IN BOX
INSIGHTS and INNOVATIONS

Parameterization of the Atmospheric Boundary Layer

A View from Just Above the Inversion

BY J. TEIXEIRA, B. STEVENS, C. S. BRETHERTON, R. CEDERWALL, J. D. DOYLE, J. C. GOLAZ, A. A. M. HOLTSLAG, S. A. KLEIN, J. K. LUNDQUIST, D. A. RANDALL, A. P. SIEBESMA, AND P. M. M. SOARES

One of the main components of the climate system is the atmospheric boundary layer, which mediates the interactions between the ocean/land surface and the free atmosphere. Several boundary layer processes are known to have a profound influence on the climate system. Relevant examples include the feedbacks between boundary layer clouds and climate. However, in weather and climate prediction models, in spite of some advances, the boundary layer is still not represented realistically. Figure 1 illustrates an aspect of this problem by showing the opposing response of boundary layer (low) clouds to perturbation experiments (e.g., double CO_2) in current climate models.

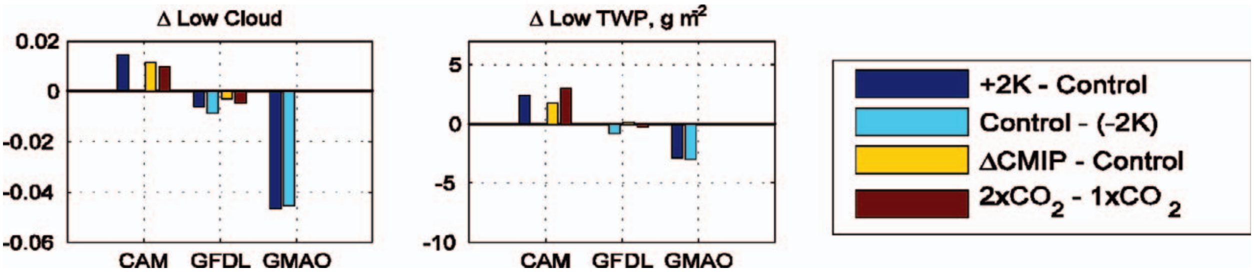

FIG. 1. Changes in low (below 700 hPa) cloud cover and low liquid + ice path (TWP) for different perturbation experiments and for three U.S. climate models (CAM, GFDL, and GMAO). Note the opposite signs, in terms of the low cloud and low TWP sensitivities, between the different models. Three SST perturbation experiments were performed with spatially uniform perturbations of +2 and −2 K and with a spatially and monthly varying SST perturbation (ΔCMIP) (adapted from Wyant et al. 2006).

The general problem of parameterization in fluids dates back to the first modern studies of turbulence during the nineteenth and early twentieth centuries. By then, it was already clear that for turbulent flows such as the atmosphere, it was not feasible (or even relevant) to try and follow every parcel of fluid in its turbulent trajectories. Instead, research should concentrate on trying to understand the statistical properties of turbulent flows. With the advent of computers came the possibility of developing numerical models for weather and climate prediction. Numerical discretizations imply a limit for the temporal/spatial scales below which the flow cannot

AFFILIATIONS: TEIXEIRA—Naval Research Laboratory, Monterey, California, and NATO Undersea Research Centre, La Spezia, Italy; STEVENS—University of California, Los Angeles, Los Angeles, California; BRETHERTON—University of Washington, Seattle, Washington; CEDERWALL, KLEIN, AND LUNDQUIST—Lawrence Livermore National Laboratory, Livermore, California; DOYLE—Naval Research Laboratory, Monterey, California; GOLAZ—Naval Research Laboratory, Monterey, California, and Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey; HOLTSLAG—Wageningen University, Wageningen, Netherlands; RANDALL—Colorado State University, Fort Collins, Colorado; SIEBESMA—Royal Netherlands Meteorological Institute, De Bilt, Netherlands; SOARES—University of Lisbon, Lisbon, Portugal, and Instituto Superior de Engenharia de Lisboa, Lisbon, Portugal
CORRESPONDING AUTHOR: João Teixeira, Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 169-237, Pasadena, CA 91109
E-mail: Teixeira@jpl.nasa.gov

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be resolved by a model. Due to the complex nonlinear nature of the atmosphere, unresolved scales can have a fundamental influence over the resolved large scales. Since explicitly characterizing the unresolved processes is not feasible, the statistical properties at these scales need to be parameterized as a function of the resolved flow.

The parameterization of the atmospheric boundary layer is a complex and important problem not only in terms of weather and climate prediction, but also with respect to several other environmental applications, such as pollutant dispersion and biometeorology.

Currently, there are some important issues that stand out and need to be addressed to improve boundary layer parameterizations:

- how to represent subgrid vertical fluxes;
- how to represent cloud fraction and cloud water;
- how to solve the equations efficiently; and
- how to develop more general parameterizations that represent all types of boundary layers.

In order to address these and other questions, a workshop on the Parameterization of the Atmospheric Boundary Layer[1] was organized in June 2005 at the UCLA Conference Center in Lake Arrowhead, California, just above the typical marine boundary layer inversion. In this paper, a summary of the main conclusions and recommendations is presented and discussed.

BOUNDARY LAYER CLOUDS. Until a few years ago, weather and climate prediction models generally produced unrealistic stratocumulus simulations with negative biases in cloud cover, liquid water, and boundary layer height. The vertical structure of cumulus boundary layers was also problematic. In the mid-1990s, a focused effort, the GEWEX Cloud System Study (GCSS), was initiated by researchers from the Large Eddy Simulation (LES) and the parameterization communities. Progress from comparing observations, LES, and Single Column Models (SCMs) of Cloud-Topped Boundary Layers (CTBLs) has led to a better conceptual understanding and to parameterization improvements that have contributed to better simulations of CTBLs in some operational models. However, there is still an urgent need for further improvement in the simulation of the CTBL vertical structure, diurnal cycle, entrainment processes, and cloud-microphysics feedbacks.

It is clear that higher resolution and better transport algorithms have improved the fidelity of LES simulations of CTBLs over the past decade. However, recent stratocumulus LES intercomparisons still show unsettling sensitivities of important quantities—such as cloud amount and mixing—to the details of the numerical implementation.

Recently, progress has been achieved in the conceptual understanding of the transition from stratocumulus to cumulus boundary layers. However, this transition remains an important parameterization problem that could provide useful test cases in the context of intercomparison studies.

Although LES and many one-dimensional (1D) CTBL models use moist conserved variables, this is not the case for global models. At this stage it is unclear what the impact of moist conserved variables is on a data-assimilation system, or even if the dynamical equations of global models need to be explicitly expressed in terms of moist conserved variables in order to produce realistic CTBL simulations. These issues need to be addressed in a comprehensive manner.

Most of the recent research efforts have been dedicated to subtropical boundary layers. Although these have been fruitful, there is a need for more concerted research on CTBLs outside the subtropics (e.g., shallow convection over land, polar clouds, fog).

Probability Density Function (PDF) approaches provide a promising framework for successful cloud parameterizations. Ideally, unified approaches for the parameterization of vertical mixing are desirable, but regime-based approaches have proven to be a successful short-term strategy. There are also major parameterization issues that need to be addressed in the near future associated with precipitation, cloud microphysics and aerosols, and mesoscale organization.

STABLE BOUNDARY LAYER. It is now well established that there are different types of stable boundary layers (SBLs), which can be classified in terms of duration (e.g., long-lived versus nocturnal boundary layers) and in terms of horizontal heterogeneity (e.g., flow over cold pools). There is also an emerging awareness within the climate community that SBLs pose important and challenging problems (e.g., high-latitude SBLs and climate change).

Observations of the SBL have increased in recent years, and the issue of nonlocal effects in SBLs is

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[1] Presentations can be found at www.atmos.washington.edu/~breth/GCSS/Arrowhead-200506/presentations.html.

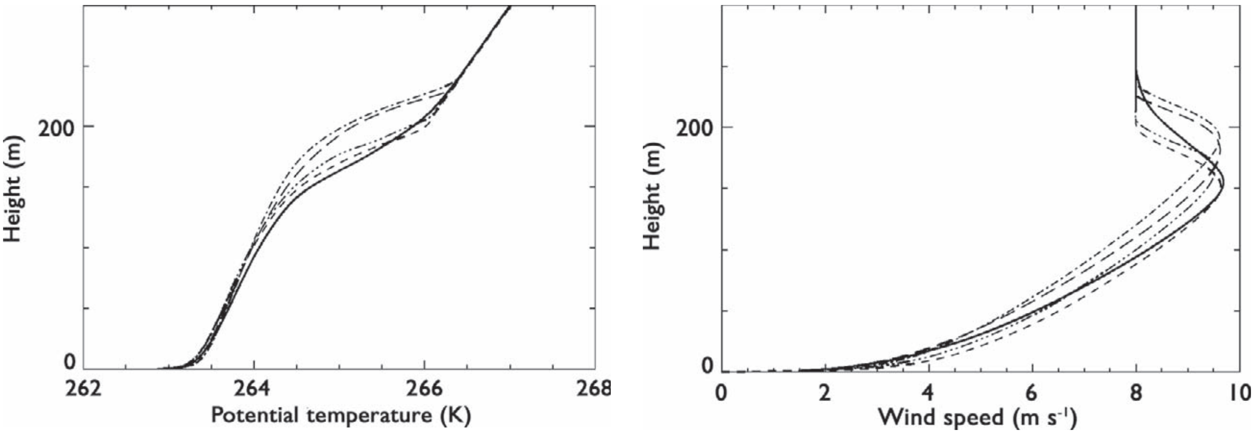

Fig. 2. (left) Potential temperature and (right) wind speed profiles from five LES models for a weakly stable boundary layer case study. For details, see Beare et al. (2006).

starting to be addressed. Some progress has been made in using LES models as a standard tool for the study of SBLs. While some theoretical questions remain concerning the fidelity of LES models in simulating the SBL, many LES models now converge in a promising way for weakly stable boundary layers (Fig. 2). This progress in LES modeling is not because of major changes in formulation, but is mainly due to improved resolution.

Some progress has also been made in understanding the transitions to and from the SBL. The evening transition is generally understood to be gradual and to start early, while the morning transition seems to be driven by entrainment.

A long-lasting problem is the fact that weather and climate models often require stronger SBL mixing than implied by Monin–Obukhov (MO) similarity and observations. Recent LES experiments performed under the framework of a GEWEX Atmospheric Boundary Layer Study (GABLS) intercomparison show that LES models agree with MO similarity. Possible explanations for the need of stronger mixing in weather and climate models include the unrealistic representation of horizontal heterogeneity, gravity waves, and intermittency.

Due to the varied nature of SBLs, it has proven difficult to provide adequate generalizations to improve our understanding and parameterization of the SBL. Also, the SBL is notoriously difficult to observe. This lack of complete observations creates a variety of problems for testing parameterizations. Some of the open issues include the SBL transitions, the impact of SBLs on atmospheric chemistry, and the validity of MO similarity.

The long-lived high-latitude wintertime boundary layer might be where the most progress can be made. One strategy would be a systematic intercomparison using and expanding long-term comprehensive datasets. Similarly, the existing nocturnal SBL datasets should be examined carefully, and new datasets spanning a variety of conditions should be assembled. In terms of operational models, there should be an emphasis on developing skill scores associated with the SBL (e.g., 2-m temperature, boundary layer height, wind angle).

Situations where a full conceptual and theoretical understanding is still lacking include the strongly-stratified intermittent SBL, gravity waves, katabatic flows and density currents, and advection of turbulence. Longwave radiation is an integral part of the problem and should be considered when setting up SBL intercomparisons, in particular for very stable conditions.

INTERACTION WITH THE SURFACE.

Ocean surface. In terms of conventional ocean surface fluxes, there is a greatly expanded observational database, and there has been some noticeable progress in estimates of the bulk aerodynamic transfer coefficients, currently within an error margin of about 5%. Significant progress has been made regarding wind–wave stress and MO stability functions. Some progress has also been achieved in terms of gas and particle surface fluxes, but more research is needed in these areas.

Several processes that pose serious challenges in terms of conceptual understanding and parameterization still exist, however. These include sea spray,

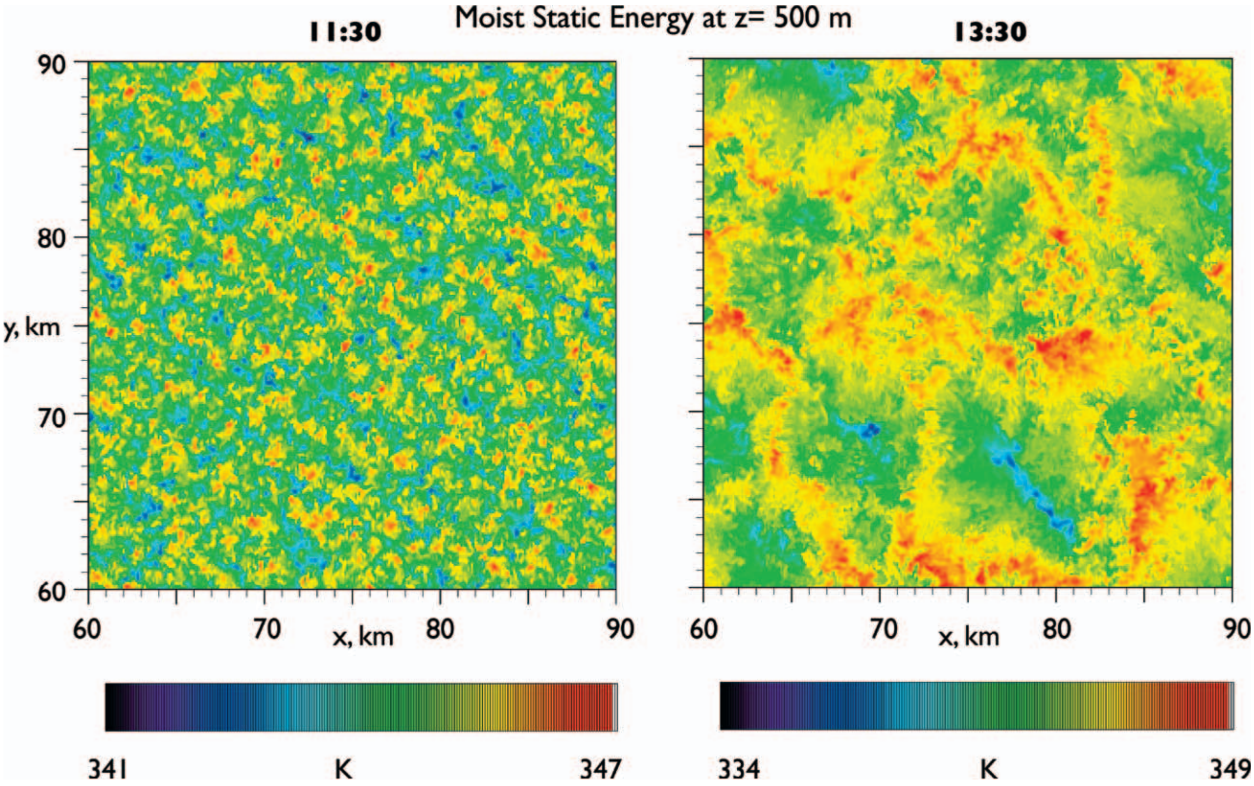

Fig. 3. Horizontal (axes in km) cross section through the moist static energy at 500 m before and after the transition to deep convection (left and right panel, respectively) from a high-resolution CRM simulation (from Khairoutdinov and Randall 2006).

breaking waves, gustiness at low wind speeds, the diurnal cycle of sea surface temperature, and the coupling between the surface and clouds.

In general, for a better understanding of the problem and for improved parameterizations, there is a need for a more integrated observational approach that couples the surface boundary conditions, the clouds, and the lower tropospheric dynamics.

Land Surface. There has been some significant progress in terms of land-surface parameterization in weather and climate prediction models. These developments are primarily due to a successful synthesis of the observational data, and in this context a major advance concerns soil-moisture data assimilation. However, it is clear that models often do not have a realistic diurnal cycle, implying that a realistic coupling between the boundary layer, the land surface, clouds, and radiation is not being achieved. A more integrated analysis of the existing datasets is necessary.

In general, coupling aspects such as the coupling between the land surface and the clouds, or the coupling that involves the canopy and the soil models, represent major problems in terms of land-surface parameterization and its interaction with the boundary layer. Additionally, more information (at the global level) is needed in terms of soil moisture, radiative surface temperature (surface roughness for heat), drag coefficients, and canopy dynamics.

Regarding the development and testing of parameterizations, a common problem is that land-surface intercomparisons are usually performed in isolation from the atmosphere. Intercomparison studies where a more dynamic interaction between the land surface and the boundary layer is taken into account should be pursued. Additional challenges include the representation of urban areas, soil model resolution, and the “tiling” approach.

Until recently, most studies of orographic flow ignored boundary layer effects. Recent studies suggest the need for more integrative approaches to address boundary layer and gravity wave interaction parameterization. Other important issues involving orography include vegetation/canopy drag effects, diurnal cycle, and the effects of orography on clouds.

INTERACTION WITH DEEP CONVECTION.

Currently, LES and cloud resolving models (CRMs) are beginning to realistically simulate the interaction between cumulus ensembles and the boundary layer (see Fig. 3). There is also a large set of observations of the diurnal cycle of shallow and deep moist convection, and of regime transitions, that should be explored.

The parameterization of boundary layer heterogeneity—and its interaction with deep convection—along with mesoscale organization are major challenges to the traditional assumptions upon which parameterizations are based (note in Fig. 3 the different eddy sizes before and after the deep convection onset). The parameterization of convective momentum transport is still an open problem, and there is a need to improve predictions of surface wind stress and fluxes. Issues associated with coupling between shallow and deep convection parameterizations may be best solved by the unification of the convection parameterizations.

Since the interaction between the boundary layer and deep convection is still an open topic, there are a few speculative ideas that deserve some consideration. These include the need for extra subgrid "memory" in the boundary layer parameterization (e.g., prognostic turbulent kinetic energy or eddy-scale information) and the need to take into account the interaction between horizontal grid boxes (e.g., cellular automata).

DISCUSSION AND RECOMMENDATIONS.

Like most parameterizations, boundary layer parameterizations often suffer from numerical problems that affect model performance. Taking into account the omnipresence of sharp vertical gradients in the atmospheric boundary layer, an obvious problem is vertical resolution. Sharp inversions, such as those found capping stratocumulus boundary layers, are hardly represented in current weather and climate prediction models. Recent attempts to tackle this problem in stratocumulus have been relatively successful, but it is unclear how to expand these ideas to other regimes. Another major problem relates to the numerical stability of the turbulent diffusion and/or mass-flux equations often used in boundary layer parameterization. Due to the nonlinear nature of these equations, this has been a difficult problem to solve in a satisfactory manner.

It is currently unclear what the adequate parameterizations are for high horizontal resolutions of the order of 1 km. At these resolutions deep convection can be partially resolved, but shallow convection and boundary layer turbulence must be parameterized. On the other hand, at these resolutions, the dynamics is starting to attempt to "resolve" boundary layer convection. It may well be that at these horizontal resolutions the 1D approach is no longer fully adequate. Ideally, parameterizations should contain information about the horizontal resolution in their formulation, which should allow for smooth transitions between different resolutions. However, this is not currently the case.

With respect to the parameterization of subgrid vertical transport, there is a general agreement that at least in the near future, approaches using eddy diffusivity, mass flux, and some combinations of both should be followed. There is also general agreement that PDF-based cloud parameterizations are a natural way of representing boundary layer clouds. A possible issue of concern is the consistency between the PDFs in the boundary layer and in the other parameterizations. The future development of boundary layer parameterizations should take into account some other components of weather and climate prediction systems, such as aerosol and chemistry prediction, ensembles, and data assimilation.

Additional topics that should be addressed by the community include the baroclinic boundary layer, the need for organizing LES databases, and the need to perform intercomparisons over a wider parameter space and over longer time scales.

An important issue is that for parameterization development, a long-term funding perspective is necessary. Much parameterization development is pursued in academia, and while this is beneficial for developing the theory, parameterizations also require careful engineering, both in terms of numerical implementation and subsequent evaluation. Such work requires long-term support and a reward structure built around the success of the final product. Partly associated with this issue is the fact that the typical time scale for operational implementation of new parameterizations is often too long (several years from original design to operational implementation). Certainly, stronger collaborations between the boundary layer community and the operational centers would be helpful.

As a summary, the main general conclusions and recommendations of the workshop were:

- Recent boundary layer intercomparison studies involving observations, LES models, and SCMs (e.g., GCSS and GABLS) have been successful and need to be pursued further;
- There are still many outstanding problems to be pursued, not only in understanding specific regimes such as highly stable boundary layers and the interaction between the boundary layer and deep convection, but also in developing more integrated approaches; and,
- Sustained funding and a culture that rewards good engineering is crucial to developing—and implementing—better boundary layer parameterizations in weather and climate prediction models.

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FOR FURTHER READING

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