Spurious Cloud Edge Supersaturations in a Lagrangian Cloud Models

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Introduction

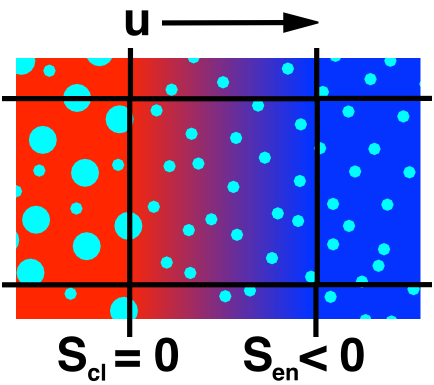
- Spurious cloud edge supersaturations are caused by the inability of Eulerian models to track the cloud boundary across the numerical grid (Grabowski, 1989, JAS; Stevens et al., 1996, MWR)
- Spurious supersaturations might alter the amount of activated droplets $\Rightarrow$ impact micro- and macro-scale cloud properties
- Many solutions have been suggested to overcome this problem (e. g., Grabowski and Smolarkiewicz, 1990, MWR; Margolin et al., 1997, MWR; Grabowski and Morrison, 2008, MWR)
- **Silver bullet** (Stevens et al., 1996, MWR): Lagrangian tracking of cloud edge
- **Lagrangian cloud models** offer free tracking of the cloud edge $\Leftrightarrow$ computation of fields of water vapor, temperature, and hence supersaturation are still based on an **Eulerian model**
- This talk will give some **preliminary insights** on the production of spurious supersaturations in Lagrangian cloud models, and how these errors can be avoided

Idealized Study: Set-up

- 1-D advection of a cloud edge across one grid cell (similar to Stevens et al., 1996, MWR)
- analytic description of advection of Eulerian supersaturation field:

$$S_{en}(t) = S_{en,0} + (S_{cl} - S_{en,0}) \frac{t}{\tau_{adv}}$$

  with $S_{cl} = 0\,\%$, $S_{en,0} = -5\,\%$, advection time scale $\tau_{adv} = \Delta / u$
- depletion/production of supersaturation by condensation/evaporation
- cloud physics calculated by a Lagrangian Super-droplet approach (called LAG):
  - linear interpolation of S on particle location
  - 50 % activated droplets
  - different initial droplet radii and concentrations are tested



- for comparison to Eulerian models (called QEU):
  - like LAG, but:
  - no interpolation of S
    ⇒ imitating grid-averaged Eulerian fields

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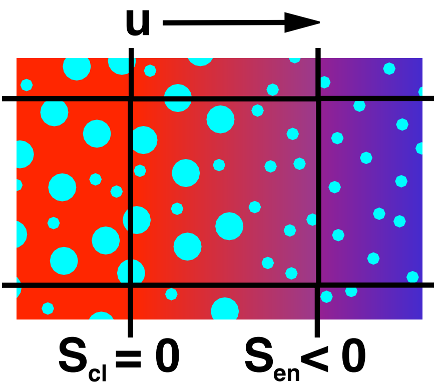

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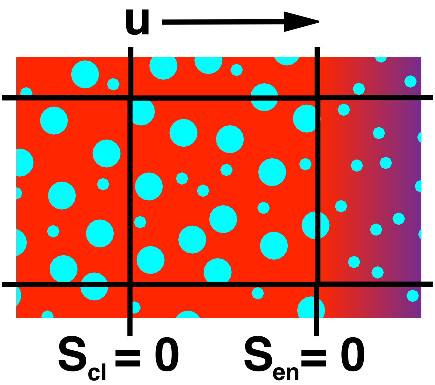

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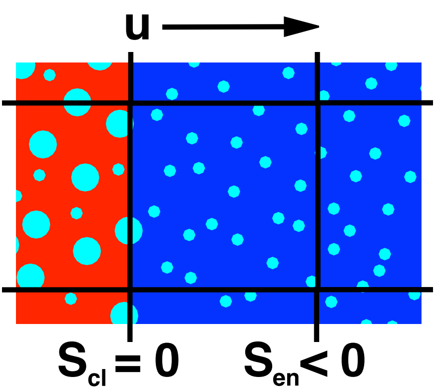

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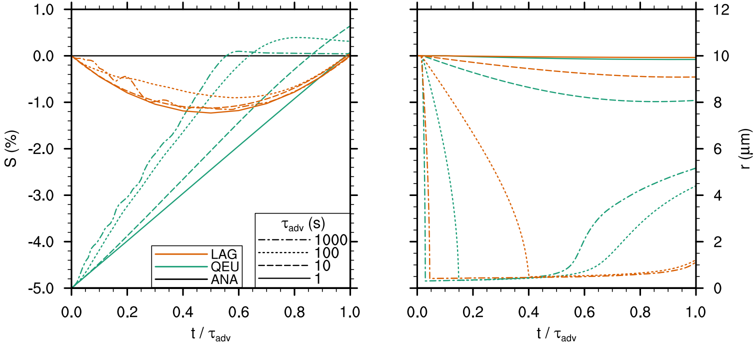
Idealized Study: Follow a Droplet at the Cloud Edge



- supersaturation experienced by a droplet at the cloud edge for different advection time scales τ_{adv}
- due to the interpolation, the sub-saturation is strongly decreased in the LAG runs
- the time-averaged sub-saturation is decreased by a factor of 3:

  $\overline{S^{QEU}} = 1/2\ S_{\text{en}}$ vs. $\overline{S^{LAG}} = 1/6\ S_{\text{en}}$
- this results in a faster evaporation of droplets in the QEU runs

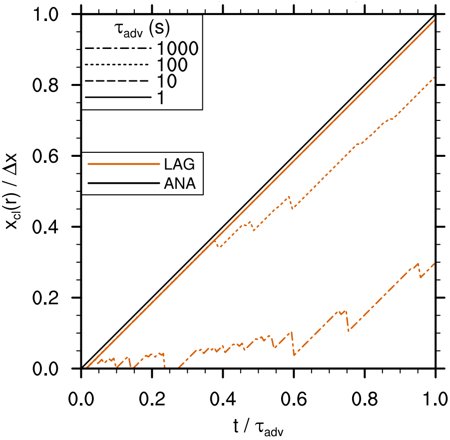
  $\Rightarrow$ **particles lose their identity much faster**

Idealized Study: Representation of the SGS-Cloud Edge

- due to the Lagrangian approach, the cloud edge can be represented on the sub-grid scale (SGS)
- this is tested by locating the rightmost activated droplet
- for low τ_{adv}, the evaporation time scale,

$$\tau_{\text{evap}} = \frac{r^2(F_{\text{k}} + F_{\text{D}})}{2S},$$

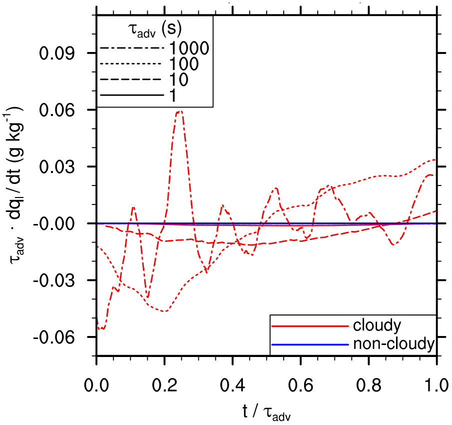
  is longer than τ_{adv} $\Rightarrow$ droplets at the cloud edge do not evaporate completely
- for high τ_{adv}, an increasing number of droplets at the cloud edge evaporates completely $\Rightarrow$ the cloud edge is spuriously shifted backwards



- **If the SGS cloud edge is maintained, will the spuriously evaporated water condense back to the original droplets?**

Idealized Study: Keeping the Identity of a Droplet

- the amount of water vapor evaporated/condensed by cloud and non-cloud particles is analyzed
- almost no supersaturations are produced nor depleted by non-cloud particles
- the phase relaxation time scale ($\tau_{\text{phase}} = (4\pi D N \langle r \rangle)^{-1}$) of non-cloud particles is larger than for cloud particles
- for long advection time-scales, however, water vapor might condense on unactivated droplets within the cloud $\Rightarrow$ **spurious activation of droplets**



- amount of spuriously released water vapor should be minimized by limiting the amount of water spuriously evaporated during the advection $\Rightarrow \tau_{\text{adv}} < \tau_{\text{phase}}$

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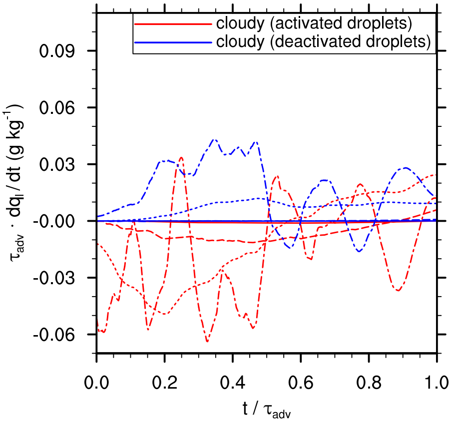

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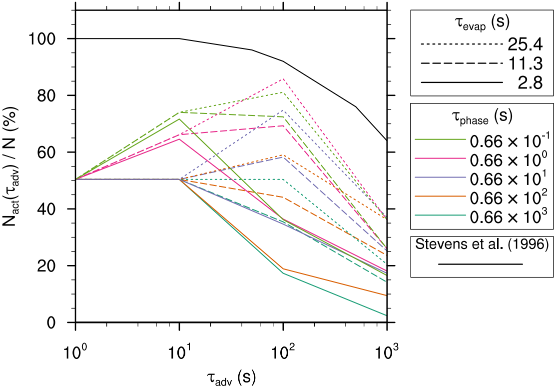
Idealized Study: Number of Activated Droplets

- number of activated droplets at $t = \tau_{adv}$ as a function of τ_{adv} (similar to Stevens et al., 1996, MWR)
- the number of activated droplets is a **measure of the impact of spurious supersaturations**:
  - $> 50\,\%$ ⇒ spurious activation for $\tau_{adv} > \tau_{phase}$
  - $< 50\,\%$ ⇒ spurious deactivation for $\tau_{adv} > \tau_{evap}$



- to minimize the impact of spurious cloud edge supersaturations, reduce τ_{adv} by **decreasing the grid spacing ⇒ this keeps the identity of a droplet**
- contrary to Stevens et al. (1996, MWR), who found no convergence for Eulerian cloud models

3D Simulation: Set-up

- **more realistic test** of the local criterion for minimizing the production of spurious supersaturations by keeping the identity of a droplet:

$$\tau_{\mathrm{adv}} < \min\left(\tau_{\mathrm{evap}}, \tau_{\mathrm{phase}}\right)$$

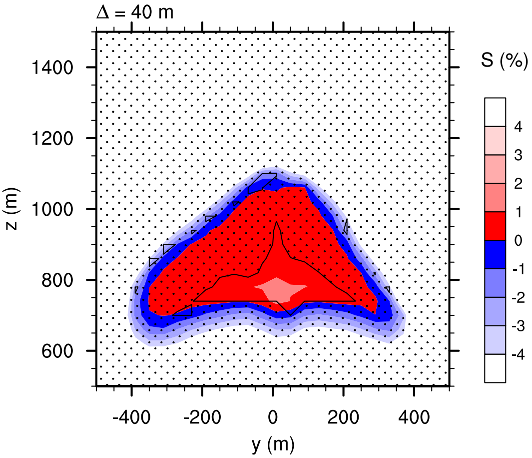
- grid spacings: 40 m, 20 m, 10 m, and 5 m $\Rightarrow$ reducing τ_{adv} by a factor of 8
- simulation of a single maritime shallow cumulus cloud
- all simulations are carried out with 125 particles per grid box
- monotone advection of Eulerian scalar fields of potential temperature and water vapor ($\Rightarrow$ avoid dispersive ripples, but no additional techniques for the mitigation of spurious supersaturations as discussed by Grabowski and Smolarkiewicz (1990, MWR))
- details of the Lagrangian cloud model and the used LES are described in Riechelmann et al. (2012, New J. Phys.) and Maronga et al. (2015, GMDD)

3D Simulation: Development of the Cloud

- contours of supersaturation S
- areas in which

$$\tau_{\text{adv}} > \min\left(\tau_{\text{evap}}, \tau_{\text{phase}}\right)$$

  are marked by dots
  $\Rightarrow$ **loss of a droplet's identity**
- τ_{evap} is determined for the mean radius
- for large grid spacings, the identity of a cloud droplet gets lost in almost every grid box
- **for grid spacing less or equal to 10 m, the whole cloud seems to be well represented**



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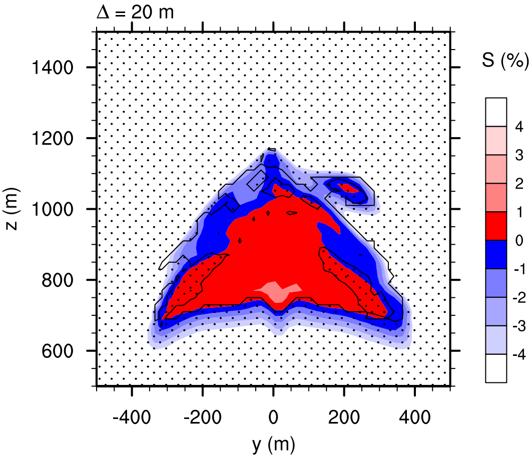

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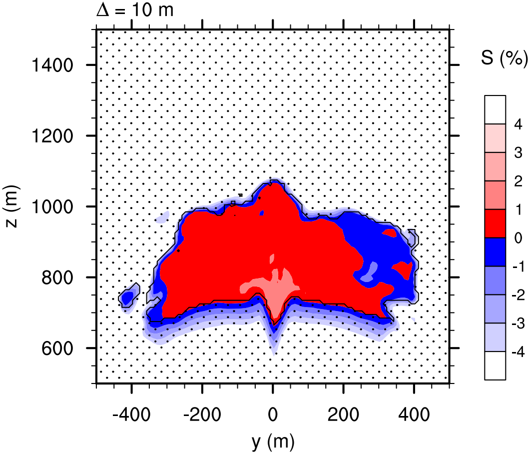

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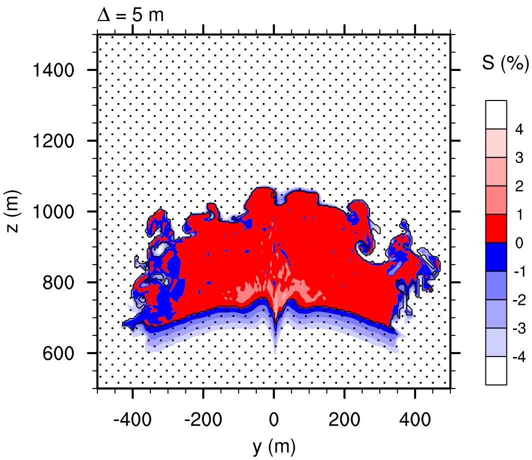
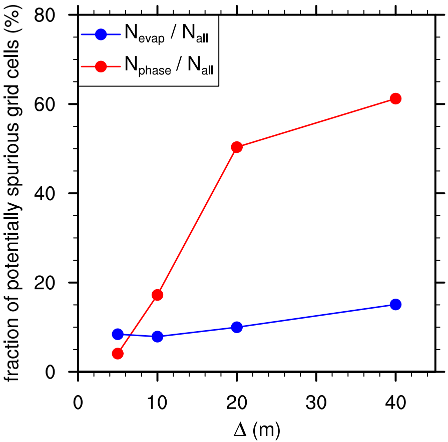


3D Simulation: Amount of Spurious Grid Cells

- fraction of grid cells in which $\tau_{\text{adv}} > \tau_{\text{phase}}$ or $\tau_{\text{adv}} > \tau_{\text{evap}}$ at the cloud edge
- the fraction of grid cells violating the τ_{phase} criterion decreases heavily for $\Delta < 20\,\text{m}$

  $\Rightarrow$ this is determined by the typical velocities, droplet radii, and particle concentration described for this case
- the fraction of grid cells violating the τ_{evap} criterion decreases moderately and increases for $\Delta > 5\,\text{m}$

  $\Rightarrow$ the increasingly better resolved cloud edge makes the representation by Lagrangian particles more difficult for very high-resolution simulations

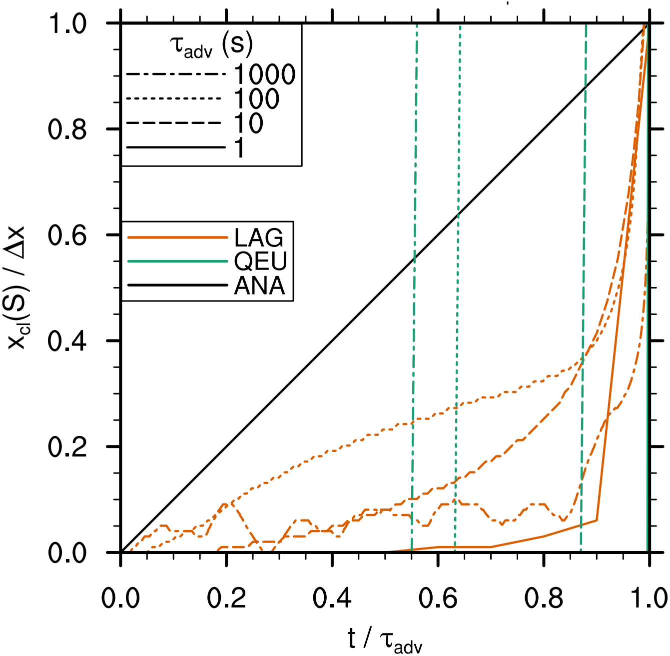


Conclusions

- as in Eulerian models, spurious cloud edge supersaturations are also present in Lagrangian cloud models
- in Lagrangian cloud models, spurious evaporation is reduced by a factor of 3 due to the interpolation of Eulerian quantities on a droplet's position
- by the explicit simulation of droplets by individual particles, the cloud edge can be represented on the sub-grid scale
- to **keep the identity of an individual droplet** on the SGS, the droplets should neither evaporate completely nor produce significant spurious supersaturations (which transport water to other particles):

$$\tau_{\text{adv}} < \min\left(\tau_{\text{evap}}, \tau_{\text{phase}}\right)$$

- **this data is obtained locally, i. e., on the basis of one grid cell, and depends on the investigated type of the cloud**
- next steps: **global** quantification of spurious supersaturations in Lagrangian cloud models


τ_{adv} (s)
1000
100
10
1
LAG
QEU
ANA
1.0
0.8
0.6
0.4
0.2
0.0
$x_{cl}(S)$ / Δx
0.0
0.2
0.4
0.6
0.8
1.0
t / τ_{adv}