Конференция «Физика атмосферы и океана»

Разработка глобальной модели атмосферы для исследований климата и прогноза погоды с высоким пространственным разрешением

Development of the global atmospheric model for high-resolution climate modeling and weather prediction

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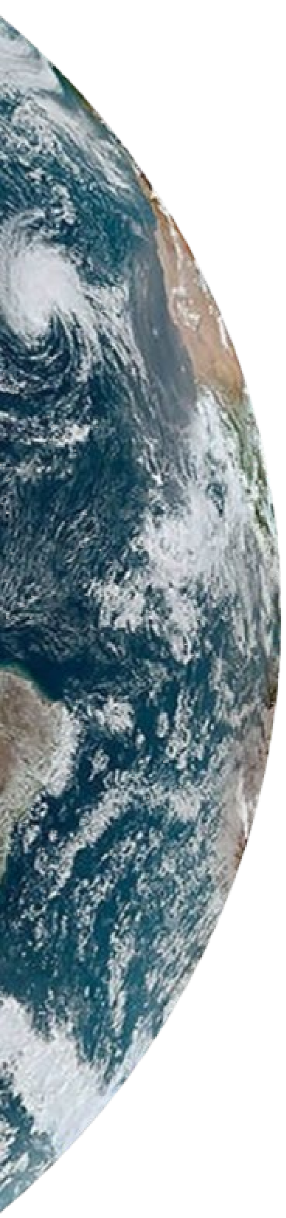
Outline

- Motivation
- Model design and features
- Test-driven development strategy
- **Aquaplanet results with full subgridscale physics**
- A word on computational efficiency
- Conclusions & outlook

Motivation



- Universal atmospheric dynamics solver for various problems:
  - Numerical weather prediction (with SLAV parameterizations)
  - Climate (with ARTS-ESM/INMCM parameterizations)
  - (Upper atmosphere dynamics)
- New features (for Russian global atmospheric codes):
  - High-resolution, non-hydrostatic, Local mesh refinement
- Better software
  - Readable & structured code
  - Flexible (various equation systems)
  - Tests for basic units and combinations
  - **Scalable algorithms & GPU**

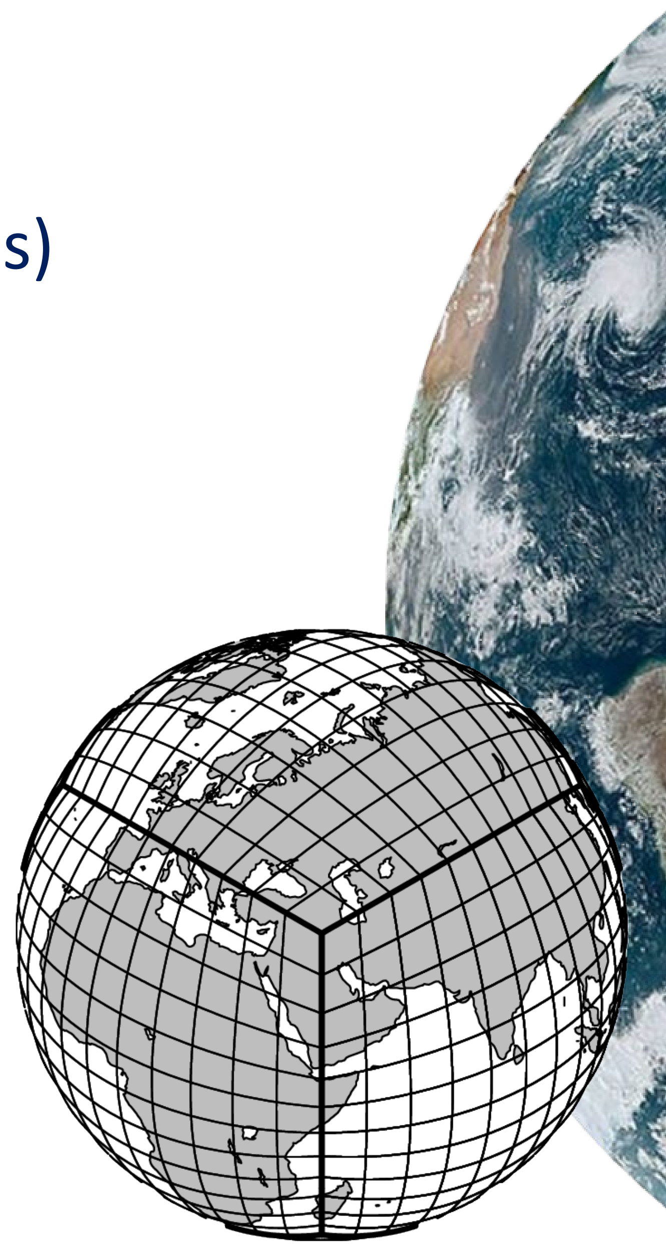
Basic features

- Cubed-sphere grid (quasi-uniform spherical grid)
- Stable and conservative high-order accurate finite-difference method (Summation-by-Parts finite-differences)

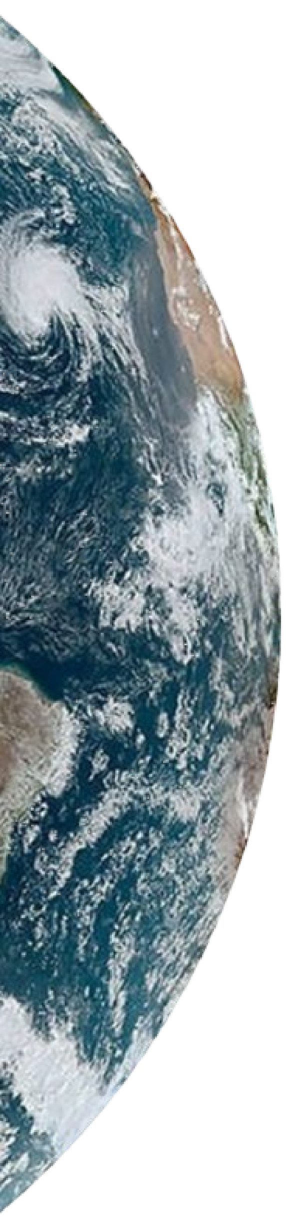
Discrete Ostrogradsky-Gauss theorem:

$$\int_{\Omega} (\vec{v} \cdot \nabla p + p \nabla \cdot \vec{v}) d\Omega = 0$$

- Hydrostatic & non-hydrostatic versions
- Collection of numerical methods (possibility to create combinations optimal for specific tasks)

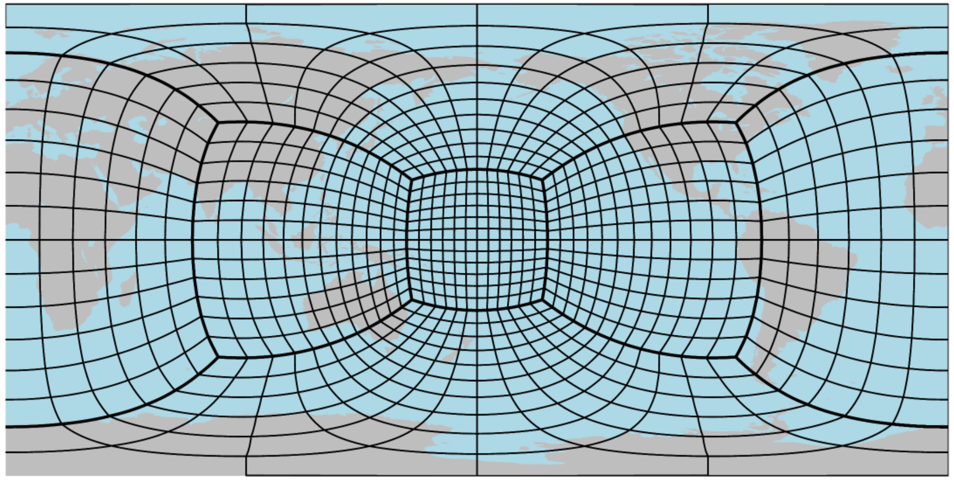


Mesh refinement strategies

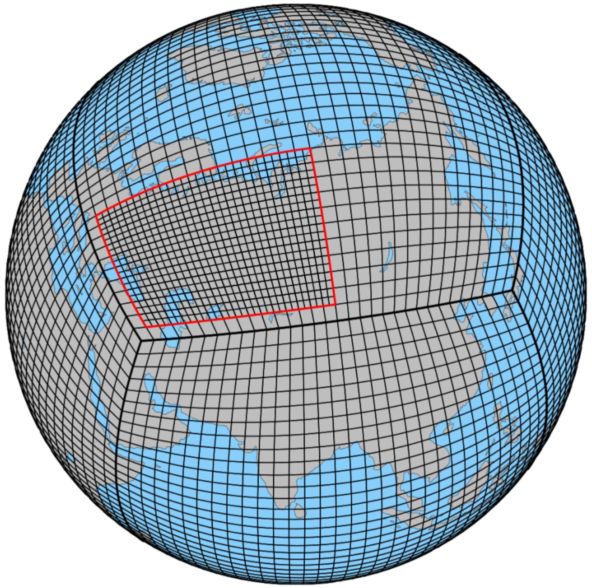


1. Schmidt transform

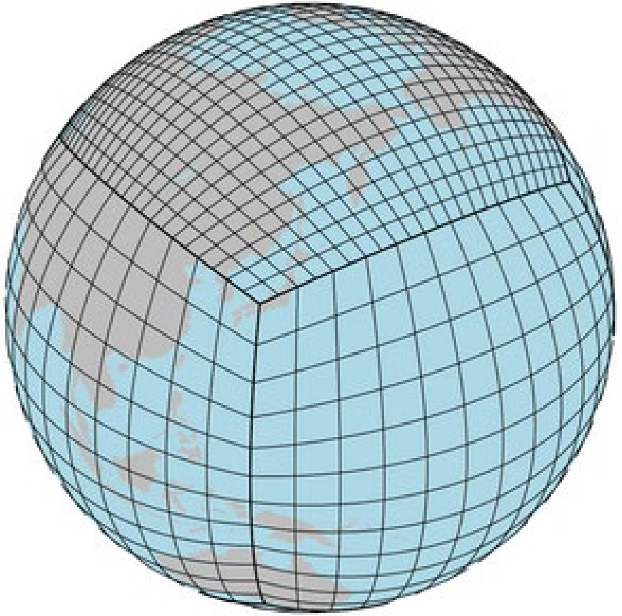
$$\sin\varphi' = \frac{c + \sin\varphi}{1 + c\sin\varphi}, \quad \lambda' = \lambda$$



2. Nesting



3. Embedding of a high-resolution region



Test-driven development strategy

All model dynamics configuration are to pass the following test hierarchy (closely following DCMIP tests):

Test type	Typical problems	Tested model components
Shallow water tests	Solid rotation, Rossby-wave, Barotropic instablity	Horizontal approximation
3D idealized tests (with and without orography)	Baroclinic instability, Mountain waves, etc.	+ vertical approximation, orography treatment, temporal splitting scheme (for NH)
Simple physics tests	Tropical cyclone, Held-Suarez	+ coupling subgridscale physics to dynamics
Real orography, real starting data test		+ accuracy and stability over complex terrain and complex flow conditions
Full physics simplified tests	Aqualanet	+ interaction of dynamics with complex subgridscale physics
Real forecast (climate) test		All

Test-driven development strategy

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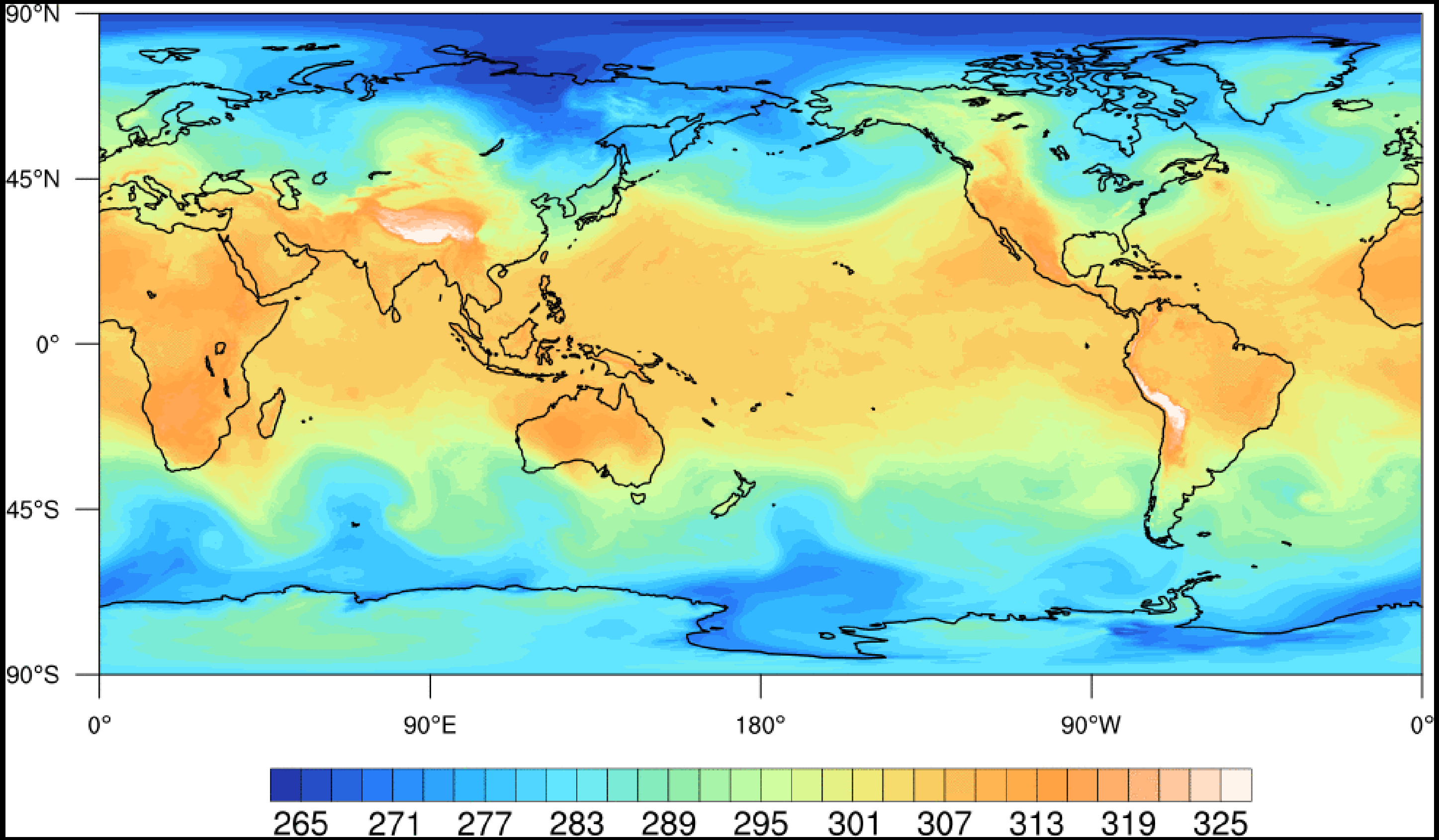
		complex subgridscale physics
Real forecast (climate) test		

The real (retrospective) forecast and historical climate simulations are final and ultimate model test. Right solutions are known (at least up to observations/(re)analysis accuracy).

But the problem is very complex and it is hard to find out what is the cause of deviations when something goes wrong

Real starting da[redacted]

H[redacted]ons



0.25^0 r[redacted]ld at level

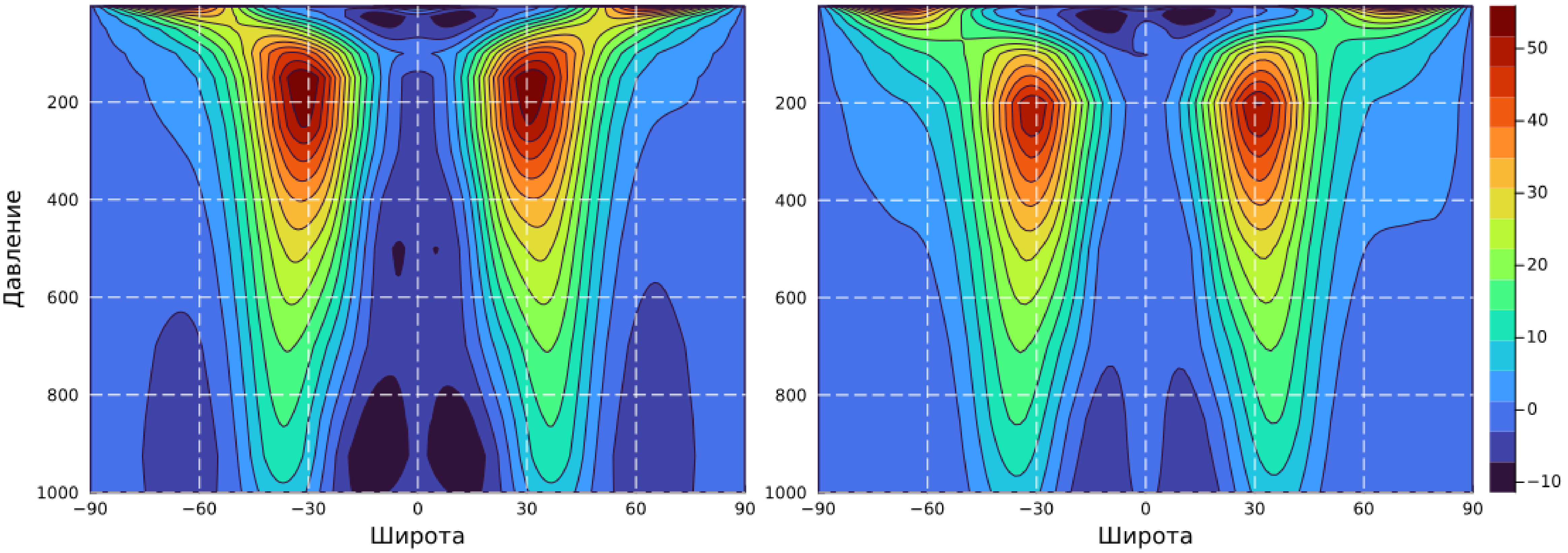
Model stability in the absence of evident artifacts is primary results

Aquaplanet experiment

- A planet covered by ocean, prescribed SST, ozone
- Diurnal cycle, perpetual equinox
- Full subgrid-scale physics package from SLAV model
- Isotermic initial conditions (6 months spin-up)
- Comparison with SLAV of comparable resolution of $0.96^{o}\text{x}0.72^{o}$ with the absolutely same subgrid scale physics package
- Cubed-sphere C90 (1^{o}) grid, 96 vertical levels (SLAV vertical grid), dynamics dt=180s, physics dt = 180s, 1800s.
- 9 simulated years per day with 576 computational cores.

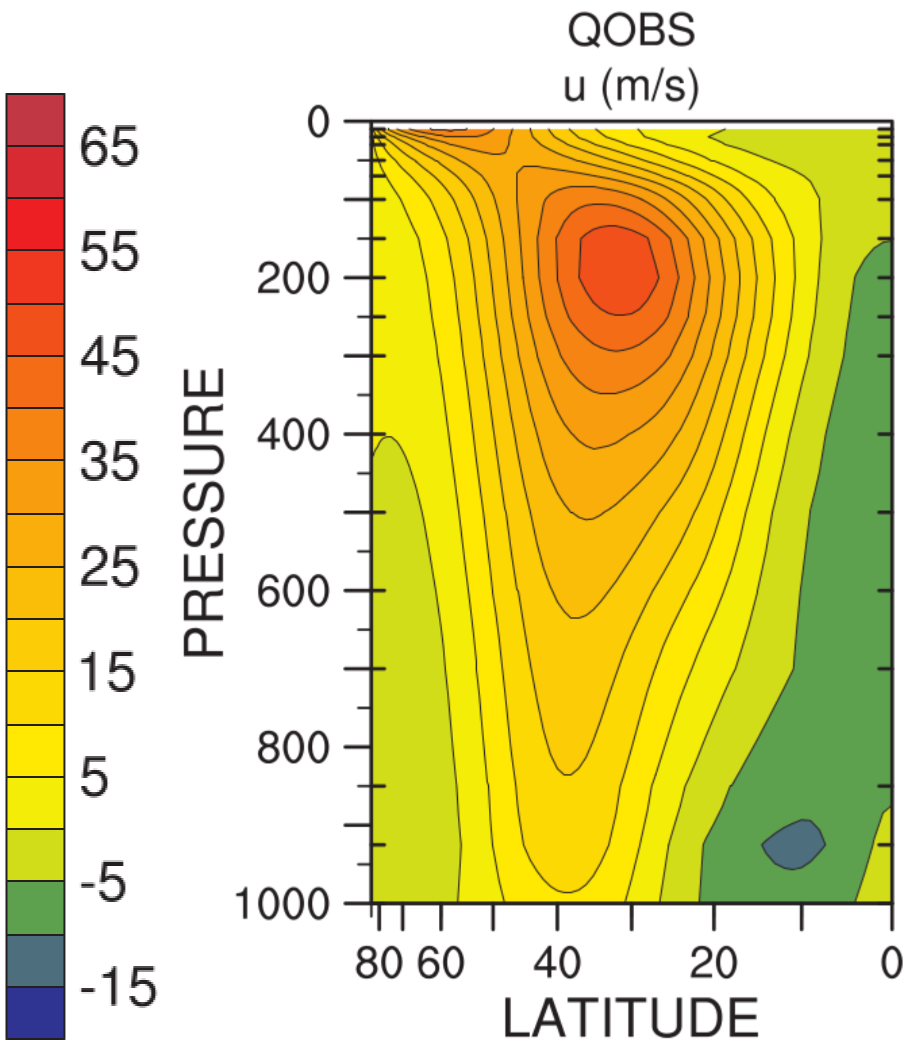
We are testing the very basic configuration of our dynamics in the very basic setup, but the first time with full subgrid-scale physics package

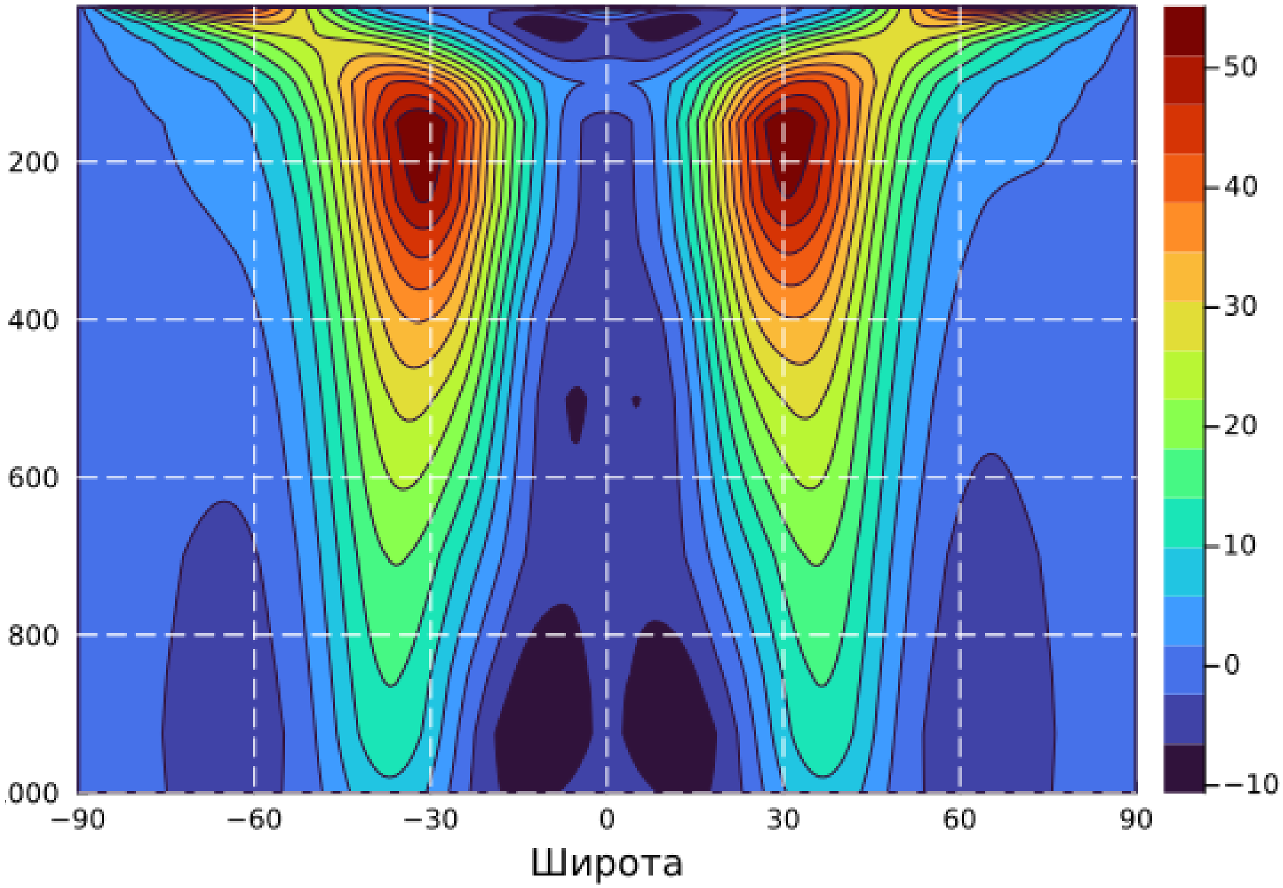
Aquaplanet experiment – zonal wind



2000 days average of zonal mean velocity according to cubed-sphere model (left) and SLAV (right)

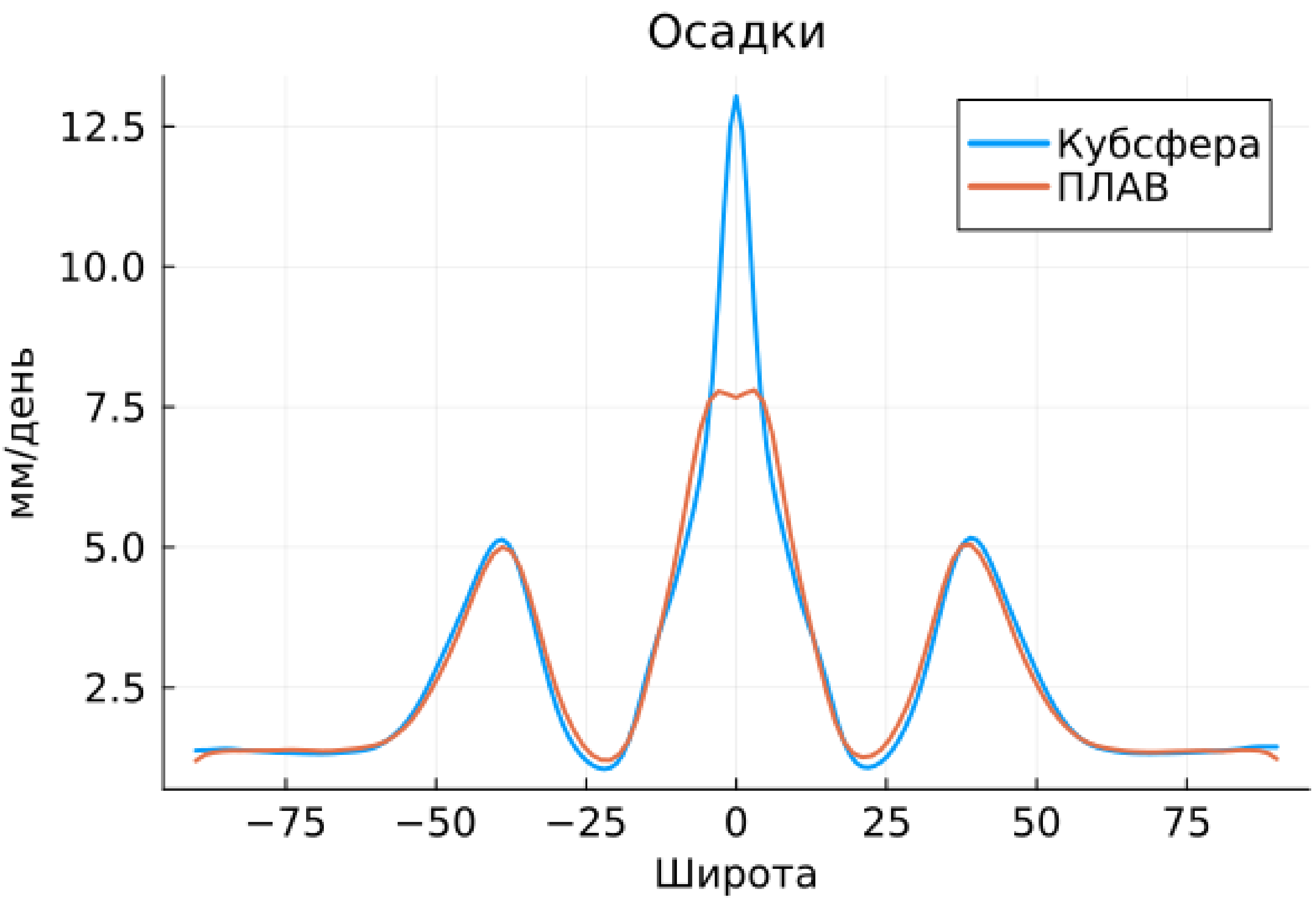
Aquaplanet experiment – zonal wind





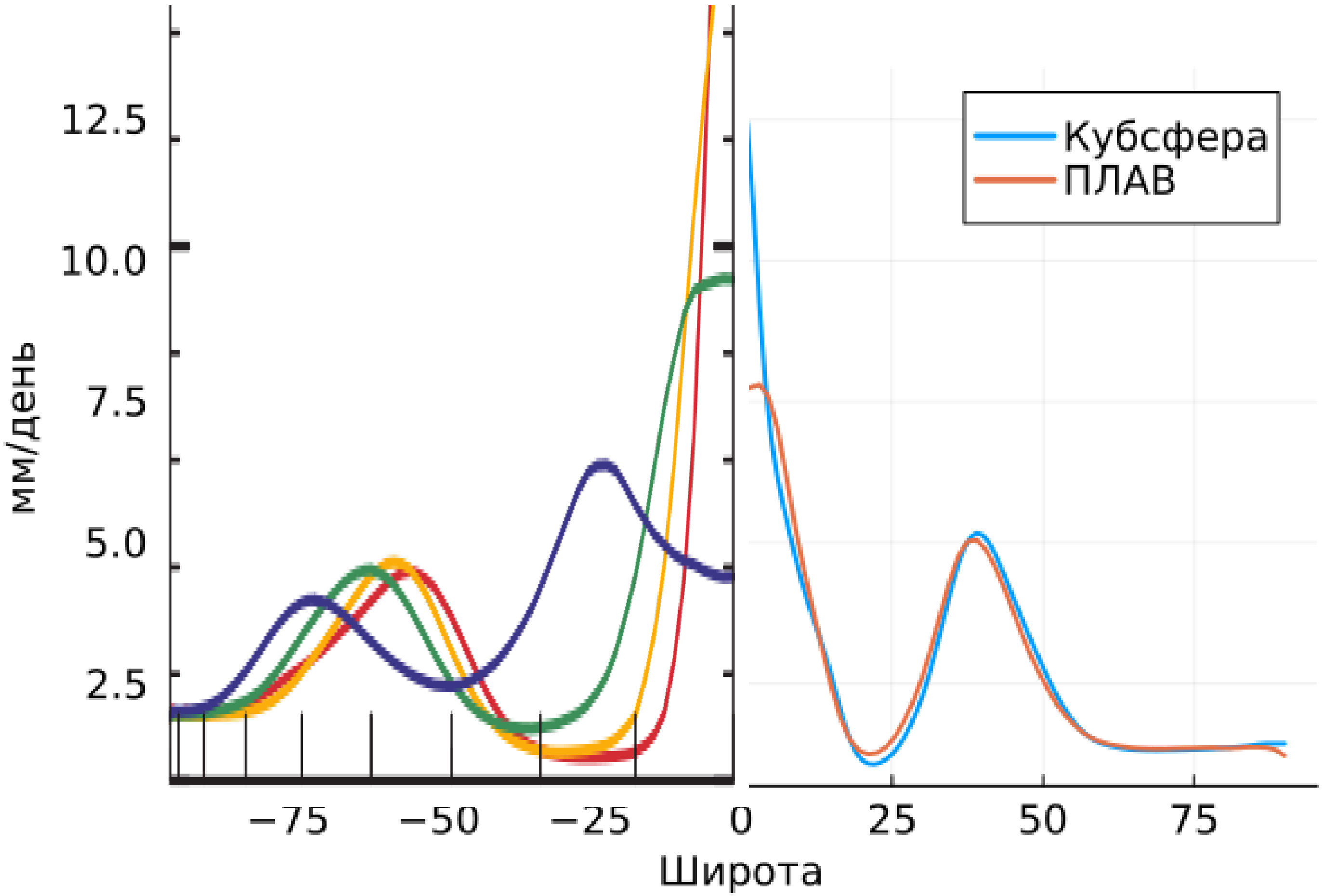
2000 days average of zonal mean velocity. Left – multimodel mean, right - cubedsphere

Aquaplanet experiment - precipitation



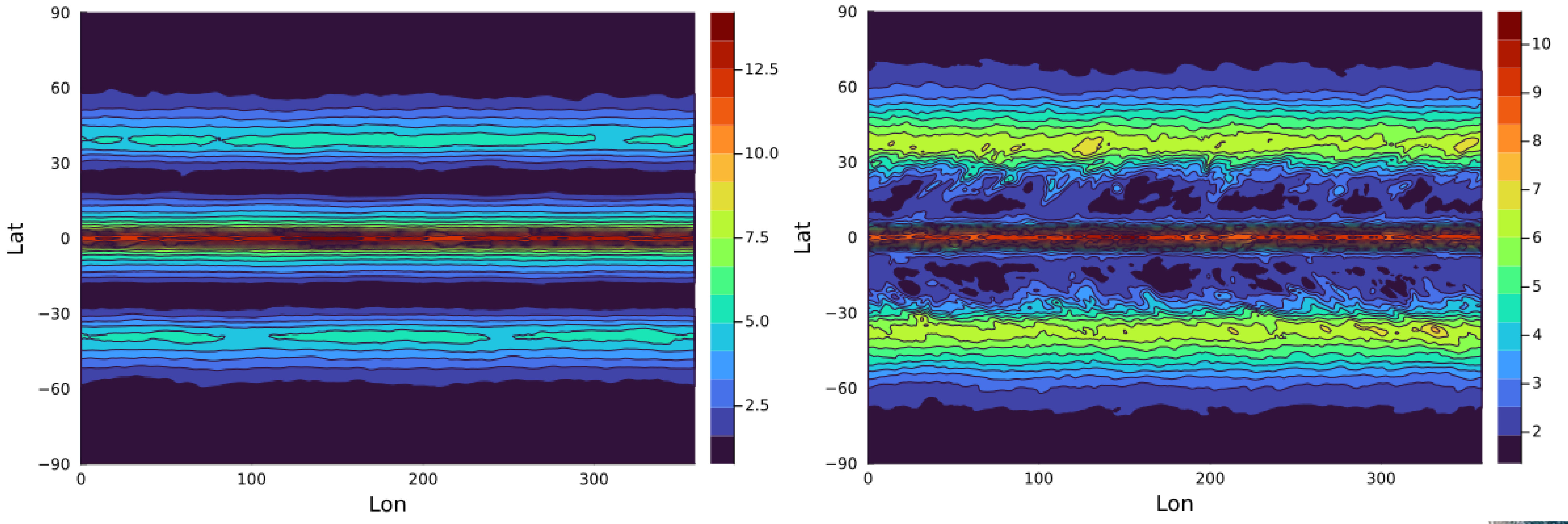
2000 days average of zonal mean total precipitation (blue – cubed-sphere, red - SLAV)

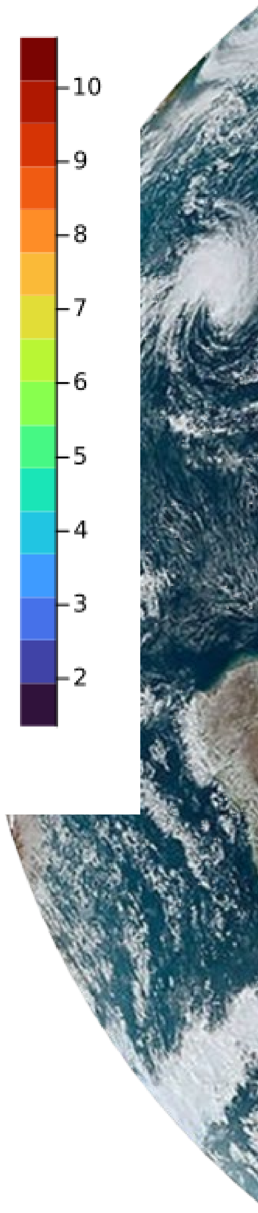
Aquaplanet experiment - precopotation



2000 days average of zonal mean total precipitation (blue – cubed-sphere, red - SLAV). Left – multimodel mean (green curve)

Aquaplanet experiment - precipitation

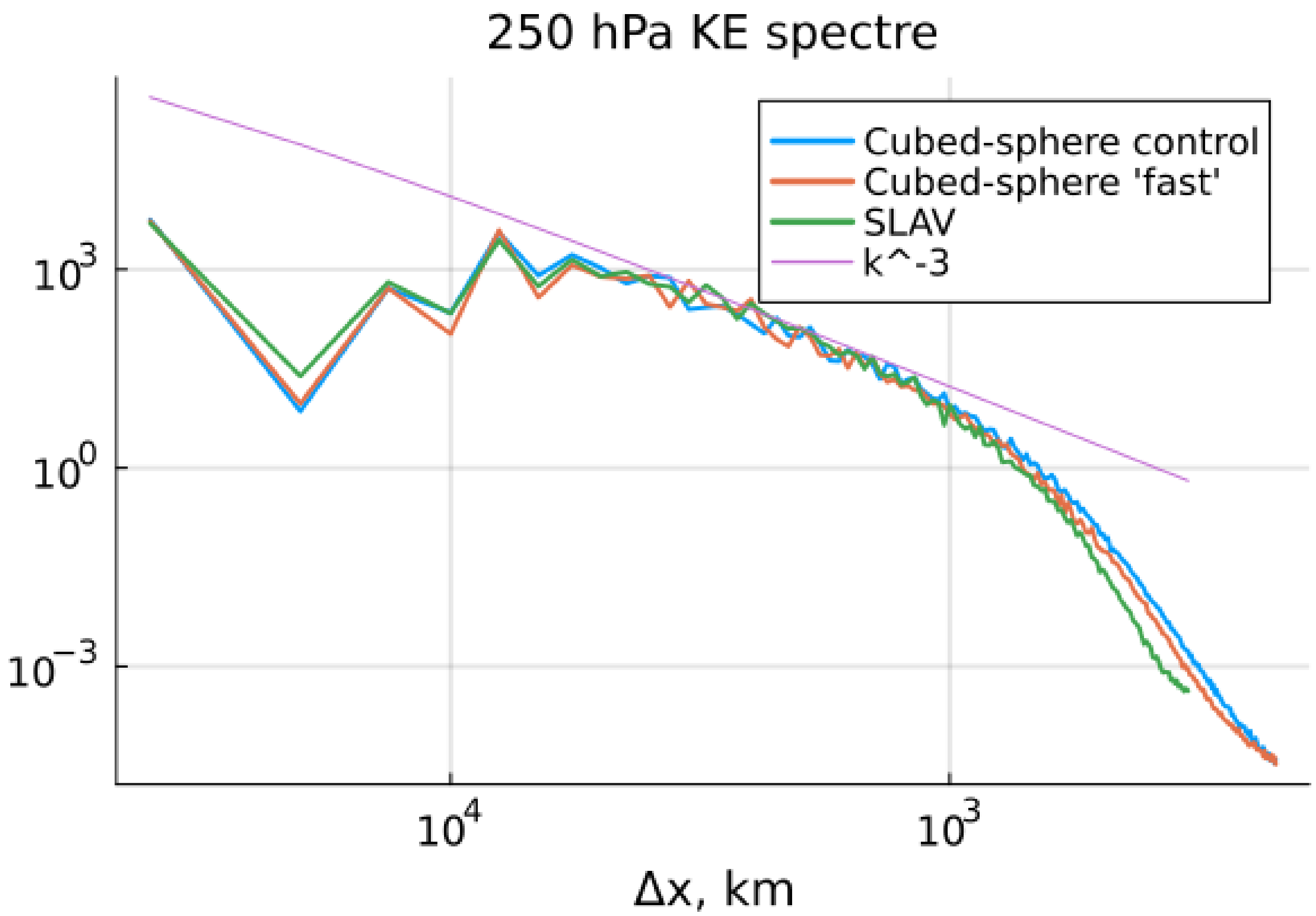




Left - 2000 days average total precipitation (mm/day). Right – 2000 days total precipitation standard deviation (mm/day). Both – cubed-sphere model.

No evident cubed-sphere grid imprinting (good)

Aquaplanet experiment - precipitation

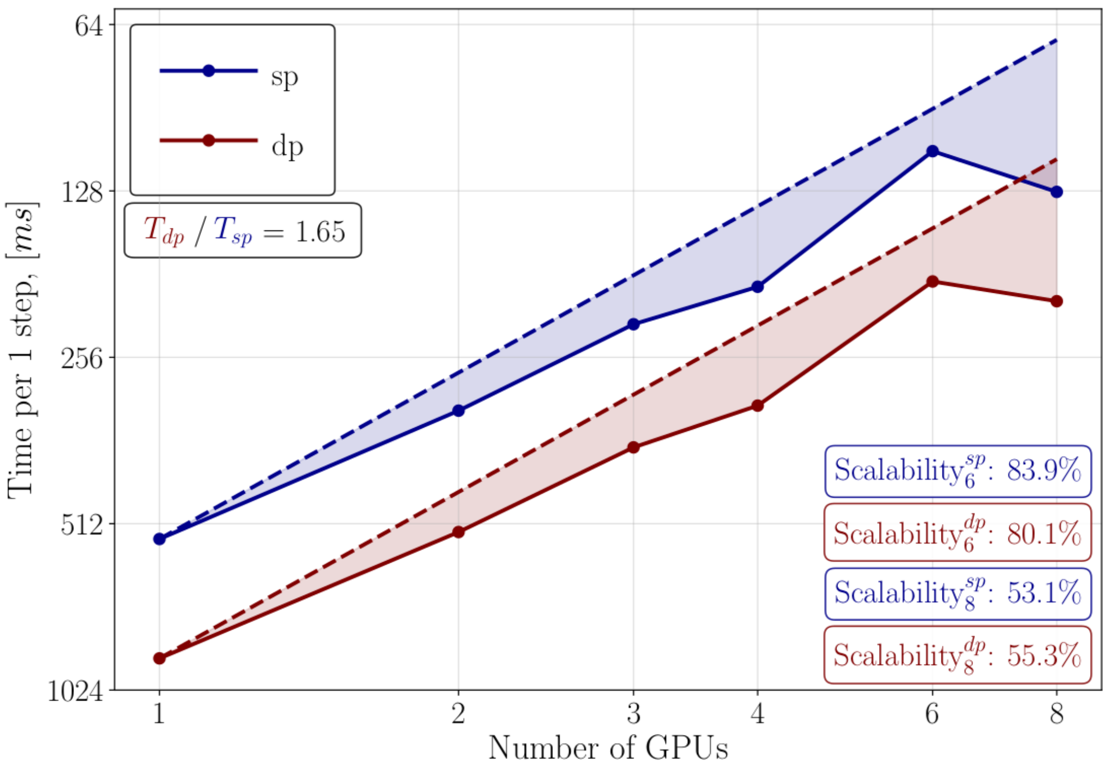


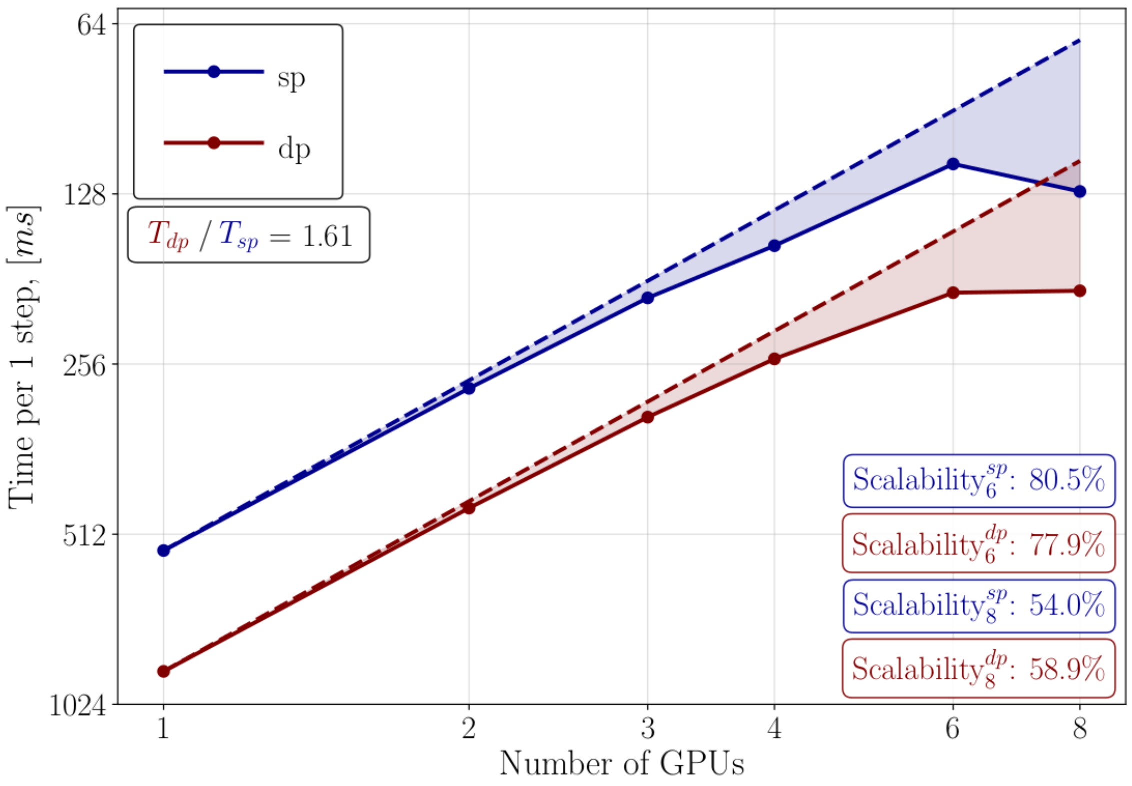
Kinetic energy spectre at 250 hPa level.

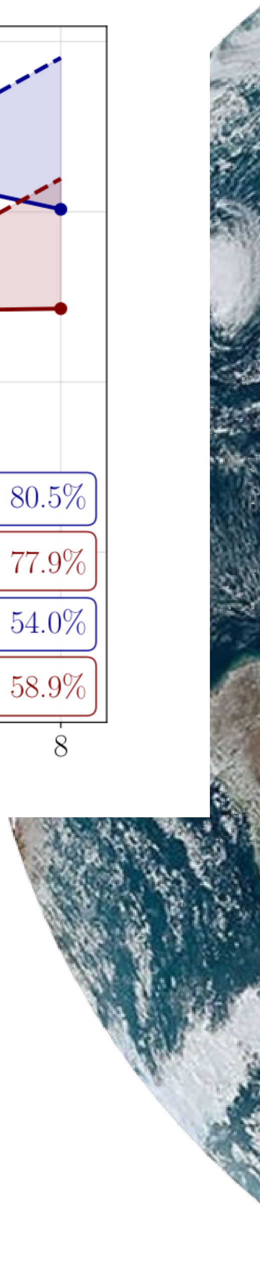
Cubed-sphere control: double precision in dynamics and physics each timestep

Cubed-sphere “fast”: single precision in dynamics, physics each 10-th dynamics timestep

A word on computational efficiency: GPU implementation performance







Strong scalability at RSK test GPU server (8 x H100). Left - standard, right using NVLink interconnect. Model configuration: C360 (0.25°), 96 levels. Dynamical core only (no subgrid-scale physics)

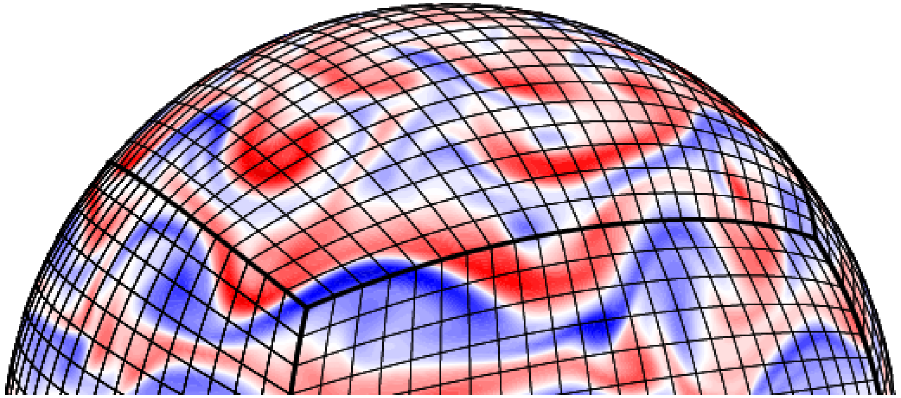
1 H100 ≈ 450 Xeon Gold CPU cores

Conclusions

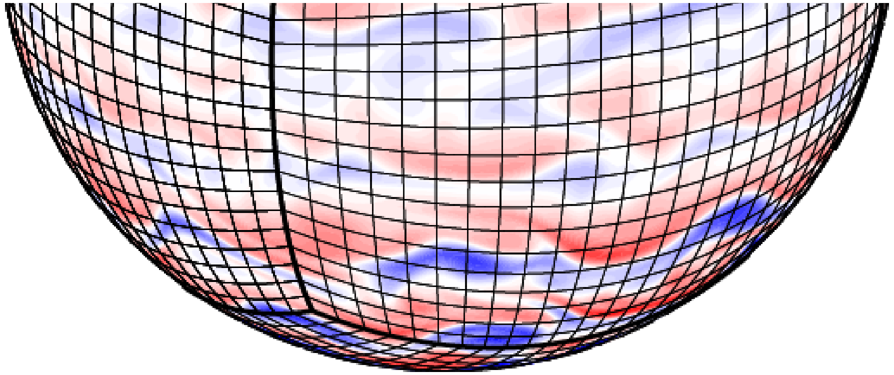
- On the way to real simulations with SLAV-model subgrid-scale physics (one step left)
- Yet to analyze and tune some things in aquaplanet experiment
- At the time results look promising

Outlook:

- Coupling with ARTS-ESM/INMCM physics
- Dynamical core code gives us much more opportunities that we can ever test (seeking for collaborations)
- A way to really high-resolution NWP and climate runs: making full-GPU code (GPU subgrid-scale physics)



Thank you for attention!



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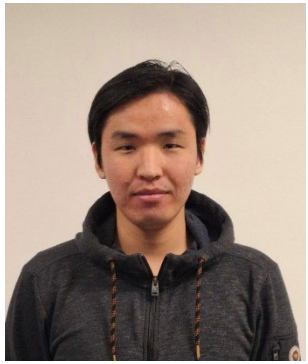

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Special thanks to Mikhail Tolstykh and Rostislav Fadeev

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https://gitlab.inm.ras.ru/vshashkin/ParCS

Non-hydrostatic equations

$$\frac{\partial \vec{v}_{hor}}{\partial t} = (\xi + f)k \times \vec{v}_{hor} - \nabla_{hor} K - C_p \theta \nabla_{hor} P, \quad (1a)$$

$$\frac{d\vec{v}_{hor}}{dt} = fk \times \vec{v}_{hor} - C_p \theta \nabla_{hor} P, \quad (1b)$$

$$\frac{dw}{dt} = -g - C_p \theta \frac{\partial P}{\partial z}, \quad (2)$$

$$\frac{d\theta}{dt} = 0, \quad (3a)$$

$$\frac{\partial \rho\theta}{\partial t} = -\left(\nabla_{hor} \cdot \left(\rho\theta\vec{v}_{hor} \right) + \frac{\partial \rho\theta w}{\partial z} \right), \quad (3b)$$

$$\frac{\partial \rho}{\partial t} = -\left(\nabla_{hor} \cdot \left(\rho\vec{v}_{hor} \right) + \frac{\partial \rho w}{\partial z} \right), \quad (4a)$$

$$\frac{d\rho}{dt} = -\nabla_{hor} \cdot \vec{v}_{hor} - \frac{\partial w}{\partial z}, \quad (4b)$$

$\vec{v}_{hor}, w$ - horizontal and vertical wind comp.

$$\zeta = k \cdot \nabla \times \vec{v}_{hor}, \quad K = \left| \vec{v}_{hor} \right|^2$$

P - Exner pressure

θ - Potential temperature

ρ - air density

Basic solver– (1a), (2), (3a), (4a)
Energy-conserving – (1a), (2), (3b), (4a)
Semi-Lagrangian – (1b), (2), (3a), (4b)

Hydrostatic equations

$$\frac{\partial \vec{v}_{hor}}{\partial t} = (\zeta + f)\vec{v}_{hor}^{\perp} - \nabla_{hor} K - \nabla_{hor}\Phi - \frac{RT}{p}\frac{\partial p}{\partial p_s}\nabla_{hor} p_s,$$

$$\frac{\partial}{\partial t}\frac{\partial p}{\partial \eta} = -\nabla_{hor}\cdot\left(\frac{\partial p}{\partial \eta}\vec{v}\right) - \frac{\partial}{\partial \eta}\left(\frac{\partial p}{\partial \eta}\dot{\eta}\right),$$

$$\frac{\partial q}{\partial t} = -\vec{v}\cdot\nabla q - \dot{\eta}\frac{\partial q}{\partial \eta},$$

$$C_p\frac{dT}{dt} = \frac{RT}{p}\omega,$$

$$\frac{\partial \Phi}{\partial \eta} = -\frac{RT}{p}\frac{\partial p}{\partial \eta},$$

$\zeta = k\cdot\nabla\times\vec{v}_{hor}, \quad K = \left|\vec{v}_{hor}\right|^2$

$\bar{v}_{hor}$ - horizontal wind, $\vec{v}_{hor}^{\perp} = k\times\bar{v}_{hor}$

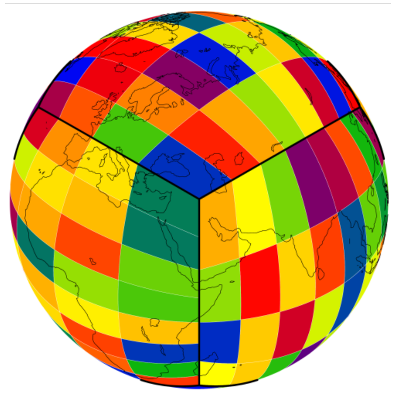
p - pressure, p_s - surf.pressure

η - vertical coordinate, $\dot{\eta} = \frac{d\eta}{dt}, \omega = \frac{dp}{dt}$

q - water vapour specific concentration,

Φ - geopotential, T -temperature

Скорость вычислений и масштабируемость на CPU



Cray XC40 (ГВЦ Росгидромета), Cray ARIES interconnect,
Intel Xeon E2697v4 18-core CPUs, 36 CPU на узле.

Конфигурации: **C90L73** (1^0, 73 верт. уровня), **C360L73** (0.25^0, 37 верт. уровня). Схема 2-го порядка, одинарная точность, эксперимент Хелда-Суареса.

C90L73

288 ядер – 41 лет/сутки
1152 ядра – 180 лет/сутки
1728 ядер – 237 лет/сутки

C360L37

1152 ядра – 5.2 лет/сутки, 26 дней/20 минут
6912 ядер – 26 лет/сутки, 130 дней/20 минут

Реальная подсеточная физика ~2x замедление расчетов