

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

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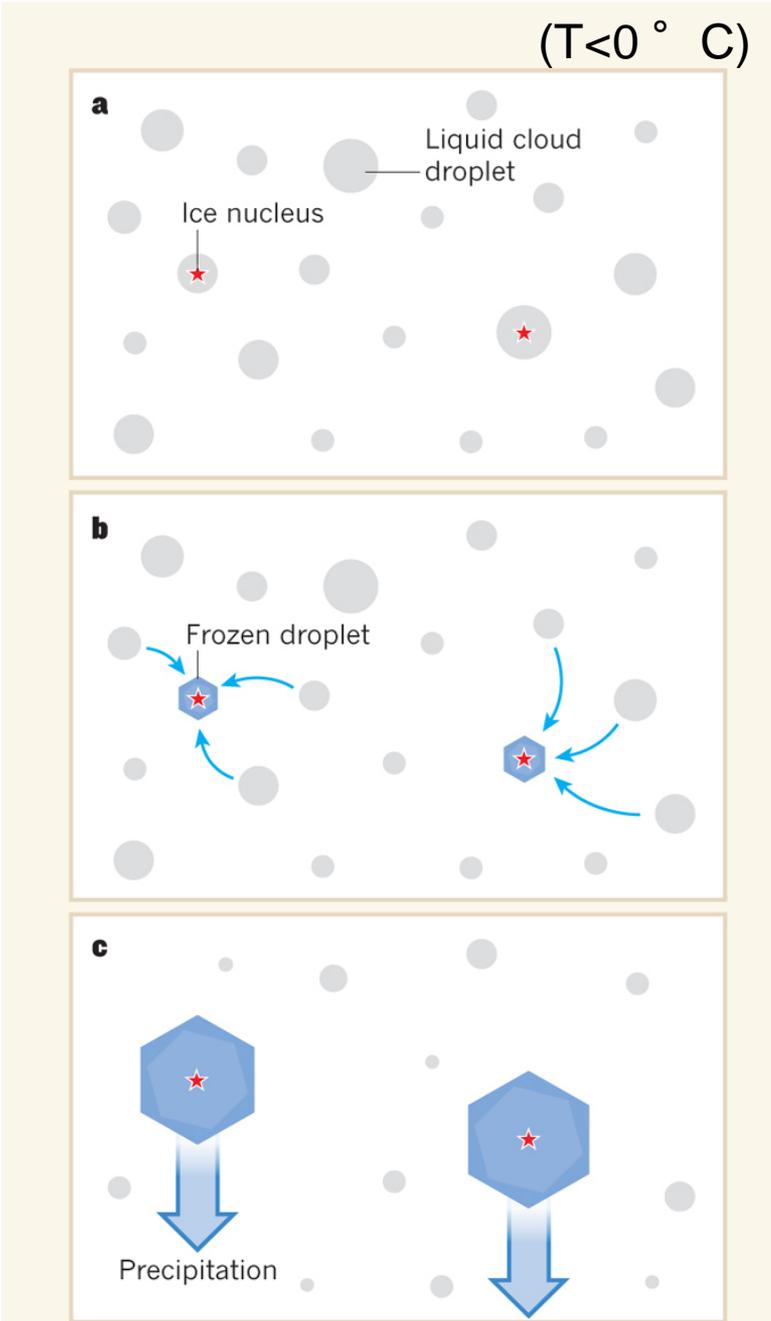
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Ice nucleation important for radiation and precipitation formation in mixed-phase clouds

Ice Nucleation

Bergeron-F. Process

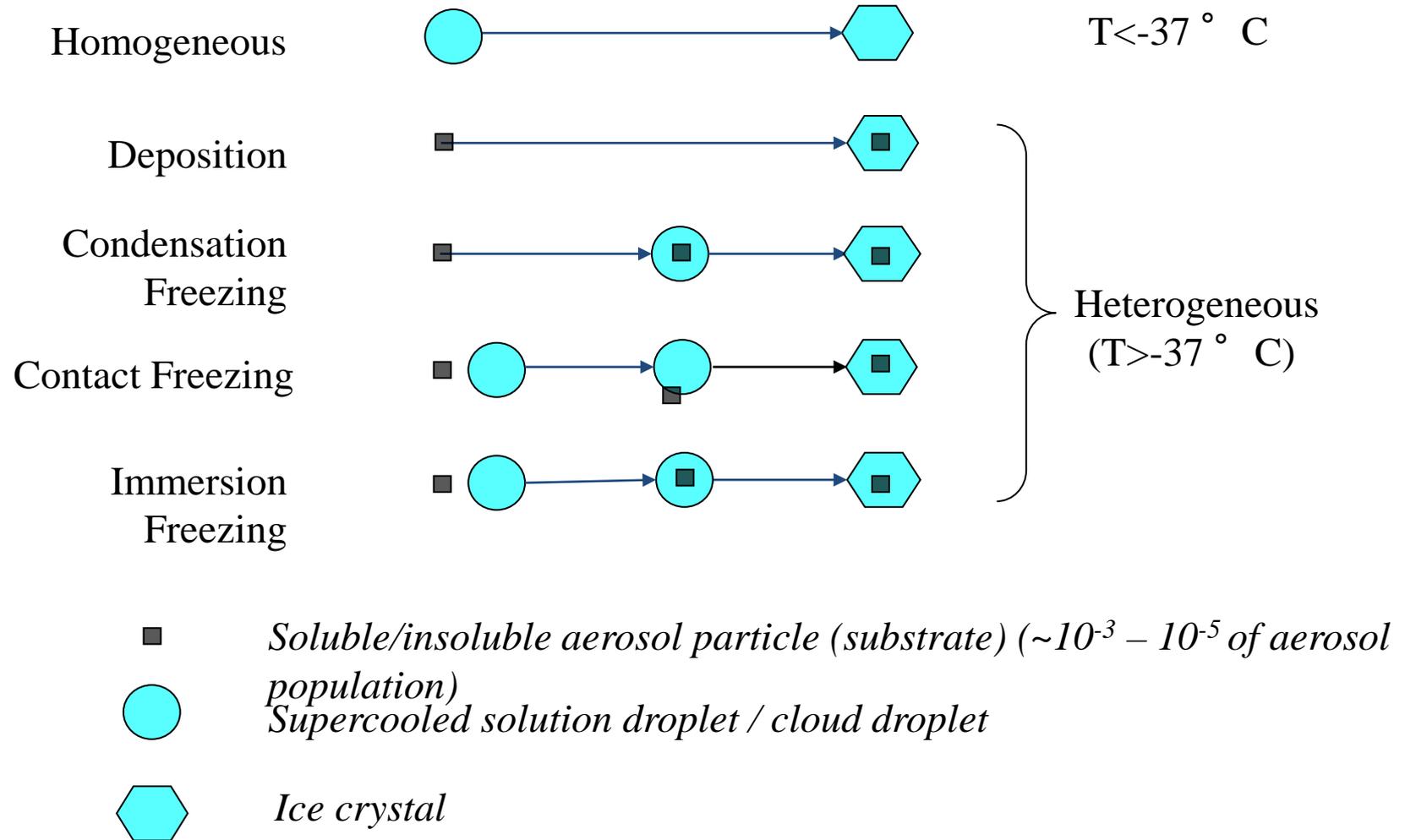
Precipitation Initiation



Koop, Nature (2013)

How ice crystals are formed?

Multiple Ice Nucleation Mechanisms



Classical nucleation theory

Nucleation rate $J = A' r_N^2 \sqrt{f} \exp\left(\frac{-\Delta g^\# - f \Delta g_g^o}{kT}\right)$
 $f(\alpha)$, α is contact angle

Immersion/condensation

Pruppacher and Klett (1997)

Hoose et al. (2010)

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

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

Activated/cloud-borne aerosol

Deposition

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

Interstitial & uncoated aerosol

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

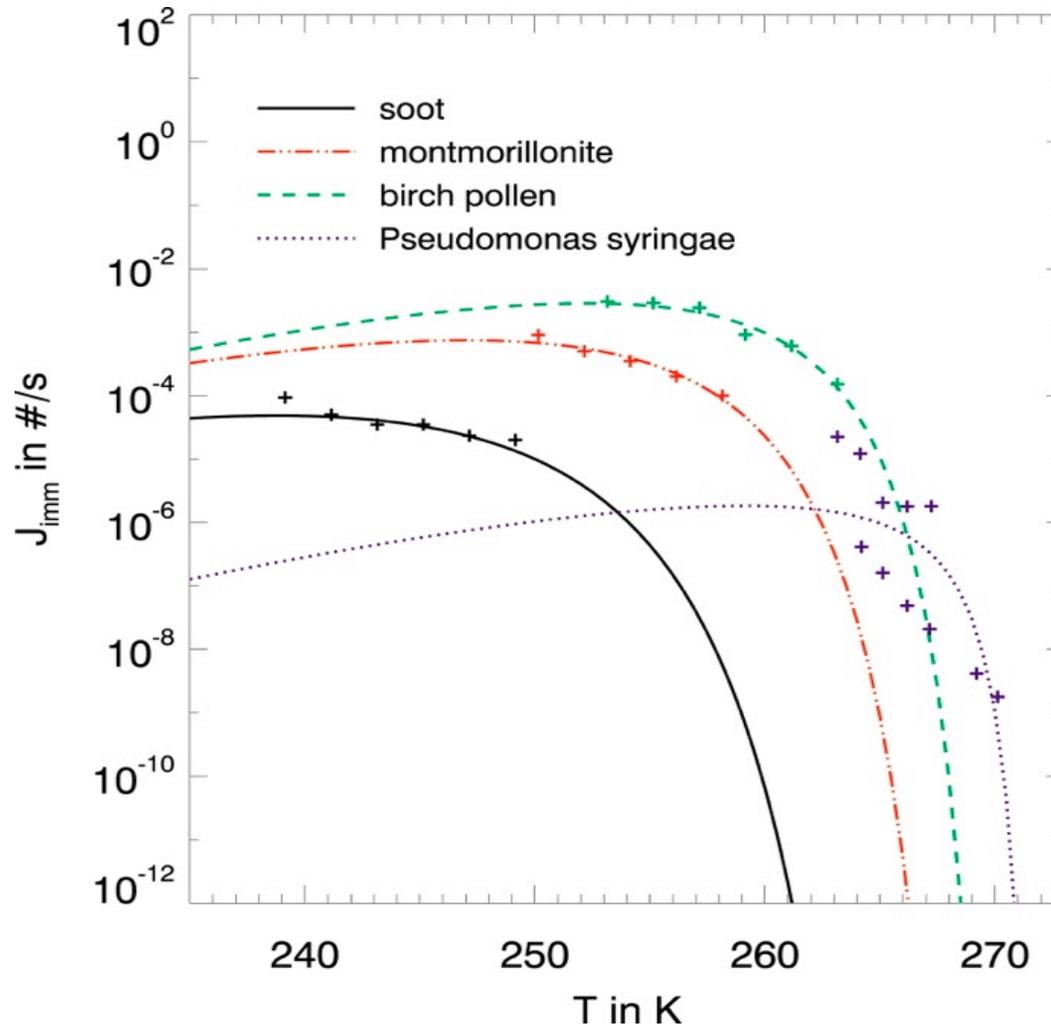
Contact

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

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

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)

$\alpha=40.2^\circ$ (soot, immersion); $\alpha=31.0^\circ$ (dust, immersion)
 $\alpha=28.0^\circ$ (soot, deposition); $\alpha=12.7^\circ$ (dust, deposition)

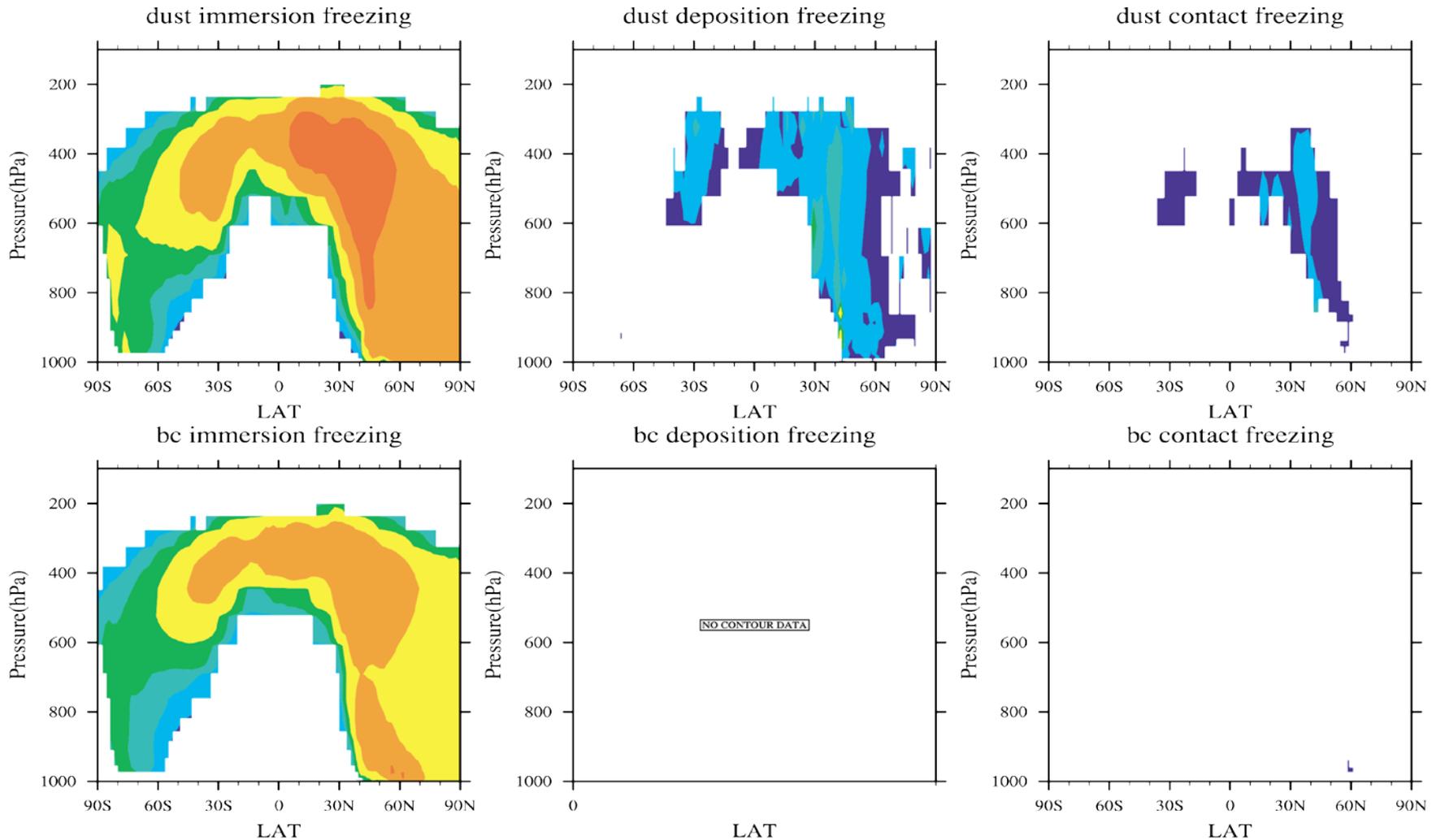
Community Atmospheric Model (CAM5)

- ▶ **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

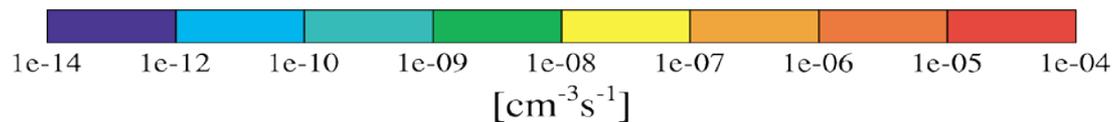
Model Experiments

- ▶ CAM5.1 with FV dynamic core, $1.9^\circ \times 2.5^\circ$, 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

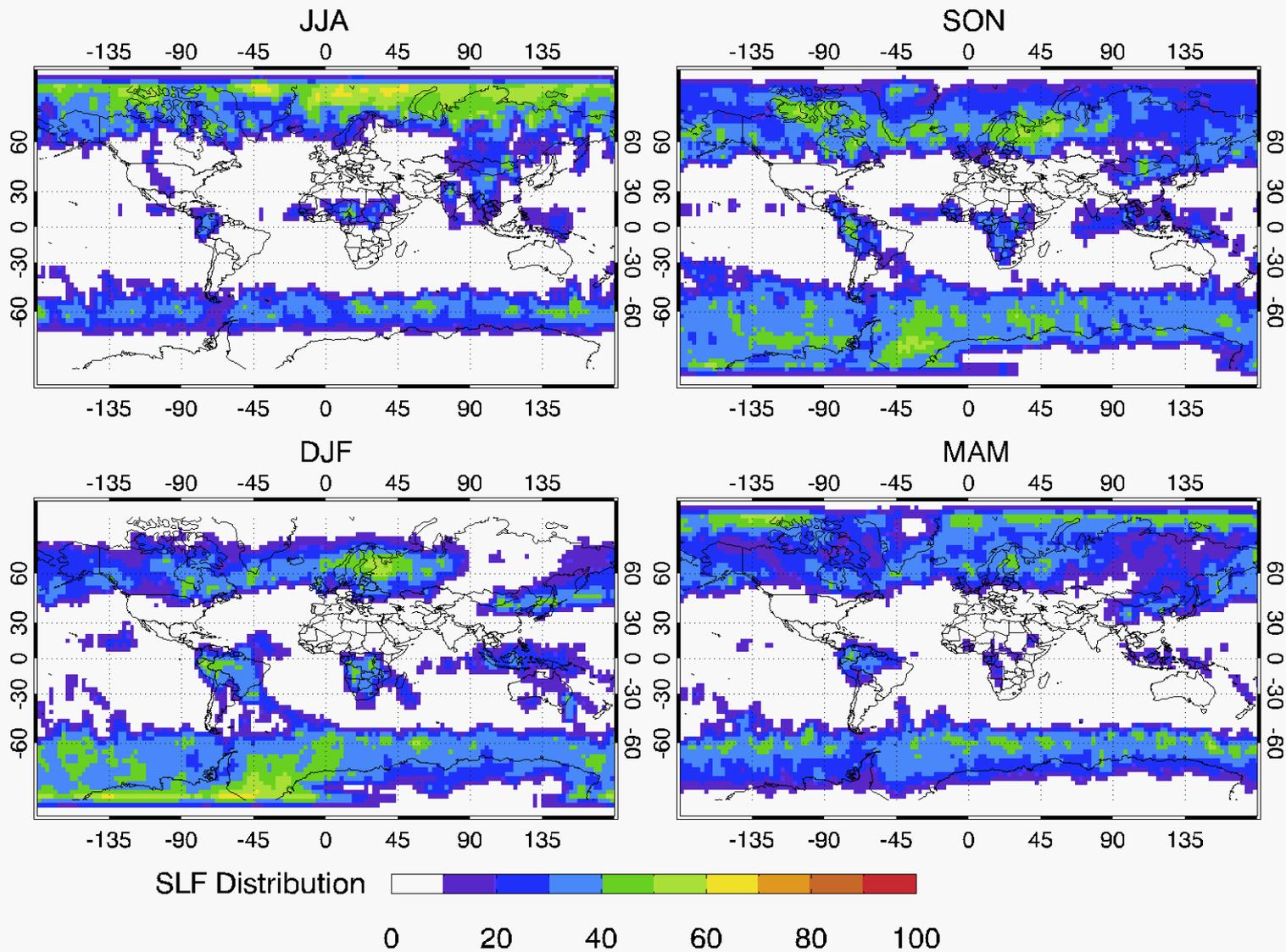


Data Sets and Methodology

- ✧ Targets: Clouds with cloud top temperature between -40 and 0 °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-dependend 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

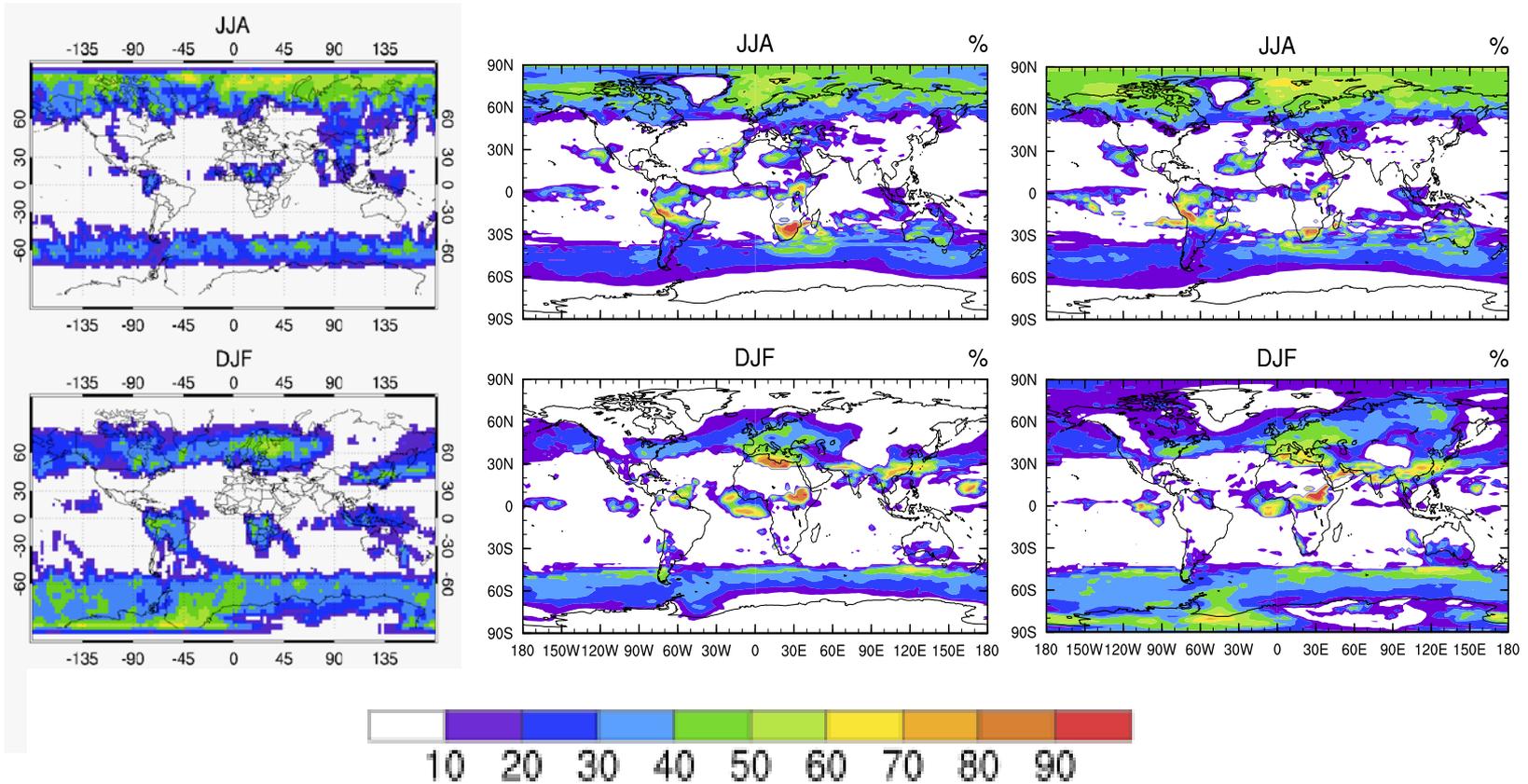


Global SLF distributions for JJA and DJF

OBS

MEY

PDF- α

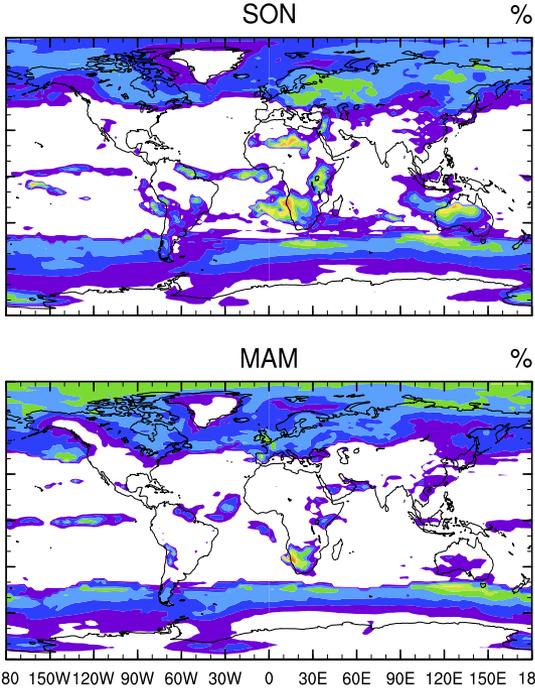
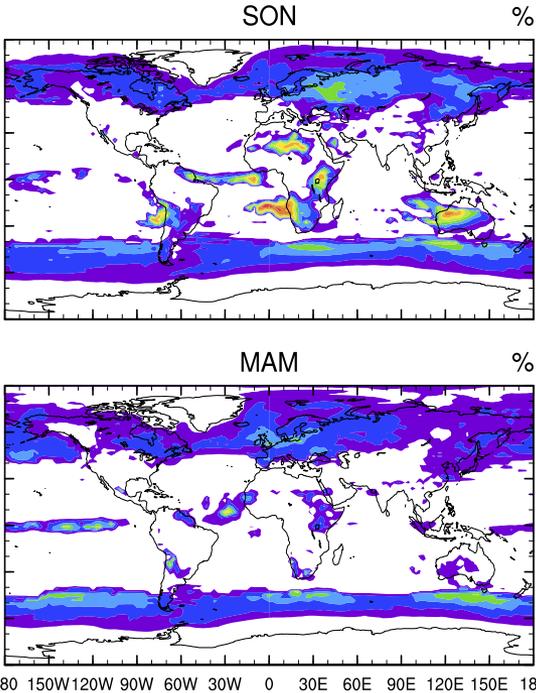
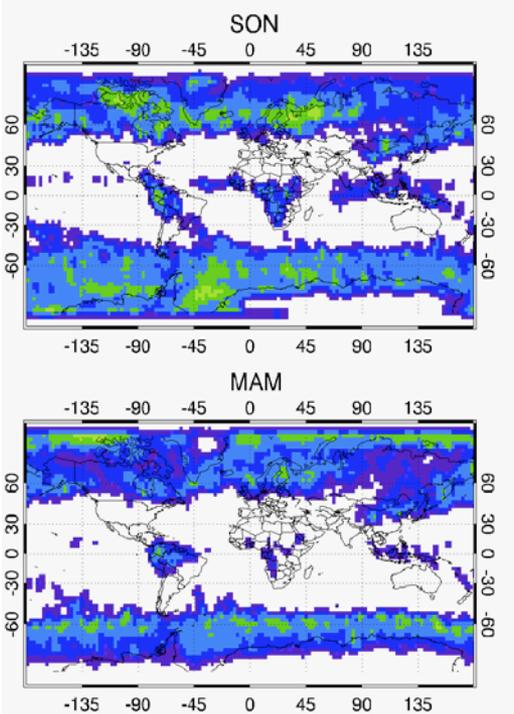


Global SLF distributions for SON and MAM

OBS

MEY

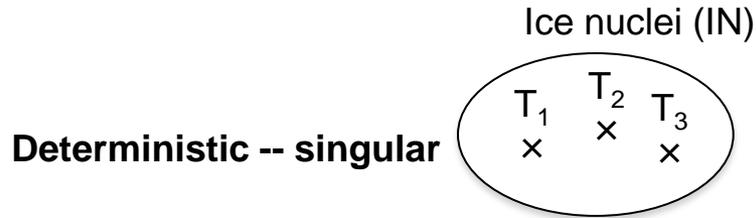
PDF- α



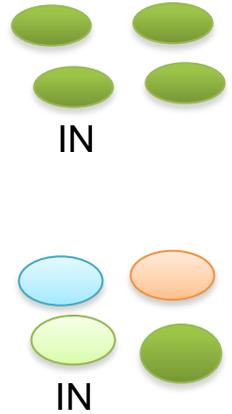
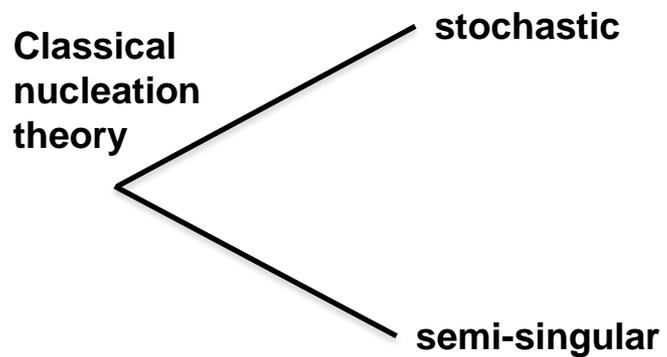
Summary

- ❑ 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 cloud-top temperature, dust concentration over different regions.

Parameterizing ice nucleation with models

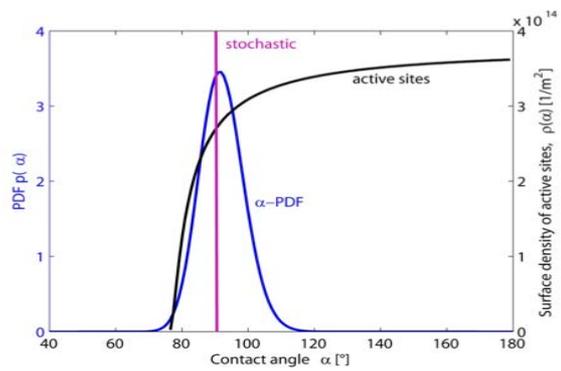


Deterministic model: Active sites with distinct freezing temperatures are randomly distributed over the IN surface (Phillips et al., 2008; DeMott et al., 2010)
 → no time dependence

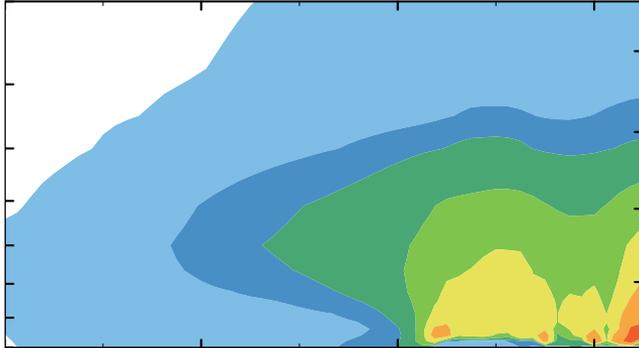


Stochastic model: All IN have the same ice nucleation properties (contact angle α)

PDF- α model: IN have different contact angles, and α is constant over each IN surface (Marcolli et al., 2007)



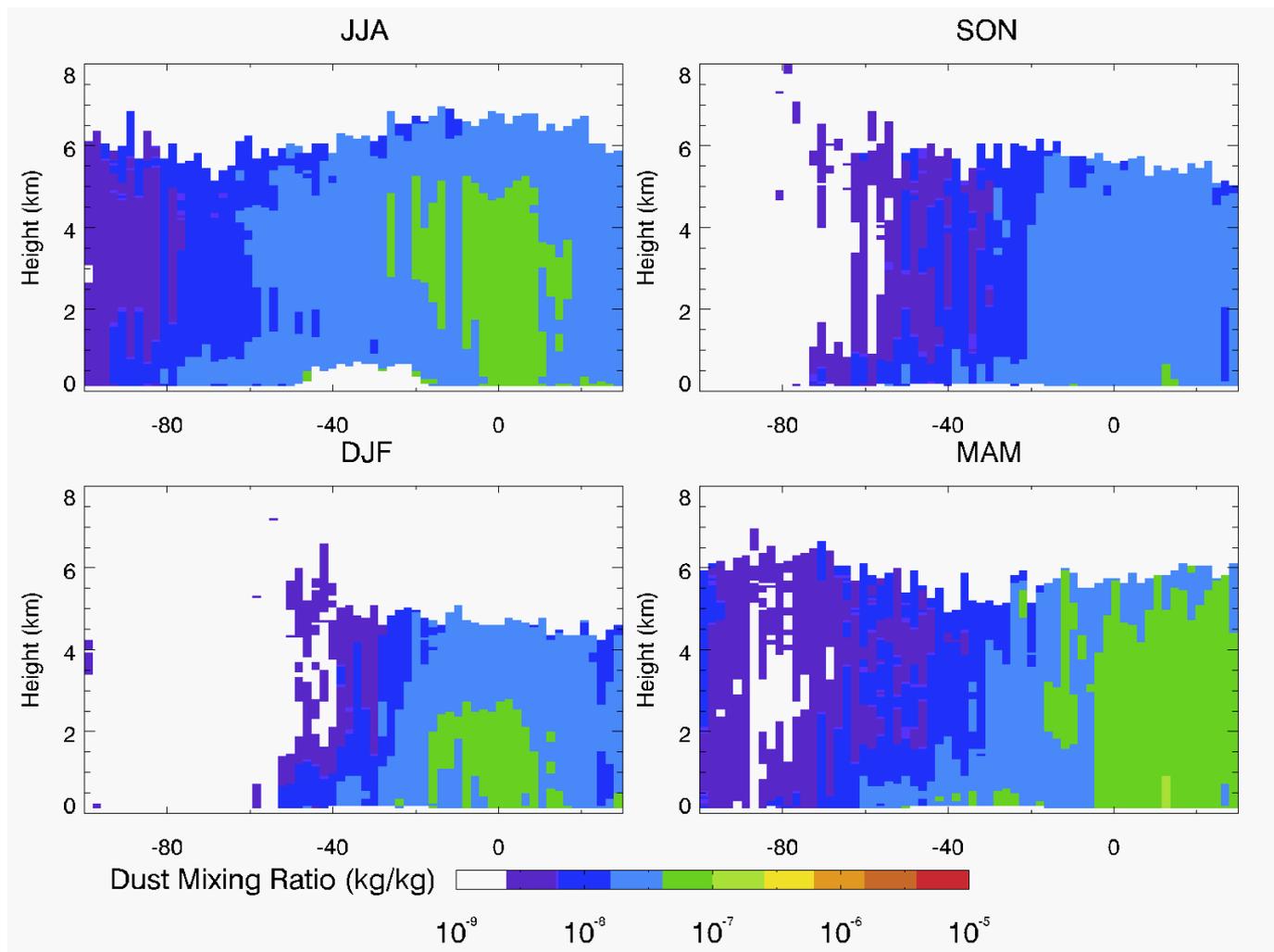
Dust concentration over Sahara & outflow from CAM5



8 1e-07 5e-07 1e-05

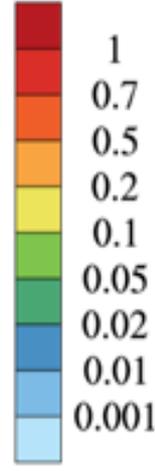
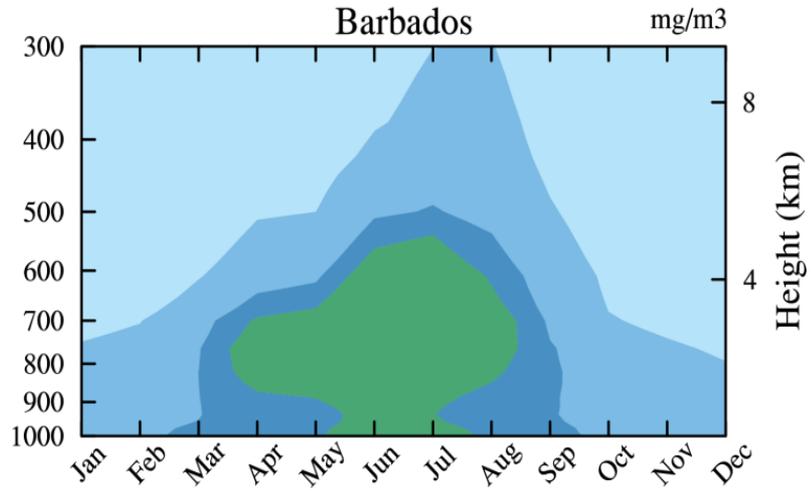
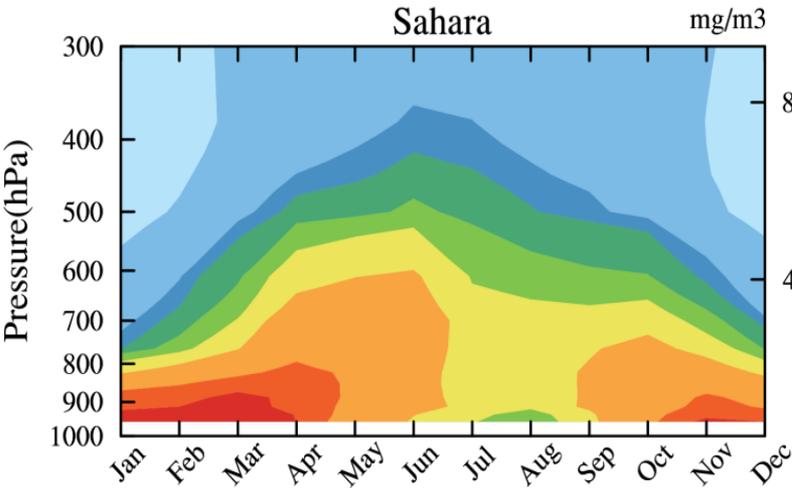
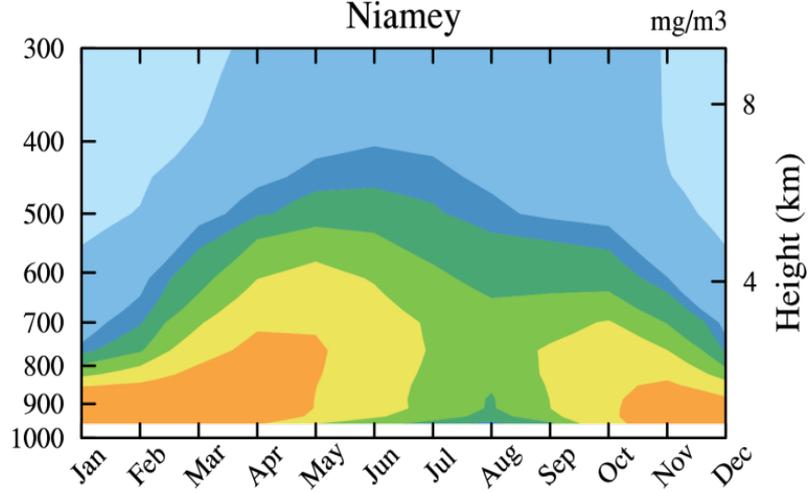
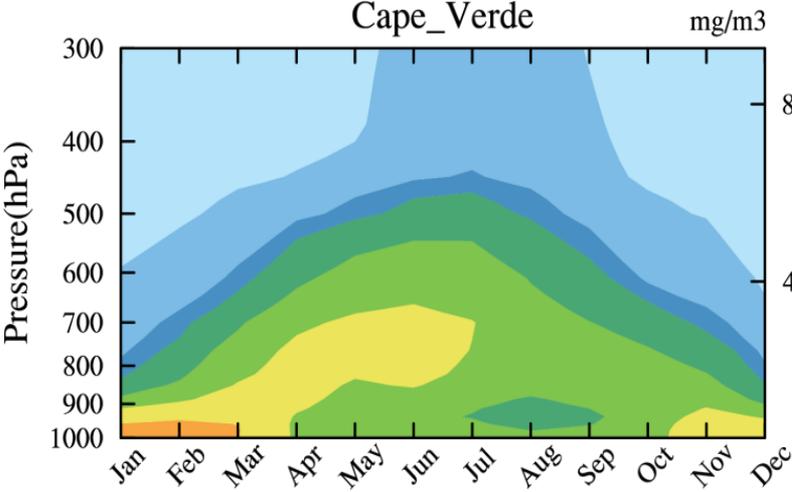
Vertical structures of cross-Atlantic Sahara dust (averaged in the grid box latitude from -15° to 45° and longitude from -100° to 30°)

Dust concentration over Sahara & outflow from CALIPSO

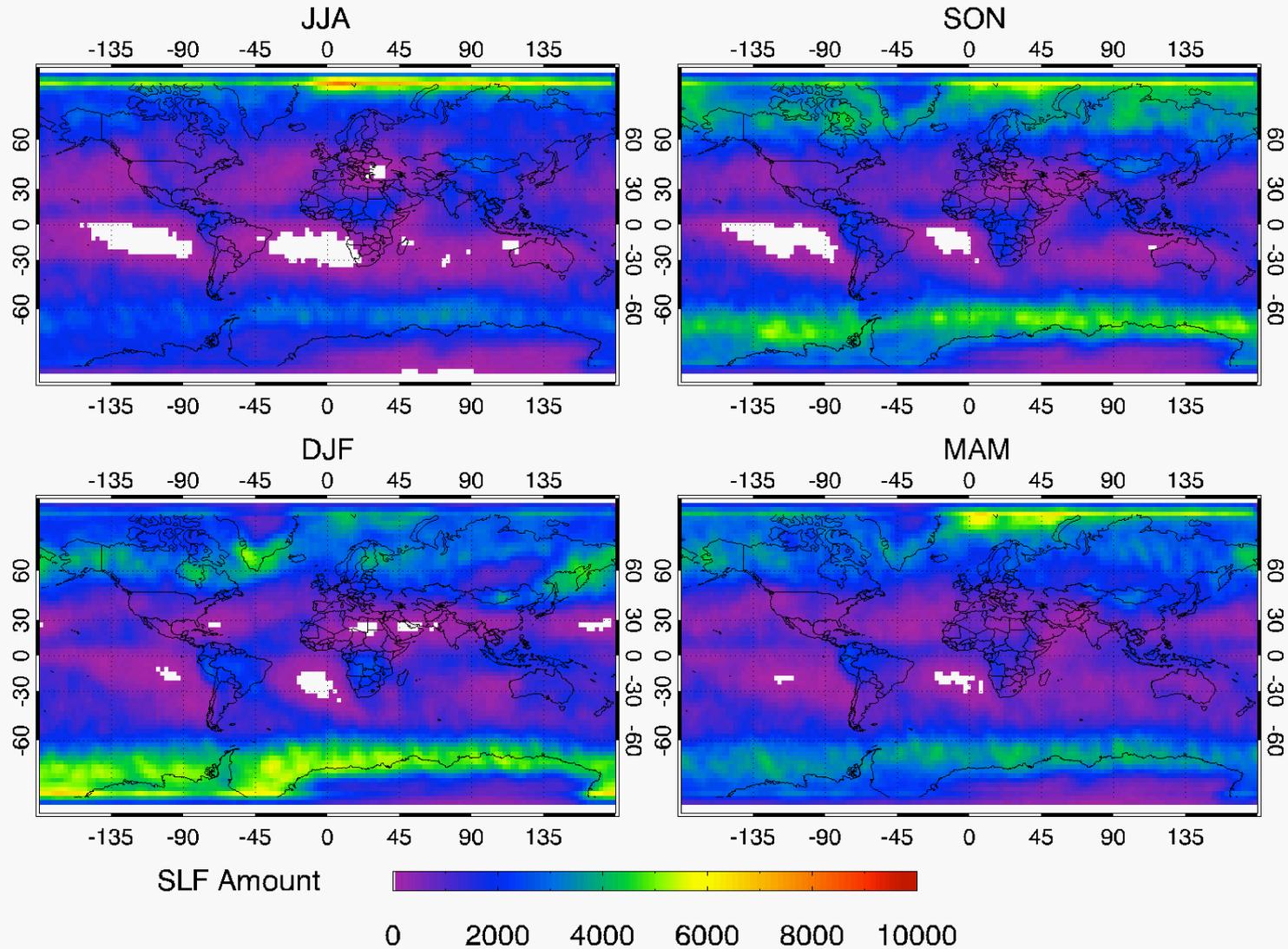


Vertical structures of cross-Atlantics Sahara dust measured by CALIPSO LIDAR (averaged in the grid box latitude from -15° to 45° and longitude from -100° to 30°).
Liu et al. (2012)

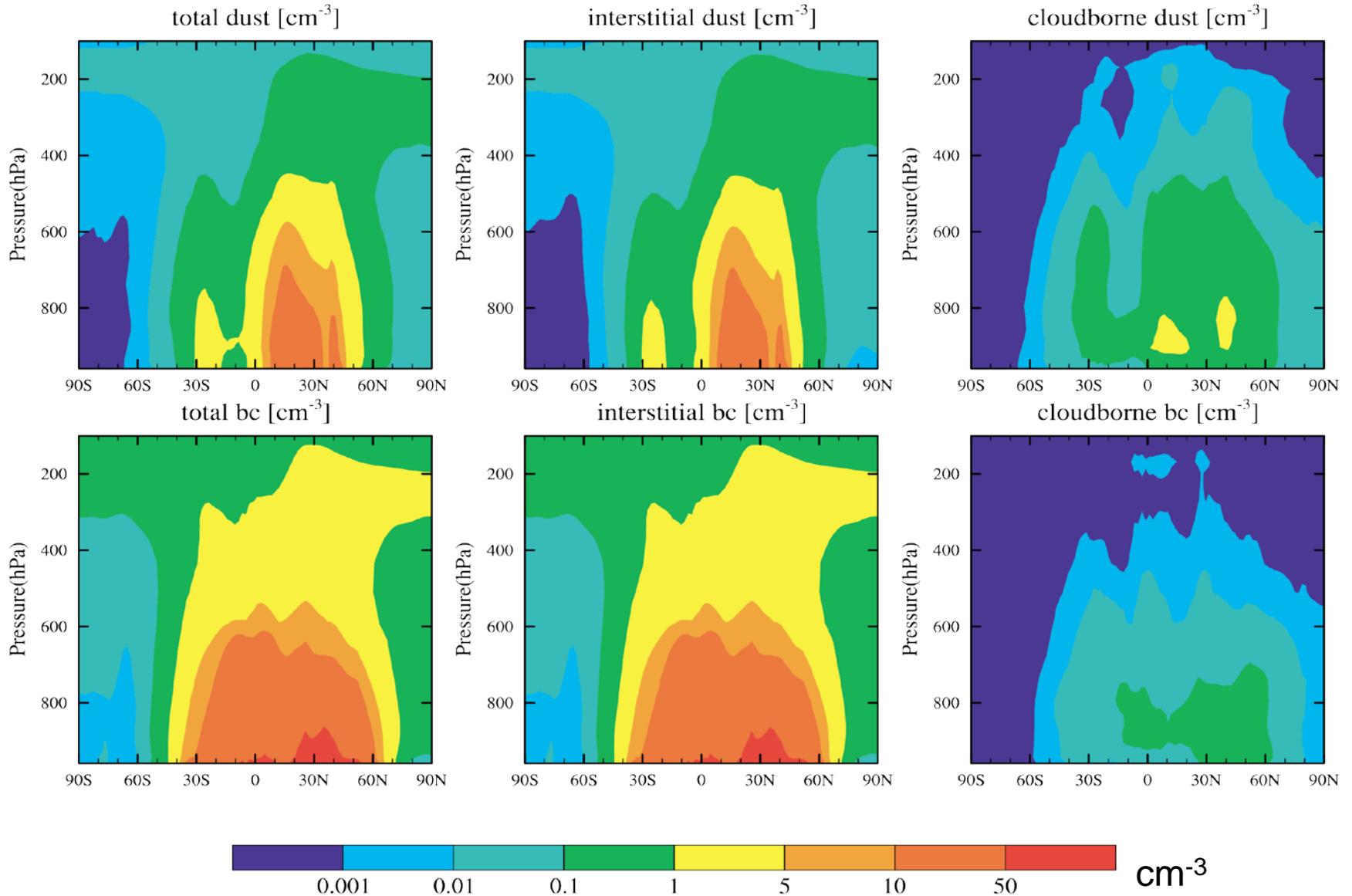
Seasonal variation of dust concentration from CAM5



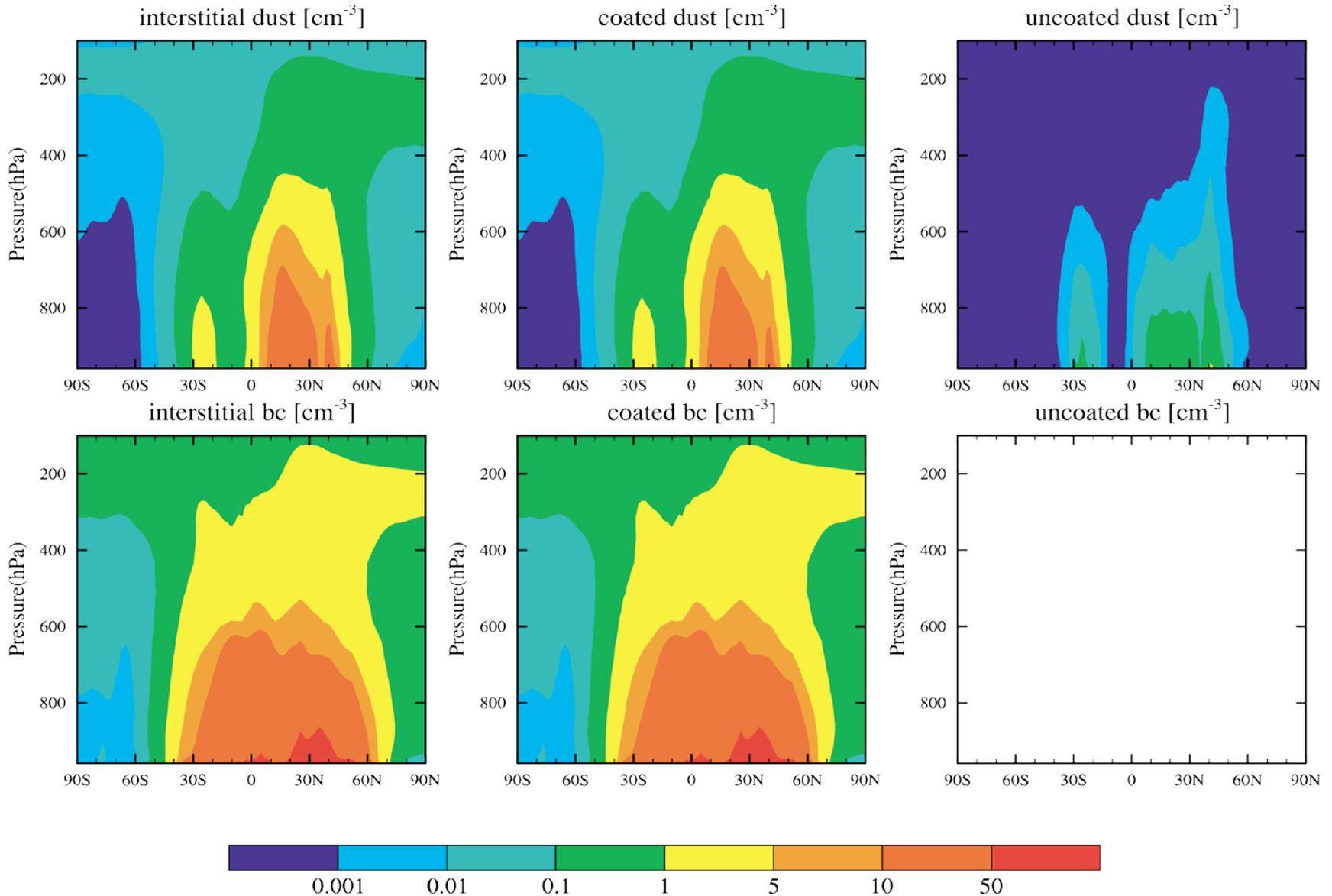
Cloud Profiles with Top Temperature between -40 and 0 °C



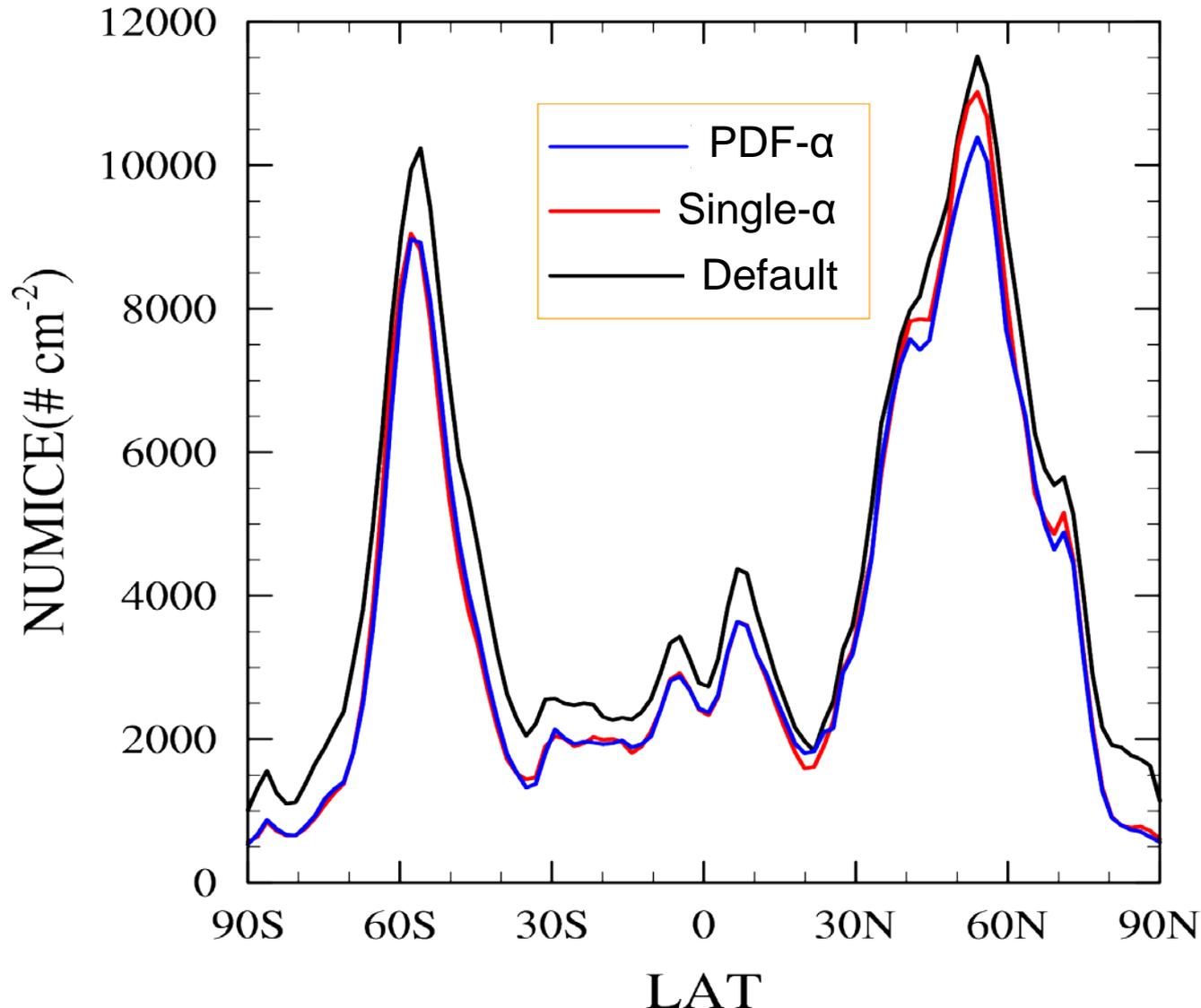
Dust and BC number (interstitial vs. cloud-borne)



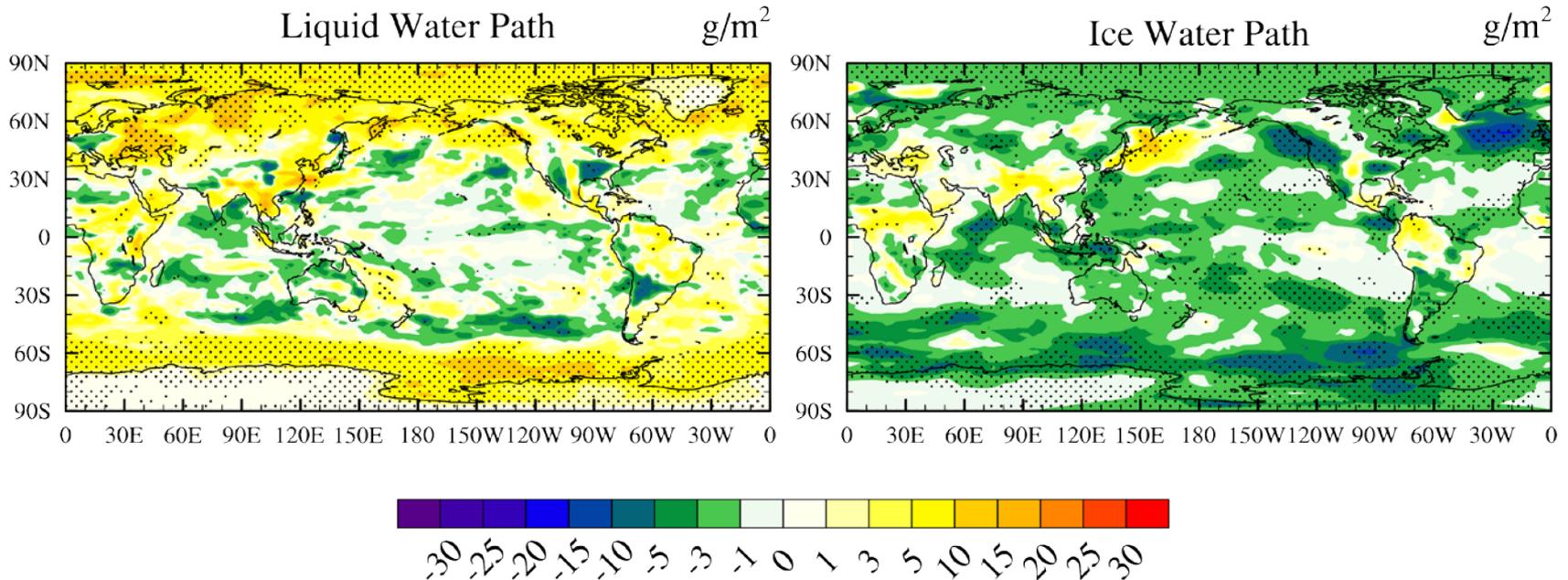
Interstitial aerosol (coated vs. uncoated)



Column Ice Crystal Number Concentration in Mixed-Phase Clouds



Difference in Cloud Water (single α - default)



Fewer Ni \rightarrow More Liquid, Less Ice

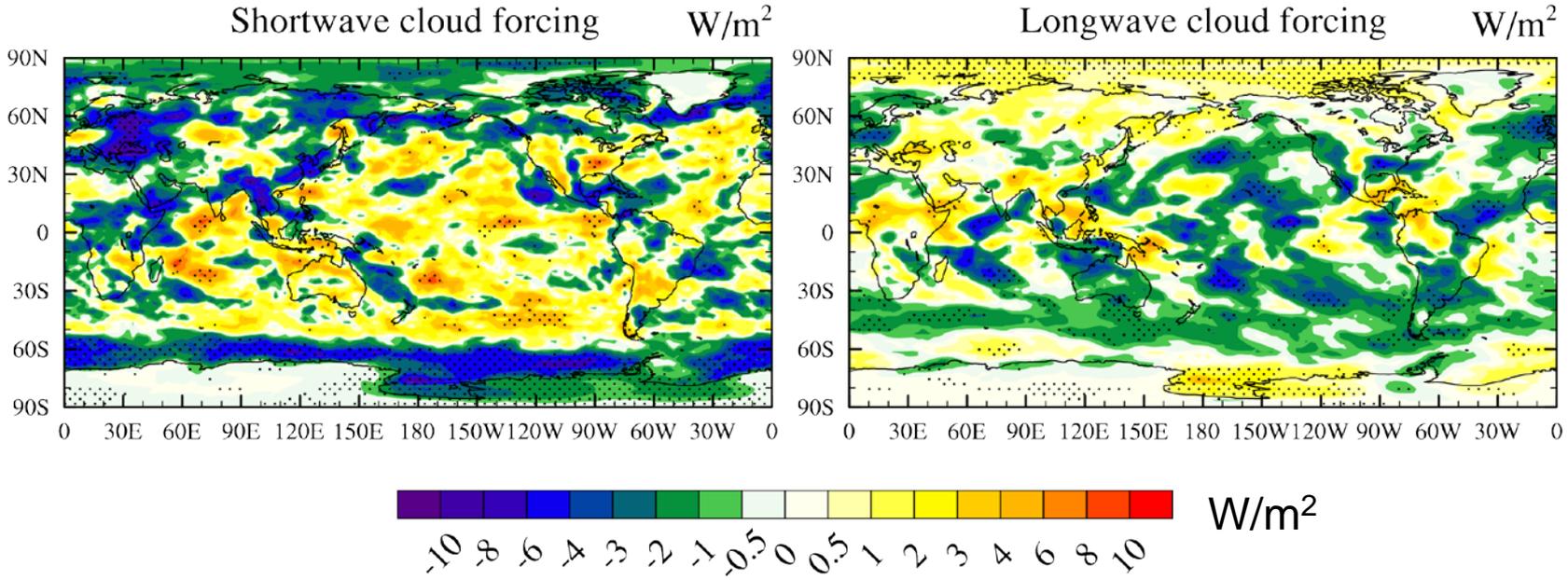
through slowing down the Bergeron process



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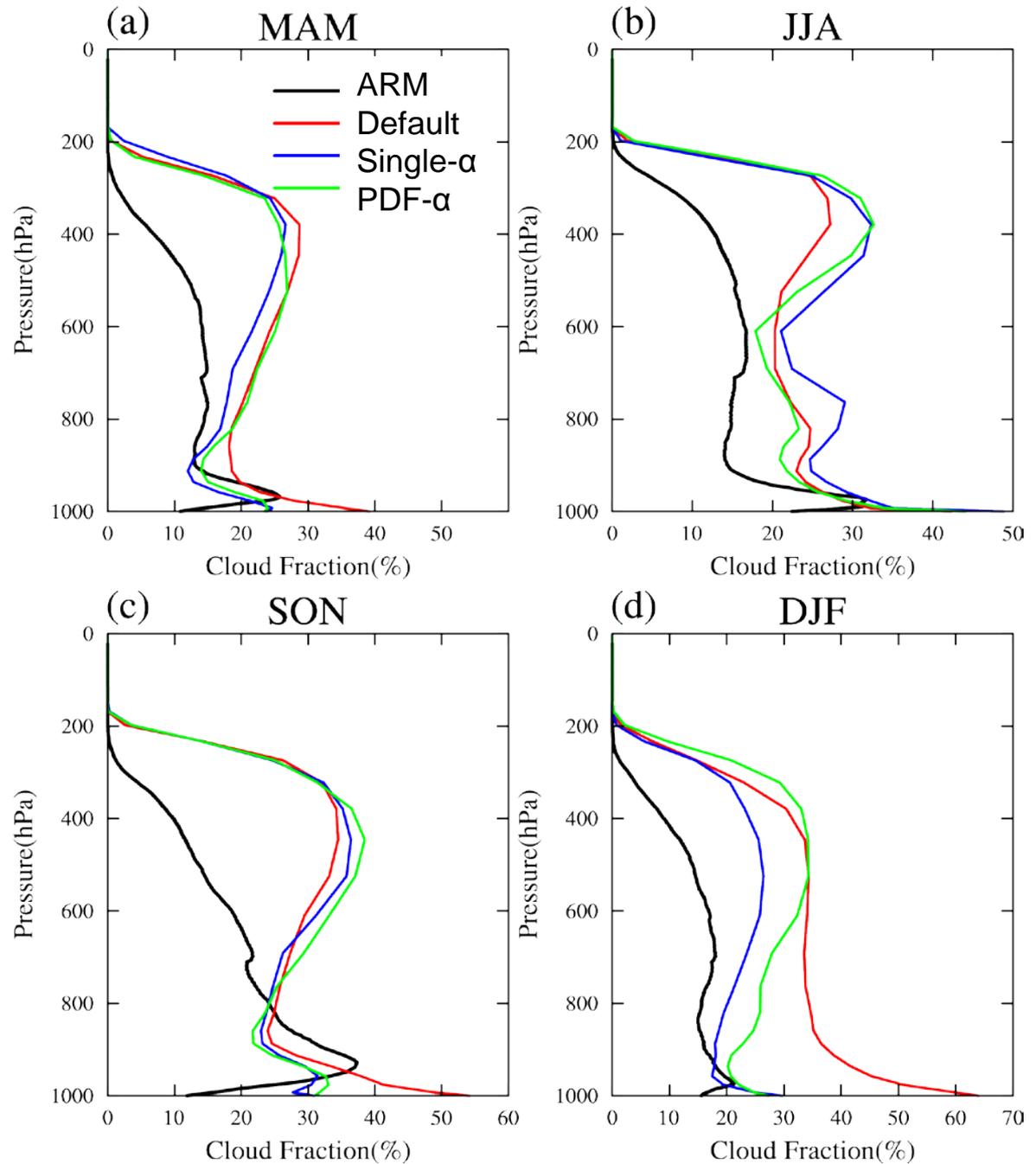
Difference in Cloud Forcing (single α - default)



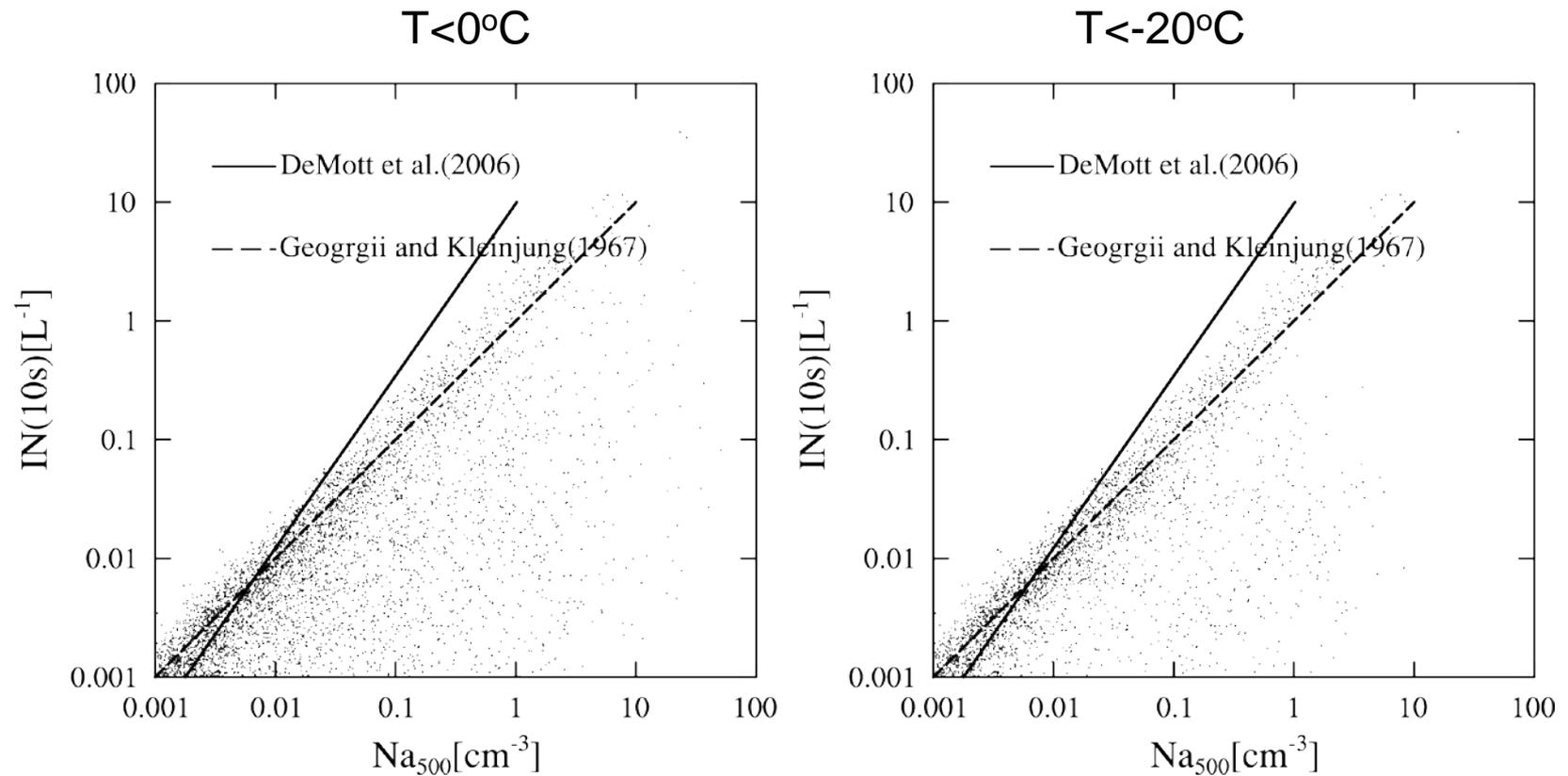
Cloud cover at ARM Barrow

LWP -> Ts -> LTS -> LLC
-> RH -> MLC & HLC

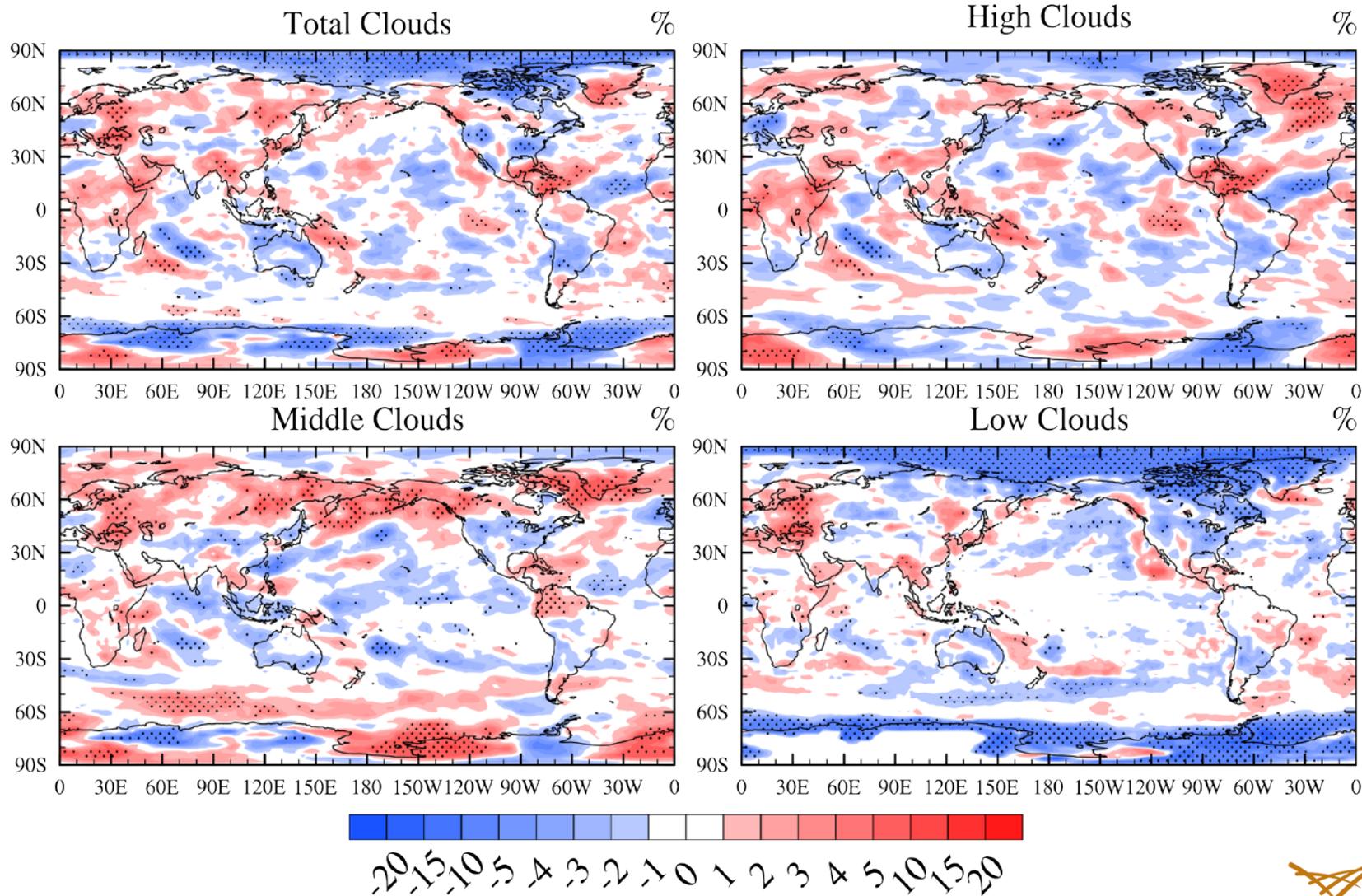
Xie et al. (2013)



Ice crystal number in mixed-phase clouds compared to observations



Difference in Cloud Cover (CNT-MEY)



Global annual mean vertically integrated nucleation rate

