Warm-Phase Spectral-Bin Microphysics in ICON

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Thanks to: Axel Seifert[4], Daniel Reinert[4]

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(2) Pacific Northwest National Laboratory
(3) The Hebrew University of Jerusalem
(4) Deutscher Wetterdienst

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Outlook

1. Overview
2. Warm-Phase SBM Implementation in ICON
3. First tests of Cumulonimbus development (Weisman-Klemp 1982)

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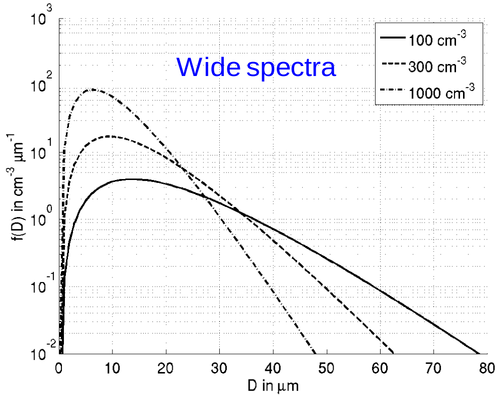
Two methods of representing cloud microphysics

<table>
<tr><th></th><th>Bulk-microphysics Parameterization</th><th>Spectral (Bin) Microphysics (SBM)</th></tr>
<tr><td>Description of size distributions</td><td>

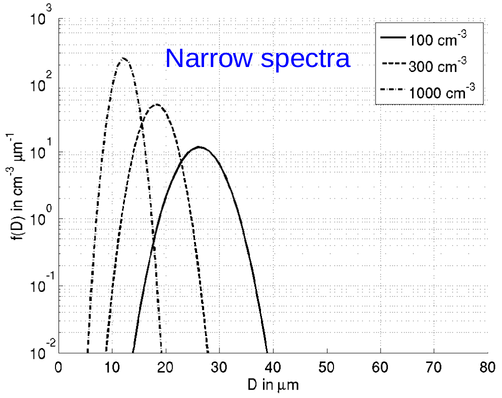
Gamma distributions with several given parameters

4 parameters formula :
(gamma distribution)

$$f(m) = N_0 m^{\nu} e^{-\lambda m^{\mu}}$$



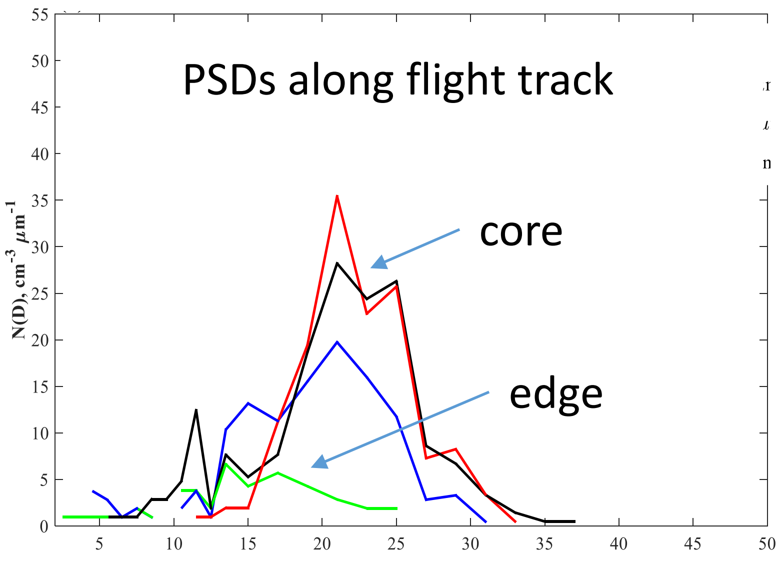
v=1, μ=1/3



v=6, μ=1

</td><td>

Examples of real size distributions (droplets)



</td></tr>
<tr><td>Basic equations</td><td>

For moments:

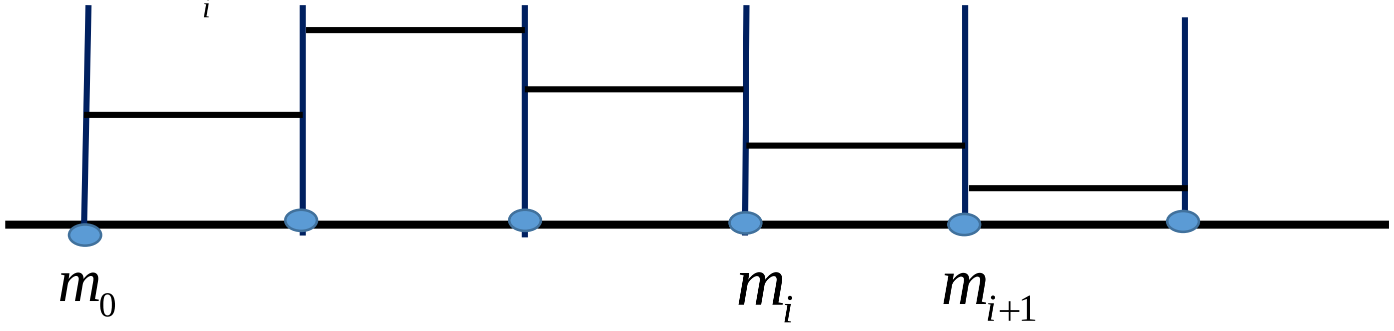
$$M^{(k)} = \int_0^{\infty} m^k f(m) dm$$

K=0 number concentration; k=1 mixing ratios; k=2-radar reflectivity.

2M → 2 parameters are free and 2 are preset

</td><td>For size distribution functions f(m)</td></tr>
</table>

$$\frac{m_{i+1}}{m_i} = \alpha$$ (= 2 in ICON)



In ICON:

- 33 drops bins
- 33 ccn bins
- 33 activated ccn (for regeneration*)

*Currently switched off

$$N = \int_{m_{\min}}^{m_{\max}} f(m)dm$$: number concentration

$$M = \int_{m_{\min}}^{m_{\max}} mf(m)dm$$: mixing ratio

Equation for size distribution is solved for each bin:

mixed phase

$$\frac{\partial \rho f_{i,k}}{\partial t} + \frac{\partial \rho u f_{i,k}}{\partial x} + \frac{\partial \rho v f_{i,k}}{\partial y} + \frac{\partial \rho (w - V_t(m_i)) f_k}{\partial z} = \left(\frac{\delta f_{i,k}}{\delta t}\right)_{nucl} + \left(\frac{\delta f_{i,k}}{\delta t}\right)_{c/e} + \left(\frac{\delta f_{i,k}}{\delta t}\right)_{d/s} + \left(\frac{\delta f_{i,k}}{\delta t}\right)_{f/m} + \left(\frac{\delta f_{i,k}}{\delta t}\right)_{col} \ldots$$

Advection
(outside microphysics)

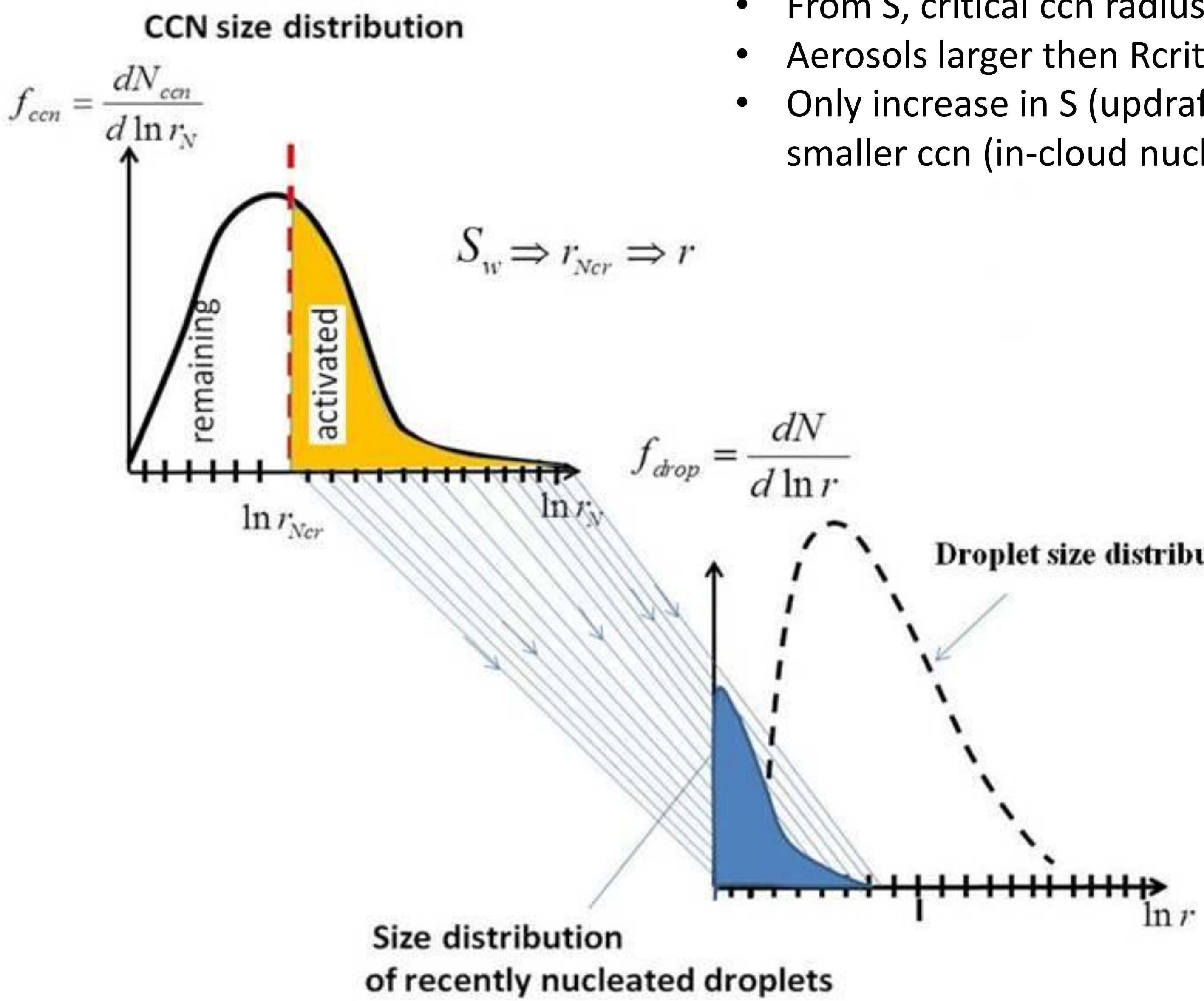
sedimentation

nucleation

cond/evap

Collisions+break up

Description of physical processes: **Nucleation** (Kohler theory)



- From S, critical ccn radius is calculated
- Aerosols larger then Rcrit → droplets
- Only increase in S (updraft) may lead to activation of smaller ccn (in-cloud nucleation) → multi modal PSD

Description of physical processes: **Cond/Evap**

Solution of 2 equations:

Eqn for Supersaturation

S increases in updraft (source) and condensates (sink)

$$\frac{dS}{dt} = \left(\frac{dS}{dt}\right)_{dyn} - \mathrm{A}\frac{dq_c}{dt}$$

S(t) = super saturation

dt = microphysical sub-step

q_c = cloud water content = integral over PSD

Eqn of diffusional growth for each bin r_i

(how the molecules condensate on droplet surface)

$$r\frac{dr}{dt} = \frac{1}{F}S$$

r(t) = super saturation → PSD(t)

$$\left(\frac{dS}{dt}\right)_{dyn} = \frac{\boldsymbol{S}\,(after\ advection) - \boldsymbol{S}\,(before\ dynamics)}{model\ time\ step}$$

On input, the microphysics needs:

- T and qv before dynamics
- T and qv after advection

Description of physical processes: **Collisions**

Stochastic equation for collisions:

Change of:
Number of droplets
of mass m

$$\frac{df(m,t)}{dt} = \underbrace{\int_0^{m/2} f(m')f(m-m')K(m-m',m')dm'}_{GAIN} - \underbrace{\int_0^{\infty} f(m)f(m')K(m,m')dm'}_{LOSS}$$

Collision Kernel =
probability of collision of 2 droplets.
Depends on rel. velocity, droplets sizes

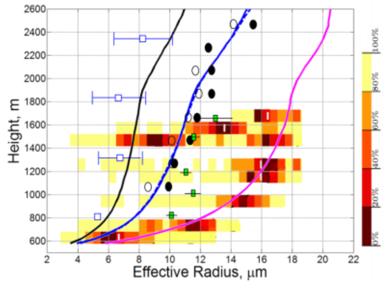
Increase of f(m) due to collisions of masses:
(m’) and (m-m’)
Such that:
(m’)+(m-m’)=m

Decrease of f(m) due to collision
of (m) with some (m’)

* Works for entire
range of drop sizes

SBM is used for various cloud-related phenomena

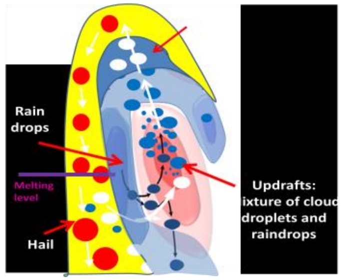
Shallow clouds (SAM-LES)



Khain P. et al. 2019

Comparison of mean effective radius profiles simulated using SAM with observations

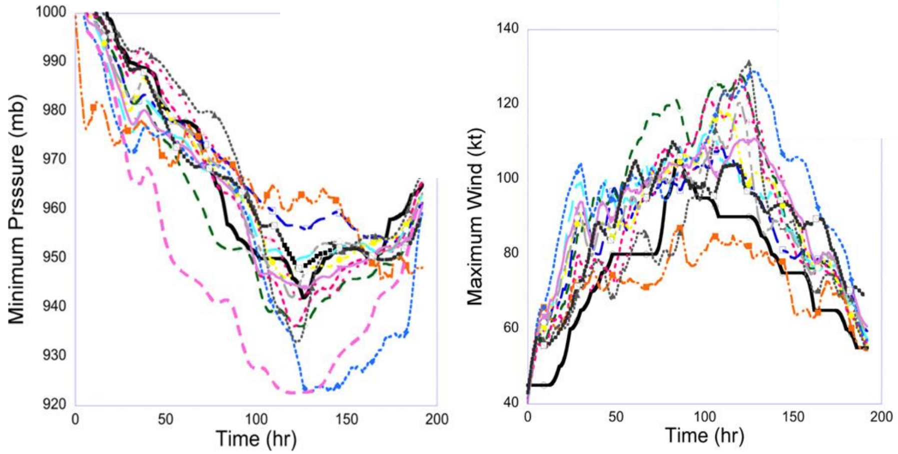
Hail storms:



Ilotoviz et al. 2019

Mechanism of large hail formation in deep convective clouds (HUCM)

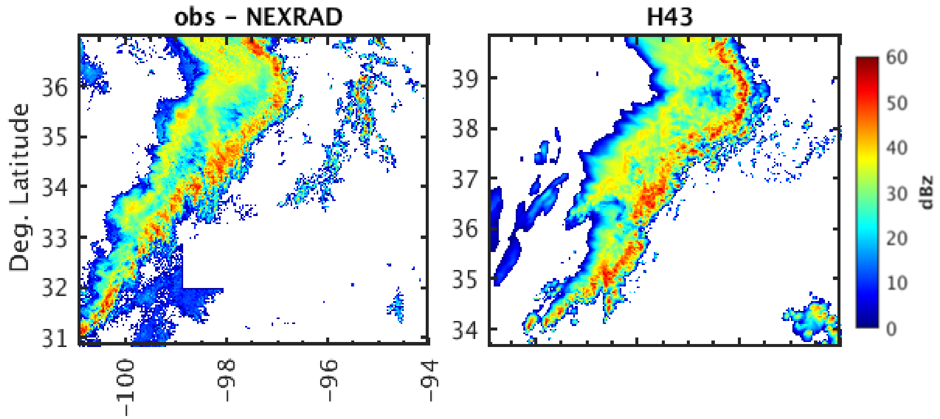
Hurricanes:



Khain et al. 2016.

Simulation of hurricane Irene (2011) using WRF-SBM and different bulk schemes

Mesoscale convective systems with squall lines:



Shpund et al. 2019

MC3E field campaign.
Simulation using WRF-SBM

SBM is also implemented in:

- The Goddard Cumulus Ensemble (GCE) model https://cloud.gsfc.nasa.gov/index.php?section=11
- JMA-NHM (Japanese model) Iguchi, et al., 2012
- HWRF: https://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php Implementation in progress

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2. Warm-Phase SBM Implementation in ICON

subr. **integrate_nh**
(mo_nh_stepping.f90)

call perform_dyn_substepping ← T,qv=?

call diffusion (numerical)

call step_advection

call nwp_nh_interface →

subr. **nwp_nh_interface** (mo_nh_interface_nwp.f90)

← High SupSat (S) after advection

call calc_old_temp (calculate T before dynamics: T_{new}-dt*dT/dt)

save T,qv (after advection and before saturation adjustment)

} new

call **satad_v_3D** (saturation adjustment, LH release, qc)

call nwp_surface (land/sea)

call nwp_turbdiff (turbulent diffusion – atmo. column) ← Problematic with high S on input. Put after microphysics or switch off See example (A)

call **nwp_microphysics** ↓

call nwp_turbtrans (atmo-surf interface)

call nwp_convection (slow)

call cover_koe (cloud cover - slow)

call set_reff (calc reff for radiation - slow)

call nwp_radiation (slow)

call nwp_gwdrag (gravity waves drag - slow)

call nwp_upatmo_interface (upper-atmo physics - slow)

2. Warm-Phase SBM Implementation in ICON

subr. **nwp_microphysics**
(mo_nwp_gscp_interface.f90)

subr. **graupel**
(gscp_graupel.f90)

1 moment

…

…

subr. **two_moment_mcrph**
(mo_2mom_mcrph_driver.f90)

subr. **clouds_twomoment**
(mo_2mom_mcrph_main.f90)

call ccn_activation_hdcp2
call ccn_activation_sk_4d
call autoconversionKB
call accretionKB
call rain_selfcollectionSB
call autoconversionKK
call accretionKK
call rain_selfcollectionSB
call autoconversionSB
call accretionSB
call rain_selfcollectionSB
call rain_evaporation

mixed phase switched off

subr. **sedimentation_explicit**
(mo_2mom_mcrph_main.f90)

subr. **sbm**
(mo_sbm_driver.f90)

PSD_{drops}, PSD_{ccn}
T,qv(b.ad), T,qv(a.ad)

subr. **warm_sbm**
(mo_sbm_main_NEW.f90)

call jernucl01_ks (nucleation) → water_nucleation
call onecond1 (diffusional growth)
call coal_bott_new_warm (collisions, break up)
call falfluxhucm_z (sedimentation)

subr. **onecond1**
call jerrate_ks (calc coefs for the diffusional growth eqn)
call jertimesc_ks (calc coefs for the supersaturation eqn)
call jersupsat_ks (calc integral S(t)*dt)
call jerdfun_ks → jernewf_ks (recalc drops size)
call jerdfun_new_ks → jernewf_ks (get new PSD - remapping)

subr. **coal_bott_new_warm**
call kernals_ks (collision efficiency X swept volume)
call coll_xxx_bott (stochastic collision eqn)
call coll_breakup_ks (collisional breakup)

subr. **satad_v_3D**
(mo_satad.f90)

subr. **satad_v_3D**
(mo_satad.f90)

~~subr. **satad_v_3D**~~
~~(mo_satad.f90)~~

PSD_{drops}, PSD_{ccn}
T,qv,qc,qr,qnc,qnr

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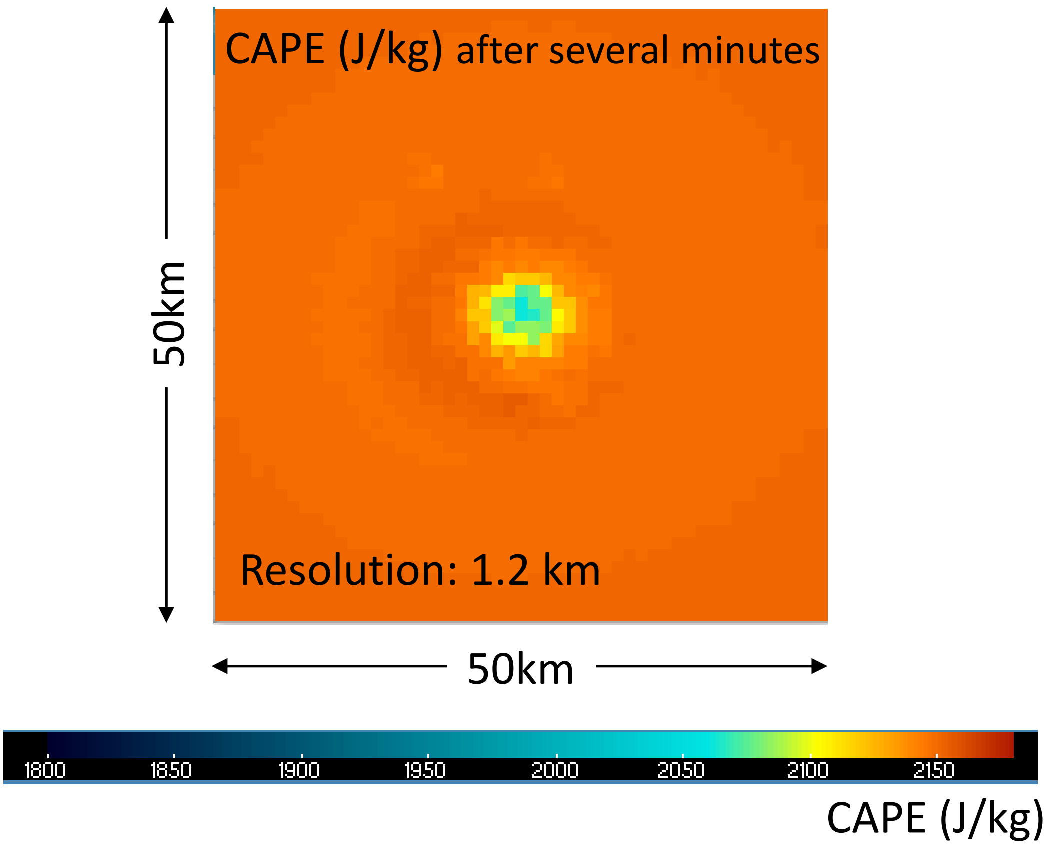
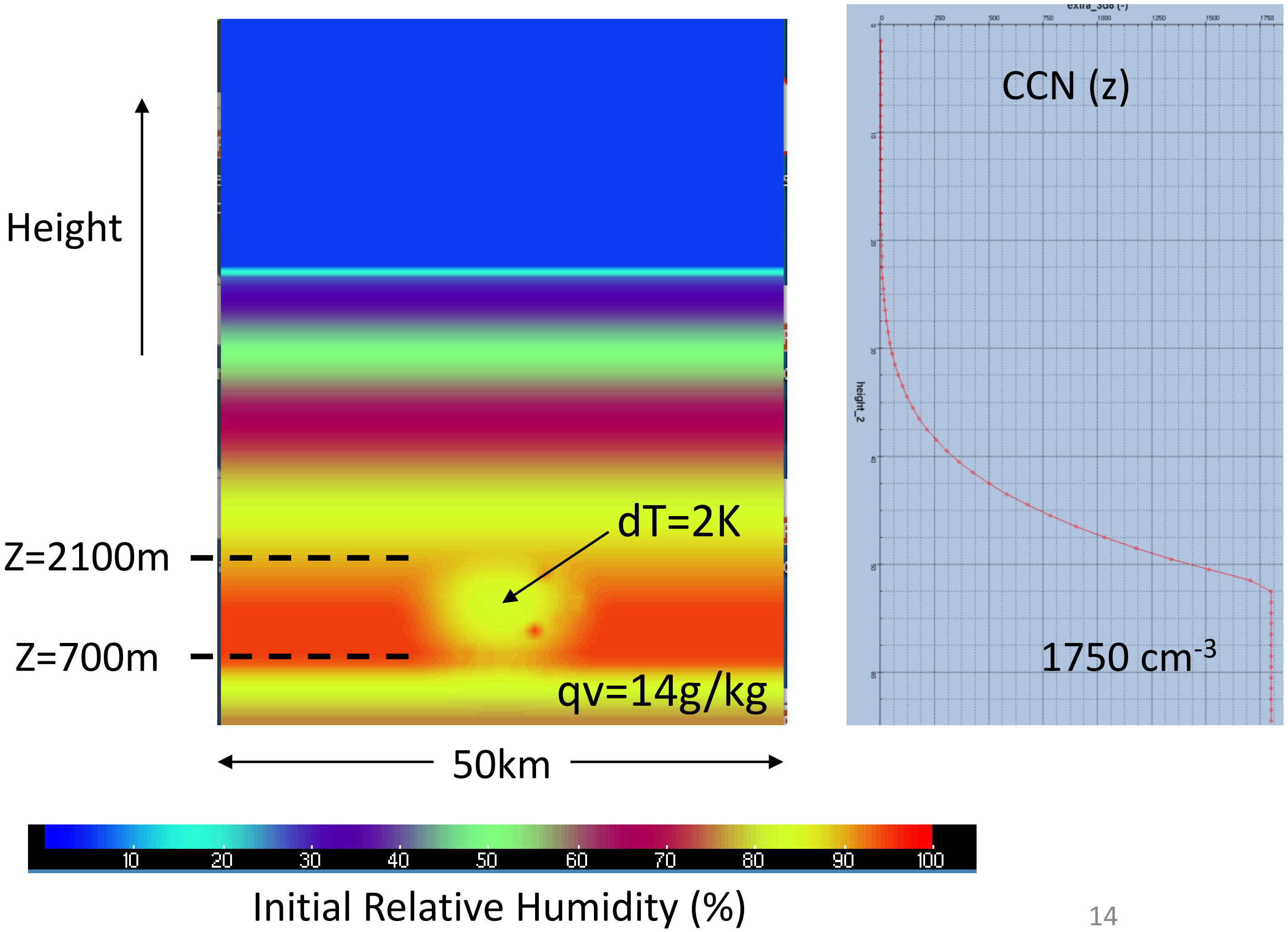
View from above



Cross section

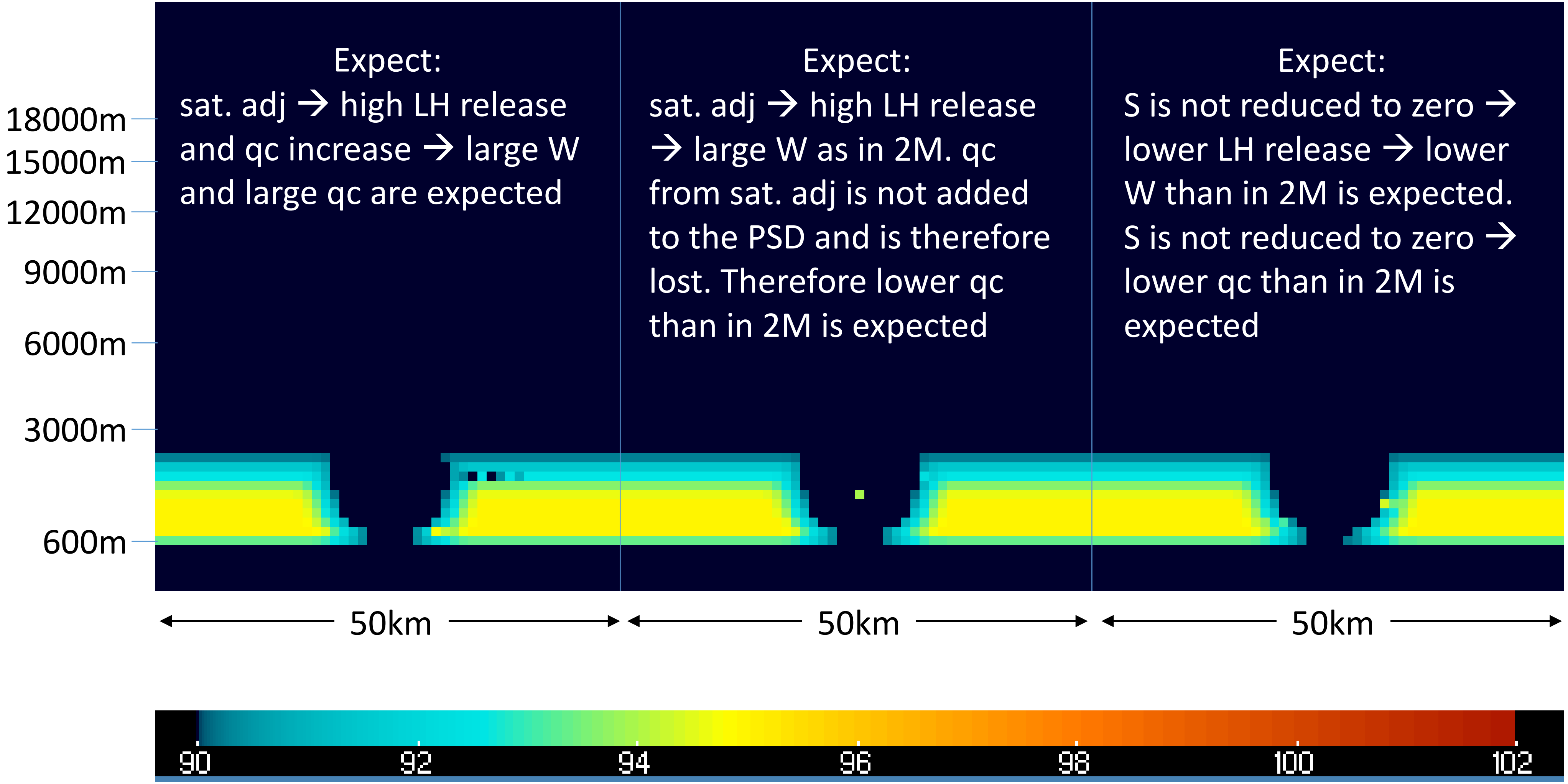


ICON run setup:
dt=1sec
dx=1.2km

Relative Humidity (%)

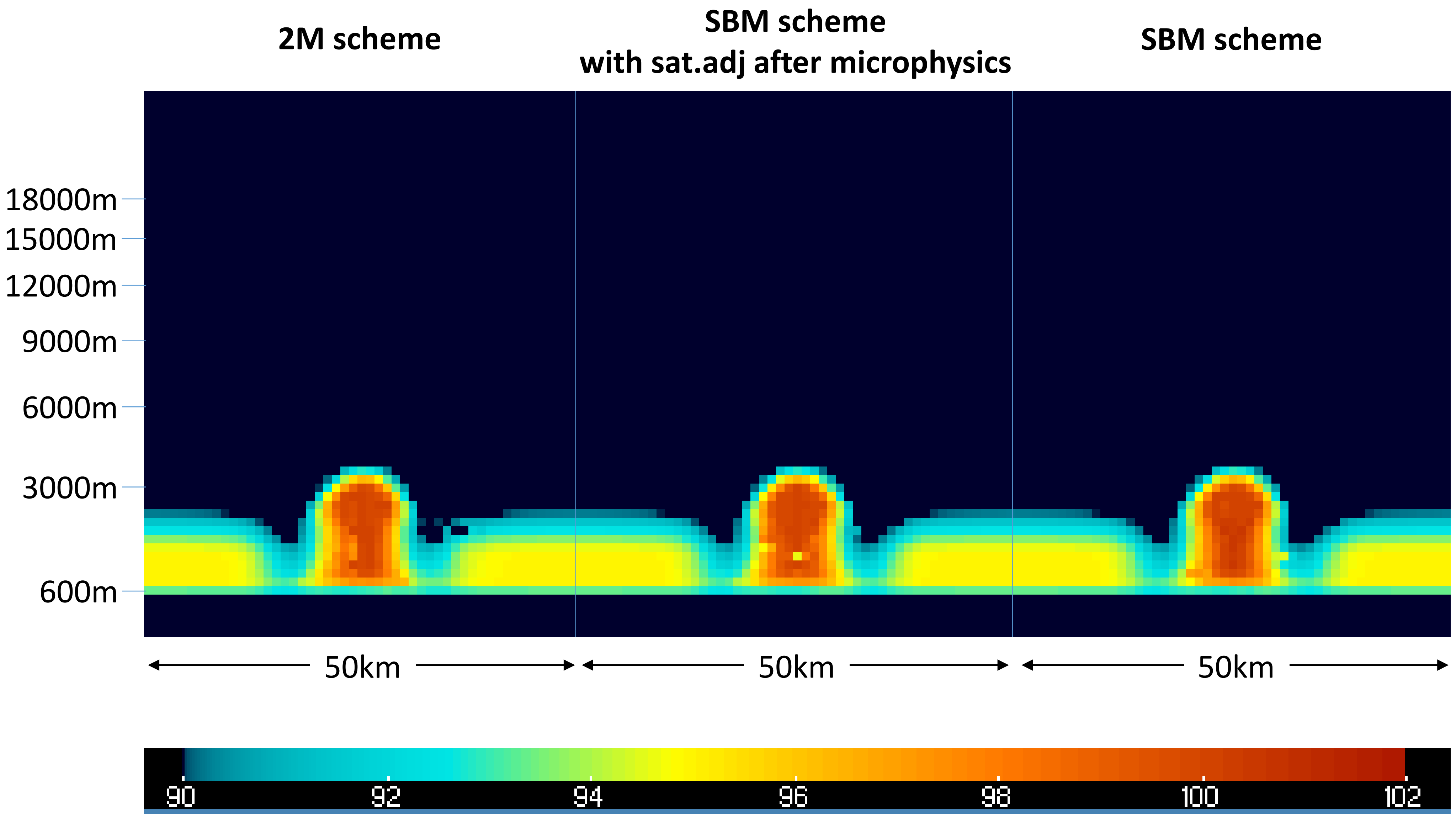
0 min

2M scheme	**SBM scheme with sat.adj after microphysics**	**SBM scheme**



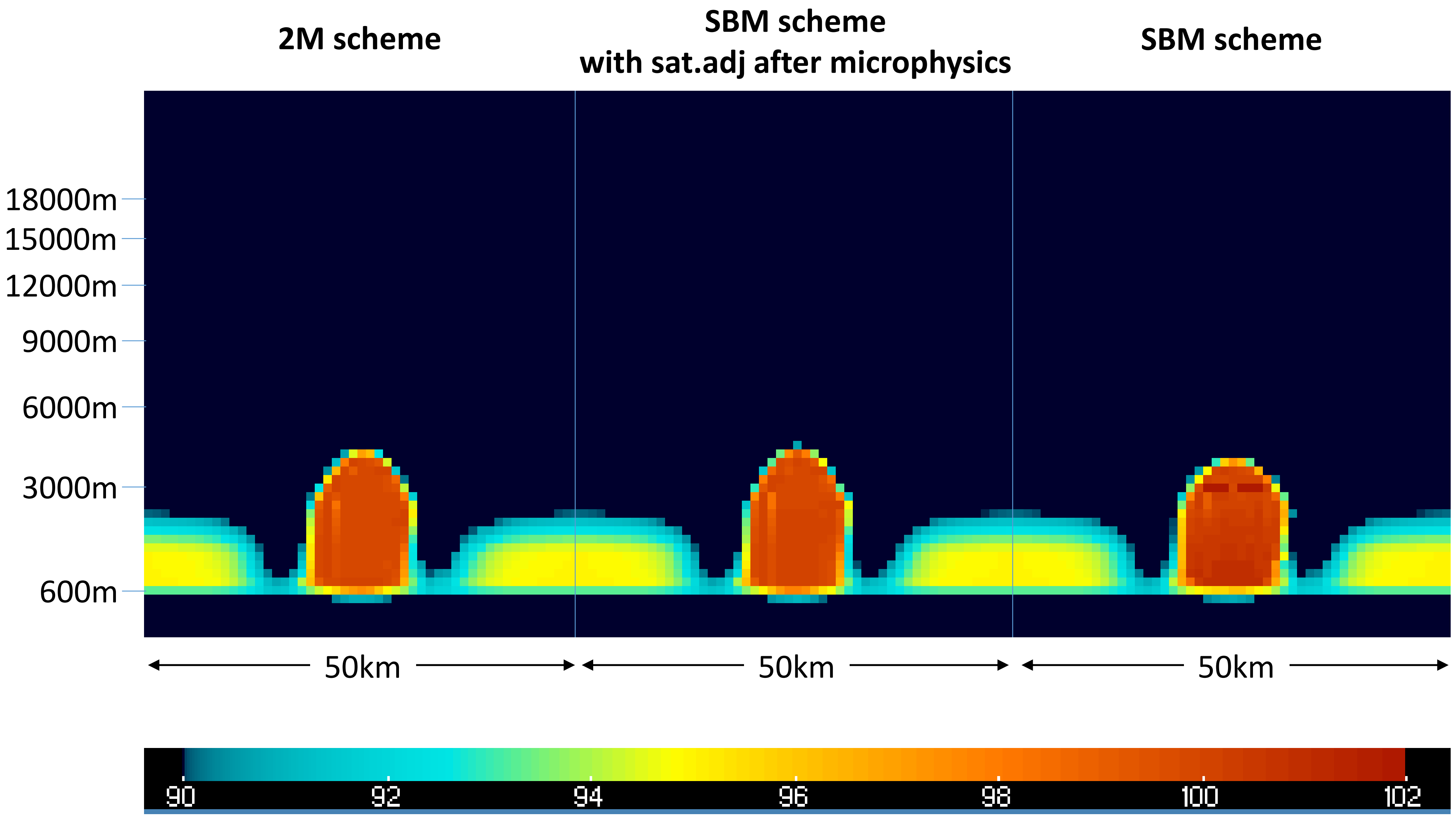
Relative Humidity (%)

6 min



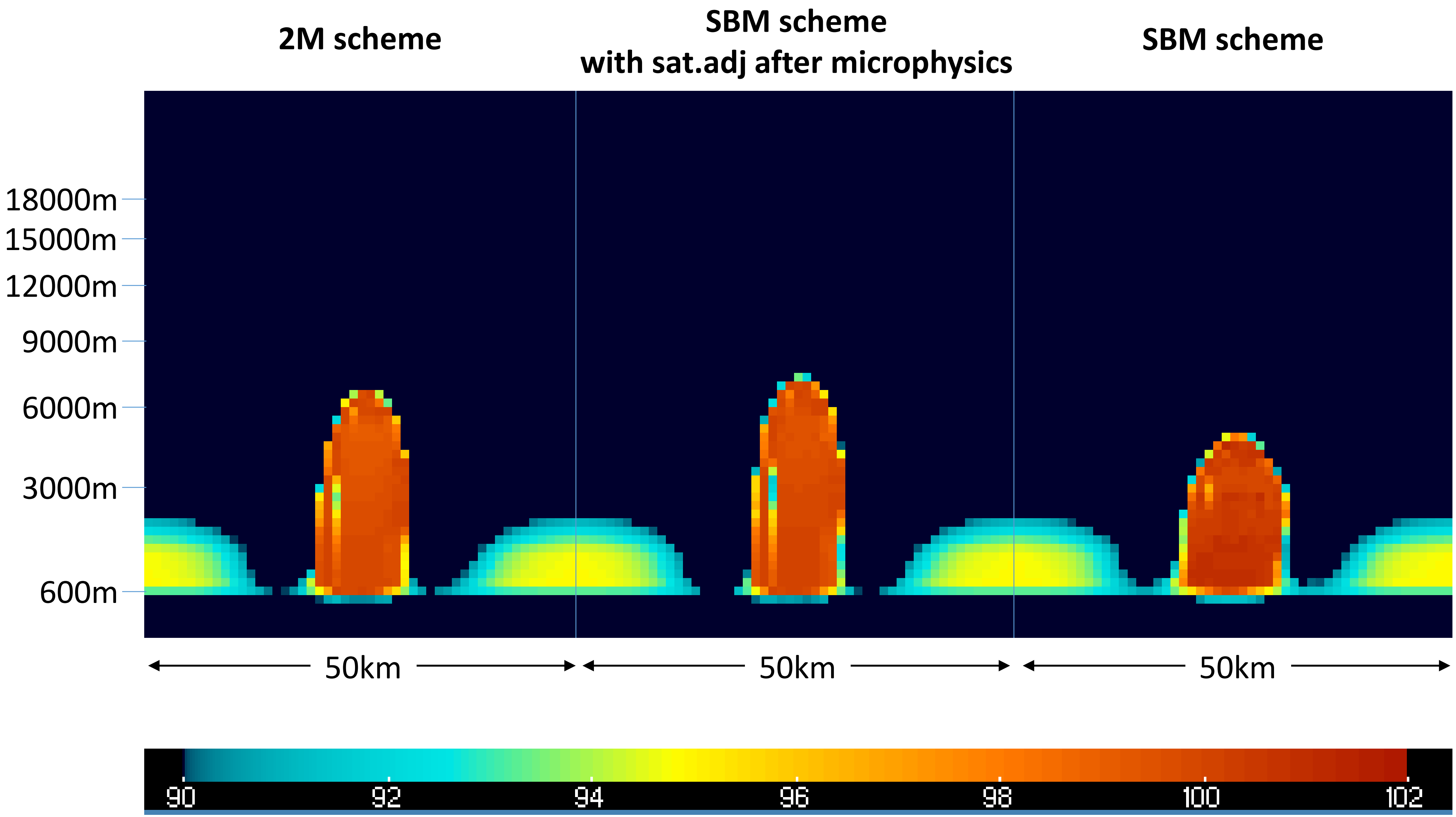
Relative Humidity (%)

12 min



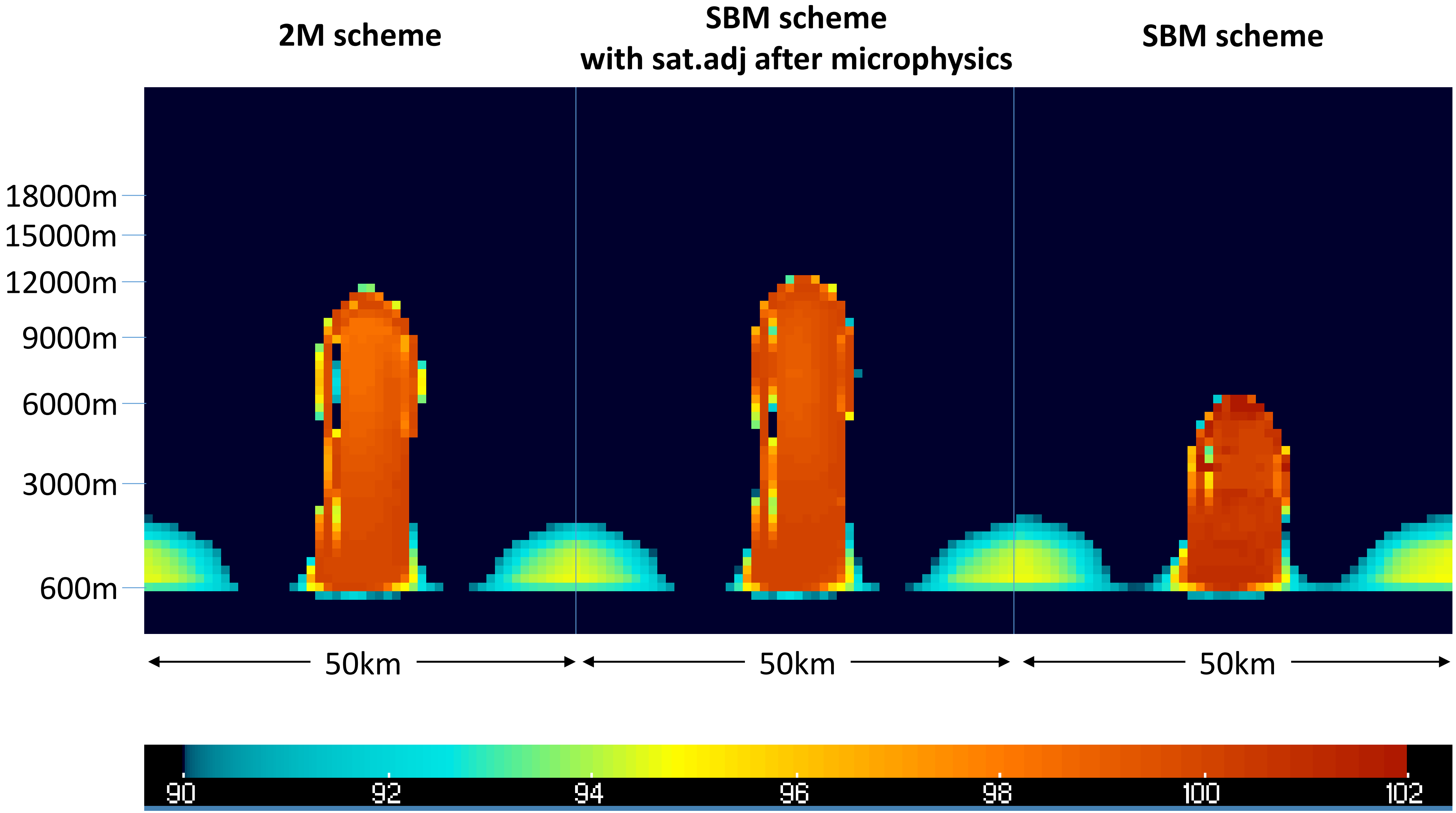
Relative Humidity (%)

18 min



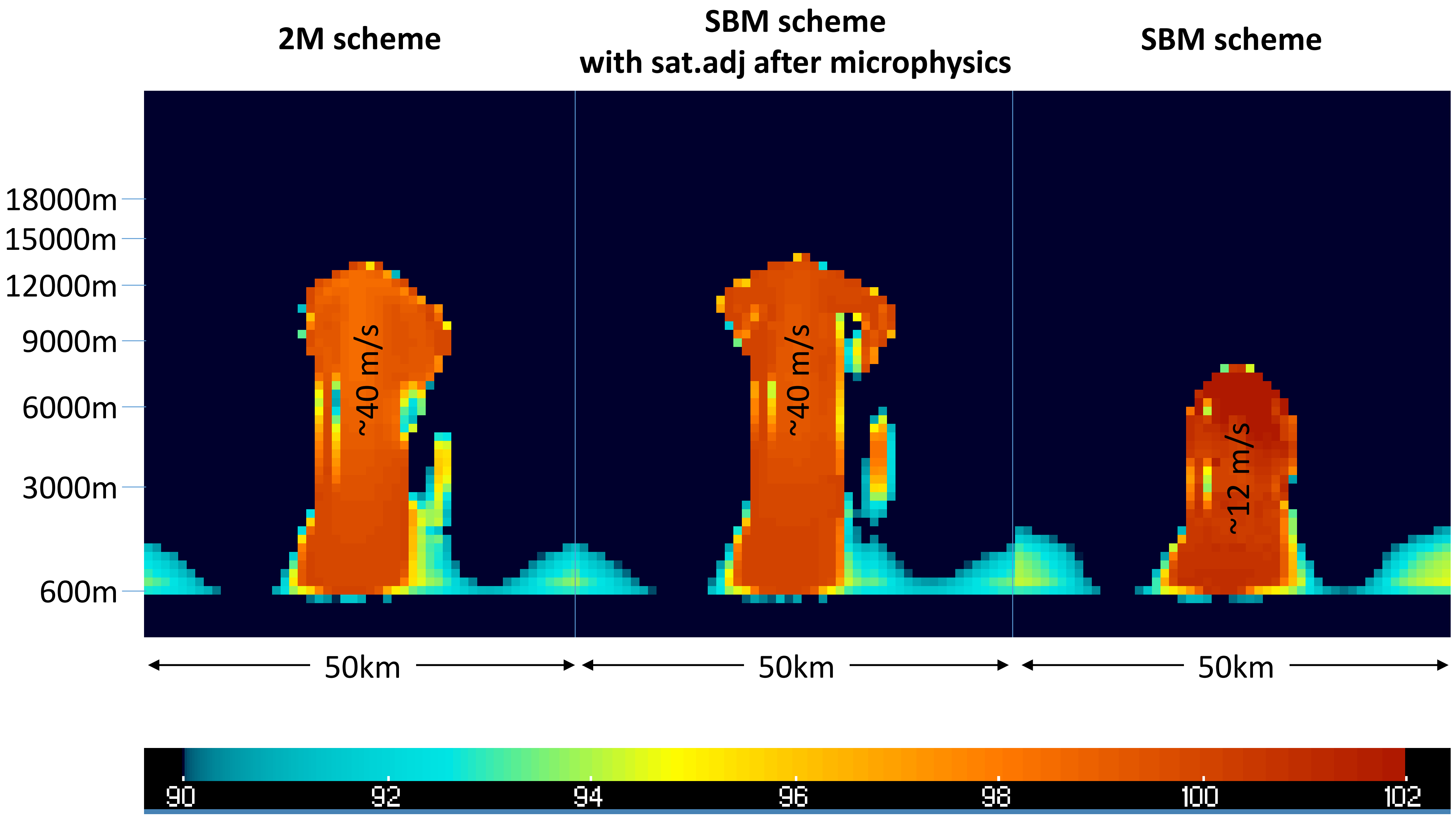
Relative Humidity (%)

24 min



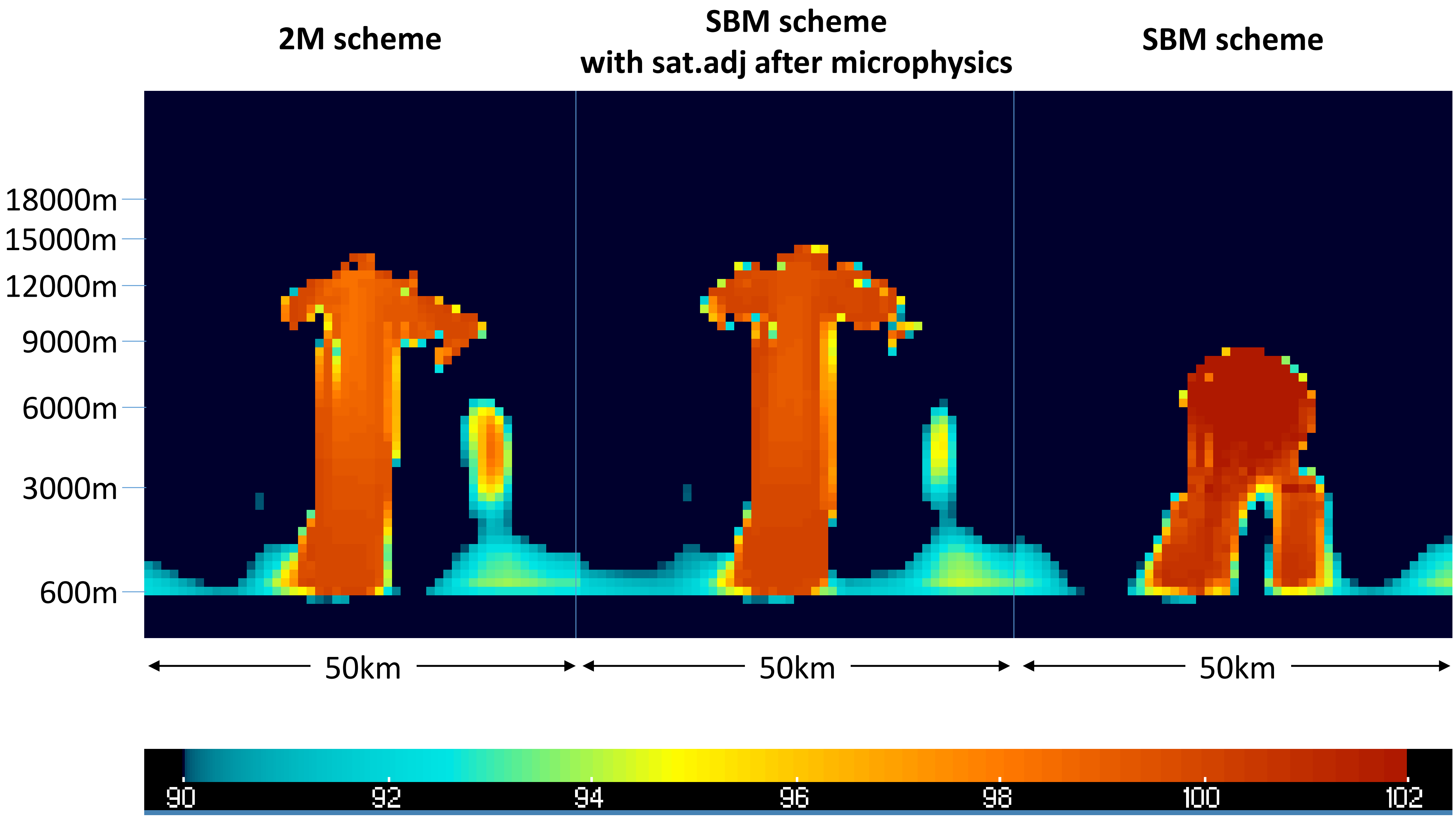
Relative Humidity (%)

30 min



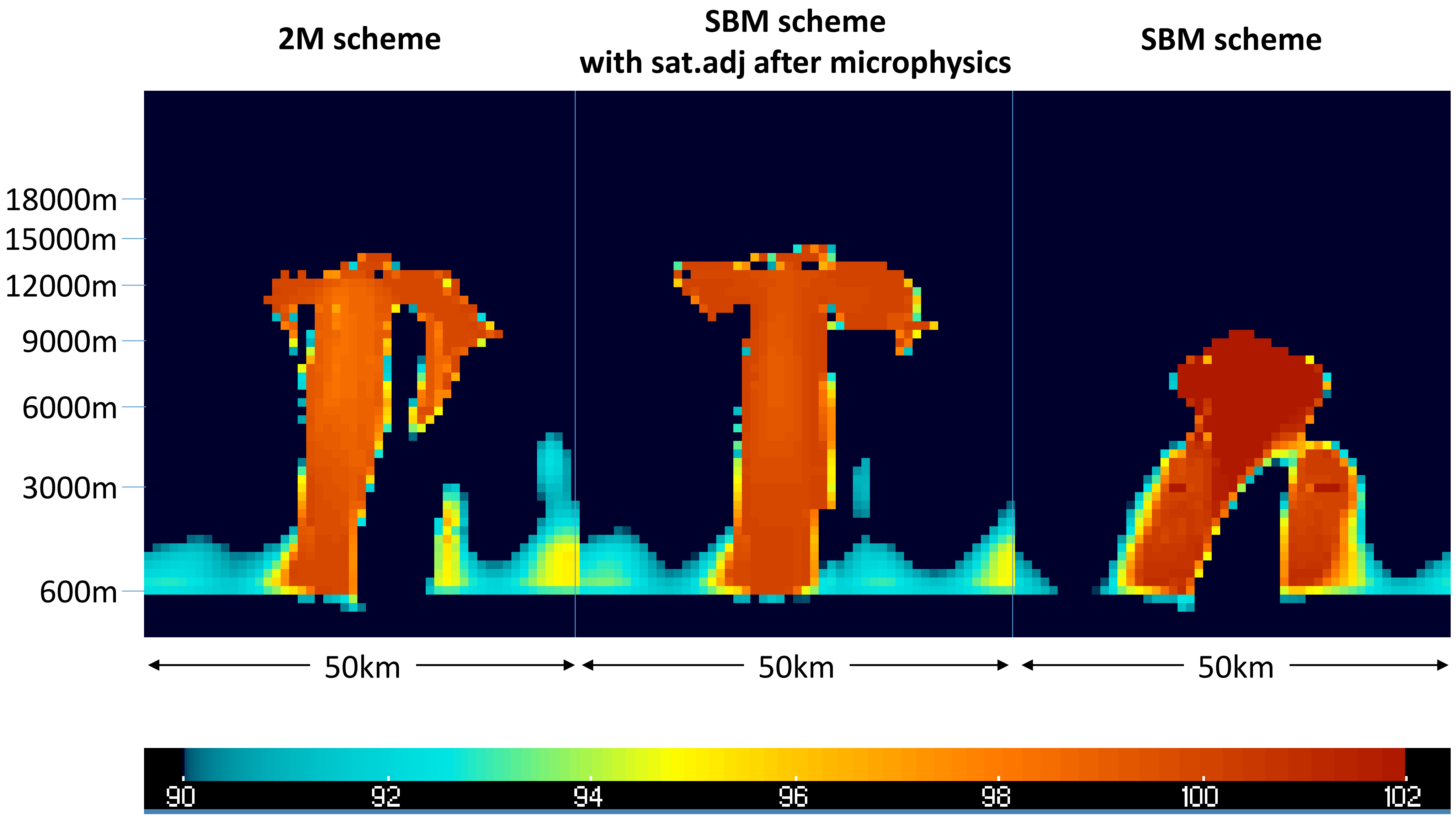
Relative Humidity (%)

36 min



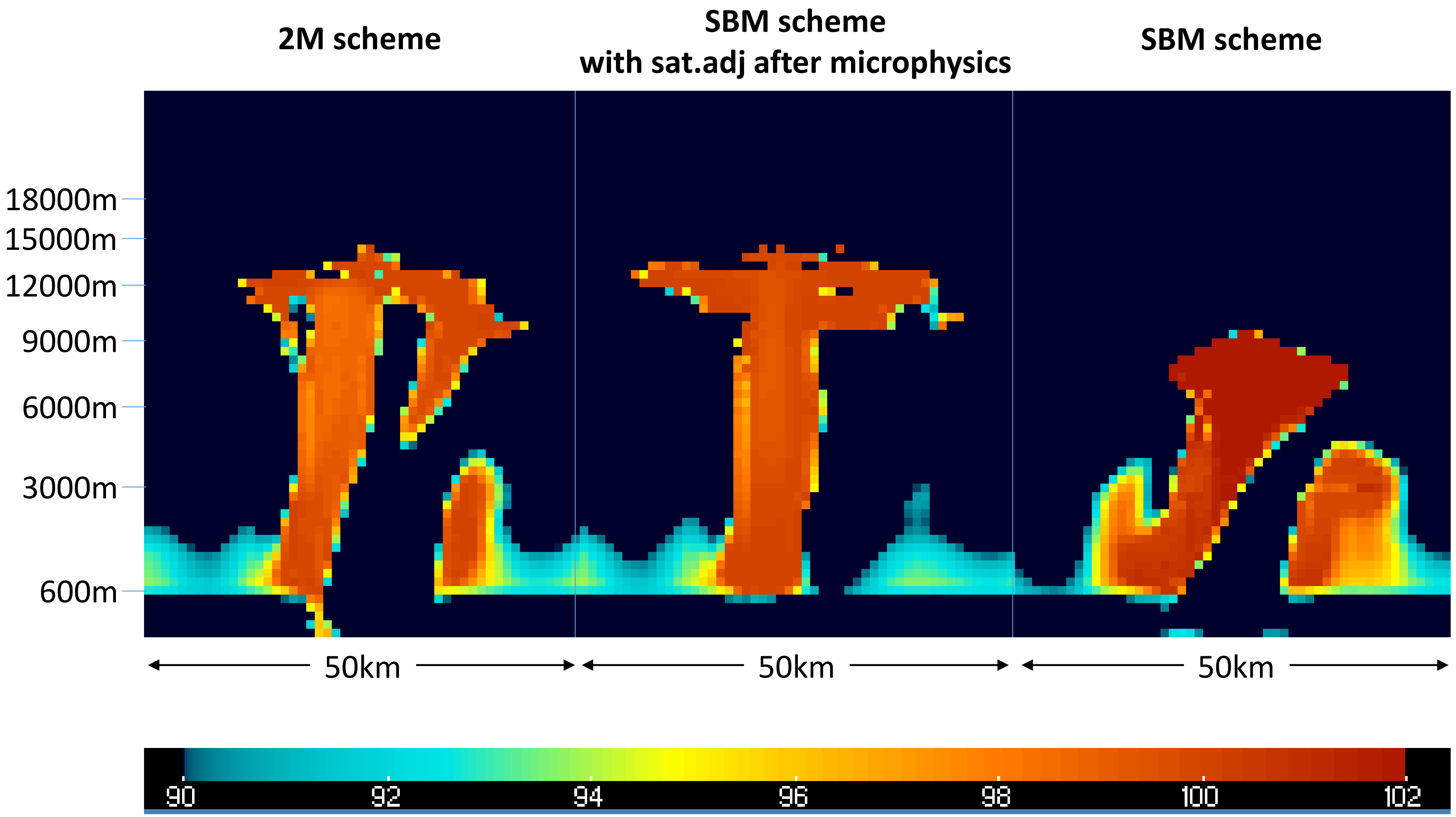
Relative Humidity (%)

42 min



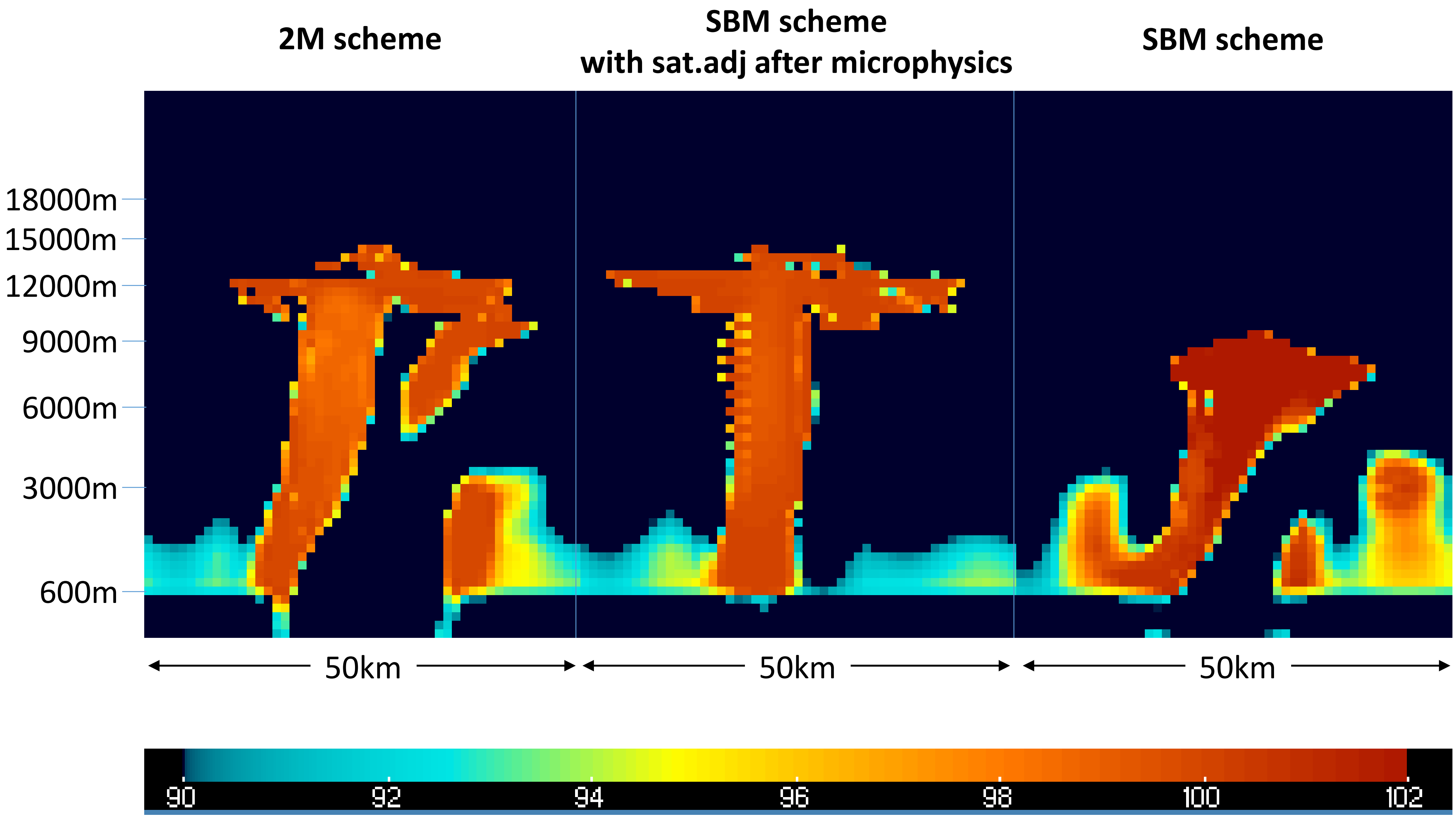
Relative Humidity (%)

48 min



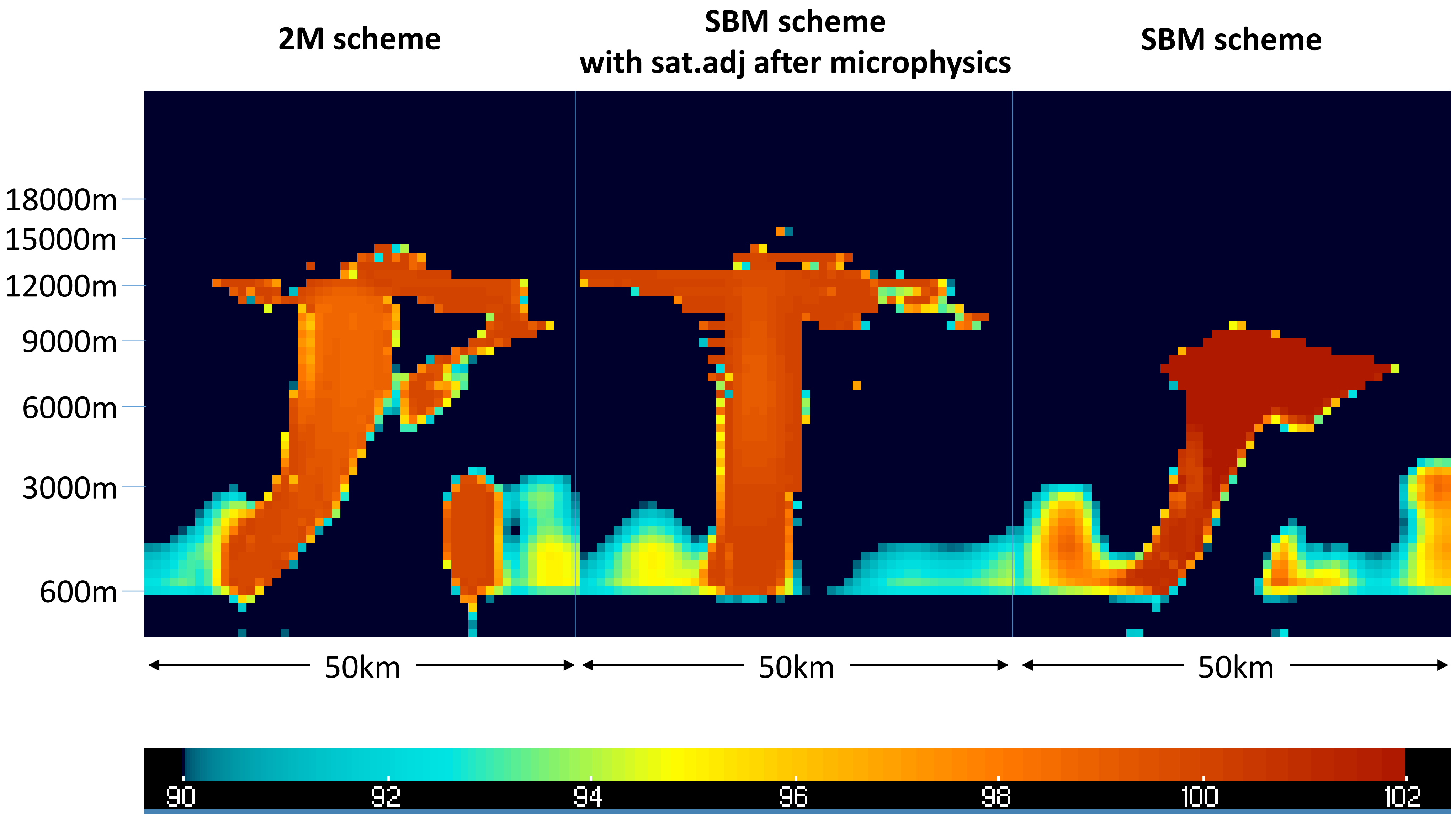
Relative Humidity (%)

54 min



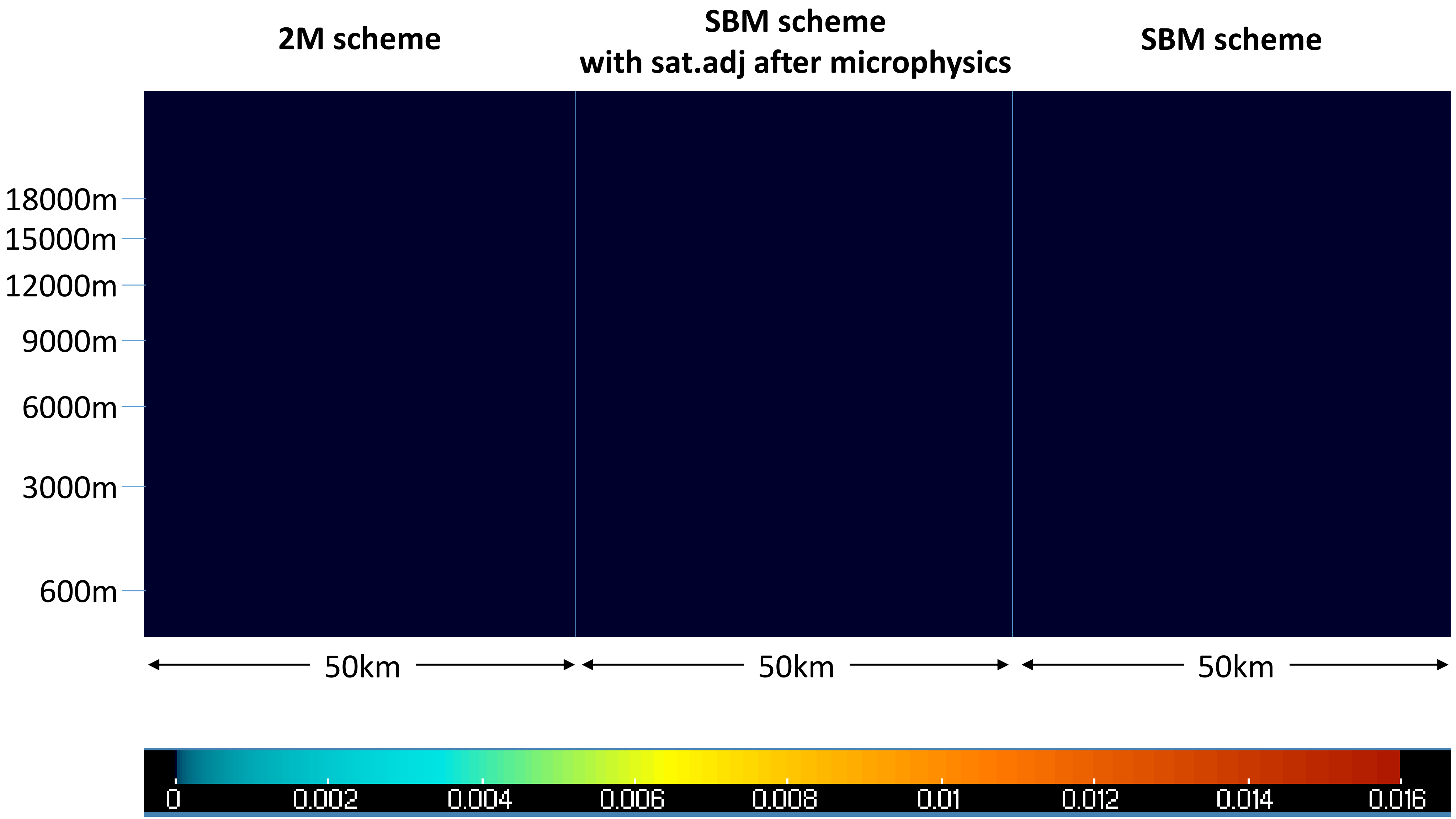
Relative Humidity (%)

60 min



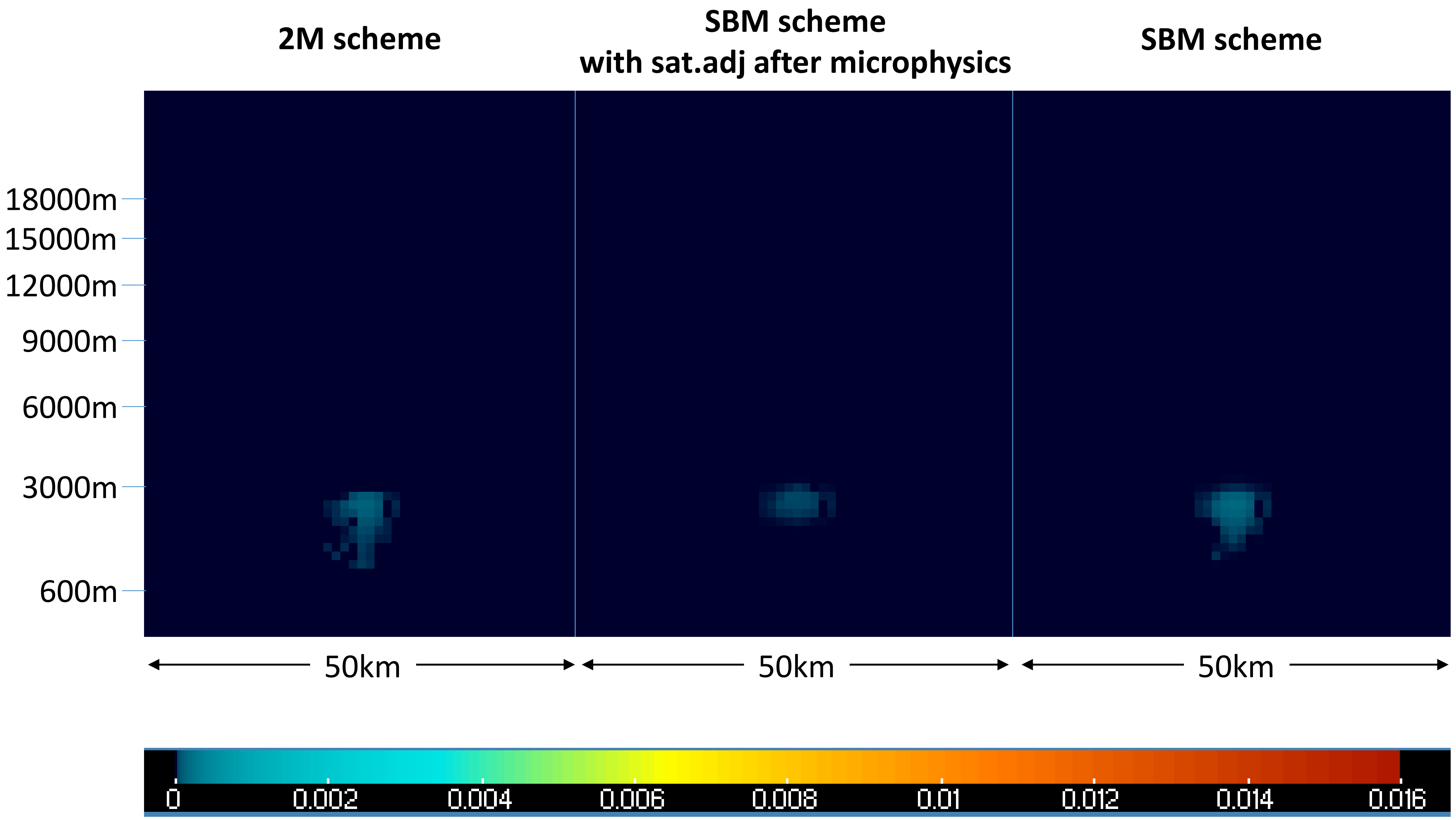
Cloud + rain water content (kg/kg)

0 min



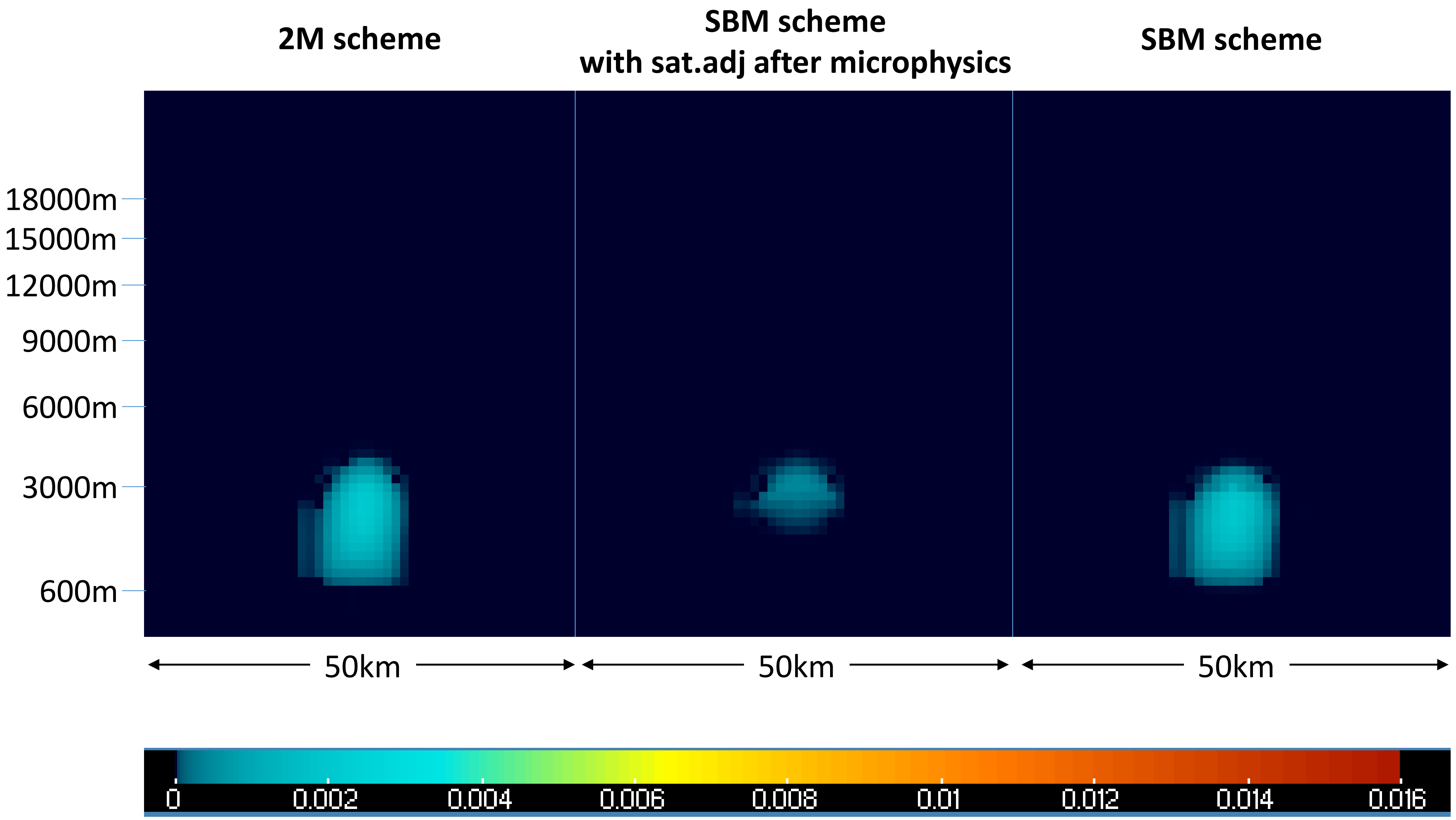
Cloud + rain water content (kg/kg)

6 min



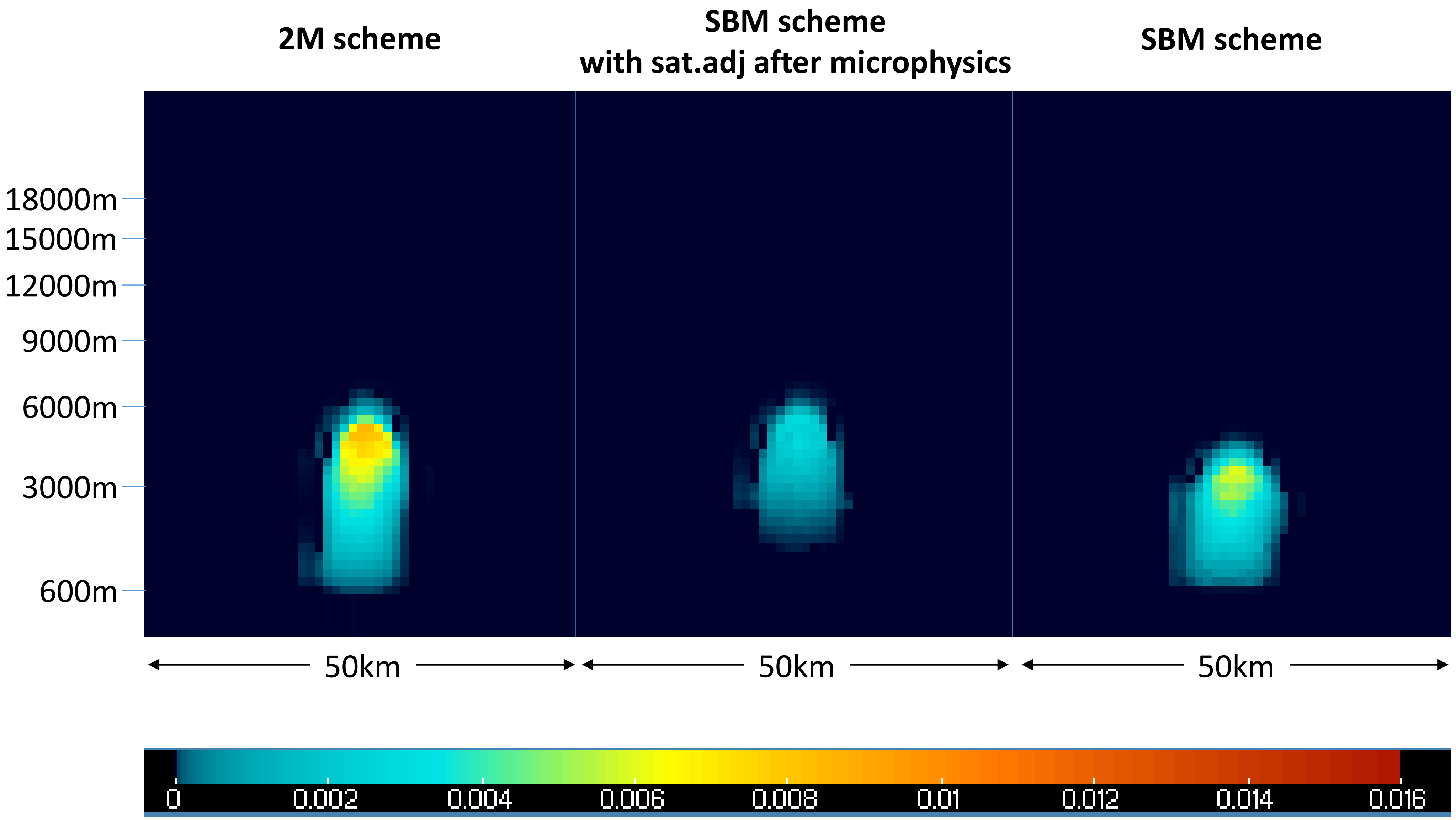
Cloud + rain water content (kg/kg)

12 min



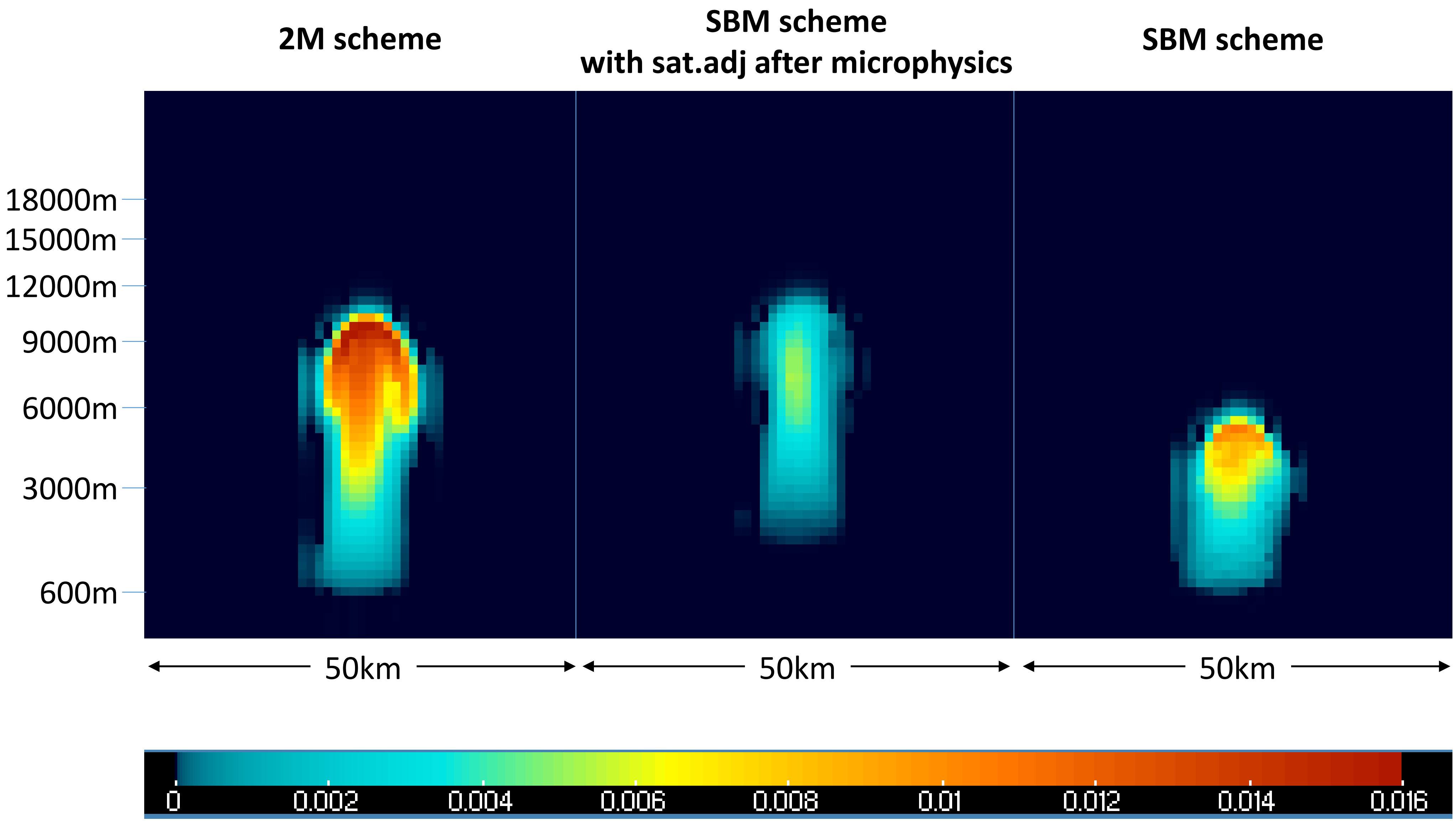
Cloud + rain water content (kg/kg)

18 min



Cloud + rain water content (kg/kg)

24 min



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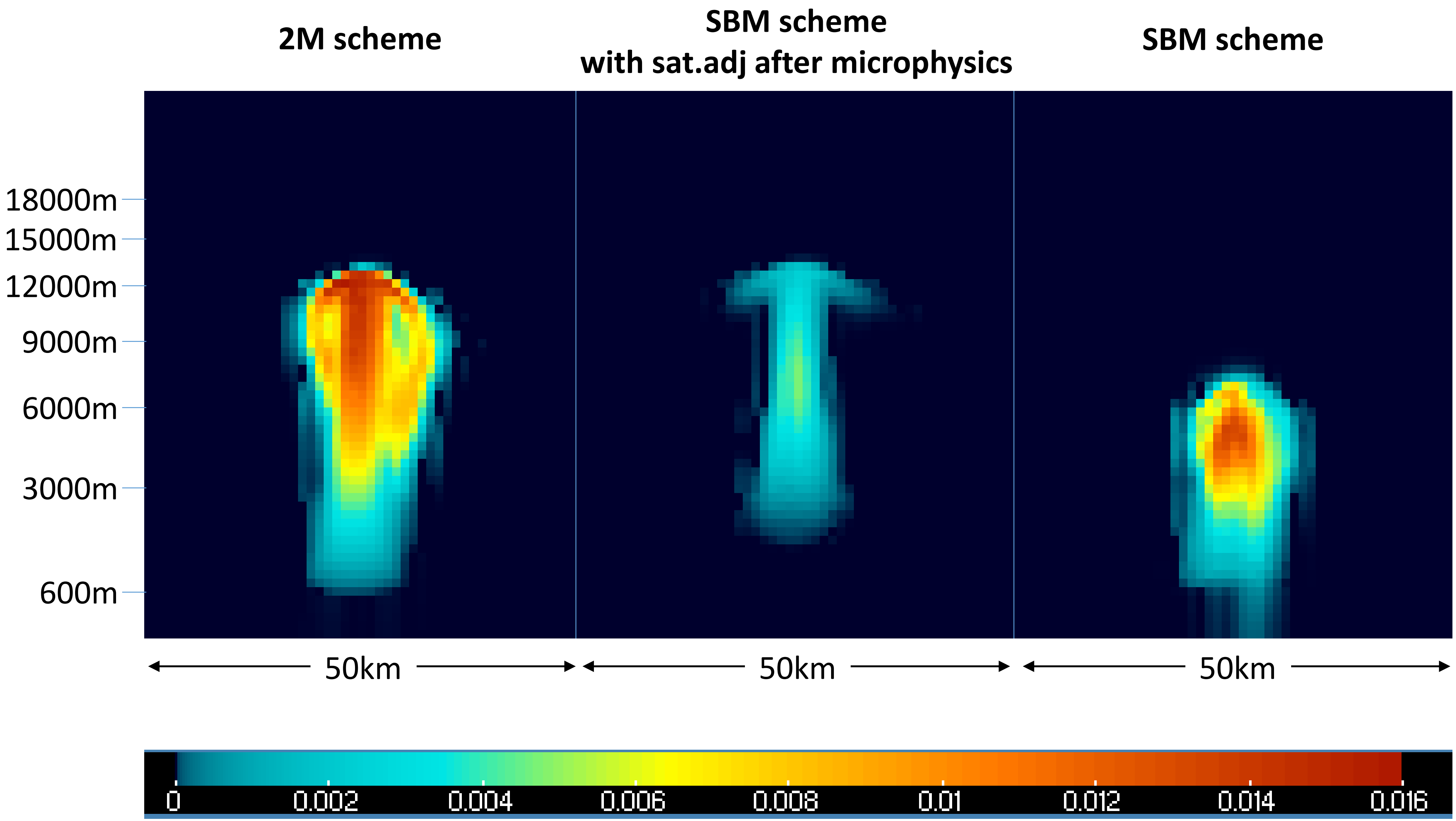
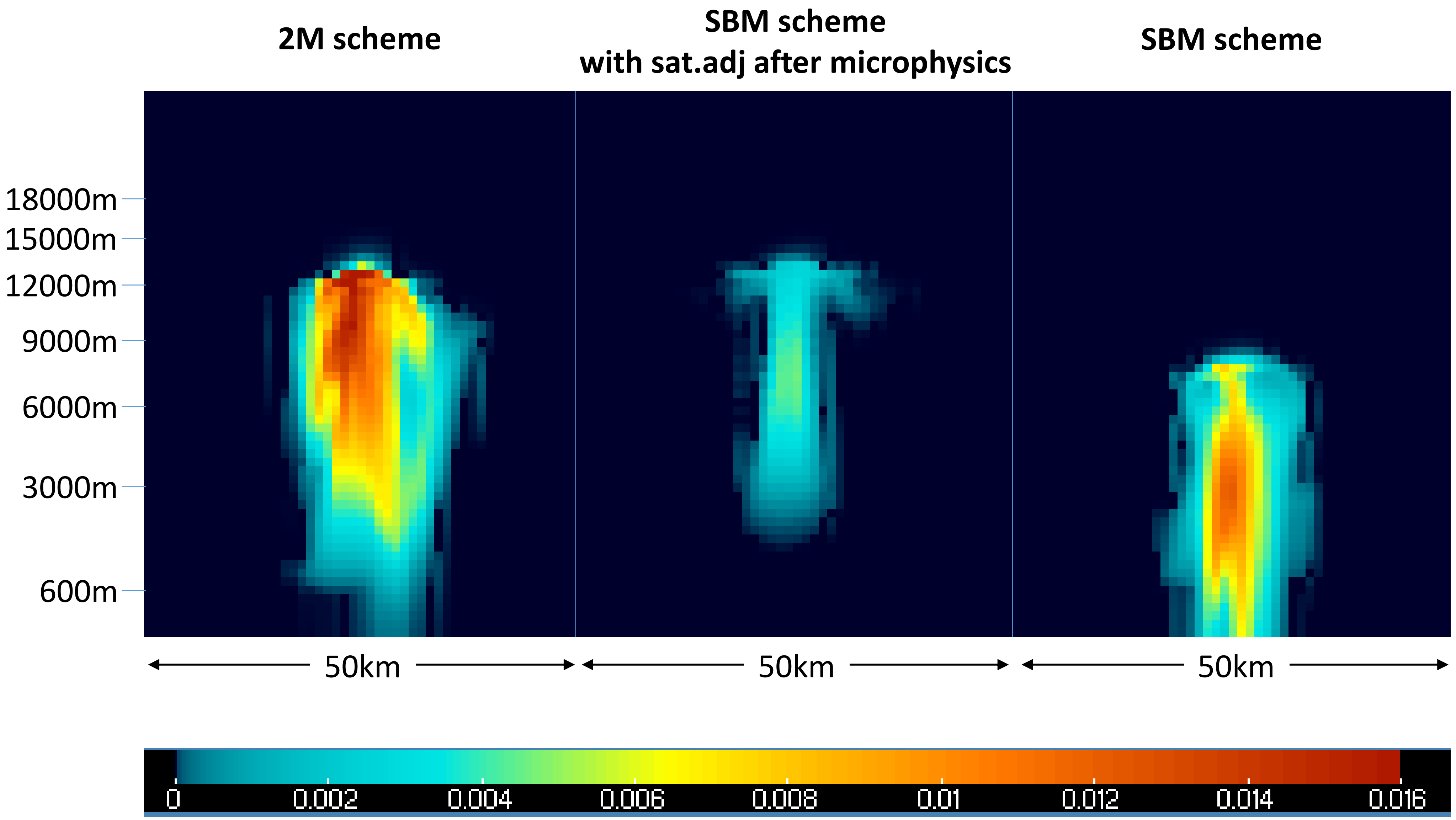
30 min



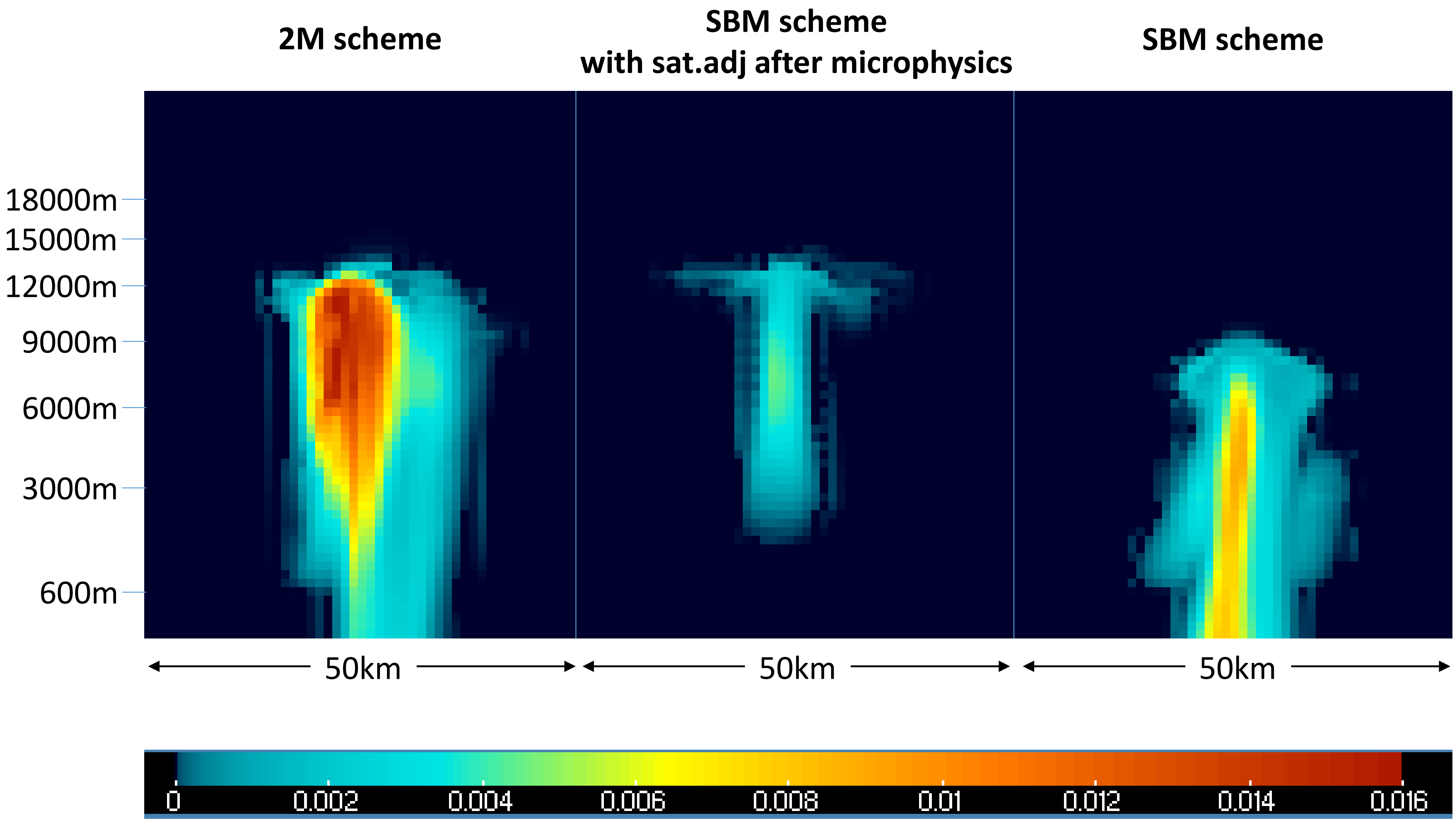
Cloud + rain water content (kg/kg)

36 min



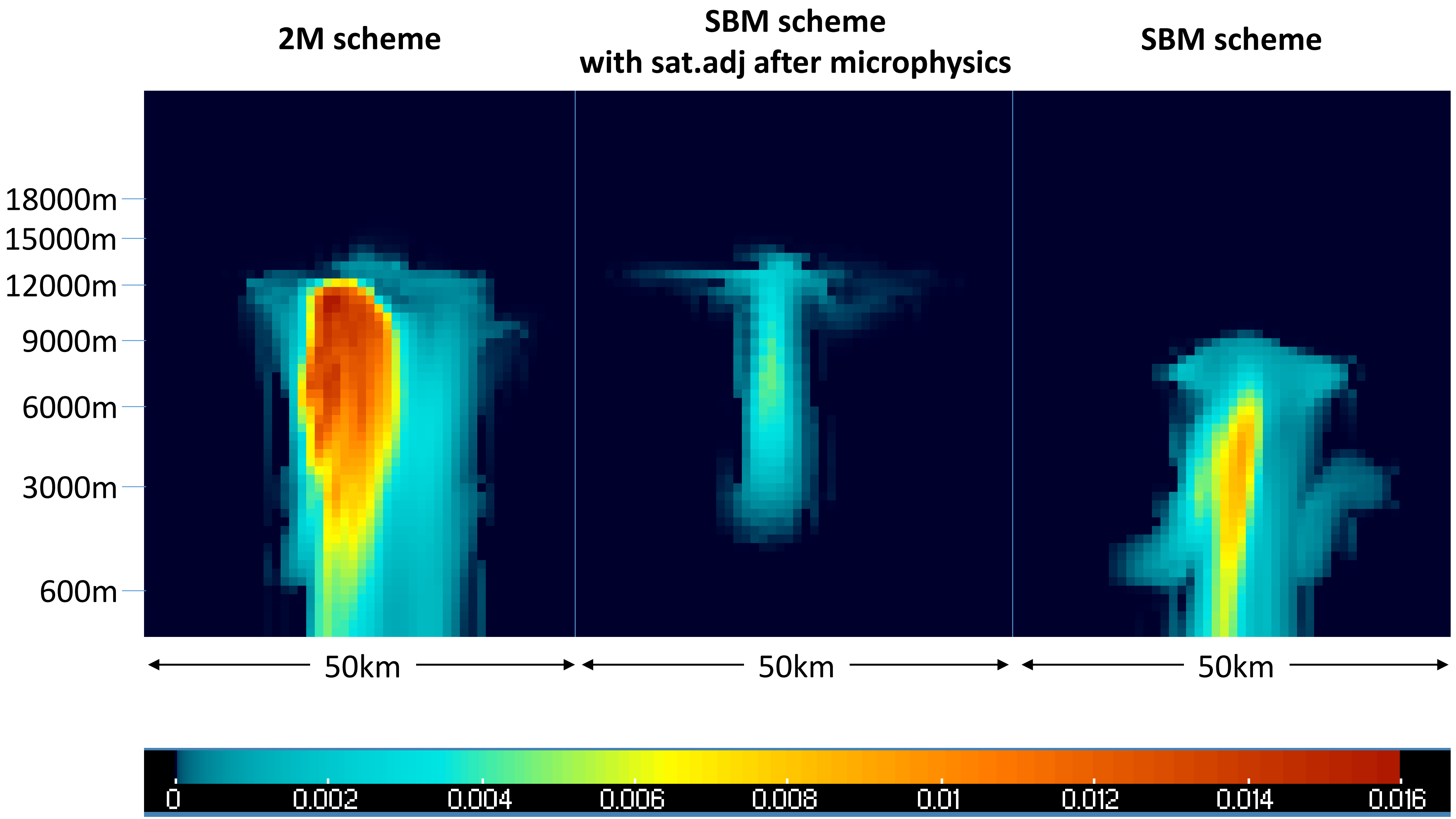
Cloud + rain water content (kg/kg)

42 min



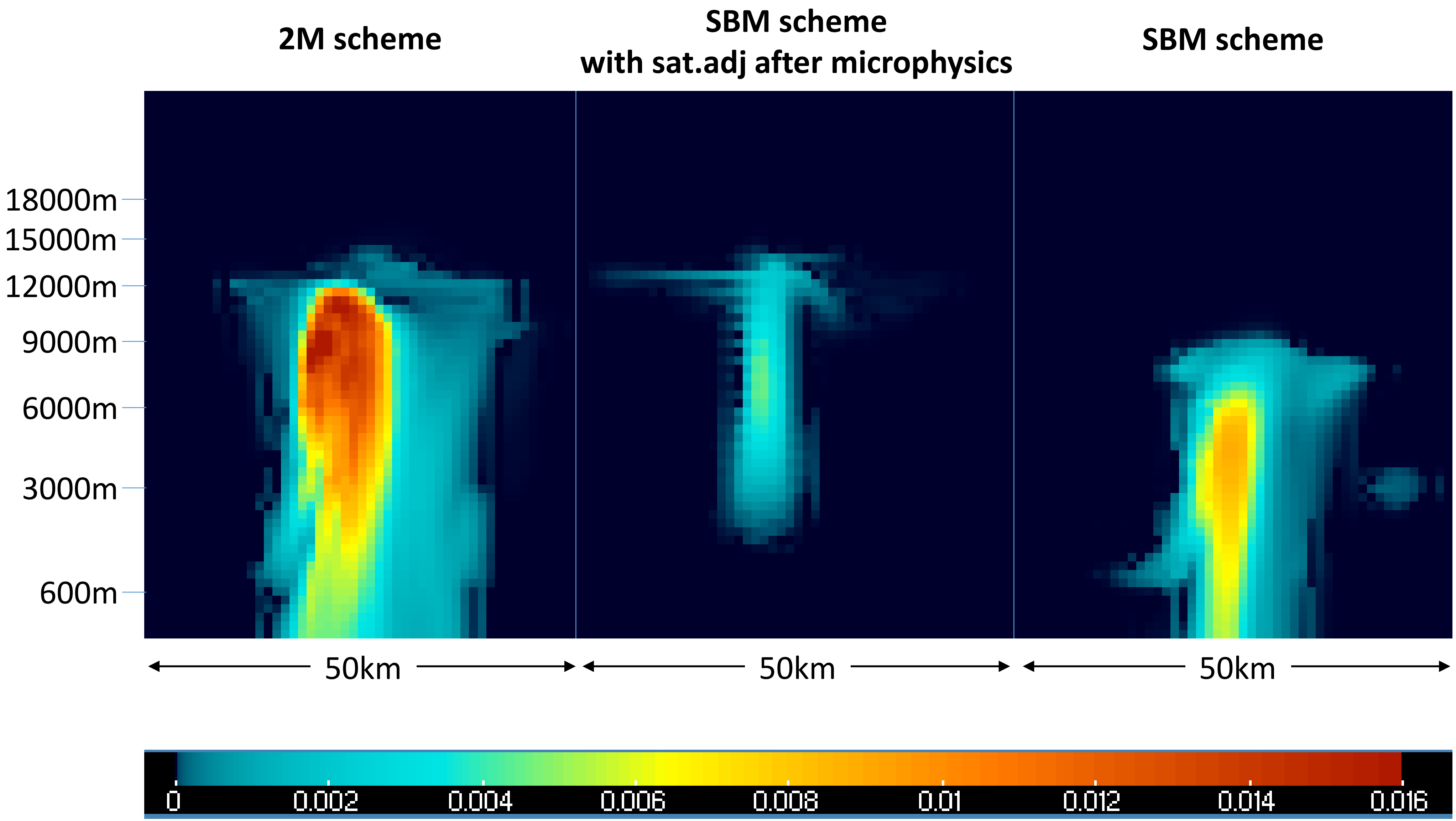
Cloud + rain water content (kg/kg)

48 min



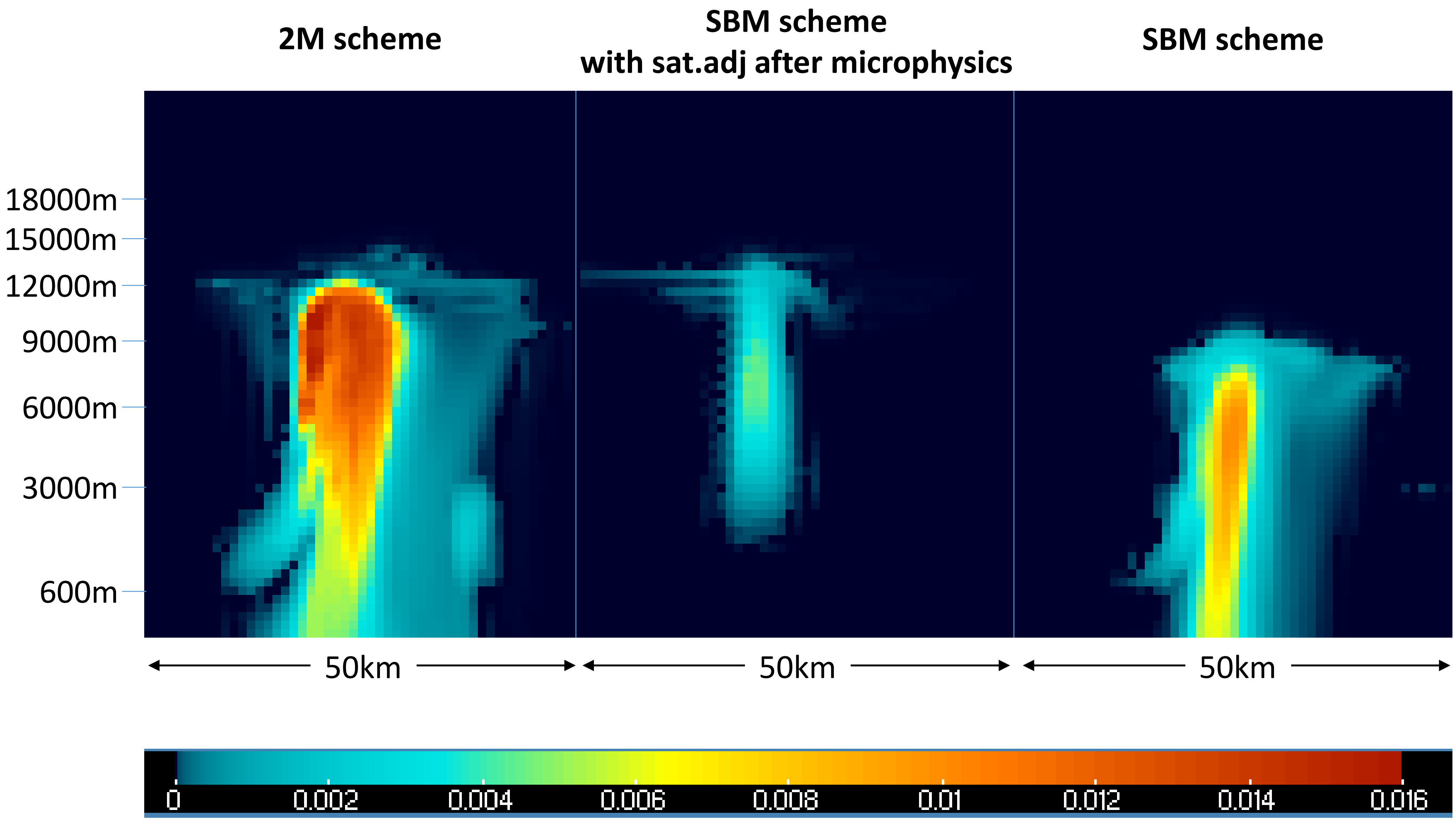
Cloud + rain water content (kg/kg)

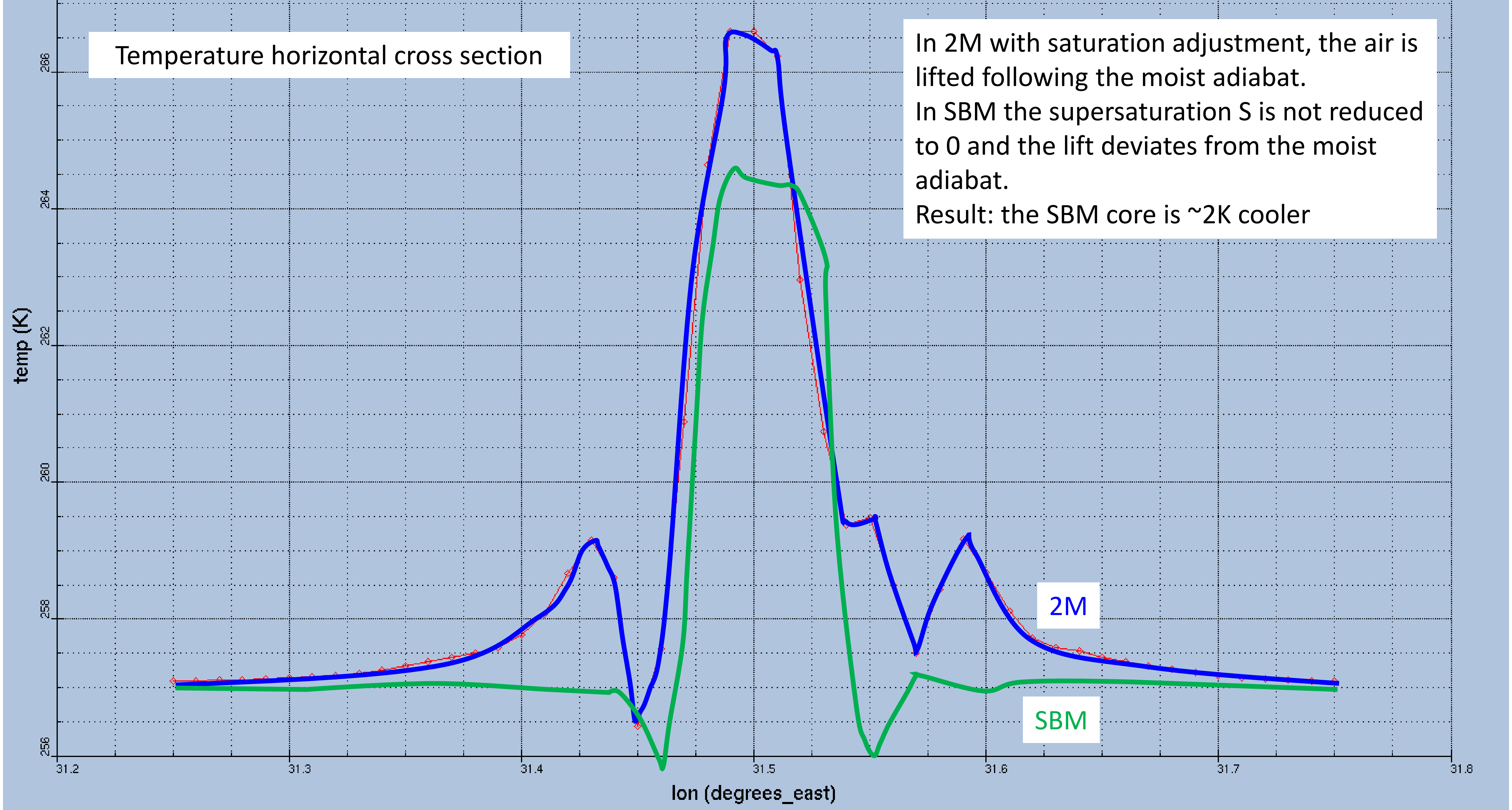
54 min



Cloud + rain water content (kg/kg)

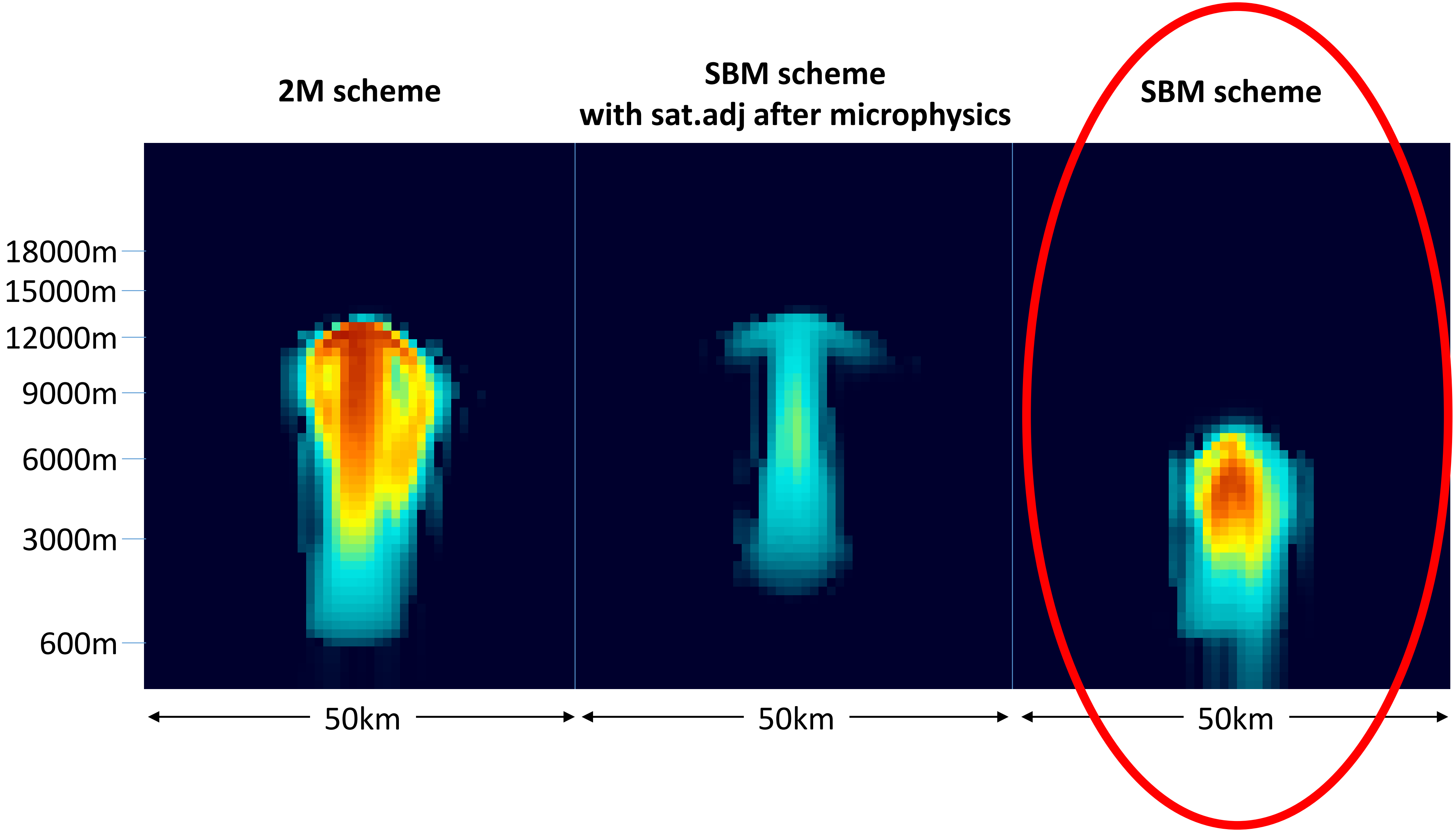
60 min





Temperature from ICON simulation

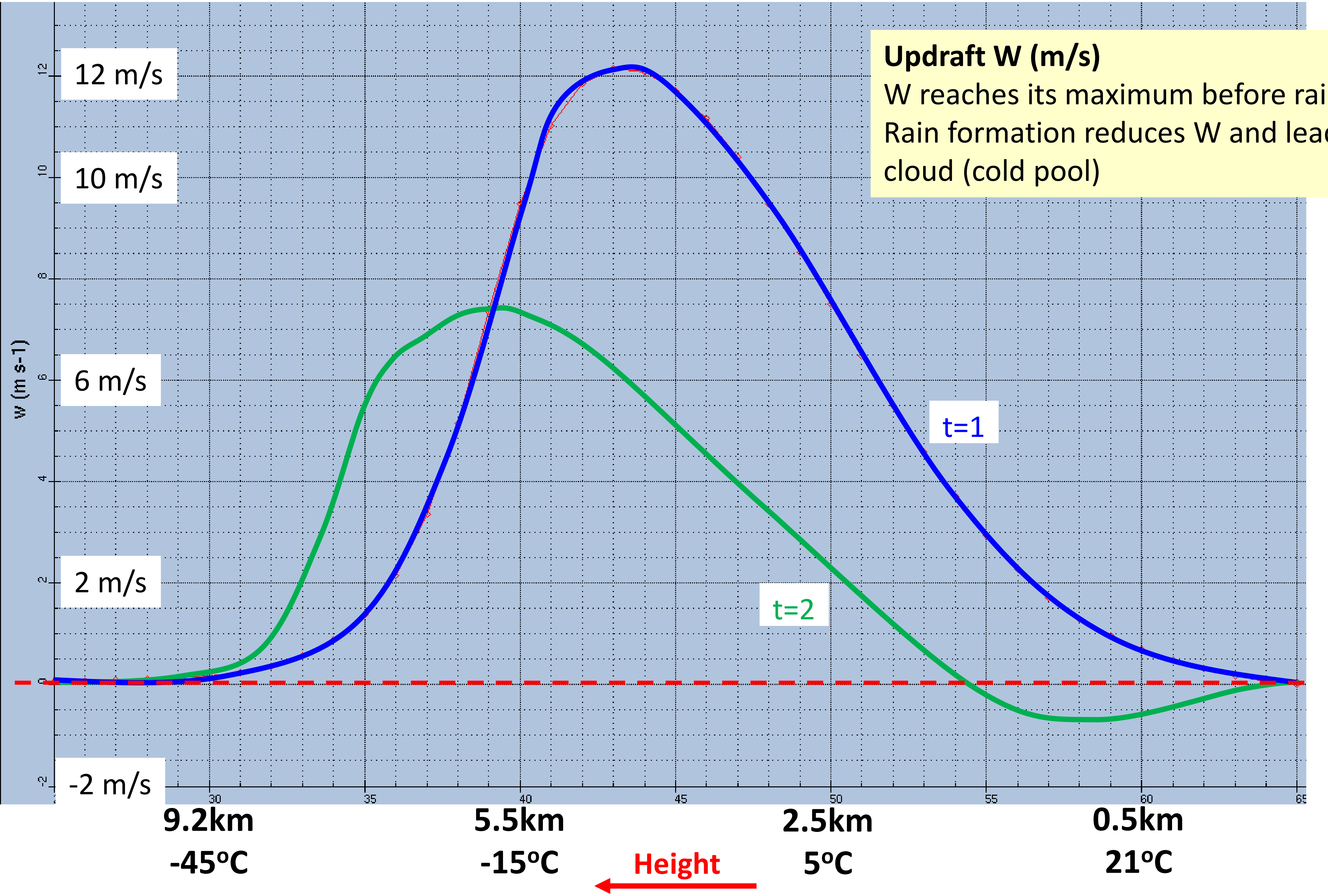
Focus on SBM cumulonimbus development

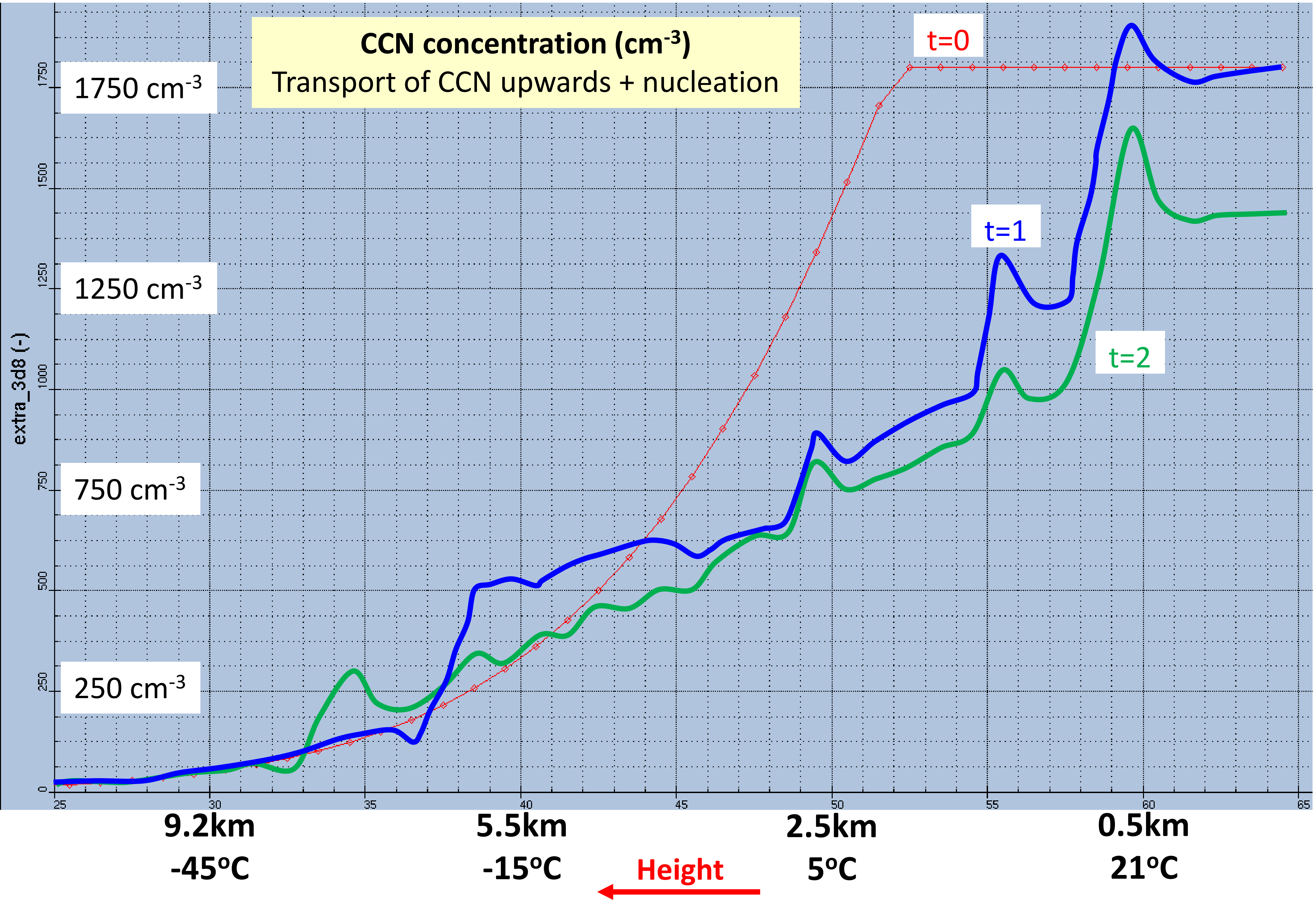


Updraft W (m/s)

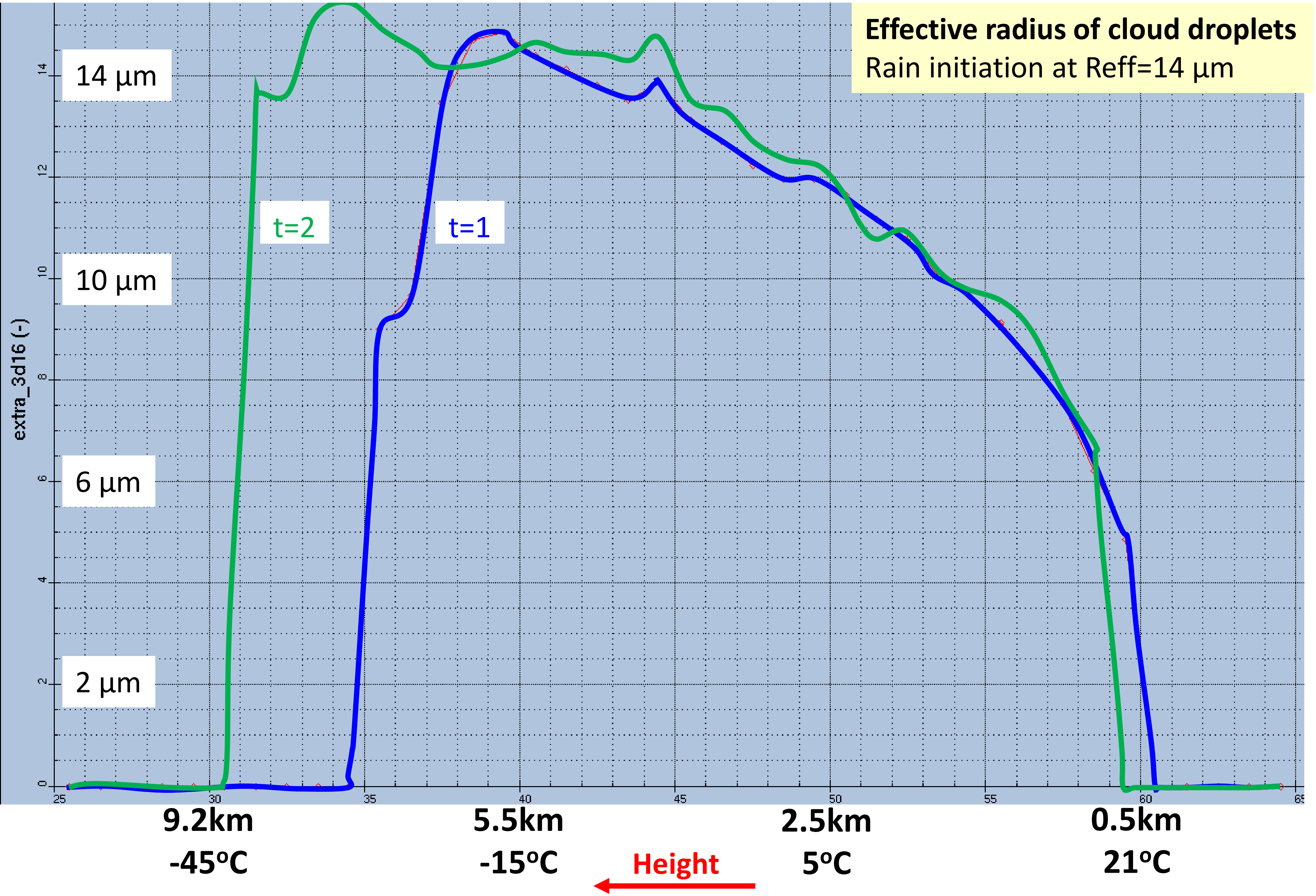
W reaches its maximum before rain initiation

Rain formation reduces W and leads to negative W below cloud (cold pool)





CCN concentration (cm-3)
Transport of CCN upwards + nucleation
1750 cm-3
1250 cm-3
750 cm-3
250 cm-3
t=0
t=1
t=2
extra_3d8 (-)
9.2km
-45°C
5.5km
-15°C
Height
2.5km
5°C
0.5km
21°C



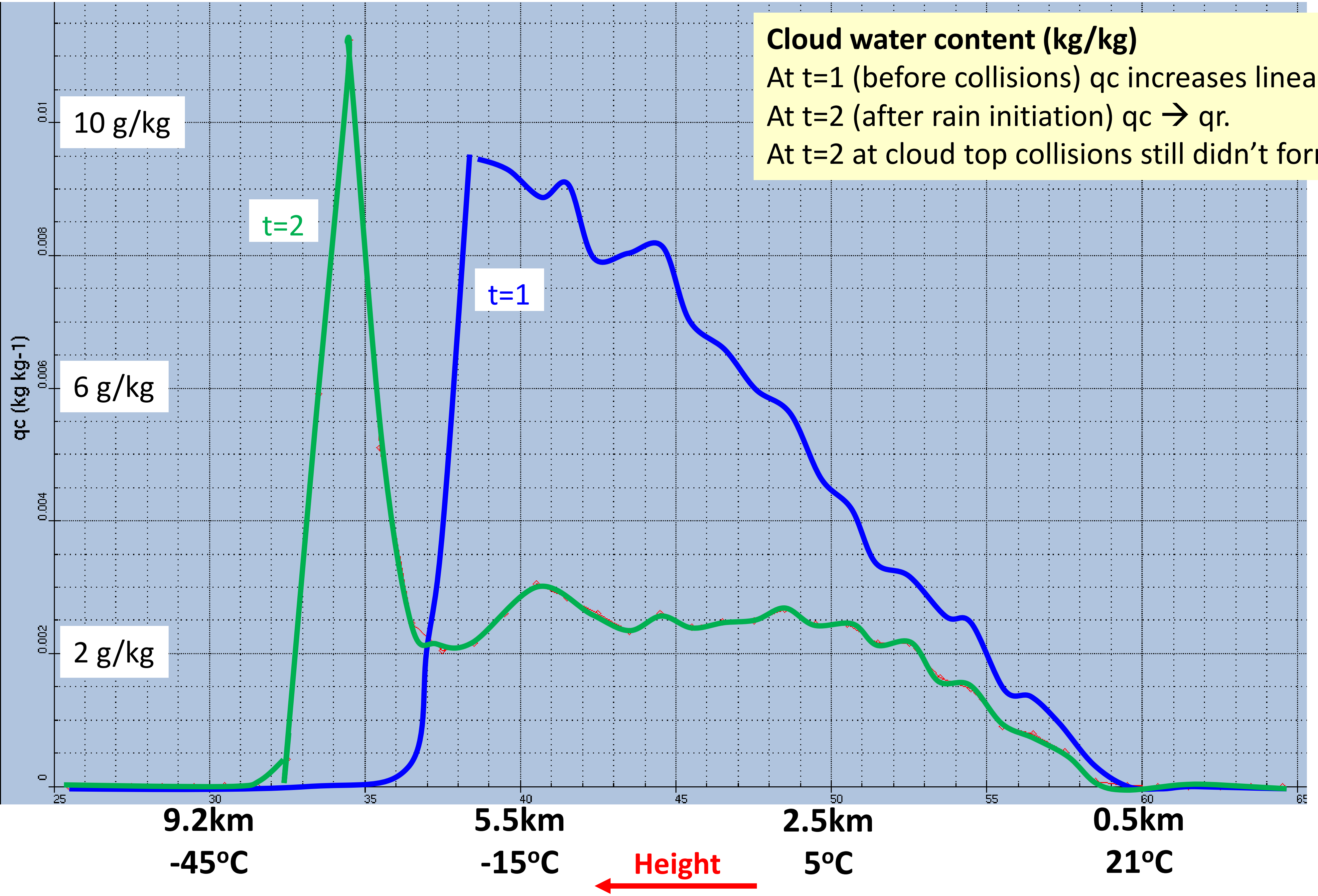
Effective radius of cloud droplets
Rain initiation at Reff=14 µm
14 µm
10 µm
6 µm
2 µm
t=2
t=1
extra_3d16 (-)
9.2km
-45°C
5.5km
-15°C
Height
2.5km
5°C
0.5km
21°C

Cloud water content (kg/kg)

At t=1 (before collisions) qc increases linearly with height

At t=2 (after rain initiation) qc → qr.

At t=2 at cloud top collisions still didn't form rain

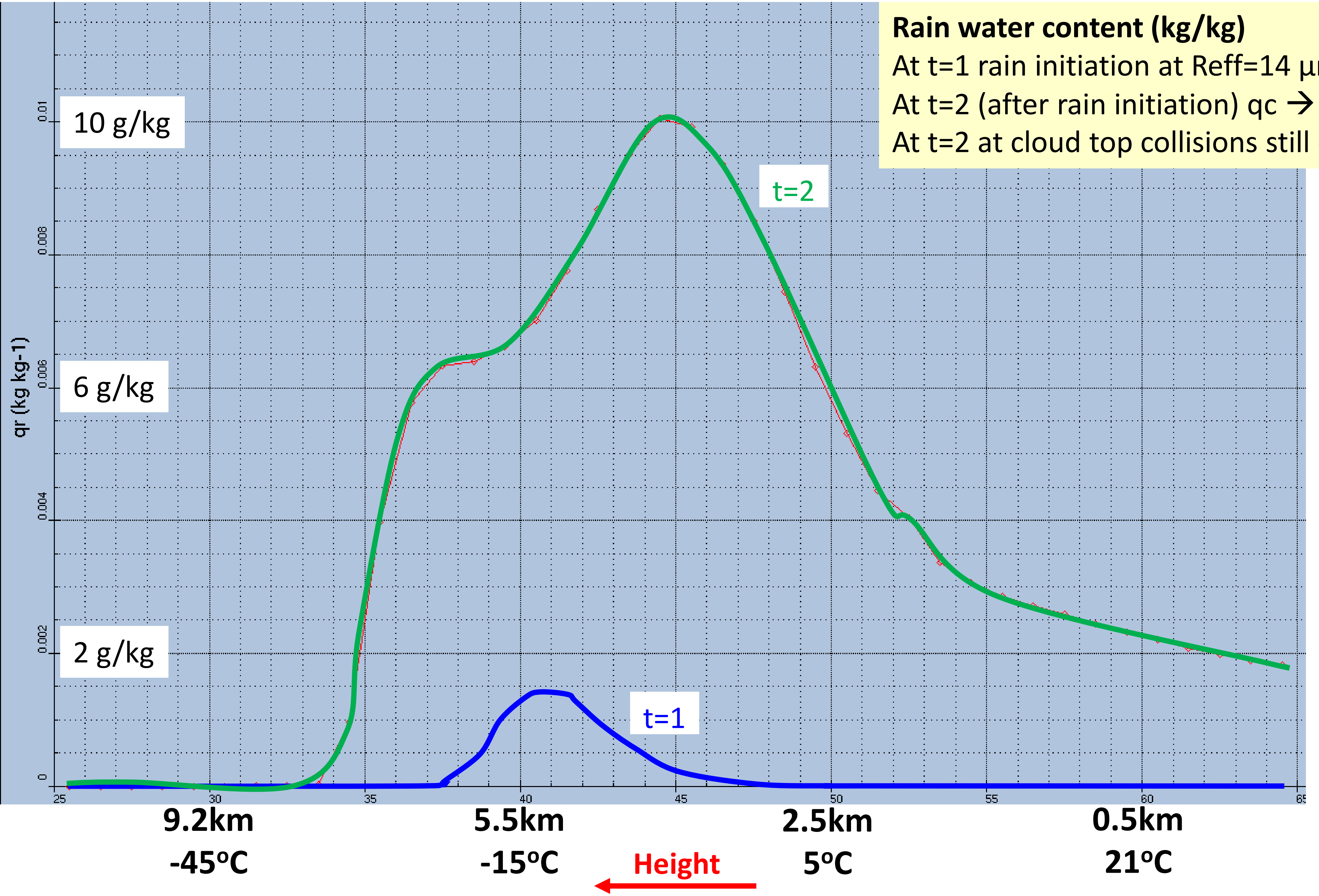


Rain water content (kg/kg)

At t=1 rain initiation at Reff=14 µm

At t=2 (after rain initiation) qc → qr

At t=2 at cloud top collisions still didn't form rain

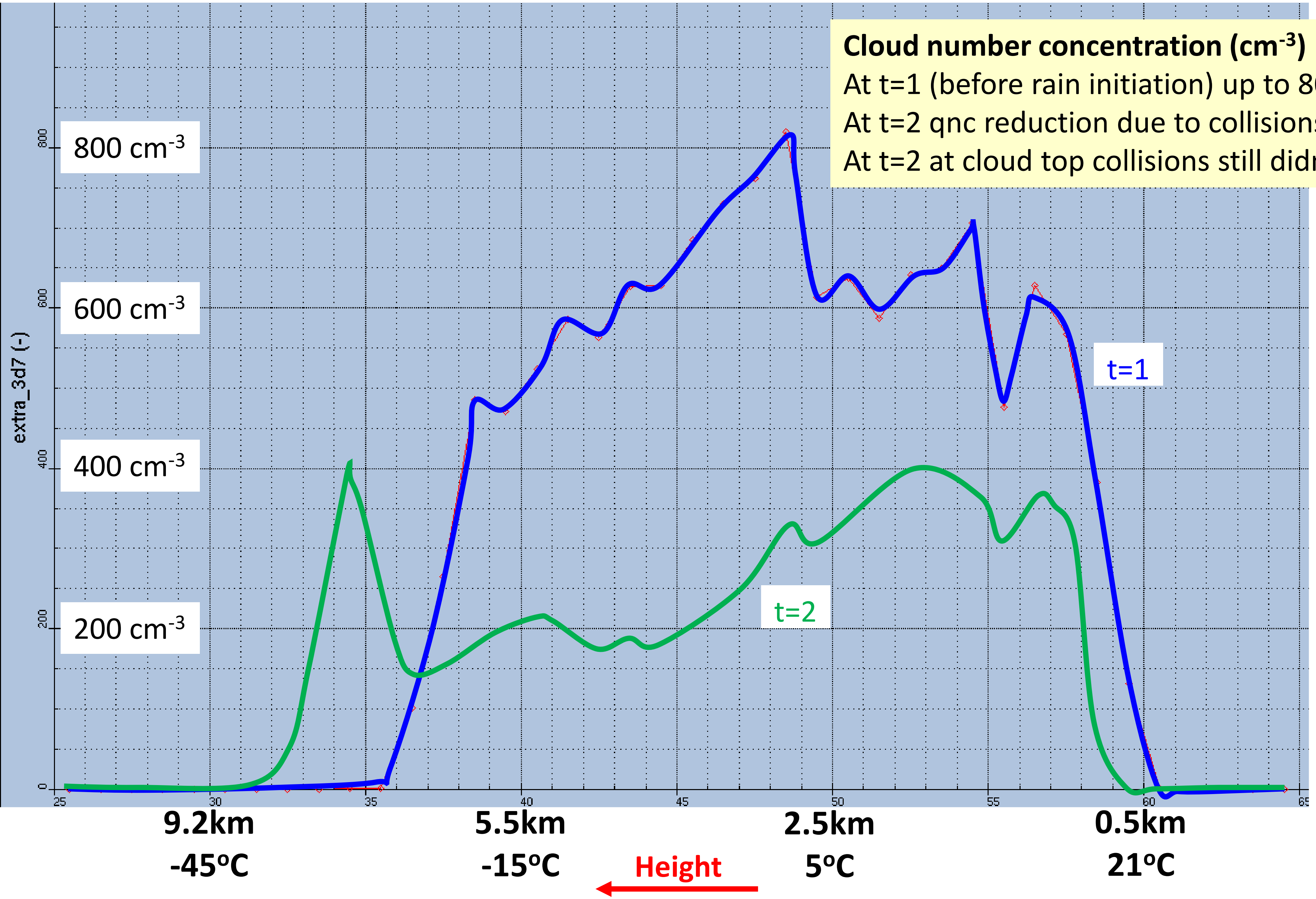


Cloud number concentration (cm^{-3})

At t=1 (before rain initiation) up to 800 cm^{-3}

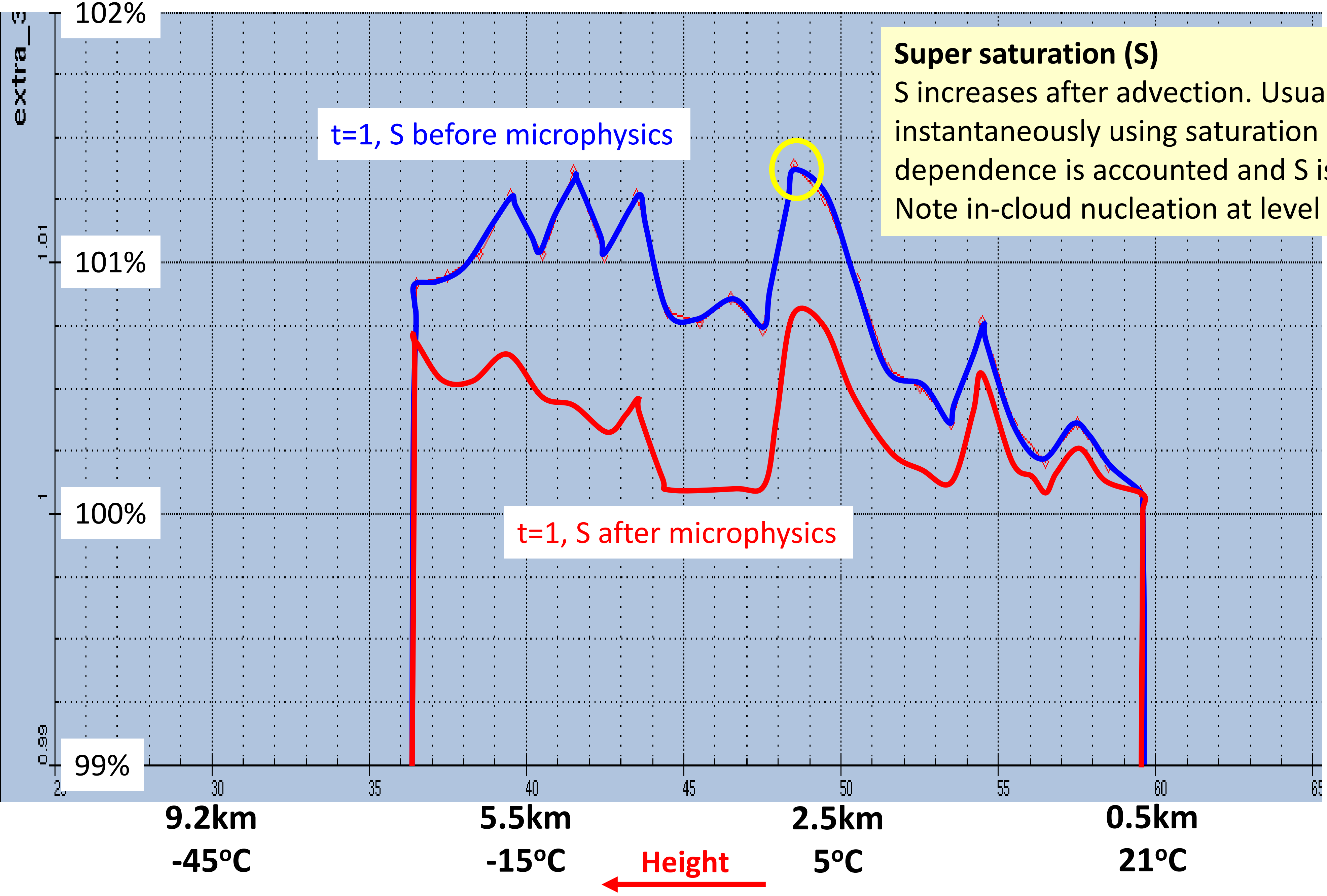
At t=2 qnc reduction due to collisions

At t=2 at cloud top collisions still didn't reduce qnc much



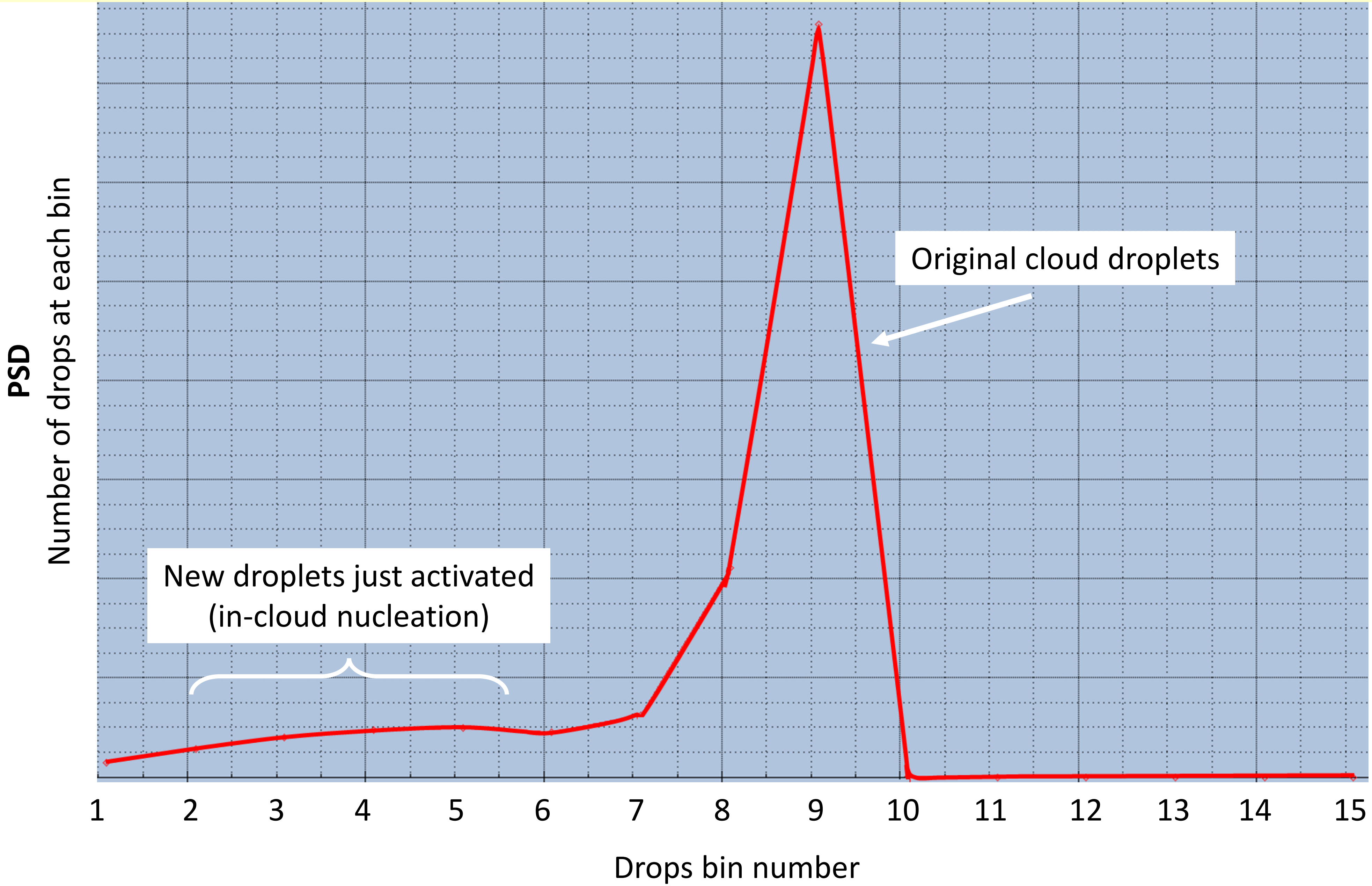
Super saturation (S)

S increases after advection. Usually S is reduced to 0 instantaneously using saturation adjustment. Here time dependence is accounted and S is not reduced to 0. Note in-cloud nucleation at level 49 since $S > S_{cloud\ base}$



Droplet Size Distribution

at cloud core, level=49, step=26min, cloud core

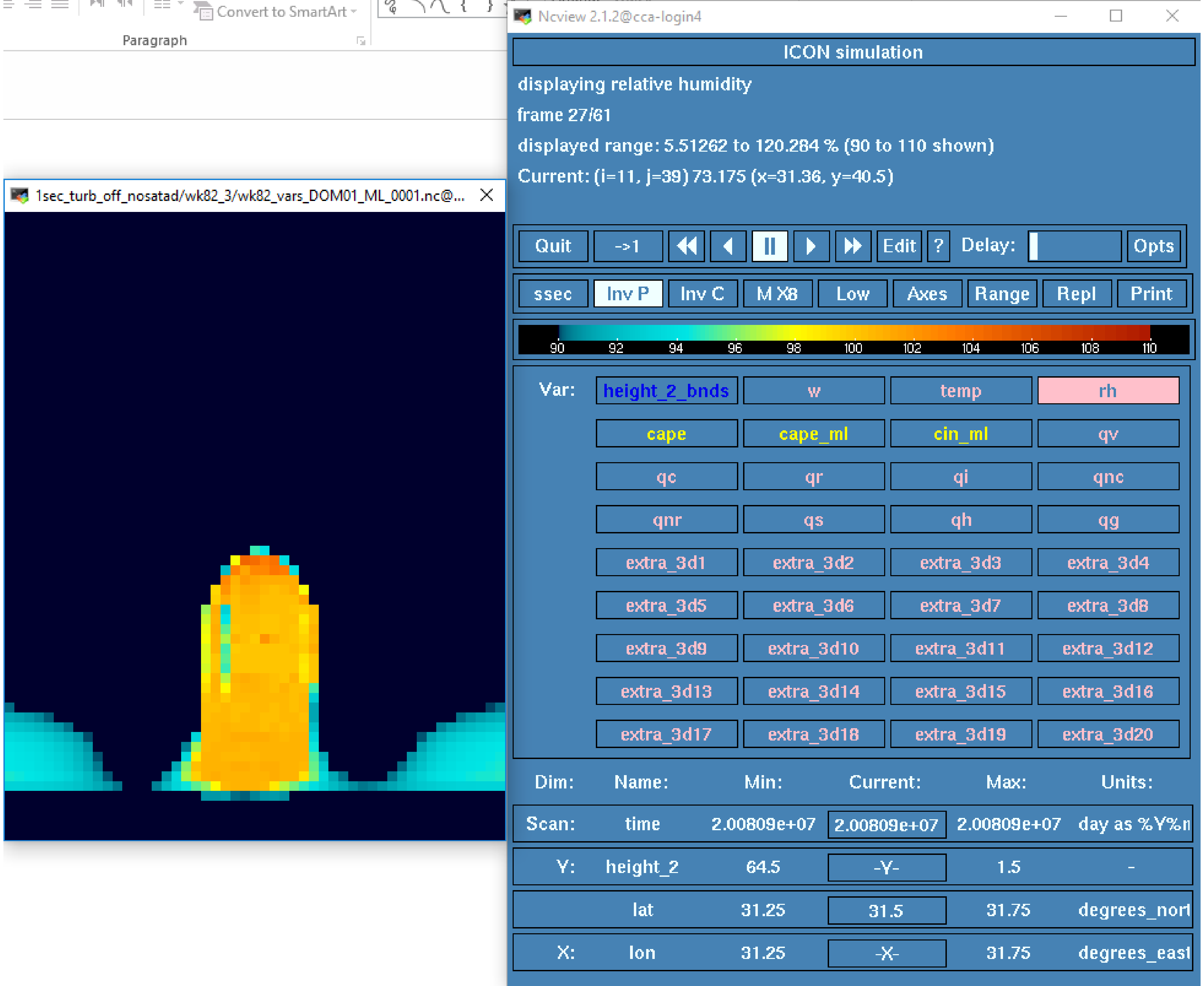


Conclusions

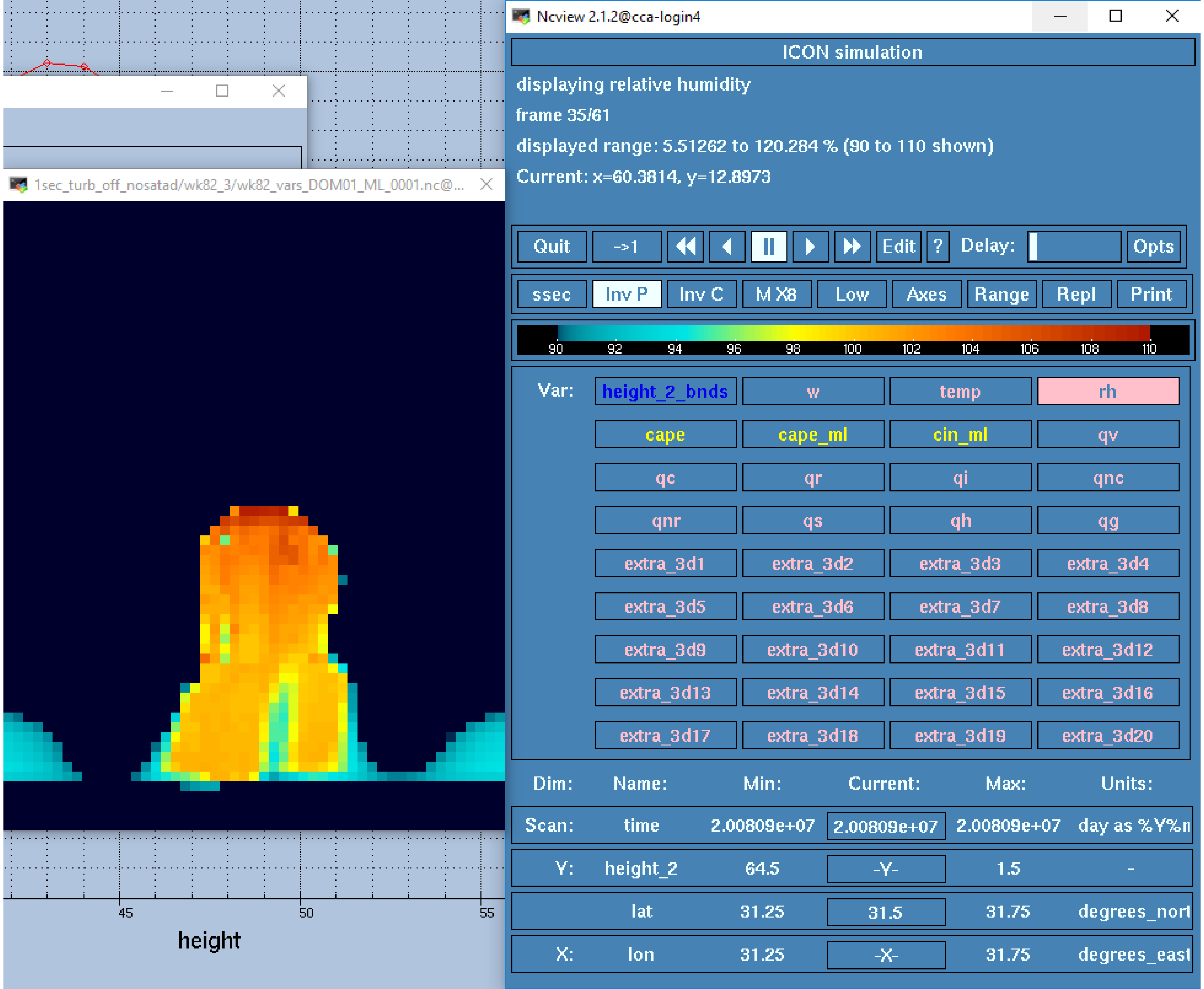
- Warm-Phase Spectral-Bin Microphysics is implemented in ICON
- First test on WK82 case show reasonable results
- The updraft is much smaller than in 2M scheme because there is no saturation adjustment
- The turbulent diffusion (call nwp_turbdiff) is problematic with high S on input. Consider calling it after microphysics
- Plan: Mixed phase SBM → ICON

Additional slides …

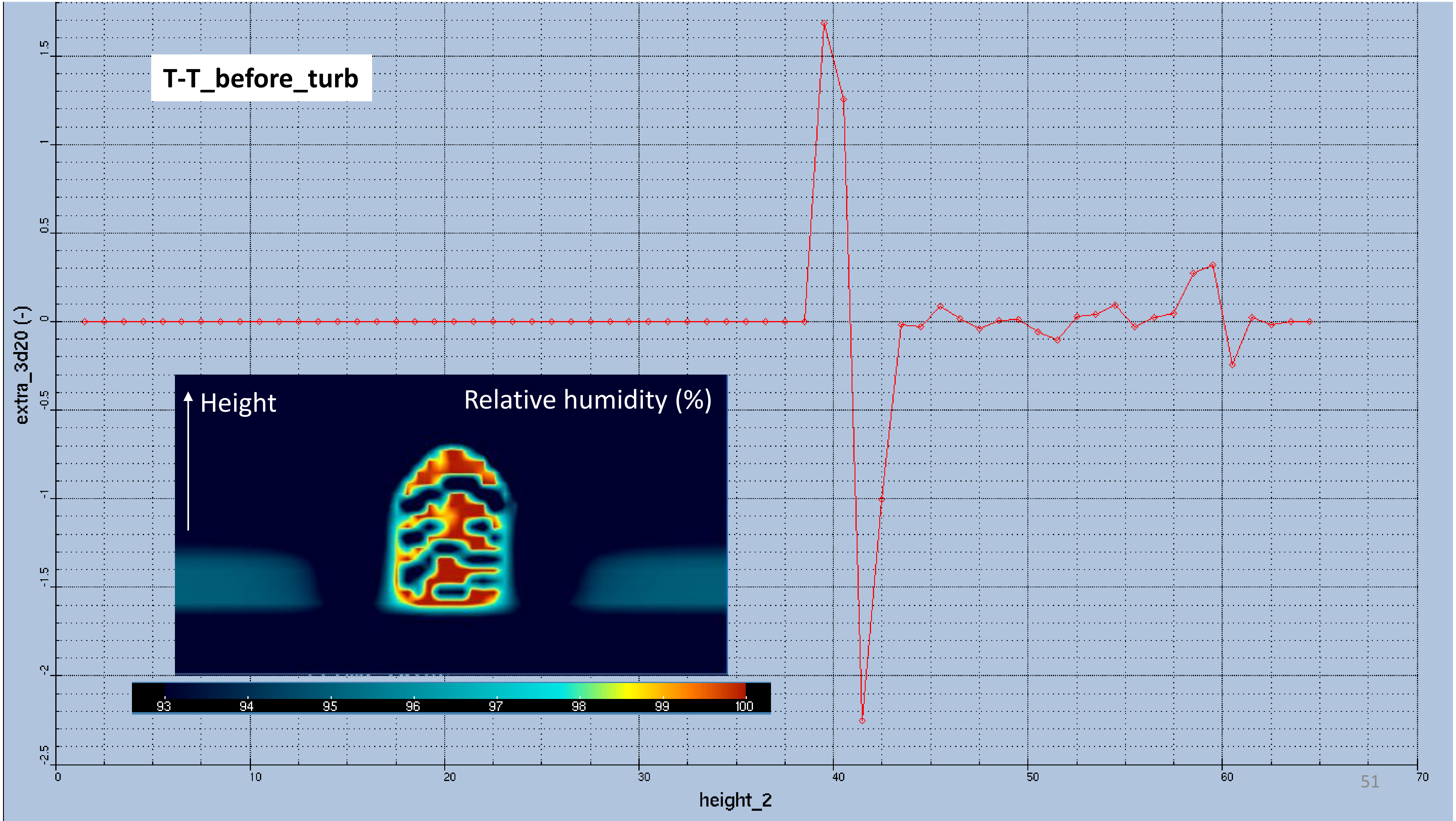
t=1


Convert to SmartArt
Paragraph
1sec_turb_off_nosatad/wk82_3/wk82_vars_DOM01_ML_0001.nc@...
Ncview 2.1.2@cca-login4
ICON simulation
displaying relative humidity
frame 27/61
displayed range: 5.51262 to 120.284 % (90 to 110 shown)
Current: (i=11, j=39) 73.175 (x=31.36, y=40.5)
Quit
->1
Edit
?
Delay:
Opts
ssec
Inv P
Inv C
M X8
Low
Axes
Range
Repl
Print
90 92 94 96 98 100 102 104 106 108 110
Var:
height_2_bnds
w
temp
rh
cape
cape_ml
cin_ml
qv
qc
qr
qi
qnc
qnr
qs
qh
qg
extra_3d1
extra_3d2
extra_3d3
extra_3d4
extra_3d5
extra_3d6
extra_3d7
extra_3d8
extra_3d9
extra_3d10
extra_3d11
extra_3d12
extra_3d13
extra_3d14
extra_3d15
extra_3d16
extra_3d17
extra_3d18
extra_3d19
extra_3d20
Dim: Name: Min: Current: Max: Units:
Scan: time 2.00809e+07 2.00809e+07 2.00809e+07 day as %Y%n
Y: height_2 64.5 -Y- 1.5 -
lat 31.25 31.5 31.75 degrees_nort
X: lon 31.25 -X- 31.75 degrees_east

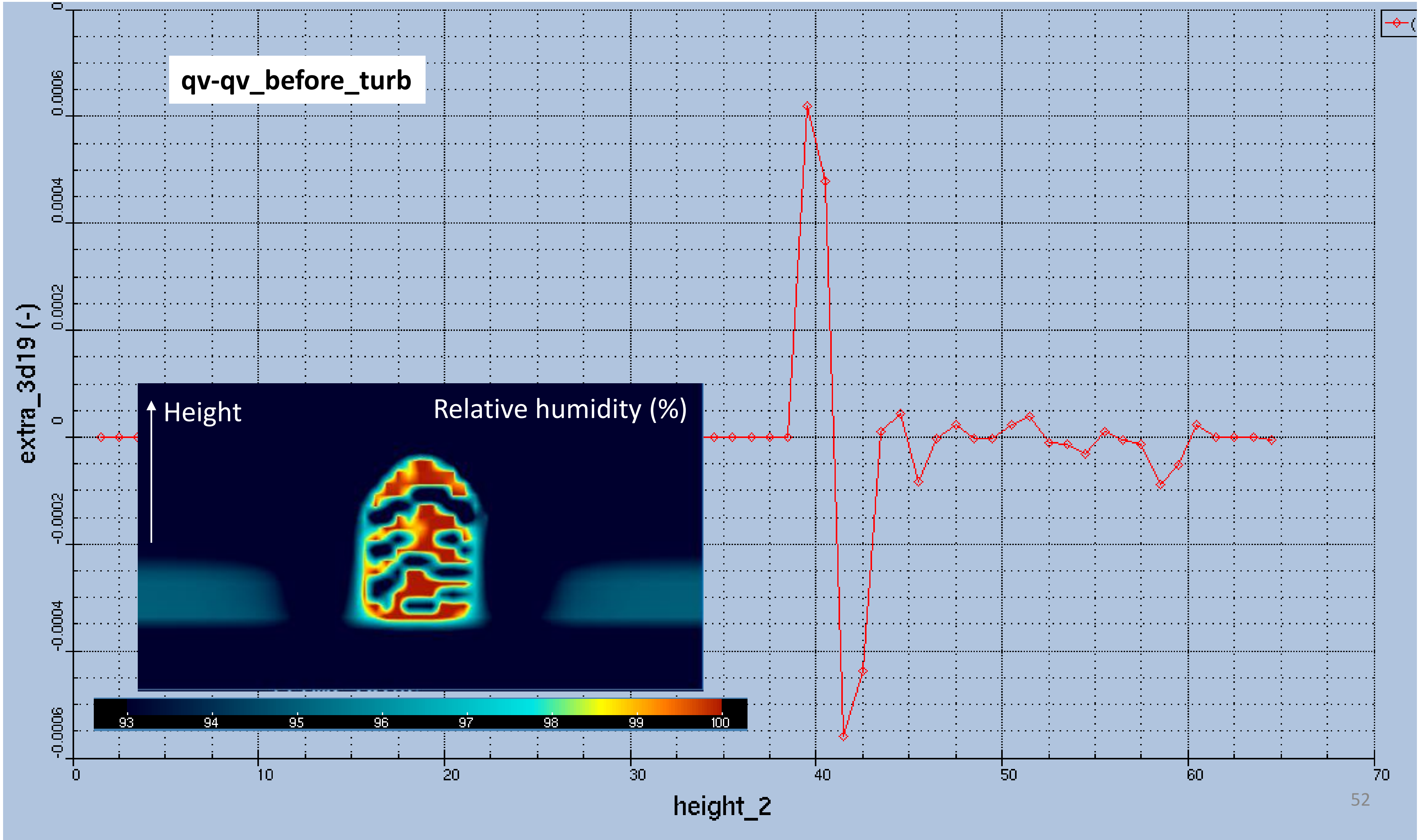
t=2

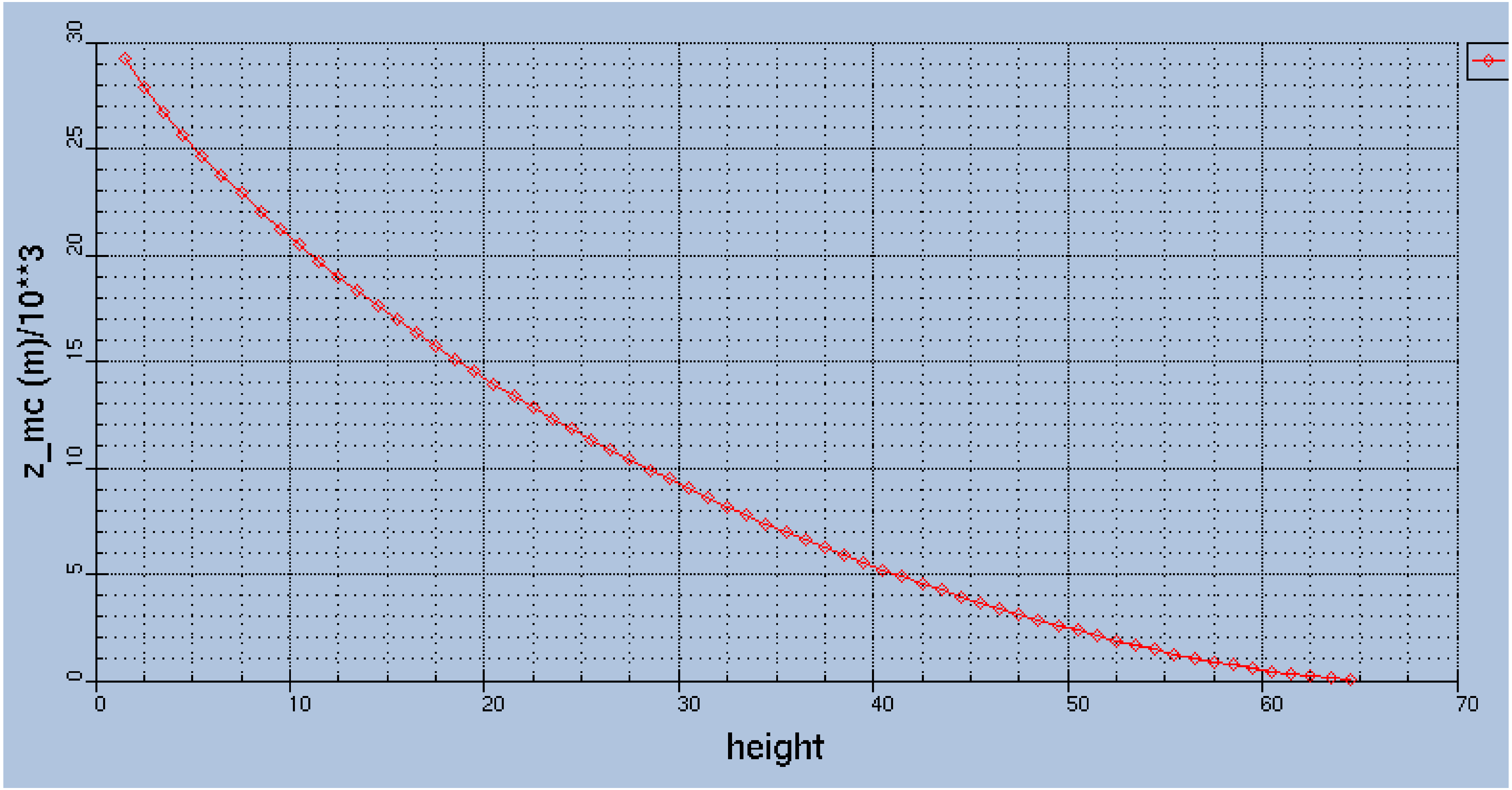

1sec_turb_off_nosatad/wk82_3/wk82_vars_DOM01_ML_0001.nc@...
45
50
55
height
Ncview 2.1.2@cca-login4
ICON simulation
displaying relative humidity
frame 35/61
displayed range: 5.51262 to 120.284 % (90 to 110 shown)
Current: x=60.3814, y=12.8973
Quit
->1
Edit
?
Delay:
Opts
ssec
Inv P
Inv C
M X8
Low
Axes
Range
Repl
Print
90
92
94
96
98
100
102
104
106
108
110
Var:
height_2_bnds
w
temp
rh
cape
cape_ml
cin_ml
qv
qc
qr
qi
qnc
qnr
qs
qh
qg
extra_3d1
extra_3d2
extra_3d3
extra_3d4
extra_3d5
extra_3d6
extra_3d7
extra_3d8
extra_3d9
extra_3d10
extra_3d11
extra_3d12
extra_3d13
extra_3d14
extra_3d15
extra_3d16
extra_3d17
extra_3d18
extra_3d19
extra_3d20
Dim:
Name:
Min:
Current:
Max:
Units:
Scan:
time
2.00809e+07
2.00809e+07
2.00809e+07
day as %Y%m
Y:
height_2
64.5
-Y-
1.5
-
lat
31.25
31.5
31.75
degrees_nort
X:
lon
31.25
-X-
31.75
degrees_east

(A) call nwp_turbdiff is problematic with high S on input



(A) call nwp_turbdiff is problematic with high S on input




z_mc (m)/10**3
0
5
10
15
20
25
30
0
10
20
30
40
50
60
70
height