University of Warsaw Lagrangian Cloud Model (UWLCM): recent developments and future plans

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ZFA seminar 08.11.2024

Agenda

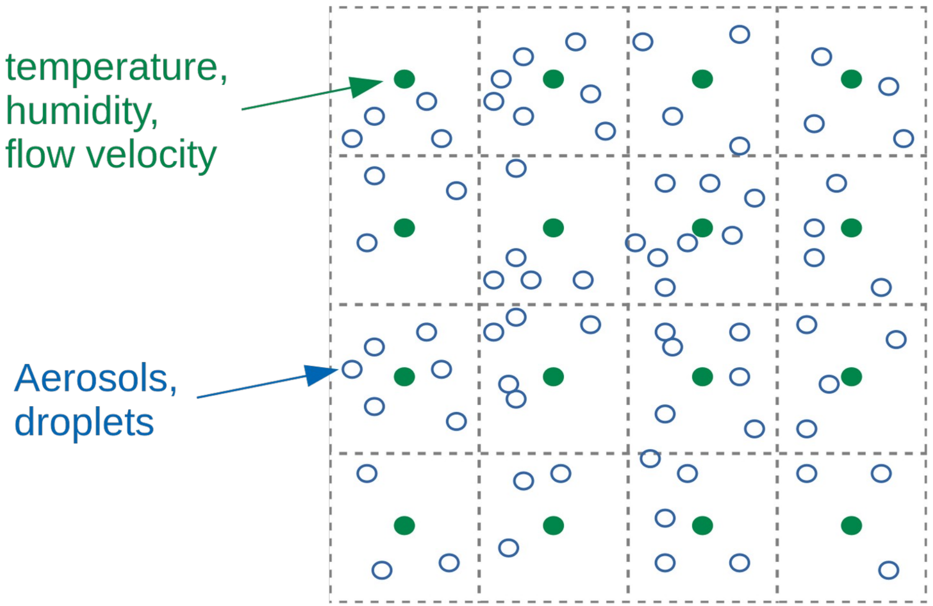
- UWLCM description
- Developments:
  - Anisotropic turbulence model and its application to Sc modeling
  - ~~Fractal reconstruction of unresolved scales~~
- Plans

University of Warsaw Lagrangian Cloud Model

Model overview

- Numerical model of clouds developed at IGF with a focus on detailed modeling of microphysics
- Large eddy simulation (LES) approach
- Resolution from centimeters to hundreds of meters
- Soundproof (anelastic) equations
- Super-droplet (and bulk) microphysics
- MPDATA advection algorithm
- SGS turbulence: Smagorinsky or ILES

Lagrangian particles (aerosols, droplets) in an Eulerian grid (thermodynamic fields)



Numerics

- Written in C++
- Simultaneous use of CPUs and GPUs
- OpenMP + MPI parallelization
- HDF5 output, ready for Paraview visualization and Xarray analysis
- Singularity container with dependencies makes it easy to run
- Most simulations are done on clusters at AGH Cyfronet
- Open source (github.com/igfuw/UWLCM)
- Automated tests

Available modeling cases

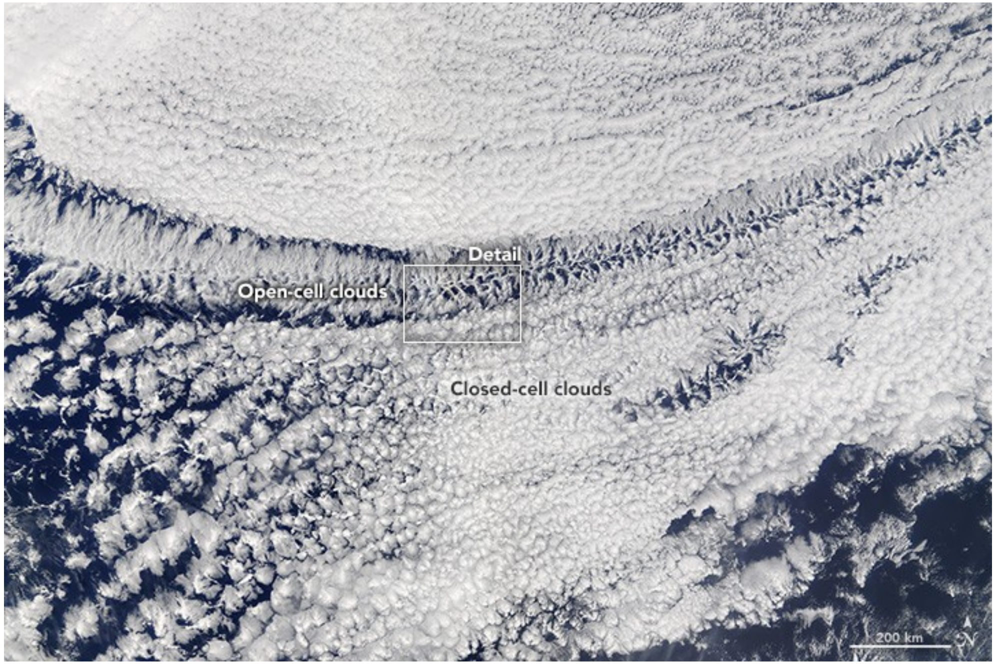
- Marine stratocumulus (Dycoms RF01 and RF02)
- Marine cumulus (BOMEX, RICO)
- Cumulus congestus
- Thermal
- Dry PBL
- Cloud chamber

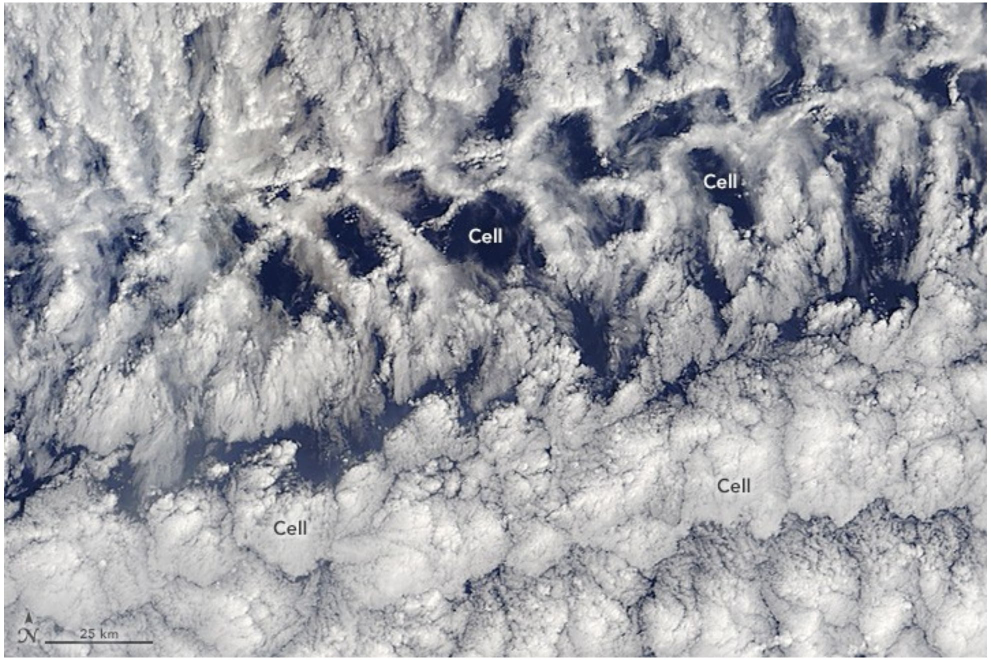
Anisotropic SGS turbulence model and low clouds in climate models

Motivation – 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 important for global albedo.
- In SRMs, Sc:
  - are susceptible to turbulence parameterisations (Nowak et al. 2024),
  - have wrong morphology (Fons et al. 2024),
  - drizzle too much (Fons et al. 2024).

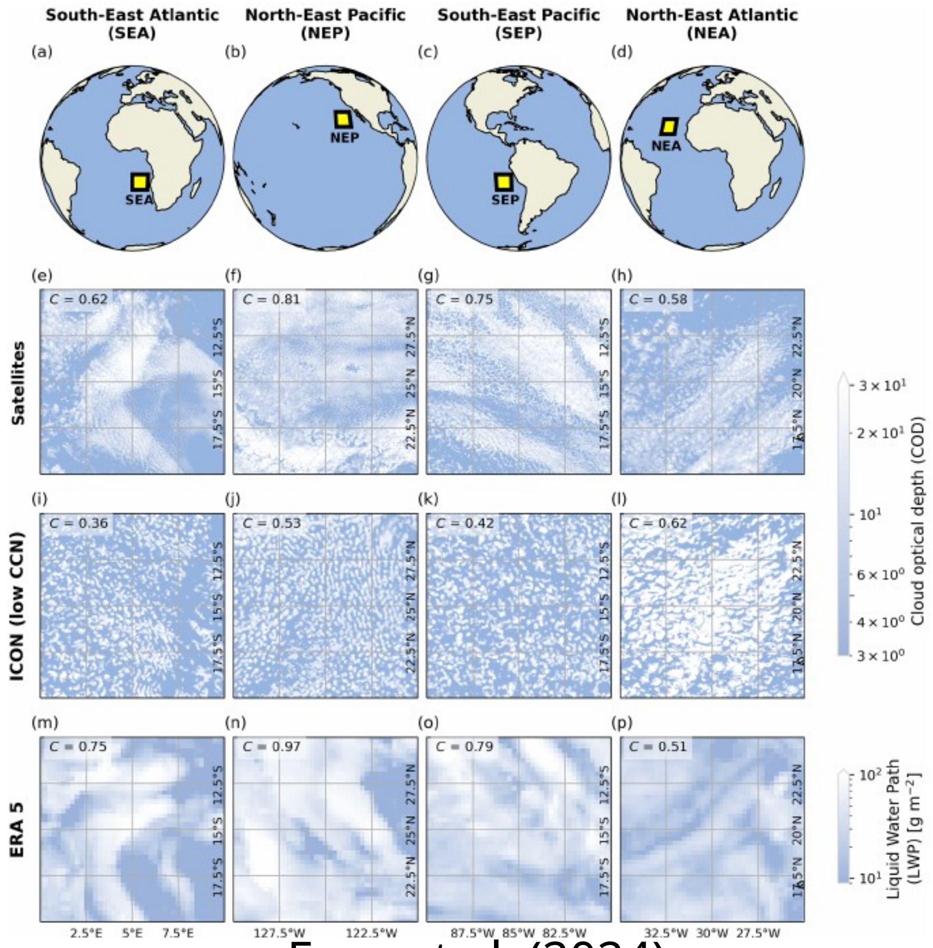
Sc morphology





https://earthobservatory.nasa.gov/images/87456/open-and-closed-cells-over-the-pacific

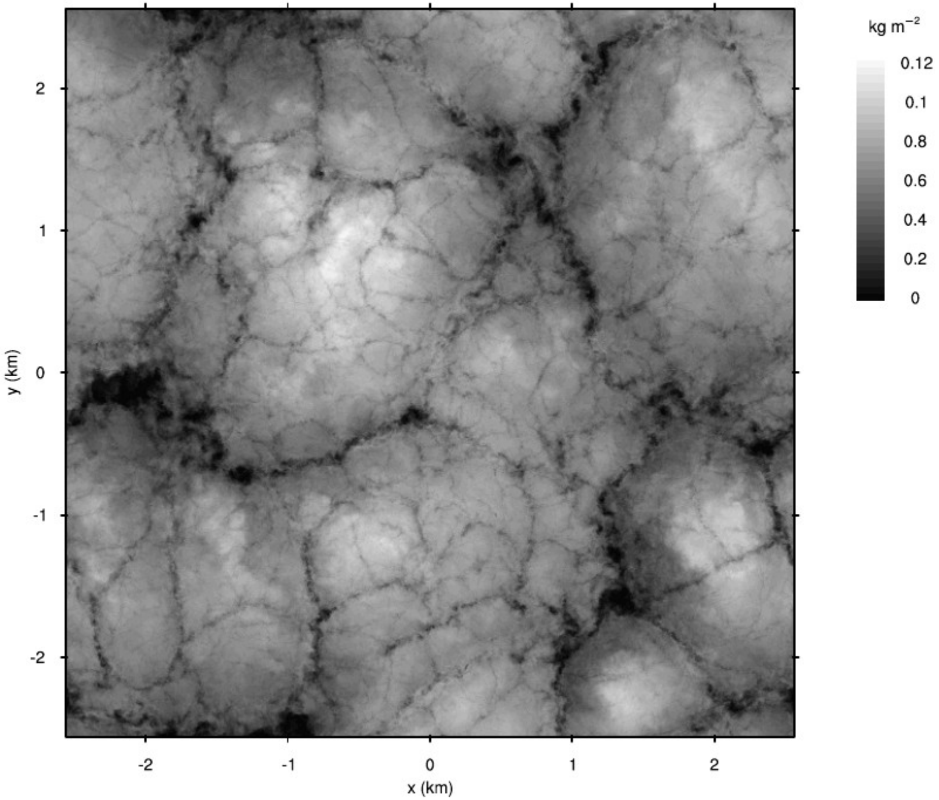
Sc morphology – models vs satellites



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)

Can models get Sc morphology right?

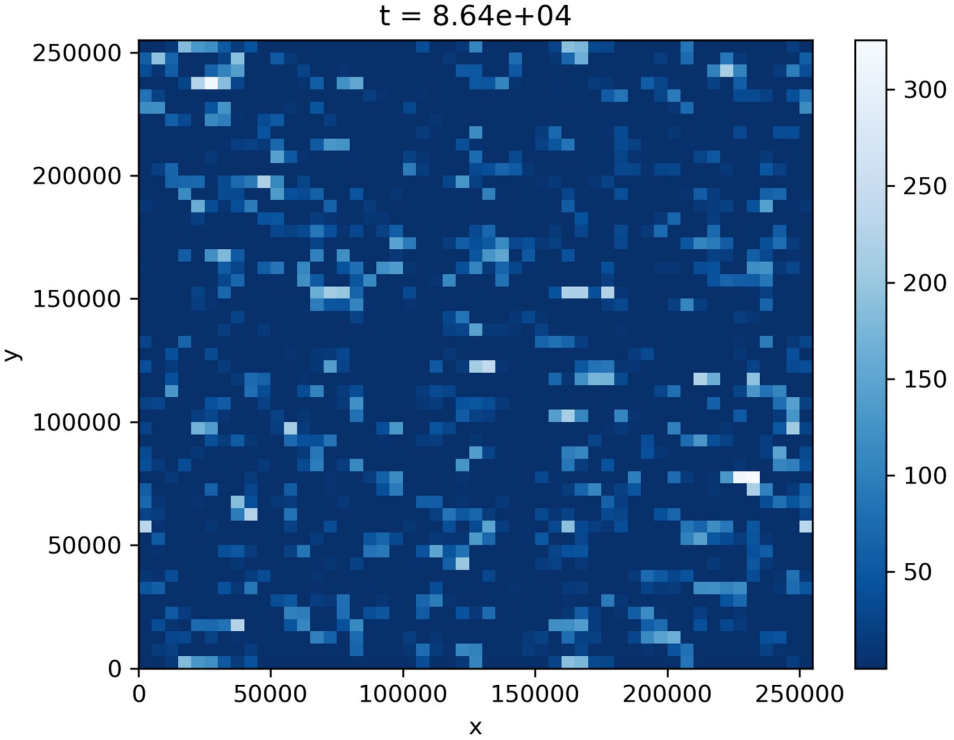


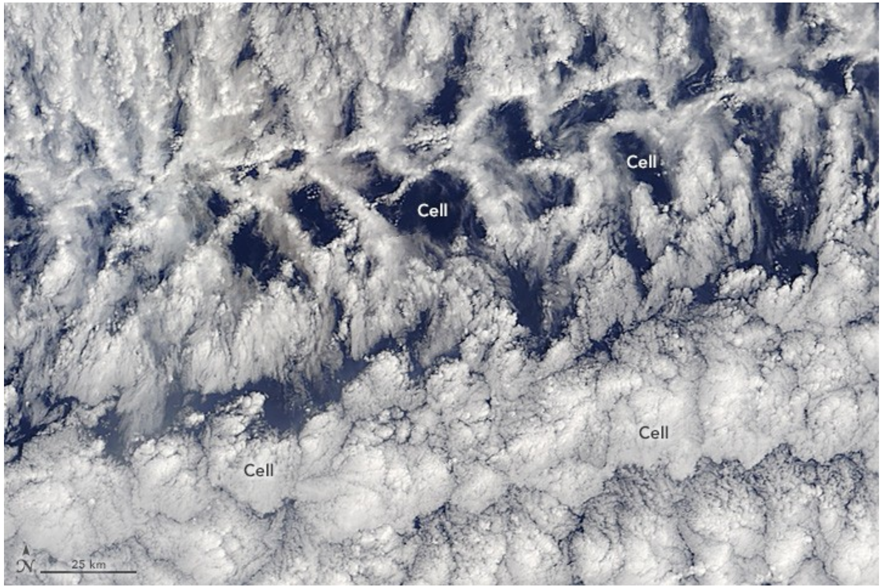
LES with ~1m resolution (Matheou 2018)

Strategy to use LES to improve Sc representation in SRMs

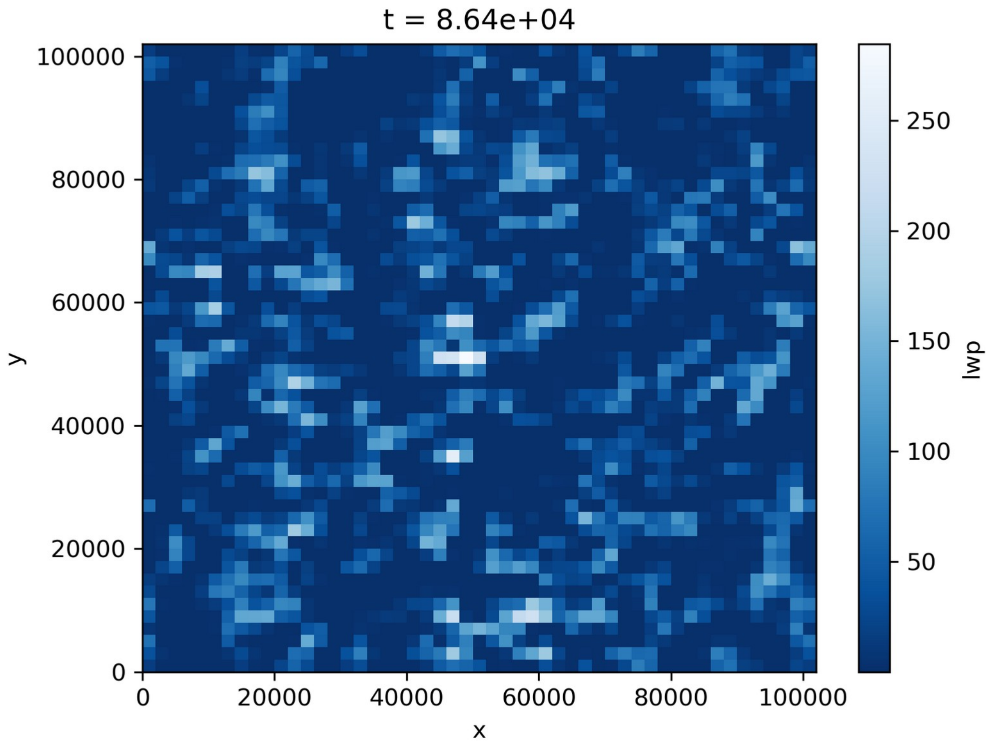
- Use UWLCM to model Sc in idealized conditions at resolutions typical for SRMs
- Test different SGS turbulence models: isotropic Smagorinsky vs anisotropic Smagorinsky (several types)
- Vary horizontal resolution (to see how scale-aware SGS turbulence models are)
- Caveats:
  - LWP is highly sensitive to resolution
  - Anisotropic cells help better represent Sc (Pedersen et al. 2018) → vertical reslution also needs to be changed

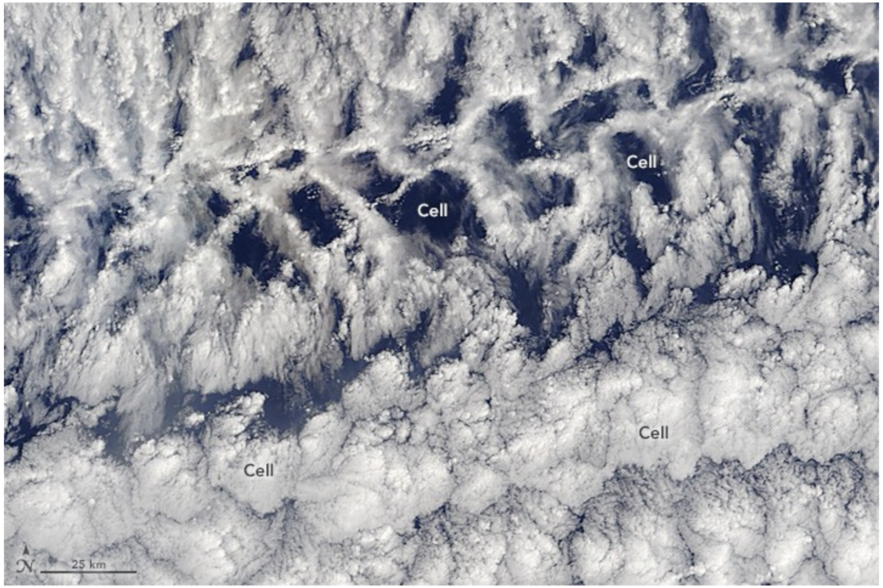
Sc morphology vs resolution:
Δx=5km Δz=50m





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





Sc morphology vs resolution:
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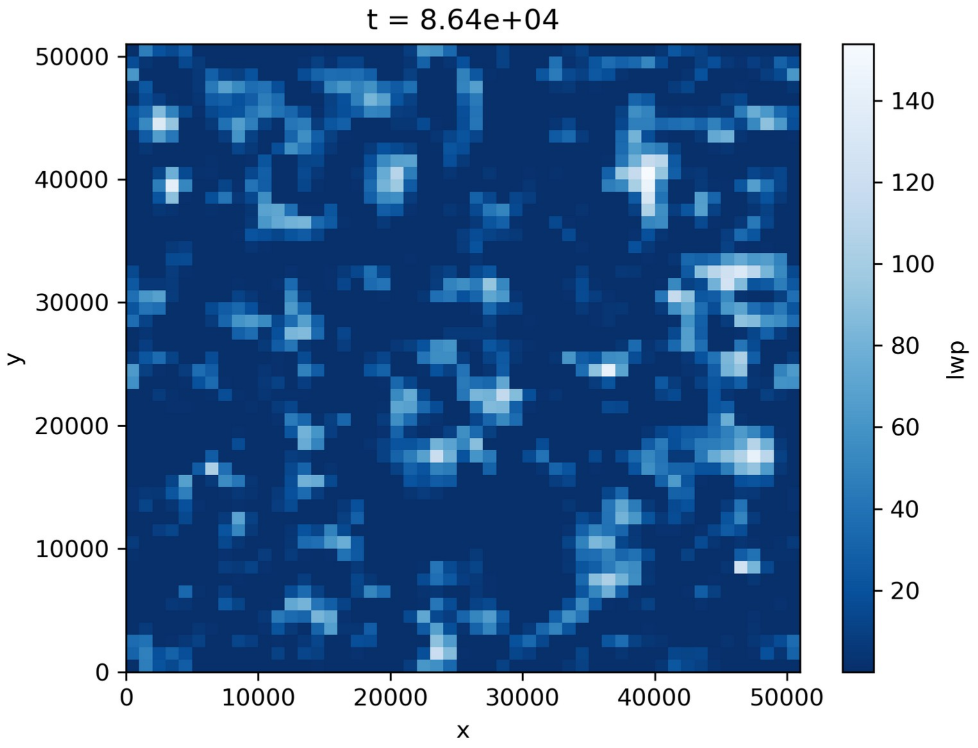
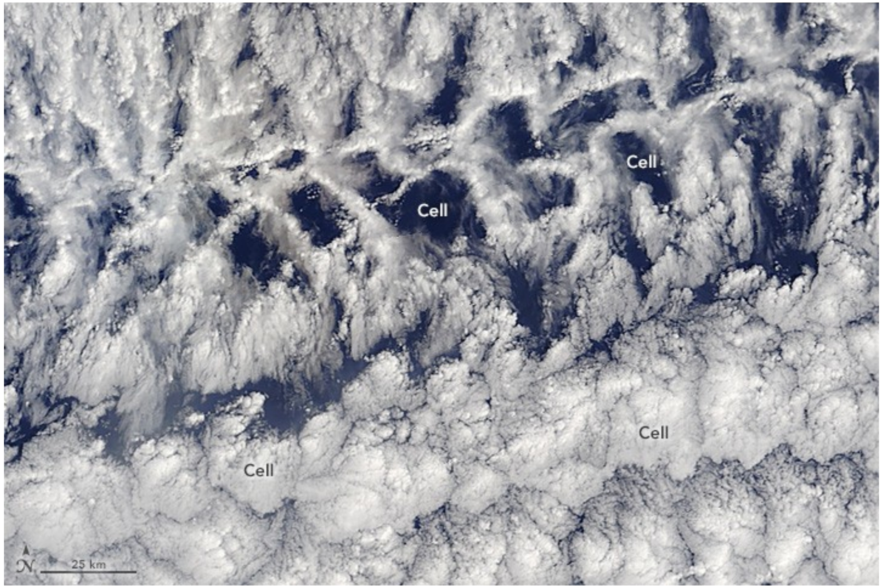
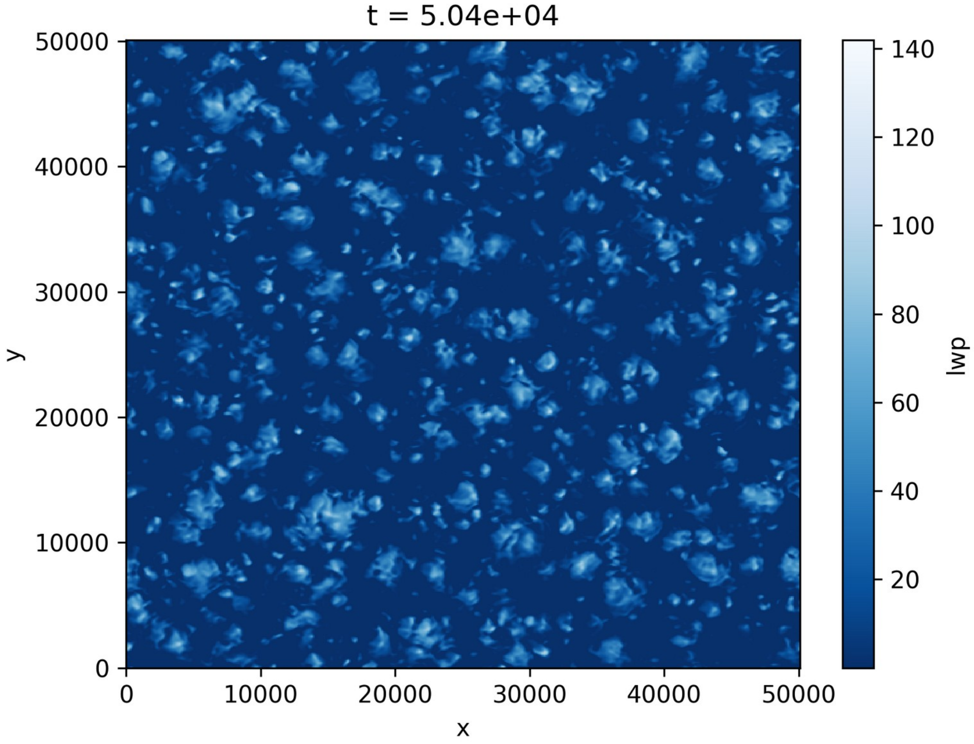
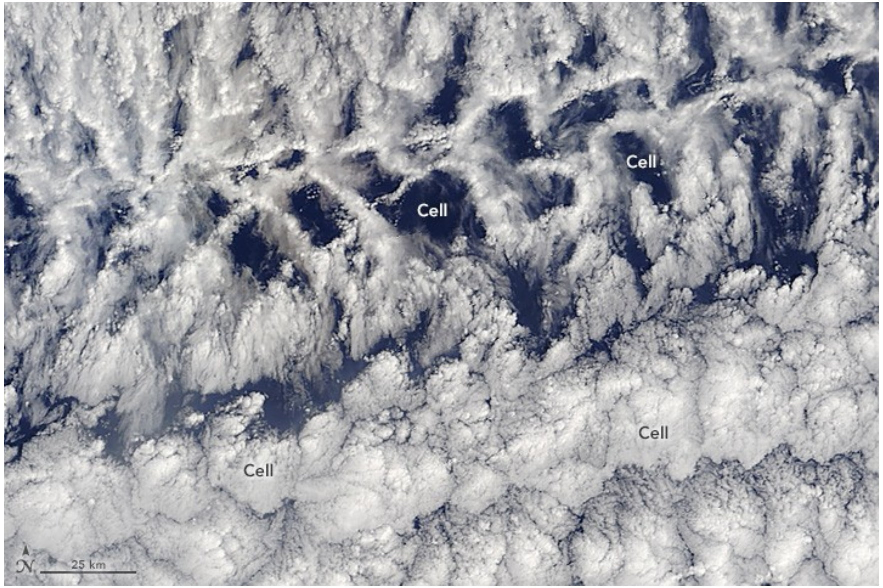


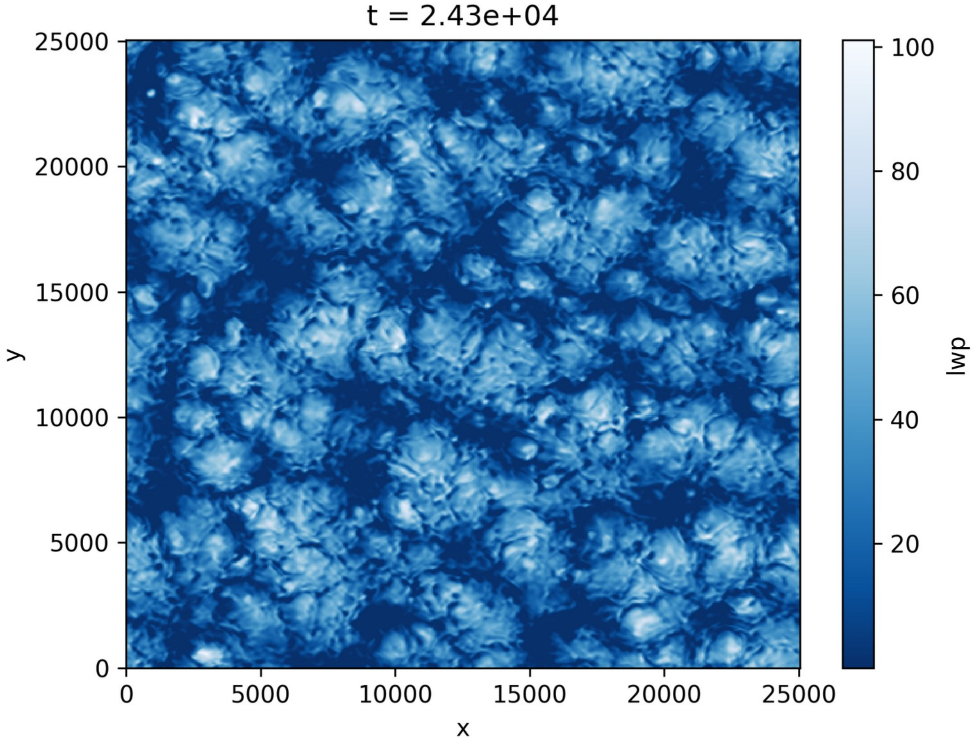


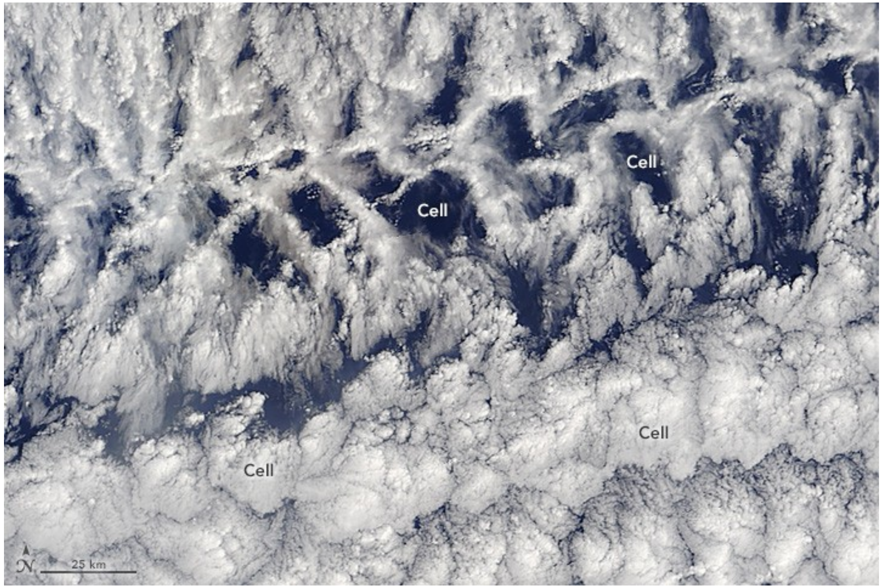
Sc morphology vs resolution:
Δx=100m Δz=10m





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





Smagorinsky 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.:

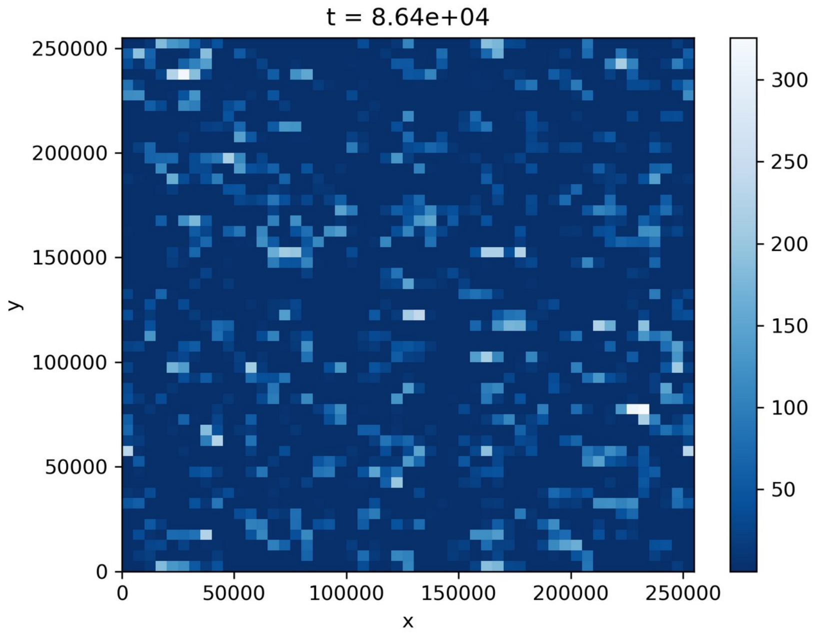
$$l = C(\Delta x \Delta y \Delta z)^{(1/3)}$$

anisotropic

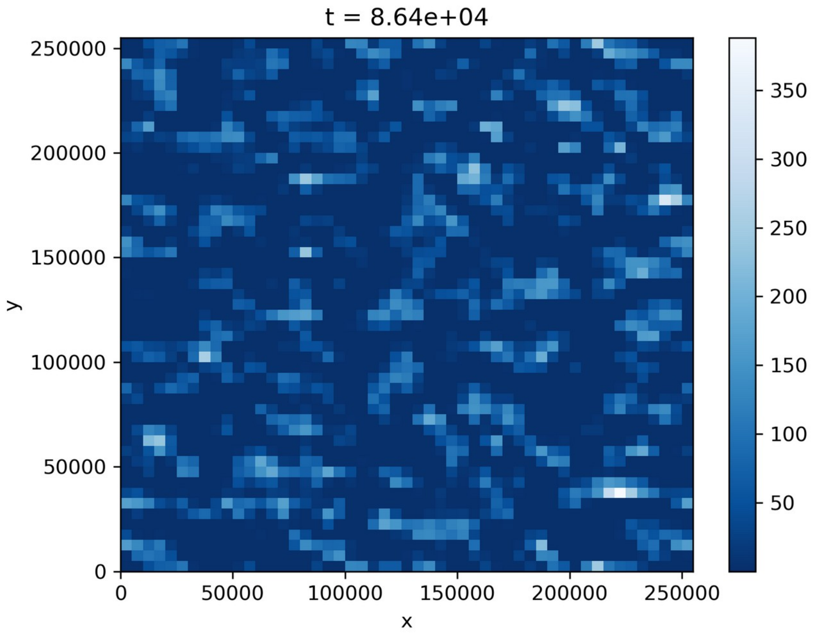
- Typically $\Delta z < \Delta x = \Delta y$
- $K_h \propto l_h |\boldsymbol{E}| \quad K_v \propto l_v |\boldsymbol{E}|$?
- $K_h \propto l_v |\boldsymbol{E}| \quad K_v \propto l_h |\boldsymbol{E}|$?
- Which K for which component of **E**?
- $\boldsymbol{E}_h$, $\boldsymbol{E}_v$?

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

isotropic

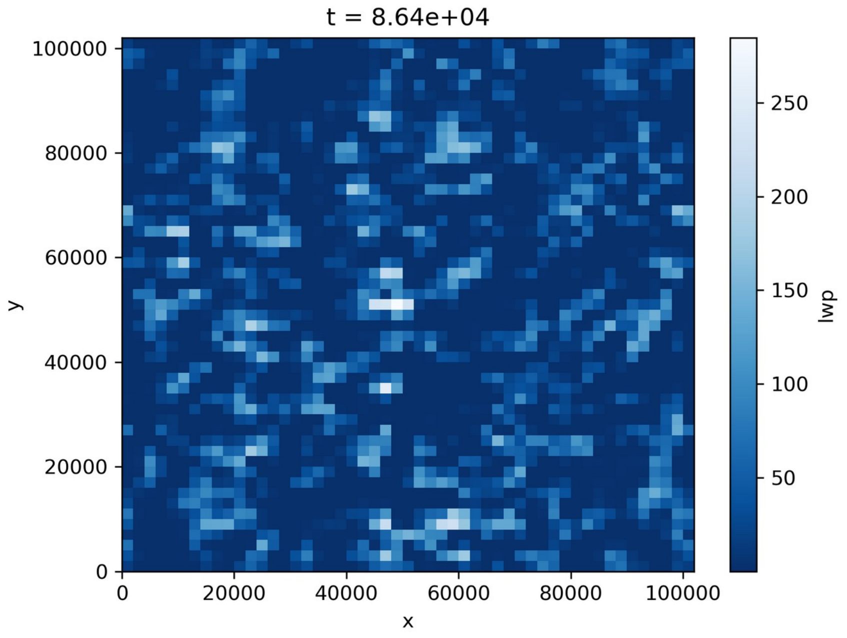


anisotropic

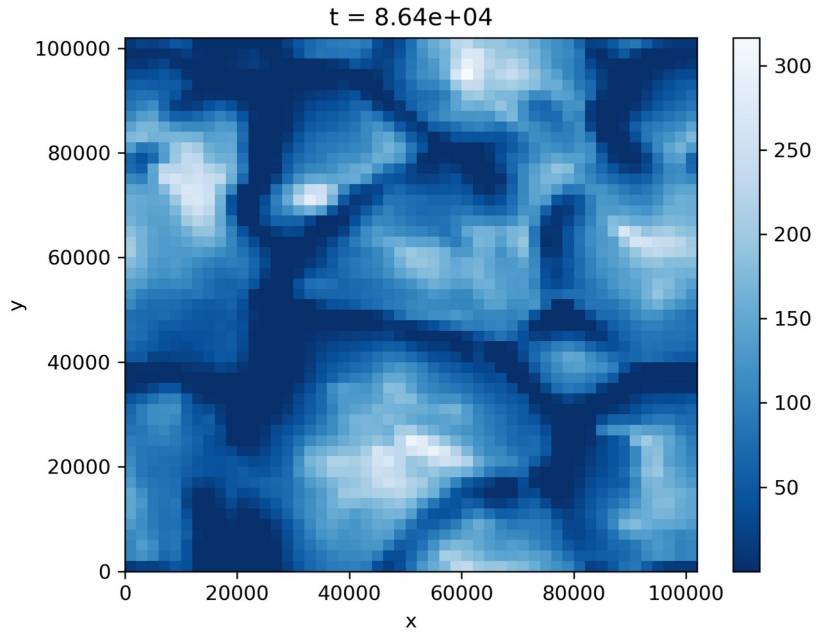


Sc morphology vs turbulence model: Δx=2km Δz=20m

isotropic

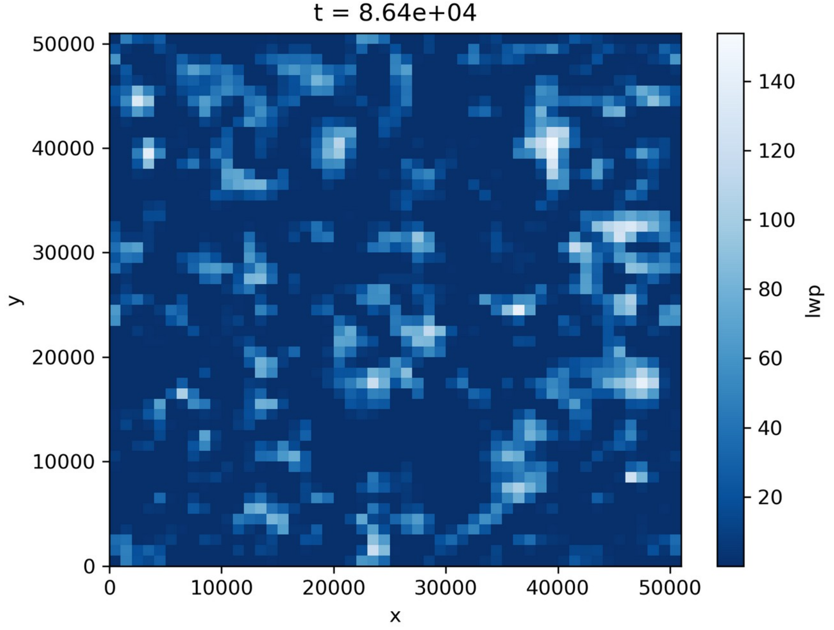


anisotropic

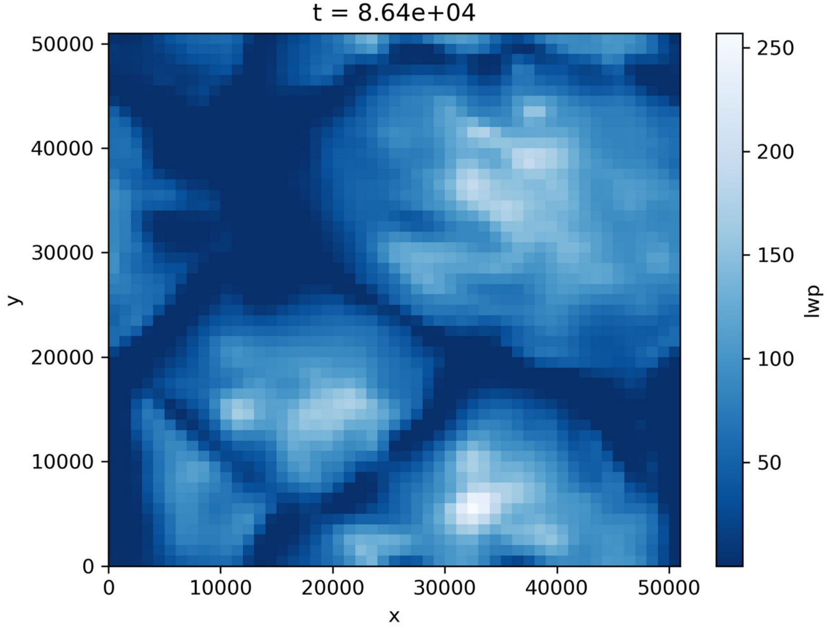


Sc morphology vs turbulence model:
Δx=1km Δz=20m

isotropic

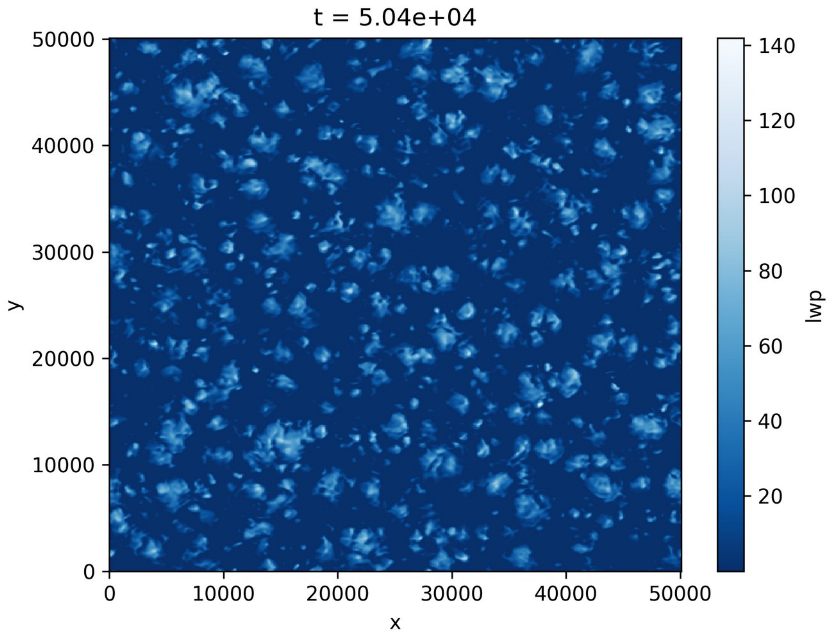


anisotropic

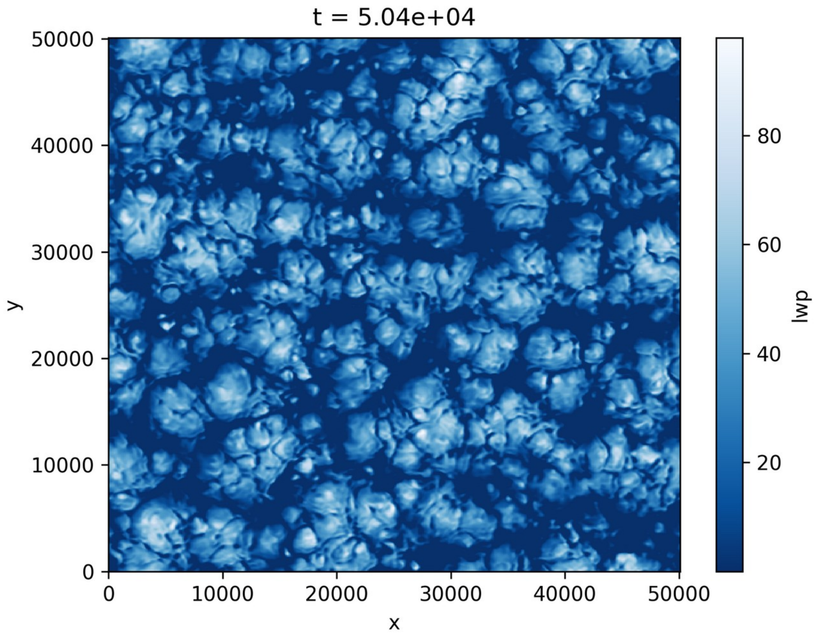


Sc morphology vs turbulence model: Δx=100m Δz=10m

isotropic

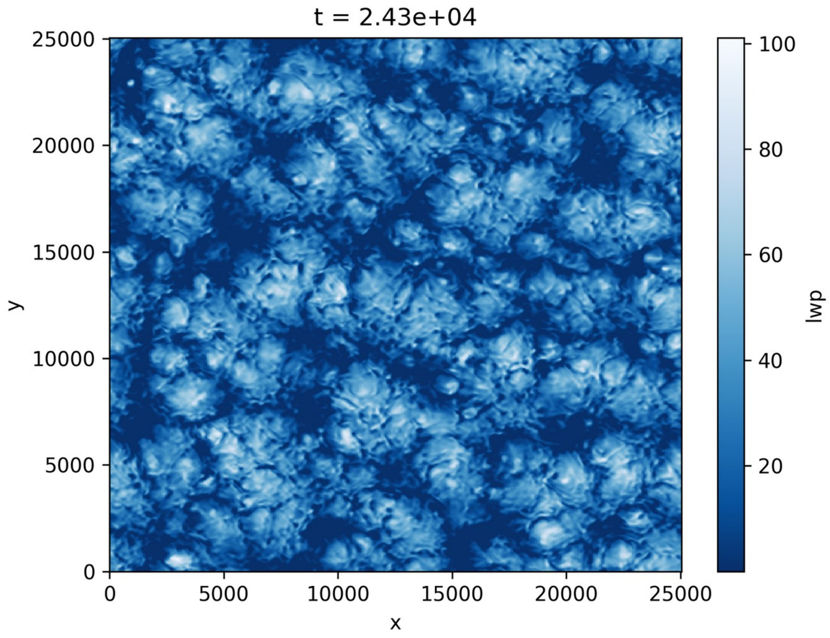


anisotropic

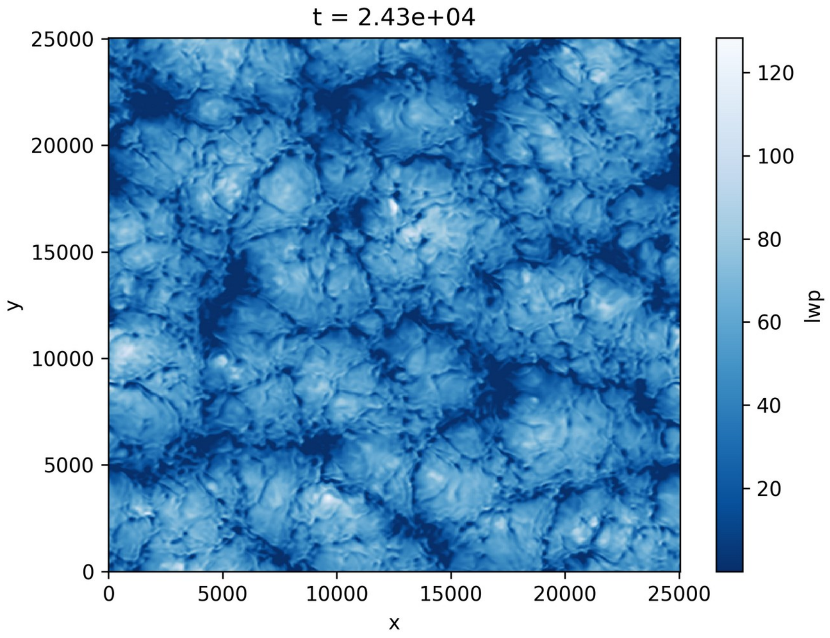


Sc morphology vs turbulence model: Δx=50m Δz=5m

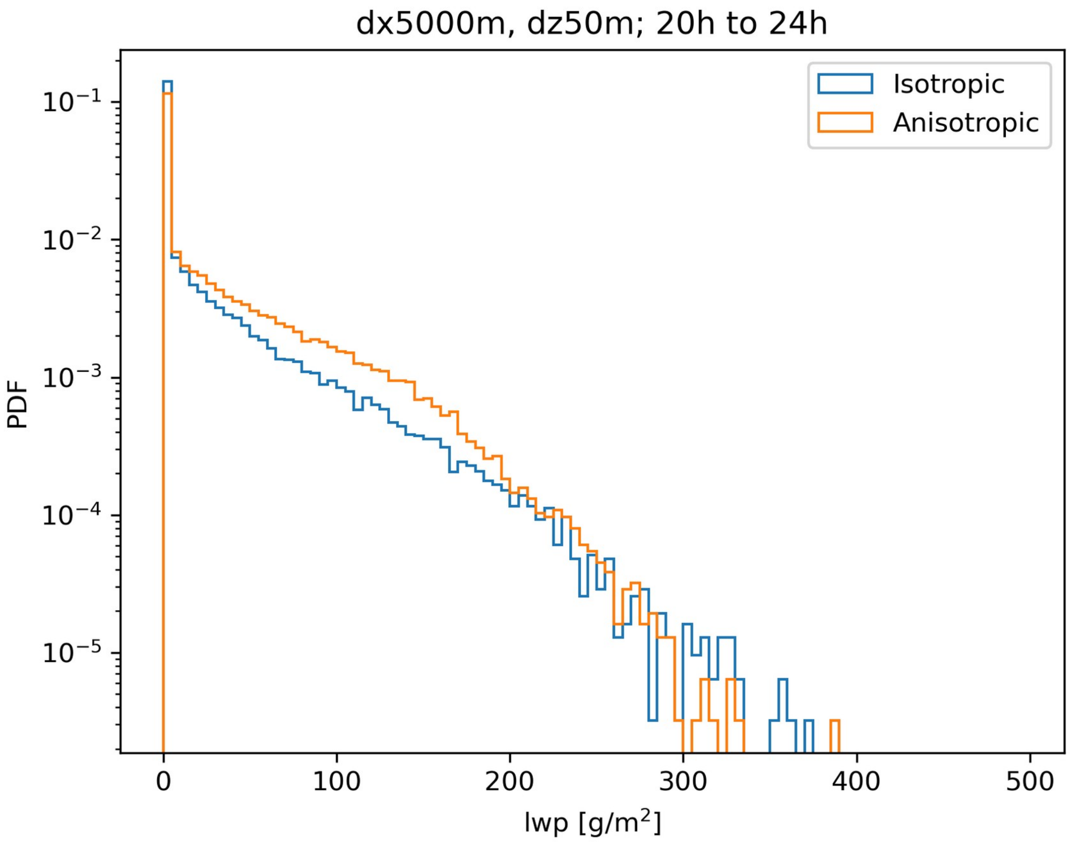
isotropic



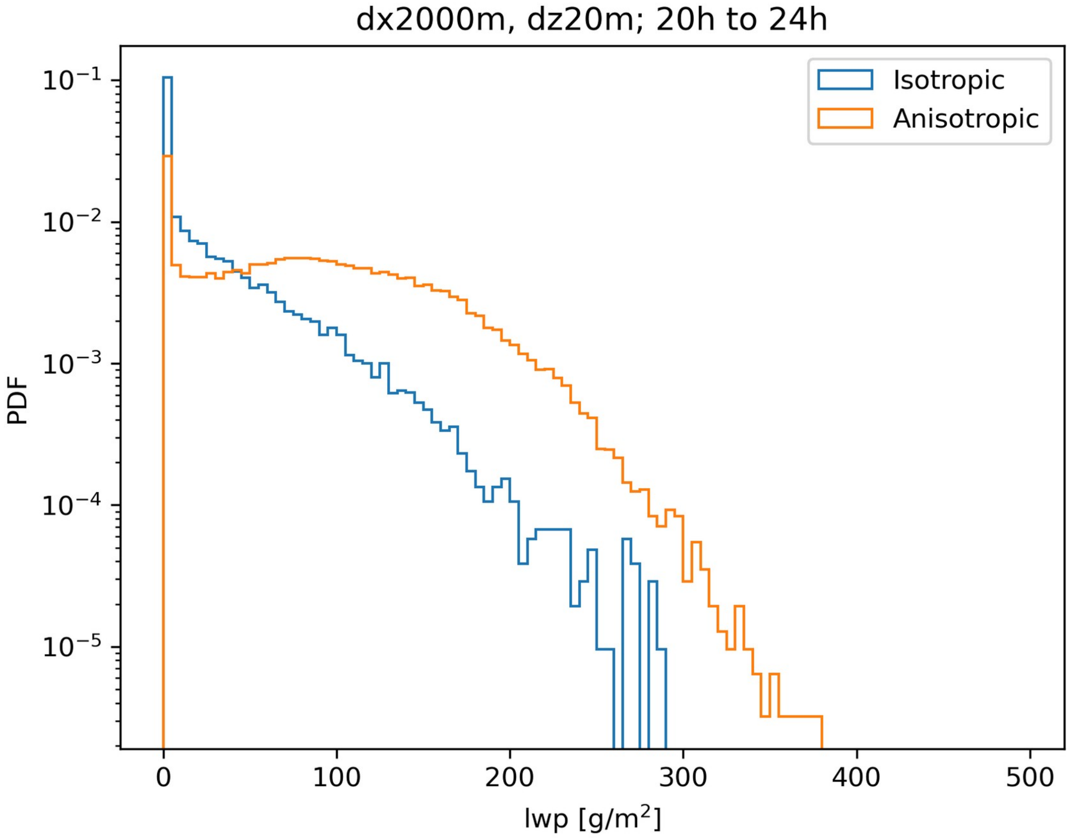
anisotropic



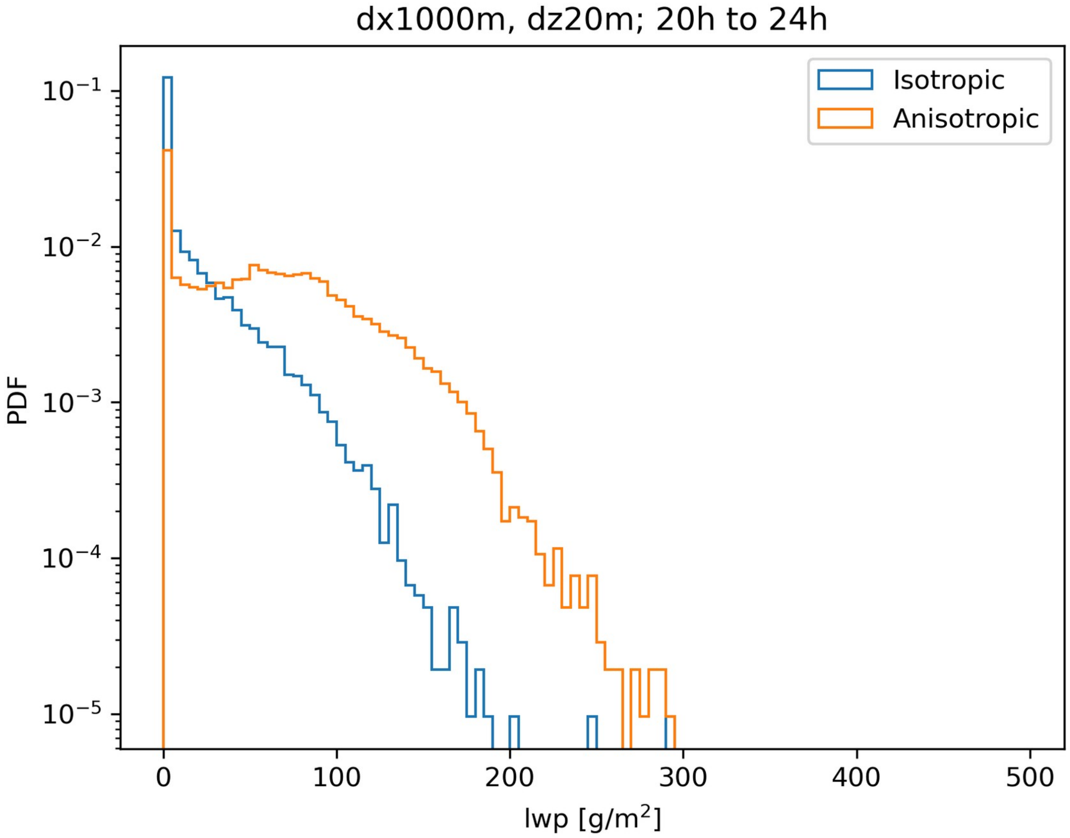
LWP histogram: Δx=5km Δz=50m



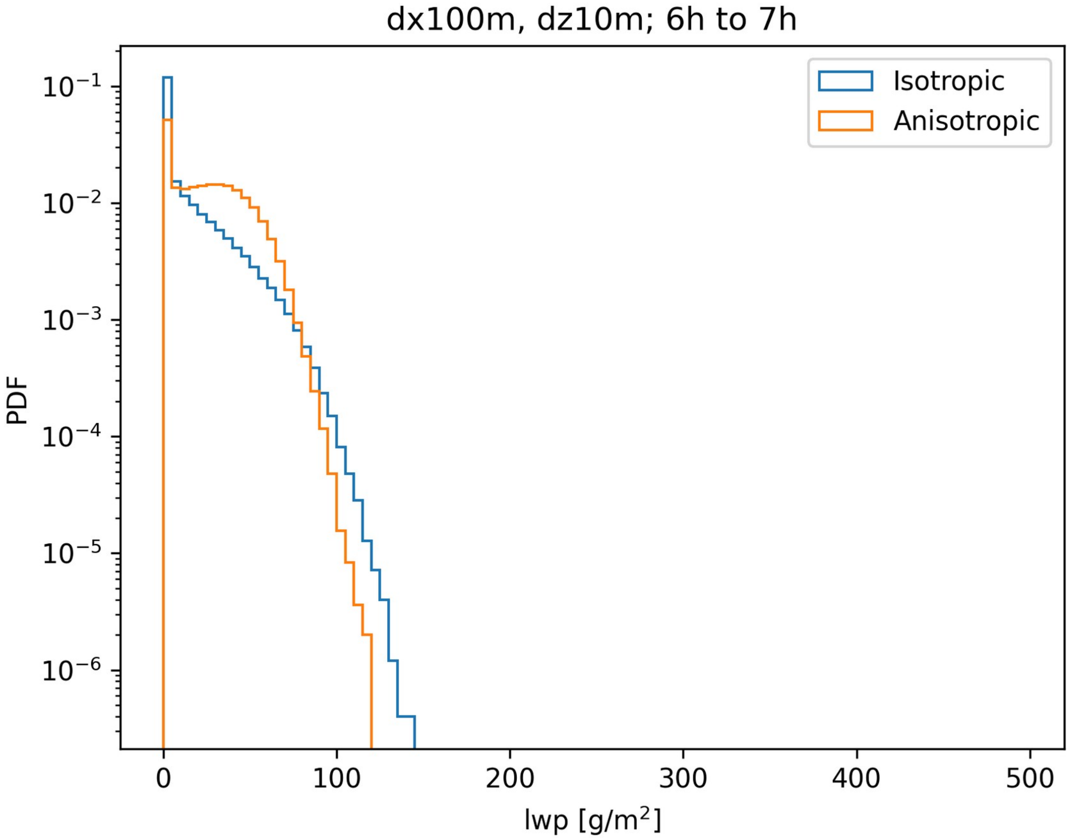
LWP histogram: Δx=2km Δz=20m



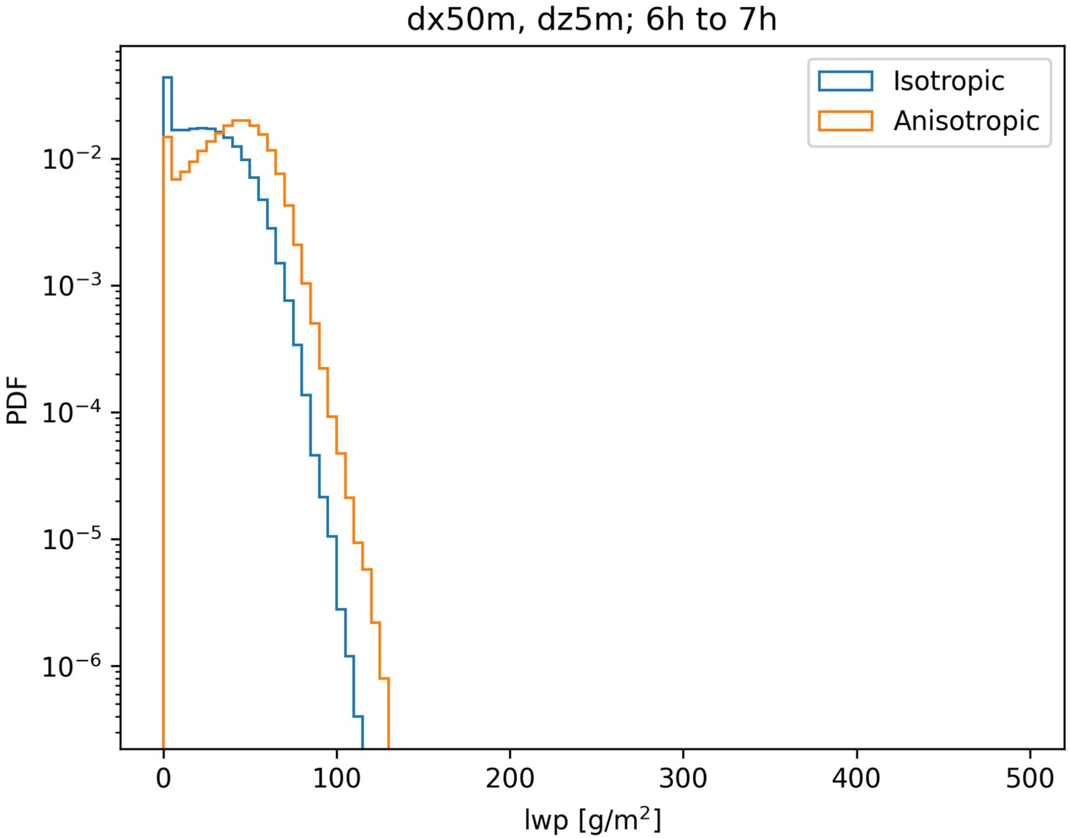
LWP histogram: **Δ**x=1km **Δz**=20m



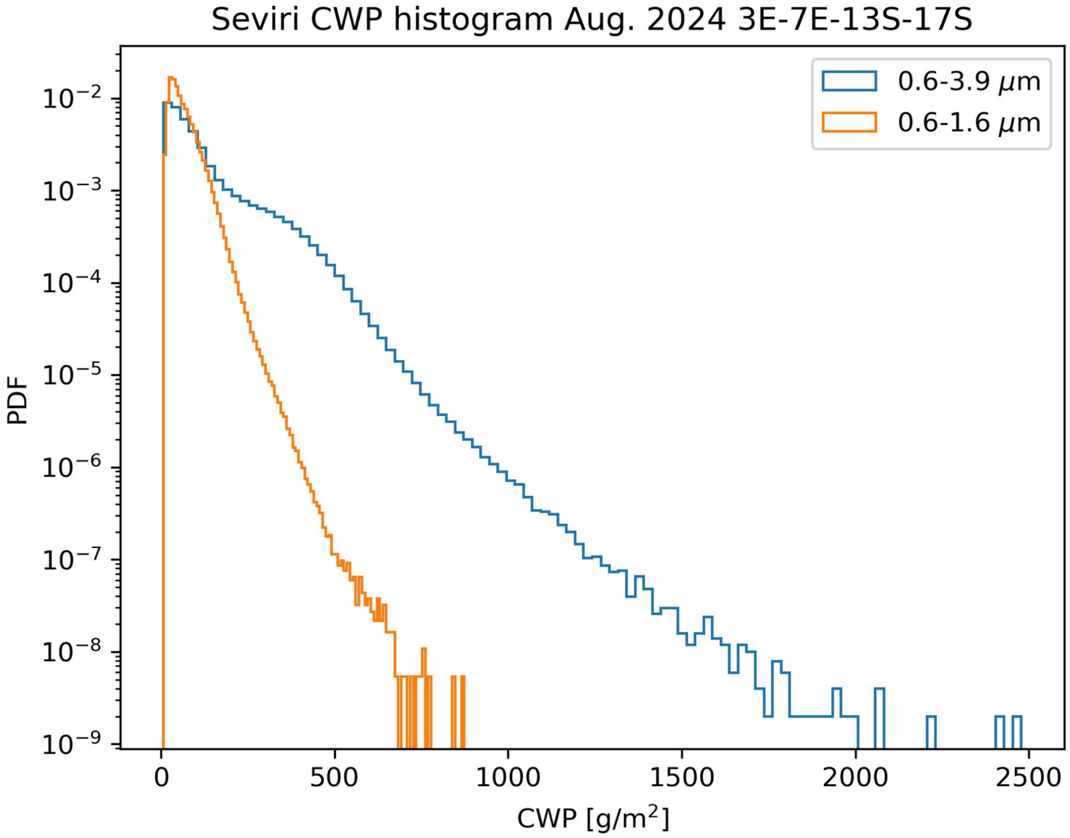
LWP histogram: Δx=100m Δz=10m



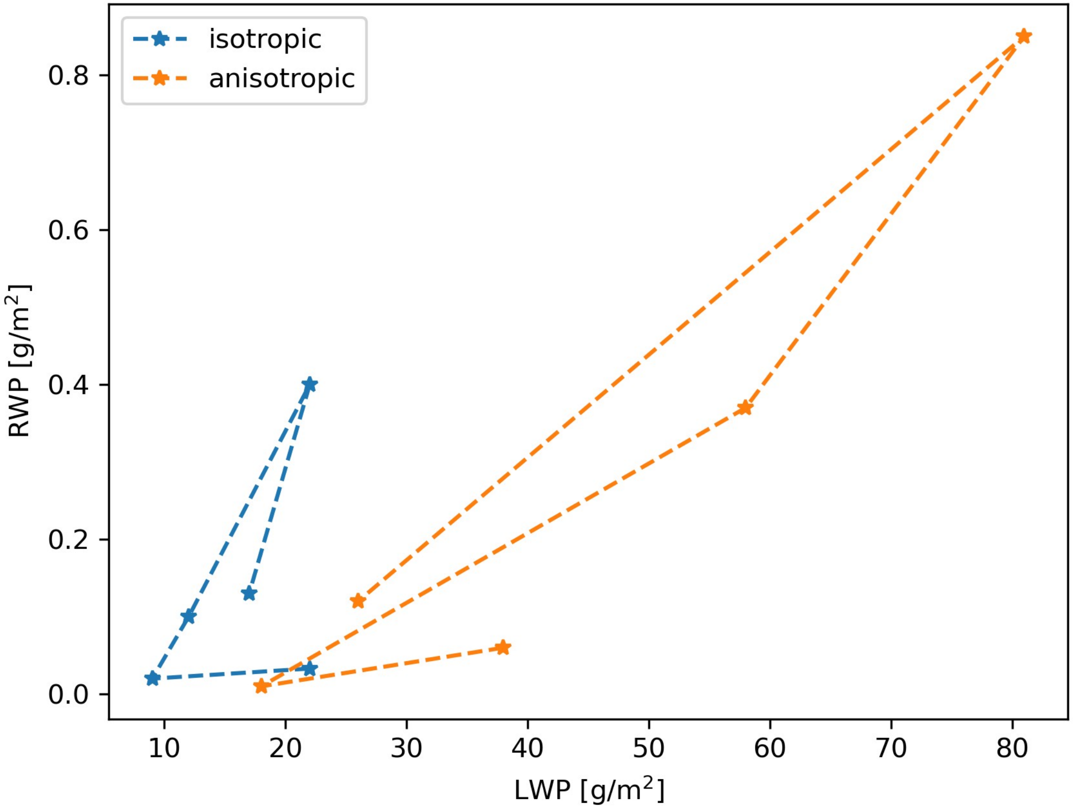
LWP histogram: Δx=50m Δz=5m



LWP histogram: satellites



Turbulence model and precipitation



Tentative conclusions

- Replacing isotropic Smagorinsky with anisotropic at grey-zone resolutions gives:
  - more uniform Sc cloud field (more realistic?)
  - less drizzle (helps with positive bias)
  - higher LWP
  - comes at no computational cost.

Plans

Ice microphysics

- Agnieszka Makulska is working on:
  - Implementing ice in bulk microphysics
  - Developing ice in superdroplet microphysics
    - Stochastic nucleation
    - SGS fluctuations
    - …
- Study:
  - stability of mixed-phase clouds
  - deep convection

HANAMI project

- Developing European HPC applications through collaboration with Japanese partners
- Funded by EuroHPC
- Collaboration with Shin-ichiro Shima (Univ. of Hyogo, Kobe)
- UWLCM:
  - Adaption to more architectures (Fugaku, Lumi)
  - Improved memory access pattern for superdroplets on CPUs
  - Neural networks for ice in super-droplet microphysics

HIGH-PERFORMANCE COMPUTING

UWLCM

NUGMLE CAL CLOUD MODEL

WARSAW