Susceptibility of TTL cirrus to heterogeneous nuclei

Eric Jensen, Rei Ueyama, and Leonhard Pfister

- How do TTL water vapor concentration, relative humidity, cirrus microphysical properties, and cirrus occurrence frequencies change if the abundance of heterogeneous ice nuclei changes?

- Ueyama et al., "Dynamical, convective, and microphysical control on wintertime distributions of water vapor and clouds in the tropical tropopause layer", *JGR*, in review. **See poster.**

- Motivation: Heterogeneous IN changes ➔ climate change

Data sources:
- ATTREX clouds (S. Woods, P. Lawson)
- ATTREX water, temp. (G. Diskin, J. DiGangi, T. Thornberry, A. Rollins, P. Bui)
- CALIOP clouds (M. Avery)

Homogeneous vs heterogeneous ice nucleation

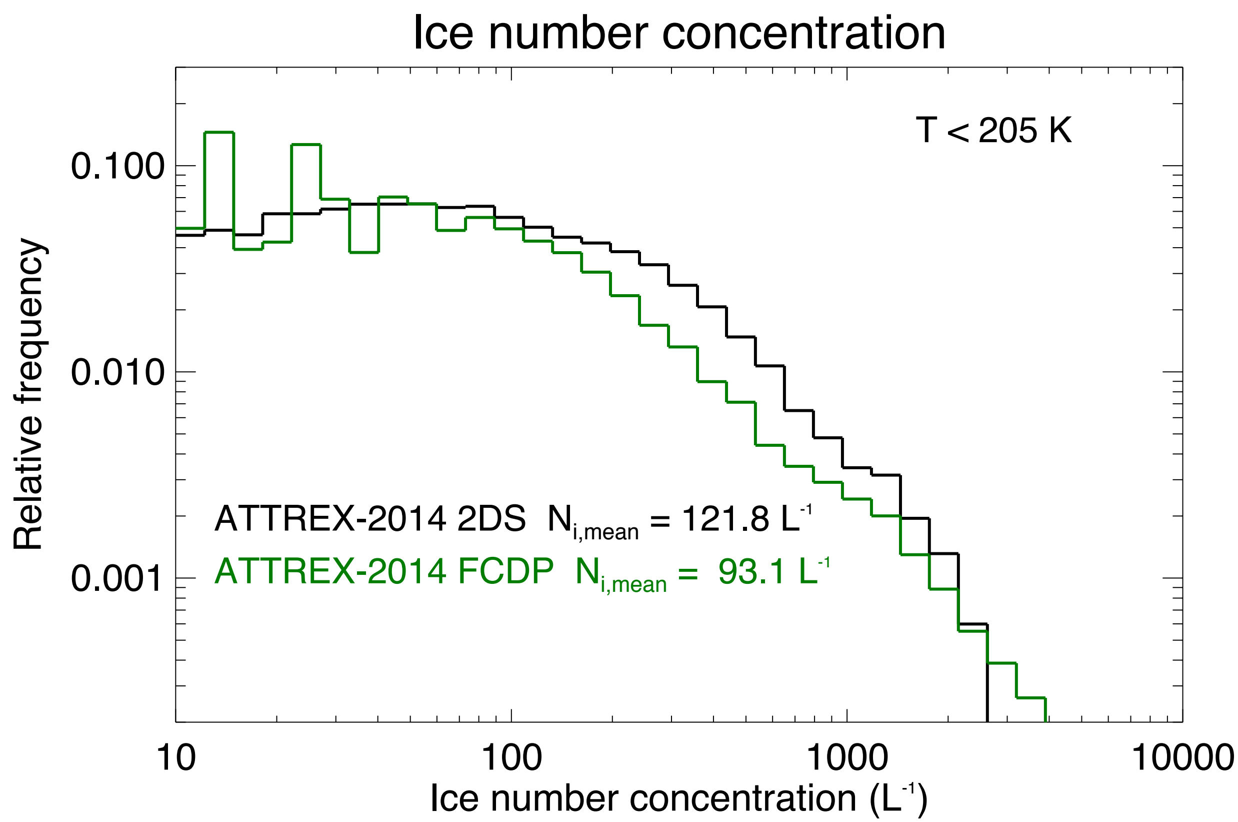
- **Homogeneous freezing of aqueous aerosols**
  - General assumption is that most aerosols are aqueous sulfates (with other stuff)
  - Freezing occurs at $S_{ice} \approx 1.6$–1.7 (RHI = 160–170%)
  - Freezing threshold is apparently composition independent, but small variations matter
  - Always plenty of aerosols (N_{aer} = 10–10,000 cm^{-3}, $N_{ice} < 1\ cm^{-3}$)

- **Heterogeneous nucleation on solid particles**
  - Heterogeneous freezing on insoluble components in aqueous aerosols
  - Deposition nucleation on dry particles
  - Occurs at lower supersaturations ($S_{ice} \approx 1.1$–1.6)
  - Limited population of heterogeneous ice nuclei (IN, $N_{IN} < 100\ L^{-1}$ (typically, no direct measurements in TTL))

- **Potential TTL IN**
  - Mineral dust
  - Metallic particles
  - Effloresced ammonium sulfate
  - Glassy organic-containing aerosols

IN potentially changing as a result of invasive humans

Hawkeye TTL cirrus measurements: ice concentration

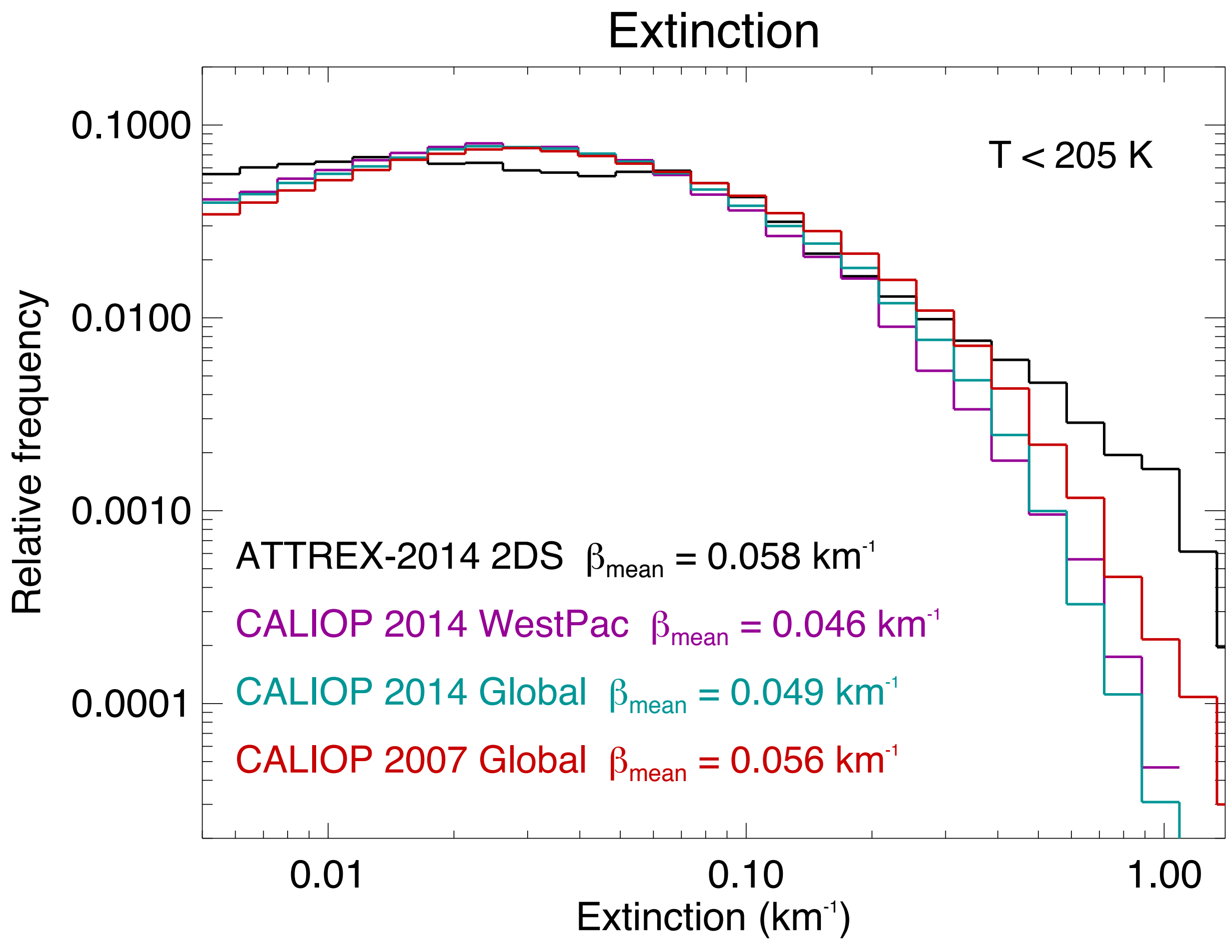


2DS: optical array probe (10–4000 μm)

FCDP: spectrometer (1–50 μm)

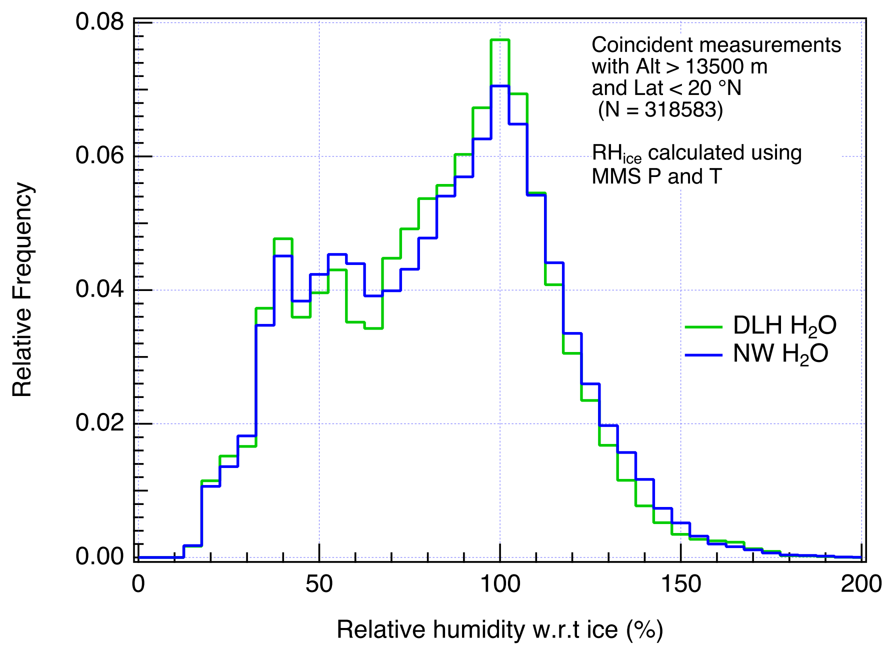
- Reasonable consistency between different measurements of ice concentration

Hawkeye/CALIOP TTL cirrus measurements: extinction

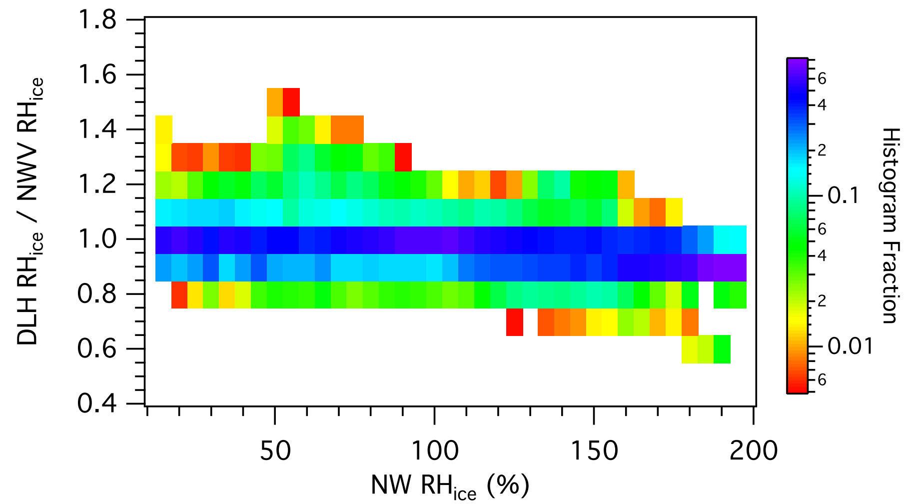


- 2D-S (direct extinction measurement) has larger values than CALIOP (sampling bias?)
- Relatively small regional and interannual differences

ATTREX relative humidity measurements



- Diode Laser Hygrometer (DLH): Open-path TDL [G. Diskin]
- NOAA Water (NW): Internal-path TDL, vapor and total H_2O [T. Thornberry, A. Rollins]

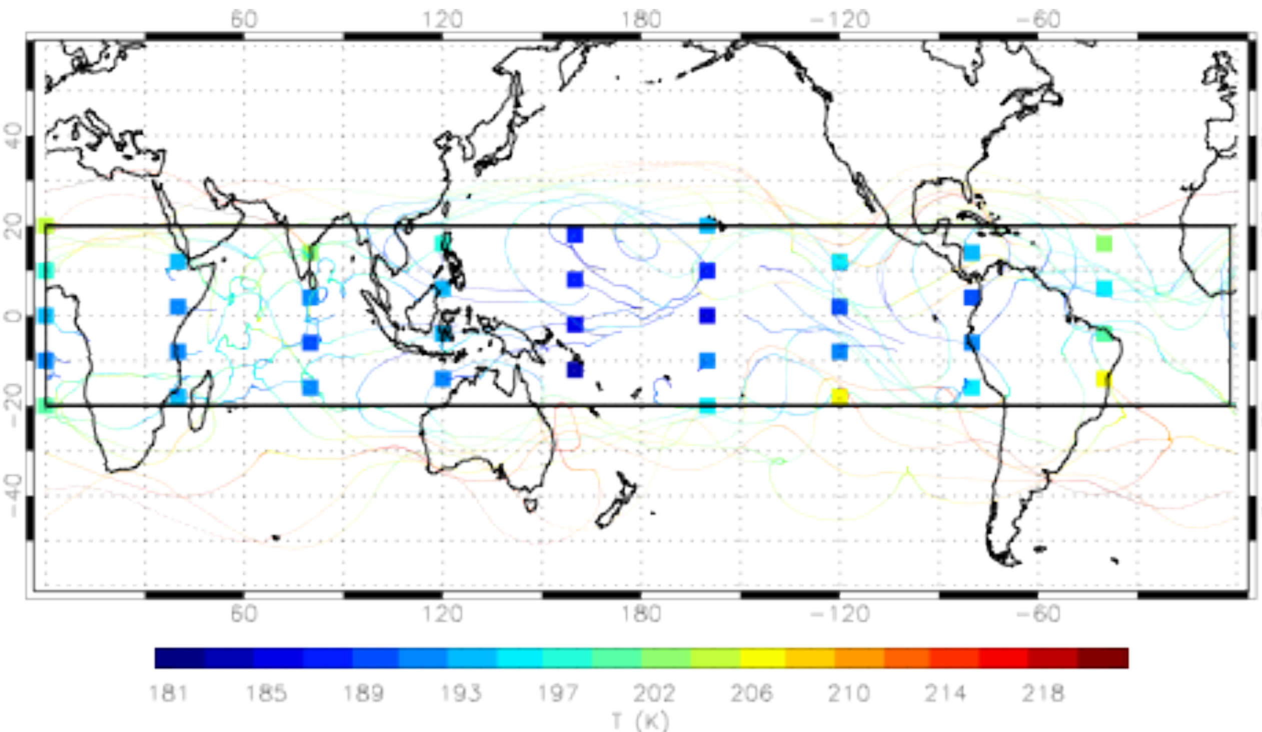


- Excellent agreement between measurements
- Peak near *RHI* = 100% physically expected

TTL cirrus modeling approach

1. Calculate 60-day backward diabatic trajectories from every 2° lat x 2° lon grid points in the tropics (20°S - 20°N) at 372 K (~100 hPa) level ending at 1 Feb 2007 using ERA-Interim temperatures and winds with enhanced wave-driven variability [*Kim and Alexander 2013*] and high-frequency waves added

a sample of the trajectories and their temperatures



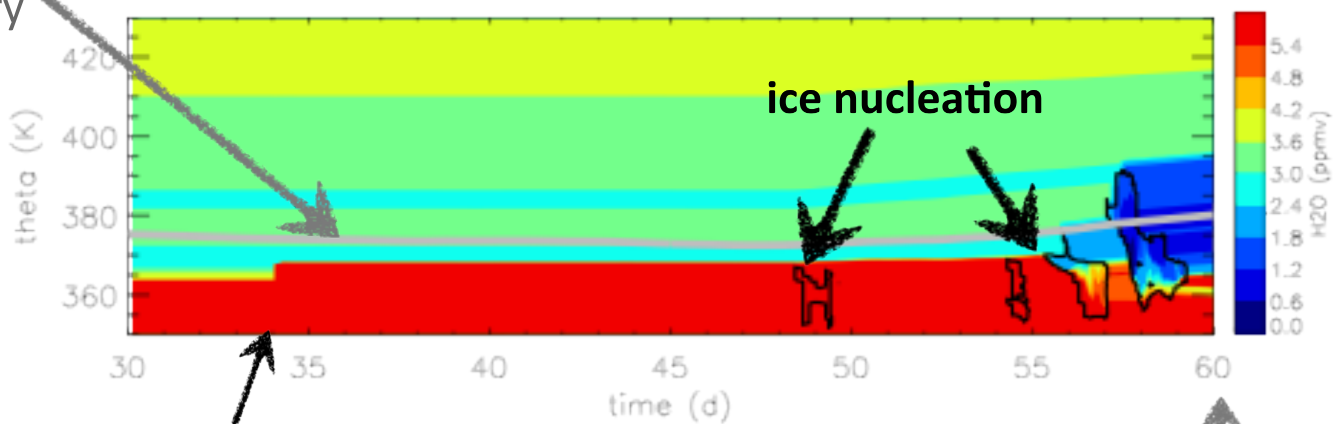
- ERAi tropopause temperature bias < 0.3 K

TTL cirrus modeling approach

2. Use 1D (height) time-dependent microphysical model to simulate clouds along each parcel trajectory temperature curtain.

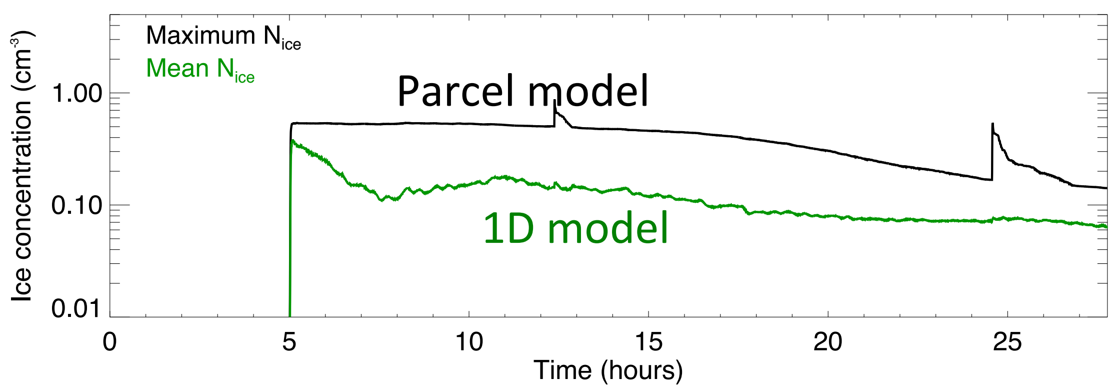
H_2O curtain
(initialized with MLS measurements at time = 0)

parcel
trajectory



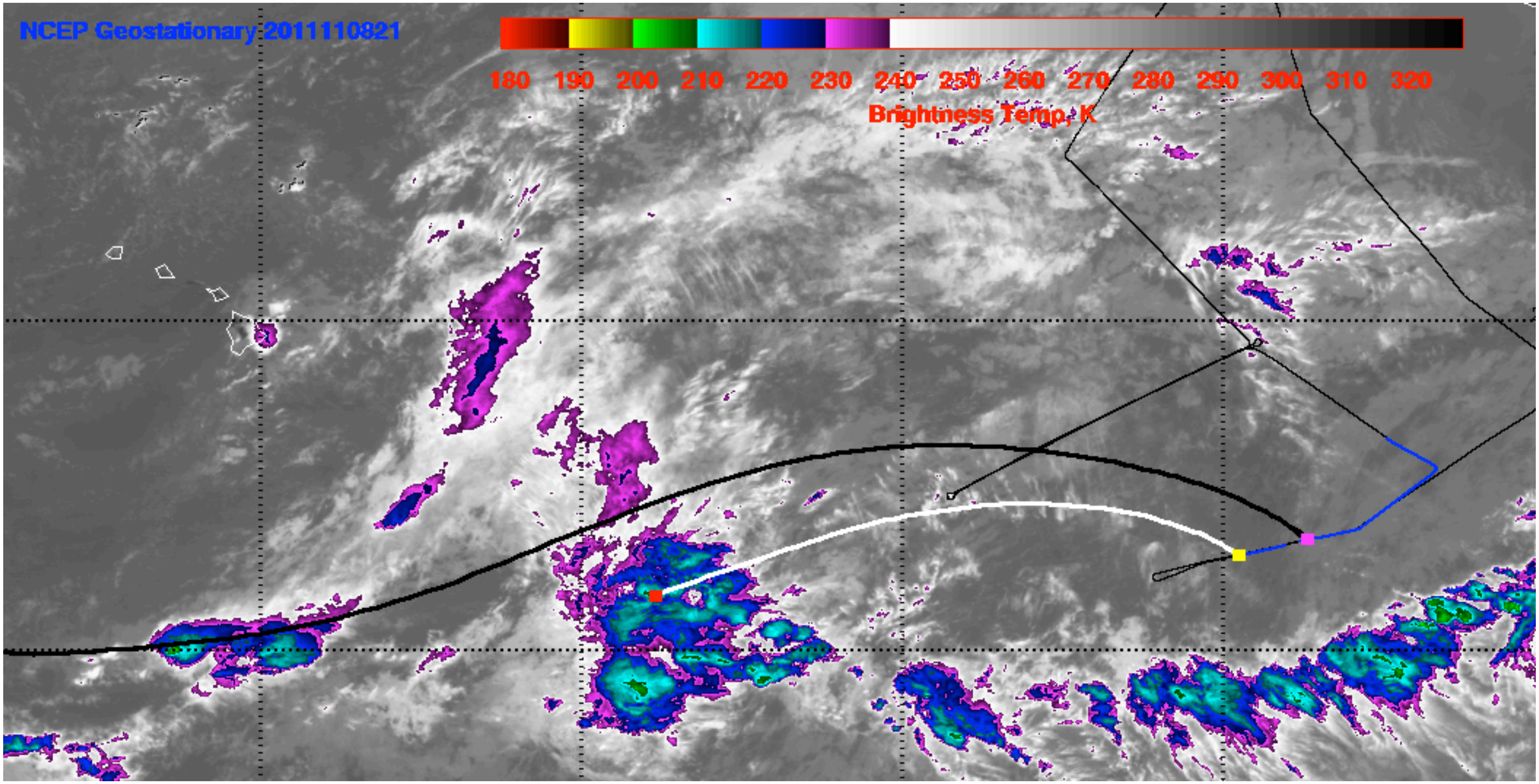
convection (air is saturated up to the cloud top height)

2/1/2007



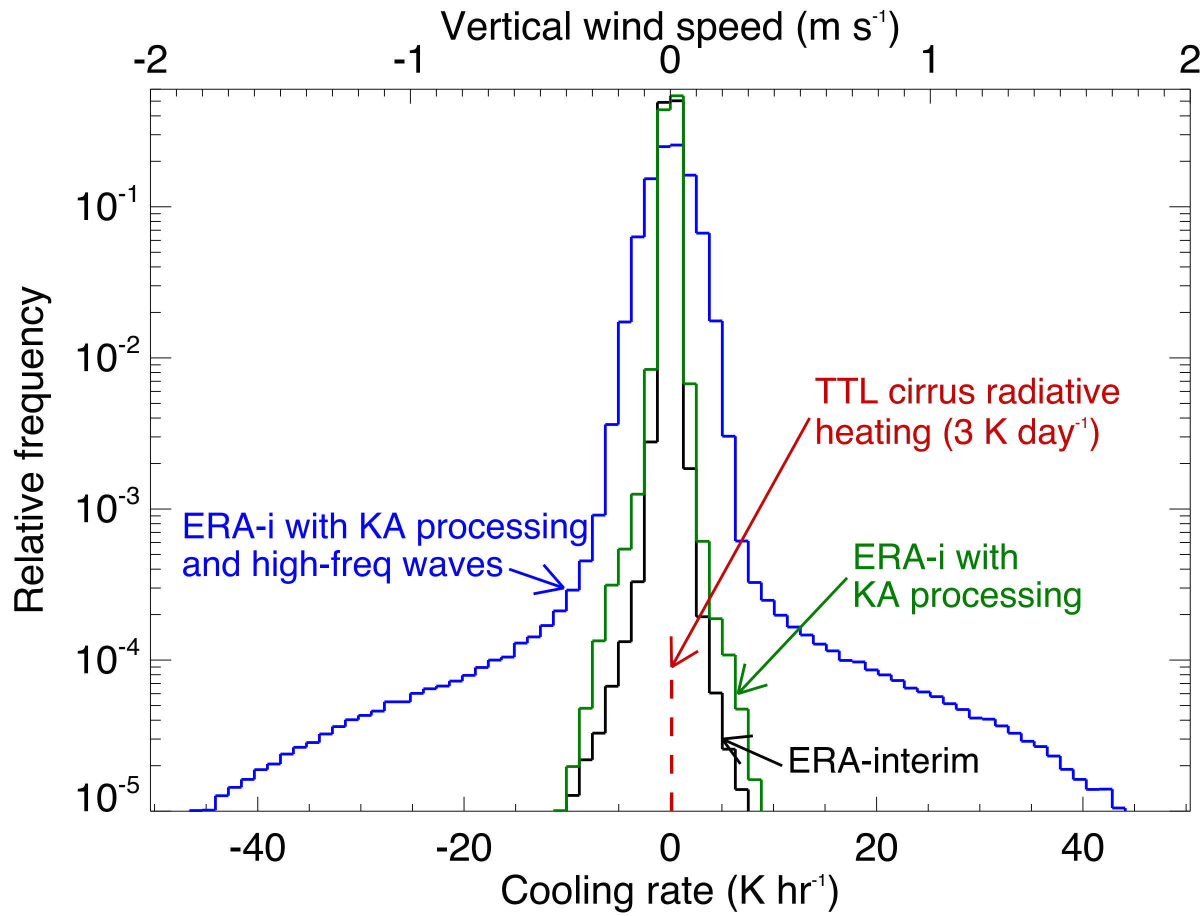
Sedimentation is important for realistic simulation of ice concentrations

Trajectories are traced through geostationary satellite convective cloud-top height fields



The model vertical column is saturated up to cloud top at intersections with convective clouds

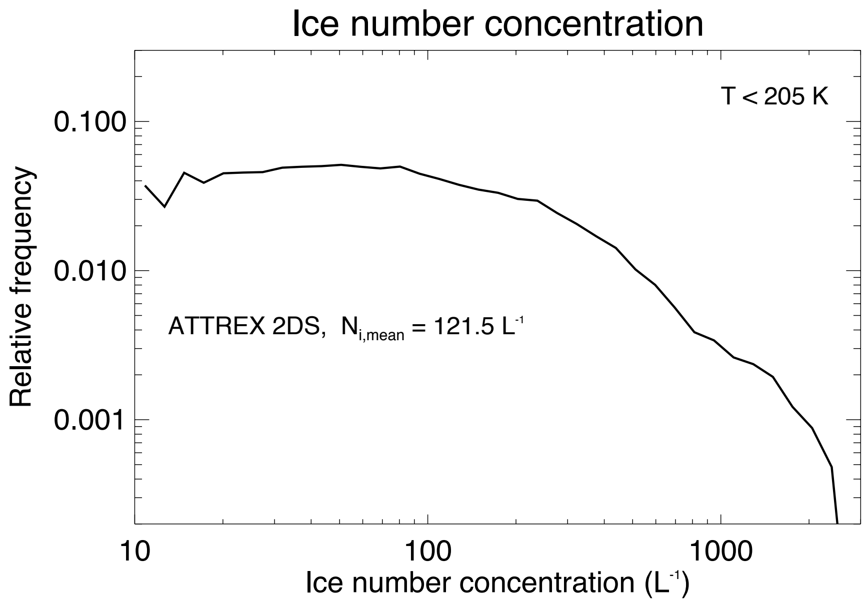
TTL temperature variability (cooling rates)



- High-frequency waves (< 2 cycles per day) produce rapid cooling events that result in large ice concentrations

- Need to evaluate with measurements (aircraft, balloon, etc.)

Sensitivity of microphysics to waves



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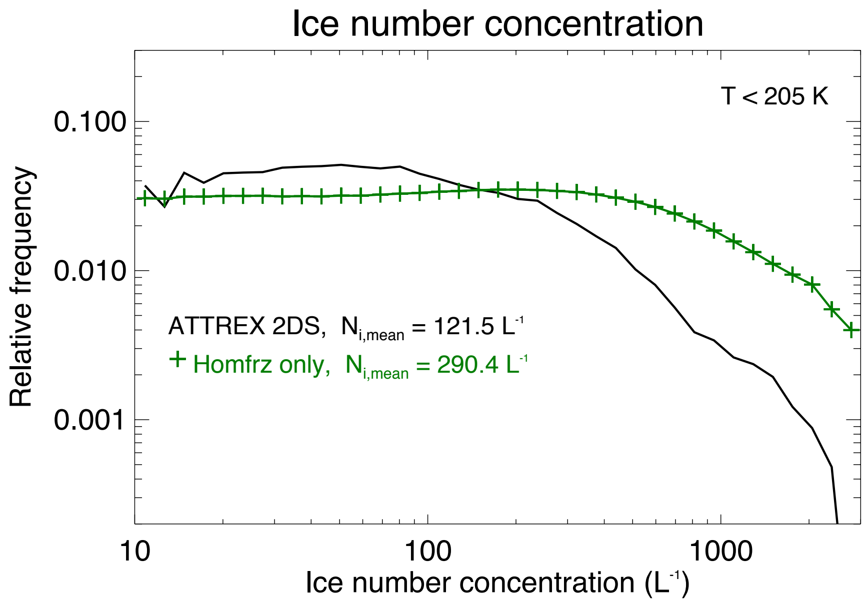
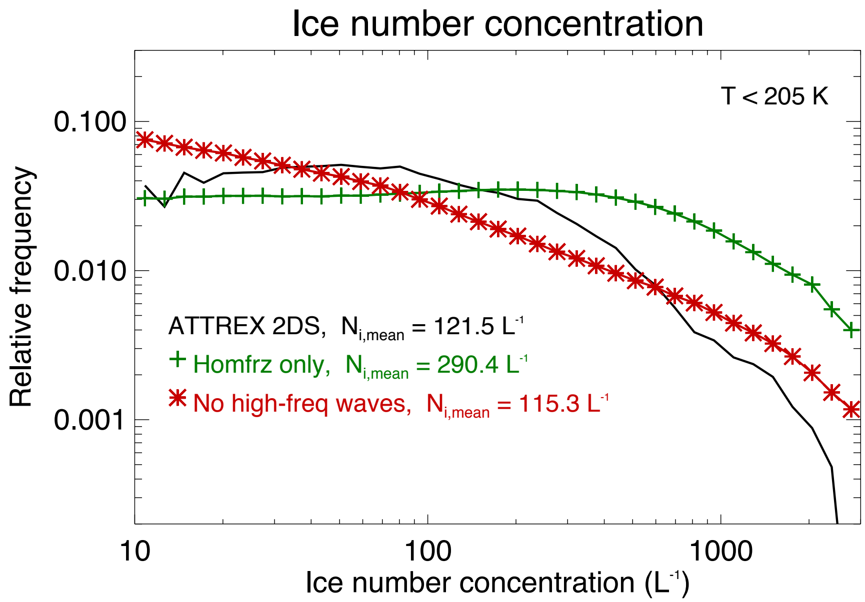


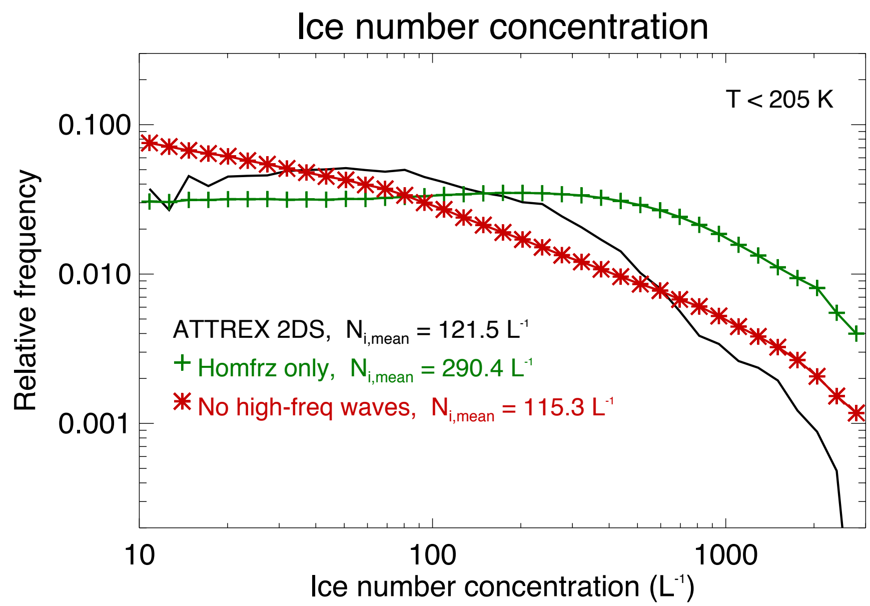
- Homogeneous freezing with nominal wave specification produces excessive ice concentrations

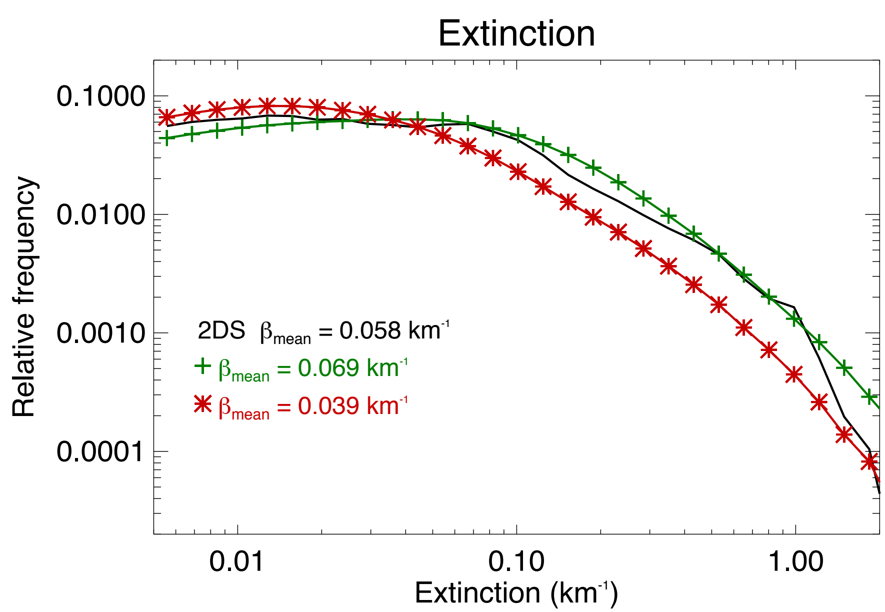
Sensitivity of microphysics to waves



- Homogeneous freezing with nominal wave specification produces excessive ice concentrations
- Strong sensitivity to high-frequency waves

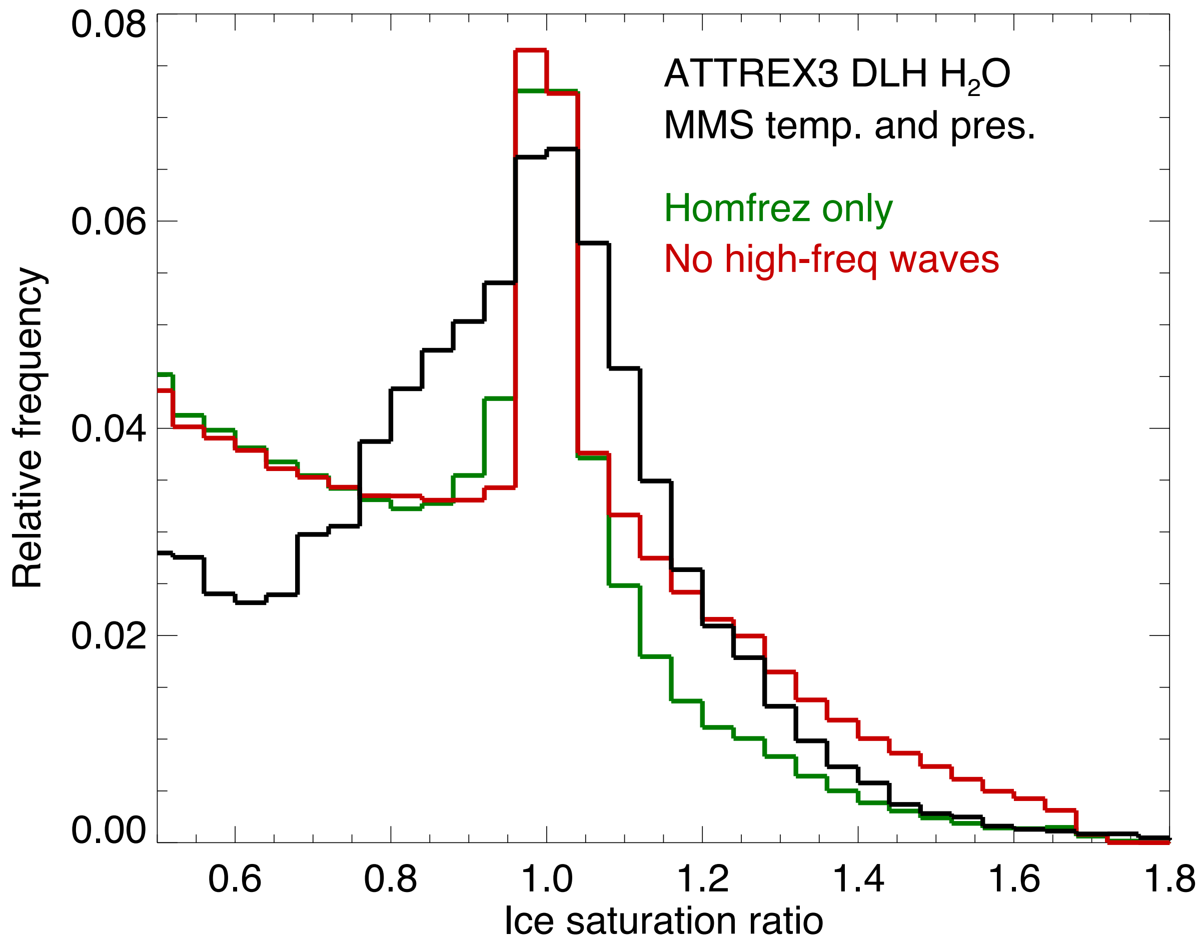
Sensitivity of microphysics to waves





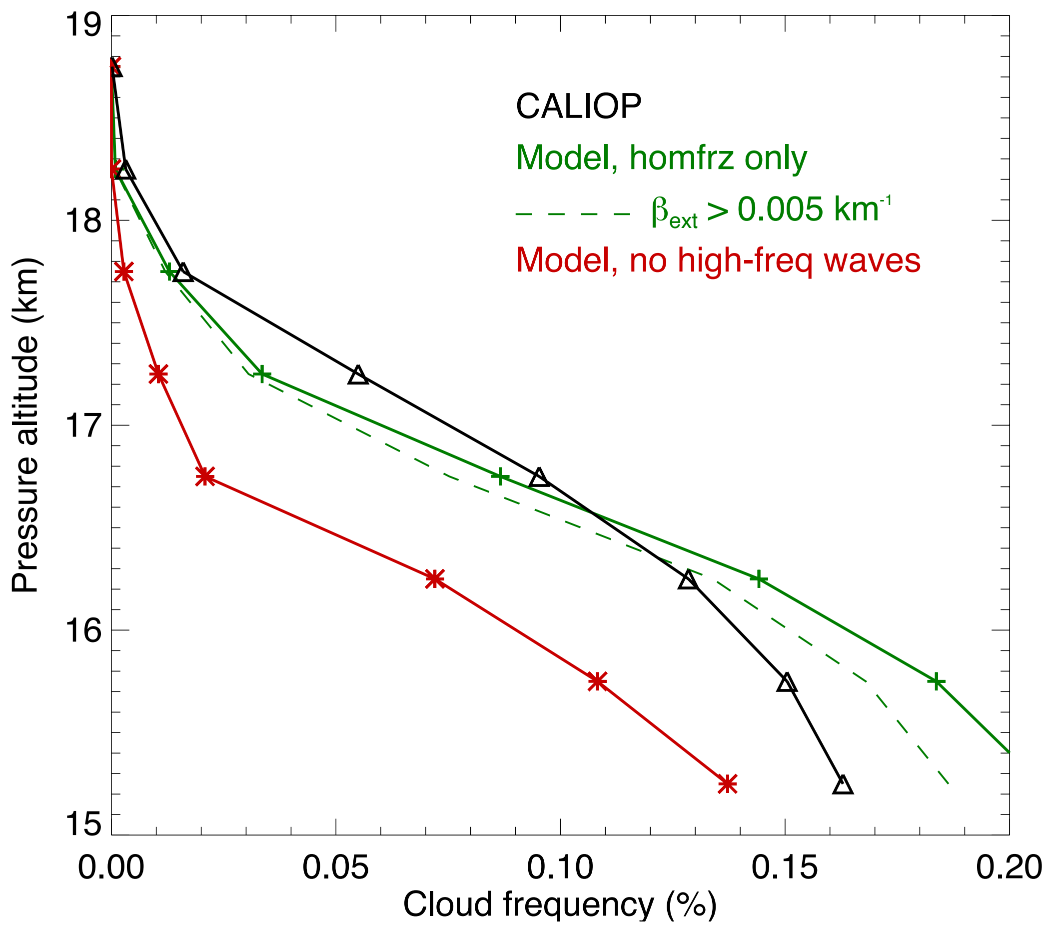
- Homogeneous freezing with nominal wave specification produces excessive ice concentrations
- Strong sensitivity to high-frequency waves
- Extinctions are too low without waves

Sensitivity of supersaturation to waves



- Homfrez only with waves ➔ too many ice crystals ➔ too little supersaturation
- No waves ➔ too few ice crystals ➔ too much supersaturation

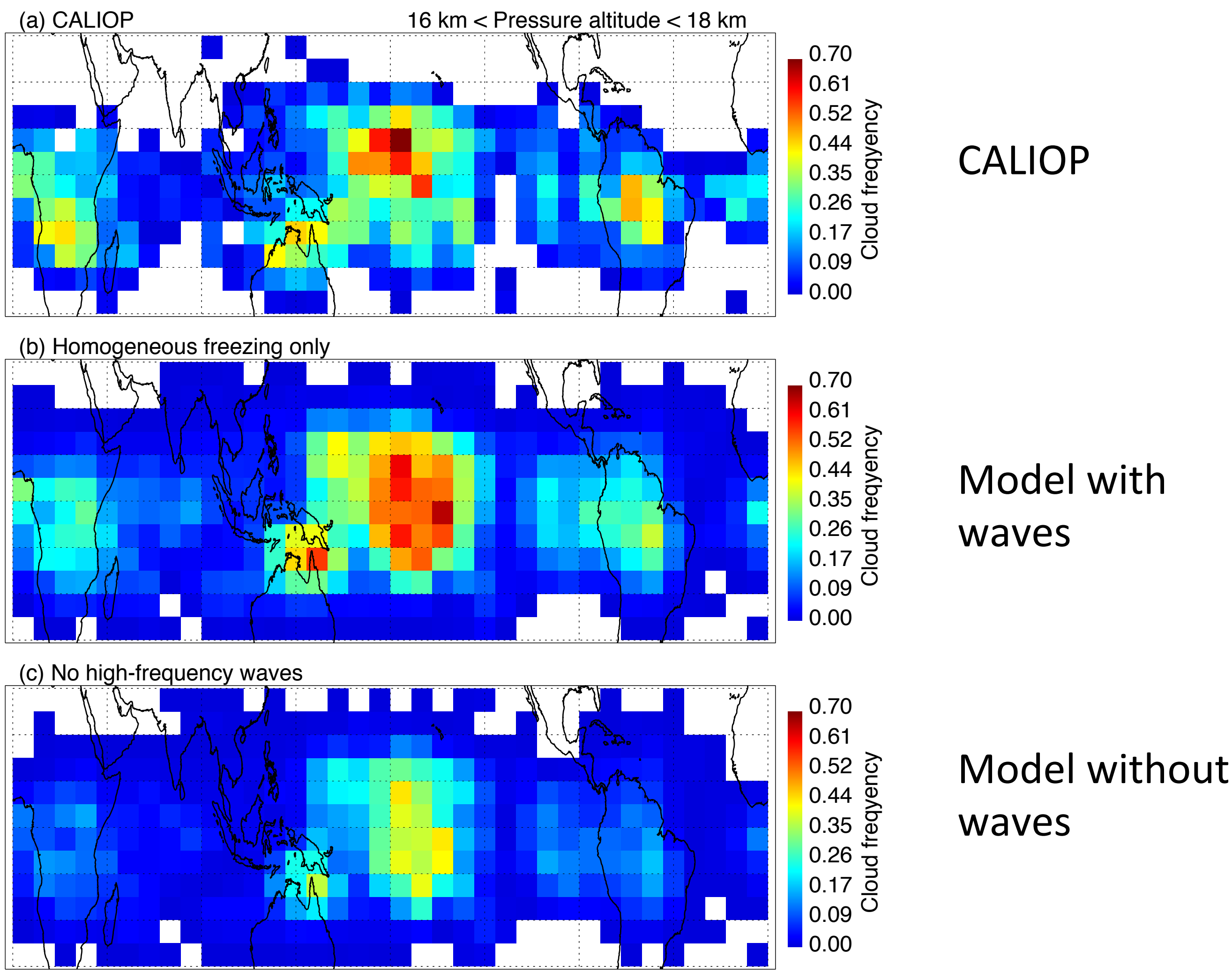
Impact of waves on cloud frequencies



- Model with high-frequency waves does a reasonable job of simulating cloud frequencies

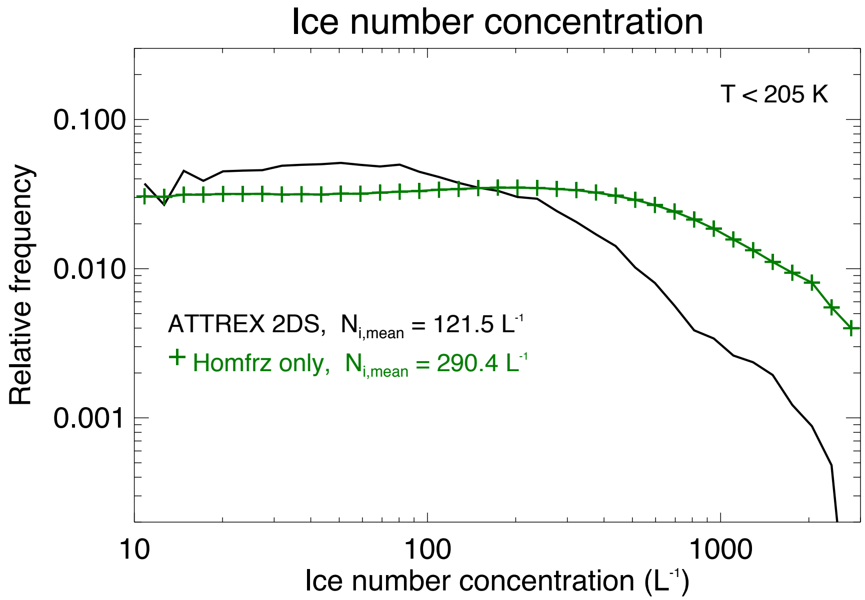
- Without waves, too few clouds
    - Primarily due to added temperature variability with waves [Kim and Alexander, *GRL*, 2015]

Impact of waves on cloud distributions



- Model (with waves) produces reasonable distribution of upper TTL cirrus, except for the south Pacific (ERA-Interim problem?)

Sensitivity of microphysics to heterogeneous nuclei



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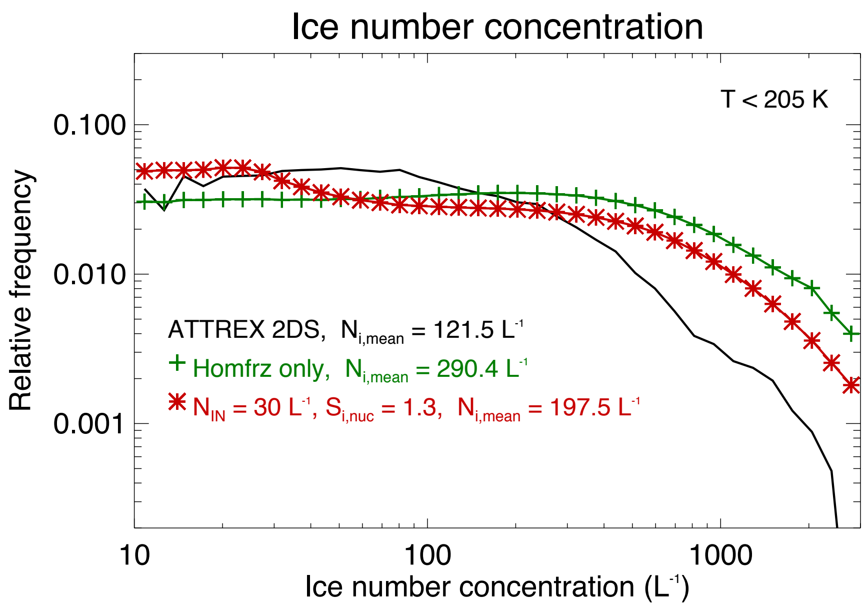

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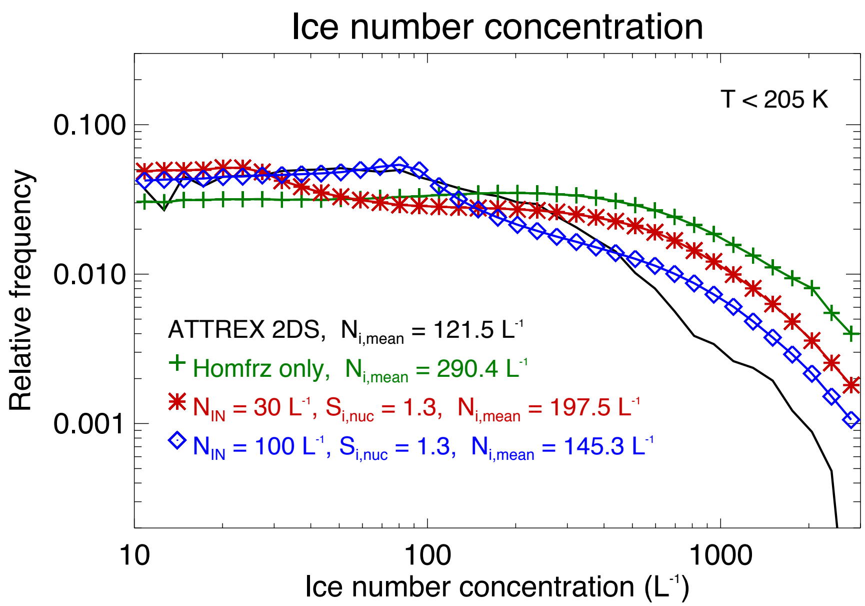

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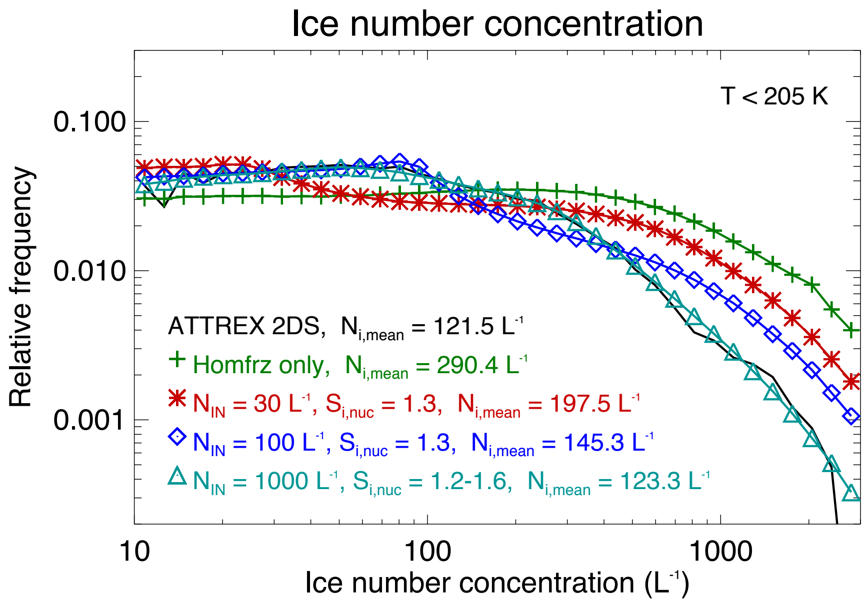
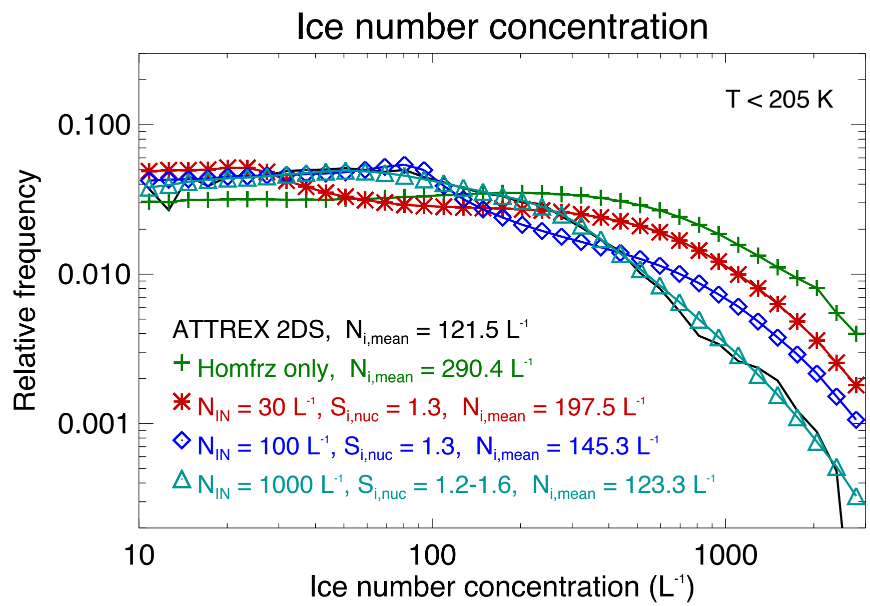
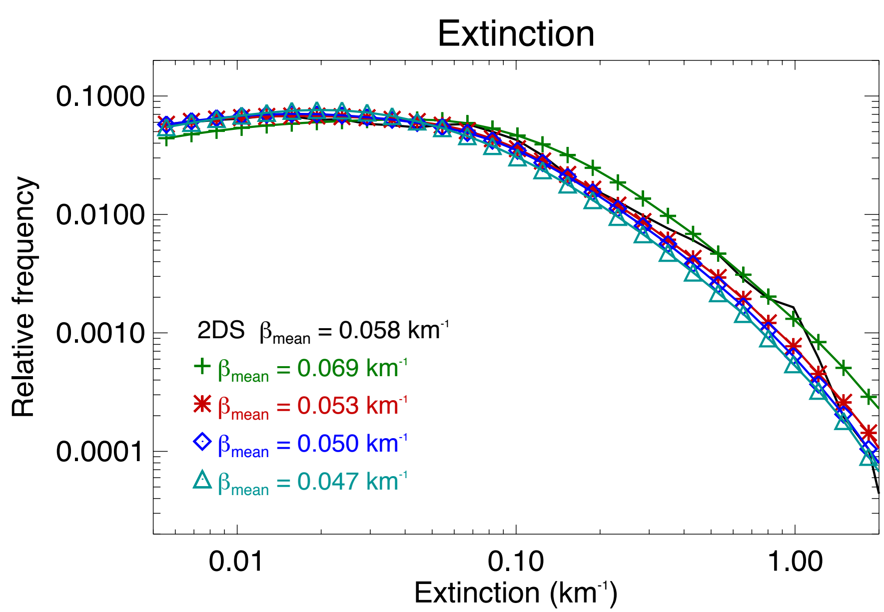


- Abundant IN improve model agreement with measured ice concentrations

Sensitivity of microphysics to heterogeneous nuclei

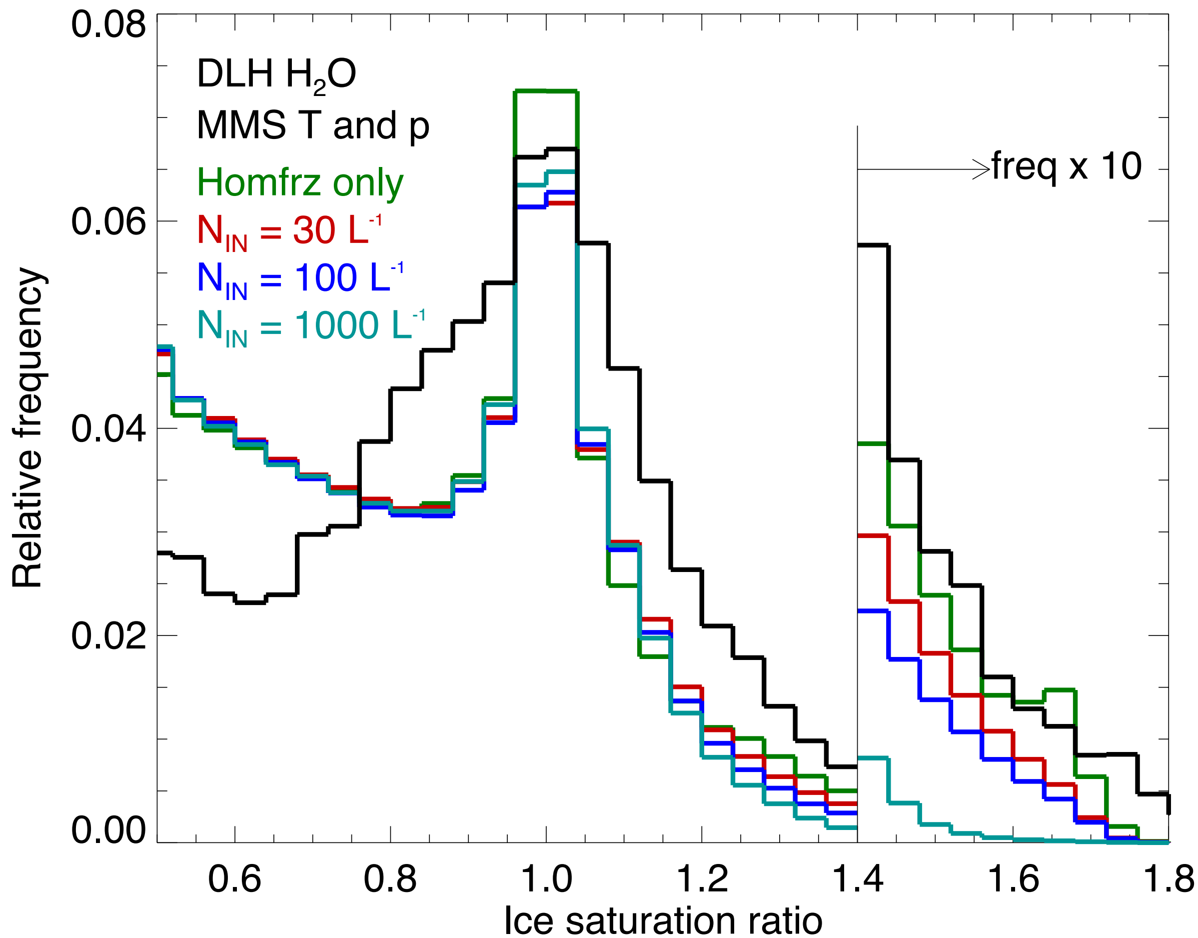


- Abundant IN improve model agreement with measured ice concentrations



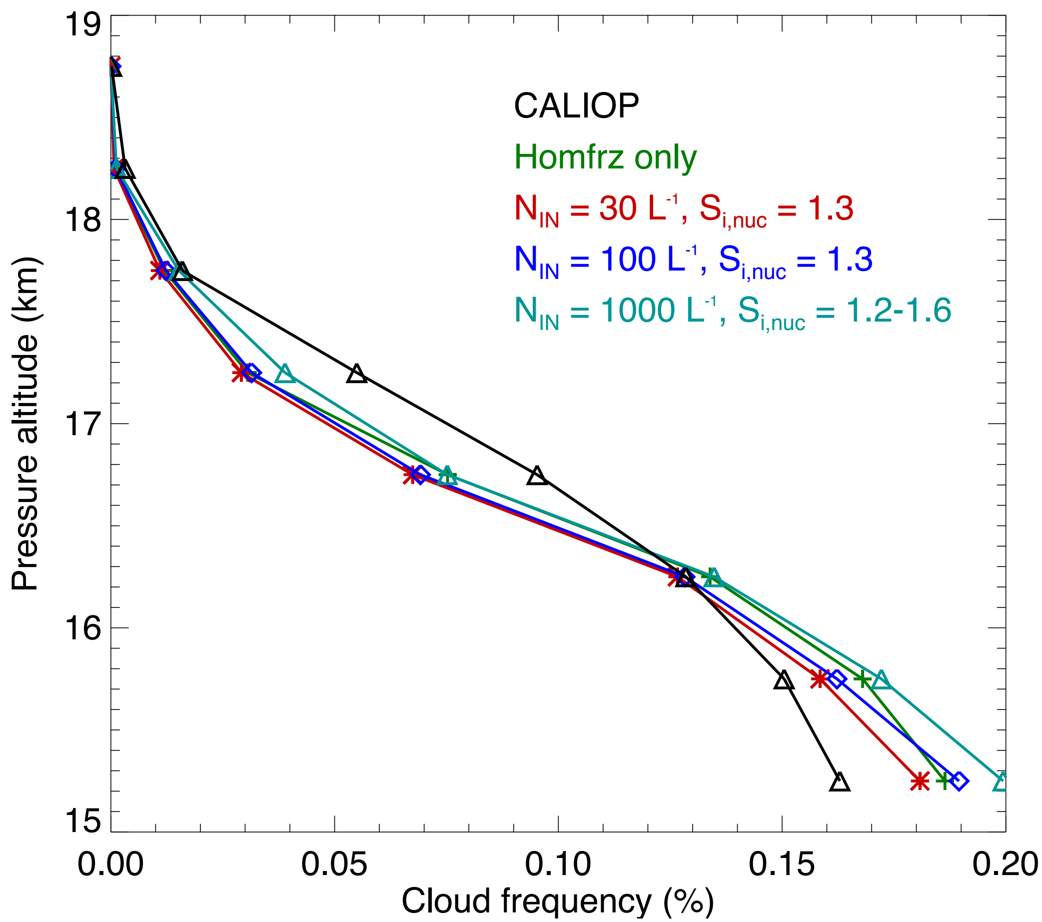
- Extinctions are less sensitive to heterogeneous nuclei (10–30% changes with increasing IN)

Sensitivity of supersaturation to heterogeneous nuclei



- With abundant IN, large supersaturations rarely occur

Impact of heterogeneous nuclei on cloud frequencies



- Cloud frequencies (and regional distributions) are insensitive to heterogeneous nuclei

Summary

- Dynamics, particularly high-frequency waves, have a large impact on TTL cirrus microphysical properties (via nucleation sensitivity to cooling rate) and occurrence frequency (via impact on minimum temperatures [*Kim and Alexander*, 2015]).
  - High-freq waves are required to explain extinctions and occurrence frequencies
  - TTL supersaturation sensitive to waves and cirrus ice concentrations
- With homogeneous freezing alone, model produces excessive ice concentrations
  - Composition dependence and high-frequency waves may reduce ice concentrations produced by homogeneous freezing
- Inclusion of heterogeneous ice nuclei improves agreement with measured ice concentrations and extinctions
  - Observed frequencies of large ice supersaturations and very high ice concentrations imply that effective IN do not dominate ice nucleation all of the time
- TTL cirrus extinctions and ice water contents are relatively insensitive to heterogeneous nuclei abundance
- Heterogeneous nuclei have very little impact on TTL cirrus occurrence frequencies

Geoengineering by seeding cirrus with effective ice nuclei

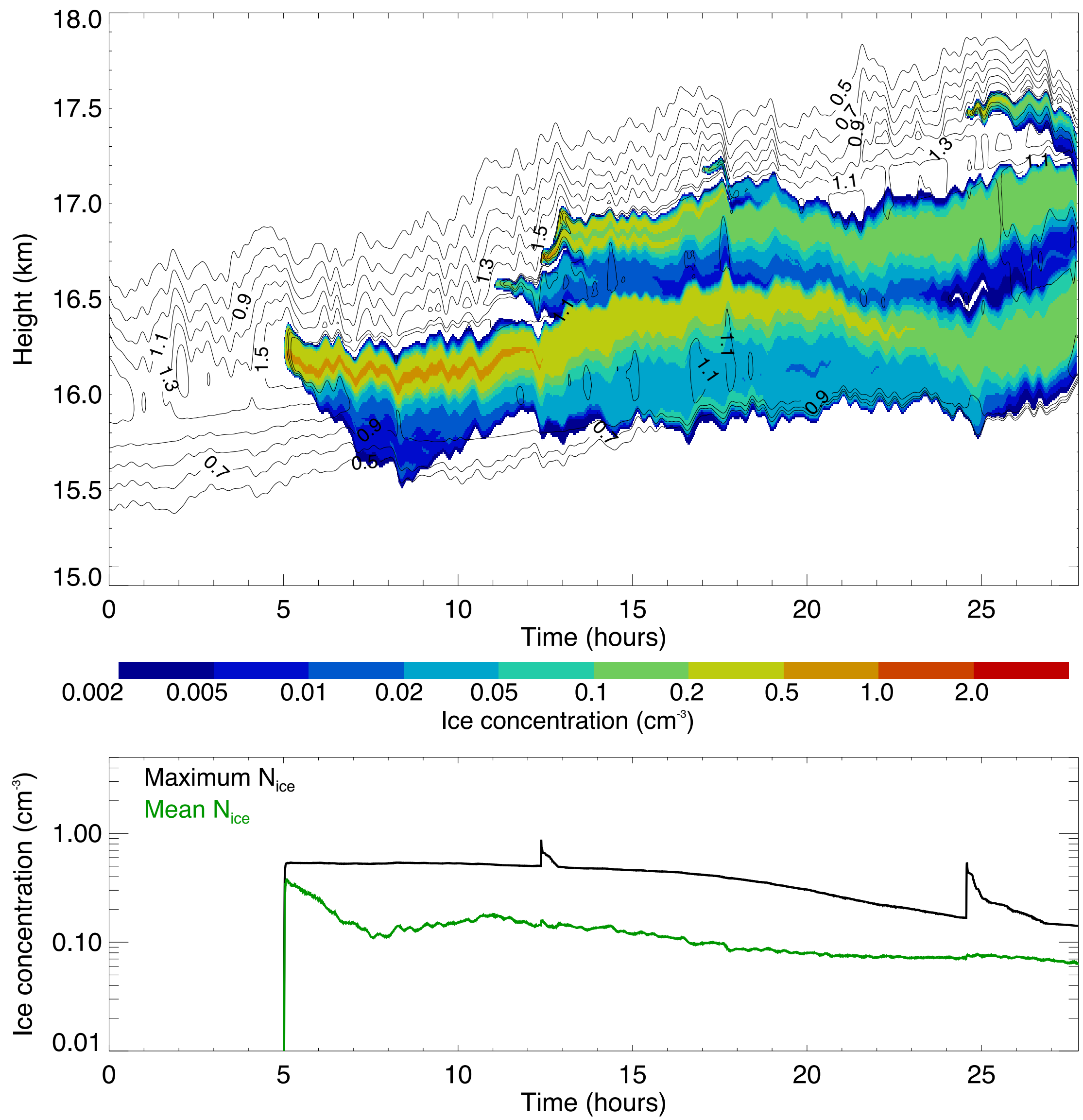
- Mitchell, D. L. and W. Finnegan, "Modification of cirrus clouds to reduce global warming", *ERL*, 2009.
    - Introduction of heterogeneous nuclei into upper troposphere will solve climate problem

- Kuebbeler, M., U. Lohmann, J. Feichter, "Effects of stratospheric sulfate aerosol geo-engineering on cirrus", *GRL*, 2012.
    - Cirrus modification side effects of stratospheric sulfate aerosol geo-engineering
    - Global model with parameterized cirrus used to estimate radiative forcings

- Cirisan, A., P. Spichtinger, B. P. Luo, D. K. Weisenstein, H. Wernli, U. Lohmann, T. Peter, "Microphysical and radiative changes in cirrus clouds by geoengineering the stratosphere", *JGR*, 2013.
    - Cirrus modification side effects of stratospheric sulfate aerosol geo-engineering
    - Trajectory aerosol simulations and cirrus box model used to provide radiative forcing estimates (?!?)

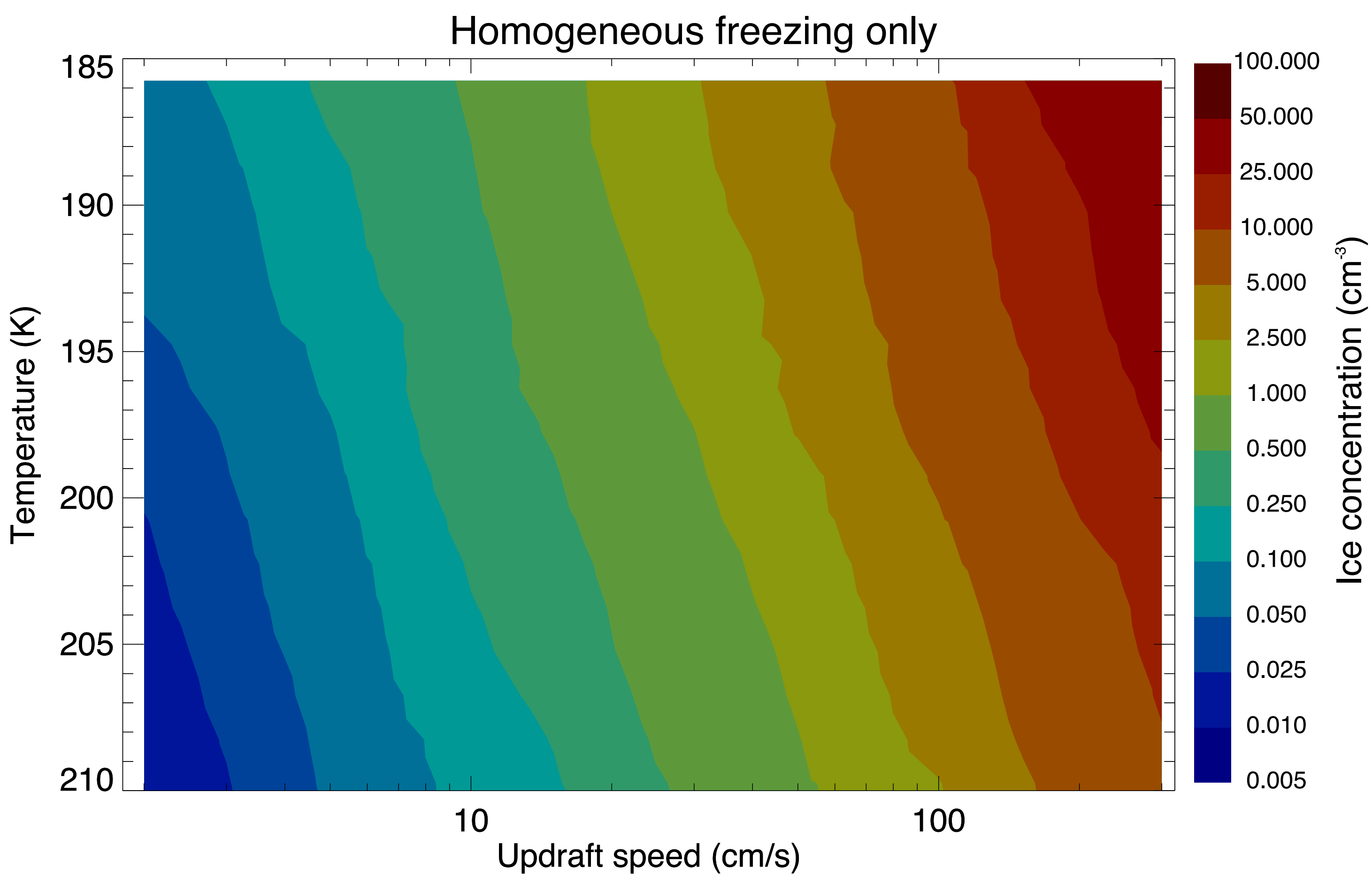
- Storelvmo, T., J. E. Kristjansson, H. Muri, M. Pfeffer, D. Barahona, A. Nenes, "Cirrus cloud seeding has potential to cool climate", *GRL*, 2013.
    - GCM with parameterized cirrus used to predict radiative forcing
    - Potential negative effects noted

Importance of sedimentation



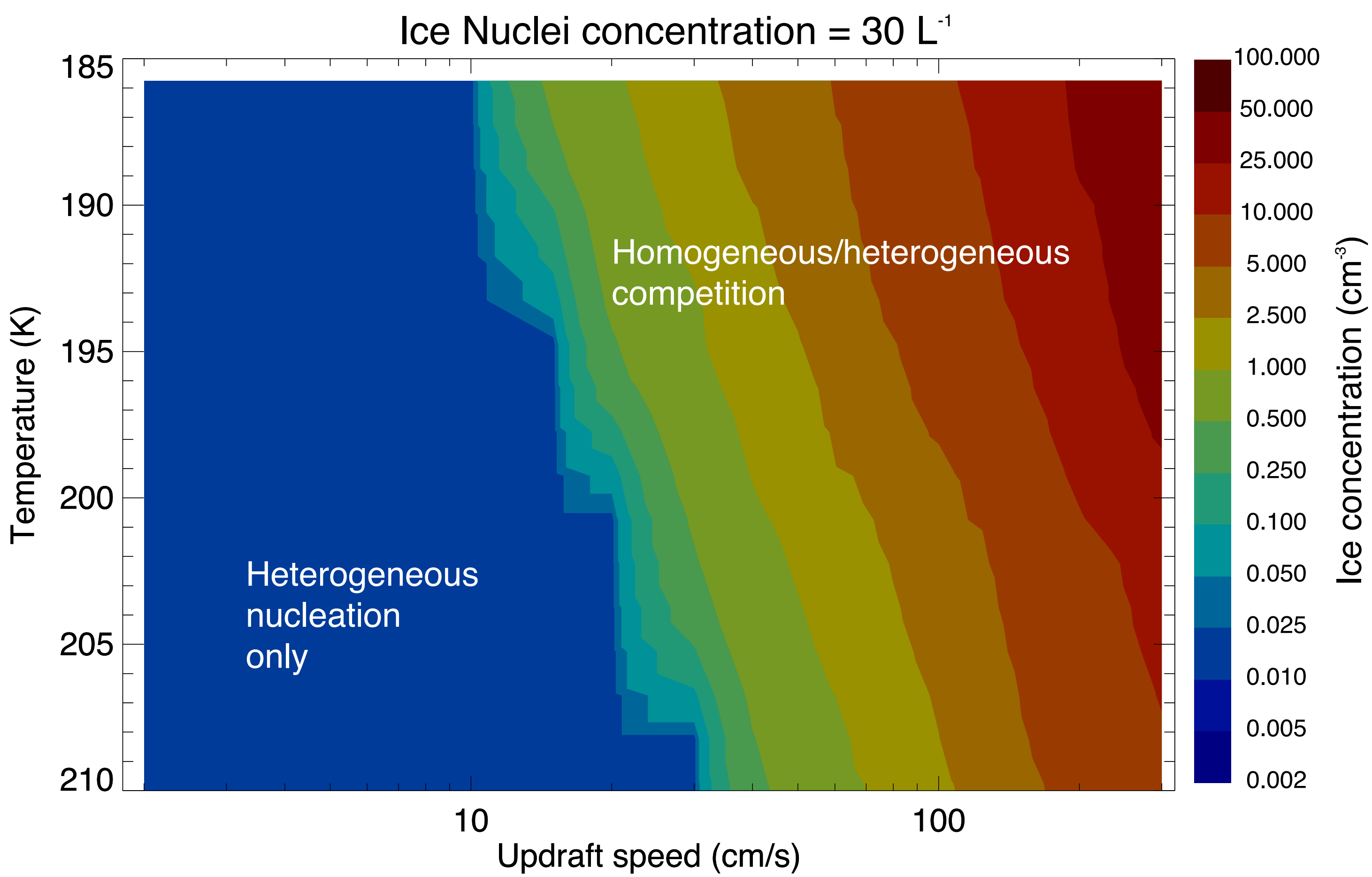
- Parcel models will overestimate ice concentrations

Expectations from parcel models: sensitivity to cooling rate



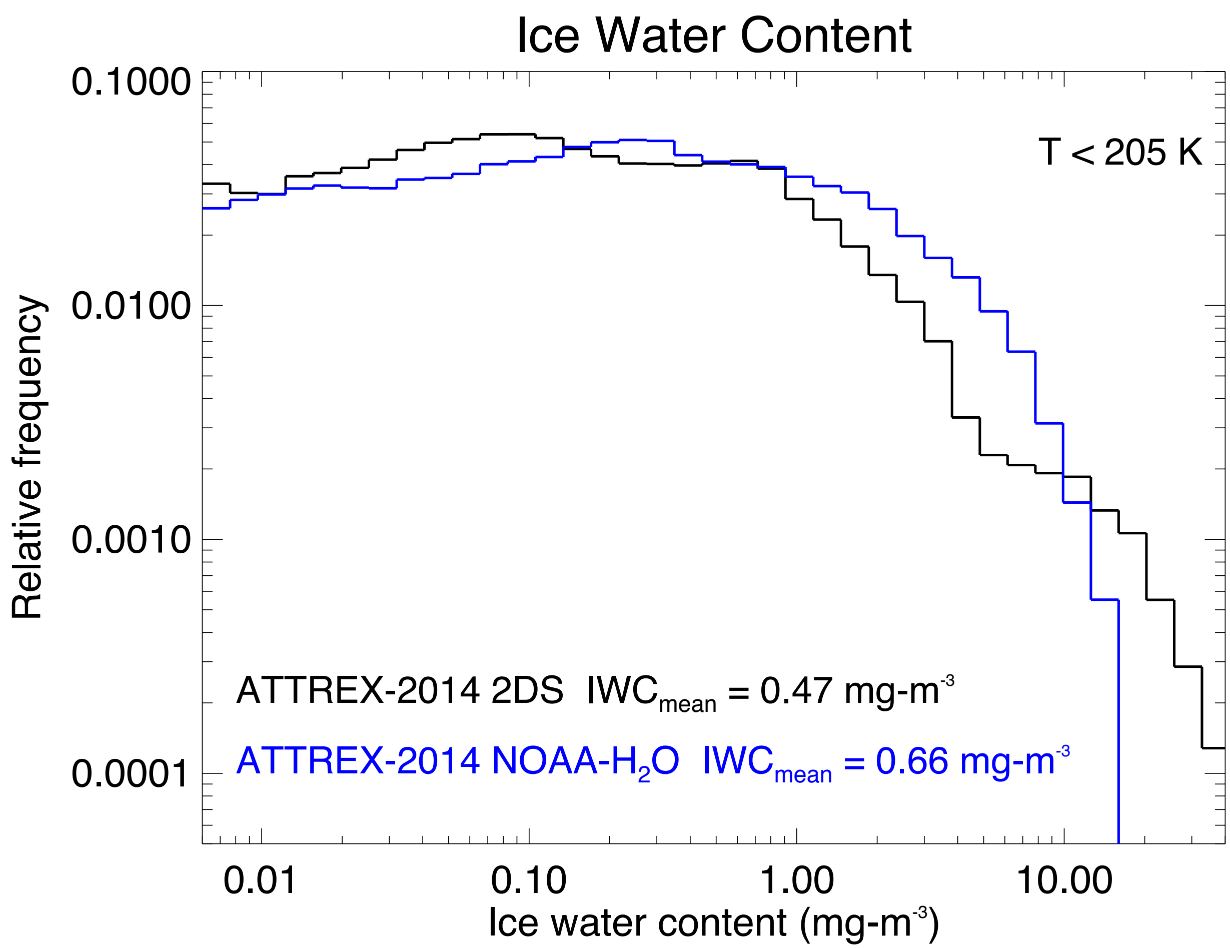
- Ice concentration (just after nucleation) increases rapidly with cooling rate

Expectations from parcel models: impact of het. ice nuclei



- Ice crystals nucleated on IN quench rising supersaturation, prevent homogeneous freezing, and limit ice concentration

Hawkeye/NOAA-WV TTL cirrus measurements: ice water content



- Ice mass from 2D-S requires area-mass relationships

Uncertainties

- Trajectory curtain approach: parcel pathway (and temperature variability) only correct for parcel along single trajectory (run from 372 K); no wind shear effects on cloud evolution
- Monthly-mean heating rates used despite large variations in actual heating rates associated with clouds
- High-frequency waves are specified with a statistical parameterization independent of latitude, longitude, and time
- No horizontal mixing included
- No interaction between cloud radiative heating, dynamics, and cloud processes
- Data sampling biases (how representative is the 30+ hour ATTREX-Guam Hawkeye dataset?)