SEVENTH FRAMEWORK PROGRAMME

“Ideas” Specific Programme

European Research Council

Grant agreement for Advanced Grant

Annex 1 – “Description of Work”

Project acronym:	PBL-PMES
Project full title:	Atmospheric planetary boundary layers: physics, modelling and role in Earth system
Grant agreement no.:	227915
Date of preparation of Annex 1:	18 November 2008
Principal Investigator:	Sergej Zilitinkevich
Host Institution:	Finnish Meteorological Institute (FMI)

Abstract

This project aims to systematically revise the planetary-boundary-layer (PBL) physics accounting for the non-local effects of coherent structures (long-lived large eddies especially pronounced in convective PBLs and internal waves in stable PBLs). It focuses on the key physical problems related to the role of PBLs in the Earth system as the atmosphere-land/ocean/biosphere coupling modules: the resistance and heat/mass transfer laws determining the near-surface turbulent fluxes, the entrainment laws determining the fluxes at the PBL outer boundary, the PBL depth equations, and turbulence closures. In this project the first round of revision will be completed, the advanced concepts/models will be empirically validated and employed to develop new PBL parameterization for use in meteorological modelling and analyses of the climate and Earth system. The new parameterizations and closures will be implemented in state-of-the-art numerical weather prediction, climate, meso-scale and air-pollution models; evaluated through case studies and statistical analyses of the quality of forecasts/simulations; and applied to a range of environmental problems. By this means the project will contribute to better modelling of extreme weather events, heavy air pollution episodes, and fine features of climate change. The new physical concepts and models will be included in the university course and new textbook on PBL physics. This project summarises and further extends our last-decade works in the PBL physics: discovery and the theory of the new PBL types of essentially non-local nature: “long-lived stable” and “conventionally neutral”; quantification of the basic effects of coherent eddies in the shear-free convective PBLs including the non-local heat-transfer law; physical solution to the turbulence cut off problem in the closure models for stable stratification; and discovery of the stability dependences of the roughness length and displacement height.

Section 1a: The Principal Investigator

(i) Sergej S. Zilitinkevich – Curriculum Vitae

Date and place of birth / citizenships
13.04.1936, St.Petersburg / Russian and Swedish

Affiliation and address
Research Professor: Finnish Meteorological Institute (FMI), PO Box 503, 00101 Helsinki, Finland. Sergej.Zilitinkevich@fmi.fi, phone +358-9-1929-4678, fax +358-9-1929-4103

Education and grades
Graduated from Leningrad State University, USSR (1959)
PhD: State Hydrometeorological University (1962)
Dr Sci: PP Shirshov Institute of Oceanology Acad. Sci. USSR (1968)
Professor of Geophysics: Presidium of Acad. Sci. USSR (1972)
Professor of Meteorology: Uppsala University, Sweden (1997)

Professional record
1959-1990 – Russia: Main Geophysical Observatory, Institute of Lake Research, Institute of Oceanology (Director of Leningrad Branch), Russian State Hydrometeorological University (Professor)
1990-1990 – Denmark: Visiting Professor, RISØ National Laboratory
1991-1997 – Germany: Visiting Professor and project director/coordinator, Max Planck Institute of Meteorology / Hamburg University, Alfred Wegener Institute of Polar and Marine Research, GKSS Research Centre
1998-2003 – Sweden: Professor and Chair of Meteorology, Uppsala University (since 2003 Professor Emeritus)
Since 2004 – Finland: Professor, University of Helsinki and Finnish Meteorological Institute (during 2004-2007 Marie Curie Chair of Boundary-layer Physics); since 2007 Founder of METEOLAB Environmental Consulting (FO-number 2113874-6)
Since 2004 – Norway: part-time Professor, Nansen Environmental and Remote Sensing Centre

Publications and participation in conferences
8 books, 162 peer-reviewed papers, during last decade: 3.3 invited lectures at international conferences per year

Supervision
20 PhD / Dr Sci candidates in meteorology, oceanography, space research; 4 of those became professors

Lecturing
Designed 7 different courses within meteorology, oceanography, geophysics and science management at universities in Russia, Germany, Sweden and Finland
Delivered a dozen short courses on boundary-layer physics at international summer schools

Funding ID (projects coordinated by Sergej Zilitinkevich are marked with asterisk)

Selected old project (total cost ~ 3500 kEUR)
*LAND-3 "Protection of coastal marine environment" (~1500 k$), ICSC-World Lab (Switzerland), Ettore Majorana Centre (Italy), 5 South. Mediterranean countries, 1992-1993
*INTAS 94-2255 "Modelling and parameterisation of convective heat/mass transfer - with due regard for coherent structures", Germany – Russia, 1994-1997
*INTAS 96-1692 "Modelling and parameterisation of the convective heat/mass transfer over rough surfaces", Sweden – Russia, 1997-1999
$^{(*)}$EU SFINCS "Surface fluxes in climate system" EU Contract ENV4-CT97 0573 (~1000 kEUR), coordinator: S Larsen (DK), SZ co-coordinator responsible for physical research, 1997-2000

*SIDA SRP-2000-036 South African – Swedish Research Partnership “Non-local turbulent transport in weather prediction and air pollution modelling”, 2001-2003

*Swedish Institute “Environmental modelling and impact assessment”, Sweden – Russia 2002-2005

*Nordic Council of Ministers – Nordplus Neighbour “Boundary-layer phenomena over partially Ice covered Arctic Sea: impact on weather, climate, ecology” FI51, 6 courtiers, 2005-2007

*Marie Curie Chair PBL-TMRES “Theory, modelling and role in Earth System” (~500 kEUR) 2004-2007

FUMAPEX EVK4-CT-2002-00097 “Integrated Systems for Forecasting Urban Meteorology, Air Pollution and Population Exposure” 2002-2005 (3 000 kEUR), coordinator A Baklanov (DK), SZ responsible for urban PBL

Selected ongoing projects complementary to PBL-PMES (grant agreement 227915)

*EU TEMPUS 26005 “Development of competency-based two-level curricula in meteorology” 2007-2009, 500 kEUR; promotes immediate educational applications of PBL-PMES

EU FP7 MEGAPOLI 212520 “Mega-cities: emissions, urban, regional and global atmospheric pollution and climate effects, and integrated tools for assessment and mitigation” 2008-2012 (5500 kEUR), coordinator: A Baklanov (DK), SZ responsible for PBL physics; PBL observations and data analyses will be used in PBL-PMES

Academy of Finland IS4FIRES “An integrated monitoring and modelling system for wild land fires, coordinated by M. Sofiev (FI), 322 kEUR, 2008-2010; SZ responsible for theory / modelling of convection; planned forest-fire experiment will essentially contribute to PBL-PMES

Membership (selected)

Committee for the Vilhelm Bjerknes Medal (European Geoscience Union)

Editorial Boards of *Environmental Fluid Mechanics* (international, established in 2000, 2000-2006), *Bulgarian Geophysical Journal* (since 2000), *Ukrainian Hydro-meteorological Journal* (since 2004), *Geography, Environment, Sustainability* (international, established in 2008, since 2008) *International Journal of Geophysics* (since 2008)

Board of C-G Rossby International Meteorological Institute (Sweden, 1998-2003)

Convener of Session AW2.1 “Atmospheric Boundary Layers”, Annual Meetings of the European Meteorological Society (EMS) http://meetings.copernicus.org/ems2007/ (since 2005)

Honours and awards

Vilhelm Bjerknes Medal 2000 (European Geophysical Society copernicus.org/EGU/awards/general.html)

Member of Academia Europaea (Earth and Cosmic Sciences Section)

Fellow of the Royal Meteorological Society (UK)

Honorary Foreign Member of the Geophysical Society of Georgia

Distinguished Professor of BWW Society / IAPGS, USA

Marie Curie Chair of Boundary-Layer Physics (EU-Commission, 2004-2007)

(ii) Scientific Leadership Profile (2 pages)

Sergey S. Zilitinkevich ("SZ" or "Z" – in references) started research career in 1959 after graduating from Leningrad University as theoretical physicist: 1962 (age 26) PhD in phys-math sciences (atmospheric physics); 1964 (age 28) Head of Section of Air Pollution at Main Geophysical Observatory, Leningrad; 1966 (age 30) established Leningrad Branch of the Institute of Oceanology Acad. Sci. USSR, which focused on planetary boundary layers (PBLs), air-sea interaction, atmosphere and ocean general circulation (during 10 years its staff approached 50, including 5 full professors); 1968 (age 32) Dr Sci in phys-math sciences (PBL physics), initiated and led inter-institutional coordination in environmental physics and modelling through annual all-USSR workshops / summer schools, appointed as leader of the physics-and-modelling sub-programme of the USSR National Space Research Programme VENERA (Venus); 1970 (age 34) appointed as the Chair of the USSR National Commission on Air-Sea Interaction; 1972 (age 36) Professor of Geophysics (Acad Sci USSR / Hydrometrological University). By 1990 SZ published a hundred peer reviewed papers and 6 books (4 in Russian and 2 in Polish) on PBLs; air-sea interaction; turbulence and general circulations in the Earth's and planetary atmospheres, ocean and lakes; theory of climate; astrophysics; and modelling water ecosystems.

In 1990 SZ moves to Western Europe: 1990 Denmark – Visiting Professor at the Wind Energy Department of RISOE National Lab; 1991-1997 Germany – Visiting Professor and projects director / coordinator at Max Planck Institute for Meteorology (MPI) / University of Hamburg, Alferd Wegener Institute for Polar and Marine Res. (AWI), and Institute for Hydrophysics at the GKSS Research Centre; 1998-2003 Sweden – Professor and Chair of Meteorology at Uppsala University; since 2004 Finland – Professor and Marie Curie Chair of Boundary-layer Physics at the University of Helsinki (2004-2007), Research Professor at Finnish Meteorological Institute (FMI), and part-time Professor at the Nansen Environmental and Remote Sensing Centre (NERSC) in Bergen, Norway. His current research works focus on the revision and further development of the PBL physics accounting for non-local features of geophysical turbulence caused by organised structures (large eddies in convective and internal waves in stable PBLs), theoretical analysis of the role of PBLs in the Earth system, and improvement of PBL parameterizations in operational models. Since 1990 SZ coordinated 7 international projects (with total cost about 4 millions EUR); and published extended English versions of his 2 Russian books (Z "Turbulent Penetrative Convection" and Z et al. "Modelling Air-Lake Interaction: Physical Background") and 70 peer reviewed journal papers. SZ is the single or 1st author in 80% of his publications.

According to ISI Web of Knowledge (covering only 9% of the world scientific literature, which however provides 77% of the world body of citation) for the beginning of 2008, the most sited 10 papers of SZ were: [1] Z: *Dynamics of Atmospheric Boundary Layer*, Gidrometeoizdat, 292 pp, 1970 (189 citations); [2] Z: *BLM* **3**, 141, 1972 (147); [3] Z: *JAS* **32**, 991, 1975 (92); [4] Z: *JAS* **32**, 741, 1975 (90); [5] NI Shakura, RA Sunyaev & Z: *Astron. Astrophys.* **62**, 179, 1978, (84) (here the authors are listed in alphabetic order; this paper contributed to the Crafoord Prize awarded to RA Sunyaev et al. in 2008,); [6] Z & DV Mironov: *BLM* **81**, 325, 1996 (67); [7] Z, DL Laikhtman & AS Monin: *Izvestia FAO* **3**, 297, 1967 (55); [8] Z & JW Deardorff: *JAS* **31**, 1449, 1974 (53); [9] Z & Calanca: *QIRMS* **126**, 1913-1923, 2000 (49); [10] Z: *BLM* **46**, 367, 1989 (46). Physical concepts developed in these works are: bulk PBL resistance and heat/mass transfer laws; diagnostic and prognostic PBL height equations; and the energetics of turbulence in extremely stable stratification.

In the beginning of 2008, ISI showed 1416 citations of 83 papers of SZ, with the average citation per item 17 and the h-index 20. During recent years his citation rapidly increased (Figure 1) and approached 100 per year in 2007 (a pronounced value in view of rather small PBL-physics community). The same tendency is seen in Figure 2 showing dynamics of his invited lectures at the variety of international interdisciplinary conferences. The increasing interest in the PBL physics from the neighbouring-field communities is quite natural. Currently used PBL parameterizations are based on the traditional theories and do not keep pace with rapidly improving spatial resolution and accuracy of the state of the art atmospheric models. In the Earth system PBLs play the role of coupling modules between the atmosphere, hydrosphere and biosphere, whose separate models show essentially higher quality than model chains coupled using current PBL schemes. This calls for advancing the PBL theory and parameterization.

PBL models developed by SZ underlie parameterizations of the PBL height and mean structure, air-water turbulent fluxes, and mean turbulent and thermal structure of lakes – in state of the art operational models of air pollution (Swedish Defence Research Establishment, Danish Meteorological Institute), wind-energy and wind-load (Genoa University, Italy), water ecosystem (Tartu University, Estonia), and lake thermodynamics (German Weather

Service; Swedish Meteorological and Hydrological Institute – Rossby Centre RCA-model; GKSS Research Centre – CLM-model), thus contributing to a range of interdisciplinary neighbouring fields.

By giving guidance on PBL theory and modelling, SZ has contributed (in Finland and beyond) to the development of the operational NWP system HIRLAM / ALADIN, in particular, to the use of observations from the boreal forest zone for HIRLAM validation in winter conditions with stable stratification.

Works of SZ are included in textbooks (e.g., Z Sorbjan *Structure of the Atmospheric Boundary Layer*, 1989; JR Garratt *The Atmospheric Boundary Layer*, 1992; EB Kraus & JA Businger *Atmosphere-Ocean Interaction*, 1994; LH Kantha & CA Clayson *Small Scale Processes in Geophysical Fluid Flows*, 2000), and comprise an essential part of university courses of BLM (e.g. at University of Helsinki; Russian State Hydrometeorological University, Ukrainian State Environmental University, San Jose State University, USA) and by this means provide a societal impact. They cover a variety of research fields. SZ has supervised 20 PhD students and postdocs in meteorology, oceanography, limnology, space research, and astrophysics; has published a novel and a few essays; and 4 of his pupils has become professors: in mathematics (B Vager – Russia), physical oceanography (DV Chalikov – Russia/USA), experimental fluid mechanics (K Kreiman – Russia/Canada), and meteorology (AA Baklanov – Russia/Denmark).

SZ's international prizes and awards include the European Geophysical Society (EGS) Wilhelm Bjerknes Medal "for his outstanding contribution to the creation of the modern theory of atmospheric turbulent boundary layers" (2000), and the EU-Commission Marie Curie Chair "Planetary Boundary Layers – Theory, Modelling and Role in Earth Systems" (2004-2007). SZ is a member of Academia Europaea. For other memberships and honours see his CV and the Prizes/Awards/Memberships table.

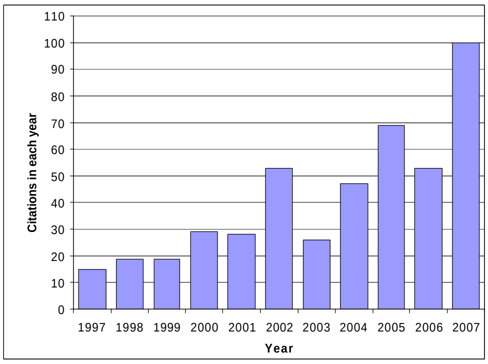

Figure 1. Citation in the last decade (Web of Knowledge)

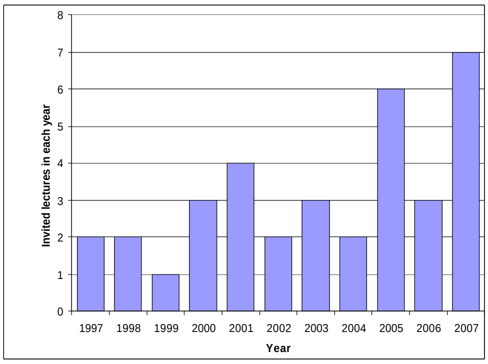

Figure 2. Invited lectures in the last decade

Published biographical notes (selected)

International Biog. Centre, Cambridge, UK: *Dictionary of International Biog.*, Eds. 24th/29th 1996/ 2001; *Men of Achievement*, 16th Ed. 1996; *Outstanding People of 20th Century*, 2nd Ed. 2000; *Outstanding People of 21st Century*, 1st Ed. 2001; *2000 Outst. Intellectuals of 20th Century*, 2000; *2000 Outst. Intellect. of 21st Century*, Eds. 1st/2nd 2001/2003; *2000 Outst. Scholars of 21st Century*, 1st Ed. 2001; *Who's Who in 21st Century*, 1st/2nd Eds. 2001/2002

American Biographical Institute, Raleigh, NC, USA: *5000 Personalities of the World*, 1996; *Internat. Directory of Disting. Leadership*, 6th Ed. 1997; *500 Leaders of Science*, 2003; *The Contemporary Who'Who*, 2002/2003; *International Directory of Experts and Expertise*, 2006

Marquis Who's Who, NJ, USA *Who's Who in the World*, 17th to 20th Eds. (2000, 2001, … 2008); *Who's Who in Science and Engng*, 6th Ed. 2002-2003

Barons Who's Who, USA: *The Europe 500 Leaders for the New Century*, 2000

The Institute for the Advancement of Positive Global Solutions , Irvine, CA, USA
500 Distinguished Professors of the BWW Society, 2003

10-Year-Track-Record

Summary

In 1997, SZ is appointed as Chair of Meteorology at Uppsala University, and in 1998 moves to Sweden. As Head of MIUU (Met Inst Uppsala Univ.) he leads research, supervises/co-supervises 6 PhD, creates a course New Chapters of BLM, co-coordinates EU project SFINCS, initiates 3 national projects and EU Marie Curie Chair project PBL-TMRES (theory, modelling & role in Earth system). In 2004 he is appointed as Marie Curie Chair holder at Univ. Helsinki (UH) and FMI, performs this project (including co-supervision of 5 PhD), initiates new projects, and after PBL-TMRES termination works at UH (leads EU TEMPUS JEP 26005) and FMI (leads PBL physics in EU FP7 MEGAPOLI and other projects). His last-decade achievements are:

1) Discovery and theory of long-lived stable (LS) and conventionally neutral (CN) PBLs – affected by the free flow stability through non-local effects of internal waves and coherent structures (Z & Calanca, 2000; Z, 2002, Z & Esau, 2002, 2003, 2005, 2007; Z & Baklanov, 2002; Z et al., 2002a,b; 2007a). These concepts have entered the terminology and recognised as key elements of the Polar climate system (Z et al., 2002b; Z & Esau, 2008).
2) Solution to old problem of the energetics critical Richardson number in turbulence closure theory (Z et al., 2007b, 2008b) – through analyses of turbulent potential energy, TPE, its exchanges with turbulent kinetic energy, TKE, and the conservation law for total energy, TTE = TKE + TPE [instead of traditional sole use of TKE – blindly following Kolmogorov (1941), which was limited to the neutral stratification where TPE = 0].
3) Non-local theory of convective PBLs: explaining the basically deterministic nature of coherent structures, their generation and interaction with turbulence (Elperin et al, 2002, 2006; authors in alphabetic order); clarifying the nature of counter-gradient transports (Z et al., 1999); and obtaining non-local heat/mass transfer laws through statistical and deterministic treatment of real turbulence and structures, respectively (Z et al., 1998, 2006).

Top 10 publications as senior author (citations are given for the beginning of 2008)

No	**Title of publication**	**Journal**	**Year**	**Volume, pages**	**No** Citations
1	An extended similarity theory for the stably stratified	*QJRMS*	2000	**126**, 1913-1923	49
2	Third-order transport due to internal waves and non-local	*QJRMS*	2002	**128**, 913-925	35
3	Calculation of the height of stable boundary layers	*BLM*	2002	**105**, 389-409	33
4	A new concept of the third-order transport and non-local	*JAS*	1999	**56**, 3463-3477	31
5	Diagnostic and prognostic equations for the depth	*QJRMS*	2002	**128**, 25-46	27
6	The effect of baroclinicity on the depth of neutral and	*QJRMS*	2003	**129**, 3339-33356	27
7	On integral measures of the neutral, barotropic	*BLM*	2002	**104**, 371-379	23
8	Near-surface turbulent fluxes in stable stratification	*QJRMS*	2002	**128**, 1571-1587	20
9	A similarity-theory model for wind profile and resistance	*J. Wind Eng. Ind. Aerod.*	1998	**74-76**, 209-218	16
10	Resistance and heat-transfer laws for stable and	*QJRMS*	2005	**131**, 1863-1892	15

Conferences Table (selected invited lectures)

No	Title of contribution	Name of proceedings	Year	Pub. details	Cit
1	Surface frictional processes	***Buoyant Convection in Geophys. Flows*** (NATO ASI, Pforzheim, Germany, 1997)	1998	Kluwer, Neth. 83-113	20
2	A new concept of the 3rd order transport	Annales Geophys. II, **16**, 1998 (23rd EGS General Assembly); full text in ***JAS***	1999	**56** 3463-3477	31
3	Near-surface turbulent fluxes in stable	Geophys. Res. Abs., GRA3, 2001 (26th EGS Gen. Assembly); full text in ***QJRMS***	2002	**128** 1571-1587	20
4	Atmospheric boundary layers in storms: advanced	***Adv. Geosci.*** (6th Plinius Conf. Medit. Storms, Genoa, Italy, 2004)	2005	**2**, 47-49	1
5	The effect of large eddies on the convective heat	***Croatian Met. J.*** (28th Int. Conf. on Alpine Meteorol., Zadar, Croatia, 2005)	2005	**40**, 20-26	1
6	Resistance and heat/mass transfer laws for neutral	Proc Work. Interdis. Asp. Turbulence, DE 2005, MPI-A 112-114; text in ***QJRMS***	2005	**131** 1863-1892	15
7	The influence of large convective eddies on the	Ext. Abst NATO ARW Air Water Soil. Mod., Georgia, 2005; text in ***QJRMS***	2006	**132** 1423-1456	2
8	Energy- and flux-budget (EFB) turbulence closure	***BLM*** (NATO ARW ABLs: Modelling & Applications, Dubrovnik, Croatia, 2006)	2007	**125**, 167-192	2
9	Similarity theory and calculation of turbulent	SABLE Work. Abstracts and Present., Sedona, USA, 2006; full text in ***BLM***	2007	**125**, 193-296	1
10	Further comments on the equilibrium height	Ext. Abst. Strat. Rot. Flows” 7th French Cong. Mech. FR, 2007; text in ***QJRMS***	2007	**133**, 265-271	2

Conference Organisation Table

No	Title of conference	Respon. sci. soc.	Your function	Place	Year
1	Int. Work. Stable Atmospheric Boundary Layer (SABLE)	US Army; Uni. Uppsala, SE	Org. Committee	Lövånger, Sweden	1997
2	Boundary Layer Physics: Sessions at EMS Meetings	EMS = Europ. Met. Soc.	Convener	New place each year	Since 2004
3	Int. Workshop: Interdisciplinary Aspects of Turbulence	Max Planck Society, DE	Org. Committee	Schloss Ringberg, Bavaria, Germany	2005
4	NATO ARW: Atmos. Boundary Layer Modelling and Application	NATO	Org. Committee	Dubrovnik, Croatia	2006
5	Int. Workshop: Stable Atmosp. Boundary Layer (SABLE)	US Army; Ariz. State Uni, USA	Org. Committee	Sedona, Arizona, USA	2006

Prizes, Awards, memberships

No	Title (< 50 characters)	Institution	Year
1	Vilhelm Bjerknes Medal copernicus.org/EGU/awards/general.html	European Geophysical Society	2000
2	Member	Academia Europaea (Section of Earth and Cosmic Sciences)	2000
3	Distinguished Professor	BWW Society / Inst. for Advancement Positive Global Solutions, Irvine, CA 92609, USA	2002
4	Fellow	Royal Meteorological Society (UK)	2002
5	Marie Curie Chair of Boun.-Layer Physics	EU Commission	2004

Section 1b: The Extended Synopsis of the Project

1. Ground-breaking nature of the research

In the last two decades, the theory of planetary boundary layers (PBLs) undergoes revision. It has been recognised that the non-regular part of the high-Reynolds-number geophysical flows, traditionally treated as turbulence, generally consists of the two principally different types of motion: (i) chaotic “real turbulence” of basically local nature and (ii) coherent structures having the form of long-lived large eddies especially pronounced in the convective PBLs (CBLs), and internal waves in the stable PBLs (SBLs) and other stably stratified flows. Coherent structures, disregarded in the traditional theory, contribute to the transports and strongly affect basic features of PBLs. They exhibit essentially non-local nature (depend of the bulk parameters such as the PBL depth, h, and the static stability outside the PBL), which makes questionable the concept of the flux-gradient correspondence underlying classical heat/mass transfer laws, Monin-Obukhov (MO) similarity theory for the surface layer, and turbulence closures employing locally determined eddy viscosity, conductivity or diffusivity.

This project focuses on the key problems of PBL physics related to the role of PBLs in the Earth system as the atmosphere-land/ocean/biosphere coupling modules, and grounded PBL parameterization schemes (sub-models) in Earth-system models including those for air quality (AQ), numerical weather prediction (NWP), climate-change and renewable energy applications. These are, first of all, non-local resistance and heat/mass transfer (RH/MT) laws determining the near-surface turbulent fluxes, the entrainment laws determining the fluxes at the PBL outer boundary, the PBL depth equations, and turbulence closures – already addressed and to some extent developed in our recent works. In this project they will be completed and empirically validated using both observational and very high resolution large-eddy simulation (LES) data complemented by data from new, unique observational sites and numerical experiments. The numerical-modelling part of the work is designed so that to advance our knowledge about functioning of the Earth system. This goal will be achieved through numerical experimentation and case studies using state of the art environmental models with improved PBL and closure schemes.

Stable boundary layers (SBLs). The traditional PBL theory for the stable stratification was limited to the mid-latitudinal, short-lived nocturnal stable (NS) PBLs developing during a few night hours against almost neutral stratification in the residual layers caused by the strong mixing during the day-time. These PBLs are characterised by the basically local turbulence energetics and are fairly well reproduced by traditional theories. However, they are not unique. As recognised recently, long-lived stable (LS) PBLs often observed in winter at high latitudes exhibit essentially non-local features. The residual layers are not present here, so that PBLs develop against the stably stratified free atmosphere and experience strong impact of the free-flow Brunt-Väisälä frequency, N. Because of internal-wave and coherent-structure mechanisms, N affects the PBL height and the surface-layer turbulence, dramatically contradicting the conventional M-O theory (see Z & Calanca, 2000; Z, 2002; Z & Baklanov,2002; Z & Esau, 2002, 2003, 2005, 2007; Z et al, 2002a,b, 2007a). The effect of N makes LS and NS PBLs much shallower (h down to ~ 30 m) than NS PBLs ($h \sim 200$ m; e.g., Lange et al., 2004). Then the basic assumption underlying modern RH/MT laws and surface-flux algorithms, namely the concept of the surface layer (the lower 10% of the PBL where the turbulent fluxes are taken independent of height) becomes inconsistent, which calls for a more general approach applicable to the entire SBL (Z & Esau, 2007). In this project the non-local theory of SBLs developed in the above cited papers will be completed and used in the climate, AQ, NWP and wind-energy applications.

Convective boundary layers (CBLs). Although the self-organisation of convective flows have been investigating already over a century (since Benard, 1900; Rayleigh, 1916), the physical theory of the CBL accounting for the effects of large coherent structures on the vertical transports is not yet developed. In the meteorological / oceanographic context the conventional format of data analysis is the Deardorff (1970) similarity theory, which uses the convective large-eddy velocity scale $W_* = (\mathrm{b}F_{qs}h)^{1/3}$. The convective RH/MT law accounting for the effect of structures is obtained heuristically – replacing the mean wind speed u by the sum $u + C_1 W_*$, where C_1~1 is an empirical constant (Beljaars, 1994). This approach provides a reasonable approximation but only for the shear-free CBLs (where the structures have the form of 3-D Benard-type cells) over not too rough surfaces. To proceed further, more advanced physical models are needed. To attack on this problem, Z et al. (1998, 2006a) have developed a method based on the deterministic treatment of large eddies as although complex but principally regular flow patterns, in combination with the statistical treatment of chaotic “real turbulence” (in the line with the perturbation and the energy/flux budget analyses: Elperin, Kleeorin, Rogachevskii & Z, 2002, 2006). On this basis they obtained an analytical solution for the surface-layer flow distorted by coherent eddies, accounting for different mechanisms of the flow-surface interaction over smooth and rough surfaces. This theory reproduces the surface fluxes with high accuracy, but is still limited to the shear-free regime with the cell aspect ratios, a = (width)/(height), of order unity.

The effect of coherent structures on the surface fluxes in the CBL with the pronounced shear, $S = \partial u / \partial z$, is not fully understood. In modelling application it is simply neglected with the following commonly accepted justification: at strong winds the contribution from W_* (usually of order 1 m s^{-1}) to the sum $u + C_1 W_*$ is small, therefore the effect of large eddies is negligible. This seemingly convincing reasoning overlooks the fact that the structures typical of the sheared CBL are no longer 3-D cells, but 2-D rolls with the horizontal velocities perpendicular to the mean flow and the aspect ratios varying over an order of magnitude: $1 < a < 10$ (e.g., Miura, 1986; Atkinson and Zhang, 1996). Then, kipping W_* as the vertical velocity scale, the 2-D continuity equation gives the estimate of the horizontal velocity scale: $V_* = a W_*$. At a = 10, it approaches 10 m s^{-1}, which is by no means negligible. A reasonable hypothesis is that the convective rolls are supplied with energy by both the buoyancy forces and the mean shear through the inverse energy cascade (e.g., Elperin et al., 2002, 2006).

In any way, the boundary-layer height, h, enters W_* and controls the convective RH/MT laws. The state of the art CBL growth-rate models are (i) the 2-equation shear-free turbulent entrainment model including prognostic equations for h, and for the heat flux, F_{qh}, due to entrainment at $z = h$ (derived and verified against lab experiments by Z, 1991); and the prognostic h-equation for the sheared CBL assuming a standard value of the entrainment coefficient: $A = F_{qh} / F_{qs} = -0.2$ (Batchvarova & Gryning, 1994; Gryning & Batchvarova, 1996). In reality A can vary from 0 to $1 < A < 1$ depending on the wind shear, condensation of water vapour, etc. Its factually observed variability, $0.05 < A < 0.5$ (see Sullivan et al., 1998; Moeng, 2000; Kim et al., 2003), is by no means negligible. Stainforth et al. (2005) have shown that the 50% reduction of A results in increasing the projected climate temperatures by several degrees. Moreover, A controls the CBL ventilation, in particular, the temperature in street canyons (Roth, 2007).

Accordingly, the first priority CBL-physics problems addressed in this project are to extend the RH/MT laws to the sheared convection accounting for the 2-D roll-type structures; and to derive and to validate a general CBL-height equation accounting for both velocity shear and variable entrainment.

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In view of the modern knowledge about coherent structures, their overall effect on the vertical transports can hardly be successfully modelled using traditional turbulence closure approach bases on the idea that the higher-order statistics are expressed through the lower order statistics. For example, in the shear-free convection the vertical heat flux (2nd moment) is controlled by the vertical velocity skewness, which is the 3rd moment (Z et al., 1999). This fact reflects the principal difference between "real turbulence" characterised by the direct energy cascade (towards chaos) and coherent structures fed by inverse cascades (towards order). In this project we attempt to parameterize the effect of structures using their deterministic models in combination with statistical treatment of "real turbulence"

PBL height as the key parameter suitable for monitoring. Traditionally the role of PBLs in the Earth system is characterised almost solely by the surface fluxes of momentum, energy and matter. In view of the above summary, we consider the PBL height as an additional key parameter. It appears in the non-local RH/MT laws (and surface flux algorithms in NWP or climate models and in data analyses); to a large extent controls concentrations of pollutants within the PBL, behaving roughly as h^{-1} (and enters the state of the art AQ models); and determines the basic features of wind profiles (such as wind shears and low-level jets needed in the wind-energy and wind-load applications). Moreover h essentially controls the sensitivity of surface temperatures to global warming. The thermal impact, $\mathrm{d}T$, caused by an increment in the surface heat balance, $\mathrm{d}F_{\mathrm{qs}}$, behaves as $\mathrm{d}T \sim \int (\mathrm{d}F_{\mathrm{qs}} / h) dt$, where t is the time. This implies that the global warming should be pronounced at high latitudes – in shallow LS PBLs with $h \sim 50$ m or even smaller, but almost undetectable at low latitudes – in deep convective PBLs with $h \sim 10^3$ m (Z & Esau, 2008) – in strict correspondence with the observed stronger temperature responses (the so called polar amplification of global warming) at high latitudes (Polyakov et al., 2002) and in the nighttimes at all latitudes (Easterling, 1997). It follows that h is a very important (and luckily quite predictable) parameter needed to quantify spatial and temporal distribution of the changes in the surface temperature caused by the global warming.

Climate and climate change. Over the last 2-3 decades the Arctic region has warmed more than other regions, and the sea ice-cover has decreased by ~ 10% (IPY-CARE 2006). It is of prime importance for Europe to better understand the Arctic climate and complex feedback mechanisms in the atmosphere-ocean-ice system (Seneviratne et al. 2006). Climate modelling at FMI makes use of a coupled atmosphere-ocean general circulation model ECHAM5/MPI-OM (Roeckner et al. 2003; Jungclaus et al. 2006) and concentrates on the aerosol-cloud-radiative transfer feedbacks (Räisänen et al. 2007, 2008; Kokkola et al. 2007; Lihavainen et al. 2007) and the air-sea interaction processes (Haapala et al. 2003). In this project, further numerical simulation and assessment of the Arctic climate change will be extended using advanced PBL schemes covering newly recognised shallow long-lived PBLs.

Numerical weather prediction (NWP) and wind energy resources. In the light of the above discussion, it is not surprising that the state-of-the-art NWP and meso-scale models (e.g. those used in wind-energy applications), including the operationally run model system HIRLAM (Unden et al., 2002) developed and maintained within the HIRLAM-ALADIN cooperation, are unable to predict correctly the very low temperatures frequently occurring in the LS PBLs (Pirazzini et al., 2002). At stations in northern Finland and north-western Russia, predicted temperatures too warm by as much as 20 K are not uncommon during the wintertime cold spells. Improving the stable PBL parameterization schemes is thus of significant practical importance. Comprehensive PBL measurements are available from the Sodankylä observatory (FMI), making it an ideal site for testing new schemes.

Transport and dispersion of atmospheric admixtures and air quality. (AQ) Most dispersion models, including the Finnish Emergency and Air Quality (AQ) meso-scale modelling system SILAM (Sofiev, 2000, 2002, Sofiev et al, 2006) and the city scale CAR-FMI (Karppinen et al, 2000a,b) use h as an integrated parameter describing the PBL (e.g. Robertson et al., 1999, Kessler et al., 2001, Sofiev et al., 2006). Analyses of the SILAM forecasts of pollution events and observational campaigns confirm necessity to improve modelling the PBL height, h, especially in very stable stratification (Sofiev, 2007, Ruuskanen et al, 2007). Another demanding problem is modelling strong plumes from buoyant sources, such as industrial installations or wild-land fires. Actual injections and downwind near-surface concentrations depend on the turbulence inside the convective zone and the background stratification (e.g. plume-rise model BUOYANT: Nikmo et al., 1999). For instance, the smoke from Russian forest fires in August 2006 was transported over the Gulf of Finland practically without vertical dispersion, which resulted in much higher than predicted concentrations of $PM_{2.5}$ in Helsinki (exceeding 150 µg/m^3).

As demonstrated above, some essential shortcomings of the state of the art environmental models are most probably caused by insufficiently advanced PBL schemes and call for improvement of precisely the aspects of PBL-physics identified above. In this project new PBLs schemes will be implemented and tested in a range of models.

2. Objectives

1. Advancing the key chapters of the PBL physics

   Completing the non-local RH/MT laws, prognostic PBL-height and turbulent entrainment equations, and surface-flux algorithms applicable to all PBL types, with particular attention to shallow, long-lived stable (LS) PBLs and sheared convective PBLs. Advancing the concepts of the momentum and scalar roughness lengths for very rough surfaces. Developing a hierarchy of turbulence closure models based on the concept of TTE and accounting for the internal-wave mechanisms.
2. New data analyses required by theoretical developments

   Empirical validation of and determining empirical constants in new theoretical models. Innovative field experiments complemented by parallel real-time LES addressing “white spots” in the external parameter space. Analysing the outcomes from numerical experimentation using new PBL and turbulence closure schemes. Formulating recommendations to modellers for improved PBL parameterization schemes.
3. New tools for modelling and monitoring the PBL height

   Assessing the remote-sensing methods applicable to all basic PBL types including shallow LS PBLs. Inter-comparison of the outcome from different instruments (ceilometers, other lidars, sodars). Refining the methodology for determining PBL parameters from practically usable instruments. Verification of the recommended PBL height models against observational data. Providing recommendations for operational monitoring of the PBL height, and estimating its added value for NWP, AQ and climate modelling.
4. Advancing the Earth-system modelling tools

   Implementation of the prognostic PBL height equation in the NWP system HIRLAM and corresponding changes in the model architecture. Creating principal linkages between the advanced HIRLAM and the PBL-height monitoring. Implementing and testing new PBL and turbulence closures schemes in the NWP, meteorological pre-processors for AQ, and coupled atmosphere-ocean models. Evaluation of the performance of new PBL schemes via direct (HIRLAM vs. meteorological observations) and indirect (SILAM and CAR-FMI vs. AQ observations) model-measurement comparisons.
5. Summarising result from numerical experimentation with improved environmental models

   Analysing improvements and remaining difficulties with emphasis on (i) extreme weather events, (ii) heavy air-pollution episodes, and (iii) fine features of the climate change. Performing pilot studies of the wind-energy recourses using new modelling tools.

3. Potential impact, enhancement of the research environment and capabilities for frontier research

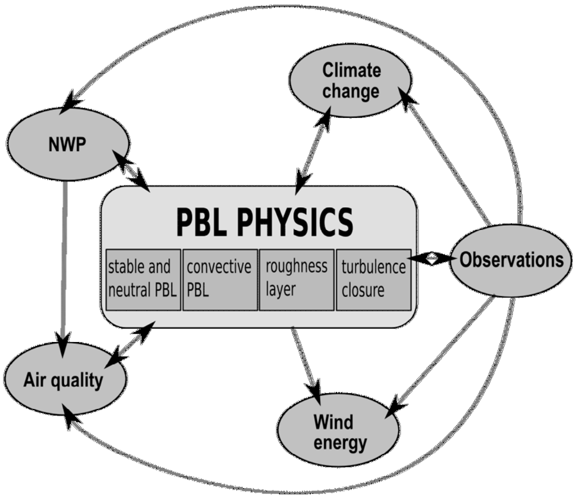
This project is motivated by the necessity to advance the PBL theory in view of its recently disclosed non-local features, and to improve PBL schemes and turbulence closures in environmental models describing the functioning of the Earth system. By this means the project contributes to better modelling of extreme weather events, heavy air pollution episodes, and fine features of climate change. It summarises and further extends our last-decade works in the PBL physics, namely, discovering new PBL types of essentially non-local nature (LS PBLs), advancing our knowledge of the basic effects of coherent eddies in the convective PBLs, physical solution to the turbulence cut off problem in closure models for stable stratification, and stability dependences of the roughness length and displacement height. The time is ripe to improve PBL schemes and closures in parallel with further advancing the state of the art NWP, AQ, climate and wind-energy models. Accordingly, the project opens the following scientific, technological and scholarly horizons.

- to revise the PBL physics with particular attention to the surface turbulent fluxes, PBL height and mean profiles, turbulent entrainment at the PBL outer boundary, and consistent turbulence closures, accounting for non-local effects of the internal wave-turbulence interaction (in long-lived SBLs) and coherent structures (in sheared CBLs)
- to include new physics in an advanced university course of boundary layer meteorology (BLM) and to compile a new textbook on BLM
- to analyse, advance and recommend feasible methods of monitoring the PBL height adjusted to the needs of NWP, AQ and climate modelling
- to replace insufficiently advanced, traditional PBL schemes in state of the art NWP, AQ and climate models and wind-energy applications by the improved schemes (to be developed in this project) and by this means to improve the general performance of the environmental modelling at the European dimension

- to improve – through numerical experimentation with the above models – our knowledge about the functioning of the Earth system

4. Project management

The conceptual project structure and information flows in it are shown in the diagram on the right. The work will be performed by the FMI team (see section 3.1 below) covering expertises in PBL physics, experimental meteorology, NWP/AQ/climate modelling, and wind-energy meteorology) and will also involve postdocs and PhD students occupied in relevant researches. The latter will benefit from this project through active participation in regular interdisciplinary (and as needed narrow-professional) working discussions / seminars that will be arranged for the entire period of the project. Collaboration with complementary projects implemented at FMI and beyond, as well as cooperative work with numerous groups and individuals all over the world is envisaged. This network will be further extended after the start of the project.



5. Feasibility and risks

The experience of the team and available facilities, observations, data analyses and numerical modelling, as well as accessibility of data from very relevant, unique observational sites (such as Sodankylä and Helsinki Testbed) and data bases, perfectly fit all needs of this project and makes its performance absolutely feasible. FMI has a long record of internationally recognised researches, covering all aspects of the project and provides excellent research environment for its performance and minimises all technical, organisational or lack-of-experience risks.

6. Expected scientific and social impact This project contributes to advancing our understanding of non-local PBL mechanisms, and to improving modelling of the basic PBL parameters: turbulent fluxes, PBL height, etc. It includes the development of fully innovative concepts and models, in particular, those for the long-lived stable PBLs affected by the free-flow static stability and the sheared convective PBLs affected by 2-D coherent rolls fed by inverse energy cascades. These developments will be included in the university course on boundary-layer meteorology and the textbook (to be prepared by S. Zilitinkevich and H. Savijärvi), not to mention publications in journals and presentations at conferences, thus making scientific and social impacts. They also will be used as the physical background for improved PBL parameterizations in the next-generation NWP, meso-scale, AQ and climate models. It is conceivable that in NWP the basic direct impact will be from the improved surface-flux schemes, and in AQ and climate modelling – from the more accurate modelling of the height of very stable, shallow PBLs. Besides the social impact (through improving operational forecasts, in Finland and elsewhere) this part of the work will have an additional scientific impact – through improving our understanding of the role of PBLs in the climate system. As already mentioned the sensitivity of the surface temperature to global warming is to a large extent controlled by the heat capacity and therefore by the depth of the layer digesting the thermal impact, in other words, precisely by the PBL height. Thus our project will contribute to refining the spatial and temporal distribution of the climate change.

7. High-gain/high-risk balance The only serious risk in this project represents the following part of Task 3: “Searching for new approaches to the CBL closure using statistical and deterministic methods for real turbulence and coherent structures, respectively”. Although we have made a promising start in this direction (Z et al., 1999; Elperin et al., 2002, 2006), the problem is strongly complicated by the lack of standard methods for analysing the principally non-linear self-organisation processes. We openly admit that the full success, namely, creation of a non-local / non-gradient closure applicable to any convective PBLs (not to mention any convective flows) cannot be guarantied. Hoverer, if quantitative estimates can be applied to basic research, it represents less than 10% of the overall high-gain input from this project. We do not foresee essential risks in all other aspects of the project.

Section 2: The Research Project

1. STATE OF THE ART AND OBJECTIVES

1.1 Ground-breaking nature of the research

In the last two decades, the theory of planetary boundary layers (PBLs) undergoes essential revision. It has been recognised that the non-regular part of the high-Reynolds-number geophysical flows, traditionally treated as turbulence, generally consists of the two principally different types of motion: (i) chaotic “real turbulence” of basically local nature and (ii) coherent structures having the form of long-lived large eddies especially pronounced in the convective PBLs (CBLs), and internal waves in the stable PBLs (SBLs) and other stably stratified flows. Coherent structures, disregarded in the traditional theory, contribute to the vertical transports and strongly affect basic features of PBLs. They exhibit essentially non-local nature (depend of the bulk parameters such as the PBL depth, *h*, and the static stability outside the PBL), which makes questionable the concept of the flux-gradient correspondence underlying classical heat/mass transfer laws, Monin-Obukhov (MO) similarity theory for the surface layer, and turbulence closures employing locally determined eddy viscosity, conductivity or diffusivity.

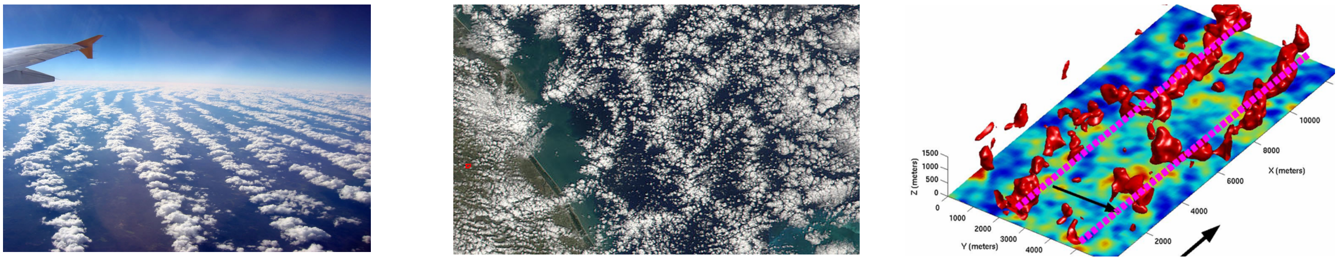


Figure 1. Observational and modelling evidences of the self-organization of turbulence into large-scale structures: rolls (left, aerial photo by J. Gratz, USA) and cells (centre, ENVISAT image A2002050, Florida, NASA) visualized by clouds; and rolls in LES by I Esau.

This project focuses on the key problems of PBL physics related to the role of PBLs in the Earth system as the atmosphere-land/ocean/biosphere coupling modules, and grounded PBL parameterization schemes (sub-models) in the Earth sciences including air quality (AQ), numerical weather prediction (NWP) and climate-change modelling and renewable energy applications. These are, first of all, non-local resistance and heat/mass transfer (RH/MT) laws determining the near-surface turbulent fluxes, the entrainment laws determining the fluxes at the PBL outer boundary, the PBL depth equations, and turbulence closures – already addressed and to some extent developed in our recent works. In this project they will be completed and empirically validated using both observational and very high resolution large-eddy simulation (LES) data complemented by data from new, unique observational sites and numerical experiments. The numerical-modelling part of the work is designed so that to advance our knowledge about the functioning of the Earth system. This goal will be achieved through numerical experimentation and case studies using state of the art environmental models with improved PBL and closure schemes.

Stable boundary layers (SBLs). The traditional PBL theory for the stable stratification was limited to the mid-latitudinal, short-lived nocturnal stable (NS) PBLs developing during a few night hours on the background of the residual layers with almost neutral stratification caused by the strong mixing during the day-time. These PBLs are characterised by basically local turbulence energetics and are fairly well reproduced by traditional theories. However, they are not unique. As recognised recently, long-lived stable (LS) PBLs observed in winter at high latitudes, exhibit essentially non-local features. This is also true for the long-lived PBLs with the zero turbulent heat flux at the surface, which we call conventionally neutral (CN) PBLs. The residual layer is not present in this case, so that the PBL develops against the stably stratified free atmosphere and experiences strong impact of the free-flow Brunt-Väisälä frequency, $N = (\beta \partial \theta / \partial z)^{1/2}$, where β is the buoyancy parameter. Because of internal-wave and coherent-structure mechanisms, *N* affects the PBL height and the surface-layer turbulence (see Z & Calanca, 2000; Z, 2002; Z &

Baklanov, 2002; Z & Esau, 2002, 2003, 2005, 2007; Z et al, 2002a,b, 2007a). In the traditional local theories, in particular, in the Monin-Obukhov similarity theory, this mechanism was disregarded.

As seen in Figure 2, the effect of *N* makes LS and NS PBLs much shallower (h ~ 30 m) than NS PBLs (h ~ 200 m; e.g., Lange et al., 2004). Then the basic assumption underlying modern RH/MT laws and surface-flux algorithms, namely the concept of surface layer (the lower 10% of the PBL where the turbulent fluxes are taken independent of height) becomes irrelevant. This calls for a general approach applicable to the entire SBL (Z & Esau, 2007).

In this project the non-local theory of stable PBLs developed in the above cited papers will be completed and used in the climate, AQ, NWP and wind-energy applications.

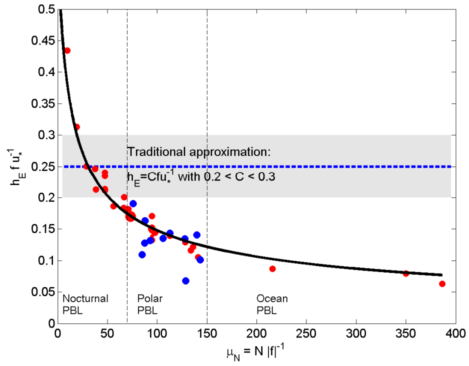


Figure 2. The dependence of the height, h_E, of the equilibrium conventionally neutral PPL on the free-flow Brunt-Väisälä frequency, *N*, after new theory (Z et al., 2007a, shown by the curve), LES (red points) and field data (blue points); $u_* = \tau_s^{1/2}$ is the friction velocity, f is the Coriolis parameter. Until recently the effect of *N* on h_E was disregarded.

Convective boundary layers (CBLs). Although the self-organisation of convective flows have been investigated already over a century (since Benard, 1900; Rayleigh, 1916), the physical theory of the convective PBLs accounting for the effects of large-scale coherent structures on the vertical transports is not yet developed. In the meteorological / oceanographic context, the conventional format of data analysis is the Deardorff (1970) similarity theory, which uses the convective large-eddy velocity scale $W_* = (\beta F_{\theta s} h)^{1/3}$. The convective RH/MT law accounting for the effect of structures is obtained heuristically – replacing the mean wind speed u by the sum $u + C_1 W_*$, where C_1~1 is an empirical constant (Beljaars, 1994). This approach provides a reasonable approximation but only for the shear-free CBLs (where the structures have the form of the 3-D Benard-type cells) over not too rough surfaces. To proceed further, advanced physical models are needed.

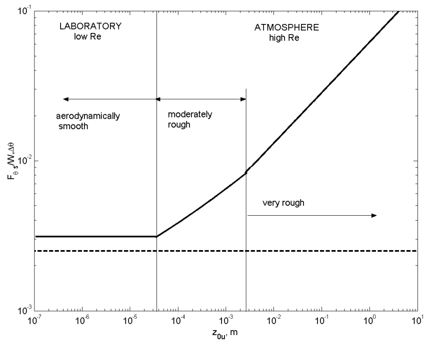


Figure 3. Heat transfer models for shear-free convective PBL: solid line shows the non-local theory (Z et al, 2006a) validated against atmospheric and LES data; dashed line, the classical law: $\mathrm{Nu} = C_{conv}\,\mathrm{Ra}^{1/3}$, where Nu and Ra are the Nusselt and the Rayleigh numbers, and $C_{conv} \approx 0.14$ is an empirical coefficient.

To attack on this problem, Z et al. (1998, 2006a) have developed a method based on the deterministic treatment of a large-eddy structure as a, though complex, but principally regular flow pattern in combination with the statistical treatment of chaotic "real turbulence" (in the line with the perturbation- and the energy/flux budget analyses: Elperin, Kleeorin, Rogachevskii & Z, 2002, 2006). On this basis, they have obtained an analytical solution for the surface-layer flow distorted by coherent eddies, accounting for essentially different mechanisms of the flow-surface interaction over smooth and rough surfaces. This theory reproduces the surface fluxes with high accuracy (Figure 3), but is still limited to the shear-free regime with the cell aspect ratios, *a* = (width)/(height), of order unity.

The effect of coherent structures on the surface fluxes in the CBL with a pronounced shear, $S = \partial u / \partial z$, is not fully understood. In modelling application it is simply neglected with the following commonly accepted justification: at strong winds the contribution from W_* (usually of order 1 m s^{-1}) to the sum $u + C_1 W_*$ is small, therefore the effect of large eddies is negligible. This seemingly convincing reasoning overlooks the fact that the structures typical of the sheared CBL are no longer 3-D cells, but 2-D rolls with the horizontal velocities perpendicular to the mean flow and the aspect ratios varying over an order of magnitude: $1 < a < 10$ (e.g., Miura, 1986; Atkinson and Zhang, 1996). Then, keeping W_* as the vertical velocity scale, the 2-D continuity equation gives the estimate of the horizontal velocity scale: $V_* = a W_*$. At a = 10, it approaches 10 m s^{-1}, which is by no means negligible. A reasonable hypothesis is that the convective rolls are supplied with energy by both the buoyancy forces and the mean shear through the inverse energy cascade (e.g., Elperin et al., 2002, 2006).

In any way, the boundary-layer height, h, enters W_* and controls the convective RH/MT laws. The state of the art CBL growth-rate models are (i) the 2-equations shear-free turbulent entrainment model including prognostic equations for h, and for the heat flux, F_{qh}, due to entrainment at $z = h$ (derived and verified against lab experiments by Z, 1991); and the prognostic h-equation for the sheared CBL assuming a standard value of the entrainment coefficient: $A = F_{qh} / F_{qs} = -0.2$ (Batchvarova & Gryning, 1994; Gryning & Batchvarova, 1996). In reality A can vary from 0 to $1 < A < 1$ depending on the wind shear, condensation of water vapour, etc. Its factually observed variability, $0.05 < A < 0.5$ (see Sullivan et al., 1998; Moeng, 2000; Kim et al., 2003), is by no means negligible. Stainforth et al. (2005) have shown that the 50% reduction of A results in increasing the projected climate temperatures by several degrees. Moreover, A controls the CBL ventilation, in particular, the temperature in street canyons (Roth, 2007).

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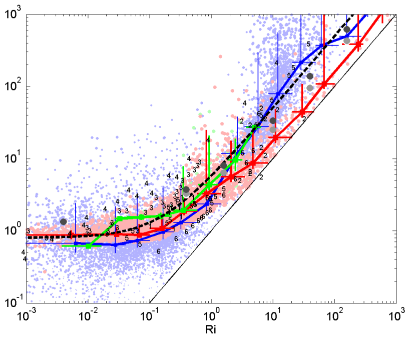

Figure 4. The Ri-dependence of the turbulent Prandtl number, Pr. The blue points and curve and the numbers 1 and 6 show meteorological data; the green curve and the numbers 3,4,5 show laboratory data; the number 2 are data on the sediment-loaded flow; the red points and curve are LES; the grey points are DNS. The dashed curve: $\mathrm{Pr}_T = 0.8 + 5\mathrm{Ri}$ is composed of the two asymptotes with the empirically determined coefficients.

Over decades, this difficulty was overcome only heuristically – using the Ri-dependent coefficients in the expressions for the eddy viscosity and conductivity. Recently an insight into this long-standing problem (since Richardson, 1920) has been gained through the revised analysis of the turbulent energetics involving additional budget equation – for the turbulent potential energy [TPE, conceptually similar to the Lorenz's (1967) available potential energy] and accounting for the energy exchange between TKE and TPE (Z et al., 2007b, 2008b). It has led to the conservation law for the total turbulent energy (TTE = TKE+TPE) and opened new prospects toward development of consistent turbulent closures based on a minimal set of equations for the basic statistical moments. This approach results in an asymptotically linear Ri-dependence of the turbulent Prandtl number $\mathrm{Pr} = K_M / K_H$ and removes the almost century-old problem of the unrealistic turbulence cut off in the traditional turbulent energy analyses. We apply this approach to derive a hierarchy of turbulence closures for environmental applications.

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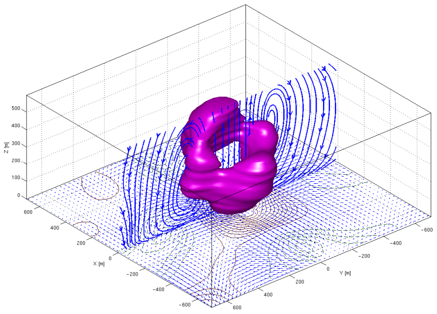


Figure 5. Large coherent eddy in the shear-free convective PBL (Z et al, 2006a). Arrows show the velocity field. The maximum horizontal velocity is 2.8 m s^{-1}. The solid contours in the horizontal plane mark updraughts and the dashed contours, downdraughts (with maximal velocities +1.2 and –0.8 m s^{-1}, respectively). The central torus visualises the iso-surface of the vorticity modulus at 65% of its maximal value.

Roughness layer The flow-surface interaction is modelled using the concepts of the aerodynamic roughness length, z_{0u}, and displacement height, d_{0u}, conventionally considered as geometric parameters characterised by the height, h_0, and the shape of and distance between the roughness elements.

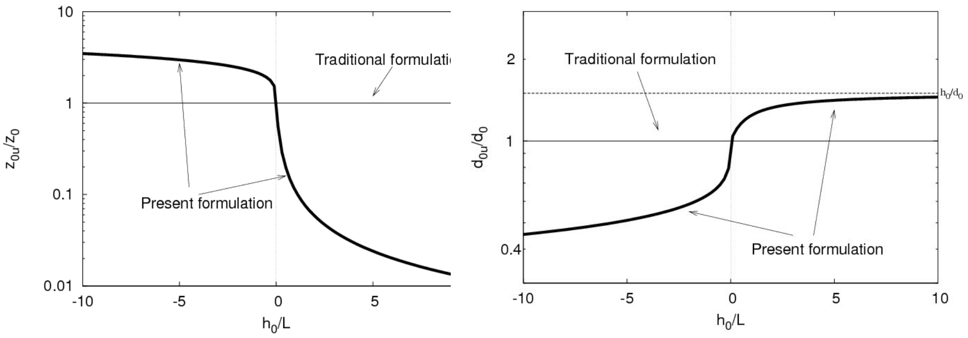


Figure 6. The roughness length and displacement height normalised by their neutral-stability values presented versus h_0/L, where $L = -u_*^3(\mathrm{b}F_{qs})^{-1}$ is the MO length scale.

Z et al. (2006b, 2008b) have obtained theoretically and demonstrated empirically that z_{0u} and d_{0u} essentially depend on the stratification (Figure 6). In the present project this analyses will be extended to the scalar roughness lengths using the concept of the scalar deposition velocity (Z et al., 2001).

The PBL height as the key PBL parameter suitable for operational monitoring. Traditionally the role of PBLs in the Earth system is characterised almost solely by the surface fluxes of energy and matter. In view of the above the modern advancements in the PBL physics, the PBL height should be considered as an additional key parameter. It appears in the non-local RH/MT laws (and enters the improved surface flux algorithms in NWP and climate models and data analyses); to a large extent controls concentrations of pollutants in the PBL – generally proportional to h^{-1} (and enters the state of the art AQ models); and determines the basic features of wind profiles (such as wind shears and low-level jets needed in the wind-energy and wind load applications). Moreover h essentially controls the sensitivity of surface temperatures to global warming. The thermal impact, $\mathrm{d}T$, caused by an increment in the surface heat balance, $\mathrm{d}F_{\mathrm{qs}}$, behaves as $\mathrm{d}T \sim \int(\mathrm{d}F_{\mathrm{qs}}/h)dt$, where *t* is the time. This implies that global warming should be pronounced at high latitudes – in shallow LS PBLs with $h \sim$ 50 m or even less, but almost undetectable at low latitudes – in deep convective PBLs with $h \sim 10^3$ m (Z & Esau, 2008) – in strict correspondence with the observed stronger temperature responses (the so called polar amplification of global warming) at high latitudes (Polyakov et al., 2002) and in the night time at all latitudes (Easterling, 1997). It follows that h is a very important (and luckily quite predictable) parameter needed to quantify spatial and temporal distribution of the changes in the surface temperature caused by the global warming.

To efficiently use new physical models (developed recently and to be developed in this project), operational methods of monitoring h are needed. Luckily, h is an integral parameter weakly sensitive to fine features of the surface and more suitable for operational monitoring than any other PBL turbulence parameters. Although with significant uncertainties, h could be extracted from routine radiosoundings (Troen and Mahrt, 1986; Siebert et al. 2000), specialised ceilometer data, and even on the global scale from satellite GPS (von Engeln, 2006) and lidar data. Remote sensing observations of turbulence and aerosol concentrations using lidars (Frehlich et al. 1998, 2006), in particular, ceilometer (Eresmaa et al., 2006, Münkel et al., 2007), and sodars (Argentini et al., 2005, 2007; Emeis, 2004, 2008; Emeis et al., 2004, 2007a,b; Wiegener et al., 2006; Mastrantonio et al., 1994; Greenhut and Mastrantonio, 1989; Martano et al, 2005; Contini et al., 2007; Kramar & Kouznetsov, 2002; Kouznetsov et al., 2004, 2007) provide reasonable tools for this purpose. In this project special efforts are devoted to improving remote sensing methods for determining the PBL height and adjusting the recommended techniques to the needs of its operational monitoring.

Climate and climate change. Over the last 2-3 decades the Arctic region has warmed more than other regions, and the sea ice-cover has recently decreased faster than climate models had predicted (Stroeve et al., 2007), with a record-minimum ice extend reached in summer 2007. It is of prime importance for Europe to better understand the Arctic climate and the complex feedback mechanisms in the atmosphere-ocean-ice system (Seneviratne et al. 2006). The Climate Change Research Unit at FMI uses a coupled atmosphere-ocean general circulation climate model ECHAM5/MPI-OM (Roeckner et al. 2003; Jungclaus et al. 2006) and concentrates its investigations on the aerosol-cloud-radiative transfer feedbacks (Räisänen et al. 2007, 2008; Kokkola et al. 2007; Lihavainen et al. 2007) and the air-sea interaction processes (Haapala et al. 2003). The Meteorological Research Unit also studies the Polar PBL and atmosphere-ice-ocean interactions (Vihma et al., 2002; 2003; 2005; Haapala et al., 2003; Vihma & Pirazzini, 2005; Lüpkes et al., 2008; Valkonen et al., 2008). In this project, our boundary layer and surface exchange studies will be applied to the ECHAM5/MPI-OM model, and the implications of the new PBL theories for the Arctic climate change will be assessed.

Numerical weather prediction (NWP) and wind energy resources. In the light of the above discussion, it is not surprising that state-of-the-art NWP and meso-scale models (in particular, for wind-energy applications), including the operationally run model system HIRLAM (Unden et al., 2002) developed and maintained within the HIRLAM-ALADIN cooperation, are unable to predict correctly the very low temperatures frequently occurring in LS PBLs (Pirazzini et al., 2002). At stations in northern Finland and north-western Russia, predicted temperatures too warm by as much as 20 K are not uncommon during wintertime cold spells. Improving the SBL parameterization is thus of significant importance. Comprehensive PBL measurements are available from the Sodankylä observatory (FMI), making it an ideal site for testing the new SBL models and parameterizations.

Transport and dispersion of atmospheric admixtures and air quality (AQ). Most dispersion models, including the Finnish Emergency and Air Quality (AQ) meso-scale modelling system SILAM (Sofiev, 2000, 2002, Sofiev et al, 2006) and the city scale CAR-FMI (Karppinen et al, 2000a,b), use h as an integrated parameter characterising the PBL (e.g. Robertson et al., 1999, Kessler et al., 2001, Sofiev et al., 2006). Analyses of the SILAM forecasts of pollution events and observational campaigns confirm the necessity to improve the modelling of h, especially in very stable stratification (Sofiev, 2007, Ruuskanen et al, 2007). Another demanding problem is modelling strong plumes from buoyant sources, such as industrial installations or wild-land fires. Actual injections and downwind near-surface concentrations depend on the turbulence inside the convective zone and the background stratification (e.g. plume-rise model BUOYANT: Nikmo et al., 1999). For instance, the smoke from Russian forest fires in August 2006 was transported over the Gulf of Finland practically without vertical dispersion, which resulted in much higher than predicted concentrations of $PM_{2.5}$ in Helsinki (exceeding 150 µg/m^3).

As demonstrated above, some essential shortcomings of the state of the art environmental models are most probably caused by insufficiently advanced PBL schemes and call for the improvement of precisely the aspects of the PBL-physics identified above. In this project new PBLs schemes will be implemented and tested in a range of models.

1.2 Objectives

1. Advancing the key chapters of PBL physics

   Completing the non-local RH/MT laws, prognostic PBL-height and turbulent entrainment equations, and surface-flux algorithms applicable to all PBL types, with particular attention to shallow, long-lived stable (LS) PBLs and sheared convective PBLs. Advancing the concepts of the momentum and scalar roughness lengths for very rough surfaces. Developing a hierarchy of turbulence closure models based on the concept of TTE and accounting for the internal wave mechanisms.

2. New data analyses required by theoretical developments

   Empirical validation of and determining empirical constants in new theoretical models. Innovative field experiments parallel with real-time LES addressing “white spots” in the external parameter space. Analysing the outcomes from numerical experimentation using new PBL and turbulence closure schemes. Formulating recommendations to modellers for improved PBL parameterizations.

3. New tools for modelling and monitoring the PBL height

   Assessing remote-sensing methods applicable to all basic PBL types including shallow LS PBLs. Inter-comparison of the outcome from different instruments (ceilometers, other lidars, sodars). Refining the methodology for determining PBL parameters from practically usable instruments. Verification of the recommended PBL height models against observational data. Providing recommendations for operational monitoring of the PBL height, and estimating its added value for NWP, AQ and climate modelling.

4. Advancing the Earth-system modelling tools

   Implementing the prognostic PBL height equation in NWP system HIRLAM and introducing corresponding changes in the model architecture. Creating principal linkages between the advanced HIRLAM and the PBL-height monitoring. Implementing and testing new PBL and turbulence closures schemes in the NWP, meteorological pre-processors for AQ, and coupled atmosphere-ocean models. Evaluation of the performance of new PBL schemes via direct (HIRLAM vs. meteorological observations) and indirect (SILAM and CAR-FMI vs. AQ observations) model-measurement comparisons.

5. Summarising result from numerical experimentation with improved environmental models

   Analysing improvements and remaining difficulties with emphasis on (i) extreme weather events, (ii) heavy air-pollution episodes, and (iii) fine features of the climate change. Performing pilot studies of wind-energy resources using new modelling tools.

Compulsory Deliverables

- Non-local RH/MT laws and advanced surface-flux algorithms for all PBL types
- Prognostic equations for the PBL height and turbulent fluxes due to entrainment
- Stability dependent formulations for the roughness lengths and displacement heights for momentum and scalars
- TTE-based turbulence closures for any stably stratified flows
- A “statistical + deterministic closure” for convective PBLs (high-risk attempt)
- Parallel observations and real-time LES – to interpret outputs from different instruments
- Interpretation of observational data using LES
- Recommendations for operational monitoring of the PBL height for use in NWP and beyond
- Incorporation of h-equation in operational surface-flux algorithms
- Operational modelling and monitoring of the PBL height (with corresponding changes in the conventional architecture of NWP systems)
- New, improved versions of HIRLAM (for NWP and wind-energy applications); SILAM and CAR-FMI (for AQ); and ECHAM5-MPI-OM (for climate change) equipped with advanced PBL schemes

- Advanced modelling of the Arctic climate, in particular, of the fine features of the spatial and temporal picture of climate change

1.3 Potential impact, enhancement of the research environment and capabilities for frontier research

This project is motivated by the necessity to advance the PBL theory in view of its recently disclosed non-local features, and to improve PBL schemes and turbulence closures in environmental models simulating the Earth system. By this means, the project will contribute to a better modelling of extreme weather events, heavy air pollution episodes, and fine features of climate change. It summarises and further extends our prior (especially last-decade) works in the PBL physics, namely, discovering new PBL types of essentially non-local nature (LS PBLs), advancing our knowledge of the basic effects of coherent eddies in convective PBLs, physical solution to the turbulence cut off problem in closure models for stable stratification, and stability dependences of the roughness length and displacement height. The time is ripe to improve PBL schemes and turbulence closures in the state of the art NWP, AQ, climate and wind-energy models. Accordingly, the project opens the following scientific, technological and scholarly horizons:

- To revise and to essentially develop the PBL physics with particular attention to the surface turbulent fluxes, PBL height and mean profiles, turbulent entrainment at the PBL outer boundary, and consistent turbulence closures, accounting for insufficiently understood non-local effects of the internal wave – turbulence interaction (especially in the long-lived SBLs) and coherent structures (especially in the sheared CBLs)
- To include new physics in an advanced university course of boundary layer meteorology (BLM) and to compile a new textbook on BLM
- To analyse, advance and recommend feasible methods of monitoring the PBL height adjusted to the needs of NWP, AQ and climate modelling
- To replace insufficiently advanced, traditional PBL schemes in the state of the art NWP, AQ and climate models and wind-energy applications by the improved schemes (to be developed in this project) and by this means to improve the general performance of the environmental modelling at the European dimension
- To improve – through numerical experimentation with the above models – our knowledge about the functioning of the Earth system

2. METHODOLOGY

2.1 Research methodology and scientific approach

In theoretical analyses, we apply a combination of the statistical description of the chaotic “real turbulence” (in terms of turbulent energies, fluxes and other moments) and deterministic models of coherent structures and internal waves. Imperative requirements to the PBL parameterizations are: availability of input data from operational models and computationally effective algorithms, which factually implies analytical solutions.

Validation of new PBL models and turbulence closures requires data under fully controlled conditions covering a wide range of stratification regimes. Accordingly, we will analyse experimental data in combination with LES, and will perform new, unique field experiments parallel with real-time LES. Besides already available LES DATABASE64, new LES will be performed using the Large Eddy Simulation Nansen Centre Improved Code LESNIC (Esau, 2004) updated to address the specific tasks of this project – to cover all PBL types. LES as such will be additionally verified against experimental data.

Special effort will be made to optimise the methodology of the remote sensing observations of the PBL height. *h*. Ceilometers measure the optical backscatter intensity, *B*, proportional to the aerosol concentration. The latter is generally lower in the free atmosphere than in the PBL; therefore h can usually be seen as the point (h_{cei}) of the strong gradient in the vertical *B*-profile. This method faces problems in polluted residual layers, in the presence of clouds or in too clean regions. Sodars measure the temperature fluctuation intensity and allow detecting h as the point of maximal fluctuations (h_{sod}). Recently, high resolution scanning Doppler lidar has been used to extract spatially averaged wind and turbulence profiles with 10 to 30 m vertical resolution providing estimates of the PBL height (h_{lid}) (Frehlich et al. 1998, 2006). The horizontal spatial averaging (1-4 km^2) provides information representative of the NWP model grid cell. This information is a critical input to dispersion calculations for the security applications (Pentagon Shield project: Warner et al. 2007).

To develop recommendations for operational monitoring of h, the above methods will be inter-compared and their interpretations will be refined and harmonised using the NERSC large-eddy simulation (LES) code LESNIC (Esau, 2004; Esau & Z, 2006).

2.2 Intermediate goals and novel aspects

Project flow

WP1 PBL physics and turbulence closure
(leader: S. Zilitinkevich; collaborators: BGU, WIS, NERSC, DMI, ISAC-CNR, IMK-IFU, IAP-RAS)

Task 1.1 SBL: Completing generalised similarity theory, analytical models, and RH/MT laws for all SBL types (start point: Z & Esau, 2005, 2007). Investigating low-level jets and capping inversions and developing their analytical models and parameterizations. Establishing connections between the MO and the Richardson-number similarity theories and the TTE turbulence closures (start point: Z et al., 2007b, 2008b). Refinement of the PBL relaxation time scales in the stable PBL height equation (Z & Baklanov, 2002; Z et al., 2007a).

Task 1.2 CBL: Investigating the energetics and aspect ratios of 2-D rolls in the sheared convective PBL through data analysis and LES, and developing analytical models of convective cells and rolls. On this basis, extending the convective RH/MT laws (Z et al., 2006a) to the sheared convective PBLs. Deriving a general convective PBL-height equation accounting for the effects of entrainment, surface shear and baroclinic shear (start points: Z, 1991; Z and Esau, 2003).

Task 1.3 Turbulence closure: Developing a hierarchy of the TTE turbulence closures for stable PBLs with due regard to (i) internal waves, (ii) third-order turbulent transports, and (iii) specific processes at the surface (start points: Z et al., 2007b, 2008b; Mauritsen et al., 2007; Z, 2002; L’vov et al., 2006). Extending the theory to turbulent diffusion (start point: Sofiev et al., 2008). Searching for new approaches to the turbulence closure for convective PBLs using statistical and deterministic methods for real turbulence and coherent structures, respectively [start points: Z et al. (1999) and Elperin et al. (2002, 2006)].

Task 1.4 Empirical verification of new models and development of new physical parameterizations: Data-analyses, observational and LES support to Tasks 1.1; development of new PBL parameterizations and their calibration: 1st stage – against empirical data; 2nd stage – within models (in WP 3).

WP 2 Remote sensing observations of the PBL-height
(leader A. Karppinen; collaborators NERSC, ISAC-CNR, IMK-IFU, CIRES, IAP-RAS)

Task 2.1 Ceilometers/sodars: Refining the method utilizing the 7 “Helsinki Testbed” ceilometers (testbed.fmi.fi/), with emphasis on cloudy conditions (start point: Eresmaa et al., 2006). Assessing the spatial and temporal variability of the PBL height utilising aerosol profile data.

Task 2.2 Parallel observations and real-time LES: Updating the LES code LESNIC (Esau, 2004) and adjusting it to specific problems of the PBL monitoring. Supplementing the LES DATABASE64 (Beare et al., 2006; Esau & Z, 2006) with data from new runs (and other available data) – to cover all the required PBL regimes. Developing methods for processing observational and LES data in a unified format.

Task 2.3 Intercomparison: Comparing current instruments and methods (sodar, lidar and Doppler lidar) between each other and with real time LES – to clarify the physical entity really measured by the instruments and to provide recommendations for operational use.

WP 3 New PBL and turbulence closure schemes in NWP, meso-scale, AQ, and climate models
(leader C Fortelius; collaborators: MPI-M, DMI)

Task 3.1 Programming and implementing the new PBL scheme in NWP system HIRLAM: Using the opportunity of modular structure of the program code of HIRLAM (hirlam.org) to replace the existing PBL module by the new one, expressed in terms of variables and parameters available in HIRLAM, and maintaining the overall consistency of the code (a particular challenge is that the new scheme involves the *prognostic* PBL height, which involves changes in the dynamical core of HIRLAM)), by taking into account interactions with the other parameterizations that depend on surface properties (Rontu, 2006).

Task 3.2 NWP: Comparing new and current PBL schemes using 1-D single-column version of FMI-HIRLAM – to ensure that the parameterized processes occur as expected, and interact realistically with other processes in the model. Assessing the new PBL scheme (i) by comparison with data from Sodankylä (sub-polar boreal forest); and (ii) in full-scale NWP experiments

Task 3.3 Wind energy: Pilot numerical experiments with the meso-scale HIRLAM equipped with specific "wind energy PBL module" (including the analytical wind profiles and the convective roll schemes).

Task 3.4 AQ: Adjusting data-utilising modules in SILAM to the new diagnostic and prognostic PBL schemes; implementing new schemes into SILAM and CAR-FMI and evaluating their performance through comparison of the output with AQ observations.

Task 3.5 Climate and climate change: Equipping the FMI version of ECHAM5/MPI-OM with the new PBL scheme; parallel simulations using the current and the new schemes and their verification against existing data sets on the current climate conditions; and, following IPCC emission scenarios, simulation of the future climate conditions and comparison with the simulated climate of the coordinated experiments of the IPCC AR4, AR5.

Milestones

M1. The stable PBL model completed and evaluated against empirical data: first version and parameterization – 2nd year; final – 4th year

M2. The convective PBL model completed and evaluated against empirical data: first version and parameterization – 3rd year; final – 4th year

M3. Turbulence closure completed and empirically evaluated: for stable flows – 3rd year; for CBLs – 5th year

M4. Improved methodology of monitoring the PBL height formulated and evaluated: 3rd year

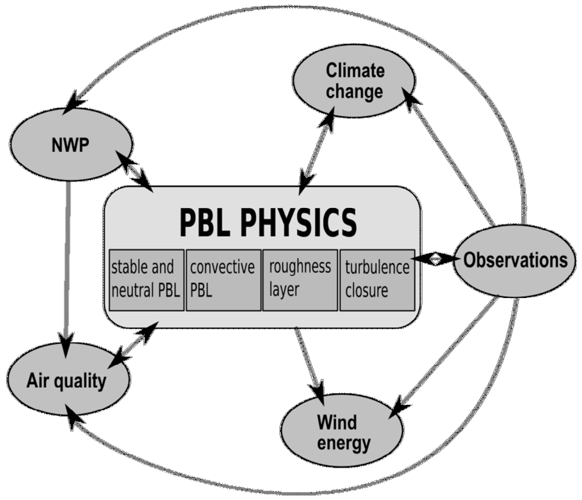
M5. New PBL parameterization (with the prognostic PBL height) implemented and tested in NWP model system: 3rd year

M6. Full package of new PBL schemes / closures implemented and evaluated in NWP, meso-scale, AQ and climate models: 4th year

M7. Summary of results from new theoretical development and numerical experimentation: 5th year

Project management

The conceptual project structure and information flows in it are shown in the diagram on the right. The work will be performed by the FMI team (see 3.1 above) covering expertises in PBL physics, experimental meteorology, NWP/AQ/climate modelling, and wind-energy meteorology) and will also involve postdocs and PhD students occupied in relevant researches. The latter will benefit from this project through active participation in regular interdisciplinary (and as needed narrow-professional) working discussions / seminars that will be arranged for the entire period of the project. Of many external groups collaborating with the team members and expressed interest in this project, those which have long records of cooperation and joint papers with PI and/or other key persons in our team and have officially confirmed their willingness to contribute to this project on their own budgets are listed below in COLLABORATORS.



The project involves three Units and several groups at FMI, whose expertises complement each other and cover all basic aspects of this project. The Meteorological Research Unit hosts the project PI, provides him with managerial and secretarial supports, and is responsible for the PBL and turbulence physics, meteorological observations, and applications to NWP (with nine external collaborators). The Air Quality Research Unit is responsible for advancing the remote sensing observations of the PBL height (with the world known manufacturer of meteorological instruments "Vaisala" and other collaborators), parallel observations and LES (with NERSC), and AQ applications (with DMI). The Climate Change Division (with MPI-M and other collaborators) is responsible for the climate modelling applications. In concrete tasks, collaboration is envisaged with other groups at FMI (see section 3), external collaborators, and the Division of Atmospheric Sciences and Geophysics of the University of Helsinki (placed at the same campus). The project management is strongly favoured by the fact that the involved FMI groups are all placed in the same building and have long record of cooperation between each other and with external collaborators (including joint peer reviewed papers involving the PI). It is already settled that the project will be performed in close cooperation with ongoing complementary activities, such as the EU FP7 project MEGAPOLI (grant agreement No. 212520 coordinated by DMI), the Academy of Finland project IS4FIRES (coordinated by FMI), etc. Efforts will be made to extend such cooperation to other internationally sound initiatives relevant of PBL physics and applications.

More practically, the management will be implemented through a Steering Group (SG) involving the WP leaders and stake holders, which will meet twice a year to monitor the advances of the work and sketch the forthcoming activities among the partners until the next SG meeting. The Steering Group will also coordinate the dissemination of current results. The activity and advances of the postdocs and PhD students involved in the project will be monitored constantly through direct interactions nearly every day, but also with dedicated seminars basically every two months.

2.3 Feasibility and risks

The experience of the team and available facilities, observations, data analyses and numerical modelling, as well as accessibility of data from very relevant, unique observational sites (such as Sodankylä and Helsinki Testbed) and data bases, perfectly fit all needs of this project and makes it performance absolutely feasible. FMI has a long record of internationally recognised researches, covering all aspects of the project and provides excellent research environment for its performance and minimises all technical, organisational or lack-of-experience risks.

Expected scientific and social impact. This project contributes to advancing our understanding of non-local PBL mechanisms, and to improving modelling the basic PBL parameters: turbulent fluxes, PBL height, etc. It includes development of the fully innovative concepts and models, in particular, those of the long-lived stable PBLs affected by the free-flow static stability and the sheared convective PBLs affected by 2-D coherent rolls fed by inverse energy cascades. These developments will be included in the university course on boundary-layer meteorology and the textbook being currently prepared by S. Zilitinkevich and H. Savijärvi, not to mention publications in journals and presentations at conferences, thus making scientific and social impacts. They also will be used as the physical background for improved PBL parameterizations in the next-generation NWP, meso-scale, AQ and climate models. It is conceivable that in NWP the basic direct impact will be from the improved surface-flux schemes, and in AQ and climate modelling – from the more accurate modelling of the height of very stable, shallow PBLs. Besides the social impact (through improving operational forecasts, in Finland and elsewhere) this part of the work will have an additional scientific impact – through improving our understanding of the role of PBLs in the climate system. As already mentioned the sensitivity of the surface temperature to global warming is to a large extent controlled by the heat capacity and therefore by the depth of the layer digesting the thermal impact, in other words, precisely by the PBL height. Thus, our project will contribute to refining the spatial and temporal distribution of climate change.

Applicability and feasibility of research results; publication and dissemination. Thanks to the concentration of efforts within one team the problems of interaction between workpackages, applicability and feasibility are solved through involvement of the key persons in all aspects of the project. Furthermore, the NWP, AQ, climate-change and wind-energy parts of the team represent also the end users, so that delivering the results to end users is done automatically. For wider dissemination, regular instruments, such as the HIRLAM-ALADIN partnership will be used. The main results will be published in peer-reviewed journals and presented at conferences. The project web site will be created within the first three months. The new concepts, methods and numerical results will be made available to relevant organisations like ECMWF, EMEP, CAFÉ (Clean Air for Europe) and EEA (European Environmental Agency) and elsewhere. The new PBL schemes will be offered as an update to the HIRLAM-ALADIN (HARMONIE) Forecasting System. Once accepted the innovations will find fast and wide-spread application in operational NWP as well as in the research, thus yielding immediate benefits to the public. Achievements in the PBL physics will be included in the university course on boundary-layer meteorology and a new textbook.

High-gain/high-risk balance. The only serious risk in the project represents the following part of Task 1.3: "Searching for new approaches to the CBL closure using statistical and deterministic methods for real turbulence and coherent structures, respectively". Although we have made a promising start in this direction (Z et al., 1999; Elperin et al., 2002, 2006), the problem is strongly complicated by the lack of standard methods for analysing the principally non-linear self-organisation processes. We openly admit that the full success, namely, creation of a non-local / non-gradient closure applicable to any convective PBLs (not to mention any convective flows) cannot be guarantied. However, if quantitative estimates can be applied to basic research, it represents less than 10% of the overall high-gain input from this project. We do not foresee essential risks in all other aspects of this project.

3. RESOURCES

3.1 The team and collaboration

Team members and their roles

1. Sergej Zilitinkevich (Professor): PI and manager of WP1, focuses on PBL physics, contributes to all WPs (full support from the project)
2. Ari Karppinen (Adjunct Prof, Dr, Head of Atmospheric Dispersion Modelling Group in AQ Research Unit): manager of WP2
3. Carl Fortelius (Dr, Head of Numerical Weather Prediction Group in Meteorological Research Unit - MRU): manager of WP3
4. Mikhail Sofiev (Adjunct Prof, Dr, Leader of SILAM Group), responsible for AQ in WP3 (50% support from the project)
5. Timo Vihma (Adjunct Prof, Dr, Senior Sci. in MRU), PBL physics and parameterization, contributes to WP1
6. Heikki Järvinen (Res. Prof., Climate Change Research, Earth System Modelling), responsible for climate in WP3
7. Laura Rontu (Dr, Senior Scientist, in MRU), wave-induced transport of momentum, contributes to WP1-3 (hired 50% on the project)
8. Markku Kangas (Dr, Senior Scientist, in MRU), HIRLAM-AROME model structure, PBL and model data file compilation, analysis and management in WP1 and WP3 (50% on the project)
8. Igor Esau (Dr, PBL physics and LES), to be hired (40%) for work in WP1-2
9. Ivan Mammarella (Dr, experimental PBL physics), to be hired (40%) for work in WP1-2
10. Rostislav Kouznetsov (Dr, PBL physics and remote sensing observations), to be hired for work in WP1-2
11. Noora Eresmaa (PhD student, air quality) to be hired for work in WP2
12. Karoliina Ljungberg (PhD student, meteorology-climate) to be hired for work in WP3

National and international cooperation

The team participates in numerous complementary projects: S. Zilitinkevich has held a EU Marie-Curie Chair “PBL-TMRES” (2004-2007; involving 42 groups from 21 countries, atm.helsinki.fi/PBL), coordinates EU TEMPUS JEP 26005-2005 (2007-2009, combat-meteo.net), and is responsible for the urban PBL physics in EU FP7 “MEGAPOLI” (No. 212520, 2008-2011; 23 EU and 15 non-EU partners; coordinated by A. Baklanov collaborating with our project). T. Vihma is the vice-chair of the steering group of BALTEX (gkss.de/baltex/baltex_frame_builder.html) and coordinates WP on air-ice interaction in EU-FP6 IP DAMOCLES (damocles-eu.org/index.shtml). M. Sofiev coordinates the Academy of Finland project IS4FIRES “An integrated monitoring and modelling system for wild-land fires (2008-2010) and participates in EU-FP6 projects “Global Earth-system monitoring using satellites and in-city data” and “European integrated project on aerosol cloud climate and air quality interactions”. L. Rontu is the co-manager of the Nordic Network on Fine-scale Atmospheric Modelling (netfam.fmi.fi/, 20 partners) funded by NORDFORSK. As a member of the HIRLAM programme, FMI maintains partnership with the ALADIN-consortium led by Meteo France involving 10 EU countries. Thus, our project will benefit from direct interaction with a very strong coalition of experts in PBL physics and NWP/meso-scale/AQ/climate modelling.

Collaborators (participate with own budgets; selected joint papers with PI / team members cited in brackets)

NERSC (Nansen Env. & Remote Sensing Centre) Norway, nrsc.no., Dr I Esau igore@nersc.no, LES of turbulence (Esau & Z, 2006, 2008; Z & Esau, 2002, 2003, 2005, 2007)

DMI (Danish Met. Instit.) dmi.dk. Dr A Baklanov alb@dmi.dk, env. Physics and modelling (Baklanov et al., 2005; Z & Baklanov, 2002; Z et al., 2002a, 2006b, 2007a, 2008a); coordinates complementary EU FP7 project MEGAPOLI FMI; Dr NW Nielsen nwn@dmi.dk (Nielsen, 2007)

ISAC-CNR (Inst. Atmos Sci., Clim.) Italy isac.cnr.it Drs G Mastrantonio g.mastrantonio@isac.cnr.it, S Argentini stefania.argentini@ifa.rm.cnr.it, exp. PBL phys. (sodar) (Argentini et al., 2007)

IMK-IFU (Institute for Meteorology & Climate Research – Atmos. Env. Res.) Germany. Dr S Emeis stefan.emeis@imk.fzk.de, experimental meteorology (Emeis & Z, 1991).

CIRES (Cooperative Institute for Research in Env. Sci., University of Colorado) USA. Prof R Frehlich rgf@cires.colorado.edu, principles of meteorological observations

IAP-RAS (Inst. Atmos. Physics – Russian Acad. Sci.) Profs G Golitsyn mail_adm@ifaran.ru, M Kalistratova, climate, PBL turbulence, sodars (Golitsyn et al., 2003)

BGU (Mech. Eng., Ben Gurion University) Israel, cmsprod.bgu.ac.il/eng/engn/me, Profs T Elperin elperin@bgu.ac.il, N. Kleeorin nat@bgu.ac.il, I Rogachevskii gary@bgu.ac.il, theor. phys. (Elperin et al., 2002, 2006; Z et al. 2007b, 2008b)

WIS (Chem. Phys., Weizmann Inst. Sci.) Israel, www.weizmann.ac.il/chemphys/, Prof VS L'vov, victor.lvov@weizmann.ac.il, theor. phys. (L'vov et al., 2006)

MPI-M (Max Planck Inst. Meteorol.) Germany, mpimet.mpg.de, Dr M Giorgetta, marco.giorgetta@zmaw.de, climate modelling (Räisänen et al., 2007)

AZU (Mechanical & Aerospace Engineering, Arizona State University) USA, efd.asu.edu, environmental fluid dynamics, Prof HJS Fernando (Zilitinkevich et al., 2006a)

3.2 Infrastructure and instruments

Models

The NWP model used in this project is developed jointly by the HIRLAM and ALADIN consortia (hirlam.org, Undén et al. 2002) – representing approximately 20 European national weather services. Presently, prognostic variables in the atmosphere are: horizontal wind, temperature, humidity, cloud condensate, surface pressure, and TKE used in the turbulence closure model (Cuxart et al., 2000). Solar and terrestrial radiation is parameterized using fast algorithms (Savijärvi, 1990). The atmosphere couples to the surface via fluxes of momentum, sensible heat and latent heat, treated in the framework of the MO surface-layer theory (Louis et al. 1981). It is this coupling that is to be improved in the project. Similar physics is employed in new meso-scale model (to be used in wind-energy applications).

The FMI regional and large-scale AQ model system SILAM (Sofiev et al., 2006; silam.fmi.fi) is used within EU-GEMS and ESA-PROMOTE projects. It has been extensively evaluated against measurements and other models (Sofiev et al., 2006). Its meteorological pre-processor (Genikhovich & Sofiev, 2003) employs the traditional MO similarity theory, and is to be advanced in this project. The FMI urban-scale dispersion modelling systems is a combination of the Urban Dispersion Modelling system (UDM-FMI) and the road network dispersion model CAR-FMI (Contaminants in the Air from a Road network) – both developed at FMI (Karppinen et al., 2000a). Its performance has been evaluated by comparing the model predictions with results from the urban air quality monitoring network of the Helsinki Metropolitan Area Council (YTV) in 1993 (Karppinen et al., 2000b) and in 1996–1997 (Kousa et al., 2001) and against field measurements (Kukkonen et al., 2001).

FMI coordinates the Earth system modelling activities in Finland and contributes to the COSMOS Network (http://cosmos.enes.org) model development activities. The coupled atmosphere-ocean general circulation climate model ECHAM5/MPI-OM is the core of the COSMOS Earth system model, with a wide development and utilization community. This project is not an isolated effort but a potentially significant and highly synergic contribution complementary to the efforts in the ongoing Finnish Academy's Centre of Excellence on Climate change. The climate model run at FMI is based on the state of the art coupled atmosphere-ocean model system ECHAM5/MPI-OM developed at Max Planck Institute for Meteorology (MRI-M, Hamburg, Germany). Our work on its modification (implementation of the new PBL scheme and new turbulence closure physically grounded up to very stable stratification) will be performed in collaboration with MPI-M.

Databases (selected)

PBL data from FMI-ARC (Sodankylä Arctic Research Centre, fmiarc.fmi.fi/, 120 km north of the Arctic circle, frequently occurring spells of long-lived SBLs; one of the sites for continuous monitoring of the HIRLAM Forecasting System): measured profiles of wind, temperature, humidity, radiative and turbulent fluxes from a 48 m high tower, and daily radio soundings. Will be used in WP1-2.

Data base of “Helsinki Testbed” (mesoscale observational network in the southern Finland coastal high-latitude area 150 x 150 km, run by FMI and Meteorological Instrument Company Vaisala, testbed.fmi.fi/): 44 meteorological masts, 7 ceilometers, 3 RAOB sounding stations, UHF wind profiler, 1 Doppler lidar and 1 Doppler sodar (for most instruments, data are available starting from January 2005). Will be used in WP2-3 to evaluate physical models and LES against atmospheric data, and for comparing different observational methods against each other.

Finnish national air-quality monitoring database (Finnish Air Quality Portal, ilmanlaatu.fi, operated by FMI): all basic atmospheric pollutants for background (20 sites) and urban (>100 sites) areas. Will be used in WP3 to assess and evaluate the performance of the AQ models equipped with new PBL schemes.

European air-quality monitoring database = EMEP (incorporates data from several European networks and databases: EMEP itself, HELCOM, OSPAR, AMAP, CREATE DB, ENVISAT Cal/Val, etc.): atmospheric concentrations of >20 substances over > 20 years (available online at emep.int >20 years). Will be used in WP3.

LES DATABASE64 (~ 200 LES runs in a wide range of governing parameters including intervals where observational data are inaccessible or of poor quality; verified against observations by Beare et al., 2006; Esau & Z, 2006; Z et al., 2006a): data on 3-D structure and 16-hour evolution of all kinds of the PBL under controlled conditions. Will be extended including higher resolution LES and used in WP1-2.

3.3 Time schedule and work load balance

Activity	1st year	2nd year	3rd year	4th year	5th year
1 Theory	••••••••••••	••••••••••••	••••••••••••	••••••••••••	•••
2 Observations	•••••••••••	••••••••••••	••••••••••••	••••••••••••	•••••
3 Modelling	••••••••••	••••••••••••	••••••••••••	••••••••••••	••••••
Reports/Publication	••	••••••••••••	••••••••••••	••••••••••••	••••••••••••

3.4 Budget

The total funding is **2 390 kEUR** for 5 years.

This includes full support for the coordinator, 3 postdocs, 2 PhD students; and 40 % support to 2 researchers – altogether 1811 kEUR.

FMI fully supports the other members of the 12-person core research team. In addition, several FMI research groups will collaborate with the project, including FMI group leaders and research professors.

The total number of man-months supported by the project is 381.

The travel and subsistence costs (22 kEUR/year), are reserved mainly to support co-operation with institutes in Europe, US, Israel and Russia.

The 20% overhead includes the general administration and management cost (125 kEUR), the cost of the office space (155 kEUR), office software (65 kEUR), and communication costs (50 kEUR) on average for the whole duration of the project. The Audit costs are 6 kEUR for the whole duration of the project.

Two technical subcontracts (6 kEUR each) will be necessary for specific laboratory and field data.

FMI provides supercomputer platform for the simulations carried out in the project, and most of the standard measurement equipment needed for the project is already available in the Helsinki Testbed (HTB) area. The equipment cost (only 20 kEUR for the whole period) is meant to acquire 3D-anenometers to supplement the HTB settings with turbulence measurements.

The consumables and publications costs are 5 and 3 kEUR/year, respectively. Consumables are for complementary field experiments with balloon-borne radioprofiling at both Sodankylä and HTB.

The budget for direct eligible cost excluding personnel cost is 171 kEUR, and the total budget for indirect eligible costs is 396 kEUR (20 % of the total direct eligible costs).

BUDGET TABLES

ERC Advanced Grants
Budget tables to be inserted in section 2. "The Project proposal", heading iii. "Ressources"

Insert first the duration in months in cell B2, then record the amounts by Cost Category!

Duration in months :	**60**

iii. Ressources - Table 1

Costs Category	month 1 to 18	month 19 to 36	month 37 to 54	month 55 to 60	TOTAL
Personnel	543 283,20	543 283,20	543 283,20	181 094,40	1 810 944,00
Subcontracting	12 000,00				12 000,00
Equipment	10 000,00	10 000,00	0,00	0,00	20 000,00
Consumables	7 717,00	7 717,00	7 717,00	2 571,67	25 722,67
Travel	36 000,00	36 000,00	26 000,00	12 000,00	110 000,00
Publications	4 000,00	4 500,00	4 500,00	2 000,00	15 000,00
Sub-total Other Directs Costs	57 717,00	58 217,00	38 217,00	16 571,67	170 722,67
Overheads	120 200,04	120 300,04	116 300,04	39 533,21	396 333,33
TOTAL	**733 200,24**	**721 800,24**	**697 800,24**	**237 199,28**	**2 390 000,00**

Amount of Receipts	**0,00**

iii. Resources - Table 2

„key intermediate goal", as defined in section 2.ii.	Estimated % of total requested grant	Expected to be completed on month :	Comment
WP1 PBL physics and turbulence closure	30 %	51	personel, consumables, travel
WP2 Remote sensing observations of the PBL height	33 %	53	personel, consumables , travel and equipment
WP3 New PBL and turbulence closure schemes in NWP, meso-scale, AQ and climate models	30 %	54	personel, consumables, travel
Reports & publications (common to all WP's)	7 %	60	
Total	100 %		

GLOSSARY

AQ	air quality
ACP	Atmospheric Chemistry and Physics
BAMS	Bulletin American Meteorol. Society
BGU	Ben Gurion Univesrity, IL
BLM	Boundary Layer Meteorology
CAR	Contamin. in Air from Road network
CBL	Convective boundary layer
CIRES	Coop. Inst. Res. Env. Sci.–Uni. CO, USA
DMI	Danish Meteorological Institute, DK
EU	European Union
FMI	Finnish Meteorological Institute
HIRLAM	High Resolution Limited Area Model
IAP-RAS	Inst. Atm. Phys.–Rus. Acad. Sci., RU
IMK-IFU	Inst. Meteorol. & Climate Res., DE
ISAC-CNR	Inst. Atmos. Sc. & Climate, IT
JAM	Journal of Applied Meteorology
JAMP	Journal of Appl. Meteorol. Climatology
JAS	Journal of the Atmospheric Sciences
JAOT	Journal of Atm. Ocean Technologies
LES	Large-eddy simulation
LS	Long-lived stable
Met. Z.	Meteorologische Zeitschrift
MO	Monin-Obukhov
MPI-M	Max Planck Institute for Meteorology, DE
NERSC	Nansen Env. & Rem. Sens. Centre, NO
NS	Nocturnal stable
NWP	Numerical weather prediction
PBL	Planetary boundary layer
QJRMS	Quart. J. Roy. Met. Soc.
RH/MT	Resistance & heat/mass transfer
SILAM	Fi. Emerg. & AQ modelling system
SBL	Stable boundary layer
TKE	Turbulent kinetic energy
TPE	Turbulent potential energy
TTE	Turbulent total energy
WIS	Weizmann Institute of Science, IL

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Section 3: The Research Environment

PI’S HOST INSTITUTION

General information

The host institution, the Finnish Meteorological Institute (FMI), is a research and service agency under the Ministry of Transport and Communications. Its main objective is to provide the best possible information about the atmosphere for ensuring public safety relating to atmospheric and airborne hazards and for satisfying requirements for specialised meteorological products.

FMI is involved in many international co-operative, research and assessment efforts. In particular, current projects address: monitoring of air quality and atmospheric composition (UN/ECE EMEP and IM, HELCOM/EGAP, WMO/GAW, AMAP); research and development in atmospheric physics, chemistry and aerosol physics (EU/GEMS, ACCENT, EC/Environment); assessment and modelling of the dispersion, transformation and deposition of airborne pollutants from the local to the continental scale (EU/GEMS, ESA/PROMOTE, COST 728) – closely related to the planetary boundary layer (PBL) physics.

The Meteorological Research Unit of FMI led by Professor S. Joffre, an expert in PBL physics, has long experience in this field including theoretical and extensive experimental studies using the most advanced instruments and the opportunities of unique observational sites. The most important for this project are:

- FMI-ARC Sodankylä Arctic Research Centre, fmiarc.fmi.fi, 120 km north of the Arctic circle, one of the sites for continuous monitoring of the HIRLAM numerical weather prediction (NWP) system: equipped with a 48 m high tower measuring profiles of wind, temperature, humidity, radiative and turbulent fluxes
- “Helsinki Testbed”, a unique mesoscale observational network in the coastal high-latitude area 150 x 150 km, run by FMI and Meteorological Instrument Company Vaisala, testbed.fmi.fi, equipped with 44 meteorological masts, 7 ceilometers, 3 RAOB sounding stations, UHF wind profiler, 1 Doppler lidar and 1 Doppler sodar.

All the available profile information can be directly utilised in assessing the vertical structure of the PBL, so it will provide perfect opportunities not only for evaluating the theoretical concepts and physical parameterizations, but also for comparing and assessing different instruments and observational methods against each other.

The total amount of meteorological measurement stations around the country operated by FMI is about 500. All data are directly available from the FMI operational database, which provides excellent opportunities for testing models and parameterizations.

The Meteorological, Climate-change and Air-quality Research Units of FMI (representing FMI in this project) possess the following environmental models that will be essentially used in the project:

- The NWP model HIRLAM developed jointly by the HIRLAM and ALADIN consortia (hirlam.org) representing ~20 European national weather services (the prognostic variables include wind, temperature, humidity, cloud condensate, surface pressure, and turbulent kinetic energy),
- Its meso-scale version
- The Finnish Emergency and Air Quality (AQ) meso-scale modelling systems SILAM and CAR-FMI
- The coupled atmosphere-ocean general circulation climate model ECHAM5/MPI-OM

A vast amount of computational work in the project requires the time allocation at the FMI supercomputer centre. At the moment the supercomputing environment at FMI consists of several parallel computers. The most powerful one is SGI Altix 3700 BX2, operating 256 parallel Intel Intanium 2 dual processors.

Research

The main subject of research at FMI is the Earth's atmosphere. In general, research activities cover meteorology, physics, chemistry, mathematical statistics, biology, and the space and the solar influences on planetary atmospheres, which create an interdisciplinary research environment beneficial for this project. Particularly important for the project are well-developed satellite and weather radars and ground-based remote sensing measurements covering the turbulent and mean structure of PBLs and the PBL height, not to mention the PBL physics and the environmental modelling researches.

Current research works at the Meteorological and Air-quality Research Units (including ongoing projects: EU MEGAPOLI – on the urban environment, and IS4FIRES – on forest fires) perfectly fit and complement this project.

The Climate-change Unit focuses on the atmosphere-ocean interaction, future climate scenarios for Finland, the carbon cycle, the greenhouse gas balance and the effect of changed climate onto the Baltic Sea ice-cover and soil frost – in cooperation with the Finnish Environment Institute and the German Max Planck Institute for Meteorology (MPI-M). Modelling of fine features of the climate change (addressed in our project through improved PBL parameterization) is among first priorities of this Division.

All three divisions involved in the project very actively collaborate with practically all well-established relevant institutions and groups in Europe and all over the world.

Assistance

The project benefits from the FMI services in the following ways:

- Access to unique collection of meteorological, turbulence and remote sensing measurements carried out continuously over several years at the Helsinki Testbed, which give a possibility to reconstruct the 3-D state of the atmosphere at very high resolution for a broad spectra of atmospheric conditions ranging from strongly convective in summertime to long-lived stable in wintertime
- Access to the newly upgraded supercomputer facility and help from the technical personal of the computer lab
- Use of the expertise of meteorologists, climatologists and modellers including creators of the models
- Immediate possibility to address, in both data analyses and numerical experiments, a wide range of conditions including extreme weather events and heavy air-pollution episodes not exceptional in the diverse Finnish environment and especially valuable for testing new physical models and parameterizations.

Broader intellectual support

At the end of 2007, FMI employed 610 persons, 179 of which funded by national and international industrial and governmental research agencies. 56 per cent of the personnel have academic degrees and 16 per cent of them, postgraduate degrees. This creates a critical mass of 250 persons involved in the project-related areas of the research. There is a close and well established co-operation between FMI and all the major Finnish environmental research institutes and Universities, especially with the Helsinki University Department of Physics co-located at the same Kumpula-campus area as FMI.