Atmospheric boundary layers: nature, theory and applications to environmental modelling and security

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This special issue presents a set of peer-reviewed papers from the NATO Advanced Research Workshop (ARW) "Atmospheric Boundary Layers: Modelling and Applications to Environmental Security", held in Dubrovnik, Croatia, 18–22 April 2006; 57 researchers from 21 countries and 4 continents participated (see the ARW web-site http://pbl-nato-arw.dmi.dk).

The principal goals of the ARW were

- to summarise and assess current knowledge on planetary boundary-layer (PBL) physics and parameterization,
- to promote the exchange of ideas and knowledge between physicists, meteorologists, and environmental modellers,
- to set a course for improving PBL parameterisations in climate, numerical weather prediction, air-quality, and emergency preparedness models.

A pleasant reason to arrange this event in April 2006 was the 70th birthday of Professor Sergej Zilitinkevich (born on 13 April 1936 in St. Petersburg, Russia). A most appropriate tribute to him is the fact that a major part of the presentations at this ARW are based on or linked with his fundamental works. His scientific biographical note by George Djolov is included in this issue. He is in perfect form, sprinkling with new ideas, and very productive scientifically.

The scientific organisation of the ARW was performed by the Organising Committee consisting of the NATO-country ARW director Alexander Baklanov (Meteorological Research Division, Danish Meteorological Institute, Copenhagen, Denmark); the Partner-country ARW director Branko Grisogono (Department of Geophysics, University of Zagreb, Croatia); Adolf Ebel (Phenish Institute for Environmental Research, University of Cologne, Germany); Sylvain M. Joffre (Finnish Meteorological Institute) and Sergej Zilitinkevich (Division of Atmospheric Sciences, University of Helsinki, Finland)—with valuable contri-

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Atmospheric Boundary Layers. A. Baklanov & B. Grisogono (eds.),
doi: 10.1007/978-0-387-74321-9_1, © Springer Science+Business Media B.V. 2007

butions from the local organisers: Iva Kavcic and Iva Grisogono (Department of Geophysics, University of Zagreb).

The programme included three introductory talks, nine key lectures, and 27 regular presentations divided into several thematic sessions. It is only natural that this issue does not cover all presentations; some of them were based on already published, submitted or still uncompleted papers.

Besides presentations, the programme included three general discussions: "Stability dependence of the turbulent Prandtl number and the critical Richardson number problem", "Turbulence closure problem", "Towards improvement of PBL schemes in operational models"; and specific discussions in working groups: (WG1) Boundary-layer physics (*L. Mahrt*); (WG2) Turbulence closure (*S.S. Zilitinkevich*); (WG3) Complex and mesoscale boundary-layer flows (*P.A. Taylor*); (WG4) Air-sea-ice interaction (*S.E. Larsen*); (WG5) Air flows within and above urban and vegetation canopies (*R. Bornstein*); (WG6) PBLs in operational models (*M.W. Rotach*); (WG7) Environmental security issues and demands from end users (*H.J.S. Fernando*). The WG chairmen (see their names in brackets) have summarised and forwarded to us the conclusions and recommendations of their groups. Below we briefly skim through working-group and general inert-group conclusions.

WG1 recommended (i) creation of a catalogue of the more extensive PBL datasets, (ii) analysing different sites with the same analysis method, and (iii) maintenance of a responsive data-base centre that can accommodate continual upgrades of datasets. More attention should be concentrated on spatial averaging of turbulent fluxes. Tower measurements can provide spatial averages, such as over a grid area, only with weak heterogeneity and the precarious assumption of Taylor's hypothesis. Most practical applications involve complex surfaces, which require more attention. The degree of failure of existing similarity theory over common complex surfaces needs to be determined to establish the likely magnitude of errors. Even modest improvements of the formulation of the flux-gradient relationships over heterogeneous surfaces would be of considerable practical use.

WG2 emphasised that traditional treatment of the turbulence energetics using solely the turbulent kinetic energy (TKE) budget equation is insufficient and causes difficulties in operational turbulence closure models. The TKE equation in combination with the down-gradient formulation for the turbulent fluxes and Kolmogorov's closure hypothesis for the eddy exchange coefficients leads to unrealistic degeneration of turbulence at Richardson numbers, Ri, exceeding some critical value, Ri_c. To Ri_c, Ri-dependent "correction coefficients" are introduced in the above formulation without physical explanation of the maintenance of turbulence in strongly stable stratification. As demonstrated at the ARW the above difficulties are caused by overlooking the turbulent potential energy (TPE) proportional to the mean squared temperature fluctuations. Together TKE and TPE comprise the turbulent total energy (TTE), whose budget equation does not include the vertical flux of buoyancy and has the form of a conservation equation securing positive TTE in any stratification. The concepts of TPE and TTE eliminate Ri_c from the turbulence closure problem and open a constructive way to create a hierarchy of energetically consistent closure schemes for operational use. The nature of organised structures in the convective PBL, namely cells and rolls in the shear-free and sheared regimes, respectively, remain not fully understood. The surface heat/mass transfer laws for the shear-free convection are obtained, but to extend the theory to sheared convection and to vertical transports within the convective zone, further observational and numerical simulation studies are needed.

WG3 identified the following mesoscale boundary-layer flows that strongly affect regional climate, weather and air quality: internal boundary layers caused by the roughness and/or thermal heterogeneity; flows over topography, such as slope winds; thermally driven features:

surface-induced convection and thunderstorms, sea and lake breezes, mountain-valley winds, urban and other heat islands, convective circulations over leads and polynias; mechanically driven flows: orographic gravity waves, downslope wind storms, retardation of frontal passages by orography or roughness; and features combing thermal and mechanical driving mechanisms, such as bora, chinook and foehn. Here the traditional computational techniques are Reynolds-averaged Navier–Stokes equation (RANS) models with varying levels of closure. TTE closures open new opportunities to improve RANS models, first of all, addressing air quality issues. Large-eddy simulation (LES) has just started to address idealised complex-terrain flows (e.g., Arctic leads, simply composed slopes, urban canopies) utilising periodic lateral boundary conditions. In view of the increasing power of supercomputers this technique will become suitable for operational modelling in the very near future.

WG4 focused on the marine atmospheric planetary boundary layer (MPBL). The smaller roughness and larger heat capacity of the ocean result in more organised convective flow patterns, such as cloud streets. Parameterization of the surface turbulent fluxes of momentum, heat and water vapour over the sea remains the key problem because of difficulties in obtaining high quality data in strong winds. Several studies revealed decreasing of the effective roughness length in very strong winds caused by the input of the sea spray into the lower surface layer. Constrained waters, coastal areas and lakes represent an even more complex problem requiring knowledge of the wind fetch and the basin depth. Modelling of the gas and particle exchange between the atmosphere and ocean still suffers from many uncertainties of both theoretical and experimental nature. For gases, an important uncertainty follows from the empirical nature of the surface exchange coefficient allowing no simple rules to account for non-stationary and heterogeneous features often found in aqueous concentration patterns and wind speeds. The mixed ice-sea surface is often highly heterogeneous with respect to the heat flux, due to the often-extreme difference in temperature between the ice surface and underlying waters. Also the drag may change strongly due to ridged borders of the ice floes. A quite successful effort has been made to understand and model the flow and fluxes for individual water openings, and also from ice-covered surfaces. However, aggregation into average surface fluxes remains strongly uncertain. Passing clouds change the radiation heat flux and thus constitute an important non-stationary effect on the MPBL. The strong wind MPBL traditionally considered as a simple neutrally stratified boundary layer exhibits novel features and, as recognised recently, should be treated as "conventionally neutral" (near-neutral close to the surface but strongly affected by the free-flow stability and stably stratified in its upper portion).

WG5 emphasised the key role of the urban boundary layer in air quality problems. Urban features essentially influence atmospheric flow and microclimate, strongly enhance atmospheric turbulence, and modify turbulent transports, dispersion and deposition of atmospheric pollutants. Considerably increased resolution in numerical weather prediction models has allowed for more realistically reproducing urban air flows and air pollution processes. This has triggered new interest in modelling and investigating experimentally specific processes essential for urban areas. Recent developments performed within the EU-funded project FUMAPEX on integrated systems for forecasting urban meteorology and air pollution and other relevant studies showed many opportunities in "urbanisation" of weather prediction, air pollution and emergency preparedness models.

WG6 and **WG3** agreed that high-resolution mesoscale RANS models and LES are complementary providing basic information on fine-scale features of air flow over complex terrain. The latter are not resolved in larger scale climate and weather prediction models and are to be parameterized through appropriate spatial averaging of turbulent fluxes (flux aggregation). This applies in particular to "hydrological heterogeneity" associated with areas with many small lakes. Currently-used flux-profile relationships determining the lower boundary conditions in both mesoscale and larger scale models need to be refined. The background Monin–Obukhov similarity theory is not applicable over complex terrain (see WG1) and does not realistically reproduce strongly stable and strongly unstable stratification regimes. Recently it has been generalised accounting for the non-local effects of the free-flow stability in stable stratification and large-scale, organised eddies in shear-free convection. Further work is needed to extend surface-layer theory to sheared convection and also to complex and sloping terrain.

WG7 considered environmental security issues and demands from end users. With growing spectra of chemical, biological and radiological (CBR) terrorism, it has become increasingly necessary to protect our ecosystems against deleterious activities of humans. The rapid rise of population in cities has created concentrated human centres that are vulnerable to extensive destruction through terrorism or by natural causes such as hurricanes, as evidenced with increasing frequency in recent decades. Increase of air pollution is another issue that is closely related to the quality of life. Given that the bulk of living entities are embedded in the PBL, it is opportune to discuss the role that boundary-layer meteorology plays in securing our environment. One of the key issues is the prediction of the pathways of CBR releases. First and foremost, suitable sensors are needed for the detection of toxins, and in the post-9/11 era such sensor technologies are rapidly advancing. What follows are in the arena of PBL modelling: optimal placement of sensor and design of sensor networks, environmental cyber-infrastructure, prediction of transport, diffusion and distribution of contaminants in the PBL, especially fast forecast models, monitoring of contaminant paths, including sensor model fusion work, long range transport and dilution, indoor air quality (air seepage through building accessories), environmental remediation, informing the authorities and providing help in emergency response.

We hope that the principal goals of the ARW will be achieved and this issue will help readers to assess the potential of recent achievements and novel ways in PBL physics and its applications. It was the unanimous opinion of all participants that the ARW has indeed made a step towards these goals, and that similar meetings, say, once in 2–3 years would strongly facilitate further progress in boundary-layer meteorology and operational environmental modelling, including the security issues.

Acknowledgements This ARW has been sponsored by the NATO Programme No. 982062 "Security through Science". Additional supports have come from Croatian Meteorological and Hydrological Service (CMHS), Danish Meteorological Institute (DMI), Finnish Meteorological Institute (FMI), the EU Marie Curie Chair Project MEXC-CT-2003–509742 "Theory, Modelling and Role in Earth Systems" and the NORDPLUS NEIGHBOUR Project 177039/VII. We thank the NATO Administration, the CMHS Director General Ivan Čačić and the FMI Director General Pekka Plathan for making this meeting possible, productive and available to many participants. We also thank the working group leaders Larry Mahrt, Sergej Zilitinkevich, Peter Taylor, Søren Larsen, Robert Bornstein, Mathias Rotach and Joe Fernando for providing us with recommendations summarised herein.

9 July 2007