Aerosol Effects on Cirrus Clouds

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Aerosol Effects
on Mixed-phase and Cirrus Clouds

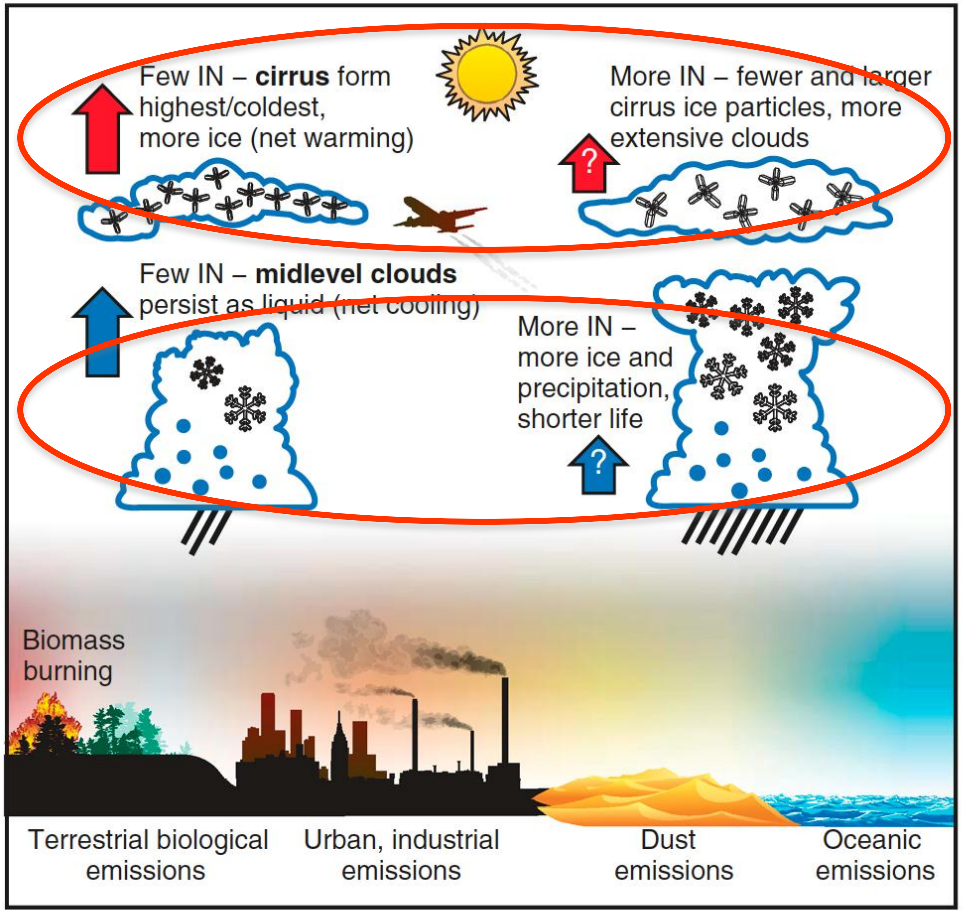

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Fig. 1. Schematic diagram of the effect of ice nuclei from various possible aerosol sources on midlevel precipitating clouds and cirrus ice clouds. The likely but uncertain change in the magnitude of the general cooling impact (blue arrows) of midlevel clouds and warming impact (red arrows) of high cirrus clouds in response to increases in the relative number concentrations of IN is indicated (see text for further description).

DeMott et al. (2010)

Cirrus (Ice) Ice Nucleation

Ice Crystal Population

Homogeneous Freezing

Mainly depends on RH_i and T

Heterogeneous Freezing

(Immersion, deposition, …)

Also depends on the material and surface area

Wet aerosol particles

+ Insoluble Material ("Ice Nuclei")

Multiple mechanisms for ice formation can be active.

Motivation

- Ice nucleation mechanisms in cirrus (ice) are uncertain
  - Heterogeneous vs homogeneous nucleation balance
  - Role of different types of aerosols as heterogeneous ice nuclei (IN) is uncertain: dust, black carbon (BC-soot), ‘glassy’ aerosol, biological aerosol
- Aerosol effects on cirrus clouds are not well quantified.
- The goal of our study is to investigate the impact of ice nucleation on cirrus clouds.

NCAR Community Atmosphere Model v5

- Two-moment prognostic cloud microphysics for liquid and ice (Morrison and Gettelman 2008)
- Modal aerosol module for aerosol microphysics (Liu et al. 2012)
- Ice nucleation in cirrus clouds (T<-37C) (Liu and Penner 2005)
  - Homogeneous freezing on sulfate in competition with
  - Heterogeneous nucleation on dust aerosol
- Ice nucleation in mixed-phase clouds (T>-37C) (Liu et al. 2007)
  - Meyers et al. (1992) for deposition/condensation nucleation
  - Bigg (1953) for immersion freezing of cloud droplets
  - Young (1974) for contact freezing of cloud droplets by dust aerosol
- Ice supersaturation, explicit vapor deposition and ice sedimentation

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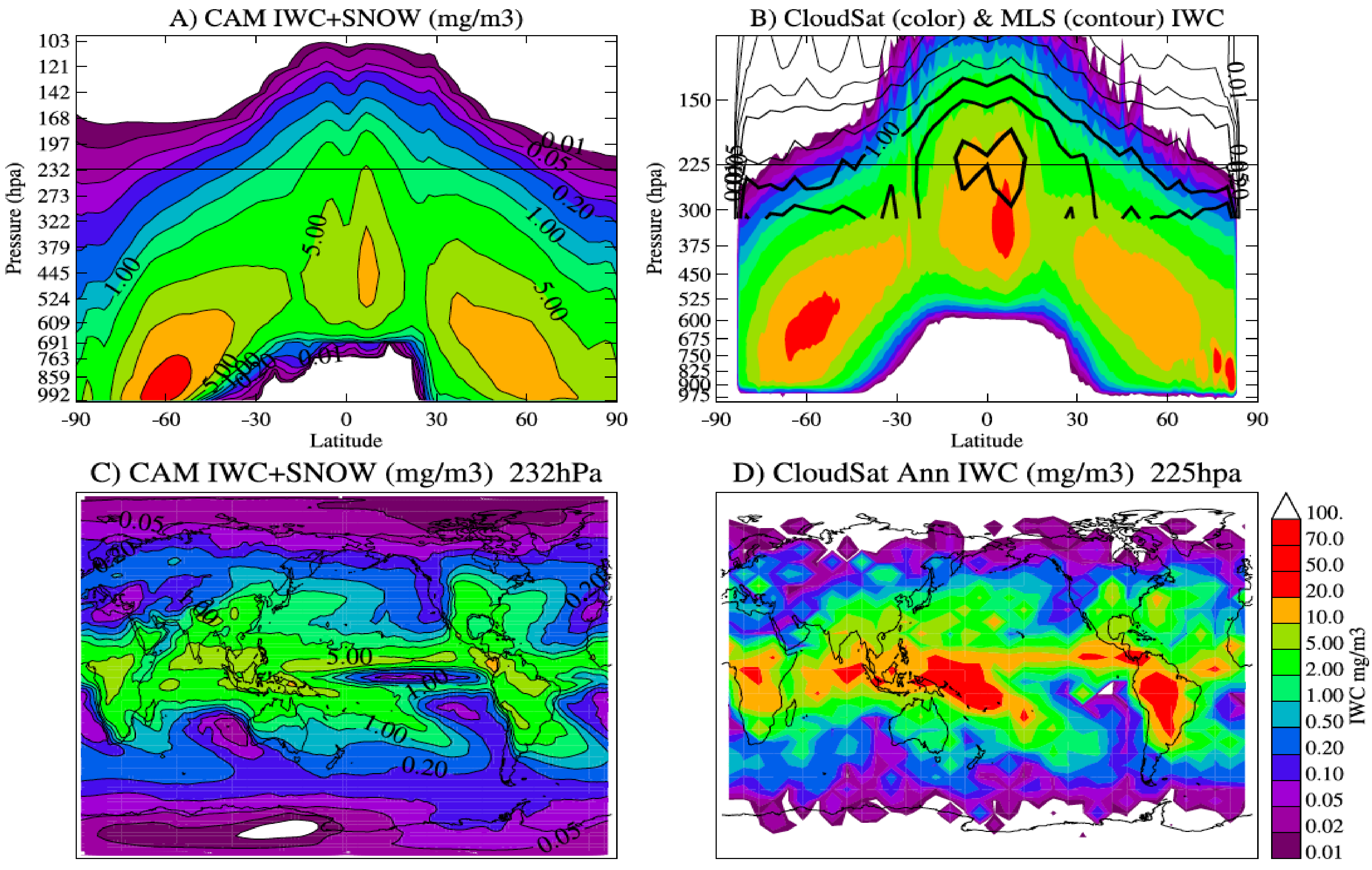
Ice Nucleation in Cirrus Clouds in CAM5

- *Liu and Penner (2005)*: consider the competition between homogeneous (HOM) and heterogeneous (HET) immersion nucleation (hereafter **LP**). Heterogeneous nucleation based on classical nucleation theory (CNT).
- *Barahona and Nenes (2008a,b; 2009)*: develop a framework that can use different IN *nucleation spectra* for HET, and consider the competition of HOM and HET (hereafter **BN**). IN spectra:
  - Classical nucleation theory (Pruppacher and Klett 1997)
  - CFDC measurement (Phillips et al. 2008)

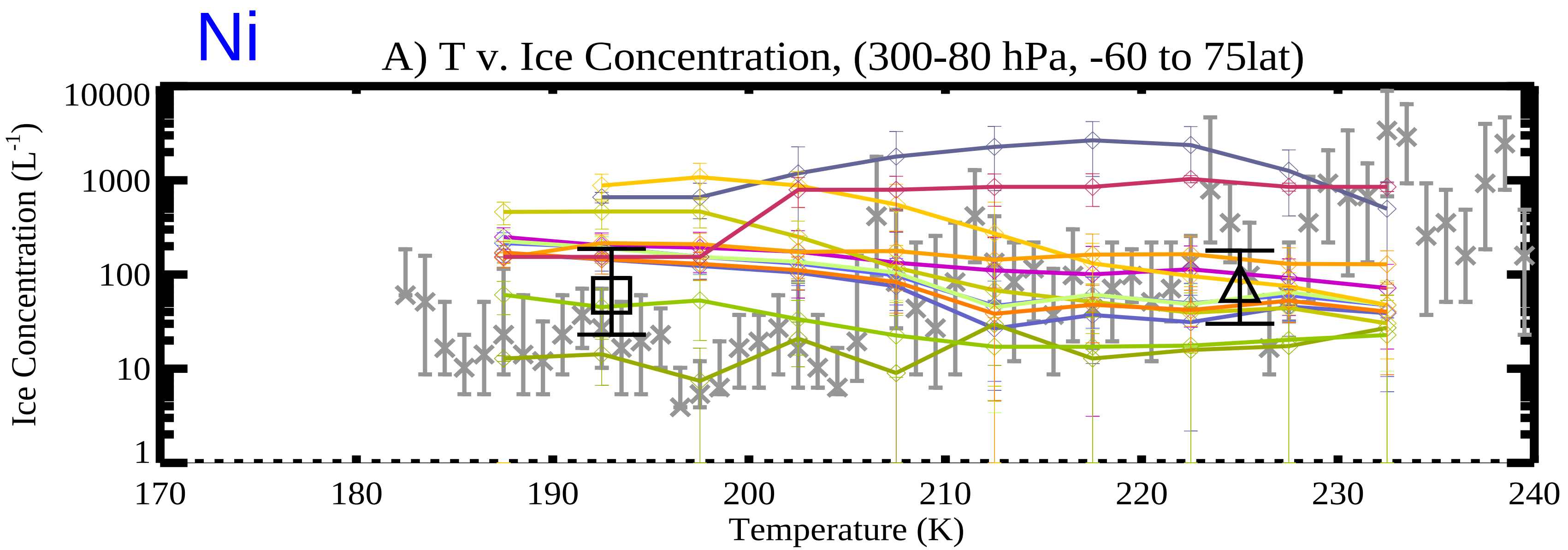
Ice Mass vs. CloudSat

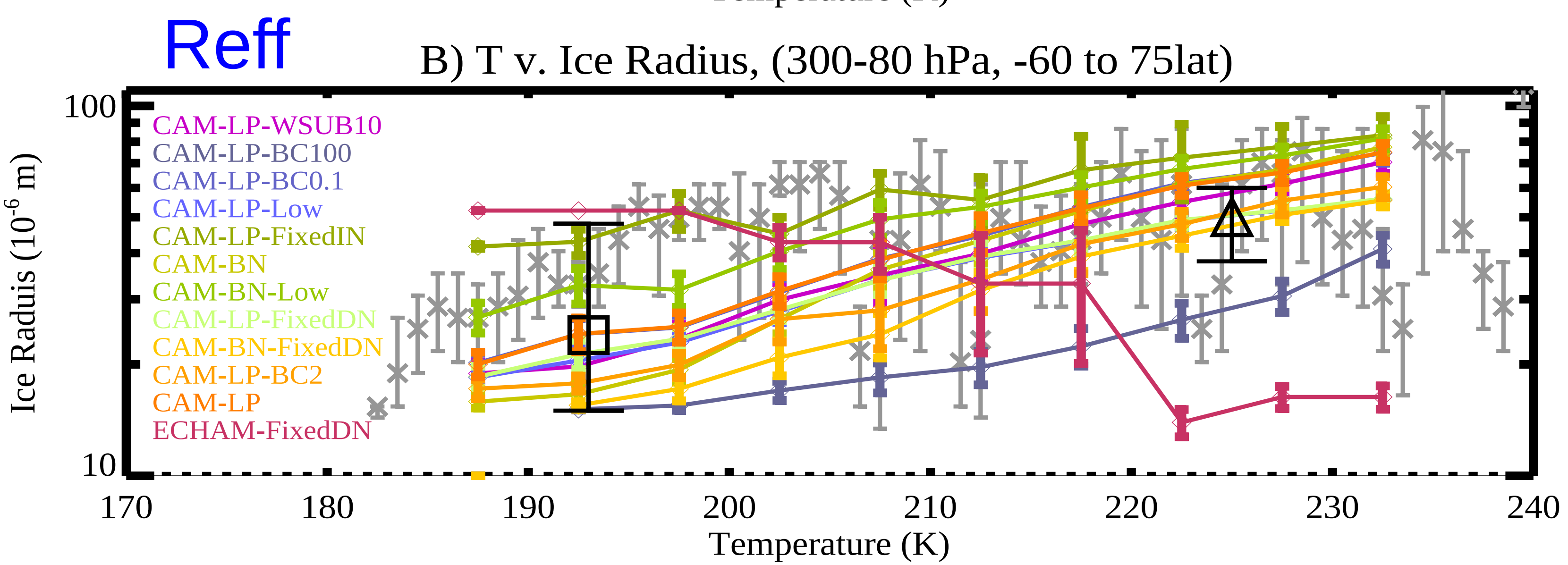


Gettelman et al. 2010

Ice Number and Size vs. Krämer Data

Gettelman, Liu et al. (2012)





Impacts of Heterogeneous IN Spectrum

Barahona and Nenes (2008a,b; 2009)

1. Philips et al. (2008): CFDC measurements

$$N_{\mathrm{het}}(s_i) = N_{\mathrm{dust}}\left[1-\exp\left(-\frac{2}{3}H_{\mathrm{dust}}(s_i,T)\frac{N_{\mathrm{het,PDG07}}}{7.92\times10^4}\right)\right] + N_{\mathrm{soot}}\left[1-\exp\left(-\frac{1}{3}H_{\mathrm{soot}}(s_i,T)\frac{N_{\mathrm{het,PDG07}}}{1.04\times10^6}\right)\right]$$

Turn off soot

1. Classical nucleation theory (CNT)

$$N_{\mathrm{het}}(s_i) = 0.05\left[\min\left(\frac{s_i}{0.2}N_{\mathrm{dust}}e^{-0.0011k_{\mathrm{hom}}(0.2-s_i)},\ N_{\mathrm{dust}}\right) + \min\left(\frac{s_i}{0.3}N_{\mathrm{soot}}e^{-0.039k_{\mathrm{hom}}(0.3-s_i)},\ N_{\mathrm{soot}}\right)\right]$$

Maximum freezing ratio

Zhang, Liu et al (2012)

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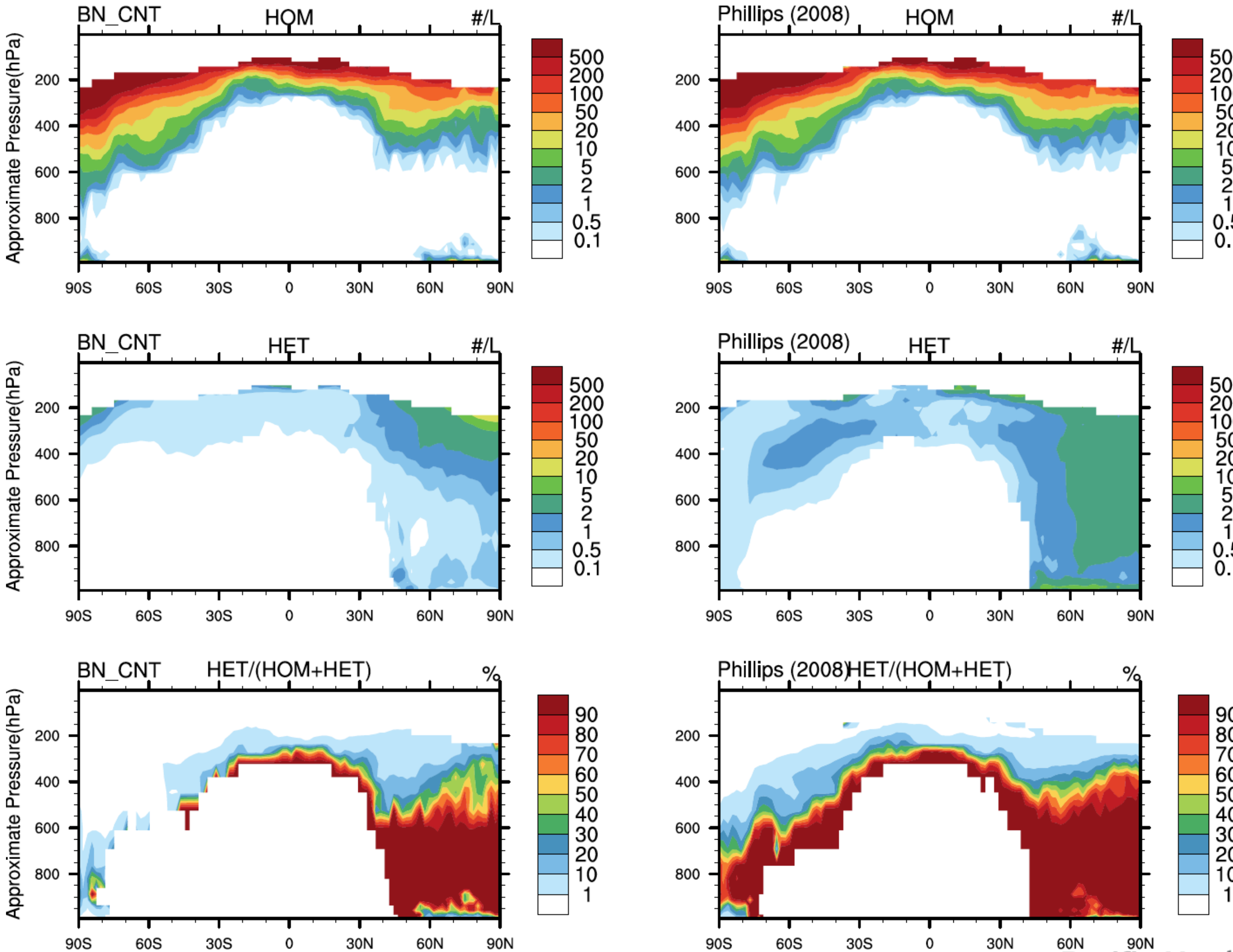
Sensitivity to Heterogeneous Nucleation



Classical nucleation theory

Phillips et al. (2008)

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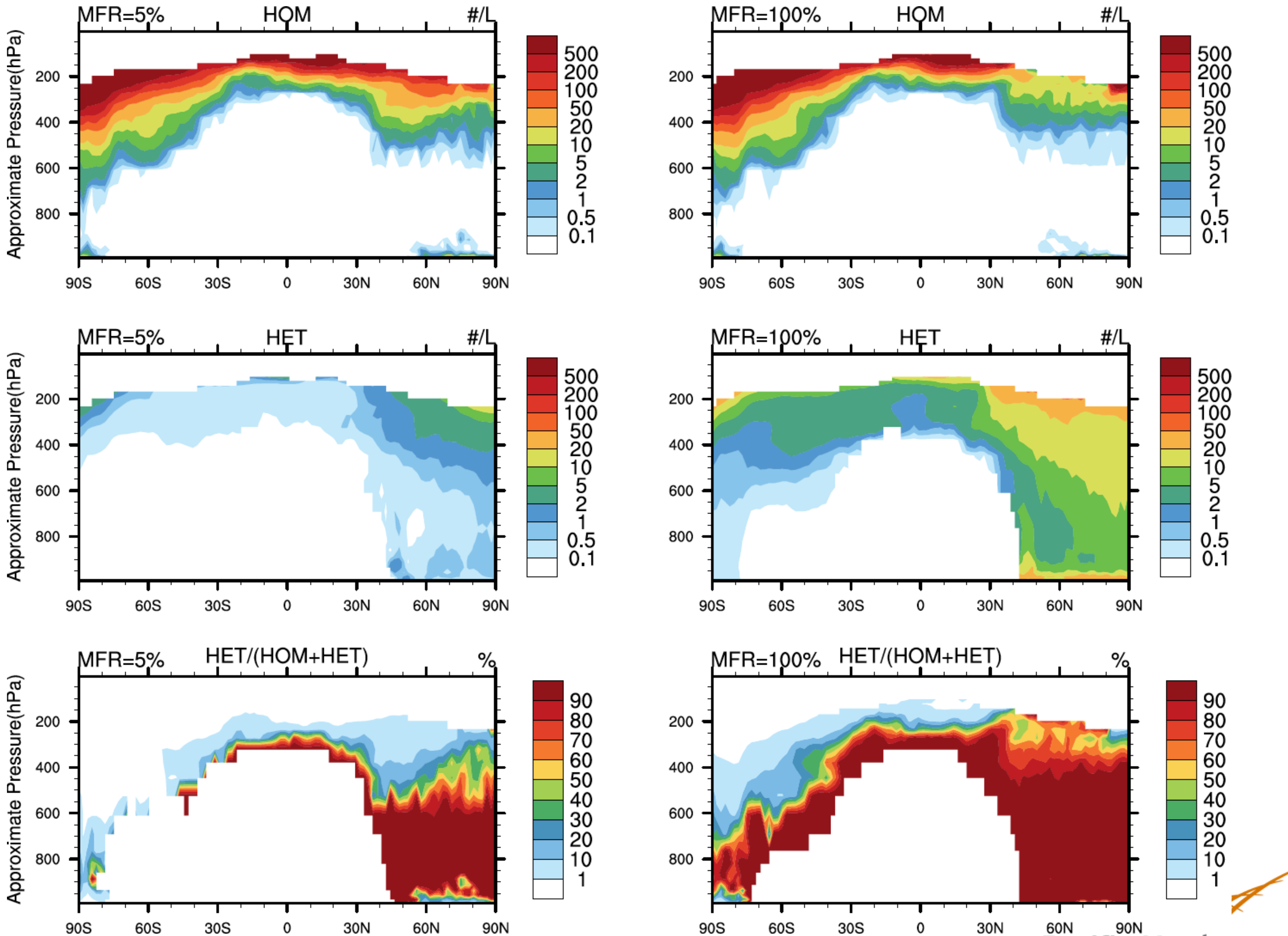
Effect of maximum freezing ratio limit (CNT scheme)



5% (Barahana and Nenes, 2009)

100% (Liu & Penner; Hoose et al. 2010)

Global Annual Means (Present-Day Climate)

	SWCF	LWCF	CLDHGH	CLDTOT
BN_Phillips	-56.2	31.9	42.7	66.6
BN_CNT_5%	-56.5	31.7	42.3	66.4
BN_CNT_10%	-56.2	31.4	42.3	66.3
BN_CNT_100%	-55.7	30.8	43.3	66.9

20 x IN →

Δ (SWCF) = +0.8 W/m2, Δ (LWCF) = -0.9 W/m2

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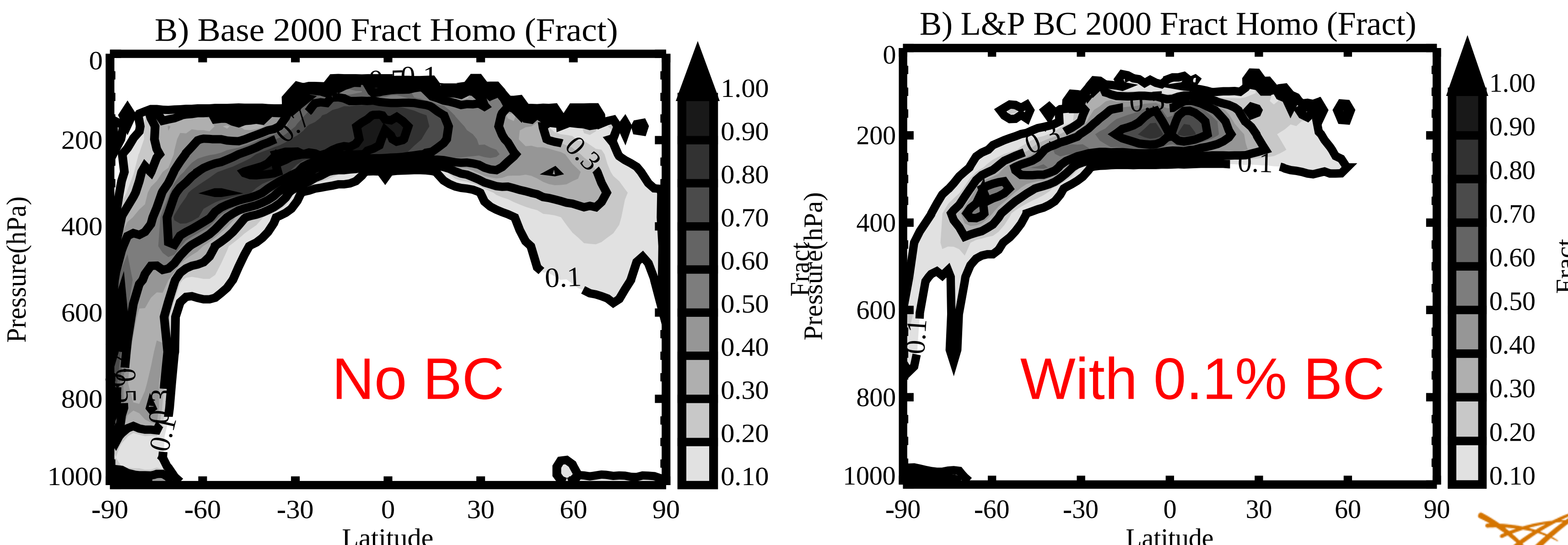
Impacts of Black Carbon

- Adding a small (0.1%) amount of BC to LP (classical nucleation theory) shifts balance of nucleation towards more heterogeneous nucleation, ice number increases for cirrus, but mass gets slightly smaller.
- Literature: BC efficiency values should be 0.1% or less…
- Classical nucleation theory very sensitive to how much BC…



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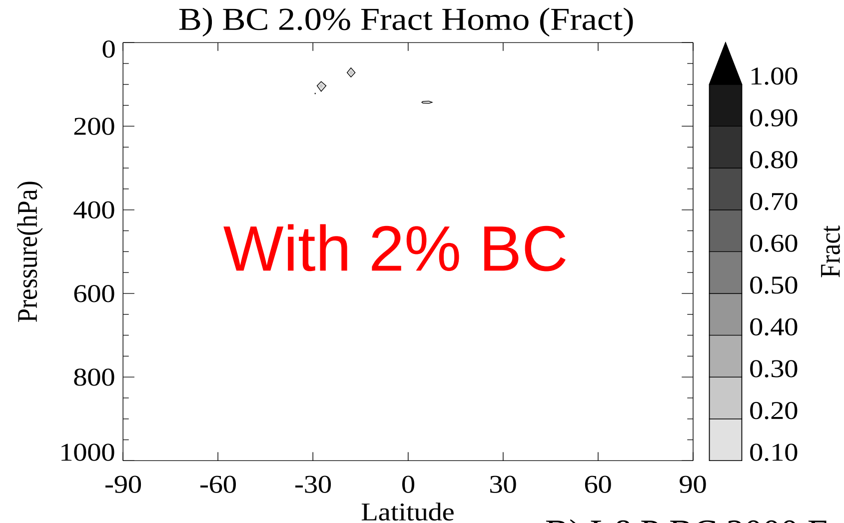
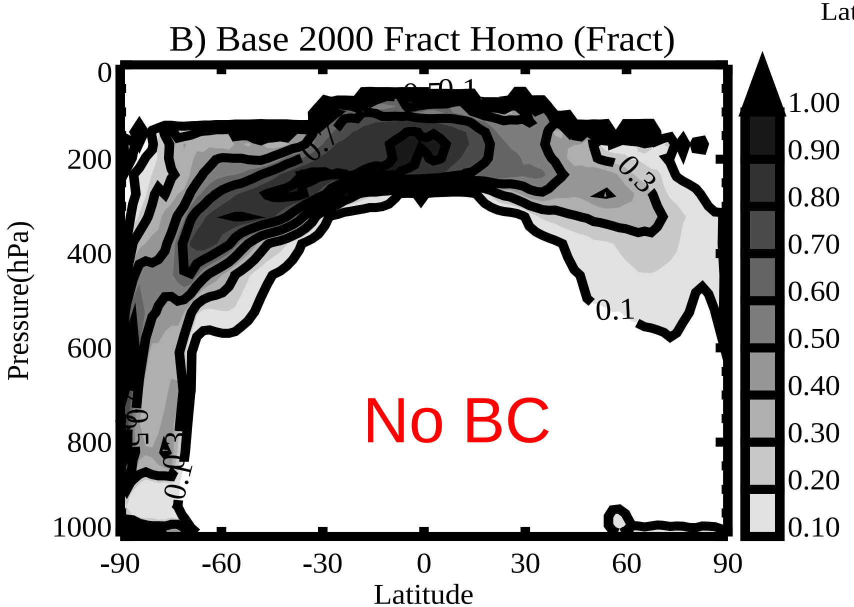
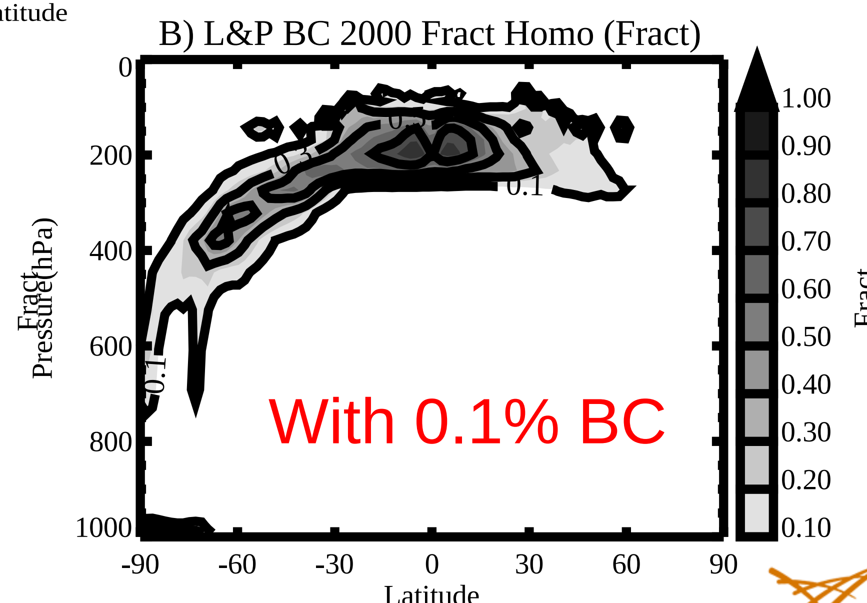
Impacts of Black Carbon







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Global Annual Means (Present-Day Climate)

	SWCF	LWCF	IWP	INC150
LP	-51.8	24.0	17.7	111
LP_BC_0.1%	-51.5	23.6	17.5	102
LP_BC_2%	-57.8	31.5	22.3	184
LP_BC_100%	-78.3	51.8	33.9	2180

0.1% BC

→ Δ (SWCF) = +0.3 W/m2, Δ (LWCF) = -0.4 W/m2

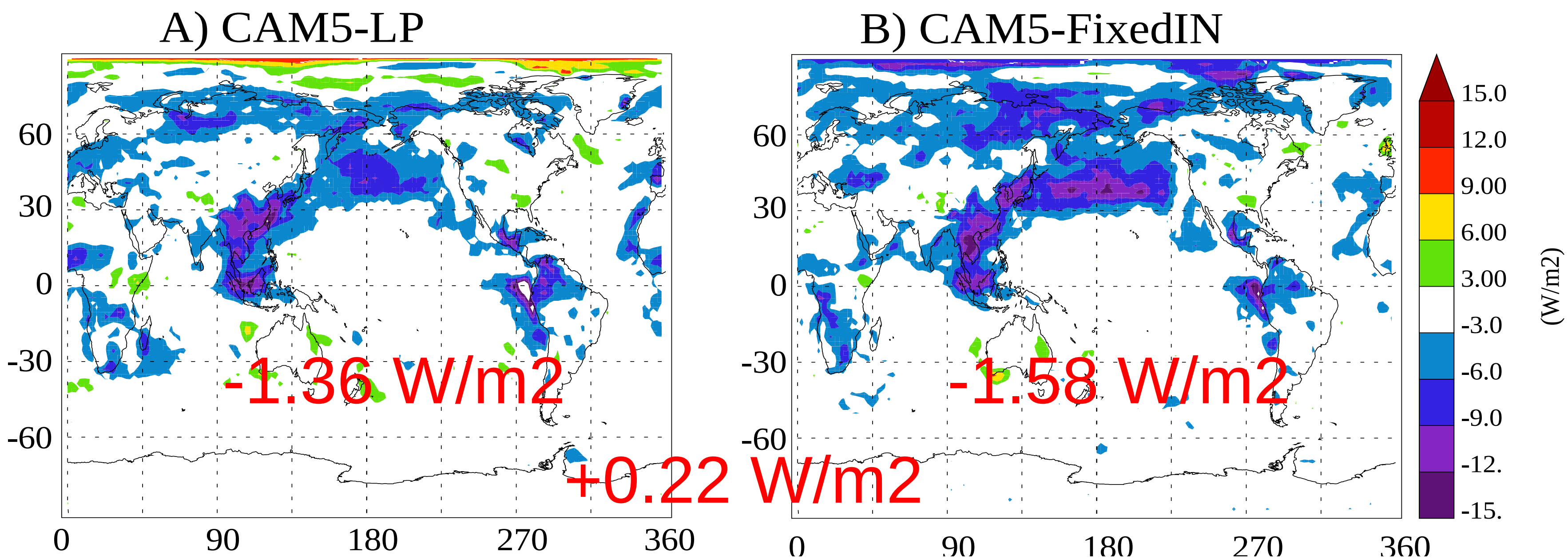
2% BC

→ Δ (SWCF) = -6.0 W/m2, Δ (LWCF) = +7.5 W/m2

Aerosol Indirect Effects on Cirrus

Gettelman, Liu et al. (2012)

- Perform RFP experiments (PD and PI) with IPCC emissions
- Climatological SST & sea ice and same GHG
- Diagnostics of ice AIE in two different ways: (1) Fixed ice nucleation in cirrus



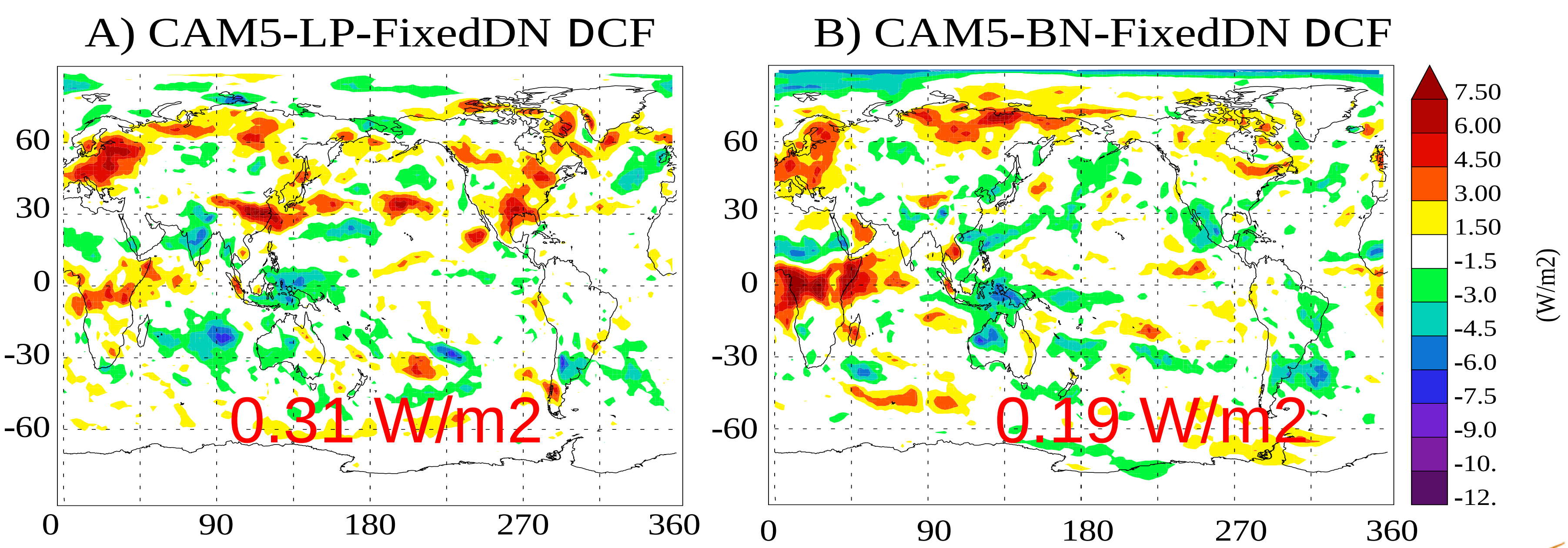
AIE (liquid + ice) = -1.36 W/m2

AIE (liquid) = -1.58 W/m2 (no aerosol effect on ice clouds by fixing Ice nuclei number in cirrus as a function of temperature)

Aerosol Indirect Effects of Ice

Gettelman, Liu et al. (2012)

- Perform RFP experiments changing emissions
- Climatological SST & sea ice and same GHG
- Diagnostics of ice AIE in two different ways: (2) Fixed droplet number



AIE (ice) = 0.31 W/m2 (CAM5)

AIE (ice) = 0.19 W/m2 (BN)

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Intercomparison of Aerosol Effects on Cirrus Clouds under AEROCOM

- Invite GCMs with capability of aerosol-cirrus cloud interactions to participate; also satellite and in situ data analysis
- Submit GCM simulations (PD & PI):
  - Homogeneous nucleation only
  - Homogeneous and heterogeneous combined
  - Fixed ice nucleation in cirrus clouds
- Analysis of variables:
  - w, Ni, Reff, IWP, cloud cover, Qv, cloud forcing

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