Cloud modeling software developed at the University of Warsaw

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Fluids ZA Seminar, MEL, PW, 17.01.25

Atmospheric research @Institute of Geophysics, UW

- Atmospheric aerosol
  - Measurements (mostly)

- Cloud dynamics and atmospheric turbulence
  - Observations, theory and small-scale numerical models

- **Microphysics of clouds**
  - **Fully developed numerical model of clouds**

Agenda

1) Cloud modeling basics
2) Overview of the University of Warsaw Lagrangian Cloud Model (UWLCM)
3) Why subgrid-scale turbulence matters: a case study

Agenda

1) Cloud modeling basics

Numerical cloud modeling

- Why?
  - Clouds are important for weather and climate
  - Cloud observations are challenging
  - Laboratory experiments do not cover all length scales

Numerical cloud modeling

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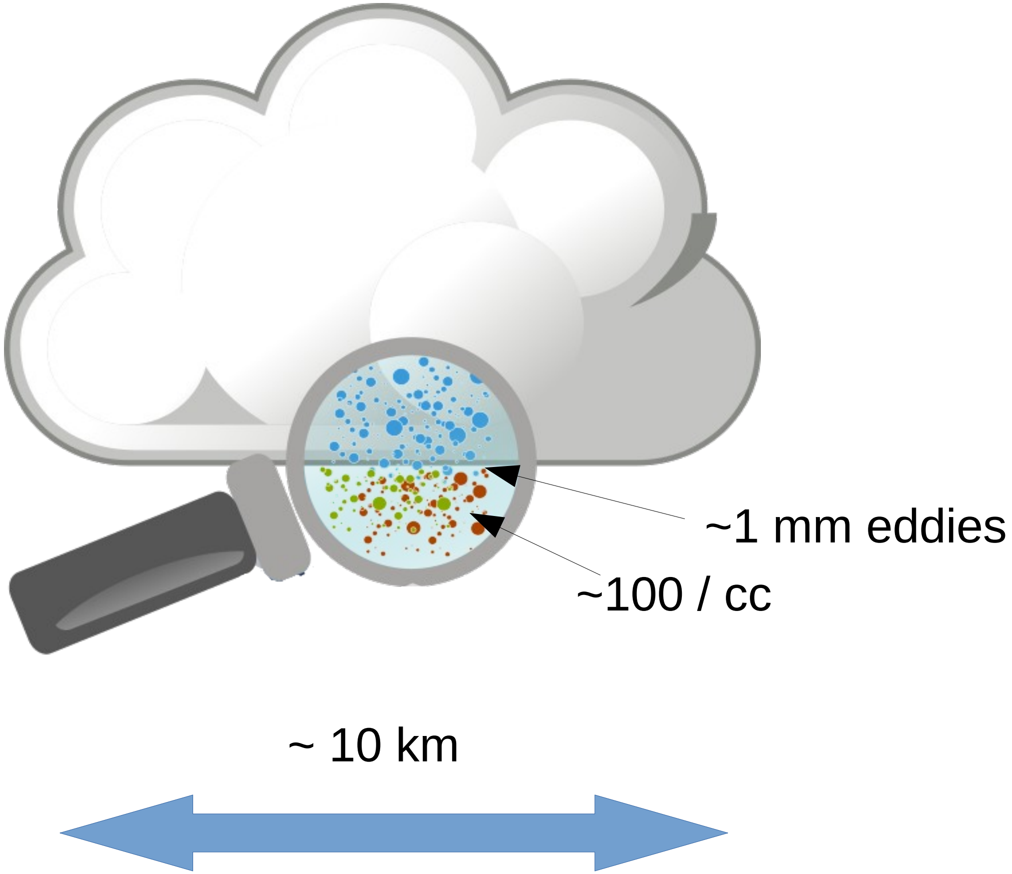
  - Clouds are important for weather and climate
  - Cloud observations are challenging
  - Laboratory experiments do not cover all length scales
- How?
  - Modeling air flow (CFD) and cloud droplets (microphysics)

Numerical cloud modeling

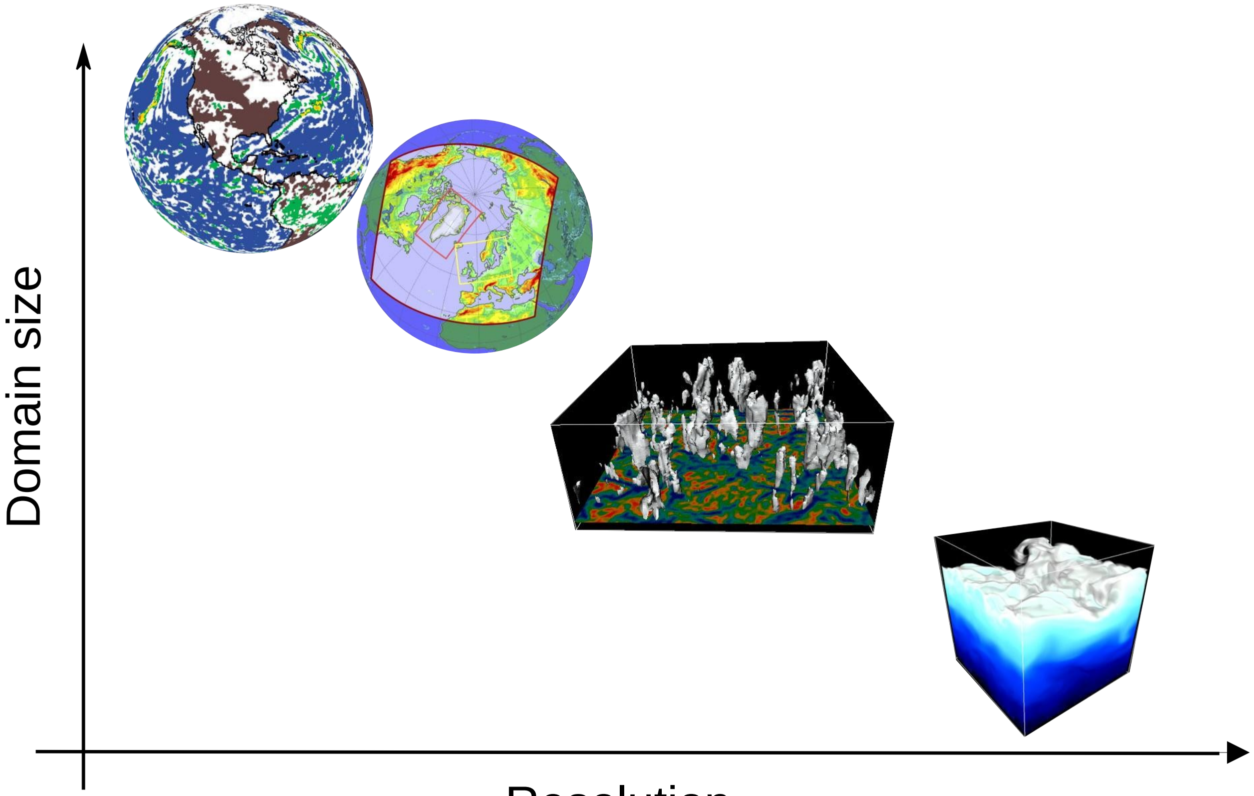
- Why?
  - Clouds are important for weather and climate
  - Cloud observations are challenging
  - Laboratory experiments do not cover all length scales
- How?
  - Modeling air flow (CFD) and cloud droplets (microphysics)
- Challenges
  - Broad range of important spatial and temporal scales

Cloud length and time scales

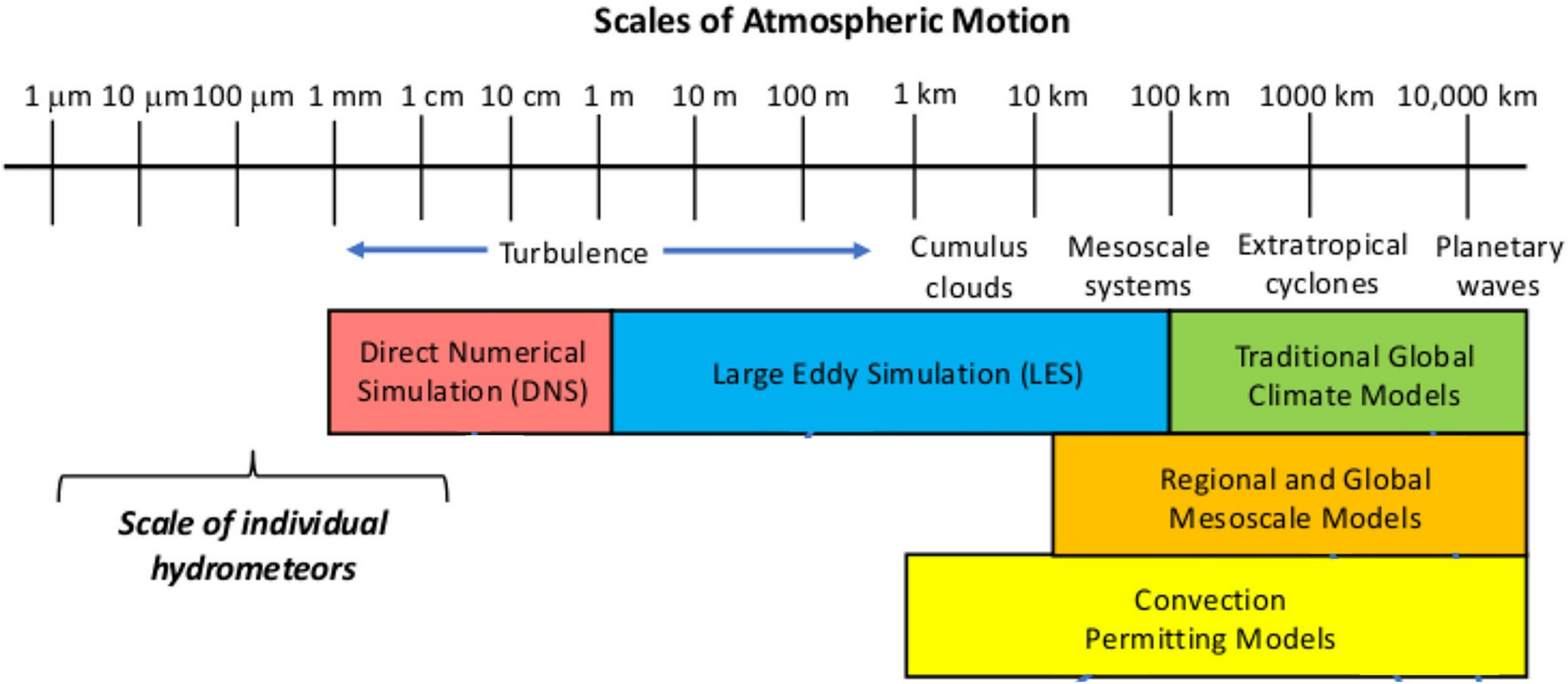


- Cloud droplet activation: ~0.01 s
- Cloud system lifetime: hours to days
- Climate prediction: ~50 y

Cloud modeling across scales

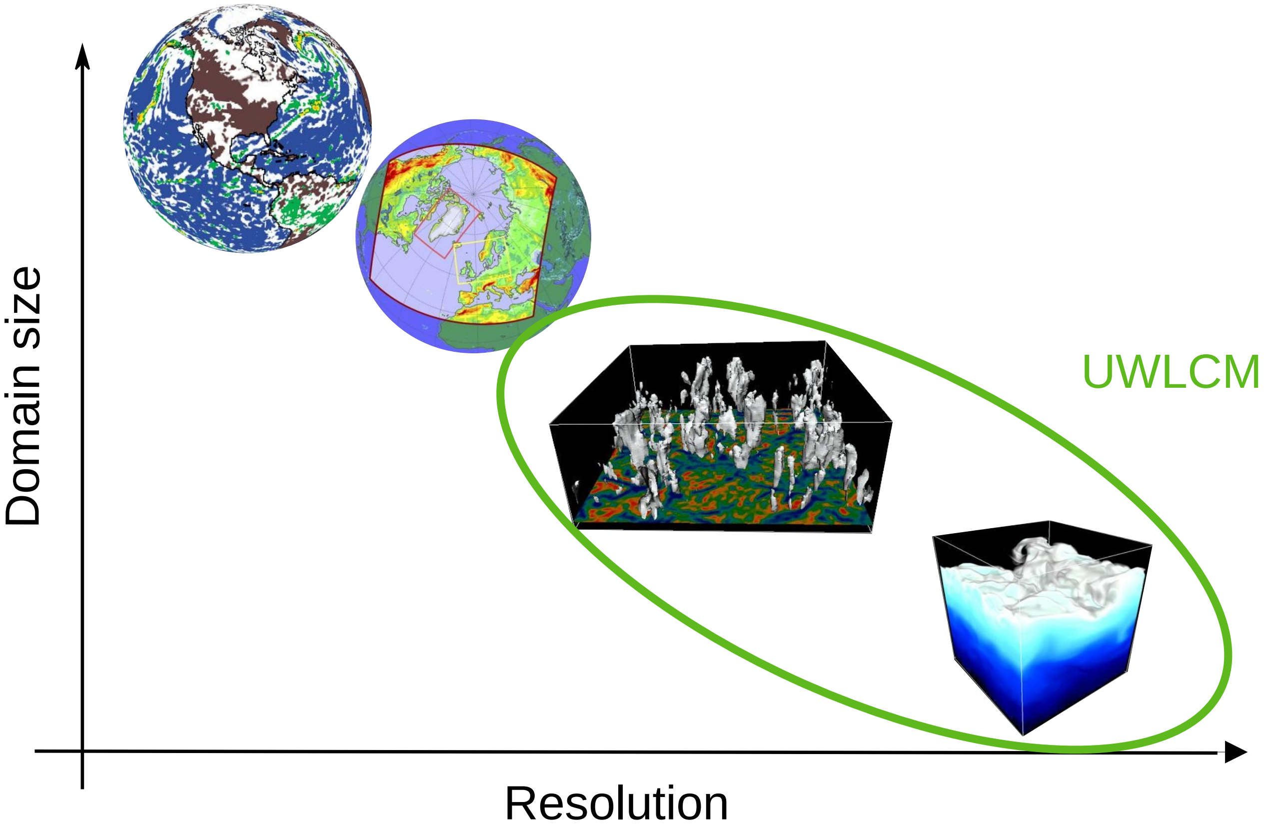


Cloud modeling across scales



adapted from Morrison et al. *JAMES* (2020)

Cloud modeling across scales



LES use cases

- Basic research in cloud physics.
- Improvement of parameterizations used in weather and climate models.
- Predictive models are starting to use resolutions close to LES (e.g. project NextGEMS). Methods developed for LES will be used directly in global models.

Agenda

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2) Overview of the University of Warsaw Lagrangian Cloud Model (UWLCM)

University of Warsaw Lagrangian Cloud Model (UWLCM)

- Tool for large eddy simulations (LES) of clouds
- Sophisticated cloud microphysics model – super-droplet method (SDM)
- Developed for 10+ years
- Written in C++
- Open-source
- Runs on accelerated computing clusters
- github.com/igfuw/UWLCM

UWLCM basics

- Modeling air flow (2d or 3d):
  - Large eddy simulations: small-scale turbulence is parameterized

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- Modeling liquid water
  - Bulk microphysics

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Eulerian

Eulerian variables

- Governed by anelastic equations

$$D_t \boldsymbol{u} = -\nabla \pi + \boldsymbol{k} B + \boldsymbol{F}_u,$$

$$D_t \theta = \frac{\theta^e}{T^e} \left(\frac{l_v}{c_{pd}} C \right) + F_\theta,$$

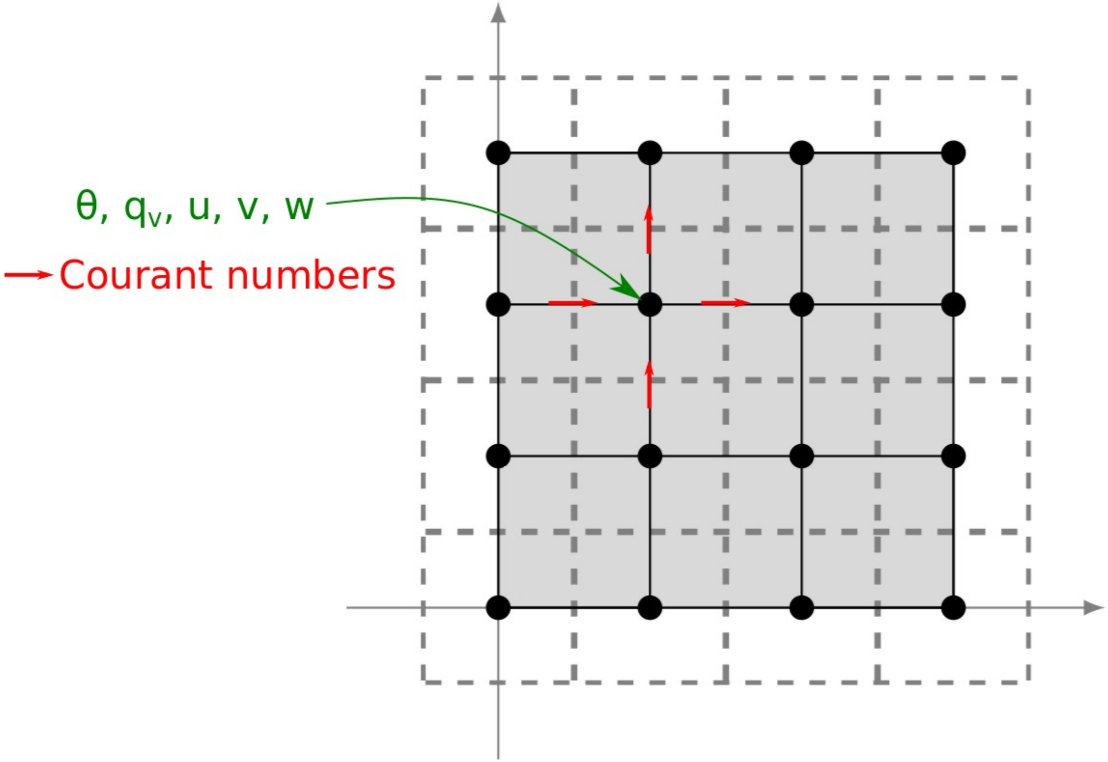
$$D_t q_v = -C + F_{q_v},$$

$$\nabla \cdot (\rho_d^r \boldsymbol{u}) = 0,$$

$$B = g \left[\frac{\theta - \theta^e}{\theta^r} + \epsilon (q_v - q_v^e) - (q_l - q_l^e) \right]$$

Eulerian variables

- Governed by anelastic equations
- Staggered rectangular grid with stretching
- Solved with MPDATA



UWLCM basics

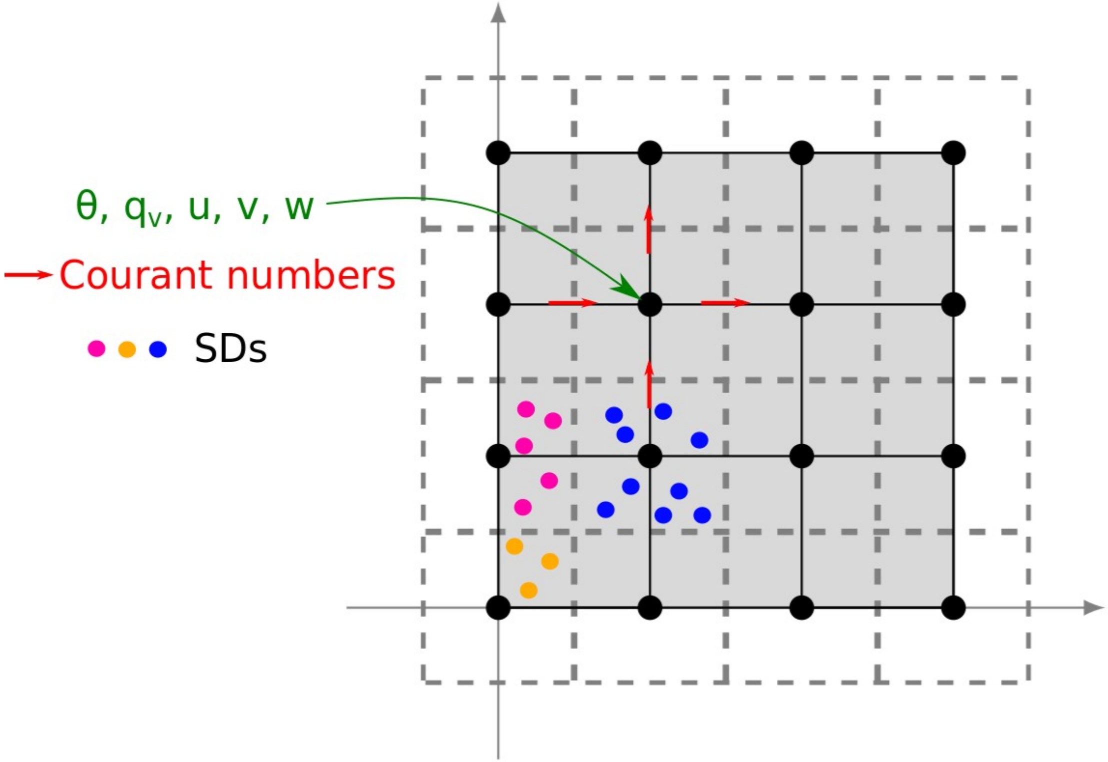
- Modeling air flow (2d or 3d):
  - Large eddy simulations: small-scale turbulence is parameterized
- Modeling temperature and humidity
- Modeling liquid water
  - Bulk microphysics
  - Super-droplet method

Eulerian

→ Lagrangian

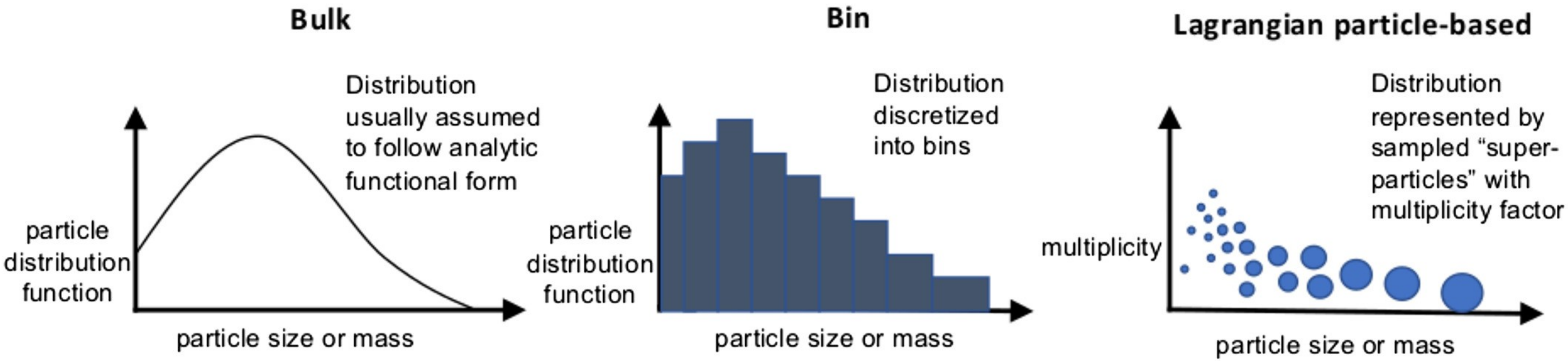
Super-droplets (SD)

- Computational particle-like objects called super-droplets represent:
    - Humidified aerosols
    - Cloud droplets
    - Rain drops



SD: Droplet size distribution

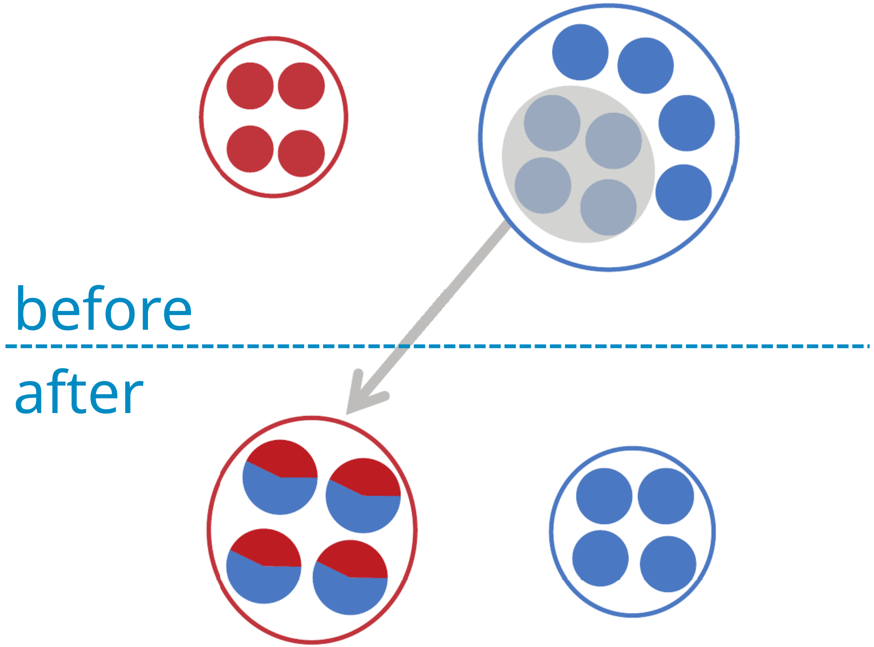
- Each SD represent multiple real hydrometeors (multiplicity) with same properties (e.g. radius)
- Evolution of the DSD is resolved, like in bin microphysics



adapted from Morrison et al. *JAMES* (2020)

Collision-coalescence in SDM

Collision of a pair of SDs (stochastic):



- Correct mean number of collisions:

$$\langle coll \rangle^{(\mathrm{SD})} = \langle coll \rangle$$

- Too high standard deviation:

$$\sigma(coll)^{(\mathrm{SD})} \approx \sqrt{\frac{N}{N_{\mathrm{SD}}}}\,\sigma(coll)$$

N – number of droplets
N_{SD} – number of super-droplets

adapted from Unterstrasser et al. *GMD* (2016)

Subgrid scale turbulence in UWLCM

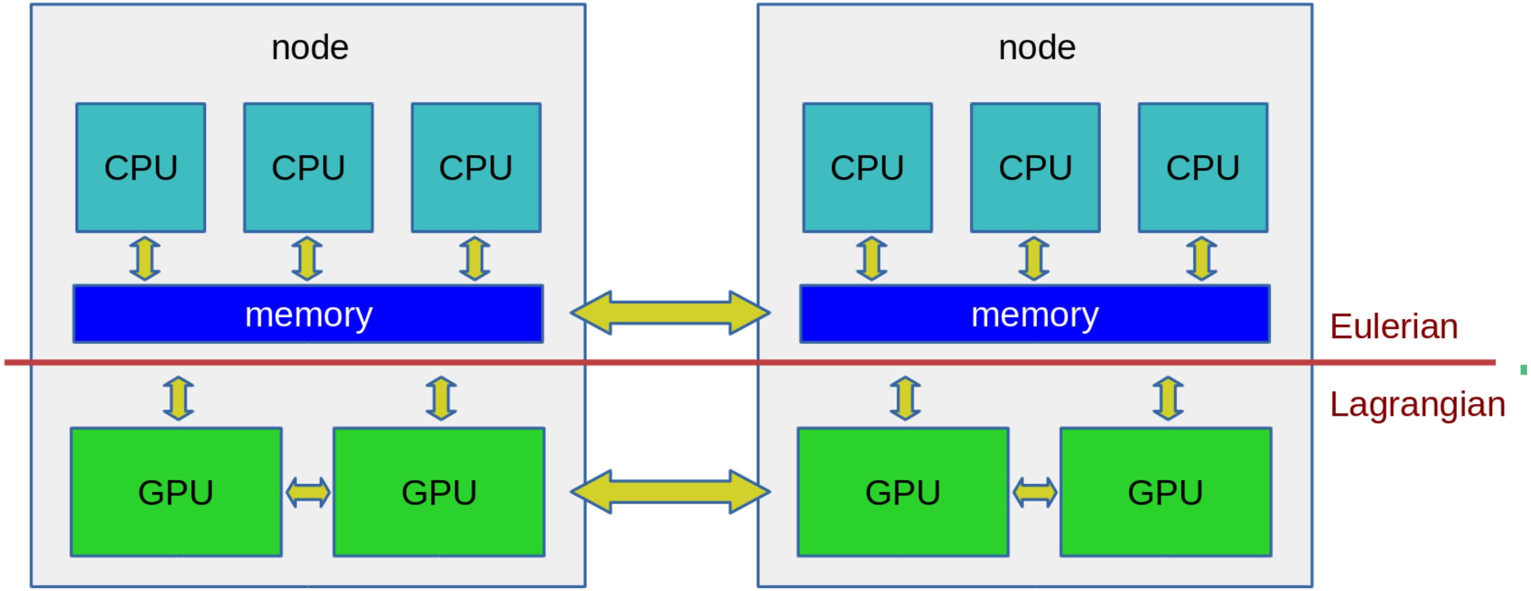
Diffusion

- Smagorinsky
- Implicit LES
- Random component of SD velocity (Grabowski&Abade 2017)

Microphysics

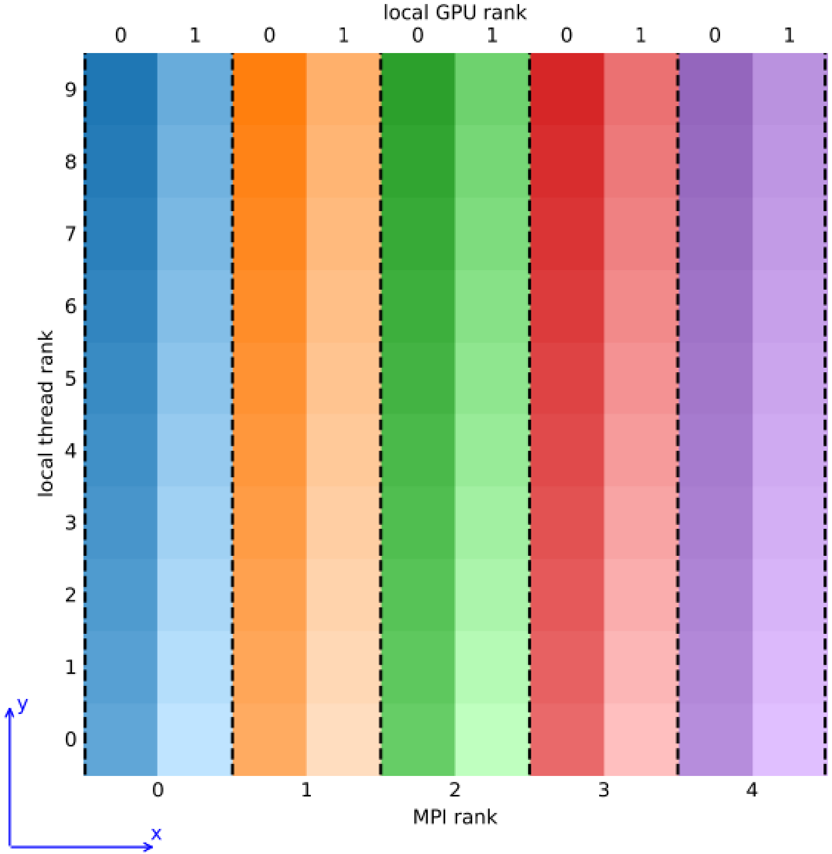
- Turbulent enhancement of collision-coalescence
- Random component of SD supersaturation (Grabowski&Abade 2017)

Use of heterogeneous (CPU+GPU) clusters


node
CPU
CPU
CPU
memory
GPU
GPU
node
CPU
CPU
CPU
memory
GPU
GPU
Eulerian
Lagrangian

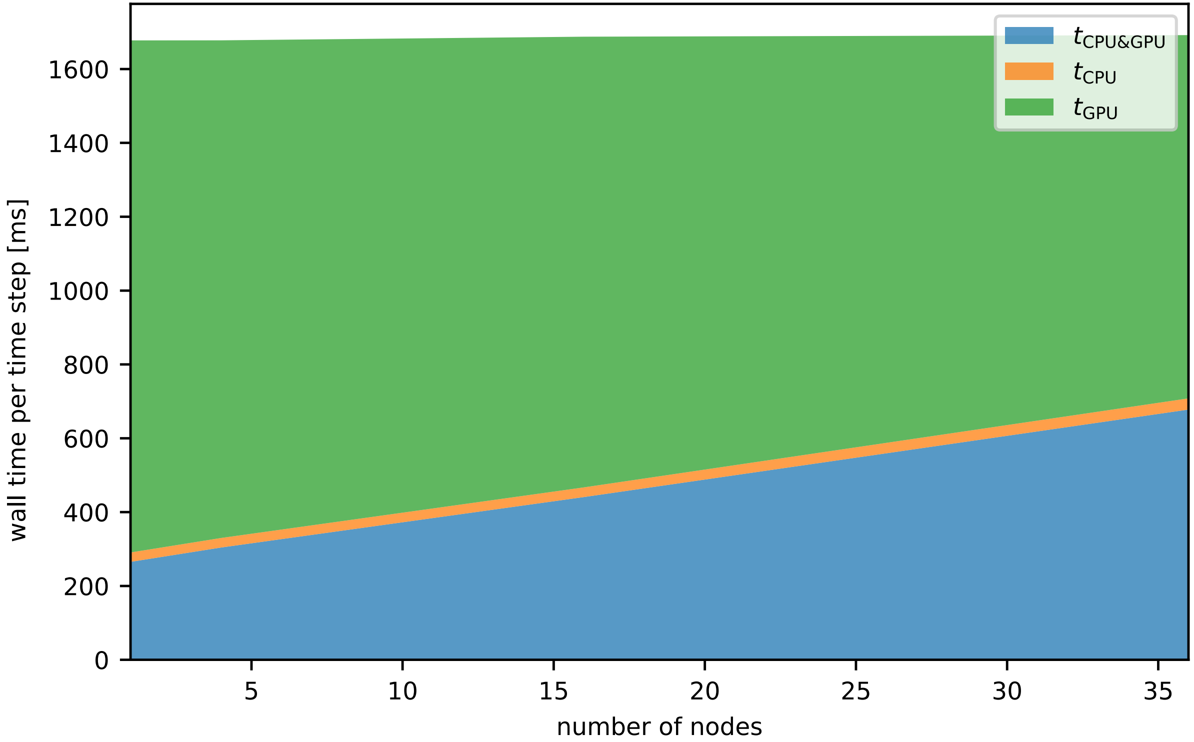
- Eulerian component: resides in RAM, computed by CPUs
- Lagrangian component: resides in GPU RAM, computed by GPUs

Domain decomposition



Top-down view of modeled domain; squares are Eulerian grid cells; coloring shows MPI, thread and GPU ranks.

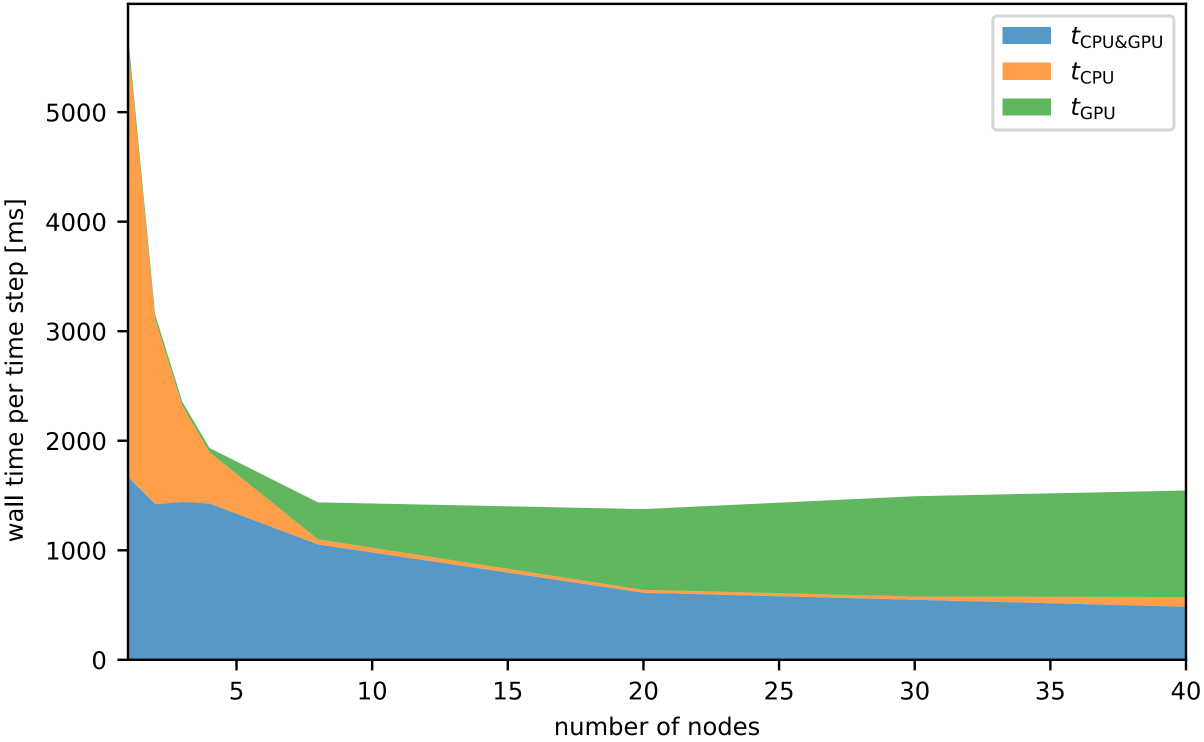
Weak scaling test



Wall time per time step vs number of nodes. Timings of simultaneous CPU and GPU computations (blue), CPU-only computations (orange) and GPU-only computations (green) are stacked.

- GPU time scales better than CPU time
- Simultaneous CPU and GPU usage should be maximized for an optimal number of nodes (larger than shown)
- Up to the optimal number of nodes, scaling efficiency of the total wall time is ca. 100%

Strong scaling on CPU, weak on GPU



Wall time per time step vs number of nodes. Timings of simultaneous CPU and GPU computations (blue), CPU-only computations (orange) and GPU-only computations (green) are stacked.

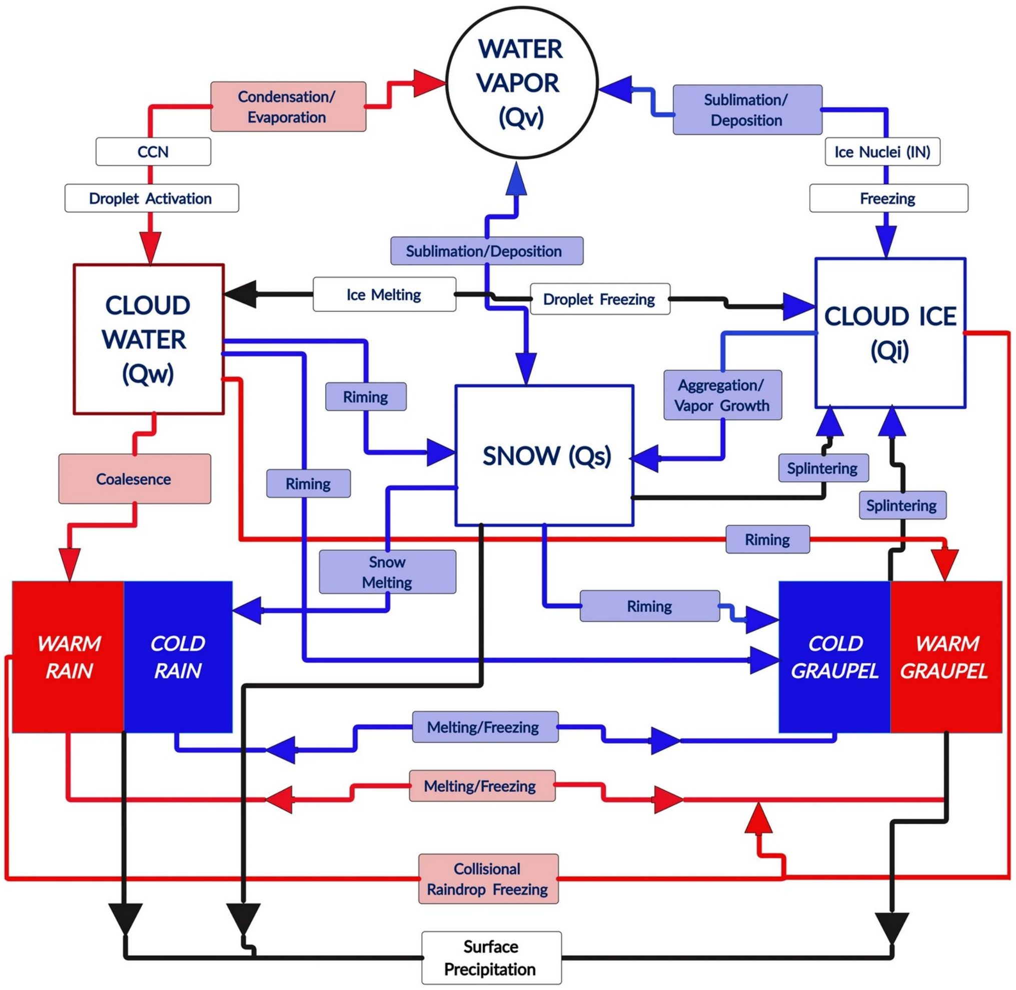
- Good balance of CPU and GPU computations (ca. 80%) for an optimal number of nodes (5-10 in this case)

Projects and Collaborations

- Large European projects we are currently involved in:
  - Next Generation Earth Modeling Systems, EU Horizon 2020
  - HANAMI, EU-Japan HPC collaboration, EuroHPC
- Long-standing collaboration with scientists from:
  - National Center for Atmospheric Research, Boulder, Co, USA
  - University of Hyogo/RIKEN, Kobe, Japan

Plans for UWLCM

- Ice microphysics



Warm-rain and Ice crystal Processes

Gupta et al. *CEE* 2023

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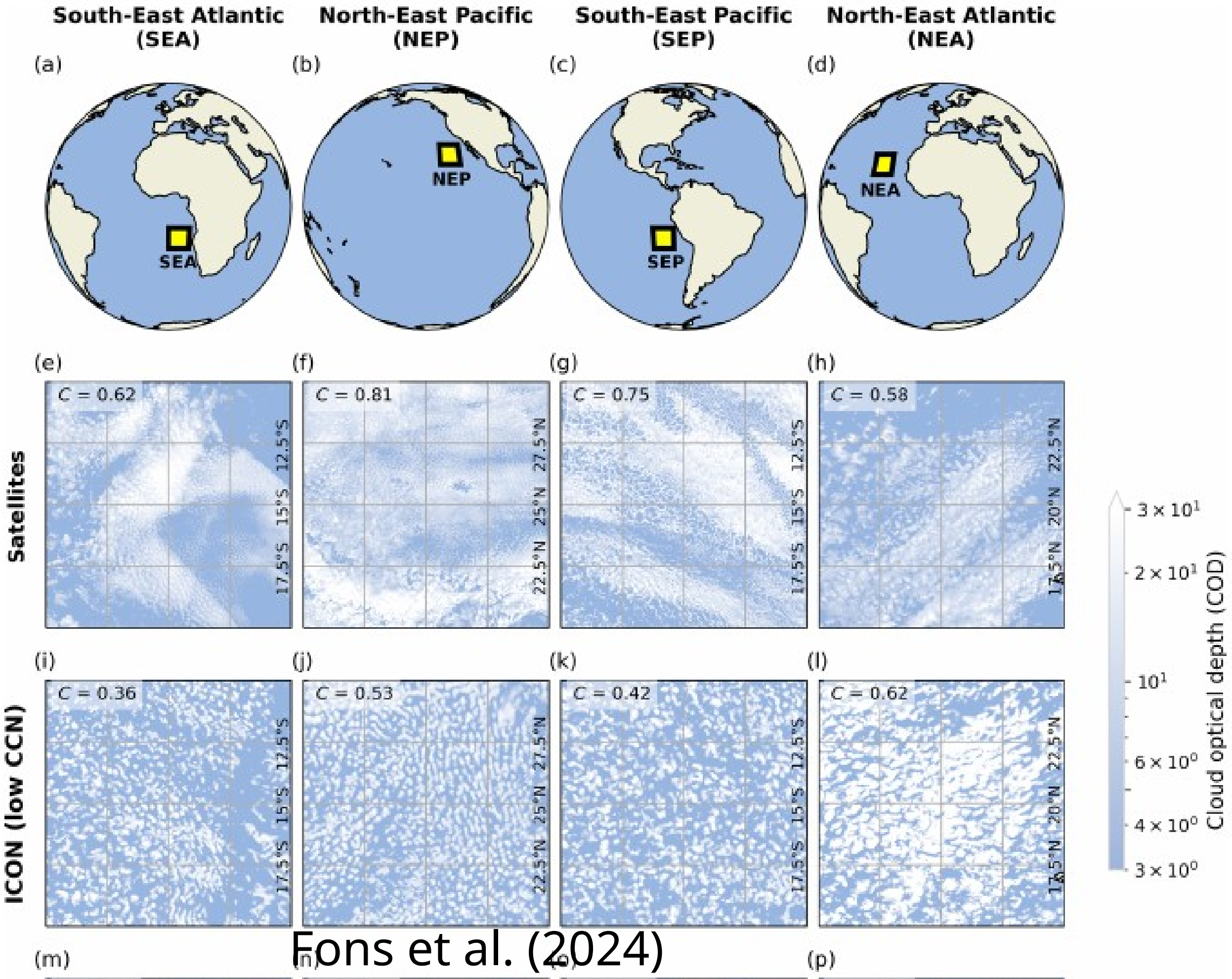
Stratocumulus clouds in storm-resolving models (SRMs)

- Climate models are evolving towards storm-resolving resolutions of the order of 1km (NextGEMS project).
- It is a “grey-zone” resolution, where neither parameterisations from LES nor from global models work properly.
- Stratocumuli (Sc) are hard to model, but important for global albedo.
- In SRMs, Sc:
  - have wrong morphology (Fons et al. 2024),
  - drizzle too much (Fons et al. 2024),
  - are susceptible to turbulence parameterisations (Nowak et al. 2024).

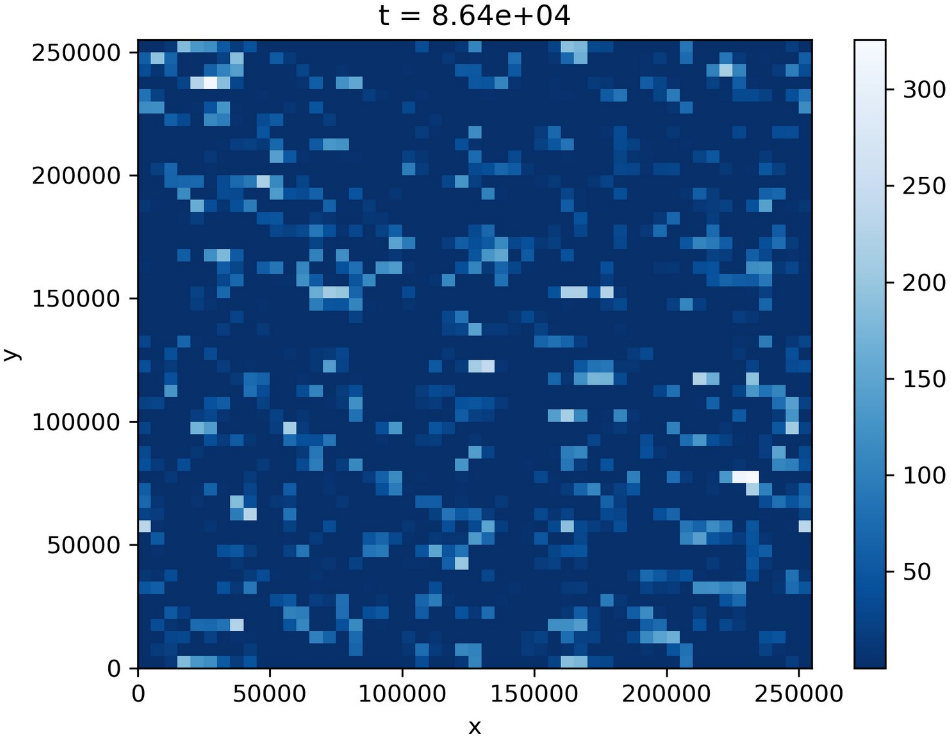
Sc morphology – models vs satellites

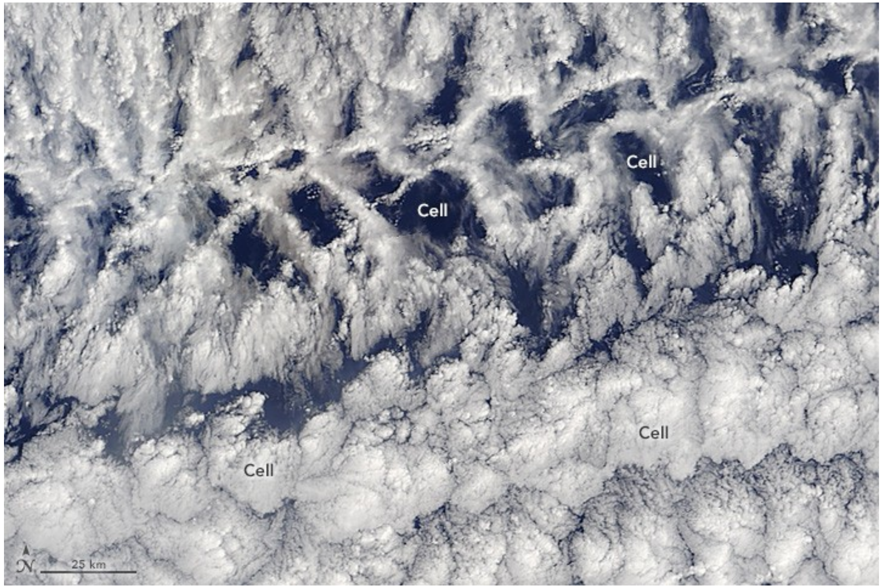


Fons et al. (2024)

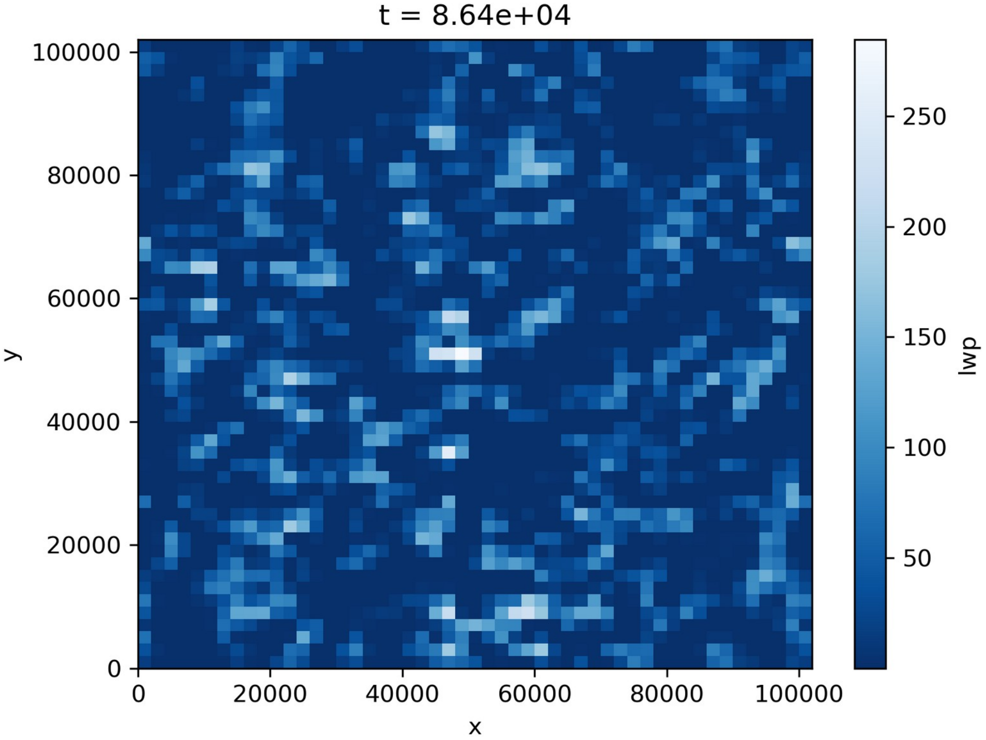
- Real Sc are aggregated in closely connected cells
- Clouds in Sc regions in ICON are made of less connected cells (sparse, larger variability in cloud depth)

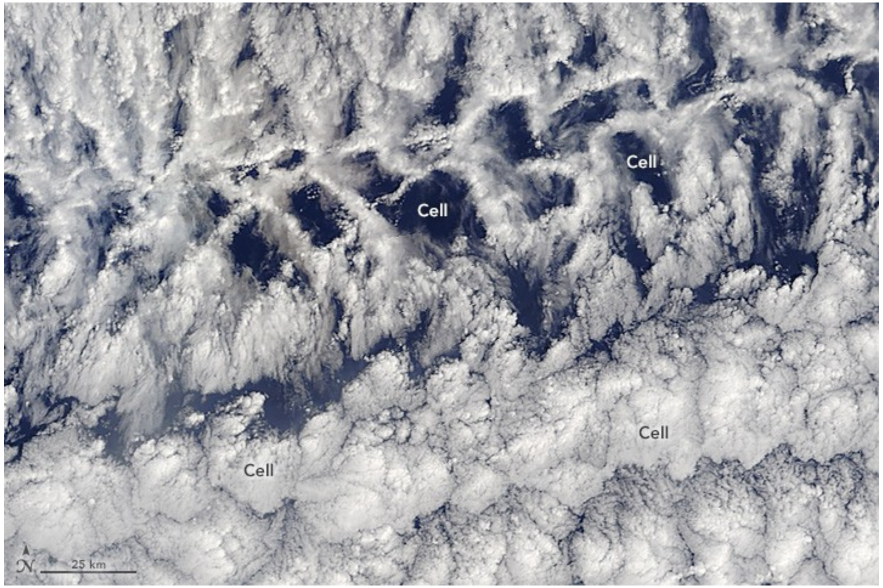
Sc morphology vs resolution:
Δx=5km Δz=50m



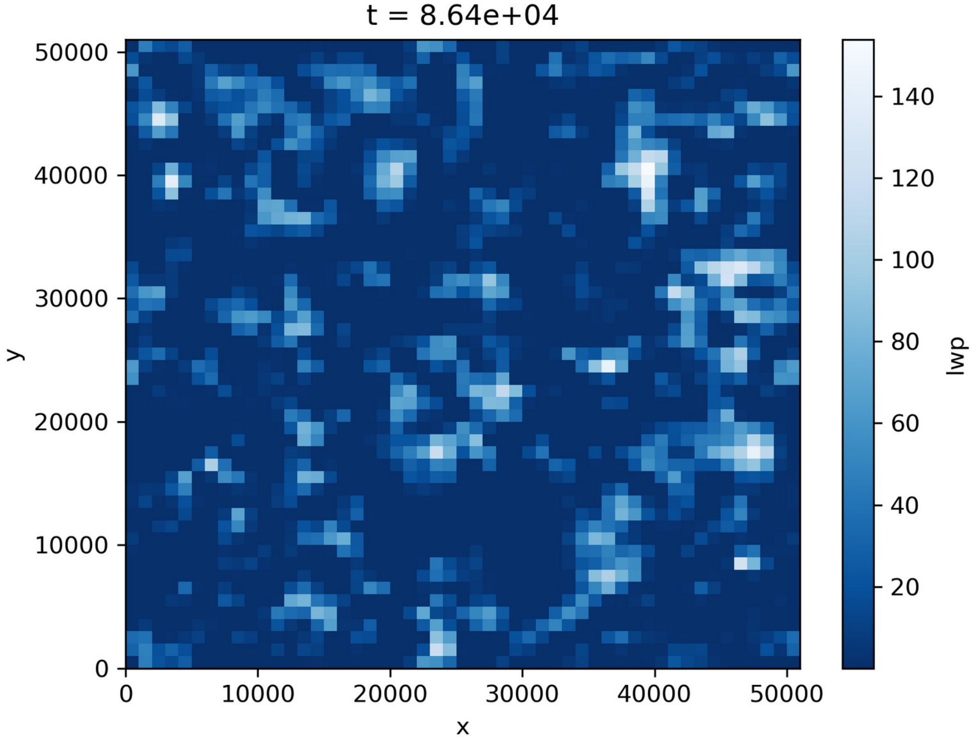


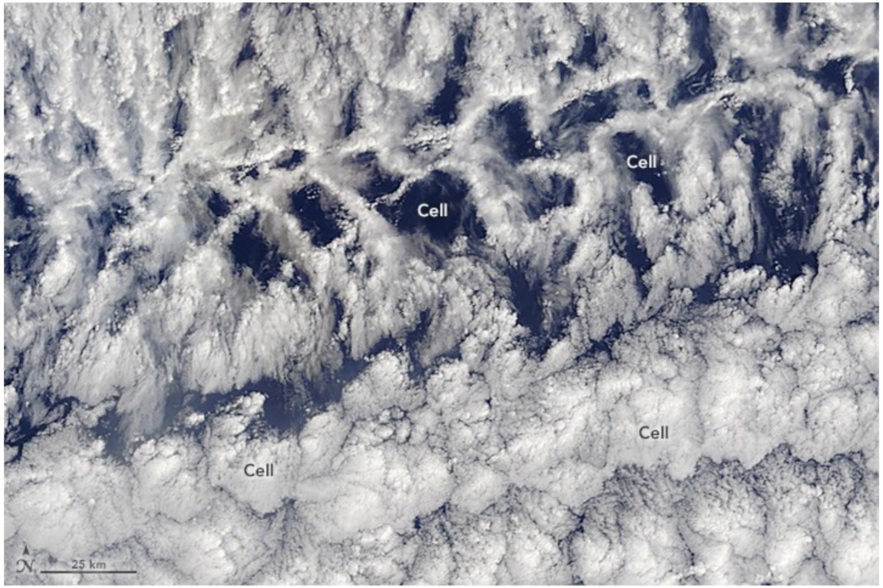
Sc morphology vs resolution: Δx=2km Δz=20m





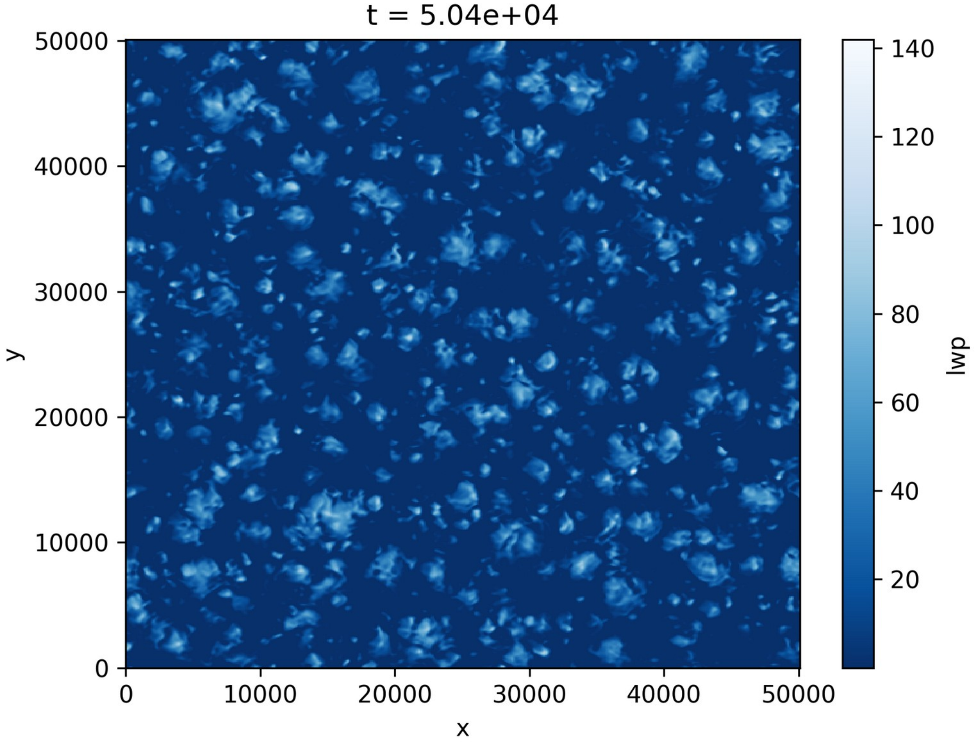
Sc morphology vs resolution:
Δx=1km Δz=20m

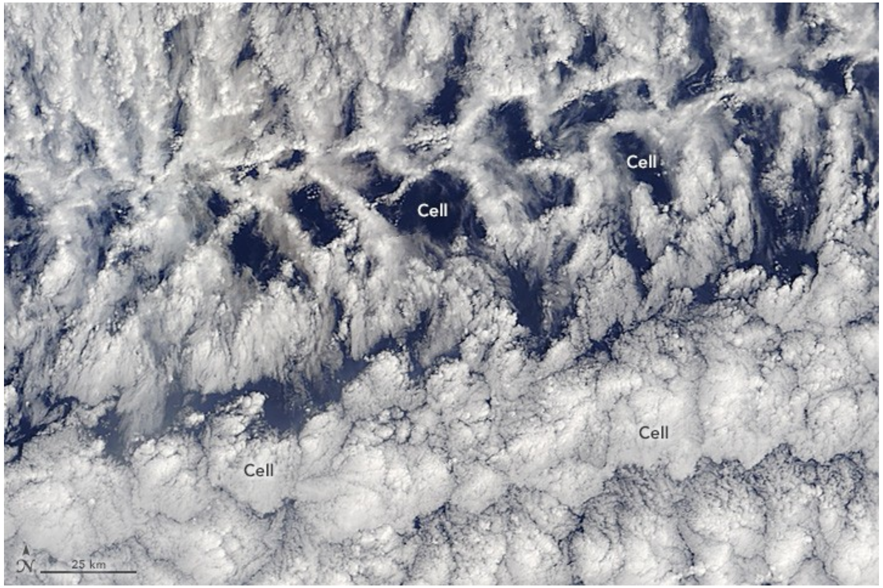




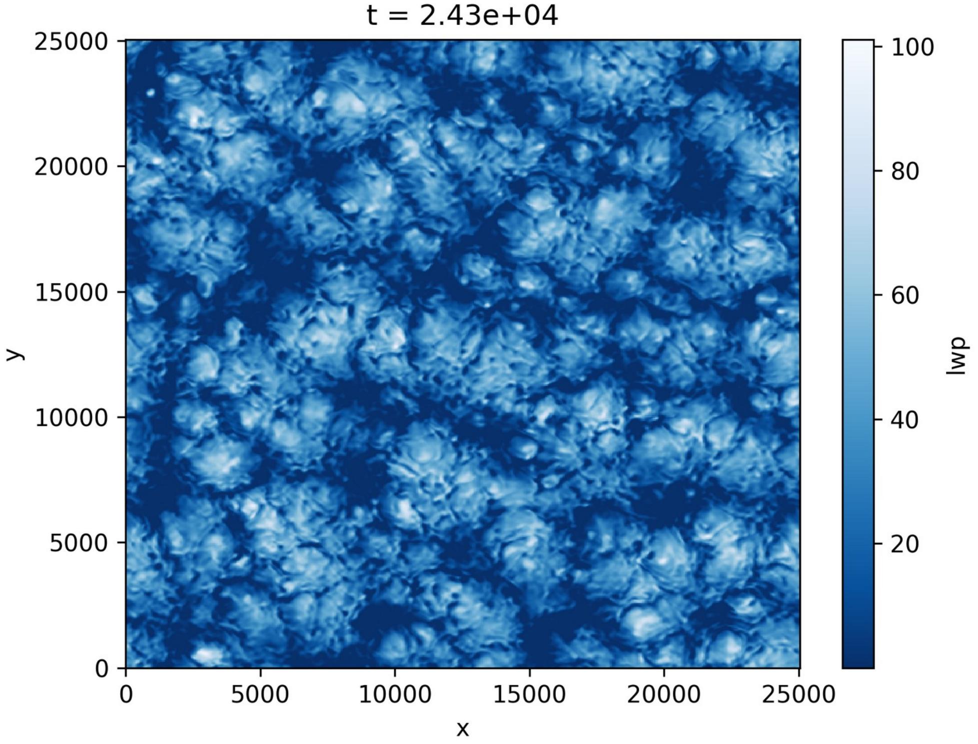
Sc morphology vs resolution:

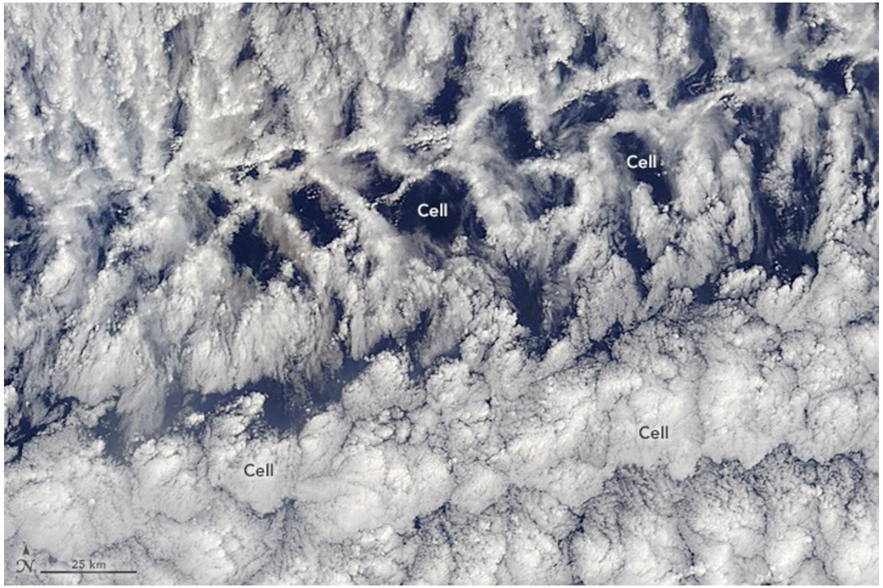
Δx=100m Δz=10m





Sc morphology vs resolution:
Δx=50m Δz=5m





Smagorinsky SGS turbulence model

isotropic

$$D_t \vec{v} = \ldots + \nabla \cdot (K \boldsymbol{E})$$

$$K \propto l |\boldsymbol{E}|$$

K – eddy viscosity

E – deformation tensor

l – length scale, e.g.:

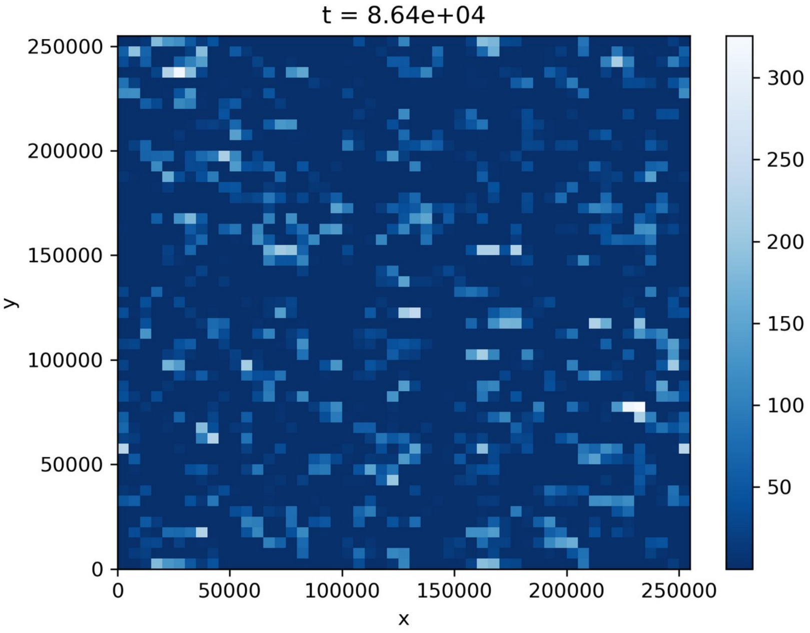
$$l = C (\Delta x \Delta y \Delta z)^{(1/3)}$$

anisotropic

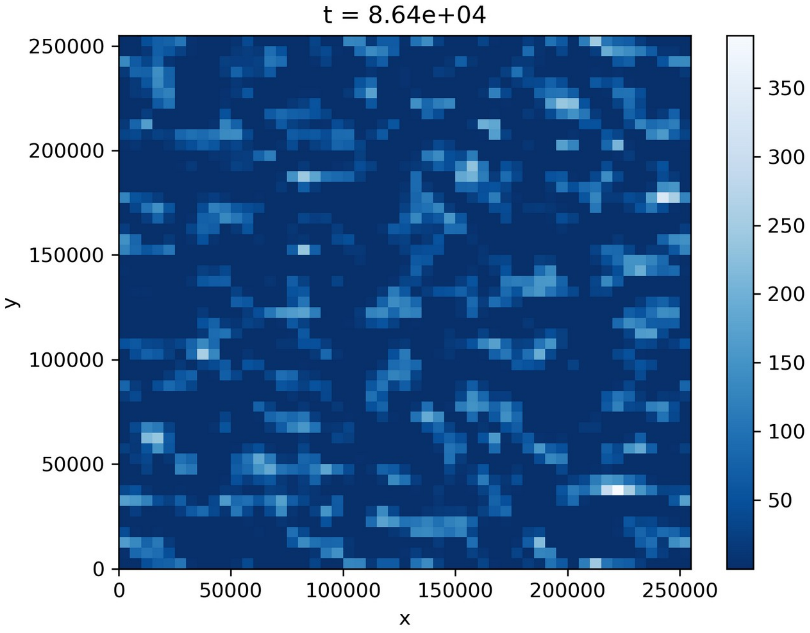
- Typically $\Delta z < \Delta x = \Delta y$
- $K_h \propto l_h |\boldsymbol{E}| \qquad K_v \propto l_v |\boldsymbol{E}|$?
- $K_h \propto l_v |\boldsymbol{E}| \qquad K_v \propto l_h |\boldsymbol{E}|$?
- Which K for which component of **E**?
- $\mathbf{E}_h$, $\mathbf{E}_v$?

Sc morphology vs turbulence model:
Δx=5km Δz=50m

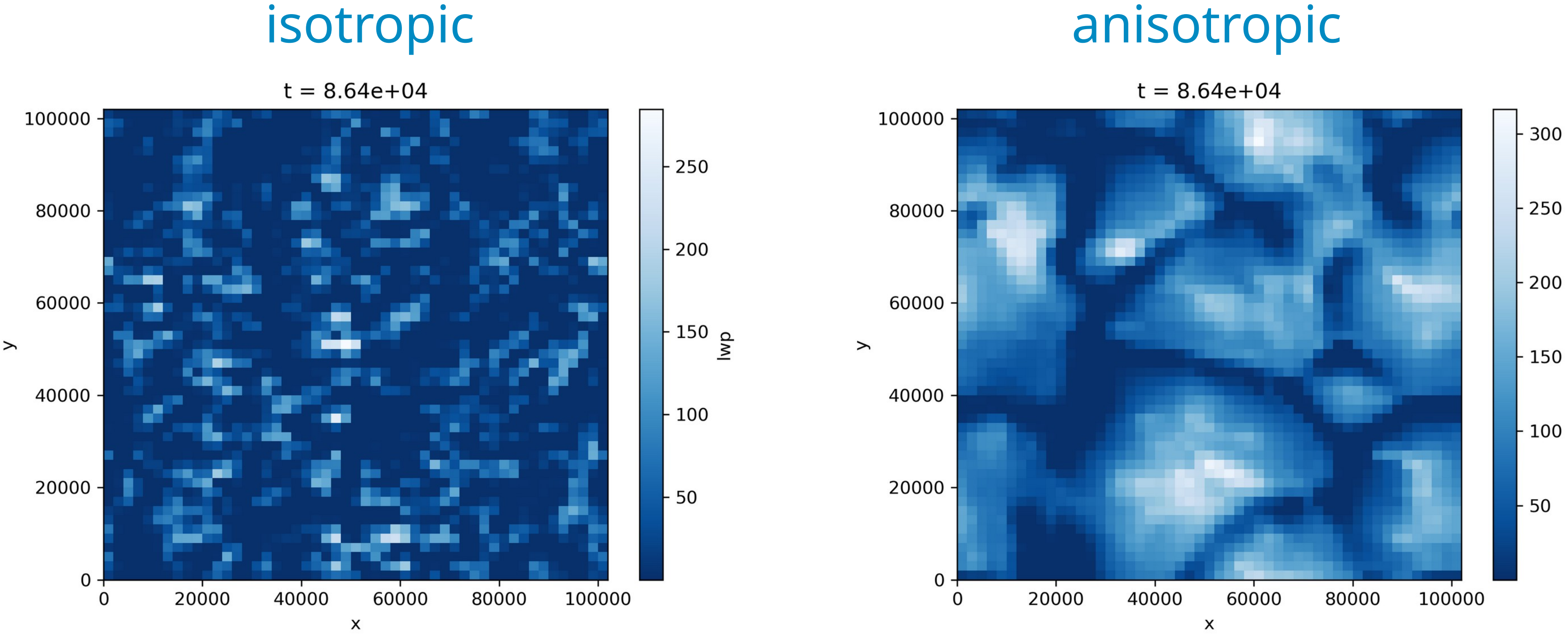
isotropic



anisotropic

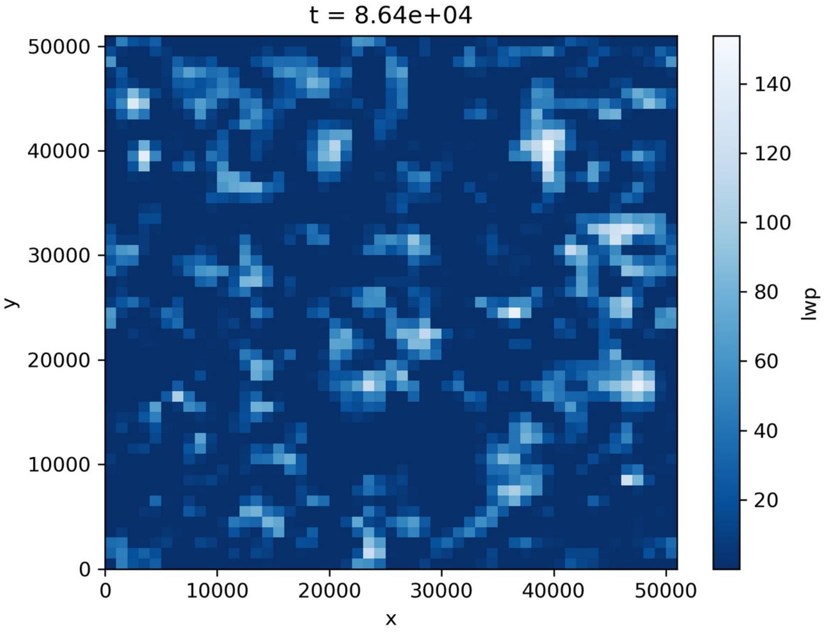


Sc morphology vs turbulence model: Δx=2km Δz=20m

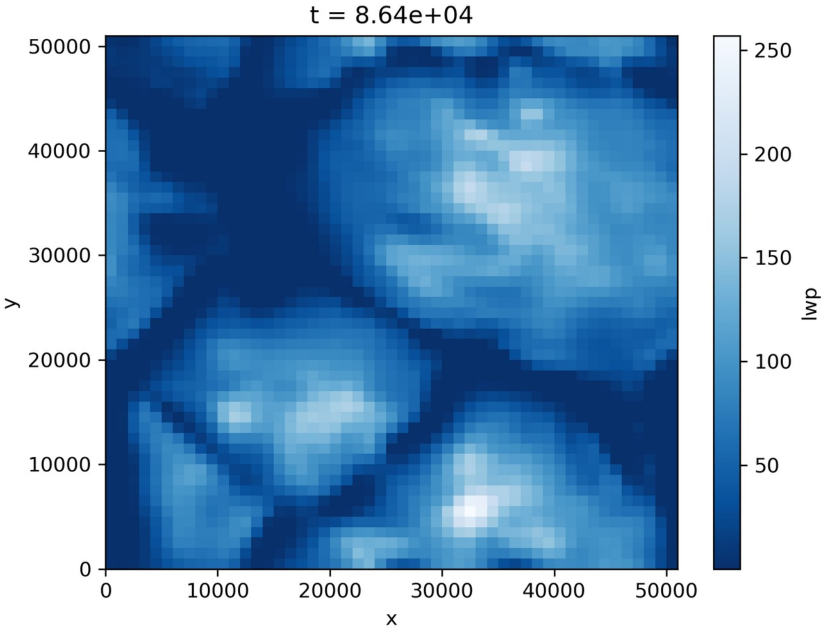


Sc morphology vs turbulence model:
Δx=1km Δz=20m

isotropic

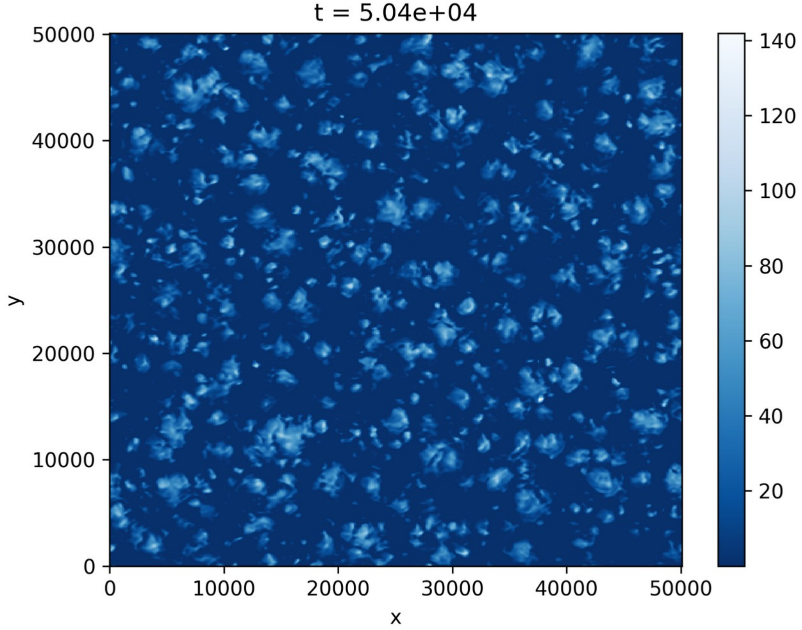


anisotropic

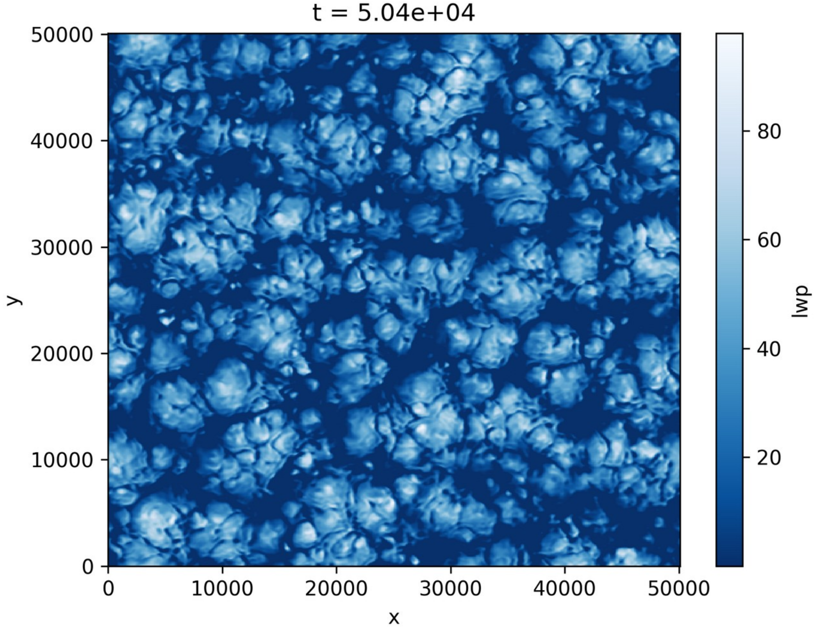


Sc morphology vs turbulence model: Δx=100m Δz=10m

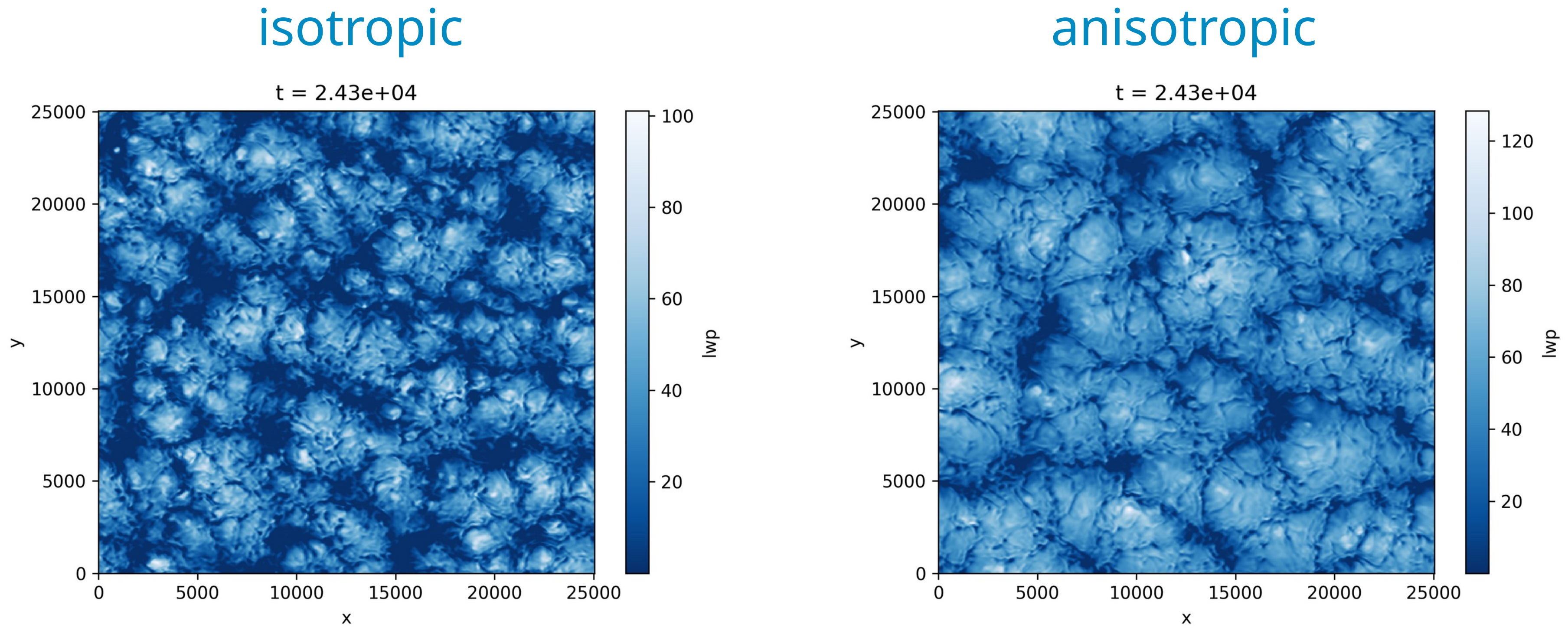
isotropic



anisotropic



Sc morphology vs turbulence model: Δx=50m Δz=5m



Conclusions / Opportunities

- Next generation climate models need new (simple) methods that would account for the effects of km-scale turbulence.
- Role of O(10m) turbulence in rain formation is an active area of research.