Simulating aerosol particles‘ influence on clouds and precipitation with the model system COSMO-SPECS

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Motivation

- Aerosol particles have a great influence on weather and climate. They influence
  - cloud microstructure,
  - precipitation formation,
  - cloud albedo.

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- Aerosol particles have a great influence on weather and climate. They influence
  - cloud microstructure,
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  - cloud albedo.
- Detailed cloud microphysics schemes in mesoscale models can serve to gain a deeper understanding of the complex aerosol-cloud-precipitation interaction under different meteorological conditions.
- But: Such schemes are pretty slow! Thus efficient numerical schemes have to be found to make them suitable for realistic case studies and larger sensitivity studies. → Part 2, Matthias Lieber

COSMO-SPECS

Spectral microphysics & coupling scheme

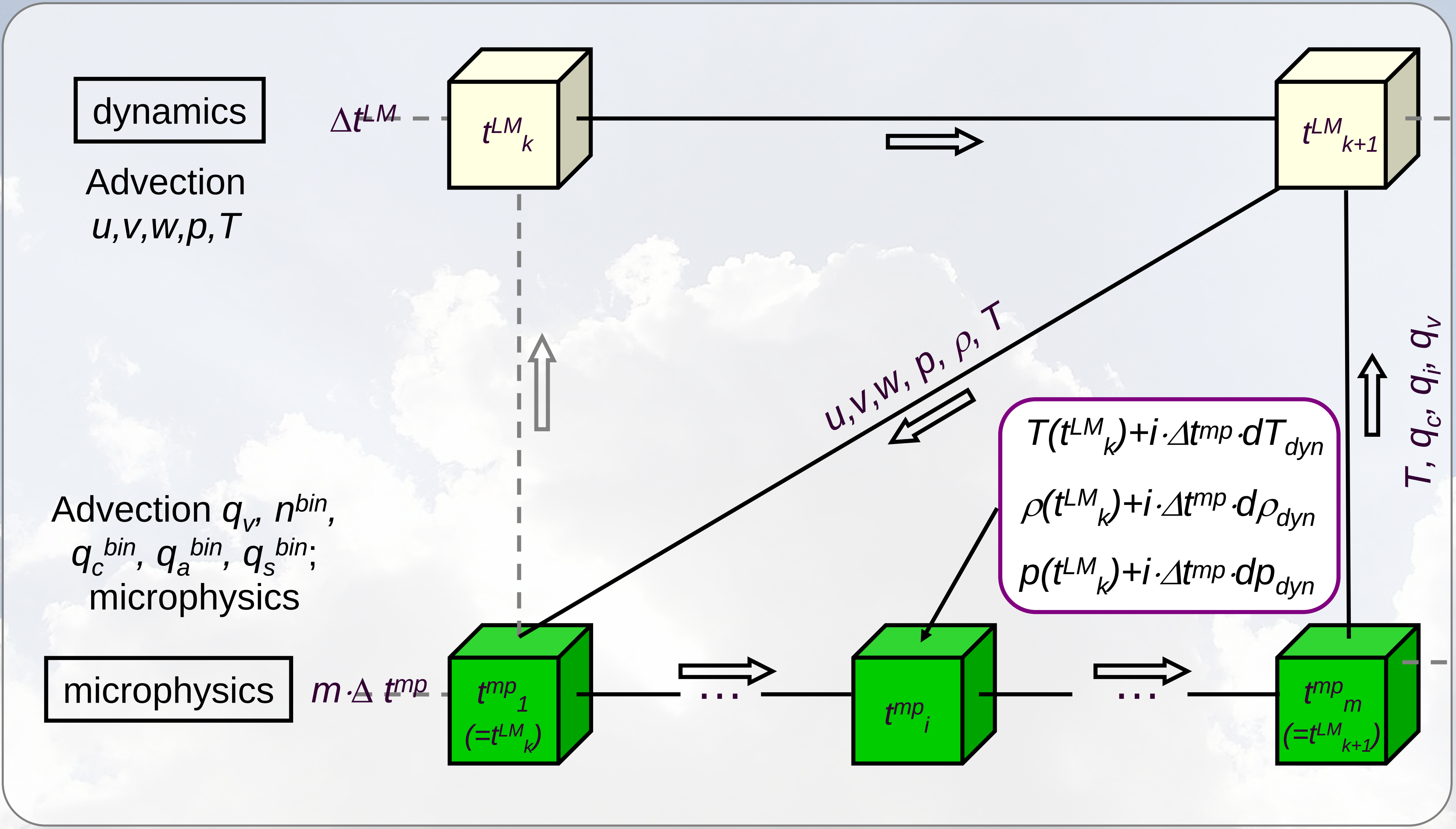
SPECS

SPECtral bin cloud microphysicS

- **Spectra:**
  - Partly insoluble aerosol particles, cloud & rain drops (joint spectrum, number density, mixing ratios (MRs) of water, soluble and insoluble aerosol)
  - Mixed phase hydrometeors (as above+frozen water MR)
  - Insoluble aerosol particles (number and mass MR)
  - 66 mass-doubling size bins each, starting at 10-15 µg (*r* =1 nm)
- **Microphysical processes:**
  - Droplet nucleation, immersion/contact freezing
  - Condensation/evaporation, deposition/sublimation
  - Collisions between the various hydrometeors
  - Freezing/melting

Coupling scheme

Additionally: mass conserving, flux based advection for hydrometeors *(Knoth and Wolke, 1998)*



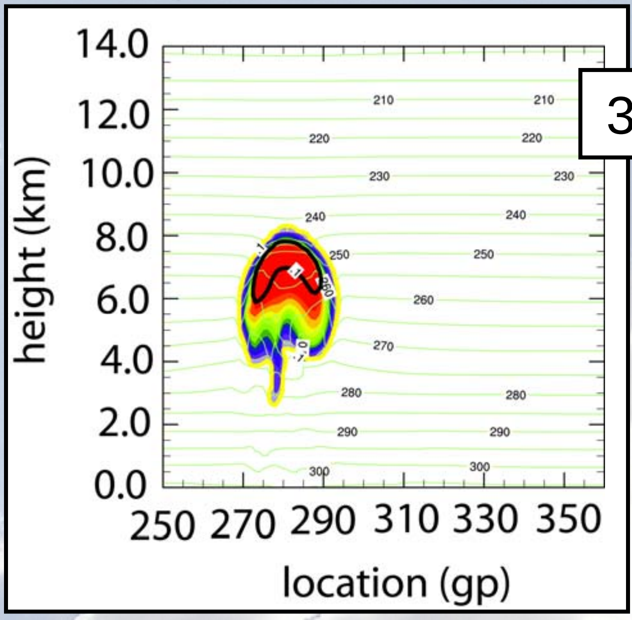
Results

Case setup

- Deep convective cloud basing on observations made in Midland, Texas, 13th August ’99 (Rosenfeld and Woodley, 2000)
- 2D Model domain: horizontal 125 km, vertical 22 km
  Resolution: horizontal 250 m, vertical 125 m
  Time step: dynamical 2 s, microphysical 1 s
- Initial aerosol distribution unimodal
  number densities: 100/566/1000/5000 cm^{-3}
- Simulated time: 3 hours, 100 CPUs, Altix (TU Dresden)
  (Time to simulate: 33-39 hours run time… ☹)

Results

- Deep convective cloud observed over Midland, Texas, 1999 (Rosenfeld and Woodley, 2000)



30 min

Initial aerosol conc.= 566 cm^{-3}

2D simulation

Δx=250 m

Δz=125m

Δt=2 bzw. 1 s

0.1 g/kg ice
0.1 g/kg cloud water
0.1 g/kg rain water
colors: condensed water MR

Results

➢ Deep convective cloud observed over Midland, Texas, 1999
(Rosenfeld and Woodley, 2000)

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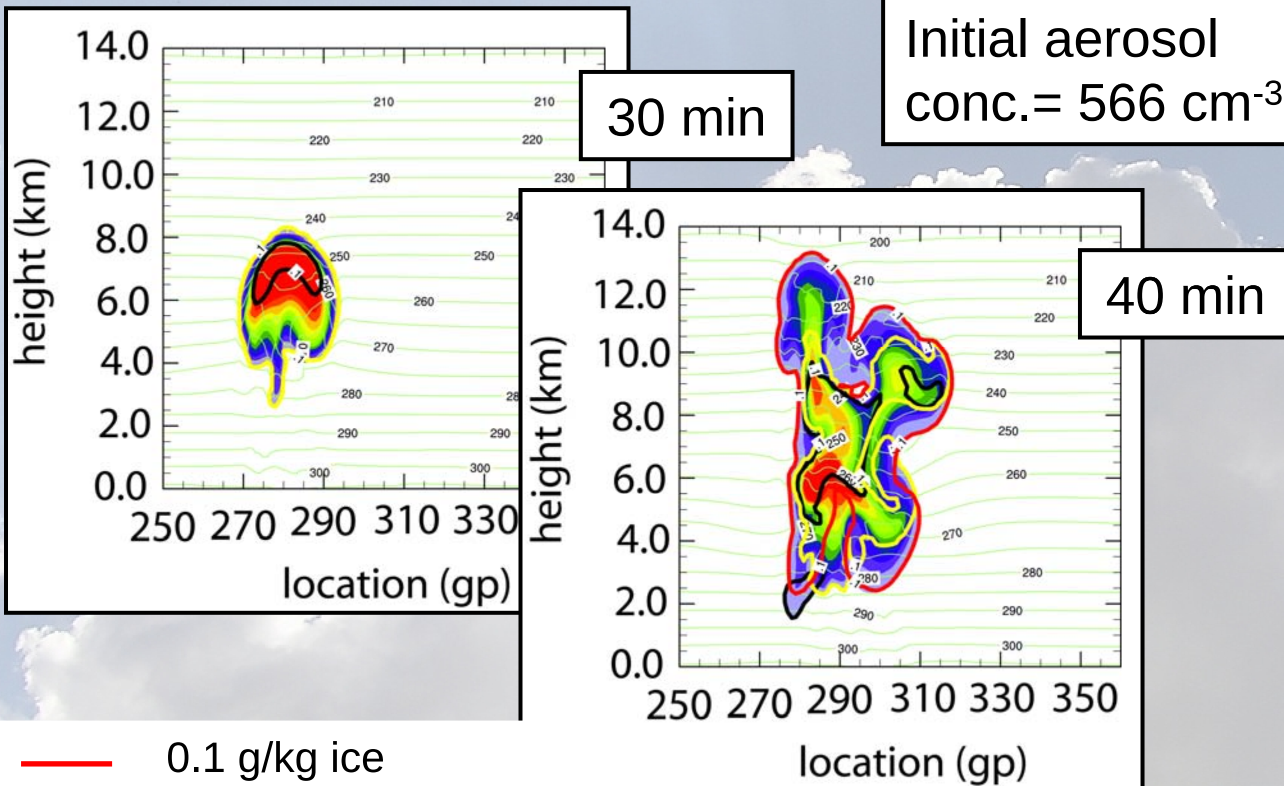

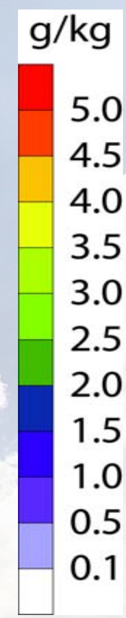

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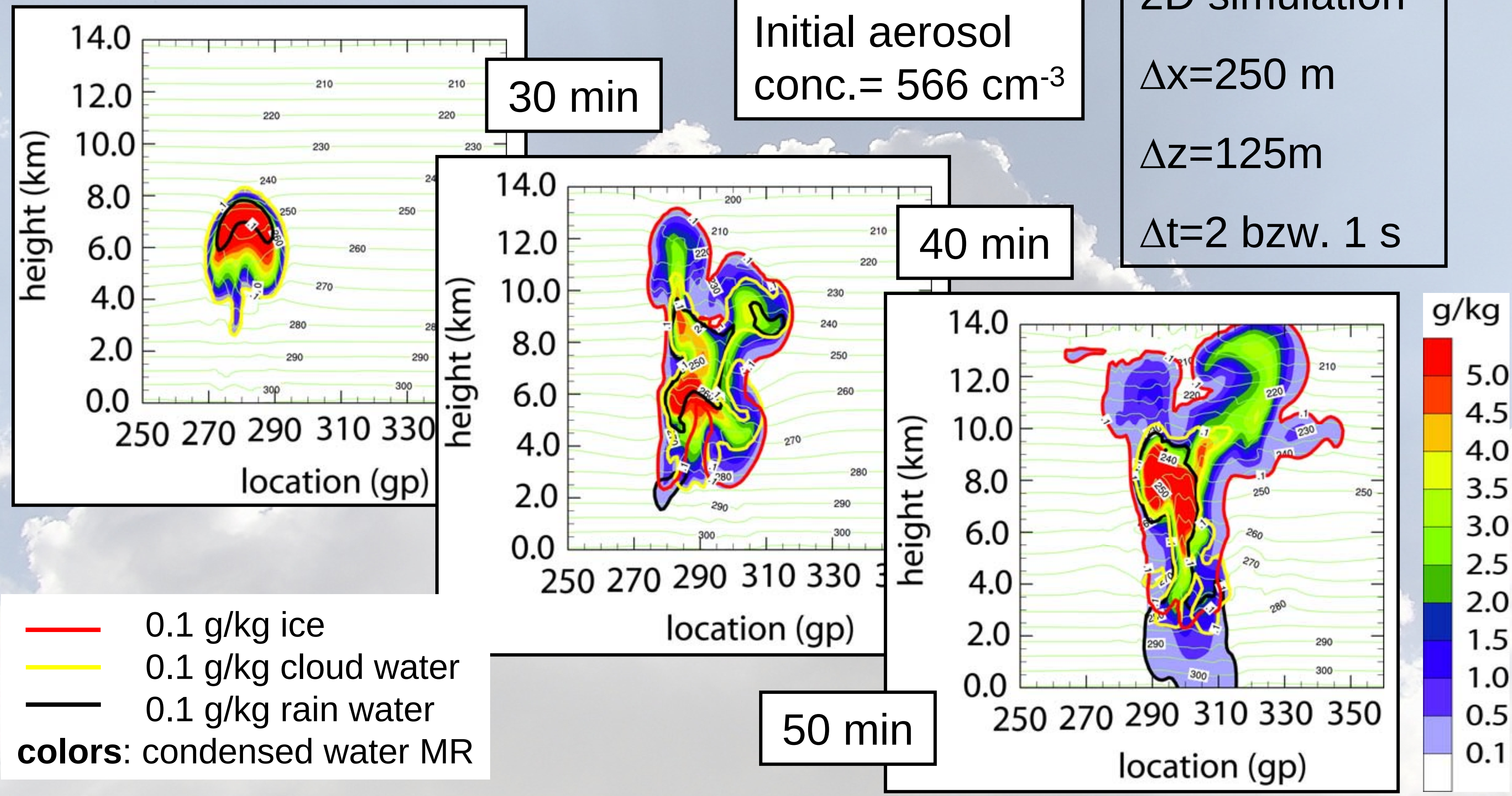
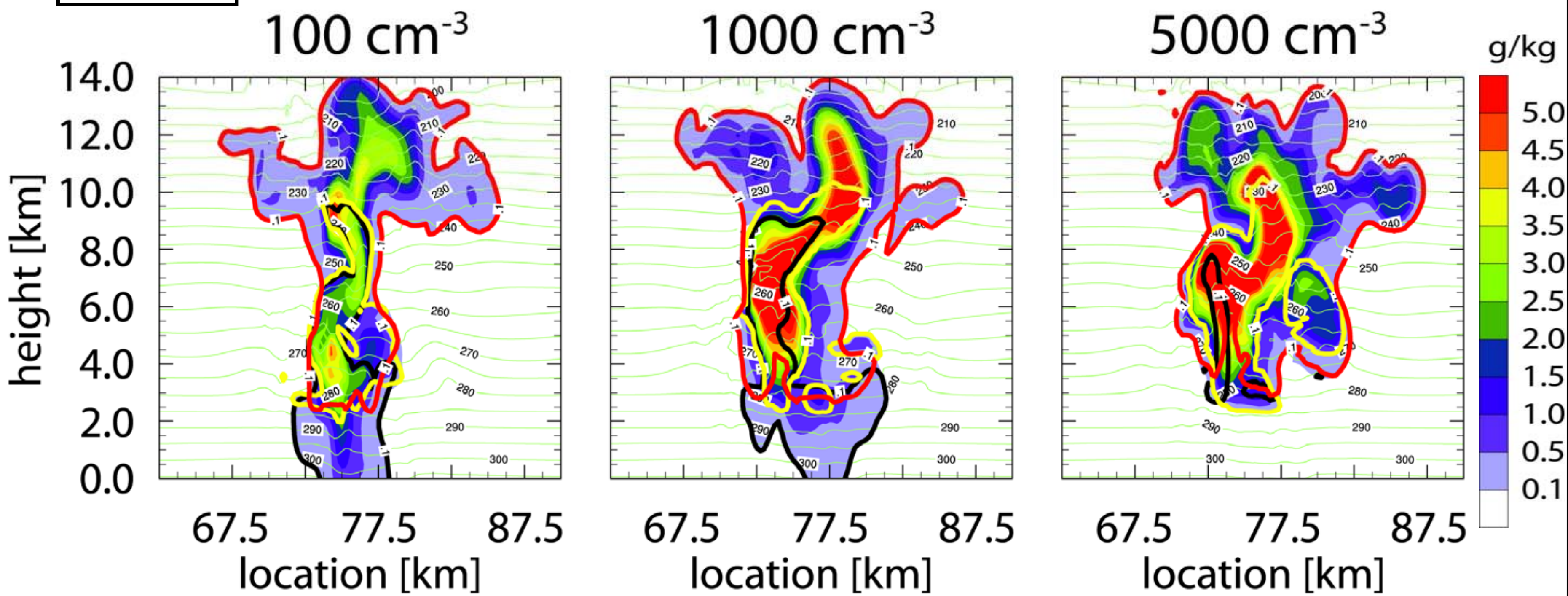


Results

- ➢ Deep convective cloud observed over Midland, Texas, 1999
  (Rosenfeld and Woodley, 2000)
- ➢ **Condensed water**

0.1 g/kg ice
0.1 g/kg cloud water
0.1 g/kg rain water
colors: tot. condensed water

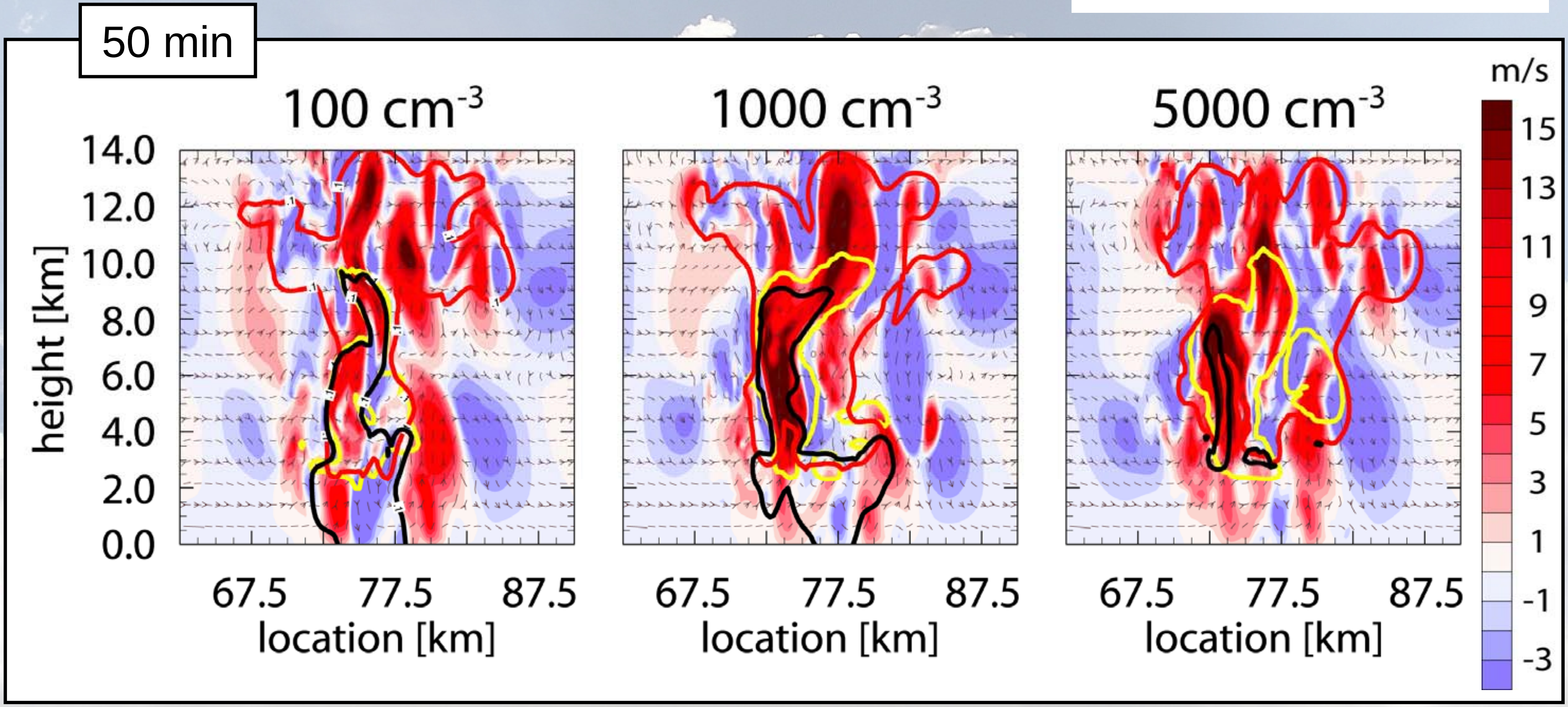
50 min



Results

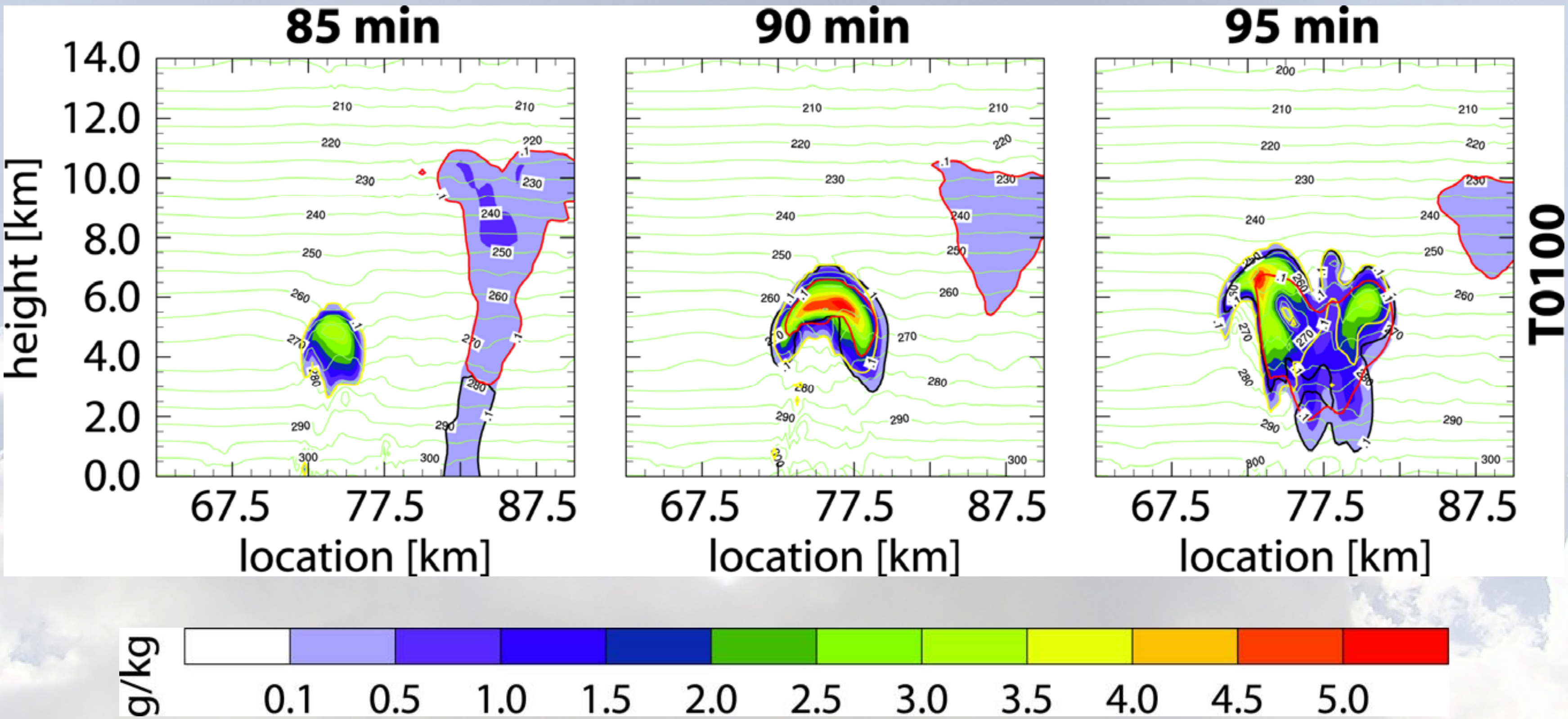
- Deep convective cloud observed over Midland, Texas, 1999
  (Rosenfeld and Woodley, 2000)
- **Vertical wind**

0.1 g/kg ice
0.1 g/kg cloud water
0.1 g/kg rain water
colors: vertical wind



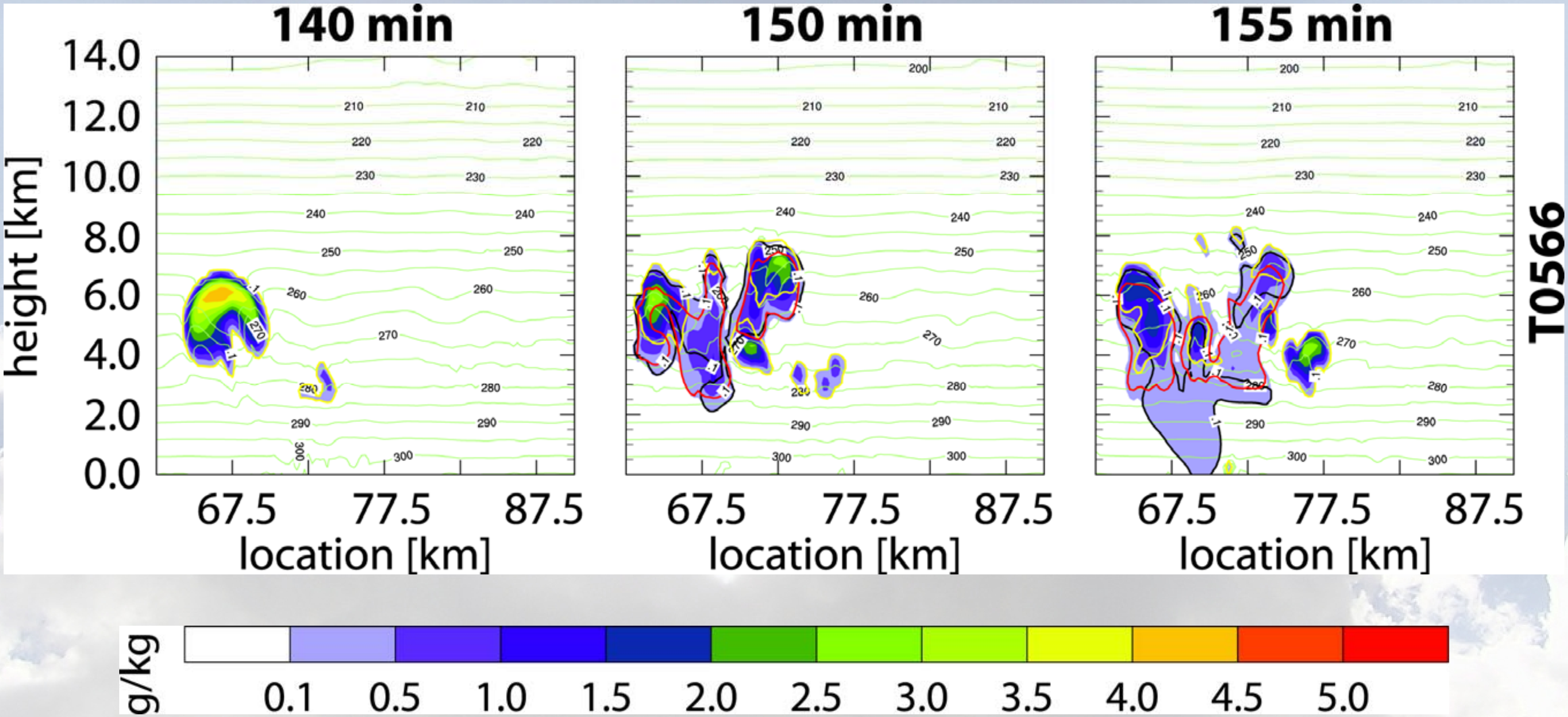
Results

- Deep convective cloud observed over Midland, Texas, 1999
  (Rosenfeld and Woodley, 2000)
- **Secondary cells – 100 cm^{-3}**



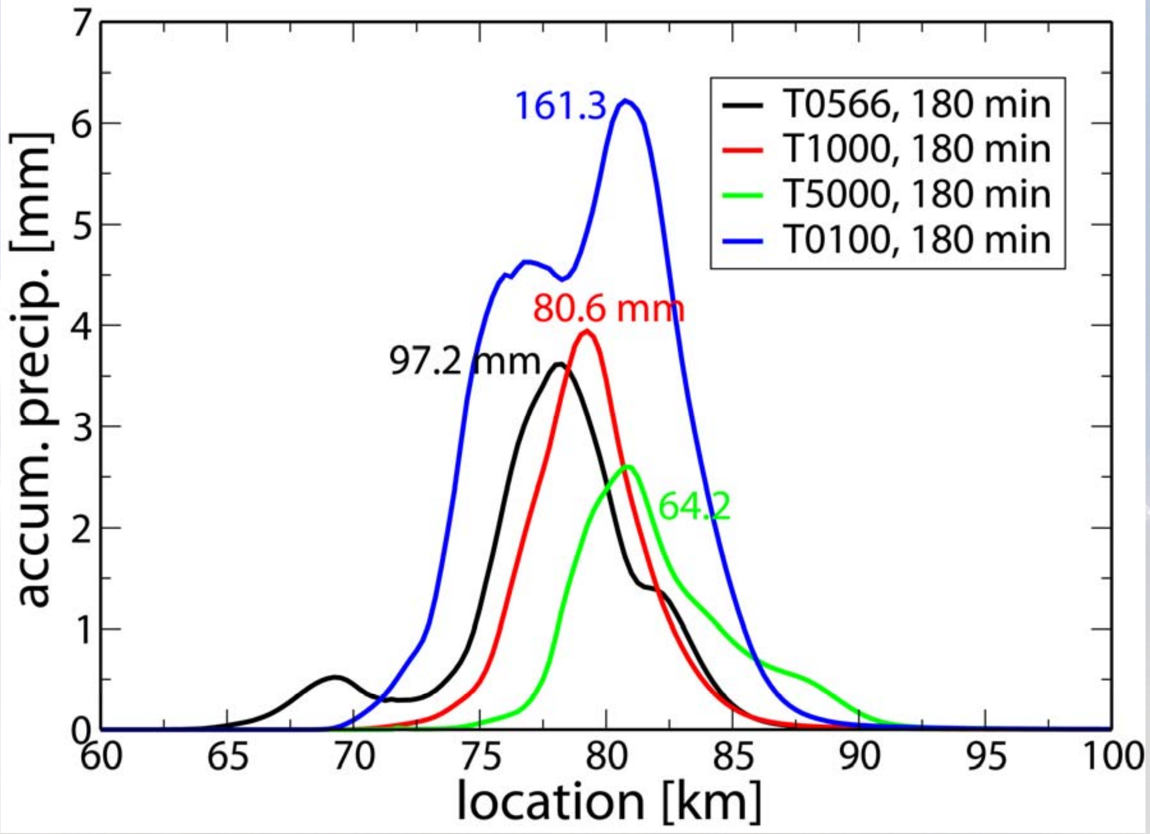
Results

- Deep convective cloud observed over Midland, Texas, 1999
  (Rosenfeld and Woodley, 2000)
- **Secondary cells – 566 cm^{-3}**



Results

- Deep convective cloud observed over Midland, Texas, 1999 (Rosenfeld and Woodley, 2000)
- **Accumulated precipitation**



Conclusions and Outlook (Part 1)

Conclusions (Part 1)

- For the “Texas case” presented it was shown that
  - Aerosol particles have a great influence on the cloud microstructure, i.e., a higher aerosol particle number yields more numerous and smaller droplets and ice particles.
  - Precipitation onset is delayed in more polluted environments and precipitation amount decreased.
  - Through these changes, the dynamics is altered as well.
  - Cleaner cases yield stronger secondary cells.

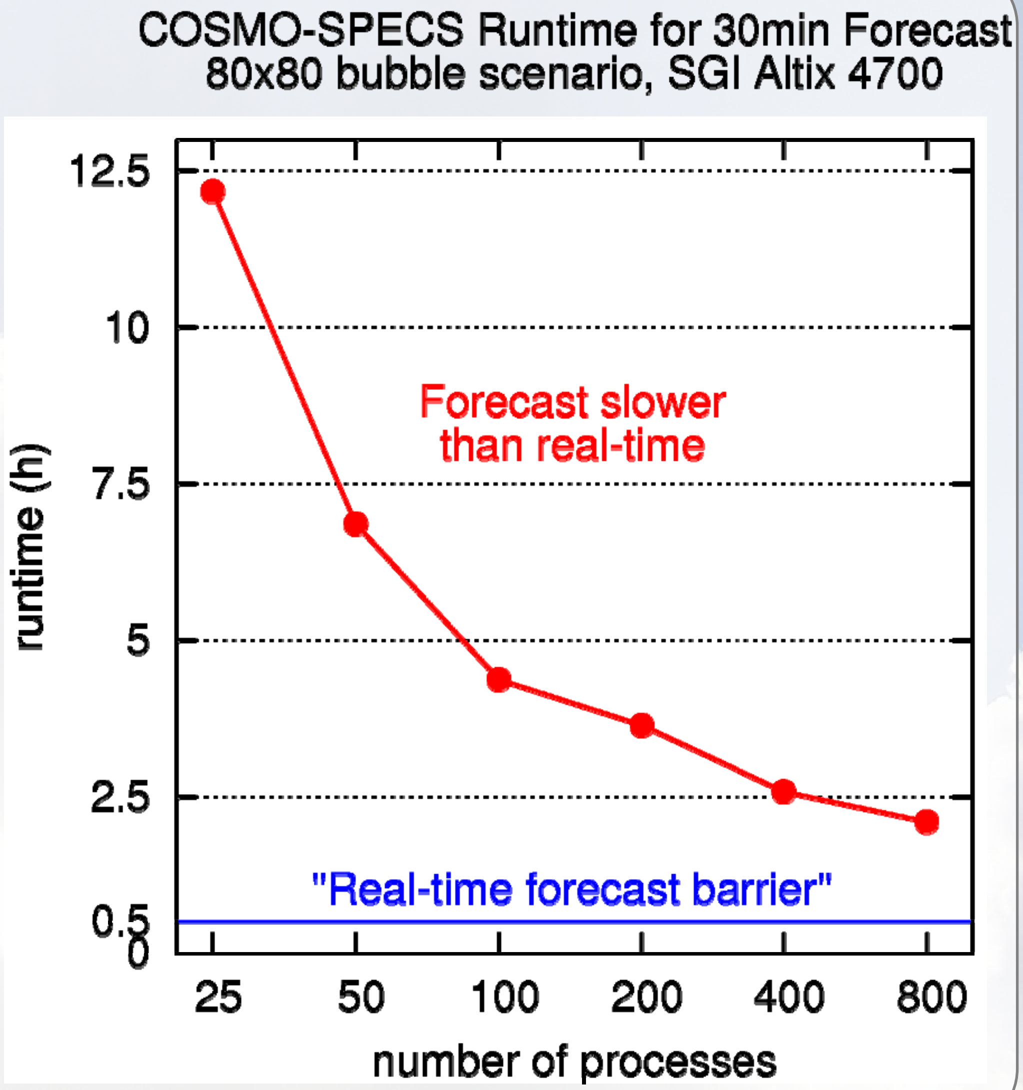
Outlook (Part 1)

- COSMO-SPECS will be used to investigate aerosols' influence on clouds under different meteorological conditions. E.g.,
  - deep convective clouds in tropics/midlatitudes (sensitivity on humidity and temperature),
  - shallow (warm) cumuli under the influence of differing aerosol particle populations.
  - Playground is very large….
- Further freezing mechanisms will be implemented into SPECS to account for a broader range of cloud types.
- The module SPECS is currently being implemented into the LES model ASAM (All Scale Atmospheric Model, http://asam.tropos.de)

Computational time

- Simple test case, heat bubble with 80X80X48 = 307200 grid points.
- Far from "real time forecast barrier".
- Doesn't even scale anymore…!
- Let's see what an expert in computational science can do about this!

⇨ **Part 2, Matthias Lieber**



Performance Problems in COSMO-SPECS

- Microphysical computations
  - Very expensive
  - Insufficient load balance
- Large amount of microphysical data per grid cell
  - Communication overhead
  - Writing GRIB output files

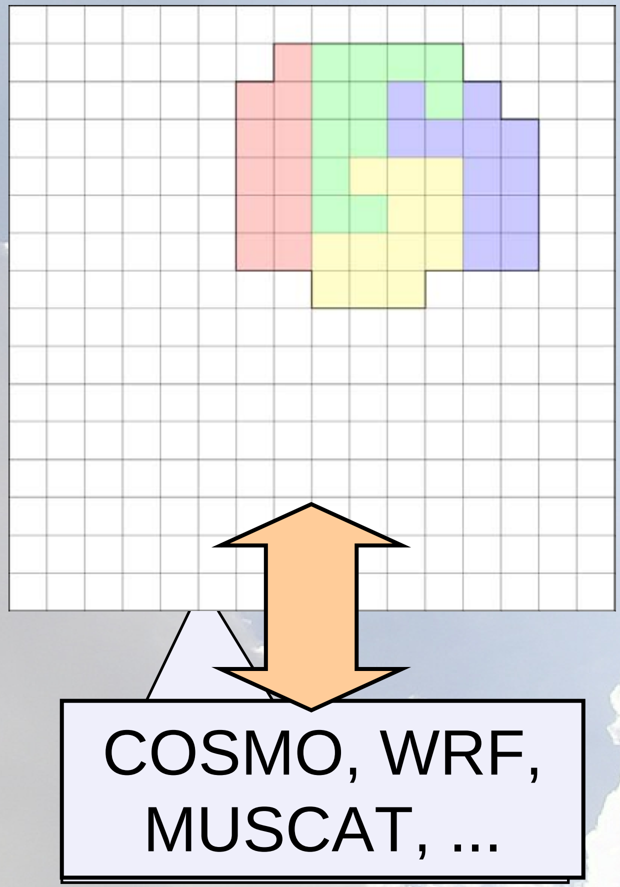
Scalability? → **We need special methods and tuning for HPC systems**

“**Parallel coupling framework** and advanced time integration methods for detailed cloud processes in atmospheric models”

- Leibniz Institute for Tropospheric Research (IfT), Leipzig
- Center for Information Services and High Performance Computing (ZIH), TU Dresden
- Project started in September 2007
- Funded by Deutsche Forschungsgemeinschaft DFG

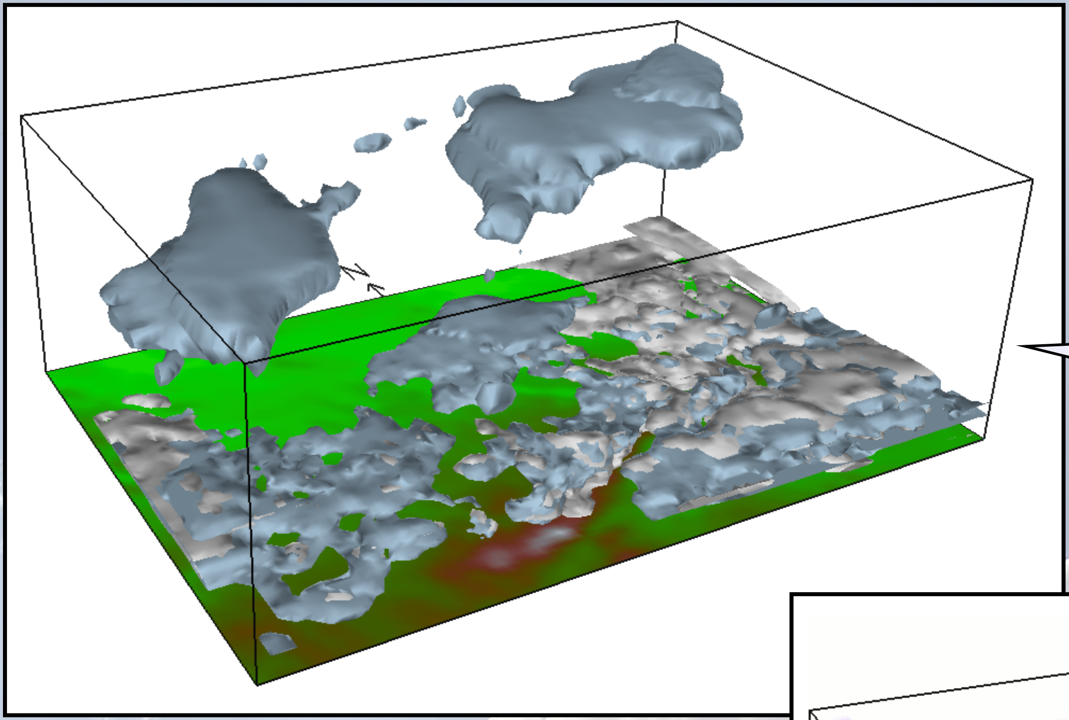
Framework FD4 = “Four-Dimensional Distributed Dynamic Data Structures”

- Work in Progress
- Fortran 95, MPI parallel
- Block-based 3D decomposition of rectangular grid
- Adaption of grid to spatial cloud structure
- Parallelization
- Dynamic load balancing (Space-filling Curve, ParMetis)
- Coupling to atmospheric Model
- General applicable for multiphase modeling

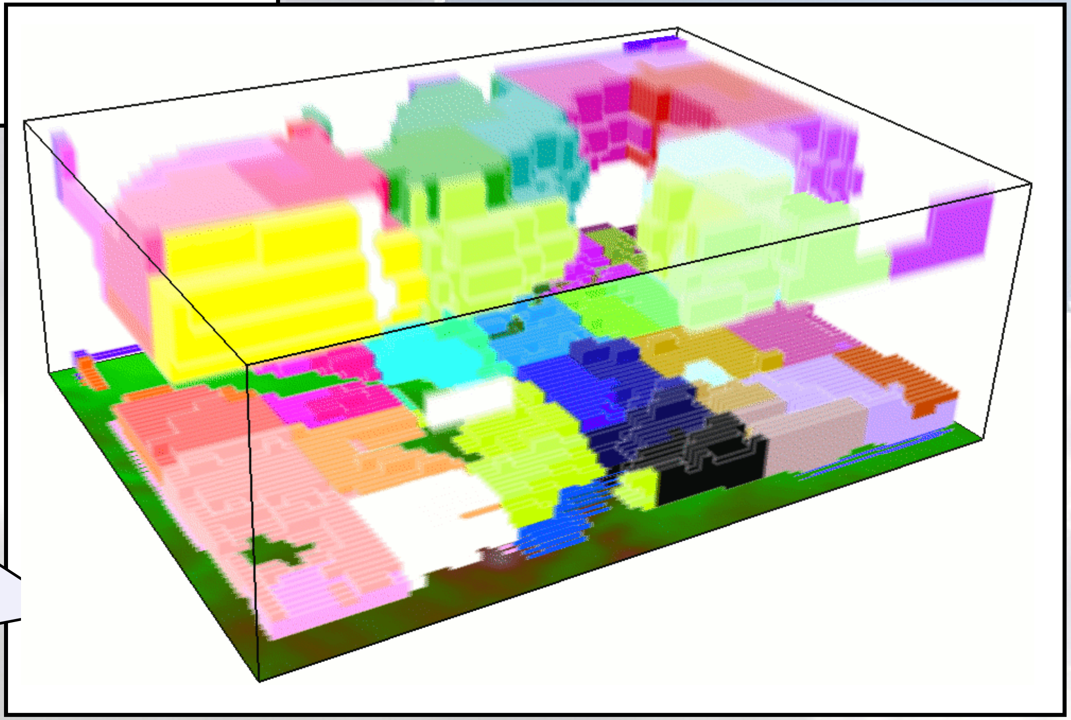


Test Application: Adaption to Cloud Structure of a real Case

- COSMO real case
  - Saxony, 102x72x50 grid
  - 2,8 km horizontal Resolution
  - 20 December 2007
- Adaption to cloud structure
  - Transfer qc and qi to FD4 each step
  - FD4 creates blocks where qc>0 or qi>0
  - Blocks and partitioning adapt dynamically to cloud structure



Cloud structure derived from qc and qi

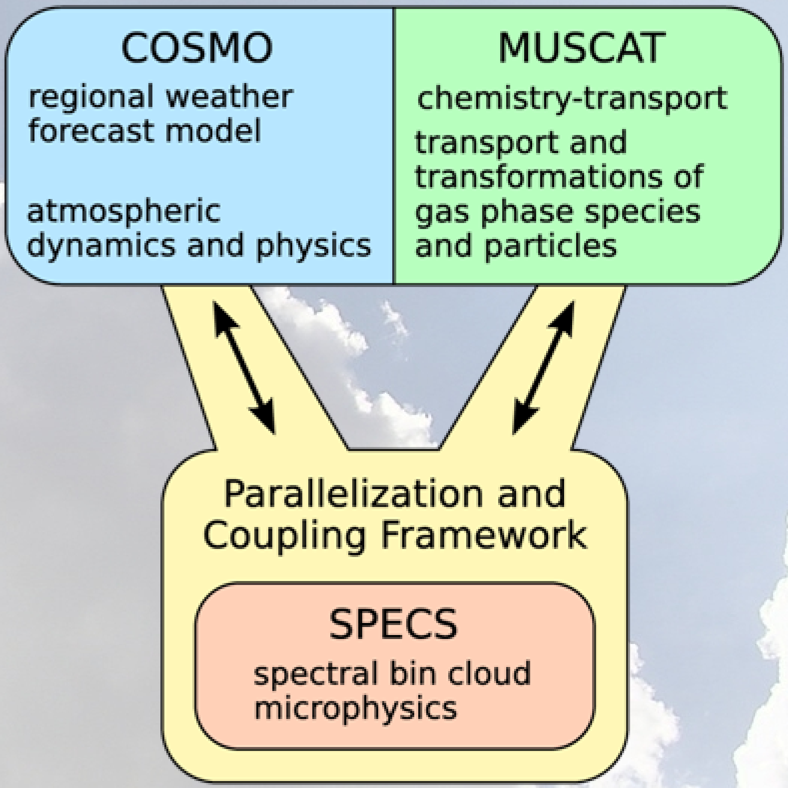


Adapted block structure with ~10,000 blocks (of max. 34,848)

64 Partitions calculated by Hilbert SFC

Outlook

- Parallel NetCDF I/O
- Use FD4 in COSMO-SPECS
- Multirate time stepping methods
- Couple MUSCAT to provide aerosol spectra and chemistry



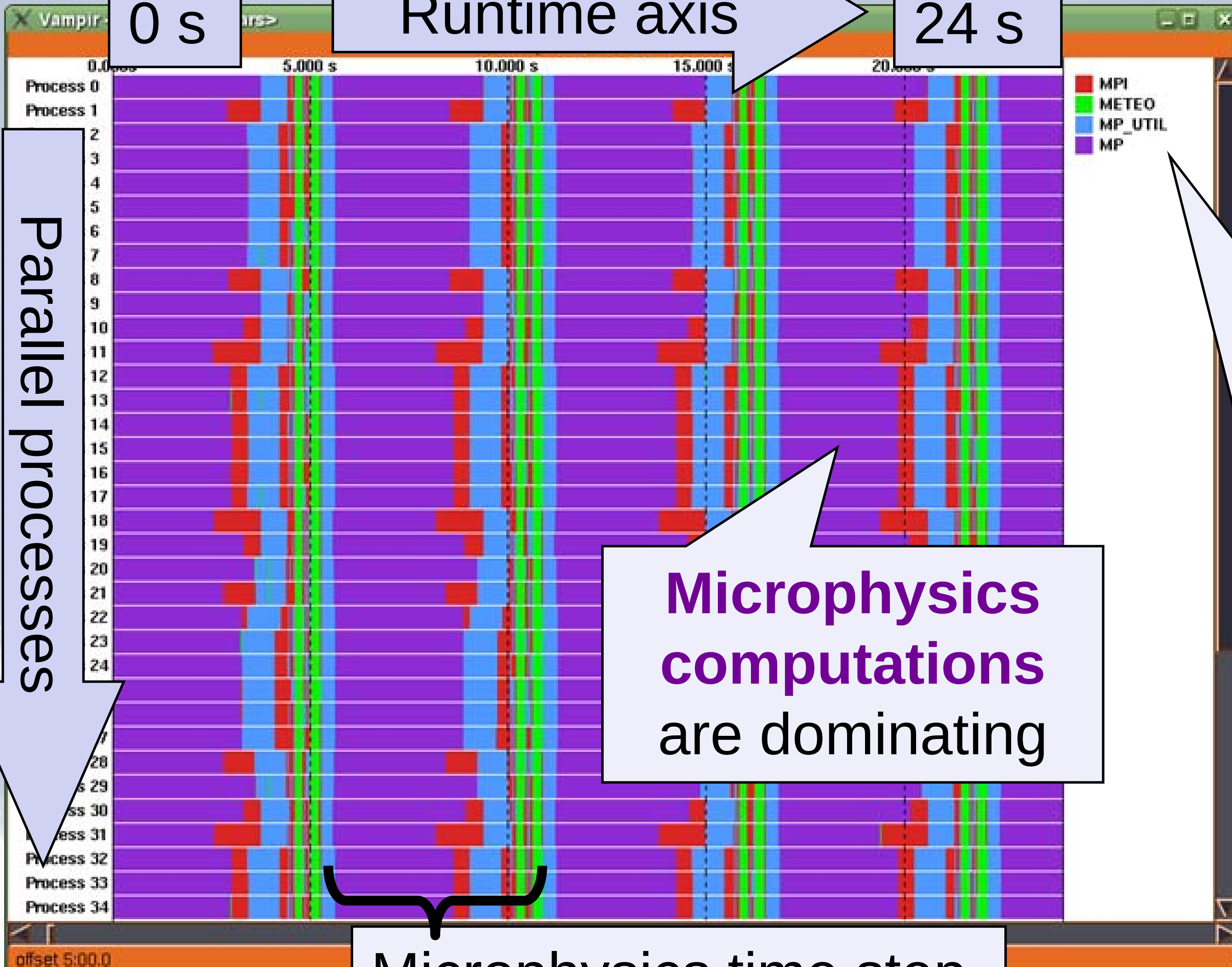
COSMO-SPECS seen in Vampir

0 s

Runtime axis

24 s

Parallel processes



Microphysics computations are dominating

Microphysics time step

No cloud existing

Activities:

MPI
(comm & sync)

Microphysics Computations
(SPECS)

Microphysics Utilities

Meteorology
(COSMO)

COSMO-SPECS seen in Vampir

0 s

Runtime axis

24 s

Parallel processes

Microphysics time step

Cloud present

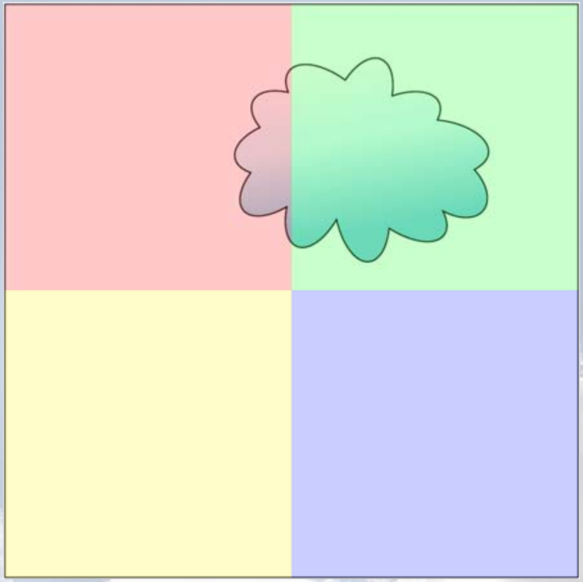
MPI overhead is large (40%) due to load imbalances

Microphysics computations are unbalanced: 2 processes do substantially more work

Workload follows clouds!

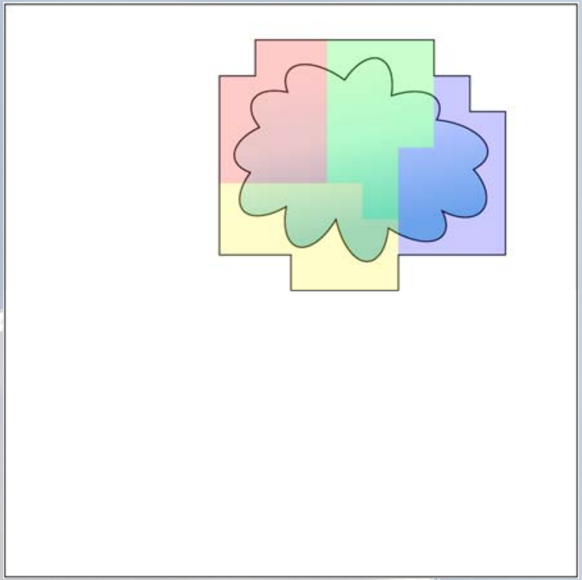
Adaptive Block Structure

COSMO-SPECS:



- Cloud causes high workload
- Static partitioning leads to load imbalance

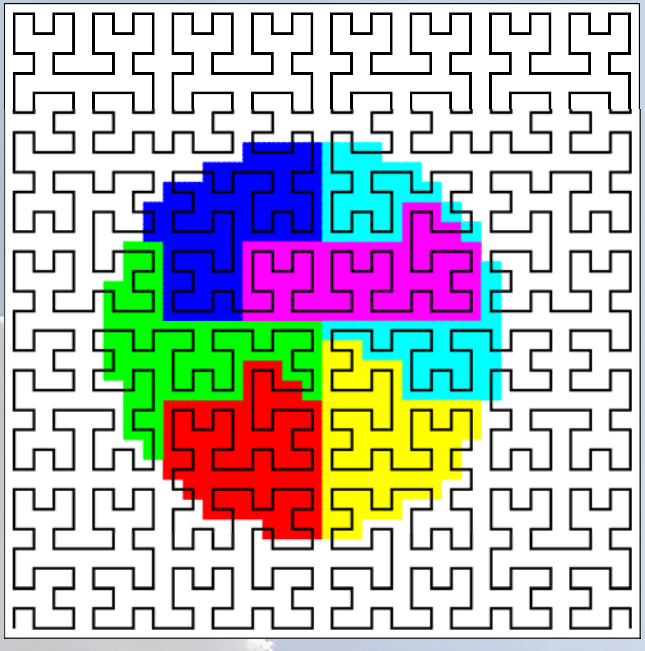
Goal:



- Run cloud model only where clouds exist
- Adapt block structure and partitioning dynamically to actual cloud structure

Load Balancing Methods

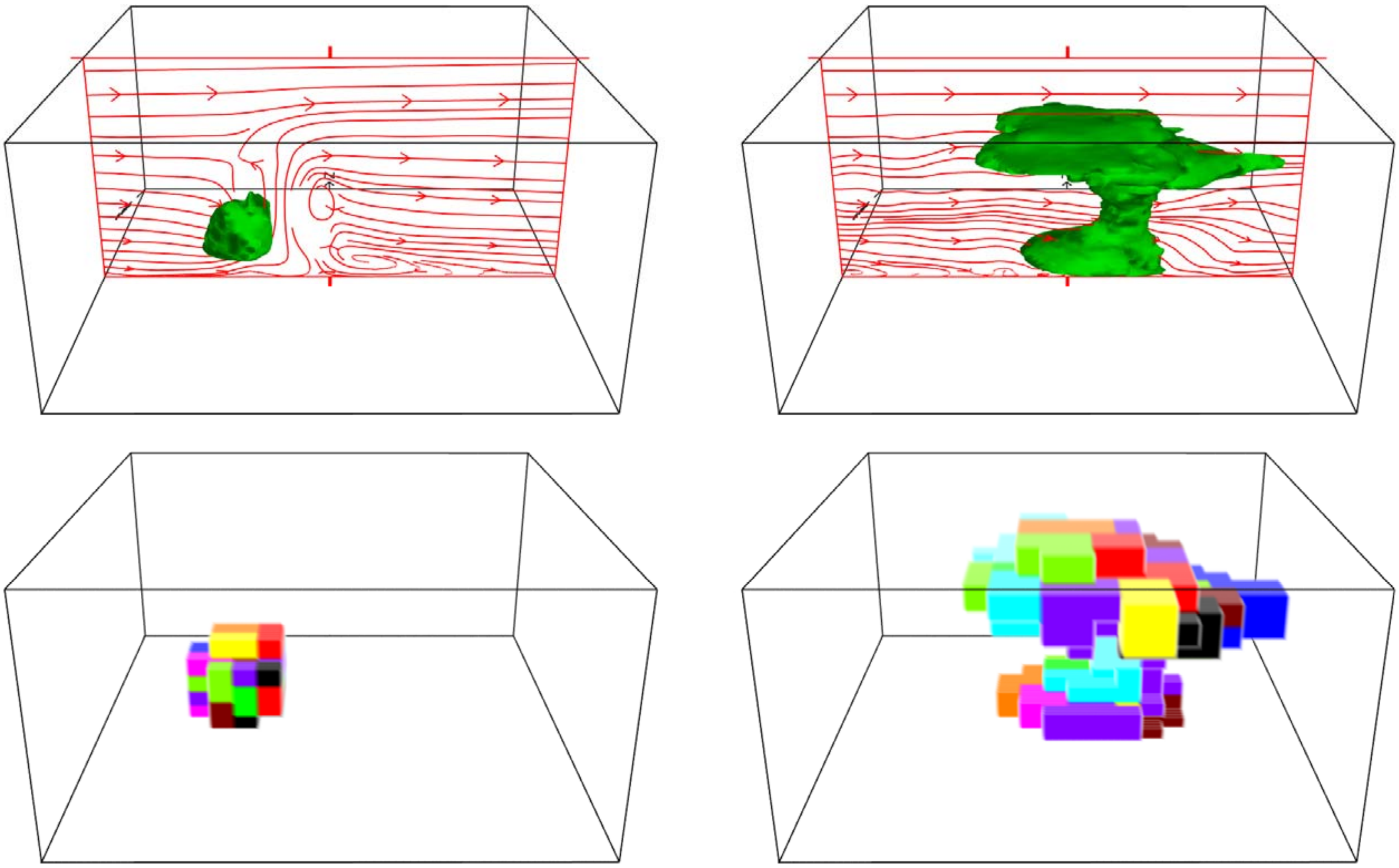
- Hilbert space filling curve
  - Continuous nD -> 1D mapping
  - Cut in equal-sized parts to obtain nD partitioning
- ParMetis
  - Library for parallel graph partitioning



Test Application: Tracer Simulation

- Artificial case
  - Vertical wind
  - Heat bubble
- Tracer advection
  - Tracer stored in FD4 block structure
  - 2nd order advection scheme uses wind fields from COSMO
  - FD4 blocks and partitioning adapt dynamically to spreading of tracer

Tracer and vertical wind



FD4 blocks and 32 partitions