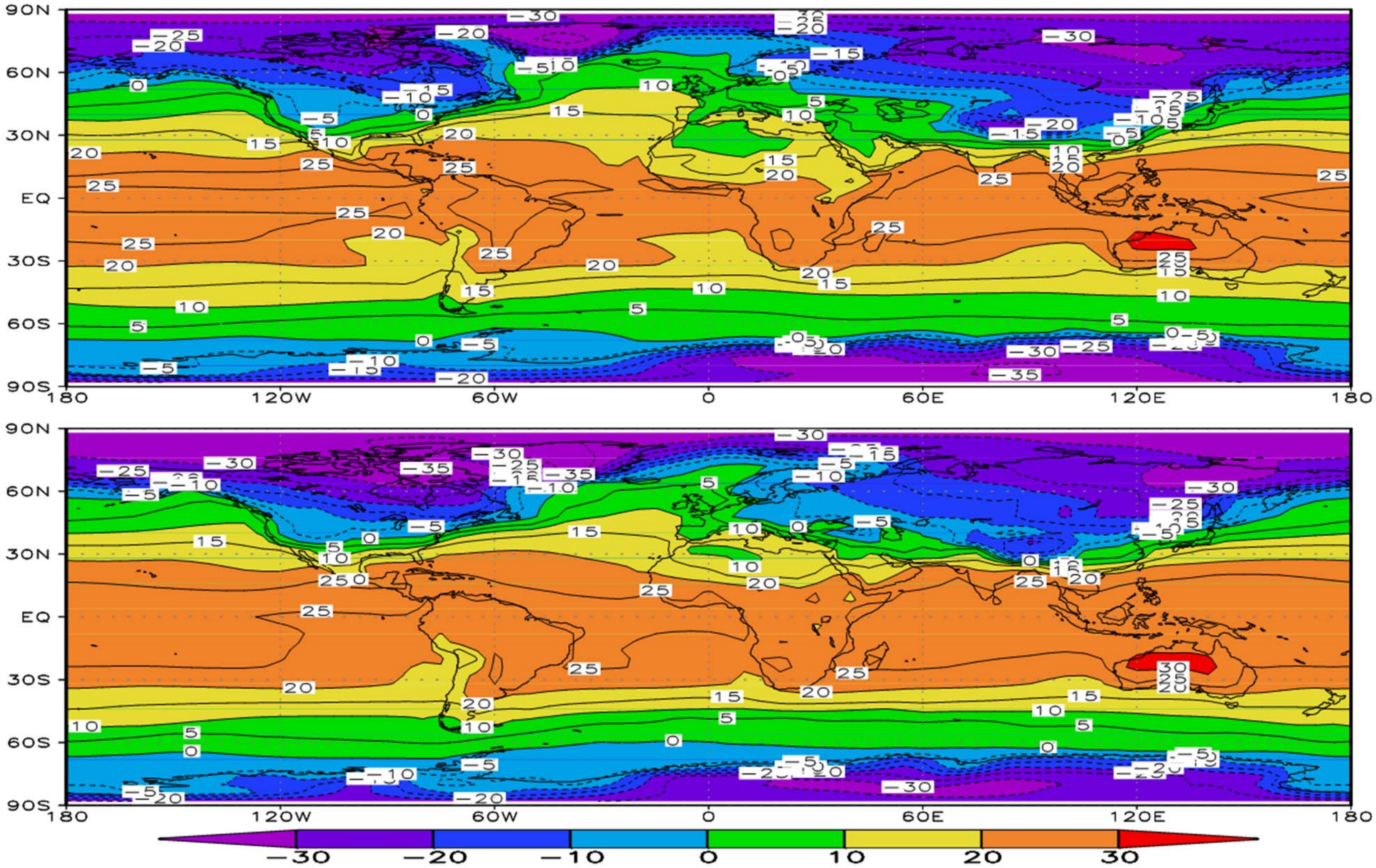
International event on Computational Information Technologies
or Environmental Sciences: CITES-2019 (27 May - 6 June 2019, Moscow, Russia)

Interaction of the atmospheric boundary layer with the active land layer and water bodies: observations and modeling

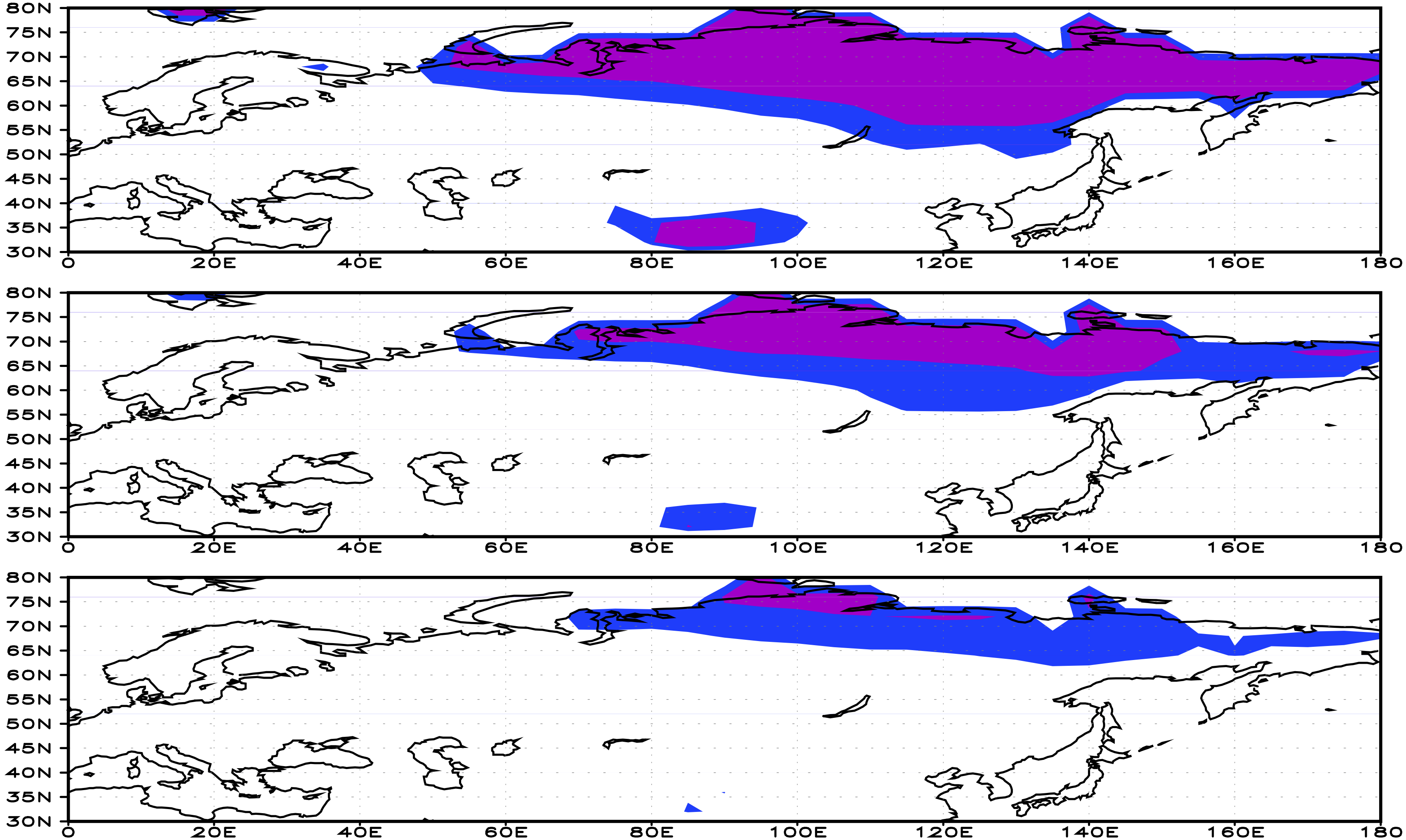
V.N. Lykosov[1,2], A.V. Glazunov[1,2], I.A. Repina [3,2],
V.M. Stepanenko[2], M.I. Varentsov[2]

[1]Marchuk Institute for Numerical Mathematics, Russian Academy of Sciences,
[2]Lomonosov Moscow State University,
[3] Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences
E-mail: lykossov@yandex.ru

Near-the-surface air temperature in winter: the INM model (top) and observations (bottom)

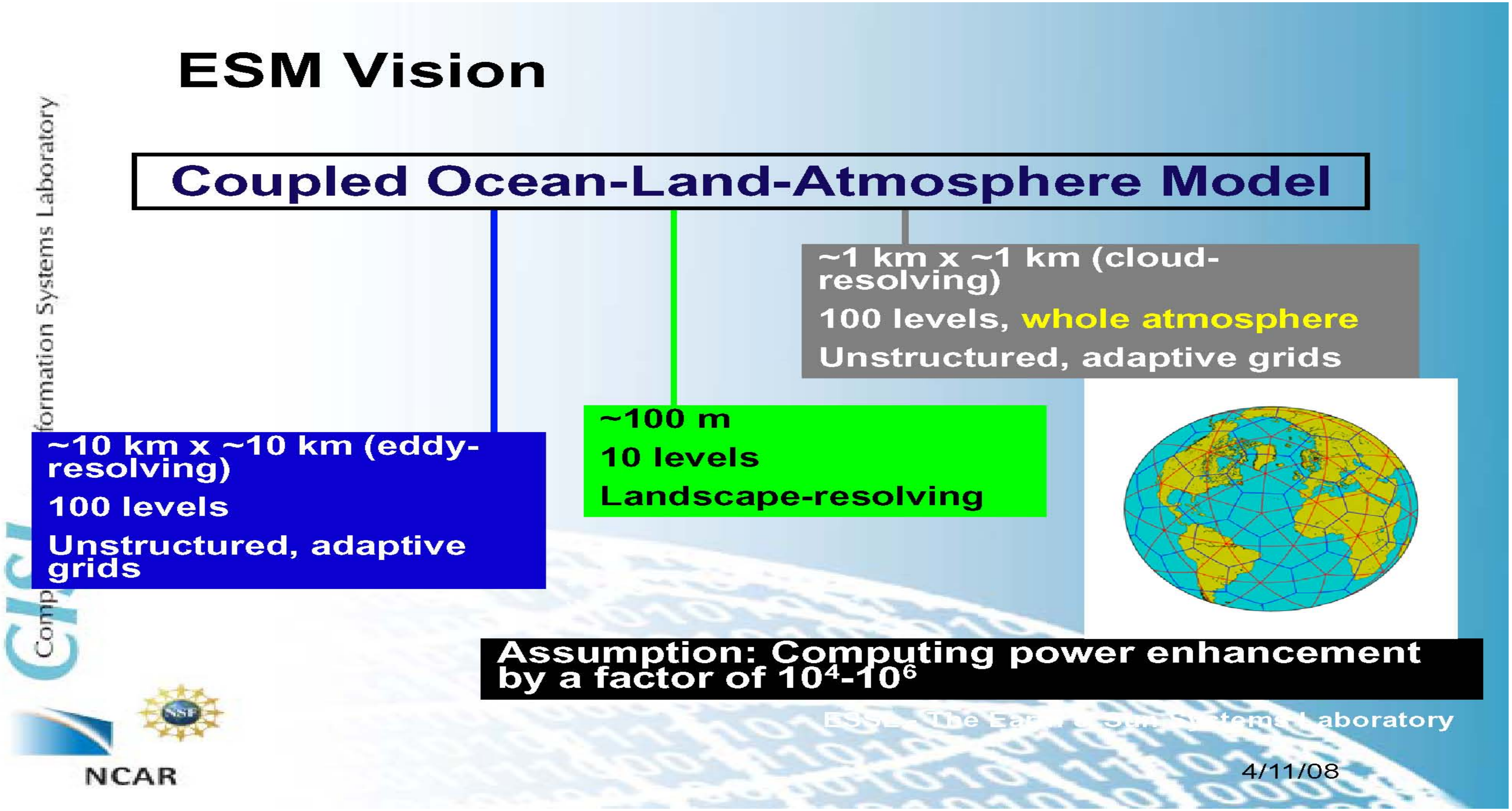


Spatial distribution of continuous (purple color) and sporadic (blue color) permafrost according to numerical experiments with the INM climate model: in 1981-2000 (top), 2081-2100 under scenario B1 (middle) and 2081-2100 under scenario A2 (bottom)



Earth System Model

R. Loft. The Challenges of ESM Modeling at the Petascale



Earth surface area: 510 072 000 км²

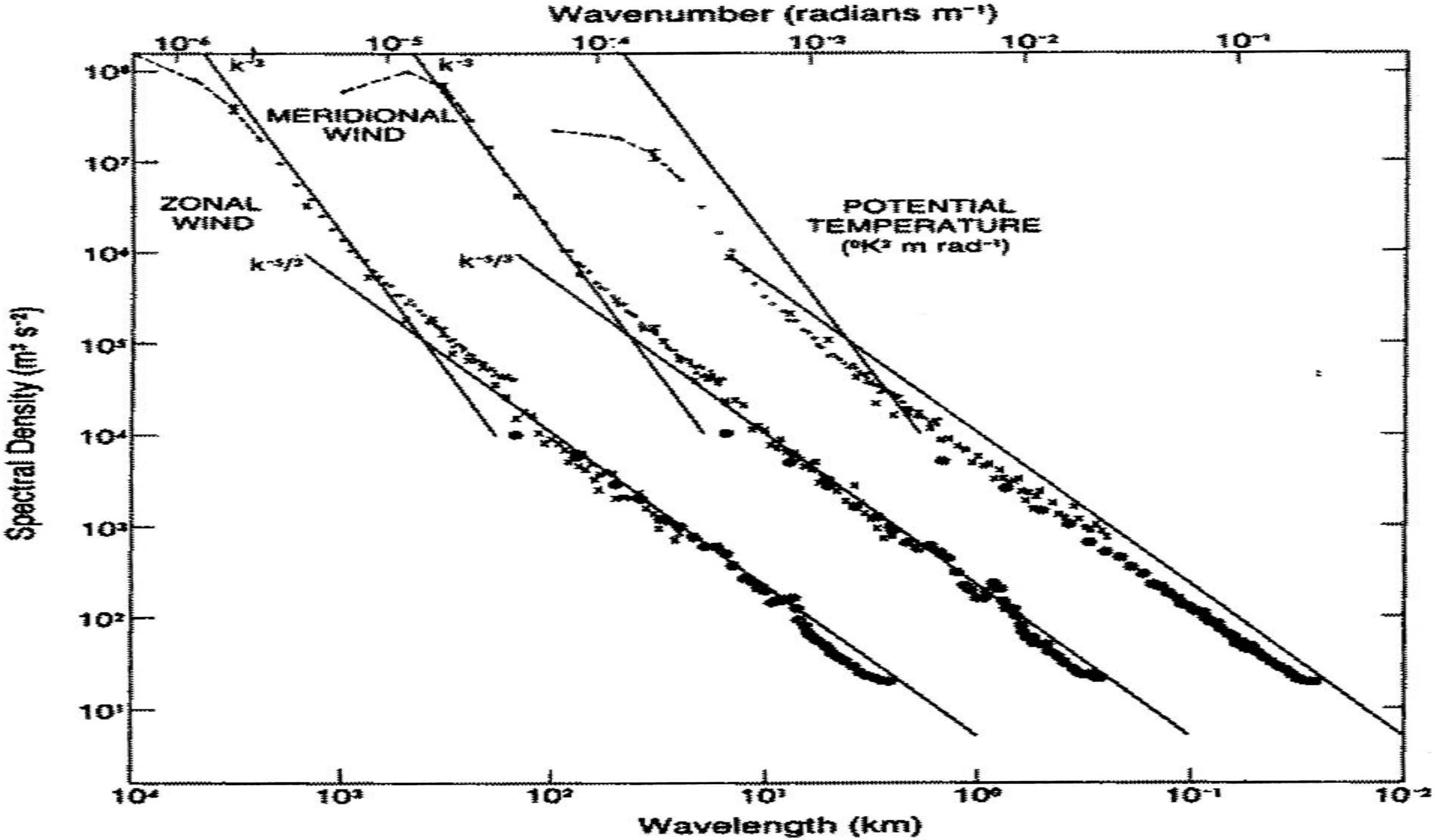


FIG. 1. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes -3 and $-5/3$ are entered at the same relative coordinates for each variable for comparison. [Reproduced with permission from Nastrom and Gage (1985).]

Palmer T.N. Towards the probabilistic Earth-system simulator: a vision for the future of climate and weather prediction. - Quart. J. Roy. Meteorol. Soc., 2012, v. 138, no. 665, p. 841-861.

Масштаб времени: $\tau(k) \sim k^{-3/2} E^{-1/2}(k), \quad [k] = м^{-1}, \quad [E] = м^3 / c^2$

Пусть $\tau(k)$ характеризует время, за которое ошибки в спектральной компоненте модельного решения с волновым числом k за счет нелинейных взаимодействий повлияют на точность воспроизведения компоненты с волновым числом $k/2$. Пусть также k_L соответствует (условной) правой границе длинноволновой (крупномасштабной) части спектра.

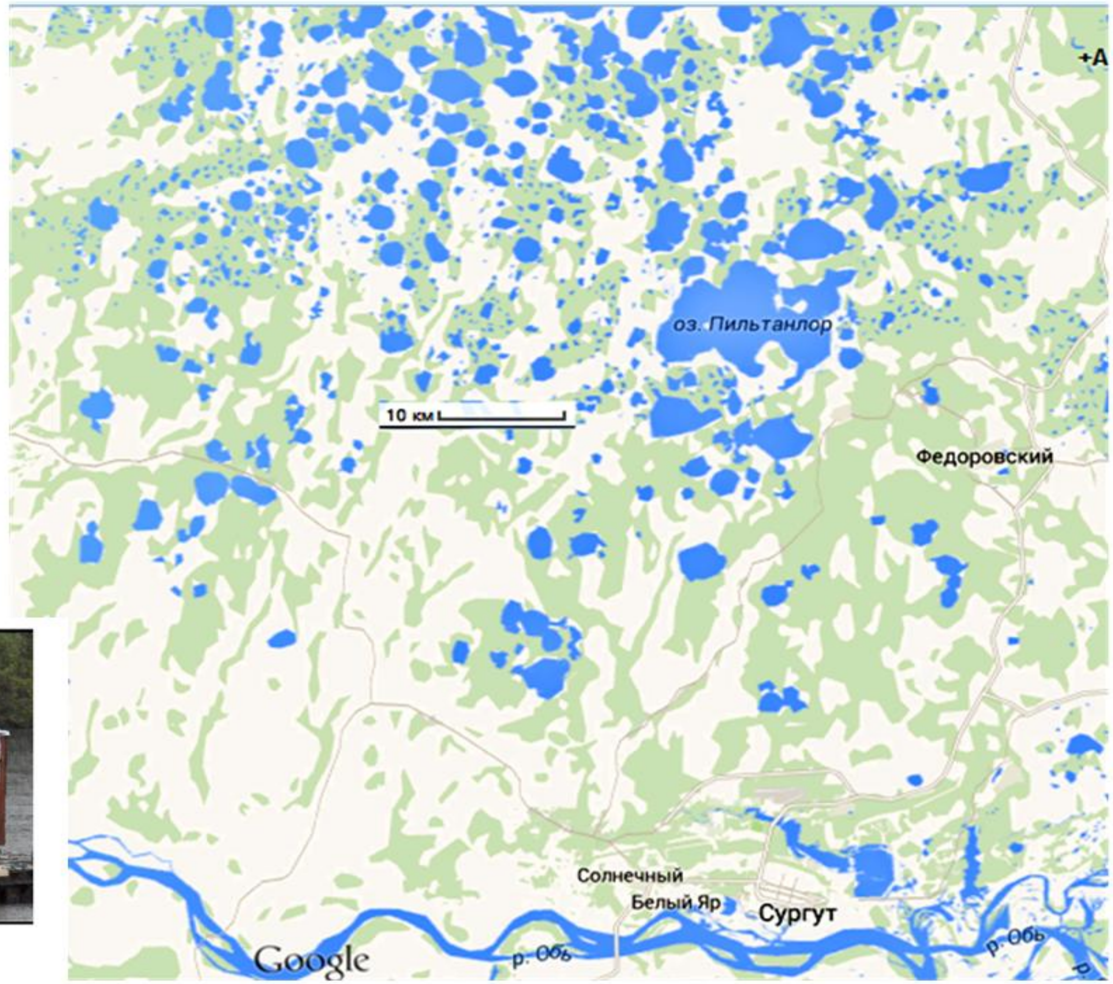
Вопрос: каково время T, за которое ошибки в коротковолновой части спектра (на больших волновых числах $2^N k_L$, $N >> 1$) повлияют на воспроизведение крупномасштабных процессов?

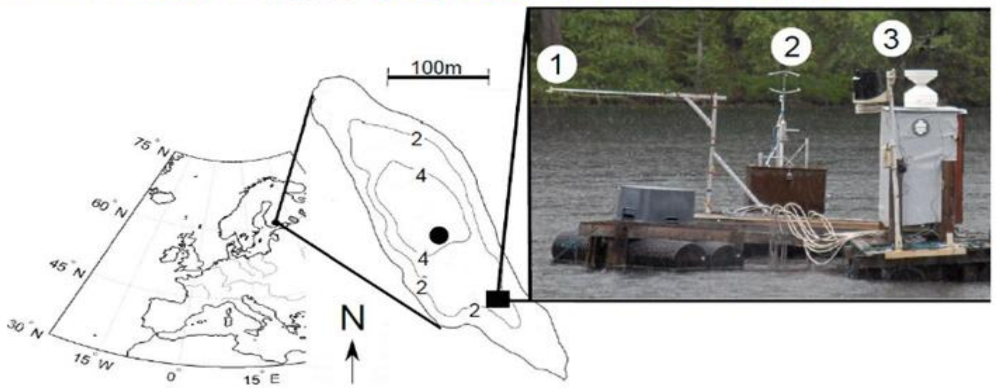
$$T(N) = \tau(2^N k_L) + \tau(2^{N-1} k_L) + \ldots + \tau(2^0 k_L) = \sum_{n=0}^{N} \tau(2^n k_L)$$

$$E(k) \sim k^{-3} \quad \rightarrow \quad \tau(k) = \text{const} \quad \rightarrow \quad T(N) \sim N$$

$$E(k) \sim k^{-5/3} \quad \rightarrow \quad \tau(k) \sim k^{-2/3} \quad \rightarrow \quad \lim_{N \to \infty} T(N) \sim 2.7 \tau(k_L)$$

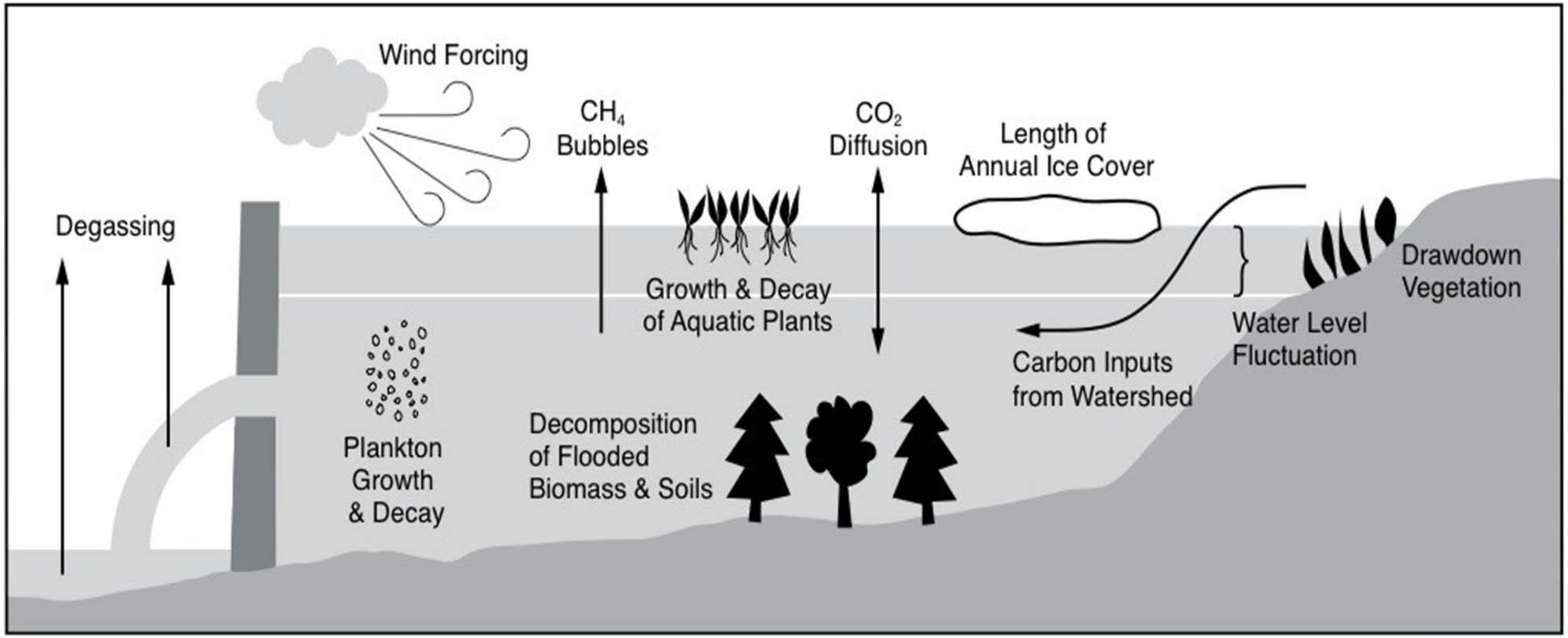
Общее количество озер с площадью менее 10 км^2 составляет 99,9 % от числа внутренних водоемов на поверхности Земли, а их суммарная территория составляет 54% от общей площади внутренних водоемов





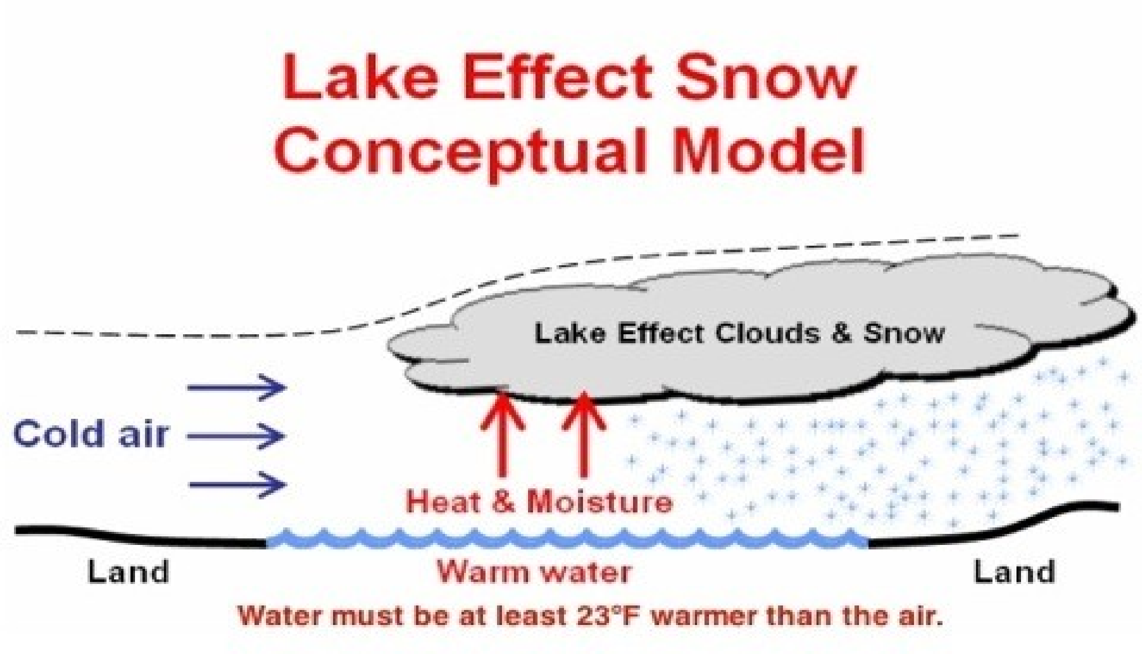
Для современных моделей прогноза погоды и климата требуется вычисление балансов тепла, влаги и газовых примесей на поверхности с учетом наличия водных объектов подсеточного масштаба.

Emission of greenhouse gases from reservoirs



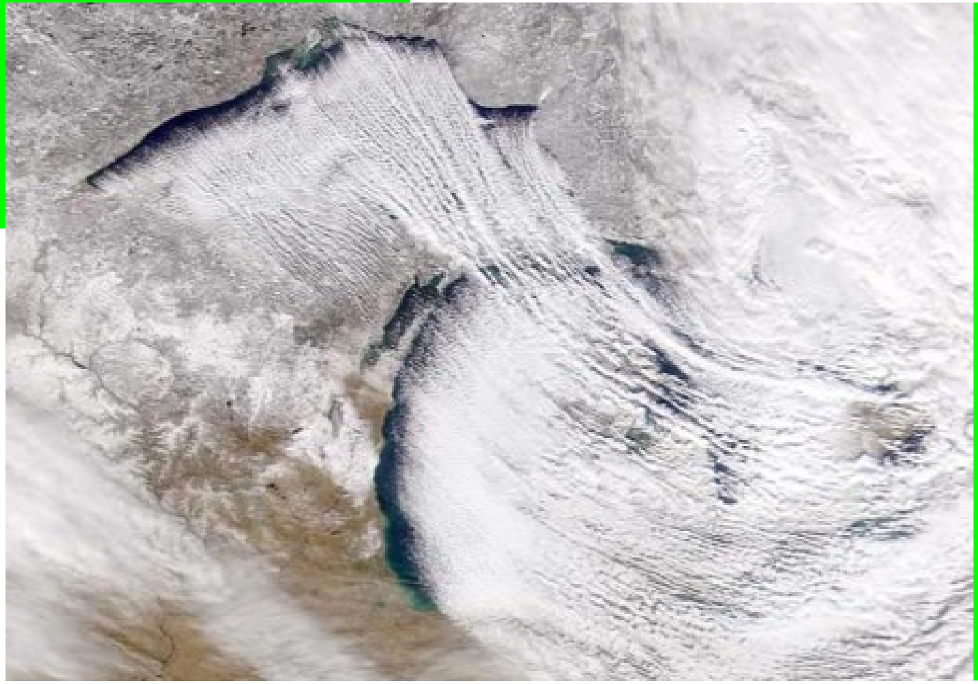
- Artificiallt flooded ecosystems are imposed to both aerobic (producing CO_2) and anaerobic (producing CH_4) degradation
- Compared to natural lakes there is an additional pathway of gases that is through turbines

Snowfall over the Great American Lakes (lake-effect snow)



During cold invasions of the continental air, intense evaporation and convection lead to clouds and precipitation.

"Lake snowfalls" paralyze the road situation, schools are closed, flights are canceled, etc. During the XX century, there is a trend of an increase in the amount of snow precipitation in the area, +1.9 cm/year



Polymeric stresses, wall vortices and drag reduction

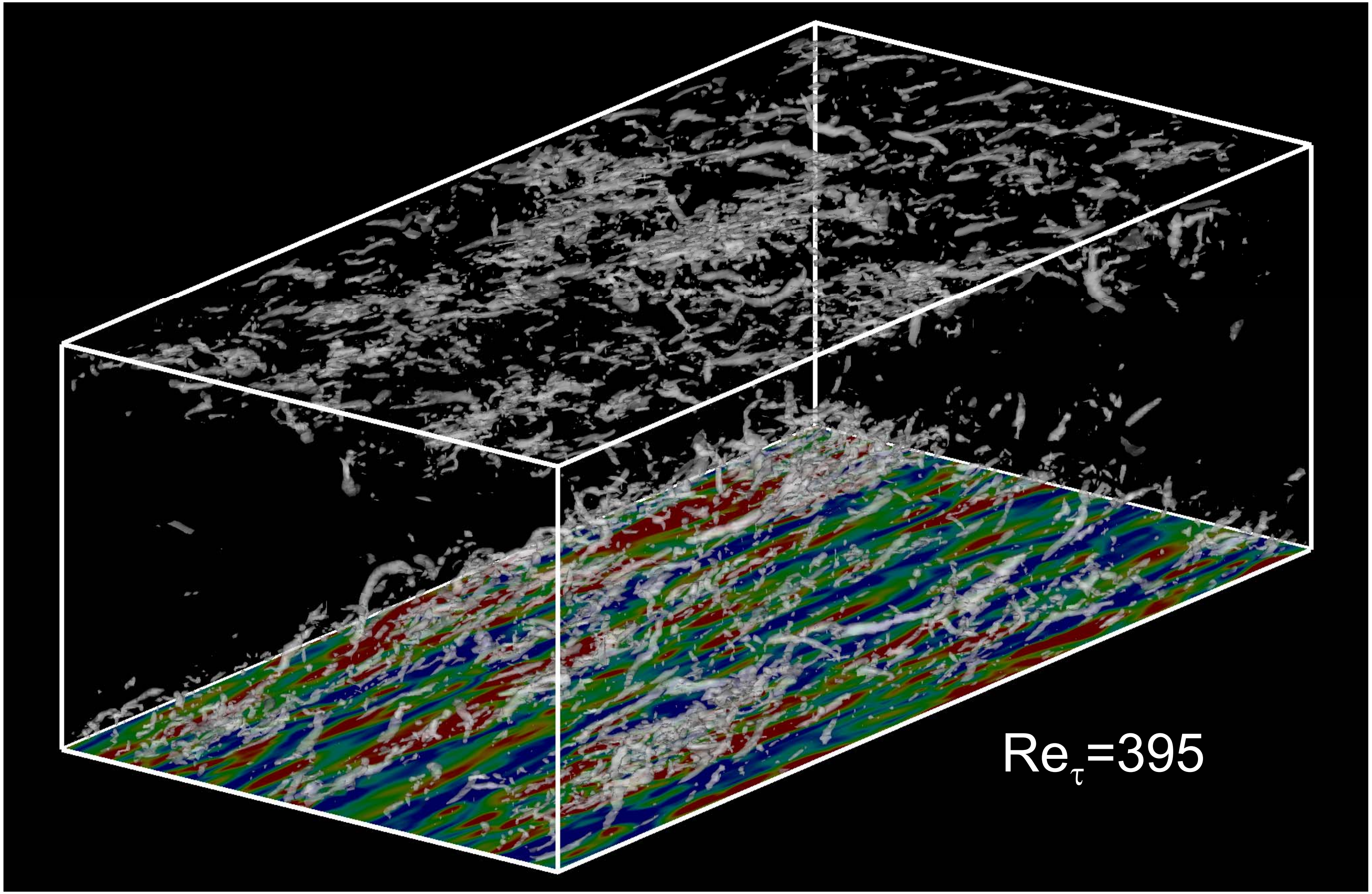
Ronald J. Adrian

Arizona State University-Tempe

Mechanical and Aerospace Engineering

"High Reynolds Number Turbulence", Isaac Newton Institute, Sept. 8-12, 2008

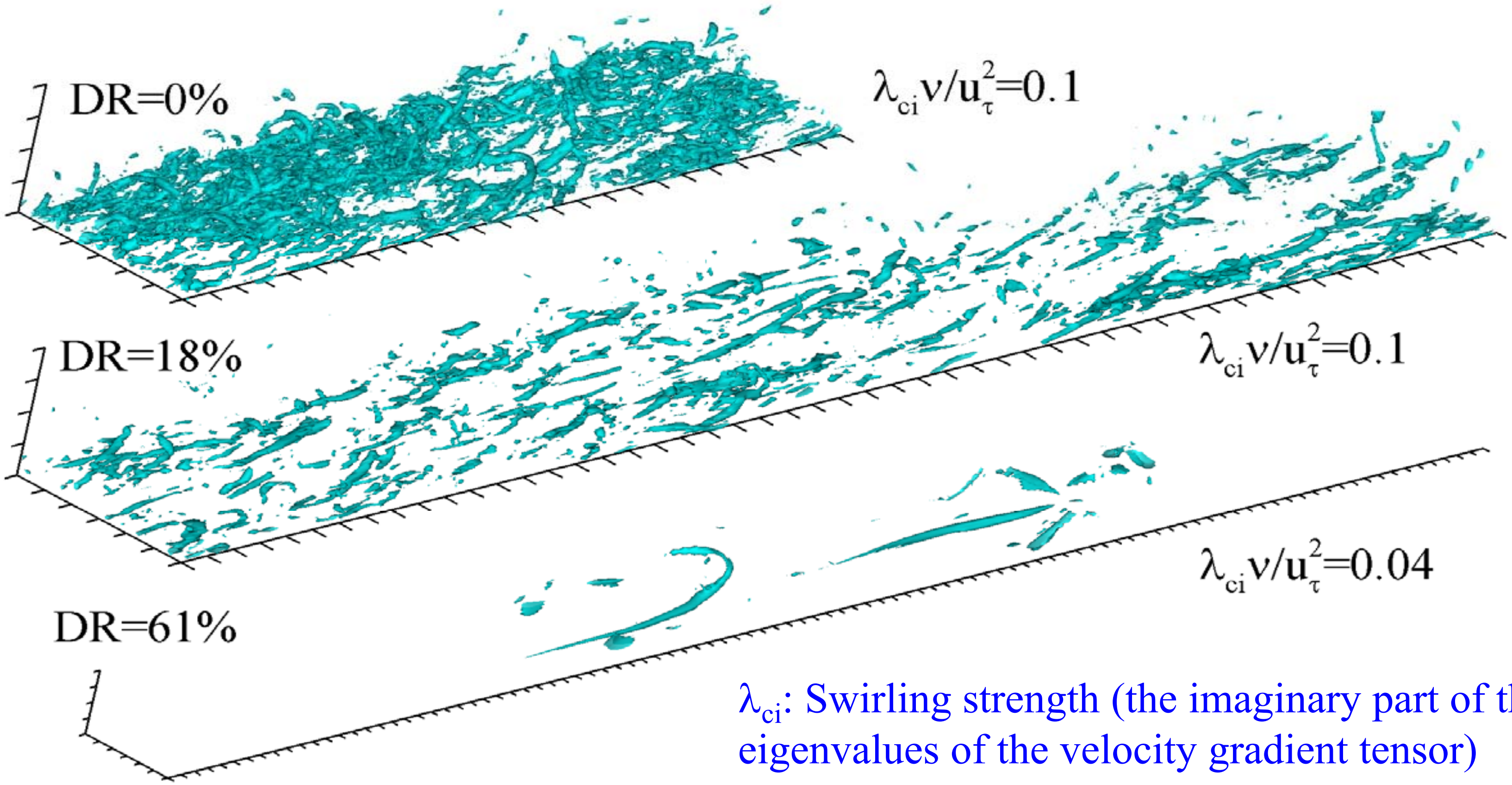
Eddies in Wall Turbulence



Near-wall vortical structures are closely related with production of Reynolds shear stress. (Quasi-streamwise vortices, low-speed streaks, hairpin vortices, vortex packets, etc)

Near-Wall Vortical Structures

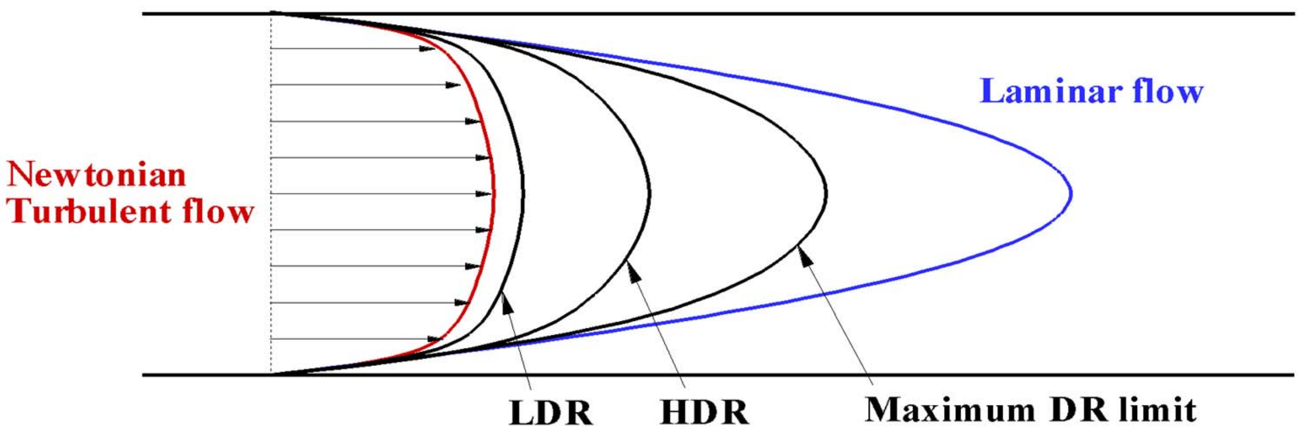
- ❑ Vortical structures in polymer solutions are:
- ❑ Weaker
- ❑ Thicker
- ❑ Longer
- ❑ Fewer



λ_{ci}: Swirling strength (the imaginary part of the complex eigenvalues of the velocity gradient tensor)

Structural changes found in experiments

- Increased spacing and coarsening of streamwise streaks
- Damping of small spatial scales
- Reduced streamwise vorticity
- Enhanced streamwise velocity fluctuations
- Reduced vertical and spanwise velocity fluctuations and Reynolds stresses
- Parallel shift of mean velocity profile in low Drag Reduction
- Increase in the slope of log-law in high Drag Reduction



Simple model of katabatic flow with suspended snow particles (Idea: Kodama et al., 1985)

$$\frac{du}{dt} = (\lambda\vartheta - gC)\sin\alpha + f(v - v_g) + \frac{\partial}{\partial z}\nu\frac{\partial u}{\partial z},$$

$$\frac{dv}{dt} = (\lambda\vartheta - gC)\sin\beta - f(u - u_g) + \frac{\partial}{\partial z}\nu\frac{\partial v}{\partial z},$$

$$\frac{d\vartheta}{dt} + S\left[(u - u_g)\sin\alpha + (v - v_g)\sin\beta\right] = \mathrm{Pr}\frac{\partial}{\partial z}\nu\frac{\partial\vartheta}{\partial z},$$

$$\frac{dC}{dt} - w_s\frac{\partial C}{\partial z} = \mathrm{Sc}\frac{\partial}{\partial z}\nu\frac{\partial C}{\partial z},$$

$$\nu = \nu(\mathrm{Ri}_C), \quad w_s > 0.$$

Stationary analytic model of katabatic flow with suspended snow particles

$$(\lambda\vartheta - gC)\sin\alpha + \nu\frac{d^2u}{dz^2} = 0,$$

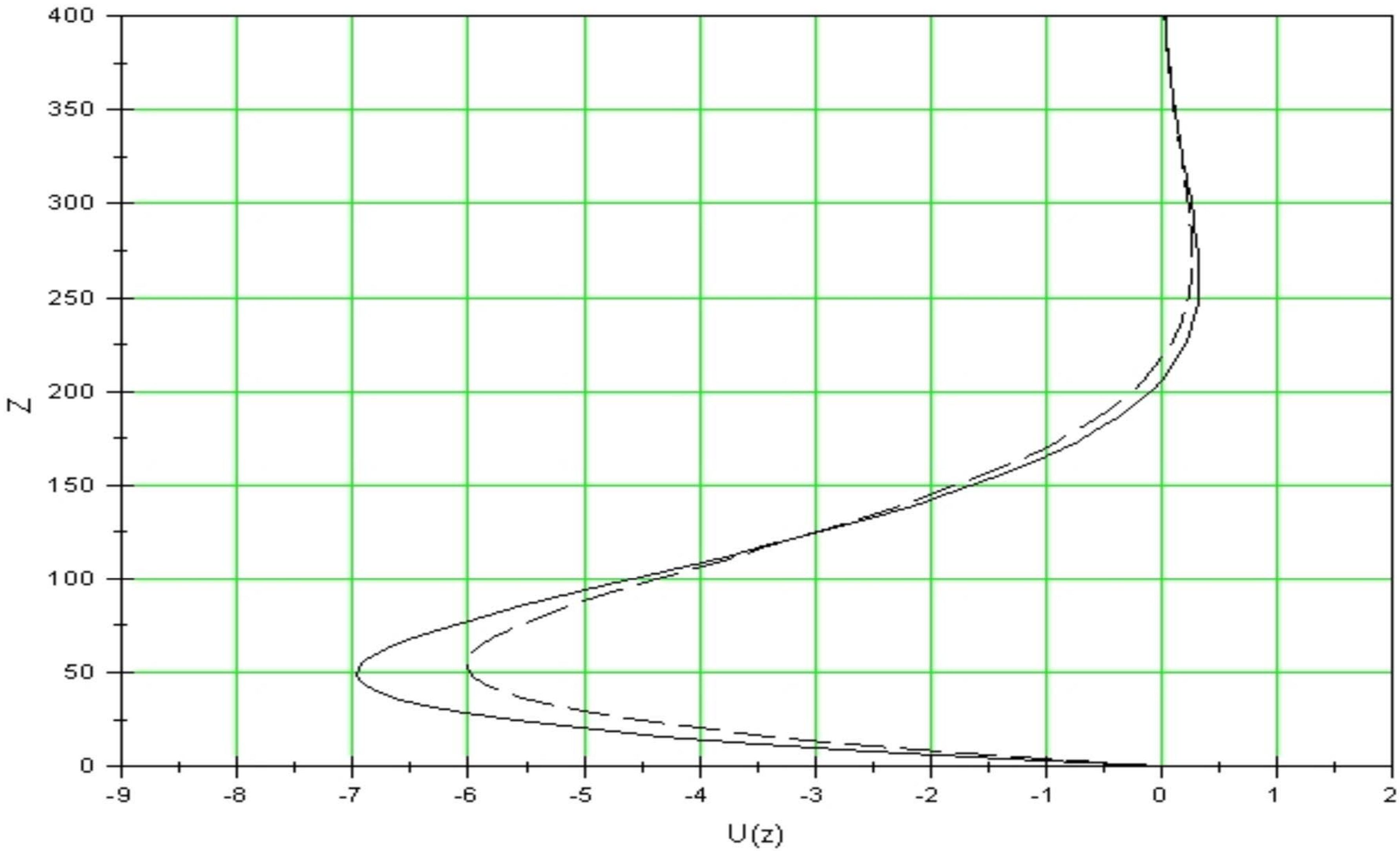
$$-Su\sin\alpha + \mathrm{Pr}^{-1}\nu\frac{d^2\vartheta}{dz^2} = 0,$$

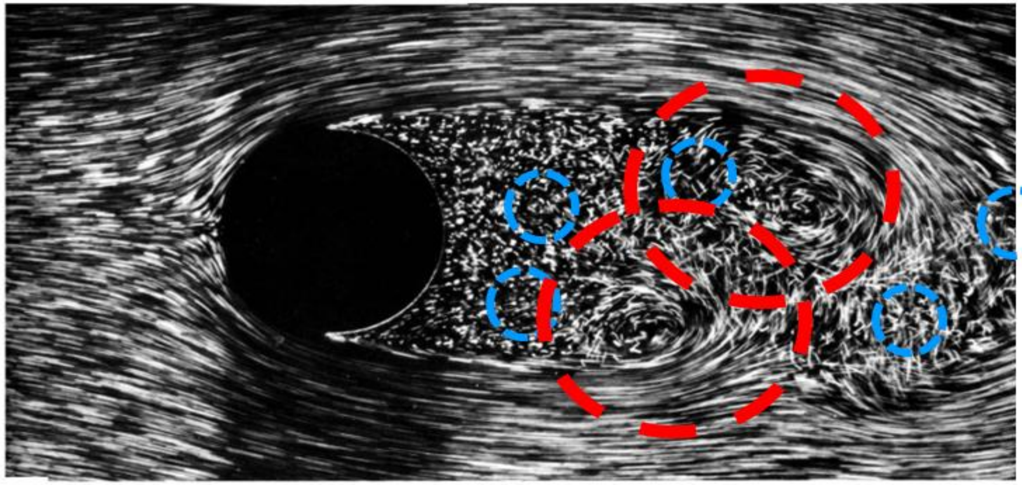
$$w_s\frac{\partial C}{\partial z} + \mathrm{Sm}^{-1}\nu\frac{d^2C}{dz^2} = 0,$$

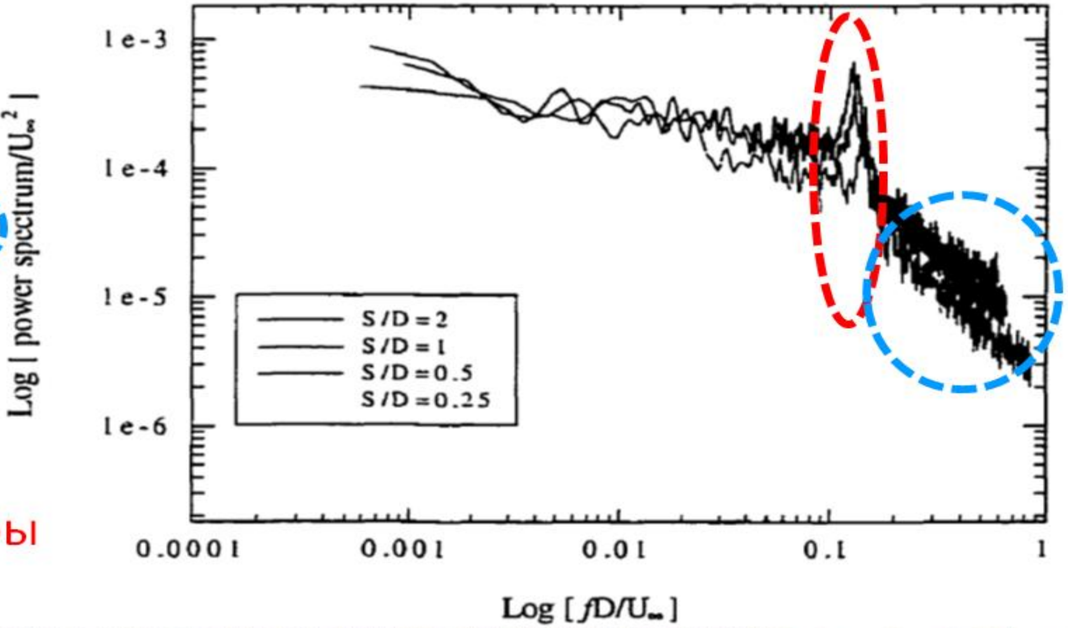
$$u \to 0,\ \theta \to 0,\ C \to 0 \quad \text{при } z \to \infty,$$

$$u = 0,\ \theta = \theta_0,\ C = C_0 \quad \text{при } z = 0.$$

Comparison of solutions to the Prandtl problem for wind velocity with (solid line) and without (dotted line) impurity



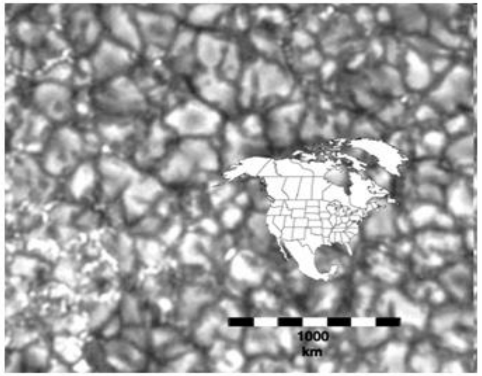


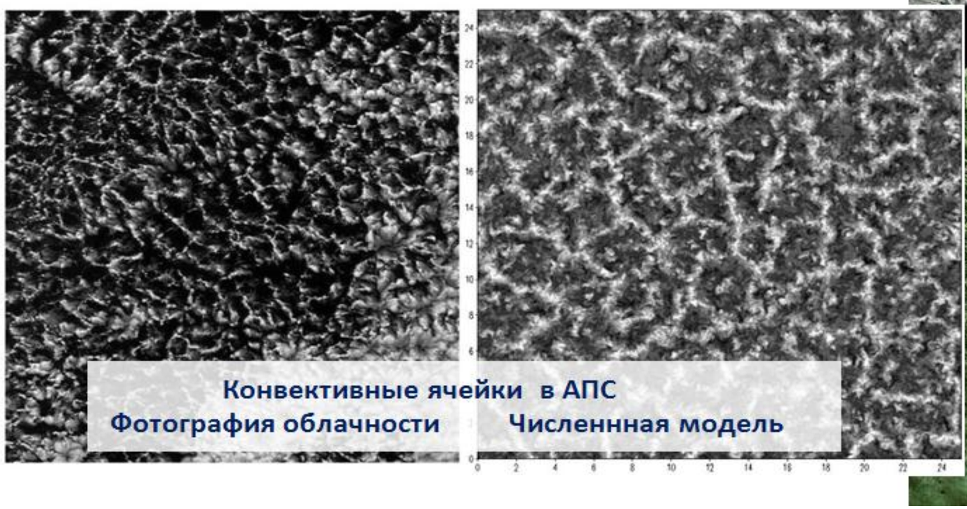


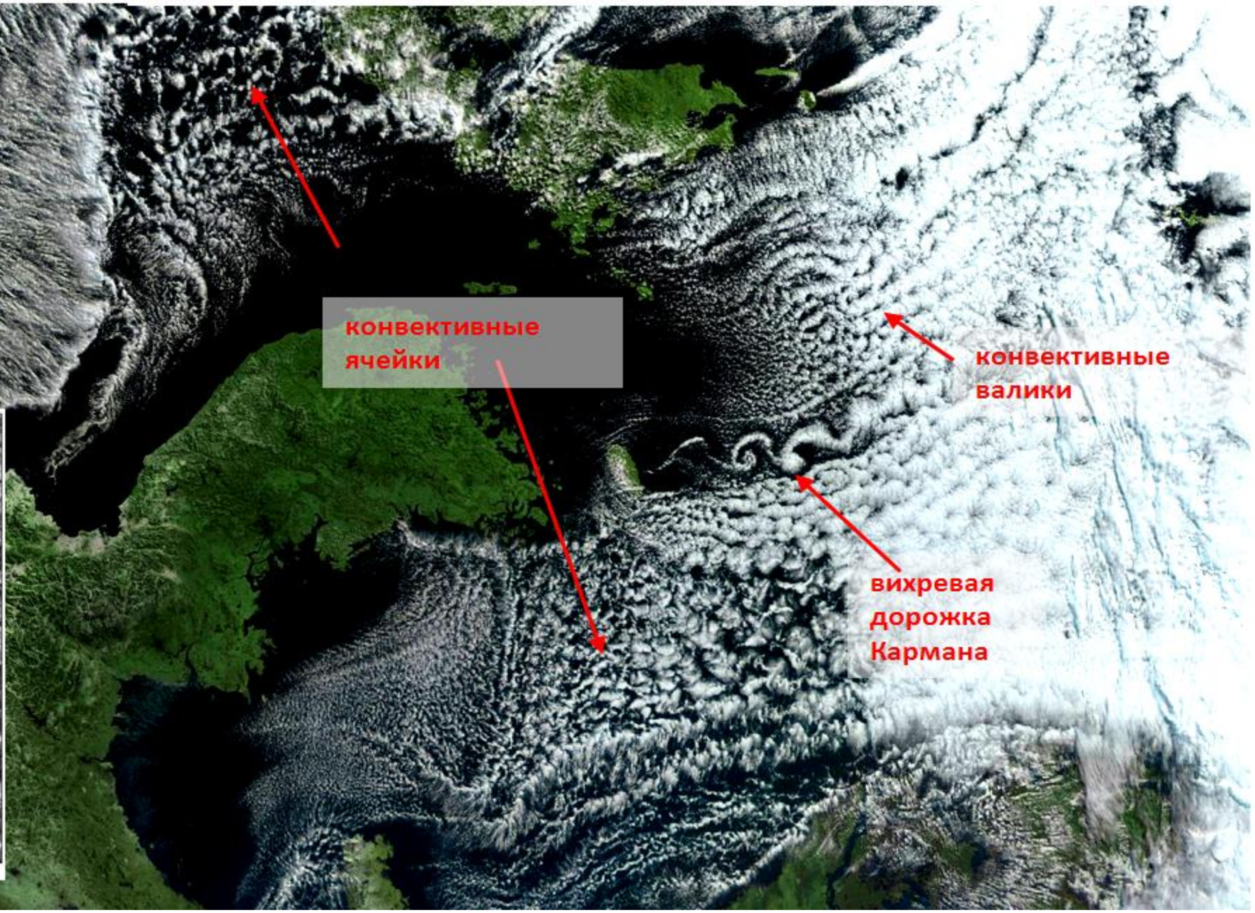
Когерентные (организованные) структуры

Мелкомасштабная турбулентность

Конвективные ячейки на Солнце (гранулы).







P. Viterbo et al. The representation of soil moisture freezing and its impact on the stable boundary layer. – Q.J.R. Meteorol. Soc., 1999, v. 125, p. 2401-2426.

- **Positive feedback between the temperature of the underlying surface and the stable stratification of the boundary layer of the atmosphere is realized in the "one-dimensional" parametrization schemes of the surface layer of the atmosphere, which is most strongly manifested at large Richardson numbers.**

- **The process of soil freezing is an important mechanism for regulating the seasonal course of temperature (in winter it prevents excessive strengthening of the stability of the boundary layer).**

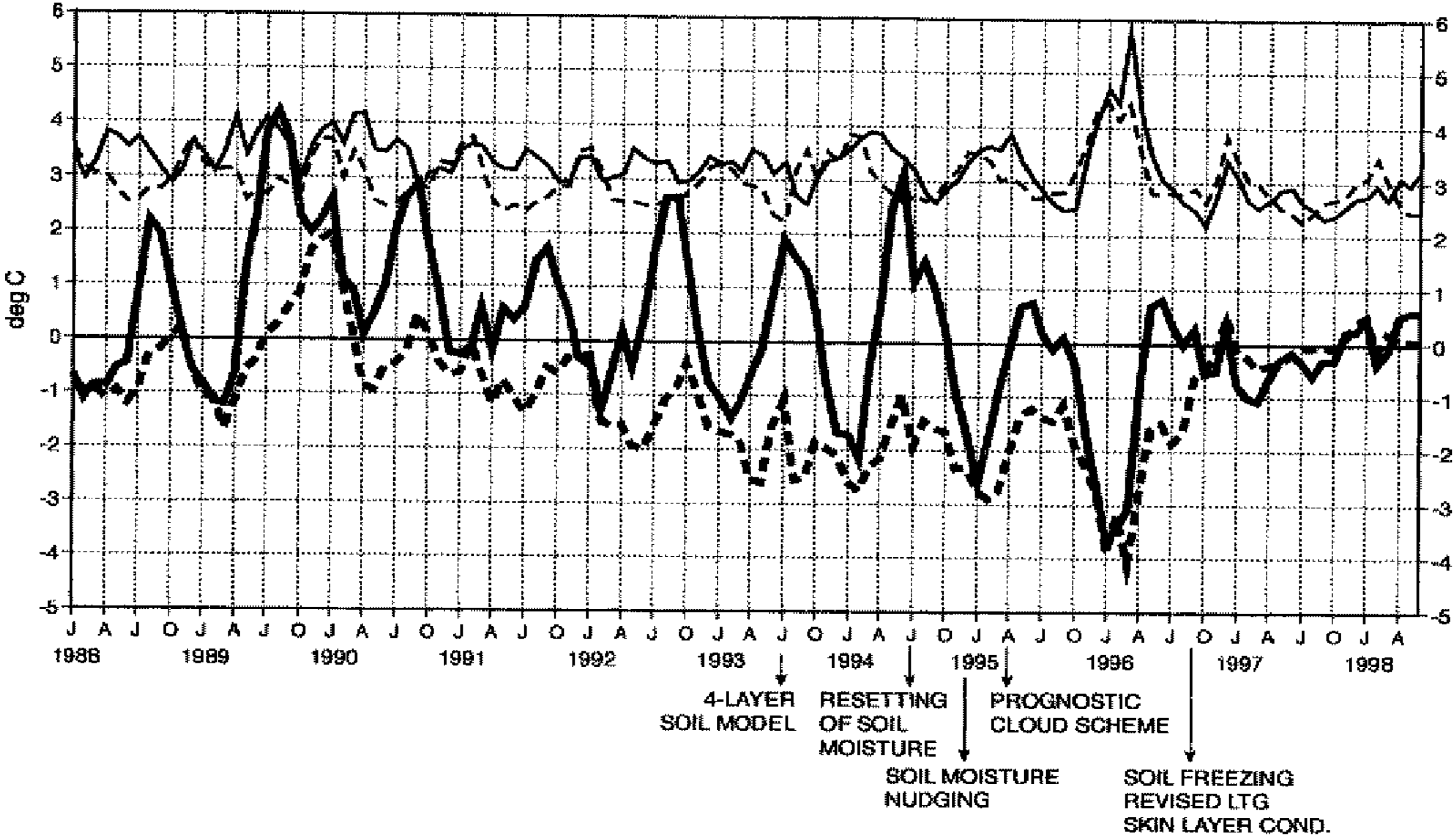
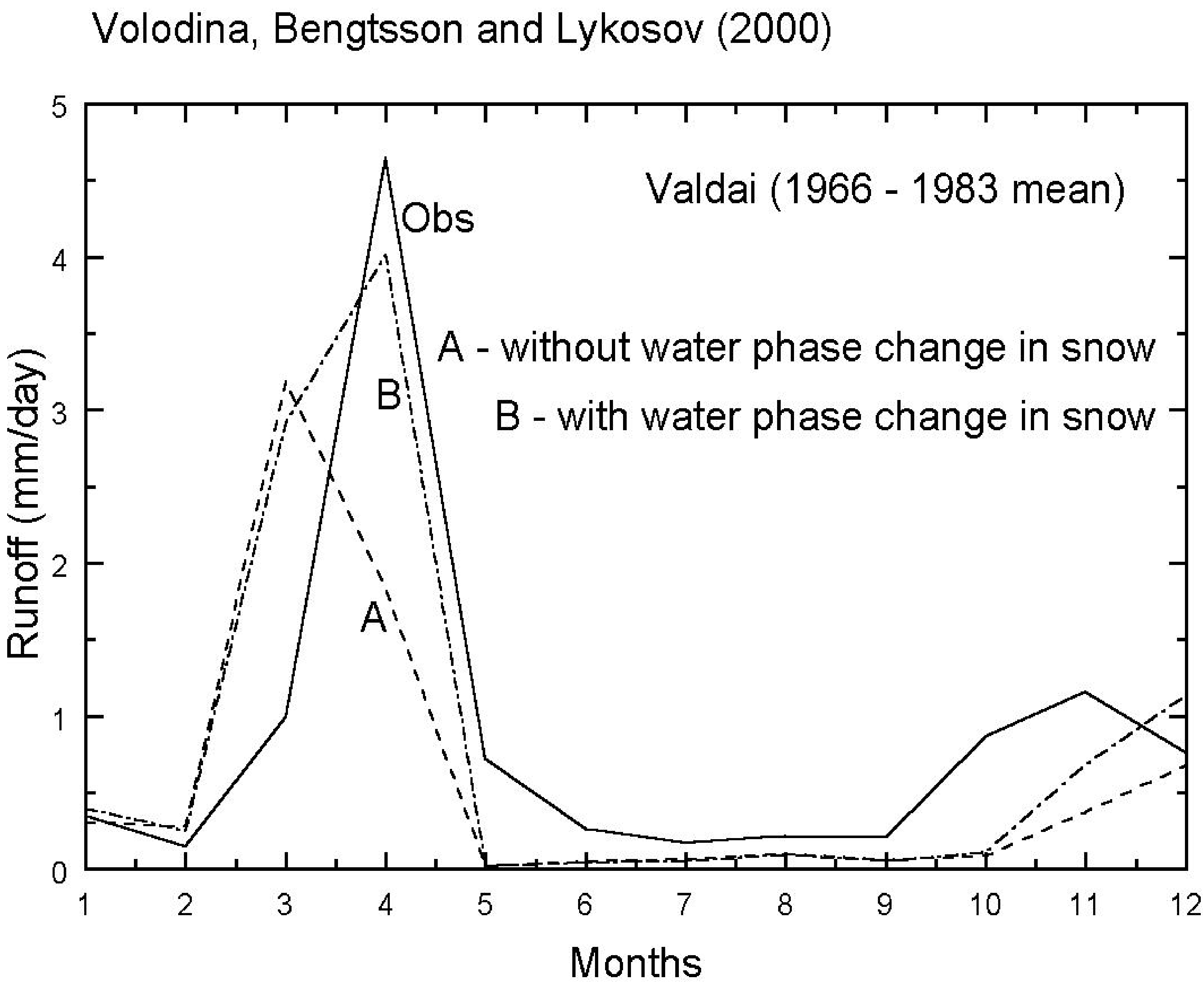
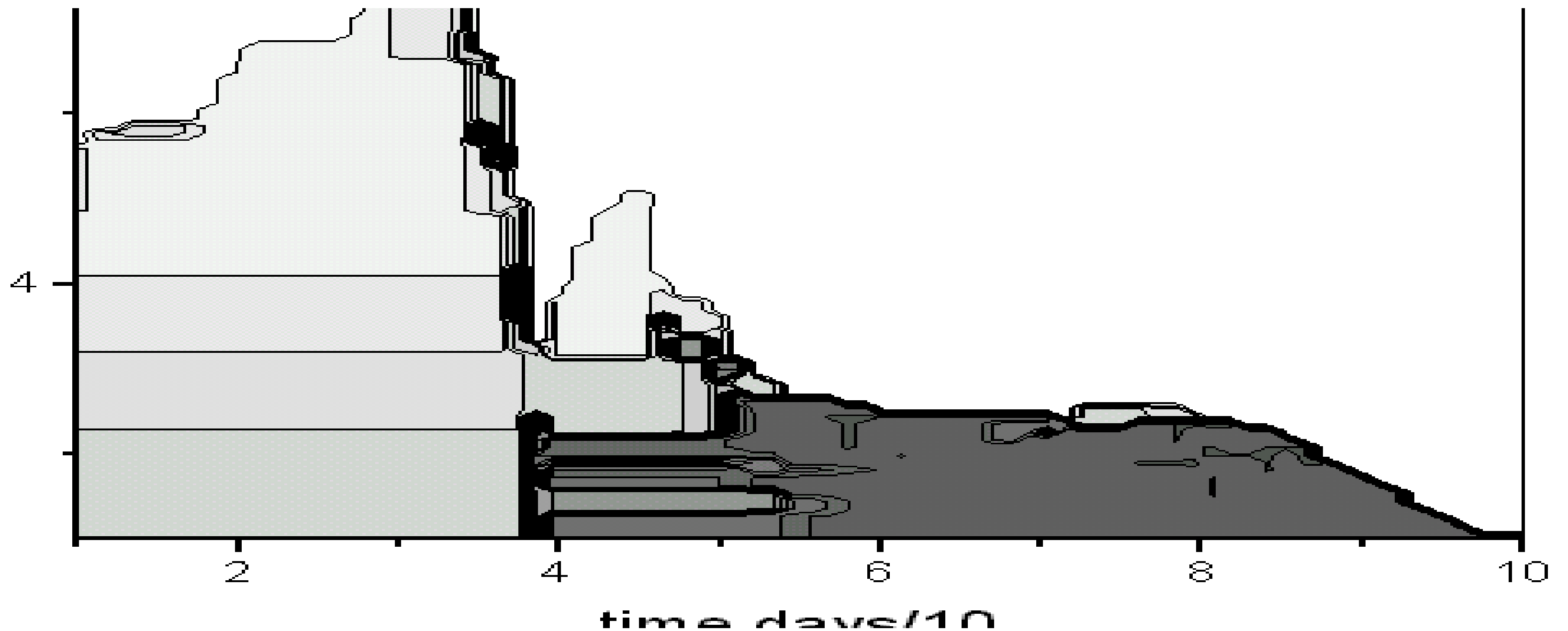


Figure 15. History of monthly biases (thick solid and dashed lines) and standard deviations (thin solid and dashed lines) with respect to observations of the daytime (72-hour: solid lines) and night-time (60-hour: dashed lines) operational 2 m temperature forecasts, averaged over all available SYNOP stations in the European area of 30°N to 72°N and 22°W to 42°E.


Volodina, Bengtsson and Lykosov (2000)
Valdai (1966 - 1983 mean)
Obs
A - without water phase change in snow
B - with water phase change in snow
B
A
Runoff (mm/day)
Months
0
1
2
3
4
5
1
2
3
4
5
6
7
8
9
10
11
12

The modelled snowpack structure with taking into account the phase transitions of moisture for Valdai station (February-April 1977). Contours: snow density



A study of the interaction of the atmospheric boundary layer in middle and high latitudes with an active layer of the land and water bodies: the development of parameterizations for the Earth system models (RSF grant No. 17-17-01210, May 2017 – December 2019).

Theoretical and experimental study of the following processes:

1. turbulent dynamics and structure of the atmospheric boundary layer over the thermally and topographically non-homogeneous underlying surface;

2. interaction of turbulence and particles in the atmospheric boundary layer (formation of two-phase stratified turbulent flows);

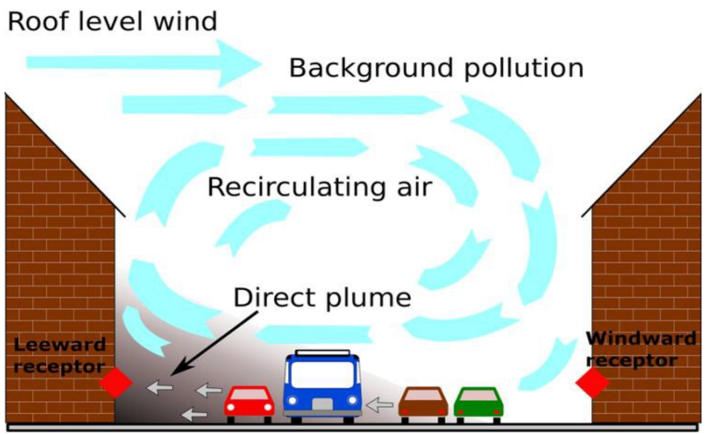
3. thermal regime, dynamics of greenhouse gases, and energy and mass transfer in the system "boundary layer of the atmosphere - the land active layer / inland water body".

Particular attention will be paid to two types of underlying surface: forests and inland waters.

Heterogeneous landscapes

The forest – field boundary, coasts

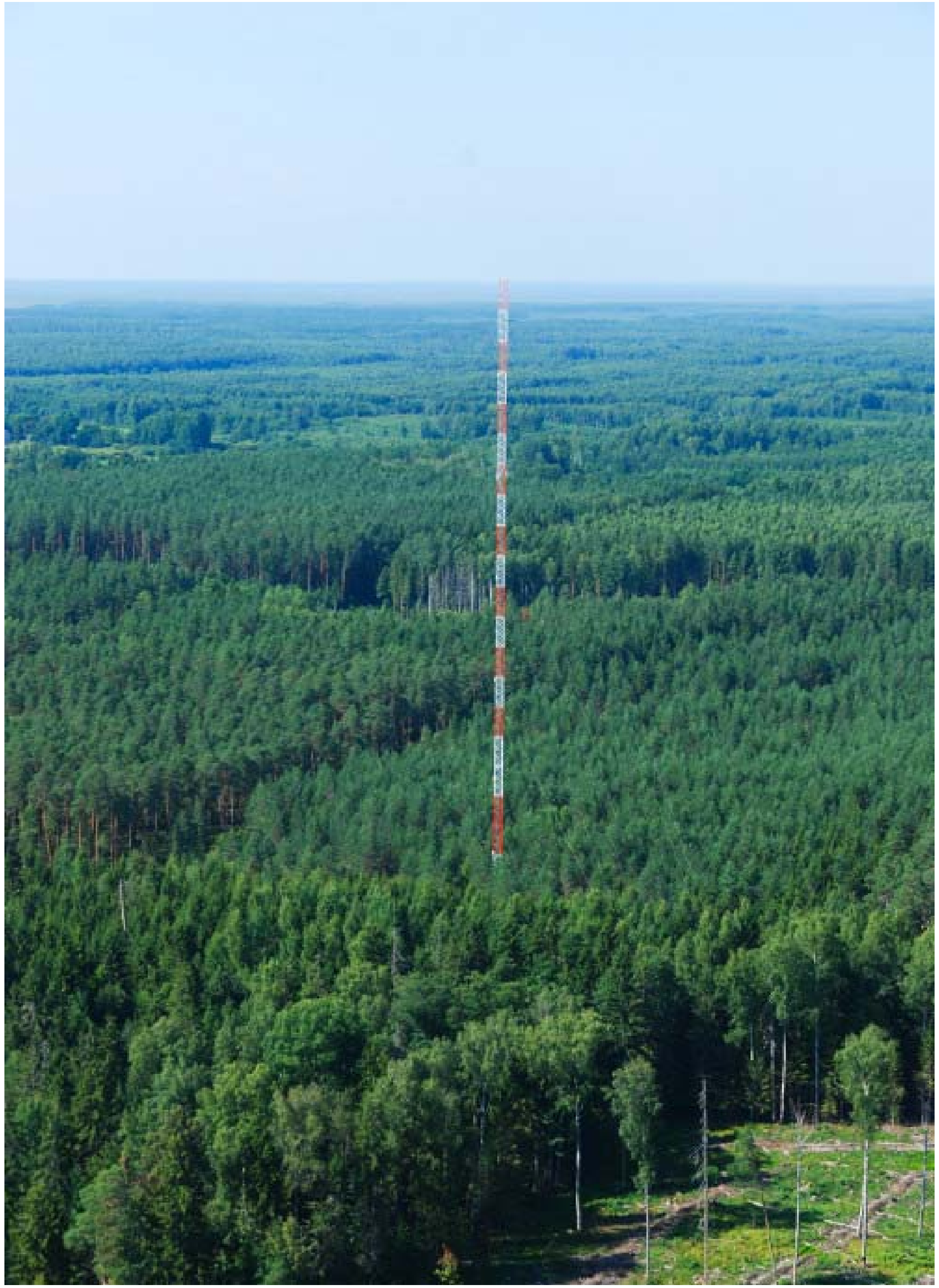
Ponds surrounded by forests, forest glades – closed open spaces

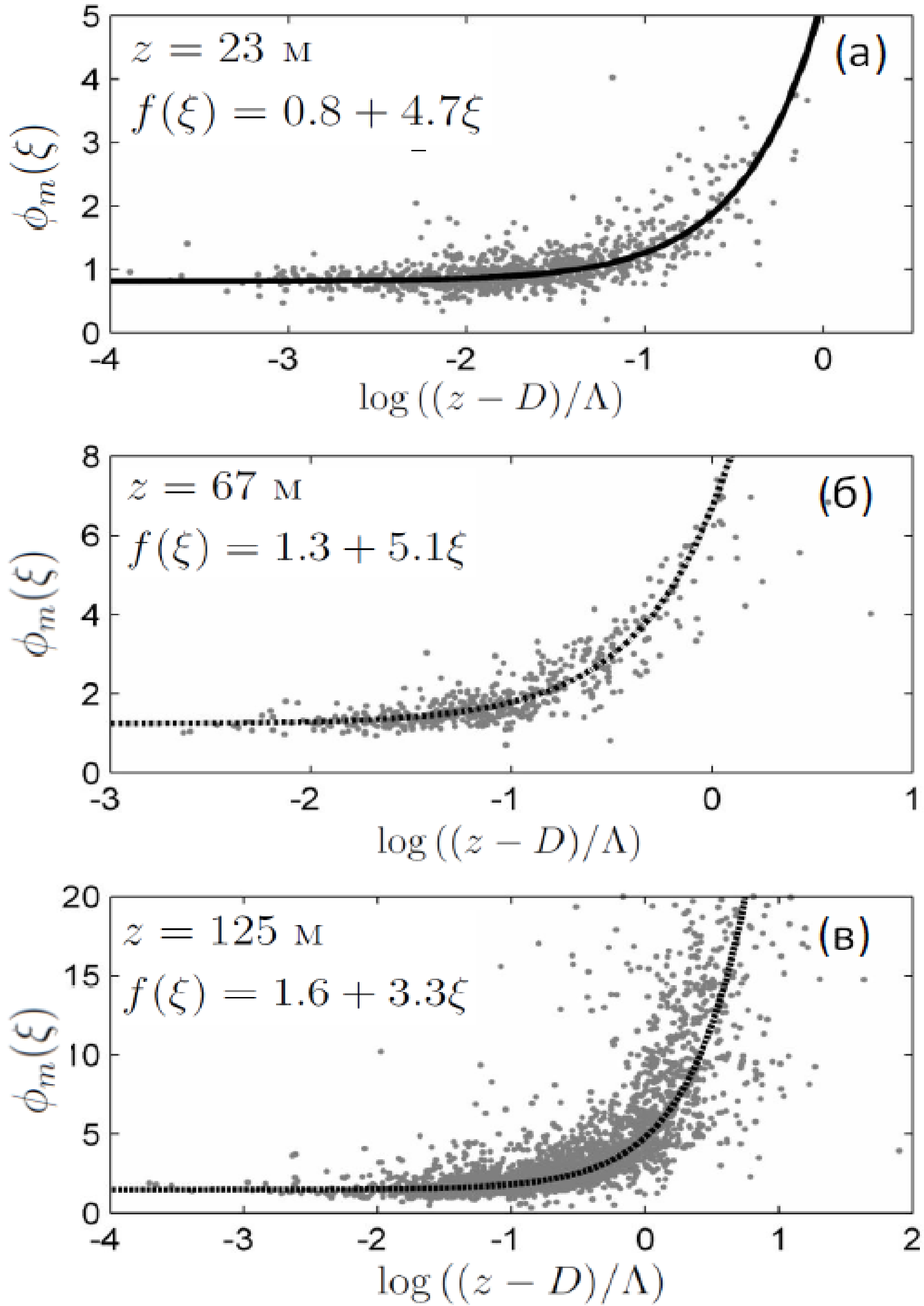


City streets – canyons

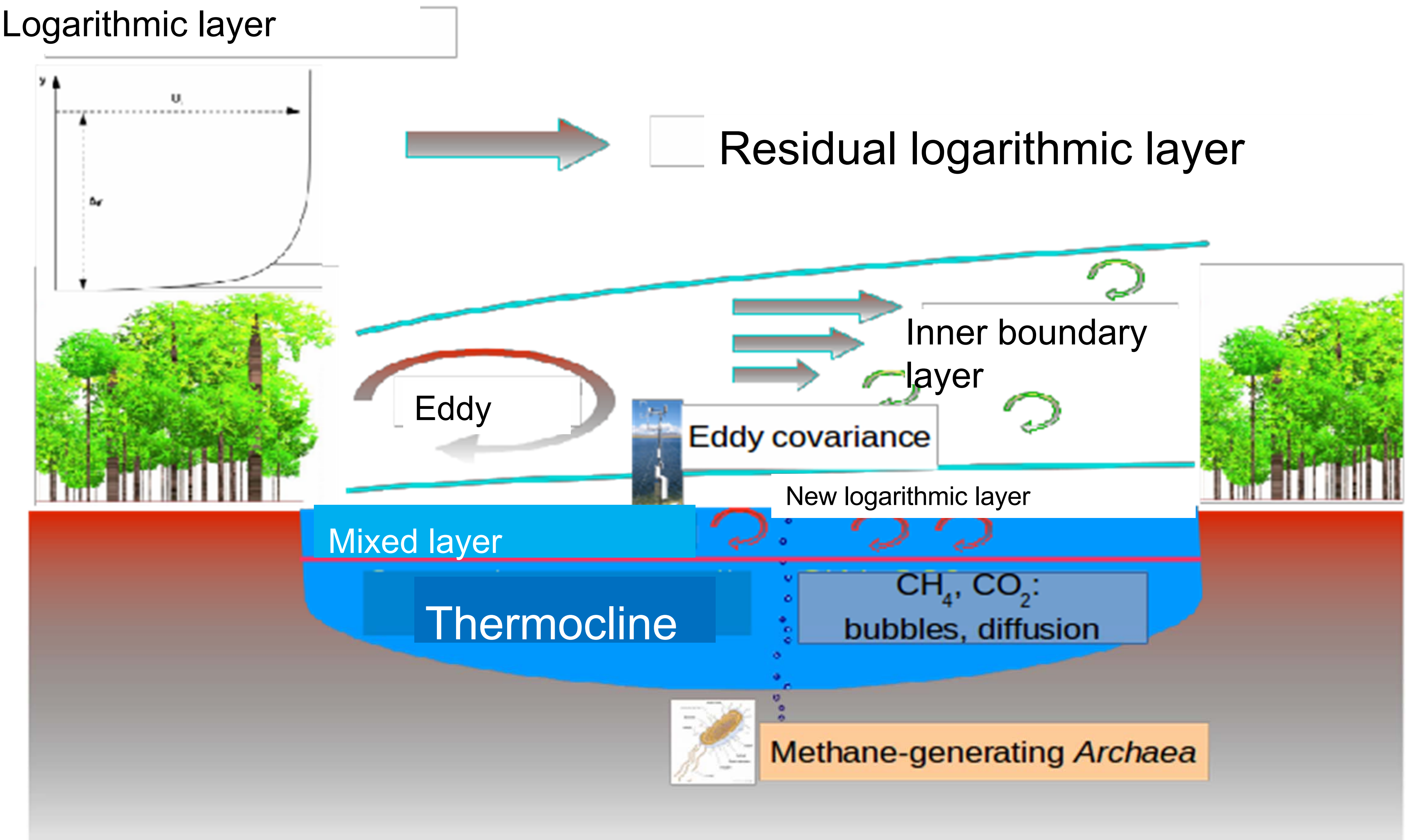
- **The conditions of applicability of the Monin – Obukhov similarity theory are not fulfilled**
- **Footprint analytical model for the method of turbulent fluctuations has not been developed**
- **The heat balance method gives only local heat flow, not representative for the landscape as a whole**

SMEAR II
(Station for Measuring Ecosystem-Atmosphere Relations)
University of Helsinki, Finland

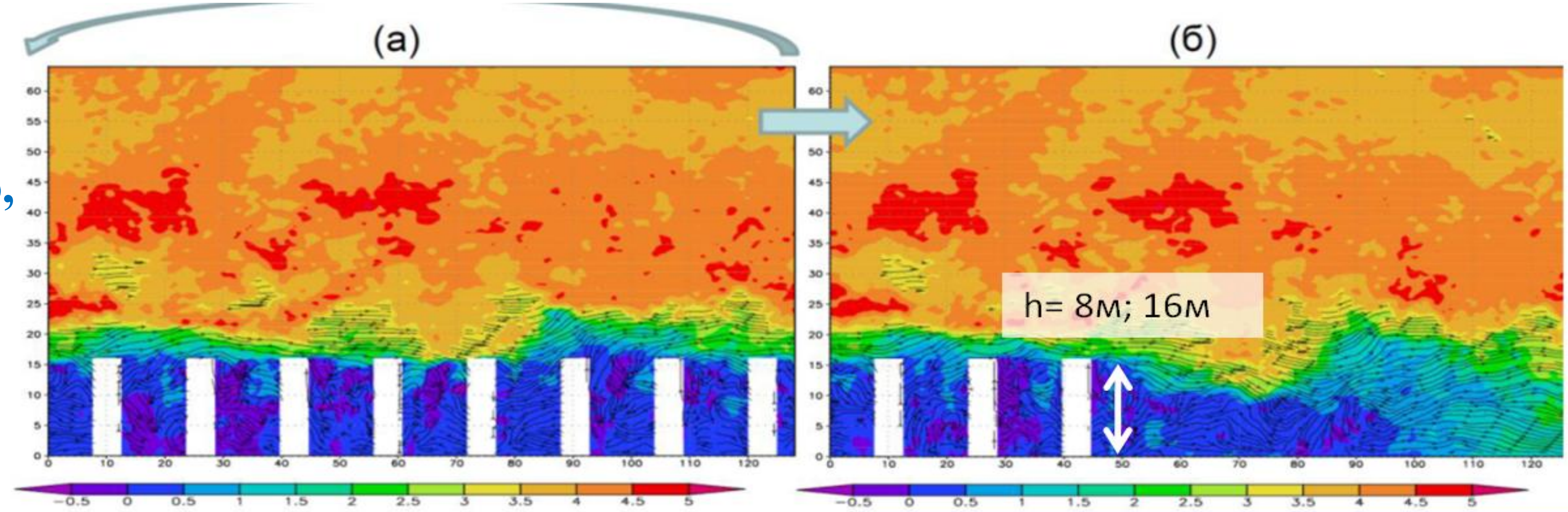




Boundary layer above the lake



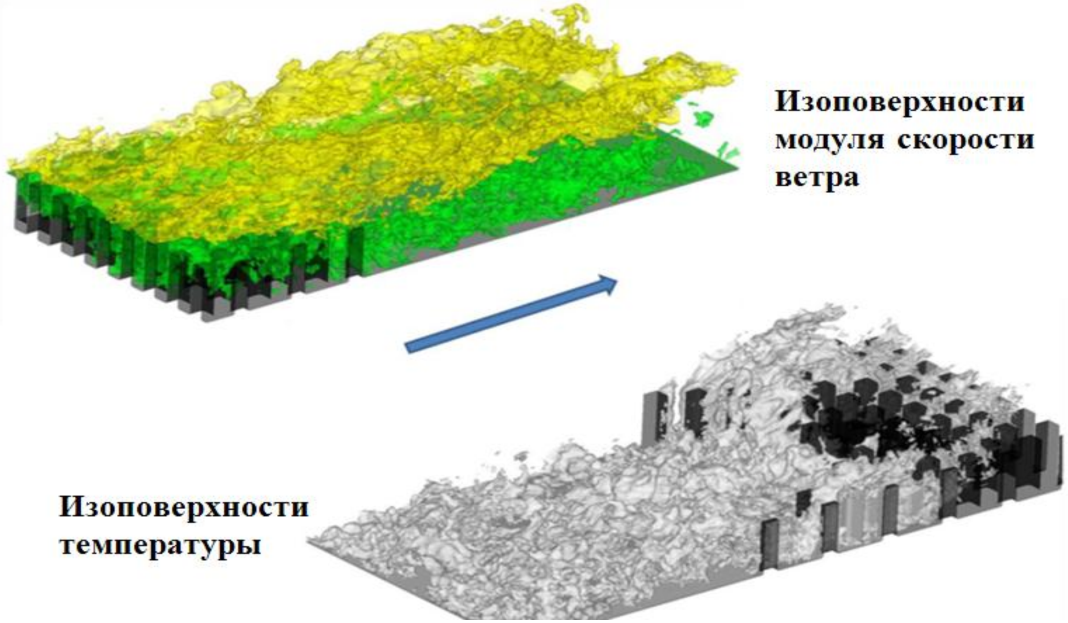
Глазунов и Степаненко, Известия РАН, сер. ФАиО, 2015

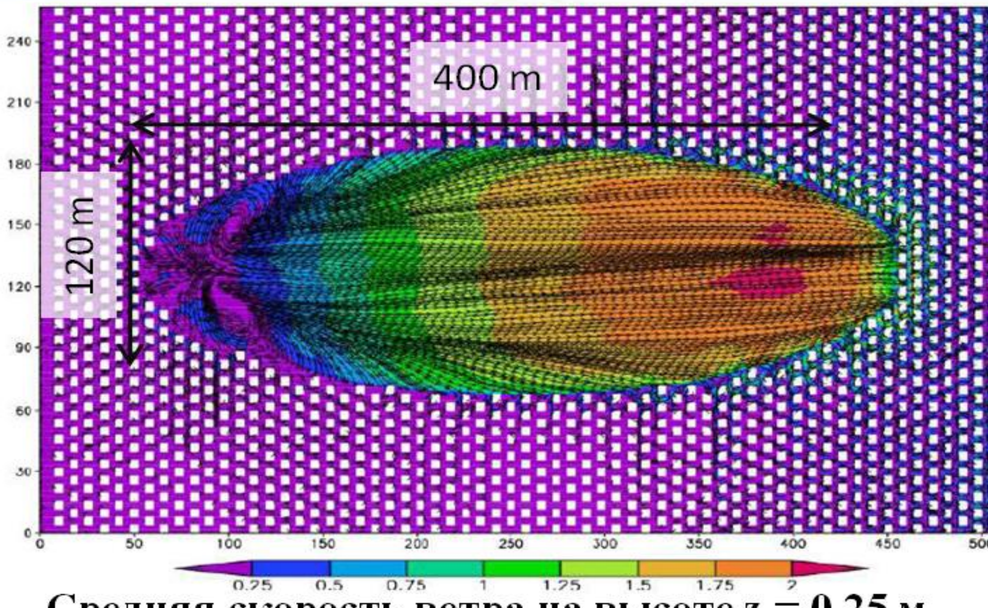


Турбулентный поток генерируется вспомогательной моделью (а) с двоякопериодическими граничными условиями и с заданным массивом объектов на поверхности. Значения z_{0w} и D соответствуют типичным значениям для лесной растительности.

Непериодическая расчетная область (б), включающая “озеро”: $z_{01} = 10^{-4}$ м, $T_s^{lake} = T^{air} \pm 5^0C$

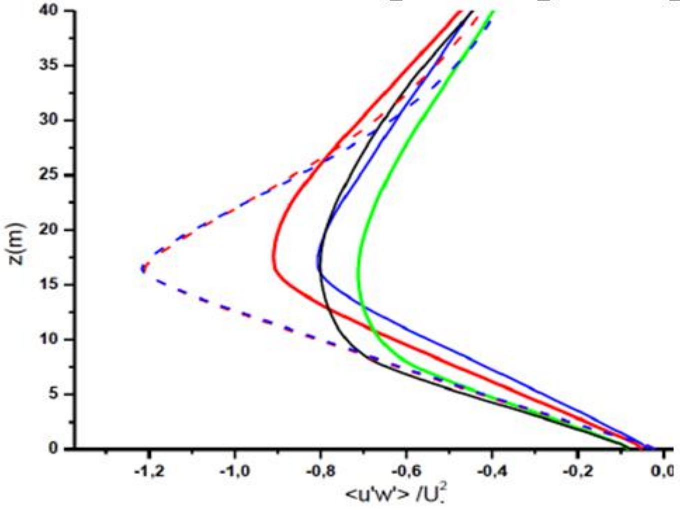
Шаг сетки $\Delta = 0.5$ м , 1024 x 512 x 128 узлов, время интегрирования: 1 час, $\Delta t = 0.025$ секунд

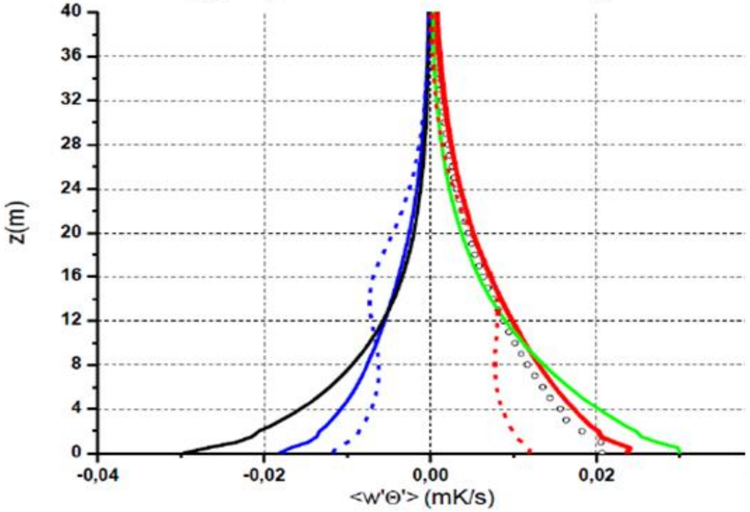


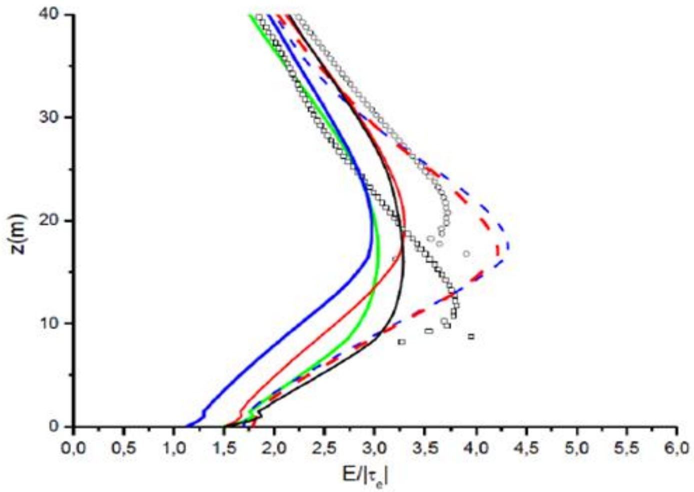


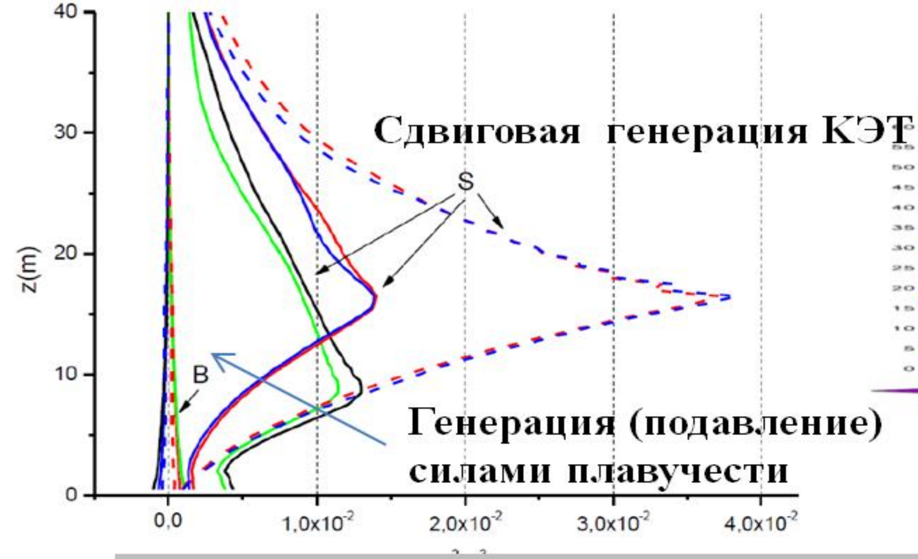
Средняя скорость ветра на высоте z = 0.25 м

Некоторые характеристики турбулентности, осредненные по всей площади “озера”

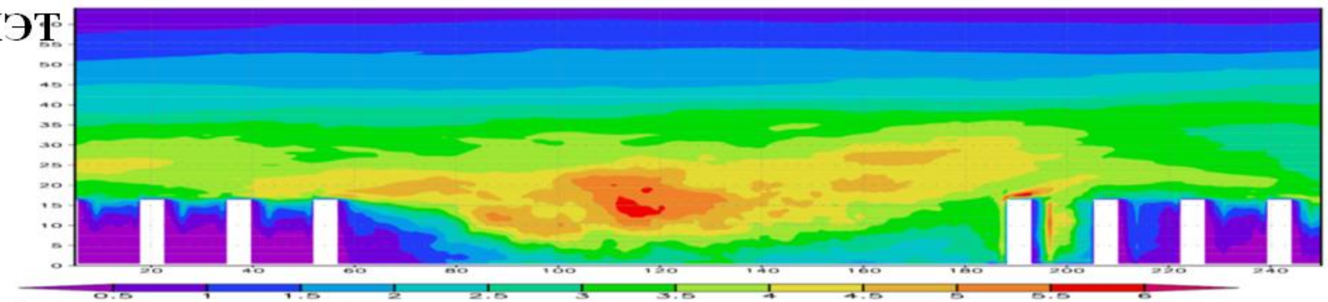






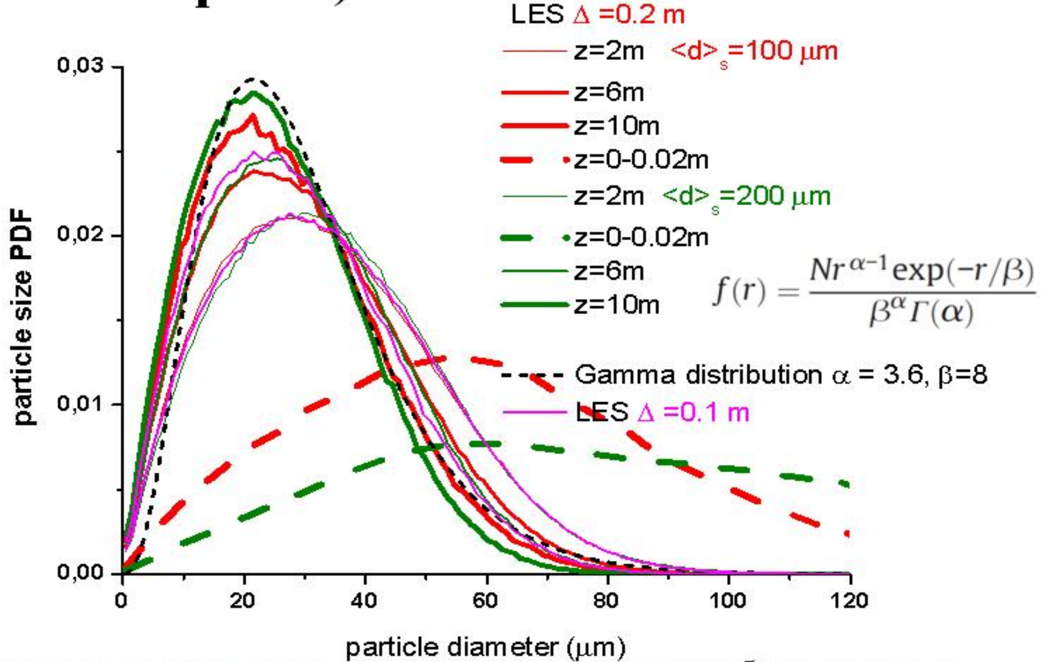


Кинетическая энергия турбулентности (КЭТ)

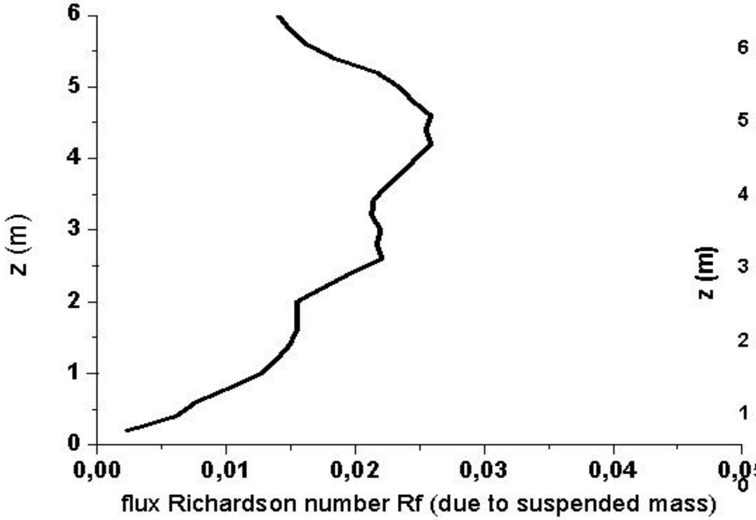


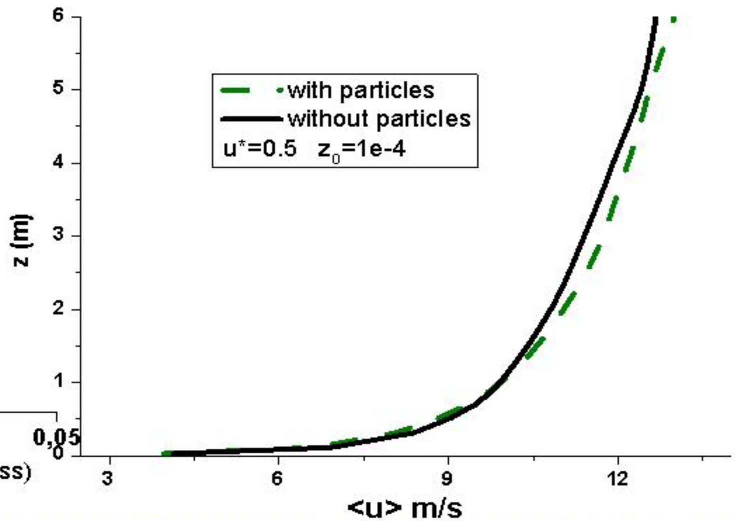
• Слой постоянных потоков отсутствует (существенная часть тепла и влаги переносится над озером в горизонтальном направлении).
• Очень слабая чувствительность к стратификации (теория подобия Монина – Обухова неприменима для вычисления турбулентных потоков над «озером»).

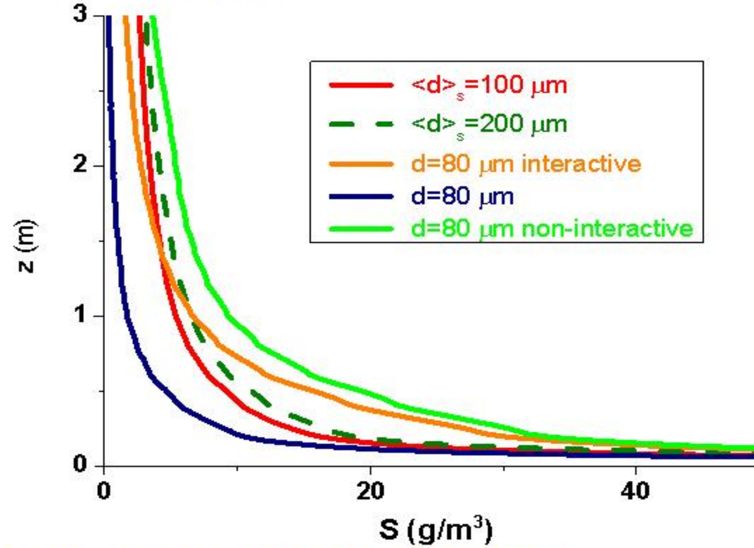
LES. Перенос взвесей тяжелых частиц в приземном слое (поземка, пылевой перенос)



Распределение частиц взвеси по размерам слабо зависит от заданного распределения на поверхности

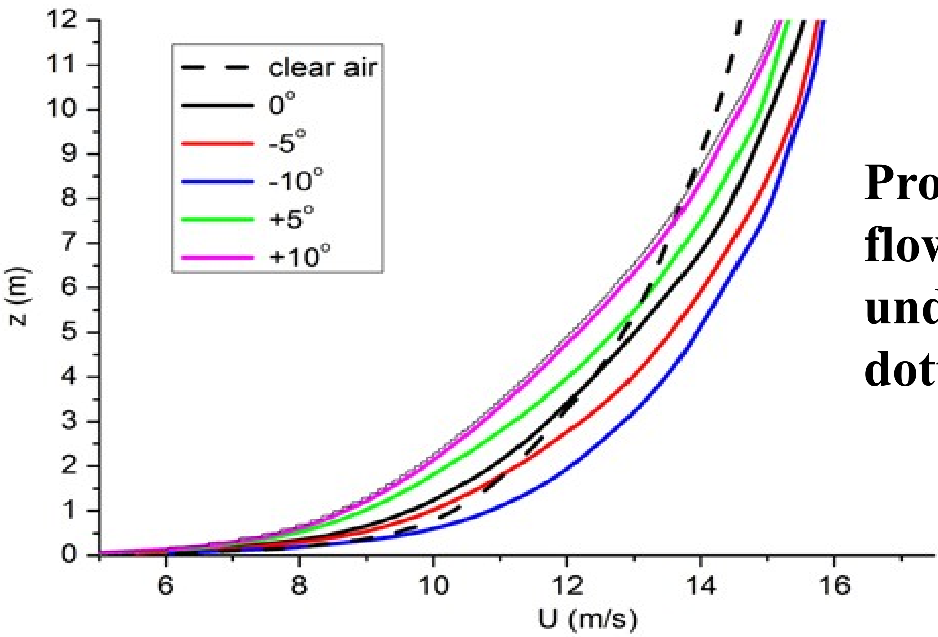




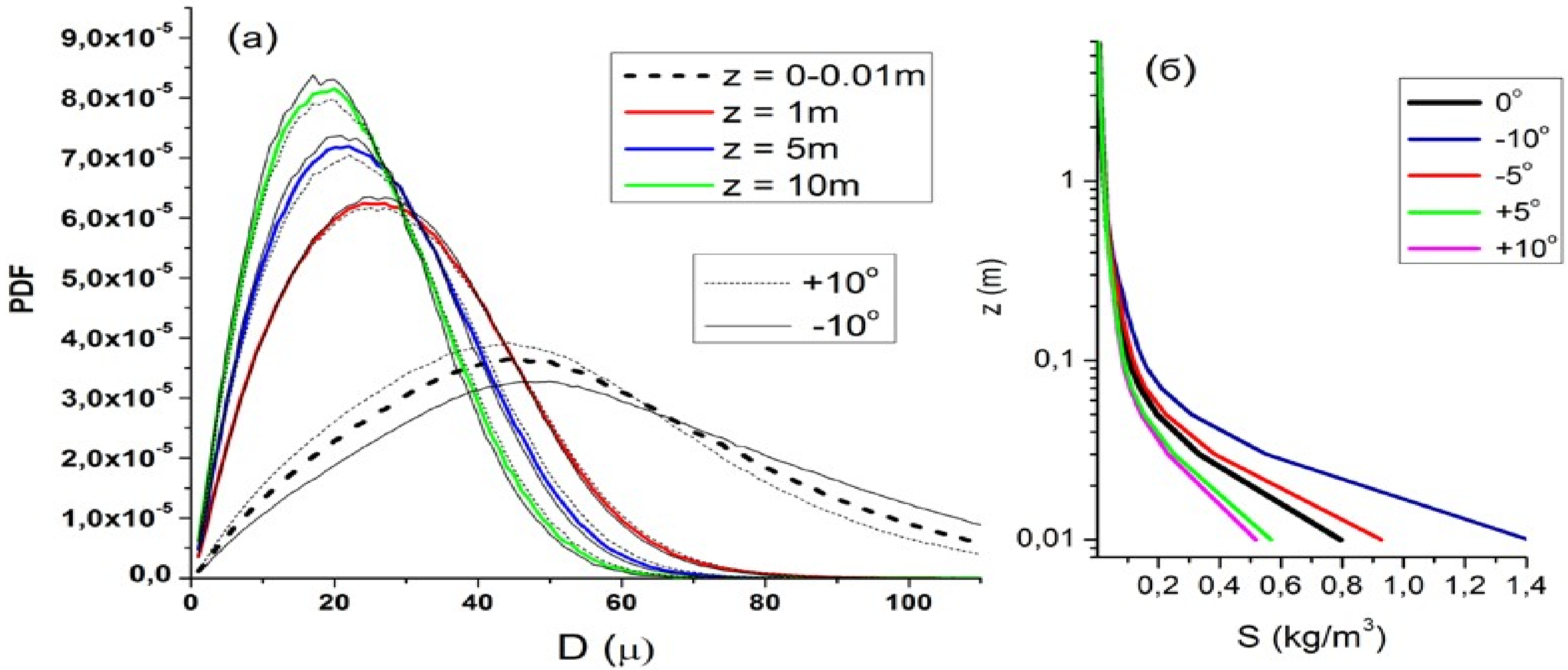


Обратное влияние взвеси на среднюю скорость ветра в приземном слое невелико, однако, тяжелые инерционные частицы имеют тенденцию к кластеризации и их локальным обратным воздействием на поток пренебречь нельзя.

Using the INM RAS LES-model with fine spatial resolution, the transport of ice and snow particles suspended above a snow-covered surface under conditions of strong wind was calculated. The balance of turbulent kinetic energy of the flow was analyzed, indicating that, along with the contribution of the buoyancy forces, the inertia forces exerted on the flow by particles have a significant effect. A series of calculations were carried out with different surface slopes for a given constant background flow. It was found that at a sufficiently large distance from the surface the size distribution of suspended particles becomes not sensitive to the surface slope. It is established that suspension has an effect on the average flow velocity: at altitudes of more than 8 meters in all calculations, the flow speed with particles exceeds the speed of "pure" flow, which means a decrease in the aerodynamic surface roughness in the presence of a suspension



Profiles of the average velocity of turbulent flows with suspensions for different slopes of the underlying surface (color curves). The black dotted curve is the flow without particles.



a) Histograms of particle size distribution depending on the distance to the surface. Thick lines – horizontal surface; thin solid and dotted lines – calculations with a surface slope of +10 and -10 degrees.

b) The mass concentration of the particle suspension depending on the height.

Diagnosis and numerical simulation of the atmospheric boundary layer dynamics and the Arctic terrestrial ecosystems state under anthropogenic stress (RFBR grant № 18-05-60126; June, 2018 – May, 2021)

Main objectives of the project

1. Development of new computational technologies for multiscale modeling of turbulent flows and transport of gas and fine impurities in the urban environment and in the boundary layer of the atmosphere over the city and its surroundings.

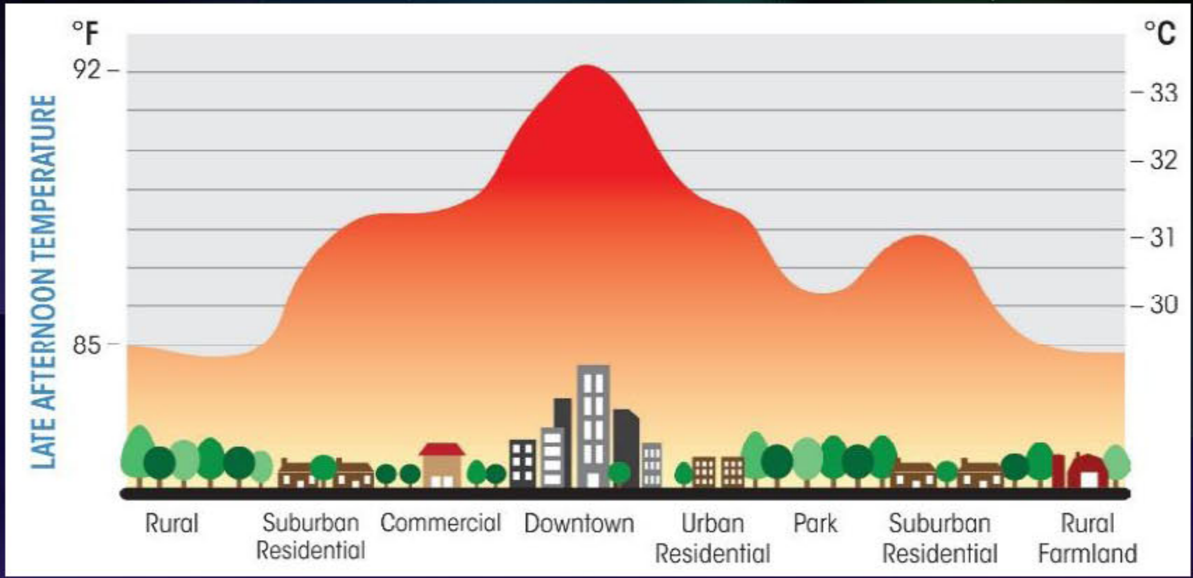
2. Diagnosis of the accumulation of impurities containing heavy metals in the vegetation cover of the areas adjacent to the city, based on observations (Nadym, Norilsk) and numerical modeling.

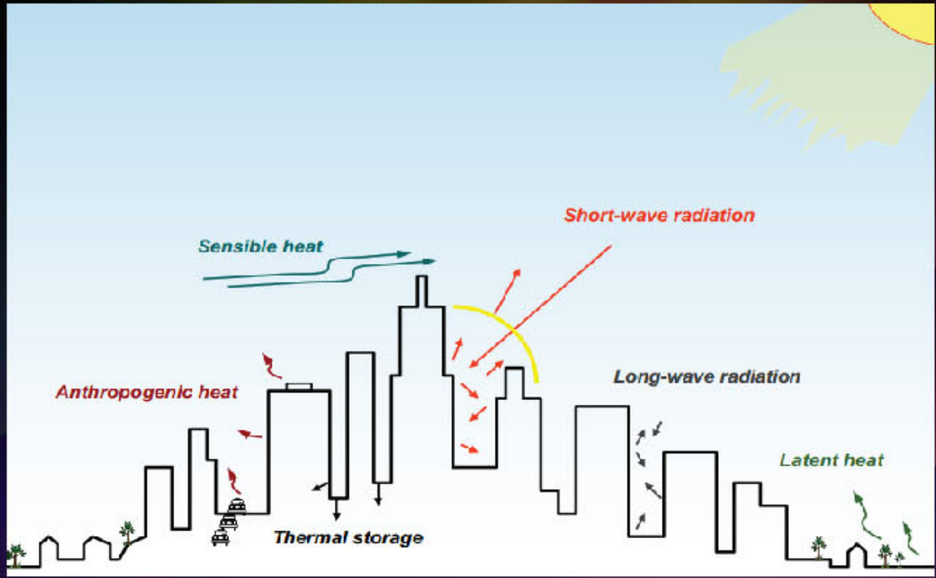
3. On the basis of remote sensing data, field observations and the results of numerical modeling to assess the impact of urbanization on the evolution of snow and ice cover of the surrounding areas, ice and biogeochemical regime of thermokarst lakes.

4. Development of new physically based parameterization of heat and moisture exchange in the moss cover, dynamic and thermal roughness and thermal balance of various types of underlying surface, including urban environment.

Мотивация

Эффект **городского острова тепла** изучен для умеренных широт, но не для Арктики





Ключевые вопросы:

1) Существуют ли острова тепла в Арктике?

2) Какая их интенсивность (величина термической аномалии)?

3) Каково их влияние на общество и экосистемы?

Scales of urban climate studies

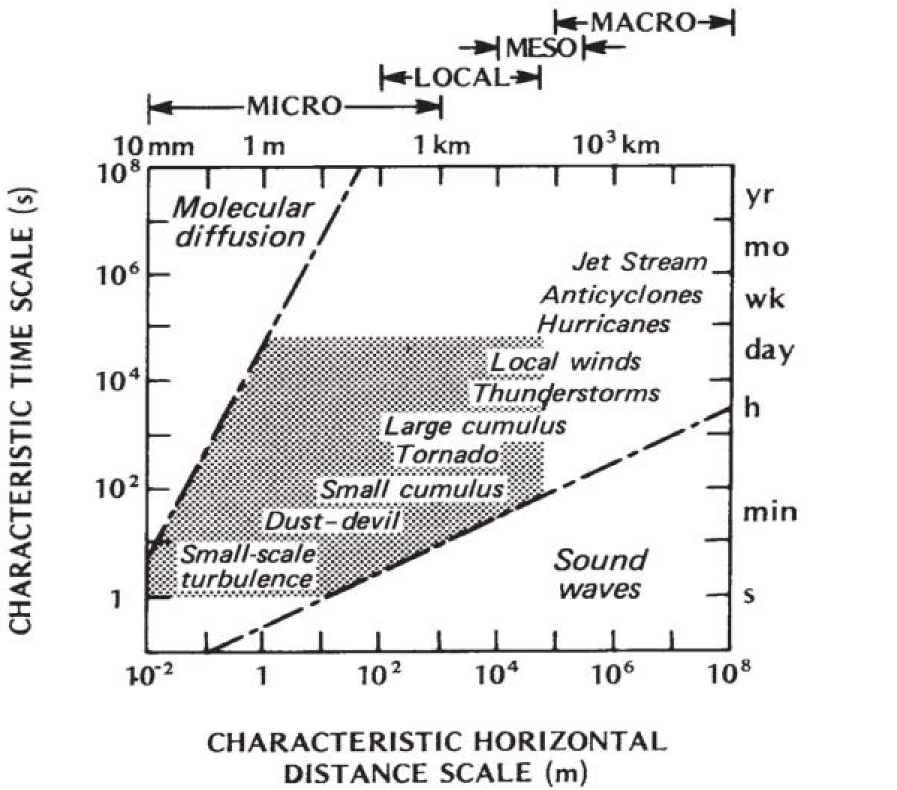


Figure 1.1 Time and space scales of various atmospheric phenomena. The shaded area represents the characteristic domain of boundary layer features (modified after Smagorinsky, 1974).

(Oke, 1987)

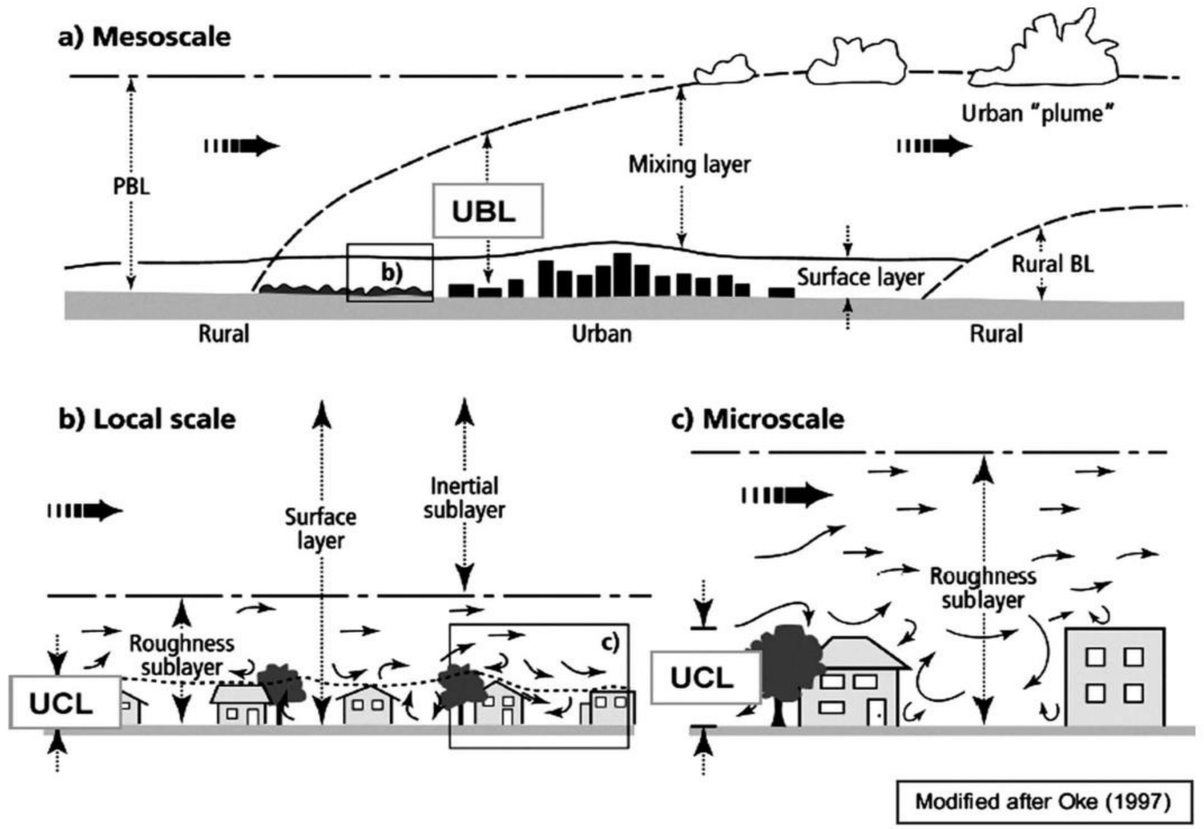


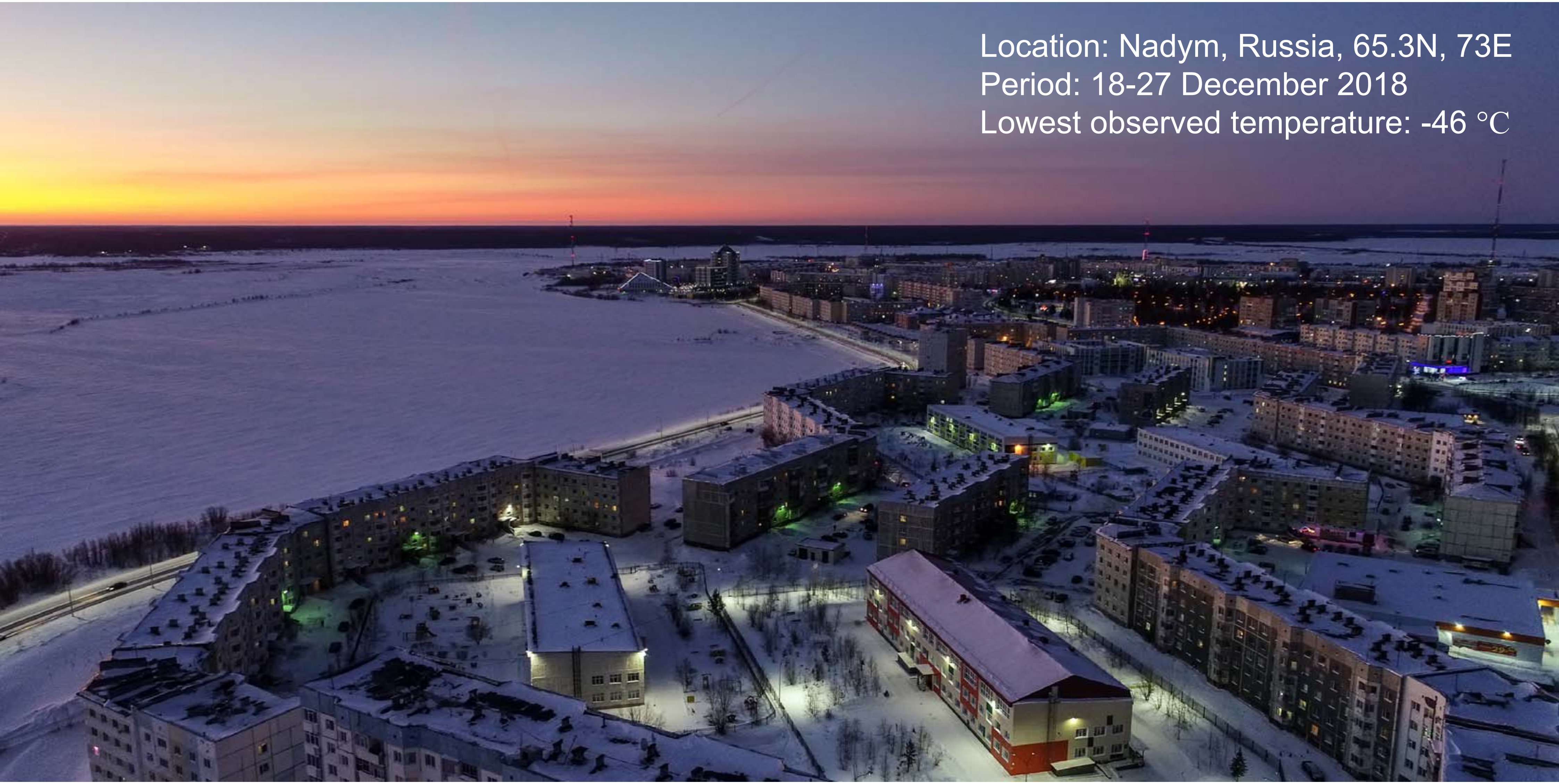
Figure 1. Various scales linking urban environments to the environmental system (modified after Oke (Oke 1987): urban canopy layer (UCL) and urban boundary layer (UBL)).

(Shepard, 2005)

Nadym topography

Nadym topography from Open Street Map and *in situ* measurements

Experimental campaign in Nadym



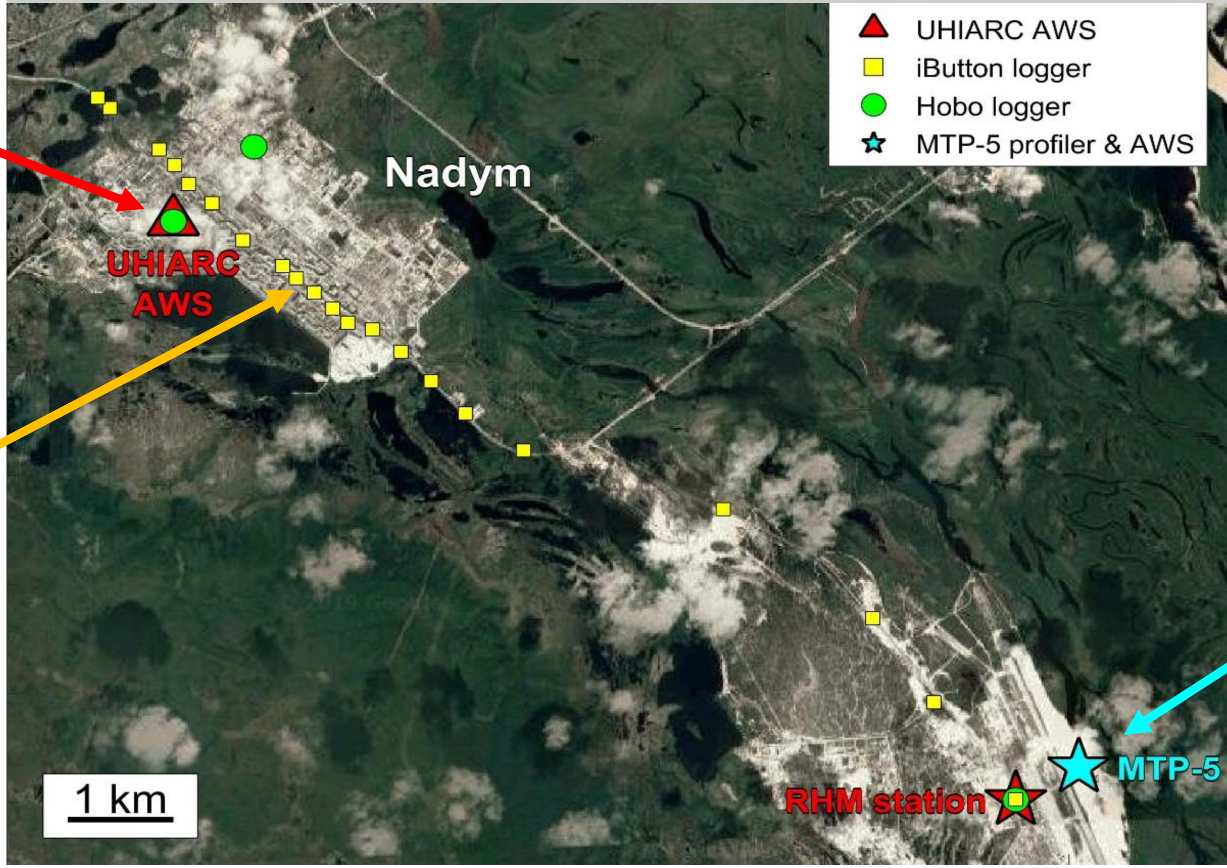
With contributions of Pavel Konstantinov (MSU), Arseniy Artamonov (IAP RAS), Artem Pashkin (IAP RAS)

Experimental campaign in Nadym

Aim of the research is to investigate the ABL behavior over the Arctic city in winter, under strongly stable atmospheric stratification

UHIARC* AWS in the city center

Quadcopter-based vertical temperature sounding over the city**



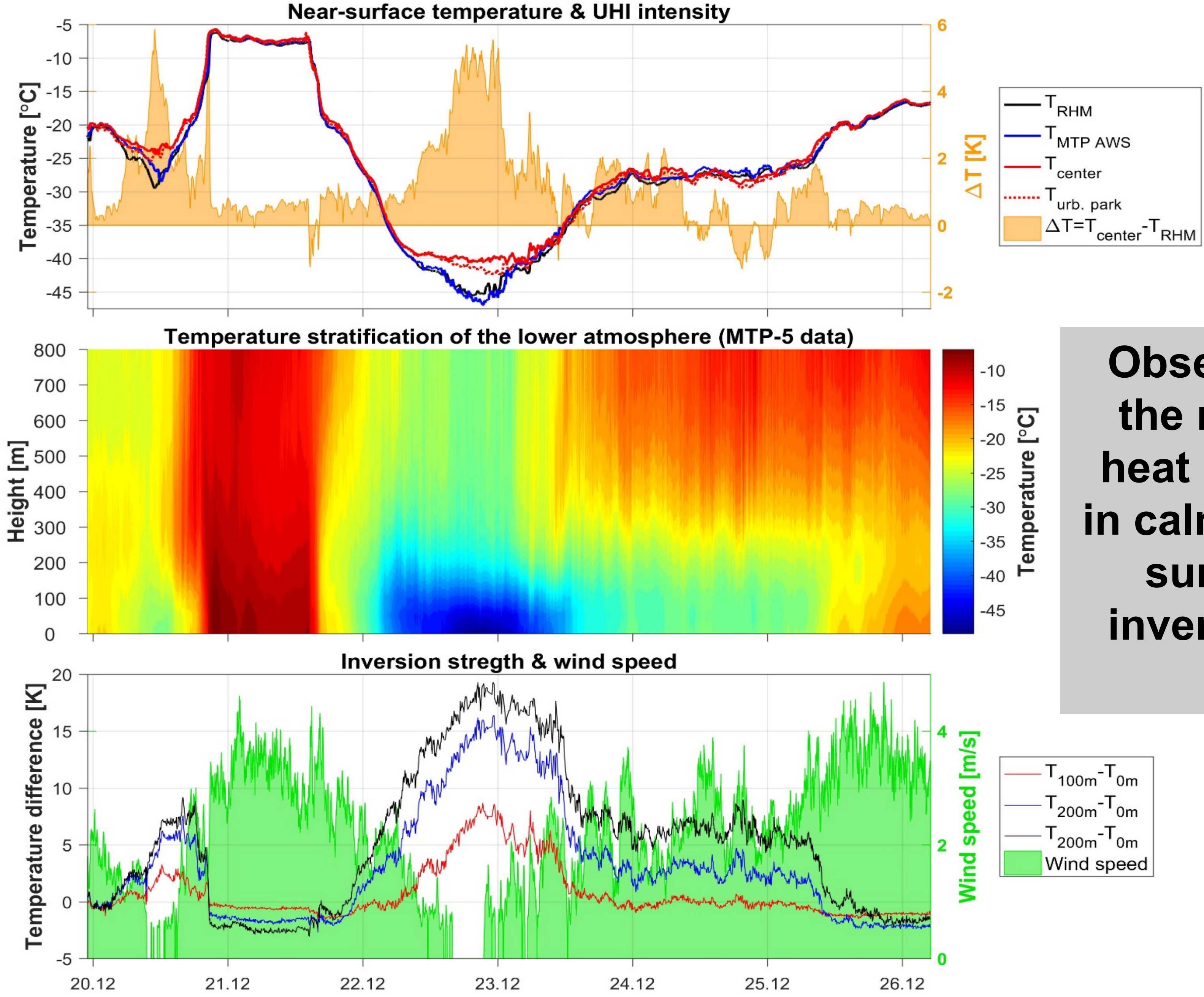
22 iButton & Hobo temperature loggers

MTP-5 microwave temperature profiler

*UHIARC (Urban Heat Island Arctic Research Campaign) AWS is deployed in Nadym since 2016 (Konstantinov et al., 2018

** Methodology of the quadcopter application for temperature measurements is described in (Varentsov et al., 2019)

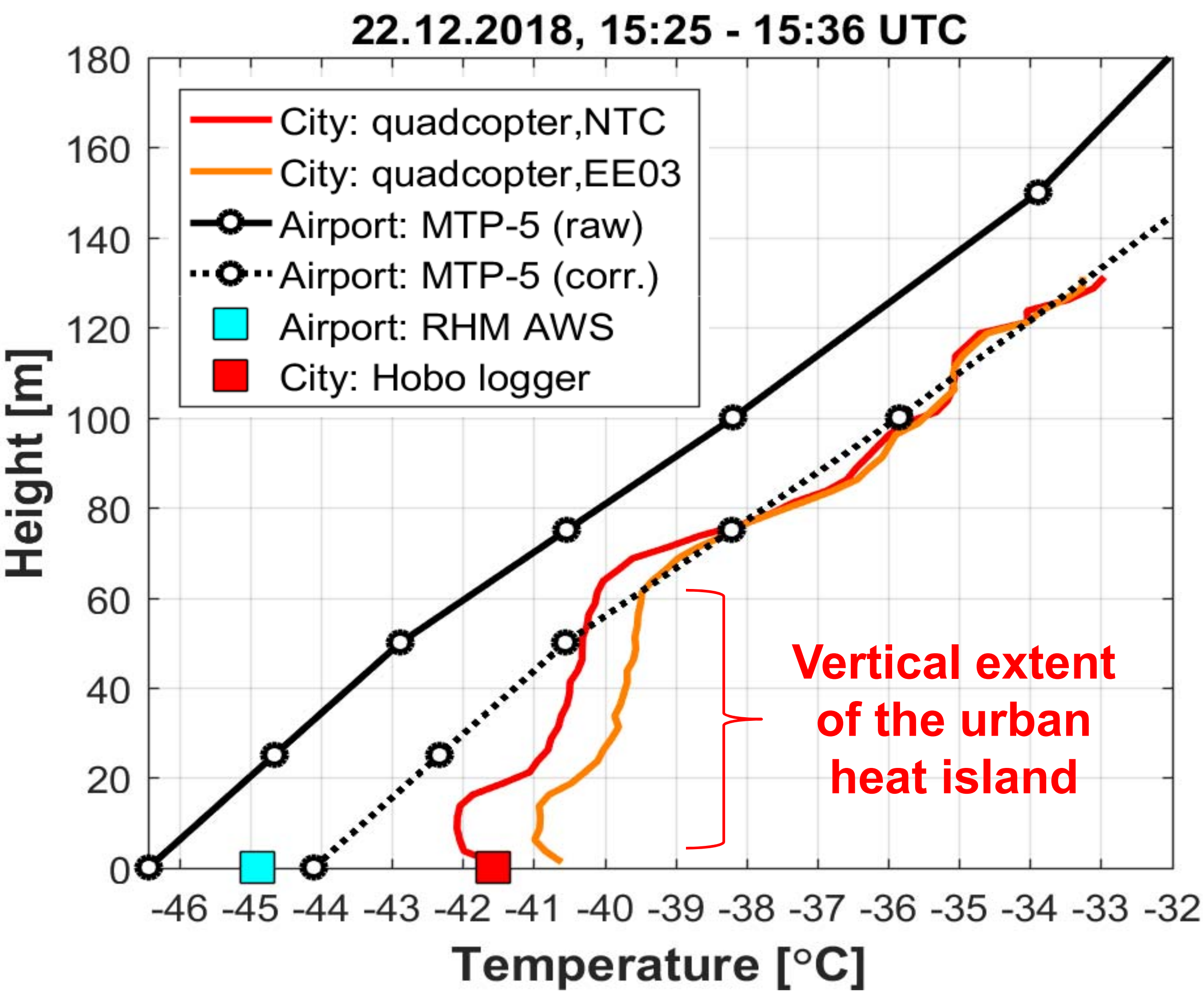
Experimental campaign in Nadym



Observations show that the near-surface urban heat island appears only in calm weather with near-surface temperature inversions in the lowest 100 m

Experimental campaign in Nadym

Quadcopter-based measurements at -42 °C

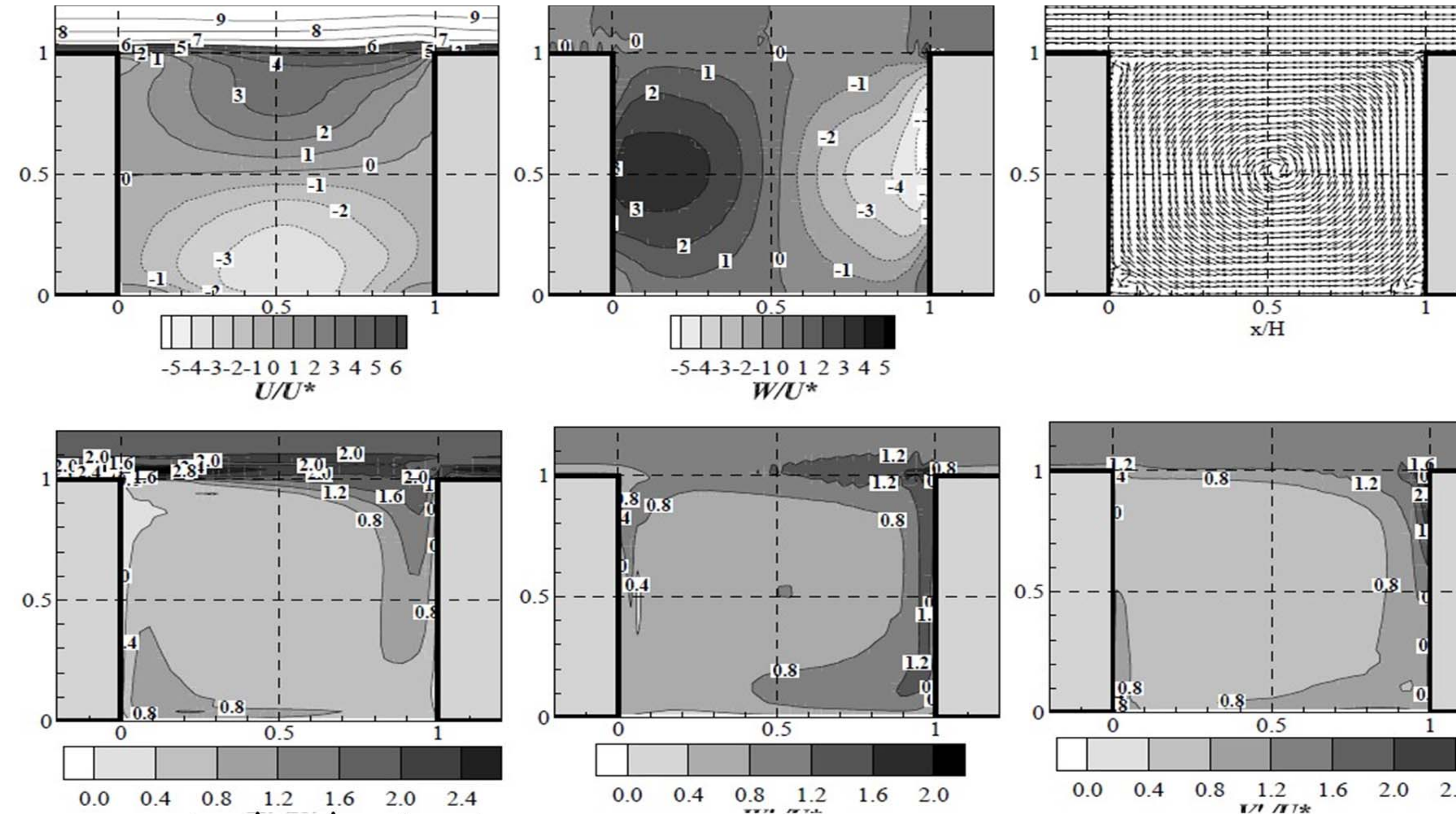


LES of particles dispersion in city canyons

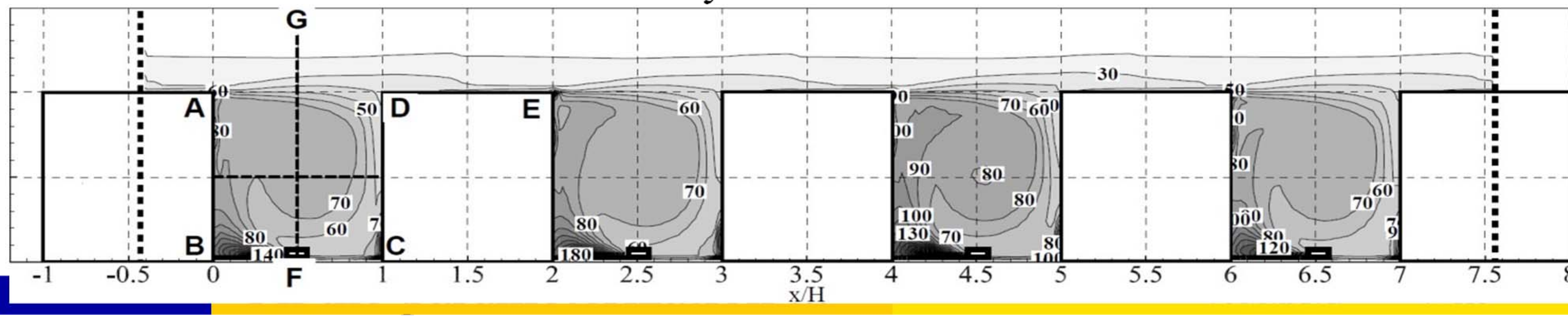
Large Eddy Simulation parameters (Glazunov, 2017):

- Re = 12000, 2×10^7
- Lagrangian transport of passive particles
- z_0=0.025 m
- street width W=30 m
- model grid step W/20, W/40, W/80 (0.375 m)

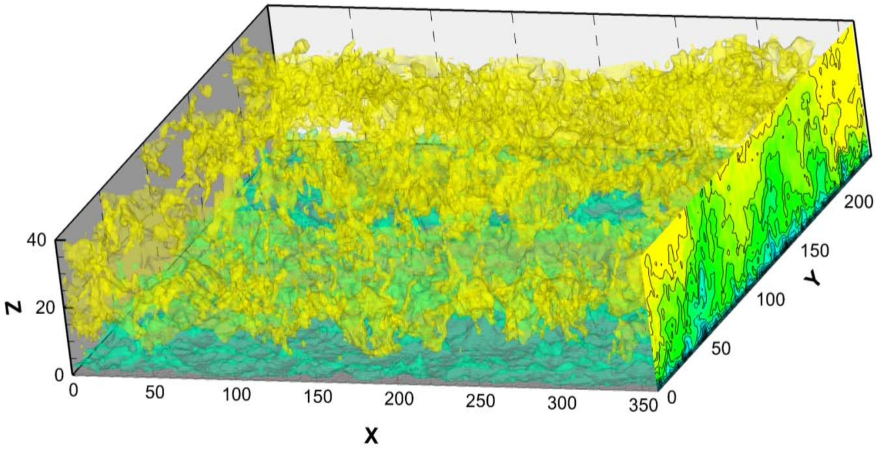
Wind components in street canyons

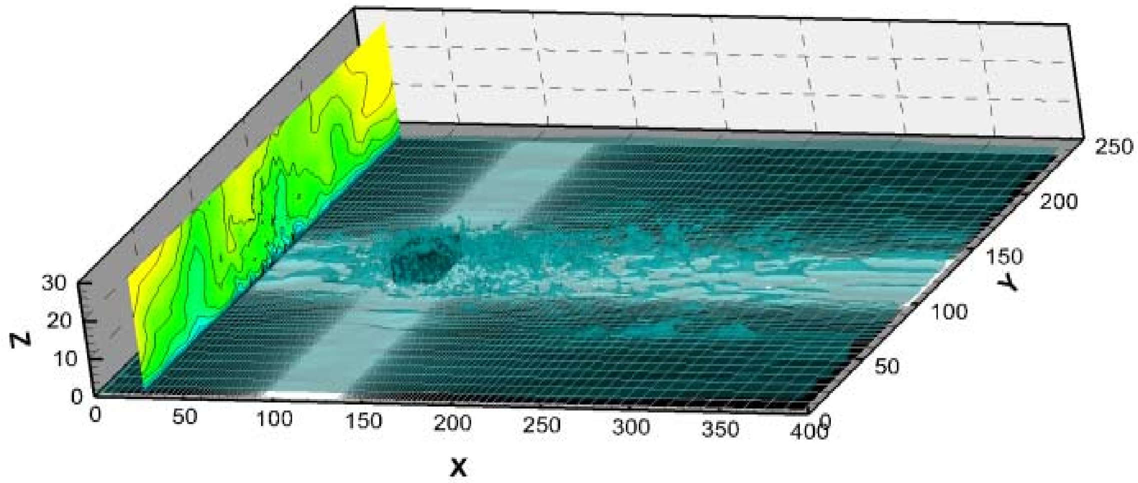


Particles concentration in street canyons

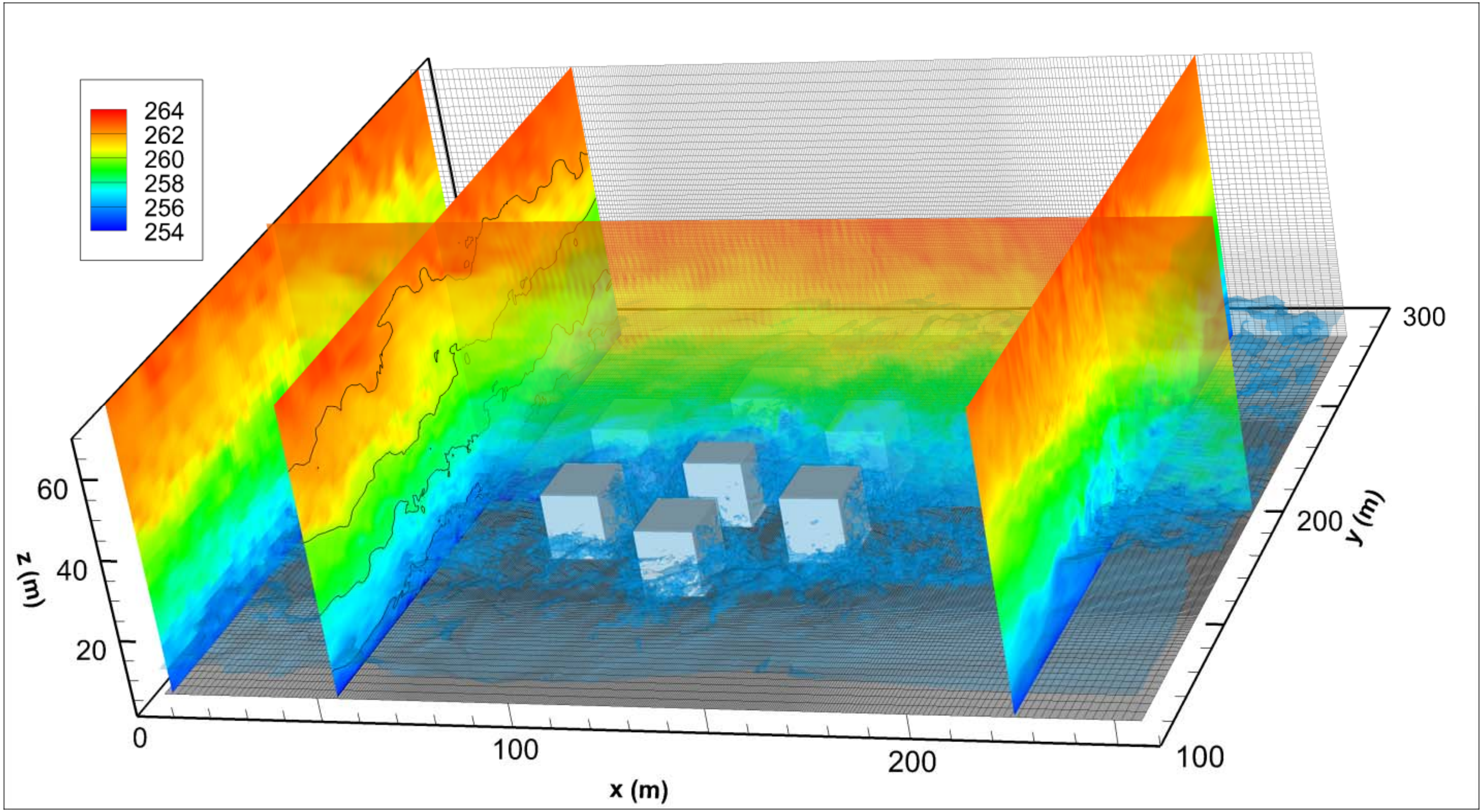


The results of calculations have shown that for correct reproduction of stable stratified turbulence in the urban environment, sufficiently detailed grids are required (about 30 knots for the characteristic size of the building; the grid step should be about 0.5 meters).



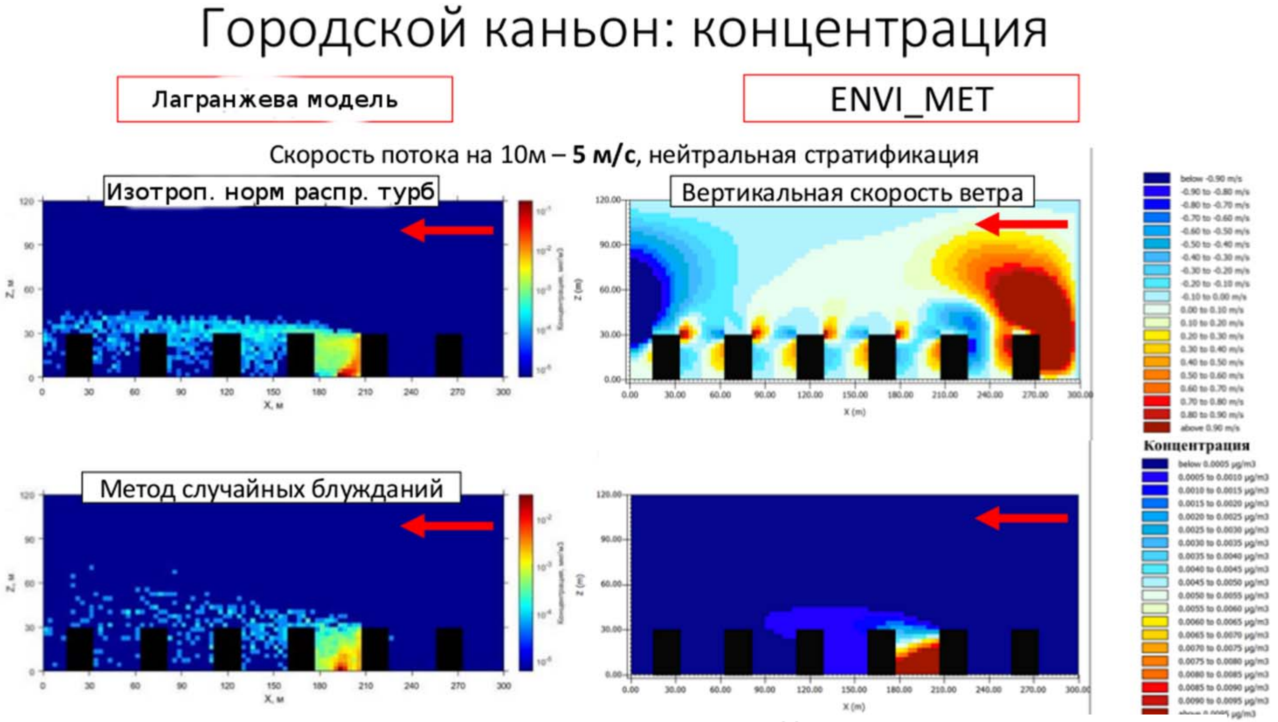


The configuration of a coupled LES-models for calculation of the flow around an object that simulates city building. Left: wind speed fluctuations calculated in the periodic computational domain. Right: the wind speed interpolated to the new mesh and used as boundary condition at the inlet (cross-section shown in colored field with contours); a streamlined object and fluctuation of wind speed around it; the grid is depicted in light lines on the bottom face of the computational region and thickens to the object.

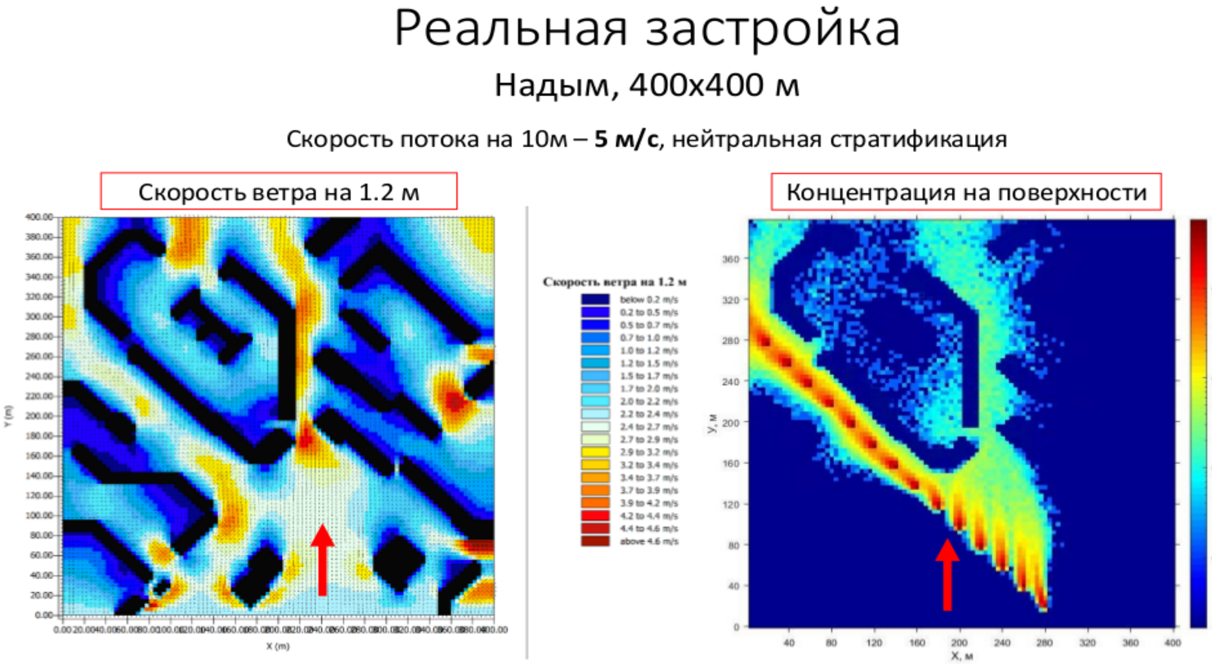


Air temperature and its fluctuations in the calculation with the coupled LES - model of a stable stratified flow around a "group of buildings". A fragment of the computational domain is shown. The gathering grid in the vicinity approaching to an equilateral steps of 0.5 m.

Alexander Varentsov, a student of the 3-rd year of education in the Lomonosov Moscow State Unversity, has developed a numerical model of Lagrangian transport of inertial particles in an urban environment. The results of RANS calculations of turbulence, namely, the averaged flow velocity, as well as the kinetic energy of turbulence and its dissipation rate, are used as input data in the model. The calculation of the particle trajectories is done by considering the force of buoyancy and the resistance to air flow by a factor given by empirical function of the Richardson number [Morsi, 1972]. Turbulent transport is calculated using two different stochastic models: (1) an algorithm that assumes turbulence isotropy and a normal distribution of velocity fluctuations, and (2) a random walk algorithm [Gosman, 1983], in which the interaction time of a particle with a turbulent vortex is limited.



Results of test calculations of the vertical velocity field and particle concentration according to the ENVI_MET model (right) and the concentration of Lagrangian particles according to the model developed in the project (left) for the flow over a series of canyons. The results of the Lagrangian model are shown for two variants of turbulence parameterization.

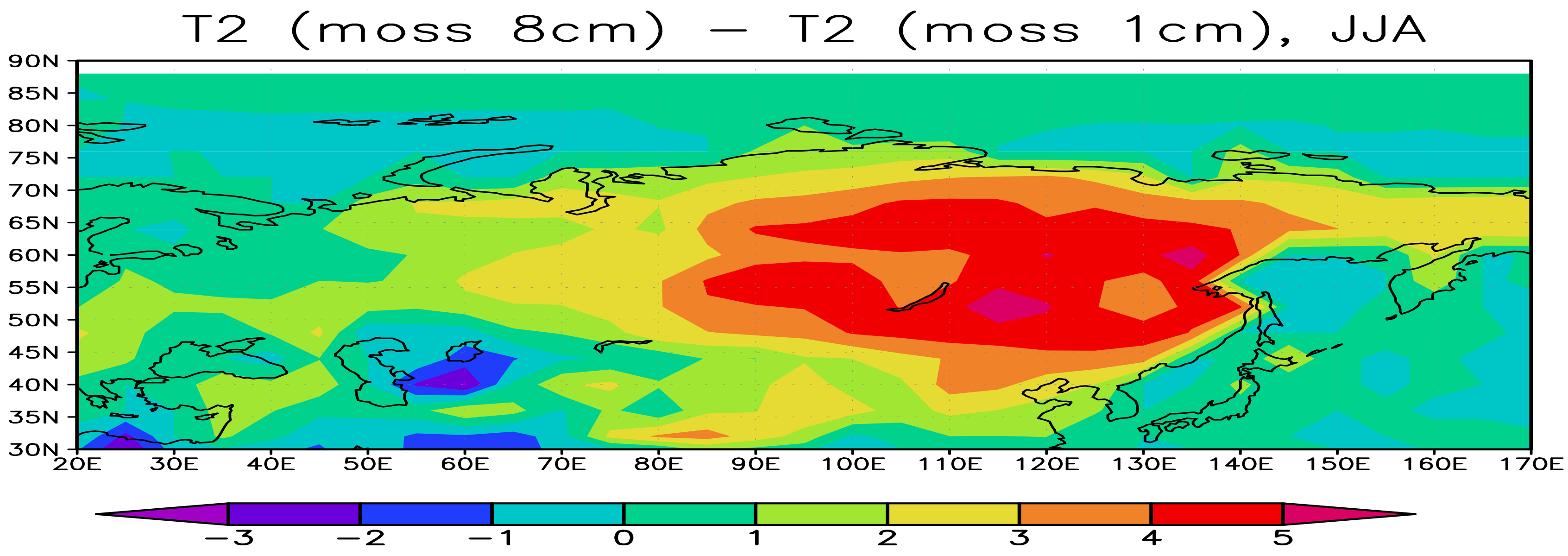


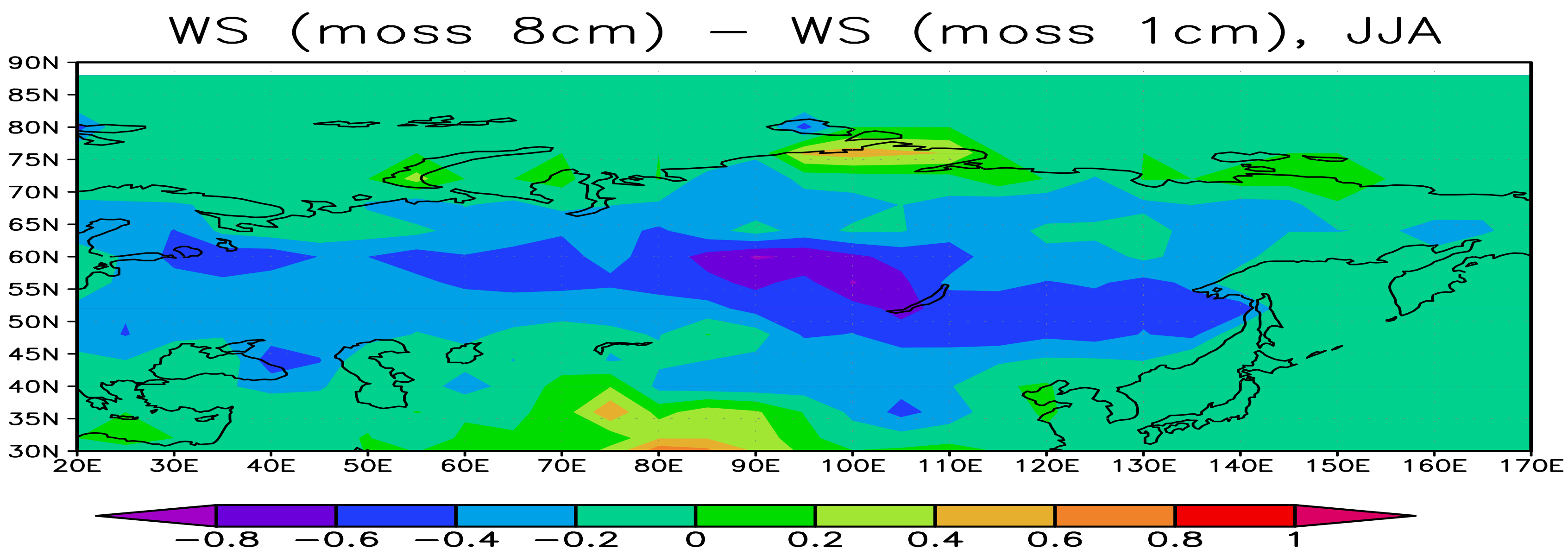
Results of test calculations of the velocity field according to the ENVI_MET model (left) and the concentration of deposited Lagrangian particles according to the Lagrangian model (right) developed in the project for one of the areas of Nadym.

Mosses

- "Mosses dominate the surface cover in high northern latitudes and have the potential to play a key role in modifying the thermal and hydrologic regime of Arctic soils. These modifications in turn feed back to influence surface energy exchanges and hence may affect regional climate. However, mosses are poorly represented in models of the land surface." (Beringer et al., J.Climate, 2001).
- Parameterizations of mosses are included in NCAR Land surface model (Beringer et al., 2001), MetOffice's JULES (Chadburn et al., 2015), ORCHIDEE (Druel et al., 2017).
- All of them treat mosses as an additional soil layer of ~5 cm, with decreased heat and moisture transfer coefficients.
- Species diversity of mosses is not taken into account.

Permafrost area climate characteristics reproduced by the INM RAS climate model





Laboratory studies of moss transfer properties

Energy and Buildings 158 (2018) 1417–1428

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Effects of convection heat transfer on Sunagoke moss green r
A laboratory study

M. Amir A. K.[a,1], Yasuo Katoh[a,*], Hiroshi Katsurayama[a],
Makoto Koganei[b], Makoto Mizunuma[c]

[a] Yamaguchi University, Department of Systems Design and Engineering, Tokiwadai 2-18-1, Ube City, Yamaguchi, 755-8611, Japan
[b] Yamaguchi University, Department of Architectural Design and Engineering, Tokiwadai 2-18-1, Ube City, Yamaguchi, 755-8611, Japan
[c] Yamaguchi Prefectural Industrial Technology Institute, Promotion of Industry-Academia-Government, Asutopia 4-1-1, Ube City, Yamag
Japan

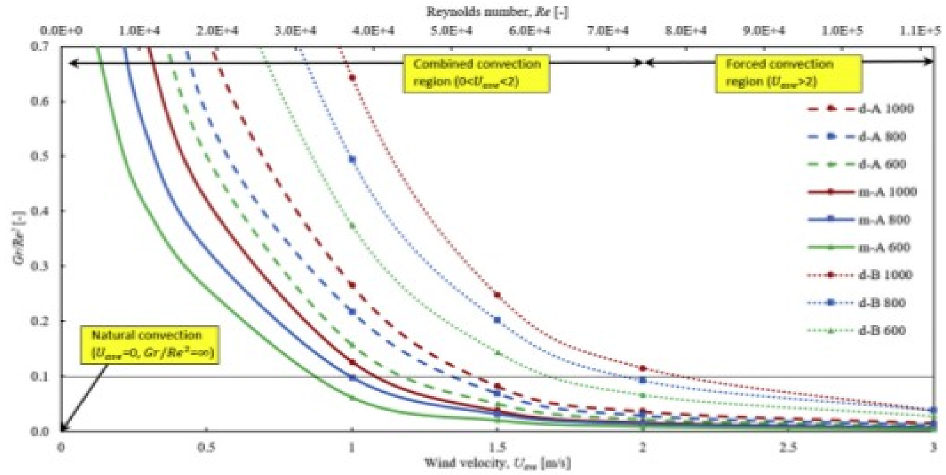


Fig. 5. Ratio of Grashof number and square of Reynolds number. Irradiance strength is denoted by color; the moss-free house is dotted, the moss covered house dashed if dry, solid if moist.

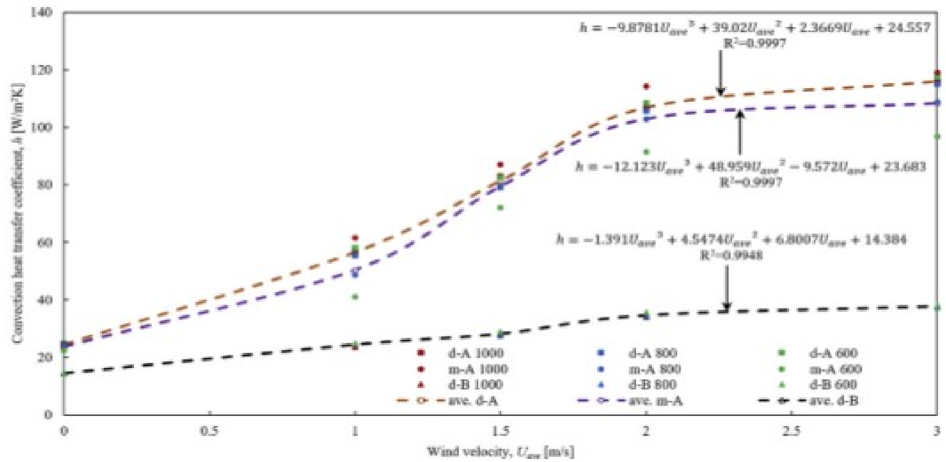


Fig. 6. Convection heat transfer coefficient for each model house in different wind velocity and irradiance. Irradiance strength is denoted by color; the moss-free house is marked by triangle, the moss covered house is marked by square if dry, circle if moist. Average data are presented with dashed lines according to wind velocity for each model house.

Heat transfer coefficient in the moss layer increases 5 times with increase of the wind speed. The same mgnitude, but of decrease, is observed in Bowen ratio.

Fluid dynamics in porous media?

Convection in Porous Media
Third Edition

Donald A. Nield
University of Auckland
Auckland, New Zealand

and

Adrian Bejan
Duke University
Durham, North Carolina, USA

Springer

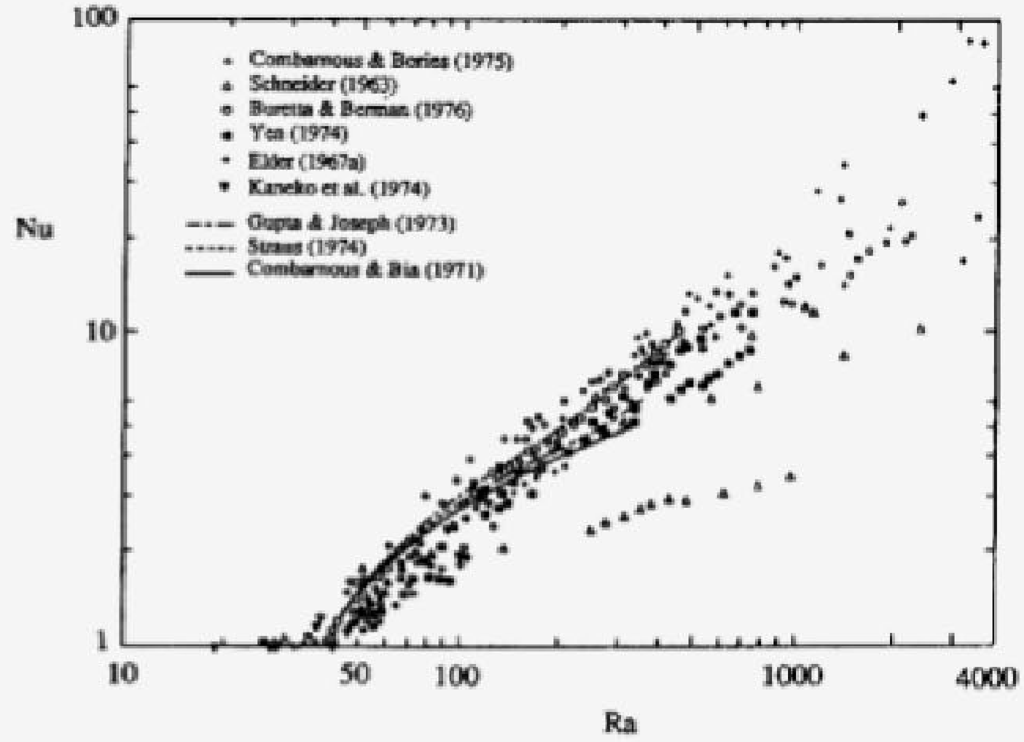


Figure 6.9. Compilation of experimental, analytical, and numerical results of Nusselt number versus Rayleigh number for convective heat transfer in a horizontal layer heated from below (Cheng, 1978, with permission from Academic Press).

Numerous analytical and experimental results for free and forced convection in porous media from literature are available.

A plan for targeted experiments

Nadym neighourhood

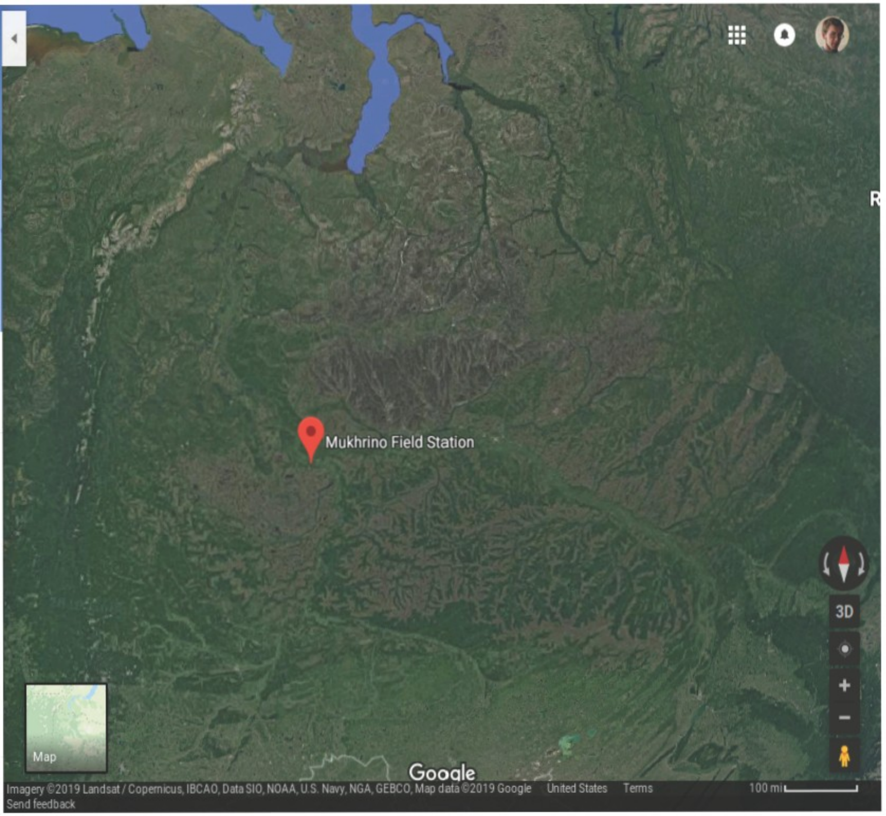
Objective: validation of new models for roughness and heat transfer in mosses

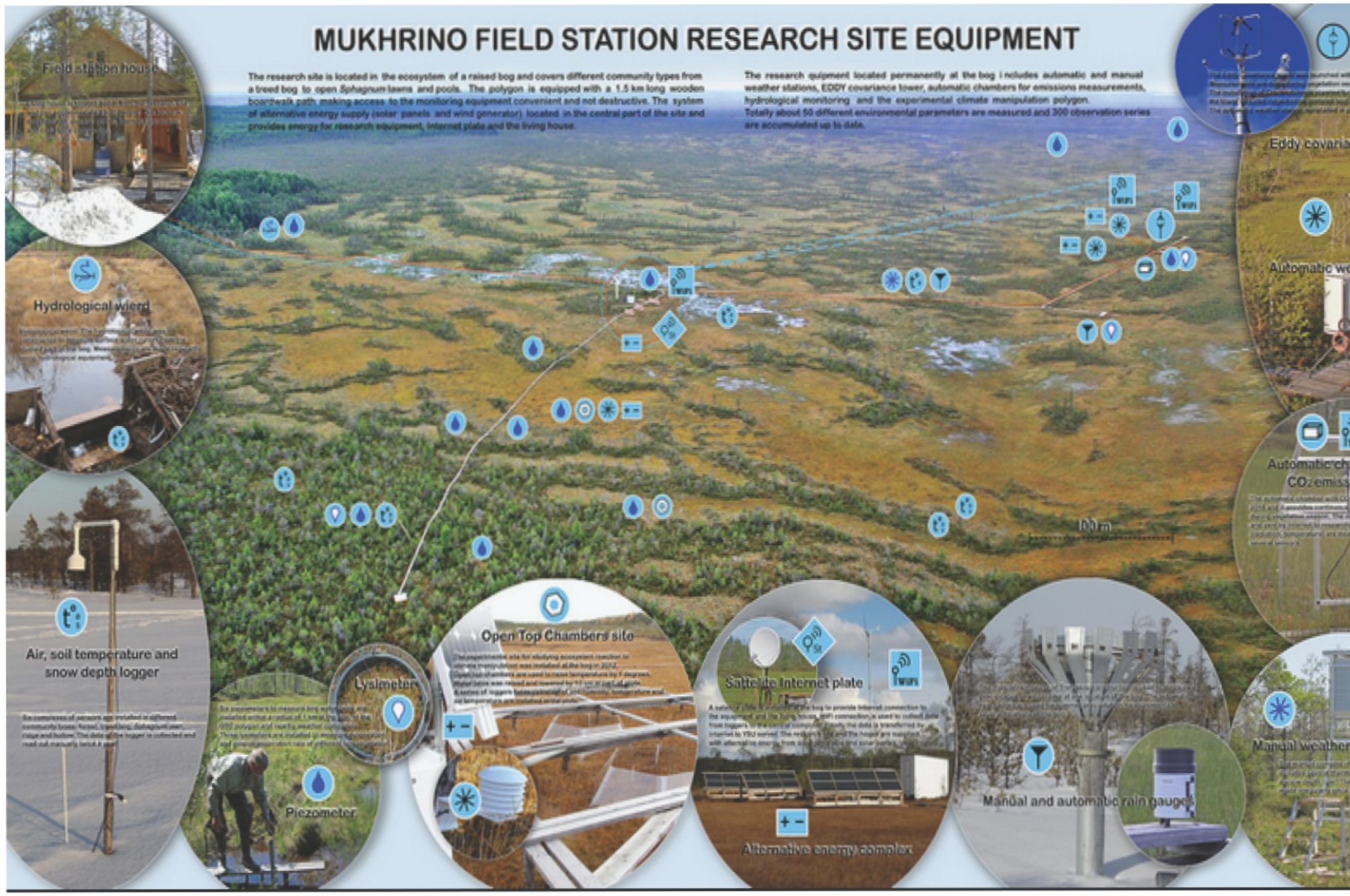
Tentative plan of measurements:

- Temperature, humidity, wind speed at ≥ 2 levels in surface air layer
- eddy covariance measurements of heat and moisture fluxes
- radiation fluxes
- surface temperature and soil temperature at different depths
- heat flux and temperature measurements inside moss layer

Mukhrino site

Maintained by Yugra State University





Thanks for your attention!