Dynamical responses of a mixed-phase cloud to ice seeding

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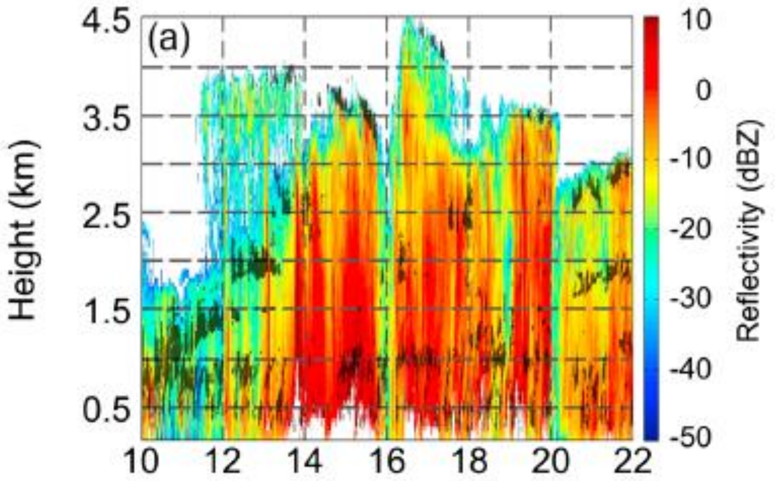
2017.05.01

Motivation

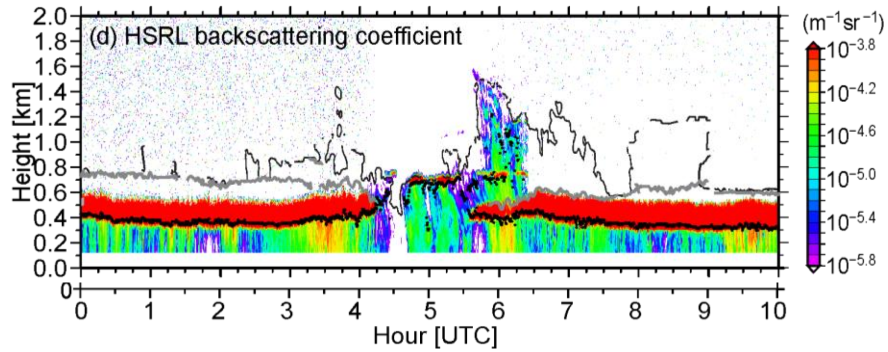
- Multi-layered mixed-phase clouds in Arctic
  - Lower level cloud often embedded in ice shower from above
- When ice falls into supercooled liquid layer
  - Compete with liquid for vapor
  - Riming
  - Secondary ice production
  - Leading to loss of liquid
- What happens when ice particles fall into the liquid layer and open a gap in the liquid cloud deck?

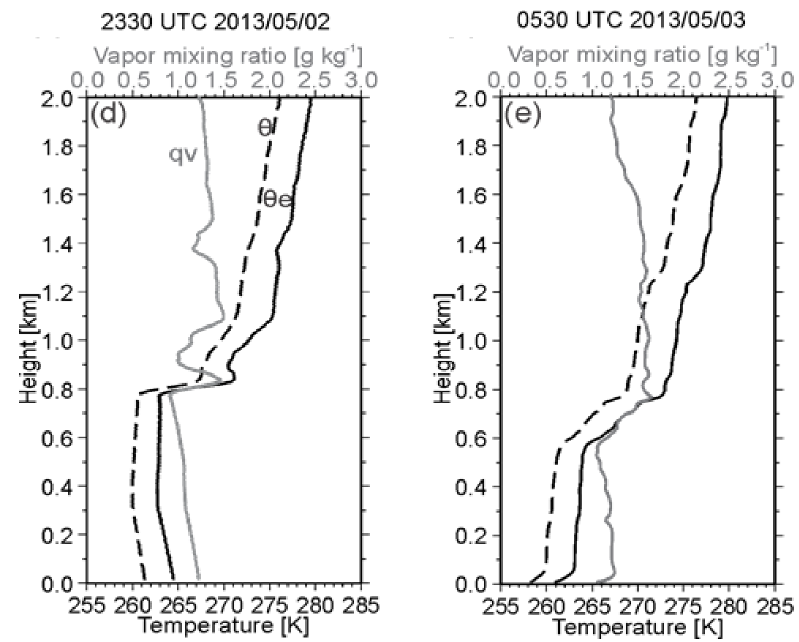


Verlinde et al. (2013)

Motivation

- An case observed on 2013.05.03 at NSA
  - A gap in the liquid cloud deck
  - KAZR reflectivity suggests ice precipitation from above
  - Warming in upper liquid layer and cooling in sub-cloud layer is similar to the outcome from the glaciation of liquid layer and precipitation of ice? (Harrington et al. 1999)
  - Is it possible that this is a gap left from ice precipitation?





Oue et al. (2017) in prep.

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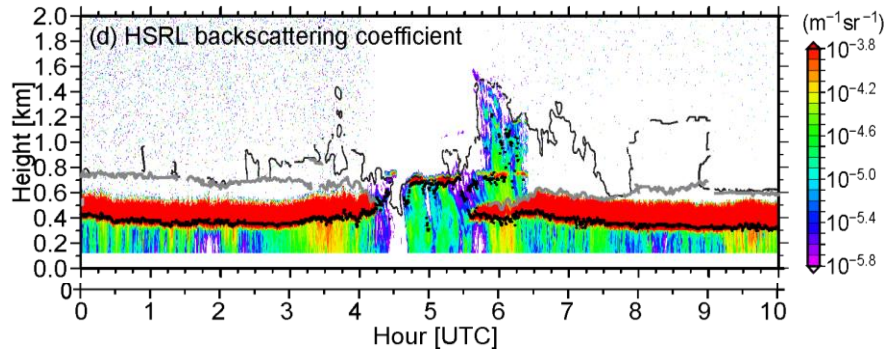

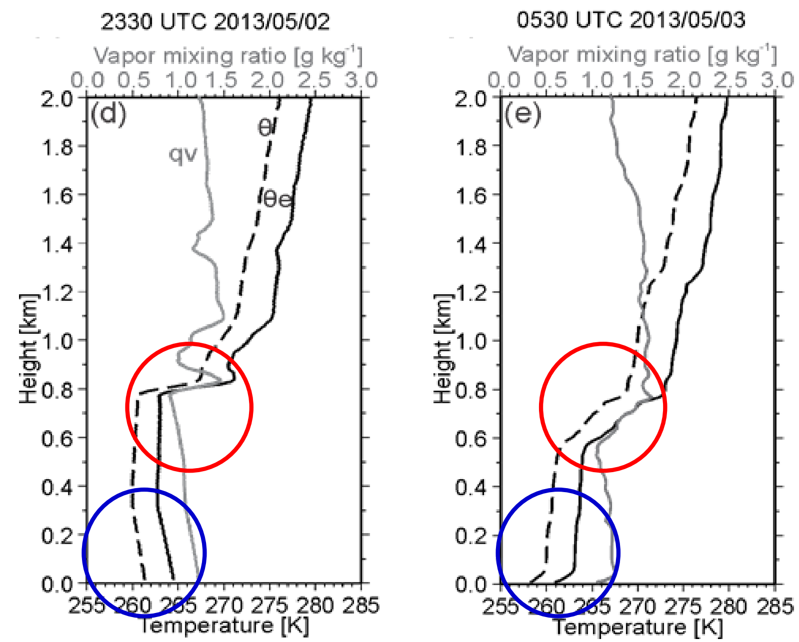

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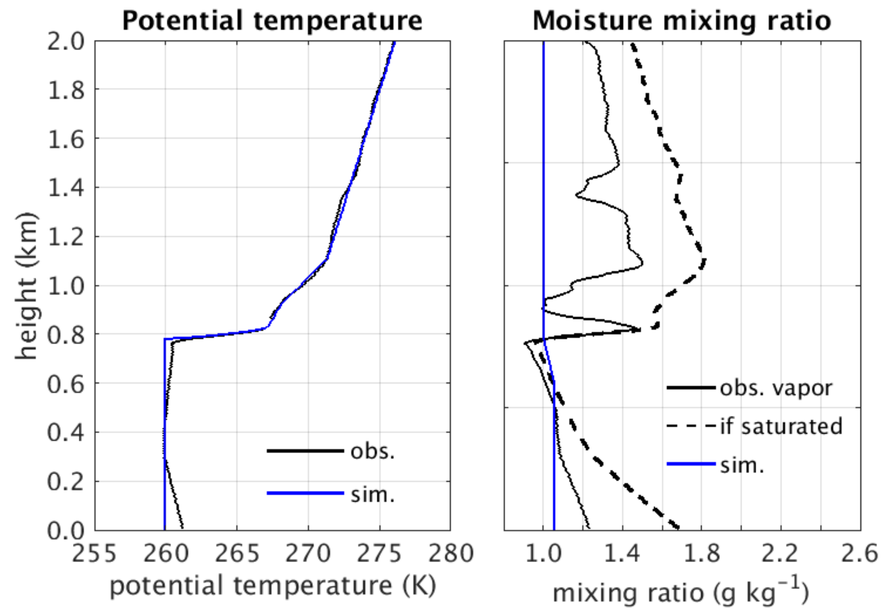
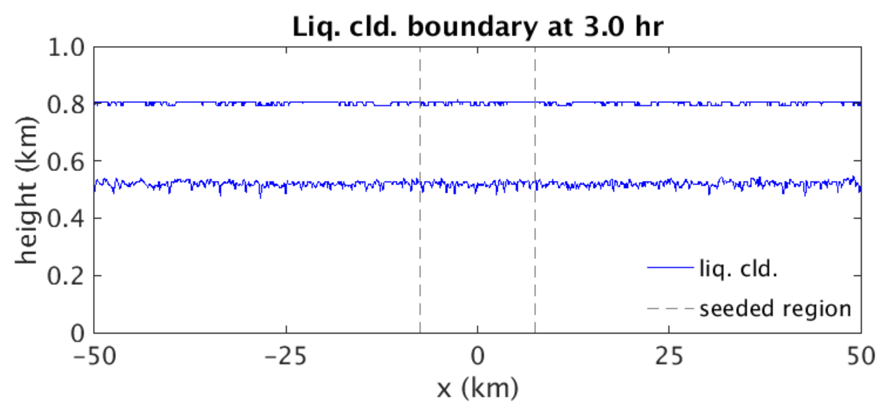
Simulation

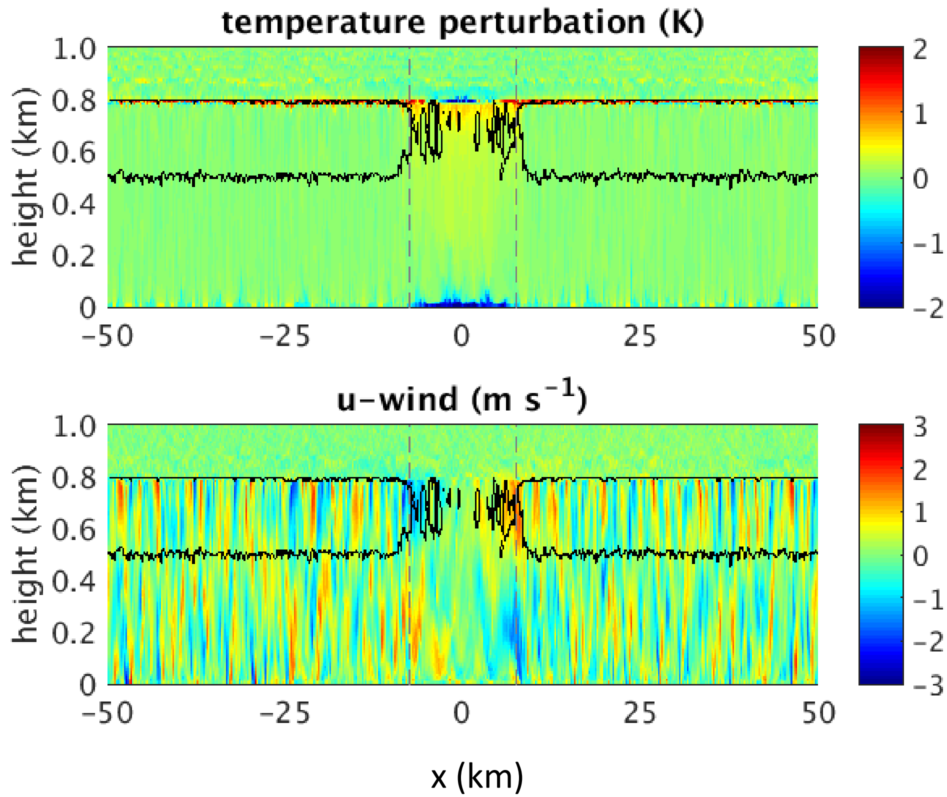
- Model
  - RAMSLES
  - 2-moment bulk microphysics
  - Ice growth from vapor only
- Base run
  - 2D domain 100 km by 2 km
  - Grid resolution 50 m by 10 m
  - Idealized sounding based on NWS sounding from 2013.05.02 23Z
  - Thick vs. thin clouds
- Seeding method
  - 0.5 mm day^{-1}; 1 ice L^{-1} per 30 sec
  - Over 15 km domain at liquid cloud top
  - Starts from the end of 3-hr spin-up, continues for the rest of the simulation





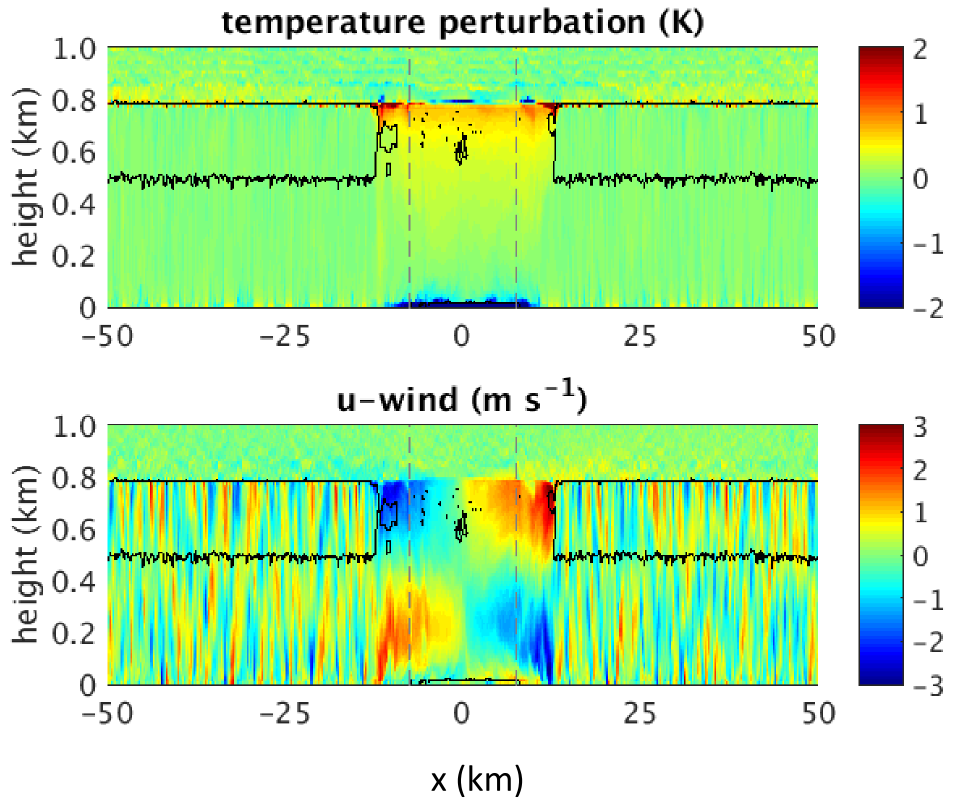
Results: Basic evolution

- Simulation at 6.0 hr
  - Ice particles deplete the liquid in seeded region
  - Continue to take up vapor as they fall through the layer saturated w.r.t. ice
  - Sublimate near surface
  - Releases/Absorbs heat
  - Creates a gap in the liquid cloud deck



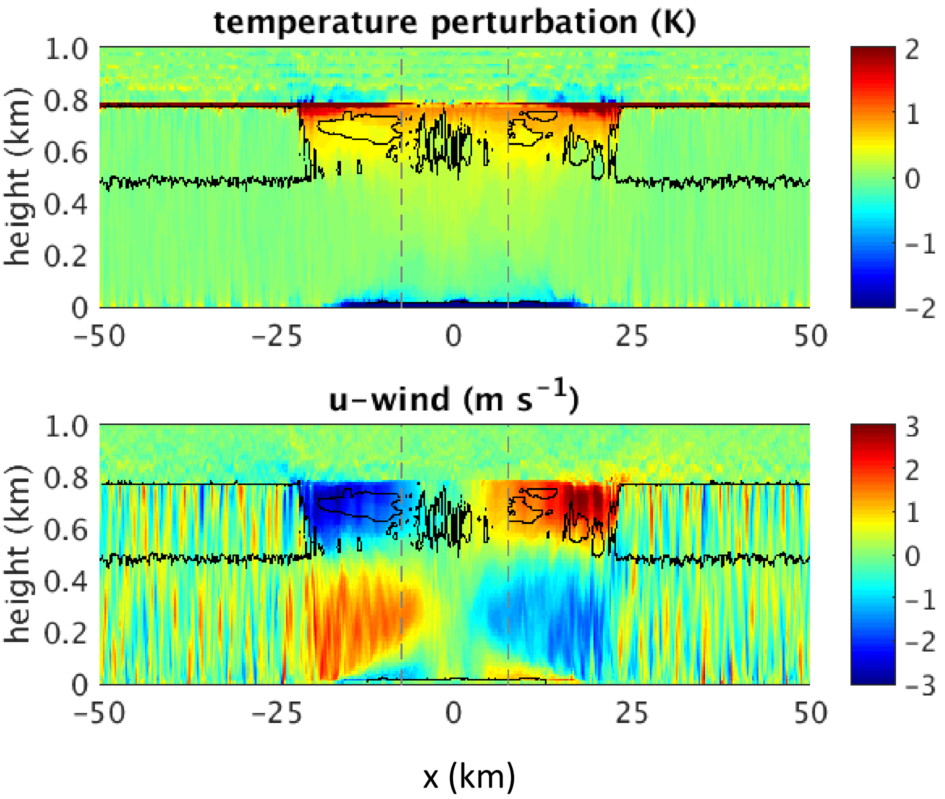
Results: Basic evolution

- Simulation at 7.5 hr
  - The warm air in the seeded region expands
  - Drives mesoscale cloud layer divergence and subcloud convergence
  - Gap grows beyond seeded region



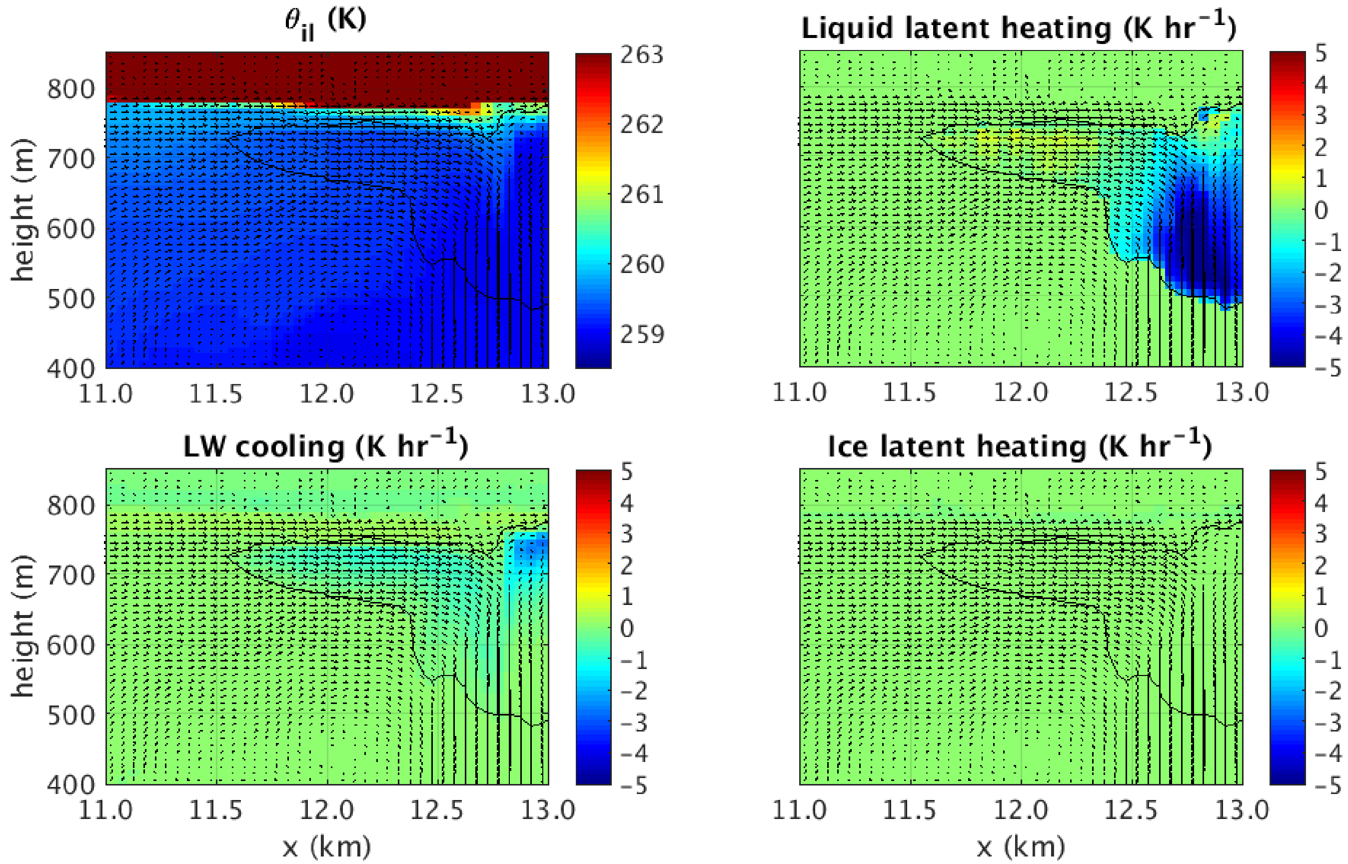
Results: Basic evolution

- Simulation at 9.0 hr
  - Gap grows wider
  - Strong horizontal diverging flow
  - Temperature in the top of the clear region warms up due to mixing with warm air above



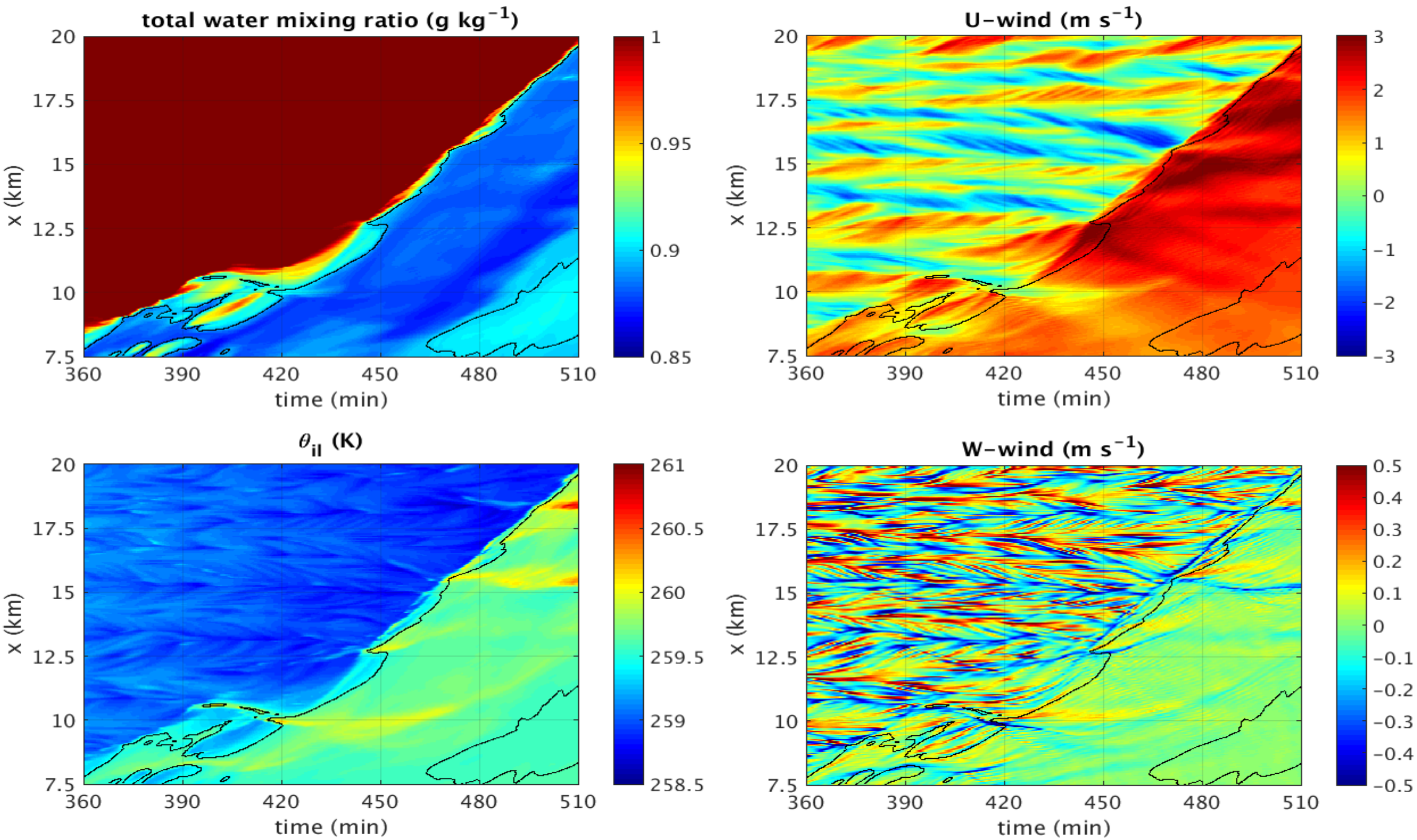
Results: Focus on cloud edge

- Simulation at 7.45 hr, zoomed in
  - Strong downdraft dissipates liquid cloud
  - Little latent heating associated with ice
  - Entrainment of warm air from aloft?



Results: A different perspective

- At a fixed height in upper part of liquid cloud



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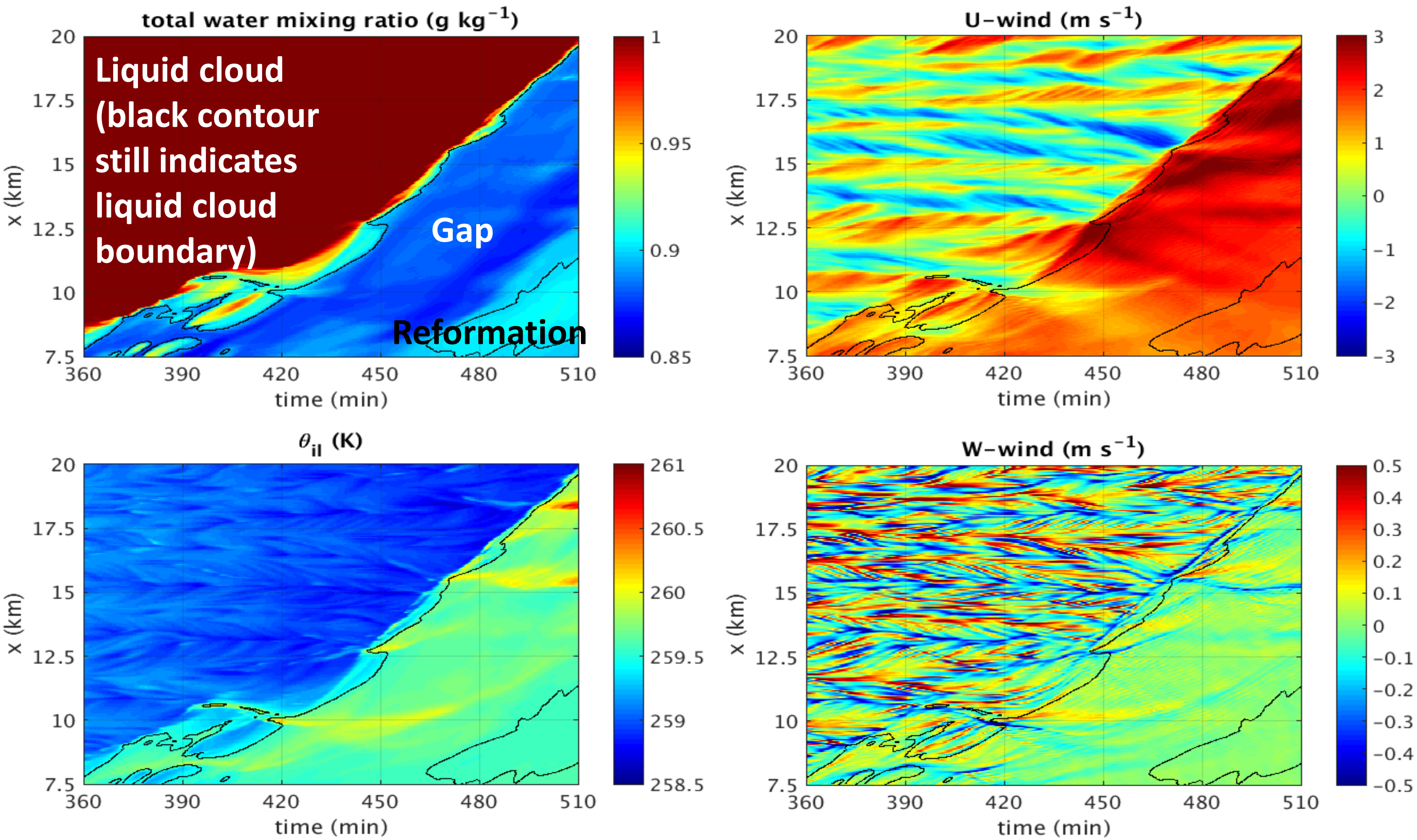

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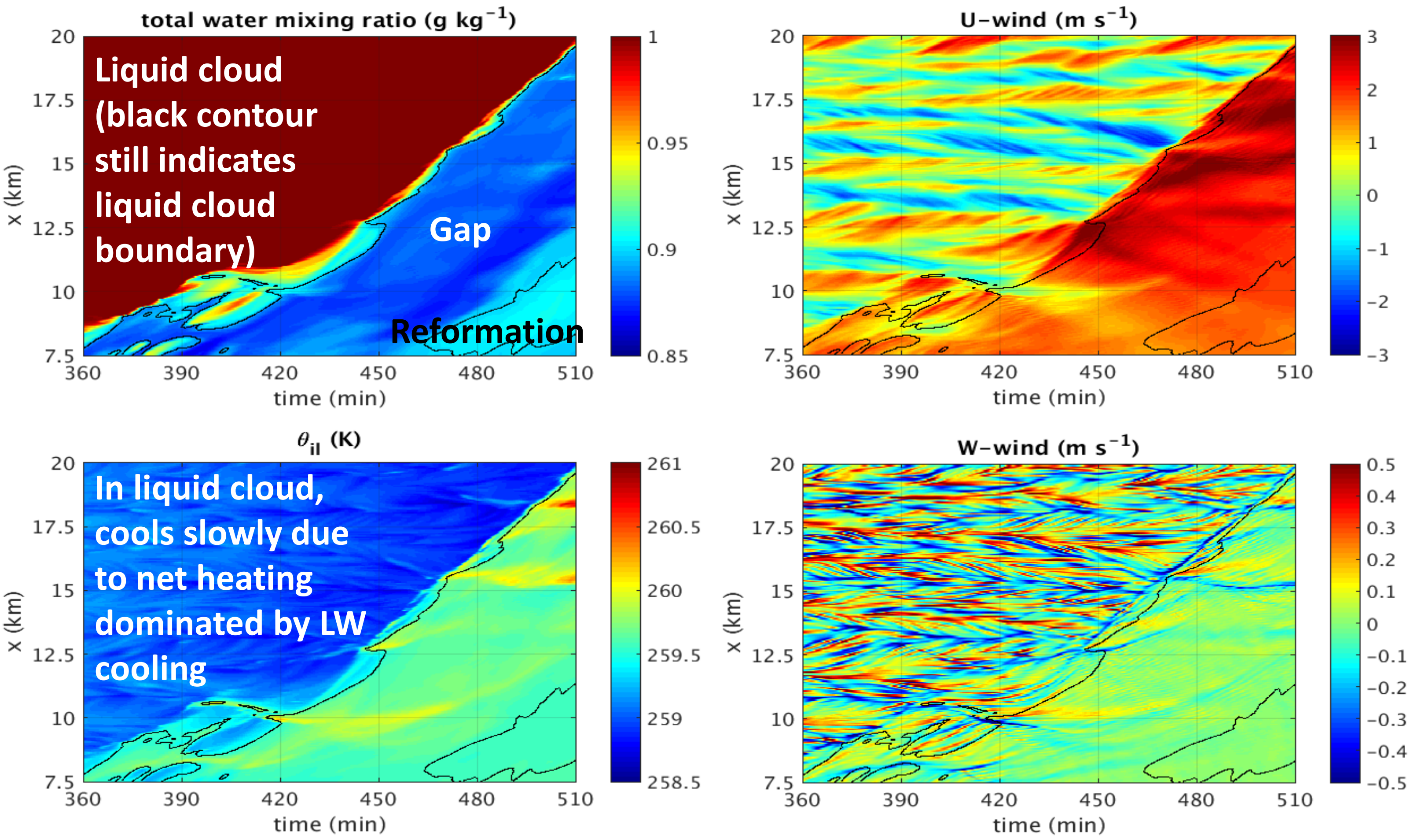

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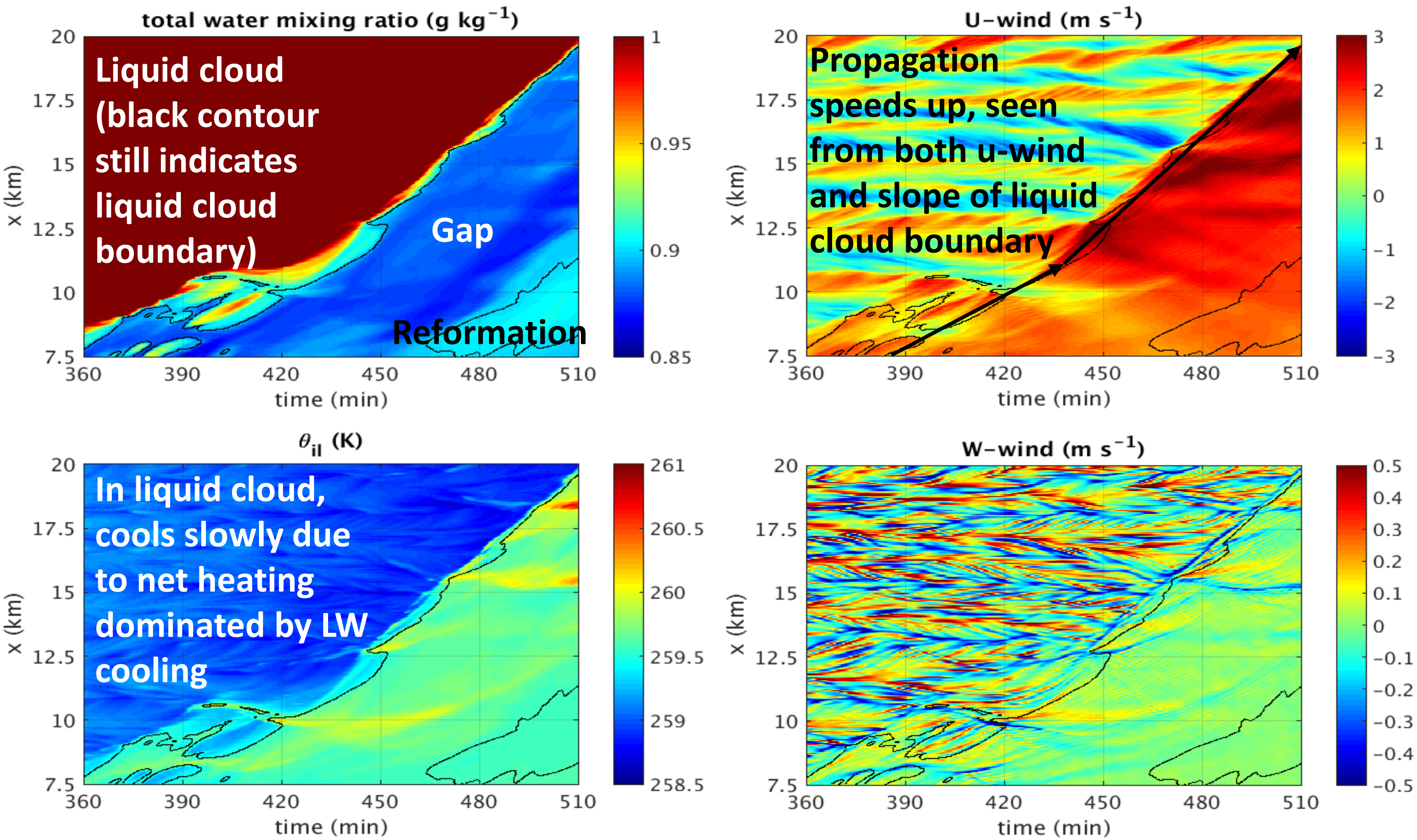

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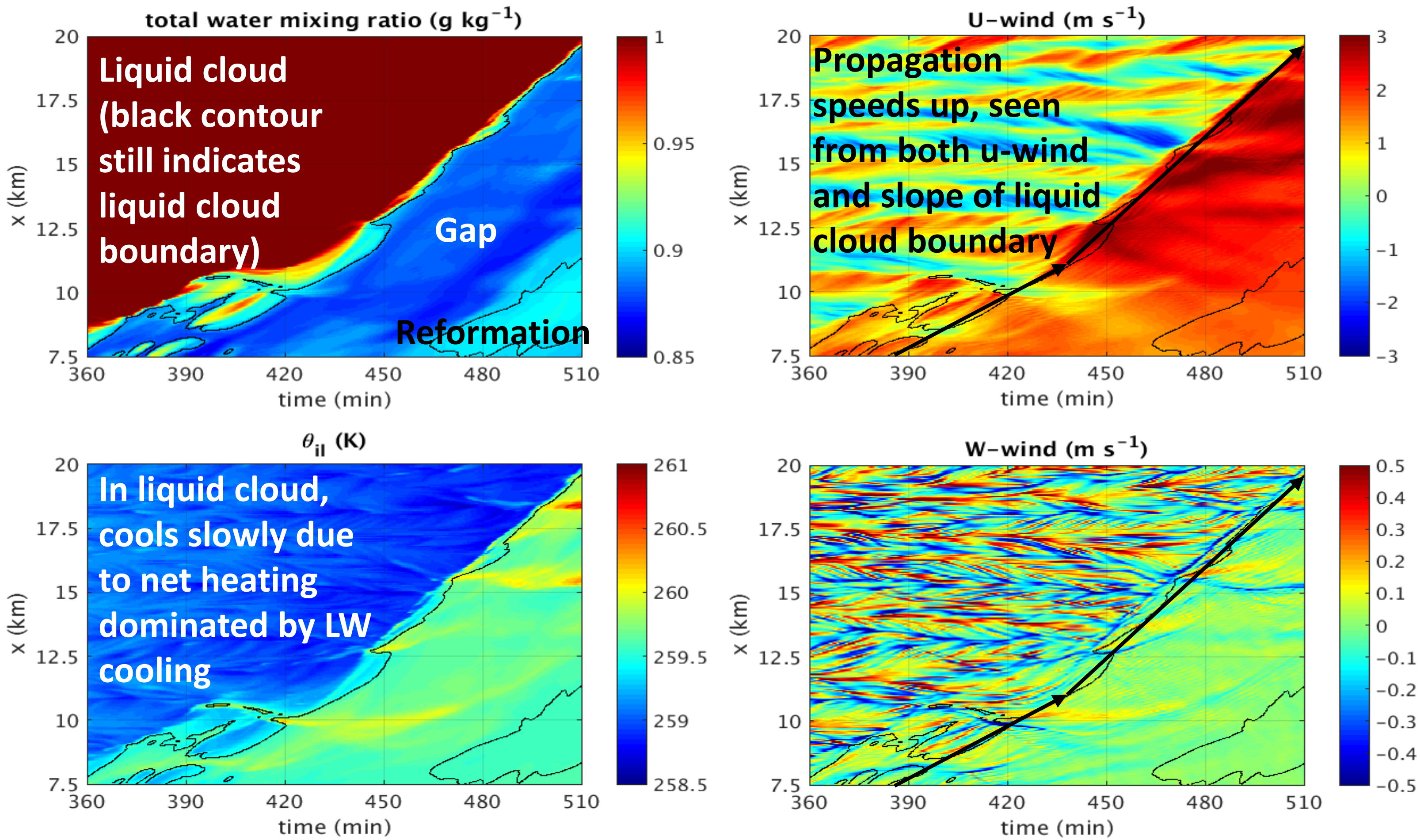


Questions to answer

- What maintains the warm bubble in the gap?
- What caused the dissipation of liquid cloud?
- What determines the rate of the expansion of the gap?

Budget analysis: Background

- Primary thermodynamic variables in RAMS-LES
  - Total water mixing ratio
  - Liquid water mixing ratio (cloud drops only)
  - Ice water mixing ratio (pristine ice only)
  - Ice-liquid potential temperature
    - Potential temperature of a parcel if all hydrometeors within transform to vapor

$$\theta_{\mathrm{il}} \approx \theta\left[1 + \frac{L_{\mathrm{v}} r_{\mathrm{l}} + L_{\mathrm{v}} r_{\mathrm{i}}}{c_p T}\right]^{-1}$$

    - Phase change: Affect θ, not θ_{il}
    - Hydrometeor sedimentation: Affect θ_{il}, not θ
    - Radiative transfer: Both

Budget analysis: θ_{il}

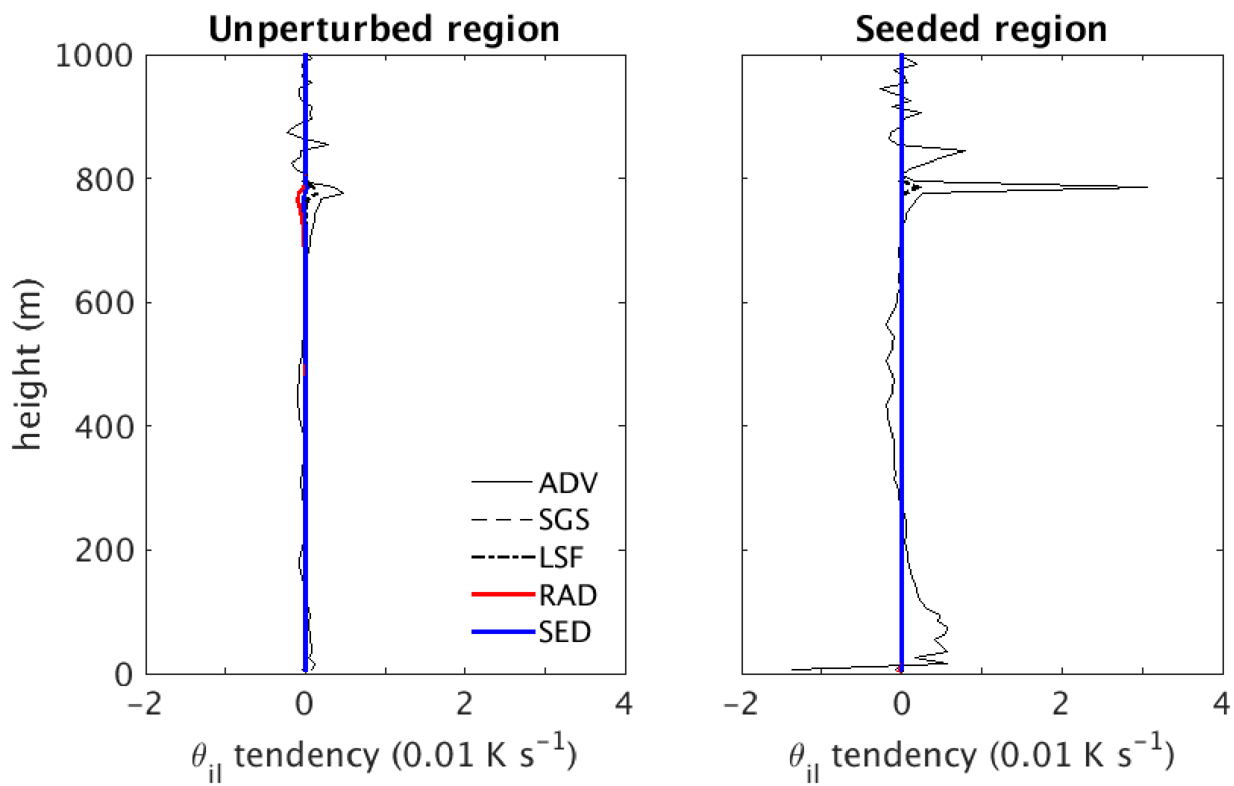
- Equation

$$\frac{\partial\theta_{\mathrm{il}}}{\partial t} = \left(\frac{\partial\theta_{\mathrm{il}}}{\partial t}\right)_{\mathrm{ADV}} + \left(\frac{\partial\theta_{\mathrm{il}}}{\partial t}\right)_{\mathrm{SGS}} + \left(\frac{\partial\theta_{\mathrm{il}}}{\partial t}\right)_{\mathrm{LSF}} + \left(\frac{\partial\theta_{\mathrm{il}}}{\partial t}\right)_{\mathrm{RAD}} + \left(\frac{\partial\theta_{\mathrm{il}}}{\partial t}\right)_{\mathrm{SED}}$$

  - ADV: Transport by resolved flow
  - SGS: Transport by subgrid scale
  - LSF: Transport by prescribed subsidence velocity
  - RAD: Long wave warming/cooling, short wave turned off in this simulation
  - SED: Sedimentaion of hydrometeor

Budget analysis: θ_{il}

- Averaged tendency profiles
  - 37 time steps from 6 hr to 9 hr (every 5 min)
  - Unperturbed region: 800 columns/40 km, unperturbed at 9 hr
  - Seeded region: 300 columns/15 km



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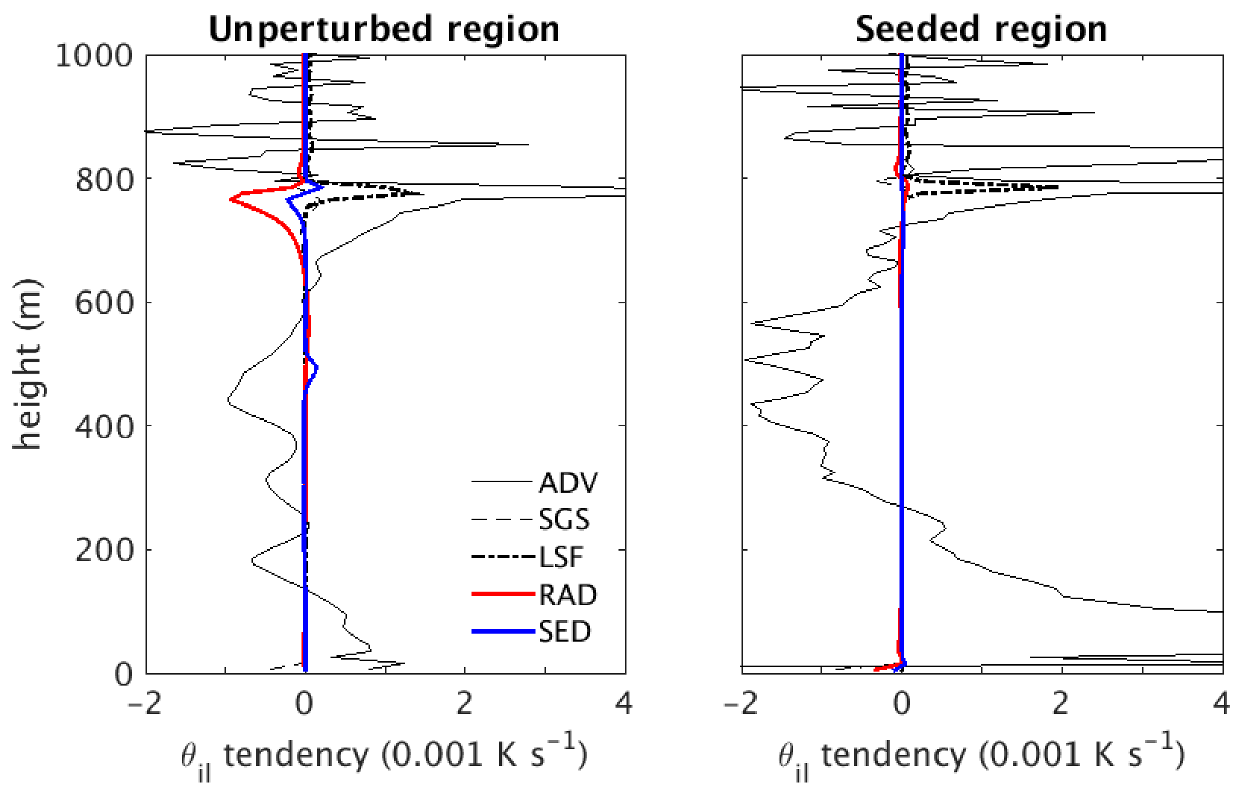
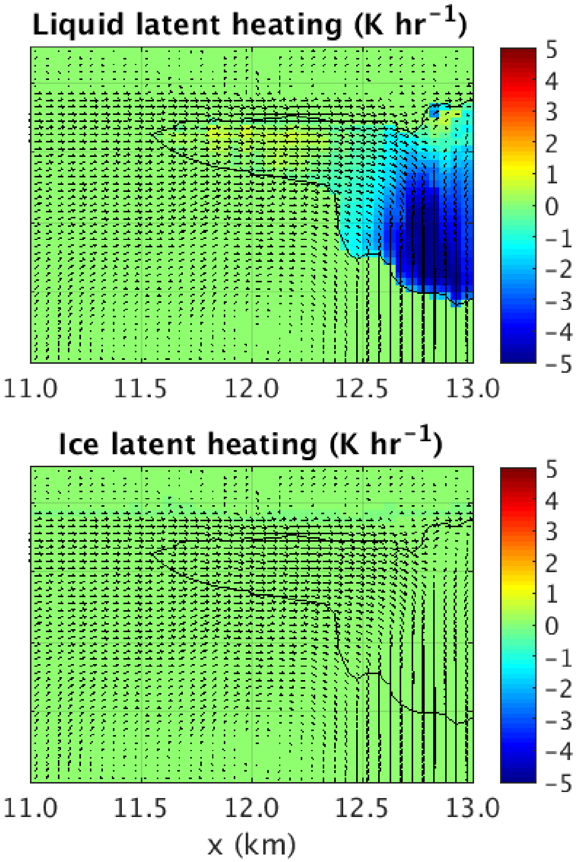


Budget analysis: r_l

- Equation

$$\frac{\partial r_\mathrm{l}}{\partial t} = \left(\frac{\partial r_\mathrm{l}}{\partial t}\right)_\mathrm{ADV} + \left(\frac{\partial r_\mathrm{l}}{\partial t}\right)_\mathrm{SGS} + \left(\frac{\partial r_\mathrm{l}}{\partial t}\right)_\mathrm{PhCh} + \left(\frac{\partial r_\mathrm{l}}{\partial t}\right)_\mathrm{SED}$$

- Partition to processes
  - Moist-adiabatic
  - Mixing
  - Radiative warming/cooling
- Need to work on this



Summary

- Perturb a mixed-phase cloud with prescribed ice flux
  - Reasonable ice flux can open up a gap in thin cloud deck
  - The mesoscale circulation driven by latent heat from ice microphysics
  - Downdraft near liquid cloud edge further dissipates liquid cloud
  - Gap grows to much beyond the seeded region
- Budget terms
  - In unperturbed region, LW cooling cools the cloud and maintains a well-mixed layer
  - In seeded region, no LW cooling, a few mechanisms maintain a warm bubble
- Future work
  - Double check the budget for θ_{il}
  - Partition liquid water phase change term into processes
  - Understand the mechanism resulting in downdraft near cloud edge