# Russian-Finnish seminar on
# Land-atmosphere exchanges in heterogeneous landscapes

*20 October 2016*

*Moscow State University*
*Research Computing Center*

*Conference Hall, 3 floor*

## Section 1 (14:00 – 16:00).
## Turbulence in heterogeneous landscapes

14:00 – 14:30
Sergej S. Zilitinkevich. **How and why turbulence sustains in super-critically stratified free atmosphere and ocean?**

14:30 – 15:00
Ivan Mammarella. **Benefits and challenges of long-term eddy covariance flux measurements over lakes**

15:00 – 15:20
Evgeny Mortikov. **Direct numerical simulation of intermittent turbulence in stably stratified plane Couette flow**

15:20 – 15:40
Yulia Mukhartova. **Modeling study to describe effects of vegetation heterogeneity and surface topography on turbulent exchange between land surface and the atmosphere**

15:40 – 16:00.
Irina Repina. **The turbulent structure of surface atmospheric layer above small boreal lakes**

## Coffee break (16:00 – 16:30).

## Section 2 (16:30 – 18:00).
## Lake-atmosphere interactions

16:30 – 17:00
Victor Stepanenko. **One-dimensional modelling of enclosed water bodies**

17:00 –17:20
Maria Grechushnikova. **Influence of stratification on methane accumulation in reservoirs of Moscow water supply system**

17:20 – 17:40
Vasily Bogomolov. **Integration of lake model into the coupled general circulation model of the atmosphere and ocean**

17:40 – 18:00
Timo Vesala. **From lakes to urban environment**

# Abstracts

## How and why turbulence sustains in super-critically stratified free atmosphere and ocean?

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It is widely believed that in very stable stratifications, at Richardson numbers (*Ri*) exceeding critical value $Ri_c$ ~ 0.25 turbulence decays and flow becomes laminar. This is so at low Reynolds numbers (*Re*), e.g., in lab experiments; but this is not true in very-high-*Re* geophysical flows. Free atmosphere and deep ocean are turbulent in spite of strongly supercritical stratifications: $1 << Ri < 10^3$. Until recently, this paradox remained unexplained.

The Energy- and Flux-Budget (EFB) turbulence-closure (Zilitinkevich et al., 2007-2016) has disclosed the following turbulence self-control mechanisms:

- Until recently, the role of negative buoyancy flux, $F_b > 0$, in turbulence energetics was treated in terms of the turbulent kinetic energy (TKE) budget equation and understood as just consumption of TKE by the buoyancy forces. This has led to the conclusion that sufficiently strong static stability causes the negative buoyancy flux sufficiently strong to exceed the TKE generation rate and thus to kill turbulence.
- However, considering TKE equation together with budget equation for turbulent potential energy (TPE proportional to the squared buoyancy fluctuations) shows that the role of $F_b$ in turbulence energetics is nothing but conversion of TKE into TPE ($F_b$ just quantifies the rate of this conversion); so that $F_b$ does not affect total turbulent energy (TTE = TKE + TPE).
- Moreover, as follows from the buoyancy-flux budget equation, TPE generates positive (directed upward) buoyancy flux irrespective of the sign of the buoyancy gradient. Indeed, the warmer fluid particles (with positive buoyancy fluctuation) rise up, whereas

the cooler particles sink down, so that both contribute to the positive buoyancy flux opposing to the usual, negative flux generated by mean buoyancy gradient.

- In this context, strengthening the negative buoyancy flux leads to decreasing TKE and increasing TPE. The latter enhances the counter-gradient share of the total flux, thus reduces $|F_b|$ and, eventually, increases TKE.

The above negative feedback was disregarded in the conventional concept of down-gradient turbulent transport. This mechanism imposes a limit on the maximal (independent of the buoyancy gradient) value of $|F_b|$ and thus prevents degeneration of turbulence.

The EFB theory has predicted that the critical Richardson number, $Ri_c$ ~ 0.25, characterising the hydrodynamic instability limit and the turbulent-laminar flow threshold at low Reynolds numbers, remains a principal threshold also in the very-high-*Re* turbulence; but here it separates the two turbulent regimes of dramatically different nature:

- $Ri < Ri_c$: the familiar “strong-mixing turbulence” typical of boundary-layer flows, wherein turbulent Prandtl number remaines practically constant: $Pr_T$ ~ 1 (the so-called “Reynolds analogy”);
- $Ri > Ri_c$: the newly revealed “wave-like turbulence” typical of the free atmosphere and deep ocean, wherein $Pr_T$ sharply increases with increasing *Ri* (asymptotically as $Pr_T$ �$5Ri$ ).

This theoretical finding fits well with experimental evidence. Modellers long ago knew that turbulent heat transfer in the free atmosphere should be taken much weaker than the momentum transfer. The EFB theory gives authentic formulation for this rule and provides physically grounded method for modelling turbulence up to very stable stratifications.

## Benefits and challenges of long-term eddy covariance flux measurements over lakes

*Ivan Mammarella  and many others*
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Advancing our understanding on physical processes controlling turbulent exchange of energy and matter over lacustrine systems is crucial in order to improve climate and weather forecast models.

The eddy covariance (EC) technique is the standard tool for long-term turbulent flux measurements at ecosystem scale. Long series would allow for detection of e.g. inter-annual variability, effects of anomalous weather episodes and trends stemming from environmental changes and climate change. We discuss on challenges for long-term EC measurements over lakes, as well as the requirements for a comprehensive measurement set-up, including auxiliary measurements. We demonstrate the benefits of long-term data for linking lake biogeochemistry and physical processes in the water column via examples from few lake sites.

## Direct numerical simulation of intermittent turbulence in stably stratified plane Couette flow

*Evgeny Mortikov*

*Moscow State University*
*Institute of Numerical Mathematics RAS*

This work uses direct numerical simulation approach to investigate intermittent turbulence in stably stratified plane Couette flow for Reynolds numbers, based on the channel height and relative wall speed between top and bottom walls, up to 10^5. Results show that the transition to intermittent turbulence under strong stratification is associated with the formation of secondary counter-rotating roll-like structures elongated in the spanwise direction and organized in two rows corresponding to lower and upper walls of the channel. The ordering of rolls define spatially confined alternating regions of laminar and turbulent flow. The spanwise length of this vortices increases with the increase of the bulk Richardson number and defines an additional constraint on the computational box size. This study describes direct numerical simulation results in spanwise-extended computational domains, where the turbulent intermittent regime is sustained without relaminarization for sufficiently higher bulk Richardson numbers than previously reported.

## Modeling study to describe effects of vegetation heterogeneity and surface topography on turbulent exchange between land surface and the atmosphere

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The main goal of the study is to describe the influence of vegetation heterogeneity and surface topography on turbulent $CO_2$ fluxes between land surface and the atmosphere using a process-based two-dimensional turbulent exchange model. Applied two-dimensional model is based on solution of the Navier–Stokes and continuity equations using the *one*-and-a-*half order (TKE)* closure scheme in the appropriate coordinate system taking into account the land surface topography. The vegetation cover is modeled as an ensemble of individual plants characterized by specific vertical distributions of leaf area density. For description of plant canopy photosynthesis and respiration an aggregated approach based on model of Ball et al (1987) in Leuning modification (1990, 1995) is applied. Parameterisation of leaf stomatal conductance assumes its dependence on incoming photosynthetically active radiation. All necessary input parameters describing the photosynthesis and respiration properties of plants and soil were obtained from the field measurements or taken from the literature.

The results of model experiments show significant influence of heterogeneous topography and vegetation cover on vertical and horizontal distribution of wind components, turbulent exchange coefficients and vertical turbulent fluxes of $CO_2$. The complex topography enhances turbulent exchange within the atmospheric surface layer and can result in increase of total vertical turbulent $CO_2$ fluxes. Ignoring the air-flow disturbance effects at the boundaries between different vegetation types and over land surface with complex topography that is usually assumed in 1D model approaches leads to overestimation of atmospheric fluxes of $CO_2$ (up to 26%).

## The turbulent structure of surface atmospheric layer above small boreal lakes

*Irina Repina, Victor Stepanenko, Arseniy Artamonov*

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*Moscow State University, Research Computing Center, Geographical Faculty*

Lakes may be a source or sink of sensible heat and often are a source of moisture for the atmosphere. Lake surfaces are aerodynamically much smoother than vegetated land surfaces, which contribute to large variations of fluxes of momentum, heat, moisture and gases between the land and the atmosphere.
Formulations of estimates of lake-atmosphere fluxes are often taken from experimental studies conducted in oceans or in lakes where the wind sheltering and mesoscale turbulence effects are not significant. The same coefficients values are most likely not applicable to all lake environments, especially over small lakes with different sheltering characteristics. Over complex terrain the turbulence is generically inhomogeneous due to both thermal (radiative) and dynamic forcing. This inhomogeneity leads to meso-scale and even sub-meso-scale flows and waves. It is argued here that these (sub) meso-scale motions can significantly contribute to the vertical structure of the boundary layer and hence vertical exchange of heat and mass between the surface and the atmosphere. Accuracy and variability of transfer coefficients for air-water momentum, heat, moisture and trace gases is currently difficult to determine and any bias in them will influence flux estimates. The turbulent exchange of heat and momentum were measured above Verkhnee lake (White sea region) using the eddy covariance method in winter season. Measurements of small-scale turbulence made in the atmospheric surface layer at the various sites above the ice cover are used to describe the structure of turbulence in wind flows above complex terrain. Turbulent data were continuously measured with 3-component and 2-component sonic anemometers during 7-day field campaign. These measurements allowed to study temporal and spatial structure of wind flow in detail, and herein we report turbulence statistics (e.g., fluxes, variances, spectra, and co-spectra) and their variations in flow above small lake surrounded by the forest. High-frequency observations also were used to examine the relative contributions of wind shear ($u_*$) and convection ($w_*$) to turbulence in the surface mixed layer.

## One-dimensional modelling of enclosed water bodies

*Victor Stepanenko*
*Moscow State University, Research Computing Center*

The widely-used concept of 1D modelling of enclosed water bodies is briefly reviewed. The approaches to simulate thermodynamic regime of lakes, including snow and ice covers and turbulent closure are exemplified. The recently emerged biogeochemical modules are also sketched. The role of vertical mixing in distribution of all water properties is underlined. The special attention is then paid on how the vertical mixing mechanisms are represented in current 1D modelling framework. The key questions are:

- what is the consequence of not taking into account the horizontal pressure gradient in current 1D lake dynamic schemes and thus the related internal wave motions for the vertical mixing?
- what could be the ways to include internal wave motions (seiches) in 1D models?

The new way of parameterizing seiches is presented and its effect is demonstrated in idealized flow simulations.

## Influence of stratification on methane accumulation in reservoirs of Moscow water supply system

*Maria Grechushnikova*

*Moscow State University, Geographical Faculty*

Inspite of broad list of water objects in Russia with information of metane sampling there is a lacuna in information for reservoirs with low water exchange.

In present work sampling was fulfilled in Mojaisk and Ozerna reservoirs – well studied water objects with a wide database about their hydrological regime and sediments. Sampling was fulfilled on stations above flooded river bed and submerged floodplane nearby. These stations have various bottom sediments with different rate of oxygen consumption.

Long anoxic conditions in the reservoir with slow water exchange contribute to methane concentration growth in bottom layer in two orders of magnitude: from 2-8 to 200-2300 µl/l.

Sampling showed a significant growth of methane in the surface layer during summer period, especially for shallow upstream (from 1-3 to 5-15 µl/l).

Seasonal changes of methane in surface layer are connected with reduction of water column stratification stability due to heating of hypolimnion, and maximum methane concentration in the surface layer is typical for shallow upstream. The obtained values exceed the published data for reservoirs with quick water exchange (Volga cascade).

In terms of significant stratification maximum values of methane diffusion flux (counted by thin layer method) are typical for shallow upstream (0,3-1,7 mgC/m$^2$ hour). Its longitudinal change is 10 times more than crosswise. During the period of opened water (May-October) the methane diffusion flux is roughly estimated as 2000 mgC/m$^2$, which corresponds to published values for other reservoirs in Brazil and Canada.

## Integration of lake model into the coupled general circulation model of the atmosphere and ocean

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Land surface schemes (LSS or terrestrial models) are a crucial component of both Numerical Weather Prediction (NWP) and Climate Modelling. One component is a lake. Lakes haven't been recognized as significant "actors" in the climate system, as they cover less than 4% of the land surface. However, regional thermodynamic and dynamic effects of lakes on weather and climate are important for most of Canada, Finland, Western Siberia and other regions (Dutra et al., 2010; Martynov et al., 2012; Eerola et al., 2014). This motivated inclusion of thermodynamic lake models into many NWP and climate models (Martynov et al.,2012; Dutra et al., 2010; Mironov et al., 2010; Subin et al., 2012; Rontu et al., 2012). This motivated inclusion of thermodynamic lake models into many NWP and climate models.

At the moment, the existing joint general circulation model of the atmosphere and ocean INM (Volodin et al., 2010) the LAKE model has been integrated (Stepanenko et al., 2011) with reverse interaction.

Connected to the model INMCM4 consisting of 14 types of land created using a digital map of inland waters for the entire globe. Create a digital map of water bodies includes the two-dimensional array on the grid climate model: the proportion of the area of the cell occupied land reservoirs, and the average depth of water bodies in the cell. This digital map is based on a database consisting of the order of 14 000 freshwater lakes and data depths (Kourzeneva, E. 2012.).

To be able to work together INM model and LAKE, in the LAKE model to epsilon-parameterization has been replaced by parameterization of the calculation of the diffusion coefficient Henderson-Sellers (Hendersson-Sellers, 1985).

With change model INMCM numerical experiments were calculated for the global experiments of the historical period of the second half of the XX century. Analyzed the difference between the values of the surface temperature and heat flow for the parameterization of the old parametrization in INMCM and new parameterization (LAKE), averaged over the year.

## FROM LAKES TO URBAN ENVIRONMENT

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We present recent developments and results on biosphere-atmosphere interactions processes, especially related to gas exchange between inland waters and urban environments with the atmosphere. We utilize the eddy covariance (EC) technique which is the only standard tool to measure fluxes of material and energy at ecosystem scale representing the larger area of the studied surface, such as lake or neighbourhood scale in cities. We discuss on challenges for long-term EC measurements over heterogeneous surfaces (small lakes surrounded by forest or urban surface) and demonstrate the benefits of EC data for carbon cycle studies via examples from four EC sites in Finland (four lakes and two urban sites). The knowledge on local micrometeorology and turbulence from atmospheric observations and flow modelling is an important pre-requisite to obtain the overall comprehensive picture on surface-atmosphere continuum.