Where are cumulonimbus anvil crystals born?

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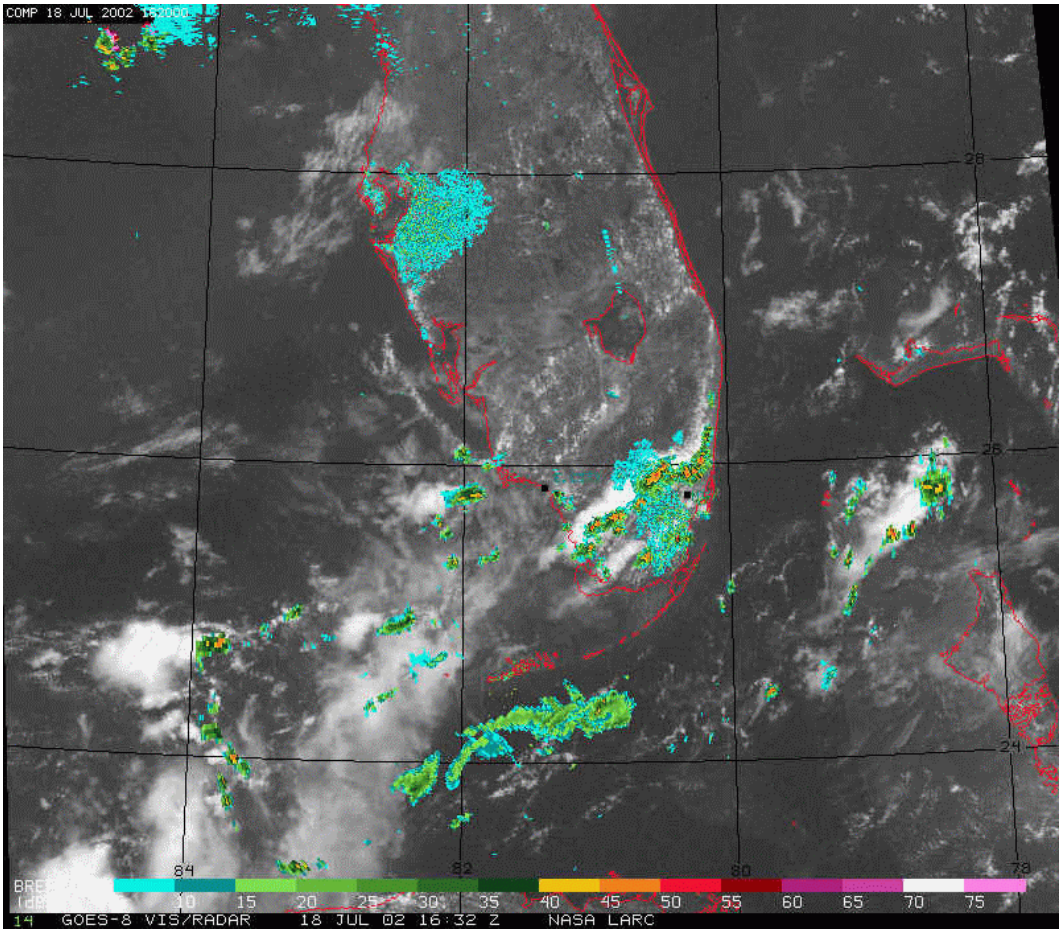
Motivation

- Anvil ice crystals are formed in strong updraft cores
  - few observations
  - high experimental uncertainty
  - complex microphysical environment
- How are most ice crystals nucleated?
  - homogeneous droplet freezing
  - heterogeneous nuclei
- What are the primary sources of CCN?
  - boundary layer
  - free troposphere
- Does Hallett-Mossop ice multiplication play a role?

July 18 case study



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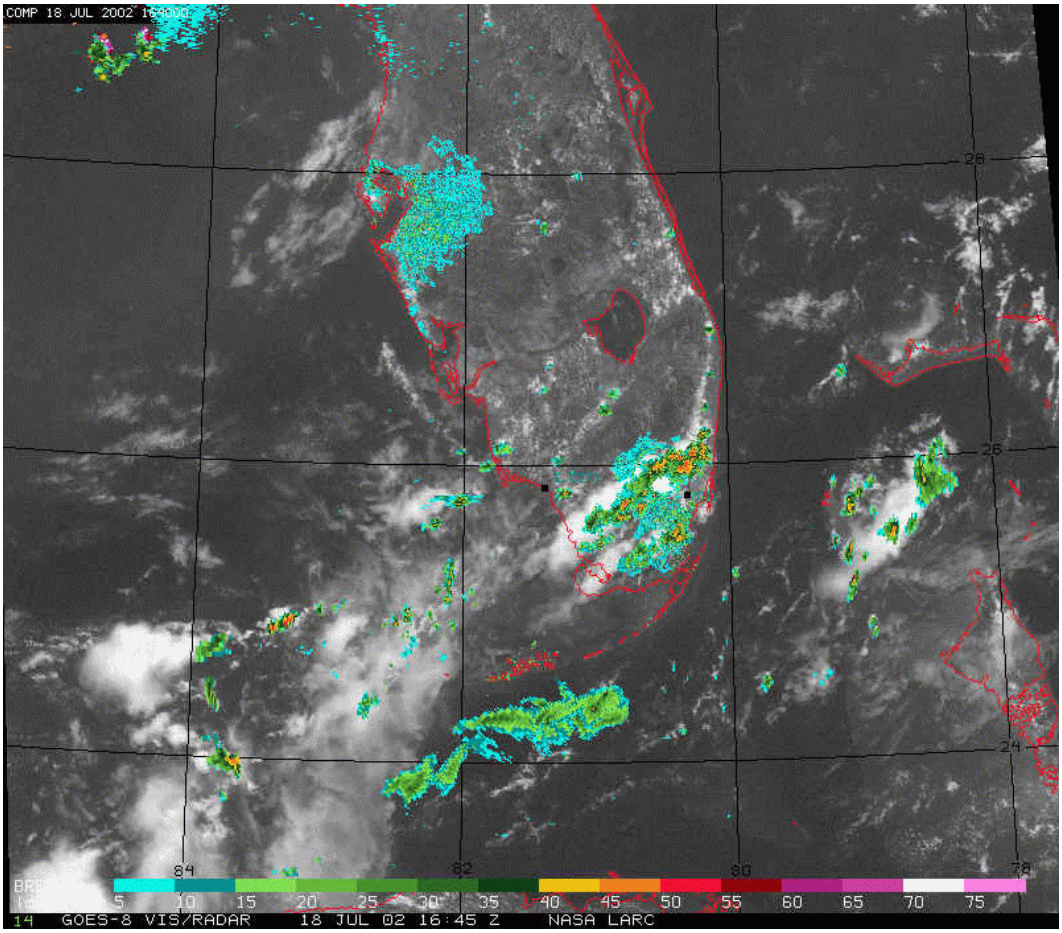

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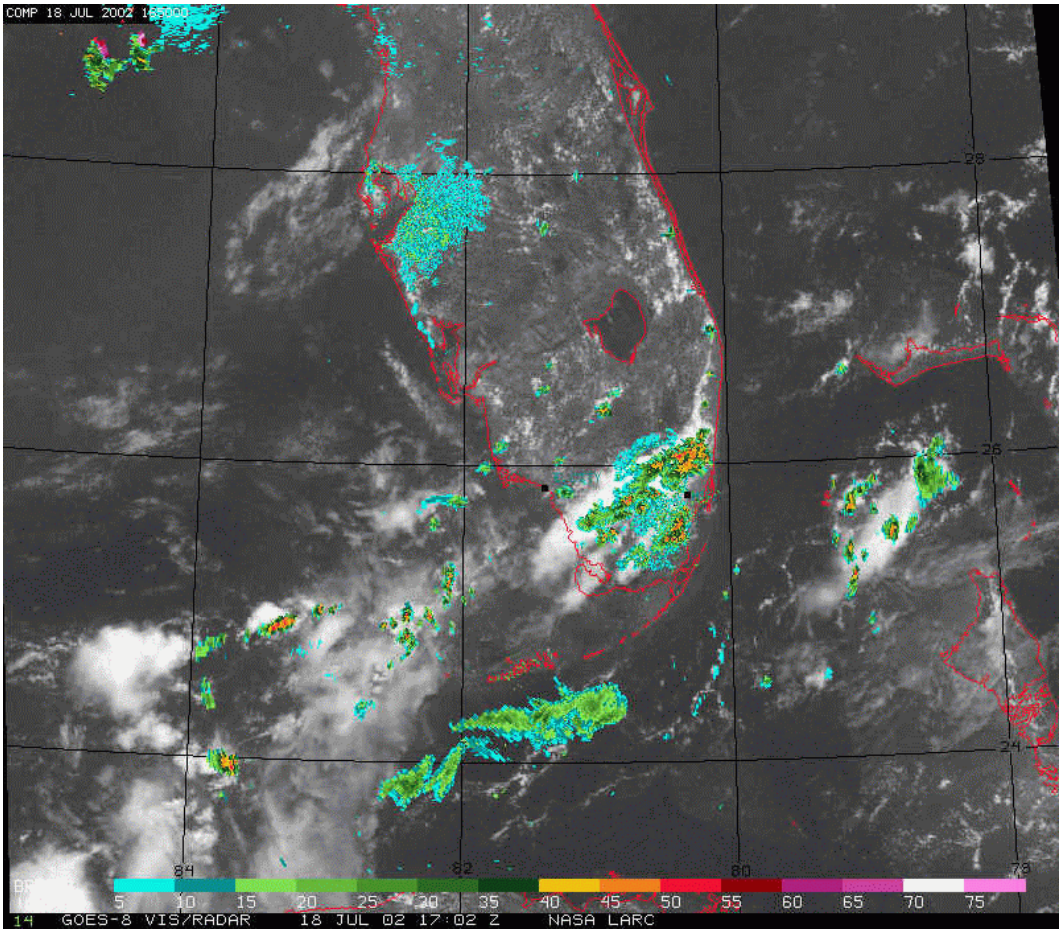

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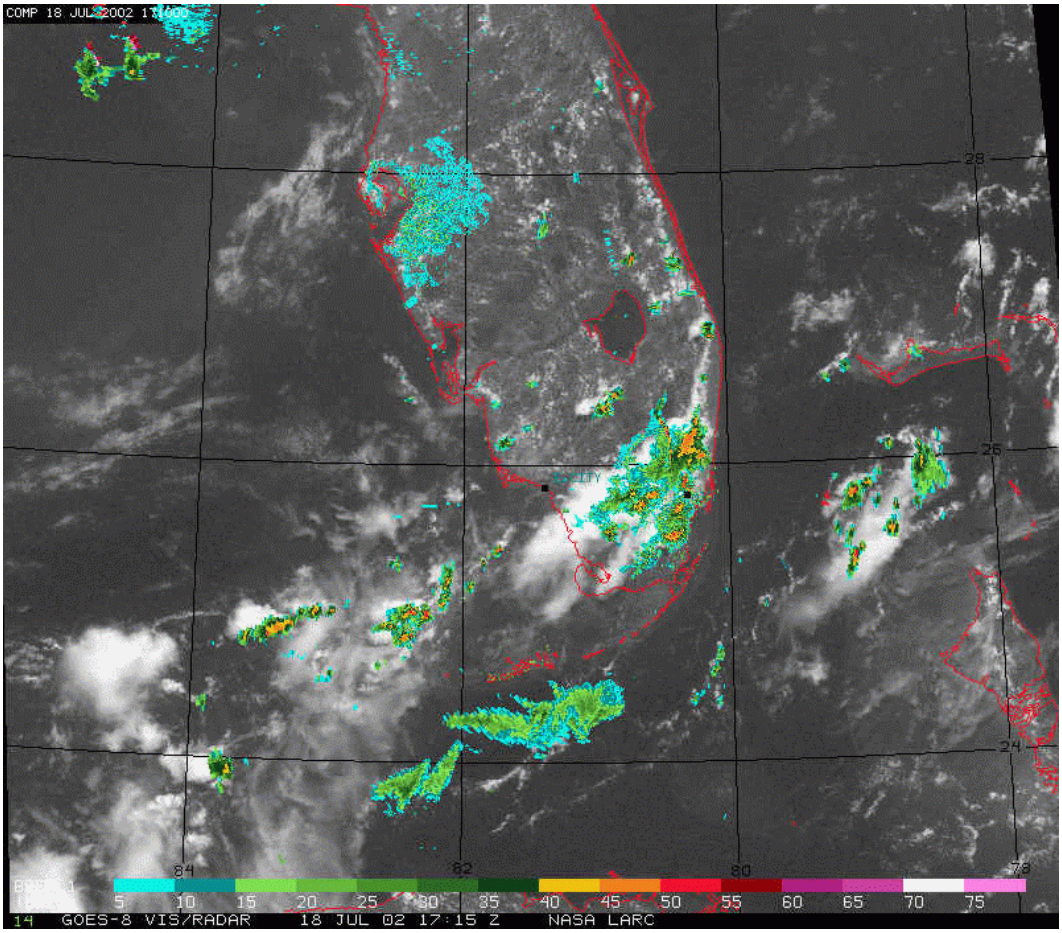

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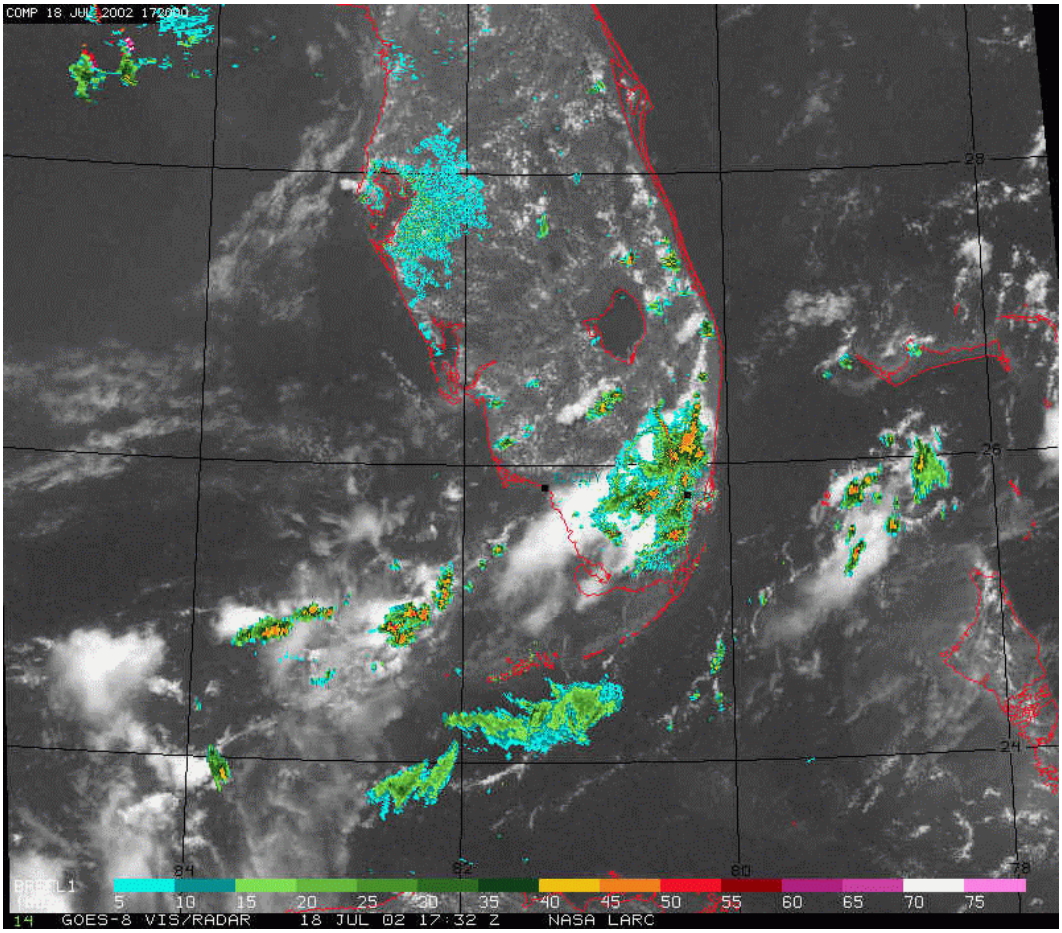

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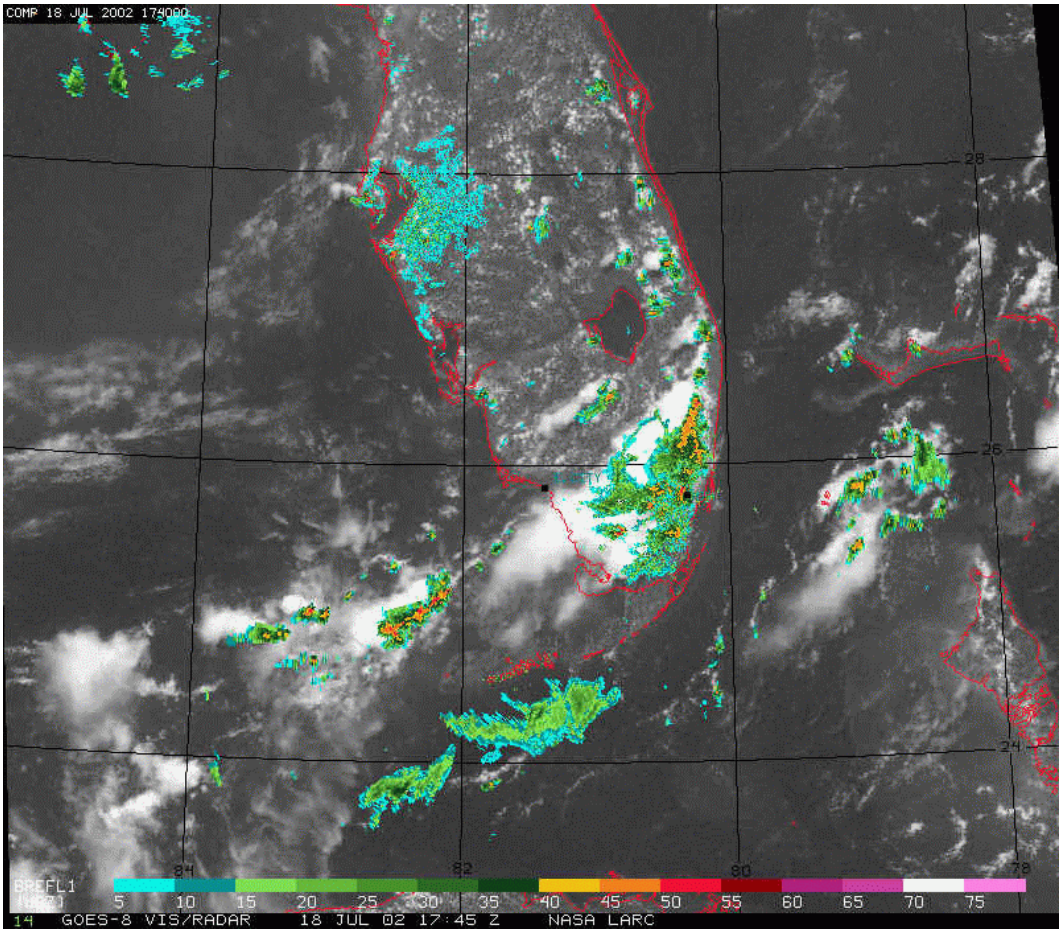

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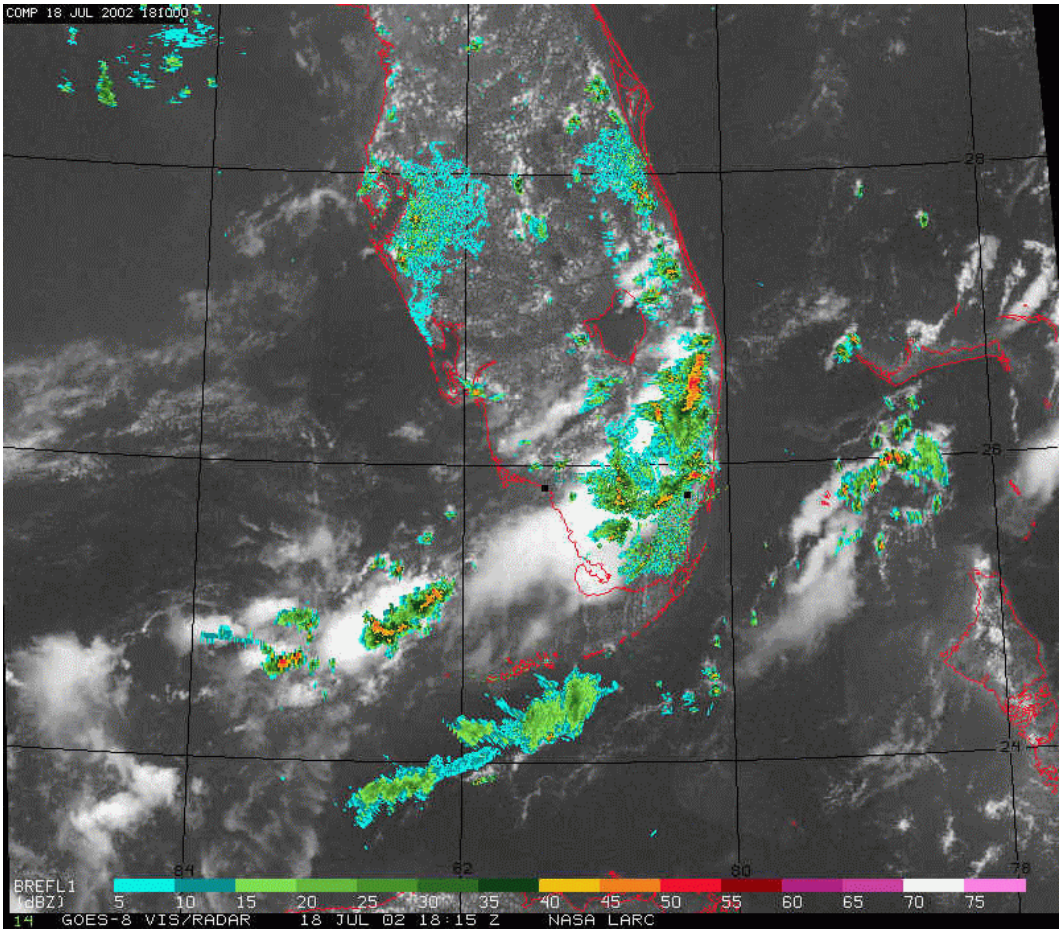
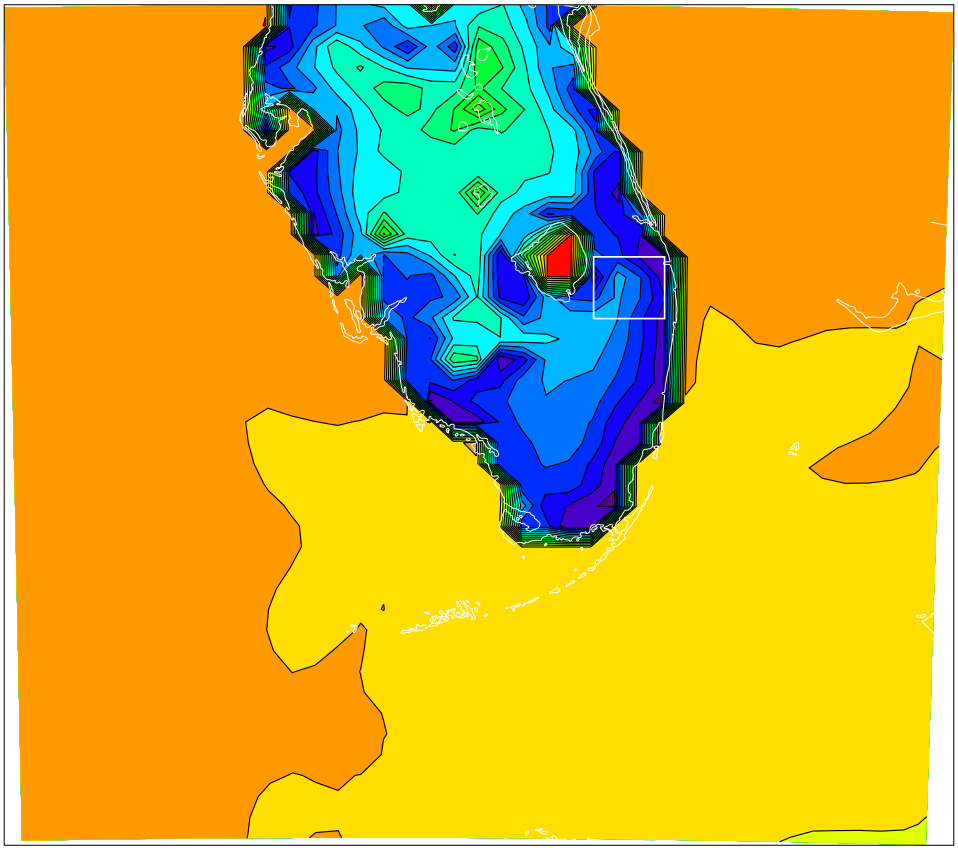


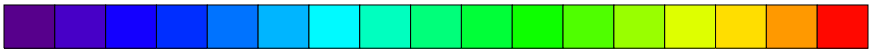
DHARMA model description

- Domain resolution
  - 48 x 48 x 24 km
  - dx = dy = 500 m, dz = 375 m
- Large-eddy simulation dynamics (dt = 5 s)
  - open boundary conditions
  - assimilated meteorology
  - assimilated surface fluxes
- Explicit microphysics (minimum dt = 0.2 s)
  - 16 bins: aerosols (20 nm–1 um), liquid and ice (2 um – 1 cm)
  - aerosol activation/freezing
  - condensation/evaporation
  - coagulation, breakup, and sedimentation
  - homogeneous/heterogeneous ice nucleation
  - Hallett-Mossop rime splintering

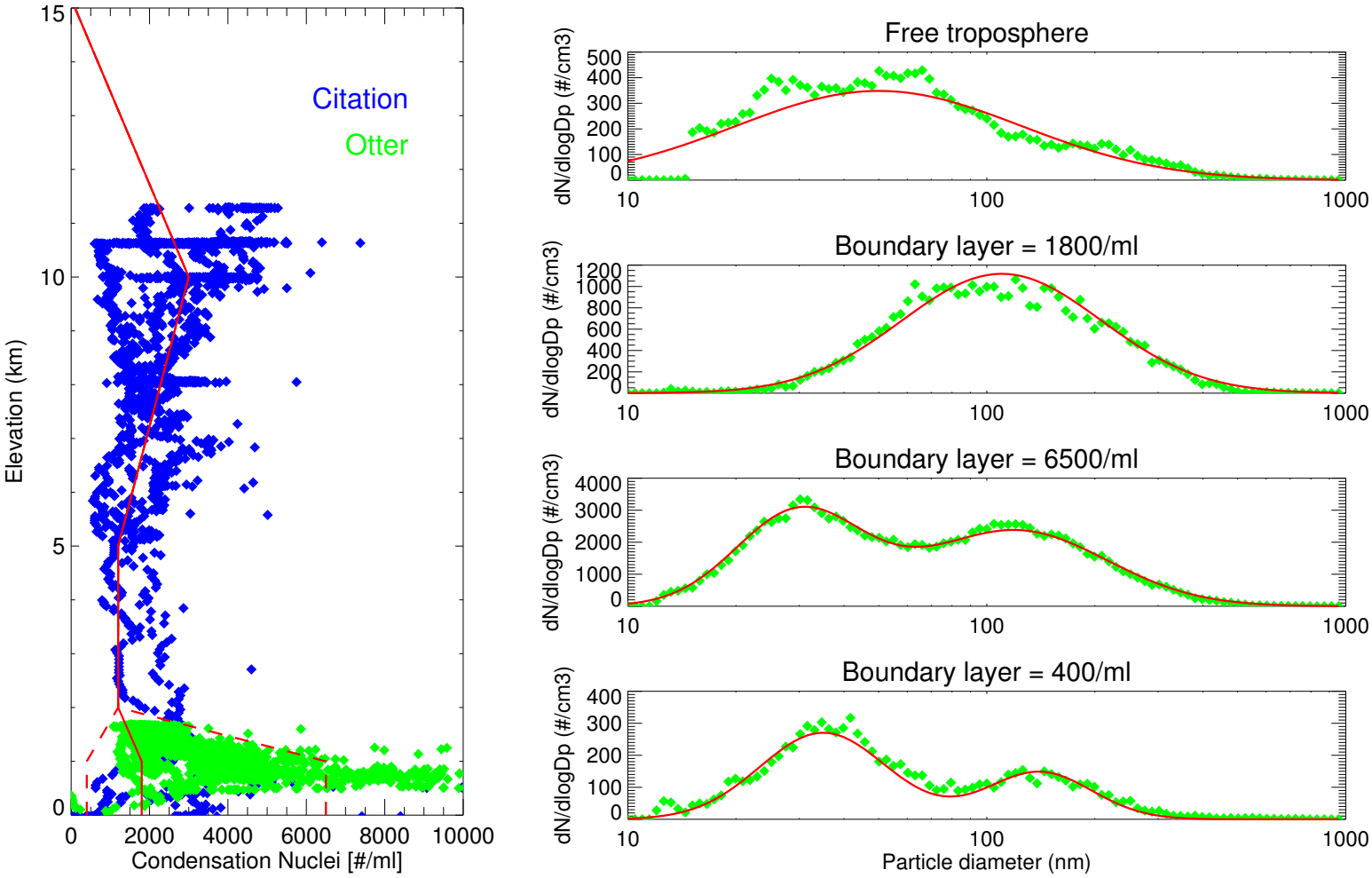
Assimilated surface fluxes: ARPS model



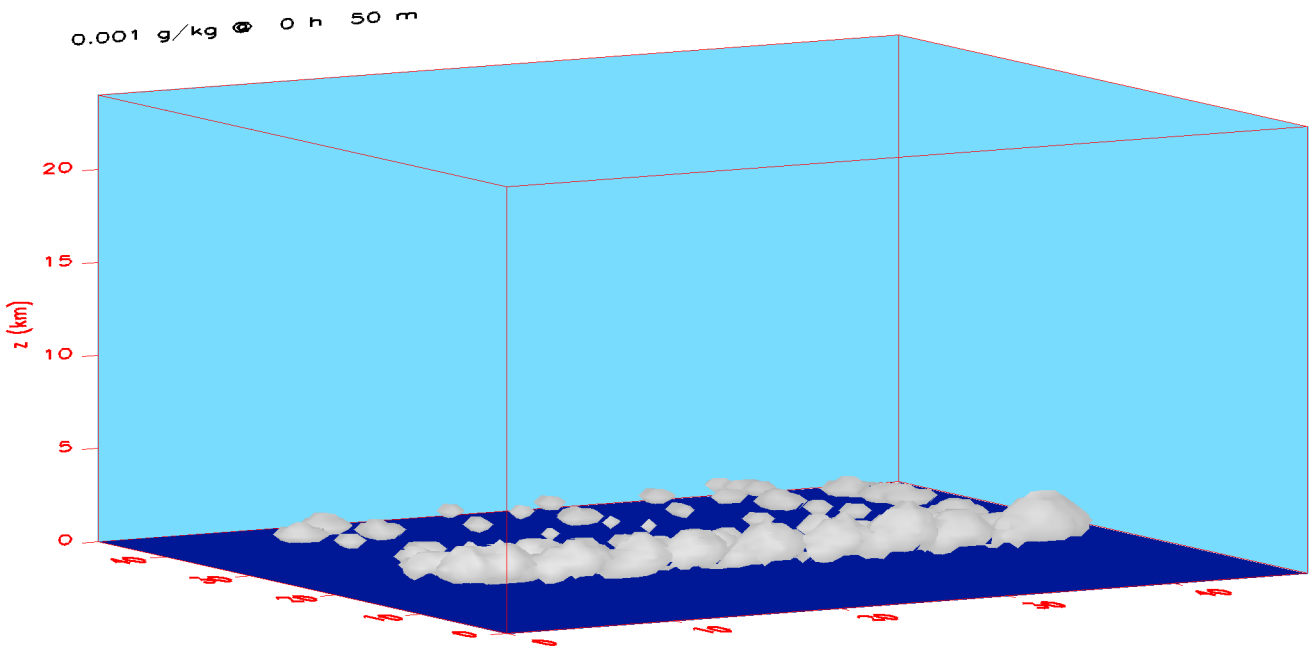
Contour color min,max,delta: -1.600e-01, 1.000e-02, 1.000e-02



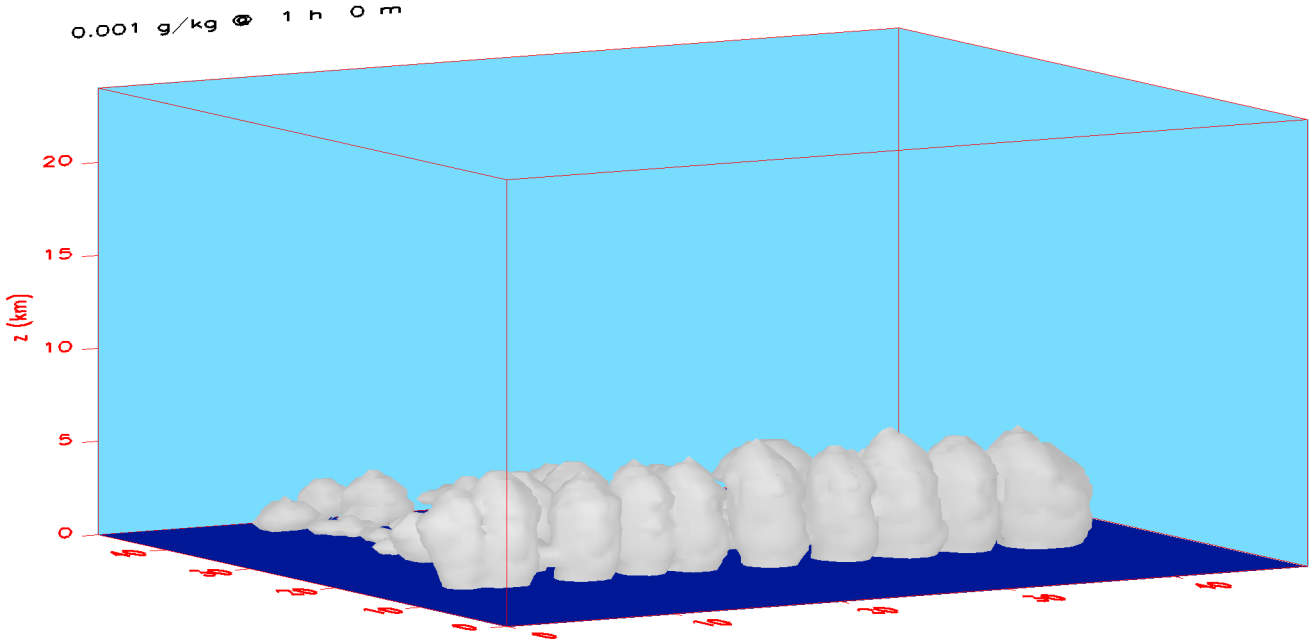
Assimilated aerosol profiles: Aircraft data



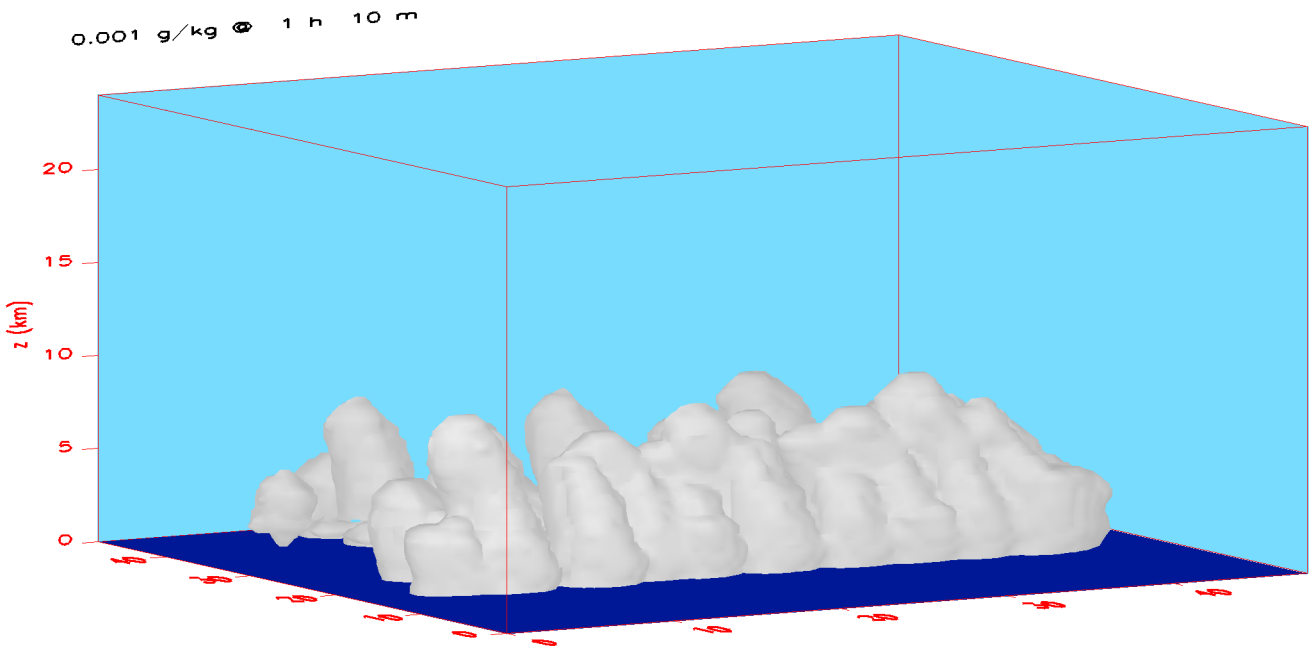
Modeled cloud isosurface



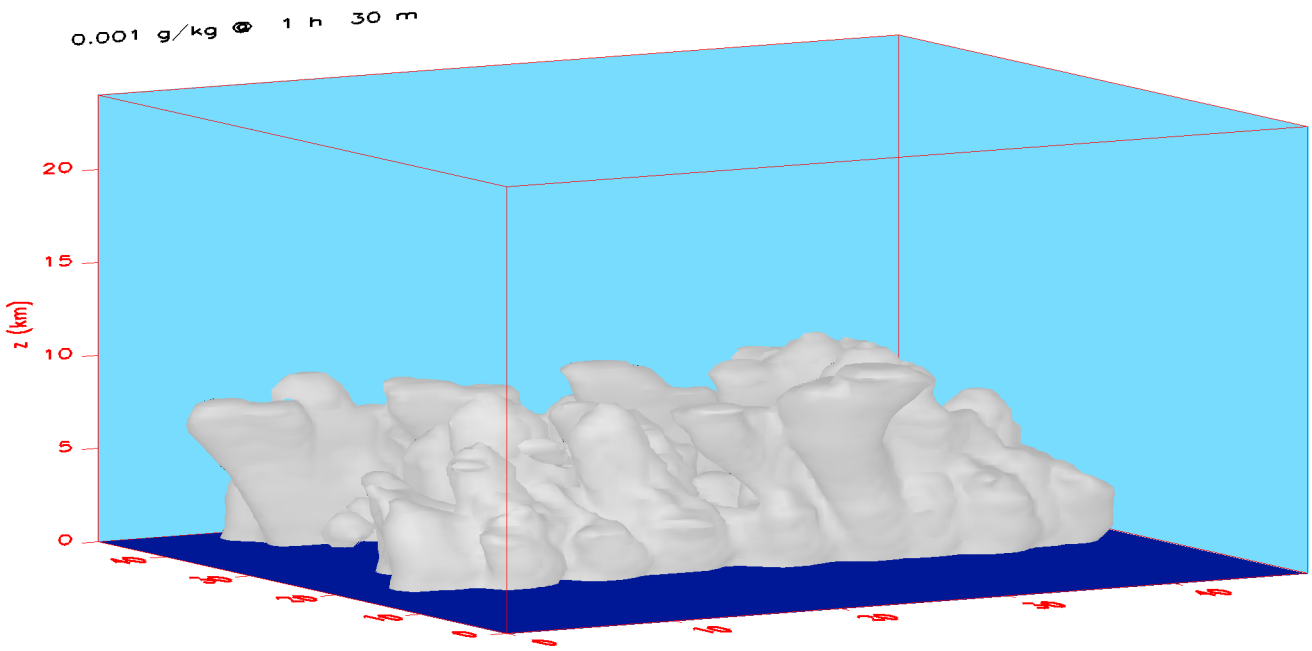
Modeled cloud isosurface



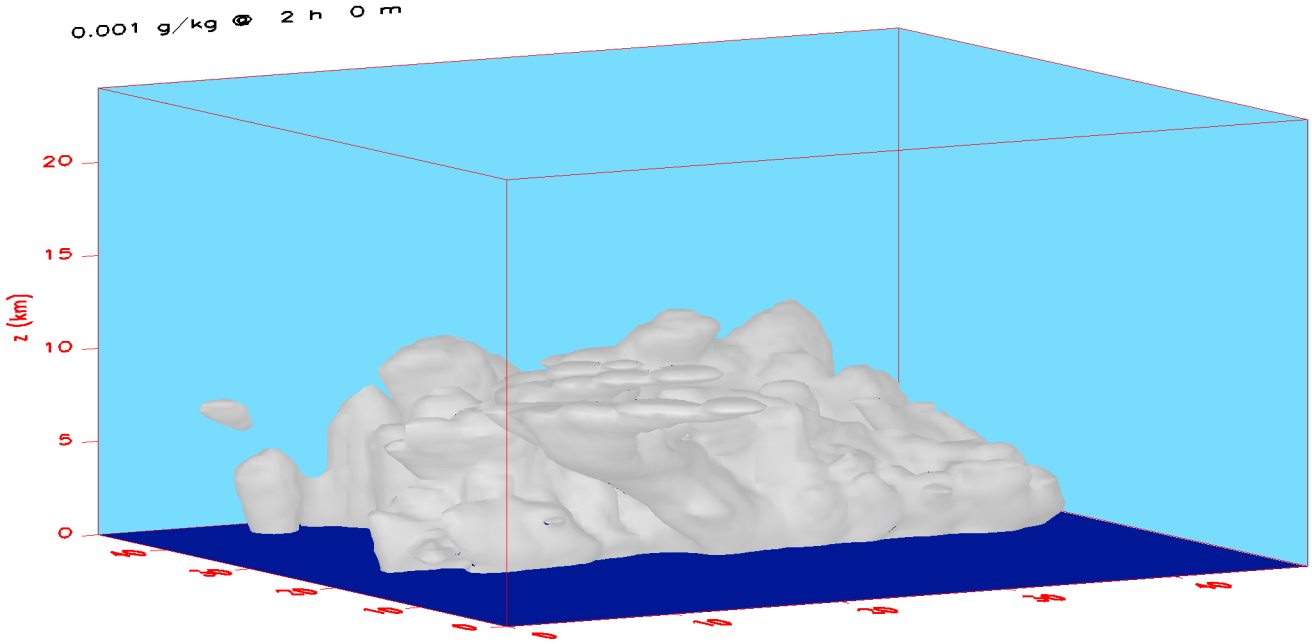
Modeled cloud isosurface



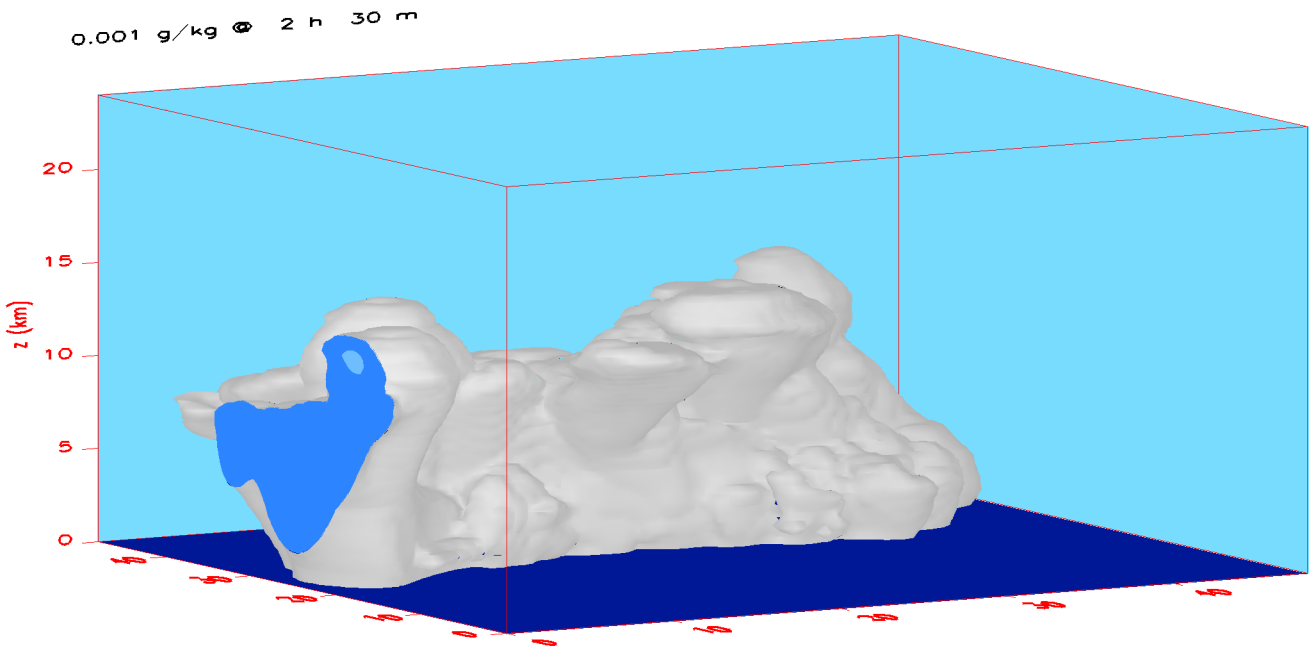
Modeled cloud isosurface



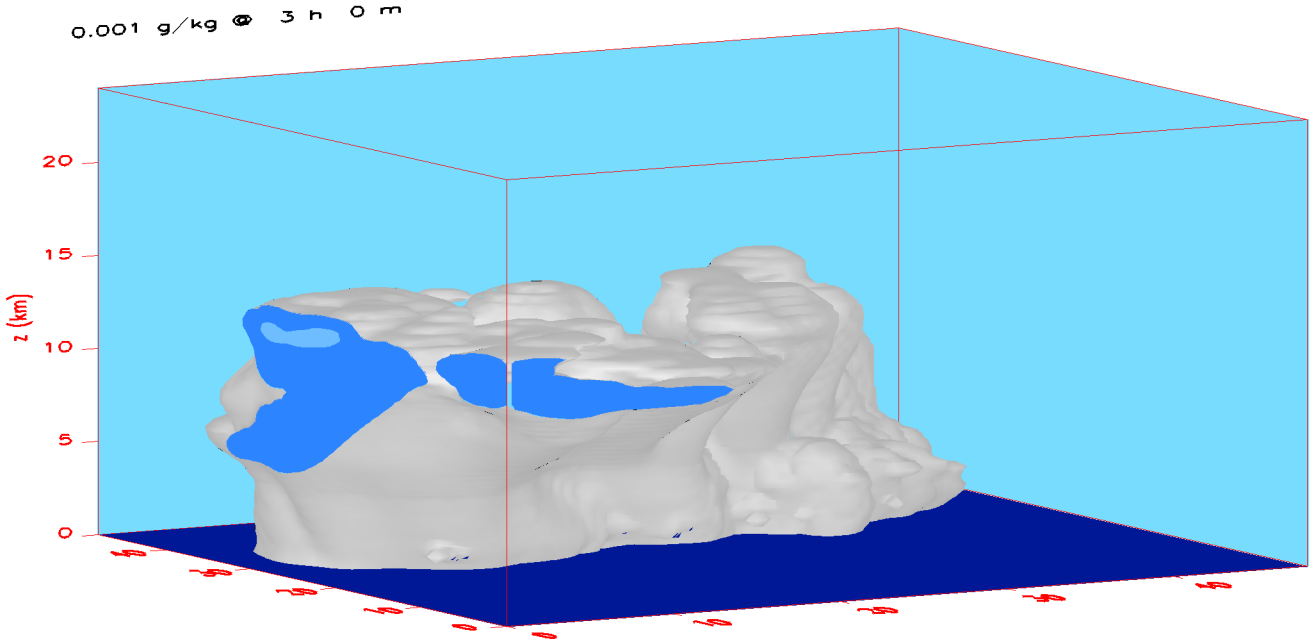
Modeled cloud isosurface



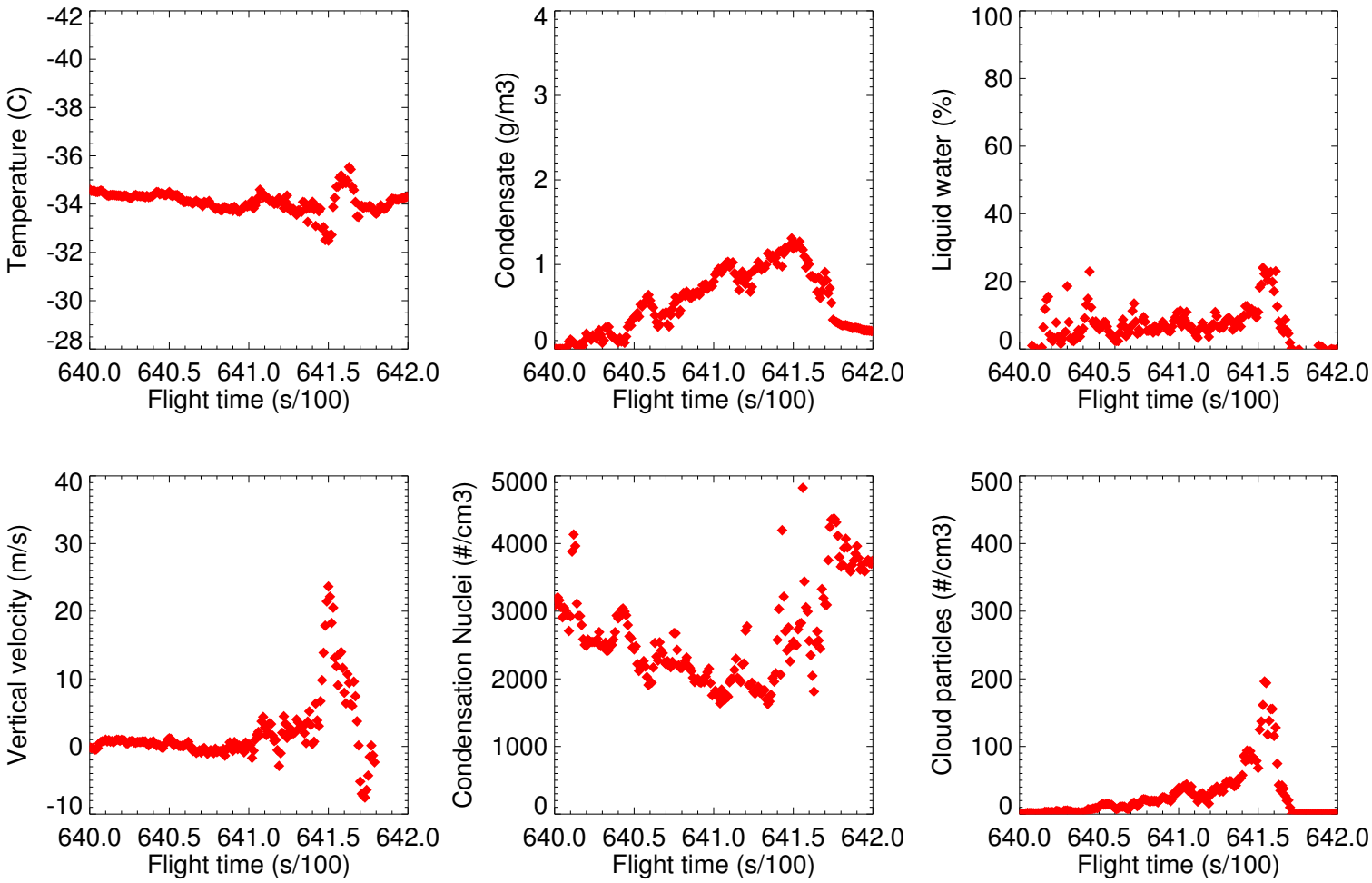
Modeled cloud isosurface



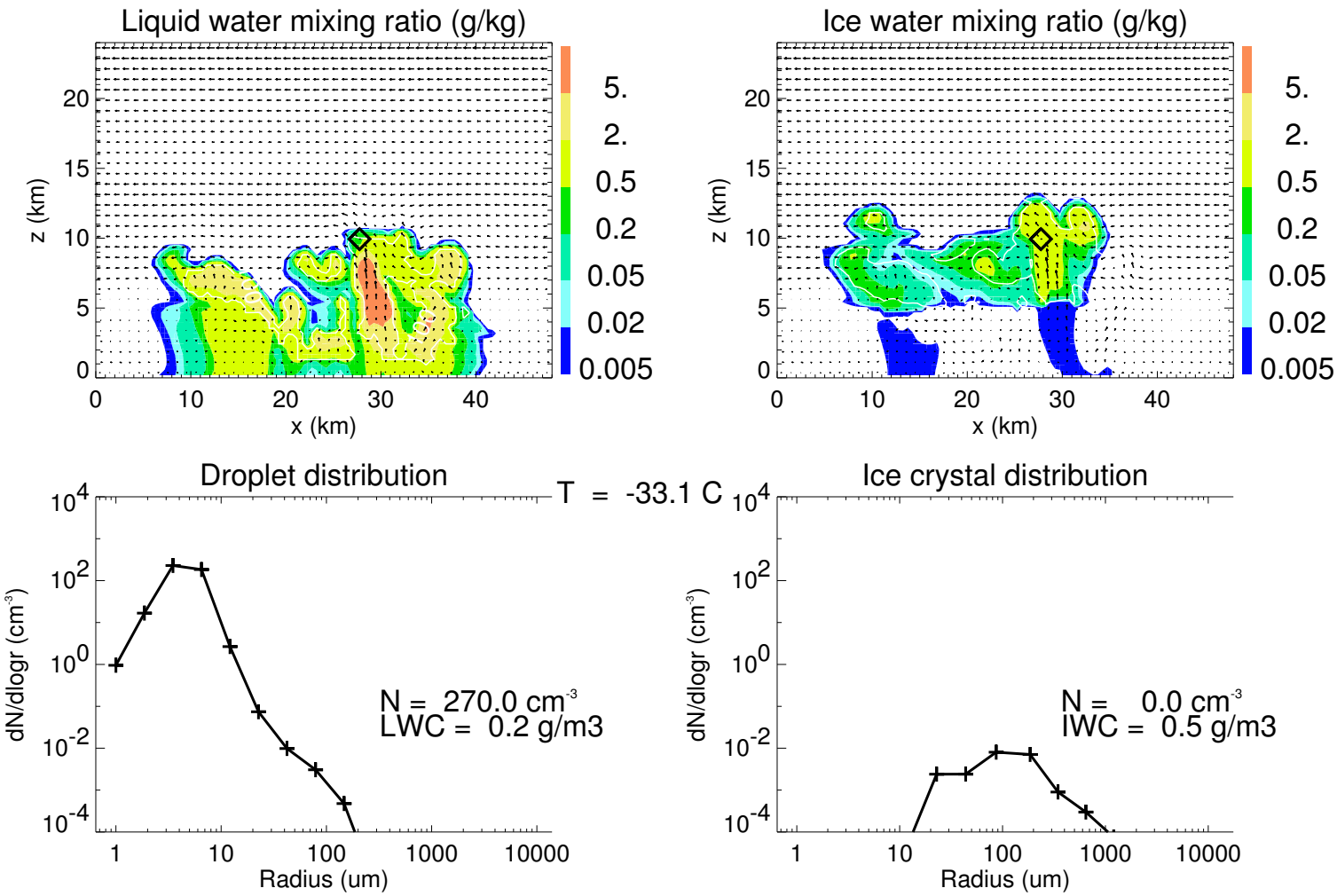
Modeled cloud isosurface



Updraft properties observed by the Citation



Modeled homogeneous ice nucleation within updraft core



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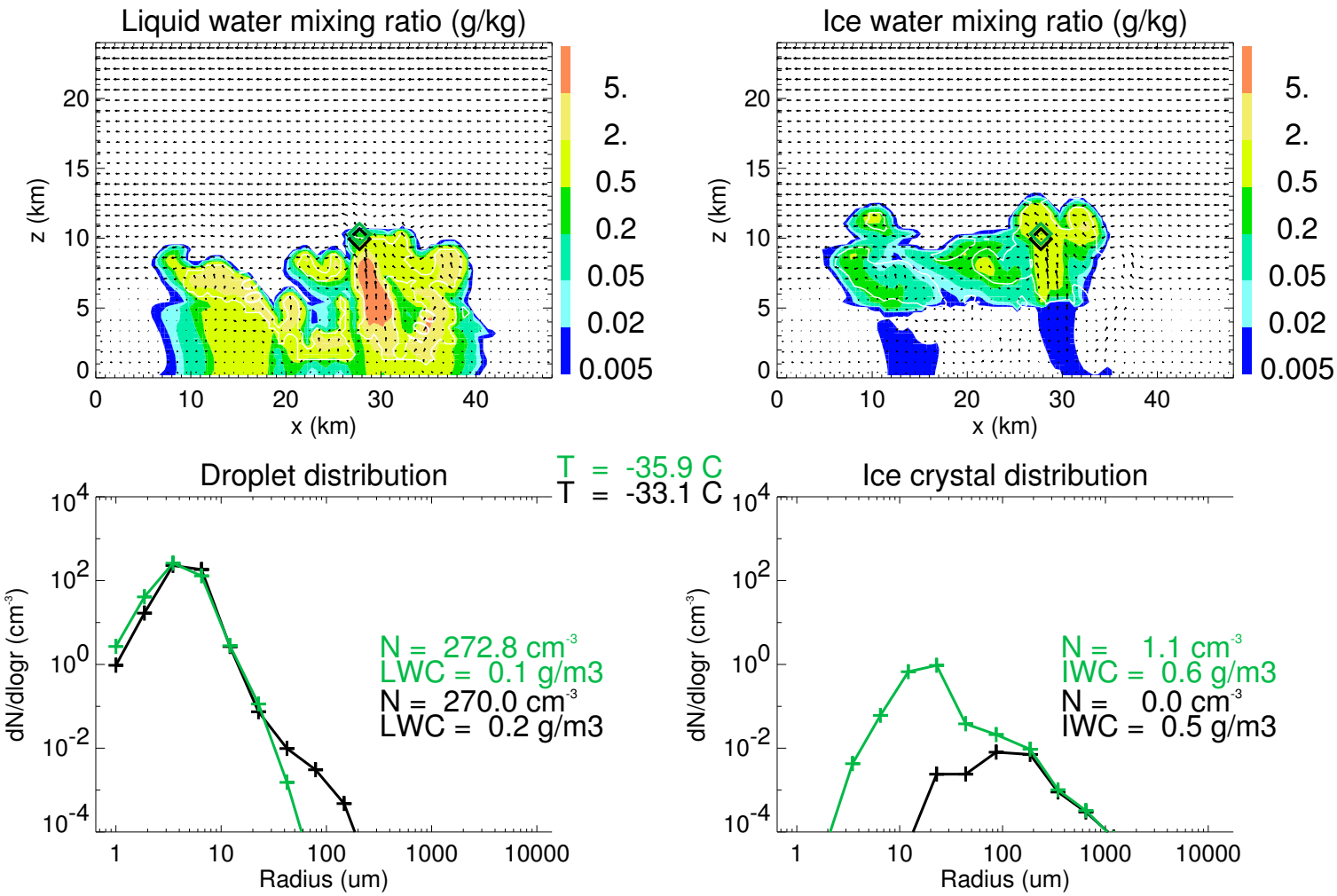

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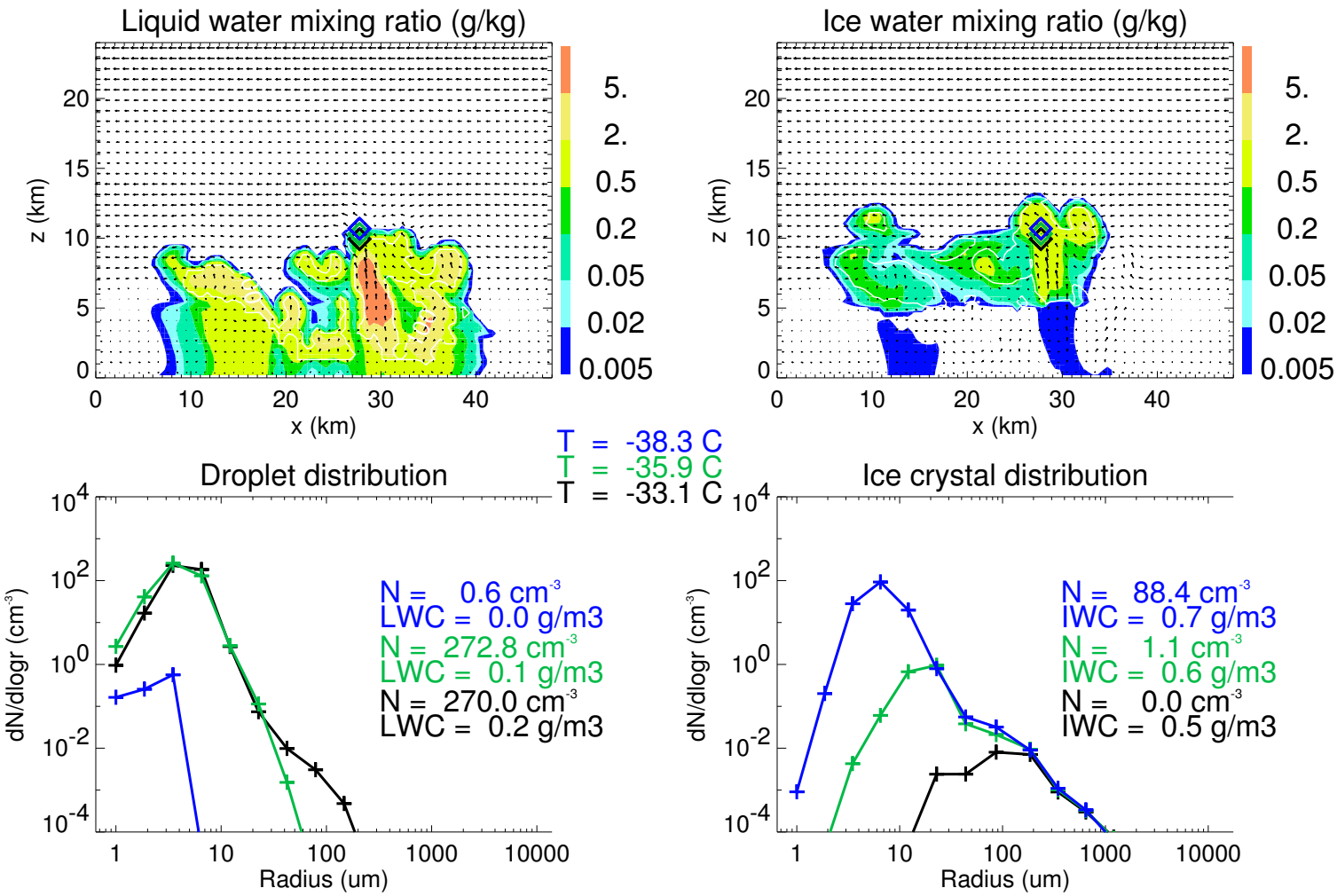

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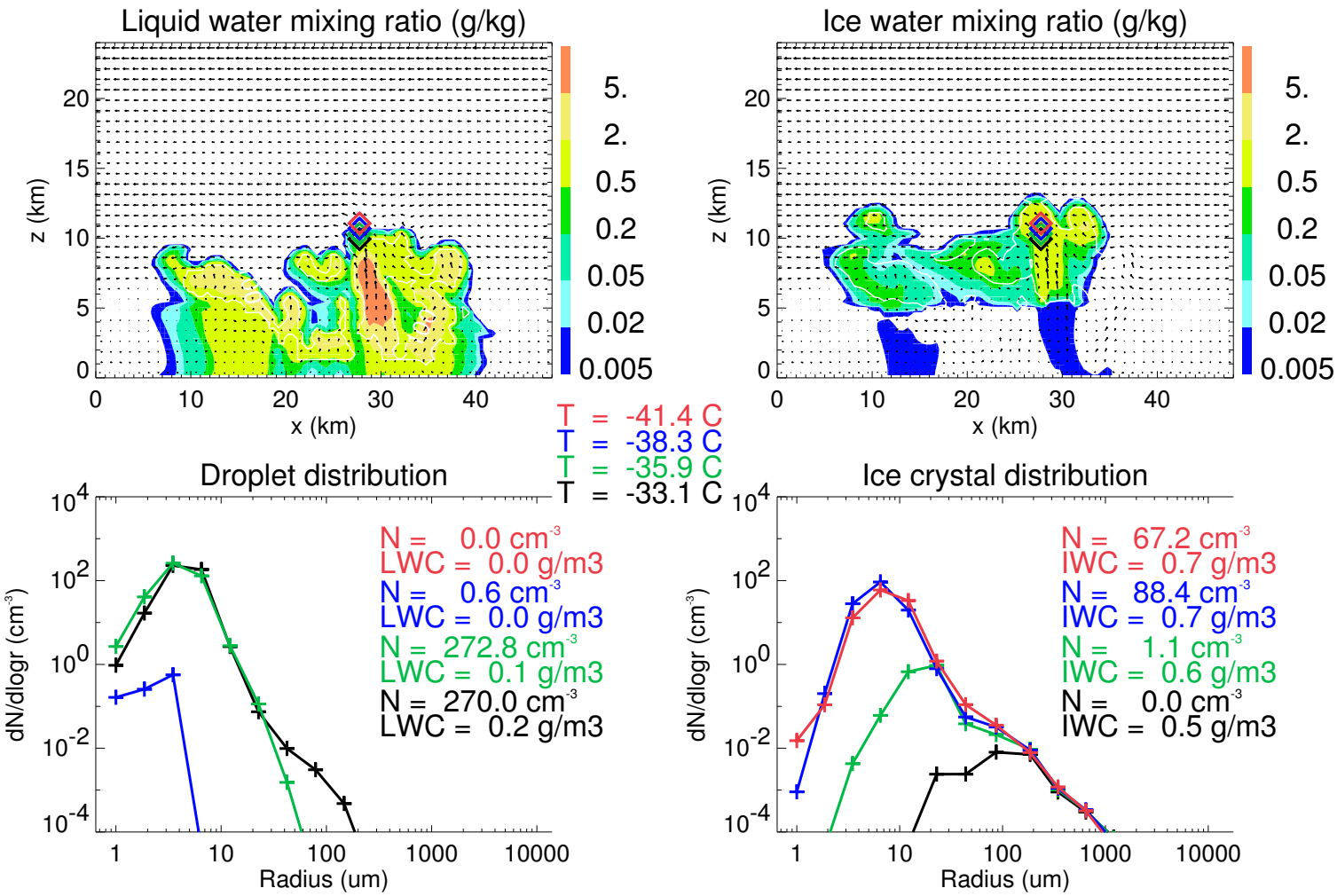

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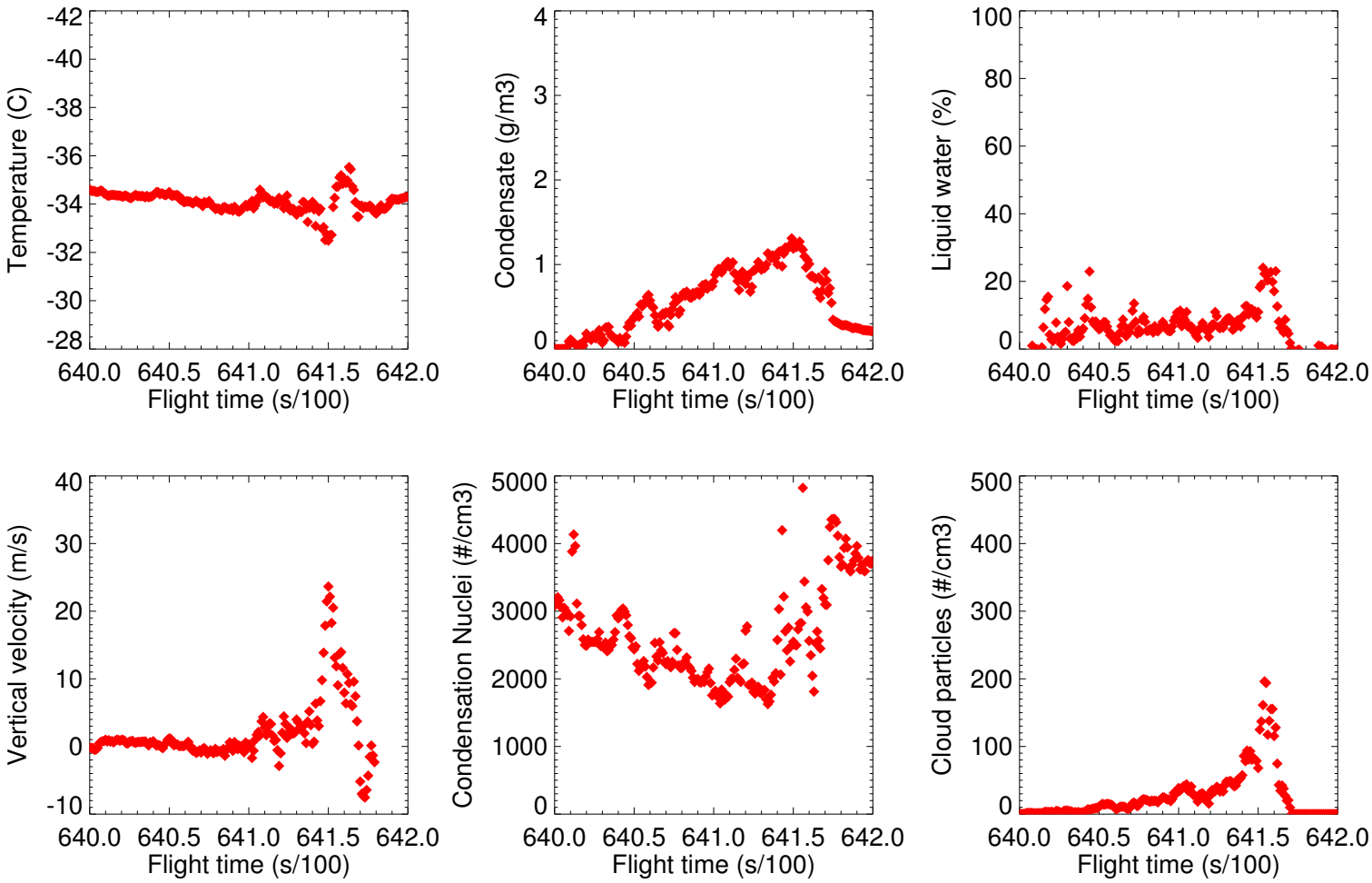
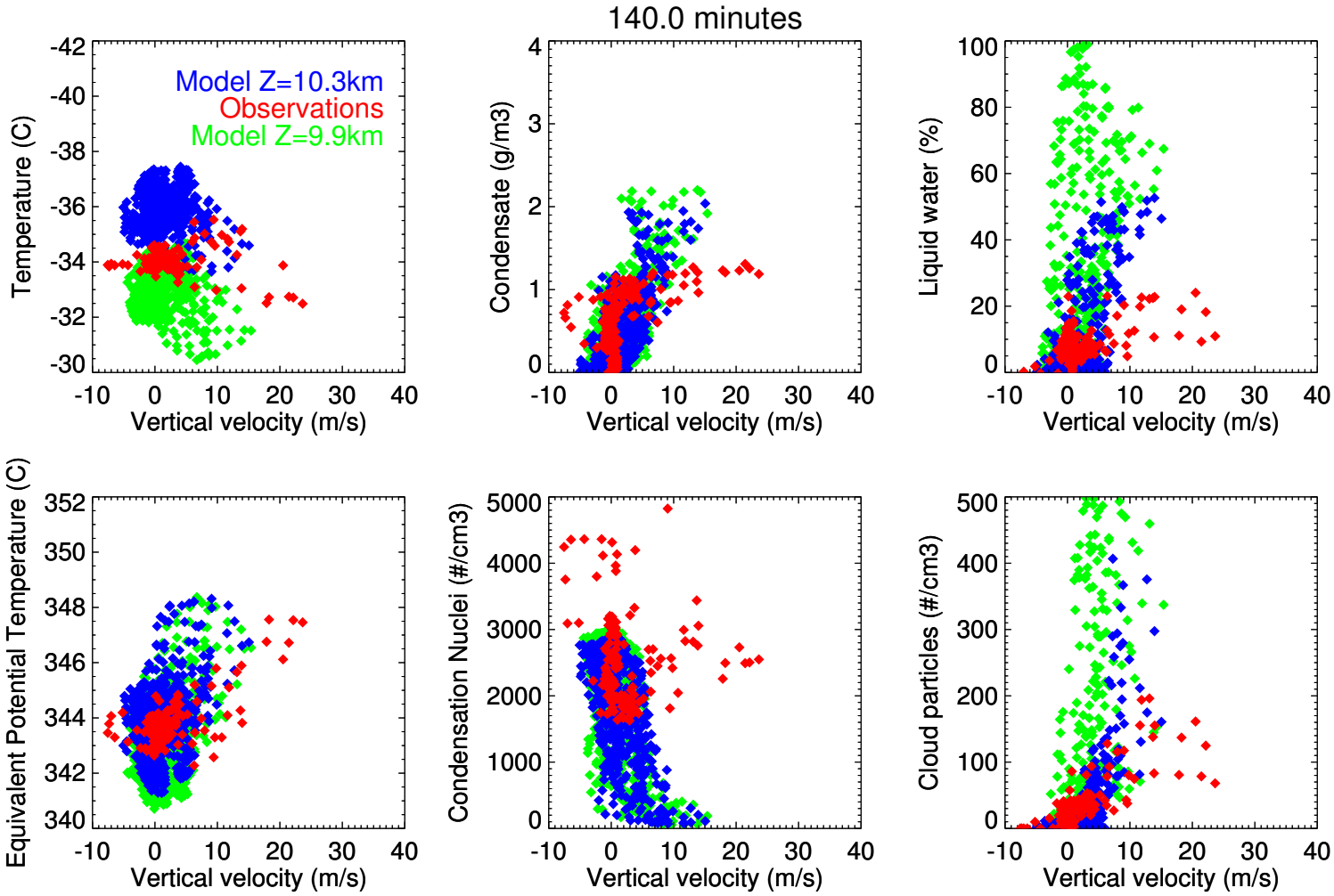


Comparison of modeled updraft properties with observations



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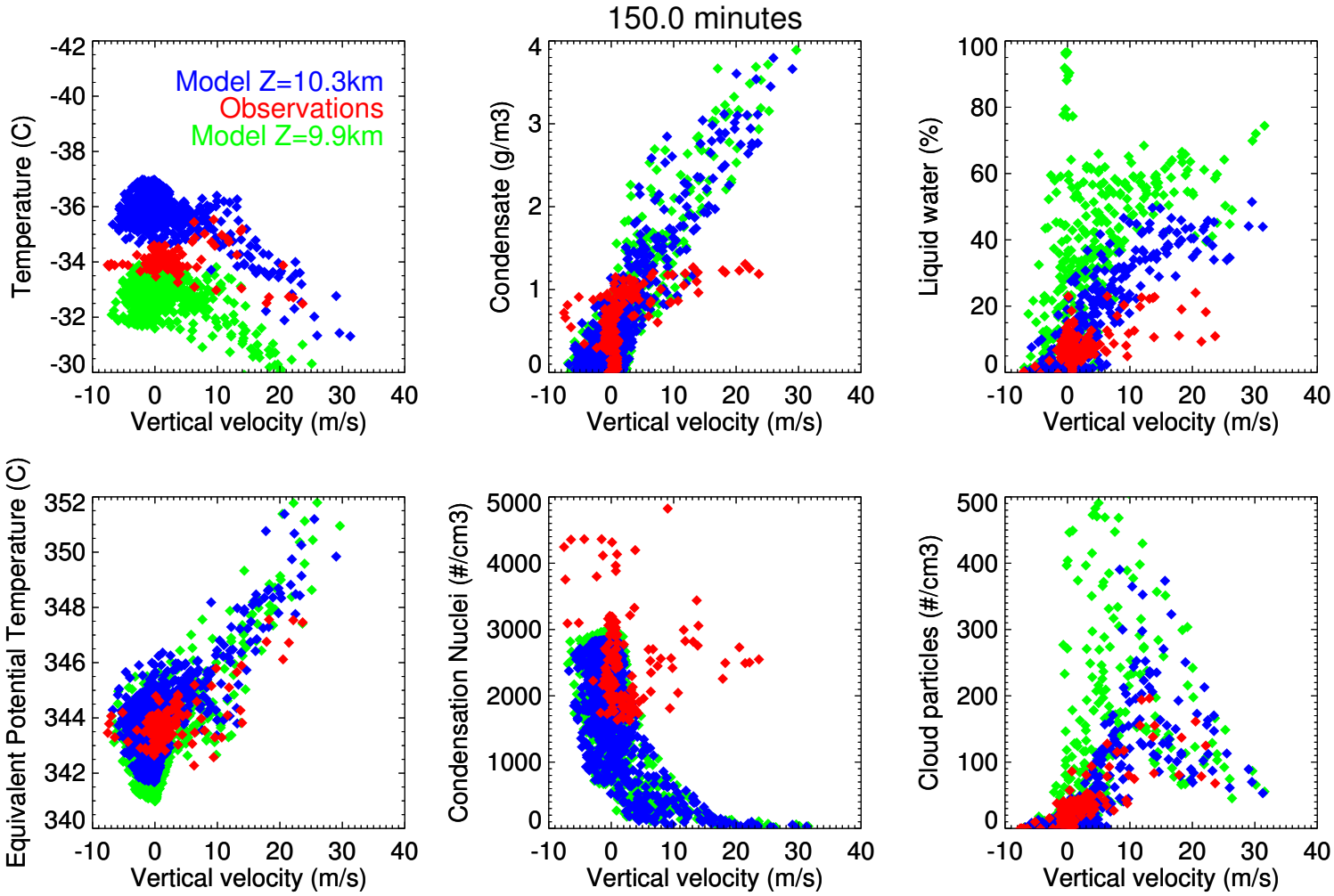

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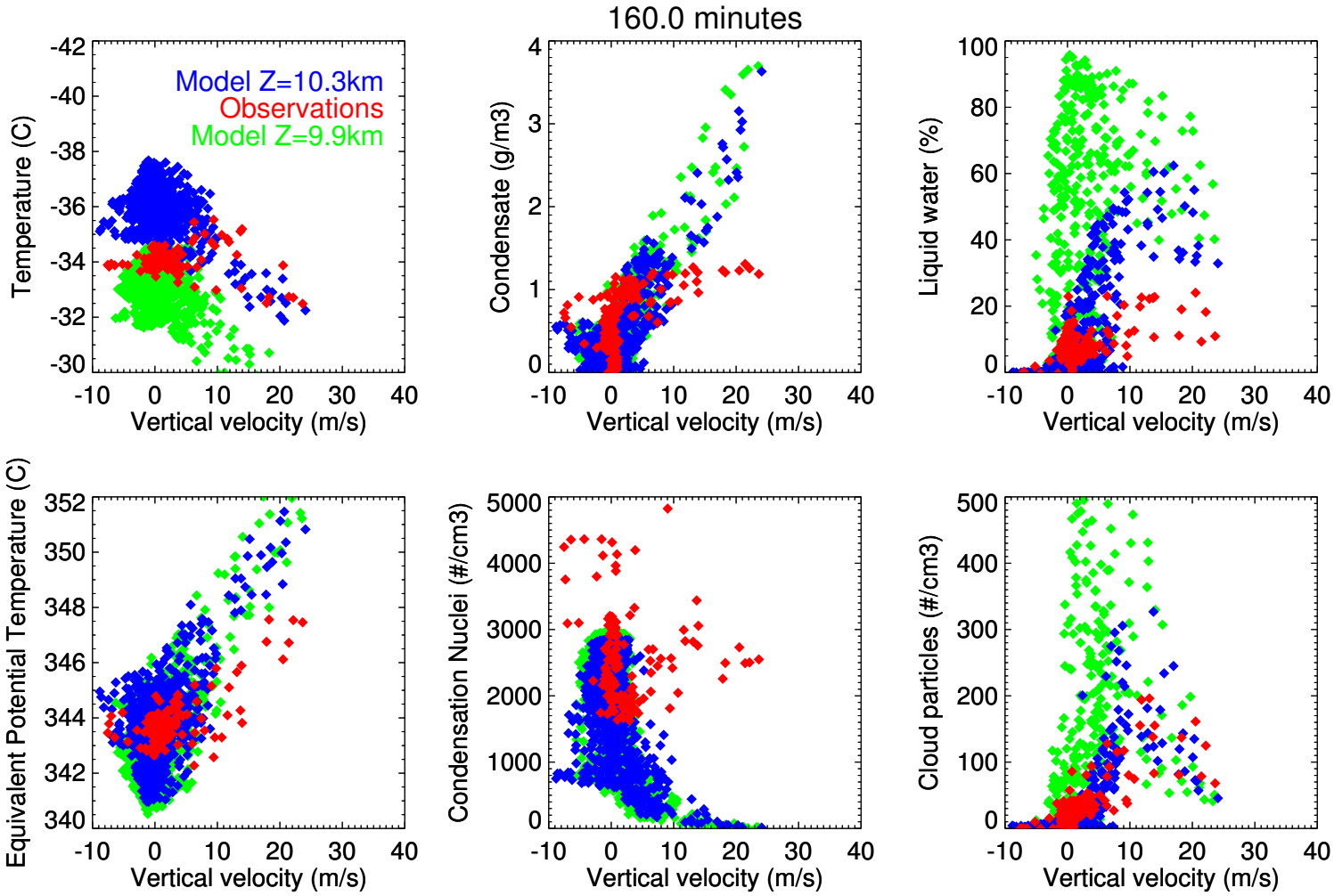
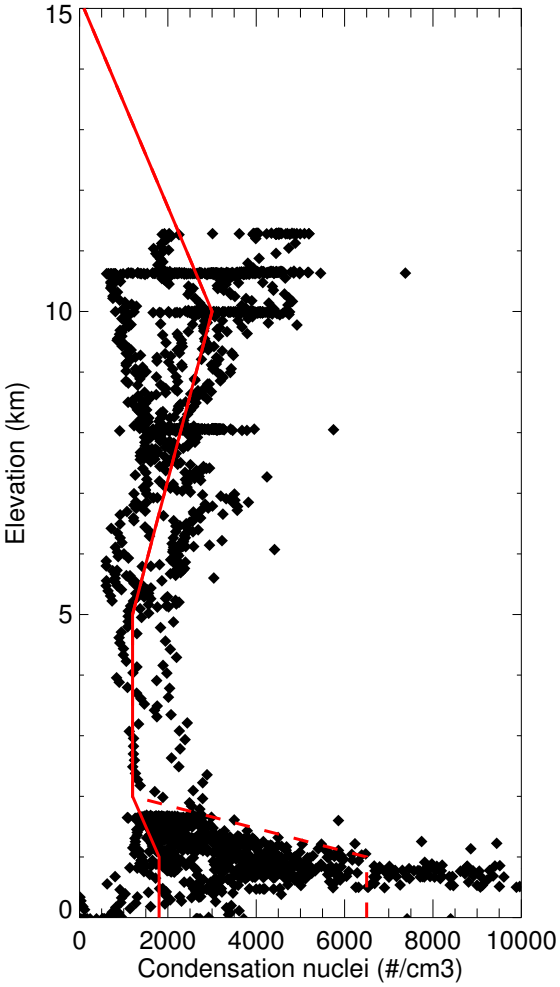
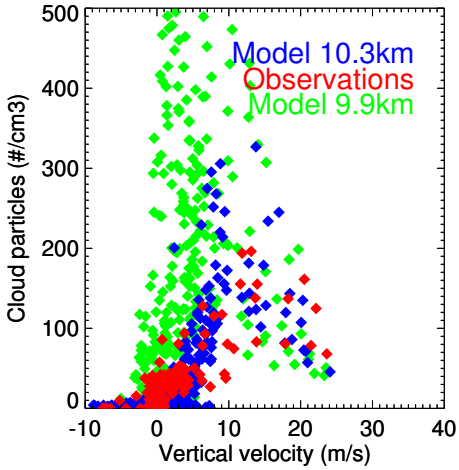


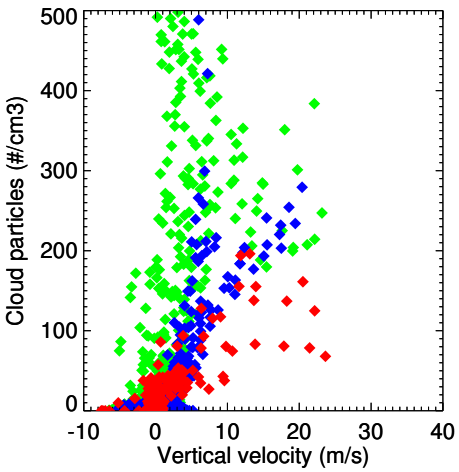
Sensitivity of modeled particle number to boundary layer aerosols



BL N=1800/ml (solid profile)



BL N=6500/ml (dashed profile)



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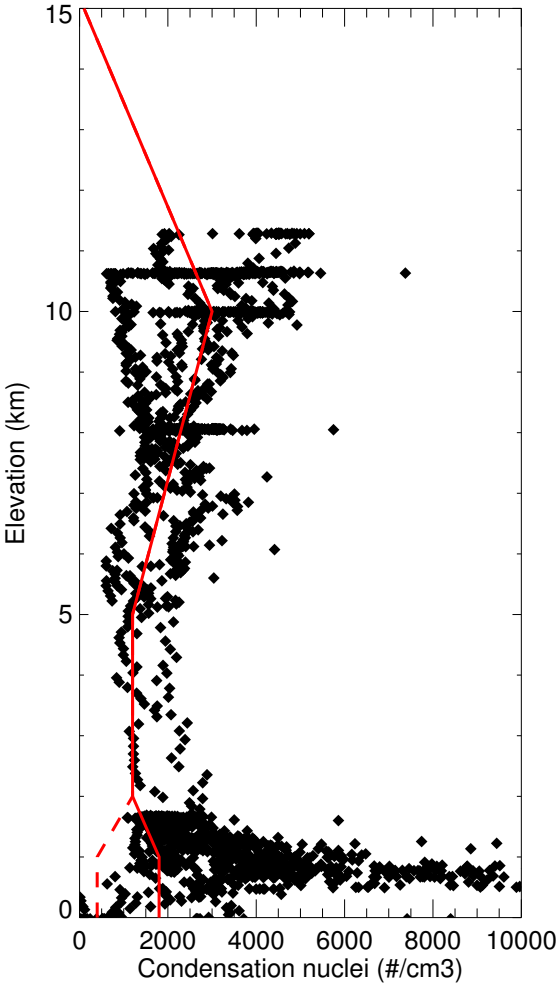
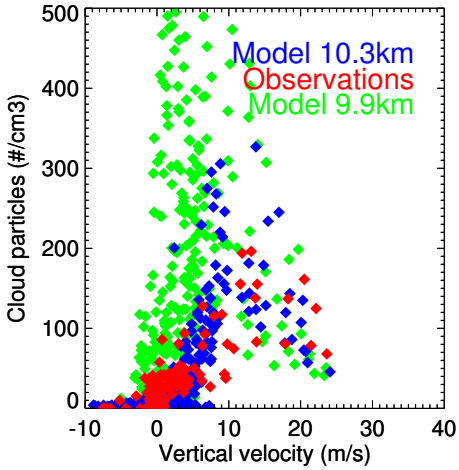
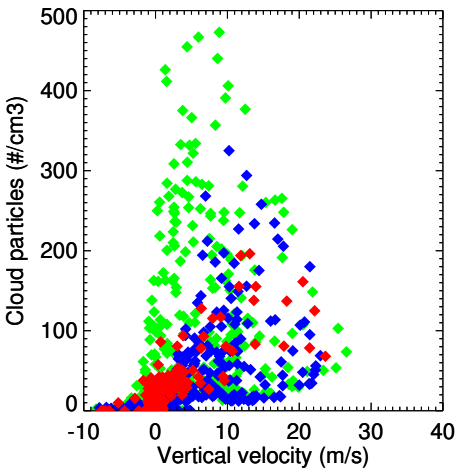


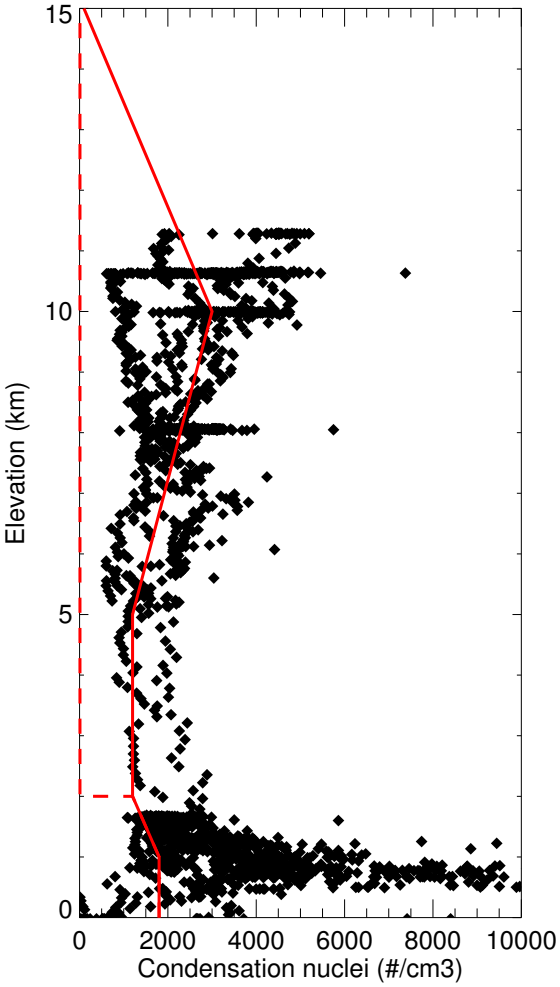
BL N=1800/ml (solid profile)



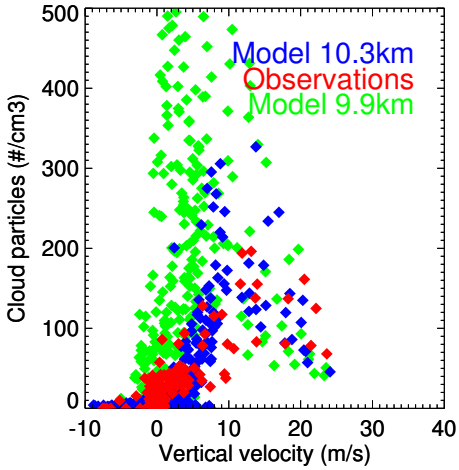
BL N=400/ml (dashed profile)



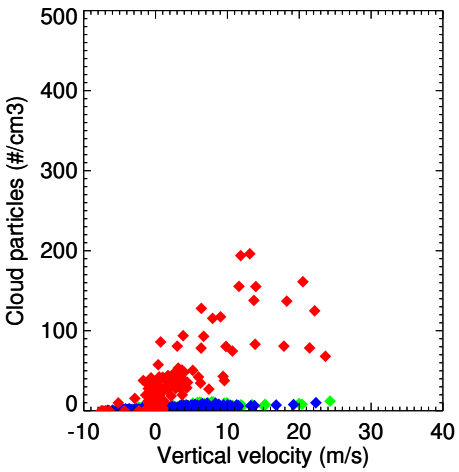
Sensitivity of modeled particle number to free troposphere aerosols



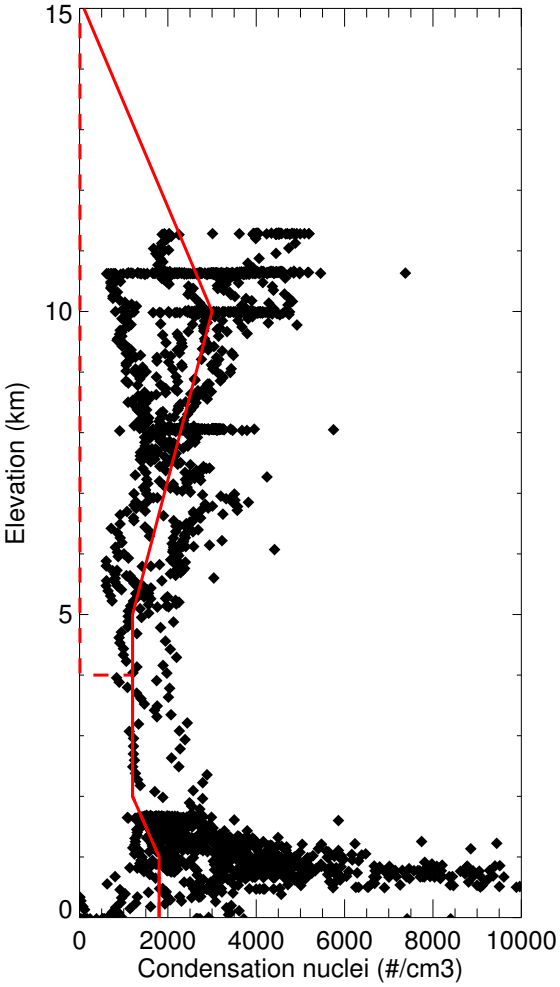
All FT aerosols (solid profile)



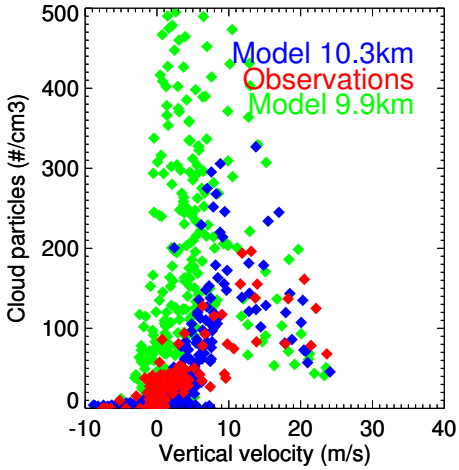
No FT aerosols > 2 km (dashed profile)



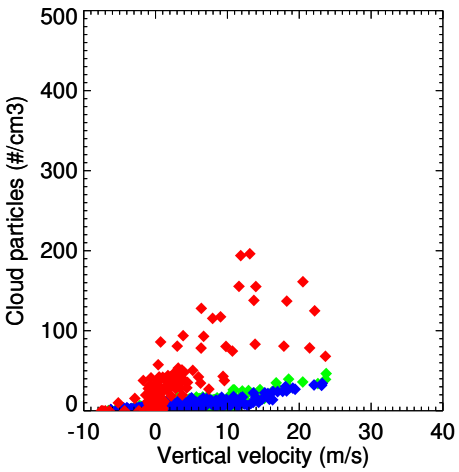
Sensitivity of modeled particle number to free troposphere aerosols



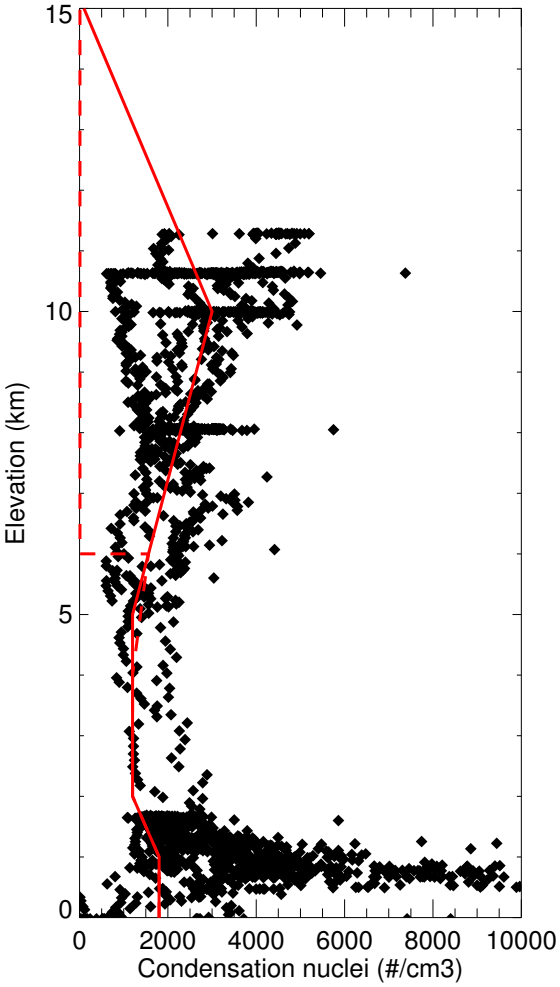
All FT aerosols (solid profile)



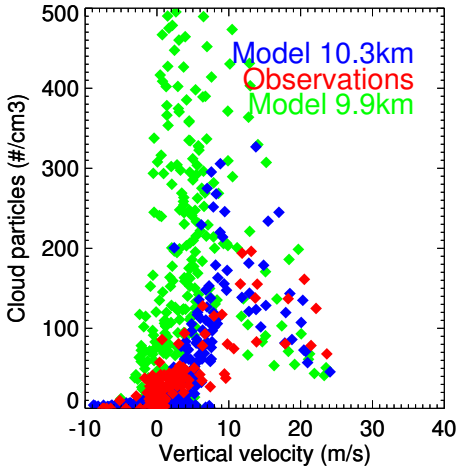
No FT aerosols > 4 km (dashed profile)



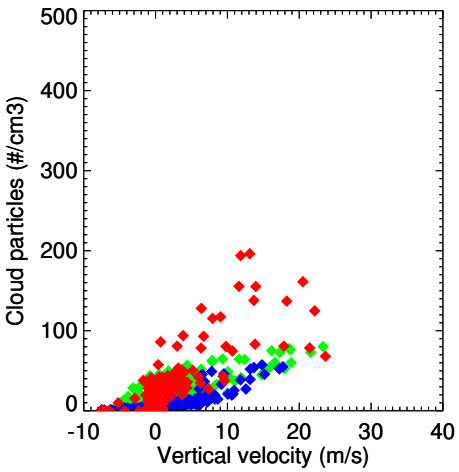
Sensitivity of modeled particle number to free troposphere aerosols



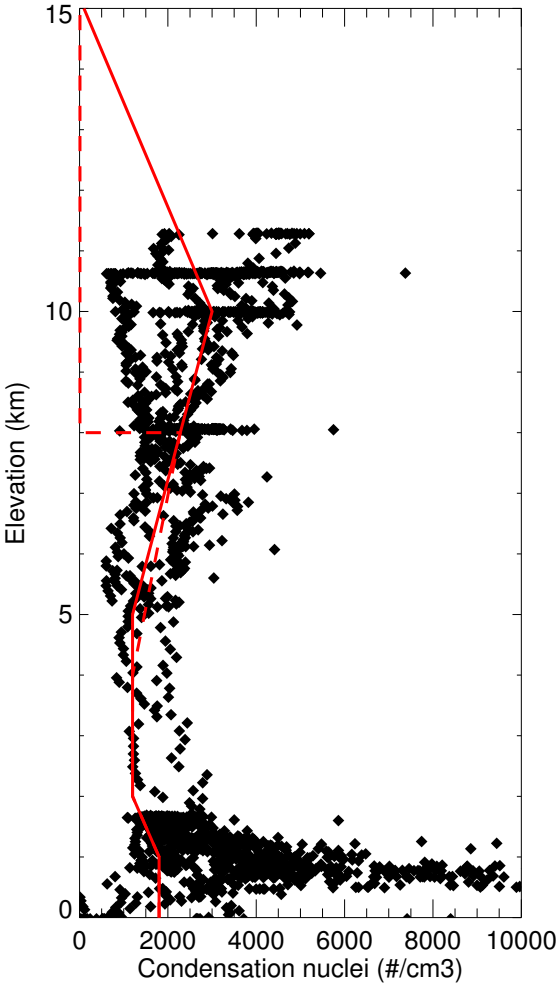
All FT aerosols (solid profile)



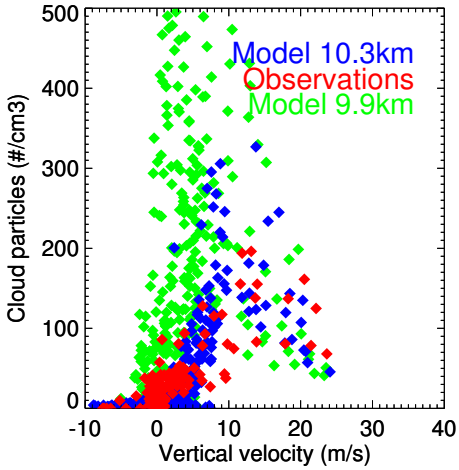
No FT aerosols > 6 km (dashed profile)



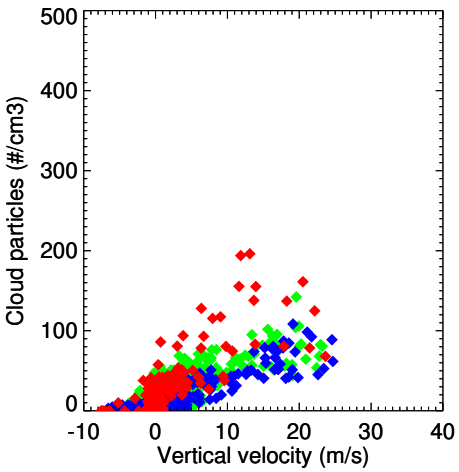
Sensitivity of modeled particle number to free troposphere aerosols



All FT aerosols (solid profile)



No FT aerosols > 8 km (dashed profile)



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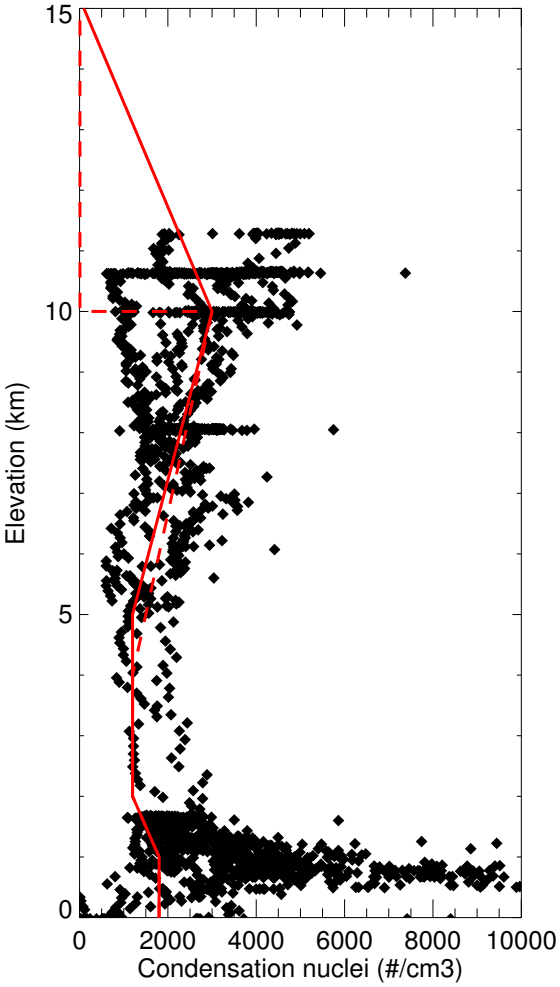

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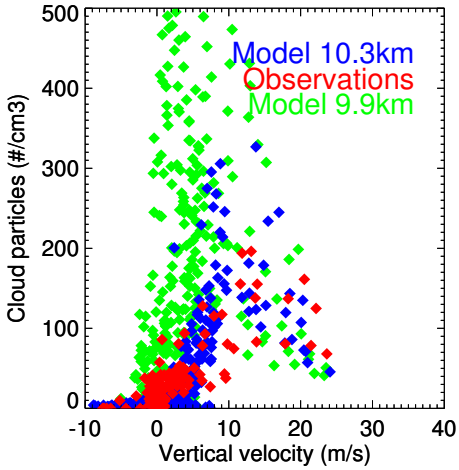
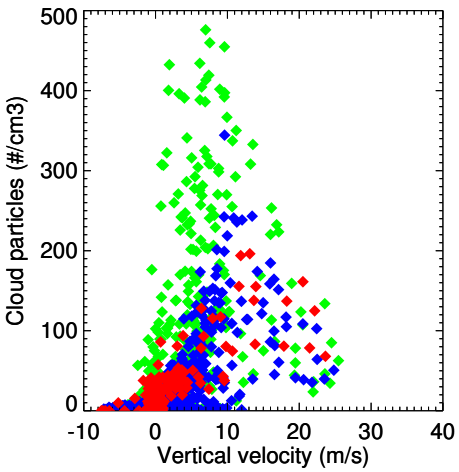
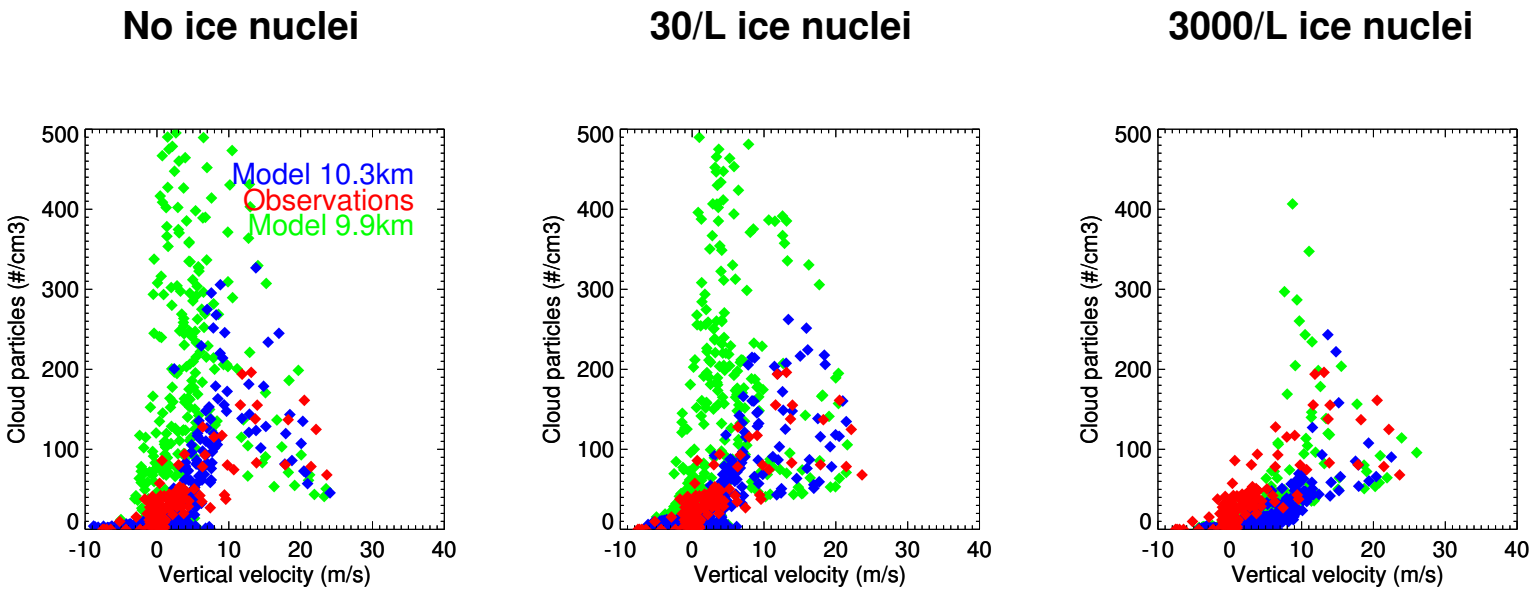


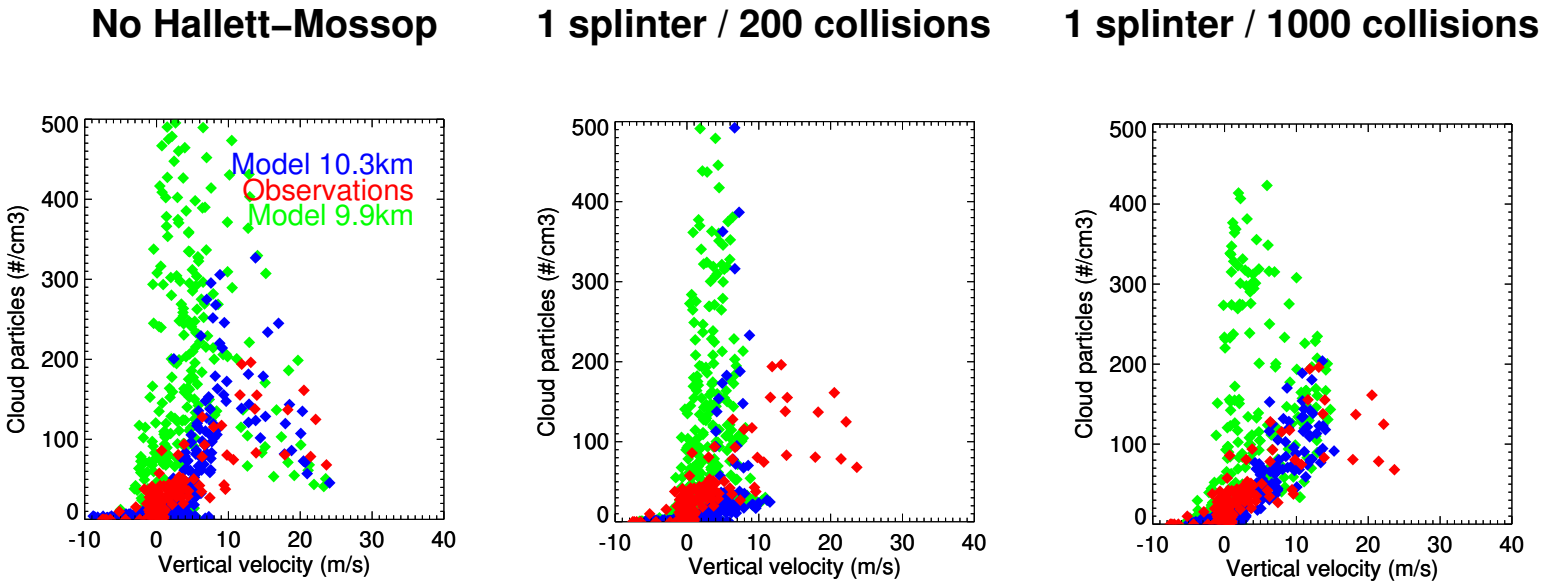
No FT aerosols > 10 km (dashed profile)



Sensitivity of modeled particle number to heterogeneous nuclei



Sensitivity of modeled particle number to ice multiplication



Preliminary conclusions for July 18

- How are most ice crystals nucleated?
  - homogeneous nucleation can account for most crystals
  - immersion nuclei can lower the number of crystals
- What are the primary sources of CCN?
  - boundary layer aerosols have a weak effect
  - free troposphere aerosols have a powerful effect
- Does Hallett-Mossop ice multiplication play a role?
  - yes, conditions are often right

Future work

- Improve aerosol representation
  - WB-57 CN size distributions
  - Citation ice nuclei
  - chemical composition
- Compare predictions with additional observations
  - Citation cloud particle number size distributions in the updraft
  - Twin Otter droplet number size distributions at cloud base
  - WB-57 crystal number size distributions
- Estimate measurement uncertainty
- Estimate model uncertainty
  - space
  - time
  - bin resolution
  - microphysical parameterizations