# Dust Indirect Effects by Glaciating Mixed-phase Clouds

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# The role of dust

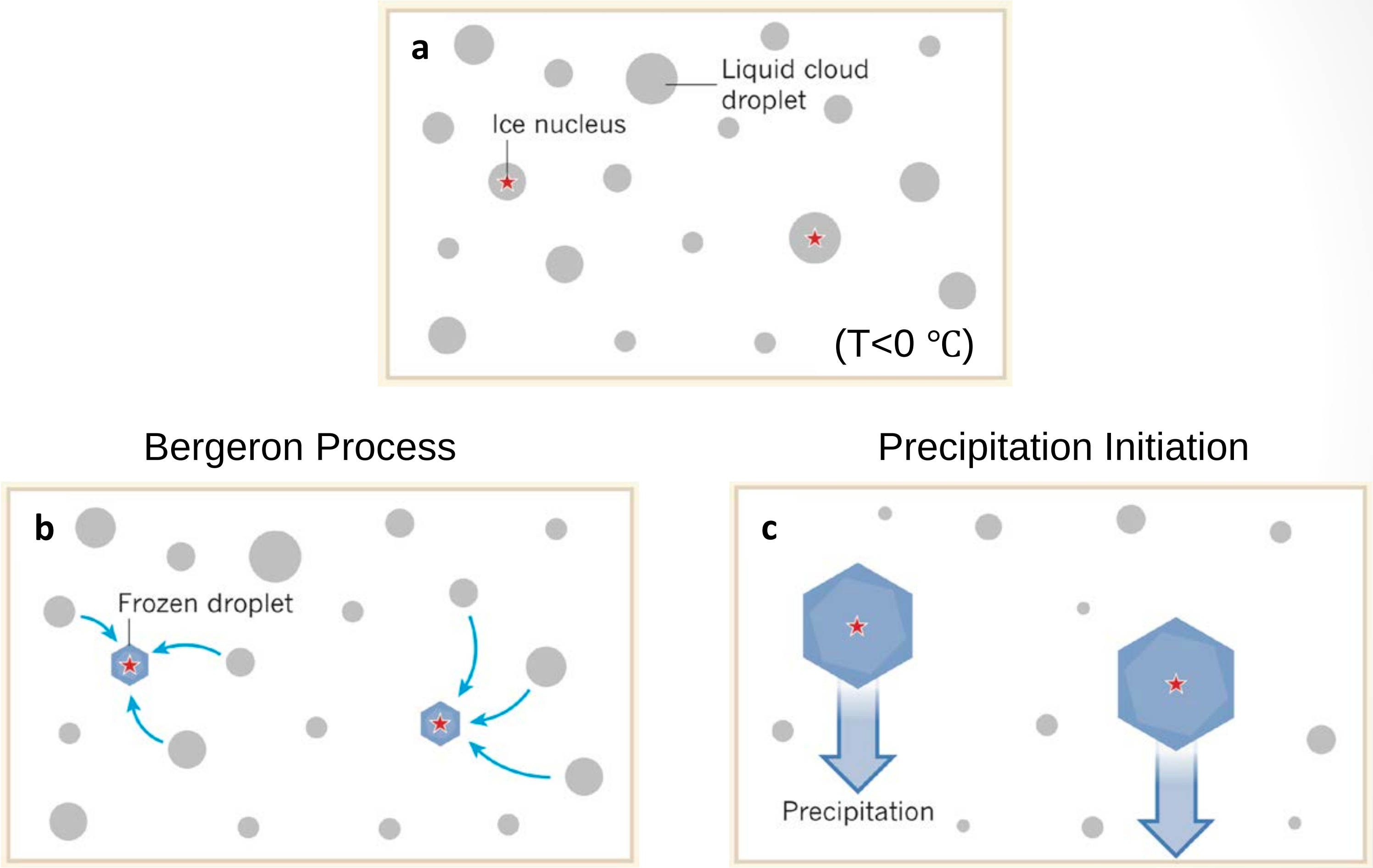
- Dust is one of the most abundant aerosol species in the atmosphere in terms of emitted mass [Forster et al., 2007].
- Dust has important climatic effects
  - Scattering and absorbing solar and terrestrial radiation
  - Influencing cloud radiative and microphysical properties as CCN and ice nucleating particles (INPs)
    - Dust is the most dominant INP at T<-15 °C
  - etc.

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

Ice Nucleation

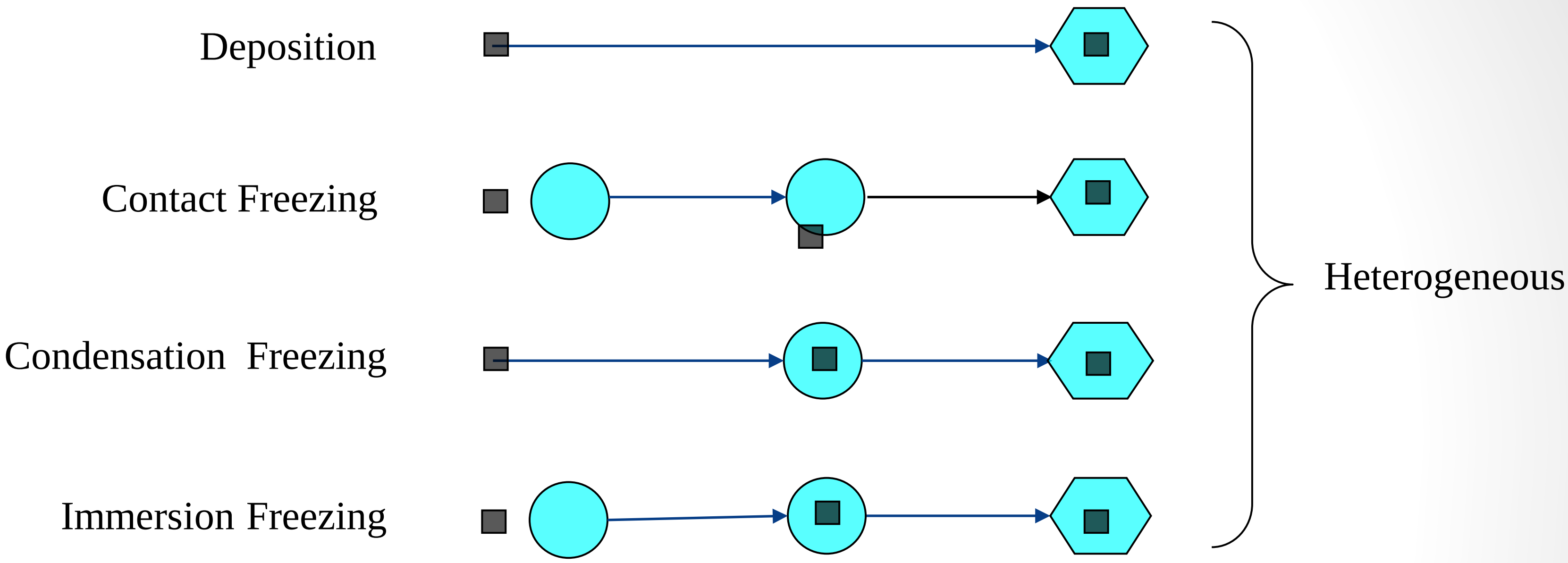
Bergeron Process

Precipitation Initiation




Koop and Mahowald et al. 2010

# How ice crystals are formed?




*Ice nuclei.*

*Insoluble/partially insoluble aerosol particle (~$10^{-3}$ – $10^{-5}$ of aerosol population)*

*Super-cooled solution droplet / cloud droplet*

*Ice crystal*

Courtesy of G. Kulkarni

# Ice nucleation parameterizations in mixed-phase clouds

**Classical Nucleation Theory (CNT)**

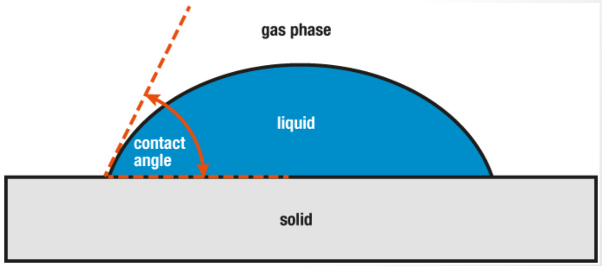
Dust and Black carbon as INP

Immersion freezing, contact freezing, and deposition nucleation

Nucleation rate

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

Surface area  f(ϴ), ϴ is contact angle




Hoose et al. 2010; Wang et al., 2014

https://www.linseis.com/en/properties/contact-angle/

# Ice nucleation parameterizations in mixed-phase clouds

## Empirical Method

### **DeMott et al. 2015** – Immersion freezing (dust)

$$N_{INP}(T_k) = (cf)\left(n_{a>0.5\mu m}\right)^{(\alpha(273.16-T_k)+\beta)} exp(\gamma(273.16 - T_k) + \delta)$$

$n_{a>0.5\mu m}$ *number concentration of dust particles larger than 0.5 μm*

DeMott et al., 2015

### **Niemand et al. 2012** – Immersion freezing (dust)

$$N_{INP}(T_k) = N_{tot} S_{ae} \exp(-0.517(T_k - 273.15) + 8.934)$$

$N_{tot}$ *dust number concentration*
$S_{ae}$ *dust surface area*

Niemand et al., 2012

# DOE’s Energy Exascale Earth System Model (E3SM)

| | E3SM v0 (CAM5 physics) | E3SM v1 |
|---|---|---|
| Vertical levels | 30 layers | 72 layers |
| Shallow convection | PB2009 | CLUBB |
| Turbulence | PB2009 | CLUBB |
| Cloud macrophysics | PBR2014 | CLUBB |
| Cloud microphysics | MG1 | MG2 |
| Aerosol Model | MAM3 | MAM4_MOM |

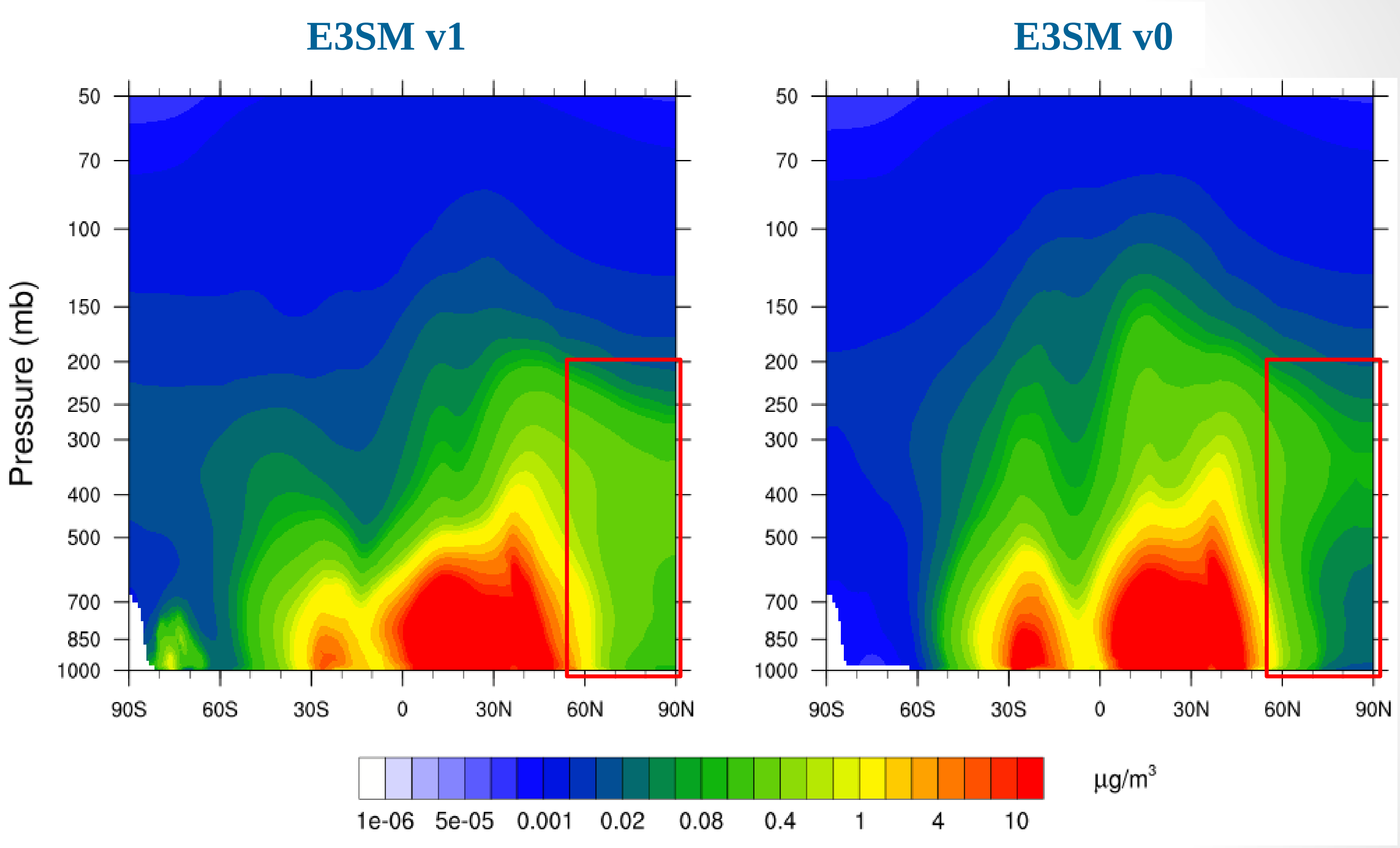
The Bergeron process is tuned down by a factor of 10 in both model versions.

# Model Experiments

| Case name | Model version | Ice nucleation parameterizations |
|---|---|---|
| CNT v1 | EAM v1 | Classical nucleation theory (CNT) |
| NIE v1 | EAM v1 | Niemand et al. (2012) |
| DEM v1 | EAM v1 | DeMott et al. (2015) |
| CNT v0 | EAM v0 | Classical nucleation theory (CNT) |
| NIE v0 | EAM v0 | Niemand et al. (2012) |
| DEM v0 | EAM v0 | DeMott et al. (2015) |

**Runtime period**: 2007.01 to 2009.12
**Meteorology**: Wind components U and V nudged to MERRA2 data
**V1 resolution:** 1 degree, 72 vertical levels
**V0 resolution:** 1 degree, 30 vertical levels

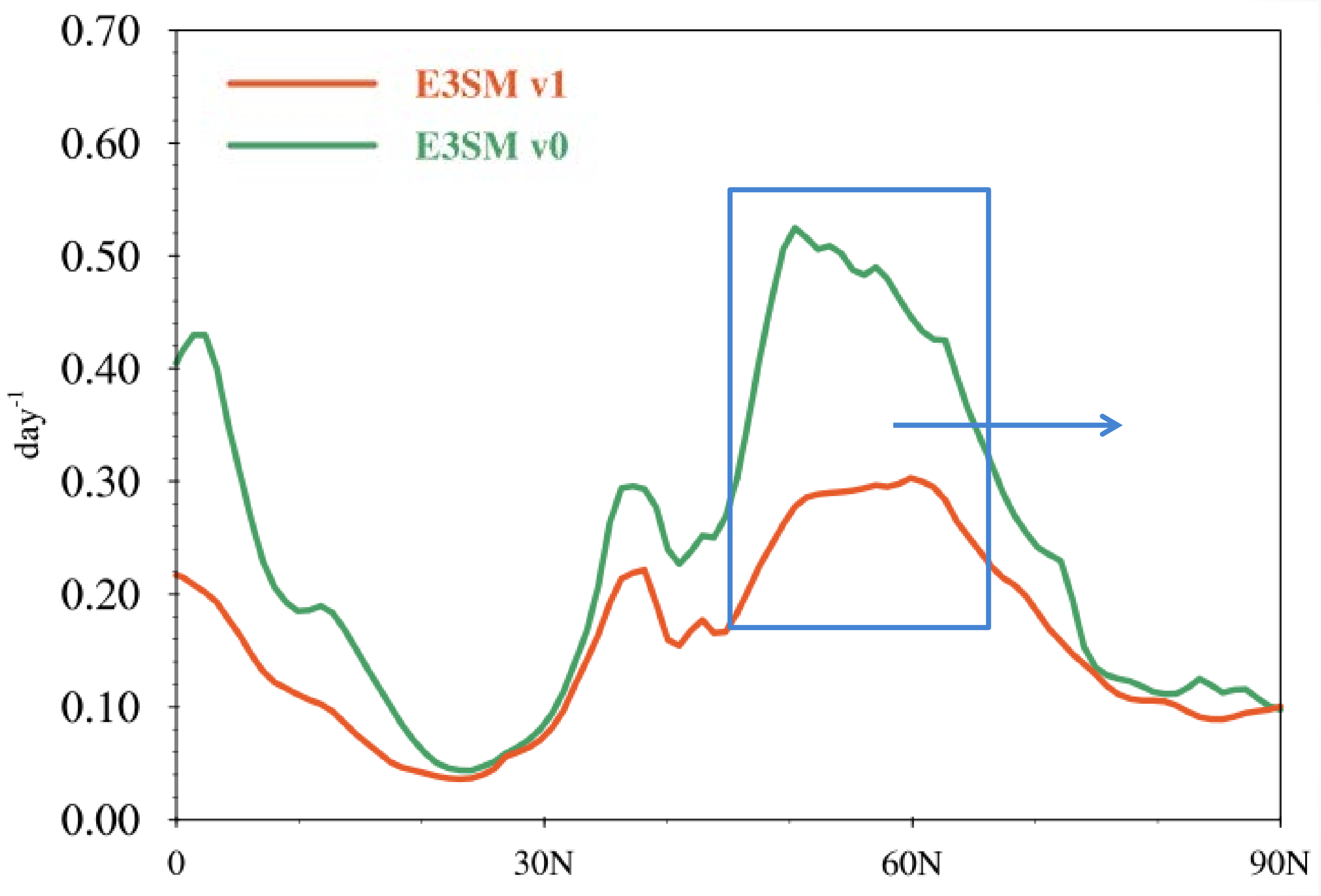
# Zonal average dust concentration




**The Arctic dust concentration is higher in E3SM v1 than v0, which indicates more efficient dust transport in E3SM v1.**

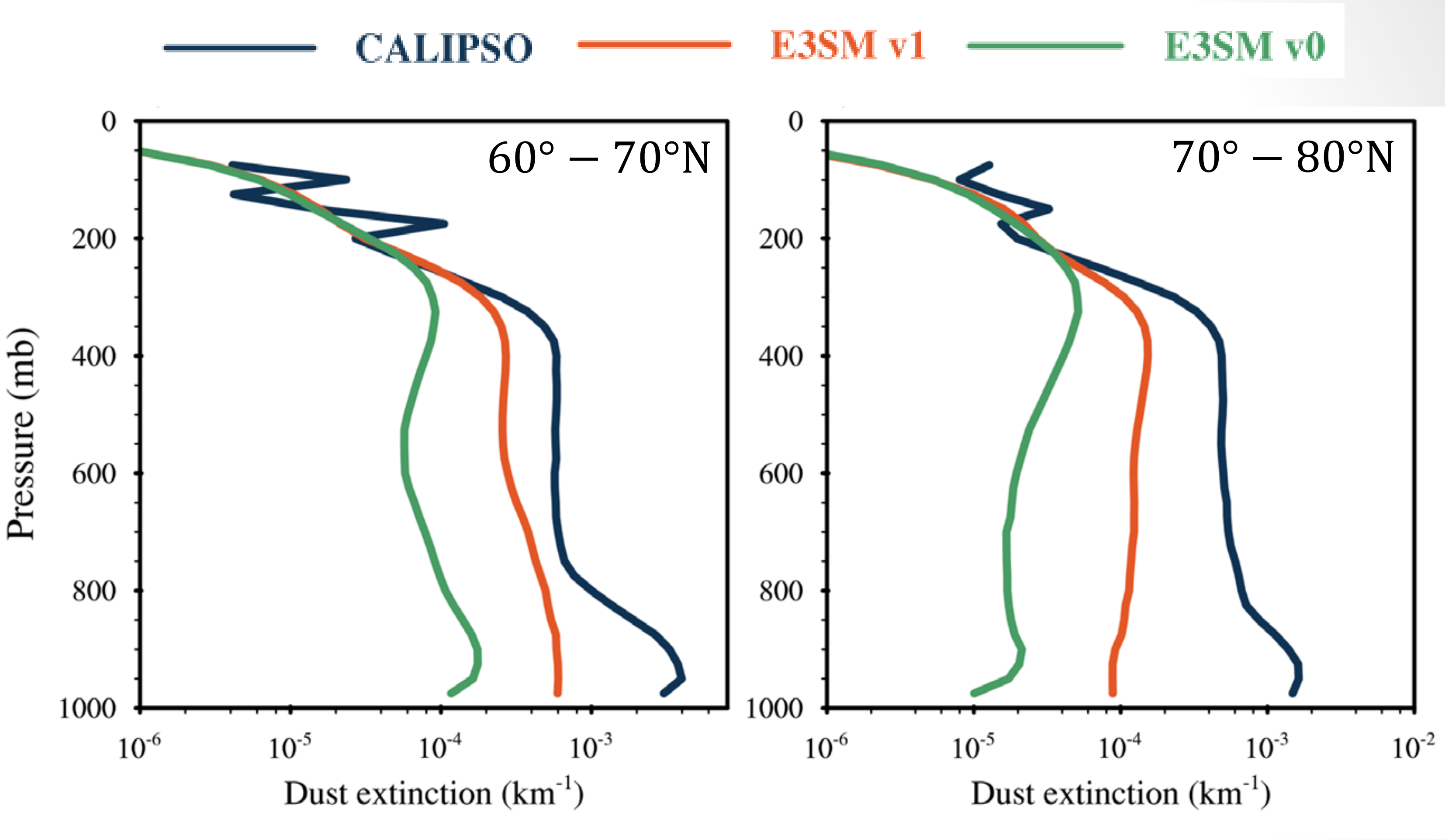
# Total wet removal rate

Wet removal rate = Wet deposition flux / Burden




**The wet removal is stronger at mid-latitudes in E3SM v0.**

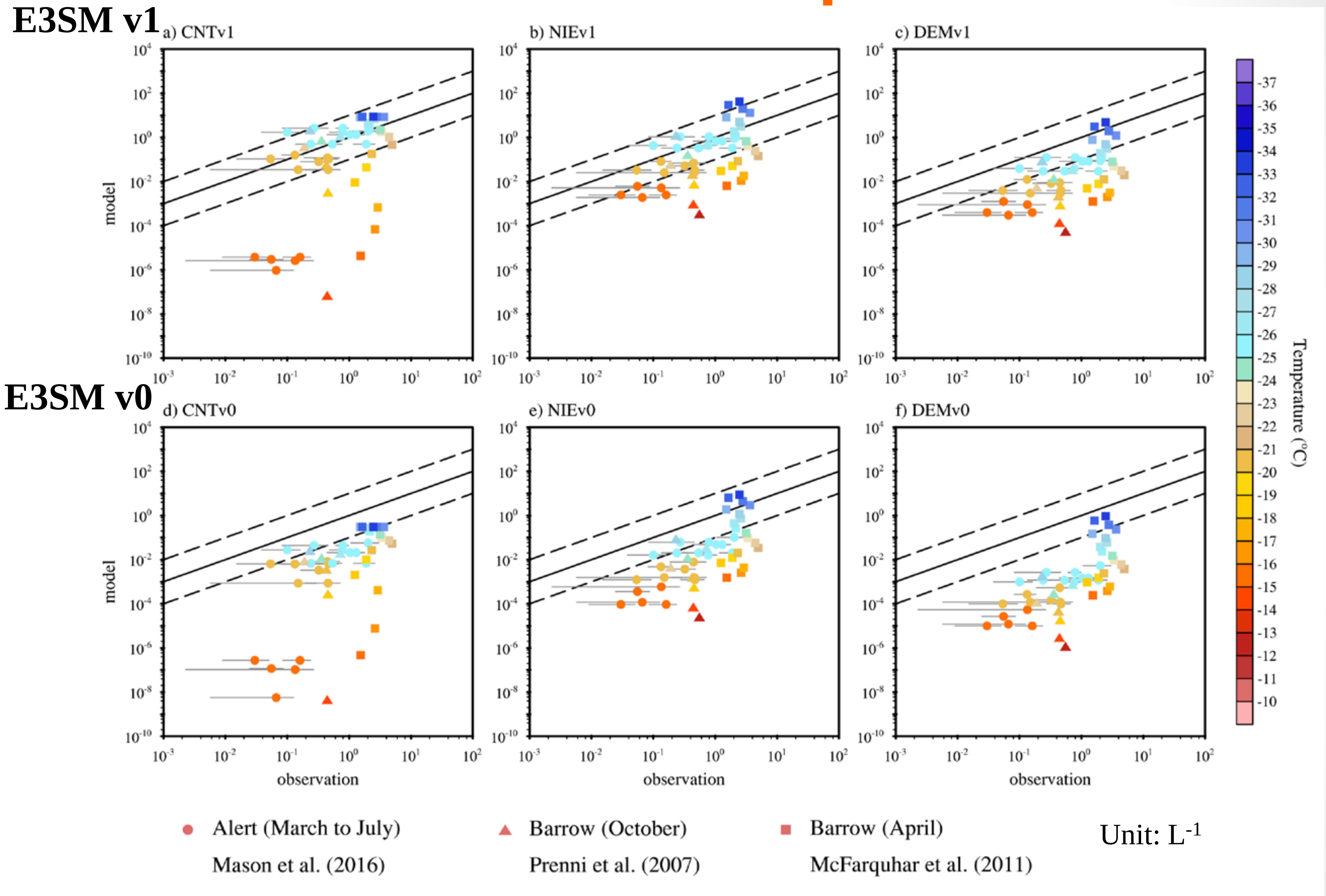
# Dust extinction vertical profiles: Comparing with CALIPSO




**E3SM v1 better simulates high latitude dust, but it is still underestimated when comparing with CALIPSO.**

Shi and Liu (2019, GRL)

# Arctic INP comparison




**E3SM v1 better simulates INP concentration than E3SM v0 at the Arctic.**

Shi and Liu (2019, GRL)

# Dust indirect effects by acting as INPs

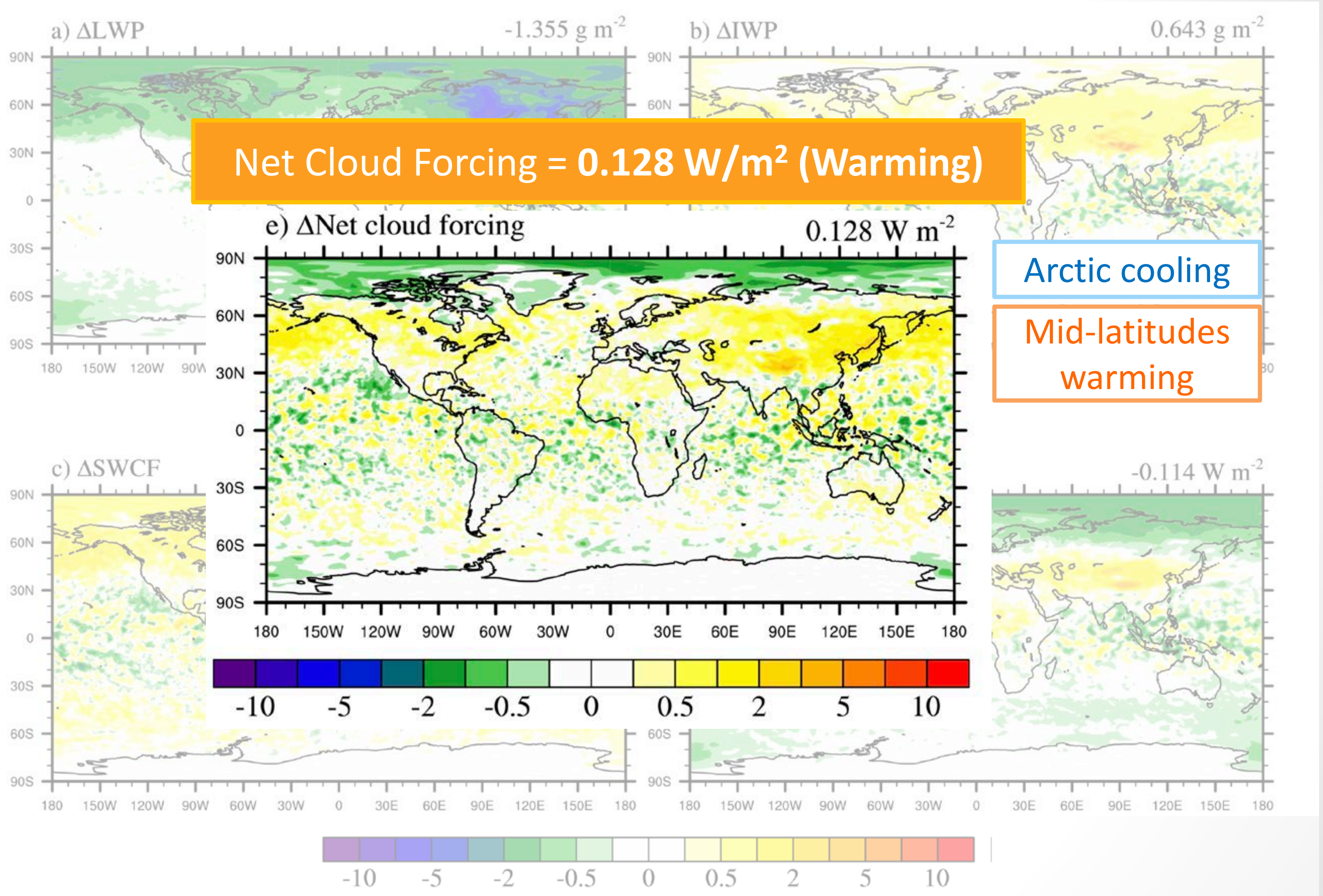
## Sensitivity experiments

**All the sensitivity experiments use E3SM v1.**

| Case Name | Descriptions |
|---|---|
| CNTv1_x0 | Turned off dust immersion freezing. |
| NIEv1_x0 | |
| DEMv1_x0 | |
| CNTv1_x10 | Enhanced dust immersion freezing process by 10 times. |
| NIEv1_x10 | |
| DEMv1_x10 | |

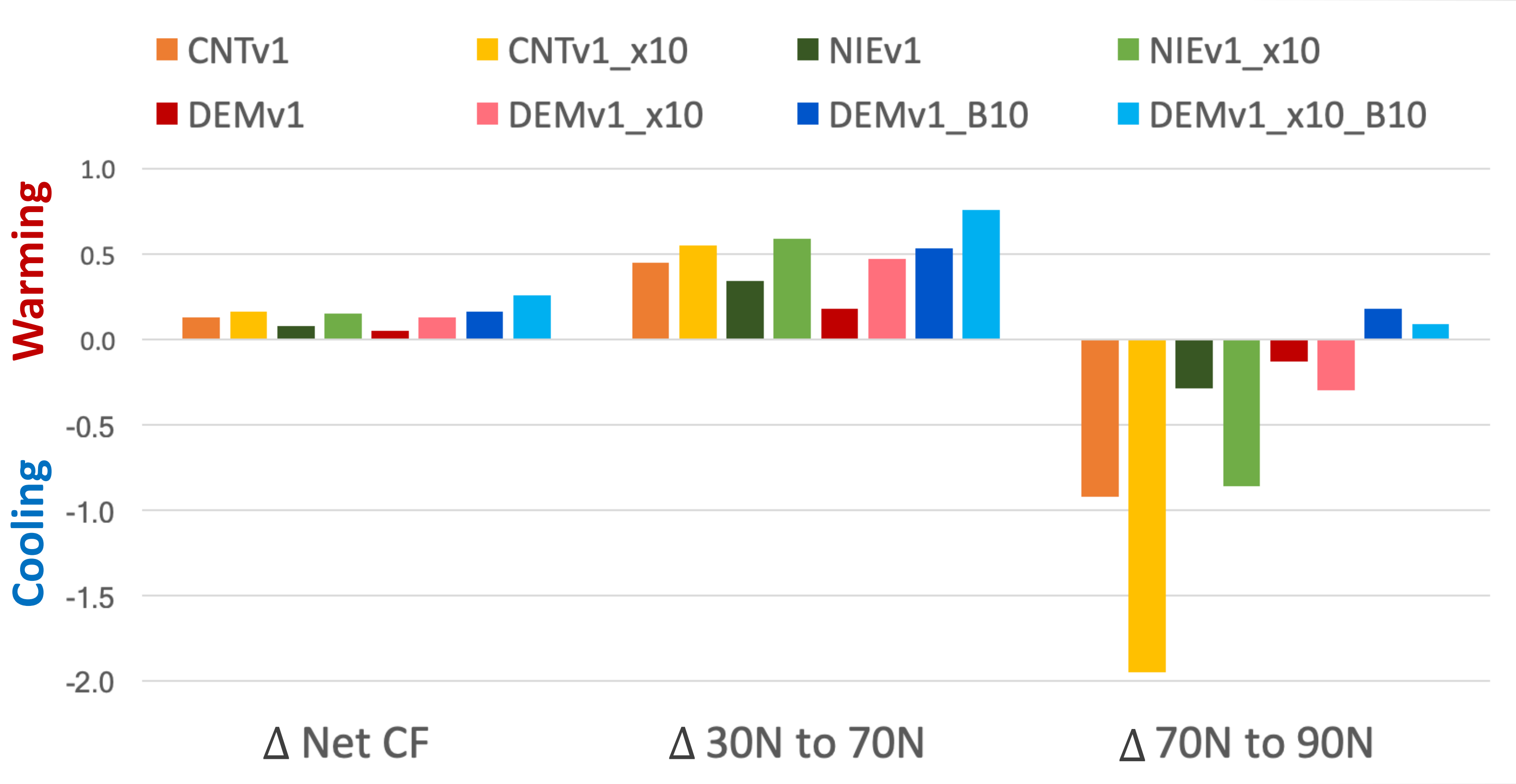
# Condensed water and Cloud forcing differences

DEMv1_x10 – DEMv1_x0 (E3SM v1)



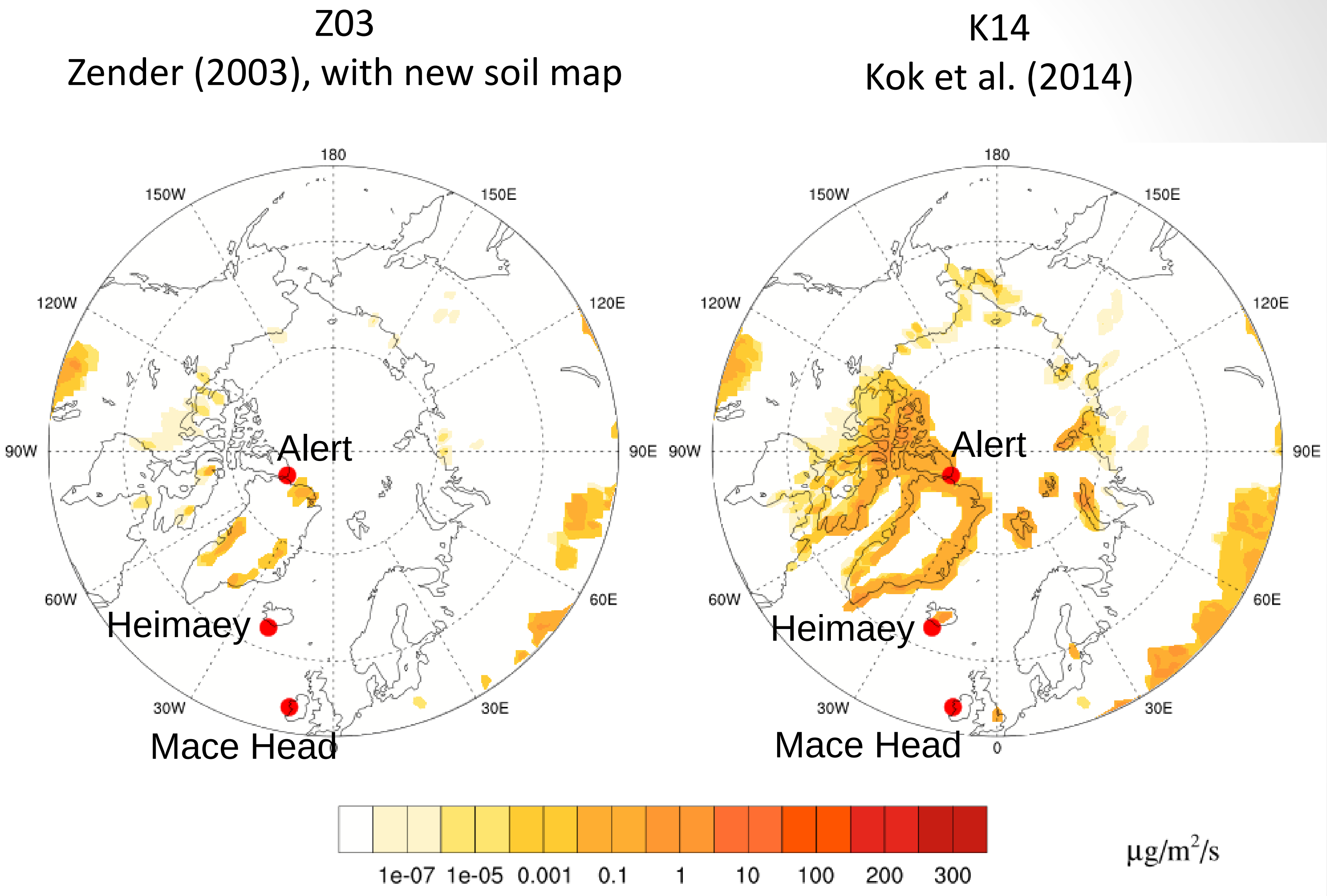

Shi and Liu (2019, GRL)

# Cloud forcing difference:
All compared with “x0” cases

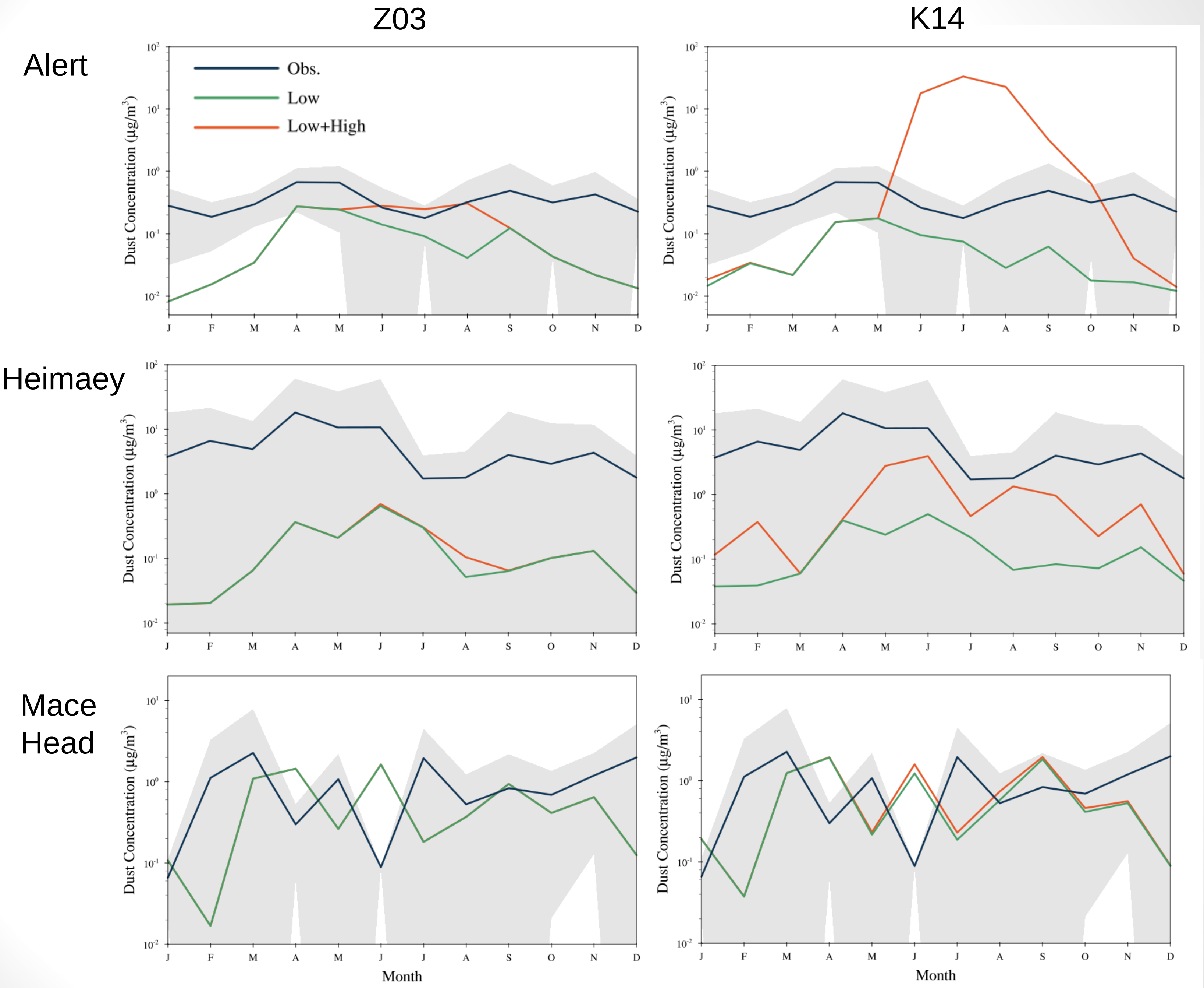



**Dust INPs induce a global net warming cloud effect.**
**NH mid-latitudes: warming; Arctic: cooling**

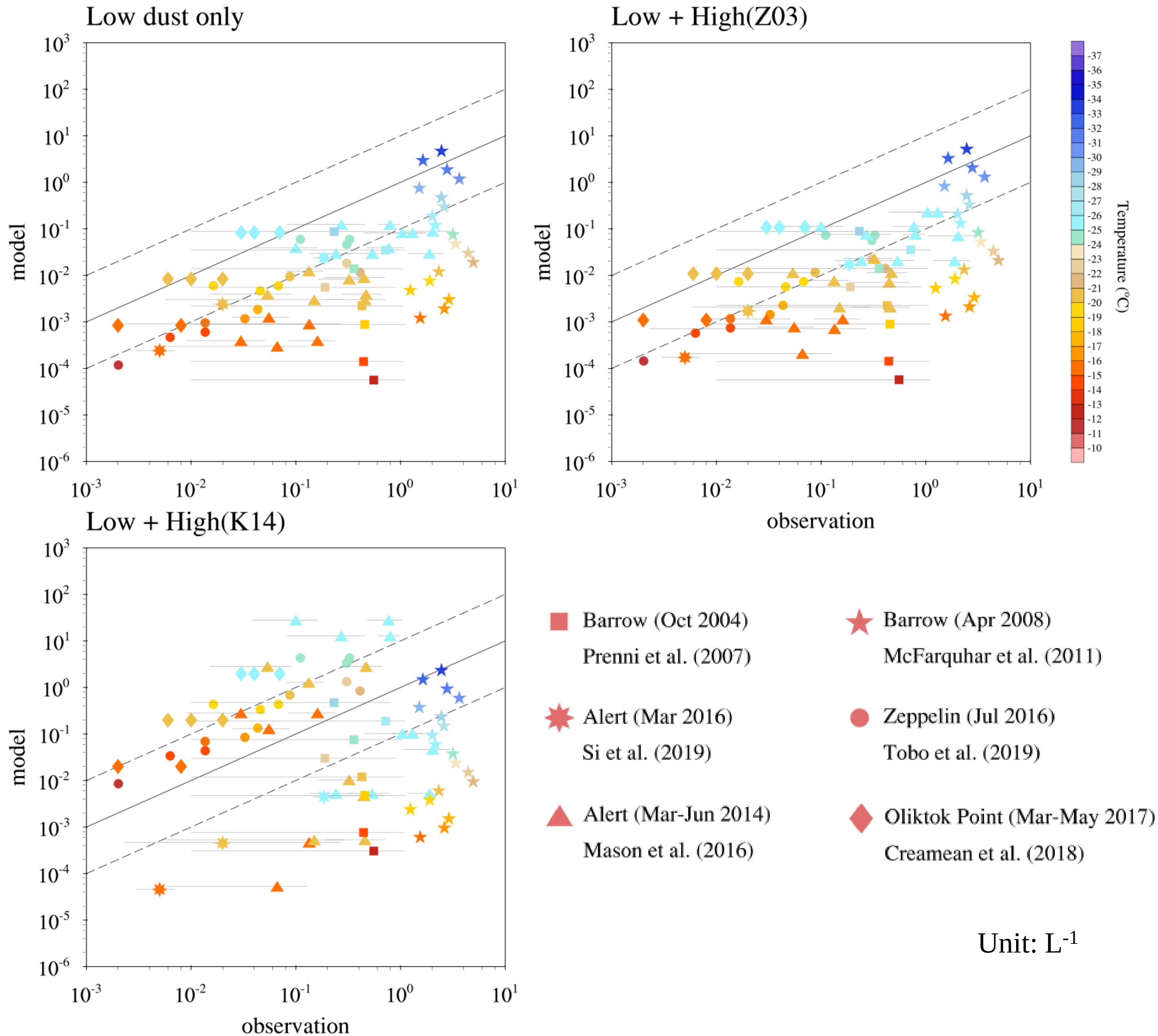
# Local dust emissions in the Arctic



# Dust Concentration Comparison



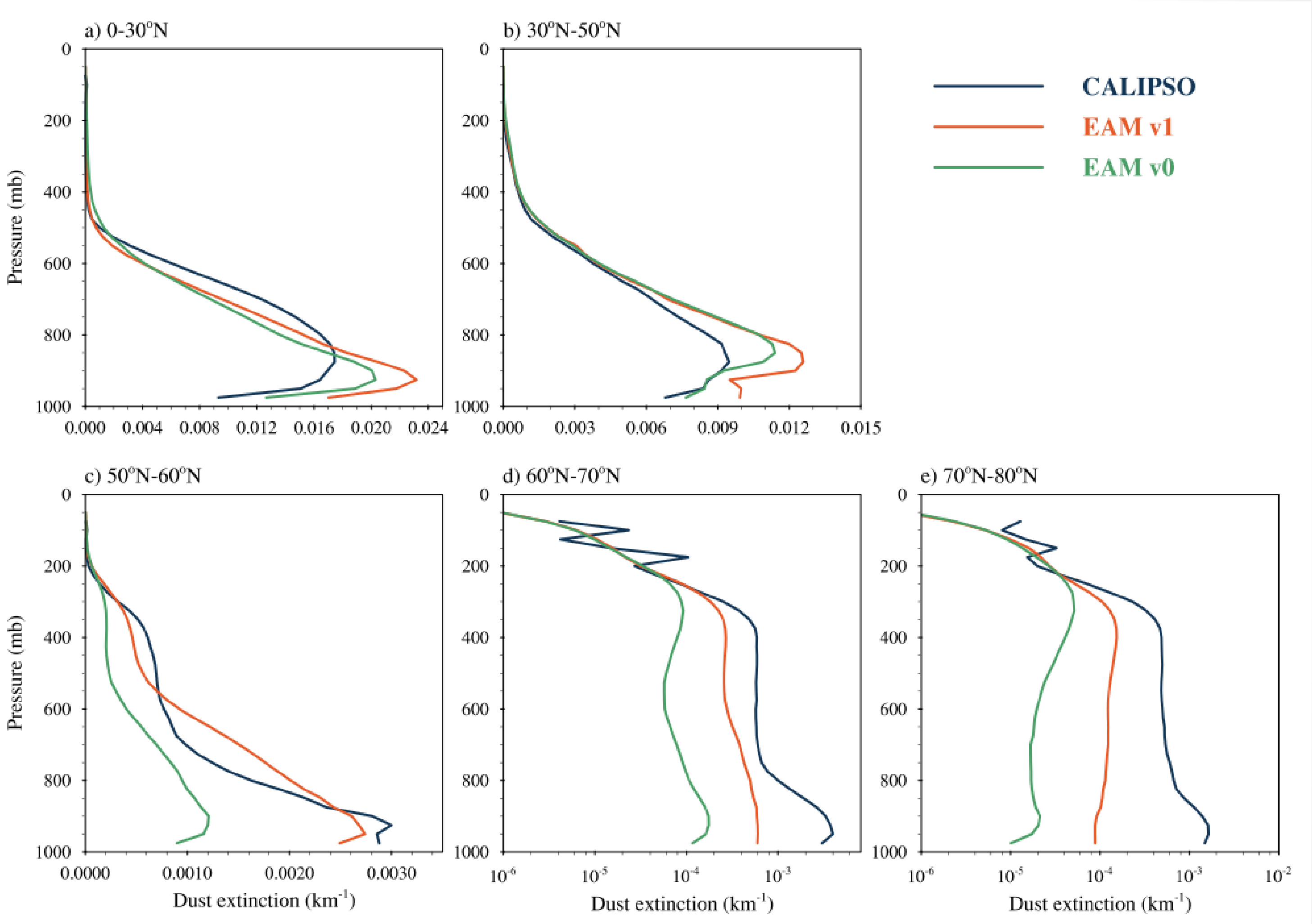
# INP concentration comparison at the Arctic



# Conclusions

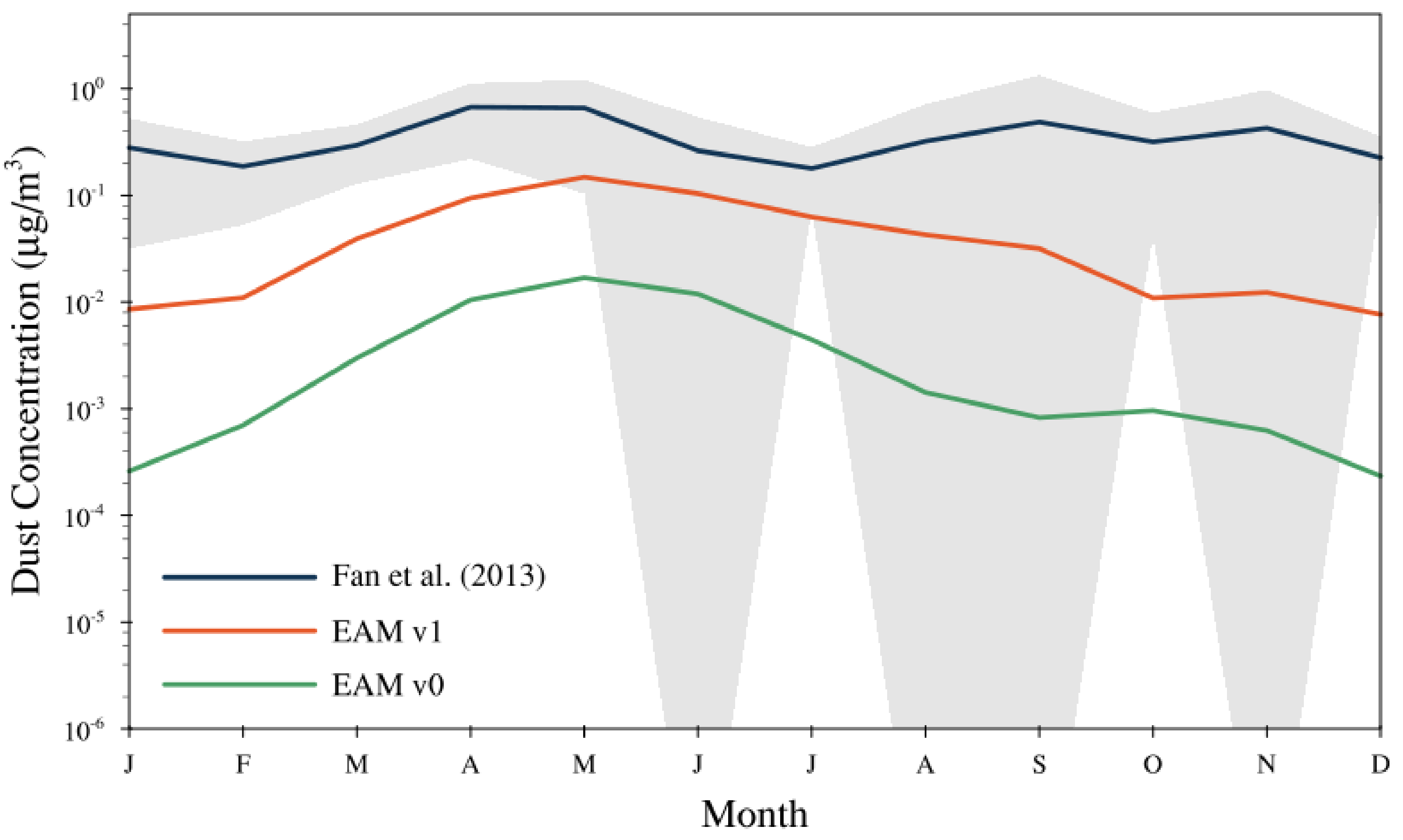
- **E3SM v1 better simulates high latitude dust than v0. However, it is still underestimated comparing with CALIPSO.**
- **Models underestimate INPs concentrations at high latitudes, though improvements are seen in E3SM v1.**
- **Dust induces a warming cloud effect (0.05 - 0.26 W $m^{-2}$ on global mean) by acting as INPs through reducing LWP.**
- **The dust warming effect is located predominantly in the NH midlatitudes, while a cooling effect is found in the Arctic.**
- **Caveat: Dust from high latitude sources may play an important role in Arctic mixed-phase clouds.**

# Dust extinction vertical profiles: Comparing with CALIPSO

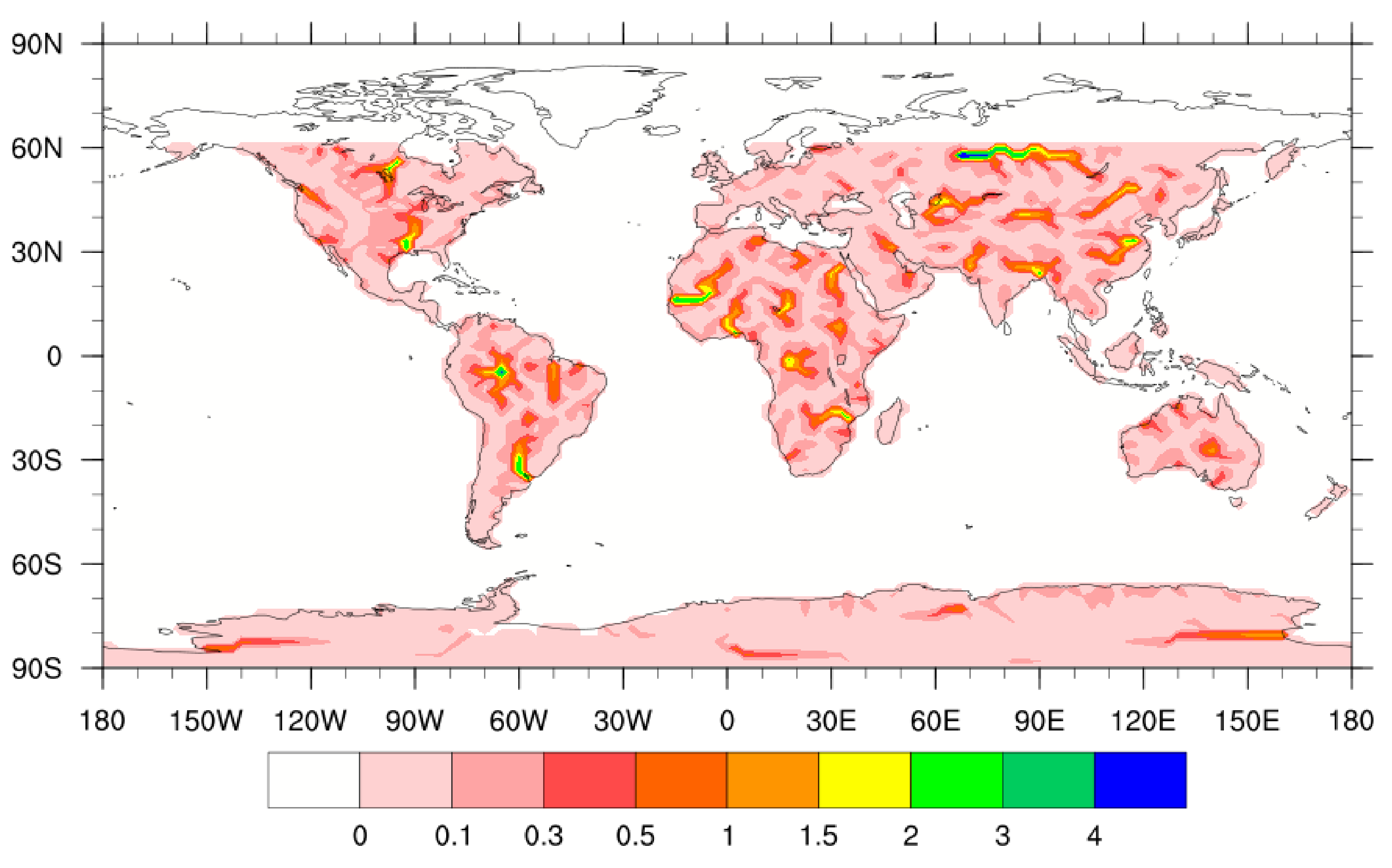



**E3SM v1 better simulates high latitude dust, but it is still underestimated when comparing with CALIPSO.**

# Surface dust concentration comparison Alert, Canada (82.39ºN, 62.3ºW)



# Soil erodibility map for EAM v1 and EAM v0




**Both model versions miss dust emission from high latitudes, Northern Hemisphere.**

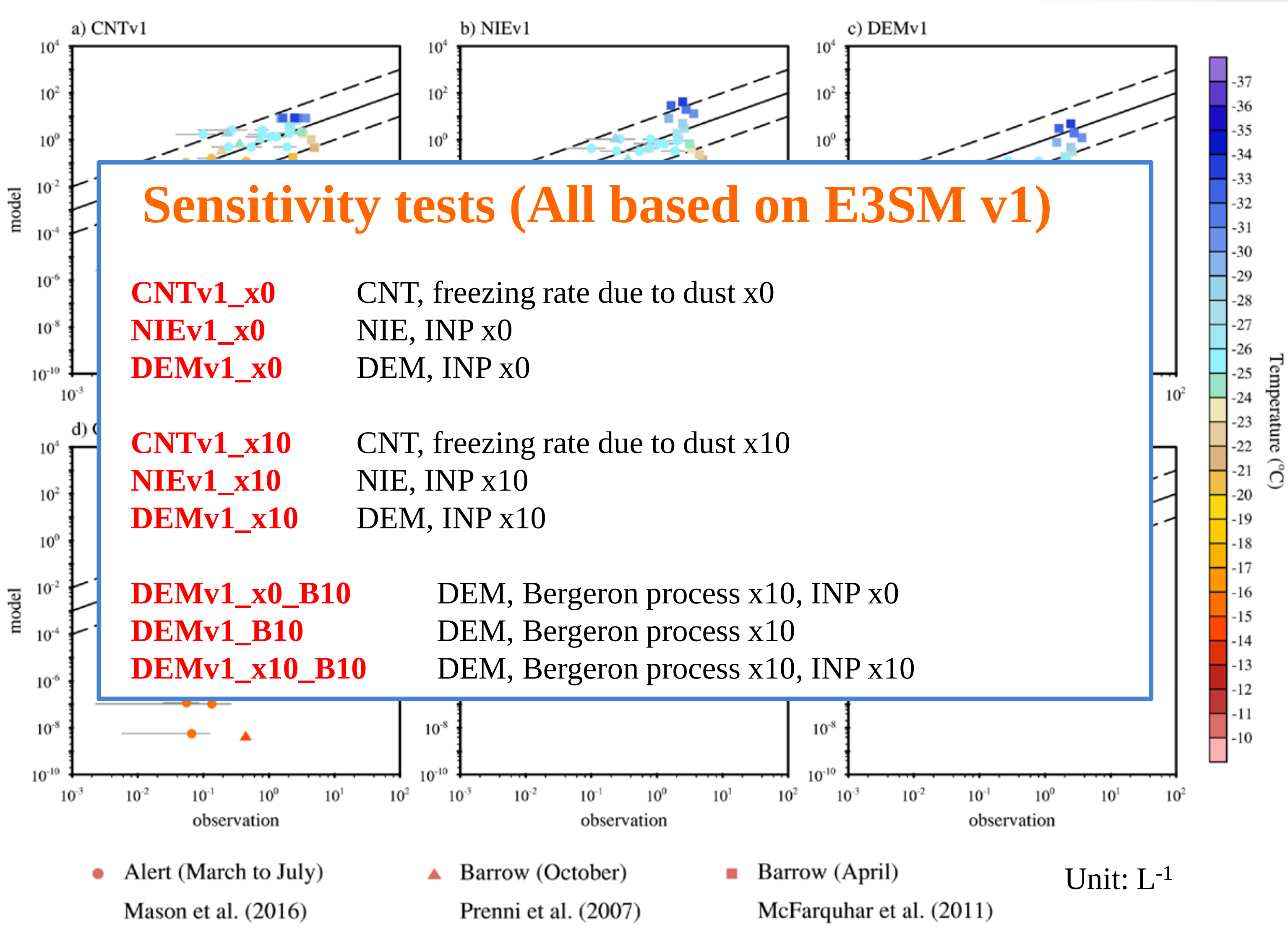
# Dust indirect effects by acting as INPs

## Sensitivity experiments

| Case Name | Descriptions |
|---|---|
| CNTv1_x0 | Turned off dust immersion freezing. |
| NIEv1_x0 | |
| DEMv1_x0 | |
| CNTv1_x10 | Enhanced dust immersion freezing process by 10 times. |
| NIEv1_x10 | |
| DEMv1_x10 | |
| DEMv1_x0_B10 | Sensitivity tests removed the tuning factor (0.1) of WBF process |
| DEMv1_B10 | |
| DEMv1_x10_B10 | |

**All the sensitivity experiments here use E3SM v1.**

# Arctic INP comparison



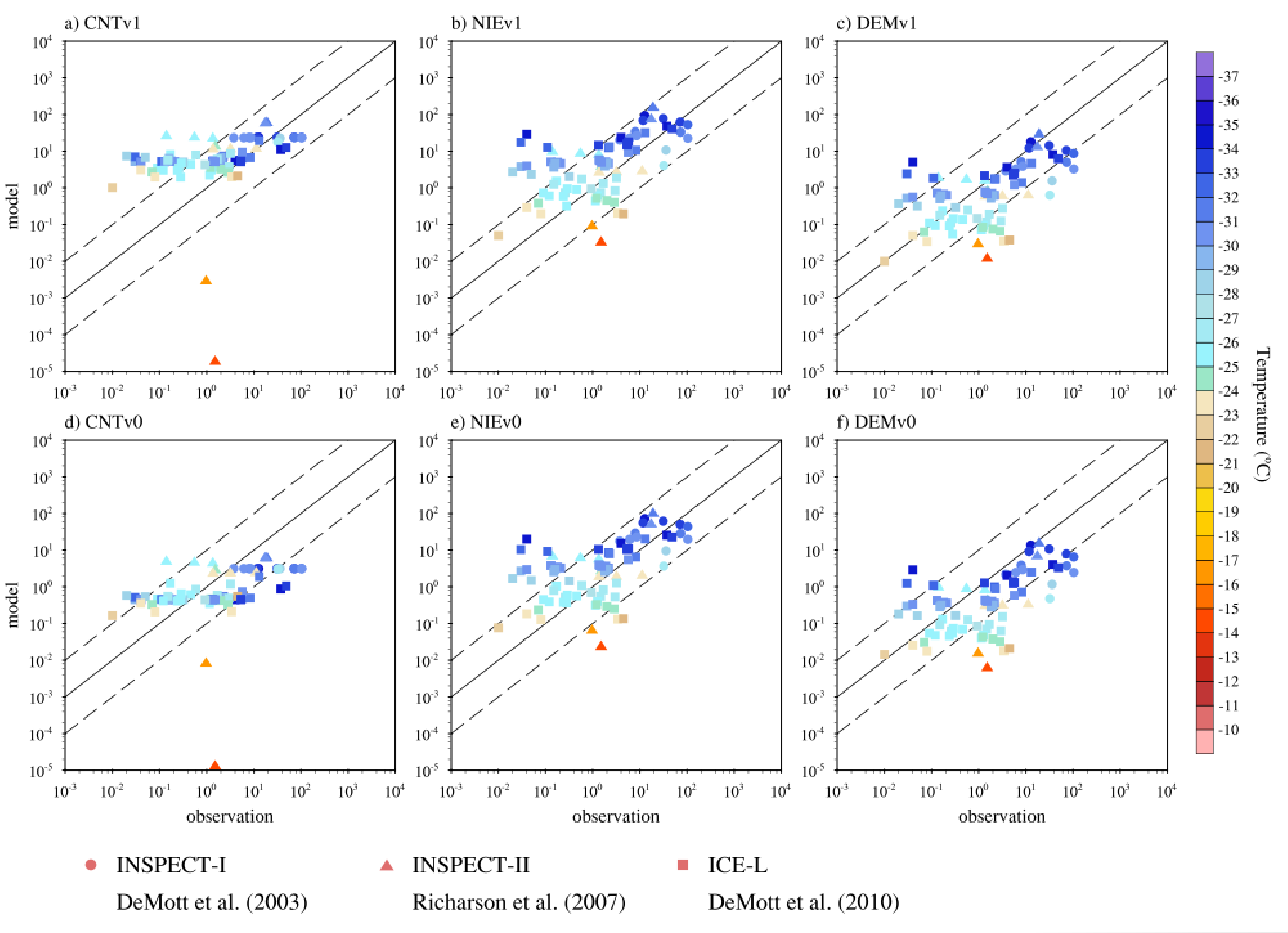

## Sensitivity tests (All based on E3SM v1)

| | |
|---|---|
| **CNTv1_x0** | CNT, freezing rate due to dust x0 |
| **NIEv1_x0** | NIE, INP x0 |
| **DEMv1_x0** | DEM, INP x0 |
| **CNTv1_x10** | CNT, freezing rate due to dust x10 |
| **NIEv1_x10** | NIE, INP x10 |
| **DEMv1_x10** | DEM, INP x10 |
| **DEMv1_x0_B10** | DEM, Bergeron process x10, INP x0 |
| **DEMv1_B10** | DEM, Bergeron process x10 |
| **DEMv1_x10_B10** | DEM, Bergeron process x10, INP x10 |

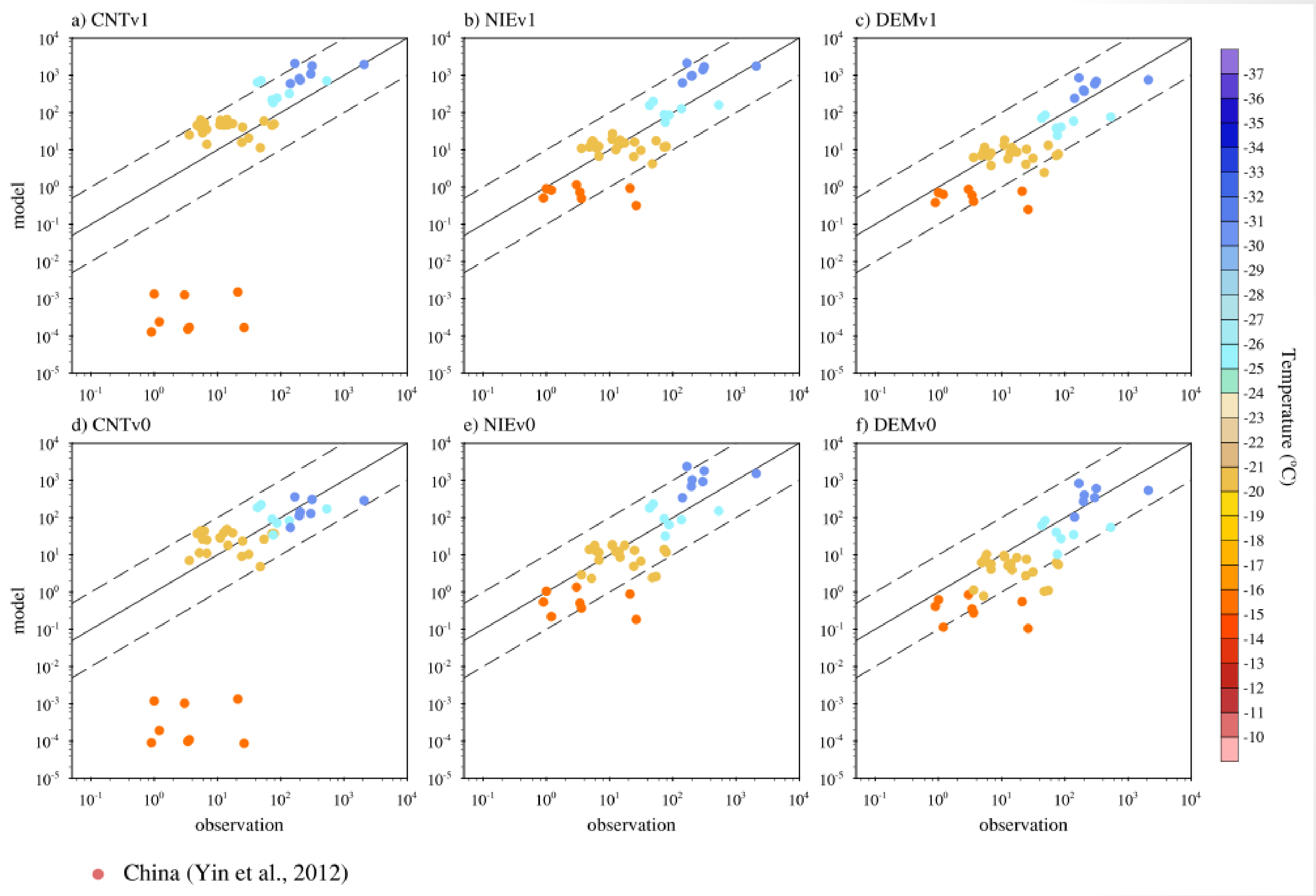
**E3SM v1 better simulates INP concentration than E3SM v0 at the Arctic.**

Shi and Liu (2019, GRL)

# INP comparison at the US

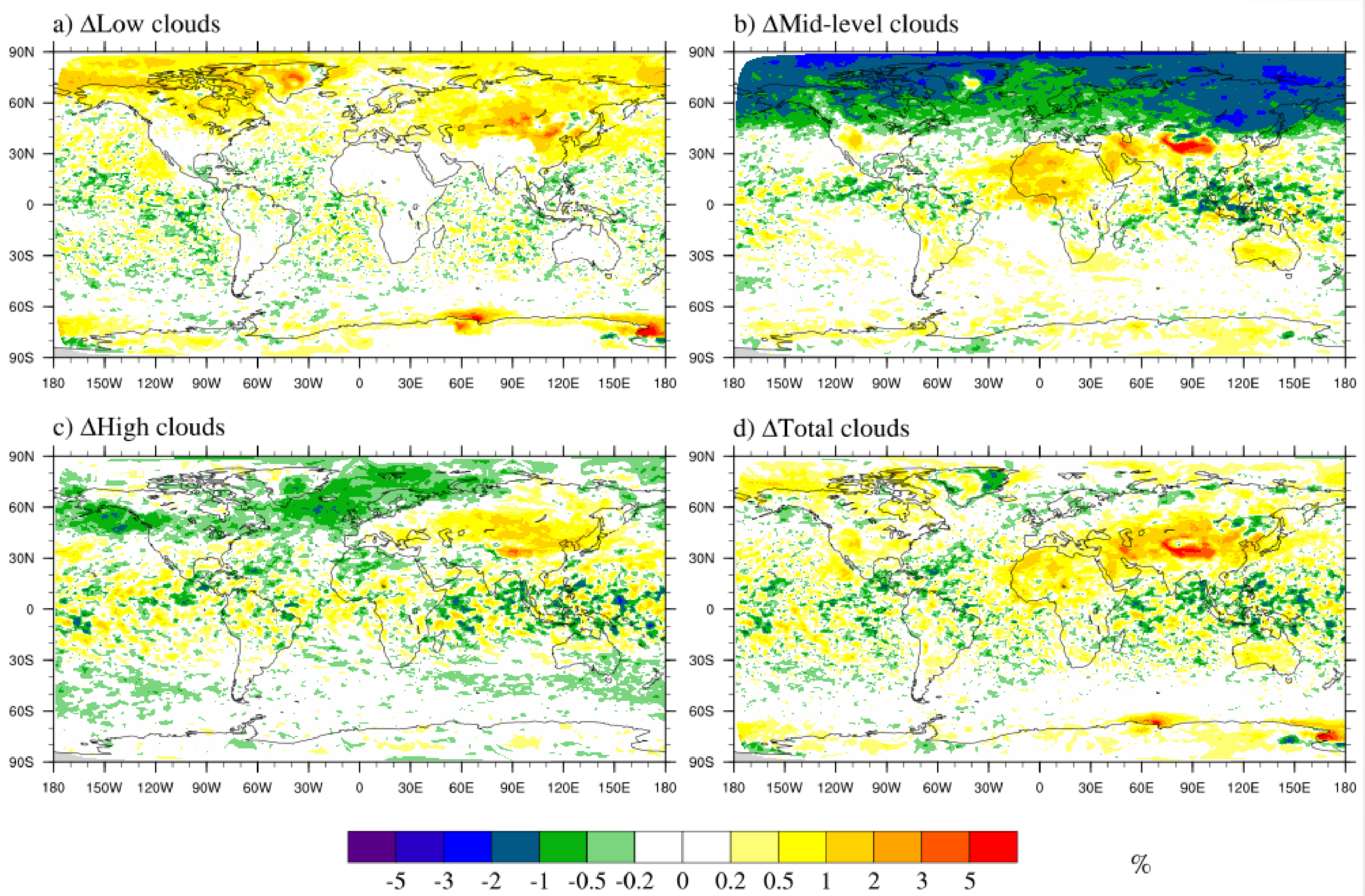


# INP comparison in North China

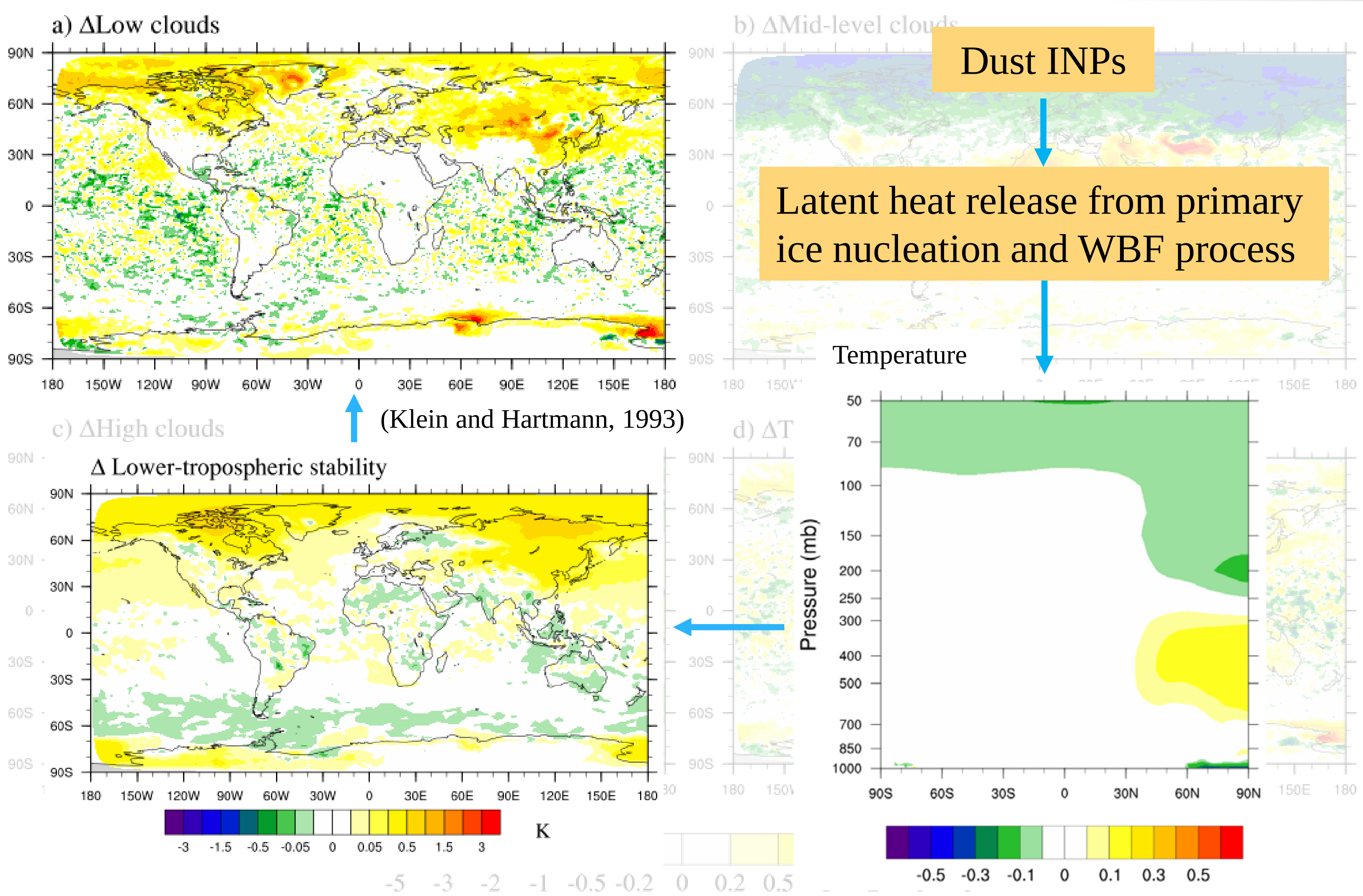


# Cloud fraction difference:

DEMv1_x10 – DEMv1_x0 (E3SM v1)

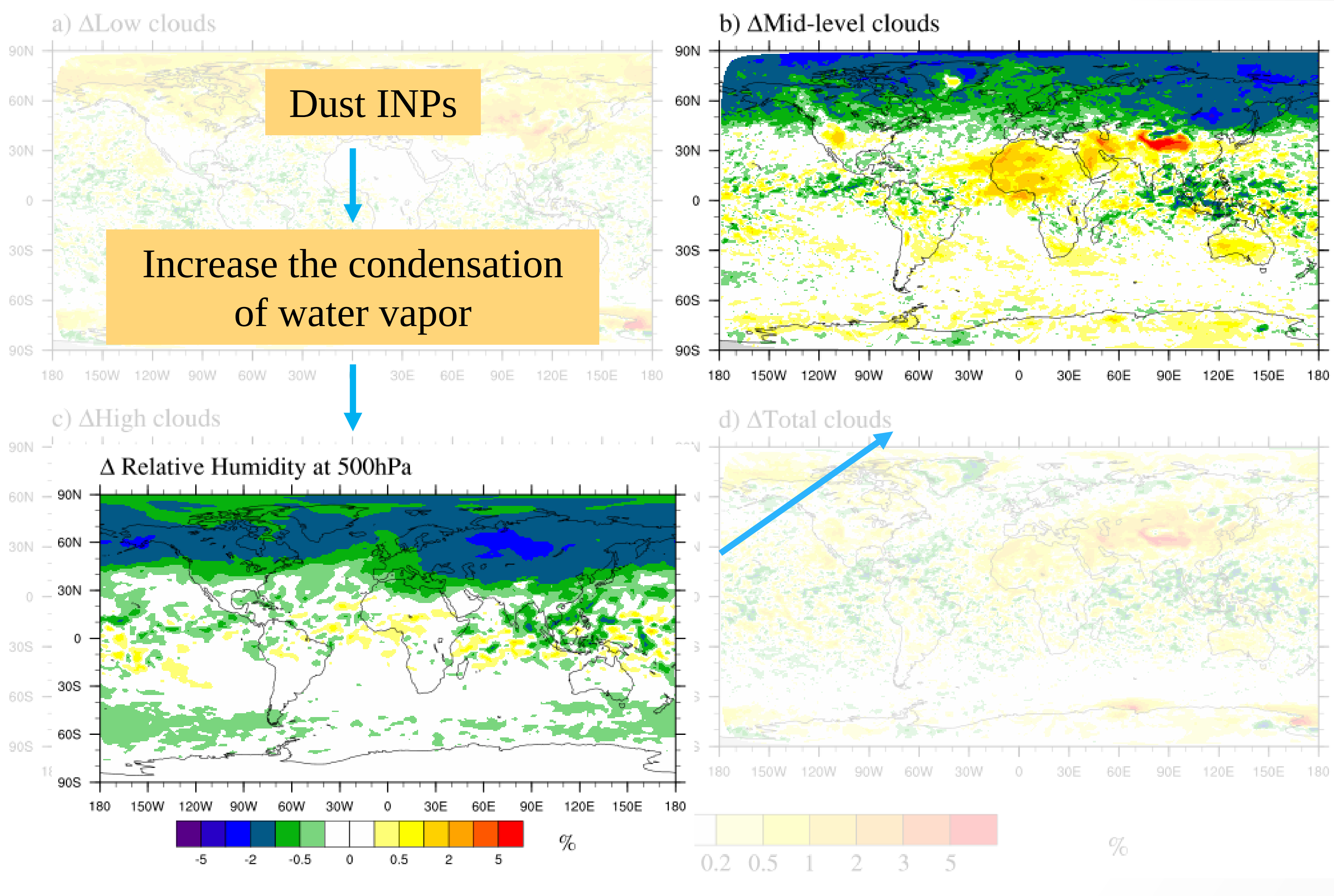


# Cloud fraction difference:
DEMv1_x10 – DEMv1_x0 (EAM v1)



# Cloud fraction difference:

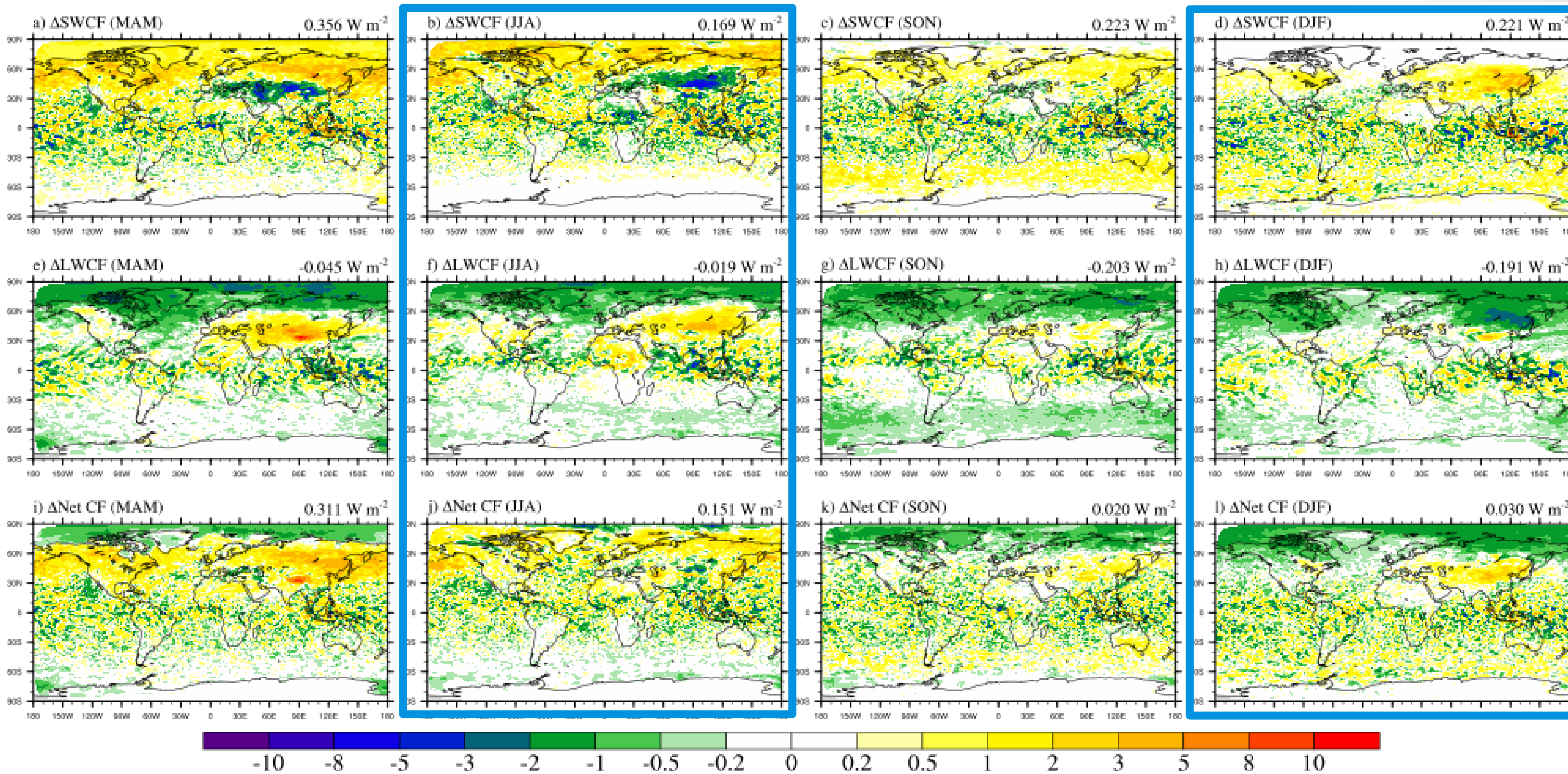
DEMv1_x10 – DEMv1_x0 (EAM v1)



# Seasonal cloud forcing difference:

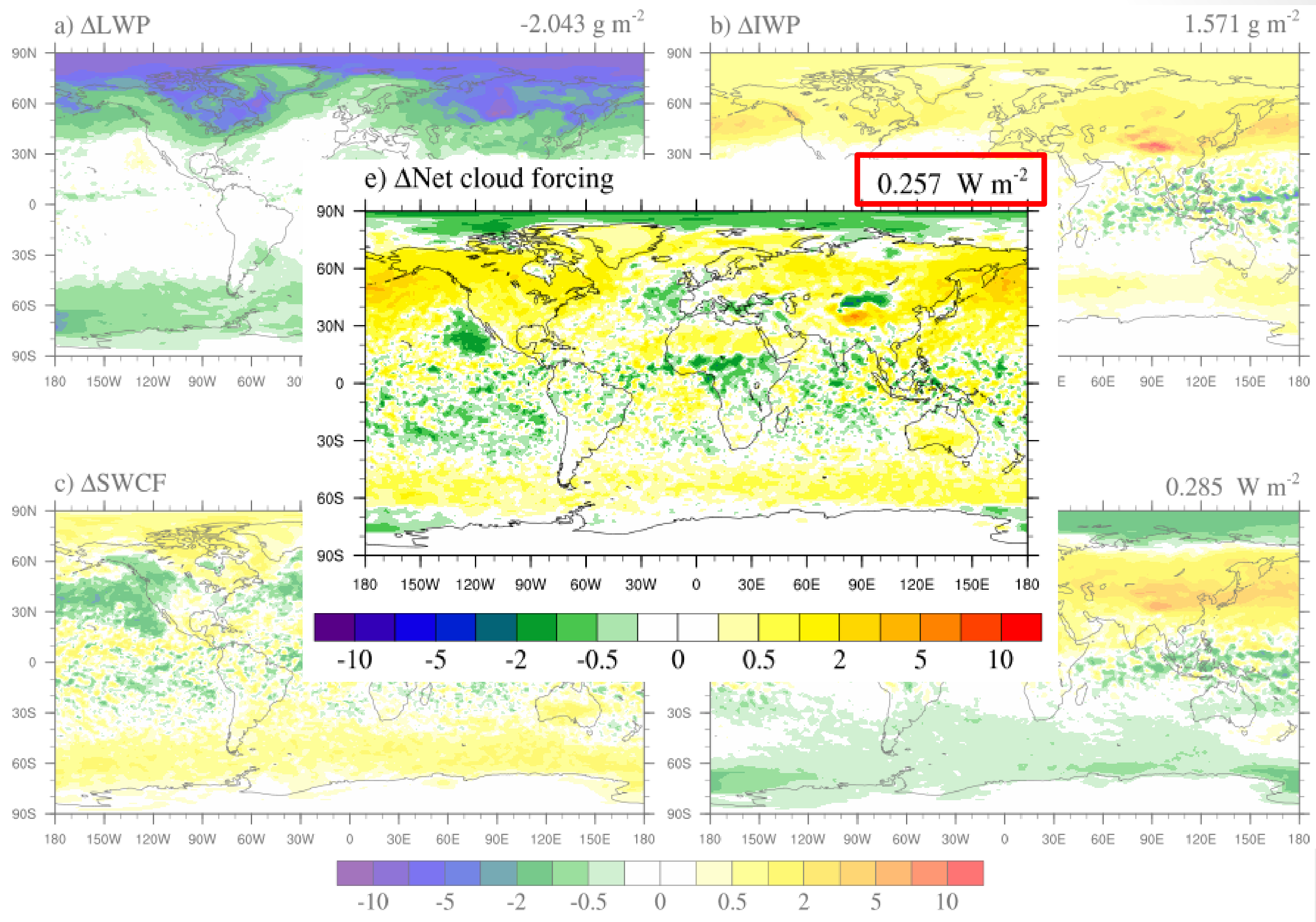
DEMv1_x10 – DEMv1_x0 (EAM v1)

MAM JJA SON DJF



# **Condensed water** and **Cloud forcing difference:**

DEMv1_x10_B10 – DEMv1_x0_B10 (E3SM v1)



# Cloud forcing difference:
All compared with "x0" cases

| Case | SWCF | LWCF | Net CF |
|---|---|---|---|
| CNTv1 | 0.72 | -0.58 | 0.13 (0.45, -0.92) |
| CNTv1_x10 | 1.50 | -1.34 | 0.16 (0.55, -1.95) |
| NIEv1 | 0.27 | -0.19 | 0.08 (0.34, -0.29) |
| NIEv1_x10 | 0.35 | -0.21 | 0.15 (0.59, -0.86) |
| DEMv1 | 0.10 | -0.05 | 0.05 (0.18, -0.13) |
| DEMv1_x10 | 0.24 | -0.11 | 0.13 (0.47, -0.30) |
| DEMv1_B10 | 0.10 | 0.06 | 0.16 (0.53, 0.18) |
| DEMv1_x10_B10 | -0.03 | 0.29 | 0.26 (0.76, 0.09) |

**Dust INPs induce a global net warming cloud effect.**
**NH mid-latitudes: warming; Arctic: cooling**