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3.7 Incorporation of the planetary boundary layer in atmospheric models

Chin-Hoh Moeng: Evaluation and development of planetary boundary layer models in mesoscale and global climate models

John Wyngaard:	*Perspectives on planetary boundary layer (PBL) measurements*
Roger Pielke:	*Current problems of PBL parameterization in mesoscale models*
Steve Krueger:	*Convective cloud-PBL interactions*

The planetary boundary layer (PBL) plays a crucial role in coupled mesoscale systems, because of its importance in transporting momentum, heat, and moisture from the surface into the systems. One must therefore accurately incorporate these PBL processes into coupled mesoscale models. Chin-Hoh Moeng introduced the colloquium participants to the PBL Model Evaluation and Development Project at NCAR. This PBL project, initiated by John Wyngaard and Peter Taylor on request by the World Meteorological Organization, is aimed at finding the most promising PBL schemes for coupled climate models. *It is highly desirable to similarly evaluate PBL schemes used in (coupled) mesoscale models.* The approach for climate applications is the following:

- Survey, review, and code six generic PBL parameterizations currently used in GCMs (R_i-dependent diffusion coefficient, single-point closure, K-profile, mixed-layer, multi-stream exchange (including transilient, Blackadar, and mass flux models), and stability-bounded models).
- Generate a database through large-eddy simulations (LESs) of different types of PBL.
- Evaluate the performance of the six models against the LES database and available observations.
- Develop the most promising PBL parameterizations for an atmosphere-ocean coupled GCM.

Over the past two years, the working group has focused on developing a PBL evaluation software package and generating the LES database. So far, the software package includes most of the above-mentioned generic PBL models, and the database consists of nine different PBL cases (including highly convective, weakly convective with strong shear, pure shear, and stratus-topped PBLs.). Both baroclinic and stable PBLs are now being simulated. Even though this PBL package and the LES database were developed for climate study, they can be used for mesoscale studies as well. Which key PBL parameters should be emphasized is the main difference between climate and mesoscale applications. In mesoscale modeling, the vertical distributions of temperature and moisture within the PBL could be important since the models may explicitly resolve cloud formation. The wind direction within the PBL can also be crucial for some mesoscale system developments. Both explicit and implicit interactions between PBL and cumulus systems have to be considered since in mesoscale modeling some cumulus clouds are resolved and some are subgrid scales. Third, many mesoscale system developments are strongly affected by heterogeneous surface conditions; the PBL scheme has to be able to transfer these effects to the mesoscale developments. *The LES database is limited to horizontally homogeneous PBL types. We must depend on observations for more complicated PBL cases. The Cooperative Multiscale Experiment hopefully will provide a useful dataset for this type of study.*

John Wyngaard discussed three historical developments which have shaped the present state of PBL meteorology:

- "Acoustic sounding" (e.g., McAllister et al. 1969) led directly to more realistic PBL models by revealing the sharp top of the growing convective boundary layer and vivid details of the eddies within it. These data led to more realistic PBL models, which at the time had predominantly tended to portray the PBL top as diffuse

- These developments fostered the growth of numerical modeling as a research medium, including three-dimensional numerical modeling (Deardorff 1973) (later renamed large-eddy simulation, or LES) and second-order closure, which was appealing and much cheaper than LES (e.g., Donaldson 1973). Such applications showed that models must be "tuned"---their closures adjusted---for different geophysical flows, and hopes for a "universal" turbulence model faded.

- The role of meticulous, quantitative observational work has diminished. This has occurred despite the fact that observationalists had extraordinary success in documenting the surface layer, filling out the details of Monin-Obukhov similarity theory, exploring second-moment budgets, mapping out spectral behavior, and making detailed measurements of the stability dependence of the mean wind and temperature profiles and their surface-exchange coefficients. Unfortunately, when they began to extend these measurements throughout the PBL, their data had much more scatter than in the surface layer, due not only to the more complicated and variable physics of the outer layers, but also to the "inherent uncertainty"---the scatter between a local time or space average and the ensemble average. Obtaining the data for tuning a model of the outer PBL, or the stably stratified boundary layer, or the interfacial layer, or the cloud-topped mixed layer, was very difficult, perhaps even impossible, and also very expensive.

Wyngaard stressed that PBL models have not been tuned (tested) extensively, due to the lack of suitable data, but also because the importance of tuning is not agreed upon. Some see it as essential because models are not predictive tools (e.g., Lumley 1990), whereas others clearly regard most models as inherently trustworthy. Numerical *simulation* using the governing equations is growing rapidly in the turbulence community, particularly for generating benchmark data for developing and calibrating turbulence *models* (which use approximations). By contrast, the decline of observational work in PBL flows is restricting the flow of data for model development and limiting the supply of well trained, new observationalists. *Progress has been slow on the question of the influence of mesoscale* *variability on PBL and turbulence statistics.* Without many samples of the mesoscale contribution, the PBL measurements will have large random errors. A critical unresolved question is whether large-scale meteorological and oceanographic models (mesoscale to global), which use submodels of the PBL, are really faithful to our understanding of the physics. We do not know, because few if any of these PBL submodels have ever been systematically and rigorously evaluated. The NCAR PBL Model Evaluation and Development Project aims to evaluate these submodels and to develop improved ones. To do this we need to develop a comprehensive data base for testing them and for inspiring the development of better ones, since direct observations cannot provide all the data we need; we must supplement them with simulation results and laboratory data. Furthermore, we must decide which issues can be addressed through observations and which cannot, and we need to design our field programs accordingly. The same judgments need to be made about numerical simulation. Funds should be provided not only for carrying out field programs, but also for their design and for the analysis of their data.

The next speaker in this session was Roger Pielke, who discussed current and related problems of PBL parameterization in mesoscale models. *He echoed the concern that the parameterization of boundary layer processes for use in larger scale models has been based almost exclusively on observations collected for horizontally homogeneous surface conditions under simple, slowly time-varying synoptic weather conditions.* Meanwhile, actual surface and atmospheric forcing is generally not so idealized. Among the main issues to be investigated in developing a more general parameterization are:

- How large does a surface heterogeneity have to be before the horizontally-homogeneous boundary layer parameterization fails? The concept of blending height has been introduced to describe this concept.
- When this parameterization fails to adequately represent heat, moisture, trace gas, and/or momentum fluxes, how important are coherent circulations vis`a-vis turbulence fluxes of these quantities?
- Since existing horizontally homogeneous parameterizations of boundary layer structure are based on time-averaged data (e.g., 20 minutes), how important are variations of similarity and mixed layer scaling parameters on the time scale of the larger scale model (i.e., the time step)? It is unknown whether these variations in what are an ensemble-based boundary layer parameterization result in significantly different larger scale model realizations.
- How do we represent rapidly-changing boundary layer structure such as occurs in the vicinity of atmospheric features like deep cumulus convection? It may be that the boundary layer fluxes are much more important at preconditioning the potentially cumulus convective environment, as contrasted with its importance during the mature stage of these storms.
- What level of complexity is required to accurately represent the coupling between biophysical and boundary layer processes? The stomatal conductance of water vapor to the atmosphere is already

known to be strongly coupled to incoming radiation (which is influenced by clouds, etc.), temperature and humidity at the plant leaf surfaces, etc.

The last speaker in this session was Steven Krueger, who talked on the topic of convective cloud-PBL interactions and its parameterization, both in terms of PBL interaction with shallow, non-precipitating cumuli and its interaction with deep, precipitating convection. Shallow cumuli are often considered to be boundary layer turbulence, while deep cumuli are clearly separated in scale from boundary layer turbulence. Cumulus-PBL interactions consist of boundary layer controls on convection initiation, intensity, and organization, as well as cumulus feedbacks on the boundary layer. The boundary layer controls convection through cumulus updraft properties, the boundary layer depth, and boundary layer convergence zones including gust fronts, horizontal rolls, and sea breezes. Cumulus convection affects the boundary layer through compensating subsidence, cumulus fluxes due to updrafts (if cloud roots exist), penetrating downdrafts, rain evaporation, and the radiative effects of cumulus clouds. Cumulus circulations in the boundary layer also affect the surface fluxes of sensible and latent heat. Parameterizations for shallow cumulus-PBL interaction include Albrecht's trade cumulus-specific model which is a two-layer model with a mixed subcloud layer and an unmixed cloud layer, and where the fluxes in the cloud layer are based on a convective mass flux model. Bougeault's third-order closure model is more general, since it includes a condensation parameterization that depends on third-order moments (though they are not very reliable). Bougeault's model could be coupled to a deep convection parameterization if the boundary layer model only operates on the atmosphere after it has been stabilized by the deep convection parameterization.

Parameterizations for deep cumulus-PBL interaction include those designed for GCMs and those designed for mesoscale models. Deep convection often becomes organized into mesoscale convective systems (MCSs). This makes modeling the cumulus-PBL interactions different in GCMs and mesoscale models. In a GCM, convection depends on the existence of destabilizing large-scale processes in the presence of conditional instability. In a mesoscale model, the destabilizing processes may be mesoscale circulations primarily forced by (parameterized) convection. The principal boundary layer features of an MCS are cool, dry convective downdrafts and a mesoscale "wake" of downdraft air. In a GCM, the time and space scales of mesoscale wakes may be sufficiently small so that the wakes may be essentially ignored. The restoration process is fast enough that only the undisturbed state need be modeled. Another motivation for this is that updraft air (usually assumed to have the mean subcloud layer properties) typically does not come from the wakes; it comes from undisturbed regions. The Arakawa-Schubert-Cheng (ASC) cumulus parameterization (Cheng and Arakwa 1990) is an example of a parameterization appropriate for GCMs, in which convective downdrafts were added to the original Arakawa-Schubert parameterization. Sarachik (1974) noted that the vertical mass flux in the environment of the cumulus clouds should be consistent with observed mixed layer depths. Later comparisons indicated that neglect of convective downdrafts in diagnostic models of cumulus ensembles leads to excessive diagnosed compensating subsidence in the environment compared to that deduced from observed mixed layer depths. The ASC scheme is coupled to a mixed layer model, in which the mixed layer height evolves due to entrainment, cumulus subsidence and large scale vertical motion. Cumulus updrafts start with mean mixed layer properties. Cumulus downdrafts can detrain into the mixed layer, but their thermodynamic effects are assumed to be locally compensated by enhanced sensible and latent heat fluxes from the surface. An alternative model of the undisturbed mixed layer (between wakes) which takes into account the inflow of relatively cool downdraft air into these undisturbed regions was proposed by Johnson (1981). This model requires knowledge about the average properties of the downdraft air, as well as how these properties are modified within the wake region by sensible and latent heat fluxes from the surface. During periods of active deep convection in GATE, environmental subsidence (away from cumulus clouds and mesoscale downdraft systems) is weak, yet the mixed layer there does not grow rapidly because of the inversion-strengthening effect of cool downdraft air outflow into the undisturbed regions.

Mesoscale cumulus parameterizations should parameterize convective downdrafts that detrain into the boundary layer. The boundary layer model used must recognize the downdraft effects and be able to simulate the recovery of a wake. Mixed layer models appear to be adequate for this (Fitzjarrald and Garstang 1981; Nicholls and Johnson 1984). In such a model, the parameterized convection will respond to the explicit mesoscale forcing (including boundary layer convergence zones) and mesoscale variations of boundary layer properties. Cloud scale models resolve the cloud-scale and mesoscale variations in boundary layer properties. Thus, modeling the evolution of the boundary layer is primarily limited by the realism of the turbulence closure and surface flux models. In such models, convection will be initiated by resolved cloud scale circulations (including boundary layer convergence zones) and cloud scale variations of boundary layer properties.