GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 16, PAGES 2557-2560, AUGUST 15, 2000

Cloud transitions and decoupling in shear-free stratocumulus-topped boundary layers.

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Abstract. Large-eddy simulations of shear-free stratocumulus-topped layers tend strongly toward a two-layer structure as the negative area in the buoyancy flux profile that would be necessary to maintain a mixed layer increases to more than 10% of the positive area. In addition to identifying a threshold for what amounts to a convective transition, the simulations provide further evidence that a commonly used entrainment closure is ill-founded. Lastly the simulations demonstrate that attempts to formulate a similarity theory for convective layers must account for the geometry of the buoyancy-flux profile, and not simply its integral.

Introduction

In attempting to understand the dynamics of the stratocumulus-topped planetary boundary layer (hereafter the STBL), an interesting (and important) question that arises is under what conditions does the STBL decouple from the surface. While the actual term "decoupling" enjoys varied usages in the literature, here we use it in its weakest sense, namely in the sense of it being associated with an initially well-mixed STBL, which despite being strongly forced in some integral sense, tends toward a two-layer structure. For the sake of simplicity our discussion will be further limited to non-precipitating cloud layers with any net radiative flux divergence confined to a vanishingly thin region near cloud top, as is characteristic of nocturnal stratocumulus.

Interest in decoupling in this sense is motivated by simulations [*Krueger et al.*, 1995] and observations [*De Roode and Duynkerke*, 1997] that show that the tendency toward a two-layer STBL is the first phase of the climatologically important stratocumulus to trade-cumulus transition. The simulations further indicate that a sufficient condition both for the decoupling and the transition is the advection of the STBL over warmer water. This implied relationship between increasing SSTs and decoupling is supported by prior work [*Lewellen et al.*, 1996] that shows decoupling to be favored as moisture fluxes become more dominant. These results have been organized into a coherent theory [*Bretherton and Wyant*, 1997] that essentially argues that enhanced cloud buoyancy fluxes must develop in response to increasing surface latent-heat fluxes.

The basic argument has two parts. First, mixed-layer theory demands that if increased turbulence production by buoyancy leads to increasing entrainment warming, as surface latent-heat fluxes increasingly dominate the energetics the cloud-base buoyancy fluxes must become negative (and then increasingly so) to maintain a mixed layer. Second, it is hypothesized that (for given boundary forcings) if the cloud-base buoyancy fluxes necessary to maintain a well mixed layer become too negative, the layer will decouple. Physically the critical hypothesis is that there is a limit to the amount of heat originating from entrainment that can be mixed through the cloud layer into the subcloud layer. Attempts to mix more heat into the subcloud layer will result in decoupling, wherein the cloud layer warms relative to the subcloud layer.

To be quantitative the buoyancy-flux integral ratio ($\mathcal{R}$) is introduced [*Turton and Nicholls*, 1987] and decoupling is associated with values of $\mathcal{R}$ greater than some critical value $\mathcal{R}_{crit}$. In mathematical terms, if we denote the flux (in kinematic units) of some scalar ϕ by F_ϕ, the flux necessary to maintain a mixed layer by $\tilde{F}_\phi$, the depth of the mixed layer by z_i, and the Heaviside function by $\mathcal{H}$ then,

$$\mathcal{R} \equiv -\frac{\int_0^{z_i} \tilde{F}_{\theta_v} \mathcal{H}(-\tilde{F}_{\theta_v}) dz}{\int_0^{z_i} \tilde{F}_{\theta_v} \mathcal{H}(\tilde{F}_{\theta_v}) dz}, \tag{1}$$

where θ_v (the virtual potential temperature) is essentially a buoyancy temperature. Low-resolution two-dimensional simulations [*Bretherton and Wyant*, 1997] suggest that the threshold $\mathcal{R}_{crit} = 0.4$ for decoupling [*Turton and Nicholls*, 1987] is too large, and that $\mathcal{R}_{crit} = 0.15$ is more appropriate.

The fundamental question posed by the previous work is how the internal structure of the STBL varies with $\mathcal{R}$. In mixed-layer theory the θ_v fluxes appearing in (1) can be linearly related to fluxes of materially conserved (following reversible moist-adiabats) variables such as liquid-water potential temperature (θ_l) and total-water mixing ratio (q_t)

$$\tilde{F}_{\theta_v}(z) \approx \alpha \tilde{F}_{\theta_l}(z) + \beta \tilde{F}_{q_t}(z) \tag{2}$$

where α is dimensionless and β has thermal units. Because $\psi \in \{\theta_l, q_t\}$ is materially conserved, mixed-layer theory requires that $\tilde{F}_\psi$ be a linear interpolation of its boundary values, i.e., $\tilde{F}_\psi(z) = F_\psi(0)(1 - z/z_i) + F_\psi(0)(z/z_i)$. (The linearity of F_ψ is important because it means that the flux-divergence is constant, hence $\psi(z)$ changes uniformly with height, i.e., an initially well mixed layer will remain well mixed.) Consequently our question is equivalently posed by asking how boundary fluxes of F_ψ affect circulations in the STBL.

Although our primary contribution is to answer this question using idealized three-dimensional numerical simulations with relatively high resolution (i.e., a factor of 2-5 higher than the previous two-dimensional simulations), some insight into the problem can be gained solely on the basis of theoretical considerations. The distinguishing feature of the STBL (compared to dry convective layers) is that α and

Paper number 1999GL011257.
0094-8276/00/1999GL011257$05.00

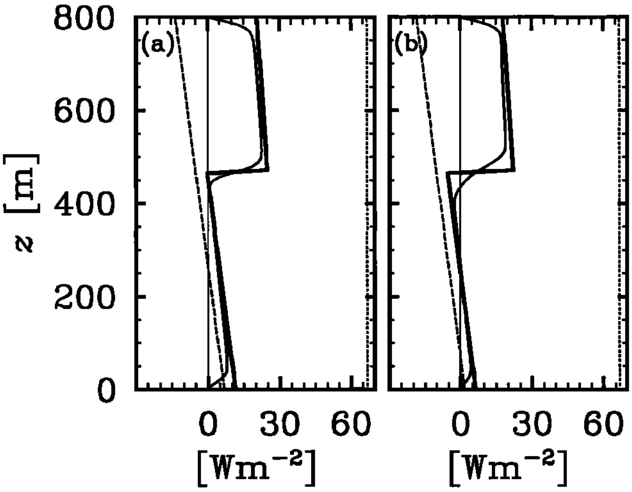

Figure 1. $\tilde{F}_{\theta_v}$ (thick solid) as a function of the $\tilde{F}_{\theta_l}$ (dashed) and $\tilde{F}_{q_t}$ (dotted lines on far right of each panel). Panel (a) $\mathcal{R} \approx 0$; (b) $\mathcal{R} \approx 8\%$. Also shown for reference are profiles of LES-derived resolved F_{θ_v}.

β in (2) vary discontinuously across boundaries separating saturated and unsaturated air,

$$\alpha = 0.53\,\mathcal{H}(\chi) + 1.01\,\mathcal{H}(-\chi) \quad (3)$$

$$\beta = 1032\,\mathcal{H}(\chi) + 175.1\,\mathcal{H}(-\chi). \quad (4)$$

here χ is the saturation deficit, $\chi \equiv q_t - q_s$ (where q_s is the saturation mixing ratio), and the Heaviside function $\mathcal{H}(\chi)$ is used to select between the saturated and unsaturated forms. Although the actual numeric values of α and β have a weak dependence on the thermodynamic state of the atmosphere, the values we quote are written as constant and are typical for the conditions we investigate (i.e., a basic state of $\Theta_l = 288$ K, $Q_t = 8.5$ g kg^{-1}). In Figure 1, Eqs. 2-4 are illustrated graphically for two different $\tilde{F}_{\theta_l}$ profiles. A striking feature for both cases is the sharp change in $\tilde{F}_{\theta_v}$ across cloud base (at ≈ 475m). As has been previously emphasized [*Bretherton and Wyant*, 1997] the magnitude of this jump follows immediately from Eqs. 2-4:

$$\Delta\tilde{F}_{\theta_v} \approx -0.48\tilde{F}_{\theta_l} + 856.9\tilde{F}_{q_t}. \quad (5)$$

This relationship is the basis for the contention that over the World Ocean F_{q_t} is very important in determining the buoyancy flux in stratiform clouds — indeed for the buoyancy-driven STBL $F_{q_t} > 0$ is a necessary condition for F_{θ_v} to change sign at cloud base.

As has previously been discussed [*Nicholls*, 1984], for the climatologically interesting case of air moving over warmer water $\mathcal{R}$ can only be less than zero if entrainment warming is sufficiently strong to offset cloud-top radiative cooling, thereby allowing the buoyancy fluxes just below cloud base (where they are largely determined by the F_{θ_l} profile) to be negative. In this case $\mathcal{R} > 0$ can be seen as an indication that the dominant source of turbulence is due to surface moisture fluxes rather than cloud-top radiative cooling. And so decoupling over warmer water, if it correlates with decreasing $\mathcal{R}$, should be seen as a manifestation of the changing energetics of the STBL. Furthermore, *when and if* this change occurs is essentially determined by how efficiently the STBL entrains warm and dry air from aloft.

Table 1. Overview of simulations

Name	$\rho c F_{\theta_l}(0)$	$\rho c F_{\theta_l}(z_i)$	$\mathcal{R}$ [%]	$\tilde{w}_*$ [ms^{-1}][a]
R00	11.6	-5.8	0	1.03
R03	2.9	-14.5	3	0.85
R08	1.50	-16.0	8	0.81
R14	0.00	-17.3	14	0.76

[a]Here w_* is the value implied by a mixed layer model given the specified boundary forcings.

Calculations

Our goal is to explore decoupling, and its relationship to $\mathcal{R}$ by using large-eddy simulation in a very simple context. Although in real clouds the fluxes at the upper boundary of the STBL (and hence $\mathcal{R}$) are selected by the flow itself, by considering simulations of flows bounded above and below by flat plates with specified boundary fluxes we can simplify the problem considerably and study how given changes in $\mathcal{R}$ affect the flow, independently of how the flow modifies the cloud-top fluxes. By specifying $F_{q_t}(0) = F_{q_t}(z_i)$ (no layer-mean moisture-flux divergence) and requiring $\Delta F_{\theta_l} = F_{\theta_l}(0) - F_{\theta_l}(z_i)$ to be near zero (although to produce a positive surface buoyancy flux yet maintain $\mathcal{R} > 0$ requires $\Delta F_{\theta_l} > 0$) we can help minimize the evolution of the mean state. This simplifies things by minimizing the effect of the additional timescale (associated with the mean forcing) on the problem. By varying $F_{\theta_l}(0)$ with a specified ΔF_{θ_l} (e.g., Fig. 1) a series of simulations with varying $\mathcal{R}$ can be constructed.

The simulations are performed using the flow solver thoroughly discussed elsewhere [*Stevens et al.*, 1999]. It is based on a finite-difference representation of the flow and has been configured to have periodic horizontal boundary conditions and rigid lids bounding the turbulent flow from above and below. Unless otherwise stated all calculations use a Smagorinsky sub-grid-scale (SGS) model (without any stability corrections); free-slip upper, and no-slip lower, boundary conditions for momentum; and constant-flux boundary conditions for scalars. The basic grid configuration uses a $96 \times 96 \times 100$ point net with $\Delta x = \Delta y = 2.5\Delta z = 20$ m. Initial conditions correspond to the basic state (given above) with a surface pressure of 1000 hPa, and a constant density of 1.156 gm^{-3}. Unless otherwise indicated, integrations are carried out for 14400 simulated seconds and the analysis is based on flow snapshots taken every 30s for the last 5400s. (A typical eddy turn-over time τ is 750-1000s.)

We have performed a large number of simulations, however our main points can be made by focusing on only the small subset summarized with the help of Table 1 and Figure 2. This subset illustrates that some degree of decoupling becomes evident for any $\mathcal{R} > 0$ and that the degree of decoupling as measured by the development of scalar gradients, or the damping of the resolved vertical-velocity variance (F_w), increases with $\mathcal{R}$. Although $\theta_l(z)$ is the only scalar profile presented, all simulations include the Wyngaard scalars (i.e., perfect top-down and bottom-up scalars [*Wyngaard and Brost*, 1984]), as well as a total water mixing ratio variable. Cloud-base gradients in these variables (scaled in accord with their fluxes) mirror those shown for θ_l.

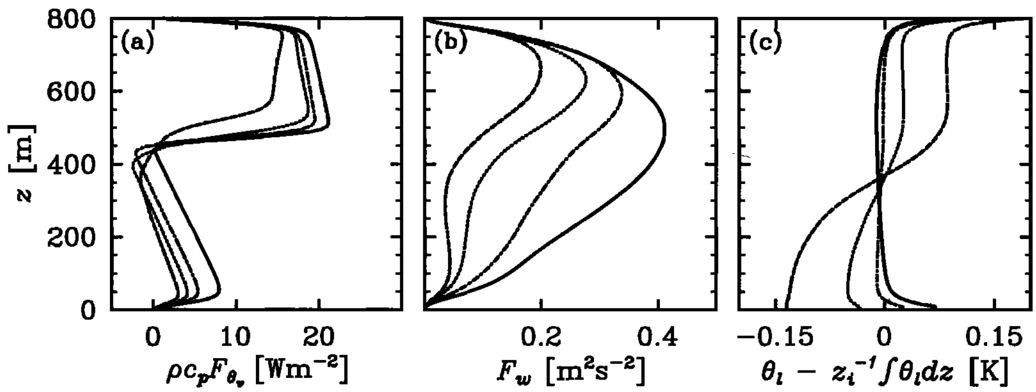

Figure 2. Resolved buoyancy fluxes (a), note the resolved fluxes go to zero near the boundaries as the near boundary flux is carried by the SGS term; resolved vertical velocity variances (b); and θ_l deviation profiles for simulations R0 (solid), R3 (dash-dot), R8 (dotted), and R14 (dash).

Averaged over the period of the analysis fluxes of all materially conserved scalars are linear functions of height in all simulations except R14. In this latter simulation cloud-base scalar gradients are increasing functions of time (and have not equilibrated even after an additional 7200s of simulation time); as a result Fig. 2 underestimates the degree of decoupling in this case. Thus decoupling as measured by the strength of scalar gradients increases nonlinearly with $\mathcal{R}$, thereby warranting identification of a threshold $\mathcal{R}_{crit}$ of between 10 and 15%. Further analysis of simulation R14 indicates that by the time of the analysis thermal gradients had sufficiently differentiated the cloud and sub-cloud layer to allow the formation of a well-defined cumulus layer, in which cloud fractions are approximately constant at around 5% in a layer of approximately 100-150m thick, under the stratocumulus layer. Hence the simulated decoupling is also associated with a cloud transition.

Regarding the velocity statistics, an absolute minimum in $F_w(z)$ becomes apparent for simulation R14. We have performed additional simulations where buoyancy generation in the sub-cloud layer relative to the cloud layer is not as dominant, and in such situations the cloud-base minimum in F_w becomes even more pronounced. While there is a clear qualitative relationship between the shapes of $F_w(z)$ and $F_{\theta_v}(z)$, the mere fact that the $F_w(z)$ profile takes on different shapes clearly demonstrates that it can not be collapsed to a universal form using a scalar functional of the buoyancy flux, i.e., a w_*, (where $w_*^3 = 2.5(g/\Theta)\int F_{\theta_v}(z)dz$). Further analysis indicates that $\int_0^{z_i} F_w(z)dz$ also does not scale with w_* alone.

In an effort to further asses the robustness of our results a series of further simulations was initiated. First the effect of the rather limited aspect ratio (5:2) or the domain was also investigated by considering simulations of case R08 with twice the aspect ratio (5:1), but the same grid spacing (i.e., we doubled the number of points in each of the horizontal directions). Second we evaluated the effect of different velocity boundary conditions on the upper and lower boundaries, and third we evaluated the sensitivity of the results to the SGS model (by considering calculations with a constant eddy diffusivity model, and by considering calculations with the Smagorinsky-Lilly model [*Lilly*, 1962]). These tests indicated that our findings are not significantly affected by either the limited domain, the choice of velocity boundary conditions, or the specific form of the SGS model.

Yet further tests were made to see whether the tendency toward decoupling as a function of $\mathcal{R}$ was simply an artifact of our chosen boundary conditions. Our preliminary analysis of a sequence of similar simulations, but with both relatively more buoyancy production and consumption, indicates that the primary sensitivity is to the value of $\mathcal{R}$ and that given some minimal amount of turbulent-kinetic-energy production the net production is not a primary factor in the tendency toward decoupling in the shear-free STBL.

Conclusions

In summary we have shown that the shear-free STBL is unable to remain well mixed for $\mathcal{R} > 0$ and that there is a pronounced development of a two layer structure for $\mathcal{R} > 10$ %. In mixed layer theory the entrainment flux is often specified as that necessary to maintain $\mathcal{R}$ at a certain value (typically 20%) [*Schubert*, 1976; *Kraus and Schaller*, 1978]. Our results indicate that such an approach is not warranted; demanding such large values of $\mathcal{R}$ is incompatible with the maintenance of a mixed layer.

Our results also provide a rational basis for distinguishing between convective regimes in parameterizations of the STBL. For instance in GCMs (such as the unified model of the UKMO) in which different boundary layer regimes are identified and then modeled in a way peculiar to their respective dynamics, the use of $\mathcal{R} \approx 10$ % appears to be a rational basis for distinguishing well-mixed stratocumulus regimes from cumulus-coupled, or cumulus-under-stratocumulus regimes.

Lastly our results emphasize that mixed-layer (w_*) scaling is not broadly applicable, but rather is an artifact of universality in the buoyancy flux profile in the convective boundary layer. Efforts to develop a similarity theory valid for the STBL must account for the varied geometry of the buoyancy flux profiles in such layers.

Acknowledgments. This project was initiated while the author was visiting the Max Planck Institute für Meteorologie courtesy of a fellowship from the Alexander von Humboldt Foundation. The Foundation and the Institute are both thanked for their support and hospitality. Support was also provided by NSF Grant ATM-9985413. Constructive comments by C-H. Moeng, C. Bretherton and S. Krueger also improved the manuscript.

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(Received November 22, 1999; revised June 6, 2000; accepted June 14, 2000.)