# Impact of Ice Nucleation on Phase Partitioning in Mixed-Phase Clouds

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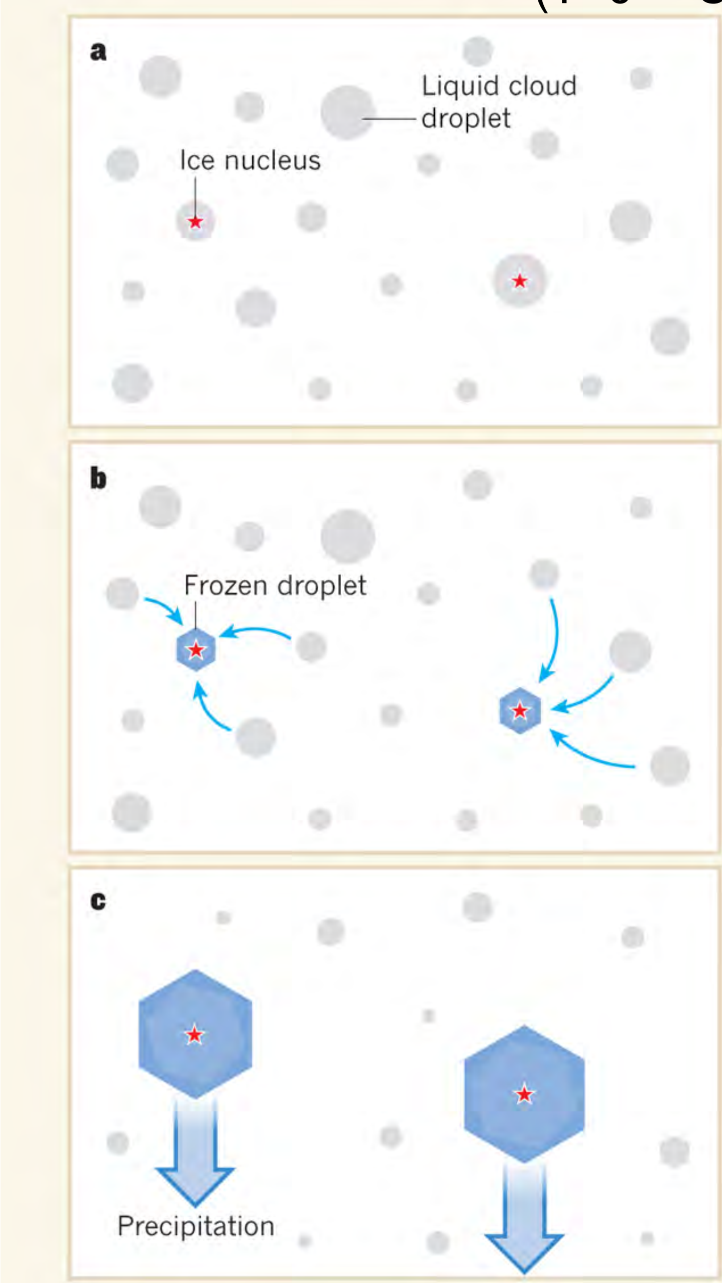
# Ice nucleation important for radiation and precipitation formation in mixed-phase clouds

Ice Nucleation

Bergeron-F.
Process

Precipitation
Initiation

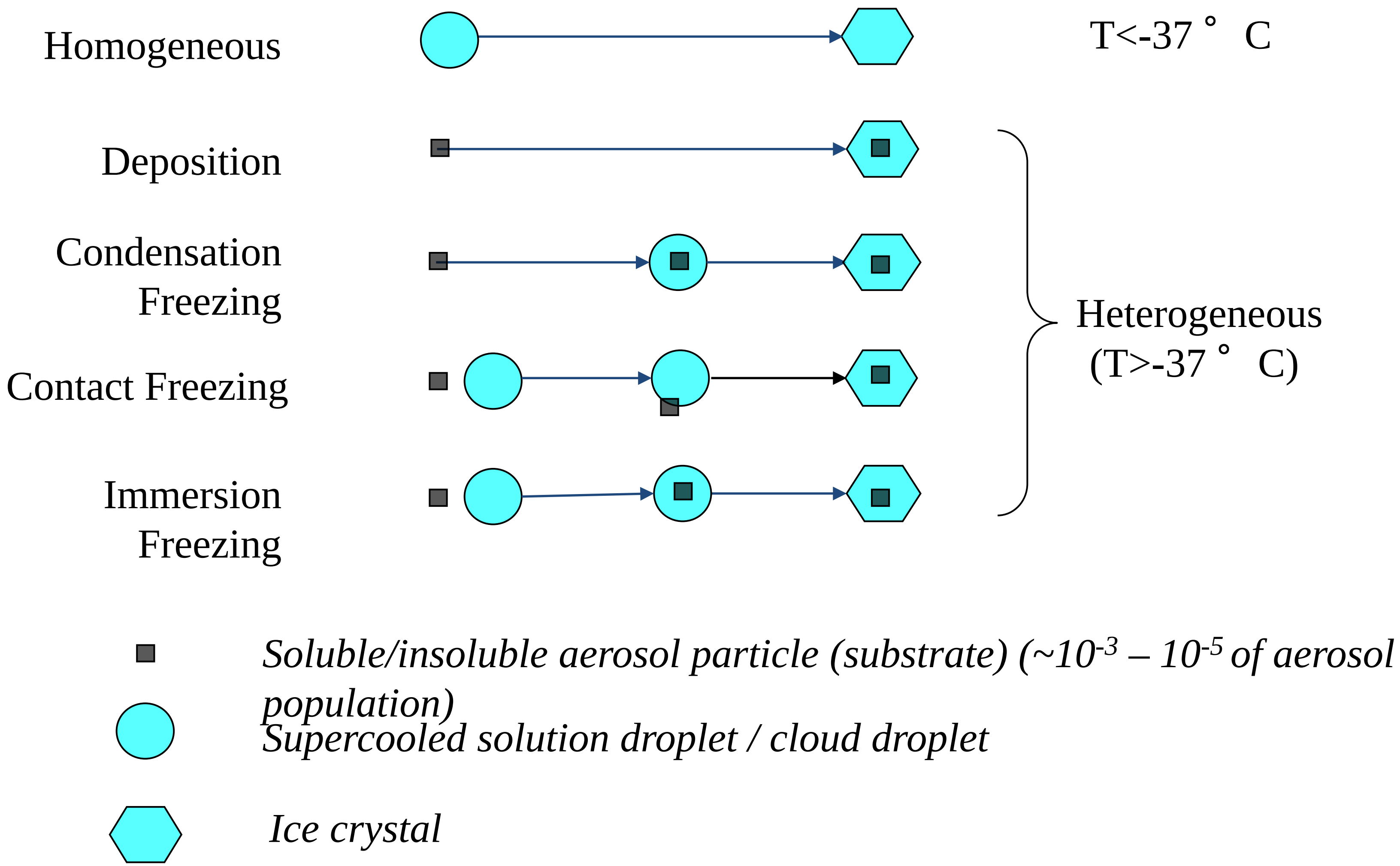
(T<0 ° C)




Koop, Nature (2013)

# How ice crystals are formed?

## Multiple Ice Nucleation Mechanisms




Courtesy of G. Kulkarni

# Classical nucleation theory

Nucleation rate $J = A' r_N^2 \sqrt{f} \exp(\frac{-\Delta g^{\#} - f \Delta g_g^o}{kT})$

f(α), α is contact angle

Pruppacher and Klett (1997)

Hoose et al. (2010)

## Immersion/condensation

$$r_{g,imm} = \frac{2\upsilon_w \sigma_{i/w}}{kT \ln(a_w e_{sw} / e_{si})}$$

$$\Delta N_{i,imm} = \sum_x Min\{f_{l,x} N_{aer,x} f_{i,\max,x}, f_{l,x} N_{aer,x} [1 - \exp(-J_{imm,x} \Delta t)]\}$$

Activated/cloud-borne aerosol

## Deposition

$$r_{g,dep} = \frac{2\upsilon_w \sigma_{i/v}}{kT \ln(e / e_{si})}$$

Interstitial & uncoated aerosol

$$\Delta N_{i,dep} = \sum_x Min\{(1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} f_{i,\max,x}, (1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} \times [1 - \exp(-J_{dep,x,RH_w=0.98} \Delta t)]\}$$

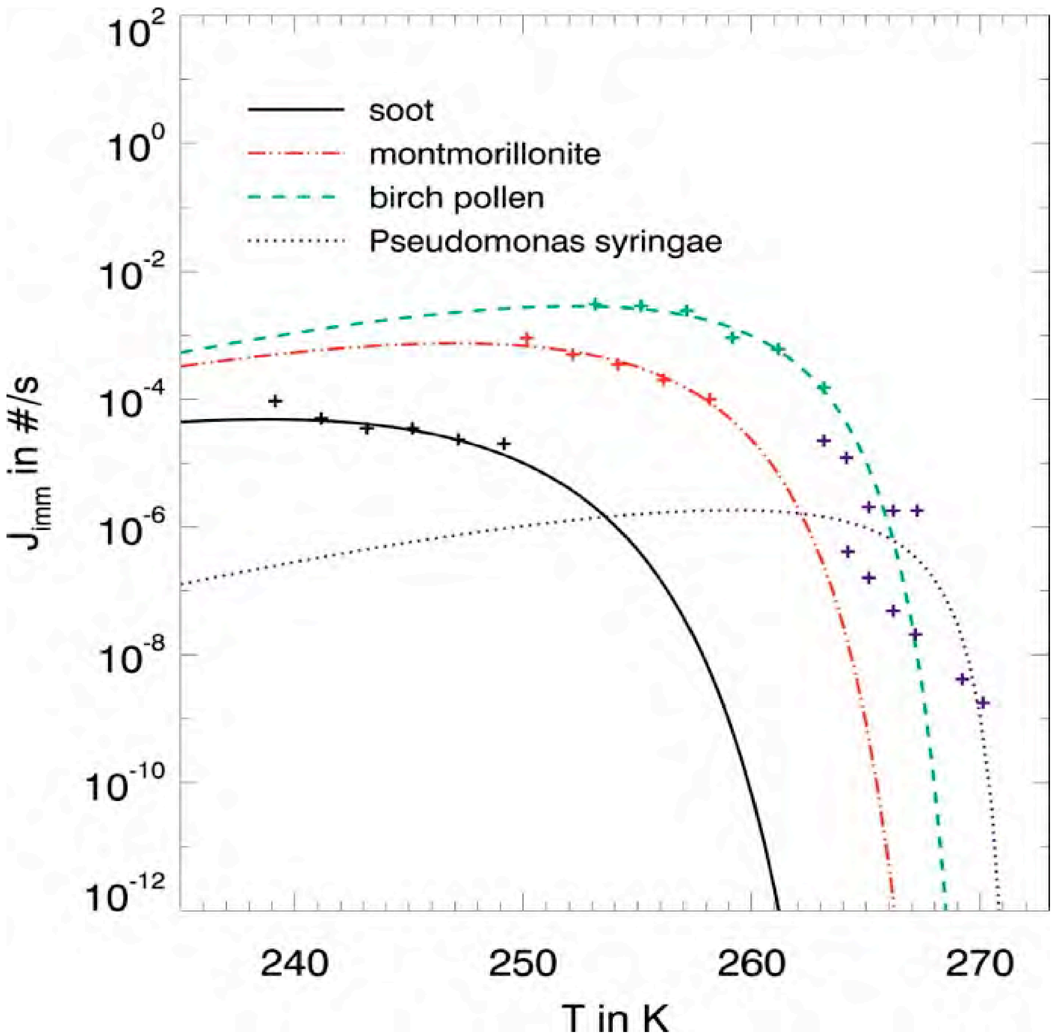
## Contact

$$N_{g,contact} \approx 4\pi r_N^2 \frac{e}{v_s \sqrt{2\pi m_w kT}} \times \exp[-\frac{\Delta g_{dep}^{\#} + f \Delta g_{g,dep}^o (r_{g,imm})}{kT}]$$

$$\Delta N_{i,contact} = \sum_x Min\{(1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} f_{i,\max,x}, (1 - f_{l,x})(1 - f_{x,coated}) N_{aer,x} \times [1 - \exp[-K_{coll}(r_{N,x}, r_l) N_l Max(N_{g.contact,x}, 1) \Delta t]\}$$

PDF-α model: integrate over the PDF of contact angle α

# Classical theory links ice nucleation rate to aerosol properties, constrained by experiments




Hoose et al. (2010)

α=40.2° (soot, immersion); α=31.0° (dust, immersion)
α=28.0° (soot, deposition); α=12.7° (dust, deposition)

# Community Atmospheric Model (CAM5)

- Modal Aerosol Module (MAM, *Liu et al. 2012)*
  - Predicting aerosol mass, number and size distribution
- Two-moment stratiform microphysics (*Morrison & Gettelman 2008; Gettelman et al. 2010*)
- Cloud liquid droplet activation (*Abdul-Razzak & Ghan 2000*)
- Cloud ice crystal nucleation (*Liu et al. 2007*)
  - *Mixed-phase clouds*:

    *Meyers et al. (1992)* for deposition/immersion/condensation freezing of cloud droplets; no link to aerosol

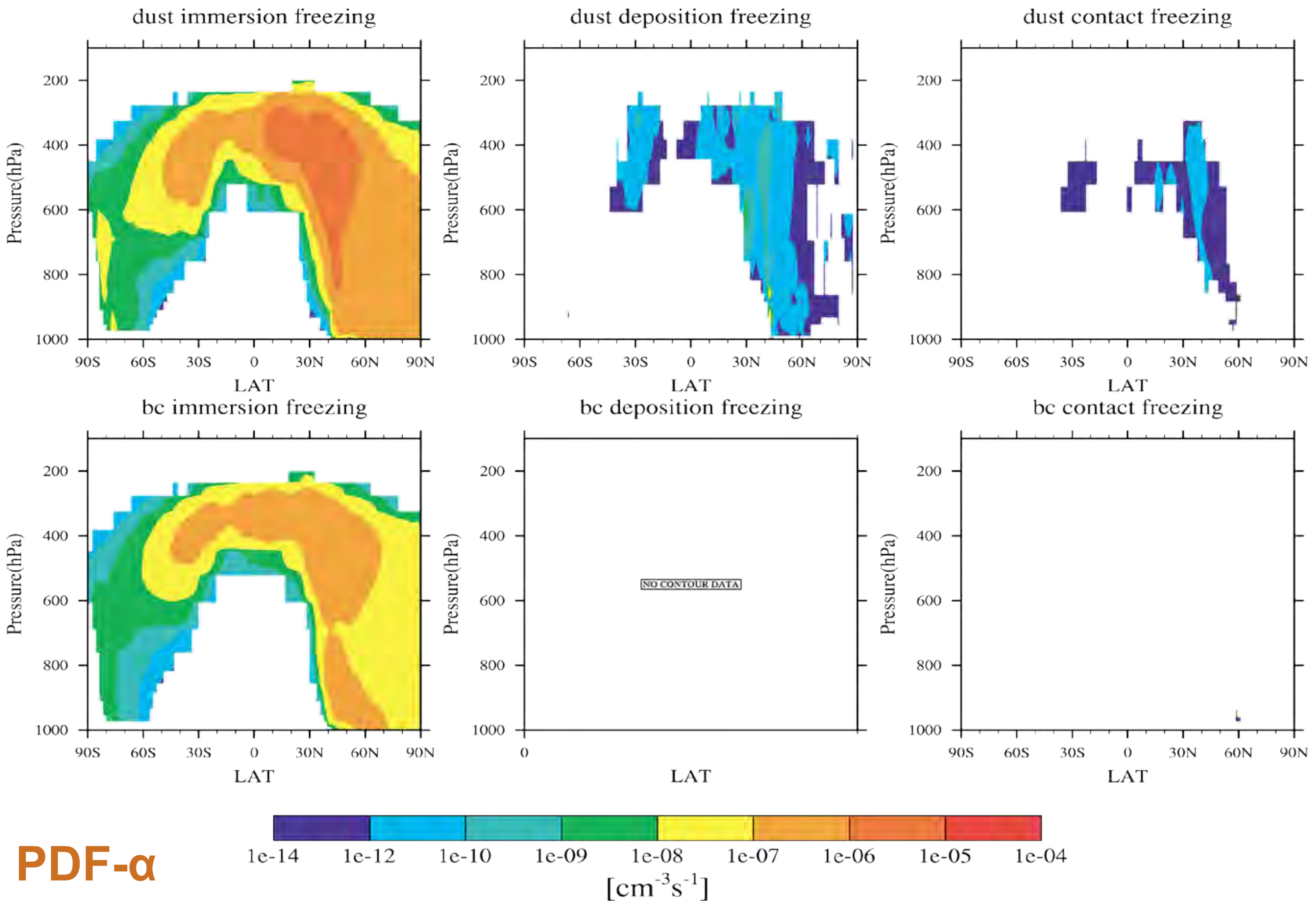
    *Young (1974)* for contact freezing of cloud droplets by dust

# Model Experiments

- CAM5.1 with FV dynamic core, 1.9° x 2.5° , 30 levels
- 6-yr climate runs with prescribed SST and sea ice (AMIP II type of run)

- Default : Meyers et al. (1992) for deposition/condensation/immersion in mixed-phase clouds, with no link to aerosol
- PDF-α : Classical nucleation theory with PDF-contact angle, with mean (46° ) & standard deviation (0.01) of PDF derived from fitting to observations of natural dust (Kohler et al. 2010)

# Ice nucleation in mixed-phase clouds: immersion vs. deposition vs. contact mode



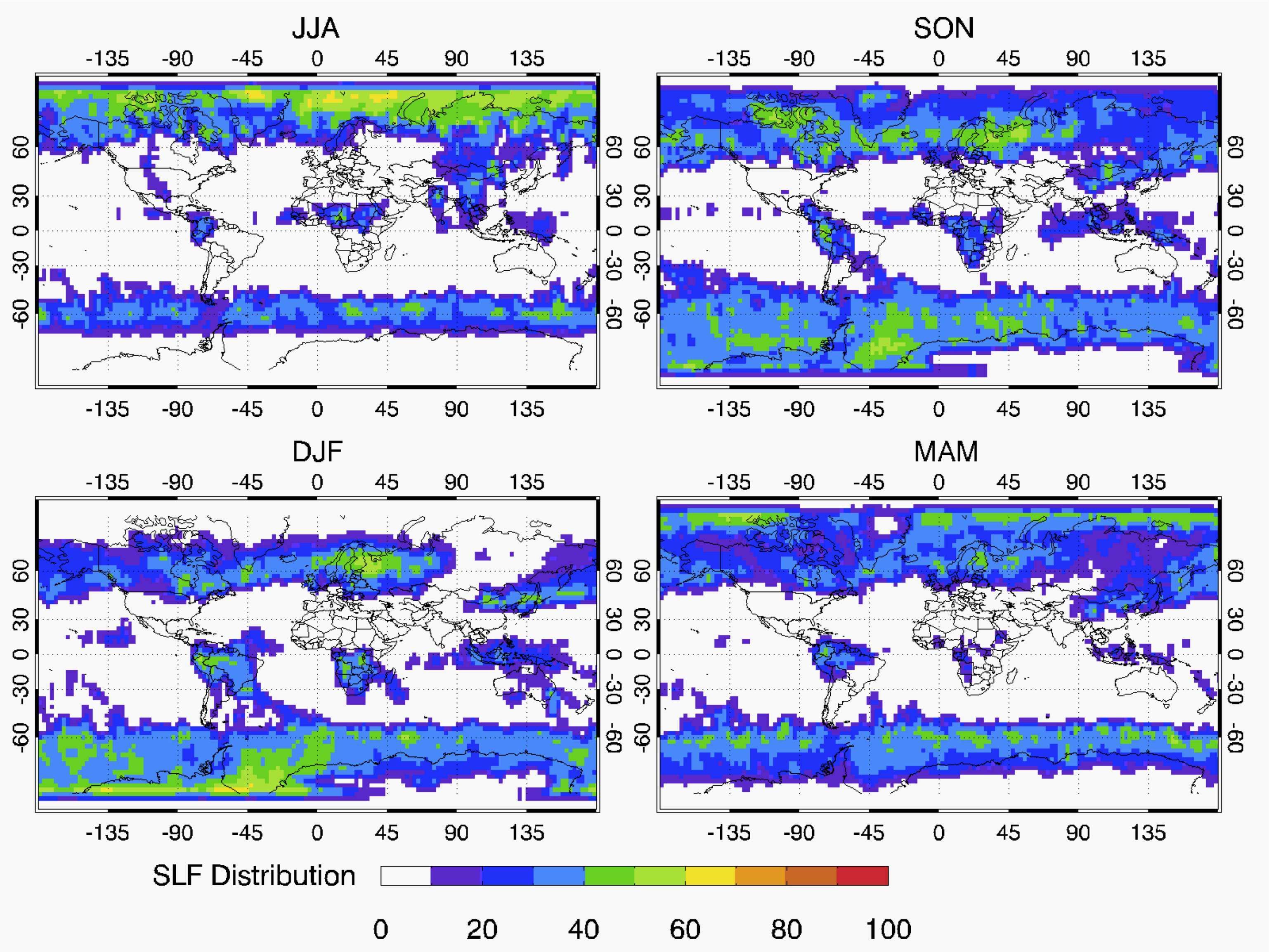

**PDF-α**

# Data Sets and Methodology

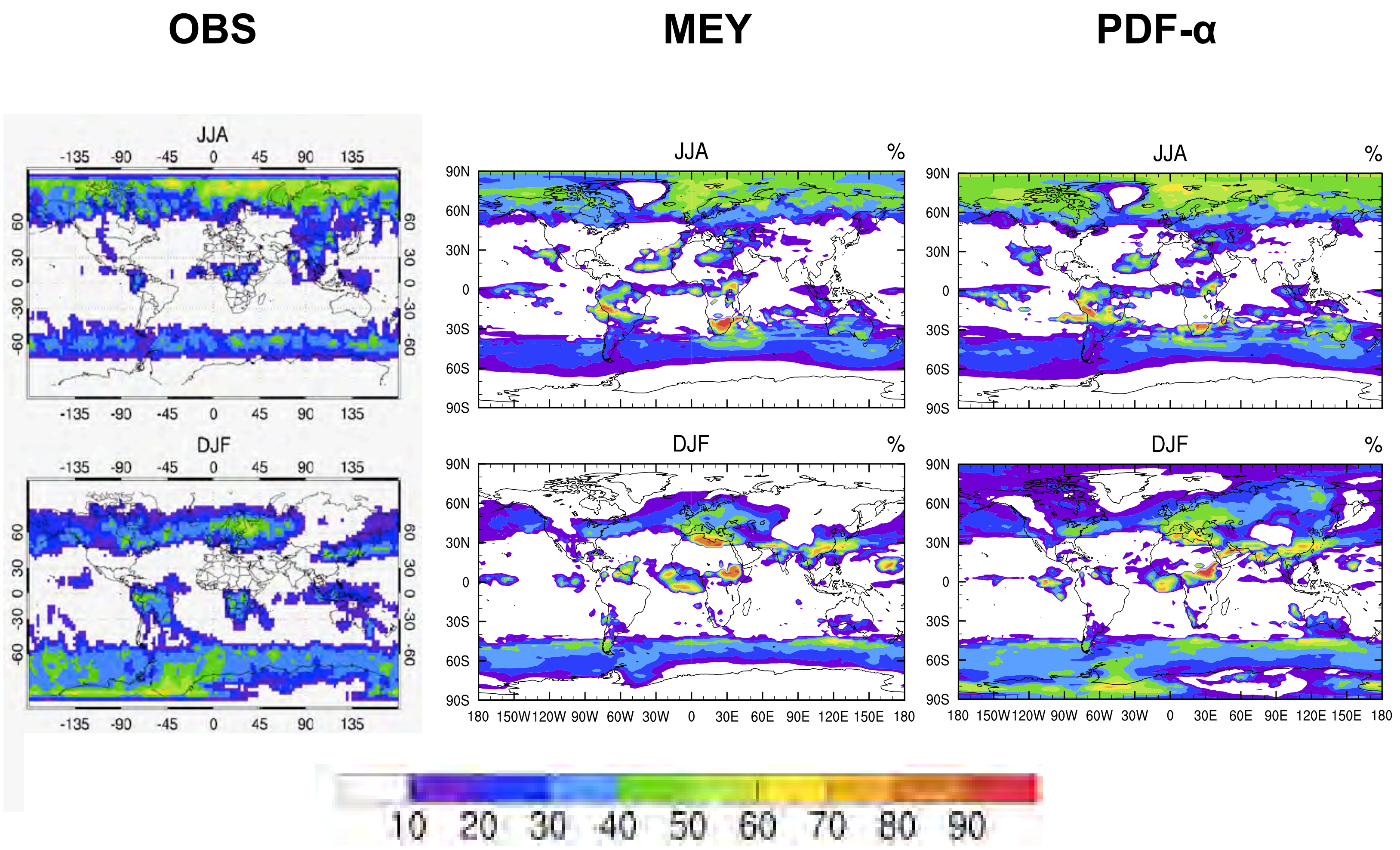
- Targets: Clouds with cloud top temperature between -40 and 0 $^{o}C$.
- Cloud Phase Partition: CloudSat 2B-CLDCLASS-LIDAR product (Wang 2013).
- LWP: MODIS (MOD06) cloud product (King et al. 2003). Only for water and mixed-phase clouds.
- IWP: Integration of IWC (using temperature-depended $Z_e$-LWC relationship (Hogan et al. 2006)) from CPR radar detected cloud base to top. Only for mixed-phase and ice clouds.
- SLF (supercooled liquid fraction) calculation:

$$SLF = \frac{LWP}{LWP + IWP}$$

# Global SLF Distribution for Four Seasons

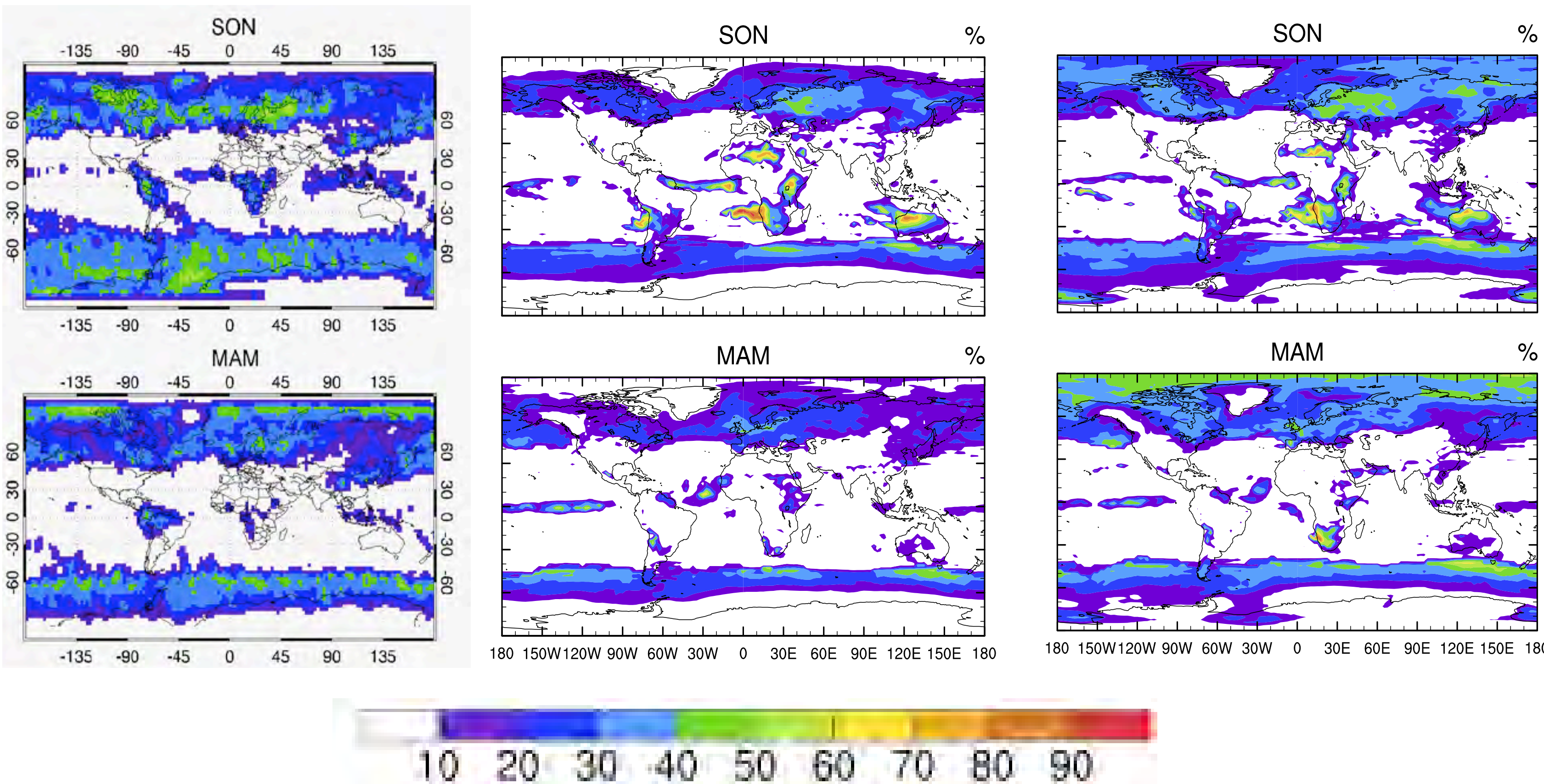


# Global SLF distributions for JJA and DJF

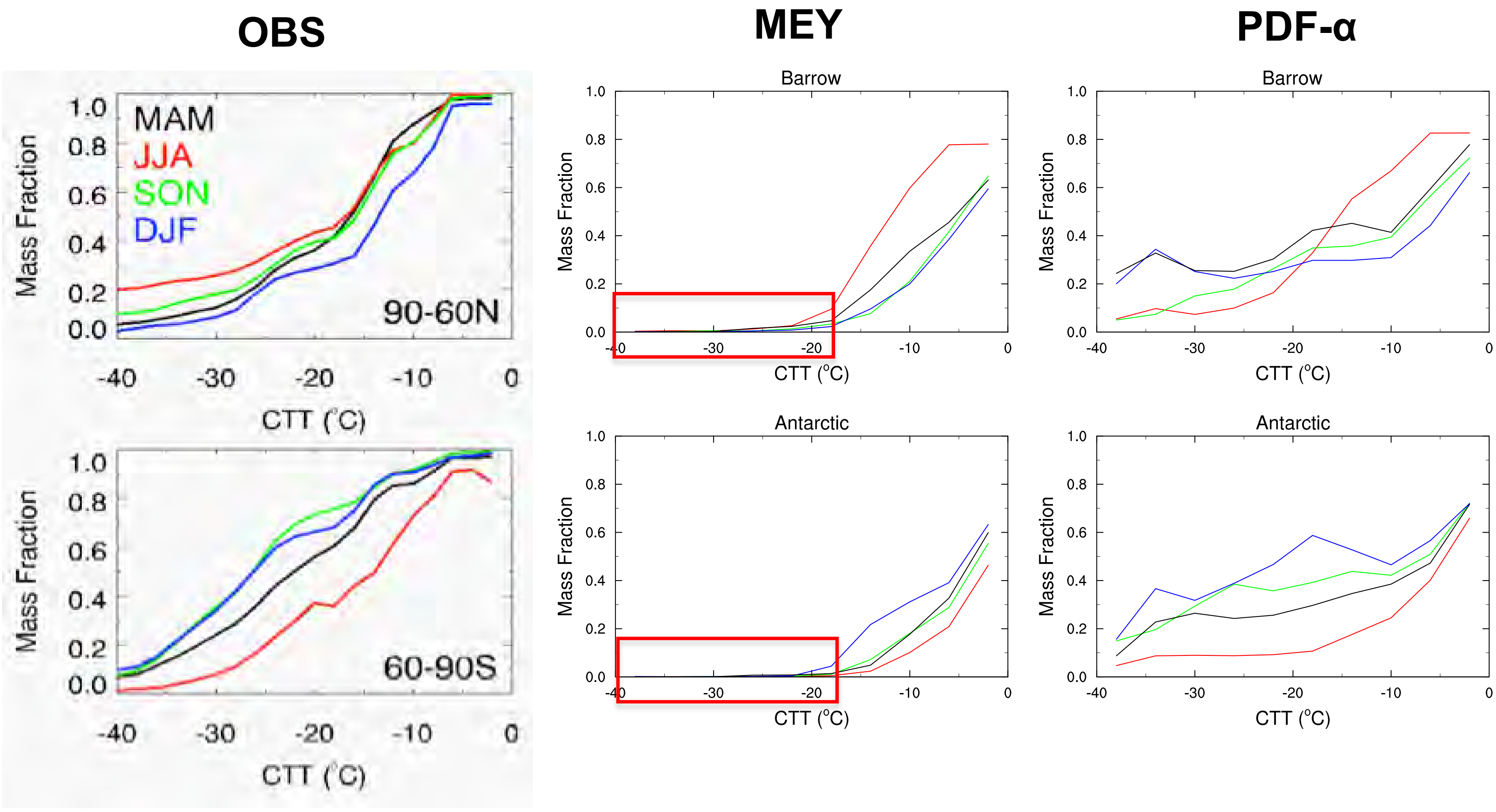


# Global SLF distributions for SON and MAM

**OBS** **MEY** **PDF-α**



# SLF as a function of cloud-top temperature



# Summary

- A ice nucleation parameterization based on classical nucleation theory has been implemented in CAM5, which links ice nucleation to aerosol (e.g., dust, soot, biological aerosol) properties

- Compared to Meyers et al. (default), new parameterization significantly increases model simulated liquid water fraction in mixed-phase clouds

  - Improved comparison with Cloudsat observations in many regions

  - Do more careful comparison with observations: supercooled liquid fraction sorted by dust concentration in different regions.