Contrail modeling with EULAG
Overview of past, present and future projects

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Structure of the talk

- Motivation & basic information on contrails
- Vortex phase simulations
- Dispersion phase simulations

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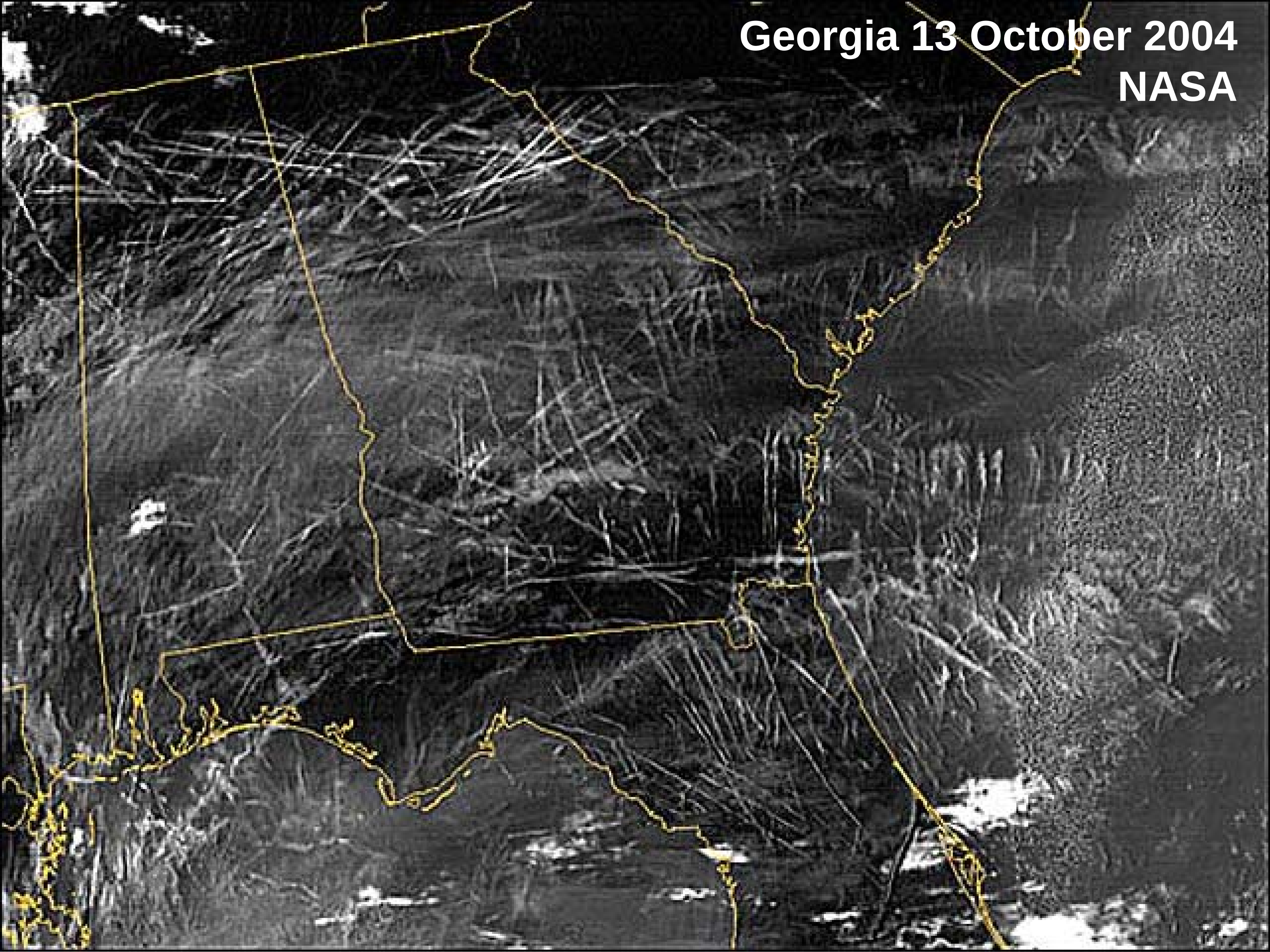
Motivation

- Supersaturation is a common feature in the upper troposphere, i.e. relative humidity RH_i > 100%
- Natural cirrus formation mostly, if relative humidity above 140%
- Contrail can form and persist in areas where natural cirrus does not form

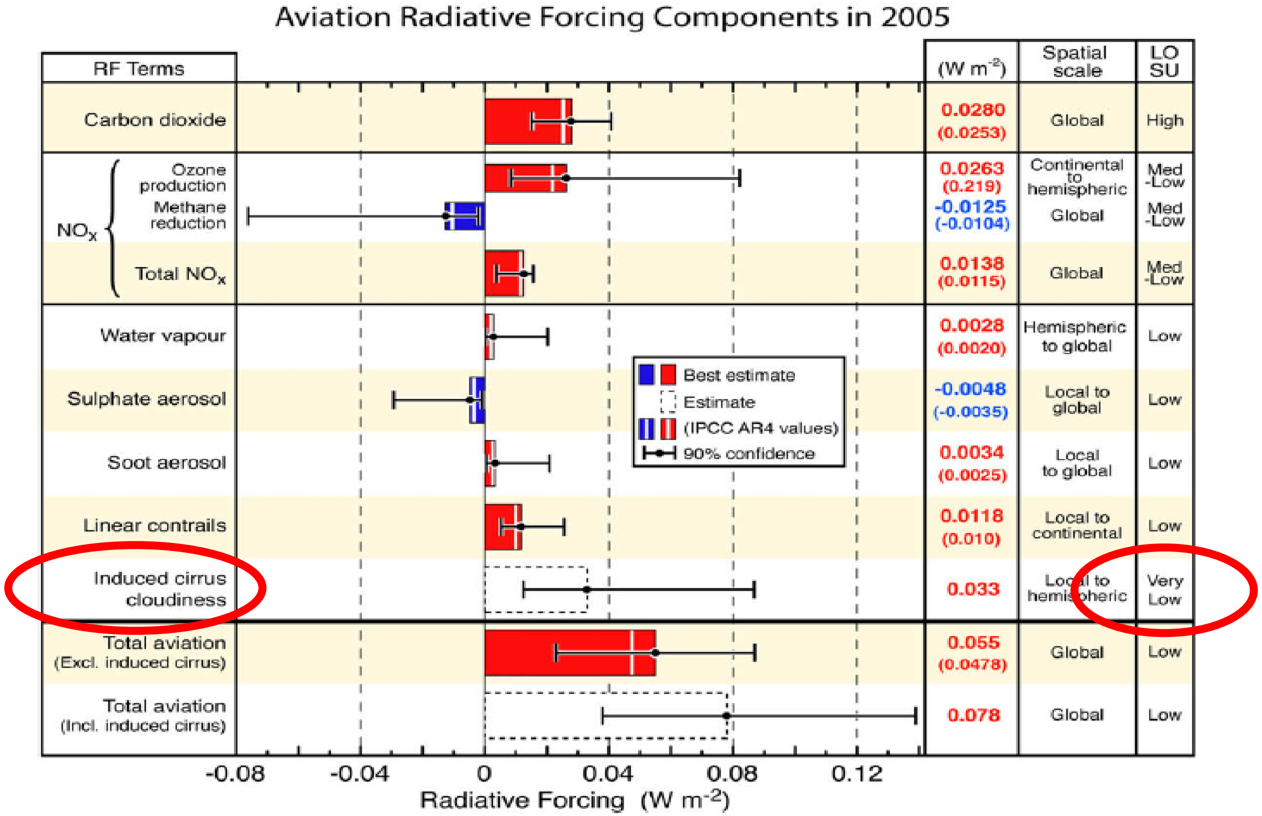
  ⟶ Additional cloud coverage by contrails

- Coverage and climate impact of line-shaped contrails can be determined with suitable accuracy
- Coverage and climate impact contrail-cirrus might be several times higher
- Can hardly be discriminated from naturally formed cirrus


Georgia 13 October 2004
NASA

Motivation

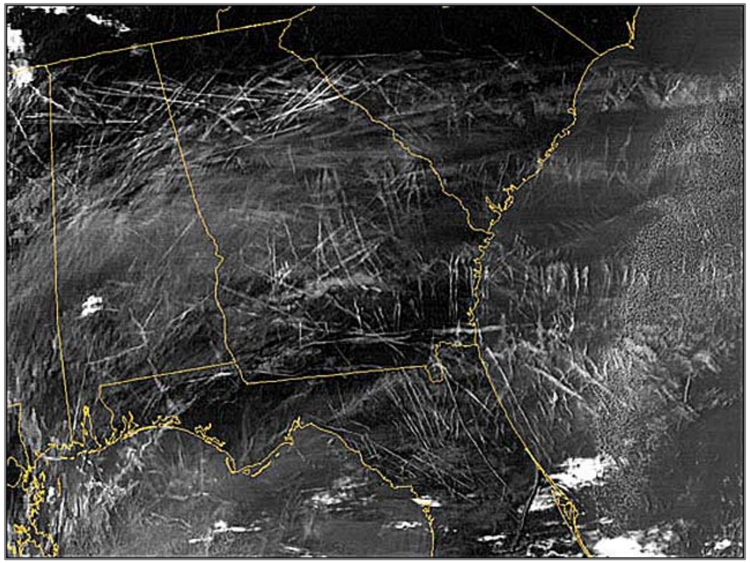
Aviation currently contributes 2 - 8% to total climate change radiative forcing



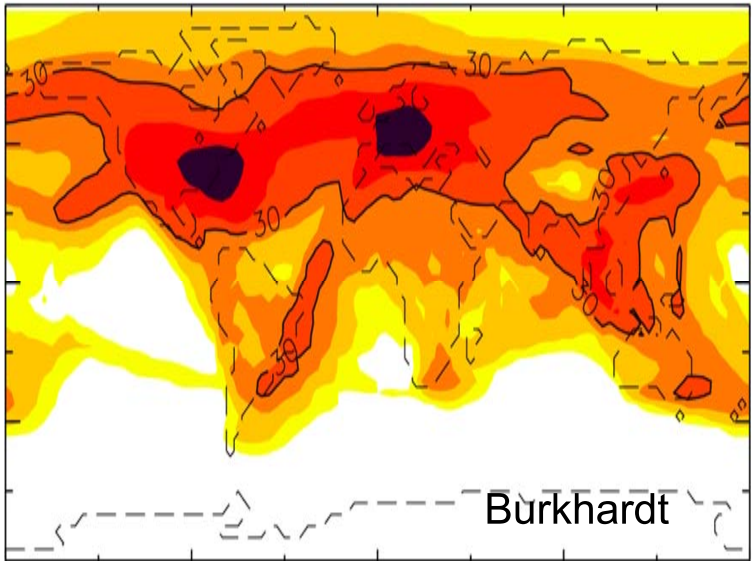
Lee et al., 2009

Motivation – Quantify climate impact

Remote sensing with satellites



Global climate models



For both pathways, more knowledge on the evolution of a single contrail or contrail cluster is needed

EULAG helps!

Motivation – Temporal evolution of a Contrail (1/4)

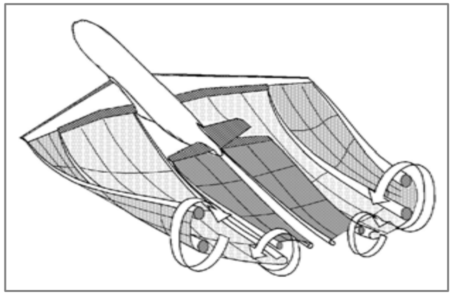
The contrail evolution can be divided into 3 temporal phases:

Jet Phase	Vortex Phase	Dispersion Phase
5 - 10s	2 - 4 minutes	Minutes to hours

Motivation – Temporal evolution of a Contrail: Jet Phase (2/4)

Jet Phase | Vortex Phase | Dispersion Phase

- The jet phase covers the first 5 - 10s
- The hot exhaust mixes with the cold ambient air. Within 1s ice crystals form
- A counterrotating vortex pair emerges from the initial vorticity distribution along the wings
- Emissions (incl. the emitted water vapour and the ice crystals) are mostly trapped inside the vortices



Motivation – Temporal evolution of a Contrail: Vortex Phase (3/4)

Jet Phase | **Vortex Phase** | Dispersion Phase

- Vortex phase (2 - 4min):
  Main feature is the descent of the vortex pair
  → crystal loss due to adiabatic warming
- Vortex decay by Crow instability

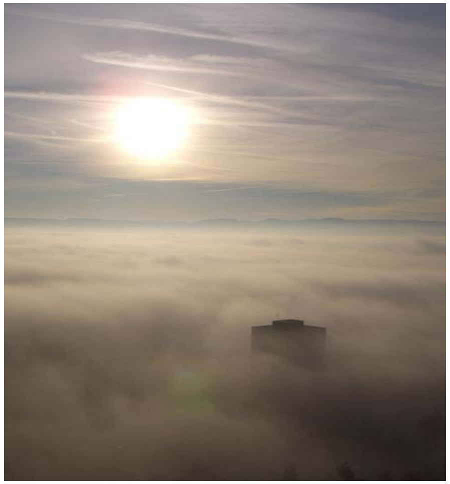
Motivation – Temporal evolution of a Contrail: Vortex Phase (3/4)

Jet Phase | **Vortex Phase** | Dispersion Phase

Motivation – Temporal evolution of a Contrail: Dispersion Phase (4/4)

Jet Phase | Vortex Phase | **Dispersion Phase**

- Dispersion phase (minutes to hours):
  spreading of contrails by turbulent mixing and vertical wind shear
- Atmospheric conditions
- Sedimentation and radiation become important



Structure of the talk

- Motivation & basic information on contrails
- **Vortex phase simulations**
- Dispersion phase simulations

Simulations of the vortex phase – Numerical setup (1/2)

EULAG
- Solves the momentum and continuity equation
- MPDATA advection algorithm
- TKE-closure
- Smolarkiewicz & Margolin, 1997

CC-Tool
- Assures a realistic vortex decay in a 2D-model,
- Unterstrasser et al.,2008

Bulk Microphysics
- Solves equation for
- Ice mass concentration and crystal number concentration
- Bulk approach assuming lognormal size distribution in each gridbox
- Spichtinger&Gierens, 2009

LCM Microphysics
- Lagrangian ice crystal tracking
- Microphysical processes are solved for all ice crystals individually
- Better analysis methods (history of ice crystals)
- Better physical treatment of sublimation process
- Sölch, 2009

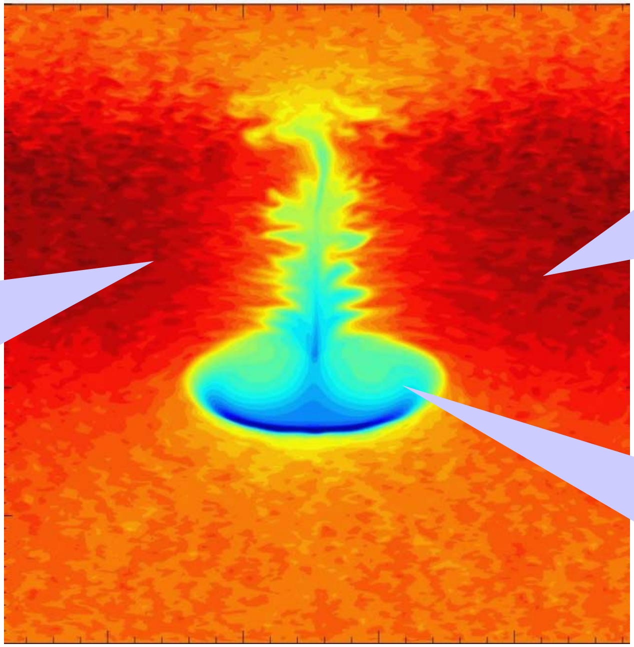
Simulations of the vortex phase – Numerical setup (2/2)

- Resolution: dx = dz = 1m , dt = 0.02s
- Domain: Lx = 256m, Lz = 500m, T = 160s
- Nr. of processor: 32 or 64
- Wall clock time: 30 min to 2h

Simulations of the vortex phase – Major features

Three major features of the
contrail evolution during the vortex phase

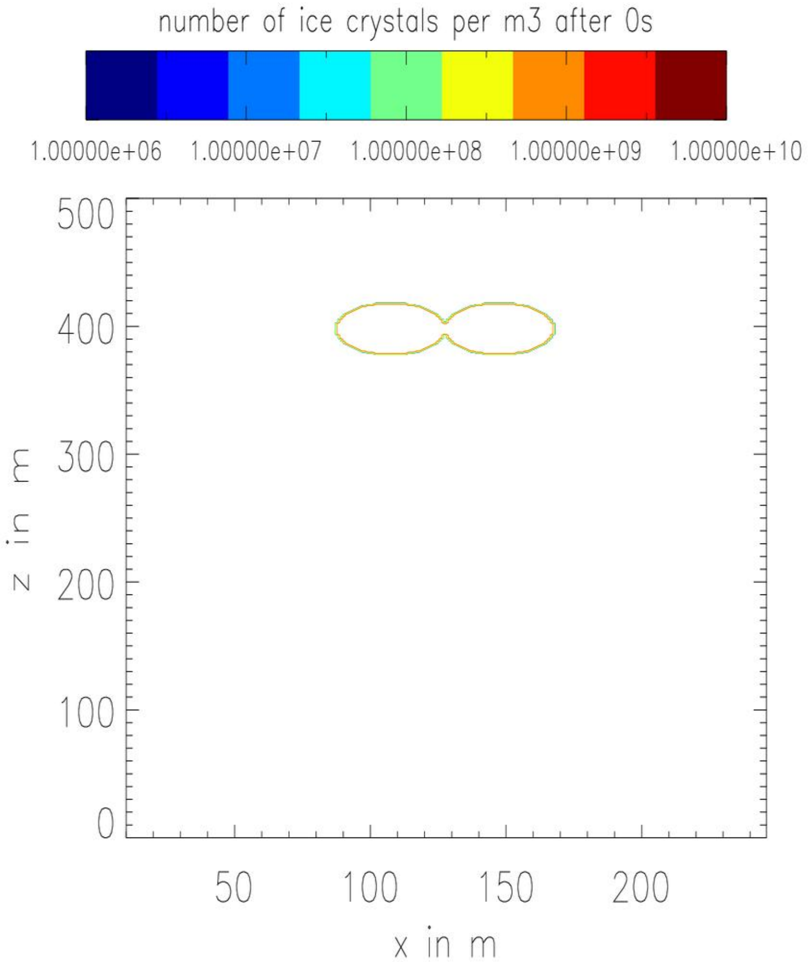
Vertical expansion



Spatial heterogeneity in ice distribution

Ice crystal loss

Temporal Evolution (T = 217K, RH_i = 105%)



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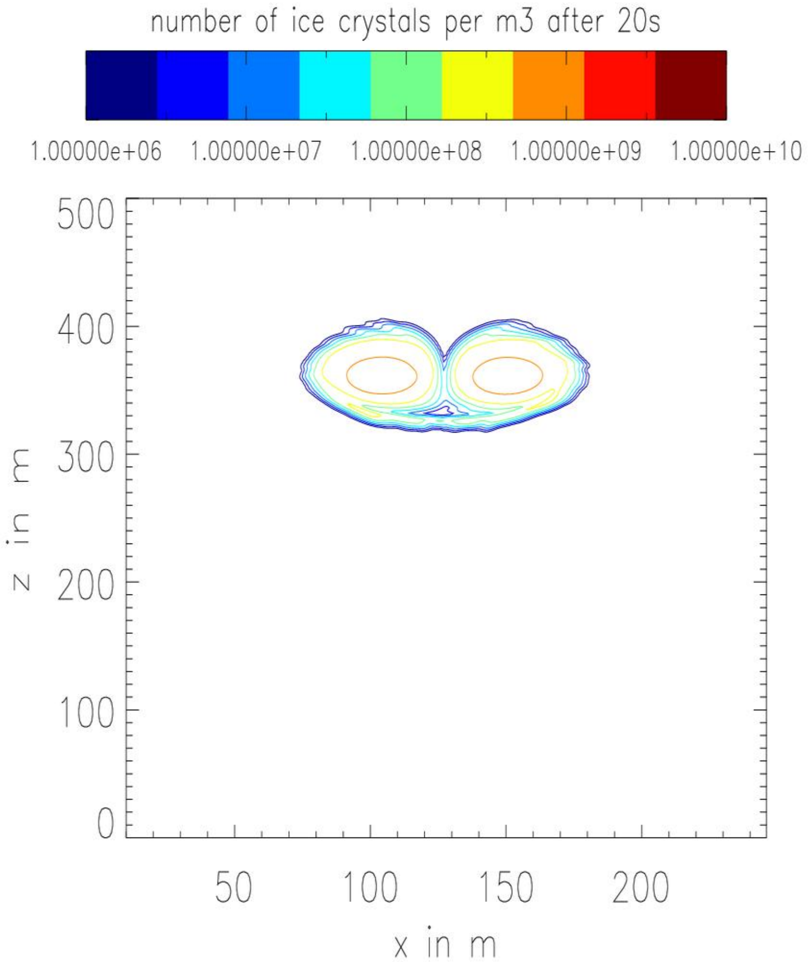

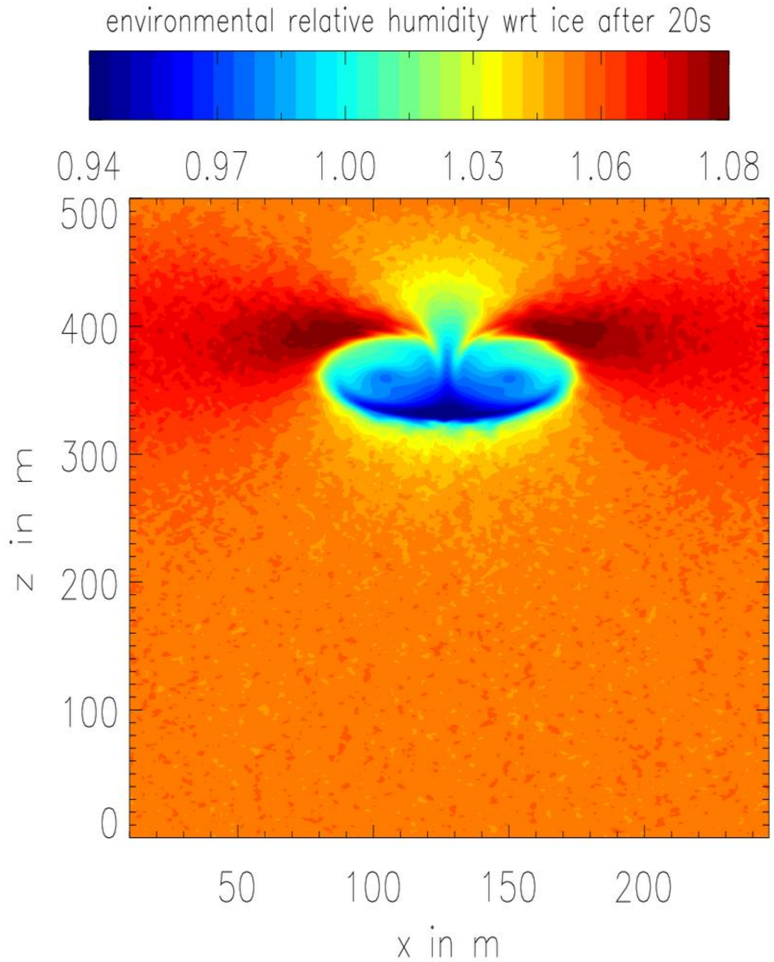

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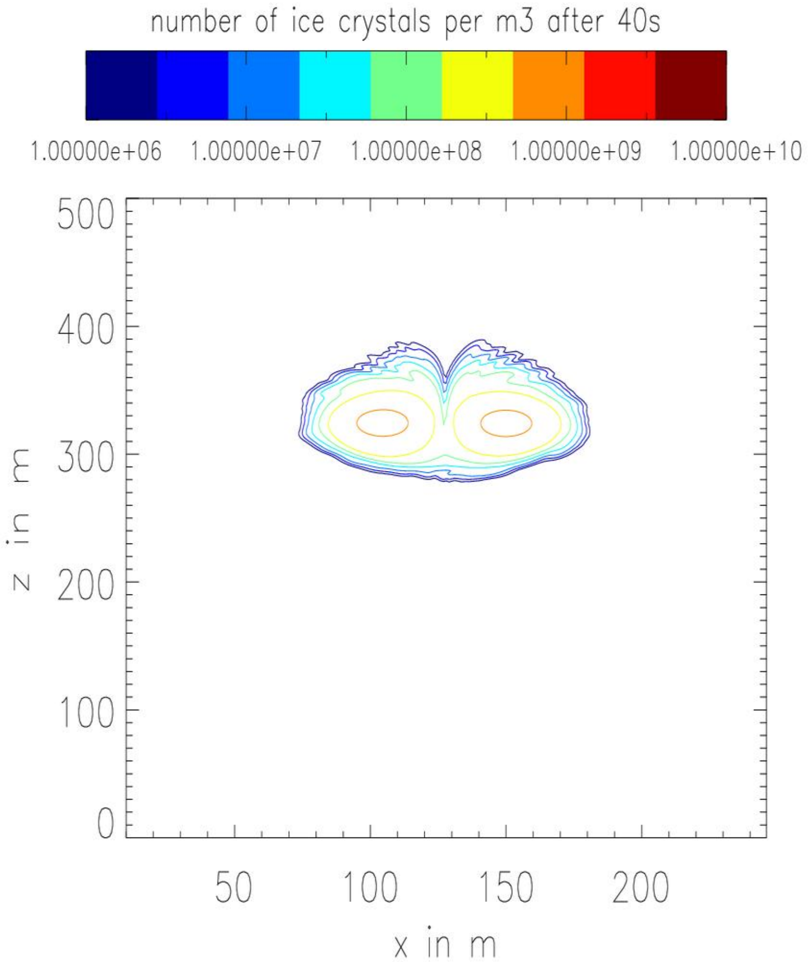

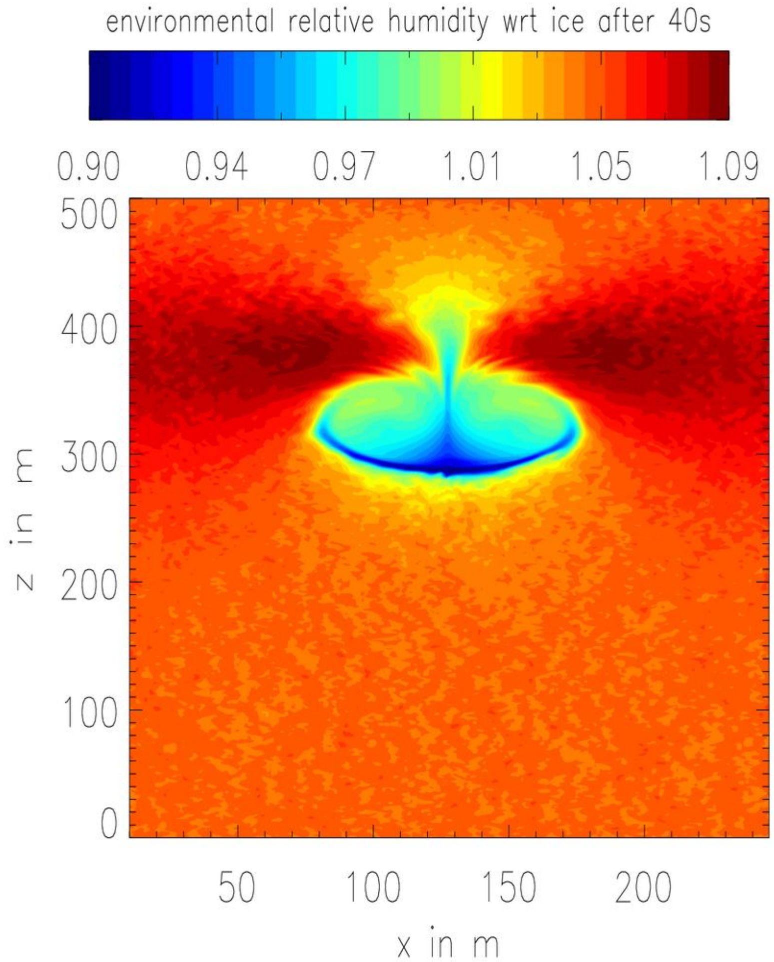

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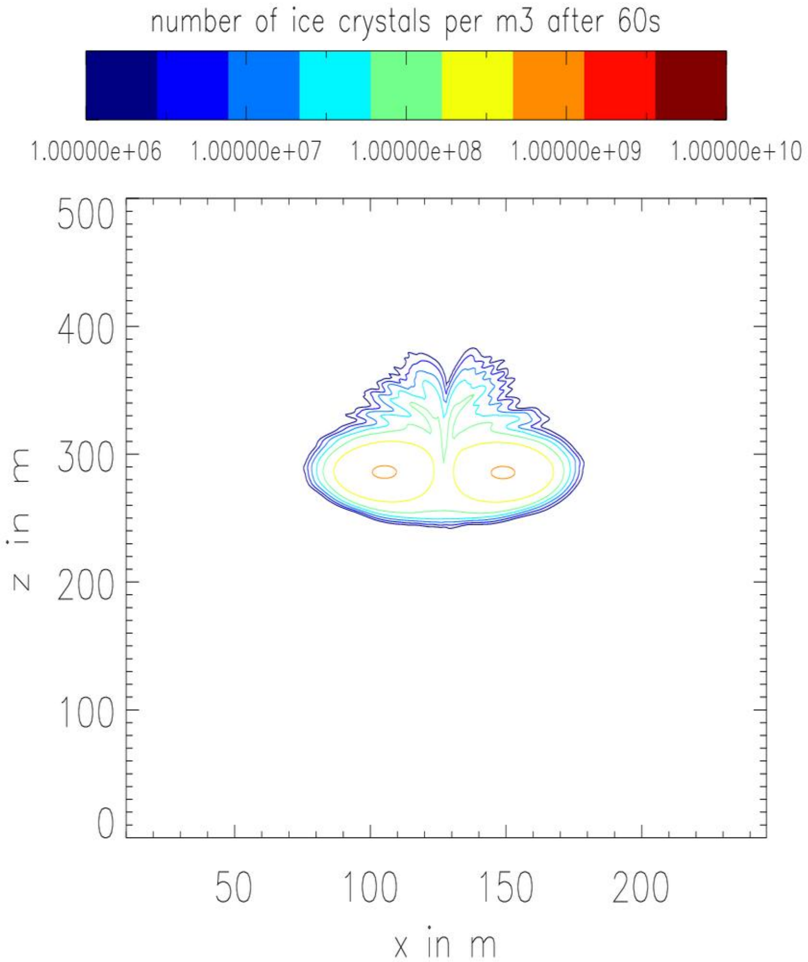

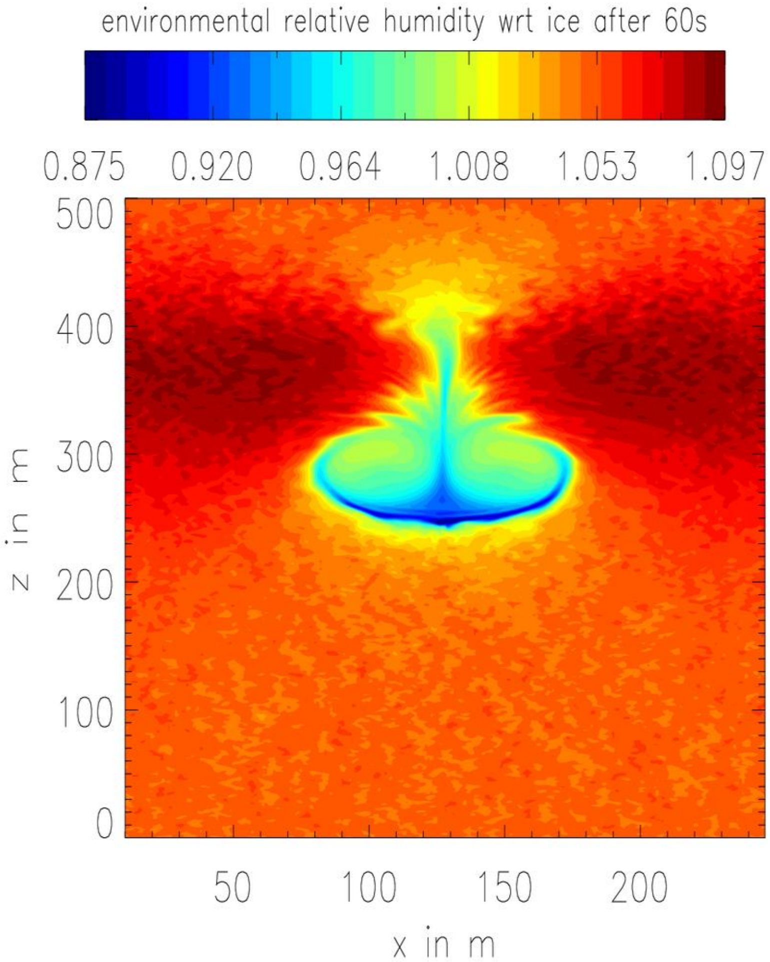

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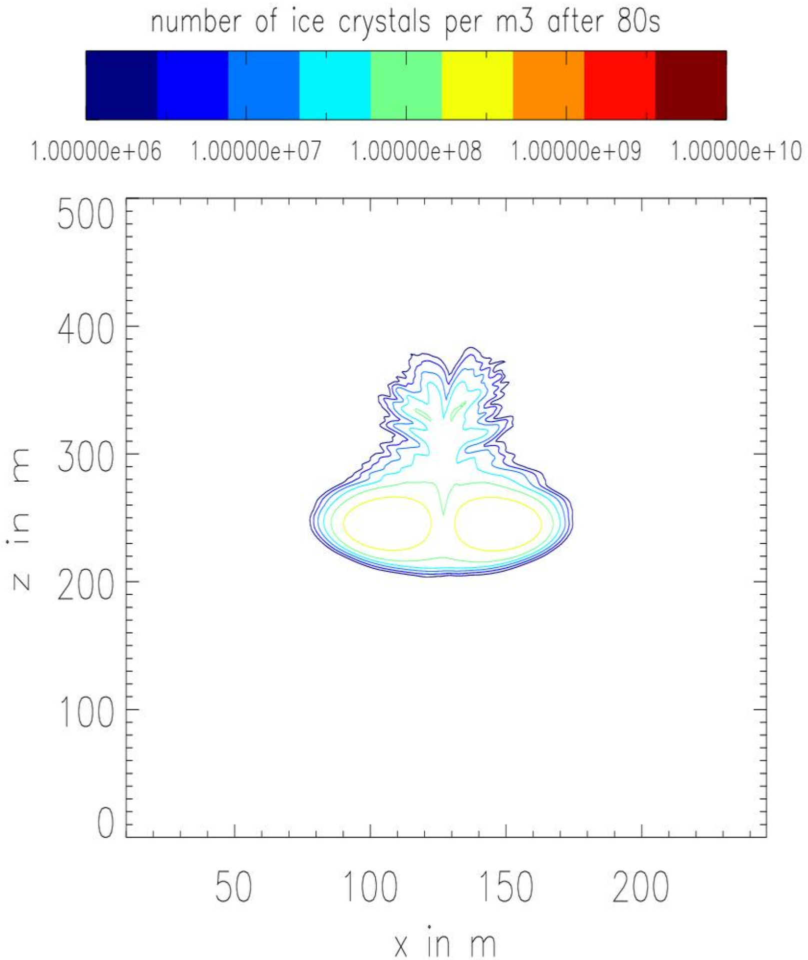

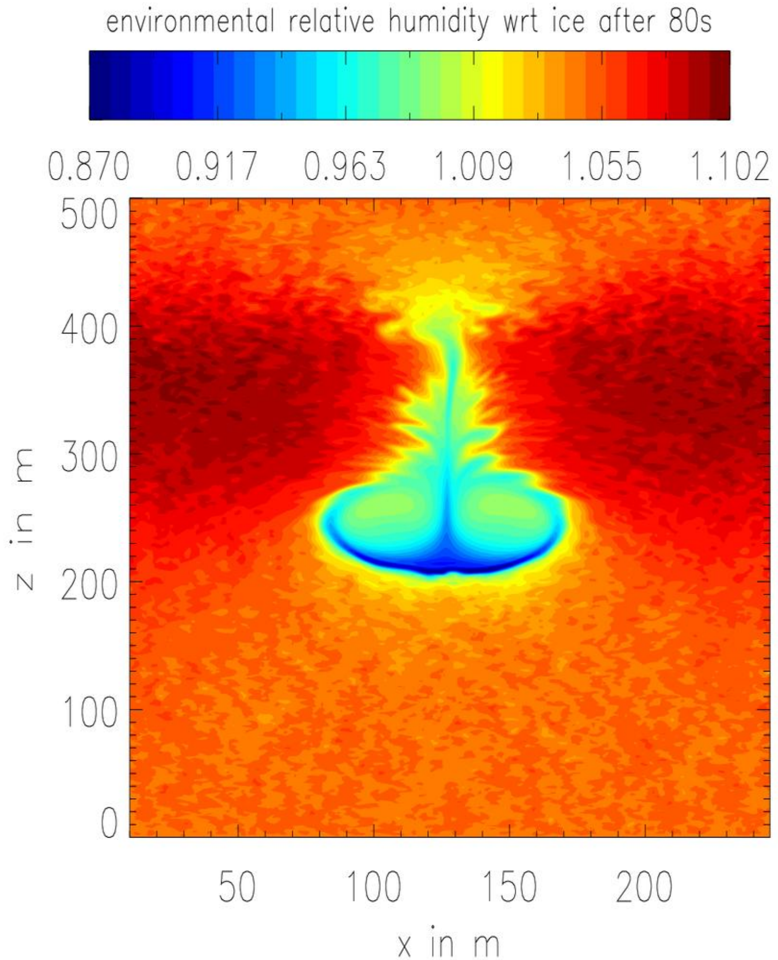

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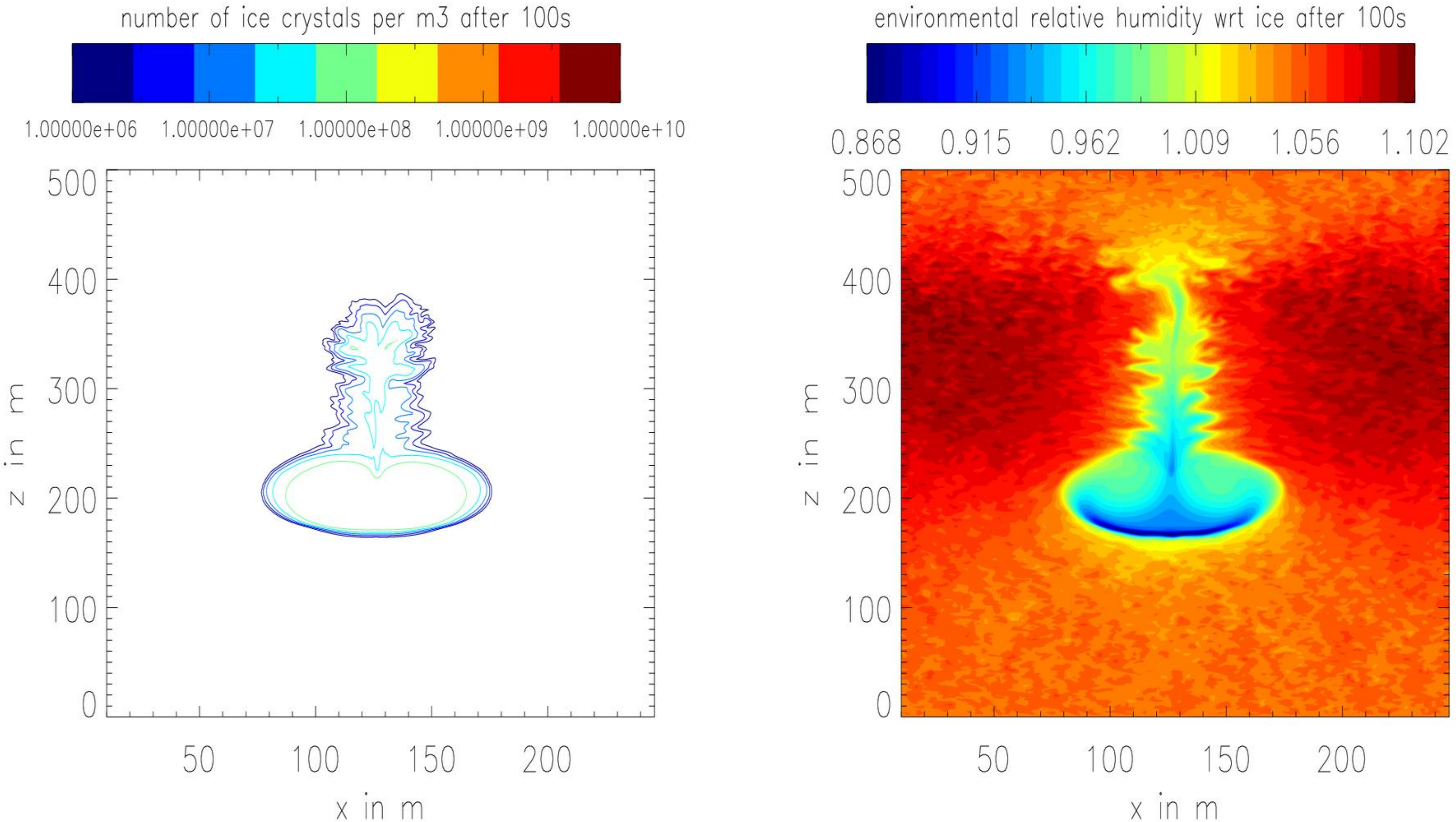

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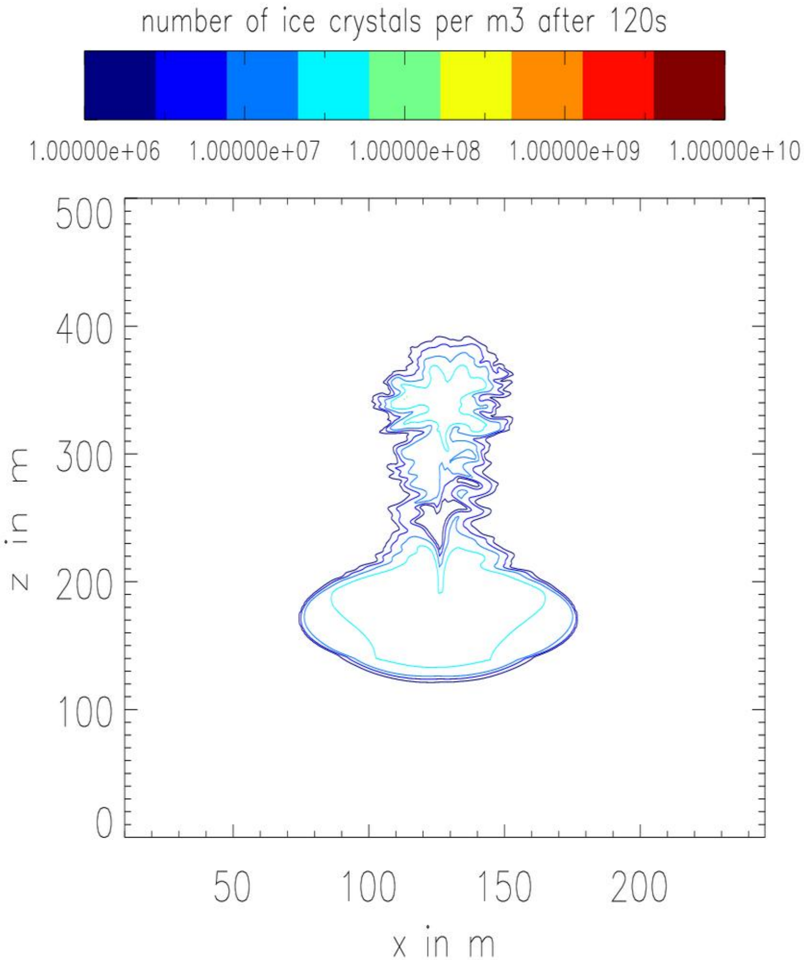
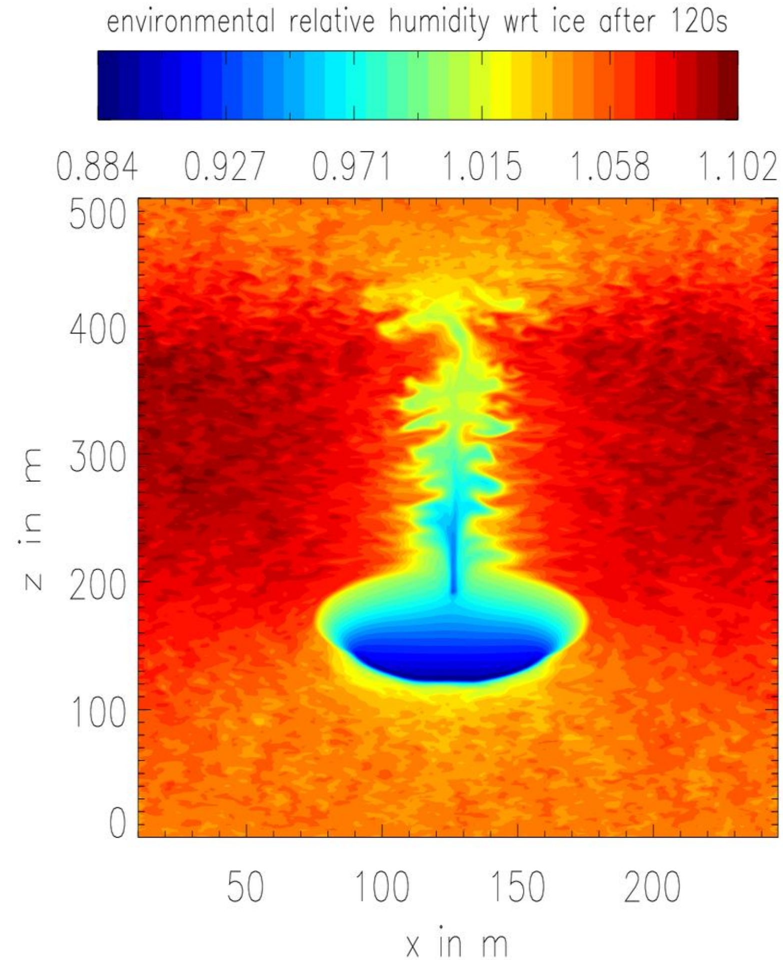
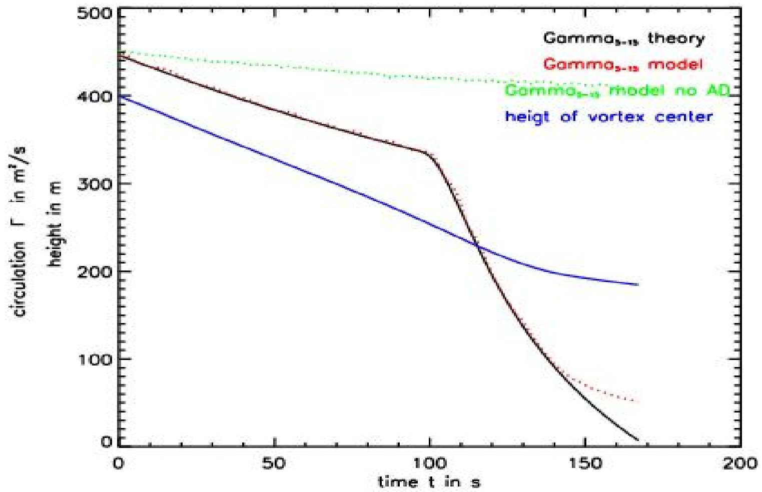




Simulations of the vortex phase – 2D approach

- 2D-code with adjusted vortex decay



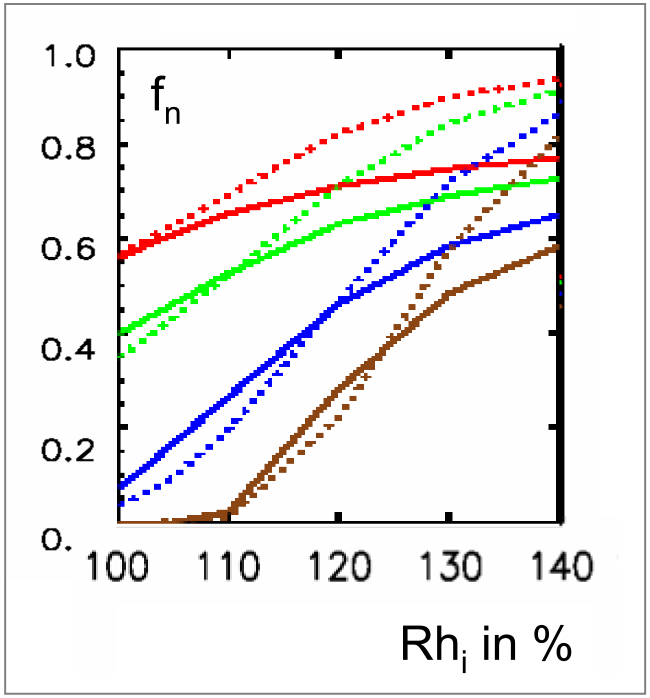
- Emphasis on microphysics
- Extensive parameter studies were carried out

Simulations of the vortex phase – Microphysical evolution, especially crystal loss (1/2)

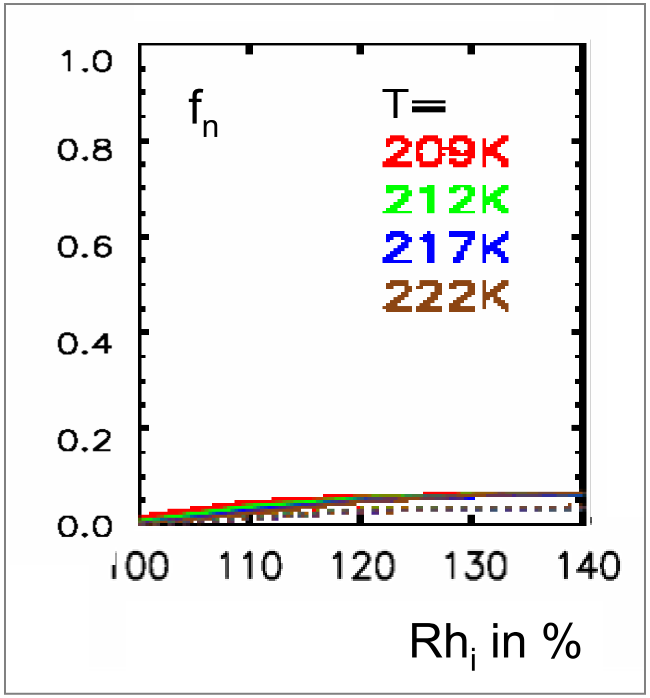
Fraction of surviving ice crystals f_n depending on relative humidity Rhi

T=
209K
212K
217K
222K

Primary Wake

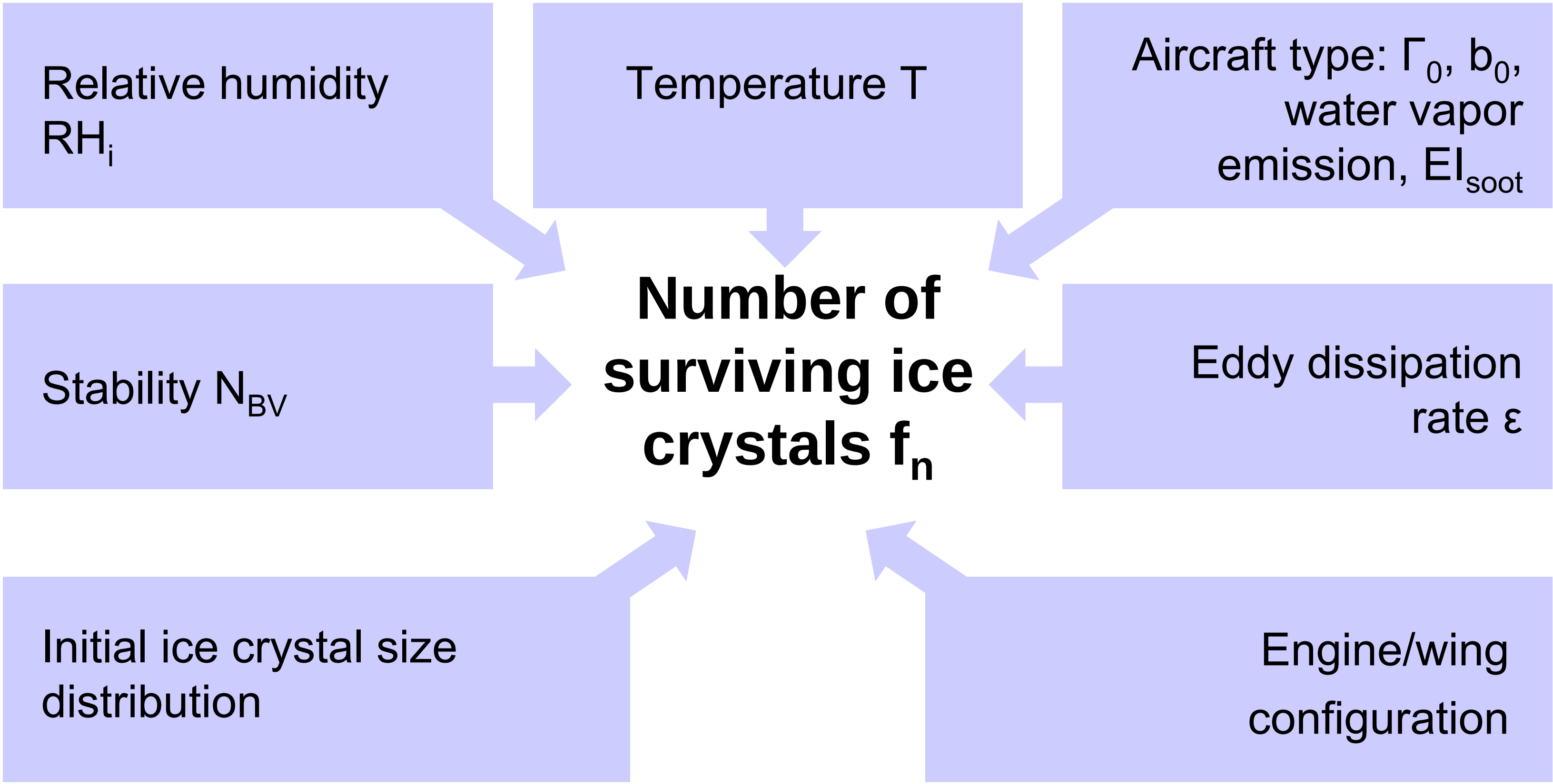


Secondary Wake



Unterstrasser & Sölch, in review, ACP 2010

Simulations of the vortex phase – Microphysical evolution, especially crystal loss (2/2)



Simulations of the vortex phase – Setup of 3D simulations (1/2)

Ongoing

- Include initial turbulent fluctuations and analytical vortex definition
- Microphysical approach: Lagrangian treatment of individual ice crystals. Each ice crystal stores its microphysical properties and subgrid-position.
  Much more precise than bulk microphysical models.
  Critical issues: memory-consuming, load-imbalancing, large amount of data
- Use 256 x 400 x 500 (spanwise, flight direction, vertical) = 52e6 grid points

Collaboration with I. Sölch, I. Hennemann, T. Misaka

Simulations of the vortex phase – Setup of 3D simulations (2/2)

Ongoing

- Resolution: dx = dy = dz = 1m , dt = 0.02s
- Domain: Lx = 256m Ly = 400m Lz = 500m T = 200s - 300s
- Nr. of processor: 320
- Wall clock time: 35 hours
- One typical simulation runs >10e4 CPUh
- 1.5Gb oder 3Gb memory per core, 96Gb memory/node
- Serial post-processing simulation, memory consumption reduced by declaring less arrays

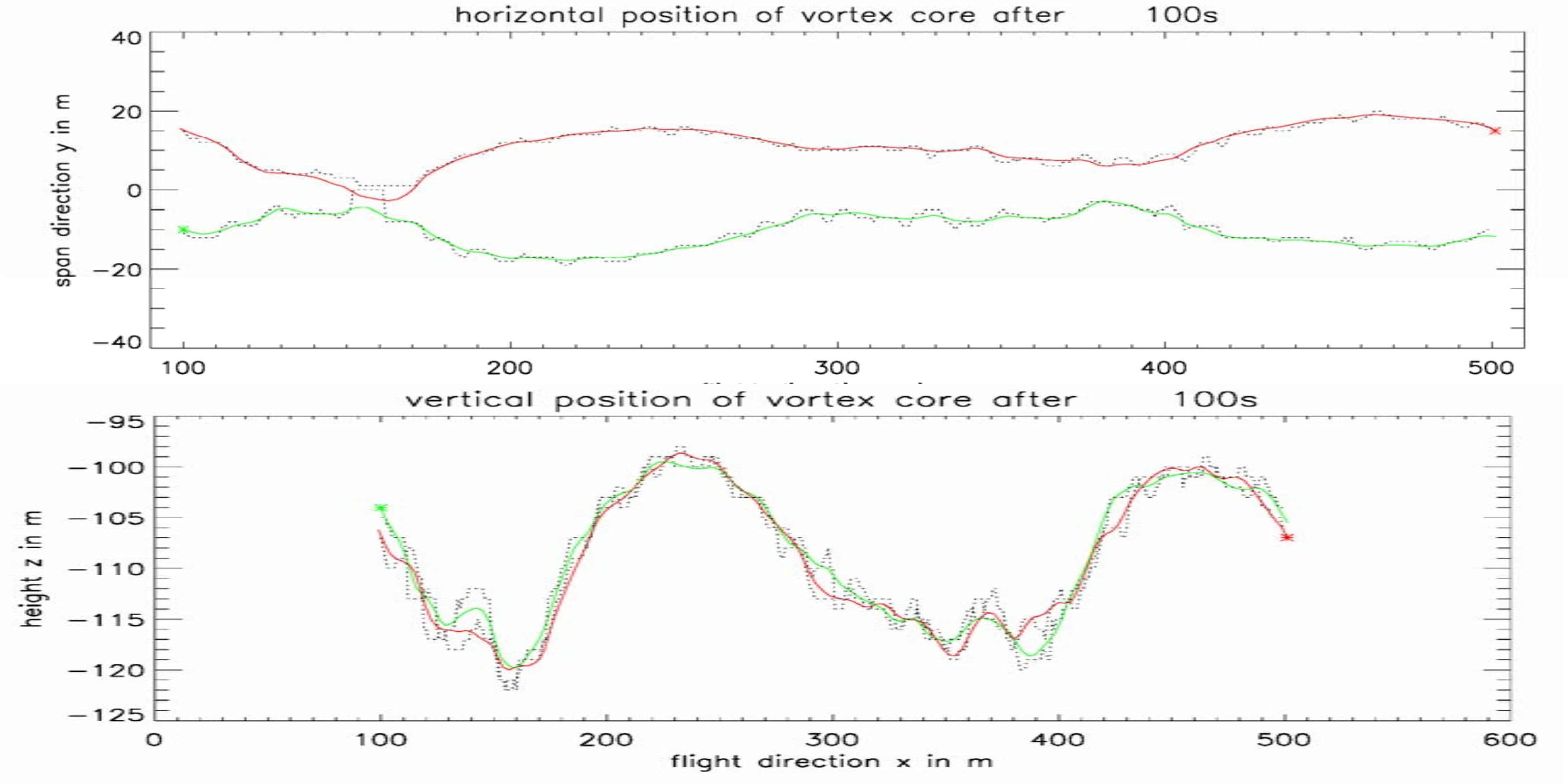
Collaboration with I. Sölch, I. Hennemann, T. Misaka

First results

A319 in a calm, neutral atmosphere

Ongoing

Evaluation of vortex cores with a newly developed tracking algorithm (I. Hennemann, PhD 2009)



Simulations of the vortex phase – Analysis of 3D simulations

Ongoing

- Now better representation of dynamics than in 2D model
- Plan: compare wake vortex evolution with two other numerical models (LESTUF and MGLET)
- Investigate descent speed, core radius, circulation, time of vortex linking, final vertical displacement
- Entrainment of moist air into the vortex system, detrainment of ice crystals out of it
- Advantage: EULAG only code coupled with microphysics to study contrails.

Collaboration with I. Sölch, I. Hennemann, T. Misaka

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Simulations of the dispersion phase – Numerical setup (1/2)

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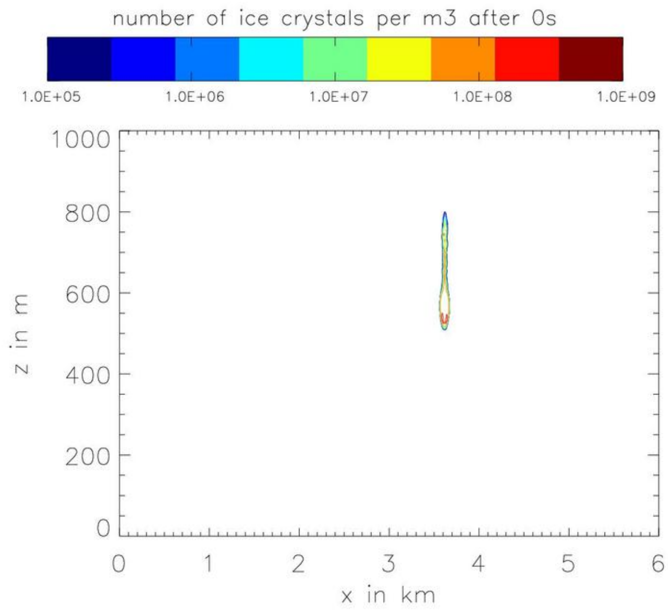
Bulk Microphysics
- Solves equation for ice mass concentration and crystal number concentration
- Bulk approach assuming lognormal size distribution in each gridbox
- Spichtinger&Gierens, 2009

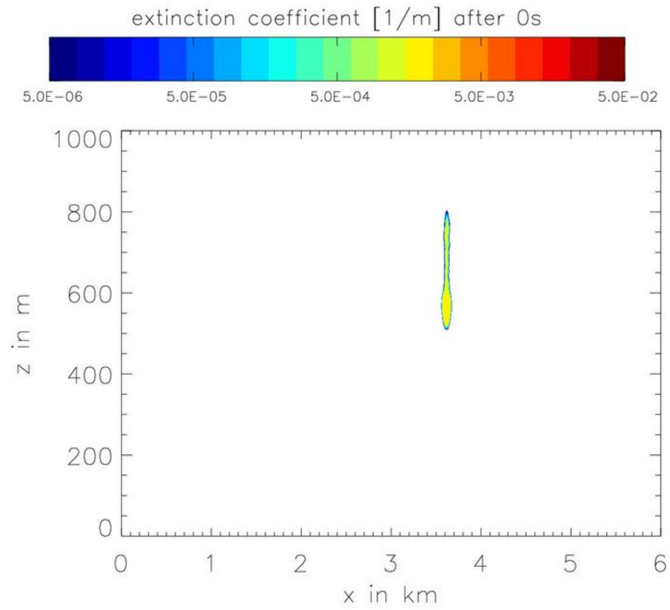
1D radiation routine
- Solar and thermal spectrum
- Atmosperic constituents and water/ice clouds
- Fu & Liou, 1996, …

Simulations of the dispersion phase – Numerical setup (2/2)

- One simulation run is divided in two subsequent sub-simulations with different resolutions and domains
- Resolution: dx1 = dz1 = 5m, dt1 = 1 - 2s,
  later dx2 = 10 - 20m, dz2 = 10m, dt2 = 5 - 10s
- Domain: Lx2 = 30km, Lz2 = 2km, T_{total} = 2 - 6h
- Nr. of processor: 32 or 64
- Wall clock time: 30 min to 2h

Simulations of the dispersion phase – Example (T = 217K, Rhi = 130%, s = 0.006s^{-1})





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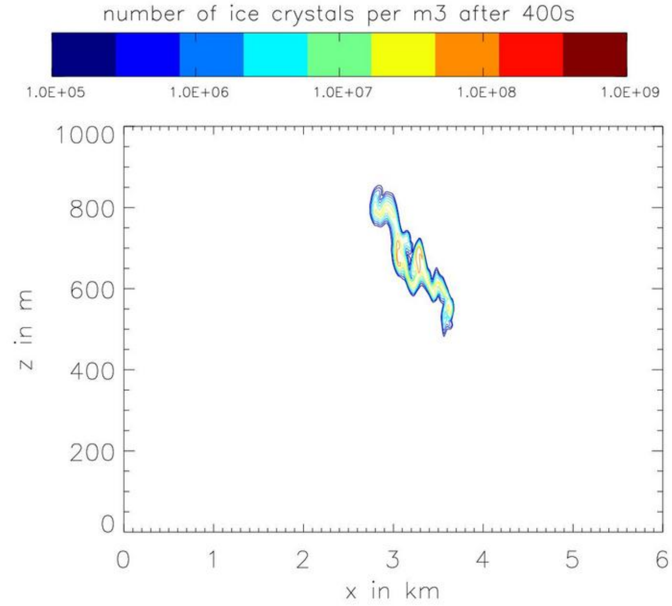

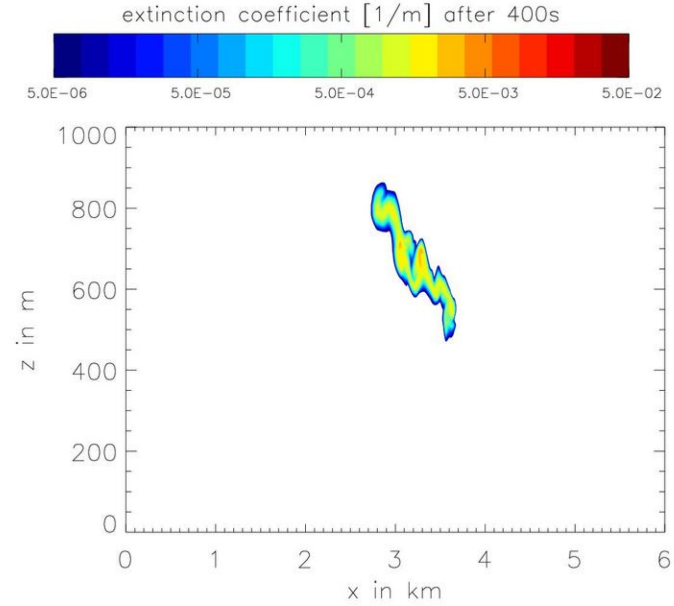

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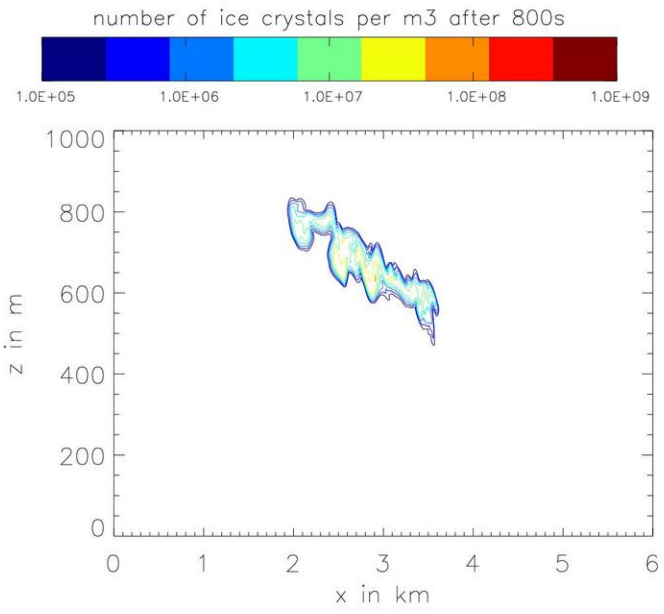

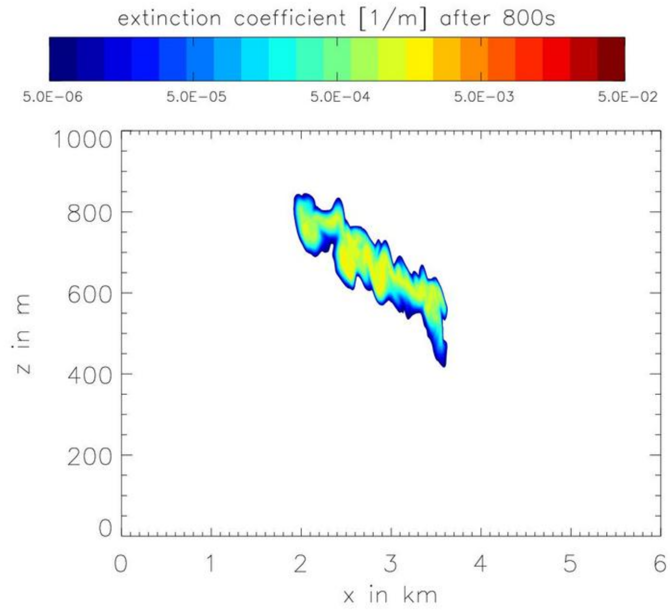

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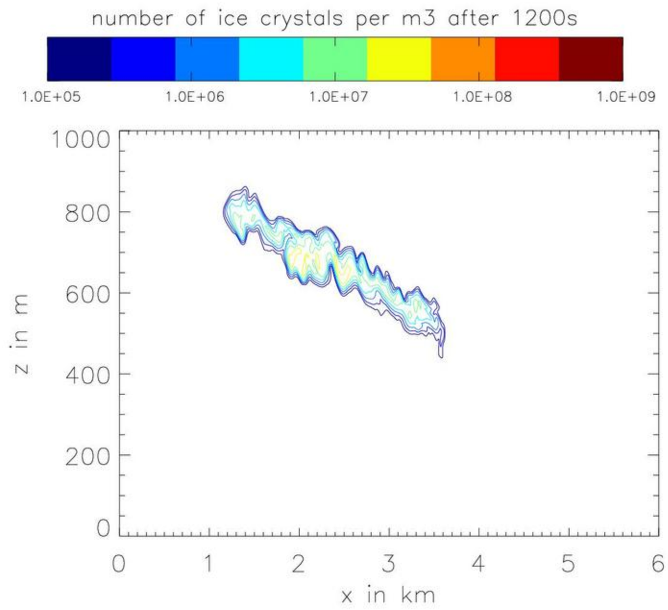

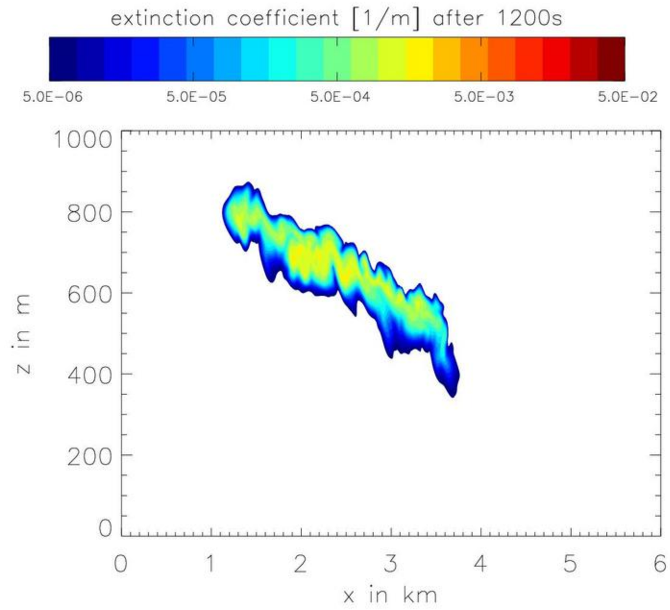

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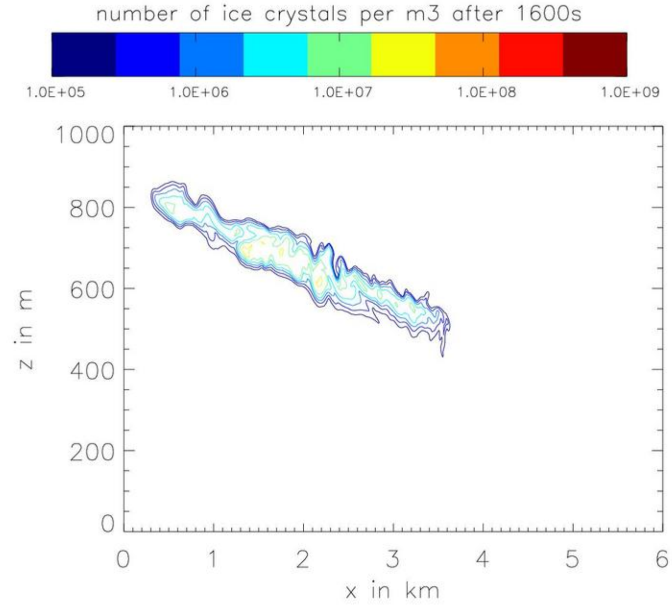

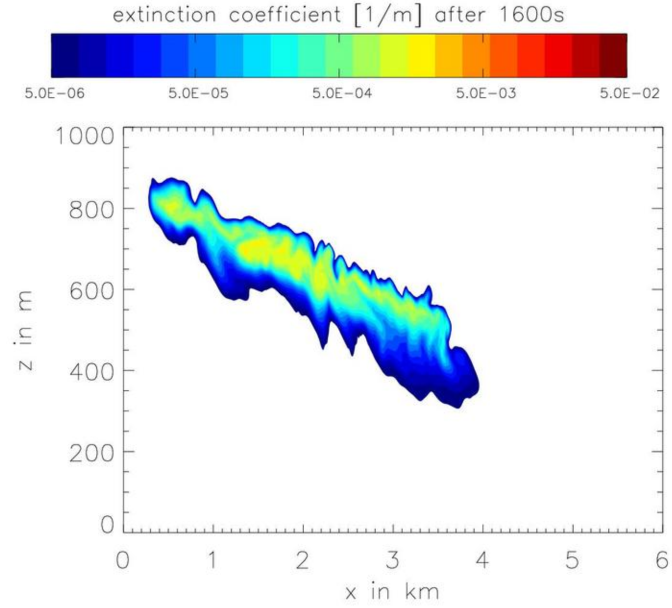

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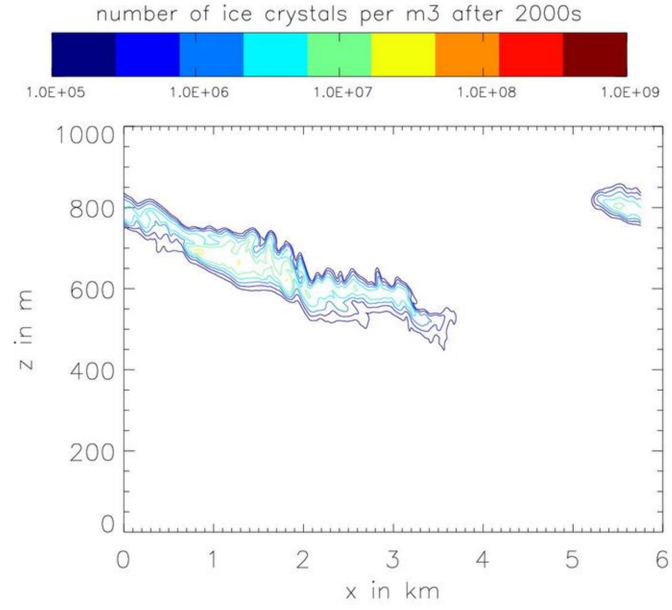

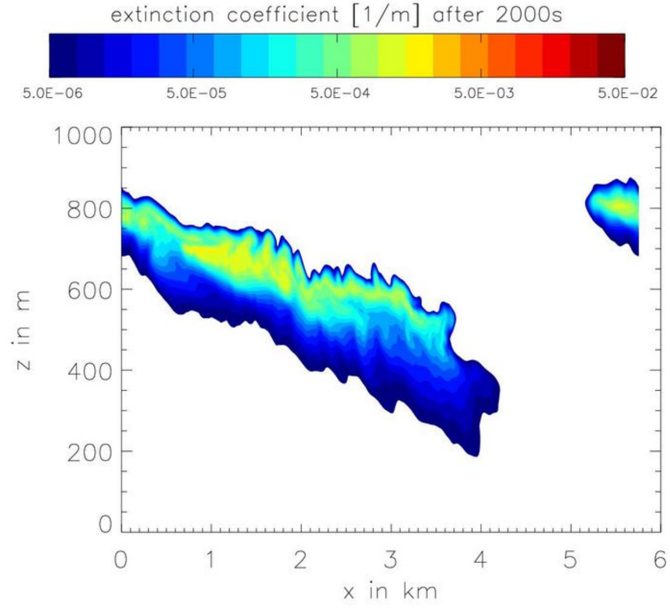

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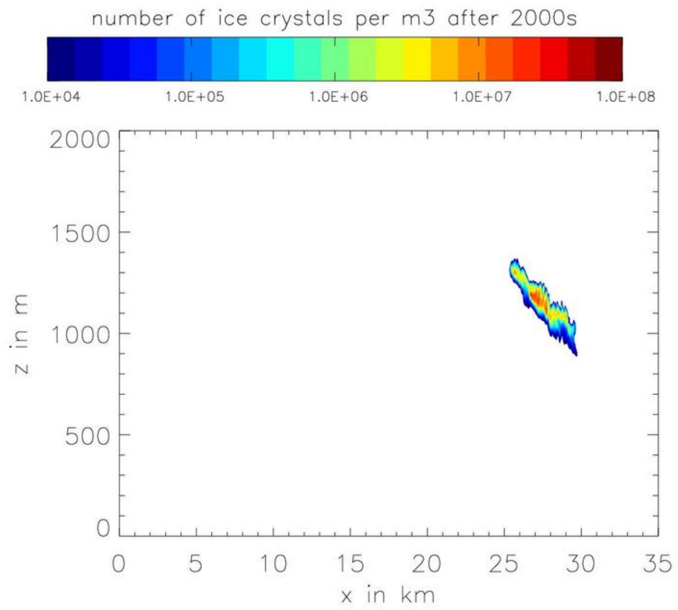

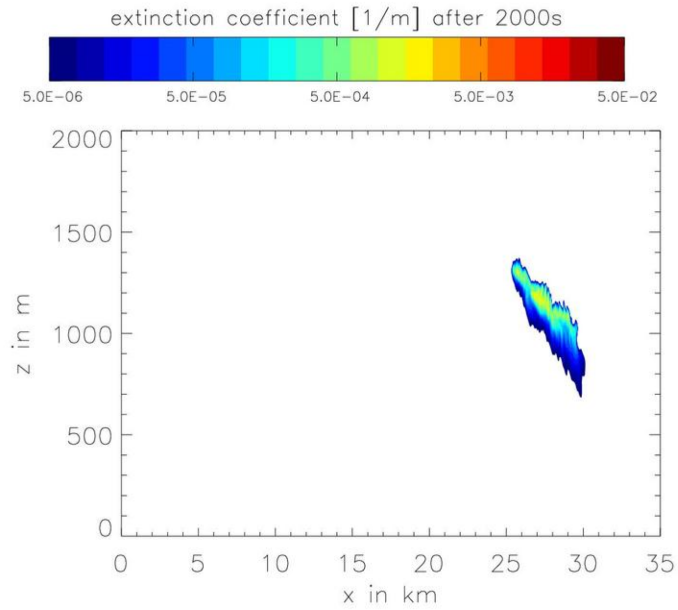

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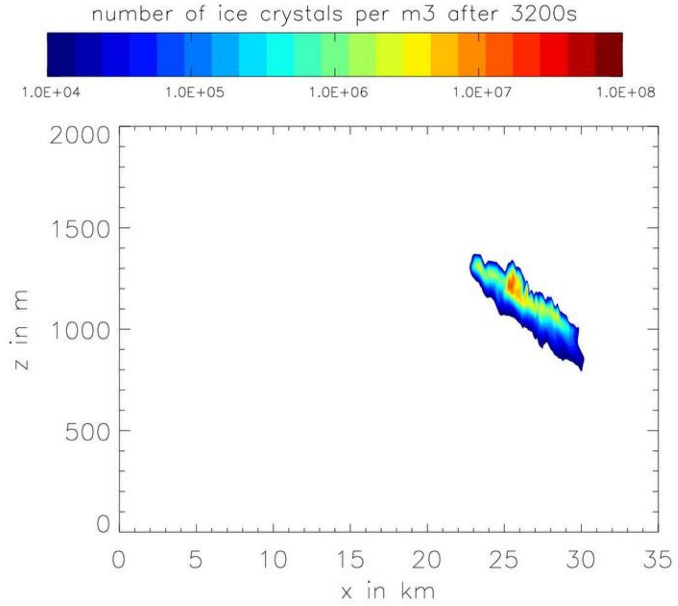

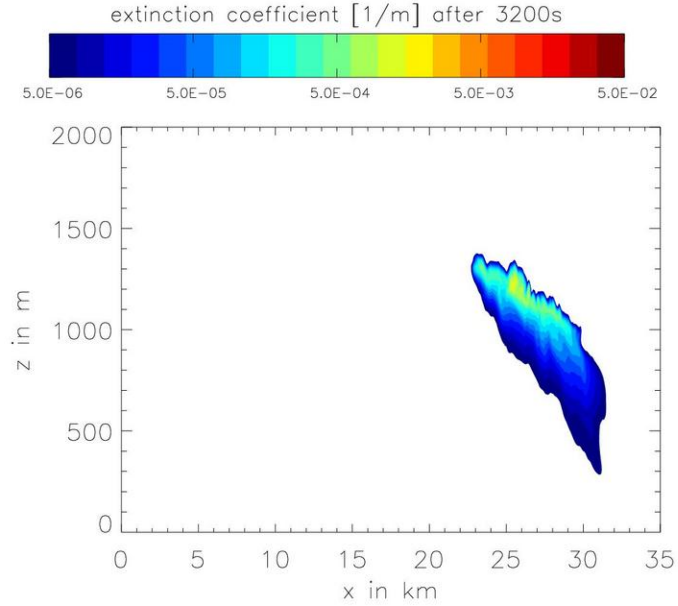

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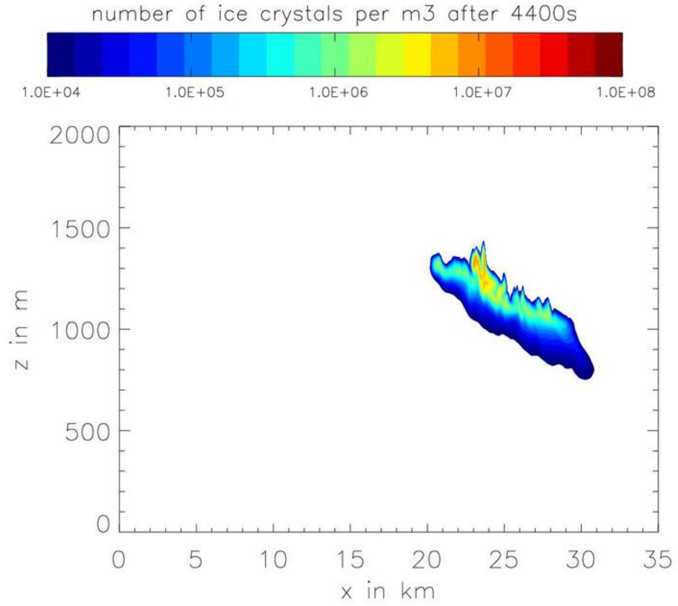

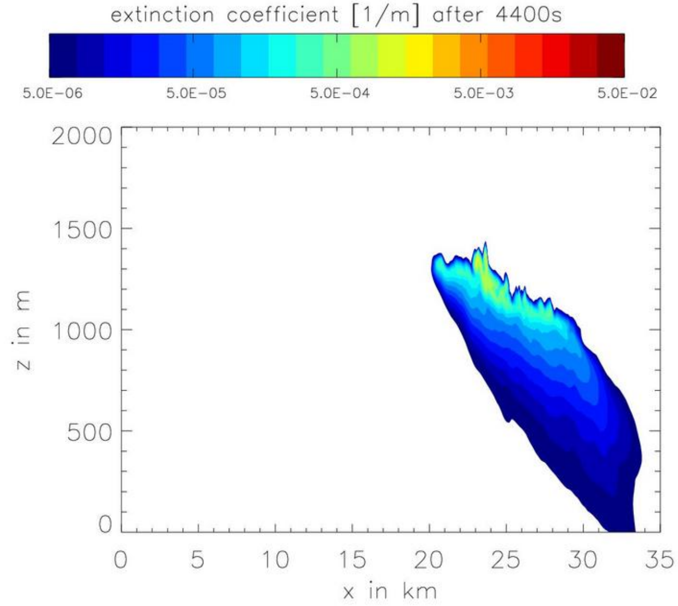

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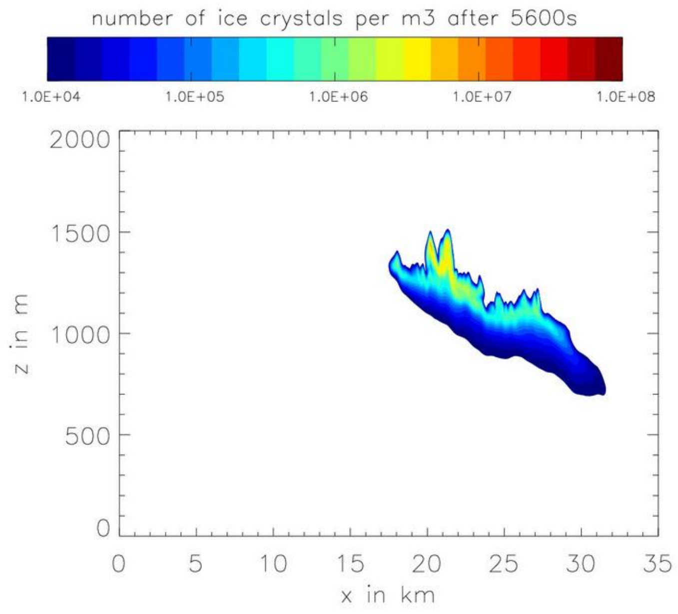

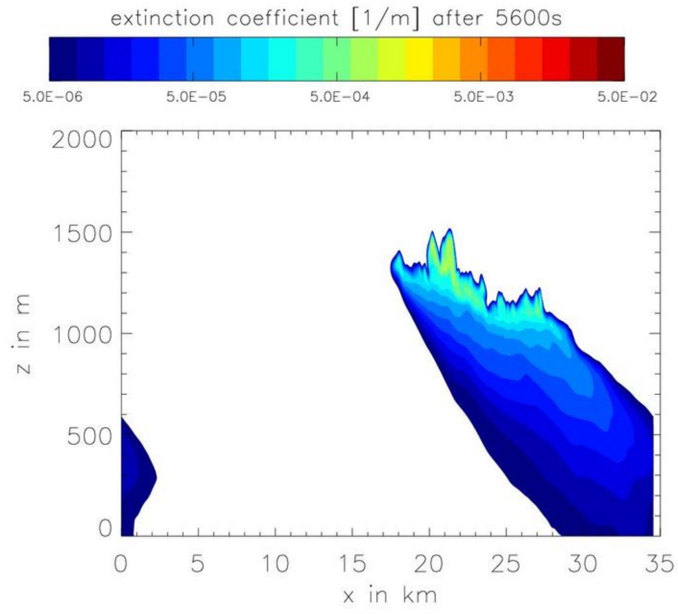

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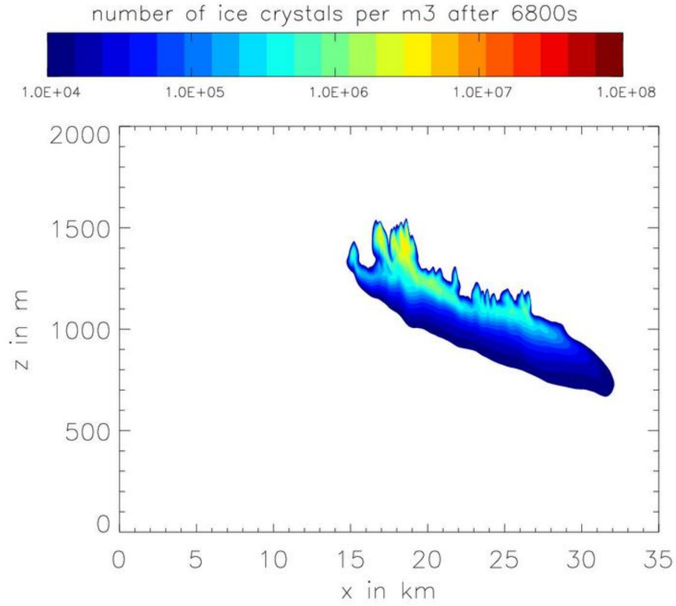

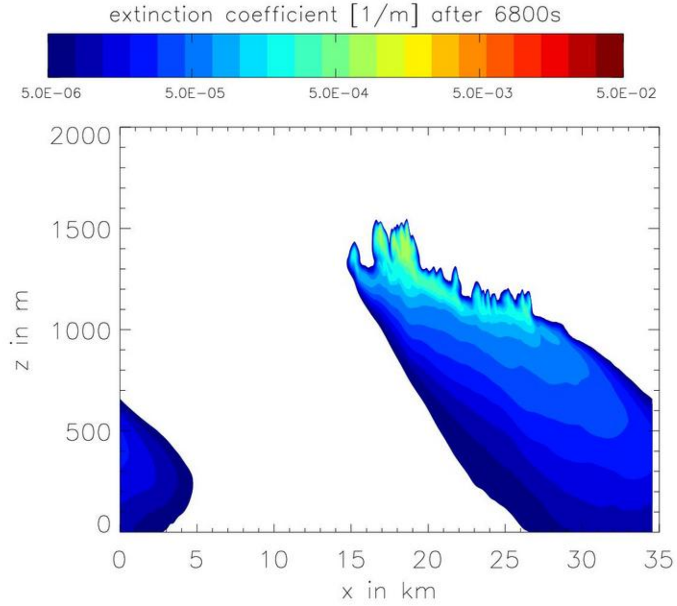

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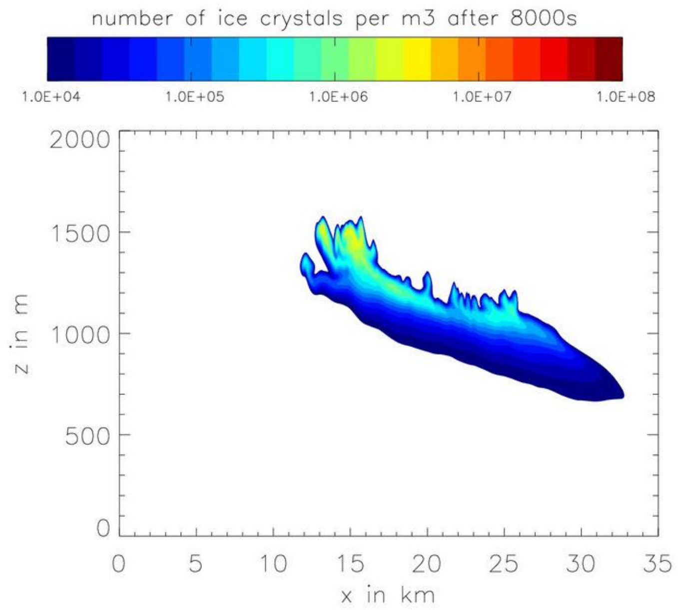

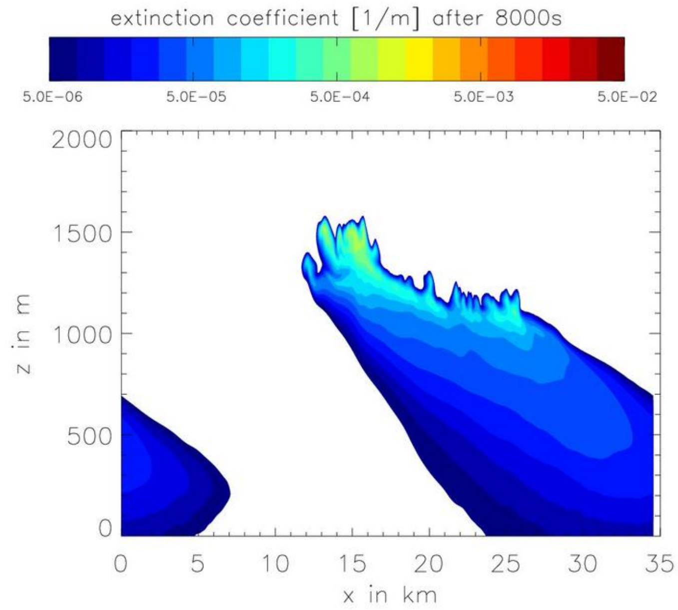

Simulations of the dispersion phase

- Investigate the impact of ambient parameters like **relative humidity, temperature**, **vertical wind shear** and **stability** on the contrail-to-cirrus transition
- So far: Individual contrails mainly in steady atmosphere
- Some cases with steady synoptic uplift (not explicitly resolved) External forcing on temperature equation

$$\frac{d\widetilde{T}_e}{dt} = \frac{dT_e}{dt} + w_0 \Gamma_d$$

- Impact of radiation on contrail evolution
- Study microphysical and initialisation uncertainties

Simulations of the dispersion phase – Plans for the near future

Status:

- So far idealized studies, now efforts towards more realism.
- Within a 3-year project (funded by the German Science foundation) the existing contrail-to-cirrus model setup will be improved in several aspects.

Simulations of the dispersion phase – Plans for the near future

Goals:

- Interaction of several (or many) contrails and formation of contrail clusters, study saturation effects in areas of heavy air traffic
- Consideration of synoptic evolution
- Coupling with real data (NWP output or analysis data)
- Competition of contrails and naturally forming cirrus
- Follow the whole life cycle of contrail clusters over days on regional scale (Lx~O(100km))

Simulations of the dispersion phase – Plans for the near future

Modifications (1/2):

- Switch to 3 dimensions
- Flexible initialization of contrails in time and space
  - depends on ambient conditions and aircraft type
  - allow for possible use of real aircraft flight data
- Inclusion of synoptic evolution
  - idealized via cooling rate
  - *Better:* coupling with real data
    advection of LES-domain with mean wind?
    Relaxation of which variables? wind only, moisture field

Simulations of the dispersion phase – Plans for the near future

Modifications (2/2):

- Increase horizontal scales (100km x 100km) and vertical scale (~5km) ⟶ massively parallel
  - 3D domain decomposition desirable
  - is it possible at all to have 2000 x 2000 x 200 grid points?
  - adapt microphysics and online-analysis tools for massively parallel application

Acknowledgement

- Piotr and the EULAG developers
- P. Spichtinger for the bulk microphysics code, I. Sölch for the LCM code
- Andreas Dörnbrack for introduction to and assistance with EULAG
- DKRZ and ECMWF for computer resources

Questions?

Comments?

Ideas?

Recommendations?

References
Contrail studies using EULAG

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