloud base. The "top" of the mixed layer is effectively separated from convective cloud base and no new convective clouds can be generated. Garstang and Betts (1974) hypothesized that under conditions of slow recovery of the mixed layer, convective cloud growth would be limited, thereby limiting the size or life of a cloud cluster.

In this paper we wish to investigate the manner in which the mixed layer over the tropical ocean is reestablished following significant suppression of the mixed layer by precipitating convection. A one-dimensional model of the growth of the unstable convective boundary layer which has been widely used and described in the literature (Ball, 1960; Lilly, 1968; Stull, 1973; Tennekes, 1973; Carson, 1973) is used to help interpret mixed-layer growth observed in the GARP Atlantic Tropical Experiment (GATE). We use the model (as developed by others) *as a tool*, in its simplest form, to generate a range of model results which can be compared with observations. We allow no basic adjustable parameters in the model other than initial environmental conditions. Comparisons are made between model results and observations of the growth of the mixed layer, with emphasis on the time changes of the temperature, humidity and depth of the mixed layer. These comparisons provide some physical insight and a basis for interpretation of the way in which the tropical oceanic mixed layer is reestablished in the wake of precipitating convective clouds.

2. The model

The one-dimensional model of the growth of an unstable boundary layer as modified by Lilly

[1] Present affiliation: CIRES, University of Colorado, Boulder 80309.

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(1968) assumes a discontinuity in specific humidity and virtual potential temperature at the interface (transition layer assumed infinitesimally thin) between the mixed layer and the cloud layer. Usually (e.g., Albrecht *et al.*, 1979; Pielke and Mahrer, 1975), the mixed layer has been assumed to grow from the surface in response to the input of buoyancy at the surface. Growth of the mixed layer also depends on the flux of buoyancy across the mixed-layer–cloud layer interface, the rate of sinking of the environmental air, and the lapse rate of virtual temperature above the mixed layer. In our application of the model, two features of the observations need to be emphasized:

1) The sea surface temperature in the GATE region changed much more slowly than that of the air. Thus, given a constant wind speed, surface fluxes will decrease as the mixed layer warms and moistens. Surface fluxes over the tropical oceans indeed behave in this fashion (Malkus, 1962).

2) Decreases in specific humidity have been noted in the wake of tropical oceanic disturbances (Zipser, 1977; Barnes and Garstang, 1981). These decreases occur well after the air temperature near the surface has begun to rise. Zipser attributed this fall in humidity to mesoscale subsidence that enhanced mixing of dry air at the top boundary into the mixed layer. Since the mixed layer is warmed at the top and bottom but moistened only at the bottom, drying and heating are compatible. Because entrainment of dry air into the mixed layer depends on the motion of this interface relative to the less turbulent air above, the observed drying could also be the result of rapid growth of the mixed layer.

Growth of the mixed layer should be enhanced by increasing surface fluxes and inhibited by increasing the strength of the capping inversion or the environmental sinking. We apply the model with initial conditions similar to those observed during the GATE to determine the relative importance of the factors affecting mixed-layer growth. Special attention will be given to the time history of the humidity in the mixed layer as an indicator of the layer growth.

With the exception of the closure assumption introduced below, model relations for specific humidity (q) and virtual potential temperature (θ_v) are the same. Either variable will be represented by X below. Lilly (1968) and Betts (1973) show that the rate of change of the mixed-layer mean of a quantity X_m is due to the convergence of the turbulent flux (F_x) in the layer. If H is the mixed-layer thickness, then

$$\frac{dX_m}{dt} = \frac{F_{x0} - F_{xH}}{H} + Q_{xm}. \qquad (1)$$

Here F_{xH} represents the flux of X below the discontinuous jump. For other variables, subscripts H and zero denote values of a variable evaluated at the top of the mixed layer (above the discontinuous jump) and the value of a variable at the surface, respectively. Subscript m refers to the mixed layer mean of a variable. For completeness, variable Q_{xm} is added to represent the sum of advective effects and radiative cooling (for θ_v) and the net result of evaporation minus condensation (for θ_v and q). Following Sarachik (1974) and others, the turbulent flux at the top of the mixed layer is related to the "jump" in the quantity at the mixed-layer top $X_H - X_m$, i.e.,

$$F_{xH} = (X_H - X_m)\left(\frac{dH}{dt} - w_H\right), \qquad (2)$$

where w_H is the vertical velocity of air at the top of the mixed layer. Surface fluxes are given by the bulk aerodynamic formulation

$$F_{x0} = CV(X_m - X_0), \qquad (3)$$

where C is a transfer coefficient and V the wind speed near the surface. We use $C = 0.0015$ both for specific humidity and virtual potential temperature, as suggested in the GATE Workshop Report (1977). The value of a variable at the top of the jump, X_H, is related to the motion of the mixed-layer top relative to the atmosphere above (Sarachik, 1974):

$$\frac{dX_H}{dt} = \Gamma_x\left(\frac{dH}{dt} - w_H\right) + Q_{xH}. \qquad (4)$$

We have added the term Q_{xH} to represent the sum of advective and radiative effects, in analogy with Q_{xm}. The gradient Γ_x of a variable above H is not necessarily constant with time. In the atmosphere above the mixed layer when diabatic and horizontal advective effects are not important (Carson, 1973), we have

$$\frac{\partial X}{\partial t} = -w(z)\Gamma_x, \qquad (5)$$

where vertical velocity in the air above the mixed layer is represented by $w(z)$. When the horizontal divergence D is constant in this layer, $w(z) = -Dz$. This leads to $\Gamma_x(t) = \Gamma_x(0)\exp(Dt)$ if Γ_x is constant with height above the mixed layer. Composite profiles of potential temperature and specific humidity observed during GATE (Fig. 1) indicate that assuming lapse rates to be constant with height above the mixed layer is consistent with the data. Carson used this relation when modeling boundary layer growth over land. Such rapid growth of gradients was not observed during GATE. Positive low-level divergence was transient during disturbed periods. In Section 3 we crudely simulate this transient divergence by assuming $D = D_0$(1

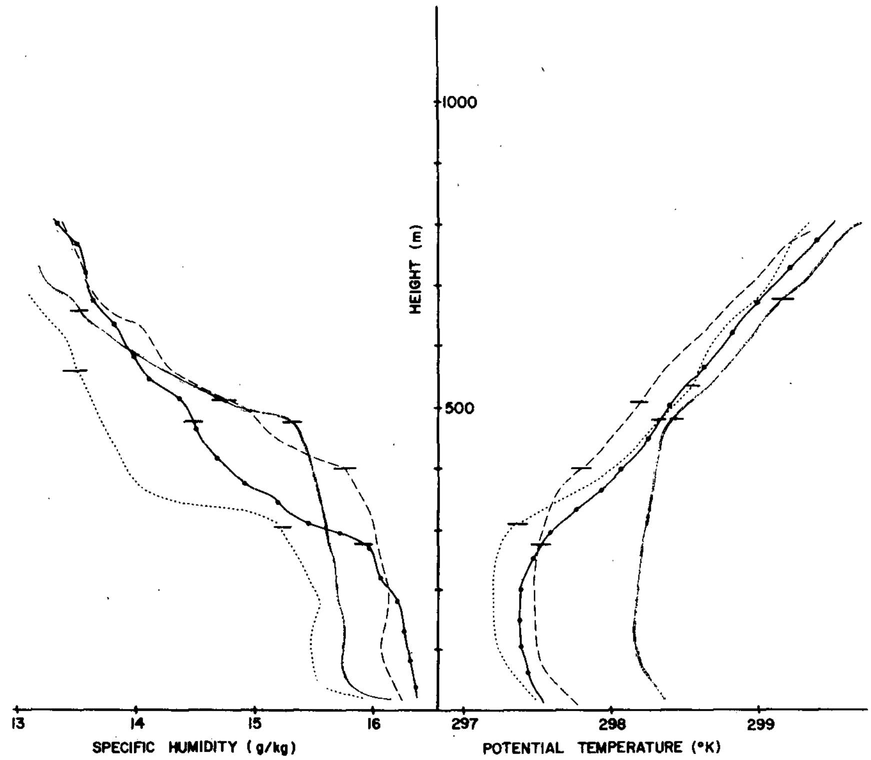

FIG. 1. Mean profiles of specific humidity and potential temperature for undisturbed (solid), weak disturbance (dashed), medium disturbance (dash-dot), and in the wake of a strong disturbance (dotted). A horizontal bar marks the level of the mean mixed-layer top and the mean LCL on each profile (after Fitzjarrald and Garstang, 1981).

$- tt_f^{-1})$ with divergence going to zero at $t = t_f$. This leads to a Gaussian expression for the gradient: $\Gamma_x(t) = \Gamma_x(0) \exp[D_0 t(1 - \tfrac{1}{2}tt_f^{-1})]$. We subsequently designate the gradient of θ_v as Γ and the gradient of q as Γ_q in this paper. We emphasize that assumptions about divergence directly affect model results through changes in gradients. Uncritical application of Carson's model can lead to realistic results for the wrong reasons.

The system of equations is completed using the conventional closure assumption (Betts, 1973; Tennekes, 1973)

$$F_{\theta_v H} = -k F_{\theta_v 0}, \tag{6}$$

where k is an entrainment parameter. Values of k in the literature vary from 0.1 to 0.9, but the majority of observations support values between 0.1 and 0.3 (Stull, 1976). If not otherwise stated, we use $k = 0.25$ in this paper (Betts, 1973). The closure assumption is only applicable to the buoyancy variable θ_v (Deardorff, 1975). The ratio of the specific humidity flux at H to that at the surface is not constant. This ratio will be designated R in this paper.

Model calculations were stopped if the mixed layer became saturated. No saturated mixed layers were observed during recovery periods in GATE. We assume that the time required to saturate the mixed layer is an upper bound on the boundary layer recovery time. Model results are presented with time series of the lifting condensation level (LCL) and mixed-layer height to illustrate approaches to saturation when they occurred. For simplicity, in this paper we present results with the diabatic Q terms equal to zero. Our tests have shown that basic thermodynamic features of the recovery of the mixed layer over a few hours are not strongly dependent on these terms. This is probably because warming rates related to surface fluxes and entrainment greatly exceeded radiative effects. During the recovery period, mixed-layer warming rates are often near 12 K day^{-1}. Cox and Griffith (1979) report observed net radiative cooling rates for clear-sky conditions in the GATE boundary layer ranging from 1 to 2 K day^{-1}. We exclude the diabatic Q terms (and hence radiative effects) in the current calculations to keep the model as simple as possible. However, with the exclusion of the Q terms, the solutions cannot be asymptotic to a complete thermodynamic equilibrium condition. The model in this form requires a constantly warming mixed layer.

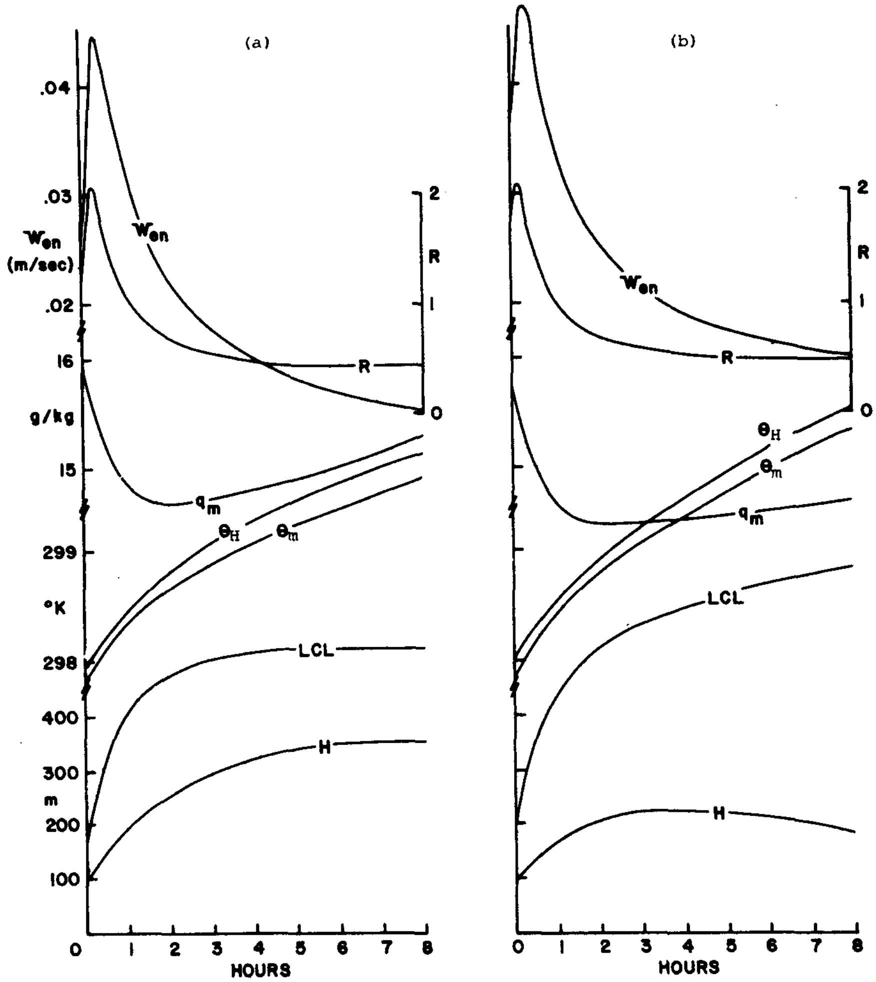

FIG. 2. Results of a one-dimensional mixed-layer model. Variables plotted against time are w_{en}, the entrainment velocity: q_m, the mixed-layer mean specific humidity; θ_m, the mixed-layer mean virtual potential temperature; θ_H, the mixed-layer thickness; and LCL, the mean mixed-layer lifting condensation level. The external specified parameters are $\Gamma = 3.5$ K km^{-1}, $\Gamma_q = -3.0$ g kg^{-1} km^{-1}, θ_{v0} at the sea surface = 302.0 K, $k = 0.25$. The diabatic terms are zero. Uniform vertical velocity above the mixed layer (w_H) is assumed. Model results are shown for: (a) $w_H = -0.01$ m s^{-1} and (b) $w_H = -0.02$ m s^{-1}.

3. Model results

Model results with constant lapse rates (Fig. 2a) illustrate the relative importance of wind speed and environmental subsidence. The ratio of the specific humidity flux at H to the flux R at the surface was not constant during growth of the model mixed layer. The time series of R in Fig. 2a illustrates that the closure assumption on the virtual temperature fluxes cannot be applied to the specific humidity fluxes. The ratio R approached 0.46 after 8 h while k was assumed constant at 0.25. The model throws little light on the physical processes involved in the heat and moisture fluxes except to indicate that both are related to vertical motion through the top of the mixed layer. The only fundamental difference in the modeled q and θ_v fluxes at H is that they are of opposite sign.

The entrainment velocity shown in Fig. 2a peaked at $t = 0.5$ h during the period of maximum dH/dt and approached a steady state after 8 h at the assumed environmental subsidence value of -0.01 m s^{-1}, a direct consequence of the fact that

$$w_{en} = \frac{dH}{dt} - w_H, \tag{7}$$

where w_H is the vertical velocity in the environment at H and w_{en} is the entrainment velocity. The specific humidity reached a minimum after 2 h and increased thereafter. The mixed-layer thickness H grew to an approximately constant value of 360 m,

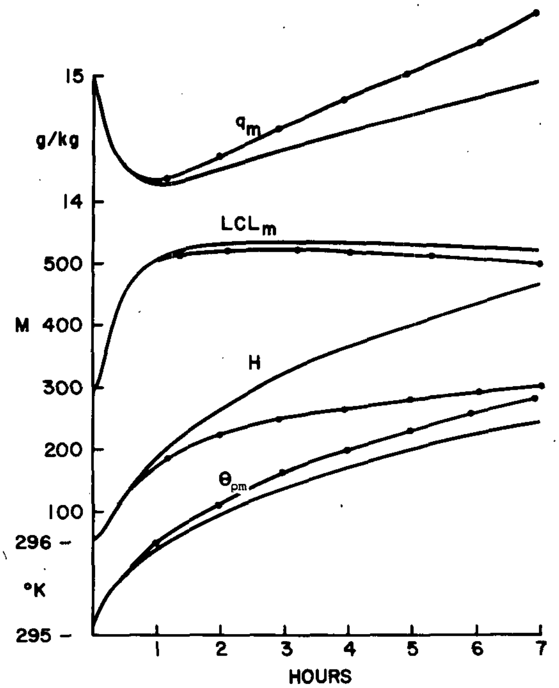

FIG. 3. Results of the one-dimensional mixed-layer model with constant and variable lapse rates of potential temperature. The time constant t_f was 8 h. θ_{pm} is the mixed-layer mean potential temperature. A constant value of the specific humidity, 13 g kg^{-1}, was assumed above the mixed layer. $\Gamma_q = 0$; $\Gamma_{p\theta} = 4$ K km^{-1}, increasing to 8.1 K km^{-1} after 7 h. The increasing lapse rate solution is distinguished by closed circles. The wind speed assumed was 3 m s^{-1}.

160 m below the LCL. Eighty percent of the mixed-layer growth occurred in the first 3 h. After 8 h, the mixed layer was warming and moistening at rates that kept the LCL nearly constant. The model-predicted mixed-layer depth in Fig. 2 of 360–500 m can be compared to the mixed-layer heights of the mean profiles shown in Fig. 1. The recovery times of 2–10 h are similarly typical of observed recovery times (e.g., Zipser, 1977; Gaynor and Ropelewski, 1979; Fitzjarrald and Garstang, 1981).

When the model wind speed is increased from 3 to 10 m s^{-1} with the same initial conditions as in Fig. 2a, the mixed layer was saturated in ~2 h; the layer moistened rapidly enough to offset the effects of the enhanced warming rate. At saturation the mixed-layer top height was 480 m. The rapid recovery for the 10 m s^{-1} case suggests that long recovery periods can occur only in regions of relatively low wind speed or sustained strong subsidence.

Fig. 2b shows growth of the model mixed layer with the wind speed at 3 m s^{-1} but with the environmental subsidence doubled from −0.01 to −0.02 m s^{-1}. For comparison, Reed *et al.* (1977) report maximum synoptic-scale downward motions at 700 mb, in the vicinity of wave disturbances in the GATE region, of ~0.01 m s^{-1}. In the environment of severe storms larger subsidence values, such as those modeled here, are sometimes observed (see Section 3). The mixed-layer top reached a maximum height just above 227 m in 3.5 h and decreased thereafter. Specific humidity decreased from 16 to 14.5 g kg^{-1} during the first 2 h and then increased slowly. This solution may simulate conditions of strong mesoscale subsidence as hypothesized by Zipser (1977). When subsidence is extremely strong, the specific humidity over the warm ocean can remain low for several hours. However, contrary to the GATE observations, such strong subsidence causes the mixed-layer depth to decrease in the model. The drying in the model is seen to be concomitant with warming at the surface and, we conclude, is a consequence of the rapid growth of the mixed layer, i.e., when w_{en} is near its maximum.

Results of the model for constant and varying Γ are compared in Fig. 3. The humidity gradient above the mixed layer was zero for this calculation. The mixed layer growing into an environment of increasing stability as given in (7) became shallower and moister than the mixed layer growing in the constant environment. The mixed layer growing in the constant environment is significantly thicker than the other. Note that the relatively small differences in thermodynamic quantities between the two calculations are enough to make a large change in the distance between the top of the mixed layer and the LCL. The effect of increasing stability appears to increase the length of the recovery time. In subsequent comparisons with observations we will assume constant lapse rates. Results for varying lapse rates are presented here to present a potentially practical situation and to illustrate the effect that the interconnection between divergence and profile modification can have on mixed-layer regrowth in the model.

Another sensitivity test checked for the importance of k, the entrainment parameter. Using the initial conditions illustrated in Fig. 3, we performed model integrations for $k = 0.25$ and $k = 0.50$ for $\Gamma = 2$ K km^{-1}. Specific humidity was assumed constant above the mixed layer. With $k = 0.25$, the mixed layer became saturated in 4.3 h. For $k = 0.5$ saturation came after 3.5 h. Differences of the variables θ_v and q at 3.5 h for these calculations were small (0.03 K and 0.14 g kg^{-1}, respectively). Doubling the parameter caused the mixed layer to grow 75 m thicker and become saturated in 3.5 h despite the small difference in thermodynamic quantities between the two calculations. With the larger value of the entrainment parameter the mixed layer quickly achieved approximate height equilibrium. Thus, the entrainment at the mixed layer top diminished and

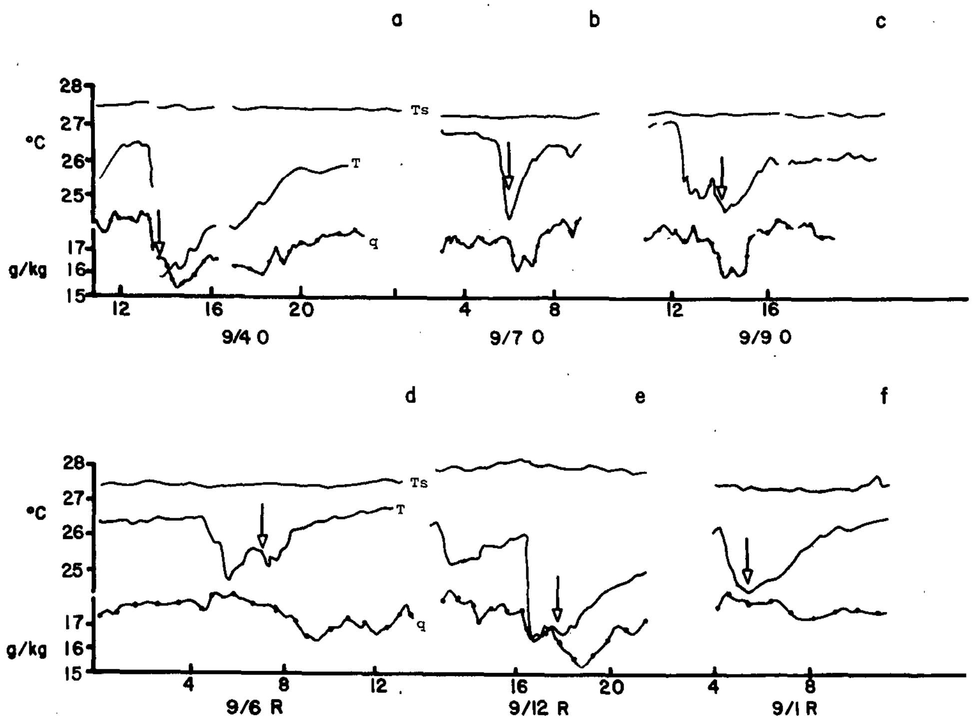

FIG. 4. Time series of boom sea surface temperature (T_s), air temperature (T) and specific humidity (q) during wake recovery periods at the *Researcher* (R) and the *Oceanographer* (O). The beginning of the recovery is marked by a vertical arrow.

allowed the layer to moisten. When $\Gamma_q \neq 0$, this does not necessarily result.

Any process that promoted rapid growth of the mixed layer in the model caused an initial drop in specific humidity. When the vertical advection of dry air is small enough (Γ_q or w small), any process that maintained a shallow mixed layer at an approximate equilibrium thickness made it moist. The model without the diabatic terms which could lead to cooling, cannot simulate periods of shallow, cool mixed layers which occur in the disturbed region prior to recovery as described by Fitzjarrald and Garstang (1981).

4. Comparison with observations

Observations used below are drawn from measurements made aboard the GATE ships *Dallas, Fay, Researcher* and *Oceanographer*. Findings cited from Brümmer (1978) also used measurements from the *Meteor* and *Planet*. Sensors mounted on a boom extending from the bow of the *Dallas, Oceanographer* and *Researcher* at 8–10 m above the sea surface provided a nearly continuous record of temperature, humidity and wind speed (Seguin *et al.*, 1977). A tethered balloon system on the *Dallas*, the BLIS, and a slow-rising radiosonde, the structure sonde, at the *Fay* provide good estimates of mixed-layer top heights. Details of the BLIS and of the observational array are described by Wylie and Ropelewski (1980) and Gaynor and Ropelewski (1979); Brümmer (1978) discussed the structure sonde. Conventional radiosondes were released every 3 h during the period of interest.

Hasse and Wuchnitz (1975), Zipser (1977) and others have drawn attention to the sharp and significant drop (often more than 3°C) in surface air temperature over the tropical oceans, coincident with the onset of a disturbance. A drop in specific humidity, usually not coincident with the temperature drop, is also observed. A lowering in mixed-layer height, temperature and specific humidity accompanies these surface changes (Fig. 2). Of particular interest in this paper is the recovery period which follows the minimum in surface air temperature.

Many examples of such temperature drops were observed in the boom temperature records in GATE. Six selected examples are shown in Fig. 4. The occurrence of the disturbance in each example is marked by the start of a sharp temperature drop. The beginning of the recovery period is taken from the point, marked with a bold arrow in Fig. 4, where the temperature begins to recover. In many instances this is a unique point, as in Figs. 4a, 4b and 4f. In other cases, where one "disturbed" situation is closely followed by another, the start of the recovery is delayed, as in Figs. 4c, 4d and 4e. We

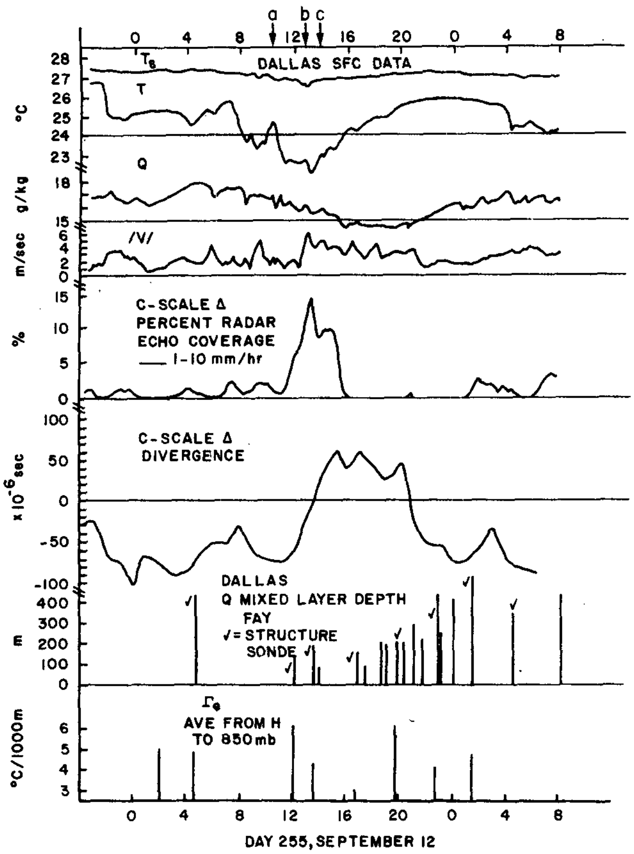

FIG. 5. Time series of boom and boundary-layer data for the squall line period of 12 and 13 September 1974 at the *Dallas*. Indicated along the top of the figure are (a) time the squall passed the *Dallas*, (b) beginning of the recovery period, and (c) the start of the model simulation. The depth of the mixed layer is represented by the height of the vertical column. A check mark next to the column indicates a *Fay* structure sonde, columns with no check marks are *Dallas* tethered balloon profiles.

wish to draw particular attention, in Fig. 4, to the behavior of the specific humidity compared to the behavior of the temperature in the recovery period. The specific humidity in nearly all instances (see especially Figs. 4d, 4e and 4f) continues to decrease after the recovery in temperature has begun. Drying may persist at the surface even when no strong subsidence exists above the mixed layer. This behavior implies continued drying of the near-surface air in the face of heat and water vapor transfer from the sea surface. The model (Fig. 2) shows a period of drying after the mixed layer begins to warm. Because the primary source of heat and water vapor is the ocean surface, it is plausible to assume that the initial cooling and subsequent drying extends through the entire mixed layer. Ample evidence exists in the literature already cited and observations presented earlier (Fig. 3) to support such an assumption.

On 12 September 1974 a well-defined squall line passed over the GATE C-scale ship triangle (an equilateral triangle 100 km on a side formed by the ships *Dallas, Meteor* and *Planet* in the center of the GATE ship array in Phase III, 30 August to 19 September 1974). Zipser (1977) discussed some aspects of this squall line. The squall line affected each of the C-scale triangle corner ships. Time series of the percent area of the C-scale triangle covered by radar echoes with an intensity equivalent to a rainfall rate of between 1 and 10 mm h^{-1}, surface divergence in the triangle (from B. Brümmer, personal communication) and surface variables observed at the *Dallas* (Fig. 5) show that heavy rainfall ended soon after 1500 GMT, although divergence of 5×10^{-5} s^{-1} in the triangle lasted until about 1800 GMT. Surface divergence was computed using a simple line integral method using observations from the ships *Meteor, Planet* and *Fay* at the corners of the C-triangle. The percentage of echo coverage of heavy rainfall (>10 mm h^{-1}) fell to zero shortly before surface divergence was observed. This was the longest period (8 h, from about 1300 to 2100 GMT, Fig. 5) of positive divergence in the surface layer during Phase III of GATE. This case was chosen not because it was typical but because the wake effects of the storm covered a large enough area that horizontal homogeneity (as assumption of the one-dimensional model) was approximated. That the areal extent of the wake was at least as large as the C-scale triangle was determined from the size of the radar echo area and from the measurements of depressed temperature, humidity and mixed layer height made at the three C-scale triangle corner ships.

Vertical profiles of horizontal divergence based upon the budget computations of Brümmer (1978) for periods before, during and after the surface divergence became positive (Fig. 6), showed that in

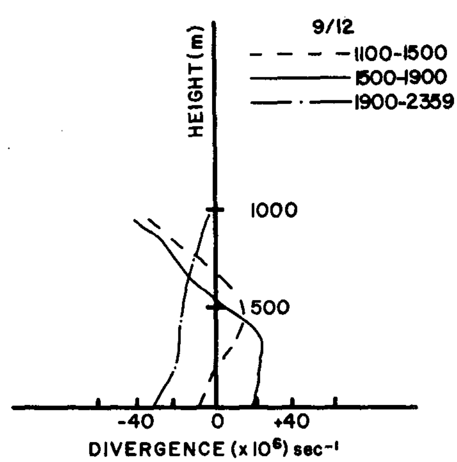

FIG. 6. Vertical profile of horizontal divergence in the C-scale triangle for selected periods on 12 September 1974 (Brümmer, personal communication).

the first 1000 m the positive divergence was confined to the lowest 500 m. The observed lapse rate of potential temperature in the region between 500 and 1000 m decreased slightly instead of increasing during the divergent period, consistent with confinement of the divergence to the lower layers. Mixed-layer heights from the *Fay* structure sondes and the *Dallas* and BLIS profiles in Figs. 5 and 7 show a very shallow (below 200 m before 1400 and at 100 m at 1330) mixed layer which grows to and remains near 200–300 m until the low-level flow becomes convergent at about 2100. The boom temperature began a monotonic increase, signalling the beginning of the recovery just after 1300 GMT. Specific humidity, on the other hand, showed a pronounced decrease between 1400 and 1600 and did not begin to increase until after 1900 GMT. The recovery period, which ended between 2200 and midnight on 12 September 1974, was probably prolonged by the low surface wind speed (3.5 m s^{-1}). *Dallas* boom data at 1350 GMT, some 50 min into the recovery period, served as initial conditions for the model. The simulation began at this point (marked c in Fig. 5) because this was the first time after the temperature minimum that representative values of H, q and θ_v could be specified with confidence.

Model predictions of the recovery of the mixed layer on 12 September 1974 are compared, in Fig. 7, to observations made at the *Dallas* and *Fay* on that day. Two time axes are shown in Fig. 7. The time of day to which the observations refer and the model run time both start near 1400 GMT. Horizontal divergence was assumed to be nonzero only within the mixed layer.

Subsidence at the top of the mixed layer was calculated from the divergence value. Although Brümmer's divergence profiles (Fig. 6) show convergence above the mixed layer in this period, observed changes in Γ above the mixed layer (Fig. 5) do not show the corresponding decrease that convergence would imply. The lapse rate of potential temperature was, in the absence of clear indications to the contrary and for simplicity, assumed to be constant above the mixed layer for the simulation.

The divergence in the mixed layer was allowed to change in two ways in the two model runs shown in Fig. 7:

1) In both model runs a divergence was chosen for the first 7 h followed by a convergence for the remaining 5 h of model run time. The divergence was allowed to change linearly to the observed convergence of -6×10^{-5} s^{-1} over a period of 2 h starting at hour 7 (2100).

2) The calculated divergence of 4×10^{-5} s^{-1} based upon observations in the surface layer was used in the first run shown in Fig. 7. In the second run, also shown in Fig. 7, a divergence (10^{-4} s^{-1}) which kept the model H close to the observed height of the mixed layer was used.

The initial rapid growth of the modeled mixed layer height from 100 m to near 300 m takes place in about 2 h (1400–1600 GMT). Model-predicted temperatures rise and specific humidities fall during this time. Model-predicted mixed-layer height reaches a constant level of ~300 m after the first 2 h of simulation. Potential temperature continues to rise and specific humidity, after the initial rapid drop, remains nearly constant. As divergence changes to convergence after 7 h (2100 GMT) the model-predicted mixed-layer height increases rapidly, but neither model-predicted temperature nor humidity show discernible responses to the change in divergence for the first run.

The model predictions, with a mixed-layer divergence of 4×10^{-5} s^{-1}, show a qualitative agreement with the observations of mixed-layer height, temperature and humidity (Fig. 7). Mixed-layer heights are overpredicted. The rapid growth of the mixed layer between 1400 and 1600 GMT cannot be unequivocably substantiated by the observation. A low mixed layer H is observed at 1330 (100 m) and a near-constant H is observed between 1800 and 2200 but noisy behavior is seen between 1400 and 1800. The pronounced decrease in model-predicted specific humidity over the first 2 h is, however, observed between 1400 and 1600 GMT coincident with the predicted rapid growth of H. The increase in model-predicted specific humidity from hour 2 (1600 GMT) is not observed. The observed specific humidity is somewhat noisy fluctuating about 14.6 g kg^{-1} between 1600 and 2000 GMT. At about 2000 GMT the observed specific humidity increases dramatically (much more so than the modeled value), coincident with the observed time of change from divergence to convergence in the mixed layer. The model predicts the sense of the change of the observed potential temperature but underestimates the magnitude of the temperature.

A model divergence of 10^{-4} s^{-1} [¶ 2) above] must be assumed, during the recovery period, to keep the model H close to the observed height. That the model divergence must be increased by a factor of 2.5 to agree with the data may indicate that the observed divergence calculated from the C-scale corner ships underestimated local conditions at the *Dallas*. Zipser (1977) places the C-scale triangle to the north of the center of the region of maximum intensity of this squall line, suggesting that there is a gradient in the subsidence over the triangle. The increased model divergence (10^{-4} s^{-1}) also keeps the specific humidity low longer than when the smaller value of divergence (4×10^{-5} s^{-1}) is

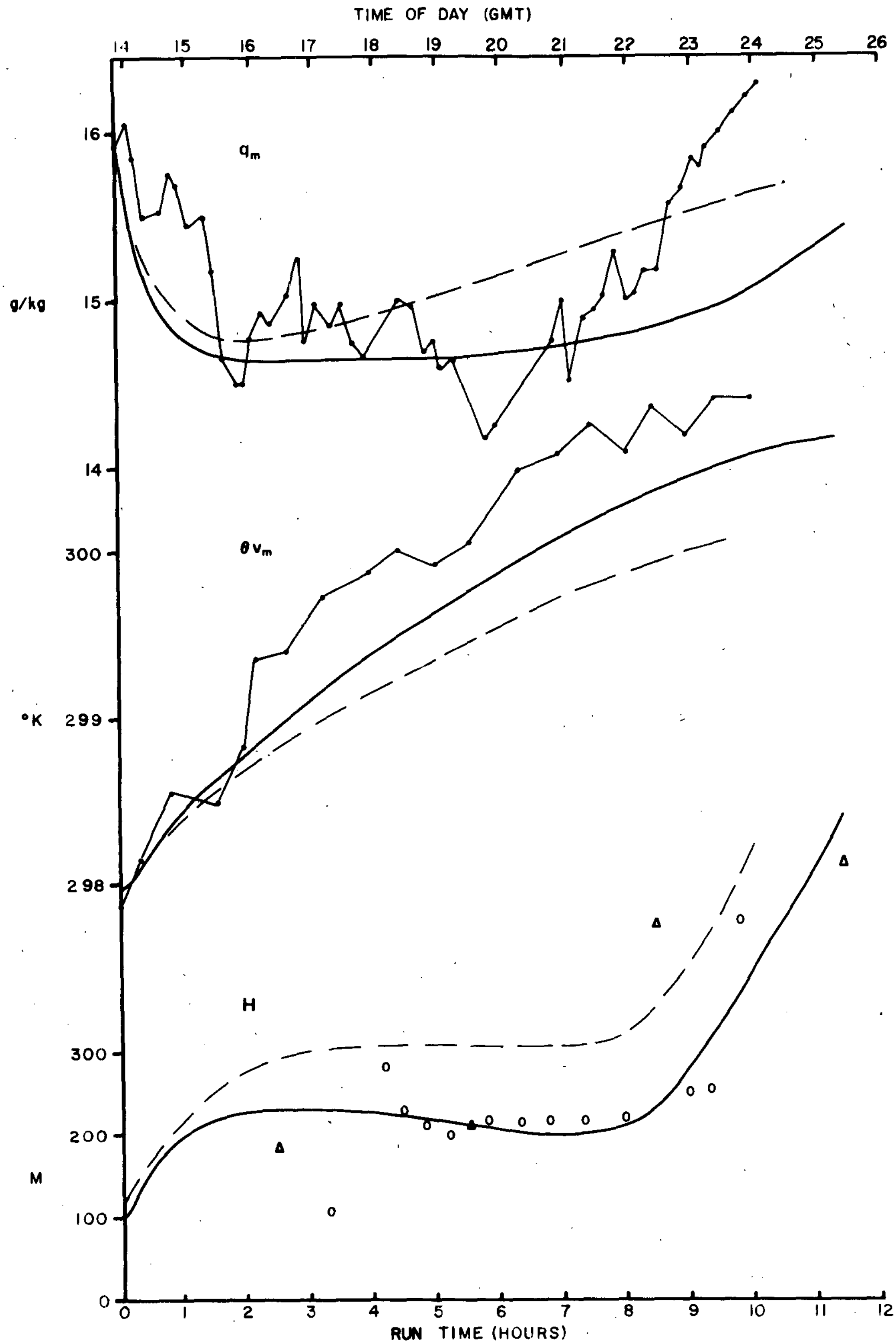

FIG. 7. Comparison of model predictions with the observed mixed layer recovery for the same situation as in Fig. 5. The simulation was begun at the time marked (c) in Fig. 5. Dashed lines indicate the solution using the observed surface divergence of 4×10^{-5} s^{-1} to determine subsidence; solid lines, model results with a divergence of 10^{-4} s^{-1}. Mixed-layer heights H from the structure sonde (triangles) and BLIS profiles (open circles) are shown. The model was initialized with observed thermodynamic values at 1350 GMT. Time in GMT and model run time are shown at the top and bottom of the figure. The ship boom measurements of specific humidity q_m and virtual potential temperature θ_m are shown by solid lines with closed circles.

used. Note that even with enhanced subsidence, the model does not warm the mixed layer as fast as the observations indicate. This may be because the boom temperature does not truly indicate the mixed-layer mean temperature. If the difference between the boom temperature and the mixed-layer mean temperature remained constant, the applicability of the model would not be greatly affected. However, the rapid change in the boom temperature may reflect changes in the surface layer structure relative to that of the mixed layer. It is also plausible that the entrainment parameter changes with mixed-layer depth and temperature. A larger value of the entrainment parameter for shallow mixed layers would be consistent with more rapid warming of the mixed layer in the initial stages of the recovery.

Specific humidity, under increased divergence, is closer to the observed specific humidity both in terms of behavior and in terms of magnitude. The rate of increase in observed specific humidity after 2000, however, is not matched by the model.

The above comparison between model predictions and observations suggests that at least two physical processes are at work in the recovery of the mixed layer in the wake of a disturbance. Neither the growth of the mixed layer nor the increase in temperature during the first 2 h of recovery permit the argument that the mixed-layer properties at this time are being controlled by direct incursions of cold, dry air from above the mixed layer. The direct incursions of cold, dry air from above the mixed layer in the form of convective downdrafts occurred prior to the start of the simulations and observations shown in Fig. 7. Such incursions resulted in the initial drop in temperature shown in Fig. 5 occurring well before the start of the model calculations. The model calculations were started *after* the lowest temperature in the surface air was reached. The specific humidity; while decreasing prior to the time of the lowest point in the temperature record, shows its most dramatic drop *after* the temperature reaches a minimum. We believe that the explanation of the rapid drop in specific humidity after the temperature has begun its recovery must be linked to the concurrent rapid growth of the mixed-layer height. If no further dry air is being supplied to the surface layer and if water vapor is being injected into this surface layer from the sea surface, then drying may be explained in terms of the rapid growth of the mixed layer, outstripping the supply of moisture at the surface. Transfer of dry air across the interface of the mixed layer and cloud layer by subsiding dry air is not ignored in this explanation. Such drying is manifested by the near-constant value of specific humidity after the initial growth of H and before mixed-layer convergence takes place. Once the initial rapid drying coincident with rapid mixed-layer growth ceases, vertical velocity (first in terms of subsidence, then in terms of upward motion), exercises control on the time rate of change of the specific humidity. Control through subsidence, which may be induced on a mesoscale by the convective system, has been postulated by Zipser (1977) and others. The observed rapid increase in specific humidity and the less rapid increase in model-predicted values after convergence in the surface layer occurs, support the argument that subsidence also plays a role in governing moisture and its time changes in the surface and mixed layers.

The long wake and slow recovery of the boundary layer described above were typical of the GATE area. The long-wake periods may have been due to relatively low wind speeds (3–5 m s^{-1}) observed in the equatorial trough location of GATE. This represents a distinctly different situation from that of the trades (wind speeds from 6–10 m s^{-1}). Long recovery periods probably do not occur in the trades.

5. Conclusions

The simple one-dimensional mixed-layer model worked reasonably well when simulations of mixed-layer temperature and specific humidity and mixed-layer depth were compared against observations over the tropical ocean. The initial drop in specific humidity often observed at 8 m above the warm ocean was a stricter test of the model than the warming and increase in depth of the mixed layer alone.

The model studies presented here show that observed low-level thermodynamic changes were strongly related to the growth of the boundary layer. Changes in the mixed-layer depth must be considered when surface layer time series are interpreted. The recovery time of the mixed layer in the wake of a storm was shown to be coupled to the wind speed (via surface fluxes of moisture and heat).

We can hypothesize that the thermodynamic recovery of the boundary layer and the reestablishment of convective activity is closely related to the dynamics of the low-level flow. It is clear that in the low surface wind speed regions which are perhaps typical of the equatorial trough regions, boundary layer recovery can be protracted and by inference cover a large area. In such an area during this time, convective cloud systems may not be able to develop even in the presence of large-scale forcing or unless large-scale forcing changes significantly. The limitation on the development of new moist convection would impose a space and time modulation on synoptic-scale systems which may be crucial to the intensification or even survival of the synoptic-scale entity.

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