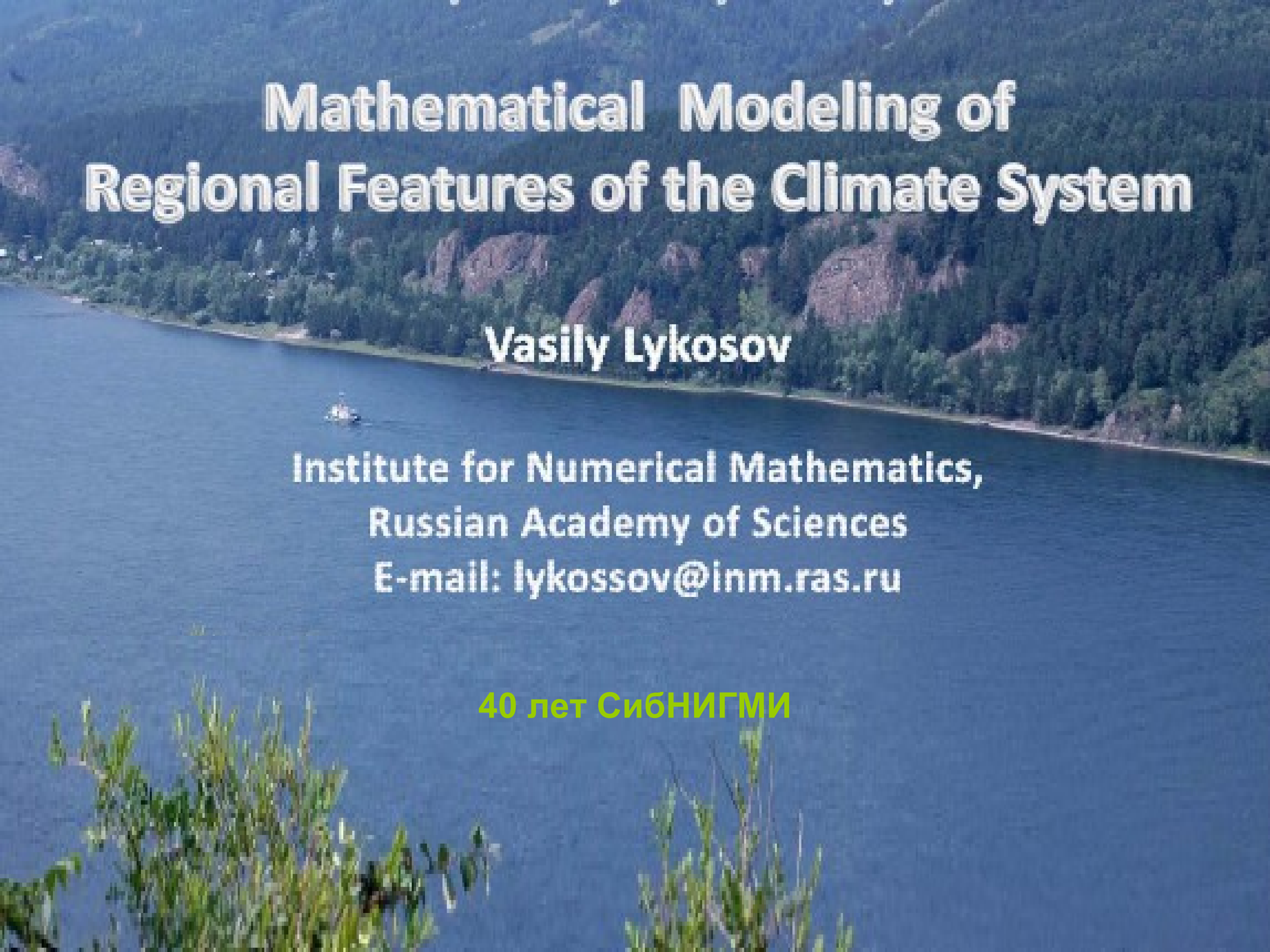


Mathematical Modeling of Regional Features of the Climate System

Vasily Lykosov

Institute for Numerical Mathematics,
Russian Academy of Sciences
E-mail: lykossov@inm.ras.ru

40 лет СибНИГМИ

In collaboration with:

- Valentin P. Dymnikov
- Evgeny M. Volodin
- Mikhail A. Tolstykh
- Nikolai A. Diansky
- Anatoly I. Chavro
- Andrey V. Glazunov
- Ekaterina E. Machul’skaya
- Victor M. Stepanenko
- Dmitry N. Mikushin
- Maria V. Sidorova

Outline

- Climate Modeling
- Regional Aspects (Mesoscale Modeling)
- Local Aspects (Large-Eddy Simulation)
- Revolutionary Perspective: from Climate Models to Earth Models
- Summary

Climate Modeling

Objectives of climate modeling

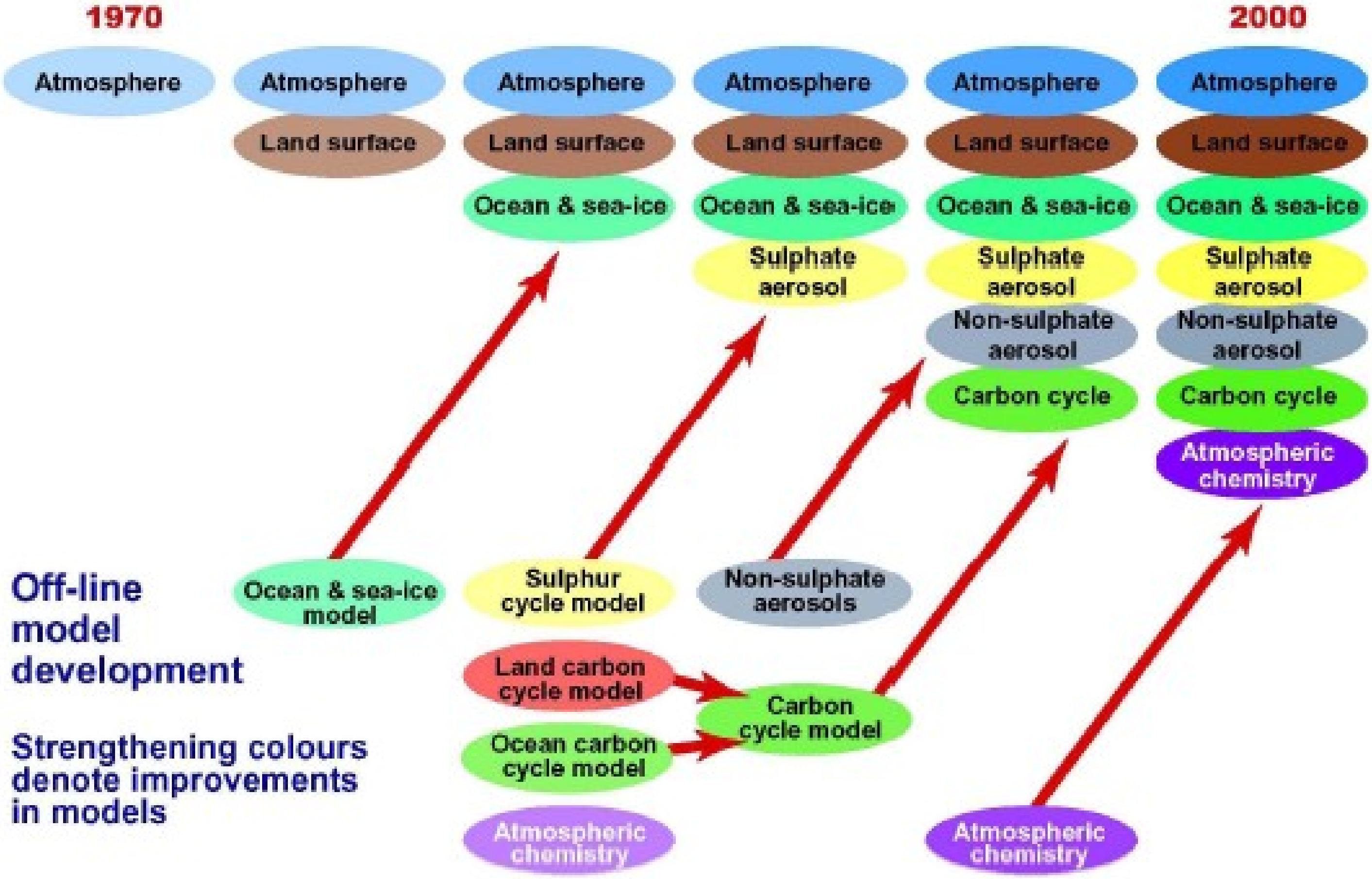
- To reproduce both “climatology” (seasonal and monthly means) and statistics of variability: intra-seasonal (monsoon cycle, characteristics of storm-tracks, etc.) and climatic (dominated modes of inter-annual variability such as El-Nino phenomenon or Arctic Oscillation)

- To estimate climate change due to anthropogenic activity

- To reproduce with high degree of details regional climate: features of hydrological cycle, extreme events, impact of global climate change on regional climate, environment and socio-economic relationships

- Fundamental question (V.P.Dymnikov): what climatic parameters and in what accuracy must by reproduced by a mathematical model of the climate system to make its sensitivity to small perturbations of external forcing close to the sensitivity of the actual climate system?

Towards Comprehensive Earth System Models



1970

2000

Atmosphere

Atmosphere
Land surface

Atmosphere
Land surface
Ocean & sea-ice

Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol

Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle

Atmosphere
Land surface
Ocean & sea-ice
Sulphate aerosol
Non-sulphate aerosol
Carbon cycle
Atmospheric chemistry

Off-line model development

Ocean & sea-ice model

Sulphur cycle model

Non-sulphate aerosols

Land carbon cycle model

Ocean carbon cycle model

Carbon cycle model

Atmospheric chemistry

Atmospheric chemistry

Strengthening colours denote improvements in models

The hierarchy of atmospheric models

GLOBAL MODELS ☐resolution 10-100 km

(GFDL, ECHAM, HadCM, INM RAS, ...)

Planetary and synoptic scale circulations:
trade-winds, monsoons, cyclones and anticyclons, ...

REGIONAL MODELS ☐ resolution 1-10 km

(MM5, WRF, Meso-NH, NH3D, ...)

Circulations of meso-α, β, γ scales:
Breezes, foehns, bora, squall lines...

LARGE EDDY SIMULATION ☐ resolution 10-100 m

Coherent structures in atmospheric boundary layer, circulations in urban areas...

General CirculationModel of the Atmosphere and Ocean
Novosibirsk Computer Center
(Marchuk et al., 1980)

- Coupled model based on the implicit scheme and splitting-up method in time. Synchronization of thermal relaxation times (1 «atmospheric» year = 100 «oceanic» years). The atmospheric resolution: 10x6 degrees in longitude and latitude, 3 levels in vertical up to 14 km (3240 grid points). Time step: 40 min. The oceanic resolution: 5x5 degrees and 4 levels (7200 grid points). Time step: 2 days.

- A single experiment: mean-January circulation, for calculations on 40 model «atmospheric» days (11 «oceanic» years) about three months of real time on BESM-6 computer are spent.

BESM-6

Mean performance – up to 1 Mflop/s

Frequency – 10 MHz , RAM – 32768 words

Supercomputer SKIF MSU - Chebyshev

60 Tflop/s, 1250 processors Intel Xeon (*4 kerns)

Climate model
Institute for Numerical Mathematics, RAS
(Dymnikov et al., 2005, Volodin and Diansky, 2006, http://ksv.inm.ras.ru/index)

- Coupled model. Atmospheric resolution: 2.5x2 degrees in longitude and latitude, 21 levels in vertical up to 30 km (272160 grid points). Time step: 6 min. Oceanic resolution: 1x0.5 degrees, 40 levels (3425600 grid points). Time step: 2 hours.

- A set of experiments for modeling the present-day climate and assessing climate change in the future (integration for 200 – 500 years) for the 5-th IPCC Report contribution (2013).

- Calculations for 8 years of model time require 1 day of real time. Thus, to carry out 1 numerical experiment
  1 - 2 months of real time should be spent.

Regional Aspects
(Mesoscale Modeling)

Regional scale modeling and assessment - I

- **Atmospheric** modeling, e.g. using global climate model with improved spatial resolution in the region under consideration and non-hydrostatic mesoscale models: parameterization of mesoscale variability

- **Vegetation** modeling, e.g. models of vegetation dynamics: parameterization of biogeochemical and hydrological cycles

- **Soil** (including **permafrost**) modeling, e.g. models of snow and frozen ground mechanics: parameterization of hydrological and biogeochemical cycles

Regional scale modeling and assessment - II

- **Catchment modeling, e.g. constructing models of river and lakes dynamics: parameterization of hydrological cycle**

- **Coupled regional models**

- **Air and water quality modeling**

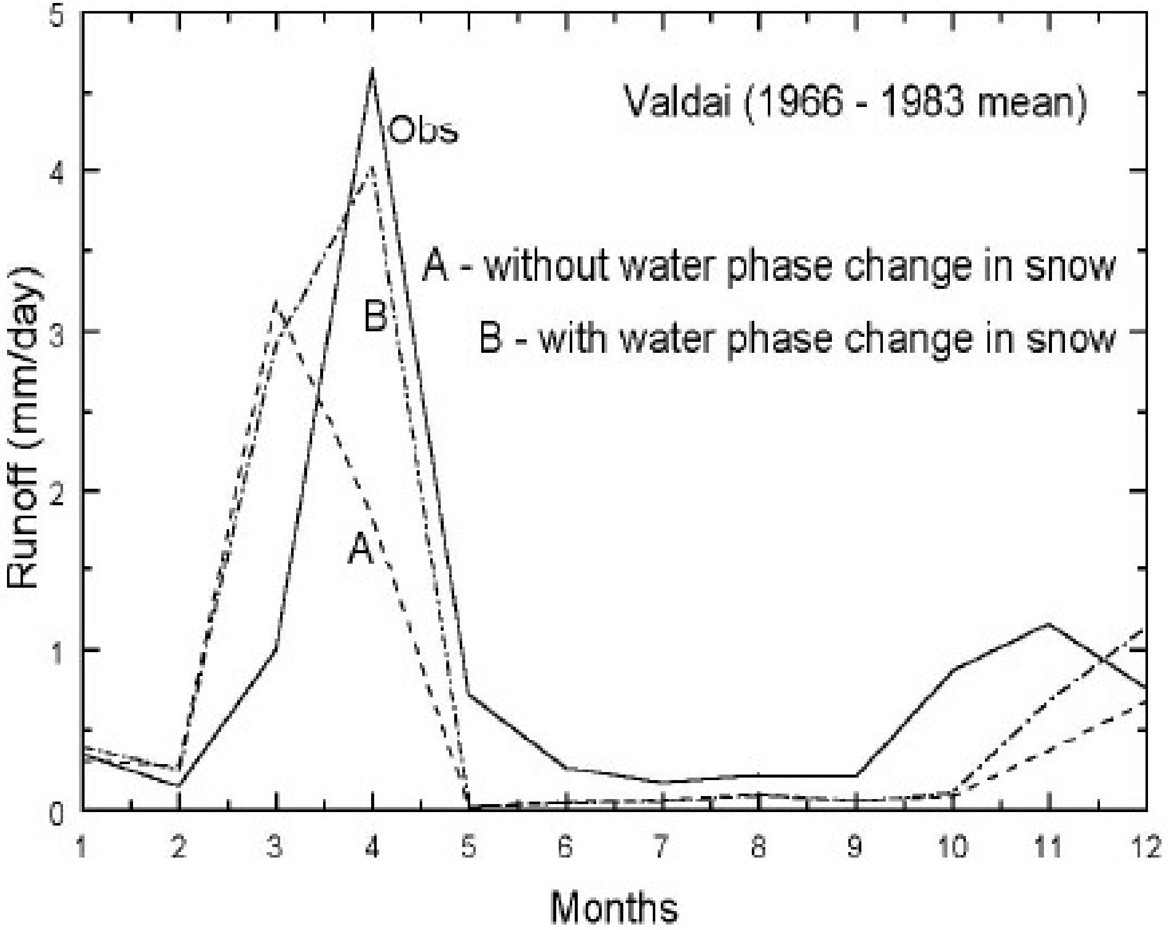
- **Statistical and dynamic downscaling (e.g. regional projections of global climate change patterns)**

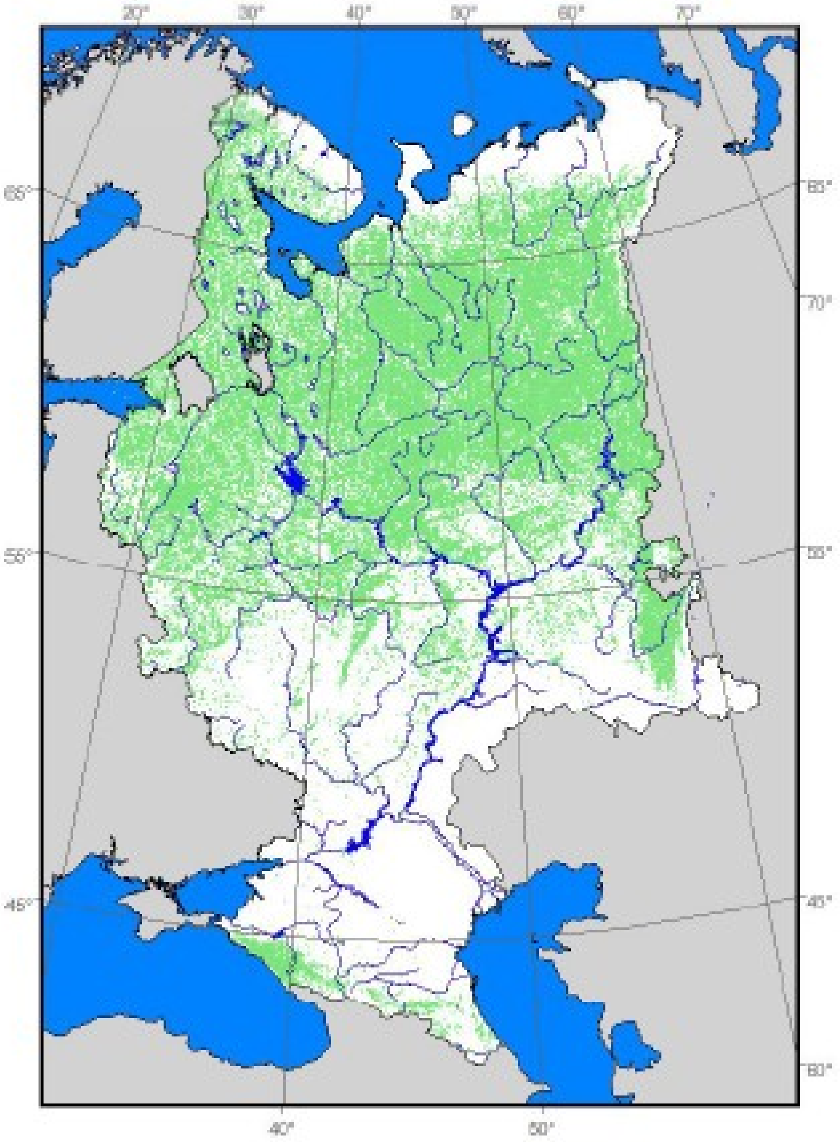
Hydrological characteristics impacting climatic processes

- Snow cover albedo (Lynch et al., 1998)
- Heat transport and water infiltration in snow cover (Mocko and Sud, 2001)
- Multi-phase porous structure of ground (Tilley and Lynch, 1998)
- Phase changes of water (Volodin and Lykosov, 1998, Takata and Kimoto, 2000)

- Hydrological heterogeneity of the underlying surface (lakes, wetlands, river systems)
- Blowing snow

Volodina, Bengtsson and Lykosov (2000)



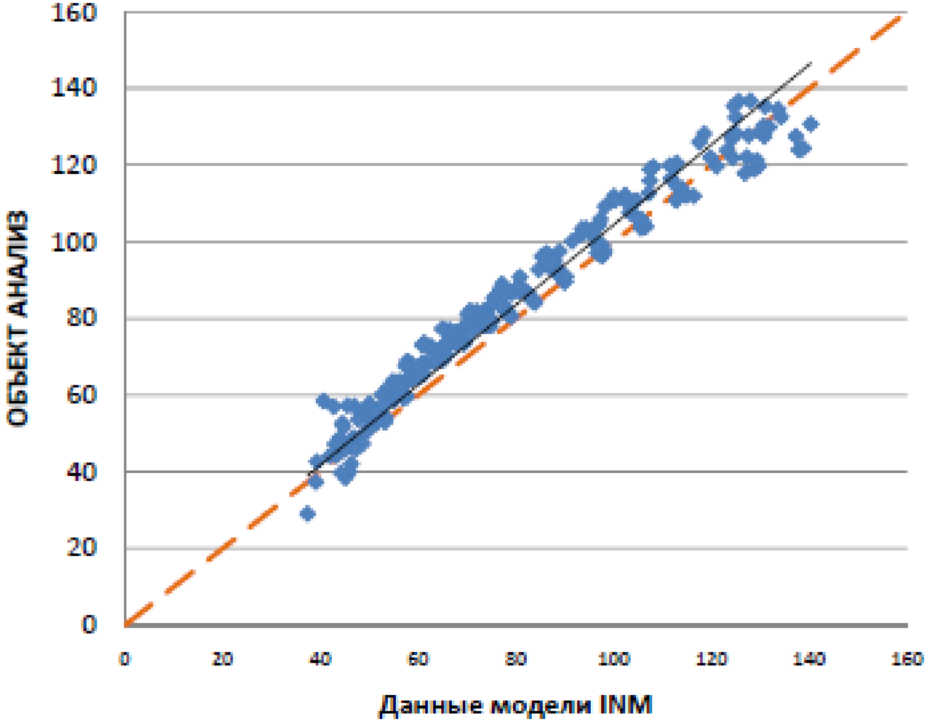


East-European Lowland

- 5 millions км²
- Significant spatial homogeneity of physical-geographical conditions
- Many hydrometeorological observational data and resulta of climate modeling

Annual sum of positive temperatures (T_0), °C as reproduced by INM climate model for the period 1961-1989 in comparison with observations.

$T_0=1{,}044T_{мод}$



коэффициент

корреляции

r = 0,975,

остаточное

среднеквадратическое

отклонение

(ост.СКО) ± 5,8°

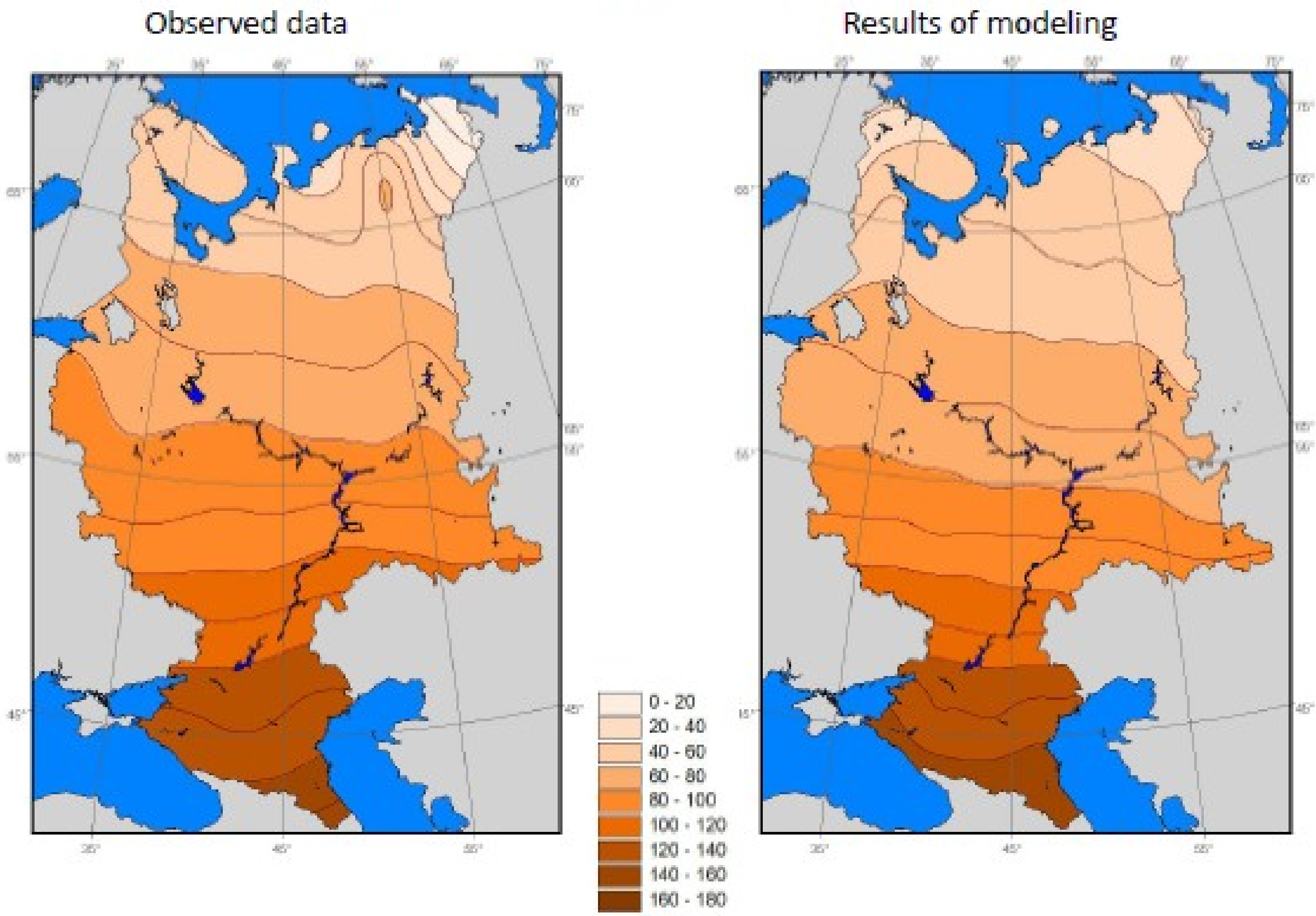
при среднем

по территории

значении 84,3°

Черная линия – линия тренда соответствующая уравнению регрессии,
Оранжевый пунктир – линия x = y

Comparison of the mean annual sum of positive temperatures (T_0), °C reproduced by INM climate model with observations

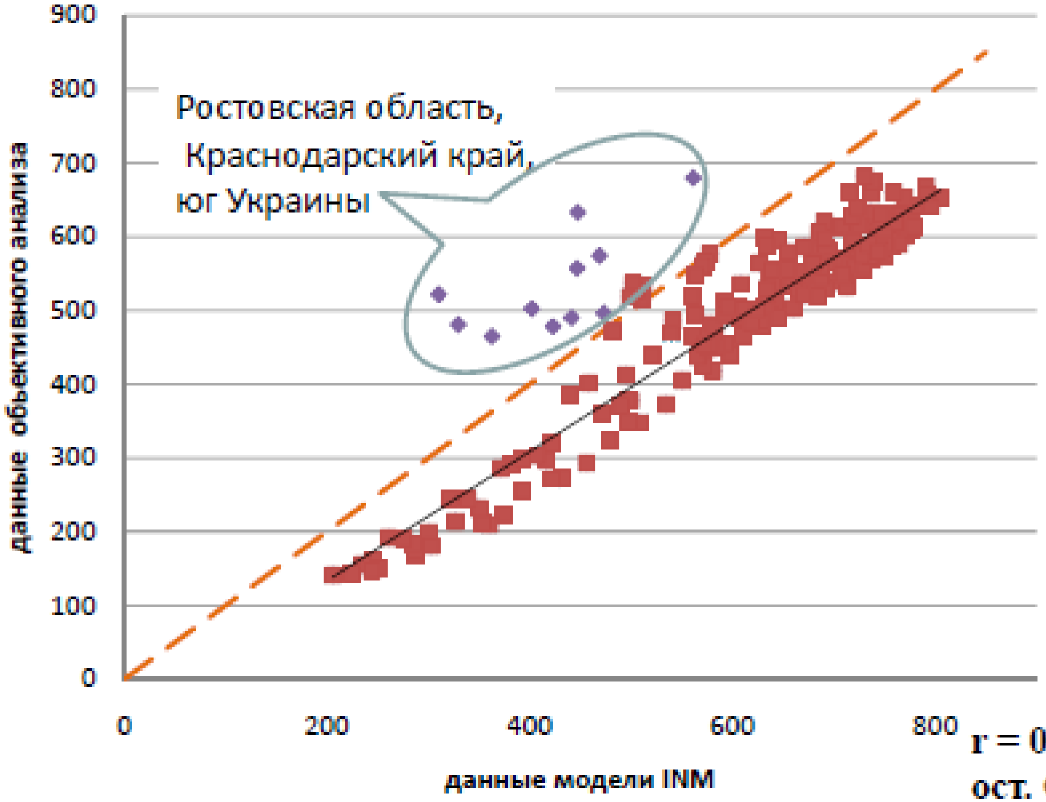


Observed data

Results of modeling

Annual sum of precipitation (P), mm as reproduced by INM climate model for the period 1961-1989 in comparison with observations.

$$P = 0.88P_{мод} - 41{,}5$$

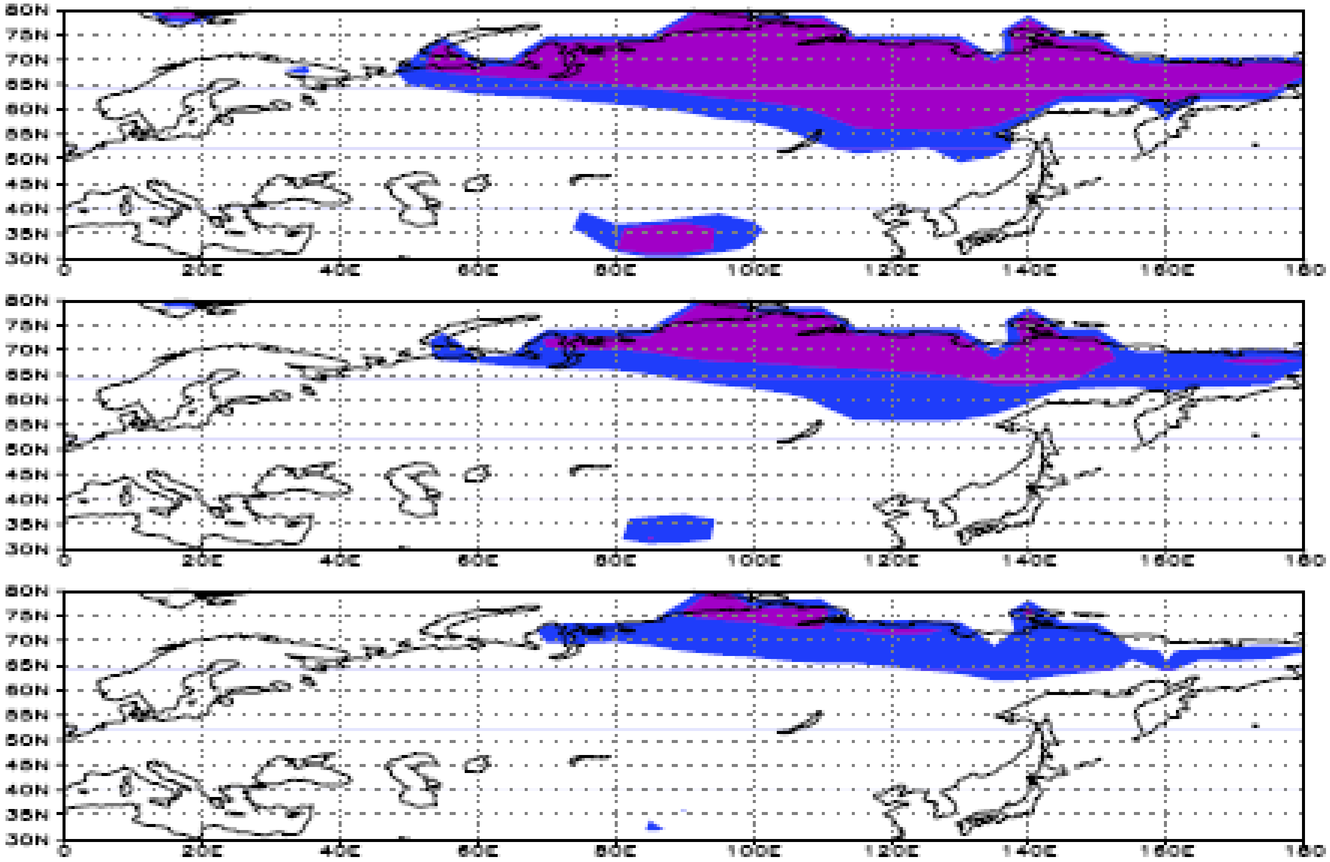


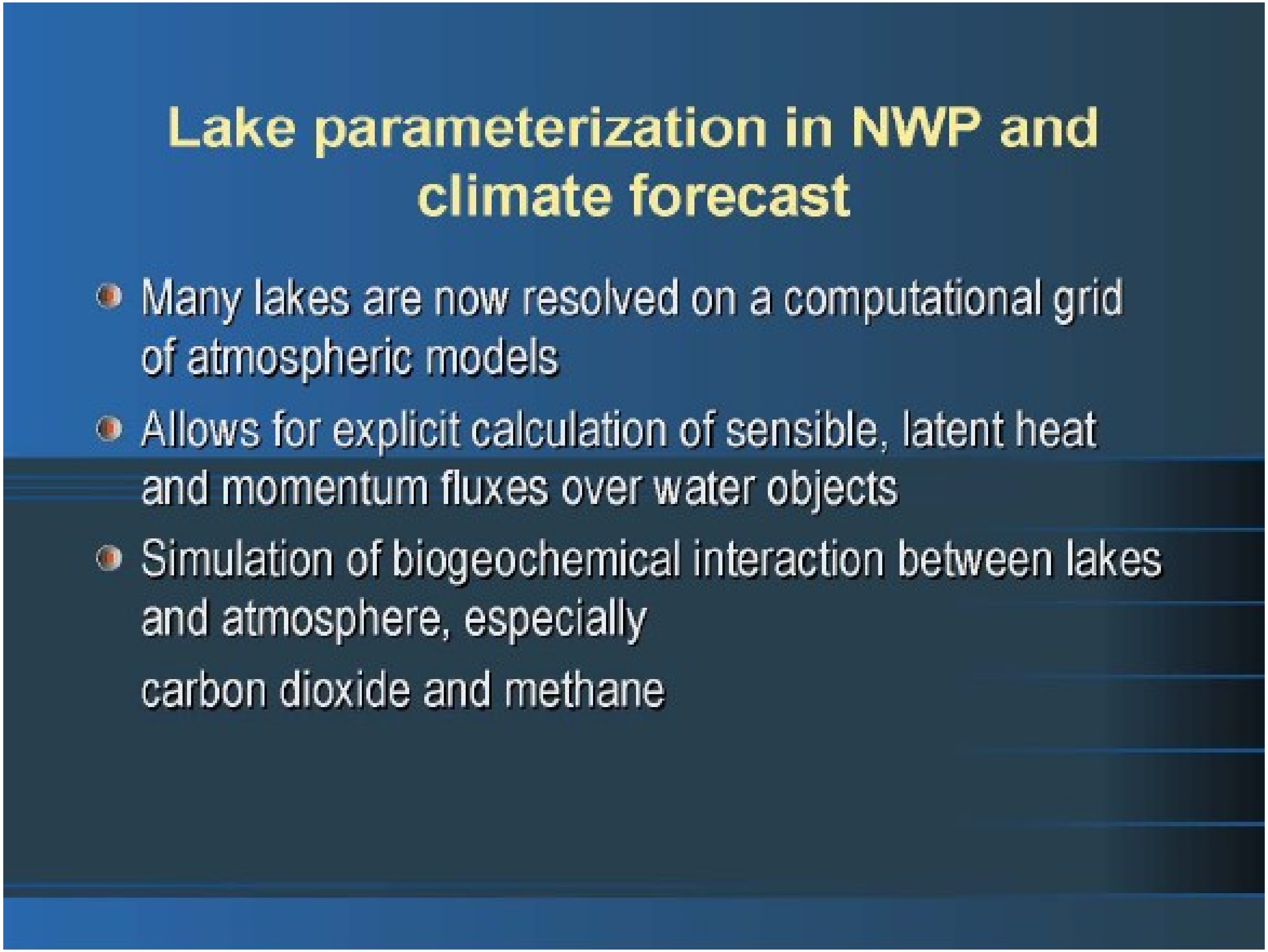
r = 0.95

ост. СКО ± 40,5 мм.

Черная линия – линия тренда соответствующая уравнению регрессии,
Оранжевый пунктир – линия x = y

Spatial distribution of continuous (violet) and sporadic (blue) permafrost as follows from INM climate model experiments: in 1981-2000 (top), 2081-2100 under scenario B1 (middle) and in 2081-2100 under scenario A2 (bottom).





Lake parameterization in NWP and climate forecast

- Many lakes are now resolved on a computational grid of atmospheric models
- Allows for explicit calculation of sensible, latent heat and momentum fluxes over water objects
- Simulation of biogeochemical interaction between lakes and atmosphere, especially

  carbon dioxide and methane

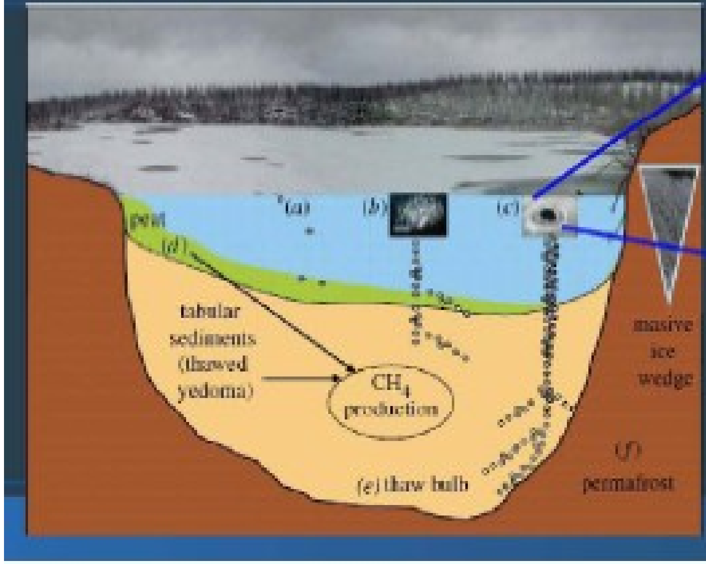
Water reservoir model LAKE

- Multilayer snow model with liquid mositure treatment
- Multilayer ice model
- Thermo- and hydrodynamics in water column
- Heat and moisture transfer in soil including permafrost

Emissions of methane by thermokarst lakes

- thermokarst lakes in Northern Siberia occupy 22-48% of the area
- satellite images indicate expanding of thermokarst lakes area

Unfreezing "hotspot" – the source of methane during wintertime

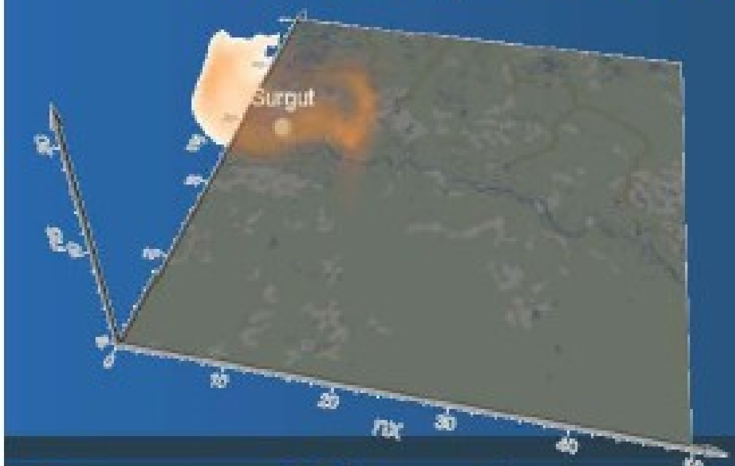


- 8 - 50% of anthropogenic emissions in XXI century depending on IPCC scenario (K. Walter et al., 2006, *Nature*)

Mesoscale processes

- Weather systems smaller than synoptic scale systems (~ 1000 and more km) but larger than microscale (< 1 km) and storm-scale (~ 1 km) cumulus systems.
- Horizontal dimensions: from about 2 km to several hundred kilometers.
- Examples of mesoscale weather systems: sea and lake breezes, squall lines, katabatic flows, mesoscale convective complexes.
- Vertical velocity equals or exceeds horizontal velocities in mesoscale meteorological systems due to non-hydrostatic processes.

Examples of model application



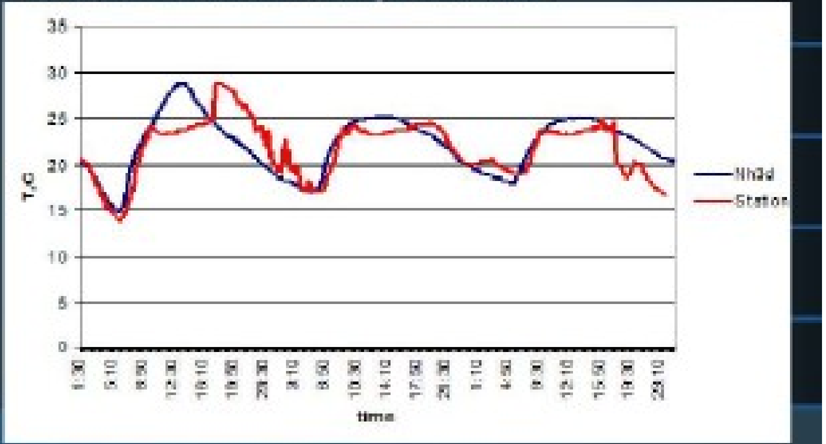
Transport of the passive tracer over hydrologically heterogeneous Ob river basin in Western Siberia

Resolution:

- Δx = Δy = 3.7 km
- 21 σ – levels
- Δt = 5 s

Black sea breeze

Screen-level temperature

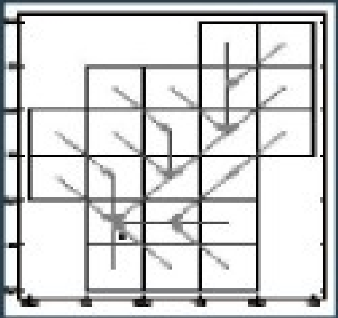


River parameterization for climate models and NWP in the petascale perspective

- in ~10 years ~1 km resolution in global models (World Climate Modeling Summit, 2008 http://wcrp.ipsl.jussieu.fr/Workshops/ModellingSummit/index.html)
- Currently used river routing schemes do not explicitely consider river channel sizes, but at ~1 km resolution many rivers will be explicitly resolved
- River velocity is constant,

  or calculated with

  semi-empirical relationships



Common river routing scheme

The need for realistic river network representation coupled with physically based river flow model

The importance of river parameterization in climate models

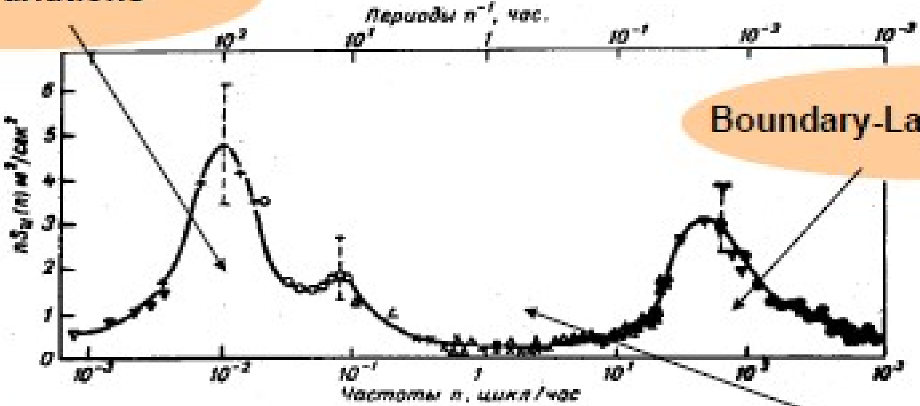
- Flow river discharge modeling as a factor of thermohaline ocean circulation
- Explicitly modeling extreme events in the river flow regime
- River discharge is an “integrator” of hydrological cycle over vast areas and thus may be used for climate model validation

Local Aspects
(Large-Eddy Simulation)

Synoptic variations

Boundary-Layer turbulence

Mesoscale processes

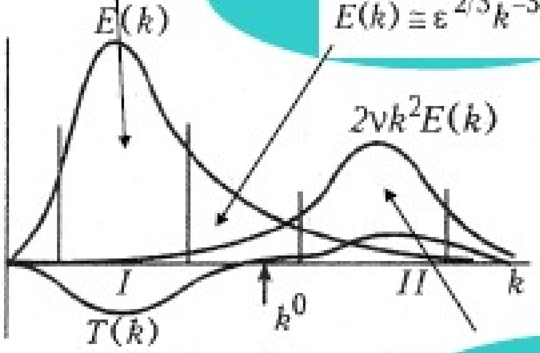


Спектр скорости ветра в приземном слое атмосферы [по Ван дер Ховену (1957), n — частота, $S_u(n)$ — спектральная плотность.

Energy range

Inertial range

$E(k) \cong \varepsilon^{2/3} k^{-5/3}$



Dissipation range

$$a(x_i, t) = \tilde{a}(x_i, t) + a'(x_i, t) + a''(x_i, t)$$

$$\overline{a}(x_i, t) = \int G(x_i - x_i')a(x_i', t)dx_i'$$

$$\overline{a}(x_i, t) = \tilde{a}(x_i, t) + a'(x_i, t)$$

$$\frac{\partial u_i}{\partial t} = -\frac{\partial u_i u_j}{\partial x_j} - \frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 u_i}{\partial x_i \partial x_j} + F_i^e,$$

$$\frac{\partial u_i}{\partial x_i} = 0,$$

Navier-Stokes equations.

Approximate form of the momentum and mass conservation laws in viscous incompressible fluid.

$$F(a(x,t)) \equiv \overline{a}(x,t) = \int_{R^3} G(x-x', \Delta_f)a(x',t)dx'$$

$$\overline{\frac{\partial a(x,t)}{\partial x_i}} = \frac{\partial \overline{a}(x,t)}{\partial x_i}; \quad \overline{\frac{\partial a(x,t)}{\partial t}} = \frac{\partial \overline{a}(x,t)}{\partial t}$$

Spatial filtering

It's usually assumed that filter commutes with operator of differentiation.

It's not always the case near the boundary and/or after discretization

---

LES

$$\frac{\partial \overline{u}_i}{\partial t} = -\frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \overline{p}}{\partial x_i} + \frac{1}{Re}\frac{\partial^2 \overline{u}_i}{\partial x_i \partial x_j} + \overline{F_i^e},$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0,$$

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\ \overline{u_j}.$$

Re-independent statistics of large-scale motions in turbulent flows (*observation and high-Re DNS data*) gives us hope of possibility:

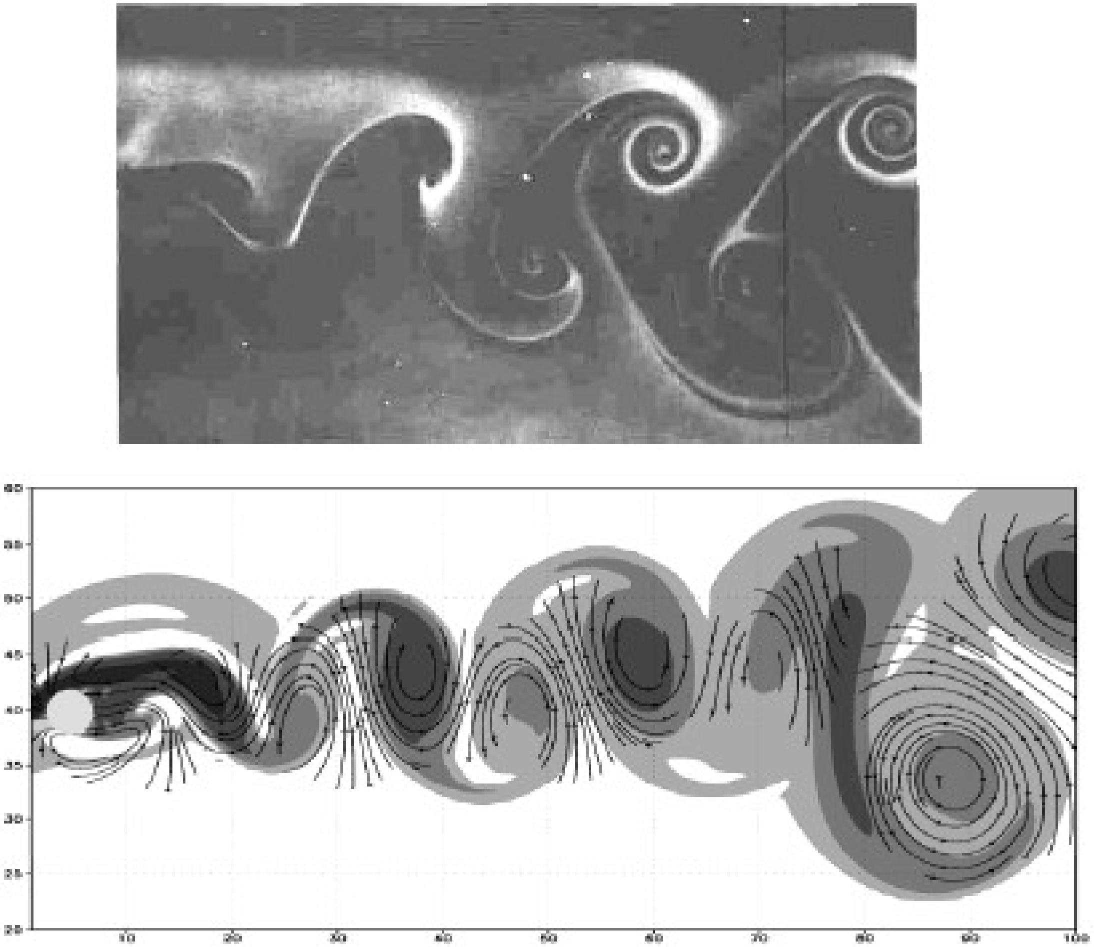
1. To neglect the viscous term.

2. To find closure:
$\tau_{ij} \approx \mathrm{T}_{ij}(\overline{u}_k, \overline{u}_l, \overline{u}_m)$

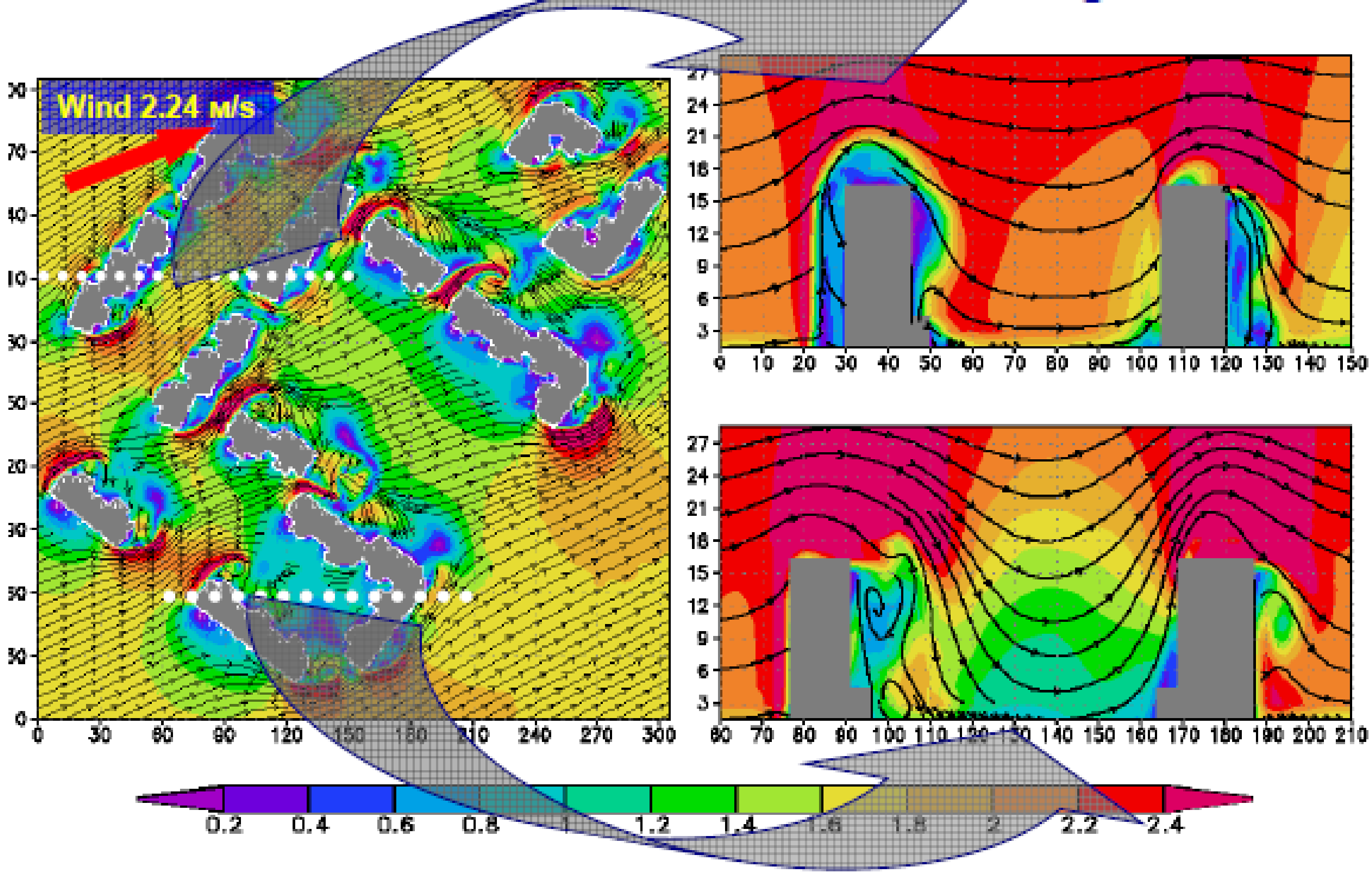
Central problem of LES modeling. Universal approach isn't known.

The most difficult in anisotropic wall-bounded flows
(if the energy production range isn't strongly separated from dissipation range and/or inertial range can't be resolved by the numerical model)

von Karman votrex street behind a round cylinder, Re =200: top - from *М. ван Дайк (1986). Альбом течений жидкости и газа,* bottom - model results



Turbulent flow between buildings



Terra Incognita for atmoispheric turbulence closures *(Wyngaard, 2004, ...)*

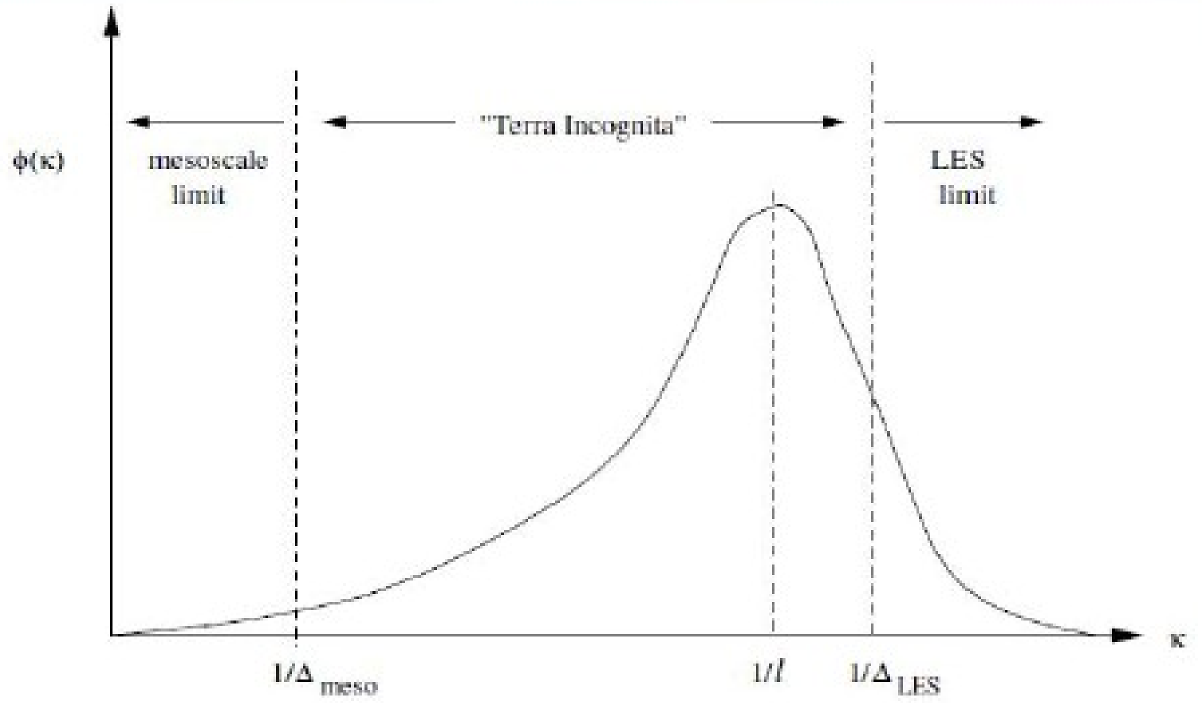
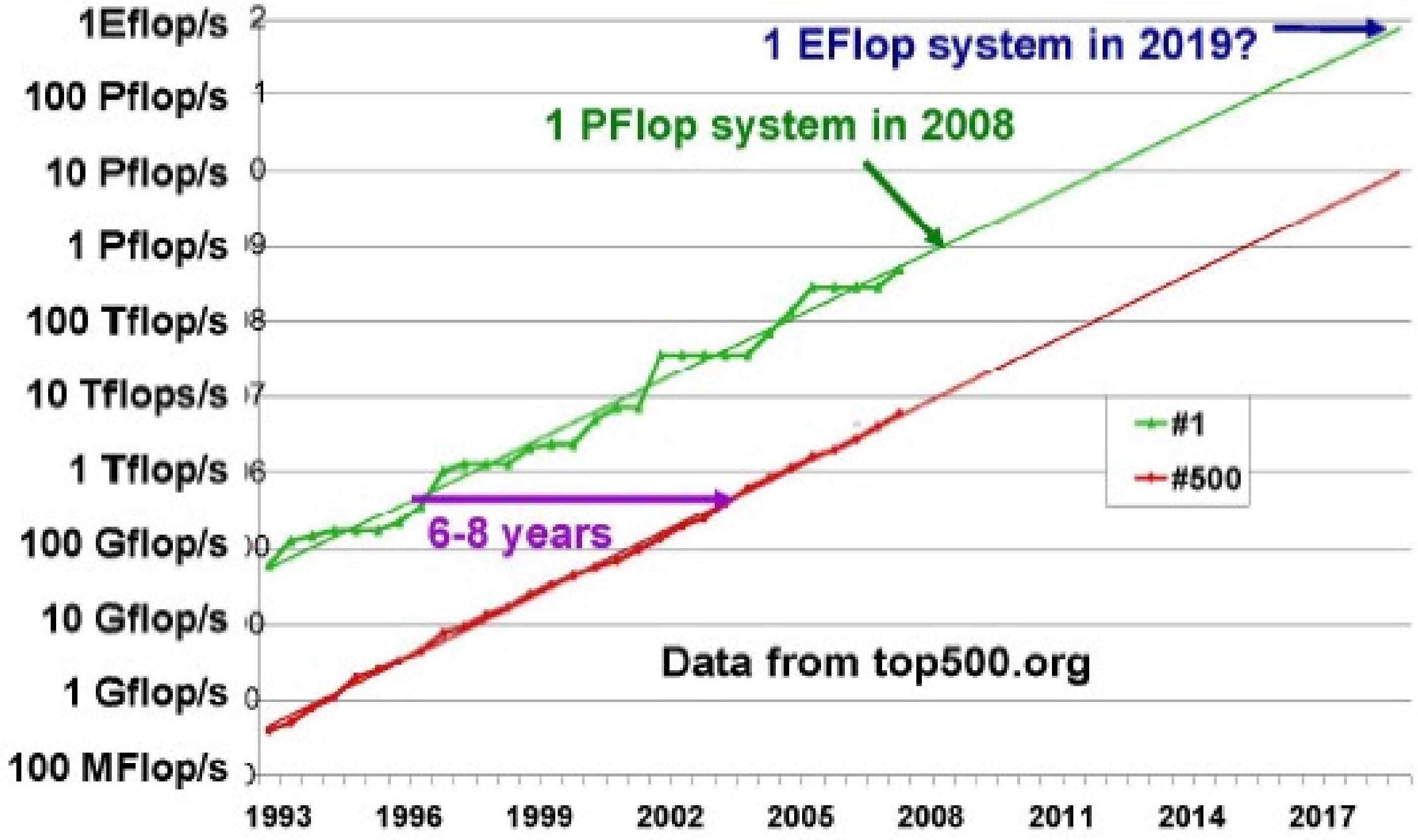


Figure 1: The wave number spectrum of turbulence and the Terra Incognita. Δ_{meso} is the scale of a mesoscale model grid, ℓ is the scale of the energy-containing turbulence, and Δ_{LES} is the scale of the LES grid.

Revolutionary Perspective: from Climate Models to Earth System Models

Petaflop with ~1M Cores By 2008



1 EFlop system in 2019?

1 PFlop system in 2008

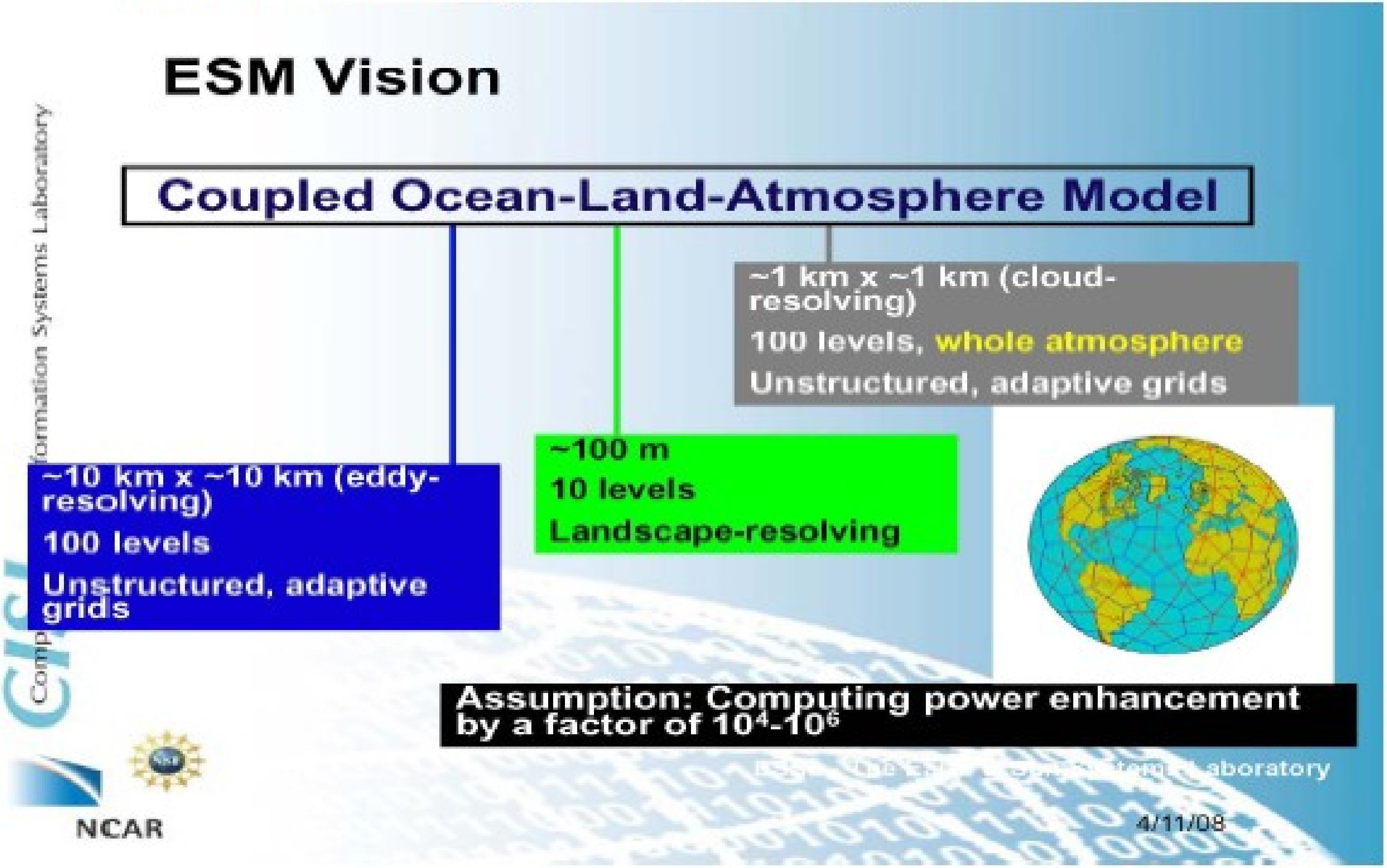
6-8 years

Data from top500.org

Slide source Horst Simon, LBNL

Earth System Model

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



ESM Vision

Coupled Ocean-Land-Atmosphere Model

- ~10 km x ~10 km (eddy-resolving)
  - 100 levels
  - Unstructured, adaptive grids
- ~100 m
  - 10 levels
  - Landscape-resolving
- ~1 km x ~1 km (cloud-resolving)
  - 100 levels, whole atmosphere
  - Unstructured, adaptive grids

Assumption: Computing power enhancement by a factor of 10^4-10^6

NCAR

4/11/08

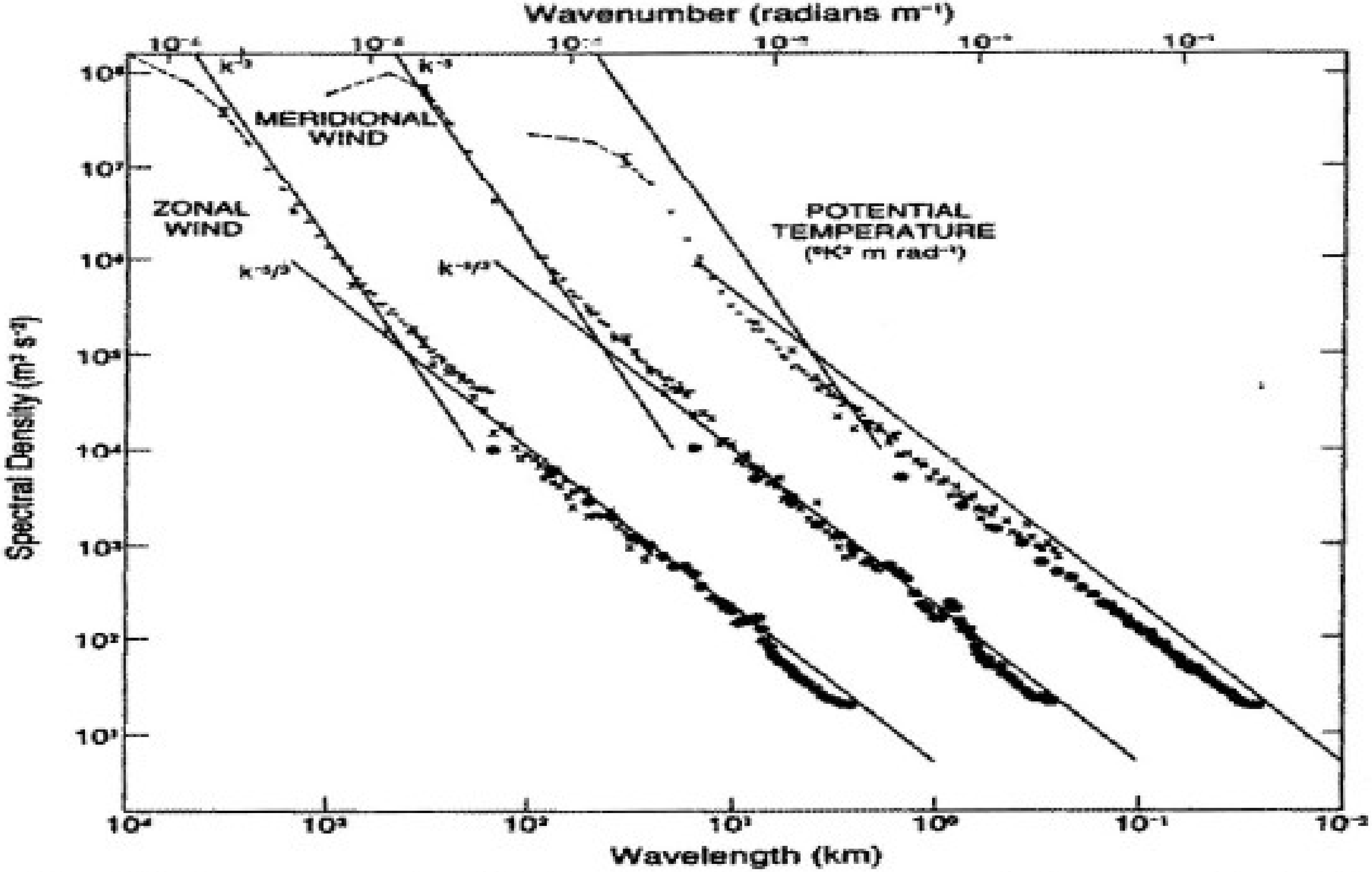


FIG. 1. Variance power spectra of wind and potential temperature near the tropopause from GASP aircraft data. The spectra for meridional wind and temperature are shifted one and two decades to the right, respectively; lines with slopes −3 and −5/3 are entered at the same relative coordinates for each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

Working out of the multiscale modelling systems will be the key moment of the further development of climate models, their ability to reproduce features of an observable spatial spectra of kinetic and available potential energy can serve one of criteria of models quality.

Koshyk and Hamilton (2001): the GFDL GCMA (USA) with the horizontal resolution about 35 km => in troposphere spectral distribution of the calculated kinetic energy corresponds to the degree law «-3» on scales from 5000 to 500 km and to the degree law «-5/3» on smaller scales. In a stratosphere and mesosphere similar distributions, but transition from one law to another took place on scales of 2000 and 4000 km, accordingly, that contradicts the observed data and can testify to parameterization lacks of sub-grid-scale processes.

Experiments with regional model WRF (Skamarock, 2004) at various horizontal resolution (22, 10 and 4 km, accordingly): the calculated spectra well coincide in a meso-scale range with observed ones, including transition from an exponent «-5/3» to degree «-3». However the modelled spectrum in its short-wave part has appeared strongly depending on properties of computational technology (in particular, from level of the scheme dissipation).

A.V. Glazunov, V.P. Dymnikov, V.N. Lykossov. Mathematical modeling of spatial spectra of atmospheric turbulence. - Russian Journal of Numerical Analysis and Mathematical Modeling, 2010, v. 25, No. 5.

The Rayleigh - Bernard thermal convection in a double-periodic channel with firm walls is investigated, using a LES model, as analogue of multi-scale atmospheric turbulence from the point of view of reproduction of spectral properties.

The large ratio of its horizontal size to the vertical has provided existence of a quasi-two-dimensional large-scale flow component, and the size of a uniform finite-difference grid in some tens millions points has allowed to reproduce explicitly dynamics of a small-scale three-dimensional turbulent component.

Decomposition of studied turbulent flow on barotropic and baroclinic components has allowed to offer the scheme of transformations of kinetic energy in the studied system, explaining some spectral properties of observed atmospheric turbulence.

Summary

1. The further development of climate models requires an explicit description of mesoscale processes (resolution, detailed representation of inhomogeneous underlying surface, etc.).
2. It means that the hydrostatic approximation should be replaced by the non-hydrostatic formulation.
3. New parameterizations of subgrid-scale processes should be developed (e.g., accounting for secondary circulations, stochastic processes, etc.).
4. The computational “environment” should be also revisited: numerical schemes (unstructured grids, in time - explicit, semi-implicit or fully implicit?), parallel algorithms, effective implementation on multi-processor computational systems, etc.