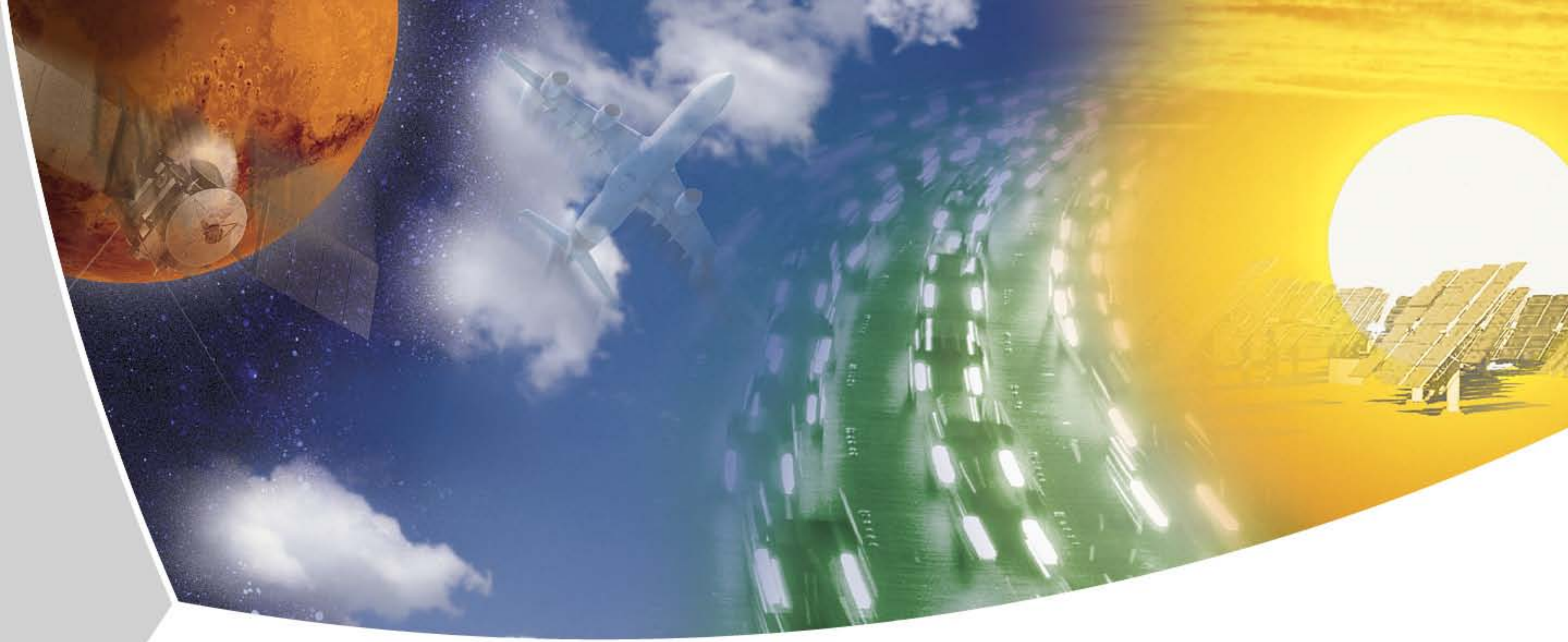

A large eddy model for cirrus clouds with explicit aerosol and ice microphysics and Lagrangian ice particle tracking - EULAG LCM

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EULAG Workshop II

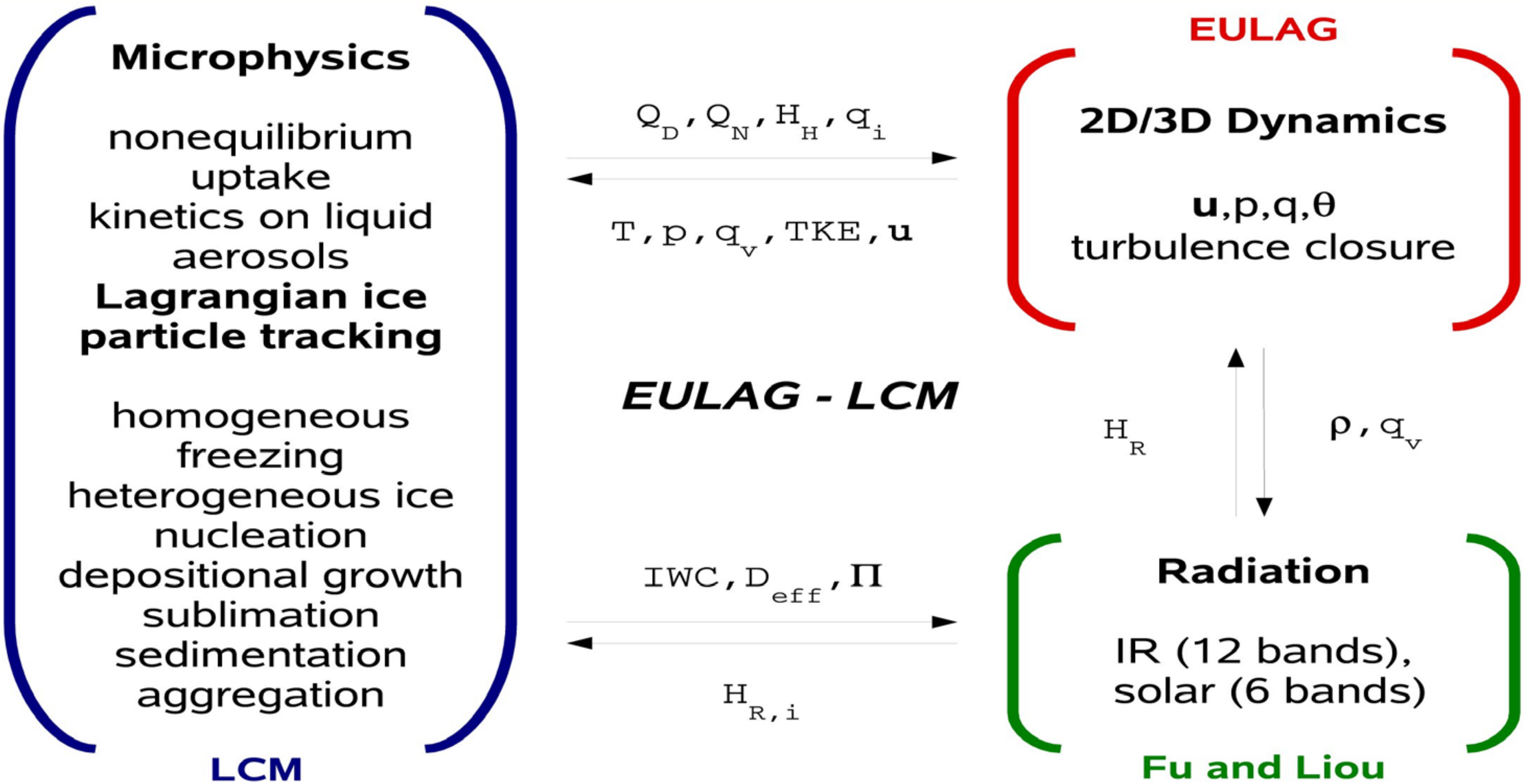
Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Outline

- The model system EULAG - LCM
- Technical aspects
- Examples for model output - Case Study ARM IOP 9 March 2000
- Outlook

Lagrangian ice crystal tracking module (Overview)

The EULAG-LCM (Lagrangian Cirrus Module) is a cirrus-cloud resolving Large Eddy simulation (LES) model to study the formation and persistence of cirrus clouds and contrails, forming below 235 K.



Mixed Eulerian/Lagrangian two phase flow approach

Eulerian approach (continuum)

- fluid variables
- water vapour
- trace gases and size-resolved aerosols

Lagrangian approach (dispersed phase)

- ice crystals

Assume typical upper-tropospheric conditions (T=220 K; p=300 hPa)
In an air volume of 1 cm^3 :

- 10^{19} air molecules
- 10^{14} - 10^{15} water molecules

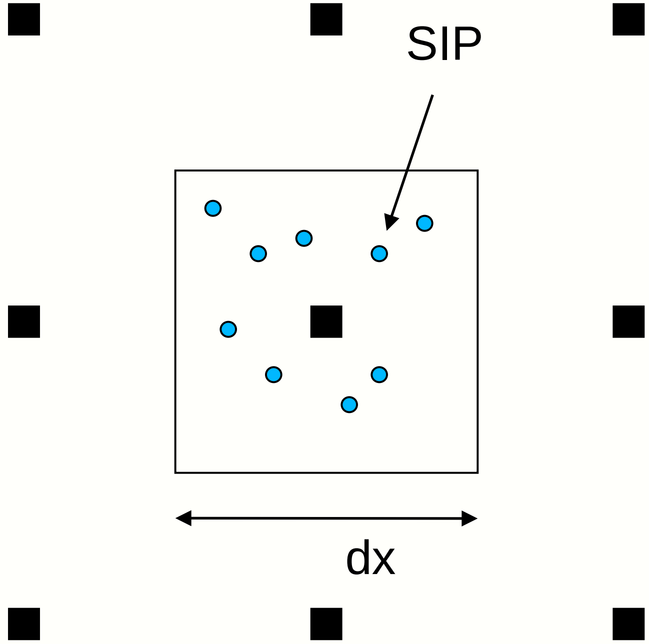
- at most on ice crystal

-> Treating the air as continuum and the ice phase as dispersed particles appears to be well suited for cirrus cloud simulations

Mixed Eulerian/Lagrangian two phase flow approach

To treat the ice phase, the LCM employs Lagrangian ice particle tracking, in which a large number of simulation ice particles (SIP), serving as surrogates for real ice crystals, are transported and modified in the trubulent flow field.

In the EULAG grid:



Main assumptions:

i) The macroscopic properties of the ice phase can be deduced from the knowledge of the properties of a limited number of SIP

ii) The SIP interact with the gas phase using the volume averaged values at the grid point

Coupling to the EULAG model equations

$$\frac{d\mathbf{u}}{dt} + f\mathbf{k} \times \mathbf{u}' = -\nabla\left(\frac{p'}{\overline{\rho}}\right) + \mathbf{g}\frac{\theta'_d}{\overline{\theta}} + \mathbf{D_u}$$

$$\frac{d\theta'}{dt} = -\mathbf{u} \cdot \nabla\theta_e + \mathbf{D}_\theta + Q_R + Q_H.$$

$$\nabla \cdot (\overline{\rho}\mathbf{u}) = 0.$$

$$\theta' = \theta - \theta_e.$$

$$\frac{dq_v}{dt} = \mathbf{D}_{q_v} - Q_{DEP} - Q_{DIS}$$

Coupling to the EULAG model equations - issues

The small mass loading of ice crystals in air allows to neglect their influence on the air motion.

Advantages of the LPT approach:

+ Individual SIPs can be associated with statistic flags (chemical nature of ice precursor, habit, time dependent variables e.g. location, supersaturation).

+ We avoid numerical diffusion solving for the growth of the ice crystals or during sedimentation compared to a continuum approach.

Disadvantages:

- Higher computational demand (we track $O(10^6\text{-}10^7)$ SIP in a typical 2D simulation with one SIP representing $O(10^4)$ real ice crystals).

- Discrepancies between the treatment of turbulent dispersion in an Eulerian and Lagrangian approach.

Modelling turbulent dispersion

For the calculation of the trajectories of an individual SIP an additional turbulent velocity component is added to the grid scale velocities..

The standard deviation of these velocities is taken to be proportional to the turbulent kinetic energy per unit mass, which is prognosed in the EULAG model and is, therefore, consistent with the subgrid scale closure scheme of the underlying dynamical core.

Additionally the turbulent velocity components are assumed to be autocorrelated over the Lagrangian time scale.

$$\frac{d\mathbf{x}_{p,i}}{dt} = \mathbf{u} + (\tilde{\mathbf{u}_\mathbf{i}} + \mathbf{v}_{t,i})$$

$$\tilde{\mathbf{u}_\mathbf{i}}(t) = R_L \tilde{\mathbf{u}}_i(t - \triangle t_{MIC}) + \mathbf{u}_i^*(t)$$

$$\mathbf{u}_i^*(t) = \sqrt{1 - R_L^2}\, \sigma_u \, \xi \, ;$$

$$R_L = \exp(-\Delta t_M / \tau_L) \, ,$$

$$|\sigma_u| = \sqrt{TKE}$$

Process-oriented simulations on scales of single clouds

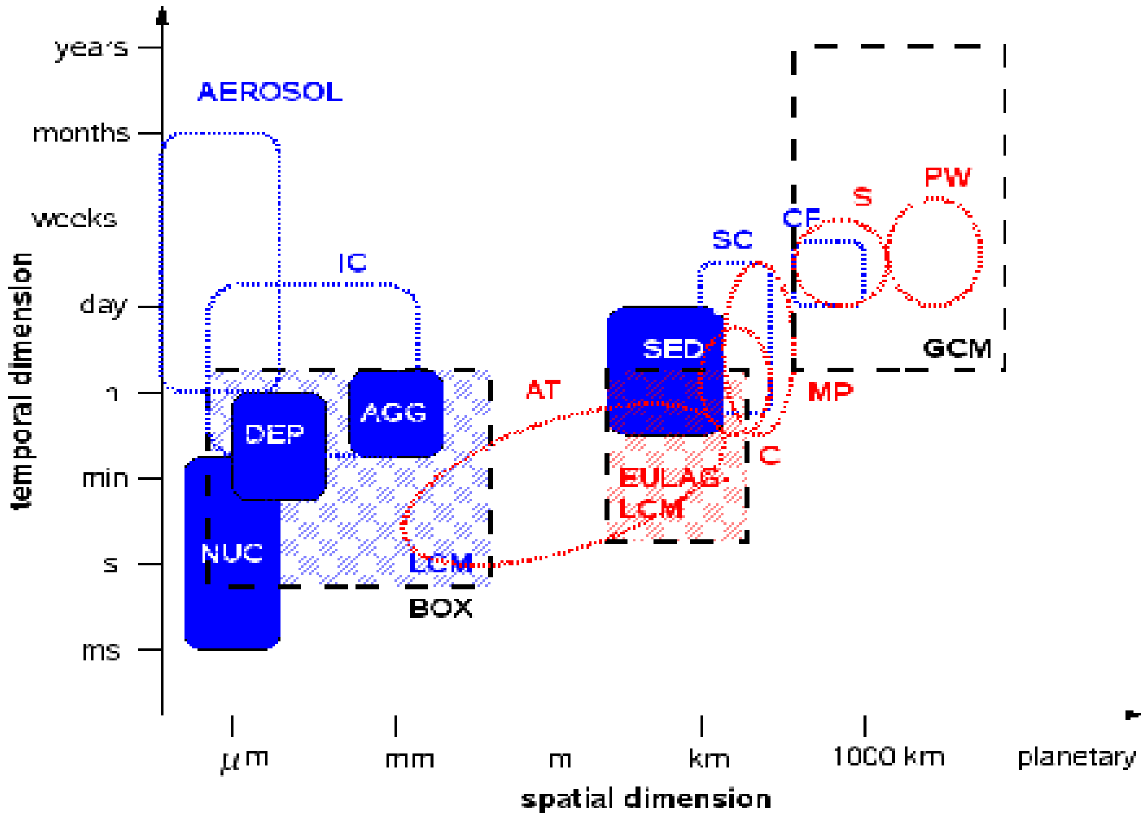
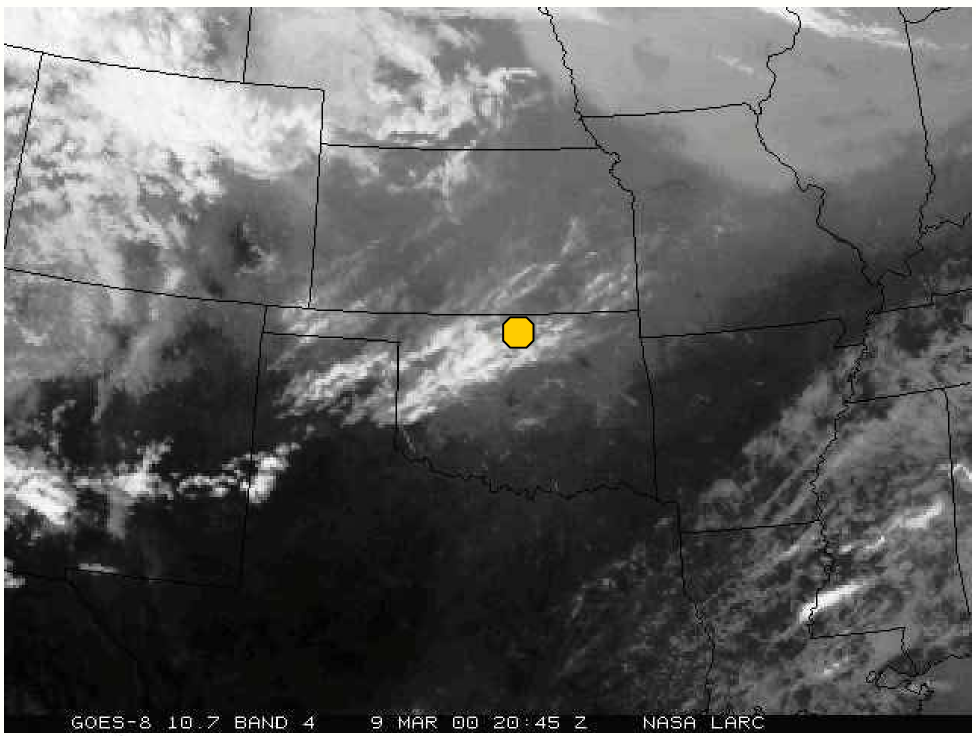
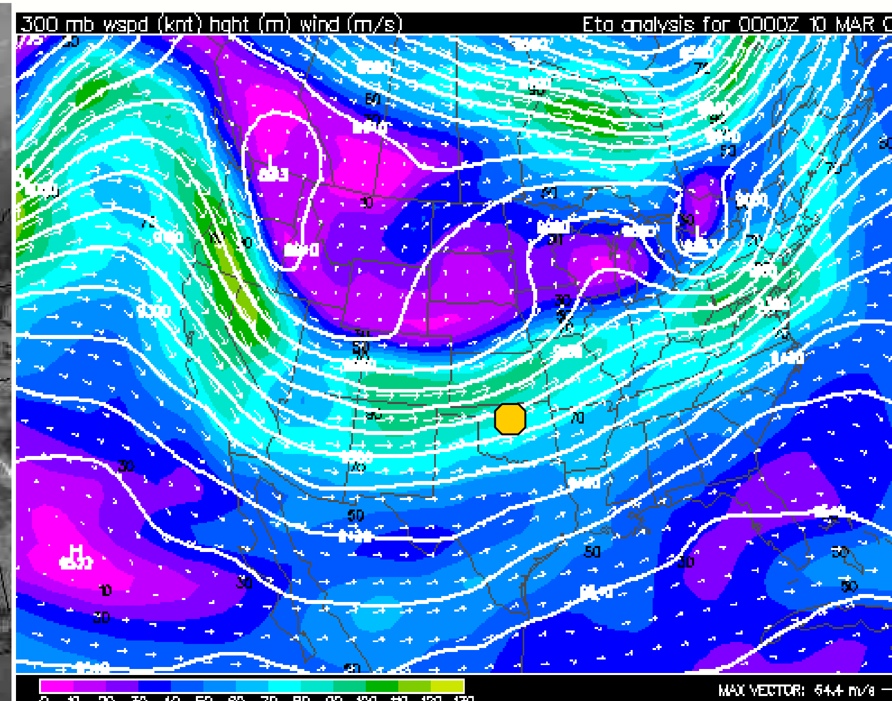


Figure 1. Typical scales of atmospheric motions (dotted red), cloud structures (dotted blue) and microphysical processes (blue boxes). AT - atmospheric turbulence; C - convection; MP - mesoscale processes; S - synoptic-scale processes; PW - planetary waves; AEROSOL - aerosol particles; IC - single ice crystals; SC - single detached clouds; CF - cirrus cloud fields; NUC - nucleation; DEP - depositional growth; AGG - aggregation; SED - sedimentation. Black boxes represent typical resolution and domain sizes of different numerical model approaches: BOX - box models; LCM - newly developed Lagrangian Cirrus Module; GCM - general circulation models.

Case Study ARM IOP 9 March 2000

As an example for the model perfomance we apply the EULAG-LCM to simulate the evolution of a cirrus cloud field observed during the U.S. Atmospheric Radiation Measurement Program Intensive Operations Period in March 2000. The data set allows us to evaluate and study the process-oriented representation of microphysical processes in great detail.





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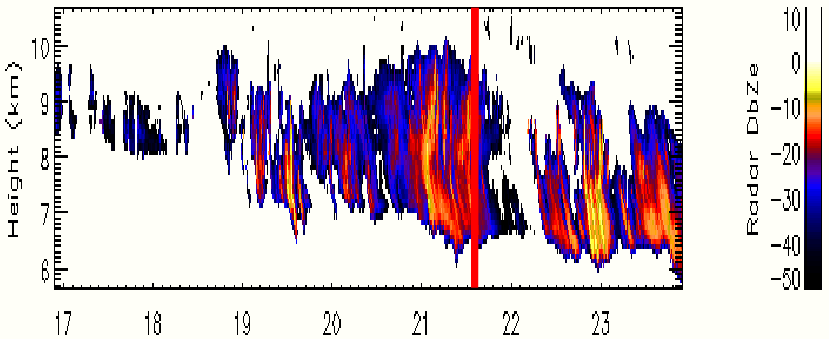
Simulation strategy

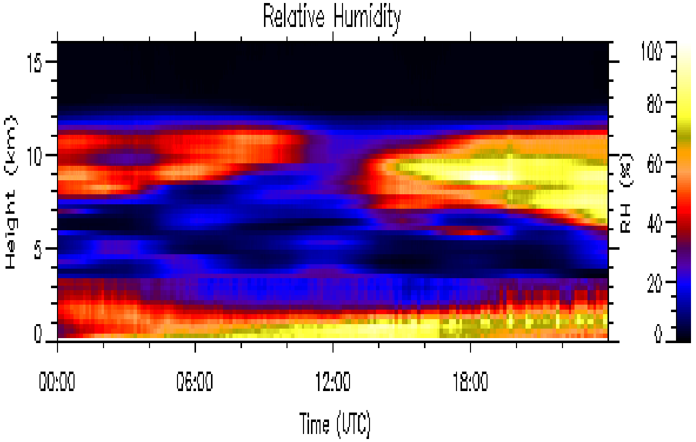
We simulated cloud formation and evolution in a 2-D or 3-D domain, initially located upstream of the site and oriented parallel to the prevailing horizontal wind direction. We follow the domain as it is advected across the site.

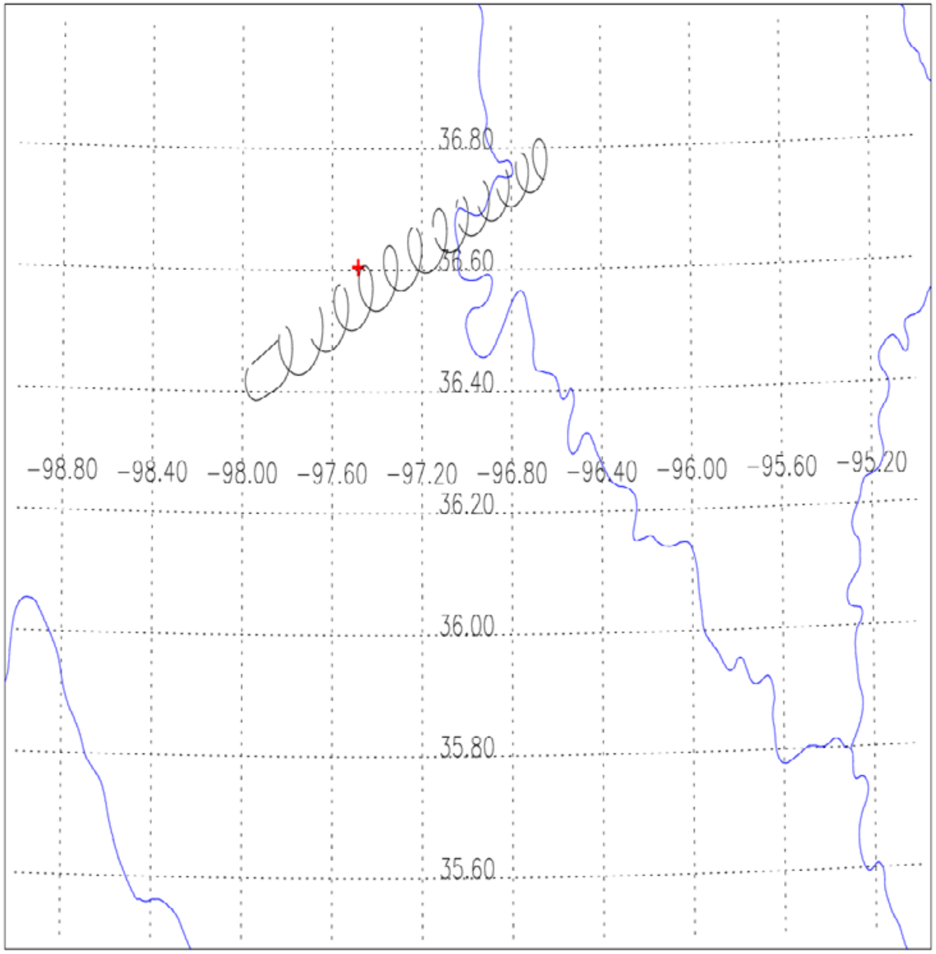
It is not possible to determine the exact moment and location when individual cirrus segments formed that where probed at the site. Hence there is no unique solution for the initialisation of the simulation.

The data sources, however, constrain the key initial profiles. Furthermore, we make plausible assumptions regarding possible ice nucleation pathways.

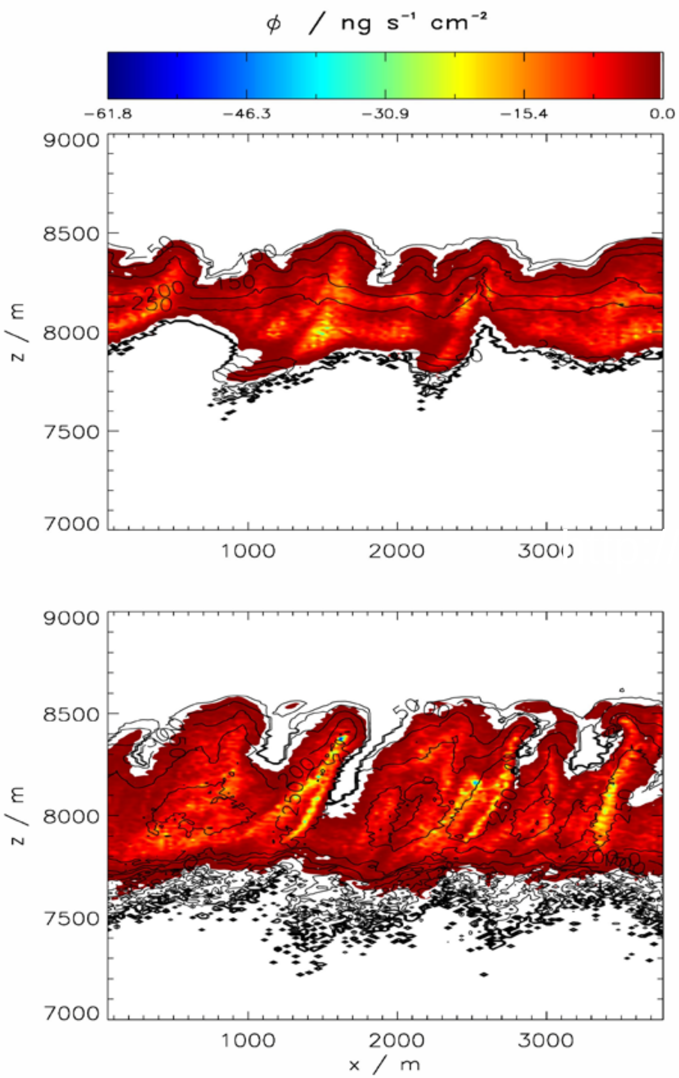
Data sources ARM IOP 9 March 2000

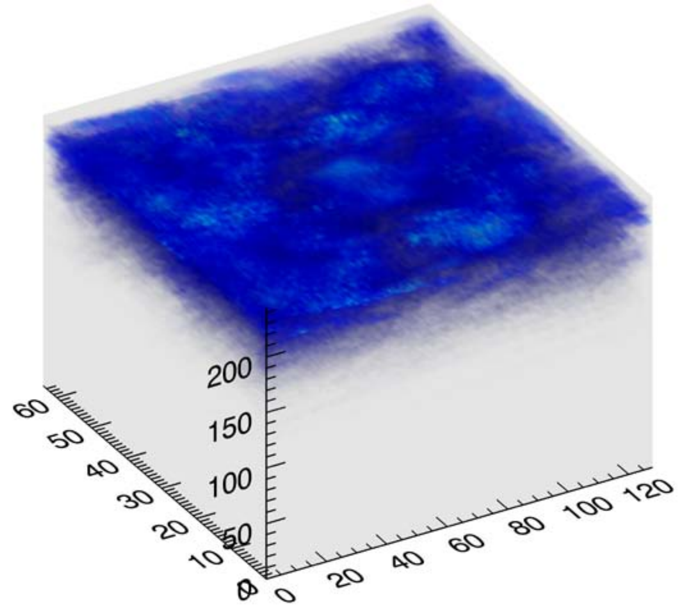






2D/3D simulation runs





2D/3D domain with periodic lateral boundary conditions.

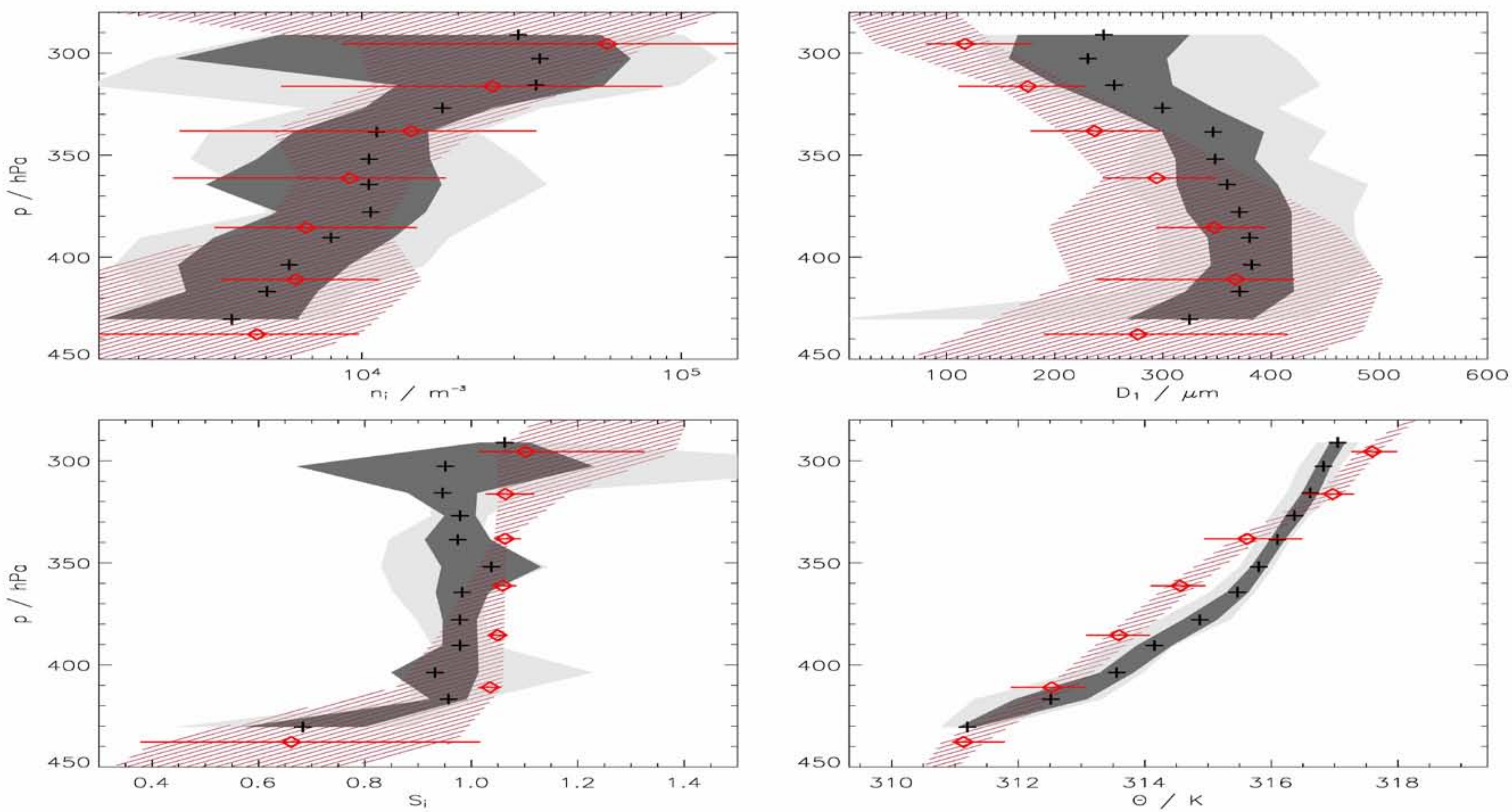
Dx=30 m, Dz=20 m; Dt= 4 s

Microphysics subcycled: Dt_m=2 / 0.25 s

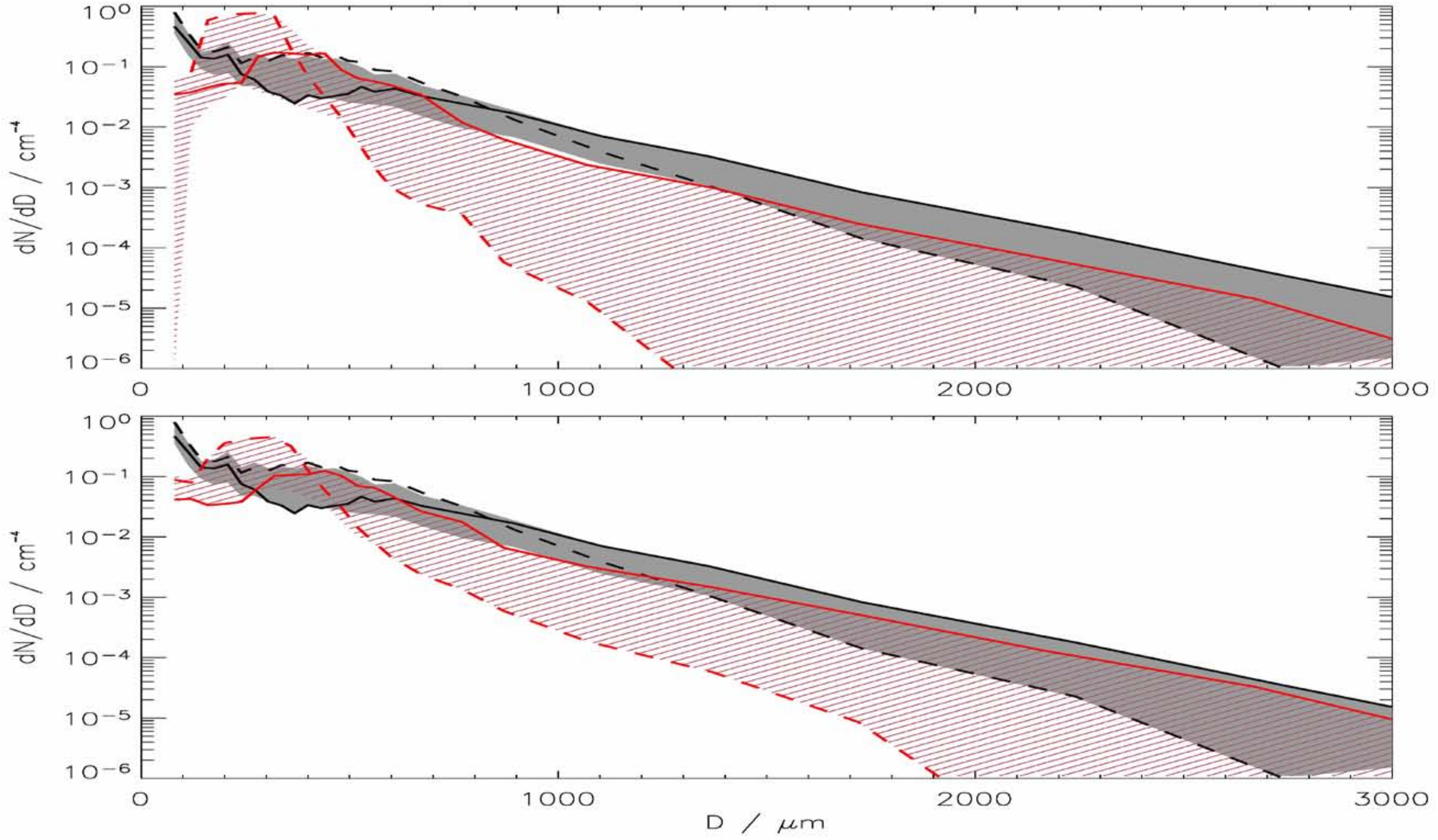
Grid scale ambient turbulence field is superimposed

Comparison to observations

We mimic the horizontally drifting spiral descent pattern when sampling air and cirrus properties in our model to enable the closest possible comparison with the in-situ data.



Ice crystal size distributions



Sensitivity Runs

Meteorological parameter

Run	Parameter	Variation	SIP×10⁶	$\overline{\Delta\tau} \pm \sigma$ / %	$\widetilde{\Delta\tau}$ (P20, P80) / %
A1	w_0 / m s^{-1}	$+0.02$ m s^{-1} ($+33$ %)	11.8	$+88.69 \pm 58.78$	$+84.24$ ($+43.19$, $+133.08$)
A2		-0.02 m s^{-1} (-33 %)	7.1	-70.54 ± 12.21	-70.45 (-74.80, -59.17)
B1	S_i	$+10$ %	10.8	$+45.18 \pm 64.81$	$+37.63$ ($+4.72$, $+72.63$)
B2		-10 %	13.7	-40.37 ± 25.29	-40.74 (-53.85, -9.01)
C1	$\partial u/\partial z$	$+0.001$ s^{-1} ($+50$ %)	11.9	-0.80 ± 21.17	$+4.15$ ($+1.78$, $+7.59$)
C2		-0.001 s^{-1} (-50 %)	12.9	-5.66 ± 8.27	-3.48 (-4.73, -1.73)
D	Radiation	off (-100) %	12.7	$+1.55 \pm 2.39$	$+1.73$ ($+0.89$, $+2.64$)

Microphysical parameter

Run	Parameter	Variation	SIP×10⁶	$\overline{\Delta\tau}$ / %	$\widetilde{\Delta\tau}$ (P20, P80) / %
E1	Habit Π_i	C2a	11.5	$+11.15 \pm 10.29$	$+9.54$ ($+5.69$, $+13.53$)
E2		C1e (60 %)	10.9	-11.57 ± 3.15	-11.90 (-12.45, -9.93)
F1	$v_{t,i}$	$+50$ %	11.2	-7.79 ± 4.61	-7.86 (-11.94, -4.63)
F2		-50 %	14.2	$+5.94 \pm 5.19$	$+7.00$ ($+1.82$, $+11.45$)
G1	E_a	$+0.25$ ($+33$ %)	12.5	-3.43 ± 2.22	-2.99 (-5.54, -0.81)
G2		-0.25 (-33 %)	12.8	$+3.39 \pm 2.99$	$+3.61$ ($+0.73$, $+6.92$)
G3	no aggregation	-0.75 (-100 %)	13.2	$+10.40 \pm 8.62$	$+8.69$ ($+3.45$, $+21.09$)
H1	α_v	$+0.5$ ($+100$ %)	12.3	-1.77 ± 0.99	-1.81 (-2.33, -1.39)
H2		-0.25 (-50 %)	13.2	$+3.05 \pm 1.59$	$+3.39$ ($+2.83$, $+3.95$)
I	$H_{R,i}$	on ($+100$) %	12.6	-0.78 ± 1.28	-0.33 (-1.94, $+0.54$)
J	Nucleation	+heterogeneous	34.2	-20.29 ± 49.68	-22.84 (-45.53, -3.03)

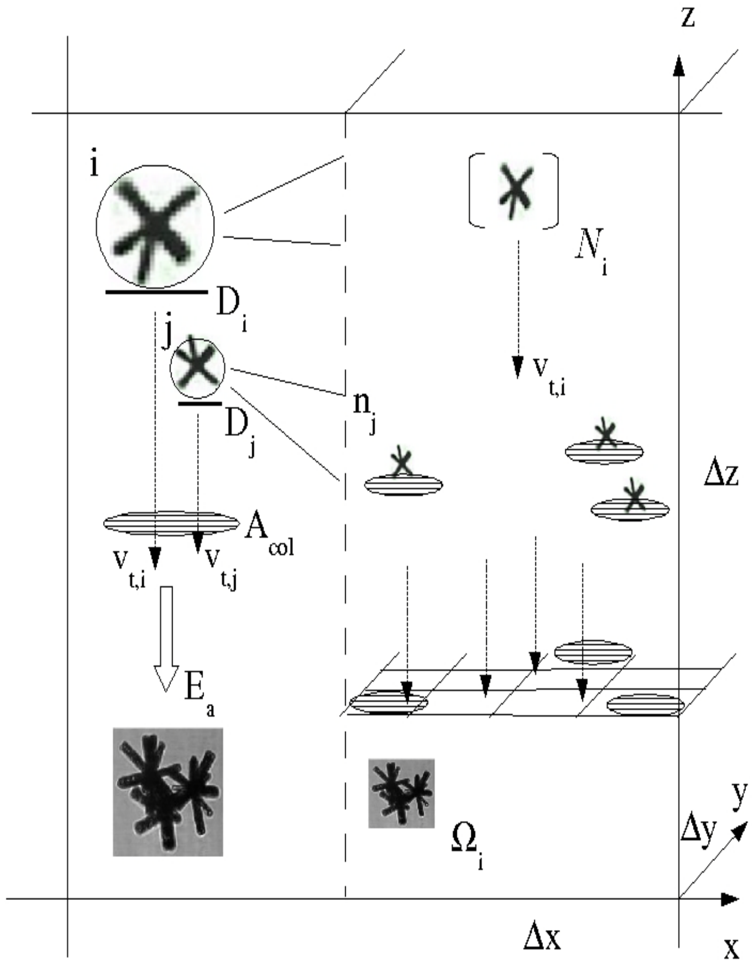
Numerical parameter

Run	Parameter	Variation	SIP×10⁶	$\overline{\Delta\tau}$ / %	$\widetilde{\Delta\tau}$ (P20, P80) / %
K	$L\Delta t$ (Radiation)	$+40$ s ($+100$ %)	12.7	-0.09 ± 0.63	-0.09 (-0.59, $+0.68$)
L	Δt (Dynamics, Microphysics)	-50 %	18.2	$+1.05 \pm 1.84$	$+1.09$ (-0.12, $+1.90$)
M	Δz	-50 %	26.3	-0.97 ± 11.14	$+0.85$ (-0.42, $+3.68$)
N1	N_{SIP}	$+5.5 \times 10^6$ ($+40$ %)	18.2	-0.32 ± 0.64	-0.23 (-0.56, $+0.17$)
N2		$+3.2 \times 10^6$ ($+25$ %)	15.9	-0.62 ± 0.76	-0.36 (-1.08, $+0.07$)
N3		-3.5×10^6 (-30 %)	9.2	$+0.82 \pm 0.94$	$+1.12$ ($+0.30$, $+1.40$)
N4		-8.8×10^6 (-70 %)	3.9	-0.29 ± 4.65	-0.12 (-1.22, $+1.67$)
N5		-10×10^6 (-80 %)	2.6	-0.94 ± 6.96	-1.56 (-2.67, $+1.65$)

Table I. Summary of the sensitivity analysis for the case study ARM IOP March 9, 2000. The columns from left to right are: run identifier, the parameter varied in the given sensitivity experiment, an estimated, typical variation of this parameter, the number of SIPs, the temporal mean $\overline{\Delta\tau}$, of $\Delta\tau$ (defined in Equation (**??**)) with associated standard deviation σ, and the corresponding median, $\widetilde{\Delta\tau}$, with associated 20 % (P20) and 80 % (P80) percentiles (in brackets). Parameter settings of the base case are provided in Table **??**.

Cluster—cluster aggregation algorithm

Aggregation: ice crystals collide and eventually stick together → larger clusters

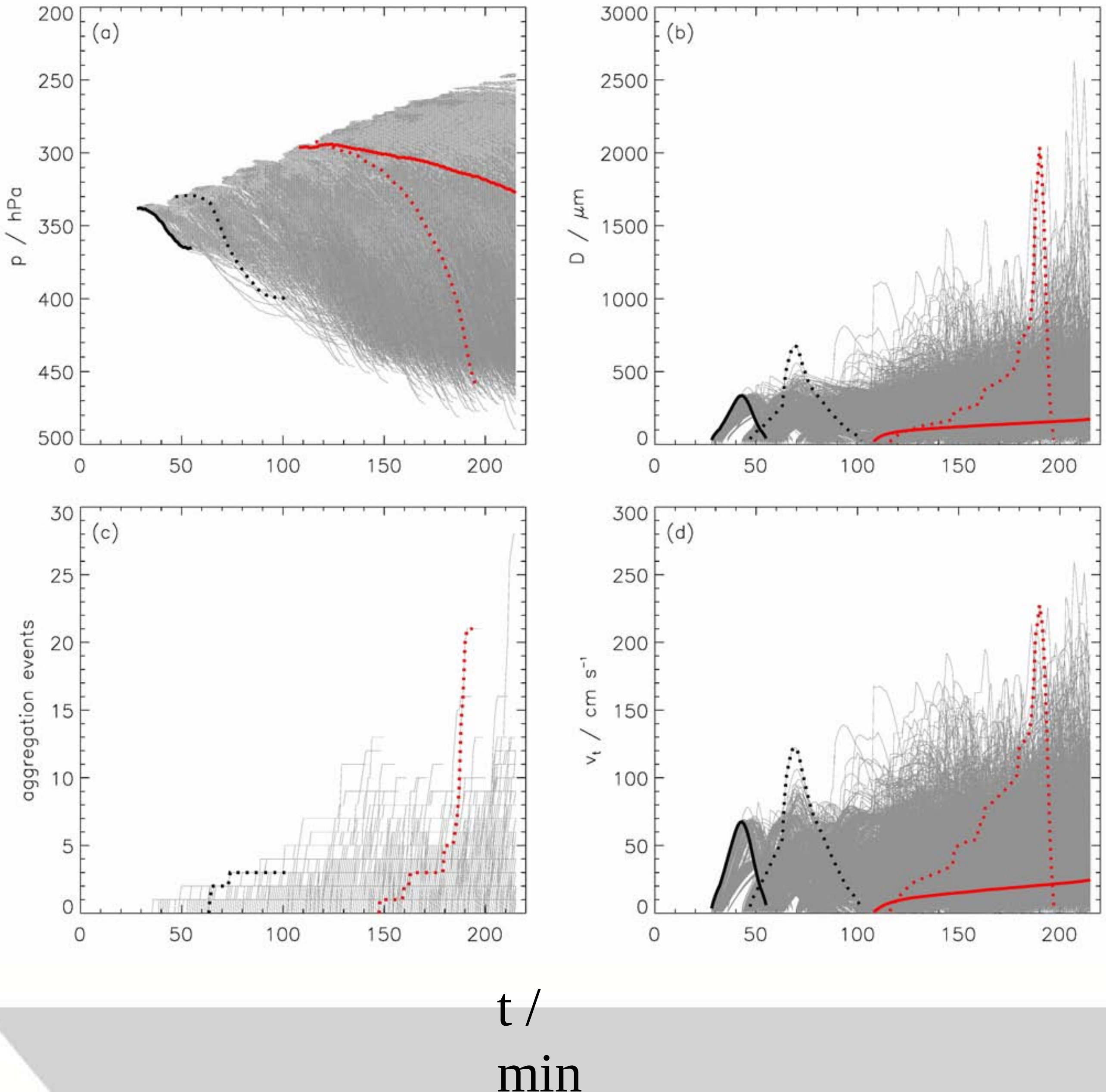


We simulate aggregation due to differential sedimentation. Compared to lower level warm clouds turbulent enhancement of the collision efficiency in stratiform cirrus is low.

We calculate the probability for the trajectory of a real ice crystal in SIP i to intersect the effective collision area surrounding the real ice crystals represented by SIP j

Formation of large ice crystals

The formation of the largest crystals in the deep cirrus is controlled in part by the nucleation of new ice crystals in dynamically active upper cloud regions.

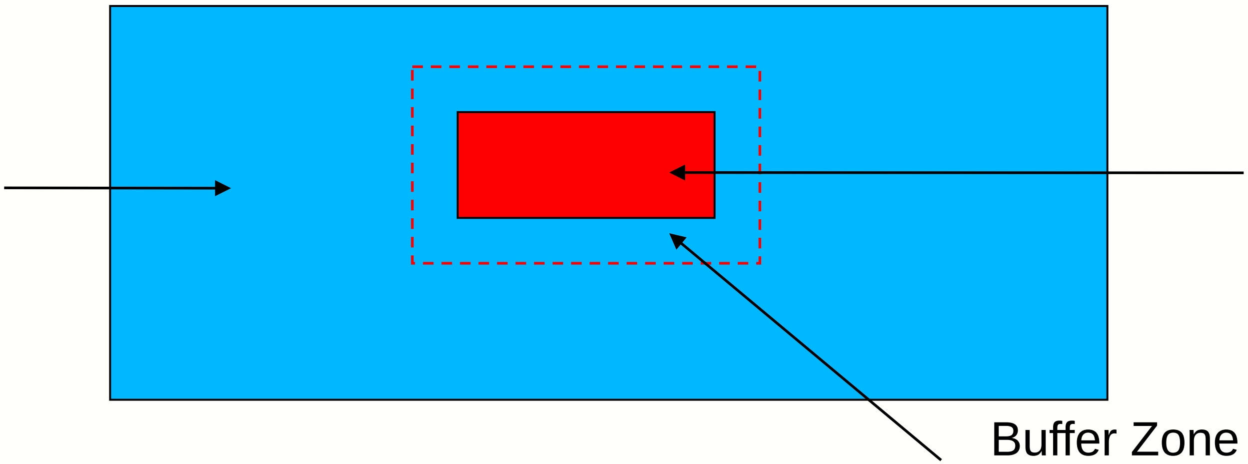


Summary and Outlook

- We have learned from the case study that the formation and evolution of the cirrus is very sensitive to the vertical updraft speed and the moisture field. In order to arrive at a more realistic scenario a coupling between the LES approach with EULAG and a numerical weather prediction model is desirable.

Which way to take?

1) Fixed multiple domains - Difficulties in tracking an evolution in the cloud



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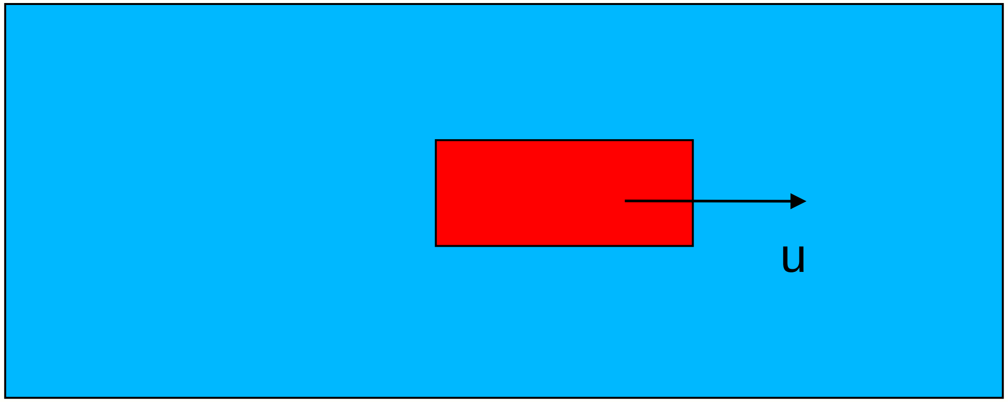
Which way to take?

2) Floating EULAG domain - How can we pass the changing environmental state to EULAG?



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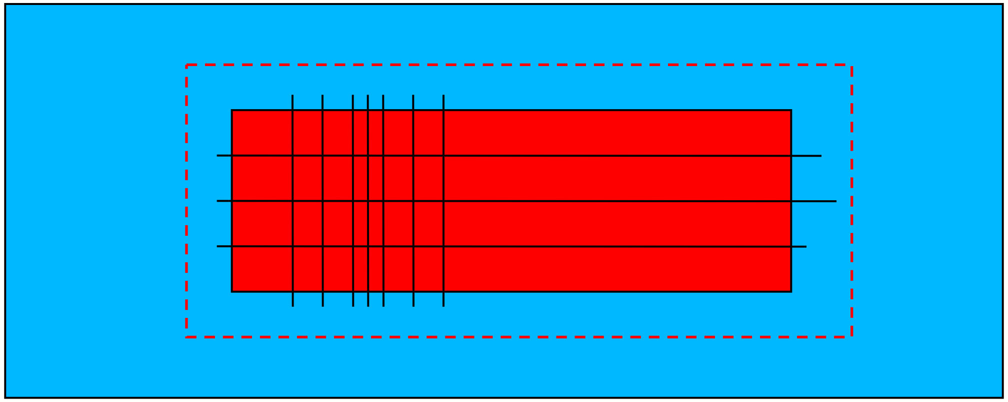
Which way to take?

3) Adaptive grid approach - Is it possible to concentrate the grid on the cirrus?



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