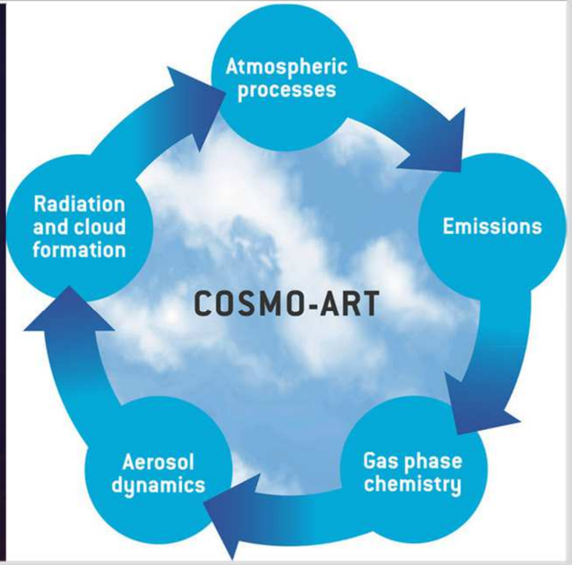
Impact of microphysics and aerosol on hailstorms simulated by COSMO-ART

Andrew Barrett | 06 March 2017
Constanze Wellmann, Michael Kunz, Bernhard Vogel, Corinna Hoose

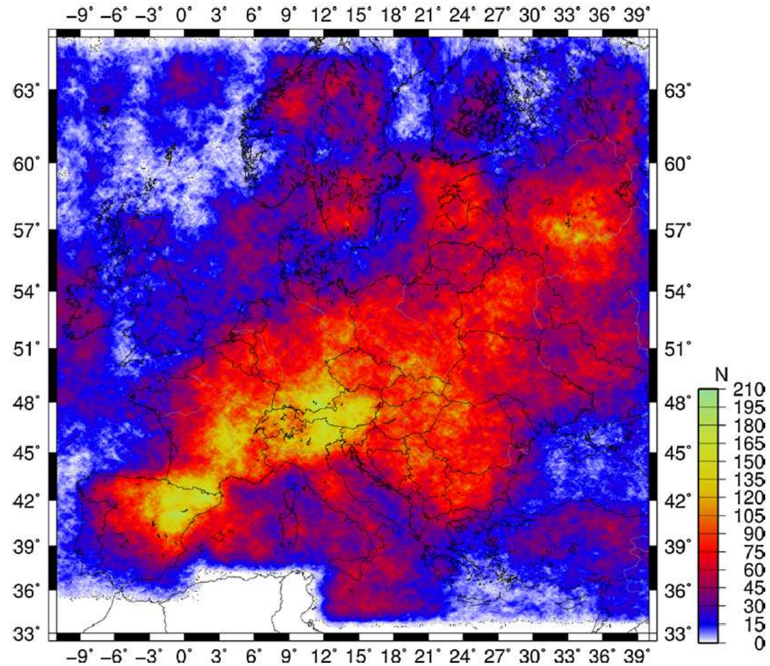
Institute of Meteorology and Climate research – Aerosols, Trace Gases and Climate Processes



Damage from hail

- Hailstones up to 20 cm diameter, >50 m s^{-1} terminal velocity

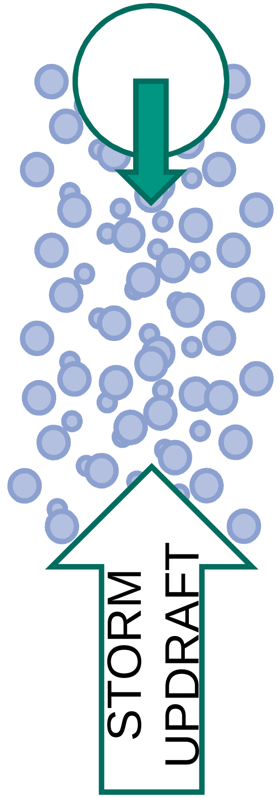
- Damage depends on size of hail
  - >0.6cm: Crops (e.g. corn, fruit)
  - >2.5cm: Buildings
  - >4.0cm: Cars
  - People and livestock



Hail (>0.69cm) frequency in Europe (Punge et. al, 2014)

Hailstone formation

- Hailstone formation requires…
  - Hail embryo
    - something frozen: raindrop, snowflake aggregate
  - Supercooled liquid
    - Liquid cloud water between 0 and -40°C
  - Strong updraft
    - prevents hail from falling
    - provides liquid water
  - Time
    - 40-60 minutes to form large hail
    - Organised convection required:
      - e.g. supercells, squall lines, multi-cell (?)



- Final size depends on: **updraft strength**, **liquid water amount**, height of freezing level, **number of hail embryos**, **storm structure**
    - **Coloured** = potentially affected by microphysics and aerosol

Aerosol effects on hail

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Atmospheric Research 96 (2010) 286–301

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Simulations of a hailstorm and the impact of CCN using an advanced two-moment cloud microphysical scheme

Heike Noppel[a,*], Ulrich Blahak[a], Axel Seifert[b], Klaus D. Beheng[a]

[a] *Institut für Meteorologie und Klimaforschung, Universität/Forschungszentrum Karlsruhe, P.O. Box 3640, D-76021 Karlsruhe, Germany*
[b] *German Weather Service, Frankfurter Str. 135, D-63067 Offenbach, Germany*

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ABSTRACT

A hailstorm that caused significant damage in South-West Germany was simulated with the numerical weather prediction model COSMO. To cover hail evolution a sophisticated two-moment cloud microphysical scheme was extended by a particle class representing hail and implemented into COSMO. The horizontal resolution was 1 km. For initialization and boundary values COSMO forecasts with a coarser resolution and the standard one-moment microphysical scheme were used. Running this model system several convective cells develop including a severe hailstorm that resembles the observations qualitatively well and produces realistic amounts of precipitation and hail at the ground. Sensitivity studies were conducted varying the concentration of cloud condensation nuclei (CCN) and the shape of the cloud droplet size distribution (CDSD). Results show that both have a significant impact on hail accumulated at the ground and on the size of the hailstones. For two of the three CDSDs assumed the intensity of the severe storm decreases with increasing CCN concentration. However, this is not true for some of the weaker storms that form as well as for the third CDSD. Two model runs are analyzed and compared in more detail revealing the strong coupling between the numerous microphysical processes and between microphysics and dynamics. The sensitivity studies illustrate that the complexity of such storms makes it difficult to foresee, what will happen, when one microphysical parameter is changed. Thus, general conclusions whether an increase or decrease in CCN concentration invigorates a hailstorm

“…the intensity of the severe storm **decreases** with increasing CCN concentration.”

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The role of CCN in precipitation and hail in a mid-latitude storm as seen in simulations using a spectral (bin) microphysics model in a 2D dynamic frame

A. Khain[a,*], D. Rosenfeld[a], A. Pokrovsky[a], U. Blahak[b], A. Ryzhkov[c]

[a] *Department of Atmospheric Science, The Hebrew University of Jerusalem, Israel*
[b] *Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT), Germany*
[c] *The Cooperative Institute for Mesoscale Meteorological Studies at University of Oklahoma, USA*

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ABSTRACT

A hail storm at Villingen-Schwenningen, southwest Germany, on 28.06.2006 was simulated using the Hebrew University Cloud Model (HUCM) with spectral (bin) microphysics. The model allows the simulation of hail stones with diameters up to 6.8 cm. To investigate whether the amount of hail is sensitive to atmospheric instabilities, the simulations were performed for two different temperature gradients within the boundary layer. The response of precipitation, the hail mass and hail size distribution to aerosol was investigated in the simulations with cloud condensation nuclei (CCN) concentrations ranging between 100 cm^{-3} and 6000 cm^{-3} (at the supersaturation of 1%). An increase in the surface temperature by one degree leads to an increase in accumulated rain by ~80% and nearly doubles the mass of hail falling to the surface. An increase in CCN concentration from 100 cm^{-3} to 3000 cm^{-3} leads to a certain increase in accumulated rain and to a dramatic increase in the hail mass, as well as to the increase in the hail diameter from a few mm to 1–4 cm. The mechanisms by means of which aerosols affect precipitation and hail stones size are discussed. It is shown that formation of hail increases the precipitation efficiency of deep convective clouds.

“An increase in CCN … leads to a certain **increase** in accumulated rain and to a dramatic **increase** in the hail mass, as well as to the **increase** in the hail diameter from a few mm to 1-4 cm.”

COSMO model setup

- COSMO 5.3
- 1-km resolution; 64 vertical levels
- Idealised simulation
  - Weisman-Klemp thermodynamic profile
  - 2K warm bubble
- 2-hour simulation
- Seifert & Beheng 2-moment microphysics
  - Two different aerosol settings:
    - itype_gscp=2463 : 100 CCN cm^{-3} = clean
    - itype_gscp=2483 : 1700 CCN cm^{-3} = continental

- Future plan to use COSMO-ART, to determine effects of fully interactive aerosol

Two-moment microphysics in COSMO

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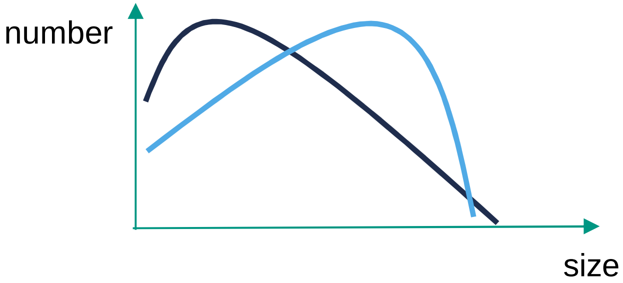
- Two-moment means that both the mass q and the number n are predicted



- With two moments, mass and number can vary separately
- Allows model to simulate important processes, e.g. size sorting
- In theory better than one-moment scheme, BUT many interactions are not well understood
  - Especially in extreme conditions

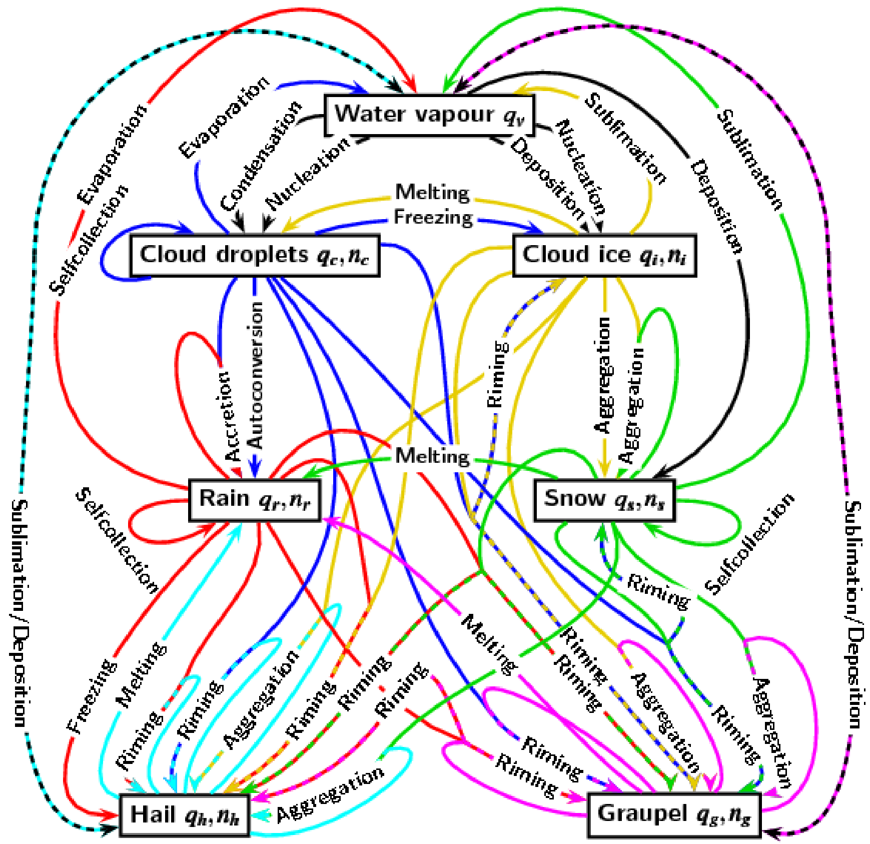
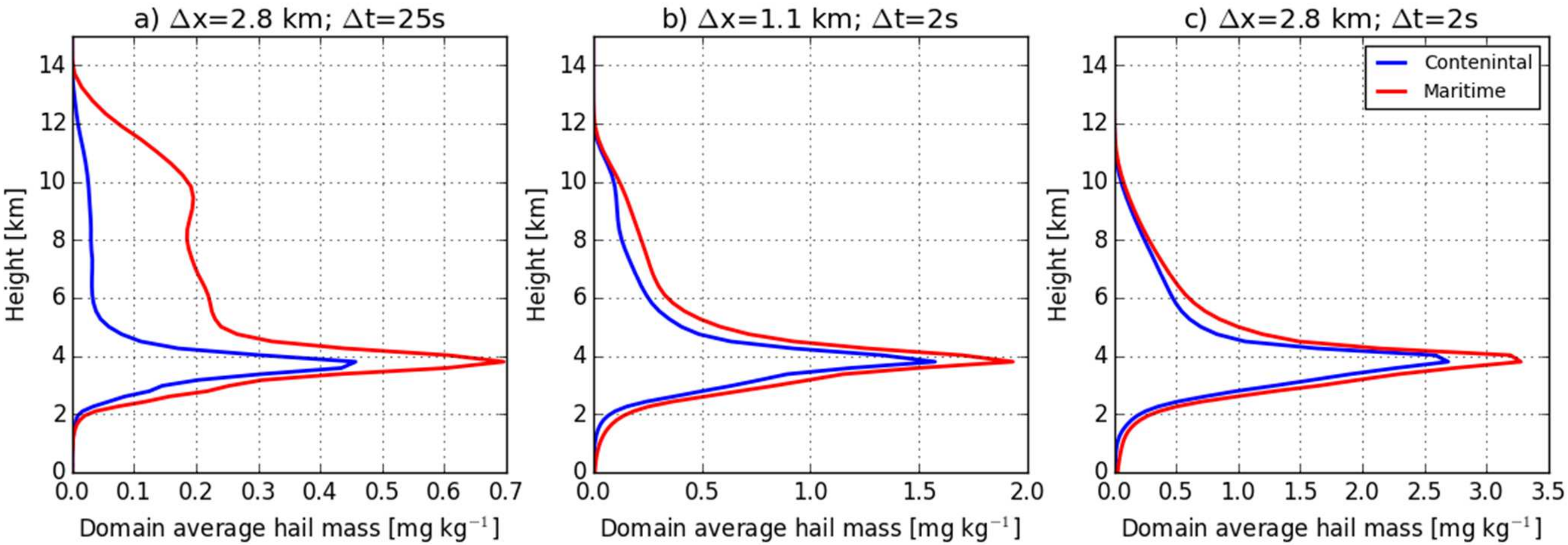


Illustration of the complexity of 6-category, 2-moment microphysics scheme

Aerosol effects on hail in COSMO

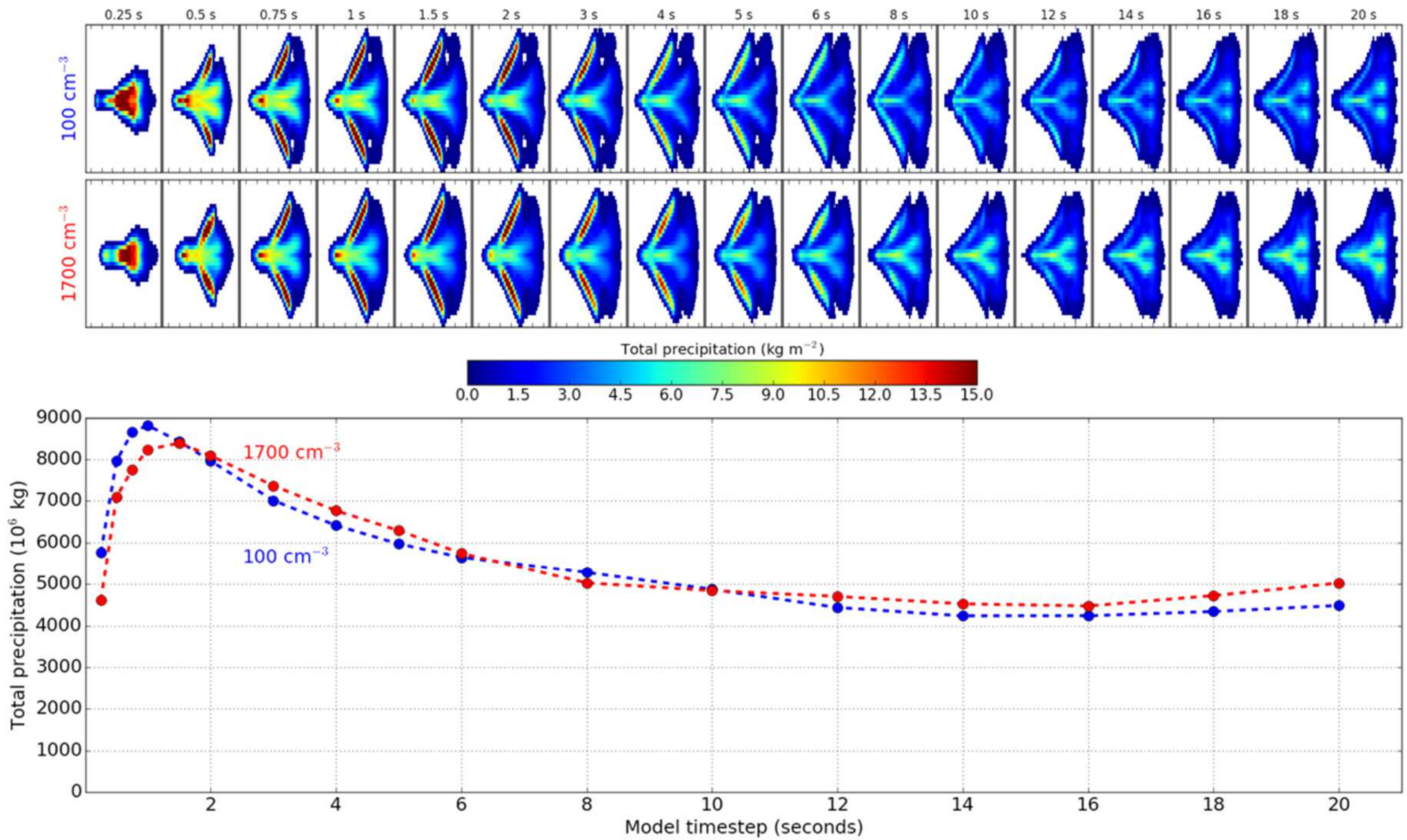


Total mass: low
Sensitivity to aerosol: high

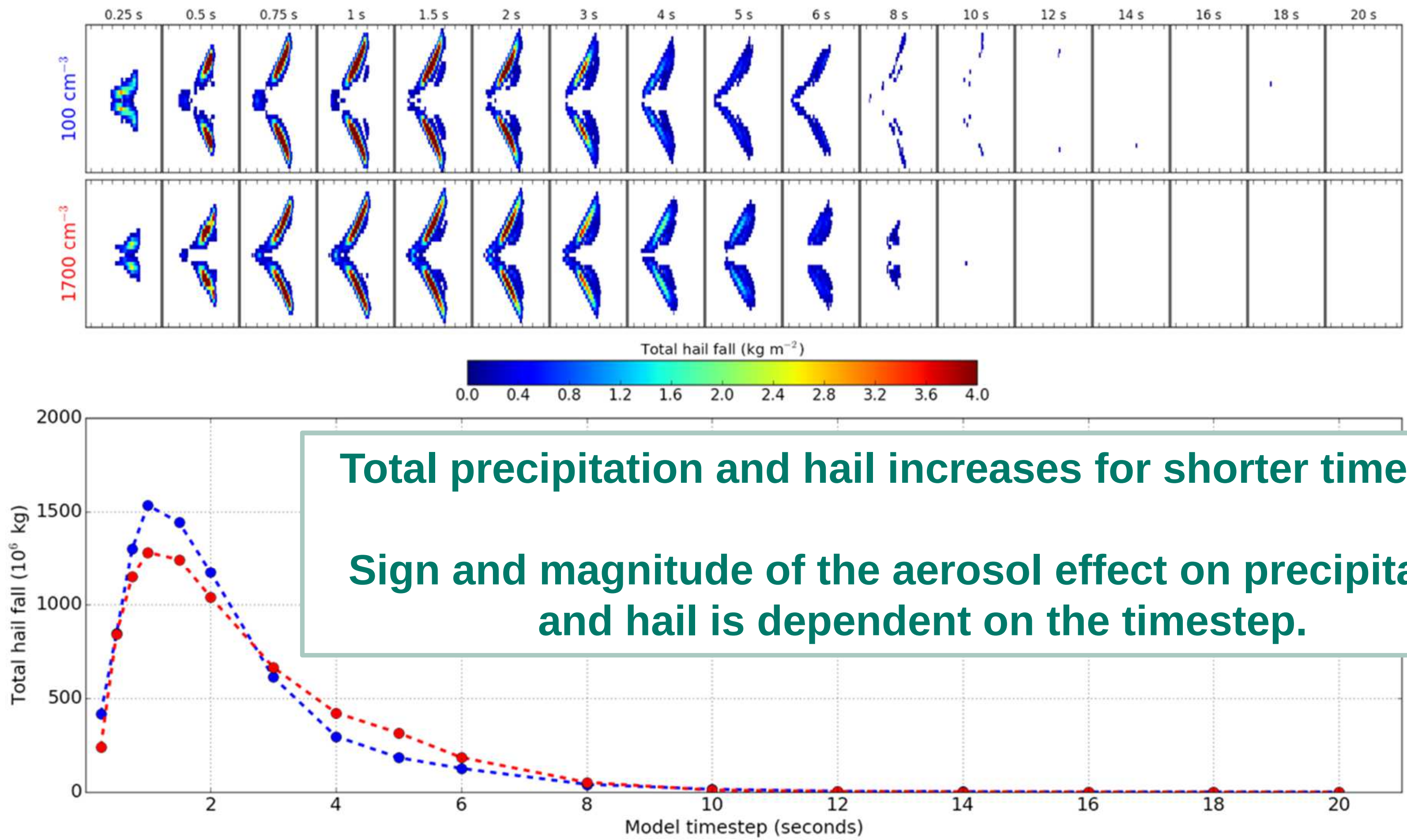
Total mass: medium
Sensitivity to aerosol: low

Total mass: high
Sensitivity to aerosol: low

Total precipitation: aerosol and timestep effects



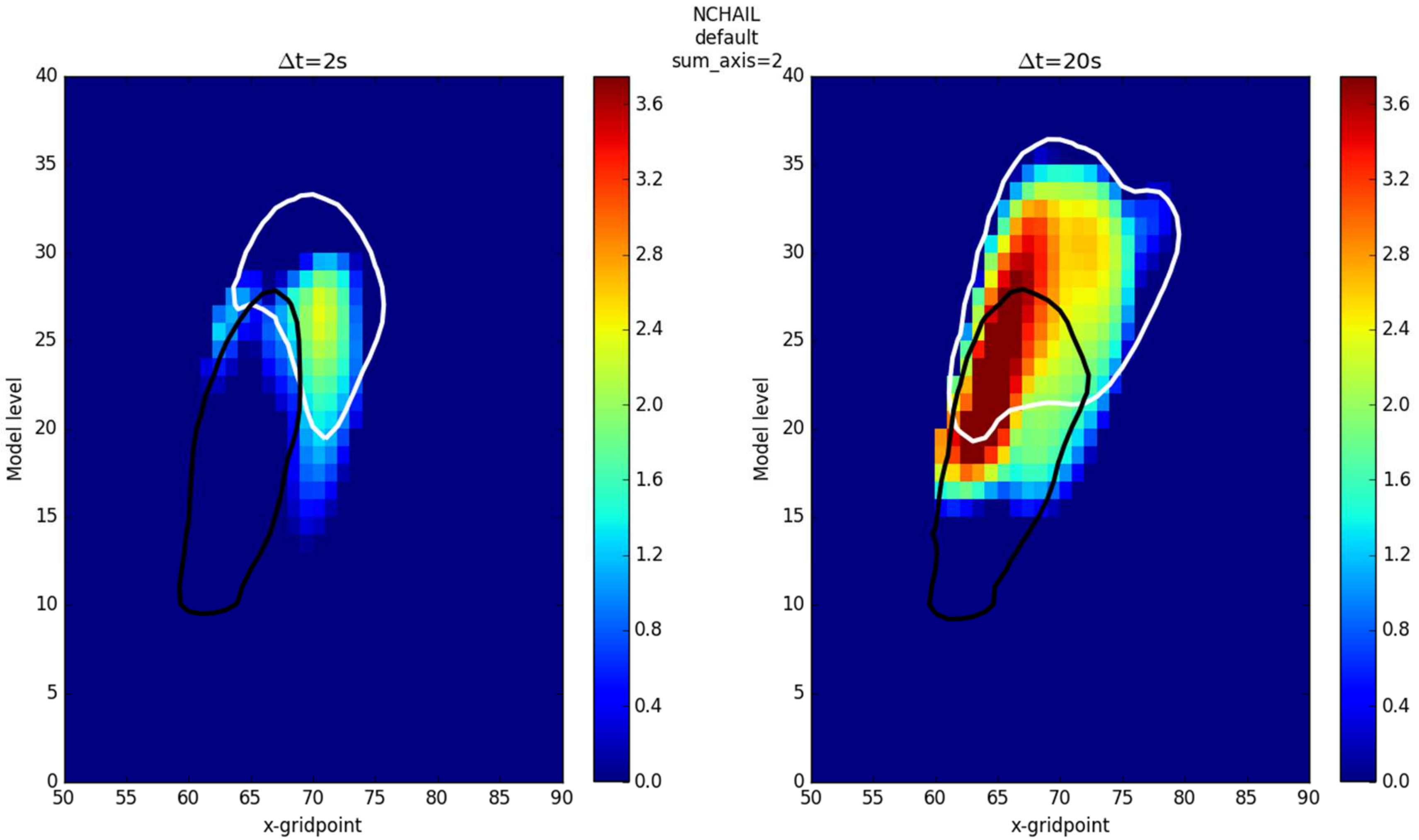
Total hail fall: aerosol and timestep effects



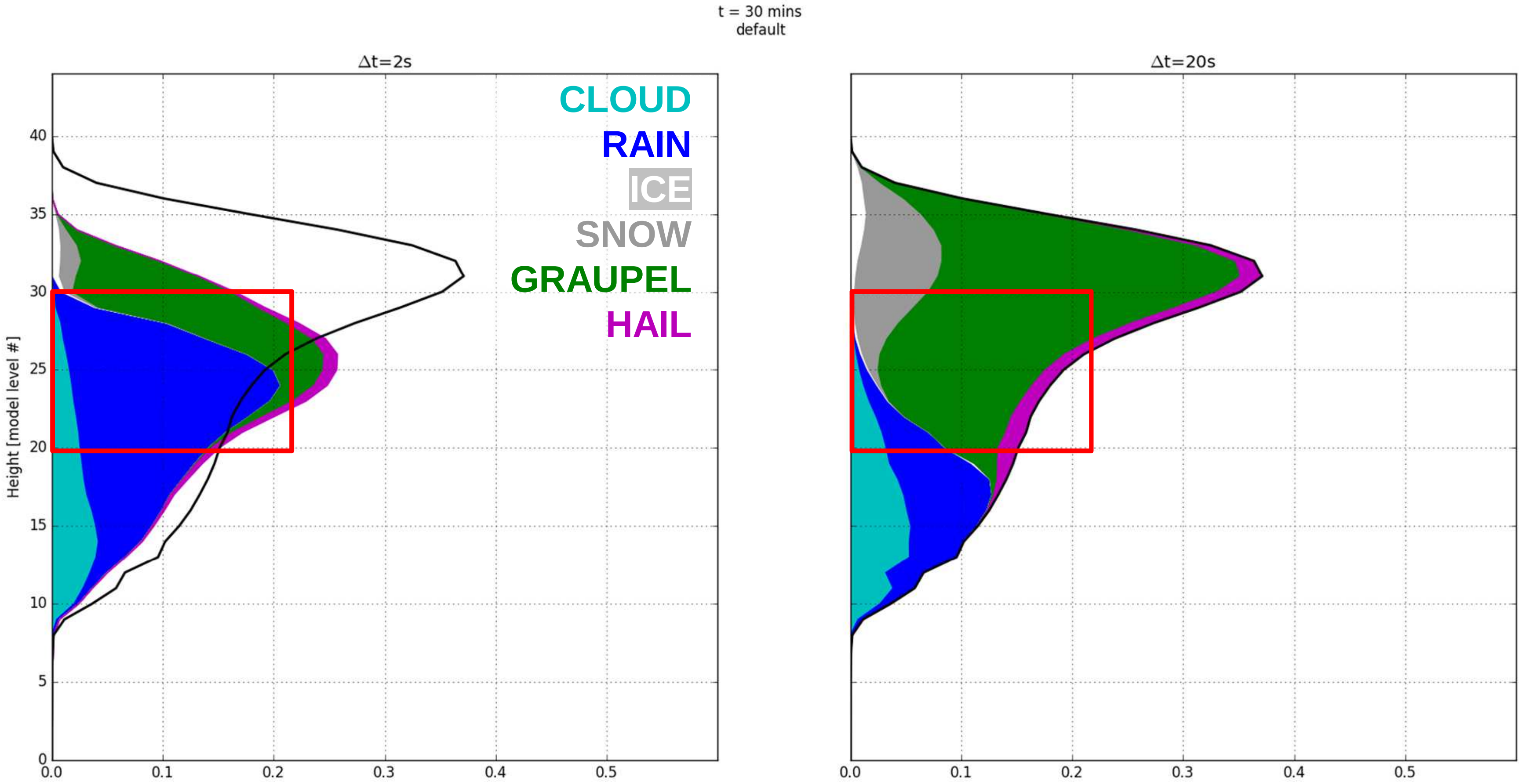
Total precipitation and hail increases for shorter timestep.

Sign and magnitude of the aerosol effect on precipitation and hail is dependent on the timestep.

Cross section: Hail number



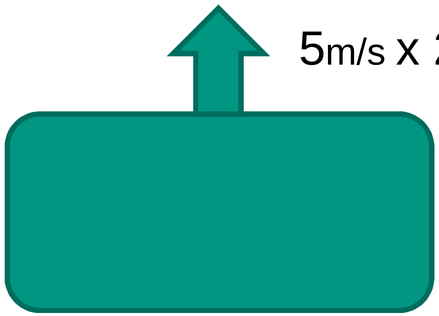
Average water content with height



Timestep sensitivity

- Hail could fall multiple grid-boxes per timestep
  - Does not interact with liquid water during sedimentation
  - Water not collected (riming) -> growth of hail much slower
- Certain model parameterizations happen “once per timestep” (instead of being a process rate)
  - Freezing of raindrops
  - Conversion of graupel to hail
  - Creation of liquid water (saturation adjustment)
- Most timestep dependence can be removed by running the microphysics parameterization multiple times per model-timestep.
  - “substepping”
  - Saturation adjustment is still a problem.

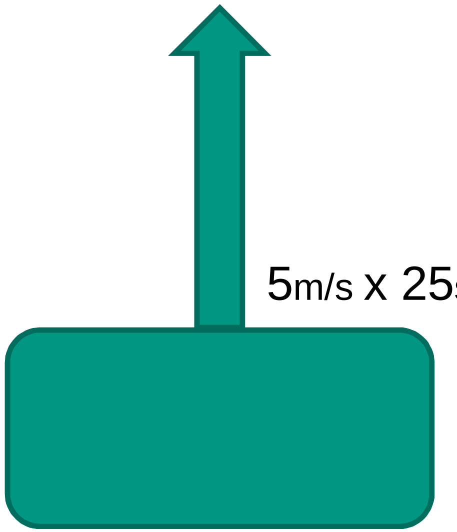
Saturation adjustment and microphysics



5m/s x 2s = 10m

= 0.1K

$\Delta q_c = 0.1 \frac{dq_s}{dT}$



5m/s x 25s = 125m

= 1.25K

$\Delta q_c = 1.25 \frac{dq_s}{dT}$

Autoconversion

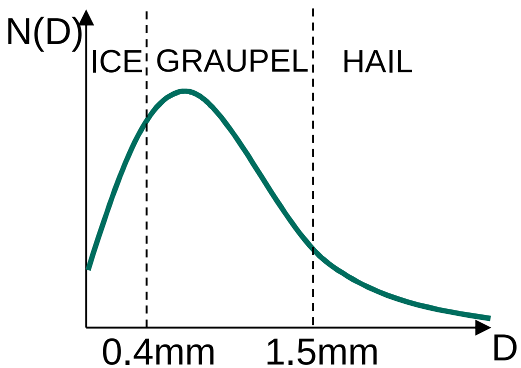
$q_c, n_c \rightarrow q_r, n_r$

$\text{rate} = k\, q_c^2\, m_c^2$

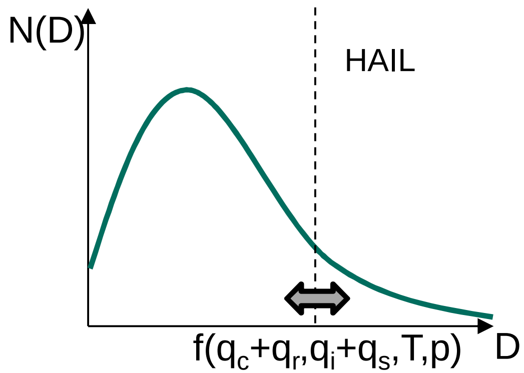
$[\, m_c = q_c / n_c \,]$

rate ~ q_c^4

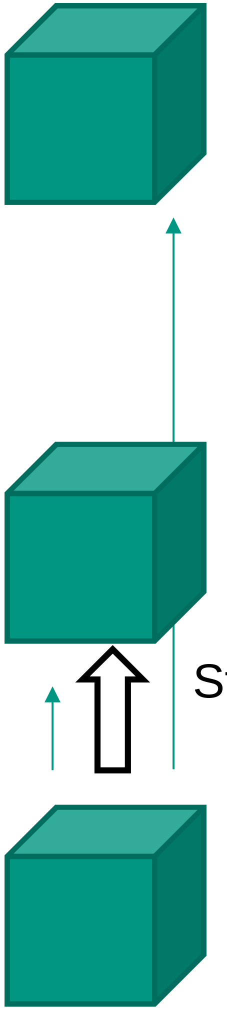
Rain freezing



Graupel "wet growth"



Air parcel in an updraft



Δt = 20 s
Δz = 200 m
T = -2.0°C
RH_w = 115.8%
RH_i = 118.1%
$q_i = q_c = 0$

Δt = 2 s
Δz = 20 m
T = -0.2°C
RH_w = 101.5%
RH_i = 101.7%
$q_i = q_c = 0$

Storm Updraft ~10 ms^{-1}

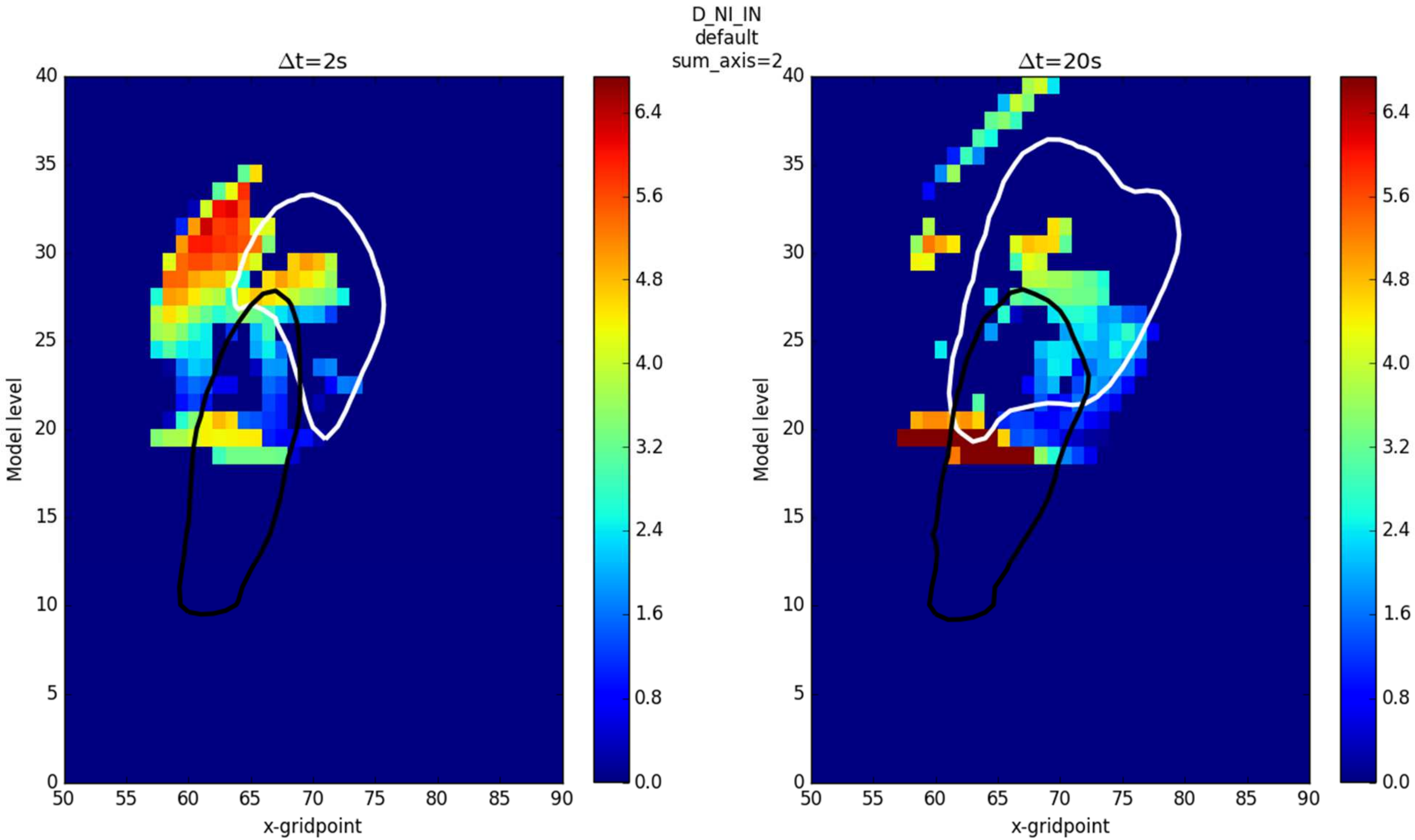
Air parcel
RH = 100%
$q_i = q_c = 0$
T = 0°C

Saturation adjustment before microphysics?

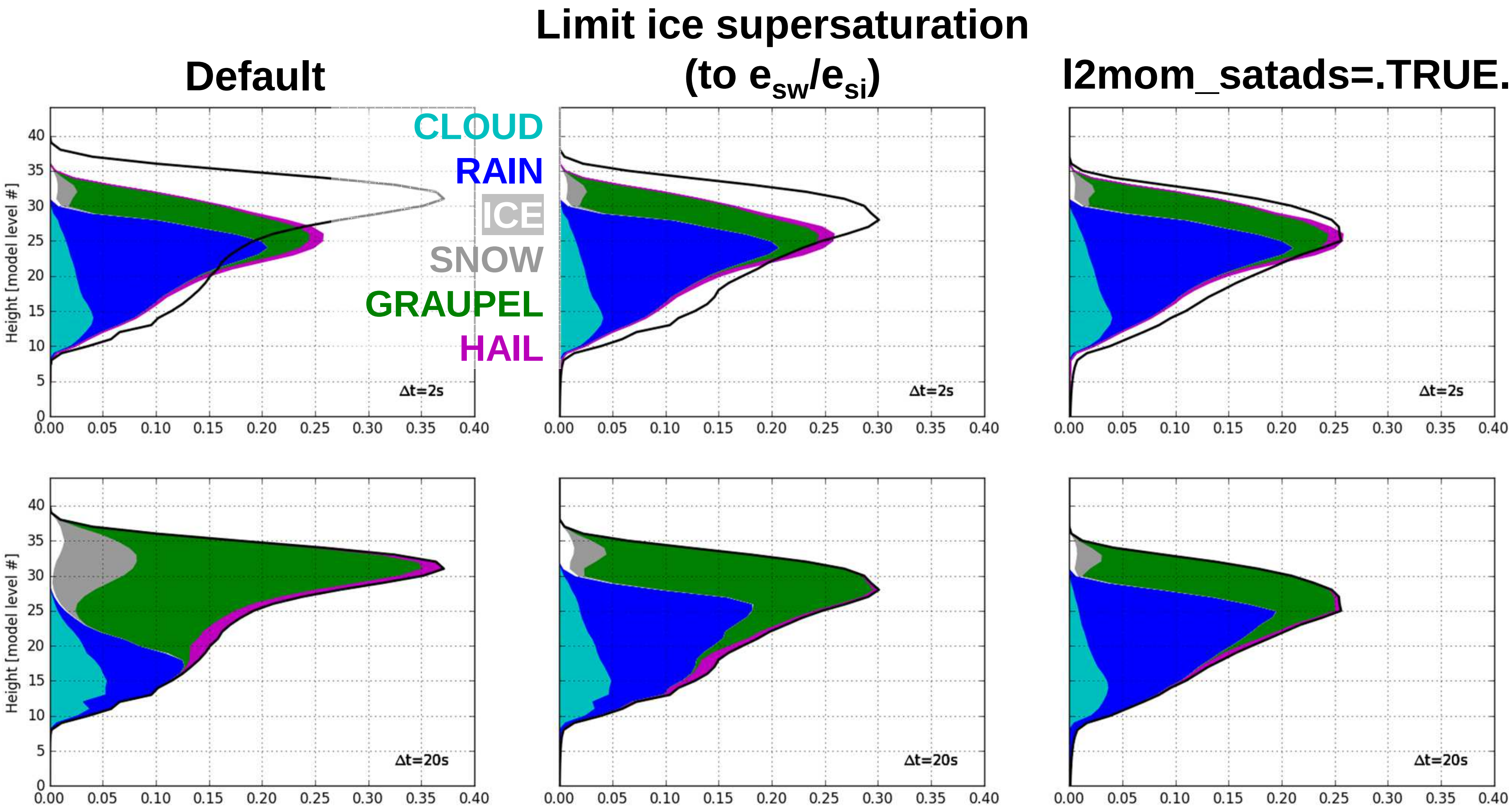
Δt = 2 s		Δt = 20 s
Δz = 20 m T = -0.2°C RH_w = 101.5% RH_i = 101.7% $q_i = q_c = 0$		Δz = 200 m T = -2°C RH_w = 115.8% RH_i = 118.1% $q_i = q_c = 0$
RH_w = 100.0% RH_i = 100.2% $q_i = 0$; **q_c = 7e-6**	SATURATION ADJUSTMENT	RH_w = 100.0% RH_i = 101.9% $q_i = 0$; **q_c = 6e-5**
RH_w = 101.5% **RH_i = 101.7%** $q_i = 0$; $q_c = 0$	WITHOUT SATURATION ADJUSTMENT	RH_w = 115.8% **RH_i = 118.1%** $q_i = 0$; $q_c = 0$

For larger Δt: Much larger values of q_c or RH_i are given to the microphysics scheme

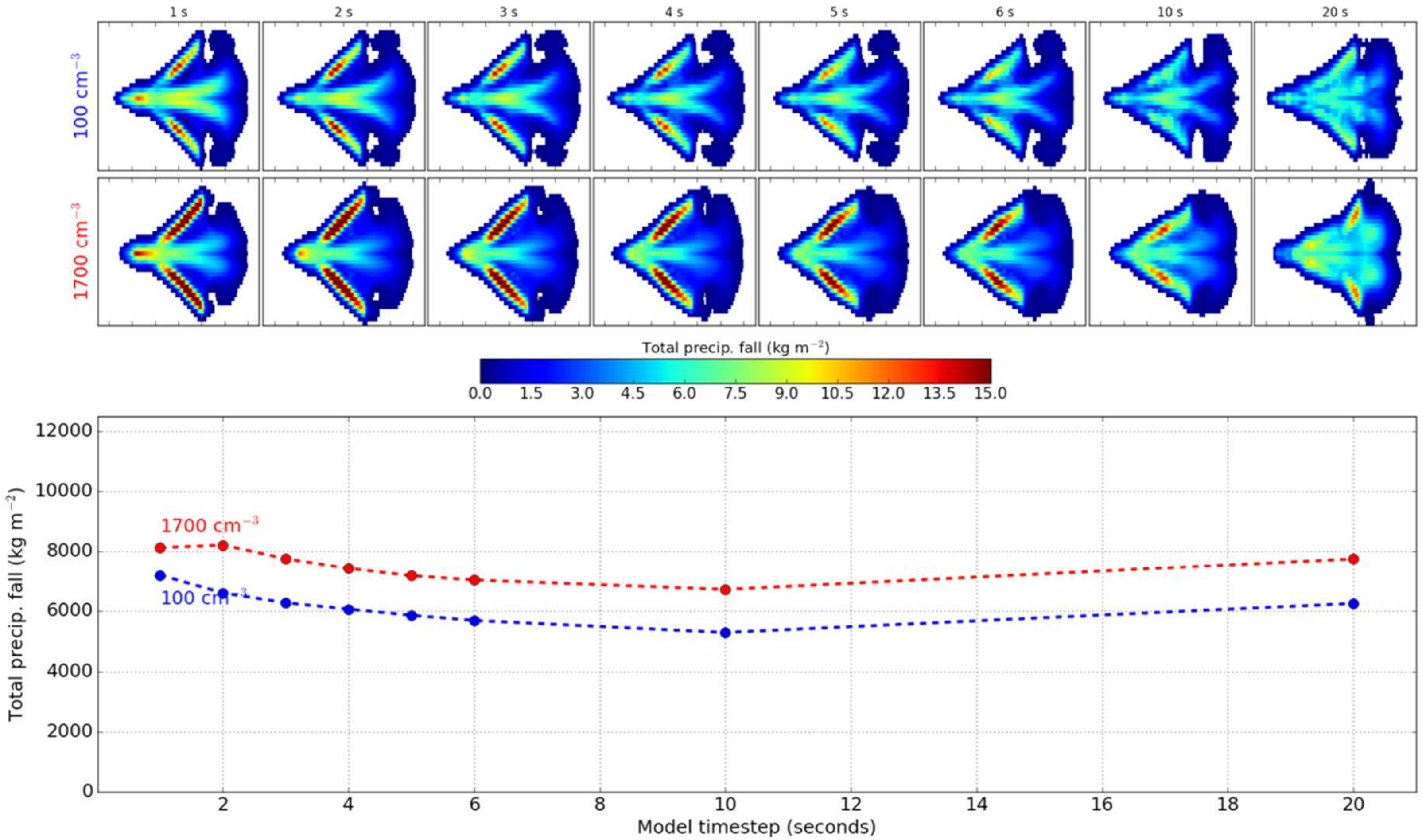
Ice number production (by ice nucleation)



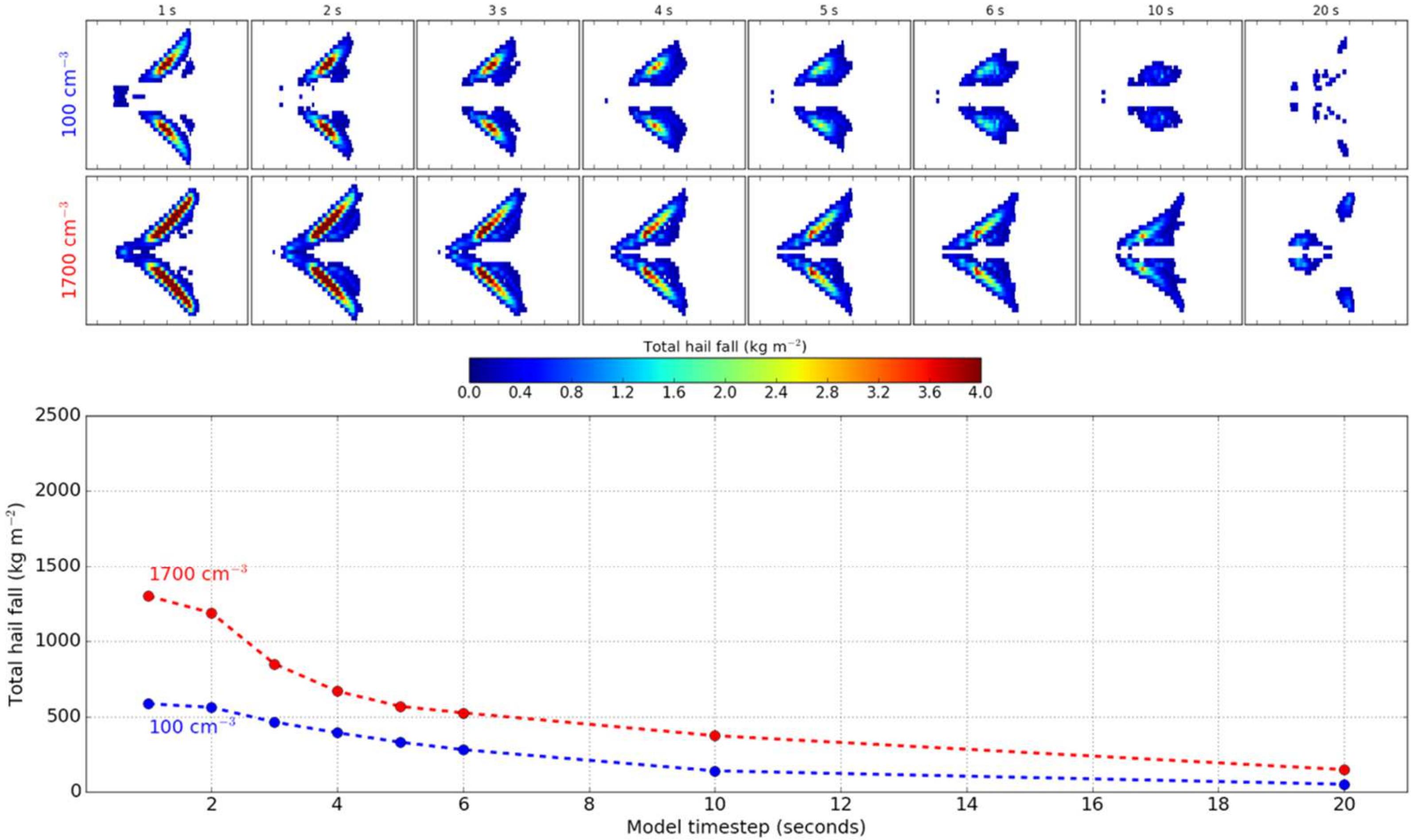
Average water content with height



Total precipitation: aerosol and timestep effects (with l2mom_satads=.TRUE.)



Total hail fall: aerosol and timestep effects (with l2mom_satads=.TRUE.)



Microphysical processes affecting hail

- Hail (number) production mostly by conversion from graupel
- Hail (mass) production mostly by collection of liquid (cloud & rain) water

- Conversion of graupel to hail affected by liquid water content

- Supercooled liquid water content affected by aerosol conditions
  - More aerosol → smaller drops → more supercooled liquid

- Hypothesis:
  - Liquid water content determines total mass of hail produced
  - Hail number determines the size of hailstones

  - Freezing mechanisms most important for final hailstone size

Summary

- COSMO5.3 + 2-moment scheme can only produce hail at surface when $\Delta t \leq 10$ seconds.
- Sign and magnitude of aerosol sensitivity depend on timestep

- Sub-stepping the microphysics is an improvement
  - Mostly because of saturation adjustment at end of microphysics

- With model switch l2mom_satads=.TRUE.
  - Saturation adjustment occurs before and after the microphysics
  - Larger sensitivity to aerosol; Aerosol sensitivity is robust across timesteps

- The cause of the timestep dependence is the formation of cloud water or large RH_i within long timesteps
- When RH_i is large, ice nucleation in the updraft produces many small hail particles

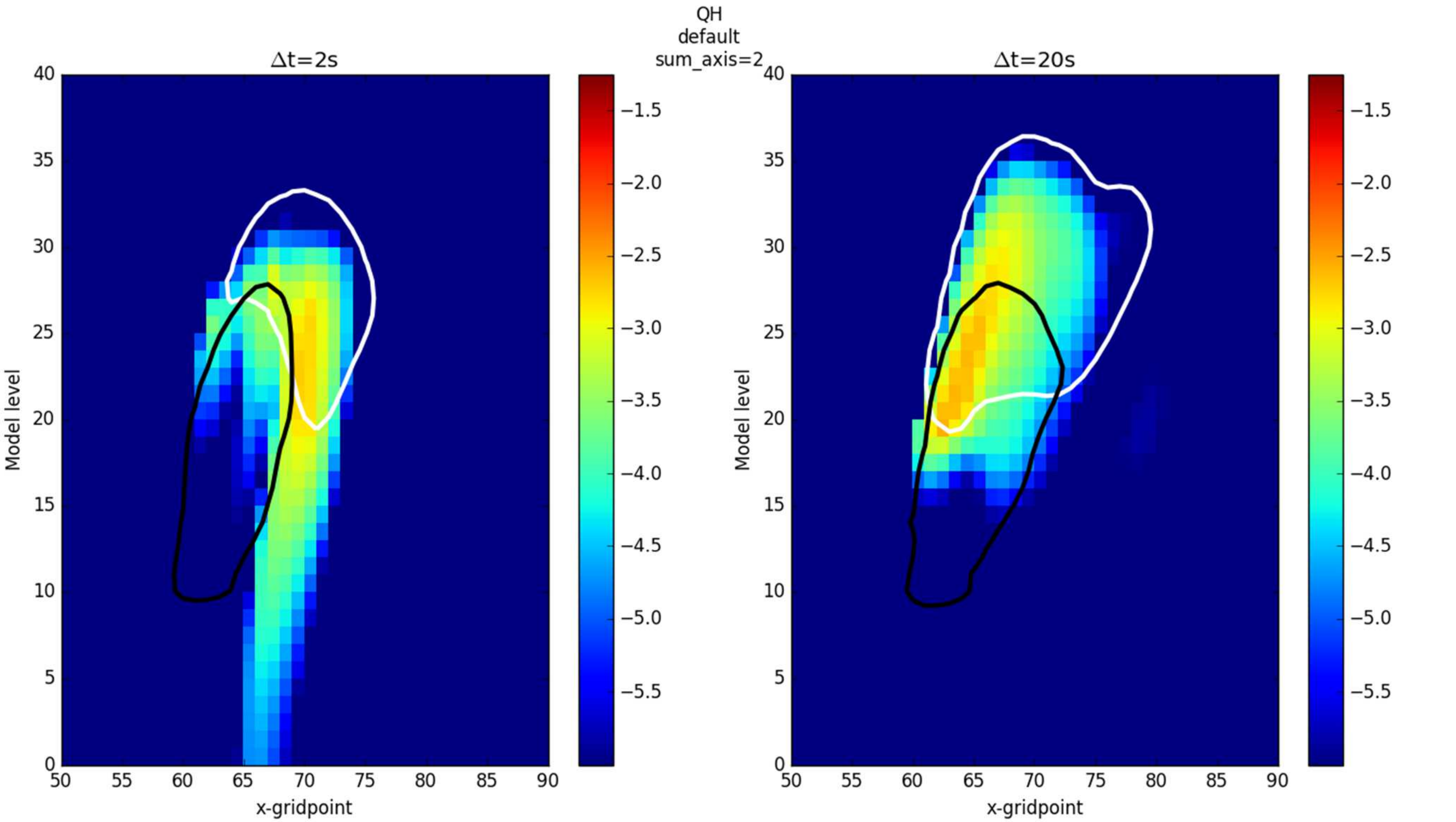
Future plans

- Simulate real cases (e.g. 27/28 July 2013, 6 Aug 2013, 11 Sept 2011)
- 1.1-km resolution, timestep still to be decided

- Implement piggybacking to determine aerosol effects (Grabowski et al.)
- Add “warm bubbles” to the flow to initiate convection in correct place
- Vary aerosol and microphysical properties

- Assess quality of simulations of cloud properties and surface precip.
  - Simulate radar and satellite observations from model output

Hail mass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Δt=20s
Model level
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30
25
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10
5
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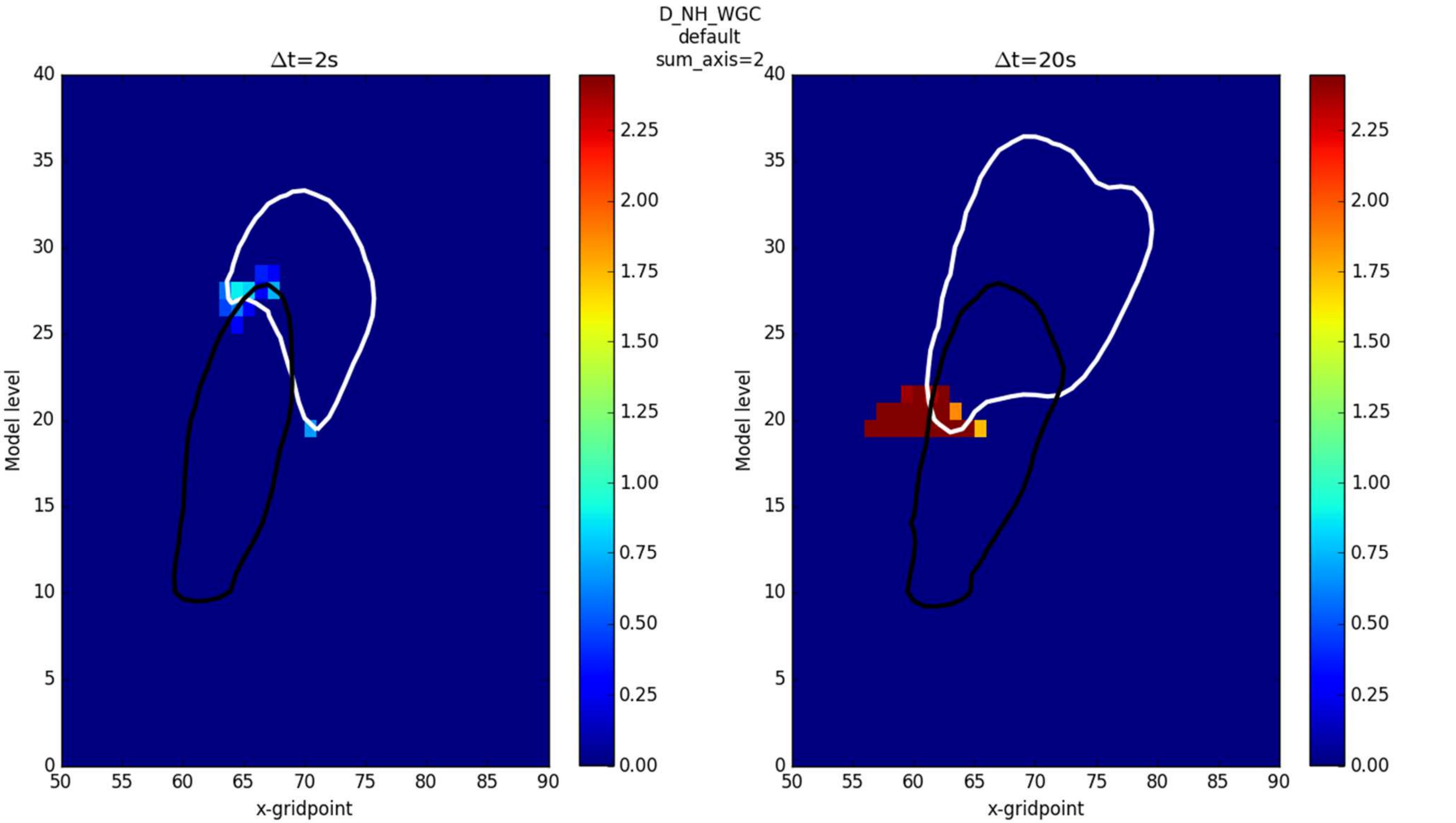
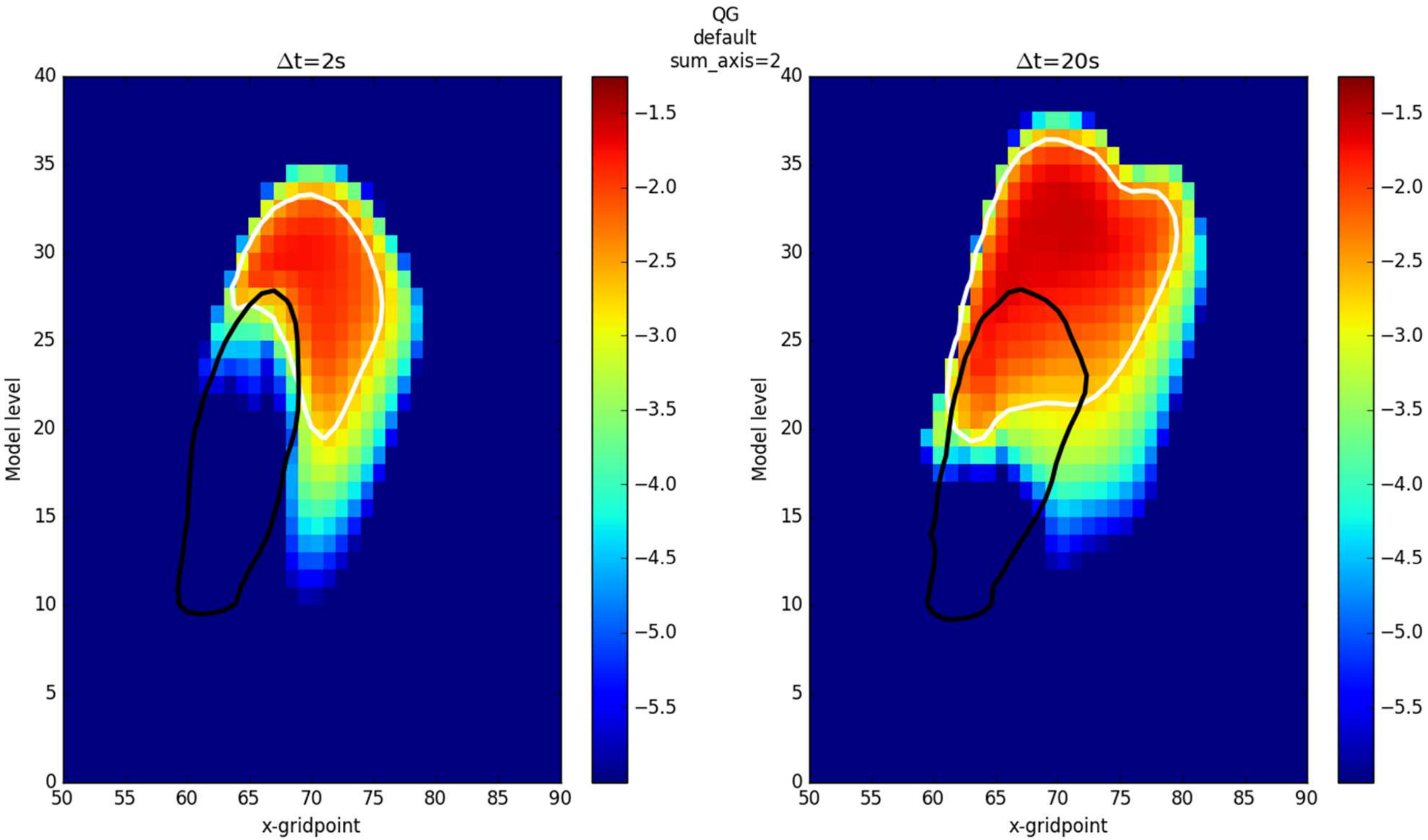
50
55
60
65
70
75
80
85
90
−1.5
−2.0
−2.5
−3.0
−3.5
−4.0
−4.5
−5.0
−5.5

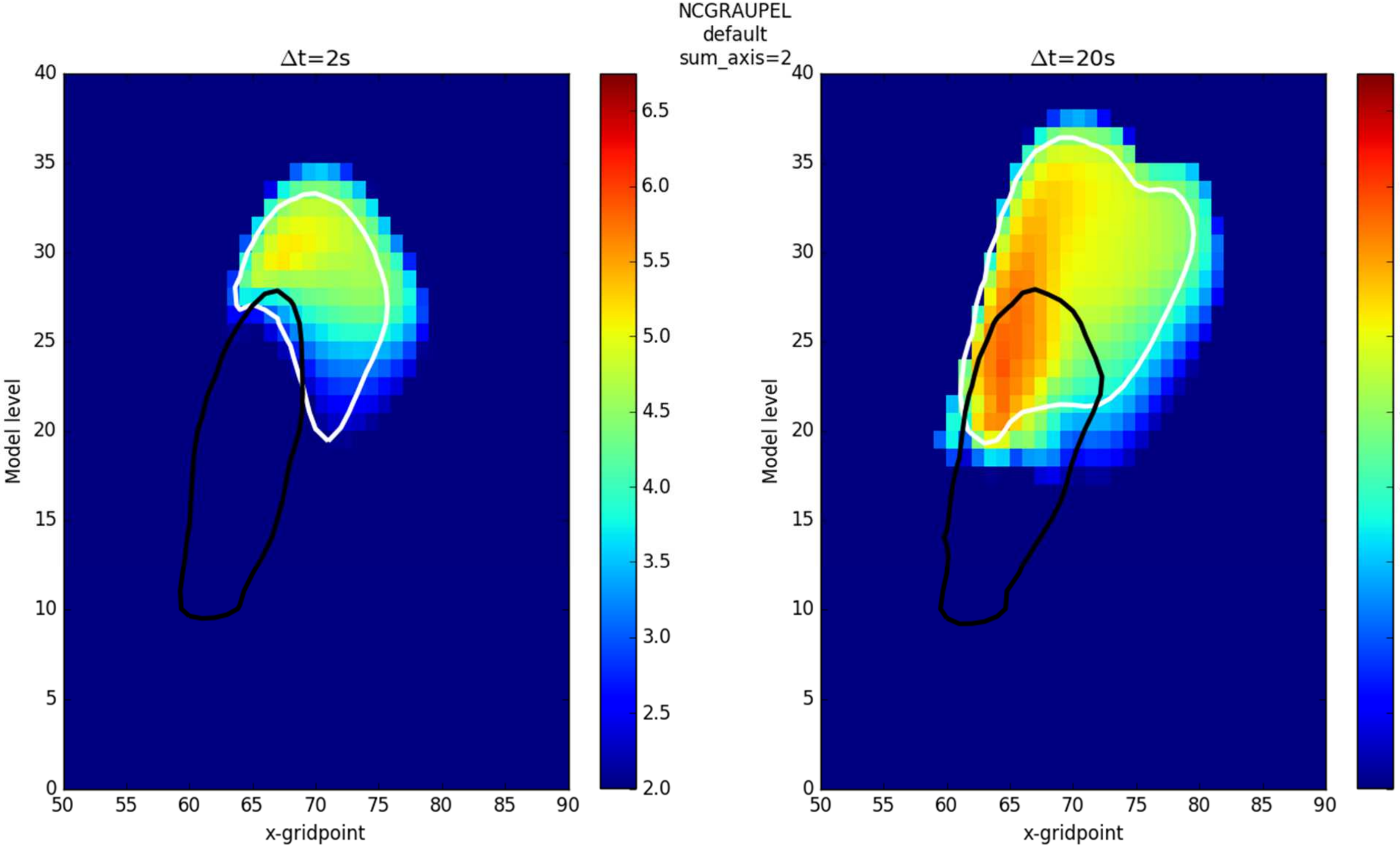
Hail number production (from graupel)



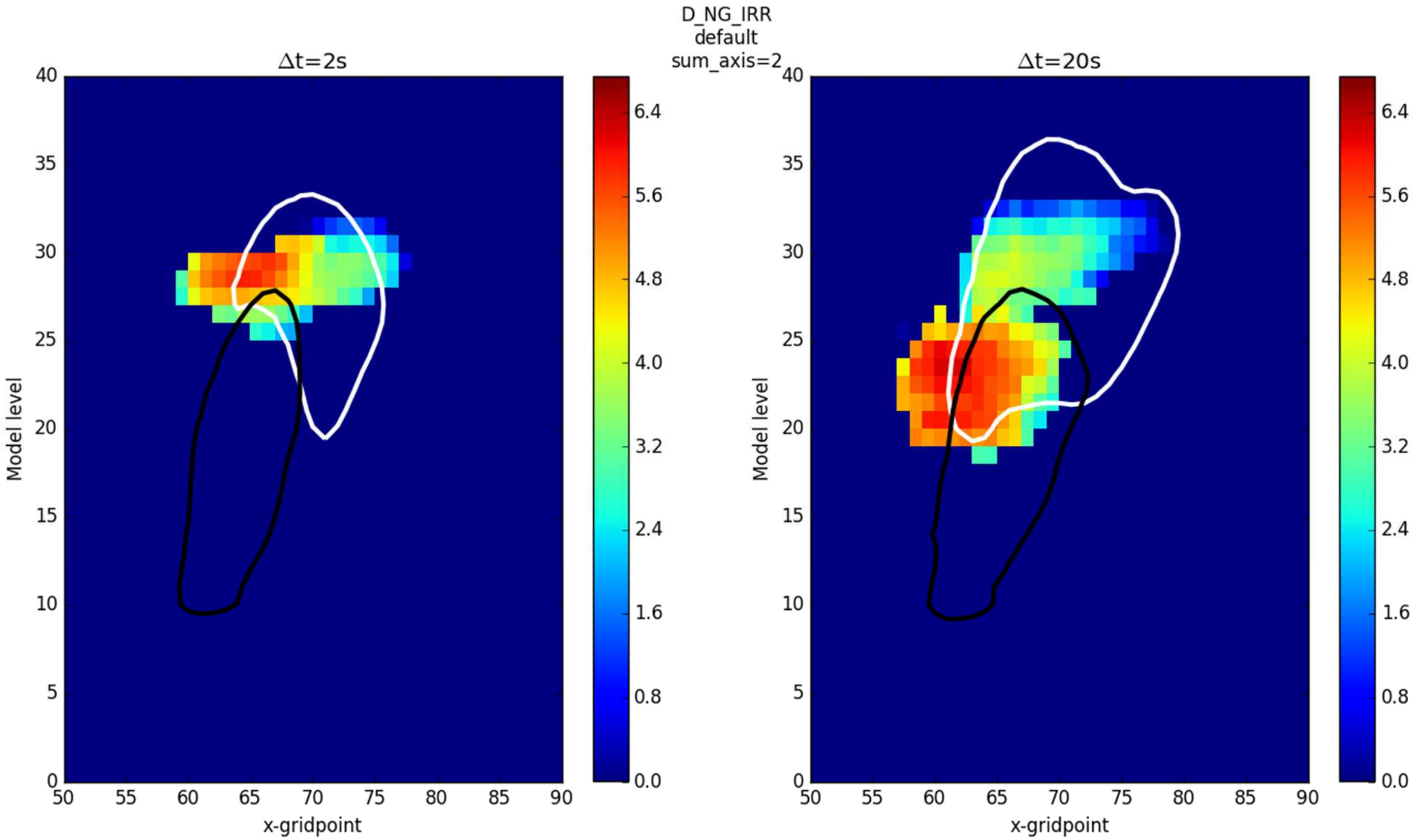
Graupel mass



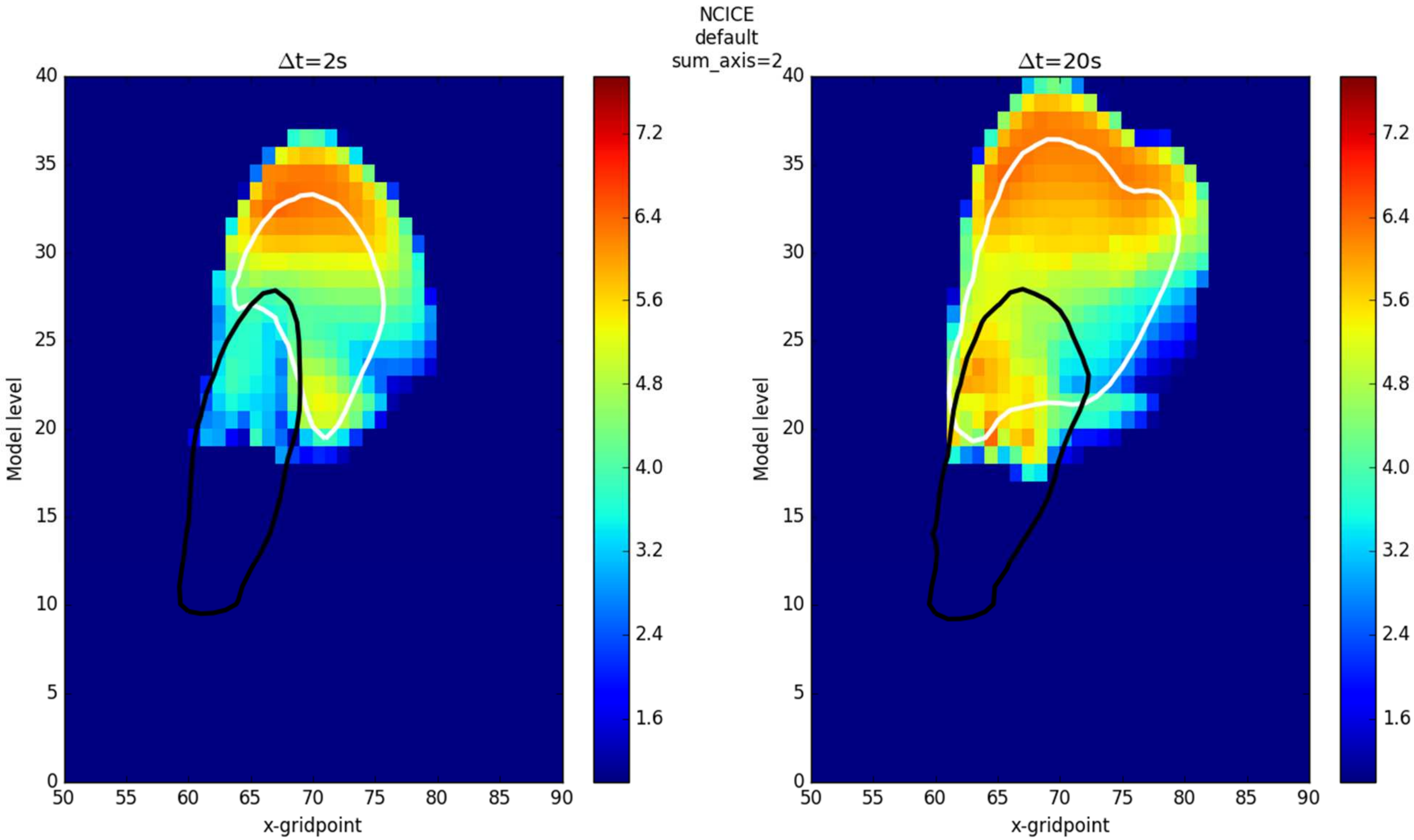
Graupel number



Graupel number production (by ice-rain riming)



Ice number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Δt=2s
Δt=20s
Model level
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50
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75
80
85
90
7.2
6.4
5.6
4.8
4.0
3.2
2.4
1.6