

Mixed-phase spectral-bin microphysics in ICON: consideration of turbulent enhancement of collisions



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Outlook

1. Reminder: SBM Implementation in ICON
2. Turbulent enhancement of collisions
3. First tests:
 - Weisman-Klemp idealized
 - Real case example
4. Onishi-Seifert turbulent enhancement in ICON-SBM: first results

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Two methods of representing cloud microphysics

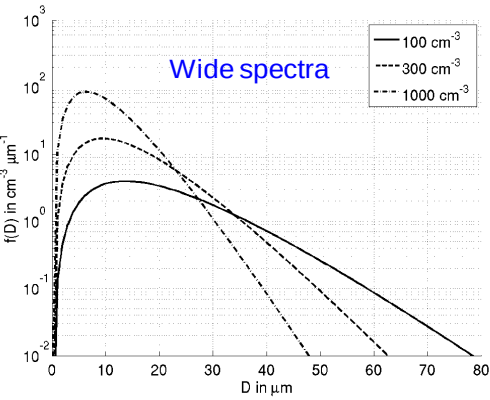
Bulk-microphysics Parameterization

Description of
size
distributions

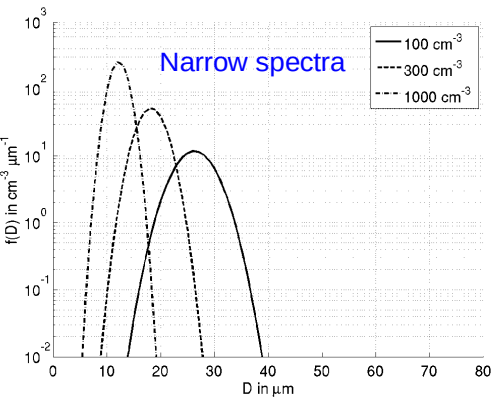
Gamma distributions with several given parameters

4 parameters formula :
(gamma distribution)

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



$\nu=1, \mu=1/3$



$\nu=6, \mu=1$

Basic
equations

For moments:

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

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

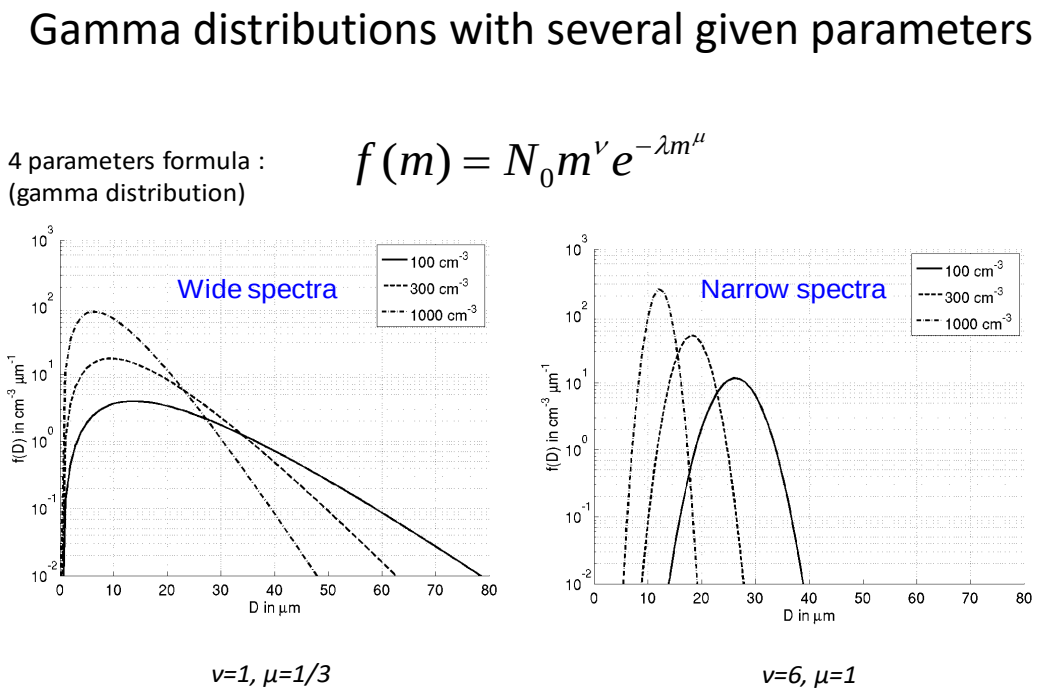
2M $\rightarrow$ 2 parameters are free and 2 are preset

Two methods of representing cloud microphysics

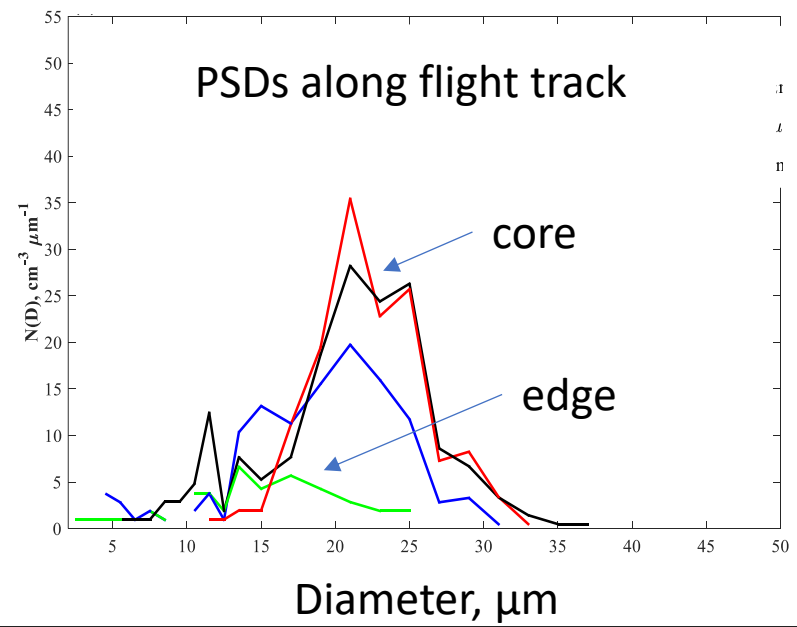
Bulk-microphysics Parameterization

Spectral Bin Microphysics (SBM)

Description of
size
distributions



Examples of real size distributions (droplets)



Basic
equations

For moments:

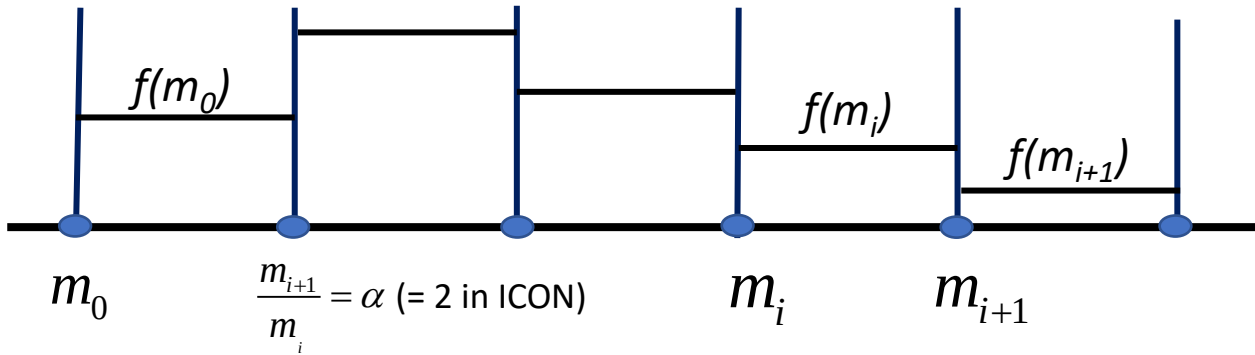
$$M^{(k)} = \int_0^\infty m^k f(m) dm$$

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

2M $\rightarrow$ 2 parameters are free and 2 are preset

For size distribution functions f(m)

SBM implementation in ICON (itype_gscp=8)



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

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

No Gamma distributions assumed.

Instead: 4 distributions are advected:

$f_{\text{drop+rain}}(m)$:	33 bins for drops (cloud and rain water)
$f_{\text{ice+snow}}(m)$:	33 bins for ice crystals (cloud ice and snow)
$f_{\text{grau/hail}}(m)$:	33 bins for graupel or hail
$f_{\text{ccn}}(m)$:	33 bins for CCN concentration

Processes which change f in the ICON code:

- advection
- sedimentation
- nucleation (Kohler)
- condensation/evaporation (eqn for diff. growth and supersaturation, i.e. NO saturation adjustment)
- freezing (both immersion and contact) and melting
- coalescence/break up (stochastic eqn for collisions)
- nucleation of ice
- Ongoing: turbulent collisions enhancement
- Merge with EMVORADO

Still to do:

- Mixed phase particles, CCN regeneration, better melting

Dec 2022: Khain P, Shpund J, Levi Y, Khain A:
“Warm-phase spectral-bin microphysics in ICON:
Reasons of sensitivity to aerosols”, Atmos. Res. 2022, 279, 106388.

July 2023: warm-phase version was implemented in ICON master. 4 new files: mo_sbm_driver.f90, mo_sbm_main.f90, mo_sbm_util.f90, mo_sbm_storage.f90

June 2025: mixed-phase version implementation in ICON master (using Fast-SBM in the WRF model)

Why Fast-SBM?

- The version we implement is so called “Fast SBM”, which contains only two size distributions of ice: low density (snow PSD) and large density (graupel PSD).
- For snow PSD: small bins are considered as ice crystals, and large bins are aggregates.
- Fast SBM is based on full SBM, that uses additionally size distributions of three types of ice crystals (dendrites, plates and columns) and hail with high density of pure ice (0.9 g/cm^3). There are also size distributions for mixed-phase particles (e.g. water mass fraction in melting ice).

ICON namelist parameters to activate SBM (nwp_phy_nml)

- **itype_gscp** Choose the microphysics scheme. Set **8** to choose SBM
- **inwp_satad** Turn on/off saturation adjustment. Set **0** when using SBM

In contrast to the bulk schemes, the SBM scheme does not use the saturation adjustment procedure before and after the call to the microphysics scheme. To solve the equation of diffusional growth/evaporation SBM uses the supersaturation change during the last time step, which occurs due to advection with contribution from other physics processes. The coupled equation system for diffusional growth and supersaturation is solved, so that supersaturations over water and ice are non-zero to the end of microphysical time sub-steps. Therefore, it is required to turn off saturation adjustment, i.e. set `inwp_satad=0`. In order to calculate the supersaturation change during the time step, a special "sbm storage" (see `mo_sbm_storage.f90`) was implemented, which allows to save and restore the temperature and water vapor of the previous time step.
- **lmicrophysicsFirst** TRUE: run microphysics before turbdiff, FALSE: after turbdiff. Set **TRUE** when using SBM

The main "fast-physics" parametrizations called in ICON every time step are the turbulent mixing "turbdiff" and microphysics. It is reasonable for SBM to use the supersaturation right after the advection, rather than the smoothed supersaturation after "turbdiff". Therefore it is required to set `lmicrophysicsFirst=true`.
- **lsbm_coupled** FALSE: use 2M scheme for feedback and run uncoupled SBM, TRUE: use SBM feedback. Recommended to set **TRUE** when using SBM

In order to fully couple SBM to ICON's dynamics, it is required to set `lsbm_coupled=true`. For testing purposes, there is an option to run ICON with 2-moment dynamics and microphysics, and on top of it, every time step run SBM with an option to analyze its output (e.g. using `extra_3d` variables). To choose this option, where SBM does not have any influence on the model dynamics or microphysics, one needs to select `lsbm_coupled=false`.

ICON namelist parameters to activate SBM (nwp_tuning_nml)

- **tune_sbmcn**
[0-1] scaling factor to reduce the ccn concentration initial profile with respect to the continental (polluted) case when using SBM. Recommended to set **1** for polluted case and **0.1** for maritime (clean) case.

In addition to already existing tracers in ICON, SBM includes 132 advected tracers. 3 hydrometeors size distributions for drops, ice/snow and graupel/hail are defined on logarithmic doubling mass grid containing 33 bins (tracers). The minimum particles radius is 2 μm , maximum radius is 3.4 mm. Drops with radii exceeding 50 μm (bin number $\text{krdrop}=15$) are attributed to raindrops, while smaller drops are considered as cloud droplets. Similarly, ice/snow particles with bin number exceeding $\text{kriice}=18$ are attributed to snow flakes and smaller particles are considered as ice crystals. In contrast, graupel/hail 33 bins are defined as pure graupel or pure hail distributions by `hail_opt` parameter.

Size distributions of dry CCN are defined on a logarithmic mass grid also containing 33 bins (tracers). The maximum CCN radius is taken equal to 2 μm .

Initial size distribution of aerosols playing the role of cloud condensational nuclei (CCN) applied in SBM are described as a sum of three log-normal distributions, representing nuclei mode (ultrafine aerosols) centered at radius of 0.005 μm , accumulation mode centered at 0.035 μm and coarse mode centered at 0.31 μm (Ghan et al. 2011). Supersaturation and CCN properties are used to calculate the critical size using the Kohler theory. The CCN with sizes exceeding the critical value are converted to droplets and corresponding bins in the aerosol size distribution become empty. Non-activated aerosols are advected similarly to hydrometeors, so wind transports both hydrometeors and non-activated CCN. Settling velocity of CCN is neglected.

There are several options in SBM to define an initial vertical profile of CCN. Among others, the code includes the definitions of theoretical maritime and continental options. By default, the SBM uses a continental initial profile. A namelist scaling factor `tune_sbmcn` [0-1] allows to reduce the CCN concentration initial profile with respect to the continental case. `tune_sbmcn=1` means the use of pure continental profile and `tune_sbmcn=0` is an approximation of maritime case.

- Documentation in: https://docs.icon-model.org/atmosphere/sbm/sbm_overview.html

Interaction with other parametrizations

- ICON uses total water and ice contents (q_c , q_r , q_i , q_s , q_g) in many places in the code. When using SBM, we keep advecting these total water contents, but overwrite them by the integrals over the corresponding size distributions, right after the call to the microphysics.
- IC/BC: QX variables are “evaporated” to water vapor, which can be then condensated in SBM
- The vertical turbulent diffusion "turbdiff" also uses cloud water, ice and snow (q_c , q_i , q_s). For consistency, the corresponding SBM bins (tracers) were added to the vertical turbulent diffusion as well.
- Convection scheme might also detrain q_c , q_i , q_r , q_s . For mass conservation, we "evaporate" this water, transferring it to water vapor q_v , and subtract the corresponding latent heat release. In appropriate conditions, this water vapor may condensate to hydrometeors as part of SBM. Total water contents are used in ICON initial and boundary conditions. In case of SBM, similar transformation to water vapor is applied.

Outlook

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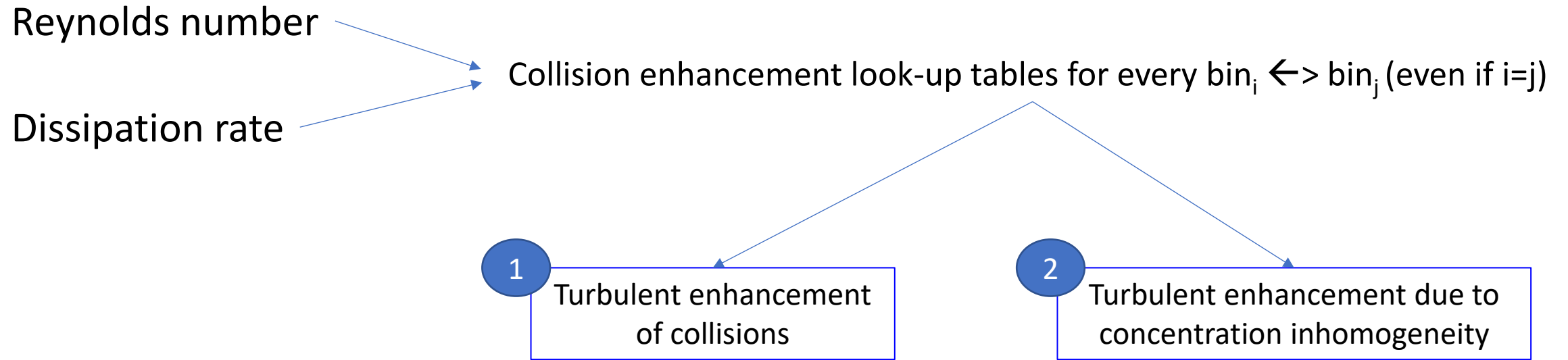
2. Turbulent enhancement of collisions

3. First tests:

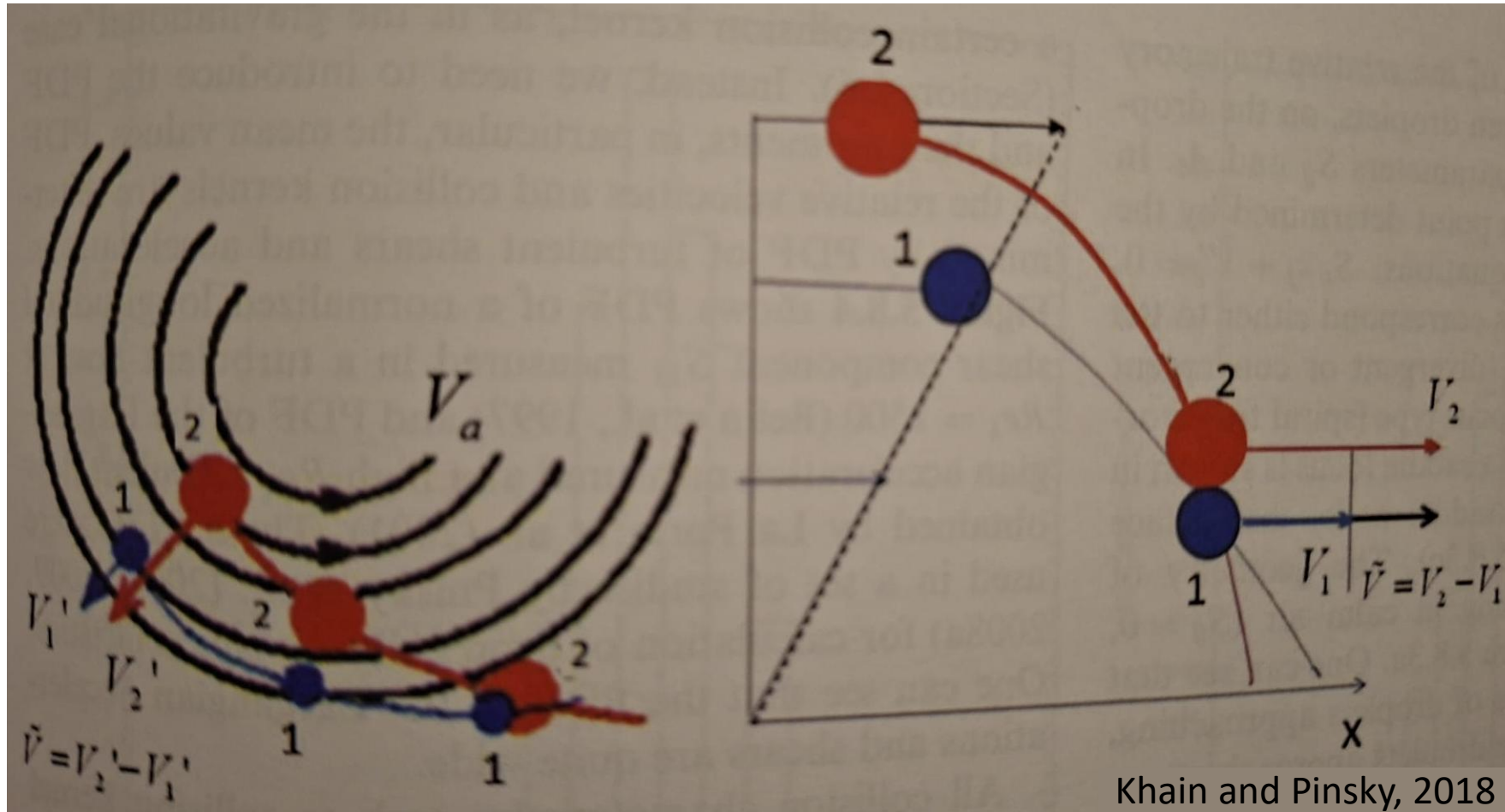
- Weisman-Klemp idealized
- Real case example

4. Onishi-Seifert turbulent enhancement in ICON-SBM: first results

Implementation in ICON considers of 2 effects:



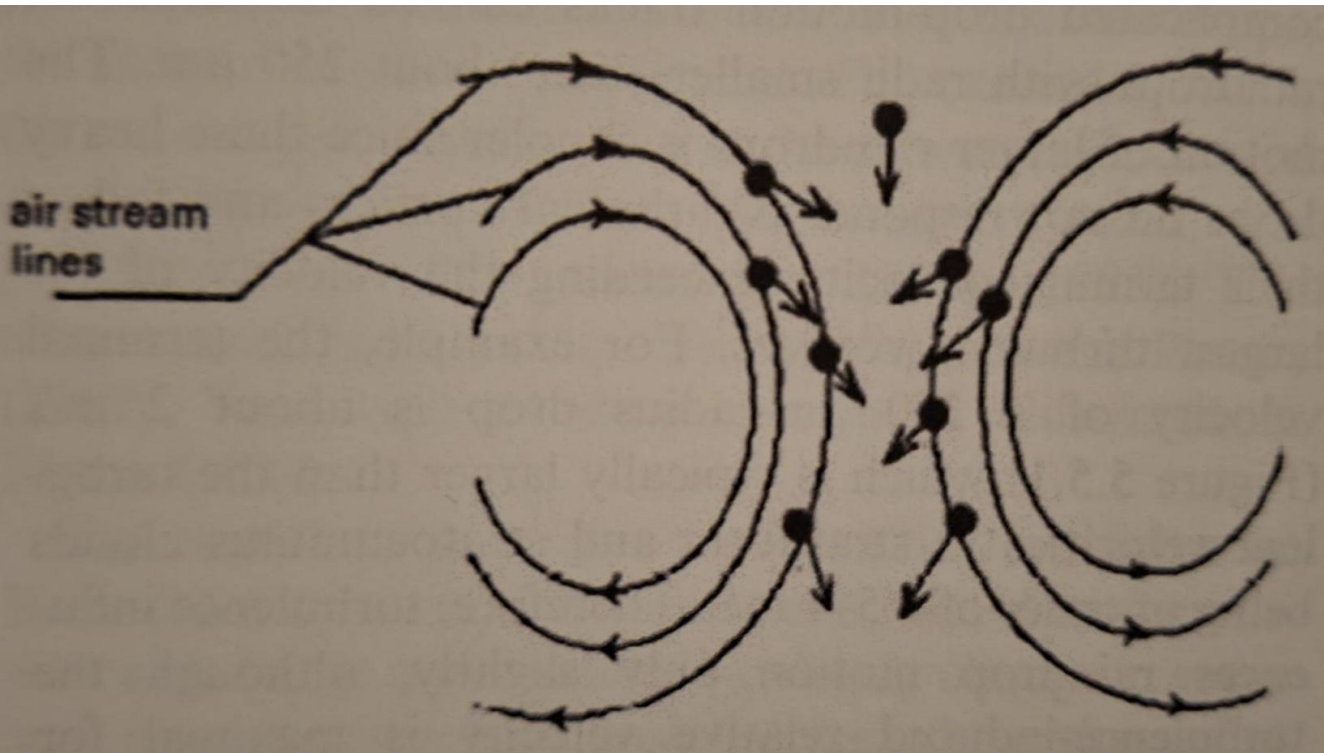
Turbulent enhancement of collisions



In turbulent vortex, drops of different mass, fly out with different velocities $\rightarrow$ additional relative velocity $\rightarrow$ higher collision rate

In sub-centimeter wind shear cases, drops of different mass get additional relative velocity $\rightarrow$ higher collision rate

Turbulent enhancement due to concentration inhomogeneity



Inertial drops leave vortices due to centrifugal force → higher concentration between vortices → higher collision rates



Small drops,
weak effect

Mid drops,
large effect

Large drops,
weak effect

Effect seen in DNS simulations (1mm res)

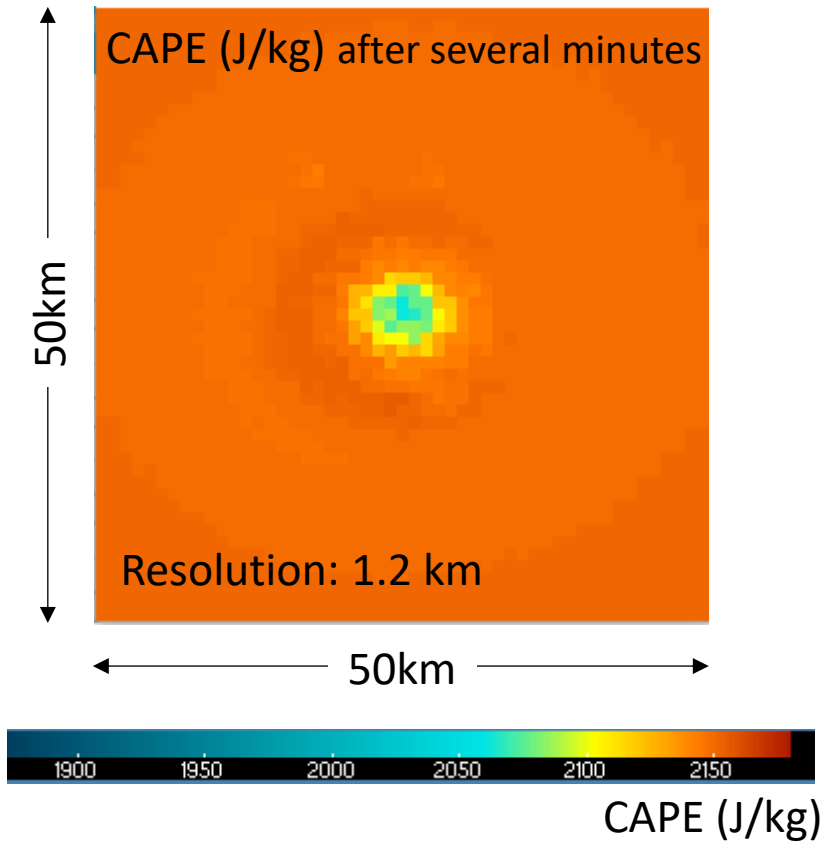
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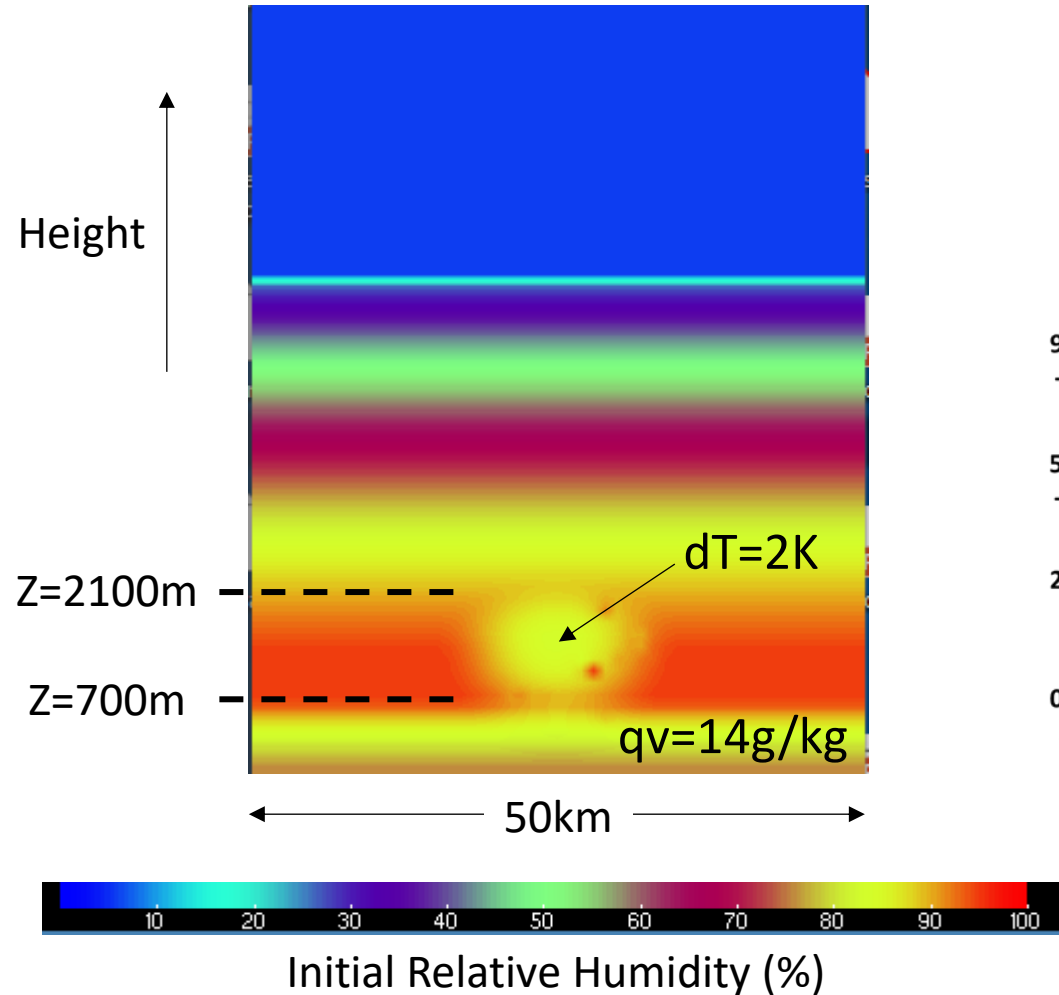
Tests of Cumulonimbus development (Weisman-Klemp 1982)

ICON run setup: $dt=1\text{sec}$, $dx=1.2\text{km}$

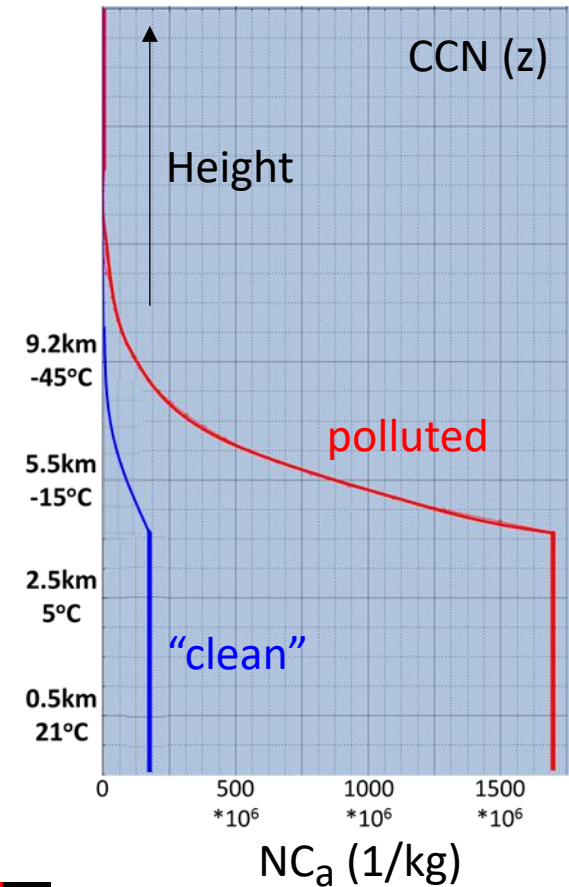
View from above



Cross section



Effect of aerosols



Effects of CCN, turbulence and freezing

It is known that higher CCN concentration → cloud invigoration. **Why?**

Typical explanation: smaller drops ascend → additional latent heat release due to **enhanced ice formation**

We show:

Even in warm case, more CCN → cloud invigoration

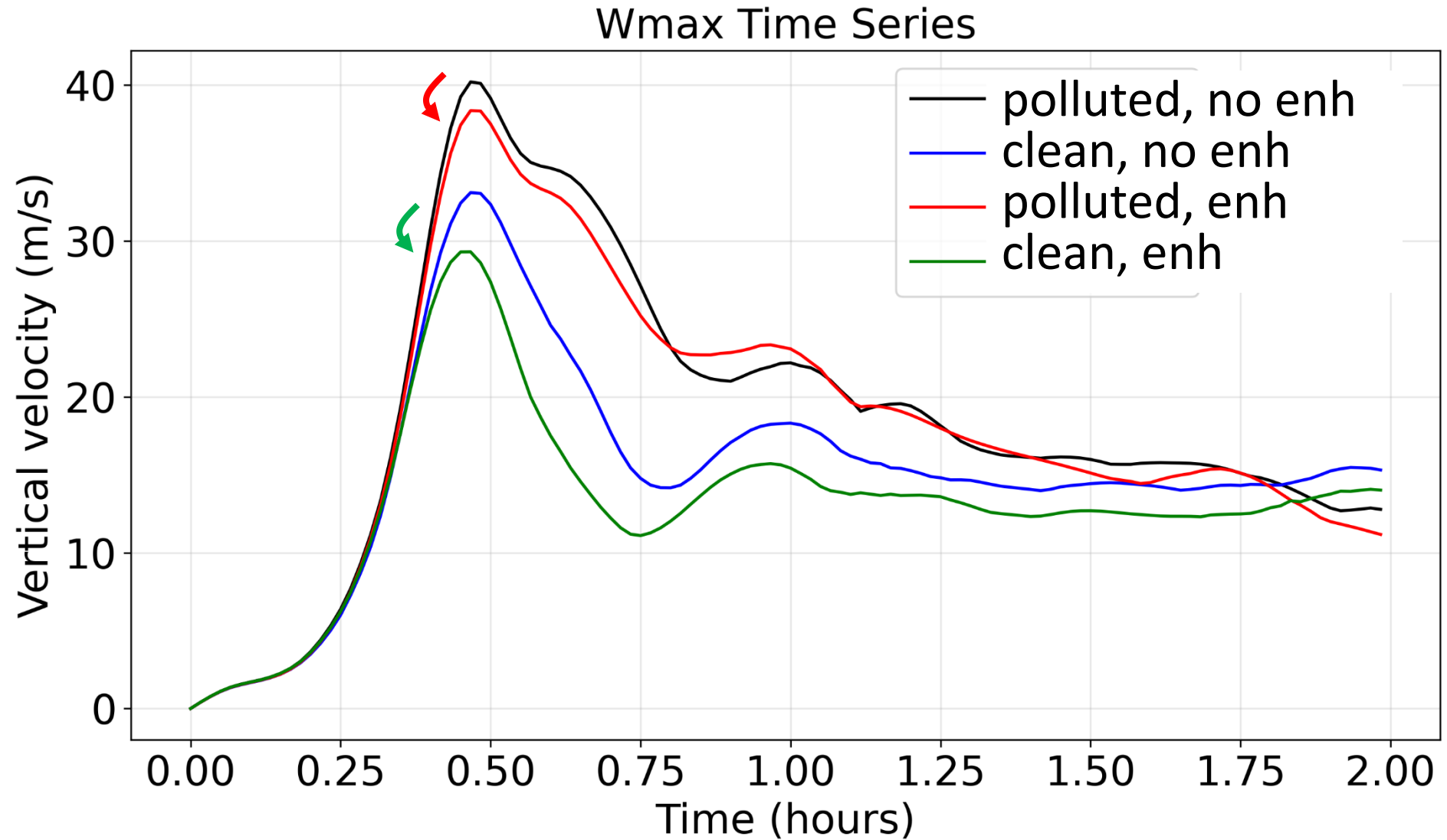
Reasons: more latent heat release and less rain loading at cloud base

What is the effect of turbulence?

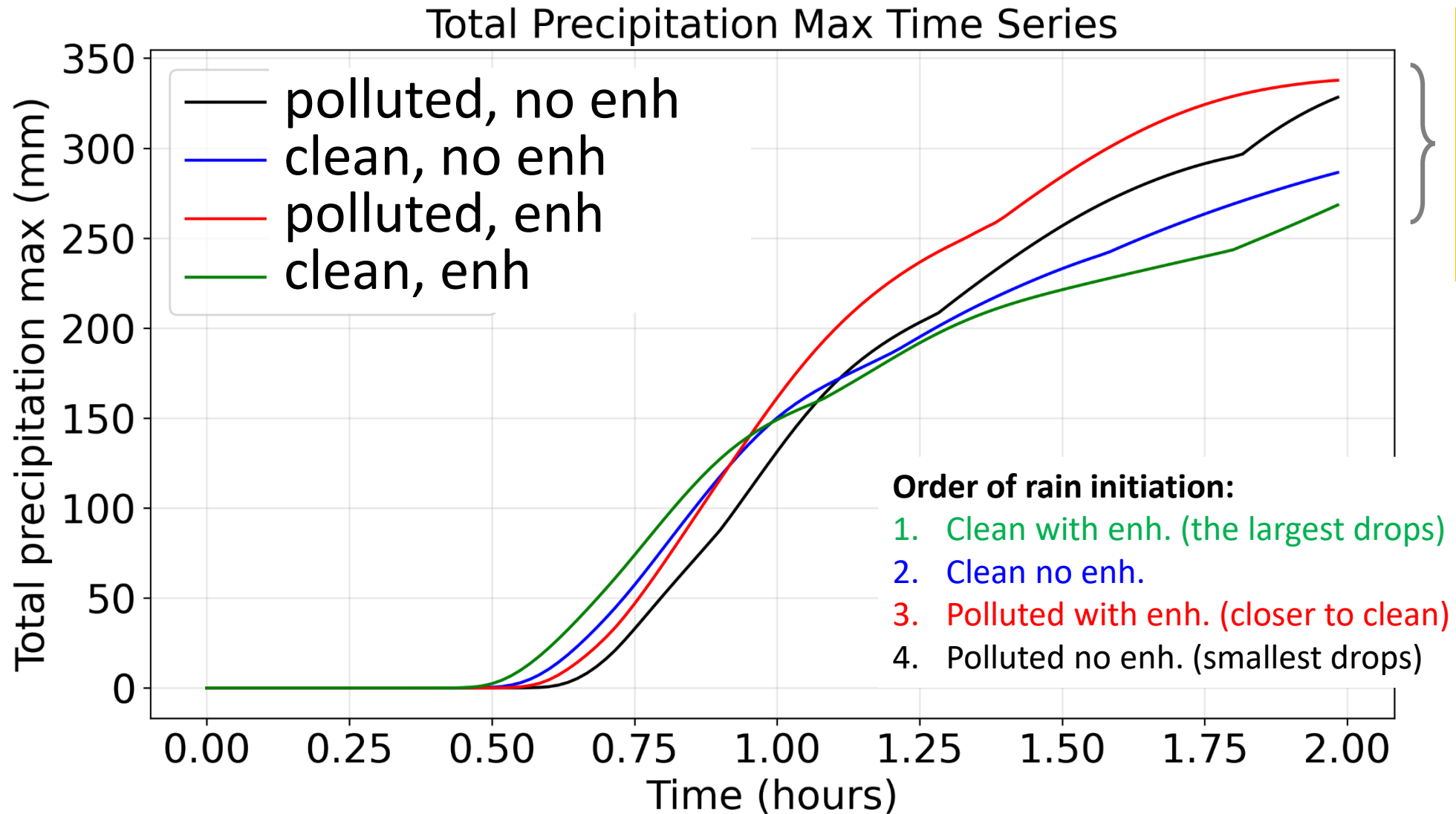
Turbulent enhancement → larger drops → higher loading → weaker cloud

The effect of turbulent enhancement similar to less CCN !

Effects of CCN and turbulence ignoring ice processes

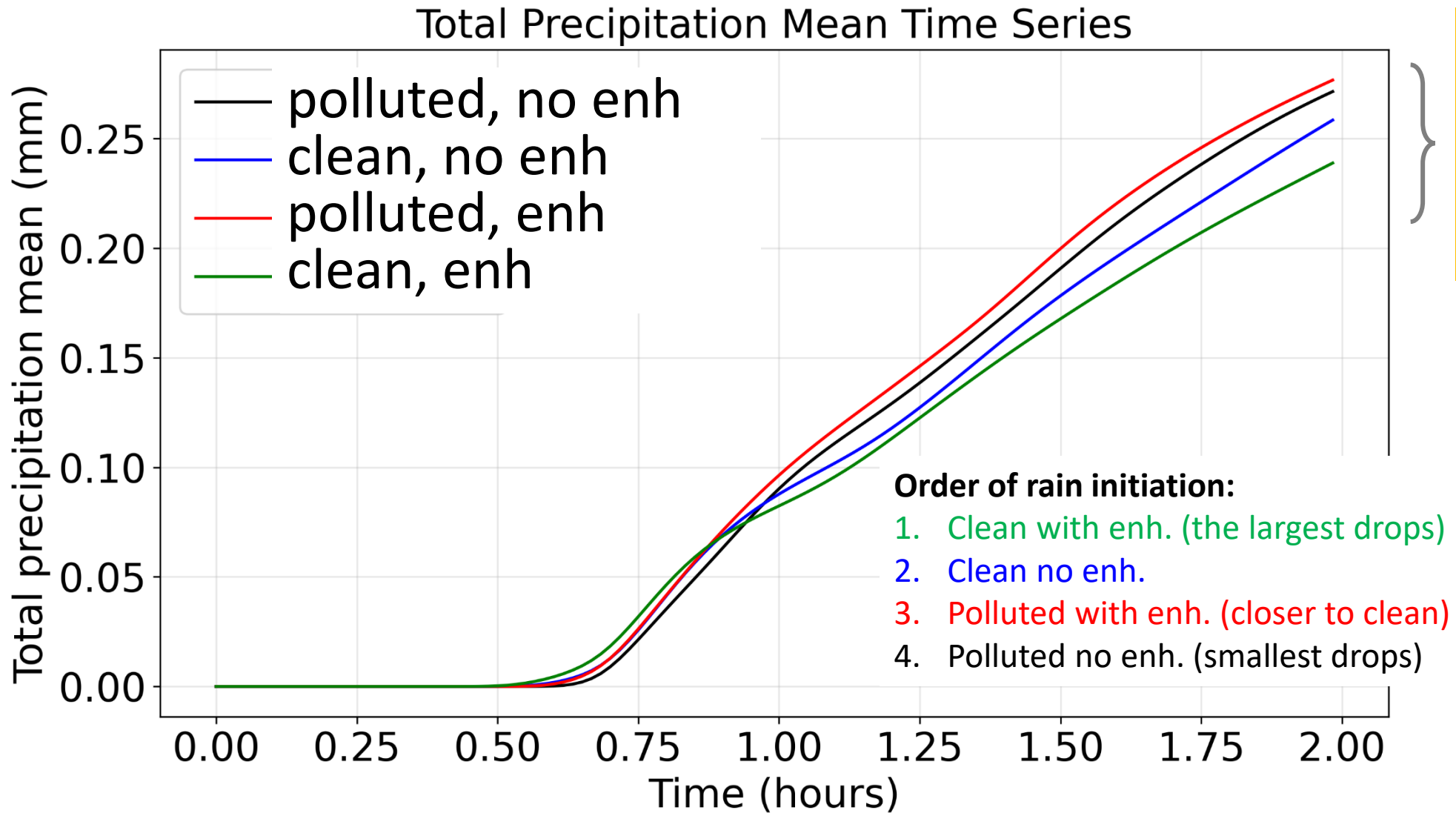


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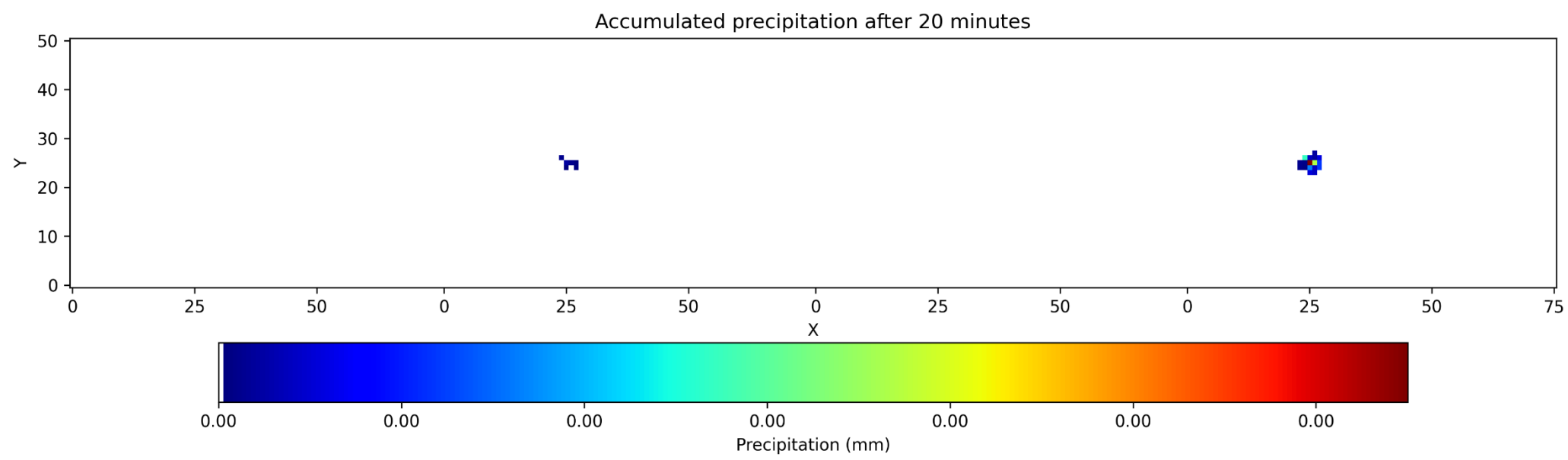
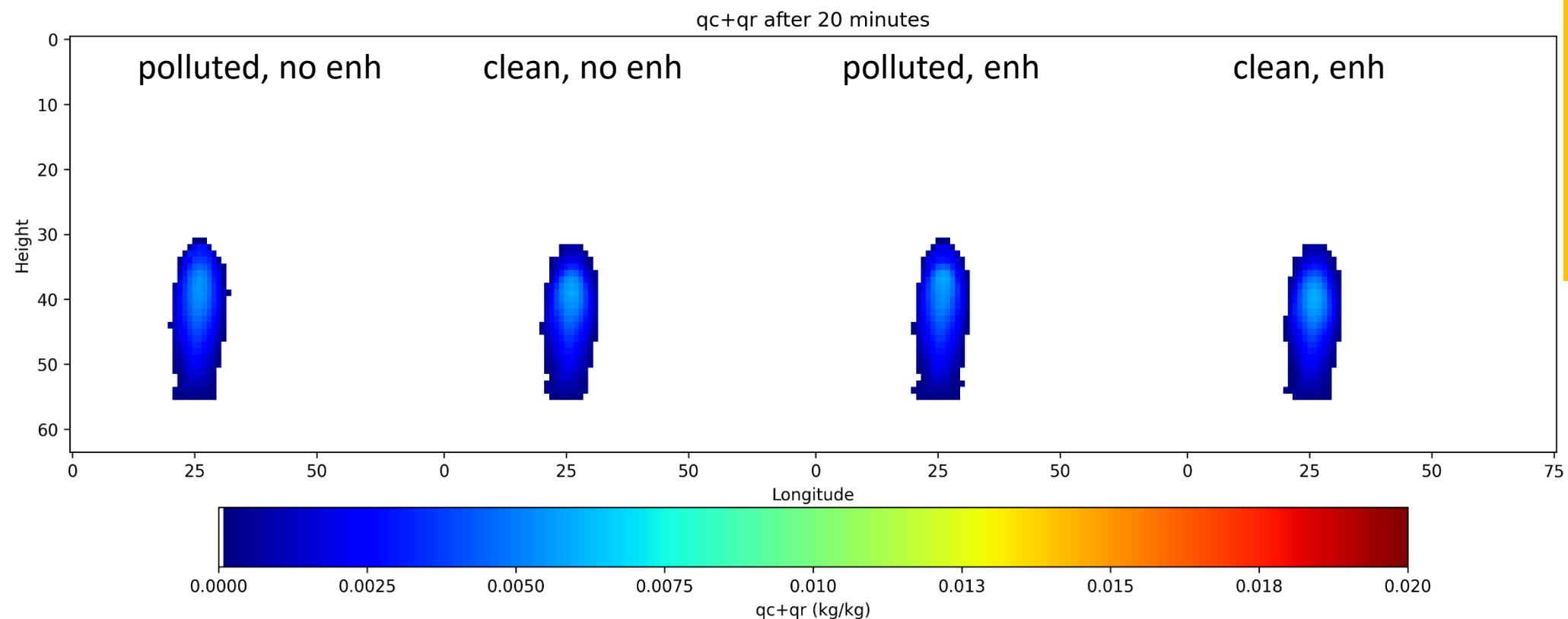
Polluted cases survive longer, earn more latent heat release, and end up with more rain

Effects of CCN and turbulence ignoring ice processes

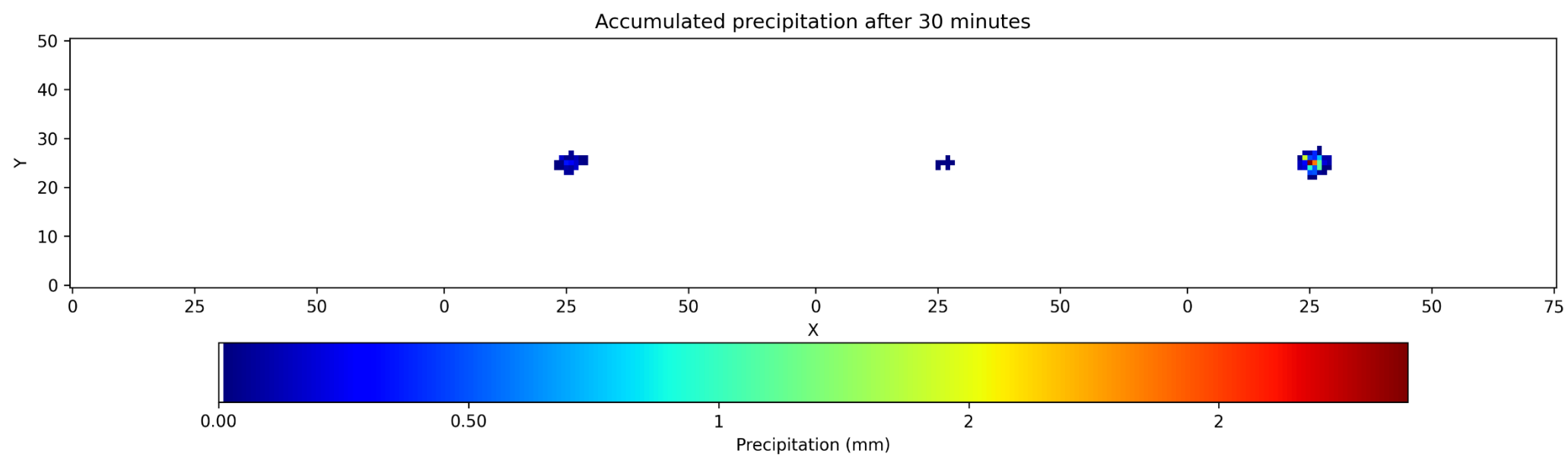
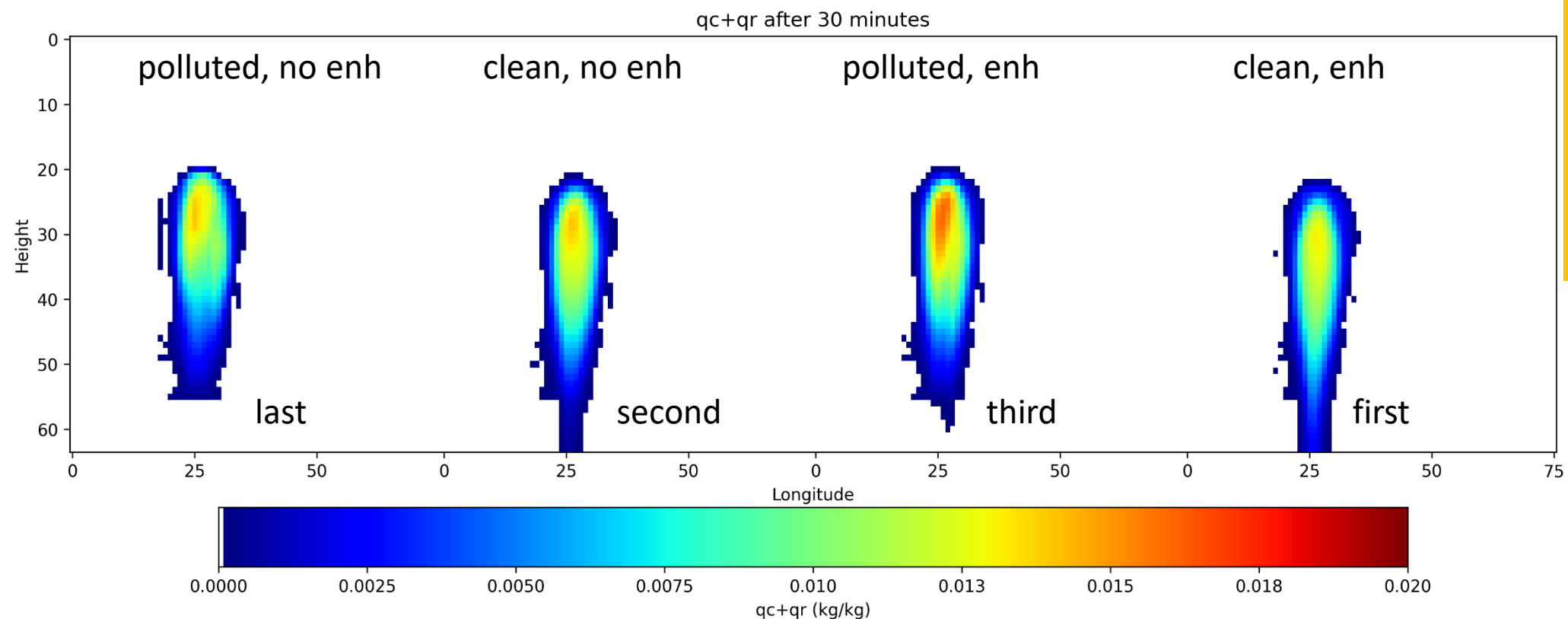


Polluted cases survive longer, earn more latent heat release, and end up with more rain

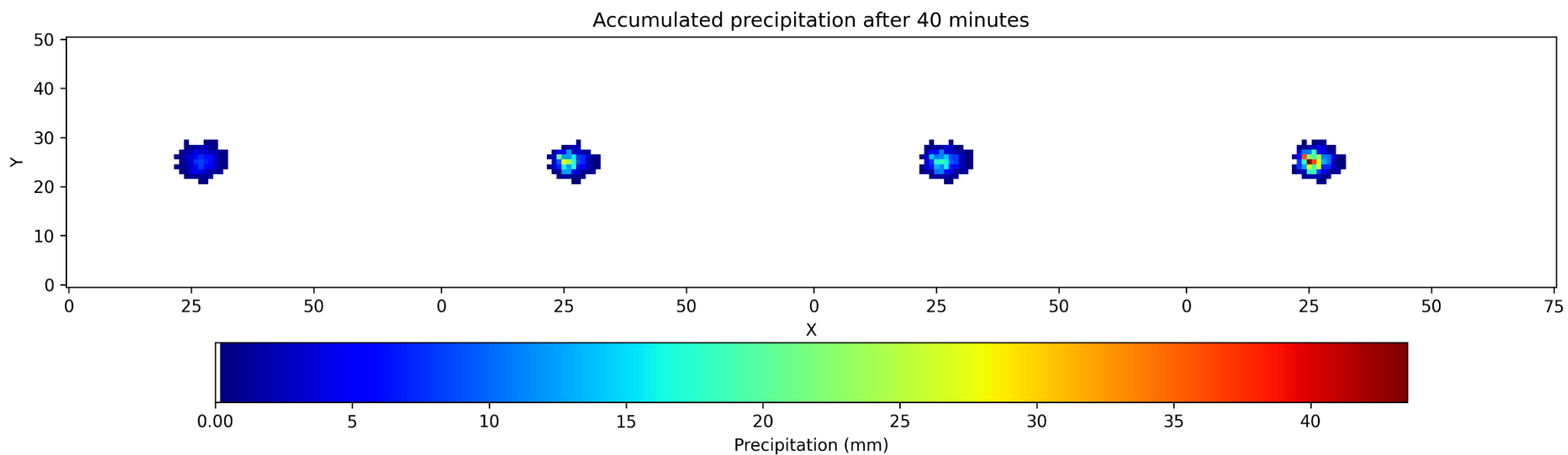
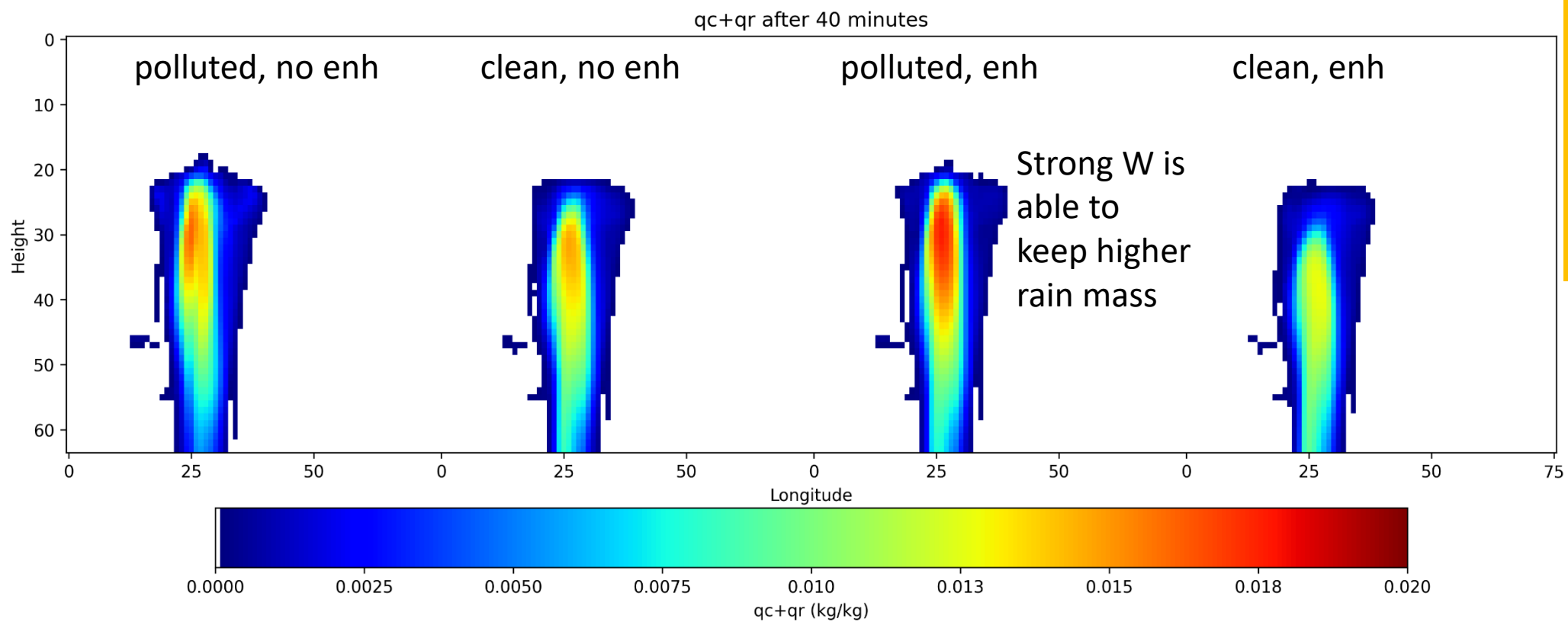
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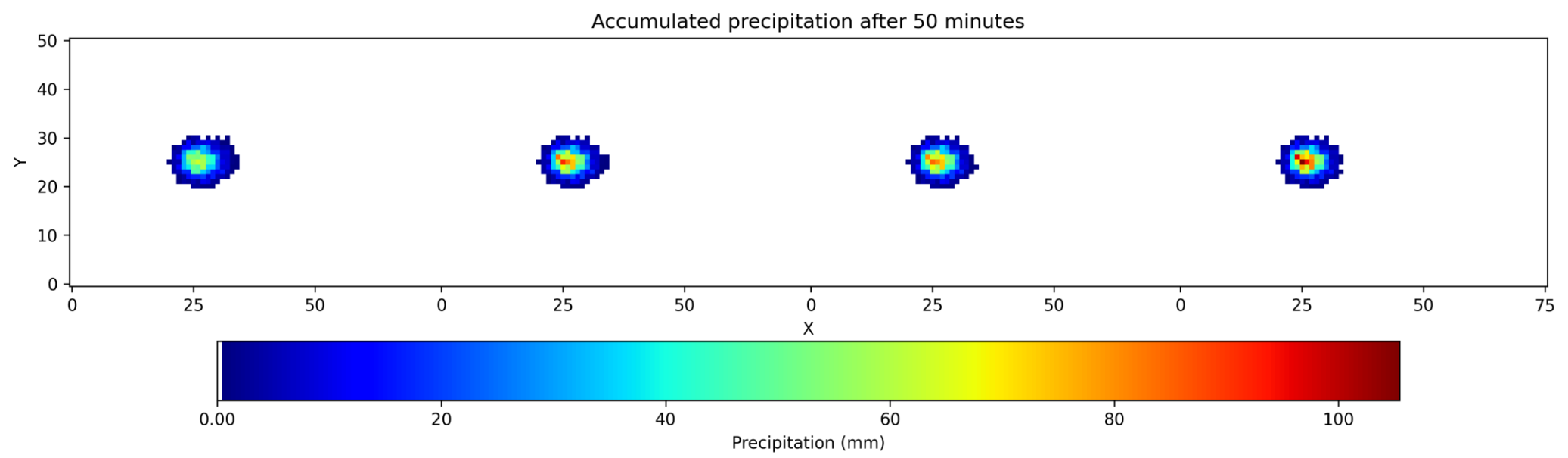
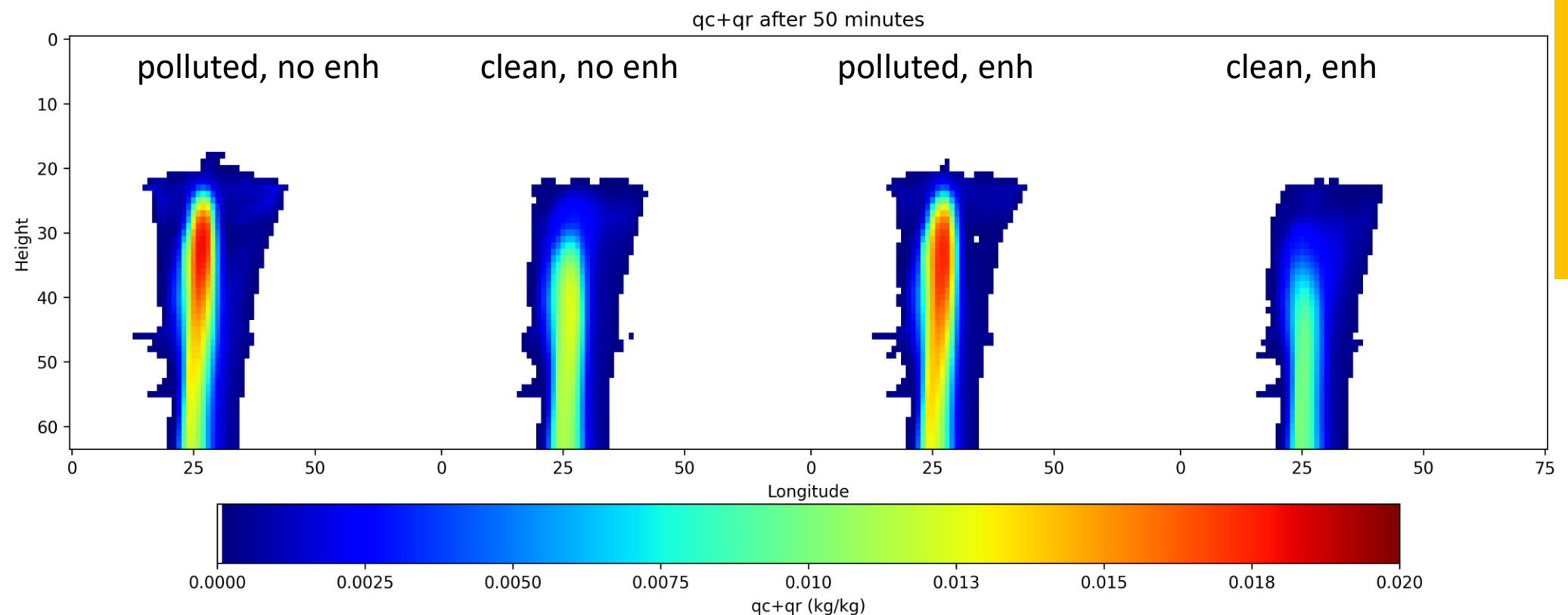
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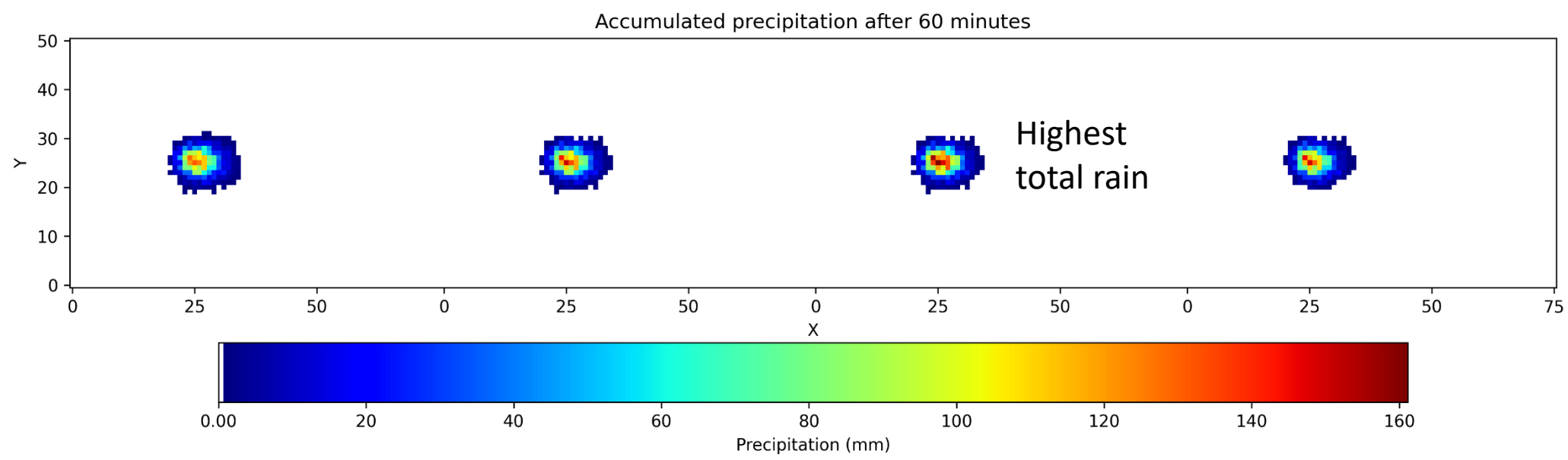
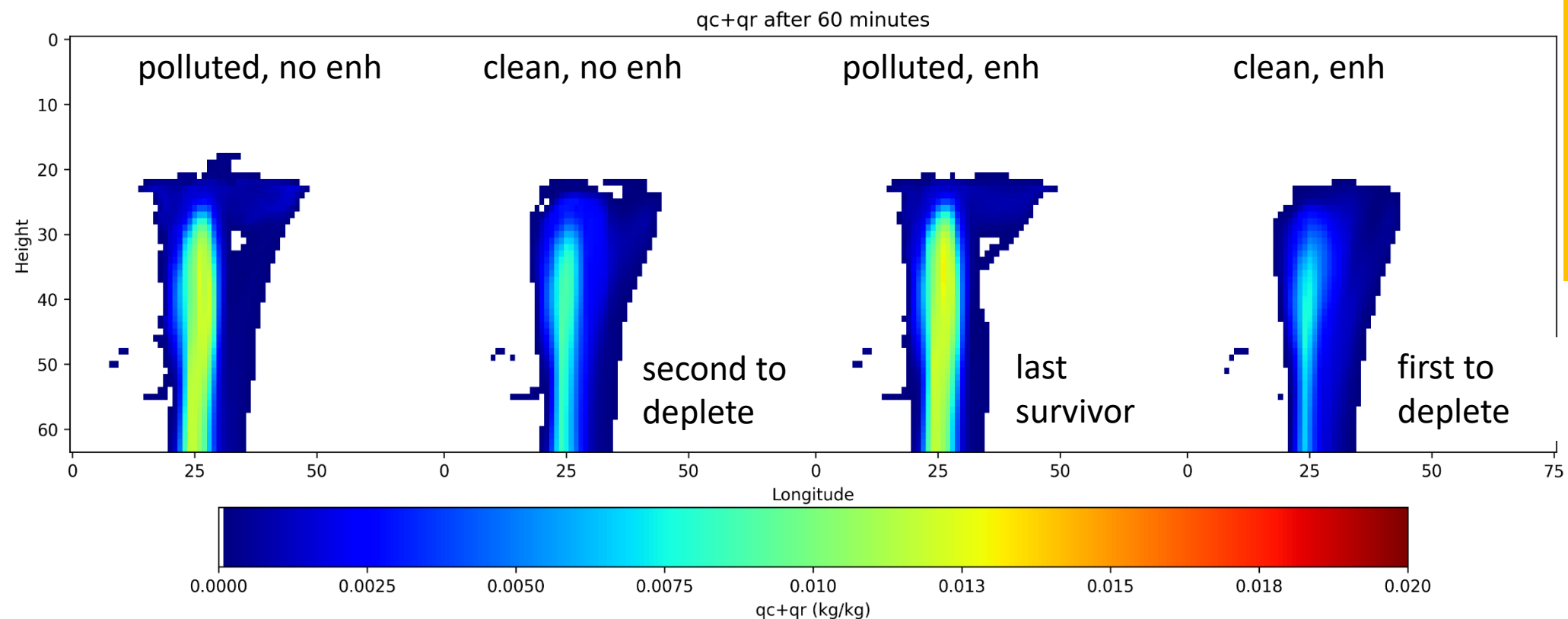
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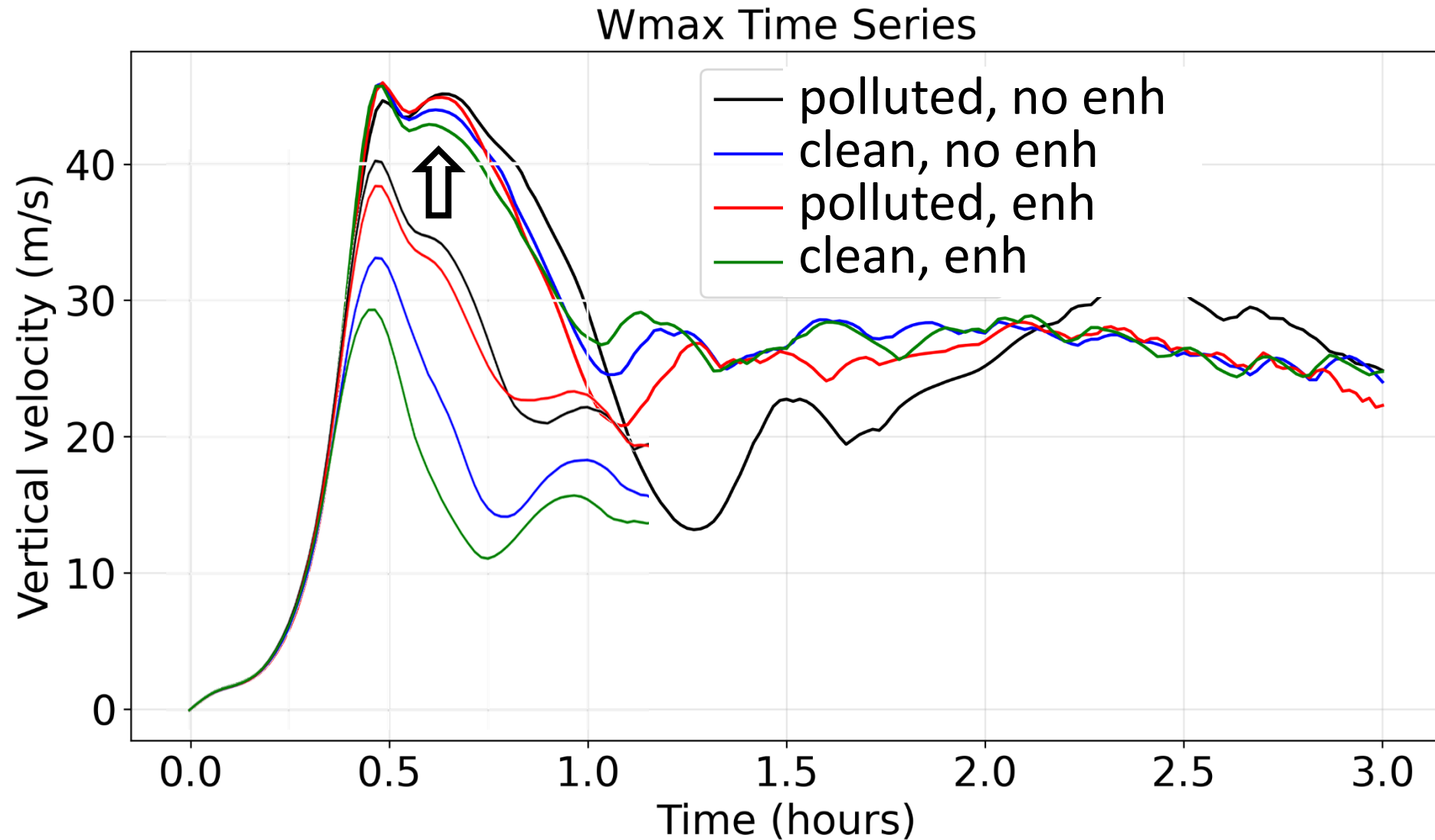


What is the effect of mixed phase?

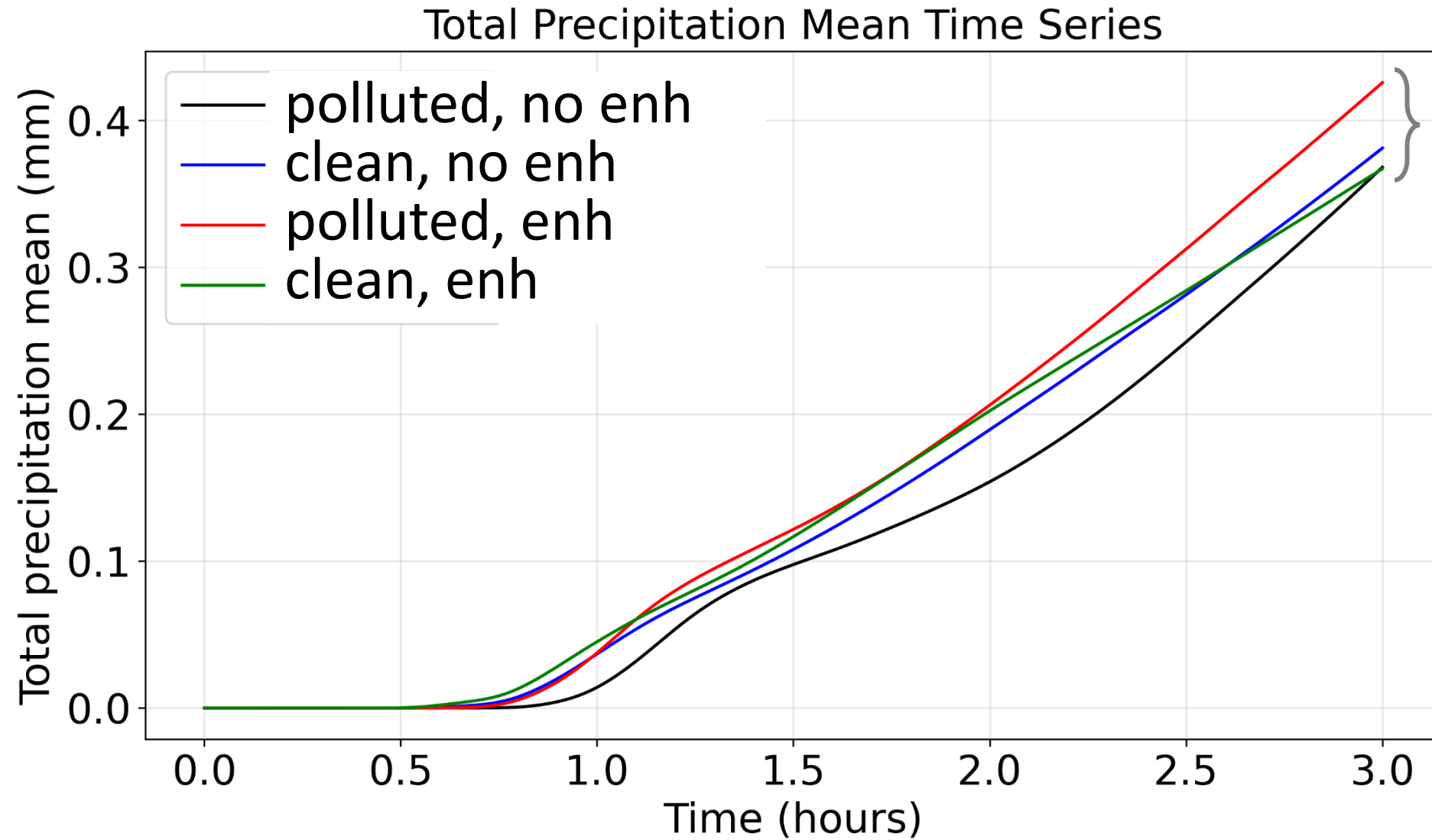
Mixed phase indeed leads to cloud invigoration due to latent heat of freezing

The effects of CCN and turb. enh. on W are smaller, but final precipitation is enhanced as in warm case

Effects of CCN and turbulence including ice processes



Effects of CCN and turbulence including ice processes



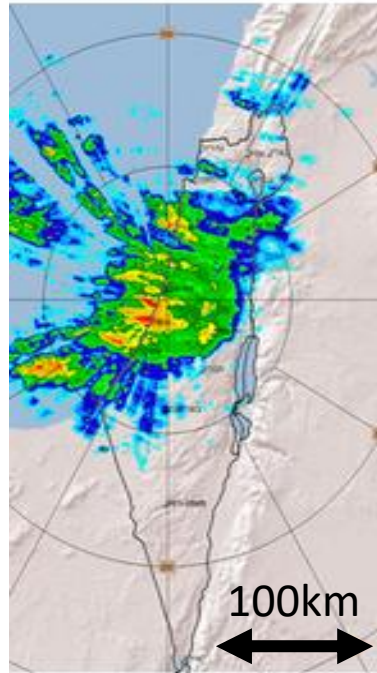
As in warm version, polluted enh. case survives longer, and ends up with more rain

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ICON 1km simulation 2025121100 06-12 UTC

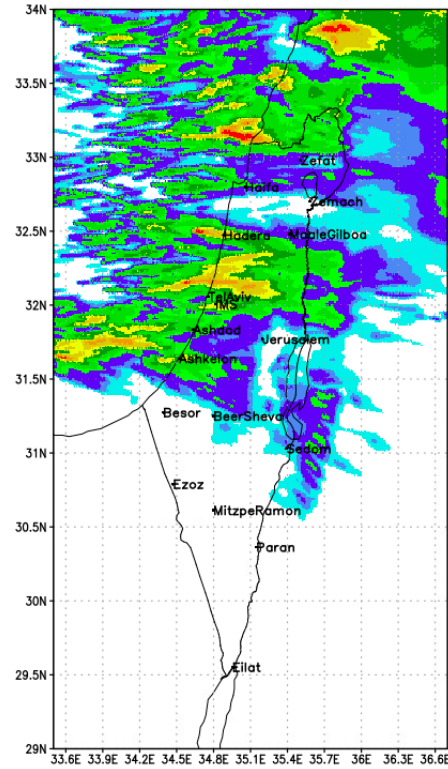
Radar



1M

(driven by ICON-EU)

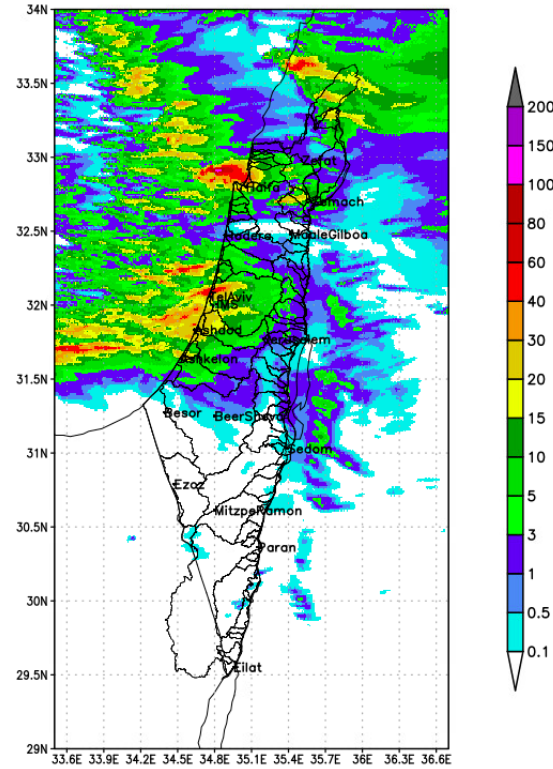
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SBM

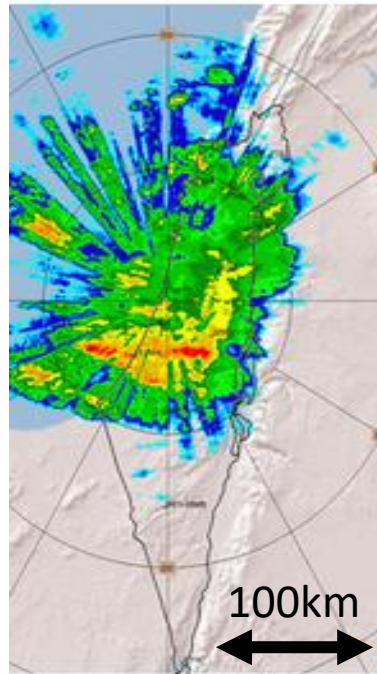
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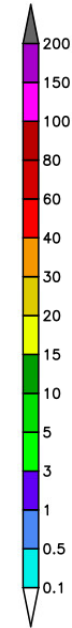
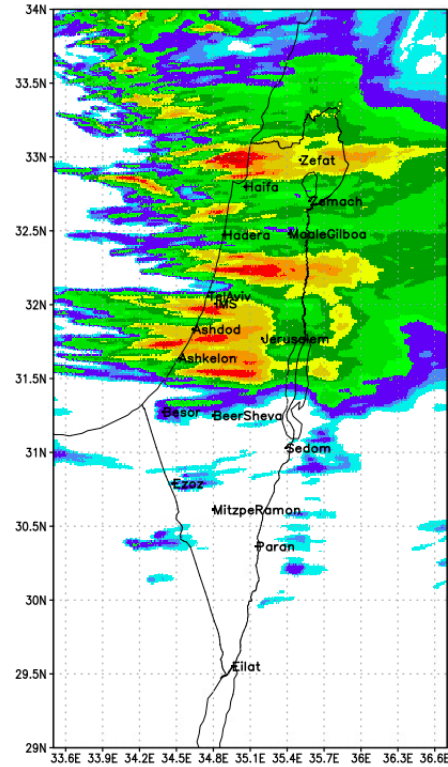
ICON 1km simulation 2025121100 12-18 UTC

Radar



1M
(driven by ICON-EU)

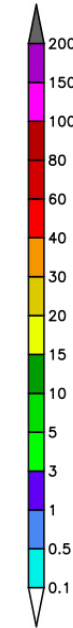
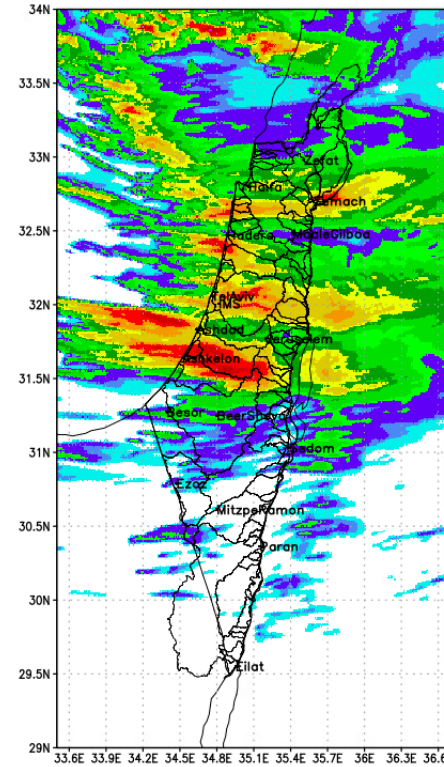
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SBM

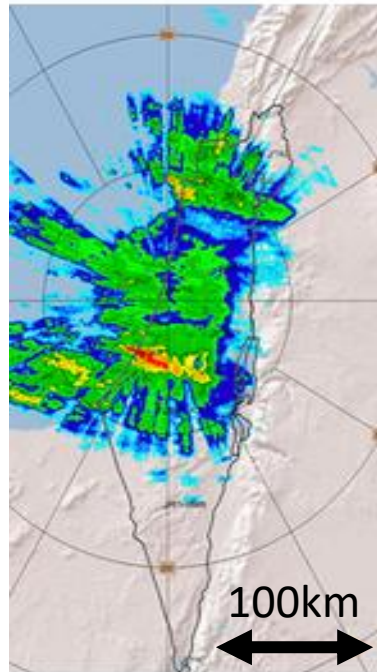
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ICON 1km simulation 2025121100 18-24 UTC

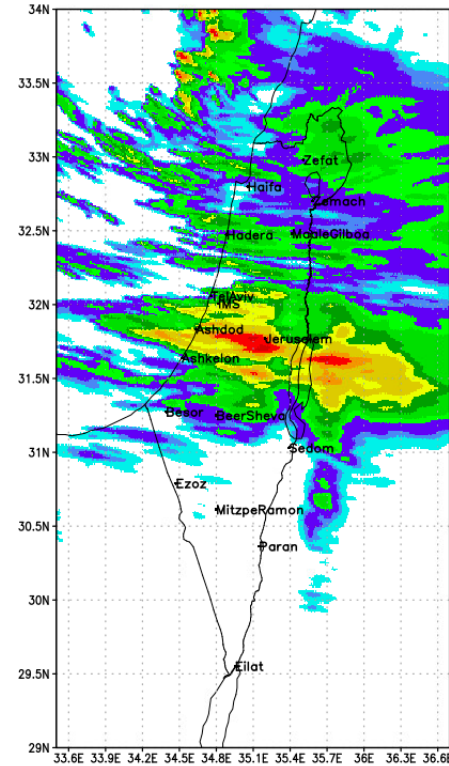
Radar



1M

(driven by ICON-EU)

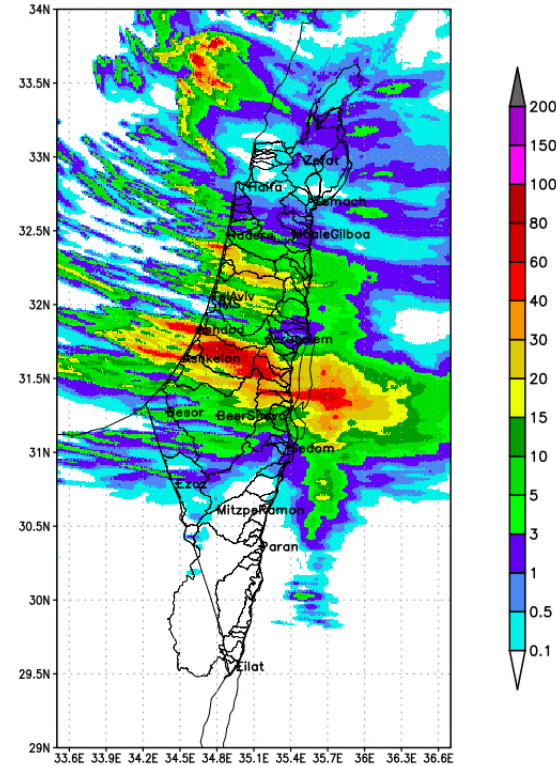
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SBM

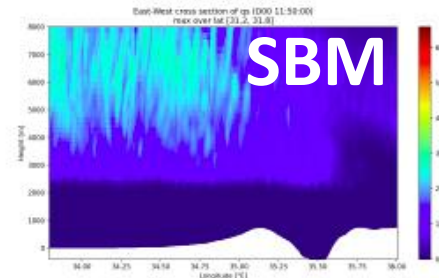
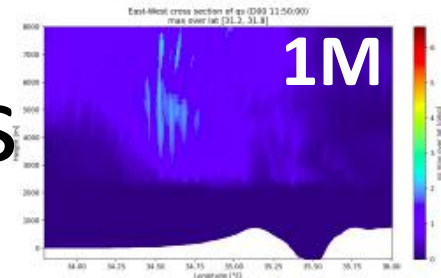
(clean, driven by ICON-EU)

TP +18h to +24h: Thu 12 DEC 00Z

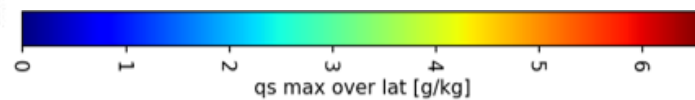


*More tests are performed over Germany (Thanks to Daniela Littmann)

qs

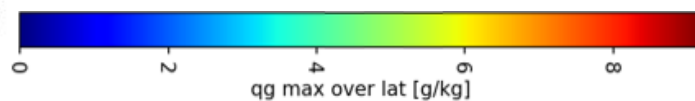
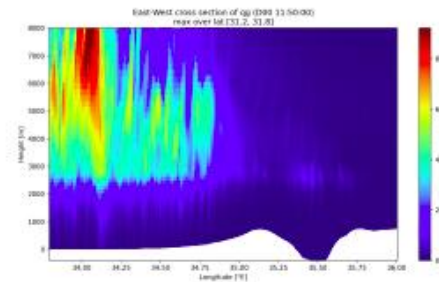
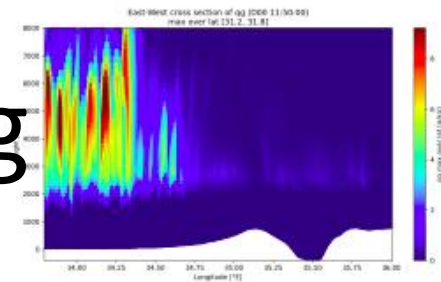


+12h

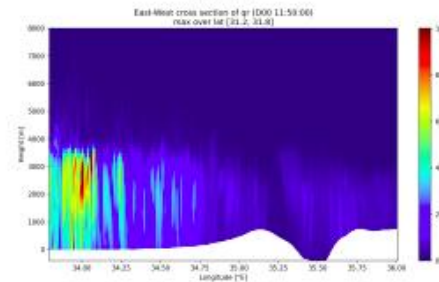
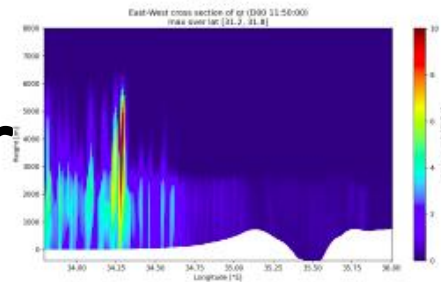


West-East cross-section:
MAX values over latitudes in the area
33.8-36 E / 31.2-31.8 N

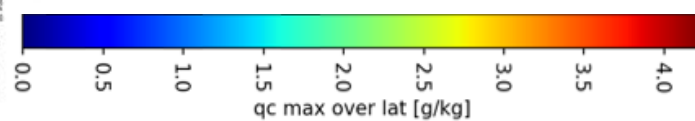
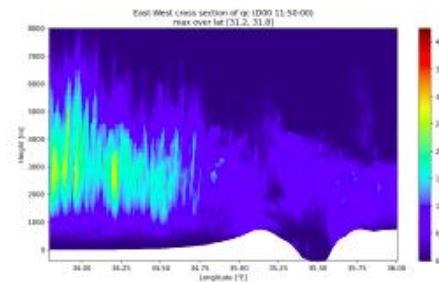
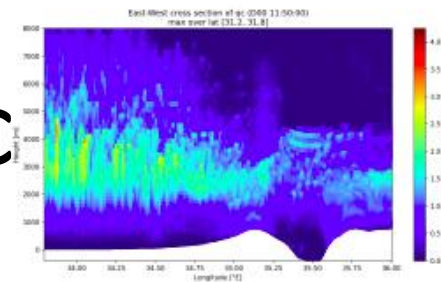
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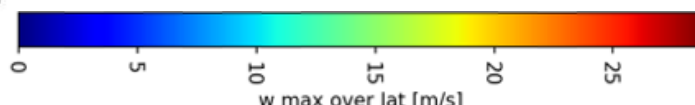
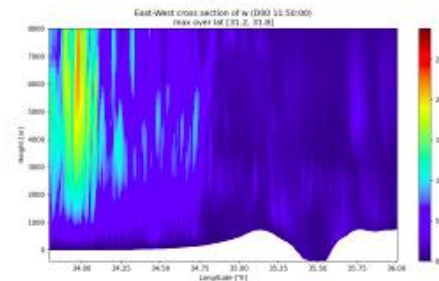
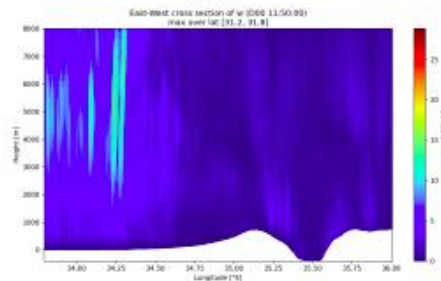
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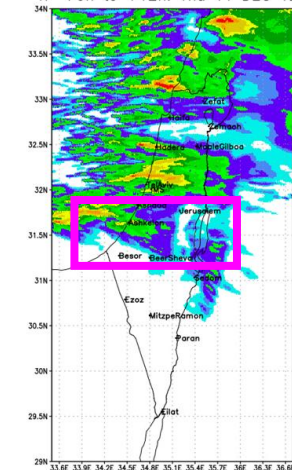
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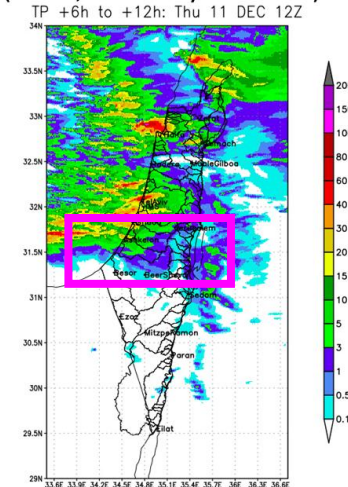
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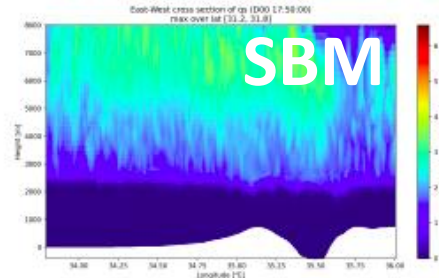
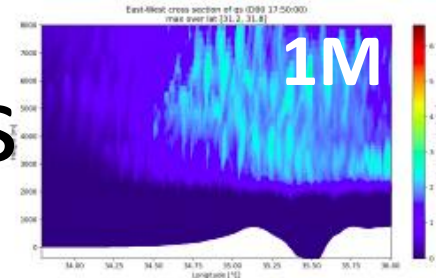
1M
 (driven by ICON-EU)
 TP +6h to +12h: Thu 11 DEC 12Z



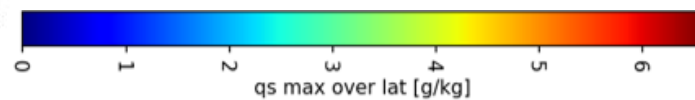
SBM
 (clean, driven by ICON-EU)
 TP +6h to +12h: Thu 11 DEC 12Z



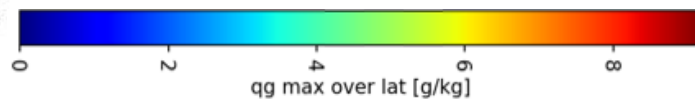
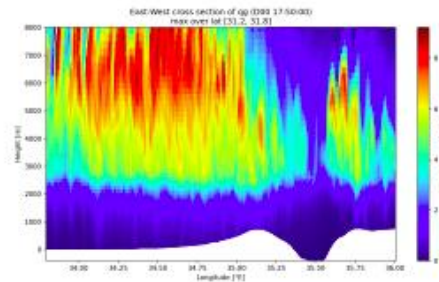
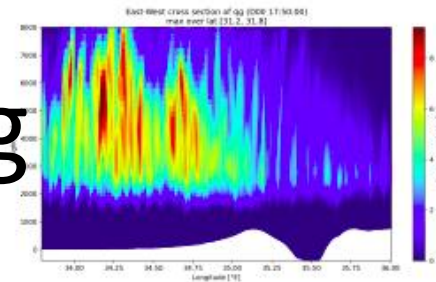
qs



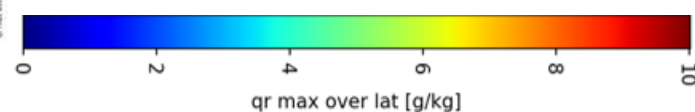
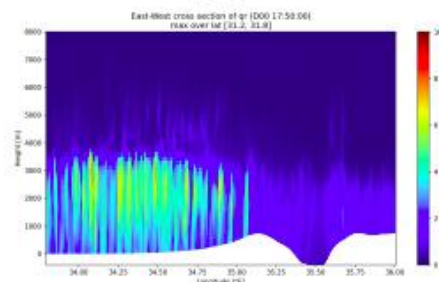
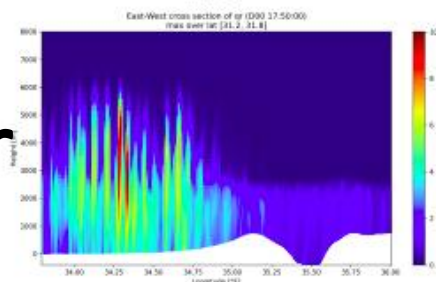
+18h



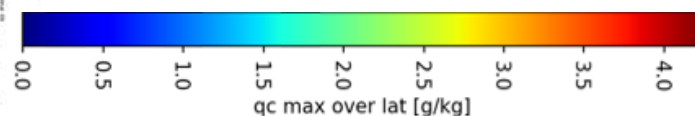
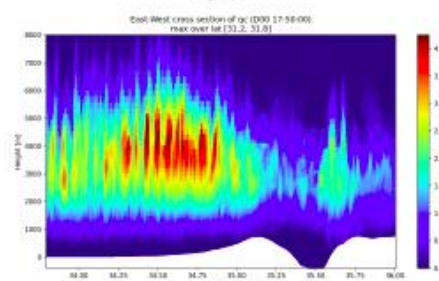
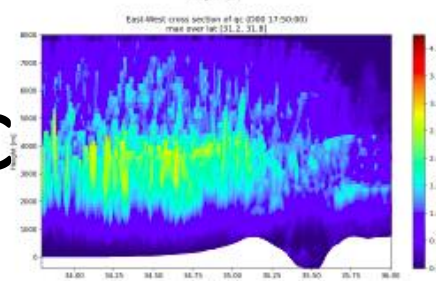
qg



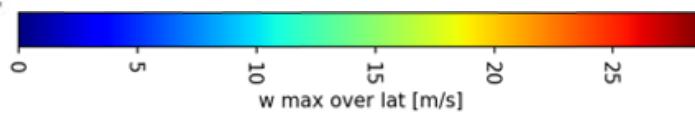
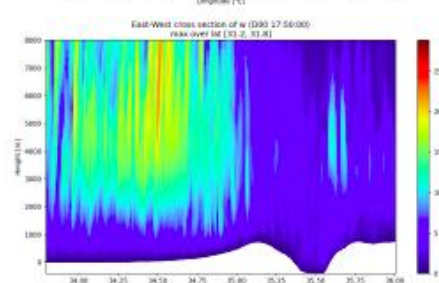
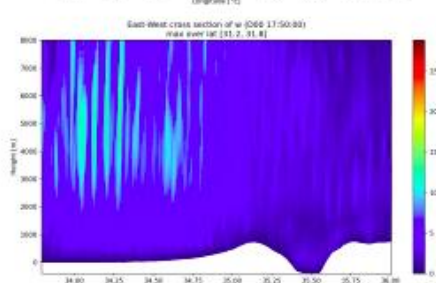
qr



qc

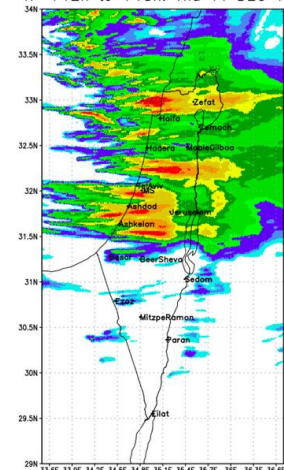


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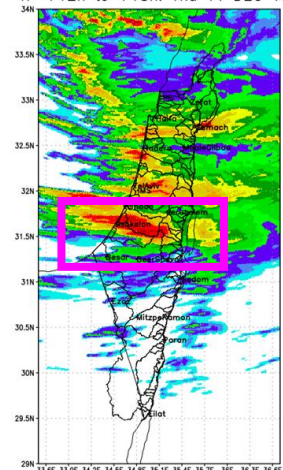


**West-East cross-section:
MAX values over latitudes in the area
33.8-36 E / 31.2-31.8 N**

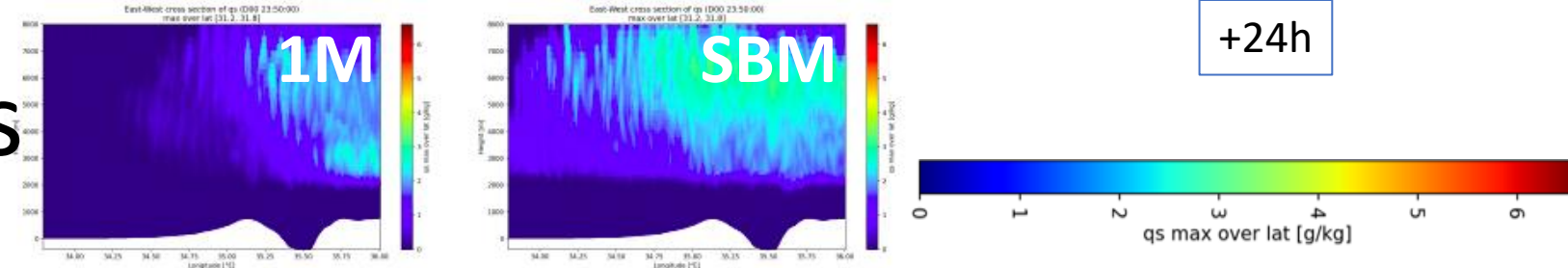
**1M
(driven by ICON-EU)**
TP +12h to +18h: Thu 11 DEC 18Z



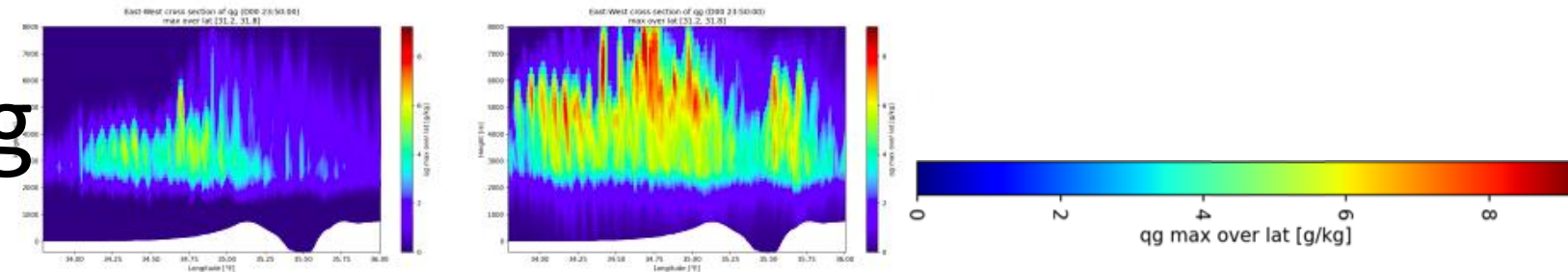
**SBM
(clean, driven by ICON-EU)**
TP +12h to +18h: Thu 11 DEC 18Z



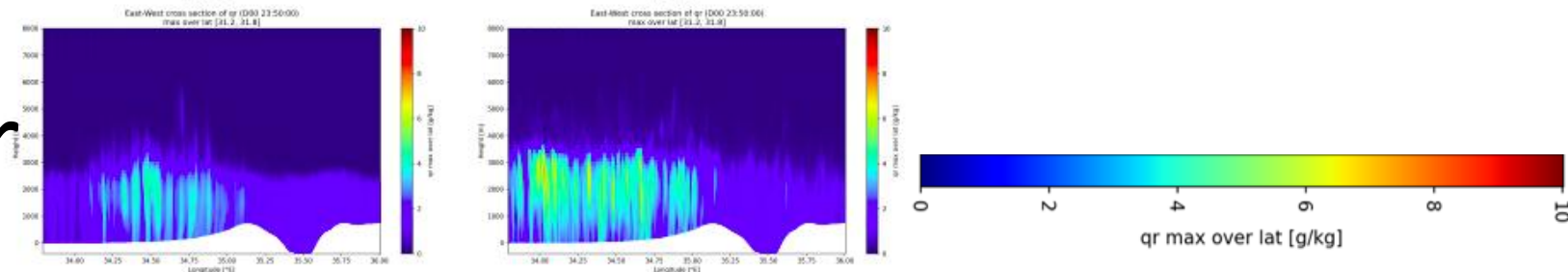
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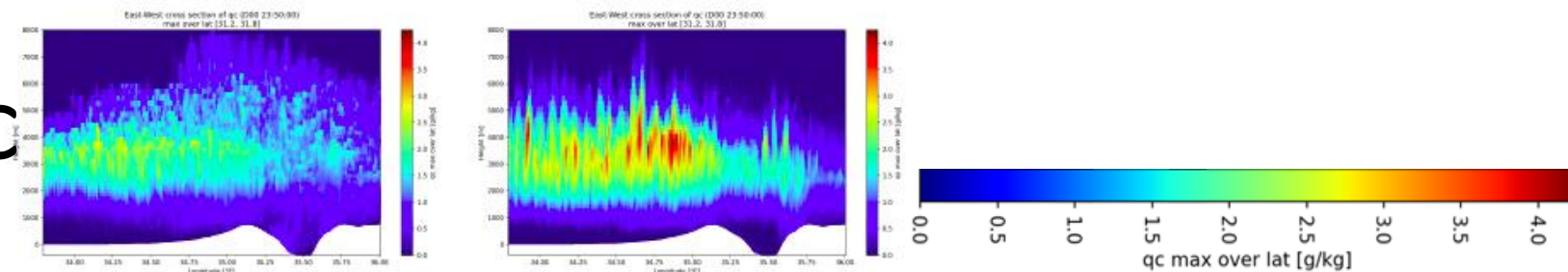
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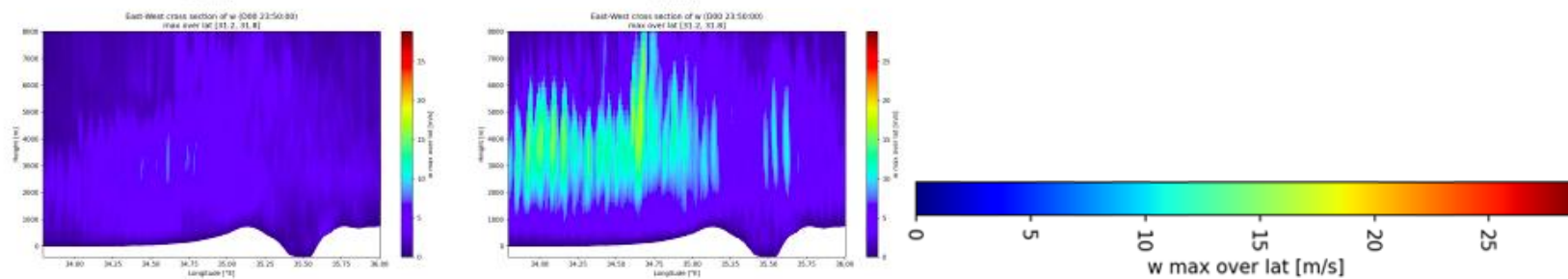
qr



qc

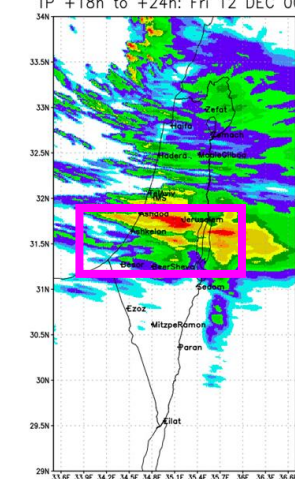


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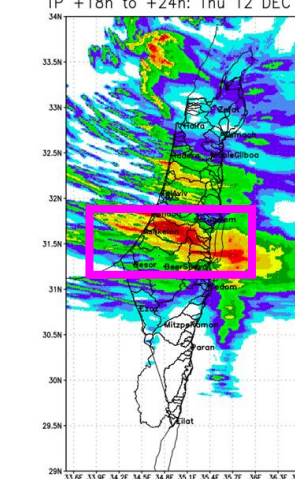


**West-East cross-section:
MAX values over latitudes in the area
33.8-36 E / 31.2-31.8 N**

**1M
(driven by ICON-EU)
TP +18h to +24h: Fri 12 DEC 00Z**



**SBM
(clean, driven by ICON-EU)
TP +18h to +24h: Thu 12 DEC 00Z**



Outlook

1. Reminder: SBM Implementation in ICON
2. Turbulent enhancement of collisions
3. First tests:
 - Weisman-Klemp idealized
 - Real case example
4. Onishi-Seifert turbulent enhancement in ICON-SBM: first results

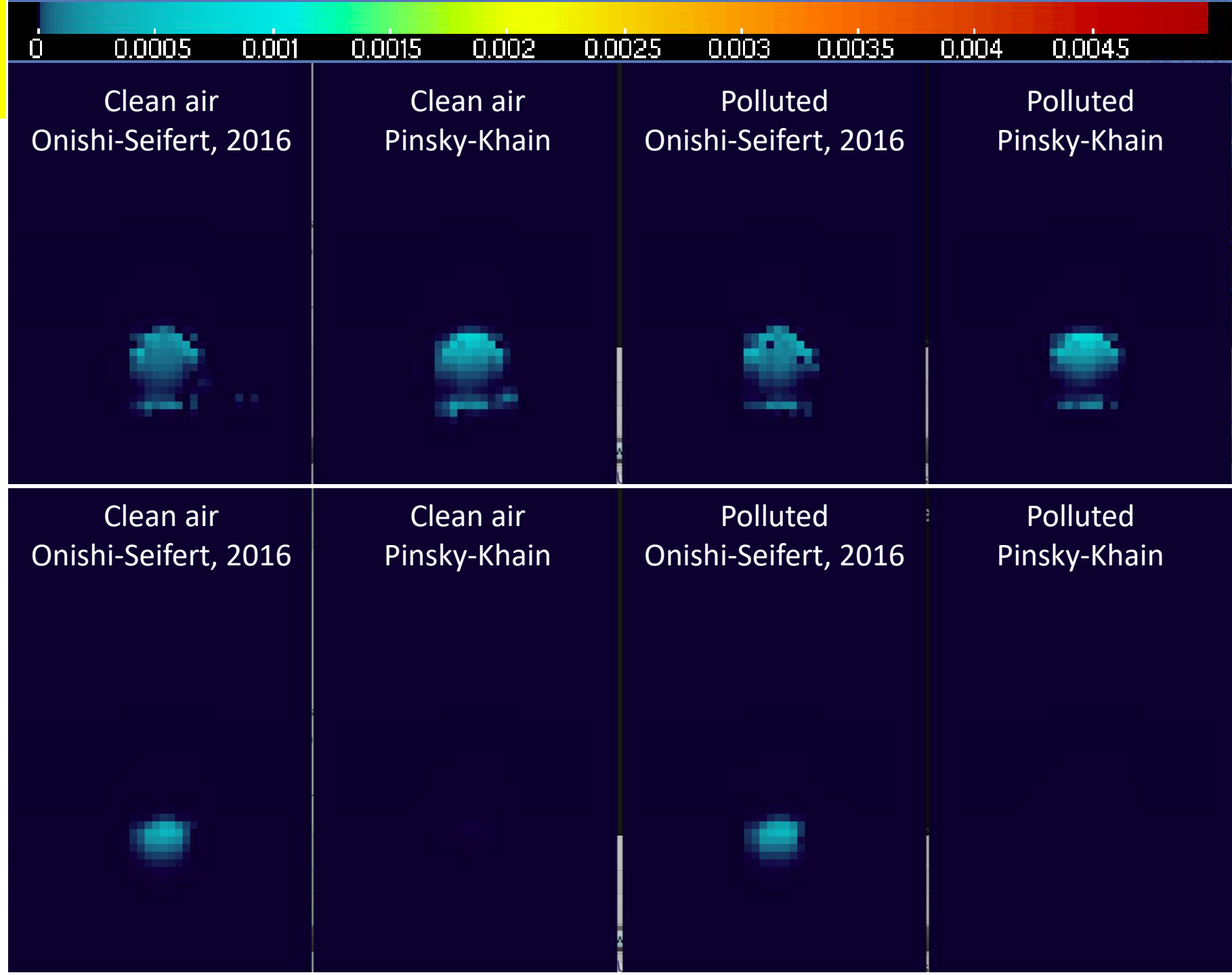
Onishi-Seifert coll. kernel.
in ICON-SBM: **preliminary!**

QC
(kg/kg)

First results show
stronger collision kernels
→ earlier rain formation
(implementation bugs possible)

QR
(kg/kg)

After 8 minutes



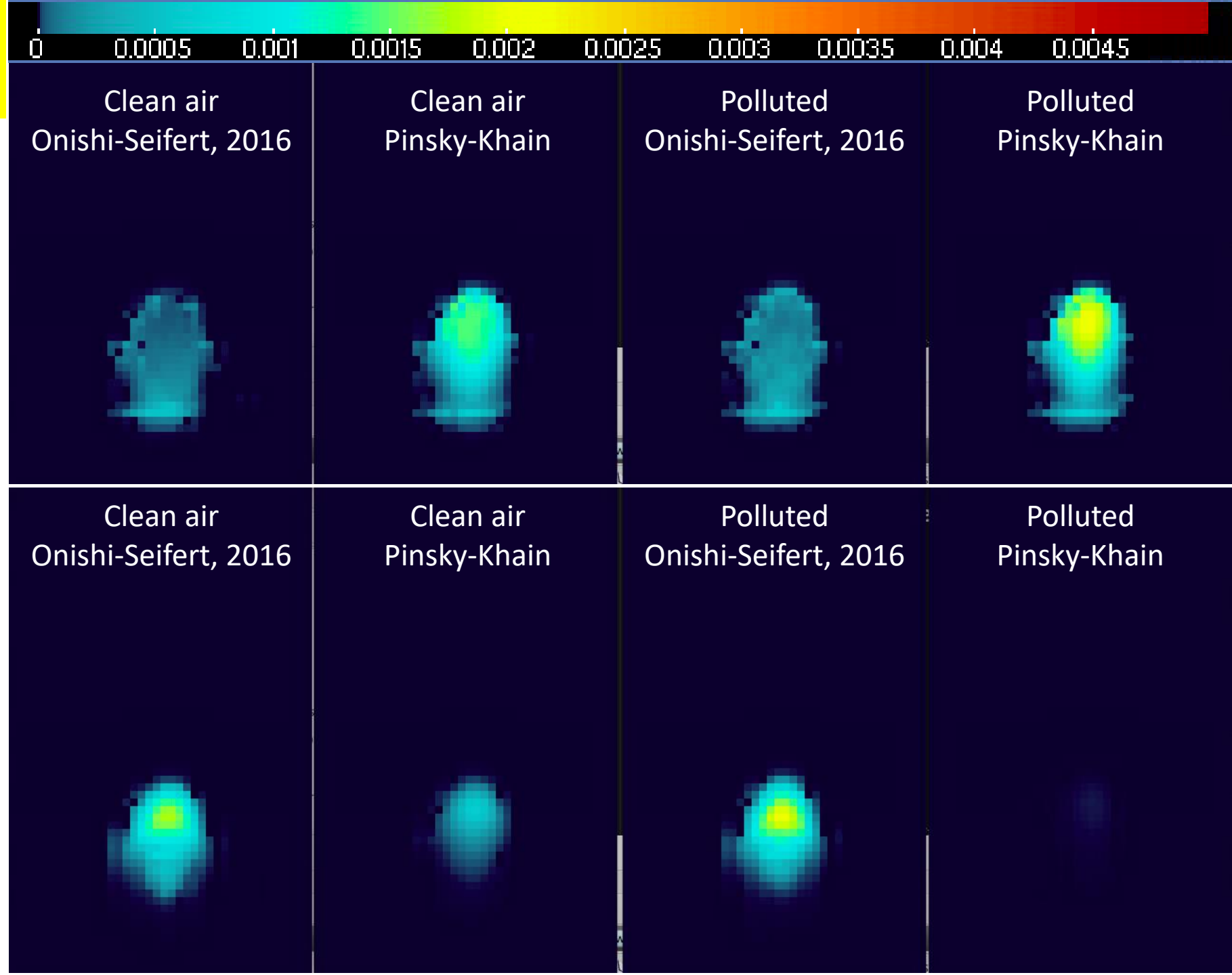
Onishi-Seifert coll. kernel.
in ICON-SBM: **preliminary!**

QC
(kg/kg)

First results show
stronger collision kernels
→ earlier rain formation
(implementation bugs possible)

QR
(kg/kg)

After 15 minutes



Summary

1. Pinsky-Khain turbulent collisions enhancement is implemented in ICON-SBM. Merge request soon.
2. Reasonable preliminary results for real case
3. Onishi-Seifert turbulent collisions enhancement implementation in ICON-SBM is ongoing.
4. More on ICON-SBM developments in Koby Shpund talk

Thanks!

More slides

SBM microphysical processes used in ICON

Diffusional growth/evaporation

The equation for diffusional growth/evaporation is solved together with the equations for supersaturation, using microphysical sub-steps, which are three times smaller than the dynamical time step, so that the local and advective tendencies of supersaturation during microphysical time steps are taken into account. In this way, the water vapor condensates on the growing droplets and the supersaturation is reduced. In strong updrafts, where the supersaturation growth rapidly or in cases of low drop concentration, this reduction does not reach zero, leading to lower latent heat release than with saturation adjustment used in bulk schemes.

Collisions

The hydrometeors size distributions evolution due to collisions between drops is calculated by solving the stochastic equation for collisions using the low diffusional method (Bott 1998). Collision kernels depend on height as described in Khain & Pinsky 2018. Probabilities for spontaneous breakup were taken from laboratory measurements (Kamra et al. 1991). The changes of size distribution function by the collisional breakup of drops are described as in Seifert et. al. 2005.

Ice formation

Ice particles are formed either by drop freezing or primary ice nucleation.

- Heterogeneous drop freezing is calculated using the method close to that of Bigg (Khain et al. 2004), where probability of freezing increases with drop mass and with the decrease of temperature. Freezing of small droplets with radii lower than 100 μm is assumed to lead to formation of ice crystals (smallest bins in the snow size distribution). Freezing of larger drops leads to formation of graupel or hail (in the hail version). Homogeneous drop freezing takes place at temperatures lower than -39°C . Droplet nucleation at lower temperatures lead to their immediate freezing.
- Rate of primary ice nucleation calculated using the parameterization of Meyers et al. 1992, depends on supersaturation over ice and temperature.

Ice-ice and ice-water collisions are calculated using a modified Bott method. Snow-snow collisions lead to formation of larger snow particles. Water-graupel/ hail collisions (riming process) lead to the formation of larger graupel or hail, respectively. Water-snow collisions lead to formation of graupel (or hail) in case the mass of liquid drop is larger than that of ice particle. Collisions of large snow with small drops lead either to the formation of larger snow if the liquid water content in the environment is less than a critical value, or to the formation of graupel/hail otherwise.

Sedimentation

Drop sedimentation is performed separately for each mass bin, so new droplet size distribution forms automatically after diffusion growth, collisions and sedimentation. Fall velocities depend on type of ice particles, their size and altitude (air density) and are taken from empirical relationships (Khain & Pinsky 2018).

Properties of ice particles (density, aspect ratios, fall velocities) are expressed via their mass. It means that the changes of ice properties by deposition/sublimation) are automatically taken into account. Dependencies of particle shape (aspect ratios) of water drops and ice particles allow one to use the output for calculation of polarimetric radar signatures. A breakup of the largest snowflakes is calculated with probability increasing with snowflake size.

The decrease in the masses of bins in ice particles by melting and the increase in mass of the corresponding drop bins by melting is calculated by prescribing the characteristic melting time scales, which depend on the ice particles type and bin number (i.e. particle size). The smallest melting time scale is assumed for snow and the largest time scale is assumed for hail. No shading is assumed in this SBM version.