IN BOX
INSIGHTS and INNOVATIONS

The Nature, Theory, and Modeling of Atmospheric Planetary Boundary Layers

by Alexander A. Baklanov, Branko Grisogono, Robert Bornstein, Larry Mahrt, Sergej S. Zilitinkevich, Peter Taylor, Søren E. Larsen, Mathias W. Rotach, and H. J. S. Fernando

Planetary boundary layers (PBLs) represent sensitive and changeable coupling agents that regulate the fluxes of energy, momentum, and matter between the atmosphere and land or sea over a range of scales, from local to global. Numerical weather prediction (NWP), climate, air pollution, and coupled atmosphere–hydrosphere–biosphere models all include PBL schemes as submodels. With the development of high-resolution models, requirements for PBL schemes have dramatically increased, making them a key element of modern model suites that address essential environmental features. Further advancements in this field are stymied, however, as long as the surface boundary conditions provided by PBL schemes remain uncertain.

AFFILIATIONS: Baklanov—Research Department, Danish Meteorological Institute (DMI), Copenhagen, Demark; Grisogono—Department of Geophysics, University of Zagreb, Zagreb, Croatia; Bornstein—Department of Meteorology and Climate Science, San Jose State University, San Jose, California; Mahrt—College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon; Zilitinkevich—Division of Atmospheric Science, University of Helsinki, Helsinki, Finland; Taylor—Department of Earth and Atmospheric Science, York University, Toronto, Canada; Larsen—Wind Energy Division, Risoe DTU, Roskilde, Denmark; Rotach*—Federal Office for Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland; Fernando—Environmental Fluid Dynamics Laboratories, Department of Civil Engineering and Geological Sciences, University of Notre Dame, South Bend, Indiana
***CURRENT AFFILIATION:** Institute for Meteorology and Geophysics, University of Innsbruck, Innsbruck, Austria
CORRESPONDING AUTHOR: Robert Bornstein, Department of Meteorology and Climate Science, One Washington Square, San Jose, CA 95192-0104
E-mail: pblmodel@hotmail.com

DOI:10.1175/2010BAMS2797.1

Traditional PBL schemes were designed in the 1970s for use in low-resolution models. They were adequate over flat, horizontally homogeneous surfaces under steady-state conditions with neutral or weakly stable or unstable stratification; however, they cannot cope with increased-resolution models that require more detailed and accurate representations of physical processes and physiographical features. For example, traditional schemes poorly predict air–sea interactions in storms and fail over complex terrain and coastal zones. They also fail to reproduce basic PBL features in extreme weather events, including dust storms, snow falls, heavy rains, hurricanes, strong convection (e.g., on hot summer days and over winter polar oceans), and in weak winds, particularly with stable stratification. For urban air quality, as well as for releases of harmful gases or radionuclides—dangerous situations for human health and security—current PBL turbulence models remain inadequate.

In the last two decades, however, major advances have been made in the quantification of PBL physics through theoretical studies; field, wind tunnel, and tank experiments; and numerical large-eddy simulations (LES) and direct numerical simulations (DNS). While the importance of turbulent processes in maintaining larger-scale phenomena has become widely recognized, our knowledge of the interactions between turbulence and large-scale geophysical processes remains insufficient to develop PBL schemes for high-resolution, operational weather models capable of correctly reproducing many fundamental PBL characteristics over complex terrain. This paper thus reviews the scientific problem areas, research needs, and new efforts necessary for development of more accurate schemes.

ISSUES AND NEEDS. Current areas that require further boundary layer theory, measurements, and/or modeling include: 1) nature and theory of turbulent boundary layer structure and flows; 2) the turbulence closure problem; 3) stability dependence of the Prandtl and critical Richardson numbers; 4) airflows within and above urban and other complex canopies; 5) air–sea–ice interactions; and, 6) improvement of PBL schemes in operational and environmental security models. These are either fundamental PBL characteristics or essential boundary layer processes insufficiently investigated or overlooked in practical applications. What follows is an exploration of each area to summarize the current state of the art and immediate needs in boundary layer theory, measurement, and modeling.

Observations of boundary layer turbulence. Observational work in the literature has concentrated on turbulence statistics in semistationary flows over near-homogeneous surfaces. Such work is based primarily on time series from fixed points, with poor spatial coverage available with studies from aircraft and remote sensing. Results from attempts to infer spatial variation from time series at a few fixed points are inaccurate, and thus the use of dense networks of fast-response measurements is required to supplement aircraft datasets. The latter are, however, expensive and relatively limited in terms of sample size, but the possible use of unmanned aircraft measurements of turbulence remains under investigation.

Most practical applications involve complex surfaces, which require even more intensive attention. The degree of failure of existing similarity theories over common complex surfaces needs evaluation to establish likely error magnitudes. Even modest improvements of flux-gradient relationships over heterogeneous surfaces would be of considerable practical use. It is not yet known, however, if existing similarity theory can be modified, or if new approaches are required.

Between-site comparisons are critical, as stable PBLs are sensitive to even weak surface heterogeneity and to the occurrence of low-level jets. Comparison of existing results from different sites is still uncertain, as different analysis methods are used in each study. Laboratory data permit examination of problems in simpler settings and allow near-elimination of initial finite-amplitude disturbances, but their application to actual atmospheric weak-wind nonstationary flow is questionable. Under weak large-scale flow, mesoscale and submesoscale motions include wind direction meandering and sudden wind direction shifts. Such PBL flows are strongly influenced by variations of largely unknown physical origins, and therefore extensive analysis is needed.

For observations of boundary layer physics, the following are thus recommended: 1) creation of a catalogue of extensive PBL datasets, 2) analyses of data from different sites with uniform analysis methods, and 3) maintenance of a responsive database center to accommodate dataset upgrades. Increased attention should concentrate on the spatial averaging of turbulent fluxes.

Turbulence closure. Use of only a prognostic equation for turbulent kinetic energy (TKE), common in operational models, has resulted in insufficiently accurate representations of turbulence energetics. The TKE equation, in combination with both down-gradient formulations for turbulent fluxes and the Kolmogorov closure hypothesis for eddy viscosity K_M, conductivity K_H, and diffusivity K_D (all taken proportional to $\mathrm{TKE}^{1/2}$ times mixing length), predicts unrealistic decay rates of turbulence at Richardson numbers (Ri) greater than a critical value Ri_c. To avoid this, Ri-dependent "correction coefficients" are sometimes introduced in the formulations. This heuristic approach, although practical, does not explain the real physical mechanisms that maintain turbulence in strongly stable stratifications.

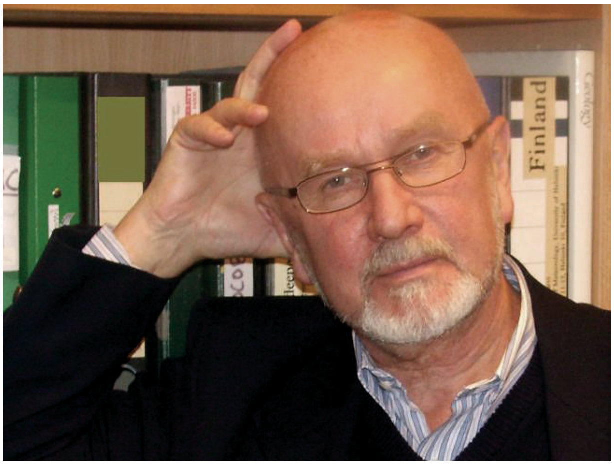
The above difficulties are caused by overlooking turbulent potential energy (TPE), proportional to mean squared temperature fluctuations. TKE and TPE together comprise the turbulent total energy (TTE), whose budget equation does not contain the vertical buoyancy flux F_B in stable stratification, and which also secures positive TTE in any stratification. As F_B appears on the right hand side of both the TKE and TPE budget equations with opposite signs, the TTE concept eliminates explicit use of Ri_c and provides a convenient way to create a hierarchy of energy-consistent closure schemes.

These developments pose opportunities for experimental, LES, and DNS investigations of turbulence in strongly stratified homogeneous sheared flows, as the new theory predicts universal Ri-dependences of basic dimensionless turbulence parameters, such as the turbulent Prandtl number $\mathrm{Pr}_T = K_M/K_H$. An overwhelming majority of data confirms the maintenance of turbulence even at $\mathrm{Ri} \sim 10^2$ and supports an asymptotic dependence of $\mathrm{Pr}_T \sim \mathrm{Ri}$ at $\mathrm{Ri} >> 1$ (e.g., see papers by Zilitinkevich et al. and Mahrt in the 2007 publication, *Atmospheric Boundary Layers*). Some data, however, do show a leveling off, or even decreased Pr_T, and a decay of turbulence with increasing Ri. To clarify this, further experiments, numerical simulations, and data analyses are needed.

Complex mesoscale boundary layer flows. The following mesoscale boundary layer features strongly affect regional climate, weather, and air quality: 1) internal boundary layers caused by surface roughness and/or thermal heterogeneity; 2) flows over topography, slope winds, and orographic waves; 3) thermally driven flows, such as surface-induced convection and thunderstorms, sea and lake breezes, mountain-valley winds, urban and other heat islands, and convective circulations over leads and polynias; and 4) flows combing thermal and mechanical driving mechanisms, such as Bora, Chinook, and Foehn winds.

Traditional computational techniques to account for such complex flow regimes employ Reynolds-averaged Navier-Stokes equation (RANS) models, with varying levels of turbulent closure. TTE closures (e.g., Zilitikevich et al. in *Atmospheric Boundary Layers*) open new opportunities to improve RANS models. For example, LES can be used to address idealized complex terrain flows (e.g., Arctic leads, simply composed slopes, urban canopies). Given the increasing power of supercomputers and parallelized computers, this technique will soon become suitable for operational modeling. Creation of a catalog of data from complex PBL field studies would be extremely useful to further develop a unifying theory of mesoscale PBL flows over complex terrain and to develop PBL schemes necessary for accurate high-resolution operational modeling.

Air–sea–ice interaction. The small surface roughness and large heat capacity of water result in well-developed mesoscale fluctuations in marine PBLs (MPBLs) (e.g., rolls with cloud streets, other convective flow patterns, and gravity waves under stable conditions). The large heat capacity makes temperature stratification over oceans more dependent on advection than over land, where it strongly follows the diurnal cycle. The characterization of mean flows and turbulence, as well as the parameterization of surface fluxes of momentum, heat, and water vapor within MPBLs, remain key problem areas to resolve because of the difficulties in obtaining high-quality data for an adequate height interval, especially in strong winds. Constrained waters, coastal areas, and lakes, in particular, produce complex boundary layer phenomena, dependent on wind fetch and basin depth.



A weeklong NATO Advanced Research Workshop (ARW) on "Atmospheric Boundary Layers: Modeling and Applications to Environmental Security" in April 2006 was dedicated to Sergej S. Zilitinkevich on his 70th birthday for almost five decades of extraordinary pioneering and fundamental contributions to PBL theory and modeling. Zilitinkevich is currently with the University of Helsinki and the Finnish Meteorological Institute. Many papers presented at the ARW were published in a special issue of *Boundary-Layer Meteorology* and as a Springer book, *Atmospheric Boundary Layers: Nature, Theory and Applications to Environmental Modeling and Security.*

Several studies reveal decreasing effective surface roughness length in strong winds, most probably caused by sea spray (e.g., see Kudryavtsev et al. in *Atmospheric Boundary Layers*); however, the wind speed at which sea spray mechanisms become important is not yet well established. This mechanism is of importance for high wind MPBLs, and it is especially critical to hurricane intensity maintenance and, therefore, for the security of subsequently impacted land areas and offshore structures.

Modeling gas and particle exchanges between the atmosphere and water surfaces still suffers many uncertainties. Small surface fluxes result in uncertainties [e.g., necessity to include corrections (such as the Webb-correction) for density variations], so that real over-water fluxes can be larger than directly measured turbulent fluxes. A special problem is the exchange of scalars at low over-water winds, when momentum exchange is controlled by swell and thus can be directed upward.

Mixed ice–sea surfaces are often highly heterogeneous due to the extreme difference in temperature and roughness between the ice and underlying water. This makes aggregation into average surface heat fluxes extremely uncertain, because of both the strong differences between the underlying flux intensities and the highly variable distributions of area elements. These issues remain unsatisfactorily clarified, but are important for the accurate determination of many MPBL features (e.g., surface roughness, thermal structure, and associated mesoscale features). To reduce these uncertainties, new measurements and modeling activities are recommended, and the need for improved high wind-wave measurements over a larger height interval is emphasized. New studies of transitional flows over land–sea, or ice–sea boundaries, with large changes in surface fluxes, are also recommended. The increased focus on mesoscale features, and the improvement of mesoscale models, suggests an increased use of such models in future MPBL campaigns.

Air flows within and above urban canopies. Urban and other complex canopies influence atmospheric flow and microclimate, enhance turbulence, and modify the turbulent transport, dispersion, and deposition of pollutants. Increased resolution in NWP models allows for more realistically reproduced urban airflows and air pollution dispersion processes, which has triggered new interest in modeling and experimental investigations of processes in urban areas for the study of urban climate, meteorology, climate change, air pollution, and emergency preparedness.

A deeper understanding of urban PBL dynamics requires development of long-term urban test beds in a variety of geographic regions (e.g., inland, coastal, complex terrain) in various climates, and with a variety of urban core types (e.g., deep vs. shallow, homogeneous vs. heterogeneous). Ideal urban test beds would include quasipermanent mesoscale networks with surface, canyon, rooftop, and PBL meteorological and air quality observations, as well as intensive short-term field studies with turbulent flux and pollutant tracer measurements. Cities with test beds in various stages of development include Helsinki, London, Hanover, Phoenix, New York, and Washington, D.C. Data from such test beds would be used to gain increased understanding of the dynamics and structure of the urban canopy and PBLs and to initialize and evaluate urbanized models.

Model types applied to urban areas include wind tunnel, outdoor scale, simple parameterized, analytical RANS, engineering computational fluid dynamics (CFD), LES, and DNS. The sophistication of urbanization within RANS models has increased during the last 10 years beyond a simple inclusion of urban effects in TKE schemes. Recent developments include canyon energy fluxes in the surface energy balance equation, and fluxes from canyon walls, roofs, and streets in each prognostic PBL equation. Results show that the Monin-Obukhov Similarity Theory (MOST) assumption of a constant flux surface layer is invalid in urban canopy and roughness sublayers, as friction velocity u_* is not constant with height, but peaks near rooftop levels. They also show urban mechanical mixing as more important than thermal mixing, as the vertical variation of u_* is nearly identical during daytime and nighttime conditions. To fully resolve urban fluxes, advanced urbanization schemes require detailed (i.e., on the scale of a few meters) urban morphological data, including land cover, surface roughness, building thermal characteristics, and anthropogenic heat fluxes.

Improvements in urban microscale canopy-layer models can include development of faster running DNS models, LES models with nonperiodic lateral and complex lower BCs, CFD models with buoyancy effects, wind-tunnel models that include stability effects, and outdoor physical models with realistic geometries. Problems include 1) determination of appropriate "wall laws" for use with vertical surfaces; 2) requirement of extremely small horizontal grid spacing to accurately calculate canyon heating rates from wall heat fluxes; 3) simulation of horizontal and vertical canyon vortices; and 4) parameterization of automobile-produced turbulence. Resolution of these problems would greatly improve the accuracy—and thus the usefulness—of urbanized models in a variety of air quality, emergency response, and climate change applications.

Another area of needed research is the nesting of microscale and mesoscale models. The simplest method is "one way" downward nesting, where the mesomet model provides 4D boundary conditions to the micromet model. This currently can only be provided if the mesoscale model horizontal resolution is as fine as a few hundred meters. In more advanced "two way" nestings, the microscale model also provides lower boundary-condition fluxes to the mesomet model. With current computer capacities, this can only be done within small parts of the mesoscale domain, which creates inconsistencies with the remaining parts of that domain. The development of faster and larger computing systems should increase the likelihood of making more complete microscale and mesoscale model linkages.

PBLs in operational models. Discrepancies exist between the current understanding of PBL processes and their parameterization in operational models. Operational NWP, climate, emergency response, and air-quality models that run on everyday schedules usually are of a RANS type and employ only first- or 1.5-order turbulence closures. More sophisticated turbulence descriptions, as in LES models, are used for research applications (e.g., Weigel et al. 2007), but are too time consuming for current operational applications.

The trend toward higher spatial resolution (1 km in NWP modeling) leads to the following problems with respect to PBL description: 1) parameterizations could be inadequate, since they were developed for coarser hydrostatic numerical models over essentially flat and horizontal terrain; 2) available surface information is not as detailed as needed, due to lumped-parameter descriptions; 3) near-surface exchange schemes are inappropriate for rough surfaces; 4) high spatial resolution in complex terrain leads to steeper slopes and thus to problems with respect to nonhydrostatic effects; 5) radiation parameterizations/schemes need to be more inclusive (e.g., to include shading from clouds and buildings) to better simulate surface fluxes; 6) numerical schemes need to be adjusted to higher resolution, or instabilities may result; and 7) local mesoscale flows need to be better resolved, as they may dominate local energetics or mass budgets (e.g., Weigel et al. 2007) for more accurate forecasts.

Areas of necessary improvement thus include turbulence closure, mesoscale convection, and the overall treatment of complex terrain and rough surfaces. It is important not to simply adjust existing schemes, but to develop new ones based on sound PBL physics. The success of PBL descriptions in operational models is also dependent upon improved assimilation techniques for PBL data, accounting for not only statistical but also physical flow properties. Other sub-grid scale issues (e.g., flux aggregation and cloud-radiation interaction) also need to be resolved.

The potential for "double counting" TKE exists in RANS models. When model resolution drops below a certain threshold, the largest turbulence scales become explicitly resolved, while the parameterization still implicitly simulates the entire spectrum. Turbulence closure schemes in operational models should thus be in agreement with model resolution.

Environmental security issues and demands from end users. With the growing spectra of chemical, biological, and radiological (CBR) terrorism, it becomes increasingly necessary to protect ecosystems against deleterious human activities, including urban air pollution. Given that most living entities are within PBLs, an understanding of PBL processes is a necessary component in development of secure living environments. Key is the prediction of CBR release pathways, and thus first and foremost suitable sensors are needed for toxin detection. While sensor development and monitoring networks are expensive, they are the most reliable way to obtain the in-situ wind and toxin concentration data needed to predict the origin and short-term evolution of toxic plumes. Techniques are under development to place sensors at optimal locations through use of ensemble model simulations to obtain 4D wind behavior. New methods and concepts are still needed to improve the tools available for planning sensor placement.

Releases in upwind areas may affect urban areas, depending on background dispersion patterns (e.g., under stable stratifications, vertical diffusion is impeded). Strong meandering during stably stratified periods can cause enhanced horizontal diffusion and perhaps also vertical plume oscillations. Many of these phenomena are not fully understood yet, let alone parameterized, but techniques such as satellite imagery can help monitor plumes and evaluate model predictions.

With urban populations now indoors for more than 90% of the time, indoor air quality has become increasingly important to urban environmental security. Significant modeling efforts are underway to develop indoor–outdoor air exchange rates for indoor air quality predictions, although fast models and validation data are needed to ensure such forecasts are accurate.

This leads to the following questions: what type of indoor air circulation equipment is needed? What are the optimal locations in which to place such equipment? And can released material be cleansed via proper ventilation? Indoor models that estimate residence times and surface contamination are being developed, especially after the anthrax attack in the Hart Senate Office Building in the United States (for which environmental remediation costs were approximately $500 million). Increasing our understanding of contaminant dispersion in air masses within isolated spaces—in particular the recirculation and deposition of such substances—is needed to improve remediation efficiency. Most critical for first responders is near-field spreading, and hence fast models that correctly incorporate submesoscale processes are required.

CONCLUSION. It is clear that PBL processes play important roles in atmospheric modeling for different applications (e.g., NWP, climate, air pollution, emergency preparedness, and coupled atmosphere–hydrosphere–biosphere modeling). The gap between the modern understanding of PBL physics and its representations in current operational atmospheric models is still large, however, and thus immediate needs exist for improved PBL parameterizations and turbulence closures for high-resolution models using applications that involve complex terrain, weak-wind conditions, urban and forest canopy flows, air–sea interactions, and other complex environmental problems. Recent advances in the understanding of PBL processes, and their potential applications within operational modeling, are just the first steps toward substantially advancing the simulation of real world PBLs, which will produce significant benefits in the areas of weather, climate, and air-quality forecasts around the world.

ACKNOWLEDGMENTS. This work was sponsored by NATO Programme No. 982062, "Security through Science." Additional support came from the Croatian Meteorological and Hydrological Service (CMHS), the Danish Meteorological Institute (DMI), the Finnish Meteorological Institute (FMI), the Croatian Ministry of Science, and the EU Marie Curie Chair Project MEXC-CT-2003-509742 on "Theory, Modelling, and Roles in Earth Systems." We thank the NATO Administration, CMHS Director Ivan Čačić, DMI Director Peter Aakjær, and FMI Director Pekka Plathan for making this effort possible, productive, and available.

FOR FURTHER READING

Baklanov, A., and B. Grisogono, Eds., 2007: *Atmospheric Boundary Layers: Nature, Theory and Applications to Environmental Modelling and Security*. Springer, 248 pp. [Available online at www.springer.com/earth+sciences+and+geography/meteorology+%26+climatology/book/978-0-387-74318-9.]

——, S. Grimmond, A. Mahura, and M. Athanassiadou, Eds., 2009: *Meteorological and Air Quality Models for Urban Areas*. Springer, 140 pp.

Weigel, A. P., F. K. Chow, and M. W. Rotach, 2007: On the nature of turbulent kinetic energy in a steep and narrow Alpine valley. *Boundary-Layer Meteor.*, **123,** 177–199, doi:10.1007/s10546-006-9142-9.