High-frequency gravity waves and homogeneous ice nucleation in Tropical Tropopause Layer (TTL) cirrus

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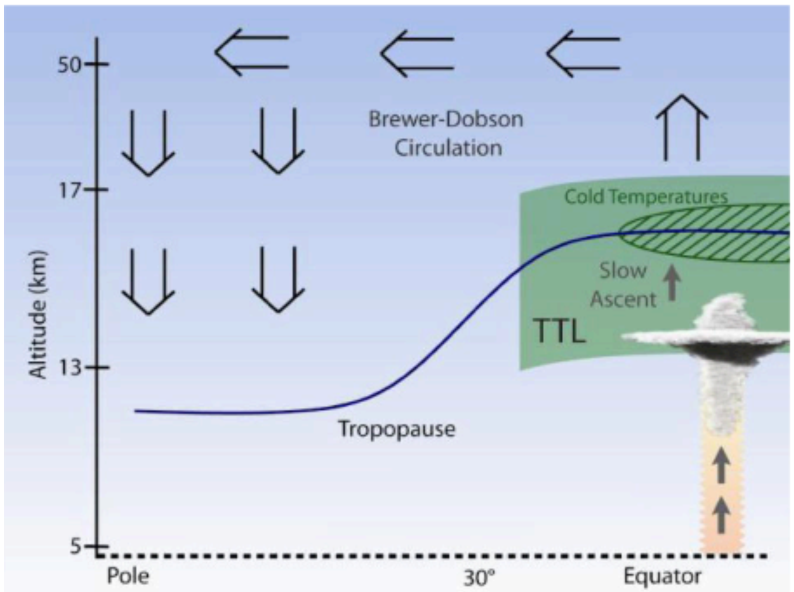
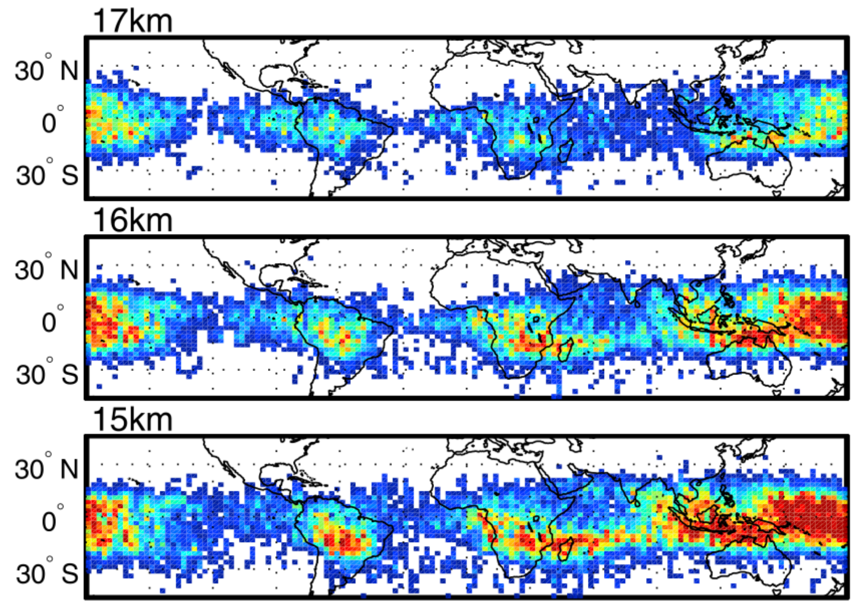




TTL cirrus regulate H_2O entering the stratosphere and tropopause region thermal budget

Gravity wave influence on TTL cirrus

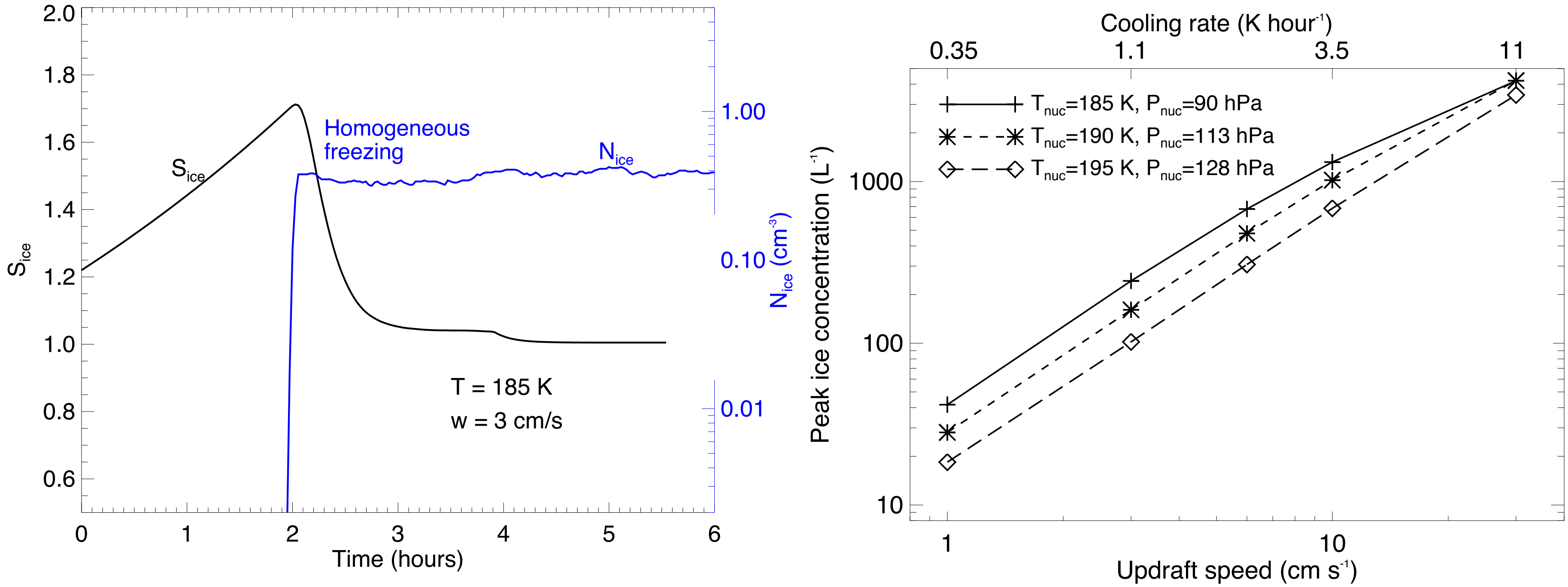
TTL gravity waves control:

1. Times and locations of cirrus occurrence (J.-E. Kim talk)
2. Cirrus microphysics (this talk and A. Podglagen talk)
3. Dehydration of air entering the stratosphere [*Schoeberl et al.*, 2015]

Science questions addressed in this talk:

1. How do high-frequency gravity waves affect TTL cirrus microphysical properties?
2. Are ice concentrations predicted by homogeneous freezing theory consistent with observations?

Homogeneous freezing of aqueous aerosols



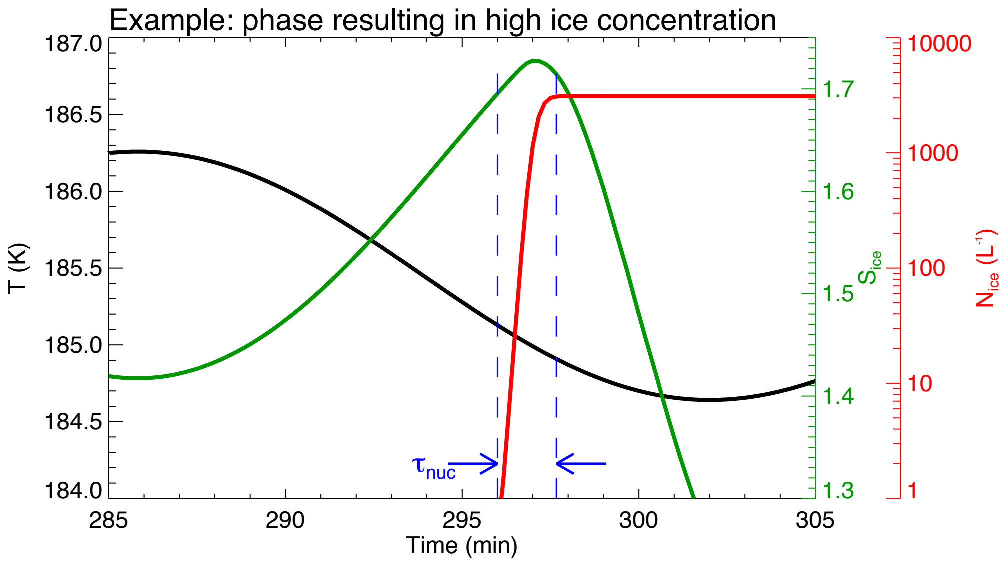
Ice nucleation halted when S↑(cooling) < S↓(crystal growth)

Implies increasing cooling rate drives increasing N_{ice}

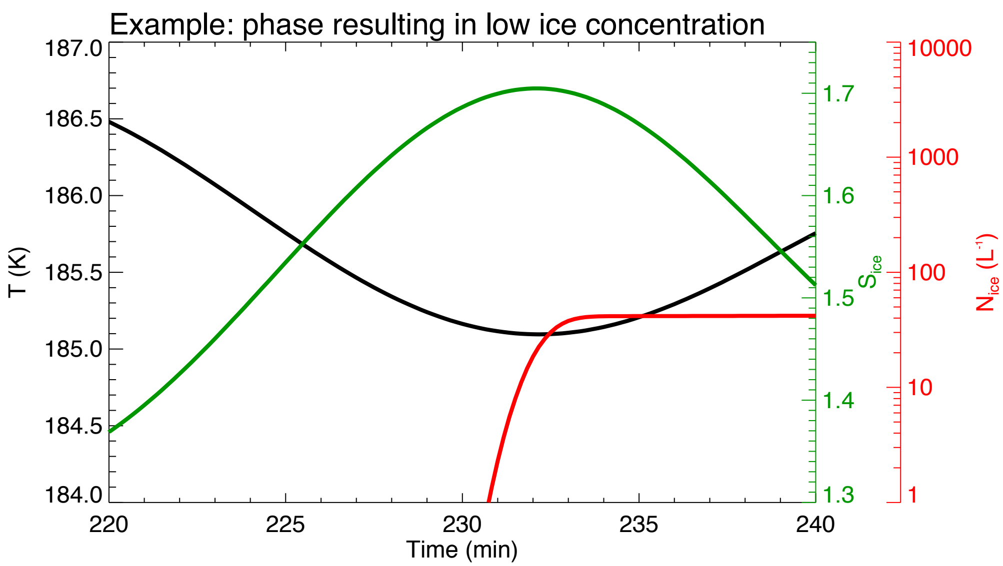
–high-frequency waves drive rapid cooling

Caveat: assuming composition-independent homogeneous freezing threshold.

Nucleation quenching by high-frequency waves

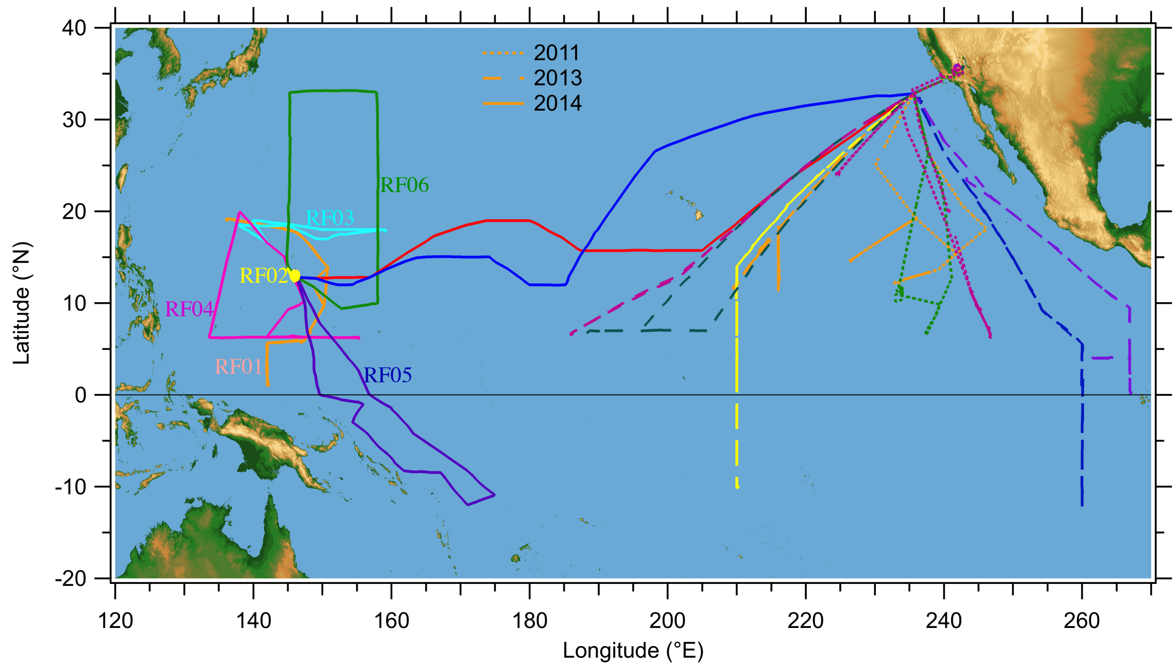


Steady cooling during nucleation event



Cooling changes to heating before nucleation event is complete ("quenching")
[*Spichtinger and Krämer*, 2013, *Dinh et al.*, 2016]

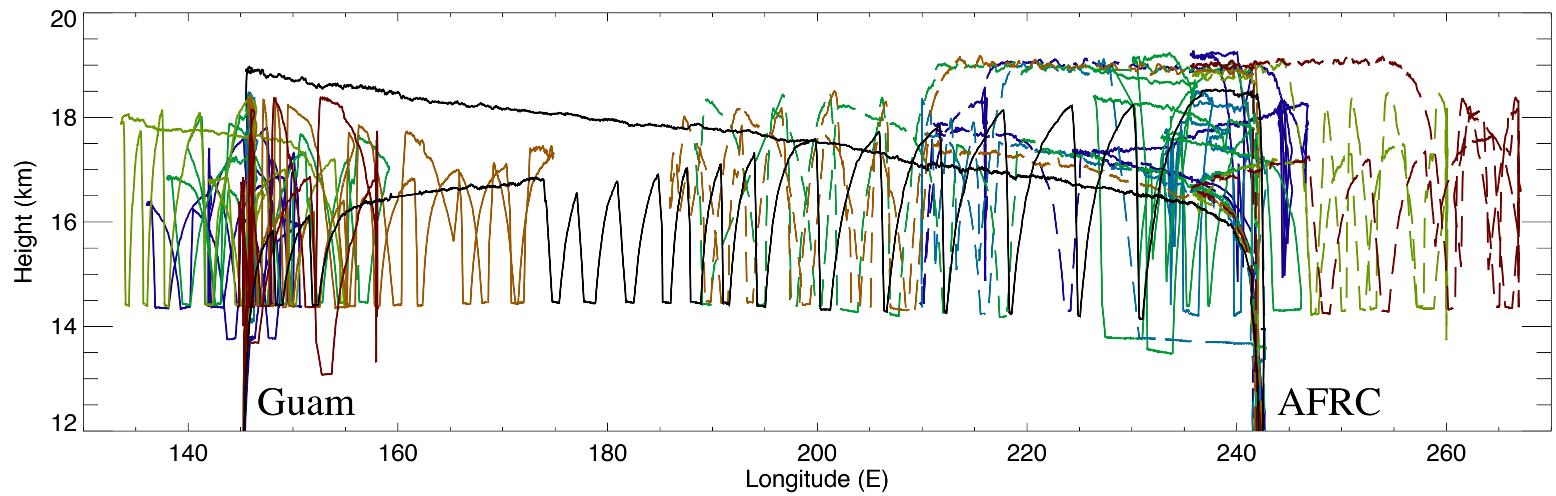
ATTREX Flights



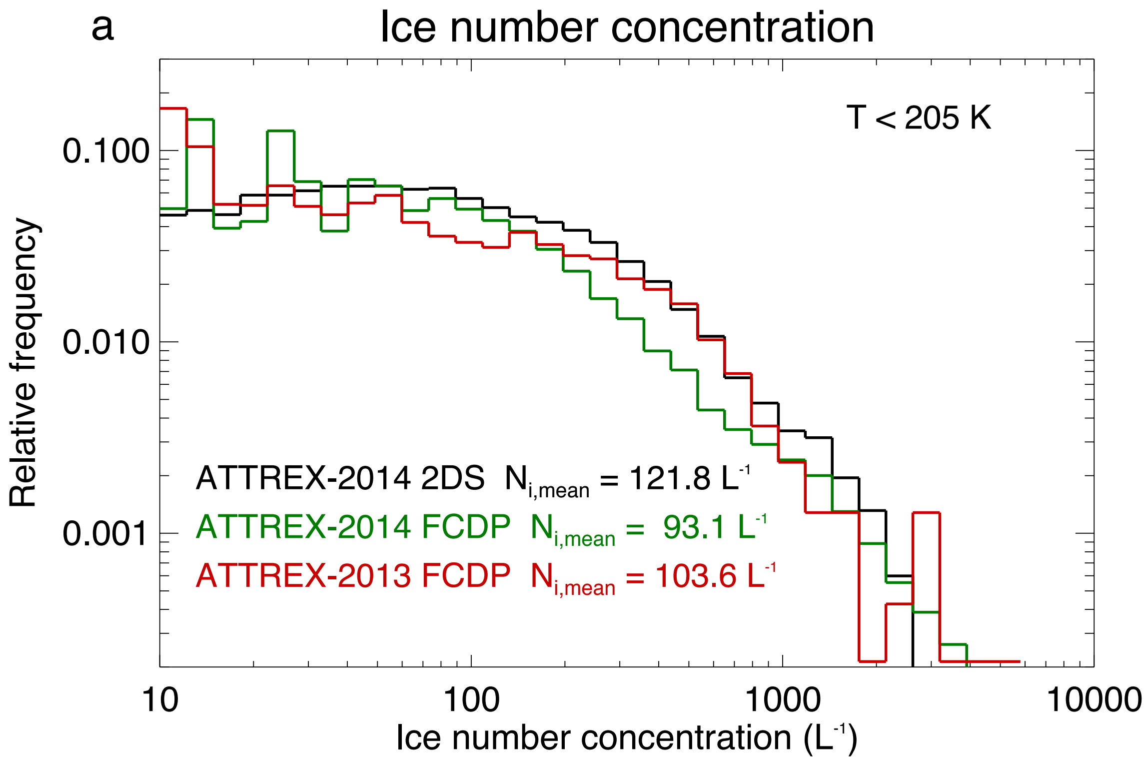
~300 TTL vertical profiles (GWAS samples on ascents)

Payload included cloud, water vapor, T, p, w measurements

~40 hours in cirrus



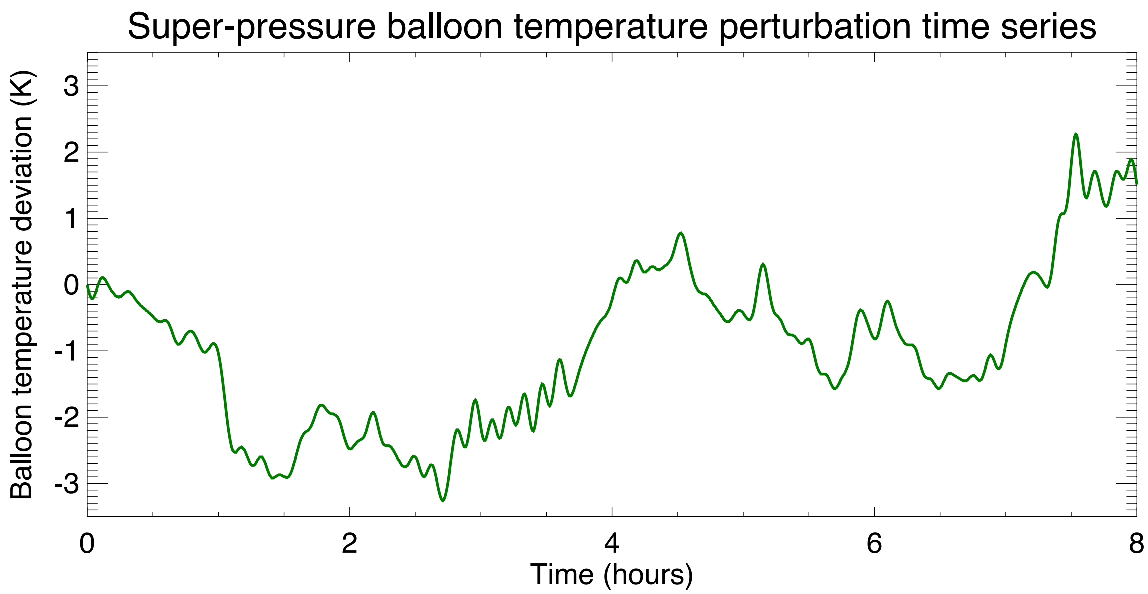
ATTREX TTL cirrus measurements



P. Lawson and S. Woods

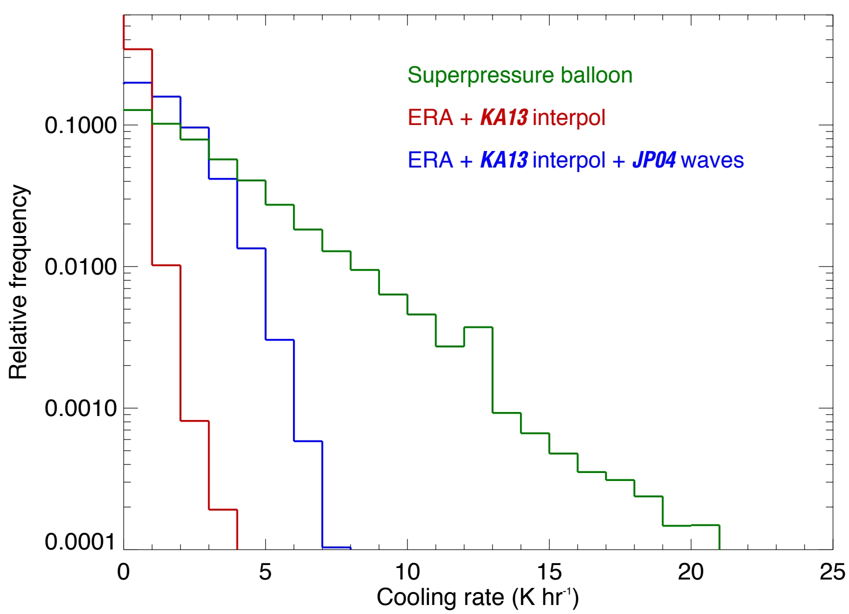
Ice concentration statistics from different instruments and different campaigns agree well.

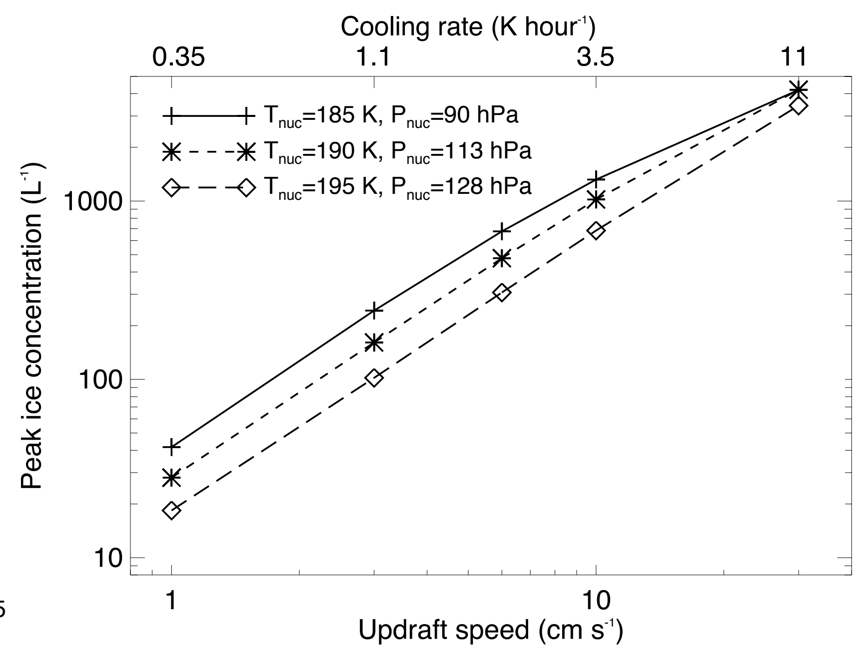
Wave-driven TTL temperature variability



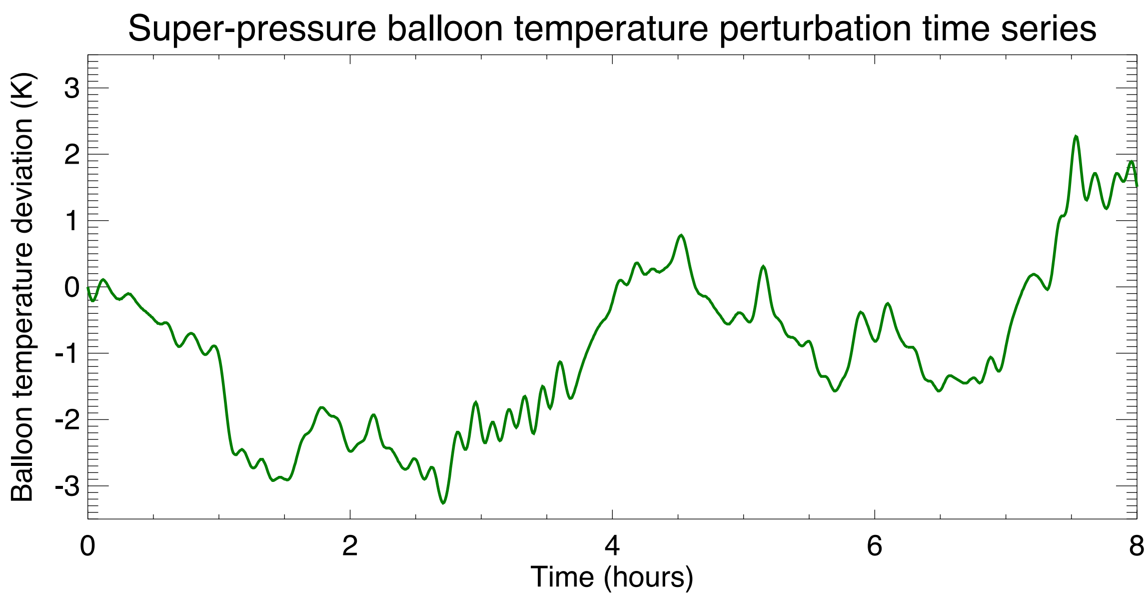
Waves with wide range of frequencies ubiquitous in TTL

SP balloons give approximation to temperature perturbations experienced by air parcel [*Podglagen et al.,* 2016]



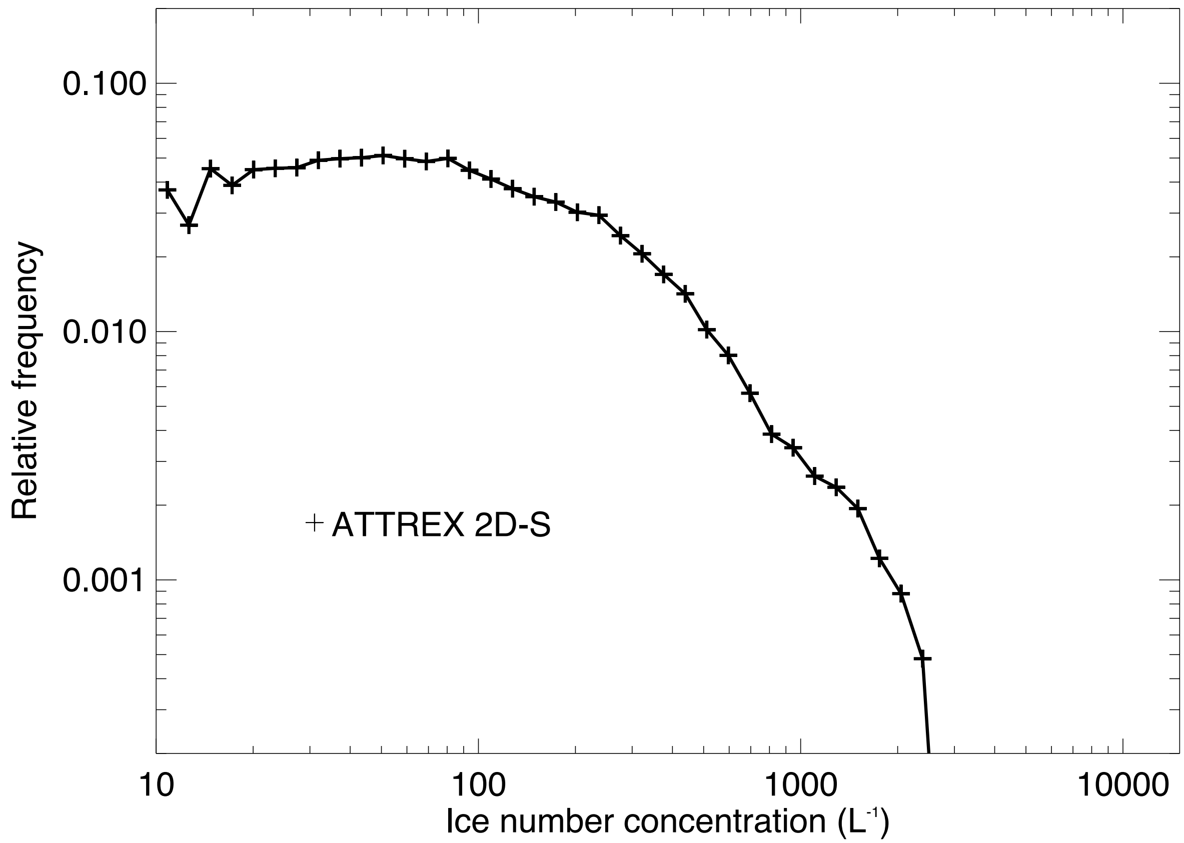


Parcel simulations of ice nucleation

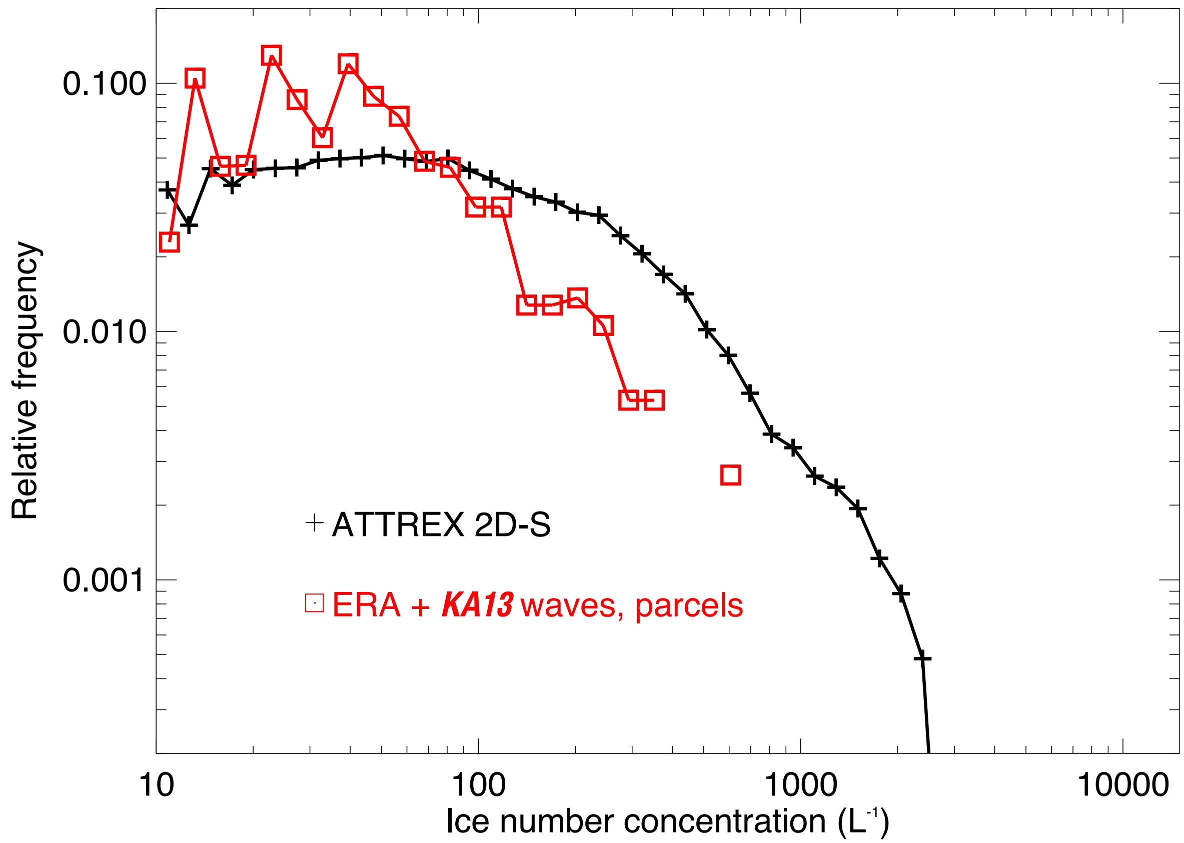


- Use super-pressure balloon temperature perturbation time series with different initial temperatures and start times (thousands of realizations)
- Also use ERA-interim trajectories with *Kim and Alexander* [2013] interpolation
- Run each simulation until nucleation event is complete (provides peak ice concentration)
- No sedimentation or entrainment!

TTL cirrus ice concentrations

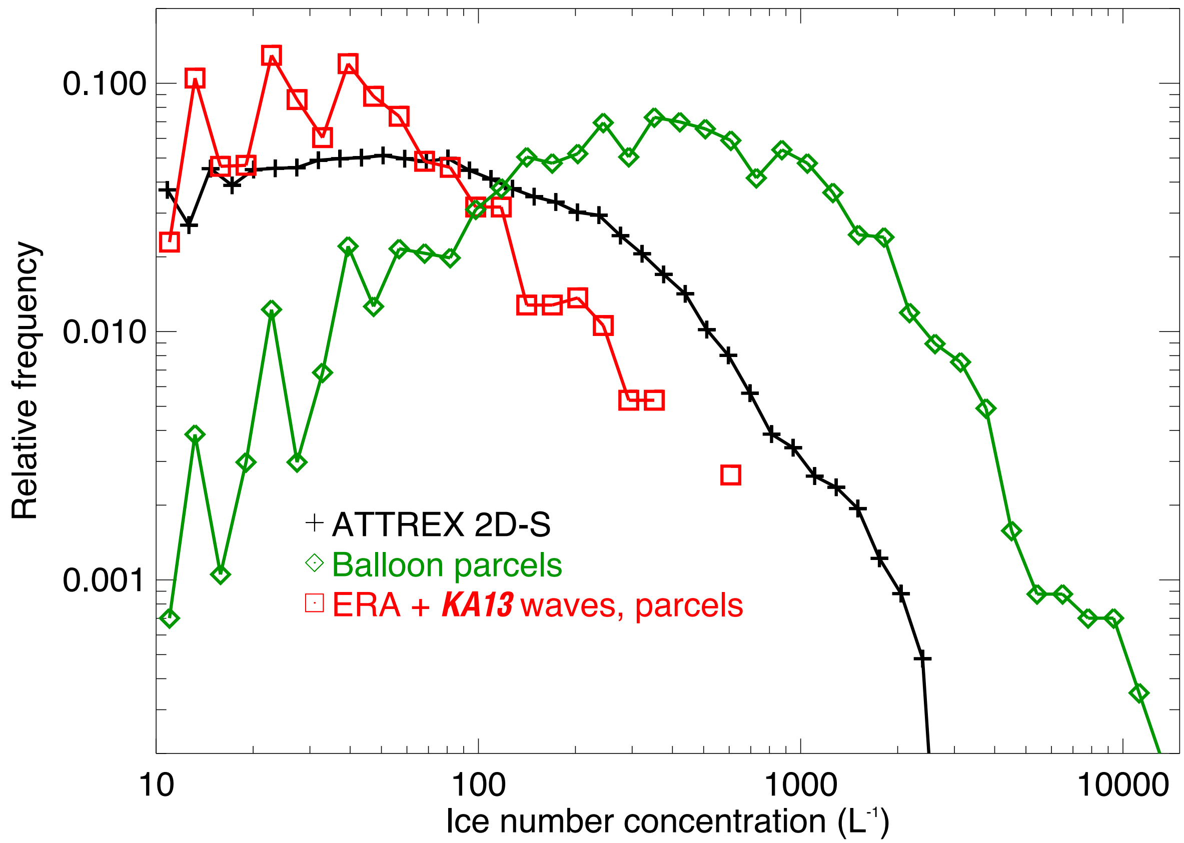


TTL cirrus ice concentrations



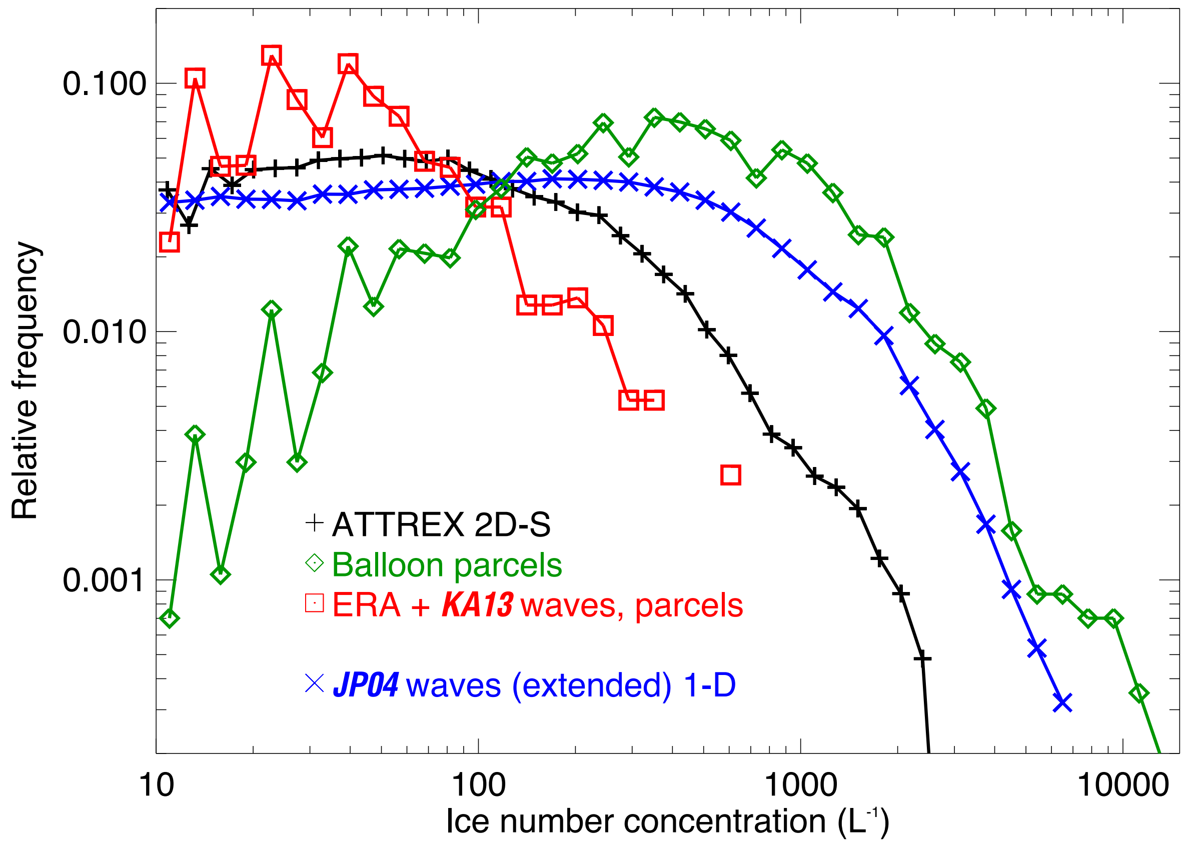
With only low-frequency waves resolved in global models, ice concentrations exceeding a few hundred per liter are absent

TTL cirrus ice concentrations



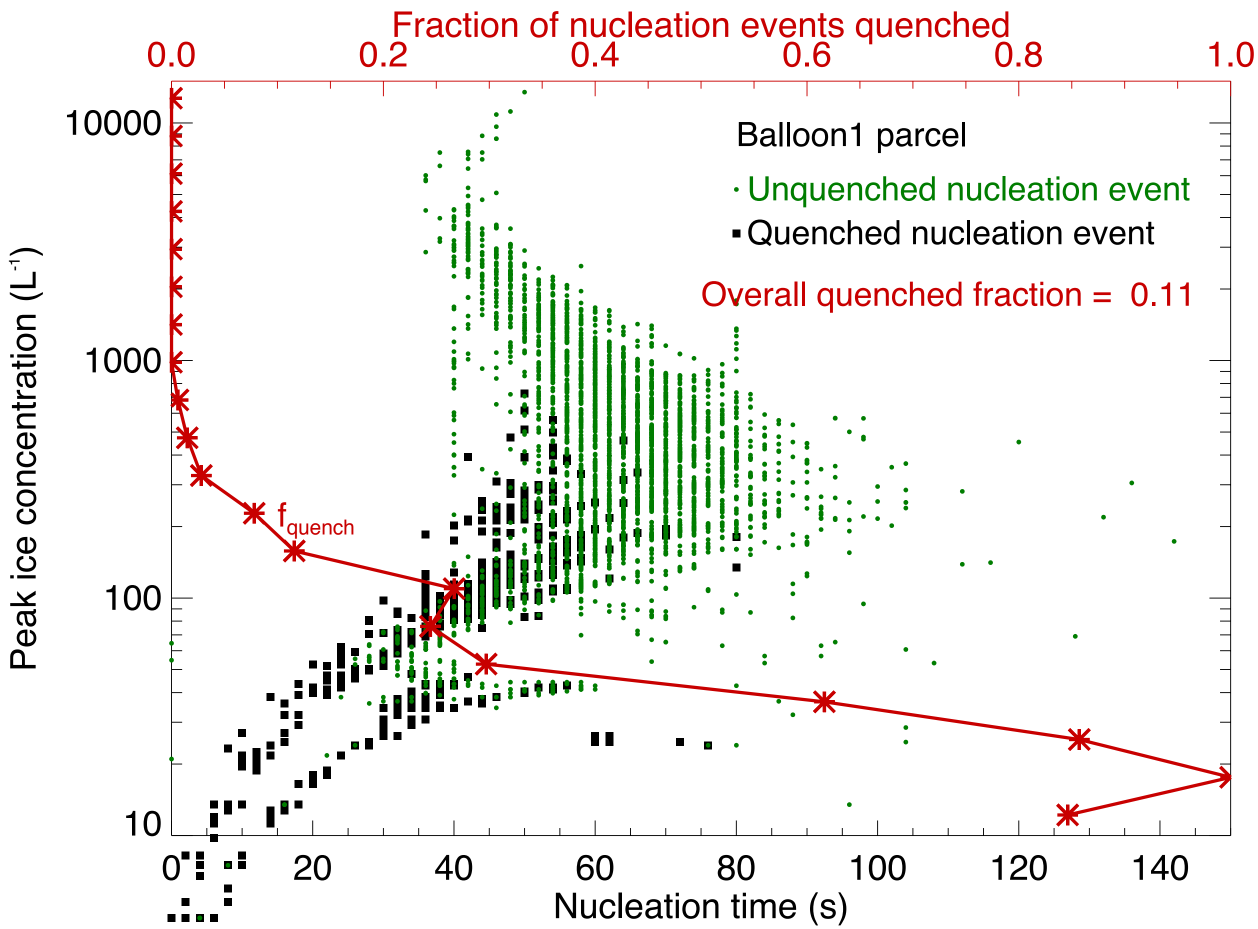
Parcel simulations driven by balloon measurements give excessive ice concentrations

TTL cirrus ice concentrations



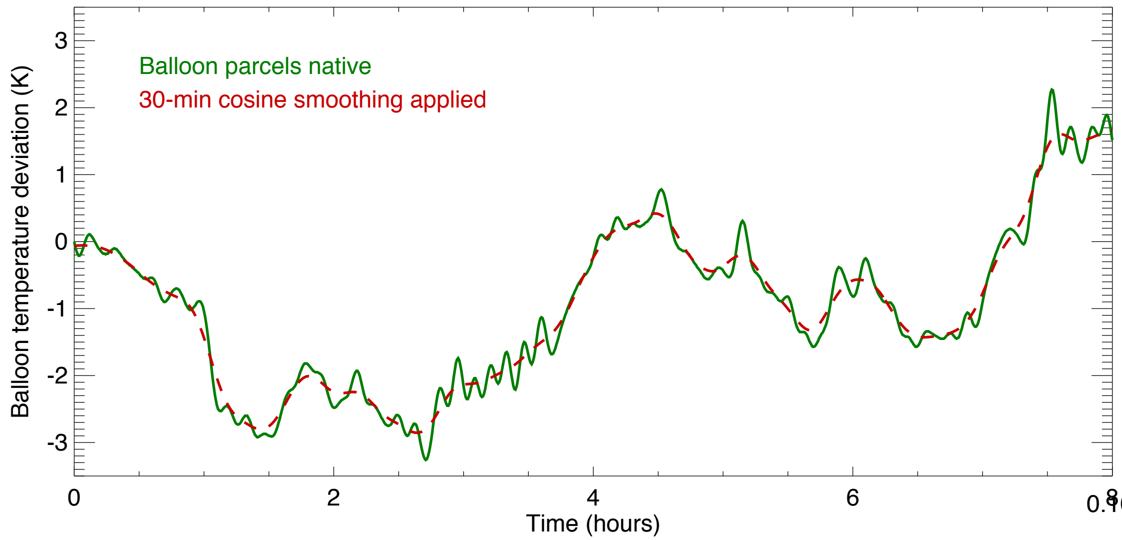
One-dimensional simulations with proper wave variance (including sedimentation) still produce excessive ice concentrations by a factor of 2–3

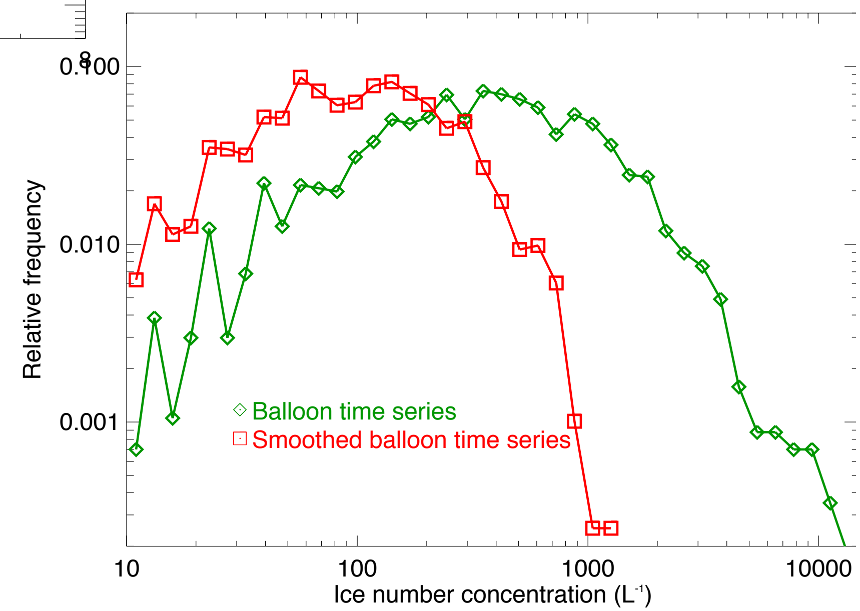
Quenching by high-frequency waves



Ice nucleation quenching by temperature reversal does occur and produces low ice concentrations; however, numerous cases of high ice concentrations still dominate N_{ice} statistics.

Net impact of high-frequency waves





Smoothing to remove high-frequency waves reduces ice concentrations

➔the dominant impact of high-frequency waves is to produce high ice concentrations

Conclusions and implications

- The primary impact of high-frequency waves on homogeneous freezing is to generate frequent occurrences of high ice concentrations.
- The quenching effect of very-short period waves reduces ice concentrations in some cases, but this effect does not compensate for the larger cooling rates associated with high-frequency waves.
- With realistic wave specification, homogeneous freezing produces ice concentrations larger than indicated by observations.
- Competition-dependent homogeneous freezing may limit ice concentrations [*Murphy*, 2014].
- Heterogeneous nucleation on solid particles may play an important role in TTL cirrus ice nucleation.

[*Jensen et al.*, 2016, GRL, in review]