

Immersion freezing in particle-based aerosol-cloud microphysics: a probabilistic perspective on singular and time-dependent models

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stonybrook.edu

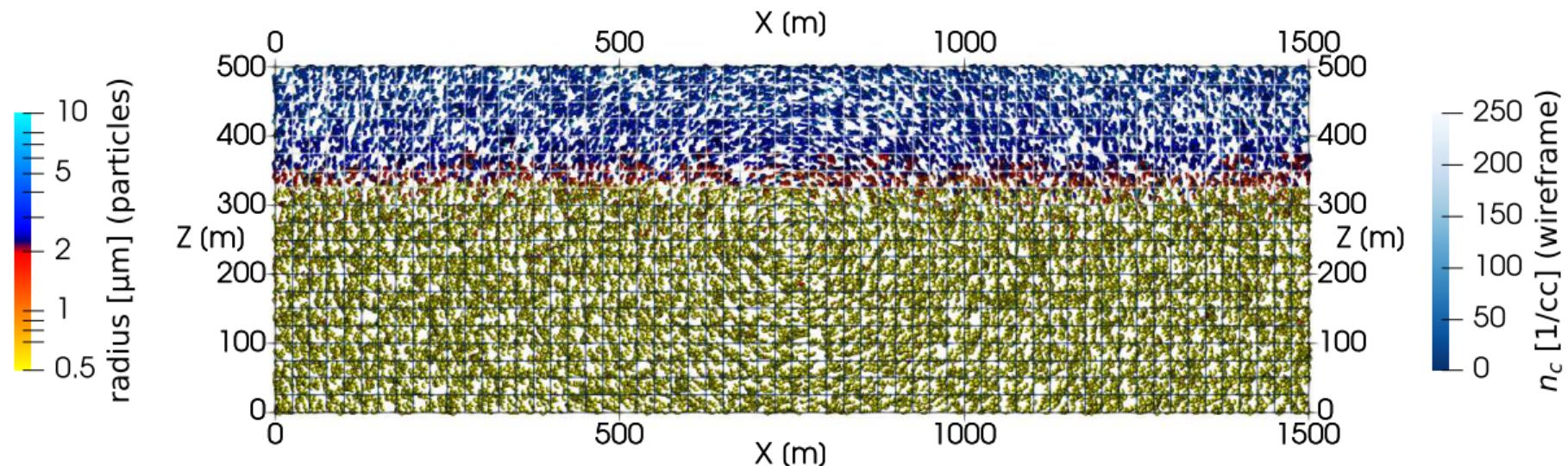


2023 ARM/ASR Joint User Facility/PI Meeting, Rockville, MD

Breakout session: Primary and secondary ice production and impacts on mixed-phase and ice clouds

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

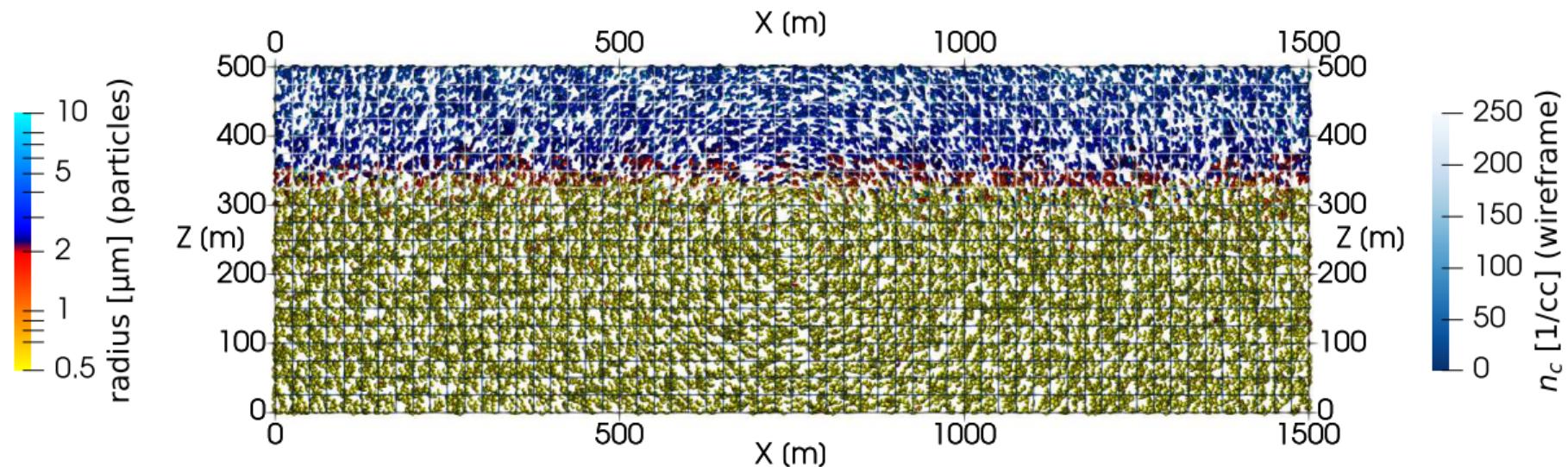
Time: 30 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

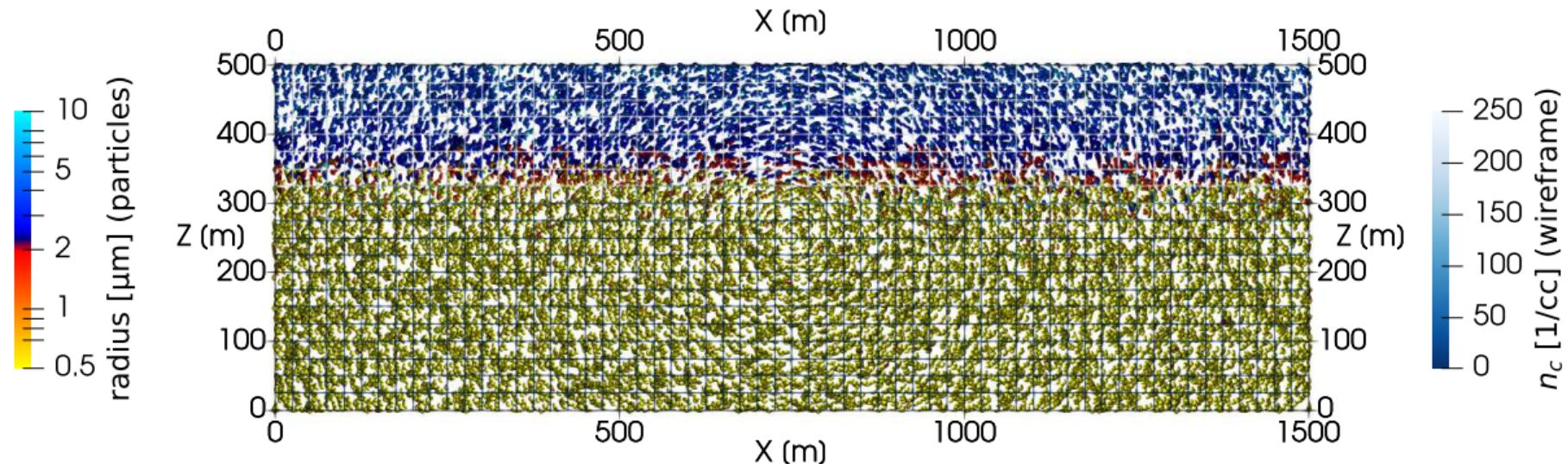
Time: 60 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

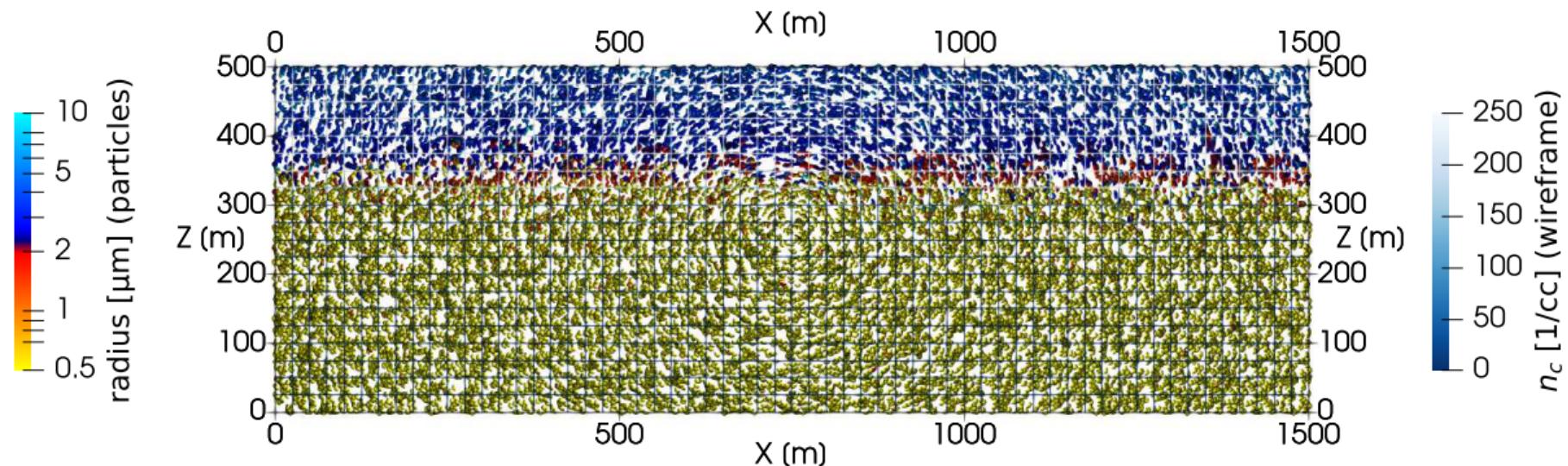
Time: 90 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

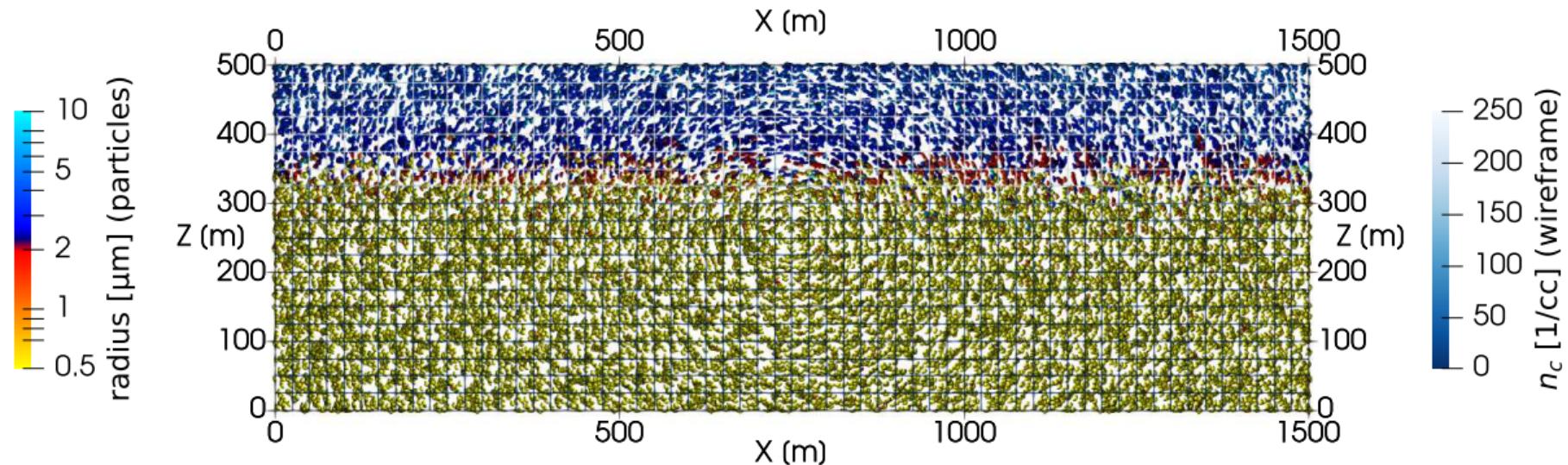
Time: 120 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

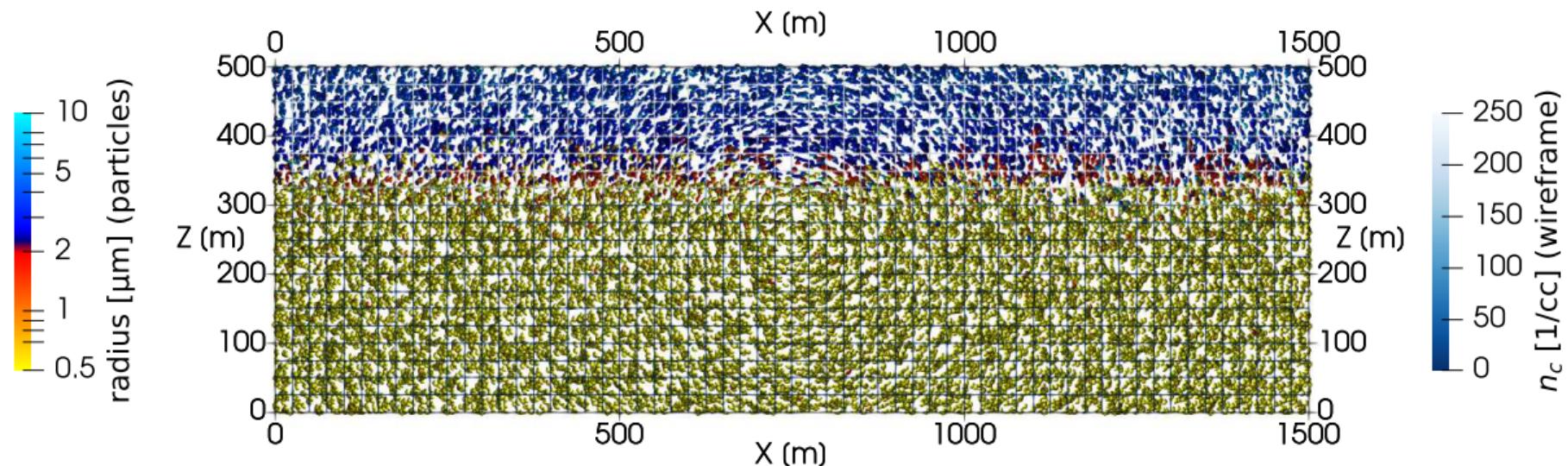
Time: 150 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

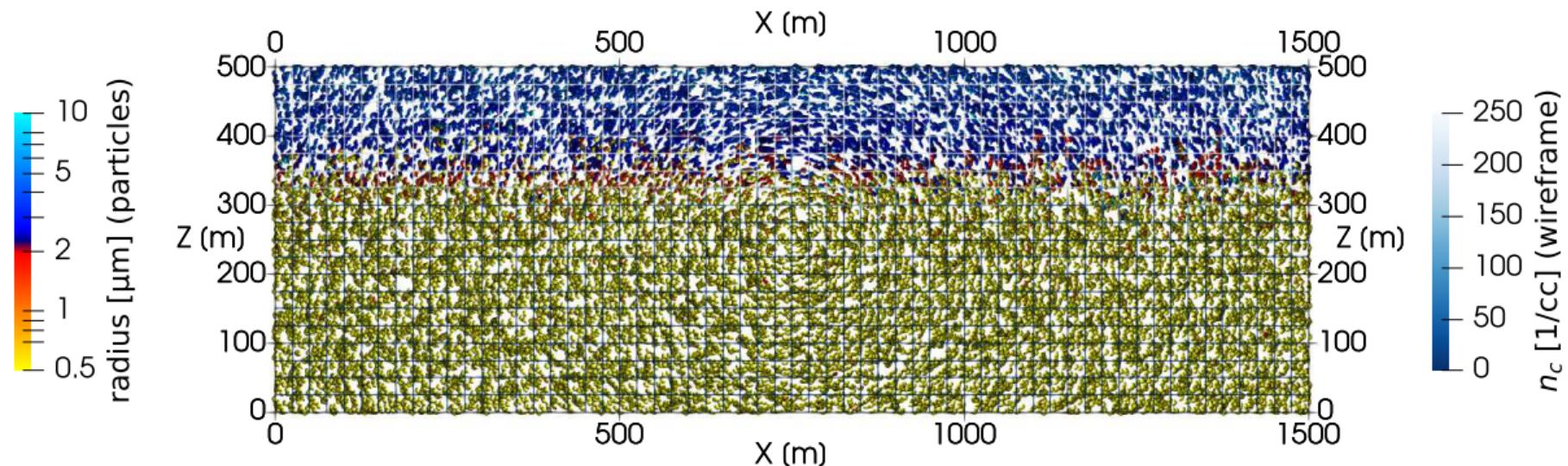
Time: 180 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

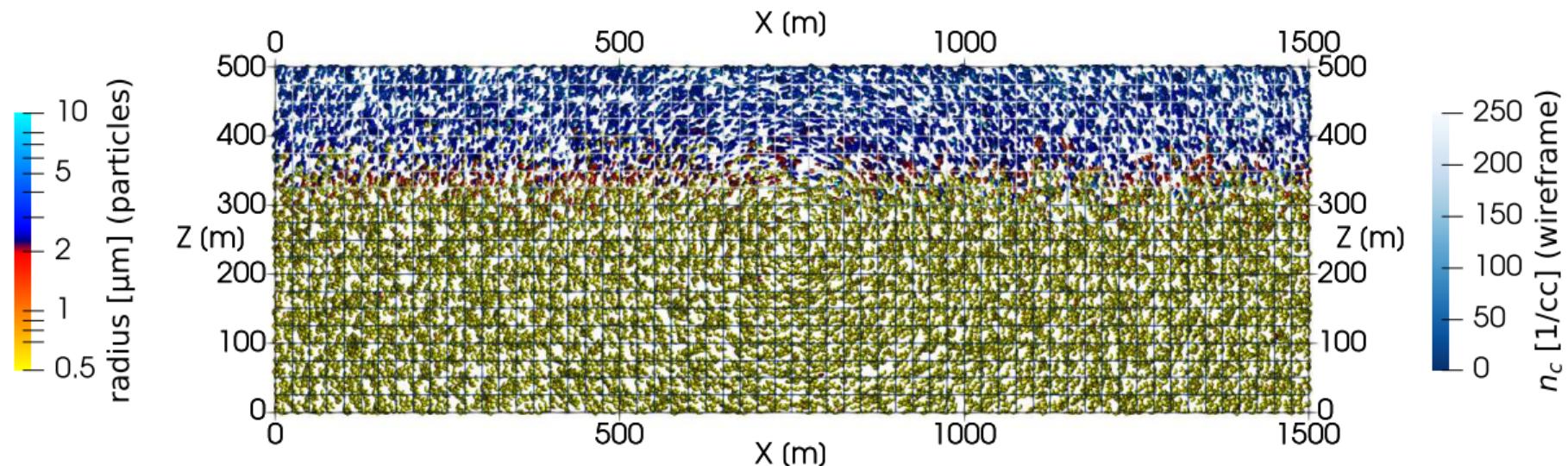
Time: 210 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

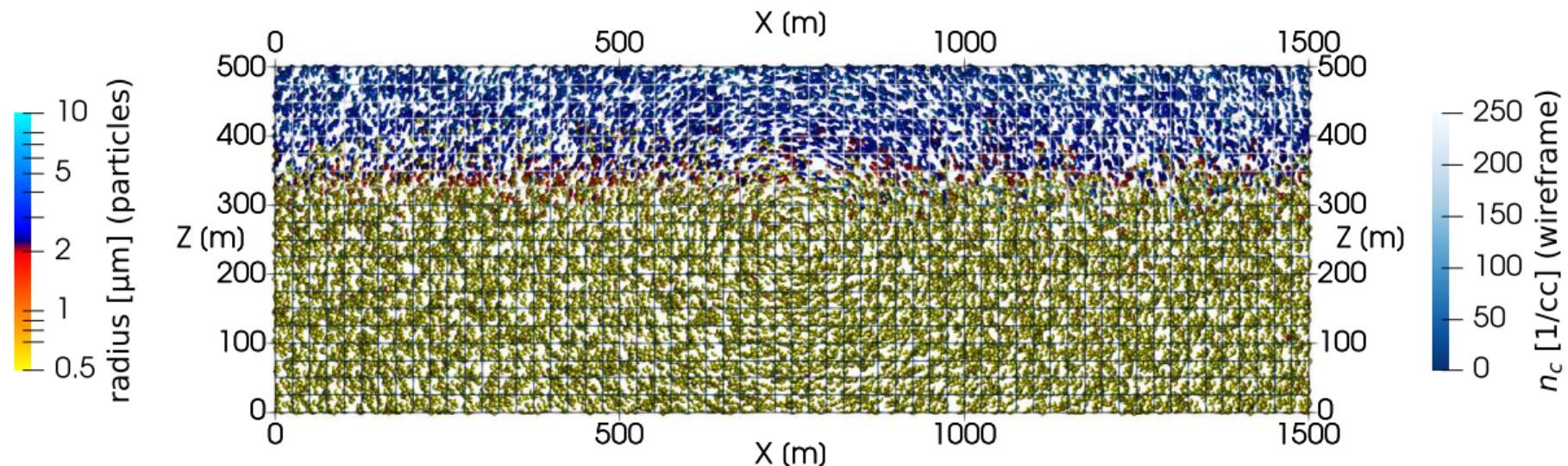
Time: 240 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

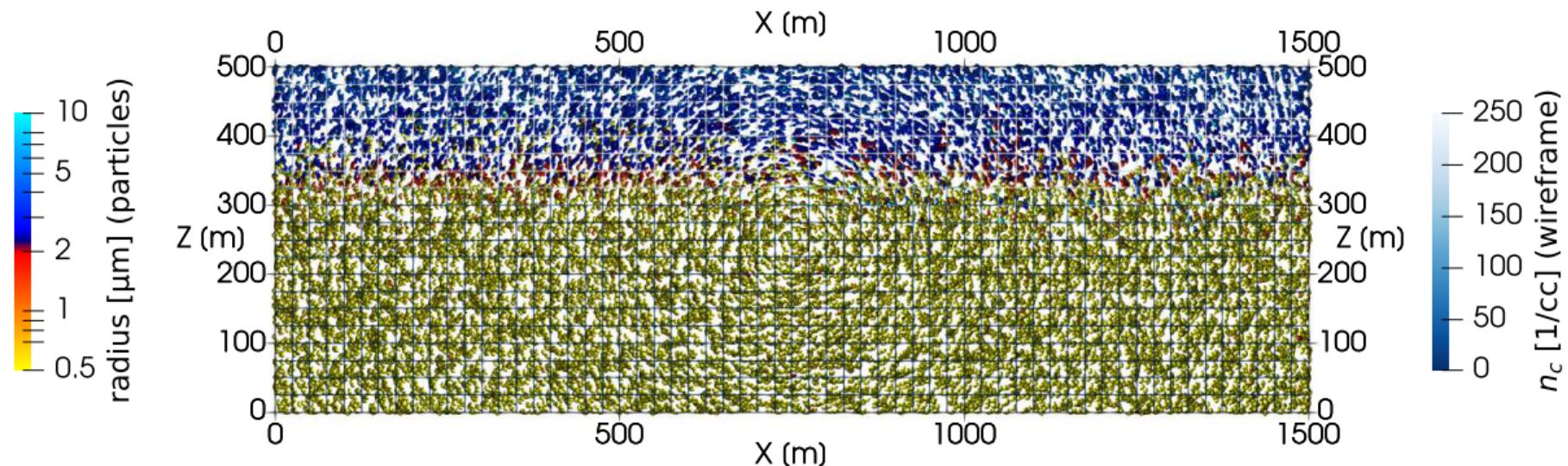
Time: 270 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

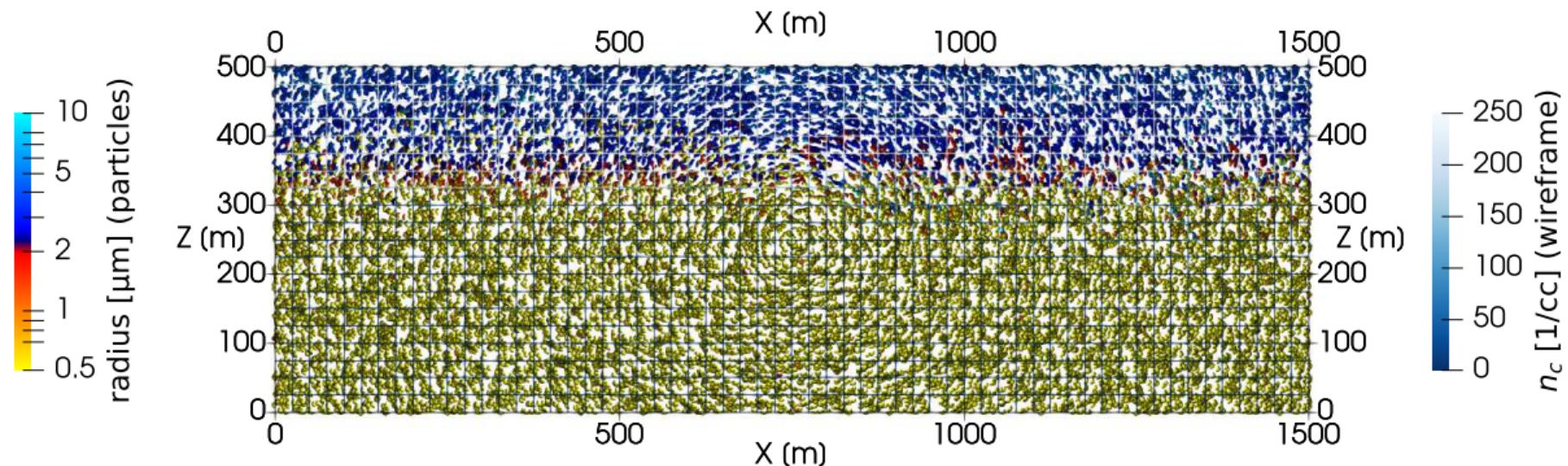
Time: 300 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

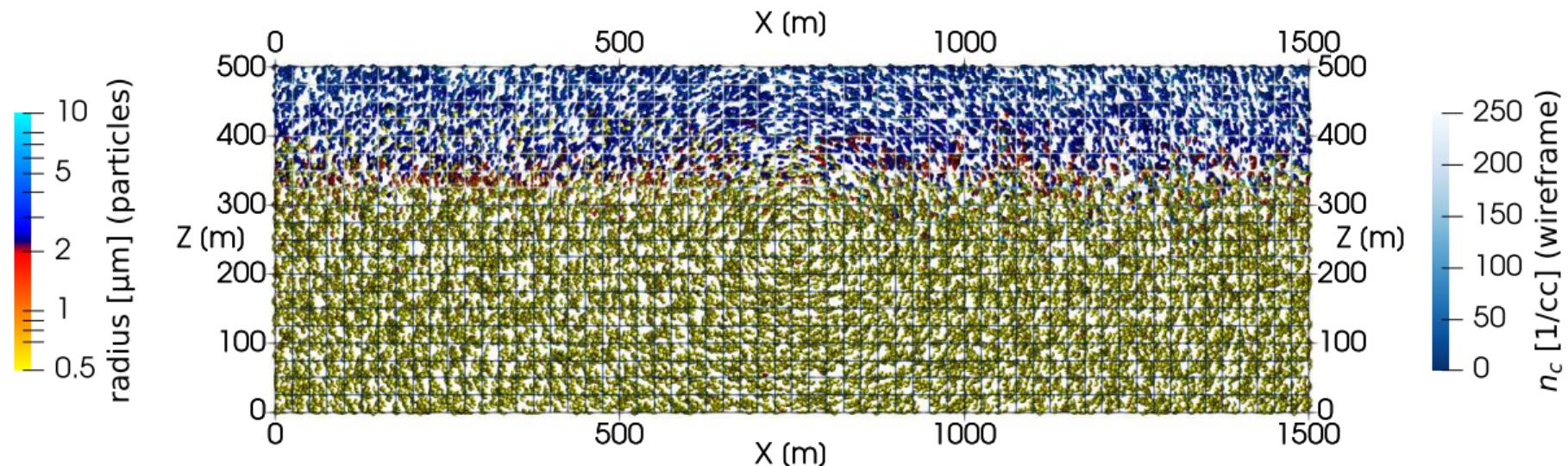
Time: 330 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

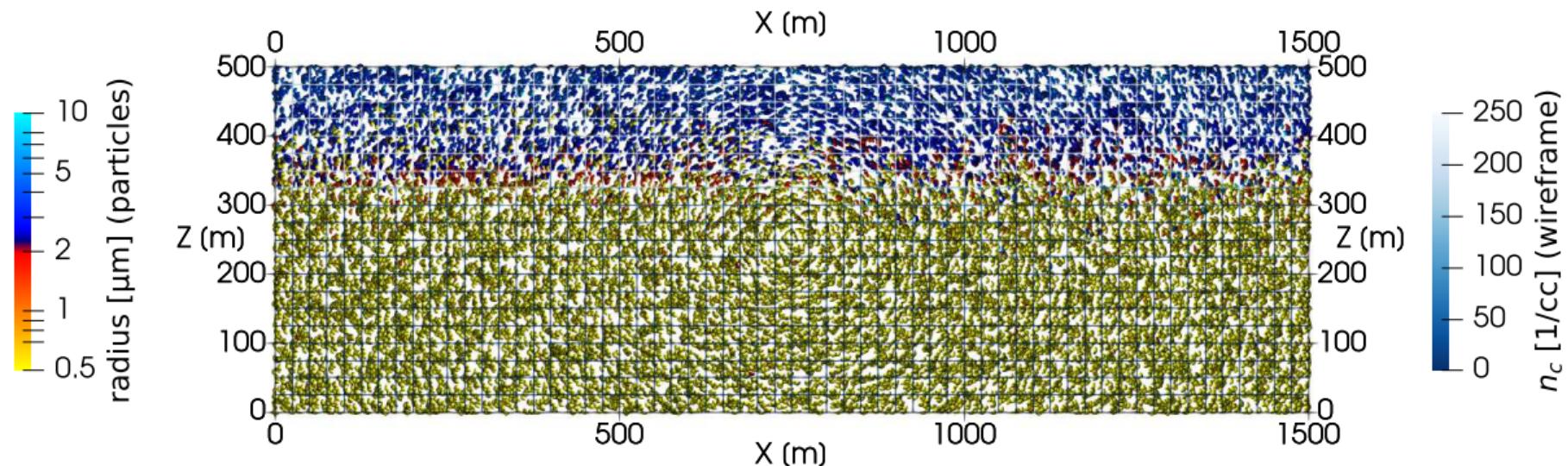
Time: 360 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

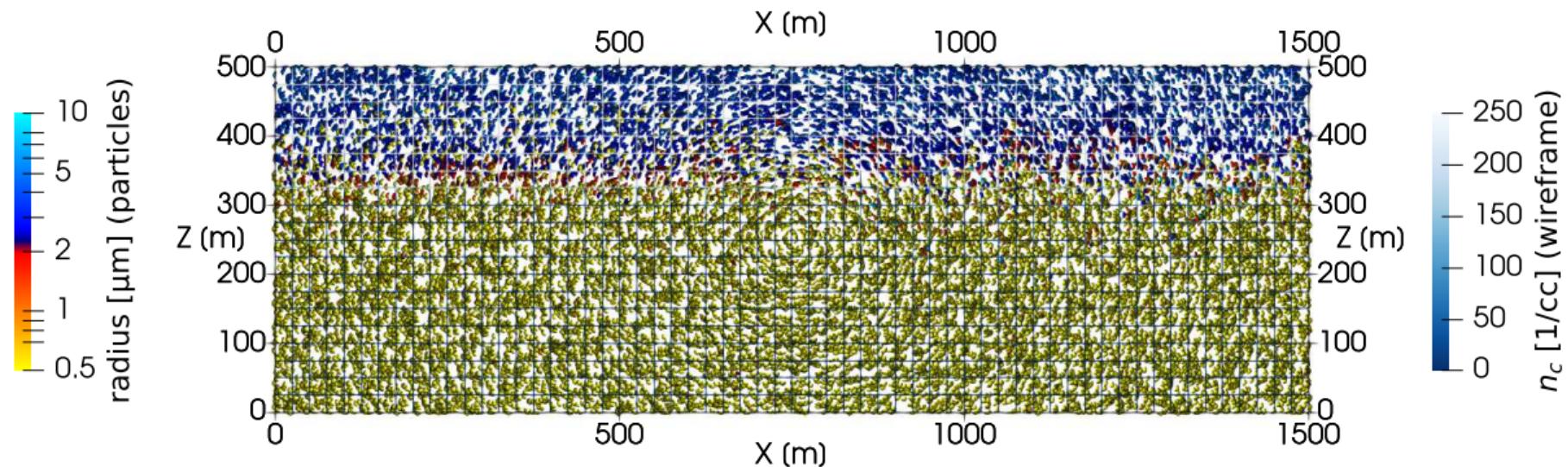
Time: 390 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

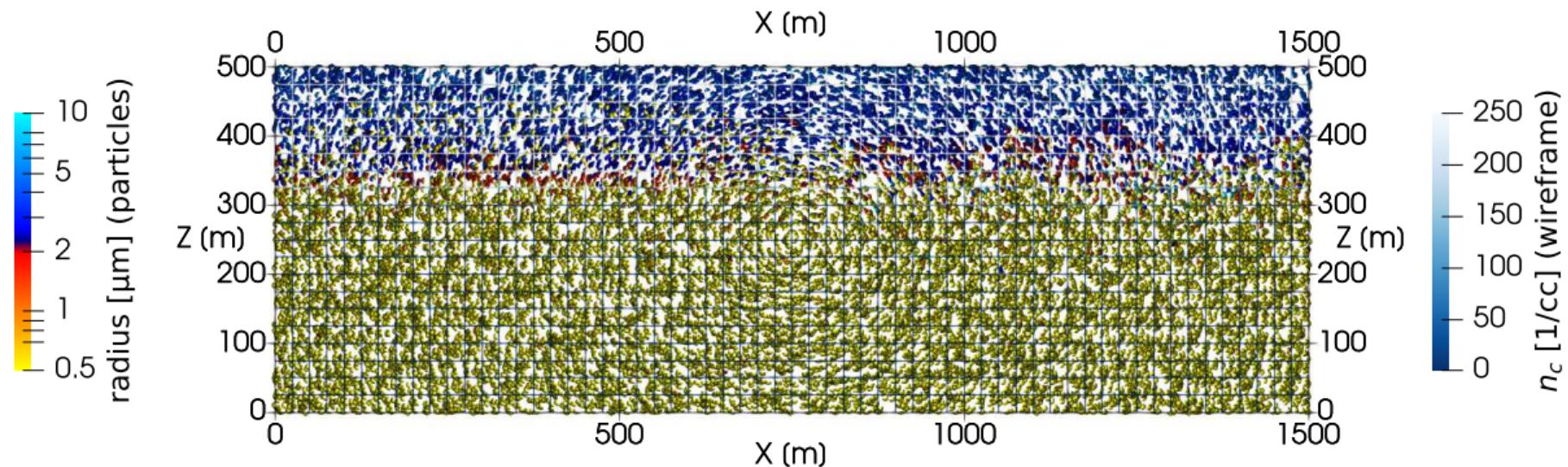
Time: 420 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

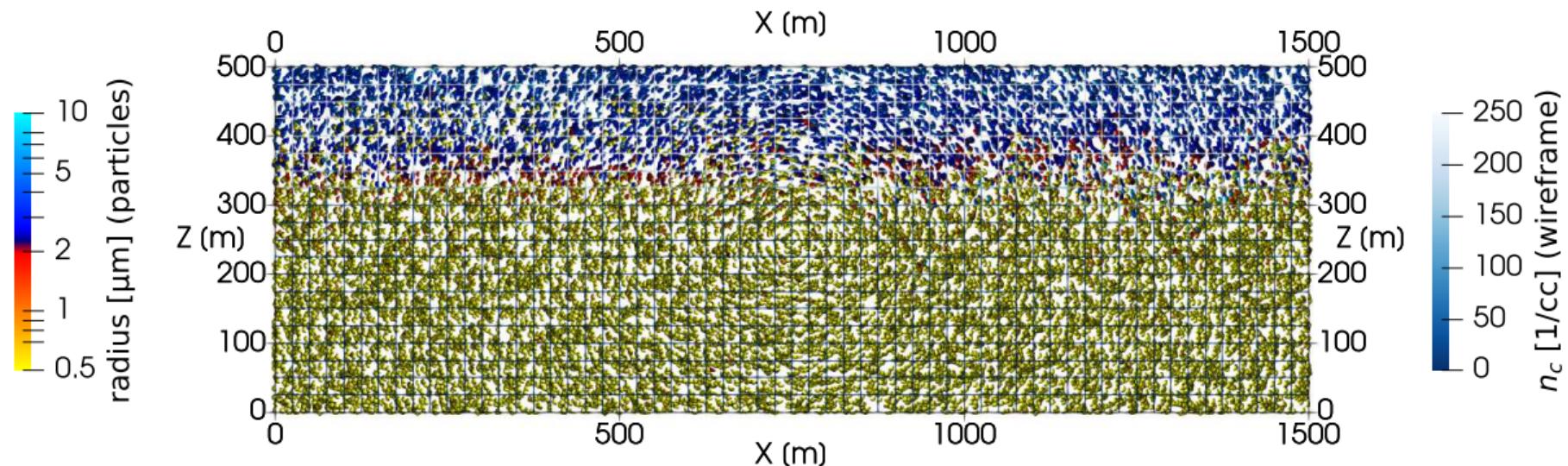
Time: 450 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

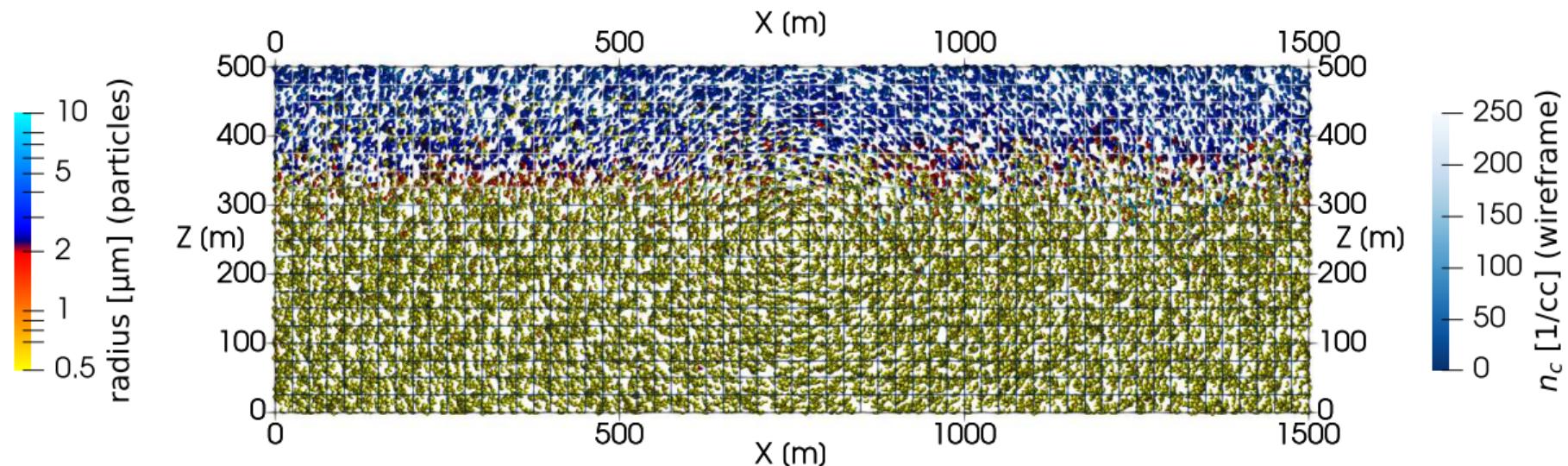
Time: 480 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

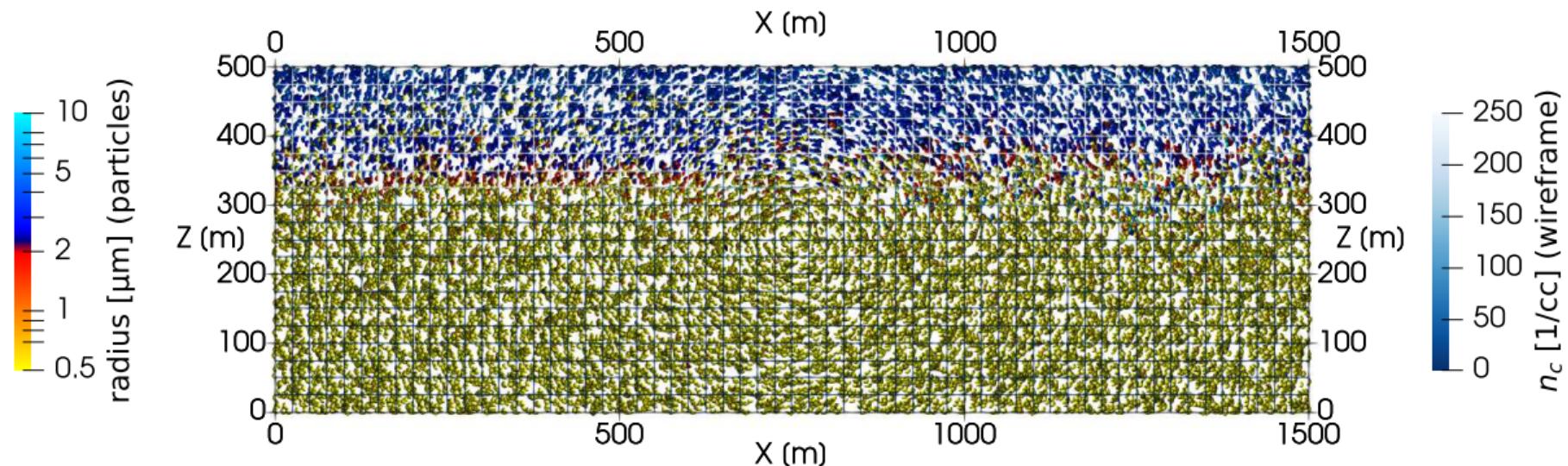
Time: 510 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

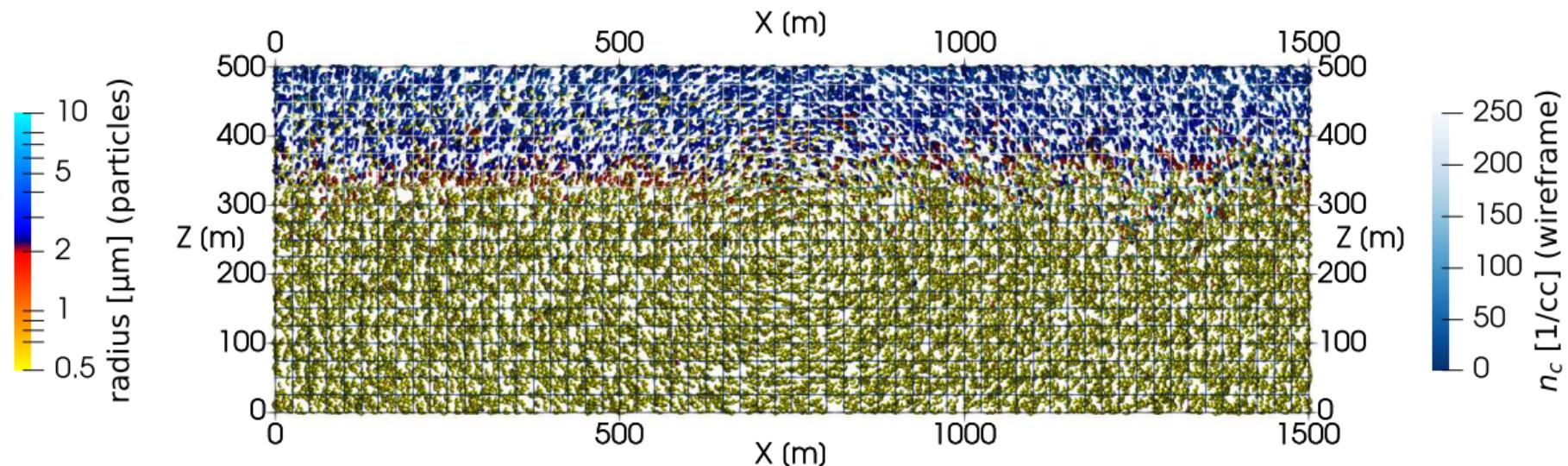
Time: 540 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

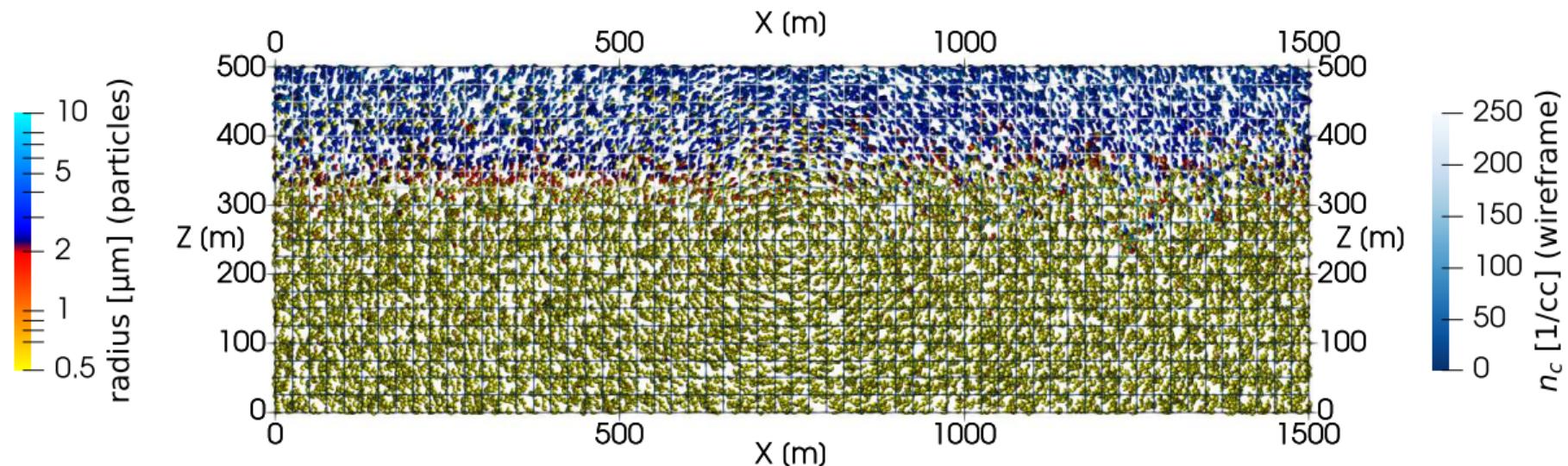
Time: 570 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

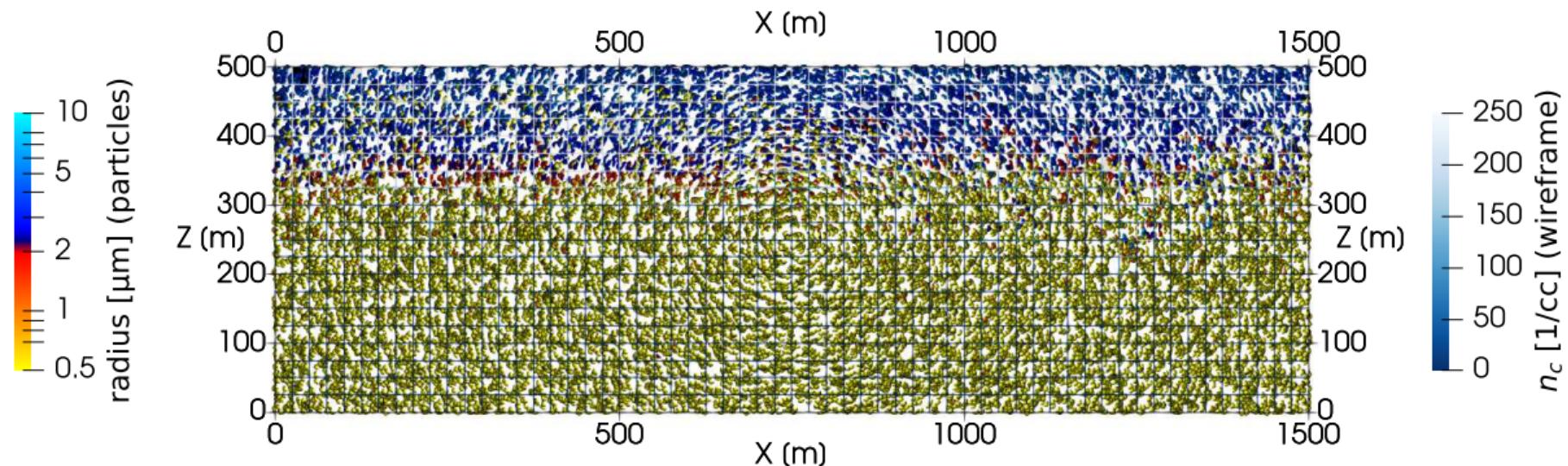
Time: 600 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

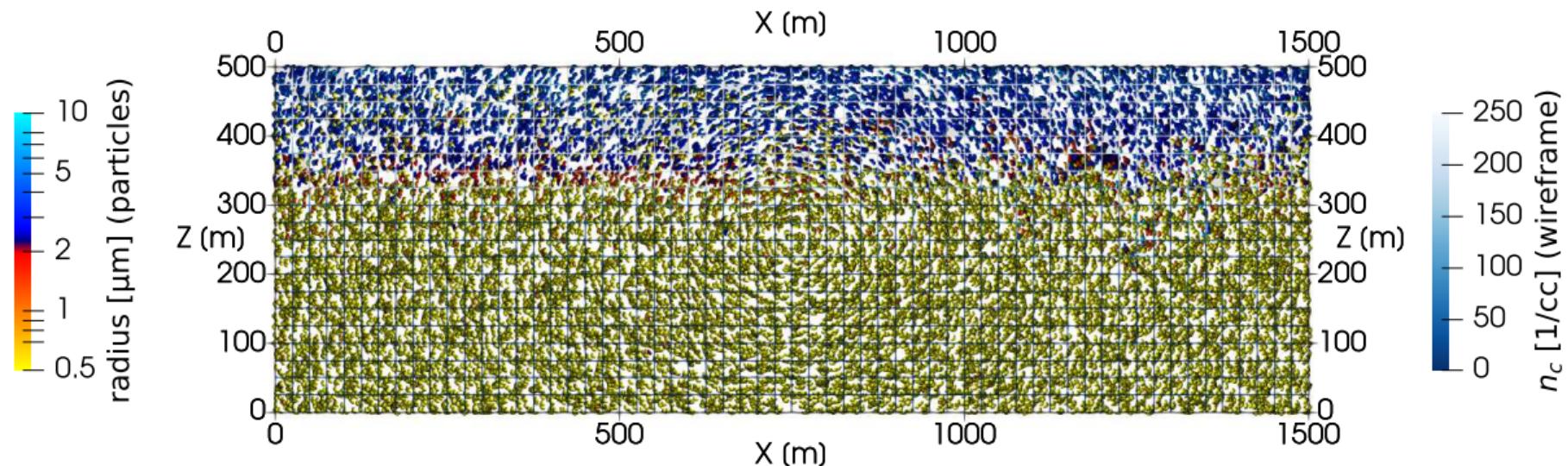
Time: 630 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

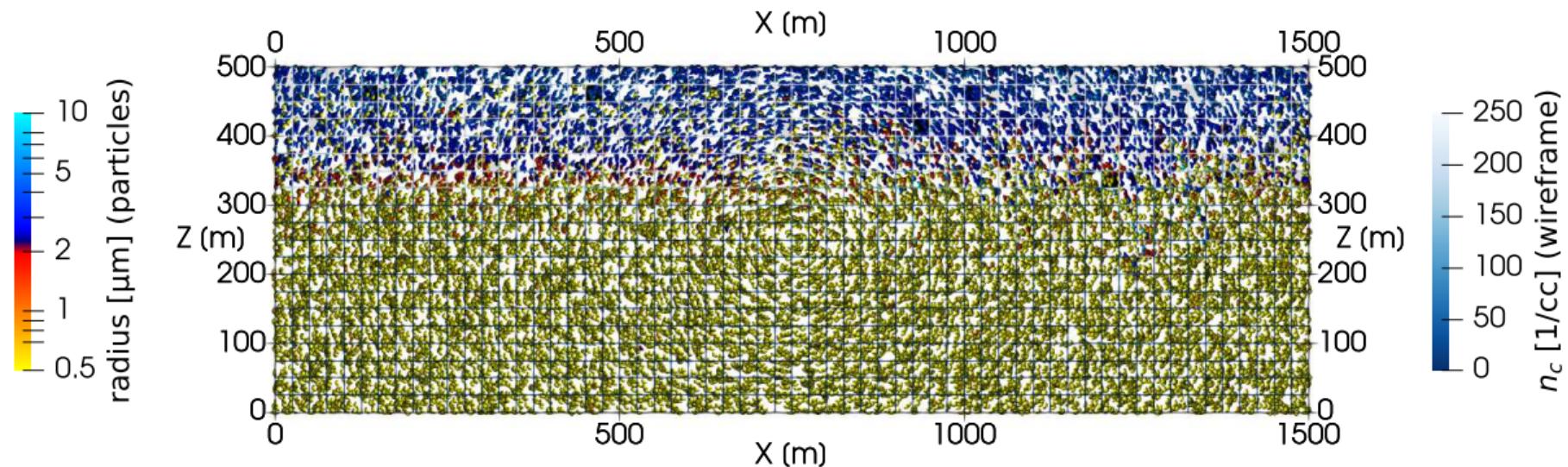
Time: 660 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

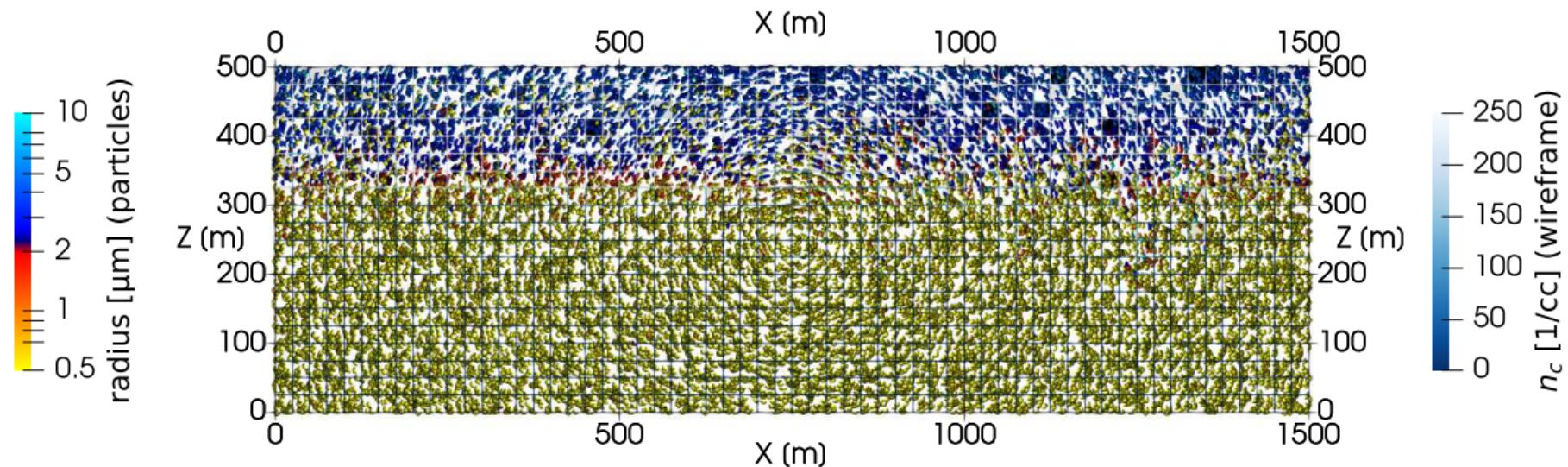
Time: 690 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

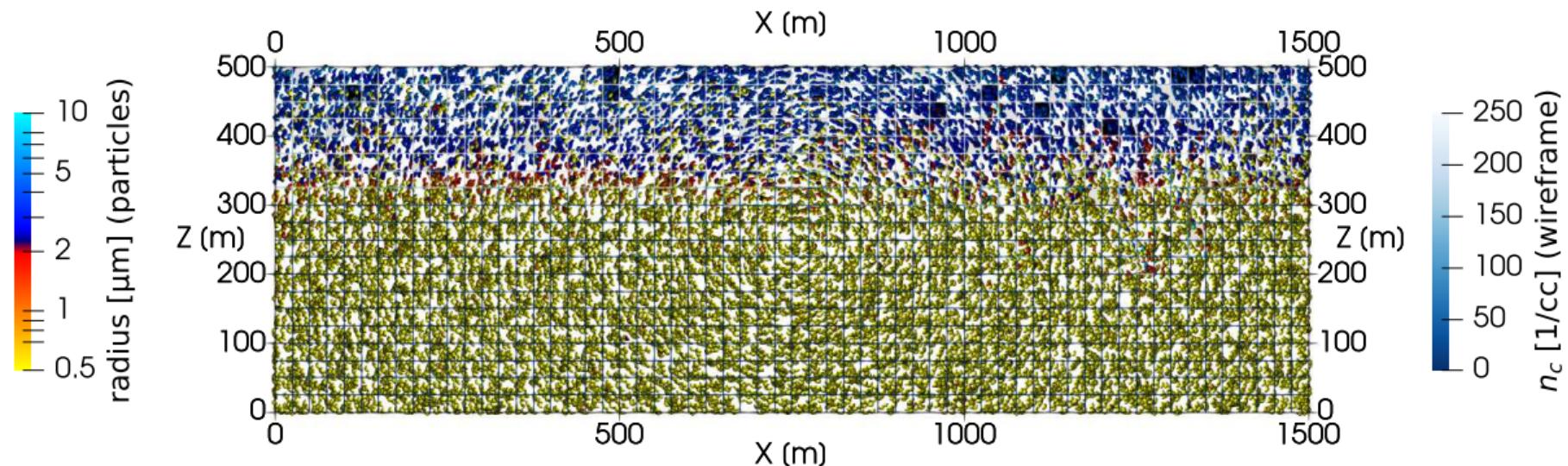
Time: 720 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

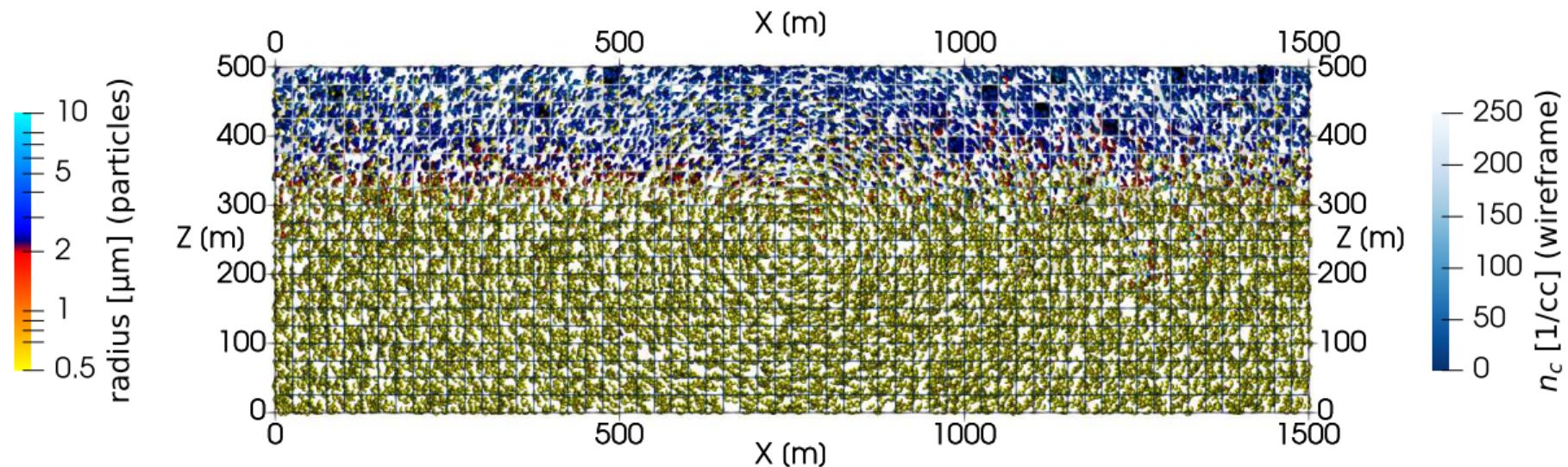
Time: 750 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

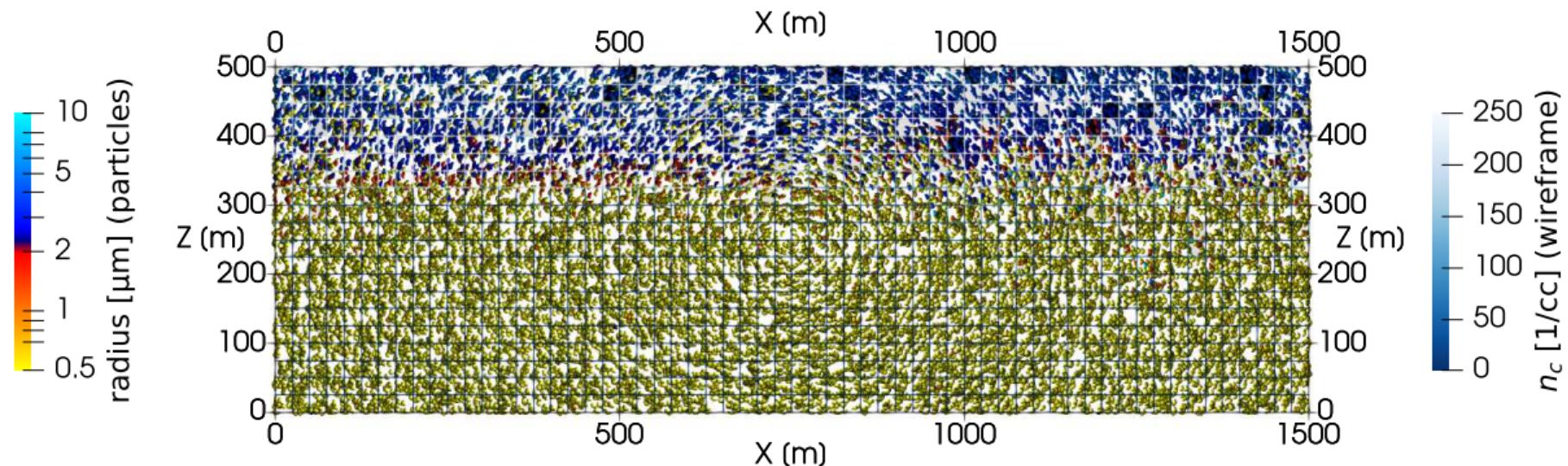
Time: 780 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

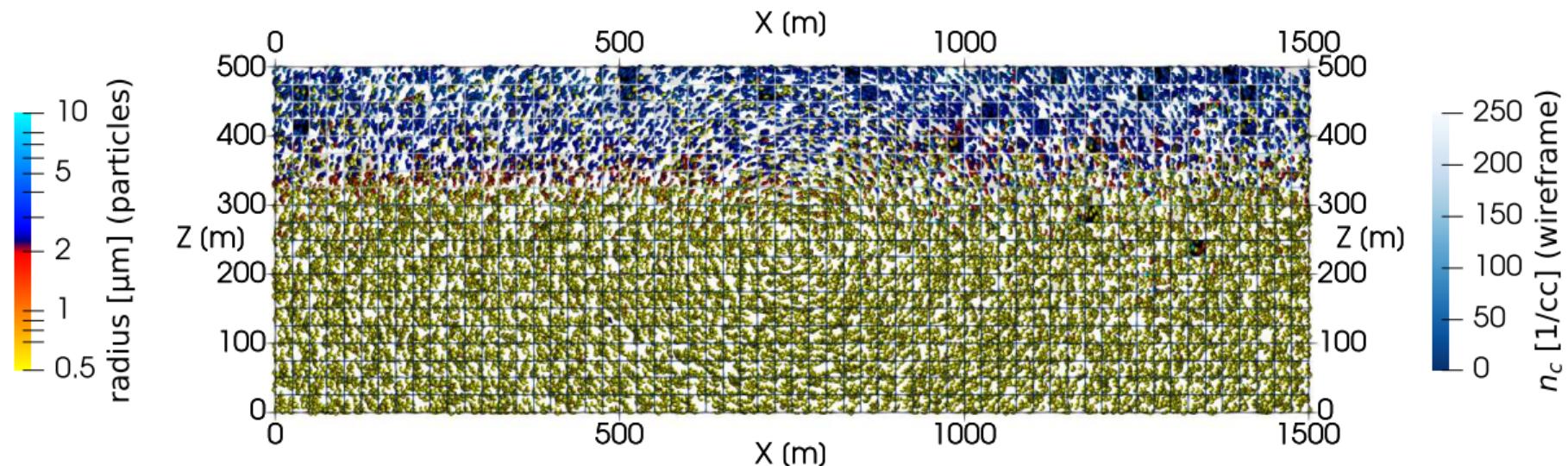
Time: 810 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

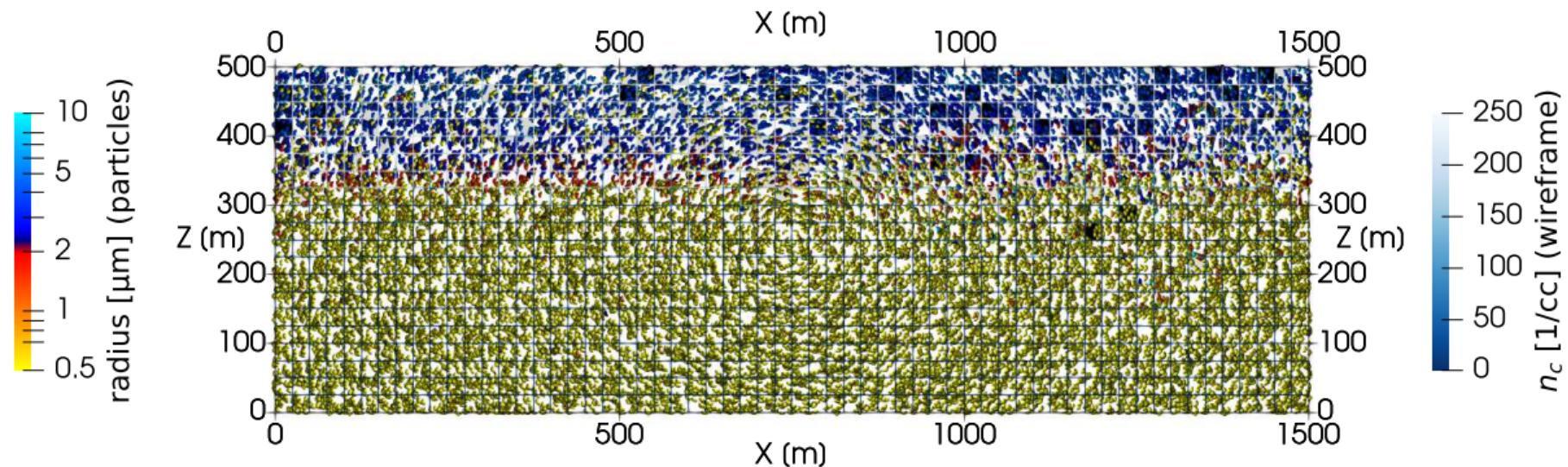
Time: 840 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

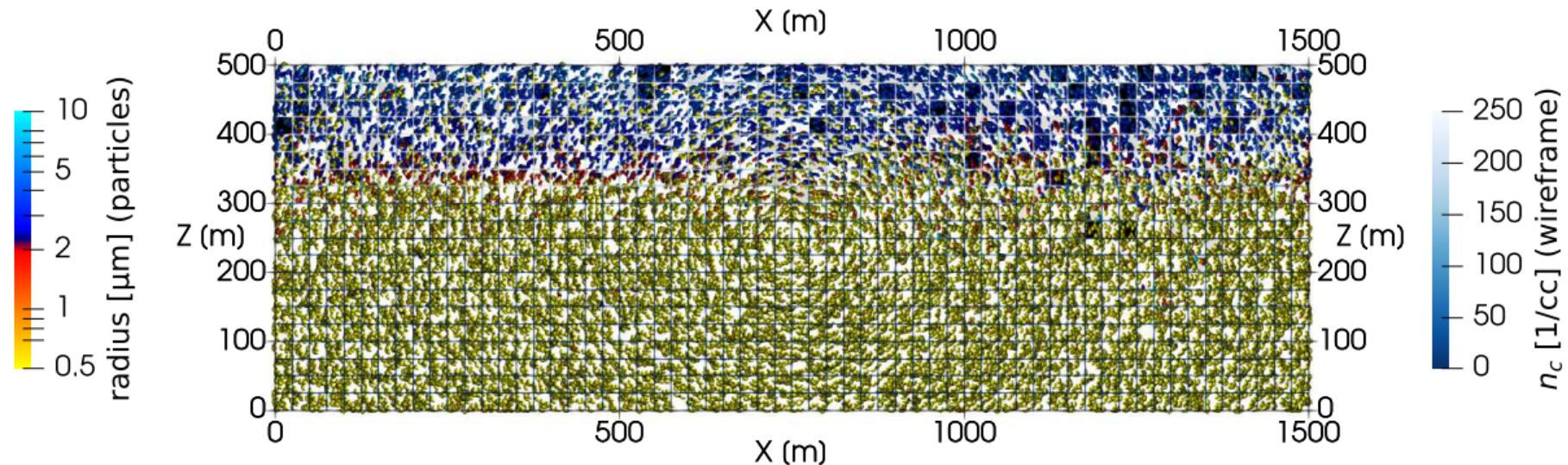
Time: 870 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

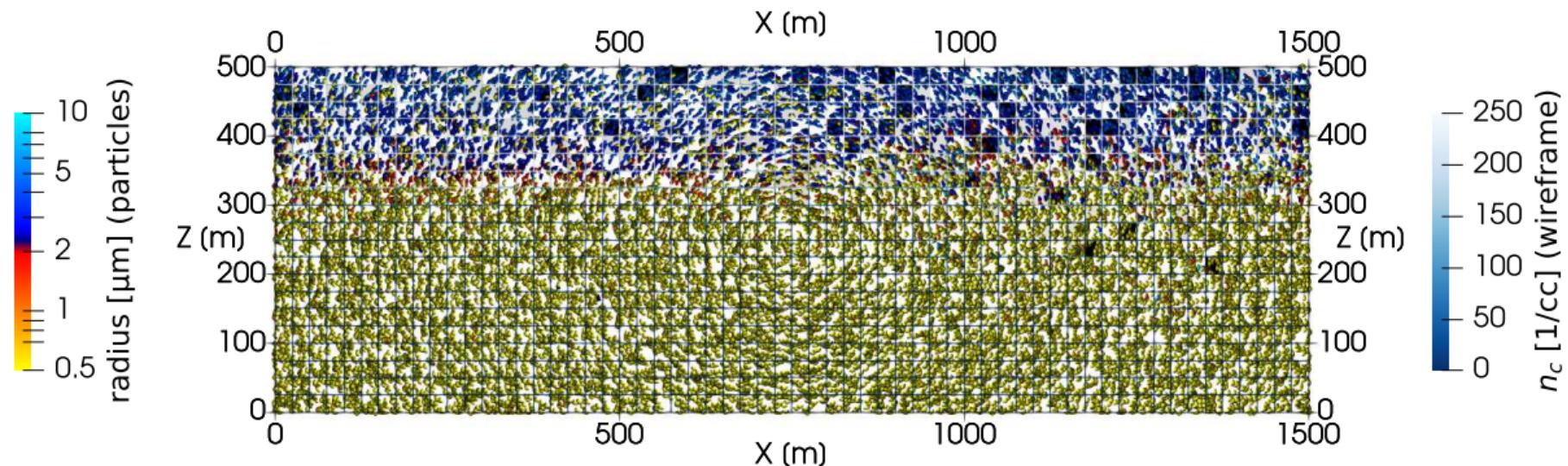
Time: 900 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
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particle-based probabilistic aerosol-cloud μ -physics (super droplets)

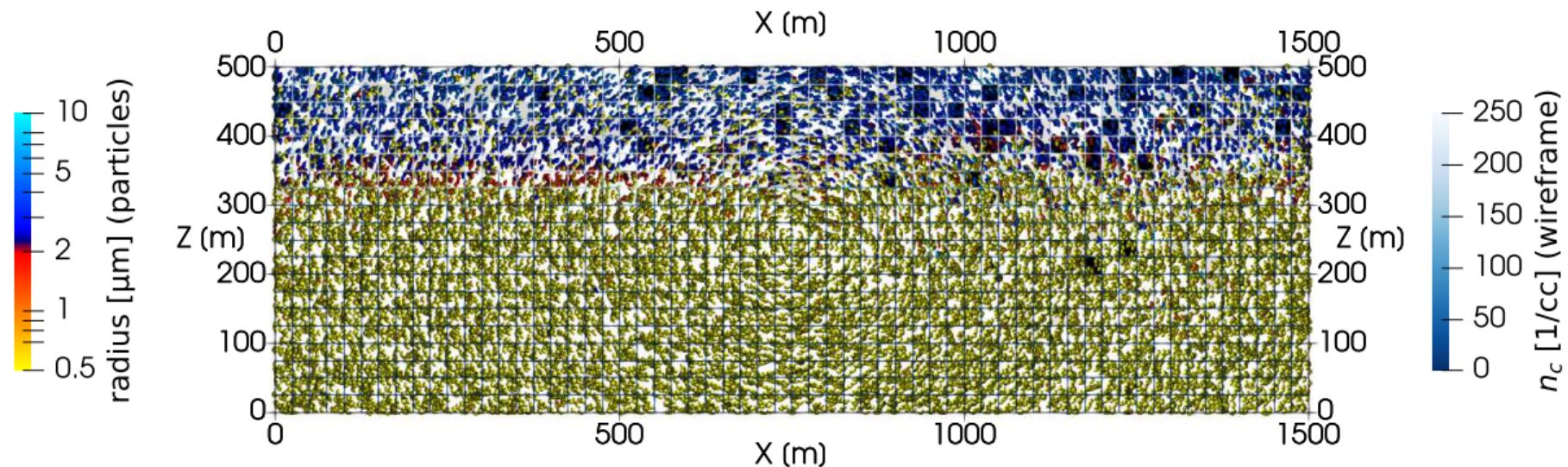
Time: 930 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

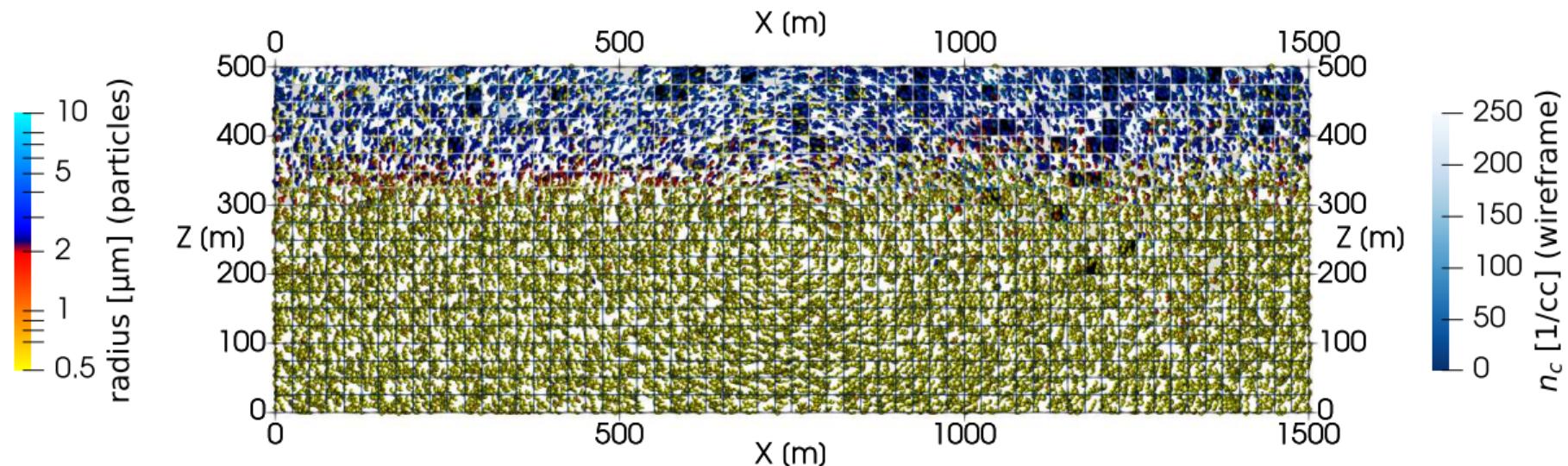
Time: 960 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

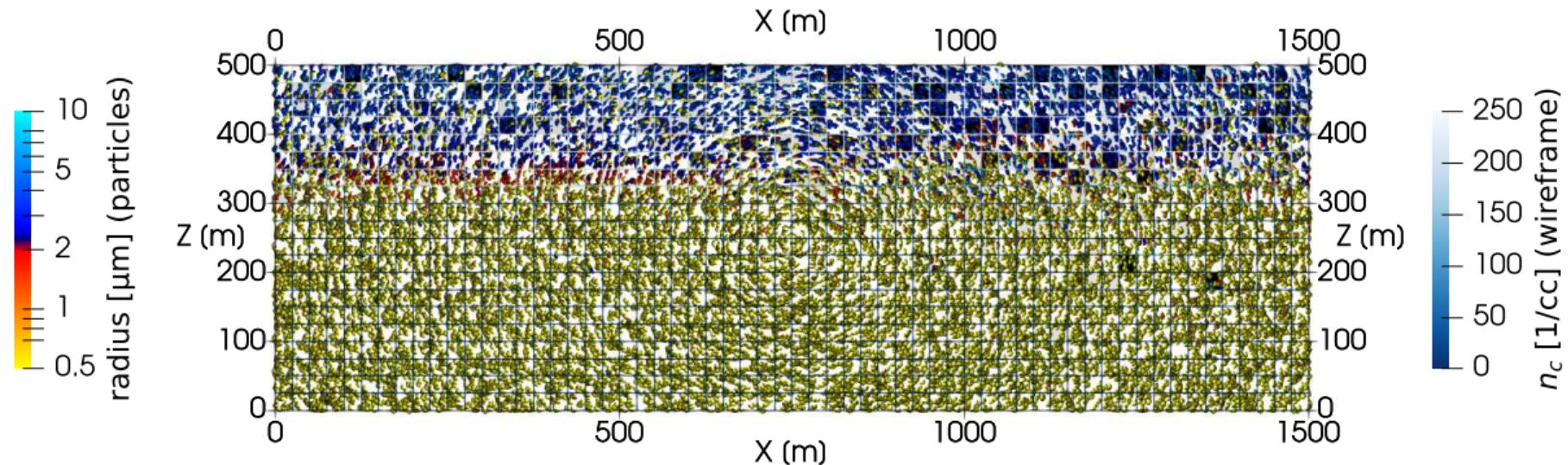
Time: 990 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
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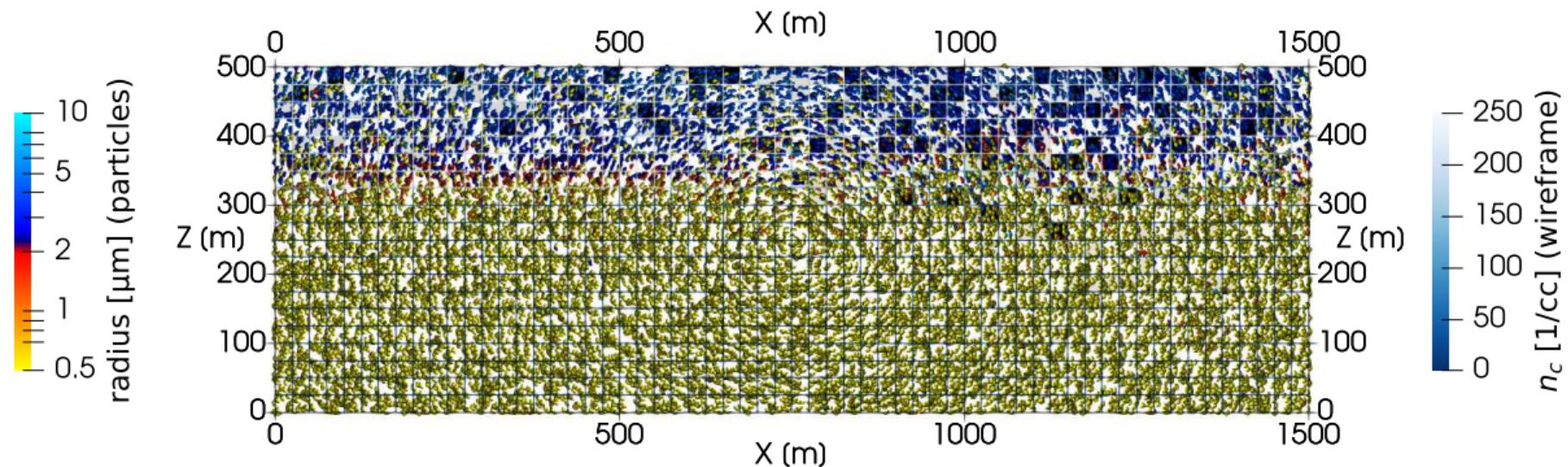
Time: 1020 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
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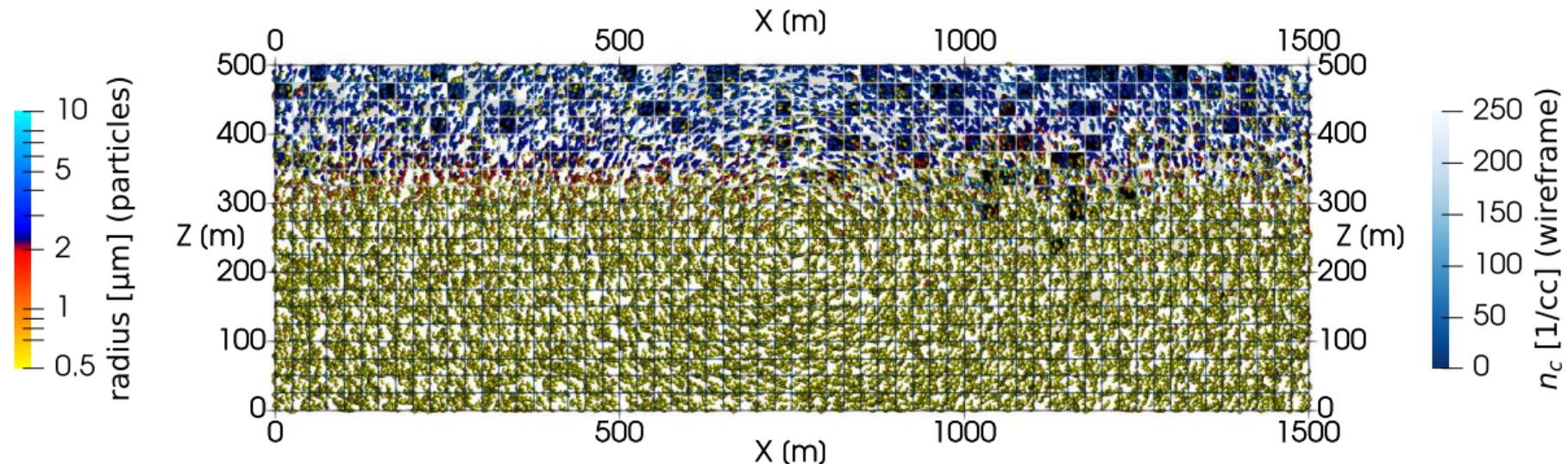
Time: 1050 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
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particle-based probabilistic aerosol-cloud μ -physics (super droplets)

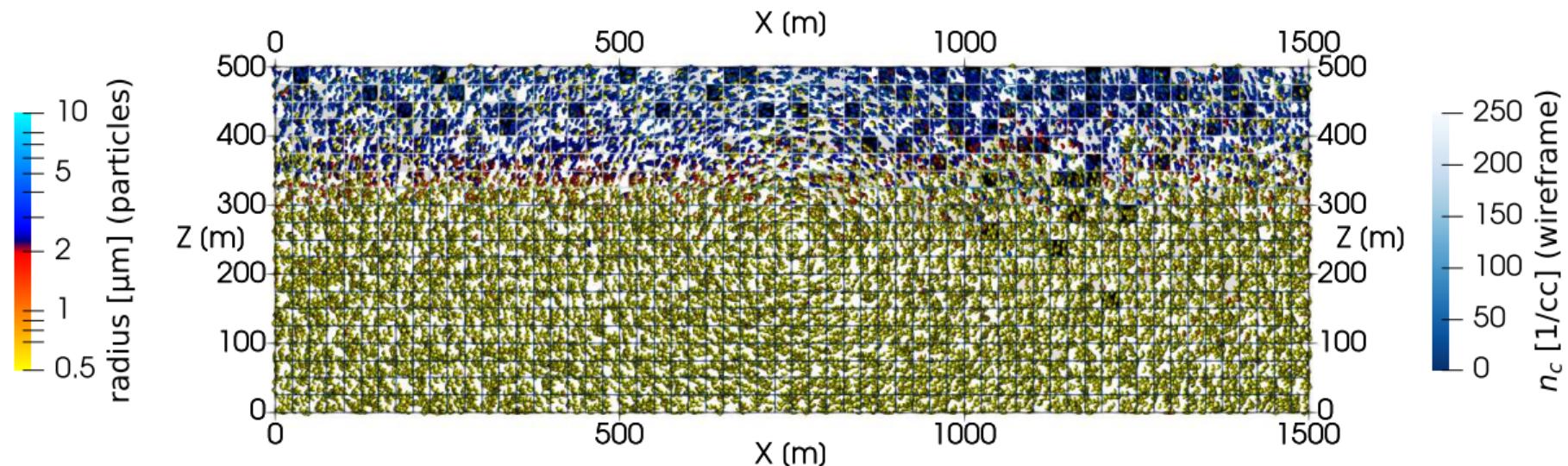
Time: 1080 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

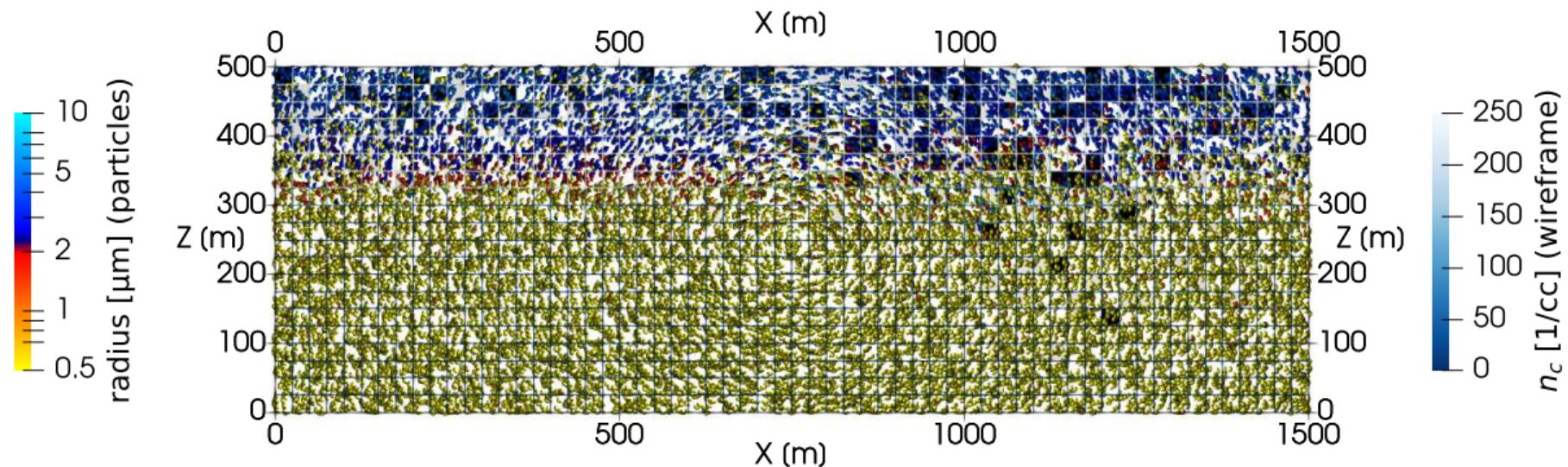
Time: 1110 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

particle-based probabilistic aerosol-cloud μ -physics (super droplets)

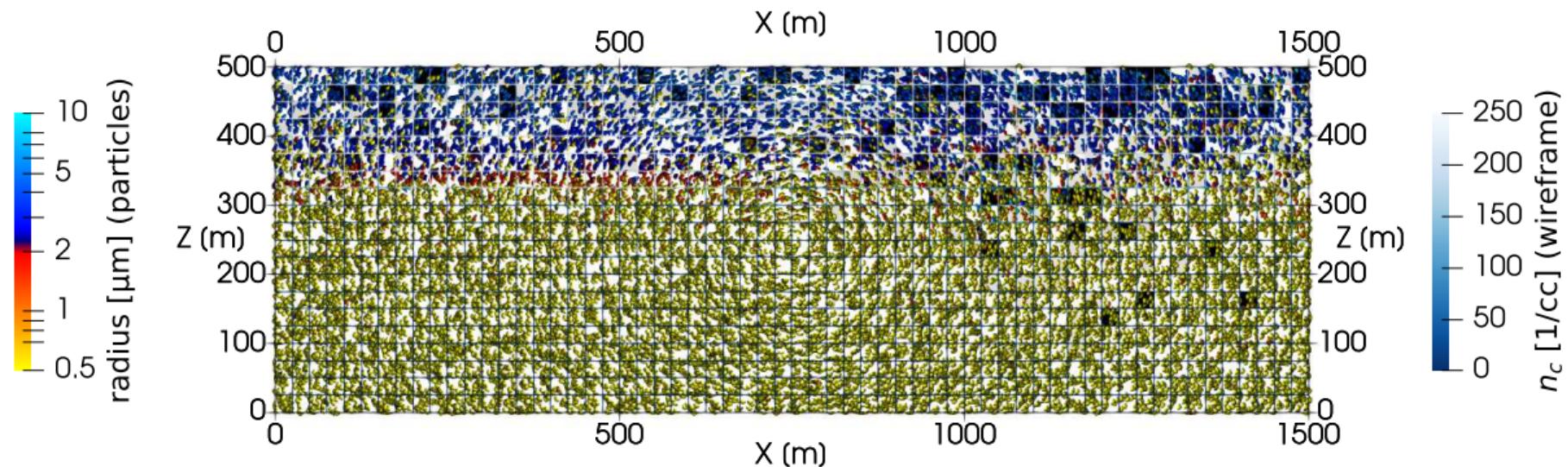
Time: 1140 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
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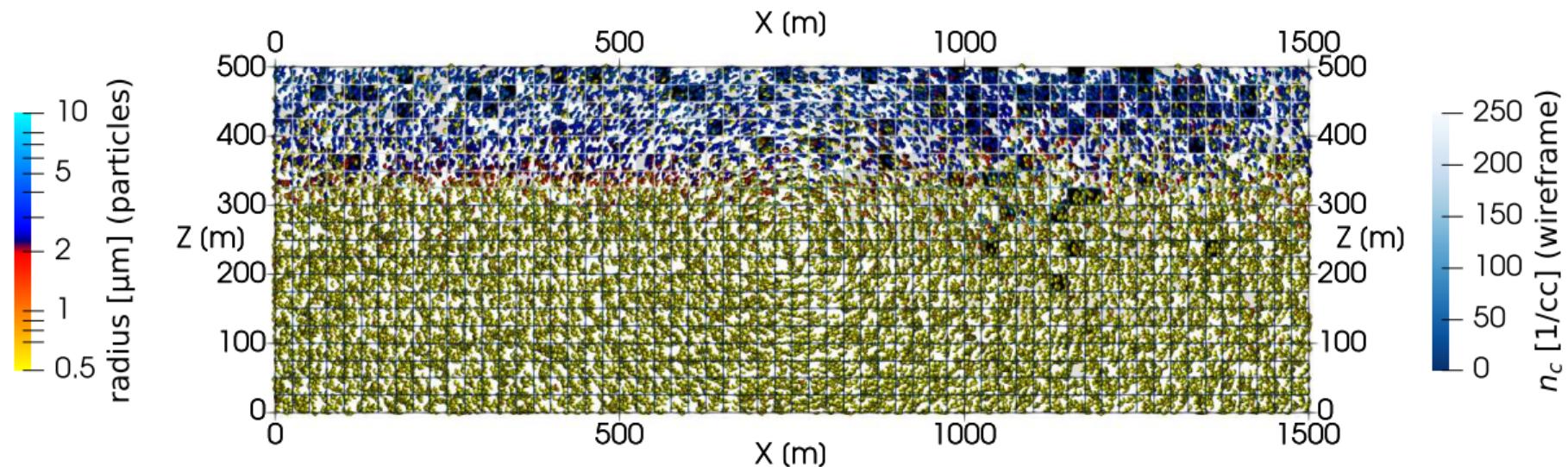
Time: 1170 s (spin-up till 600.0 s)



16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \mu\text{m}$, $\sigma_g = 2.55$)
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particle-based probabilistic aerosol-cloud μ -physics (super droplets)

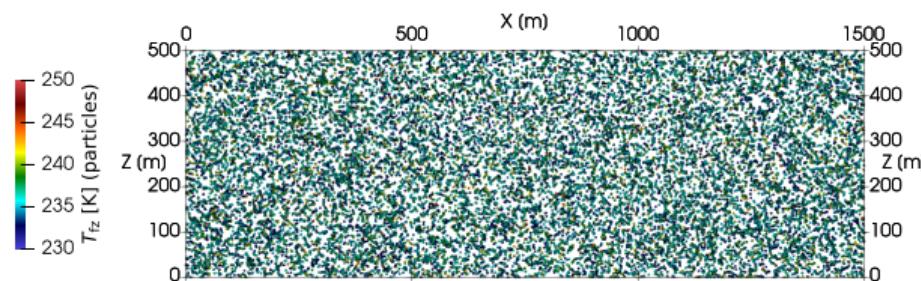
Time: 1200 s (spin-up till 600.0 s)



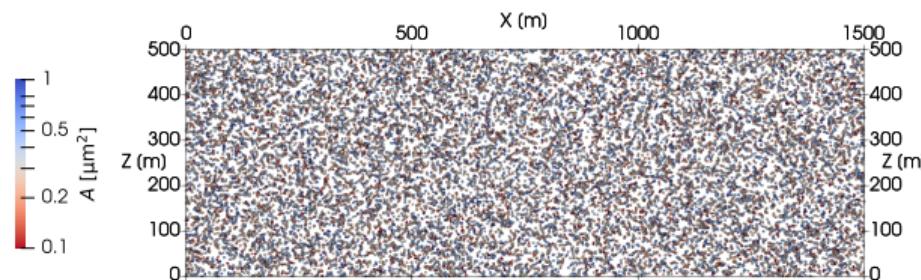
16+16 super-particles/cell for INP-rich + INP-free particles
 $N_{\text{aer}} = 300/\text{cc}$ (two-mode lognormal) $N_{\text{INP}} = 150/L$ (lognormal, $D_g = 0.74 \text{ } \mu\text{m}$, $\sigma_g = 2.55$)
spin-up = freezing off; subsequently frozen particles act as tracers

Monte-Carlo immersion freezing: singular vs. time-dependent

singular Monte-Carlo (as in Shima et al. '20)



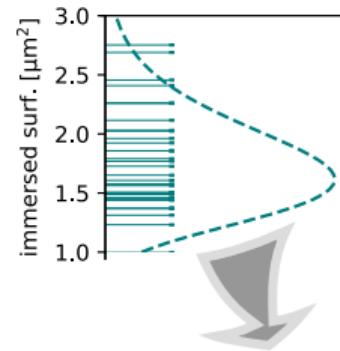
time-dependent Monte-Carlo (as in Alpert & Knopf '16)



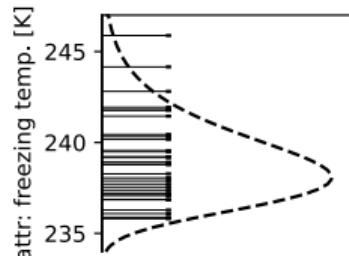
Monte-Carlo immersion freezing: singular vs. time-dependent

particle attribute sampling

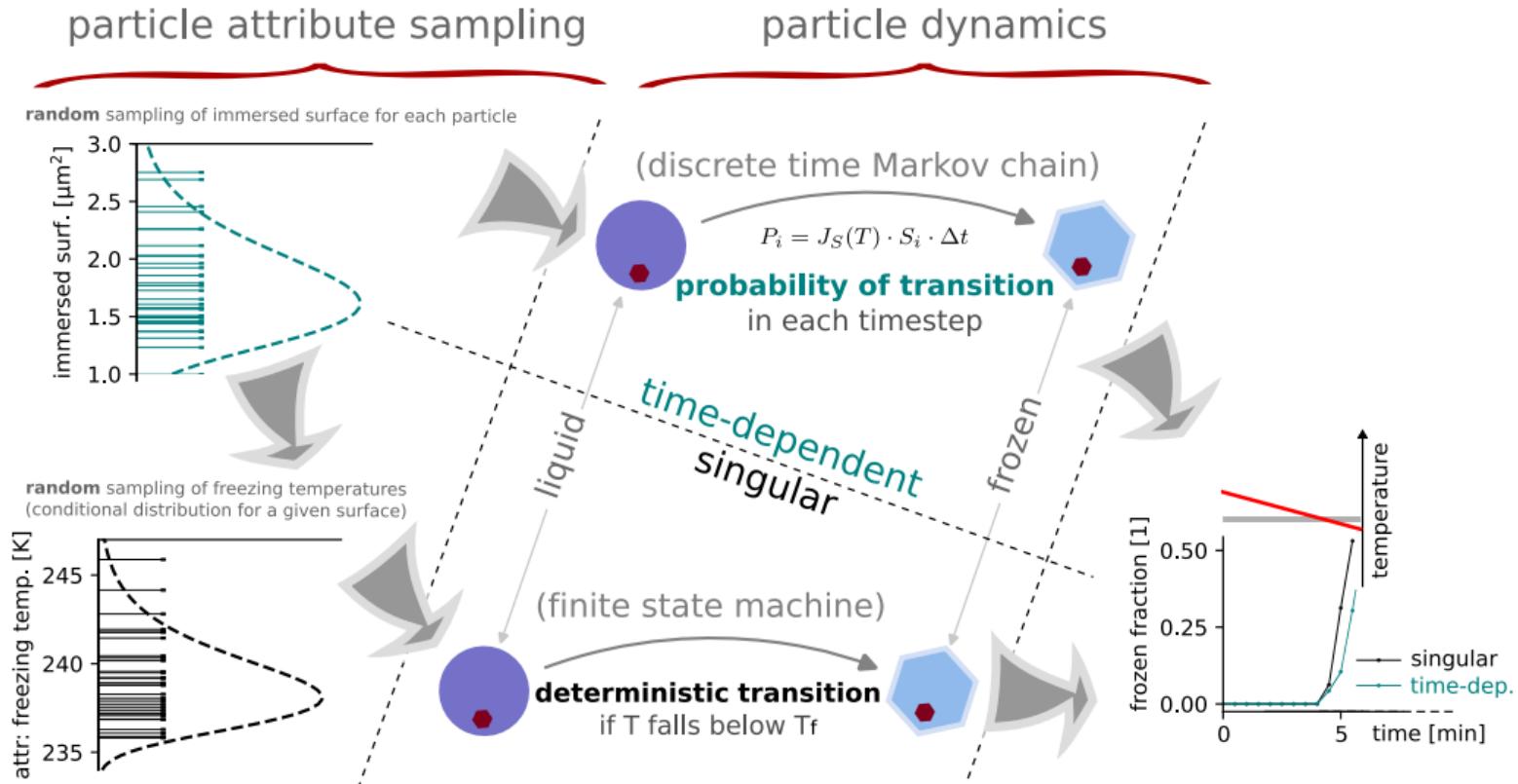
random sampling of immersed surface for each particle



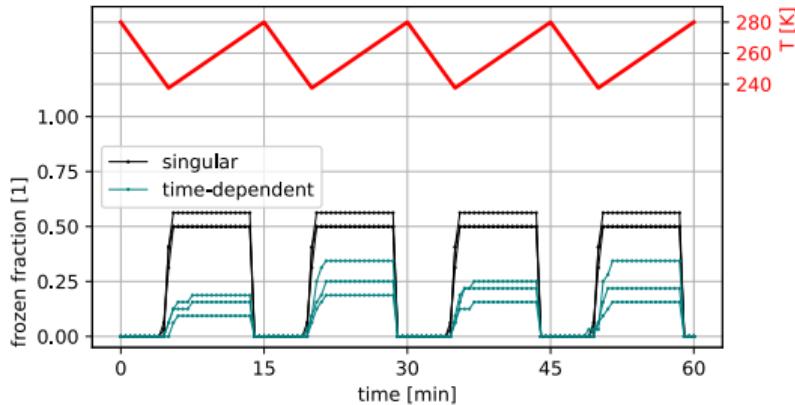
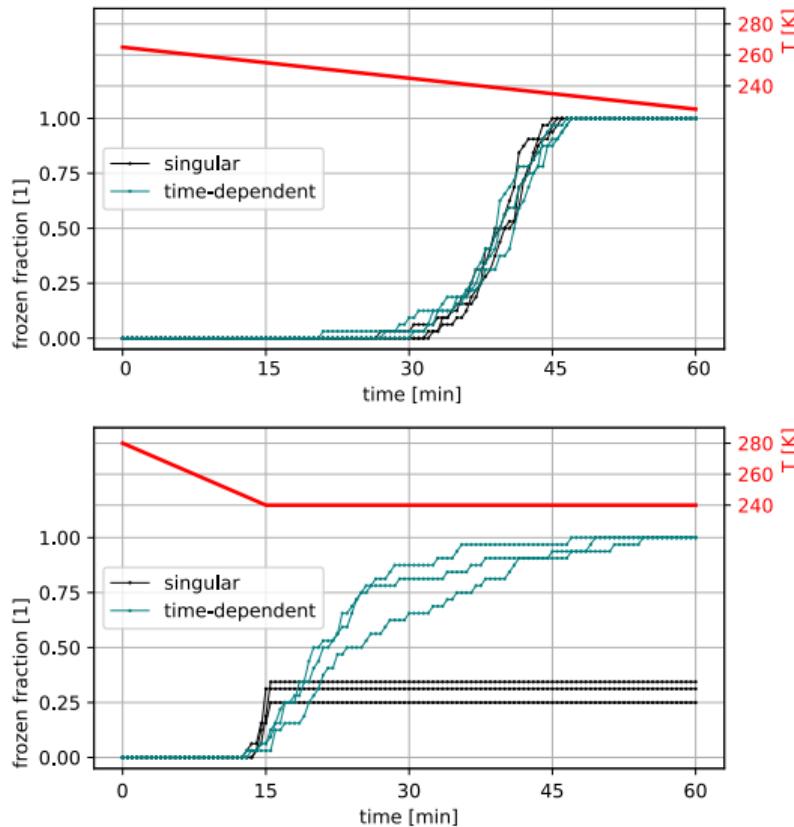
random sampling of freezing temperatures
(conditional distribution for a given surface)



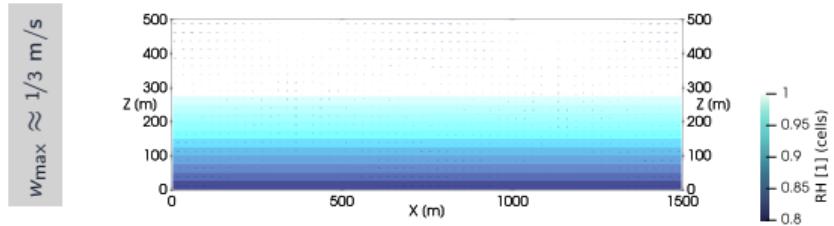
Monte-Carlo immersion freezing: singular vs. time-dependent



cooling-rate response (box model): singular vs. time-dependent



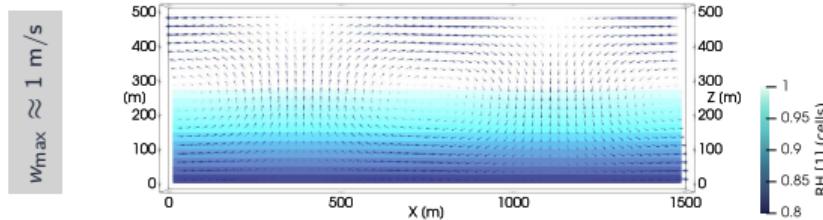
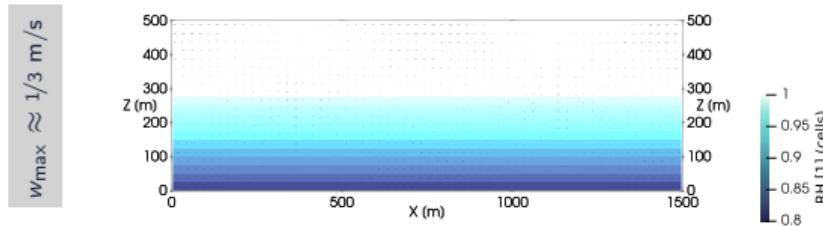
cooling-rate response (2D flow): singular vs. time-dependent



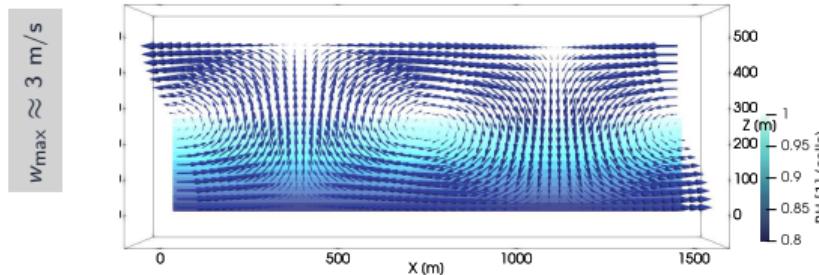
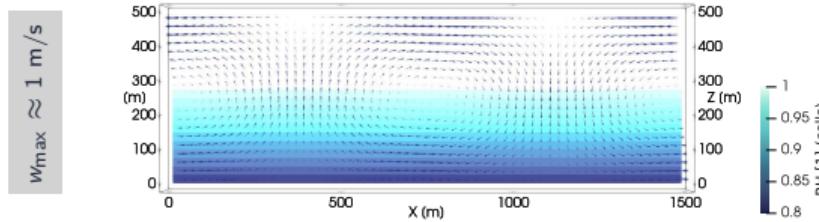
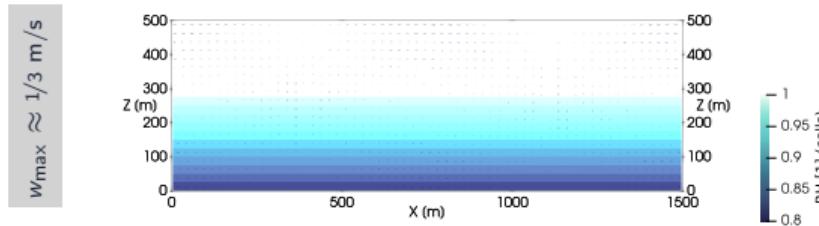
$w_{\max} \approx 1 \text{ m/s}$

$w_{\max} \approx 3 \text{ m/s}$

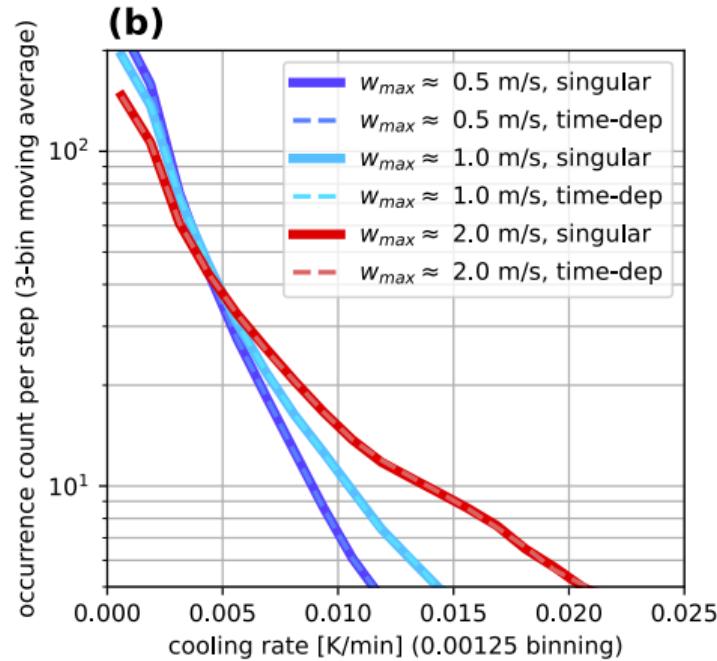
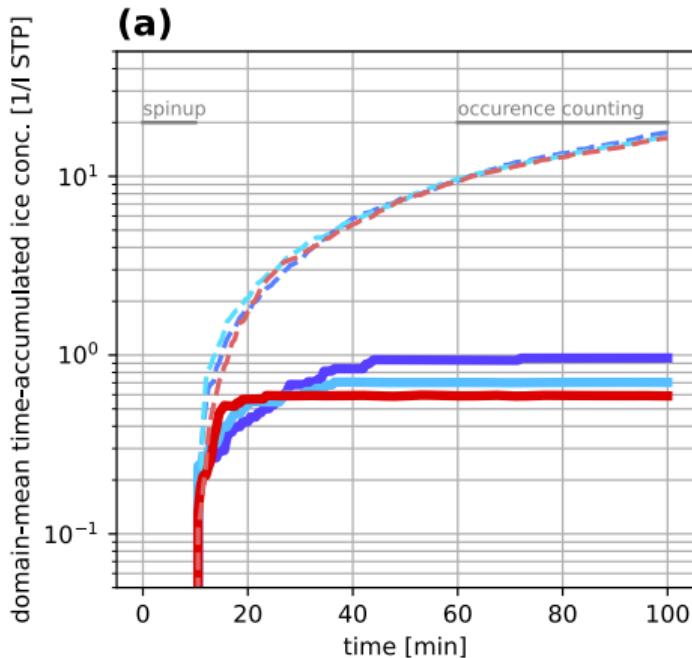
cooling-rate response (2D flow): singular vs. time-dependent



cooling-rate response (2D flow): singular vs. time-dependent

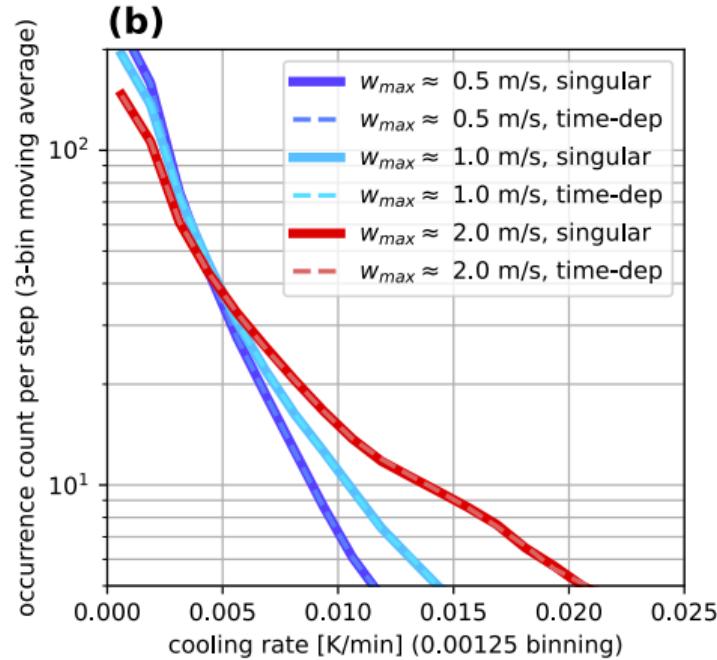
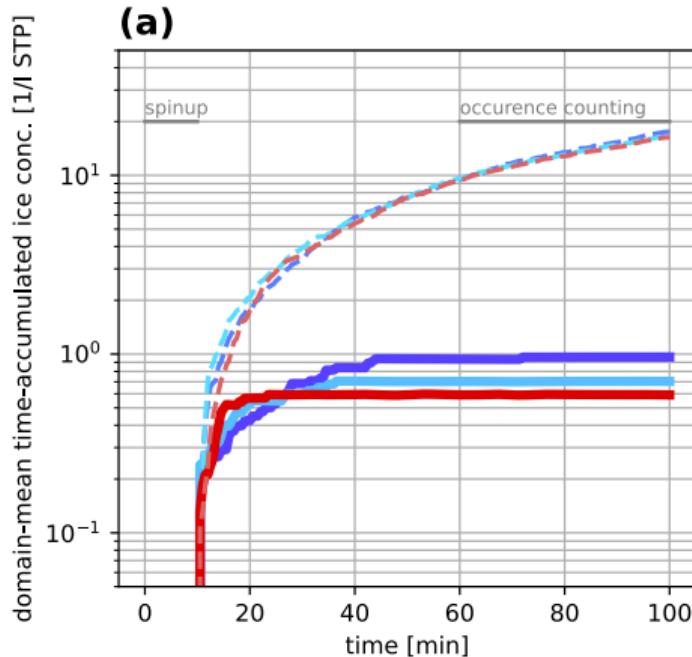


cooling-rate response (2D flow): singular vs. time-dependent



- ▶ singular vs. time-dependent markedly different (as in box model for $c \ll 1K/min$)

cooling-rate response (2D flow): singular vs. time-dependent



- ▶ singular vs. time-dependent markedly different (as in box model for $c \ll 1K/min$)
- ▶ diverse cooling rates even in a simple flow (far from $c \sim 1$ K/min for AIDA)

e-print:
arXiv/2308:XXXX

100% Python & open-source:
github.com/open-atmos/PySDM

contact:
sylwester.arabas@agh.edu.pl