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The Sensitivity of Large-Scale Models to Boundary-Layer Parameterization

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Recent studies have demonstrated, through numerical experiments, the sensitivity of general circulation models to certain aspects of boundary layer parameterization. Specifically, these studies have emphasized the effects of clouds, vegetation, and subgrid-scale terrain, as well as the question of how a PBL of highly variable depth can be represented in a model of limited vertical resolution.

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**SYMPOSIUM ON BOUNDARY-LAYER PARAMETERISATION
AND LARGER-SCALE MODELS**

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1. INTRODUCTION

An excellent and extensive summary of the state of planetary boundary-layer (PBL) parameterizations for large-scale models was prepared by Carson (1981); the current brief review will describe some developments since that time. Emphasis will be on the role of the PBL parameterizations in general circulation models (GCMs).

We begin by asking a very practical question: What is the role of the PBL parameterization, from the point of view of the large-scale modeler? Although the atmospheric general circulation is ultimately driven by solar radiation, most of the solar energy absorbed by the earth is deposited in the oceans. This energy becomes available for conversion into the kinetic energy of large-scale atmospheric motions only after it has been removed from the sea surface, primarily through turbulent fluxes of latent and sensible heat that are produced by the eddies of the PBL. In this way, the PBL acts as a *valve* that controls the energy and momentum exchanges between the atmosphere and the Earth's surface. The setting on the valve is determined by the surface transfer coefficients and the wind speed.

The turbulent fluxes must be determined not only at the Earth's surface, but throughout the depth filled by the PBL turbulence. This PBL depth is highly variable in space and time, and represents a *reservoir* of air that has been charged with surface properties. The amount of mass contained in the PBL determines the "inertia" of the layer. For example, a given upward surface sensible heat flux can rapidly increase the temperature of a shallow PBL, while the same flux will warm a deep PBL more slowly. Since a warming of the PBL tends to reduce the surface flux, what actually happens is that a shallow PBL normally has weak surface fluxes, while a deep PBL can have much stronger fluxes.

We have concluded, then, that the PBL acts as both a valve and a reservoir. It regulates the fluxes of surface properties across the Earth's surface, and at the same time stores these properties for eventual release into the free atmosphere.

Micrometeorologists have justifiably expended great efforts to discover and empirically document "similarity laws" for the surface transfer coefficients and also for the fluxes in the PBL interior (e.g., Monin and Yaglom, 1971). GCMs do exhibit sensitivity to these coefficients (see, e.g., the references discussed by Carson, 1981; Miyakoda *et al.*, 1983; also, C. Blondin, personal communication, 1989). The surface roughness distribution has been shown to play a role in the climatology of deserts (Sud and Smith, 1985).

Recent GCM studies have tended to focus, however, on aspects of the PBL parameterization that are not closely related to the surface transfer coefficients. Specifically, they have emphasized the effects of clouds, vegetation, and subgrid-scale terrain, as well as the question of how to incorporate a PBL of highly variable depth into a GCM with limited vertical resolution.

2. CLOUDS

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A deep PBL is favorable for cloud formation, since it allows moisture evaporated from the surface to penetrate to higher levels in the troposphere. Boundary-layer clouds are of major climatic importance because they tend to cool the earth radiatively by reflecting solar radiation back to space without producing any compensating large changes in the outgoing longwave radiation. Key boundary-layer cloud types include both stratus/stratocumulus clouds with large cloud fractions, and shallow cumuli with much smaller cloud fractions. Besides their radiative effects, these clouds tend to cause a deepening of the PBL, which has the effect of maintaining a relatively deep moist layer. This has important consequences for infrared radiative transfer, and it also represents a copious fuel supply for deep moist convection. Studies emphasizing the importance of these shallow boundary-layer clouds have been presented by Randall *et al.* (1985) and Tiedke (1985).

The PBL also serves as the source of the air that rises into the deep cumulus clouds that provide the main heat source for the general circulation of the atmosphere. These deep clouds tend to reduce by depth of the PBL by draining away its mass. A GCM experiment indicating substantial climate sensitivity to this convective sink of PBL mass was reported by Randall *et al.* (1985). Deep convective clouds can also inject mass into the PBL in the form of convective downdrafts. The downdraft-injections usually consist of dry, cool air, and can be accompanied by locally gusty winds and so they tend to lead to enhanced surface fluxes (e.g., Johnson, 1976). Efforts are under way to incorporate these effects into GCMs (e.g., A. Arakawa, personal communication, 1989), but there is little to report in the way of results at this time.

3. VEGETATION

Major efforts have been expended to incorporate into GCMs realistic parameterizations of the effects of land-surface vegetation on PBL processes, and especially on evapotranspiration (e.g., Dickinson *et al.*, 1986; Sellers *et al.*, 1986). Results of these labors are beginning to appear (Dickinson and Henderson-Sellers, 1988; Sellers *et al.*, 1988), and show interesting sensitivities of the climate to vegetation. Much more work is needed to explore these sensitivities, particularly as they relate to deforestation, desertification, paleoclimate, and greenhouse climate change scenarios.

4. SUBGRID-SCALE TERRAIN EFFECTS

The effects of subgrid-scale terrain on climate have received much attention in connection with gravity wave drag, which typically extracts momentum from small-scale orography and deposits it in the upper troposphere or lower stratosphere (or above). What has not been emphasized in the literature, however, is that the same form drag that serves as a lower boundary condition for the gravity-wave momentum flux can also act directly on the PBL, in cases for which gravity wave propagation cannot occur. The nature of the form drag due to subgrid-scale terrain has recently been explored by Deardorff *et al.* (1984) and Taylor (1988). In the context of a discussion of gravity-wave drag, Palmer *et al.* (1986) mentioned that in their numerical results the "form-drag" momentum flux is in fact sometimes deposited into the PBL itself. This subject merits much further exploration.

5. VERTICAL STRUCTURE

There are two relatively new approaches to resolving the PBL in GCMs. The first is higher-order closure, which has been used for a number of years by K. Miyakoda and his colleagues (Miyakoda and Sirutis, 1977), who report encouraging results and significant sensitivity to the PBL parameterization, for example in the simulation of blocking (Miyakoda *et al.*, 1983). The approach of second-order closure has the advantage of a sound physical basis, and the disadvantage of relatively high computational expense, especially when adequate vertical resolution is provided to resolve both the surface layer and the inversion layer. It may also be relatively difficult to couple this type of PBL parameterization with a cumulus parameterization.

The second approach is that of incorporating a bulk boundary layer model, such as a mixed-layer model, directly into the GCM, for example by using a stretched vertical coordinate in which the PBL top is a coordinate surface. This approach has been used experimentally at the U.K. Met Office, and is in routine use in several versions of the UCLA GCM and its offspring (e.g., Randall, 1976; Rosmond, 1981; Suarez *et al.*, 1983; Tokioka *et al.*, 1984; Randall *et al.*, 1985). These authors have also reported encouraging results and strong sensitivity to the formulation of the parameterization. (For a discussion of sensitivity, see especially Randall *et al.*, 1985). An advantage of this "bulk" approach is that the physical processes associated with the fine vertical structures at the PBL top can be parametrically represented, while maintaining computational economy. A disadvantage is that the internal structure of the PBL is not resolved.

It may be possible to combine the bulk approach with second order closure. This would entail allowing more than one vertical degree of freedom within the PBL, while retaining an explicit PBL depth and a parameterized inversion structure. In the simplest case, we might introduce two layers within the PBL (although having two layers is not the only way to have two degrees of freedom in the vertical). Second order closure would then be used to vertically couple the two layers, by predicting the turbulent fluxes at the interface between the layers. This approach, which is currently being explored, retains computational economy while allowing limited resolution of the PBL's internal structure.

6. CONCLUSION

PBL parameterization continues to be an active area of research among those developing the next generation of global models. Coupled ocean-atmosphere models, which have been talked about for so many years, are finally appearing on the scene, mainly in connection with studies of CO₂-induced climate change. This means that modeling what goes on at the air-sea interface will take on added importance in the next few years. It also suggests that many of the lessons learned in parameterizing the atmospheric PBL will soon be applied to parameterize the turbulent mixed layer of the upper ocean.

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