

CME planning committee should incorporate satellite remote sensing technologies, especially FIFE results, into the project design and operation. Existing observational opportunities should be exploited, such as WSR-88D, the Oklahoma mesonet, and the profiler network. In addition, CME should establish a linkage with other programs (ARM-CART, GCIP, USWRP, etc.) and disciplines (hydrology, chemistry, ecology), and also leverage existing technologies and data sources (EROS, etc.).

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4.4 Joint sessions on modeling of boundary layer and radiative transfer processes

4.4.1 Session on modeling of boundary layer processes

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The following topics were addressed in the PBL session of the Workshop: (1) current PBL parameterizations used in mesoscale models, (2) critical issues in improving PBL parameterizations for mesoscale models, (3) suggestions for future modeling efforts, and (4) suggestions for observing system strategies.

a. Current PBL Parameterizations Used in Atmospheric Models

Current general circulation and mesoscale models employ either a bulk or multi-layer PBL scheme. The former includes mixed-layer modeling while the latter encompasses Richardson number-dependent K models, Mellor--Yamada one-equation models, transilient theory, and the Blackadar model. A common advantage of all parameterizations is that they are simple and computationally economical for mesoscale and climate models. The shortcomings of these models are the following:

- These models were developed for horizontally homogeneous PBL flows. They also were meant to account solely for turbulent fluxes (because the closures in the models were determined based on turbulent flows and turbulence theories)
- Some of the models, viz., mixed-layer and Blackadar models, are appropriate for convective PBLs only
- Interactions between cumulus clouds and the PBL are absent in most models
- PBL stratus-type clouds are usually neglected

b. Critical Issues for Improving PBL Parameterizations for Mesoscale Models

We have identified three critical issues in developing improved PBL parameterizations.

- *First, how should inhomogeneous surface features be incorporated into PBL schemes?* All current PBL models were designed and built for statistically horizontally-homogeneous PBLs. However, in mesoscale environments, PBLs are often horizontally inhomogeneous owing to heterogeneous land surfaces, the presence of cumulus clouds, and problems near fronts. Heterogeneous surface conditions, such as land-sea contrasts and nonuniform terrain, can strongly affect many mesoscale systems. Thus, PBL parameterizations must be able to account for these surface effects if they are to be successfully used in mesoscale systems.
- *The second issue concerns how cumulus-induced subgrid-scale effects should be included.* Clouds in mesoscale systems strongly modify the underlying PBL structures. For example, cumulus downdrafts bring cooler and drier air into the PBL, cumulus-induced subsidence in the environment suppresses the PBL growth, cloud cover modifies radiation inputs into the PBL, and rain evaporation cools the PBL. Often, these modifications change the subsequent mesoscale system development. It is therefore important to incorporate these modifications into PBL parameterizations.
- *The third issue concerns how to incorporate the formation and dissipation of PBL stratiform clouds in models.* Many frontal storms are preceded by low-level PBL stratiform clouds, but it is not clear how these clouds affect storm development. Often too thin to be resolved in the vertical grid, these stratiform clouds need to be included in the PBL parameterization.

c. *Suggestions for Future Modeling Efforts*

- *A working group should be formed to evaluate and develop PBL models in the mesoscale context.* Group tasks would include, first, surveying and reviewing the currently-used PBL models; second, designing a comprehensive database (through both large-eddy simulations and field measurements); third, systematically evaluating the model performance against the database; and finally, developing better schemes. This evaluation exercise would also provide users with both an assessment on the adequacy of PBL model vertical resolution, and information on the limitations of each type of PBL model that would help in interpreting model results. We may also want to apply this evaluation process to coupled land process-PBL models, coupled cumulus parameterization-PBL models, and coupled air chemistry-PBL models. This will depend partially on whether a good database for such evaluation can be identified.
- *Include unresolved mesoscale fluxes in multiscale models.* In mesoscale modeling, some parts of the mesoscale circulations are subgrid-scale motions that coexist with turbulent motions. Roger Pielke, using a mesoscale model, showed that the heterogeneous-surface-induced mesoscale motions could generate fluxes that are comparable to and/or larger than the turbulent fluxes in windless environments. We propose more studies in this direction in order to develop a PBL parameterization to incorporate these combined fluxes. This may require more observational data and the use of large-eddy simulations with a numerical domain large enough to cover some mesoscale circulations.
- *Use cloud-resolving models to study PBL-cumulus interactions.* Most current PBL models do not consider PBL-cumulus interactions, which may be crucial for convective storm development. Cumulus circulations extending into the PBL (downdrafts and cloud roots) also produce non-turbulent fluxes that are not included in PBL models. We propose to use a cloud-resolving model with a comprehensive PBL parameterization (or, if possible, a nested LES model) to study and subsequently develop parameterizations to incorporate these interactions, both in quiescent and more disturbed (e.g., frontal or topographically-forced) cases.

- *Improve PBL models to accurately represent stable PBLs.* Many convective storm systems develop at night. However, current PBL models are unable to accurately represent the stable PBL. For example, models underpredict the height to which surface cooling reaches, due to the fact that stable PBL structures are strongly affected by gravity waves, terrain-induced drainage, longwave radiative cooling, and turbulence intermittency---all of which are not considered in current PBL models. We propose to use a nested-grid large-eddy simulation method to better understand stable PBLs.
- *Study PBL stratus clouds and their effects on mesoscale systems.* PBL stratus-type clouds play an important role in the climate-radiation budget. They may also be important for the development of mesoscale frontal system circulations, as discussed by Steve Koch (Session 3.4). A stratus-topped PBL is much more complicated and less understood than clear PBLs, because its structure is strongly affected by many additional physical processes (e.g., longwave and solar radiation, condensation and evaporation, and drizzle). How the stratus-topped PBL grows (i.e., its entrainment rate) is still not understood. We propose using large-eddy simulations, together with observations, to study PBL stratus clouds and their role in mesoscale development.

d. Suggestions for Observing System Strategies

Coordinated efforts between modeling and observation should be strengthened in order to meet the many scientific challenges we have identified in this Colloquium. The following are some specific suggestions for PBL studies.

- In order to better understand (and subsequently parameterize) the underlying PBL effects on a mesoscale convection system, we need to learn first how the PBL structure (e.g., height, flux profiles, etc.) evolves along with the overlying convection and how it varies spatially within the system. For this purpose, *we need to design field experiments that can simultaneously measure the PBL and the overlying convection.* This may require using aircraft, acoustic sounders, wind profilers, lidars, and radars simultaneously. So far, several experiments (e.g., FIFE) have been carried out to study the inhomogeneous surface effects on weather and climate. Others (e.g., CINDE and CaPE) have collected data on convection initiation. Before the Cooperative Multiscale Experiment takes place, we need to gather information on what those experiments have and have not learned in this area.
- To study the stable PBL and its effects on storm development, we need to combine observations with certain PBL modeling that can isolate the effects of gravity waves, cold-air drainage, longwave radiative cooling, and intermittent turbulence. For example, a PBL model combined with a linear gravity wave model may be used to study the gravity wave effect, while a nested-grid large-eddy simulation code can be used to study turbulence intermittency, in the context of observational studies.
- We also need to learn more about the types of convective storms that are preceded and strongly affected by PBL stratus clouds. Marine PBL stratus clouds were observed extensively during the FIRE field experiment. We need to observe continental PBL stratus clouds and their interaction with mesoscale systems.
- *We further recommend the use of chemical species as tracers in observing the transport properties of PBL turbulence and clouds.* Different chemical species have different sources and sinks. Most species do not affect mesoscale, cloud-scale, or turbulence dynamics. They can be useful, therefore, in studying and isolating different transport processes (e.g., top-down and bottom-up diffusion).