11.1 WHAT CONTROLS THE CLIMATOLOGICAL DEPTH OF THE PBL?

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1. INTRODUCTION

An understanding of both the vertical structure of the atmosphere and the mechanisms underlying the exchanges of heat, water, and momentum between the surface and free atmosphere requires detailed knowledge of the dynamics of the planetary boundary layer (PBL). In this study we address two fundamental questions about the PBL: (i) what controls its climatological mean depth and (ii) how is the mean depth modulated by the diurnal cycle?

The answers to these questions are not only important for those interested in boudary layer dynamics, but for a wide range of specialties. Understanding the depth of the PBL is important because it enters as leading order in most simple or bulk representations of PBL processes (e.g., Stevens et al. 2002; Lindzen and Nigam 1987). The role of the diurnal cycle is critical because it rectifies surface exchange processes (cf., Denning and Randall 1996).

To explore these questions, results from two 10-year simulations using the UCLA general circulation model (GCM) are analyzed. This GCM is fairly unique in that it explicitly tracks the evolution of the PBL depth, h, which it treats as a coordinate surface. This significantly simplifies analysis of the PBL by eliminating ambiguity involved in defining the PBL and by generating variables that characterize PBL processes.

An interest in the climatological effects of the diurnal cycle initially motivated the two simulations. One experiment has diurnal variations in solar insolation while the other does not. Preliminary analysis made it apparent that in order to fully appreciate the climatic role of the diurnal cycle, an understanding of processes that regulate h must be achieved. The simulations show that the presence of the diurnal cycle reduces h over tropical continents and mid-latitudes during summer, but has little effect on h over the oceans and mid- to high latitudes during the remainder of the year. Diurnal variations of solar insolation have a profound effect on ground temperature, which in turn directly affects h. Under normal circumstances, the PBL rarely reaches its equilibrium depth for significant periods of time, but by eliminating the diurnal cycle, heat fluxes from the surface can be considered relatively constant, allowing the PBL to reach an equilibrium depth. This simplifies analyses of the physical processes involved in building the PBL.

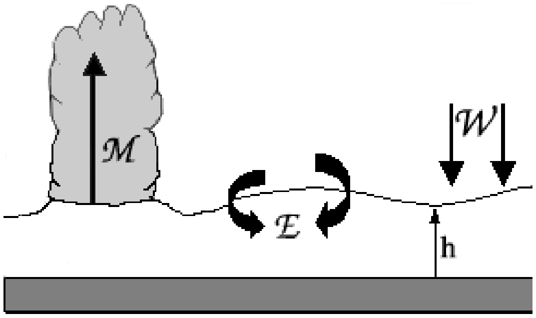

Figure 1: Schematic representation of physical processes which determine the PBL depth, h. These processes are cumulus mass flux, $\mathcal{M}$, entrainment of free tropospheric air, $\mathcal{E}$, and effects of large-scale vertical motion, $\mathcal{W}$. See text for detailed description.

2. ESTIMATING h

The physical processes involved in determining the depth of the PBL in the equilibrium scenario are conceptually simple. Figure 1 shows a schematic representation of these processes in terms of their physical manifestations. These are essentially the terms in the mass budget equation,

$$\frac{\partial h}{\partial t} + \mathbf{u} \cdot \nabla h = \mathcal{W} + \mathcal{E} - \mathcal{M} \qquad (1)$$

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The GCM uses (1) to calculate the height of the PBL, h (Suarez et al. 1983). The locally generated terms are the cumulus mass flux, $\mathcal{M}$ and the entrainment, $\mathcal{E}$. The cumulus mass flux is a loss process in the PBL; when cumulus convection is triggered, the convective motion removes mass from the PBL by building cumulus clouds which rise out of the PBL into the free troposphere. Entrainment, on the other hand, is generally a source term. The PBL grows due to heating at the surface, creating a layer of warm, well-mixed air which mixes down even warmer air from aloft, increasing the mass and thus the depth of the PBL. These diabatic processes are balanced by the adiabatic compression of the PBL by the large-scale vertical velocity, $\mathcal{W}$.

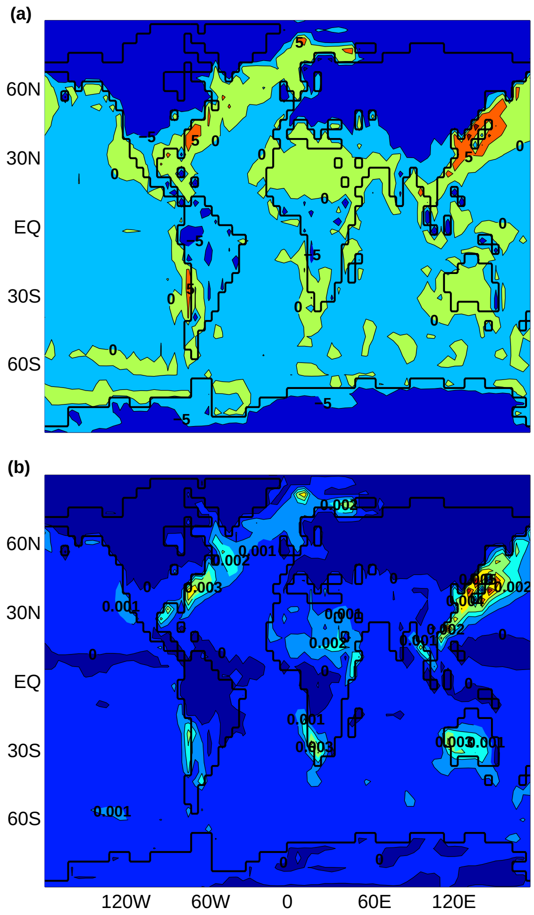

Figure 2: (a) The entrainment (mb/hr) as calculated by the GCM. (b) The local bouyancy fluxes as determined by (3) for DJF. Note the similarities in relative magnitude, especially pronounced in the mid- to high latitudes. An analogous relationship exists for the other seasons.

Not immediately obvious in (1) is that knowledge of $\mathcal{E}$, $\mathcal{M}$, and $\mathcal{W}$ is not enough to fully describe the climatological mean of h. For instance, consider the stationary homogeneous limit in which LHS of (1) vanishes. If $\mathcal{W}$ is significant, by making the substitution $\mathcal{W} = \mathcal{D}h$, where $\mathcal{D}$ is the large-scale divergence, one can simply solve for the mean depth, $\overline{h}$

$$\overline{h} = \overline{\left(\frac{\mathcal{E}-\mathcal{M}}{\mathcal{D}}\right)} \tag{2}$$

The quantity on the right hand side of (2), when expanded, contains covariances, $\overline{\mathcal{E}'\mathcal{D}'}$ and $\overline{\mathcal{M}'\mathcal{D}'}$, which may be important terms in determining $\overline{h}$.

To investigate the relative strength of these mechanisms, we turn to the results of the 10-year GCM simulation in which the diurnal cycle has been eliminated. In this scenario, the daily solar insolation at all grid points remains unchanged from normal, but is spread evenly over all 24 hours of the day. The resulting world would experience something akin to perpetual twilight. This eliminates the diurnal variations in variables like h. Without a diurnal signal obfuscating the relationship between the three mass budget terms, comparisons of the three mechanisms responsible for the mean climatological PBL depth become more straight forward.

The analysis suggests that the local mechanisms (i.e. $\mathcal{M}$ and $\mathcal{E}$) are the dominant processes involved in determining the boundary layer depth for most of the globe.

The entrainment term can be understood in terms of locally generated buoyancy fluxes. These fluxes are created by the sensible and latent heat fluxes from the surface and the top of the PBL. Equation (3) shows the scheme used to calculate the buoyancy fluxes from the heat fluxes.

$$\overline{w'b'} = \frac{g}{\rho}\left(\frac{0.608\mathcal{L}}{L_v} + \frac{\mathcal{S}}{c_pT_g} + \frac{\mathcal{J}}{c_pT_g}\right) \tag{3}$$

Here $\overline{w'b'}$ is buoyancy flux, ρ is the density of air, c_p is the isobaric specific heat of the surface, L_v is the latent heat of vaporization, T_g is the ground temperature, $\mathcal{L}$ is the surface latent heat flux, $\mathcal{S}$ is the surface sensible heat flux, and $\mathcal{J}$ is the long-wave cooling jump at the top of the PBL.

Using (3), a map of buoyancy can be generated. Comparing this map to the entrainment variable that is produced by the model(Figure 2), it is apparent that they are intimately linked, as is expected. Where entrainment is large, there is a large buoyancy flux. The buoyancy flux indicates that air is moving vertically through the boundary layer and mixing with free tropospheric air, thus forming a deep PBL. The entrainment term in the mass budget is the dominant term over most of the mid- to high latitudes in the absence of the diurnal cycle (Figure 3). Over the continents in winter, for example,

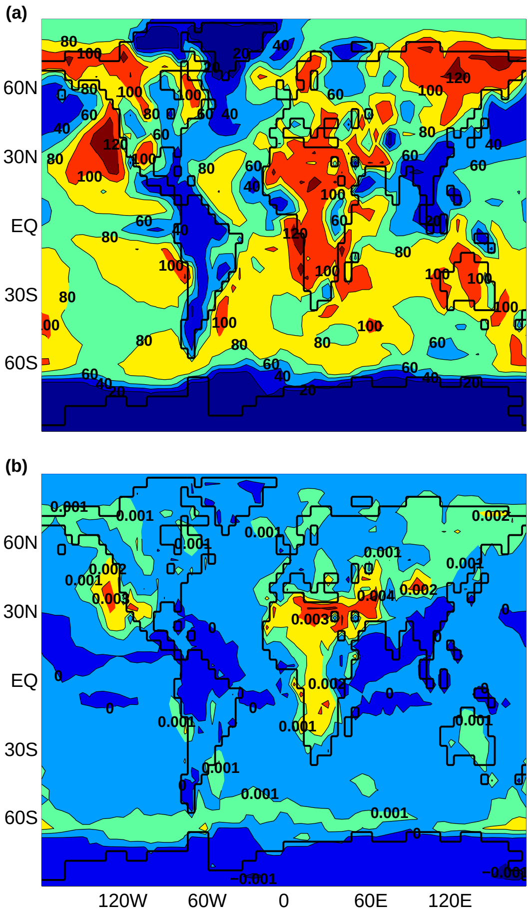

Figure 3: PBL depth and locally generated buoyancy fluxes. (a) PBL depth (mb) as determined by the GCM for JJA. (b) The buoyancy flux as determined by (3) for JJA. Local buoyancy appears to be the dominant mechanism in establishing PBL depth for most areas in the mid- to high latitudes. In the tropics, the relative contributions of E, M, and W are more complex. Simliar relationships exist during the rest of the year.

the frigid surface extracts heat from the boundary layer, so locally generated buoyancy is exceedingly small or even negative, producing a minimal PBL. Over the oceans in winter, cold air advected over the warm sea surface creates a large buoyancy flux resulting in a deep PBL. The buoyancy flux generated by the longwave cooling at the top of the PBL can account for much of the geographical variation in the PBL depth over subtropical regions where stratus clouds are climatologically persistent.

In the tropics, buoyancy becomes less dominant due to the relative strength of cumulus mass flux and large-scale vertical motions. This regime change is clear over areas like the Congo Basin, where a large cumulus mass flux acts to create a shallow PBL depth.

When the diurnal cycle is restored, PBL depth is dramatically reduced over continental regions where the land surface is significantly warmer than the PBL during the daytime and significantly colder at night. The ground slowly warms during the morning in these regions, so buoyancy fluxes are initially small. When the sun sets and the ground begins to cool, a layer of cool, dense air forms near the surface, quickly destroying the PBL that had formed. This cycle of slow growth and rapid decay lead to a much shallower PBL over these regions. A simple model of the PBL shows that this diurnal cycle in PBL depth is the expected result where large variations occur in ground temperature. Where the surface temperature lacks strong diurnal variability, there is little difference between the two simulations, so the terms in the mass budget equation are the significant factors controlling the climatological mean PBL depth.

3. SUMMARY

Two 10-year simulations using the UCLA GCM are analyzed in an attempt to better understand the climatological mean depth of the PBL and the modulation of the depth by the diurnal cycle. Comparing the two simulations, the results show that the presence of the diurnal cycle dramatically reduces the mean PBL depth over tropical continents and mid-latitudes during the summer. A simple model of the diurnal evolution of the PBL demonstrates that this is the expected result for continental regions. The two simulations produce very similar results over the oceans and in mid- to high latitudes during the rest of the year. Where the diurnal cycle is not a significant factor, the terms in the mass budget given by (1) are the only mechanisms controlling the PBL depth. Analysis of the simulation without the diurnal cycle shows that locally generated buoyancy, which is essentially the entrainment term in (1), is the dominant process for mid- to high latitudes. Cumulus mass flux and large-scale divergence become significant in the tropics.

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