Geo-engineering of clouds – Focus on the Arctic

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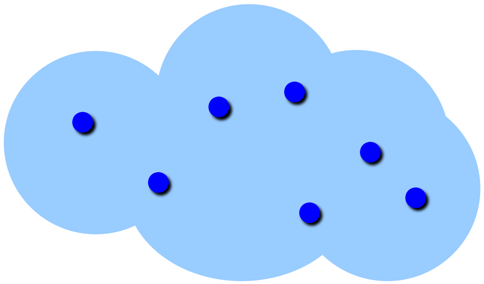
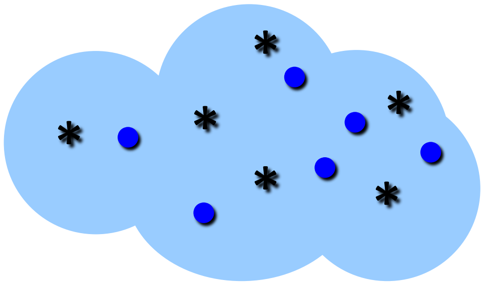
Warm and cold clouds

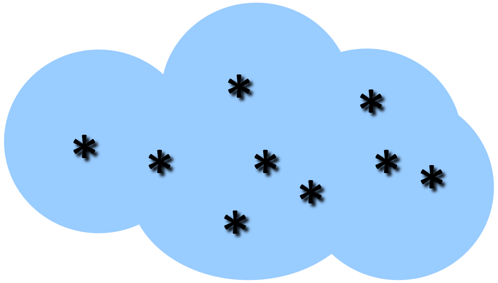
Warm clouds → clouds with $T > 0^{o}C$



Cold clouds → mixed-phase clouds ($\sim -35^{o}C < T < 0^{o}C$)



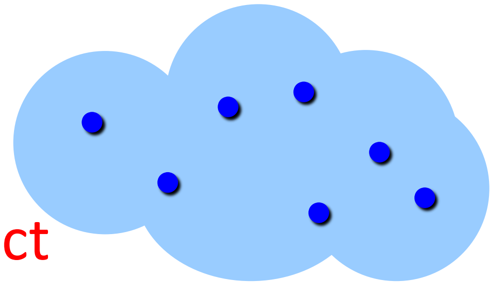
Cold clouds → ice clouds (cirrus) ($T < \sim -35^{o}C$)



Warm and cold clouds

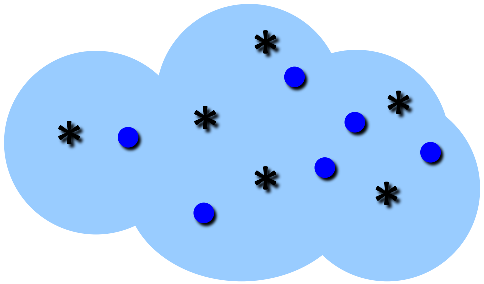
Warm clouds → clouds with T > 0°C

adding CCN makes
them brighter: **cooling** effect

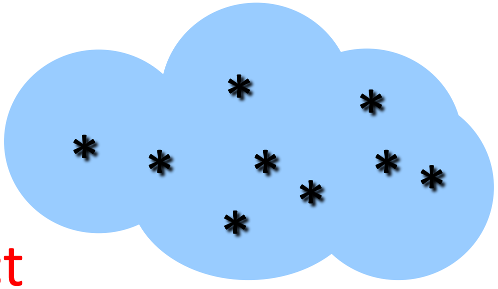


Cold clouds

→ mixed-phase clouds
(-40°C < T < 0°C)

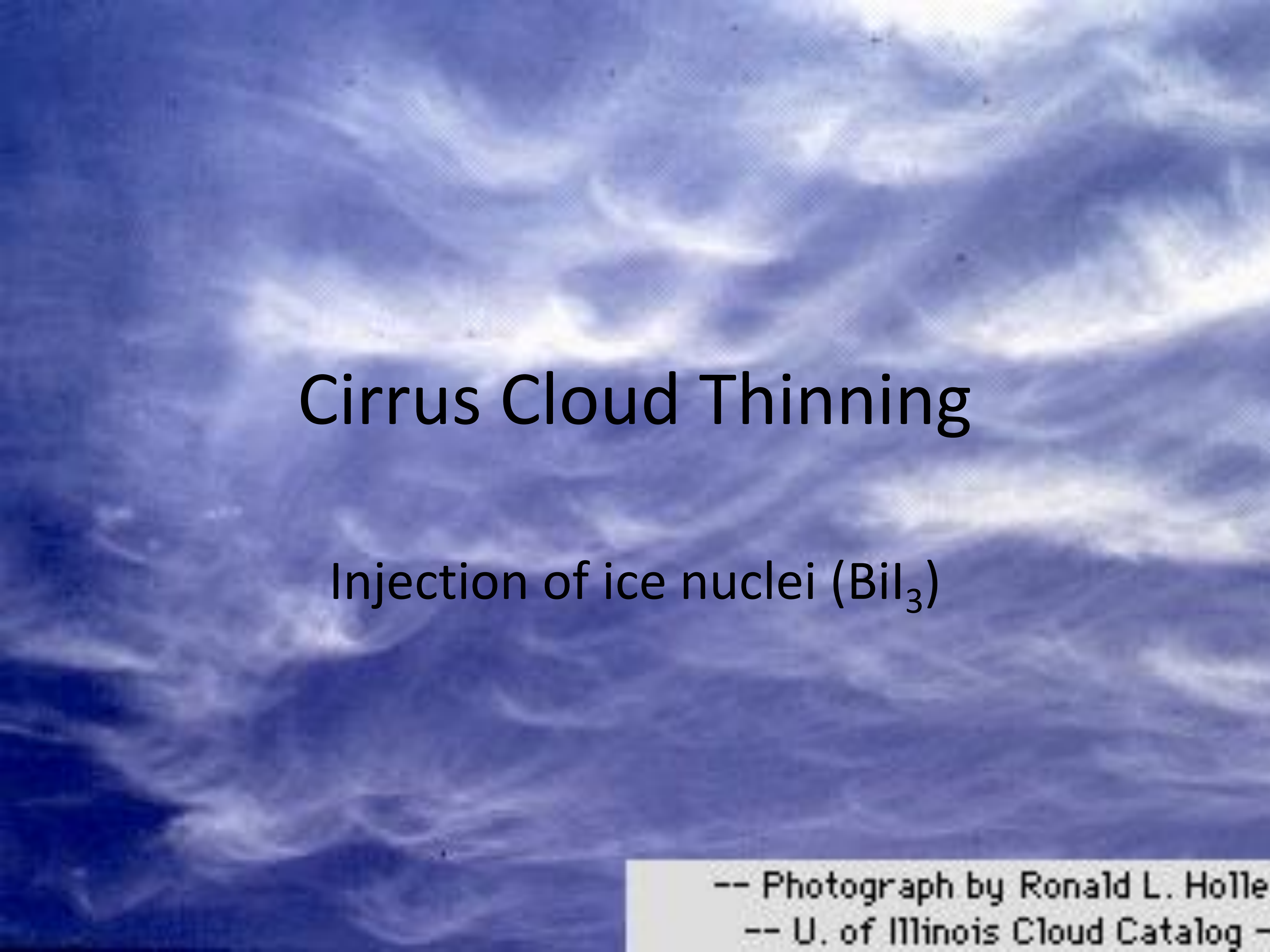


→ ice clouds (cirrus)
(T < -40°C)
adding IN makes
them thinner: **cooling** effect



Cirrus Cloud Thinning

Injection of ice nuclei (BiI_3)



Geo-engineering of cirrus clouds (*Mitchell and Finnegan, 2009: ERL*)

- Cirrus clouds have a net warming effect on climate
- They form at temperatures low enough (< -40°C) that ice crystals form by **homogeneous nucleation** at **high supersaturations**
- Injections of efficient ice nuclei (IN) cause **heterogeneous nucleation** at much **lower supersaturations**

⇒ shutting off homogeneous nucleation

⇒ greatly lowering the number of ice crystals

- The fewer ice crystals will grow rapidly

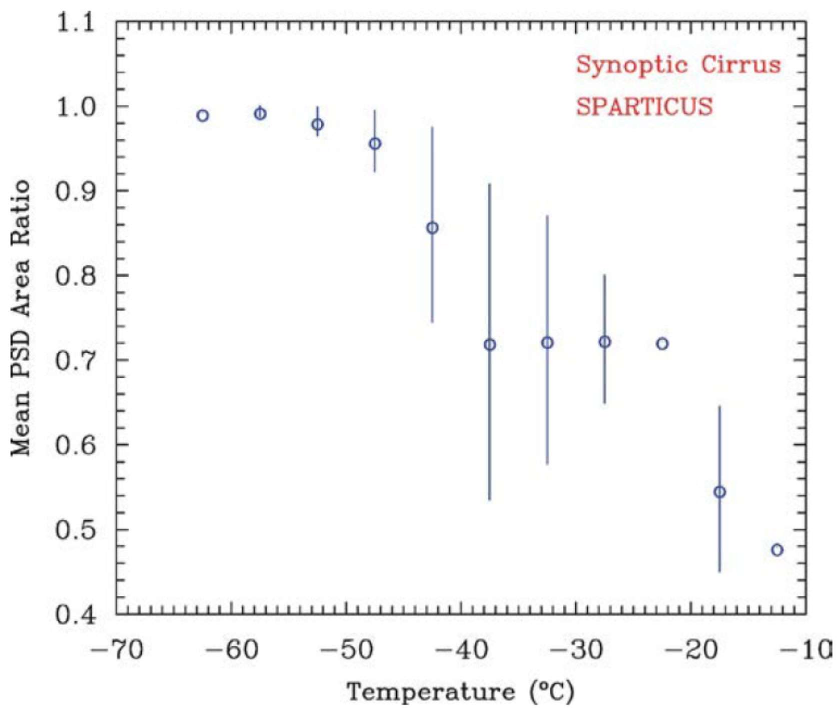
⇒ large fall velocities

⇒ the cloud will be depleted

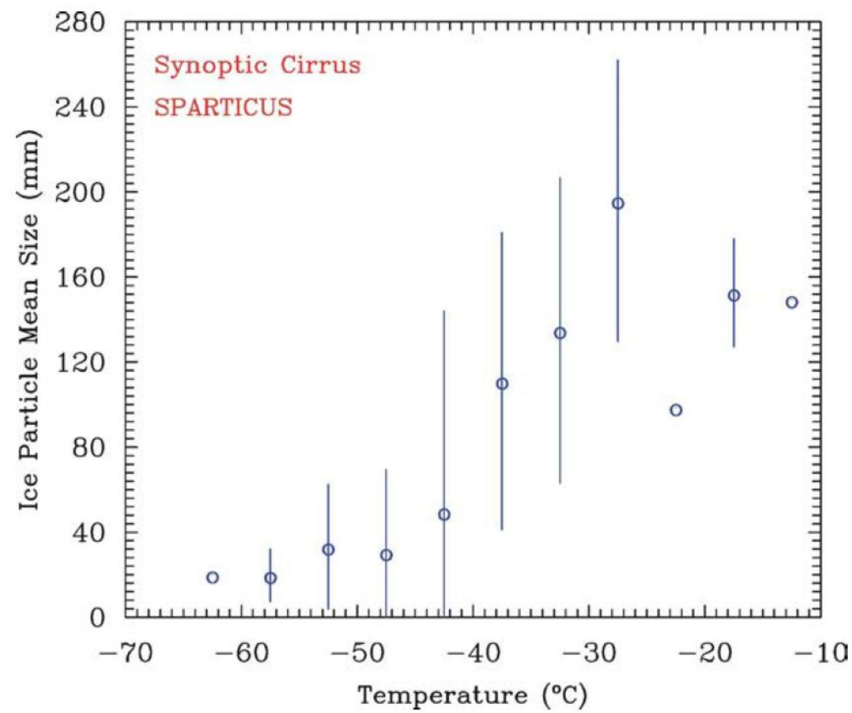
⇒ **the cloud radiative forcing** will be **significantly reduced**

Ice Crystal Properties change around -40ºC

Ice Crystal Shape

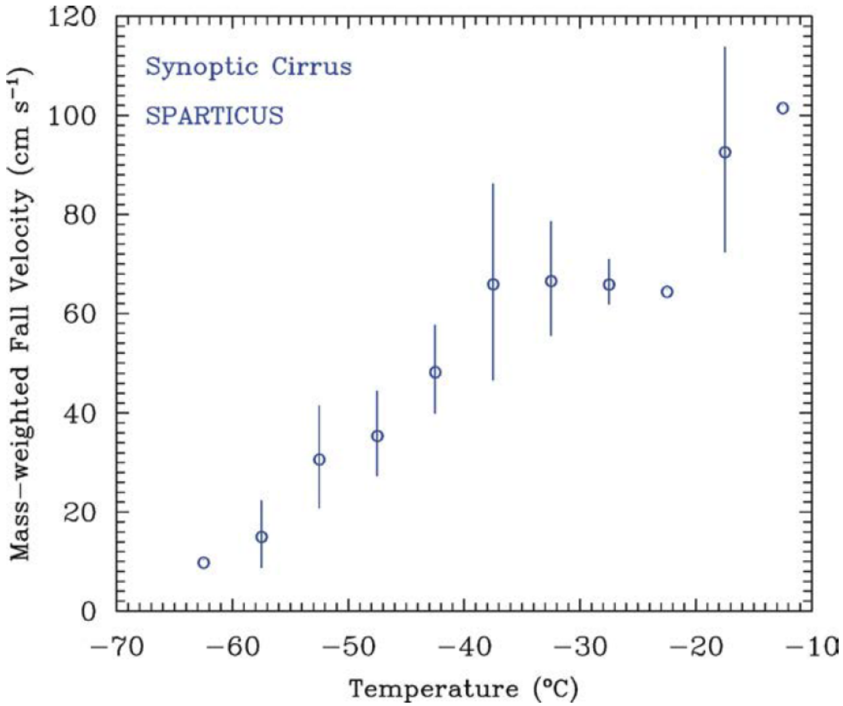


Ice Crystal Size



Mitchell et al. (2011: In.Tech.)

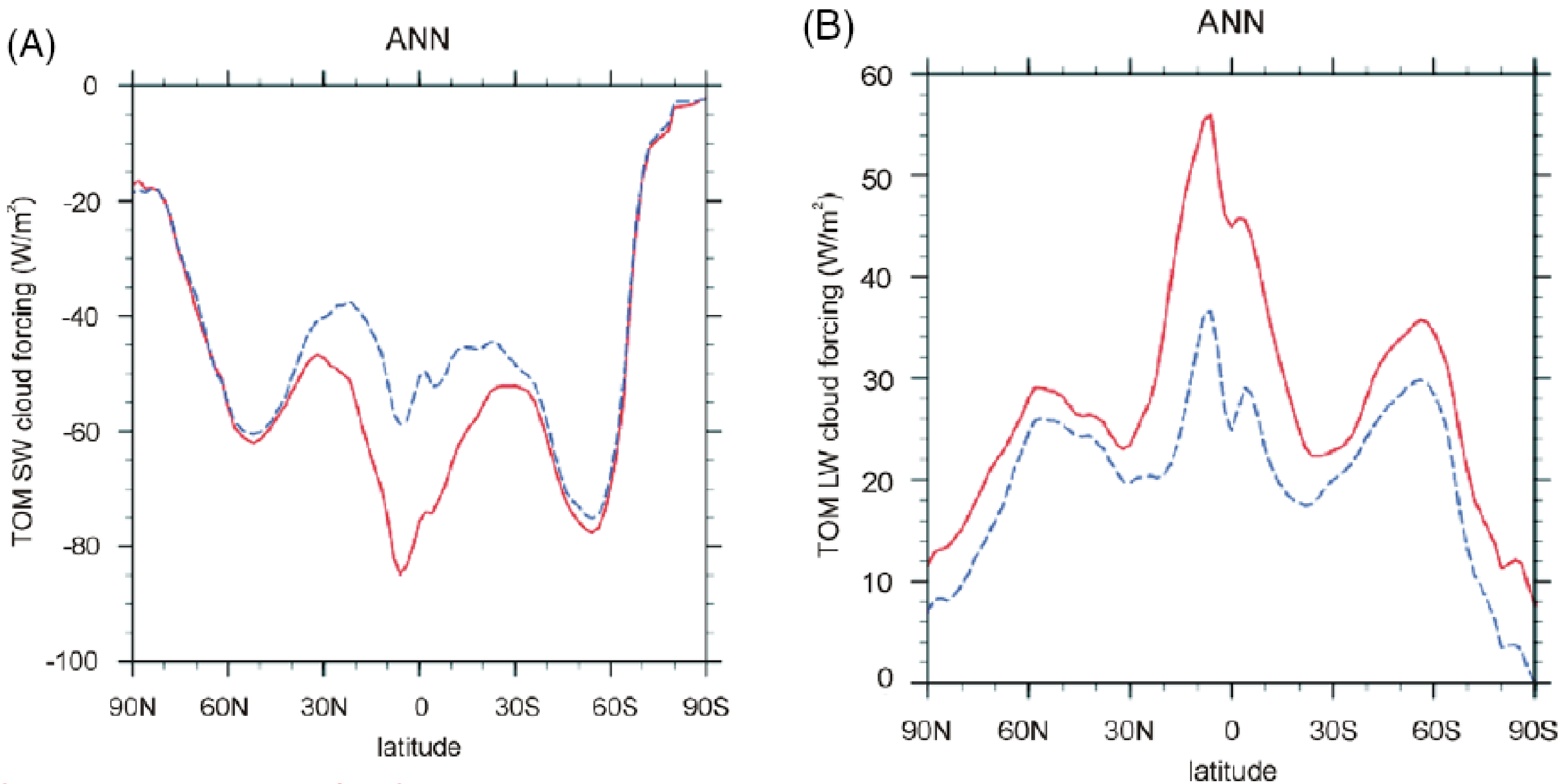
Ice Crystal Fall Speed



- At the **natural transition** between homogeneous and heterogeneous freezing, ice crystal fall speed sharply increases
- The geo-engineering technique would **force** that **transition**

Mitchell et al. (2011: In.Tech.)

Reduced cloud forcing due to enhanced fall speeds of ice crystals



Red curves: Unperturbed case

Blue curves: "Ice Nuclei injections" => Both SW and LW effects reduced, but **LW effect dominates**

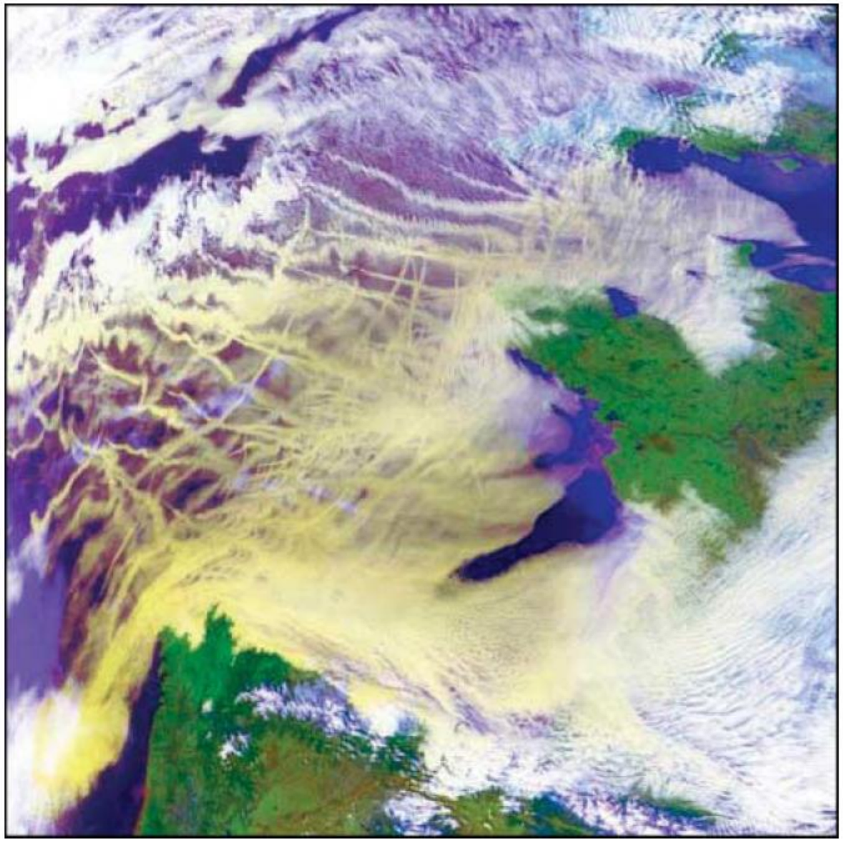
Mitchell et al. (2008: Geophys. Res. Lett.)

Marine Cloud Brightening

Sea Salt Injections

Marine cloud brightening

- **Injecting sea salt** particles into the marine boundary layer => Smaller, more numerous cloud droplets => The clouds **reflect more solar radiation** (Latham, 1992)

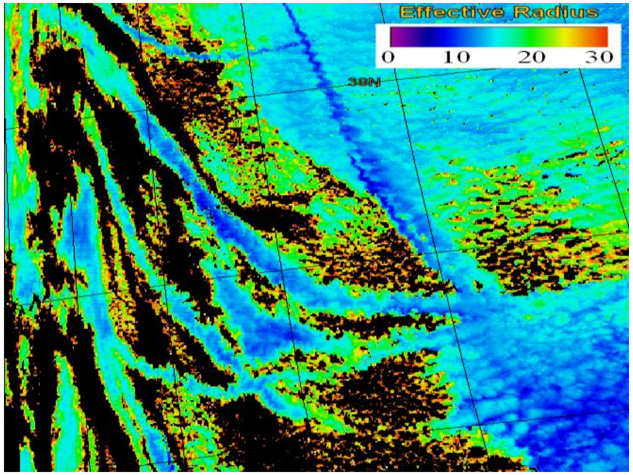


Salter et al. (2008: PTRSA)

Cloud model studies (Wang, Rasch & Feingold, 2011: *ACP*)

Favorable Conditions

- Weakly precipitating boundary layer
- Clean conditions preceded by heavy / persistent precipitation

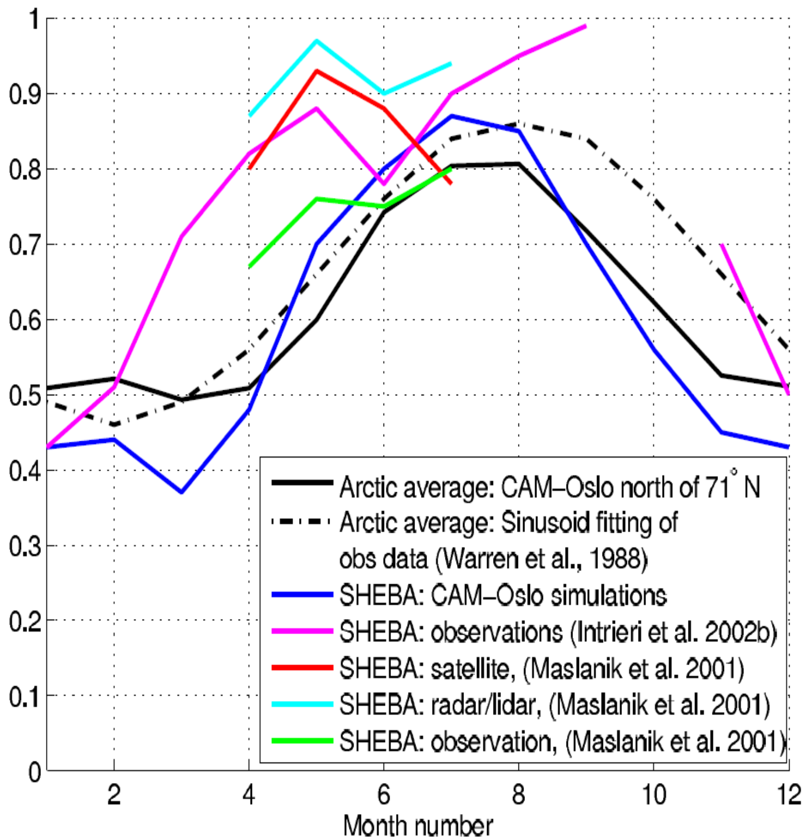


Unfavorable Conditions

- Strongly precipitating clouds
- Polluted clouds
- Thin non-precipitating clouds

Clouds in the Arctic

Cloud Cover

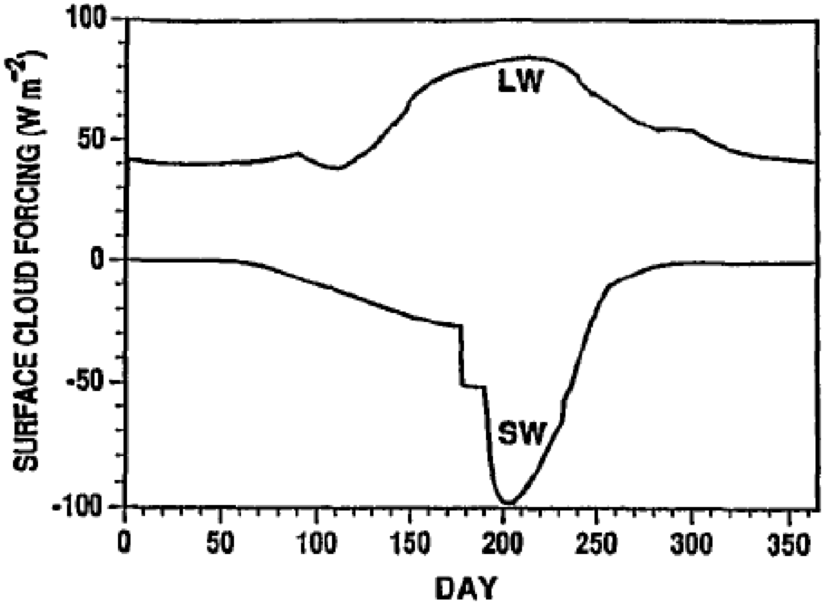


- Annually averaged cloud cover of about 70%
- Summer and early autumn are the cloudiest season (**Arctic Stratus**), while late winter is the least cloudy season

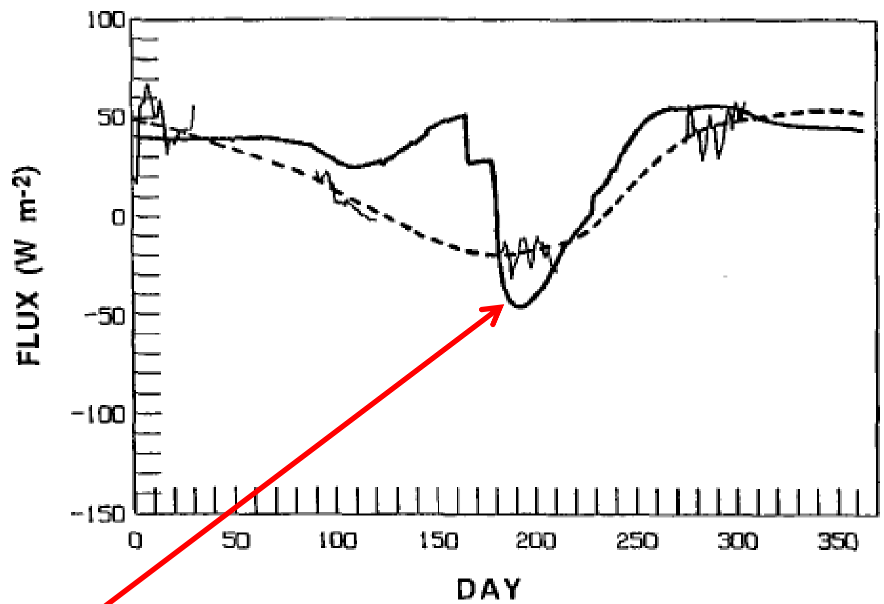
Alterskjær, Kristjánsson, Hoose (2010: JGR)

The influence of clouds on the Arctic surface energy balance

Solar (SW) and terrestrial (LW)



Net



Arctic clouds exert a **positive radiative forcing at the surface**, annually averaged. Only in mid-summer is the forcing negative.

Will geo-engineering have the desired effect?

Curry et al. (1996: J. Climate)

Arctic Clouds and the Surface Energy Balance

- What happens if we add CCN to Arctic Stratus clouds?
- For thin clouds (LWP < 23 g m^{-2}): **warming effect**
- For thicker clouds (LWP > 23 g m^{-2}): **cooling effect**

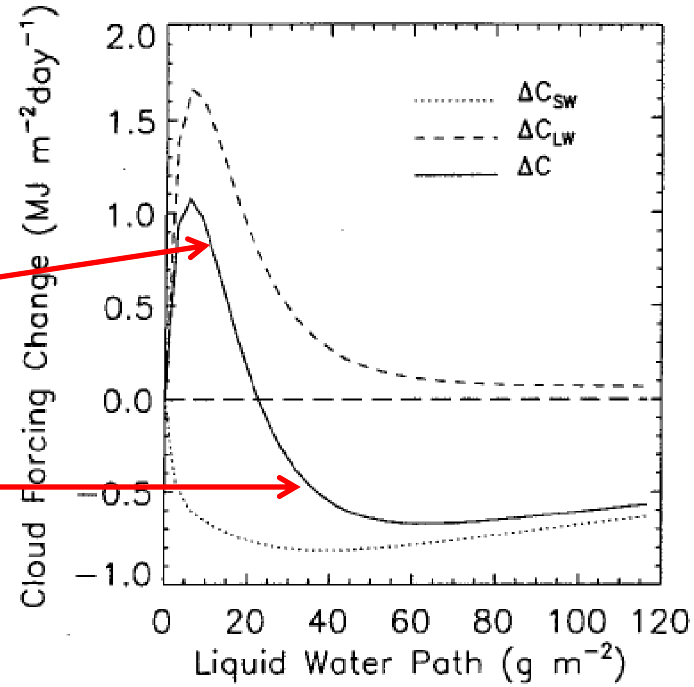
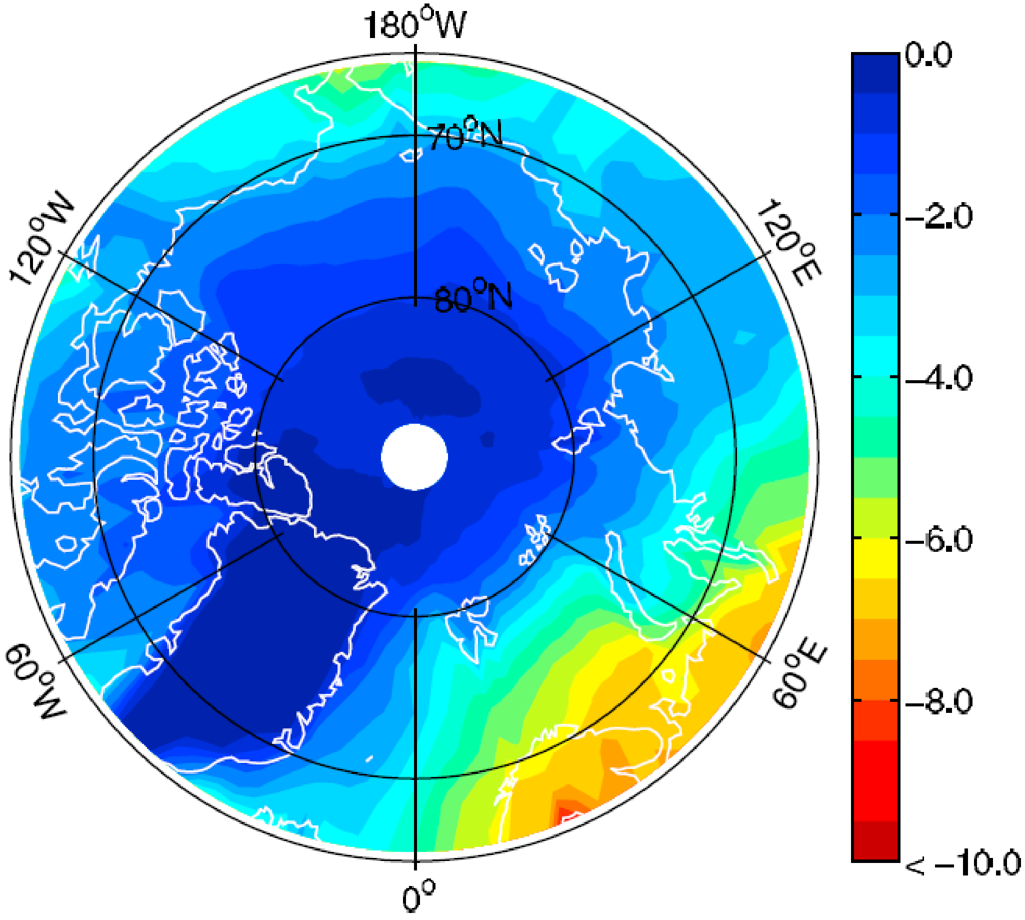


FIG. 3. Effect of changes in cloud liquid water path and equivalent radius on changes in the surface cloud–radiative forcing, where $\Delta C_{SW} = C_{SW}^{r_e=4\mu m} - C_{SW}^{r_e=11\mu m}$, $\Delta C_{LW} = C_{LW}^{r_e=4\mu m} - C_{LW}^{r_e=11\mu m}$, and $\Delta C = C^{r_e=4\mu m} - C^{r_e=11\mu m}$. The overall effect of the cloud equivalent radius on the cloud radiative forcing is positive when cloud liquid water path is small and negative when the cloud liquid water path is large. The crossover occurs at about 23 g m^{-2} for the current case.

Zhang et al. (1996: J. Climate)

JJA Net Indirect Effect at the Surface



Alterskjær, Kristjánsson, Hoose (2010: JGR)

Global Climate Model simulations

IMPLICC: EU FP7 project, 5 partners, coordinated at MPI-M,

http://implicc.zmaw.de, 2009-2012

Model tool

Norwegian Earth System Model (NorESM)

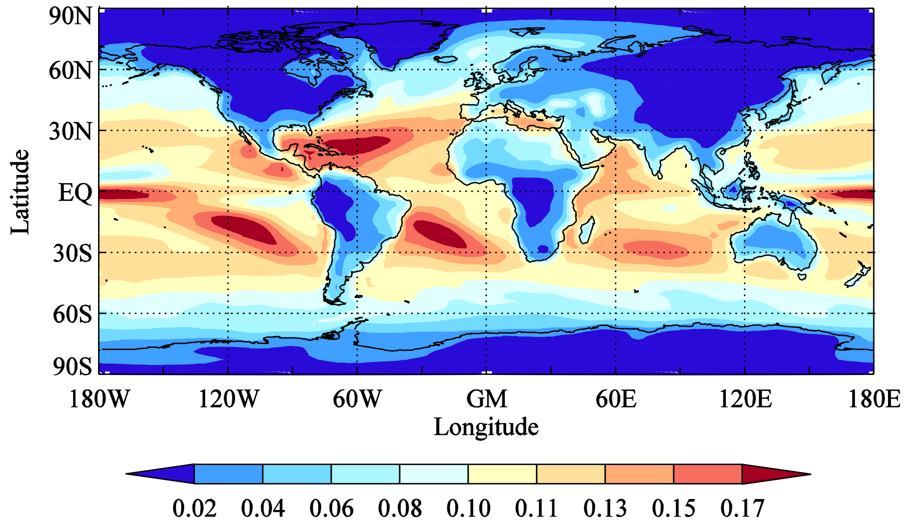
- Based on NCAR CAM4 + Oslo aerosols + MICOM
- **Five prognostic aerosol species**: SO_4, BC, OM, MD, SS (*Seland et al., 2008*)
- Prognostic cloud droplet number (Storelvmo et al., 2006; Hoose et al., 2009)
- **Cloud droplet activation** following Abdul-Razzak & Ghan (2000); **sub-grid scale vertical velocity** following Morrison & Gettelman (2008)

Sensitivity experiment

Uniform increase of 10^{-9} kg $m^{-2}s^{-1}$ (~350 tonnes s^{-1} globally) in the emissions of sea salt over ocean (93% increase of emitted sea salt mass):

- R-0.13: Dry modal radius of 0.13 µm

  Particle size suggested by Latham (*2002*)



Change in column integrated sea salt [g m^{-2}]

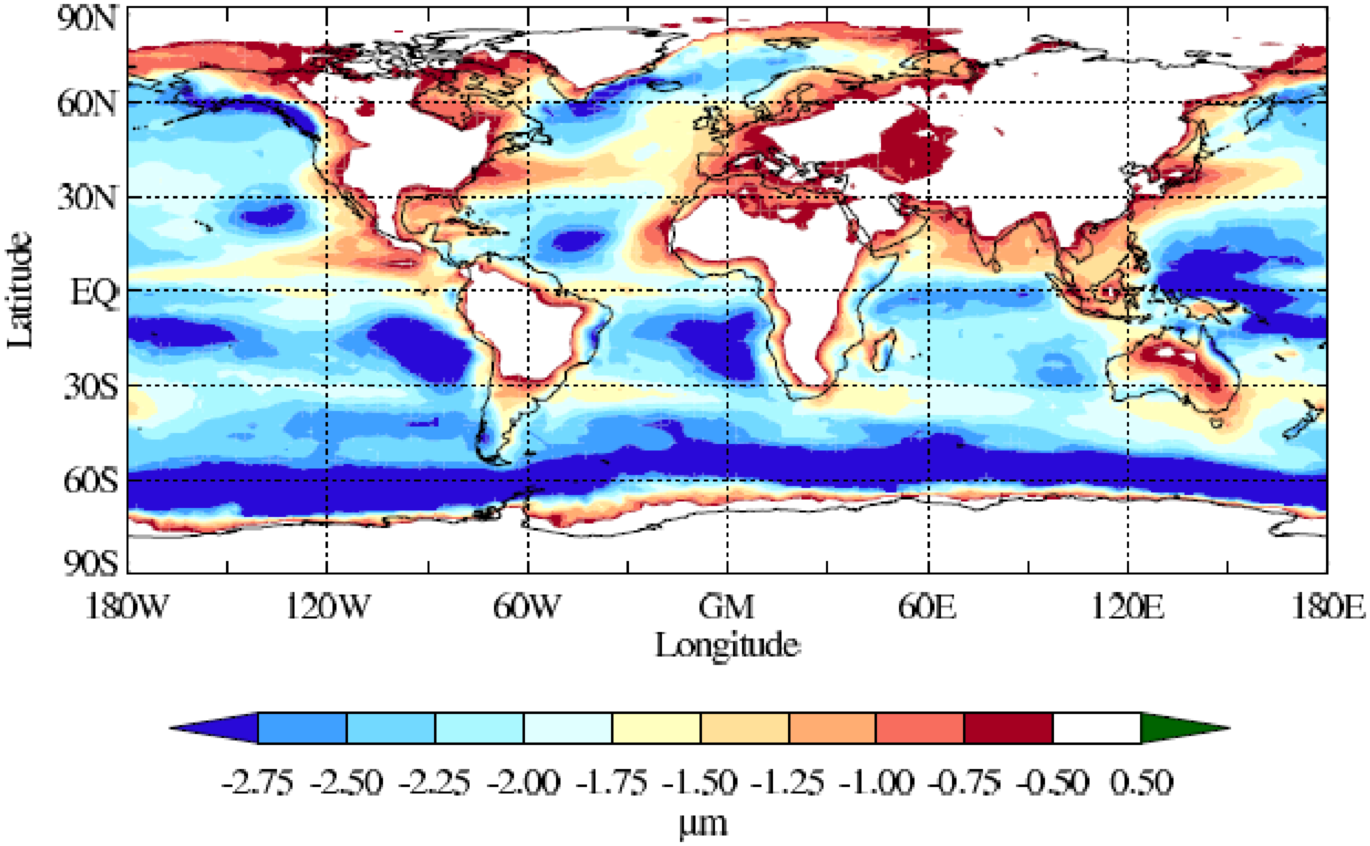
Comparison to earlier studies

The study differs from earlier studies (*Latham et al. 2008, Salter et al. 2008, Jones et al. 2009* and *Korhonen et al., 2010*):

- We add SS everywhere over open ocean *without any assumption on suitable regions*
- We use a model that **predicts cloud droplet nucleation** based on e.g. aerosol properties
- Each sea salt particle may be too small to be activated, the updraft velocities may be too weak, etc. Such limitations were ignored in most earlier studies

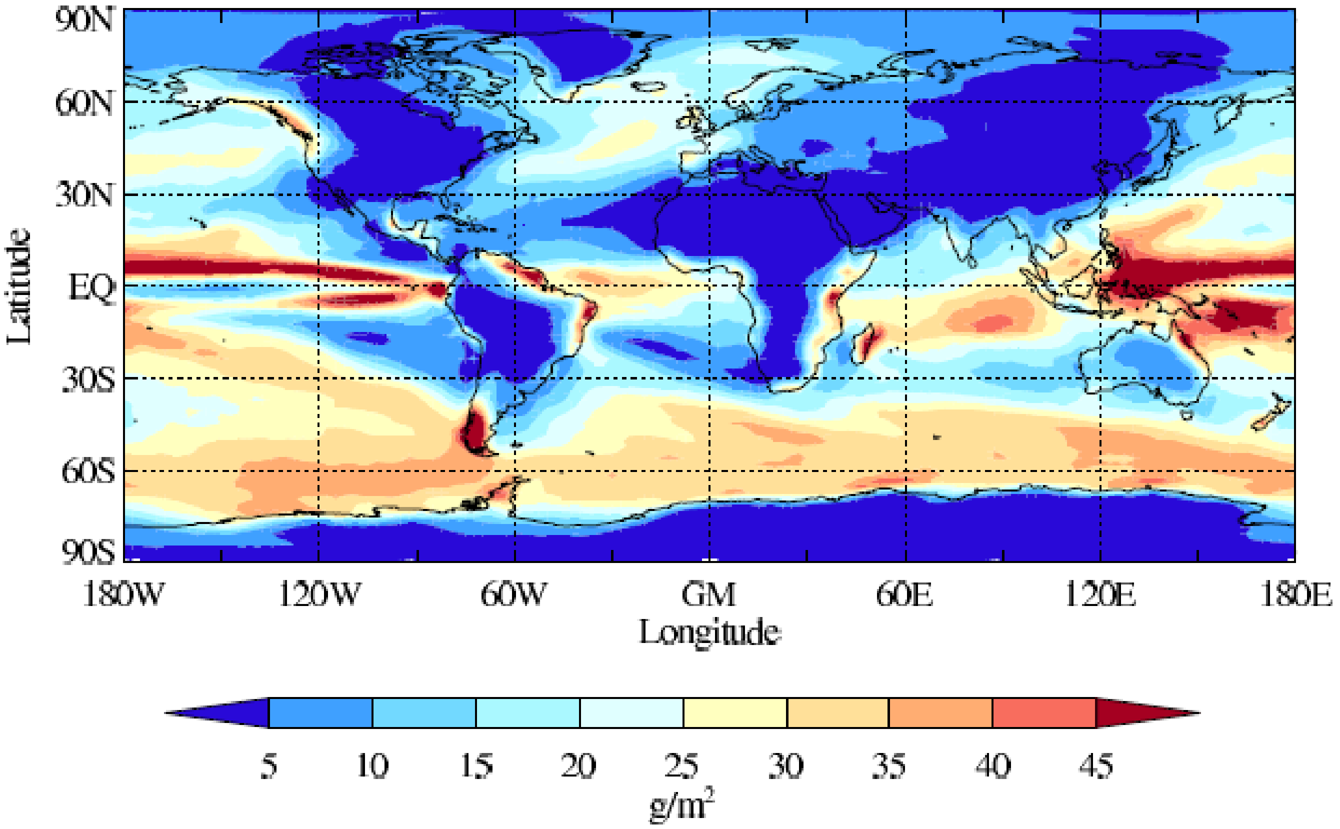
⟹ **We increase sea salt emissions rather than cloud droplet number itself**

Changes in cloud droplet size



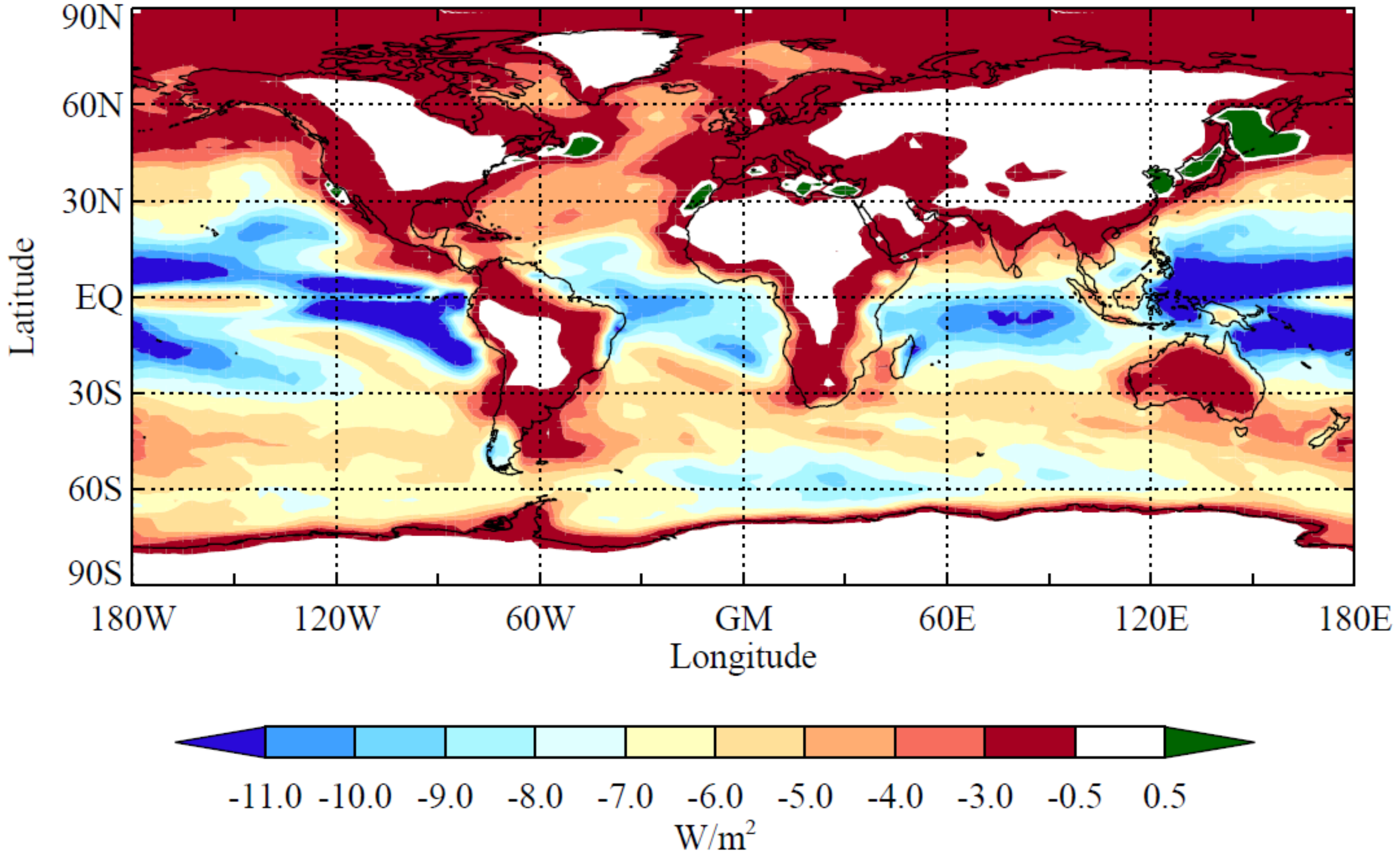
Alterskjær, Kristjánsson, Seland (2011: ACPD, in press)

Changes in cloud liquid water path



Alterskjær, Kristjánsson, Seland (2011: ACPD, in press)

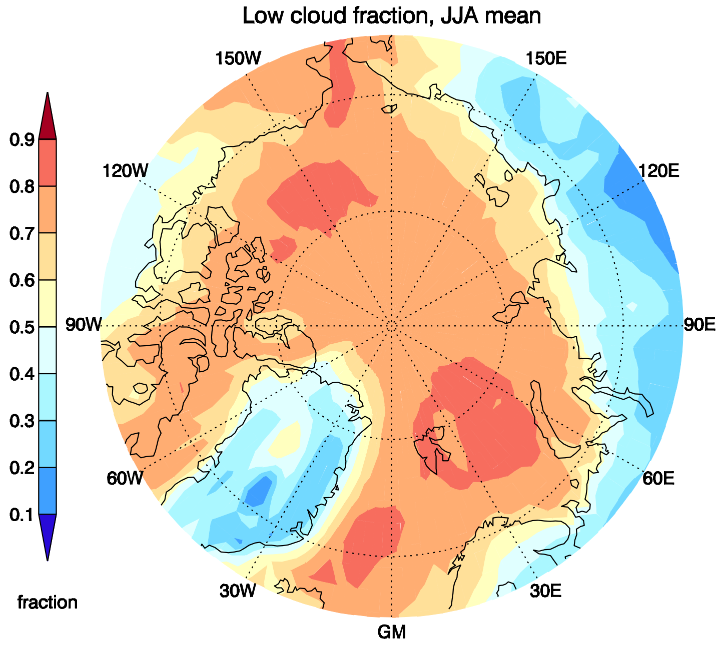
Radiative Forcing: - 4.8 W m^{-2} (compared to +3.74 for CO_2 doubling)



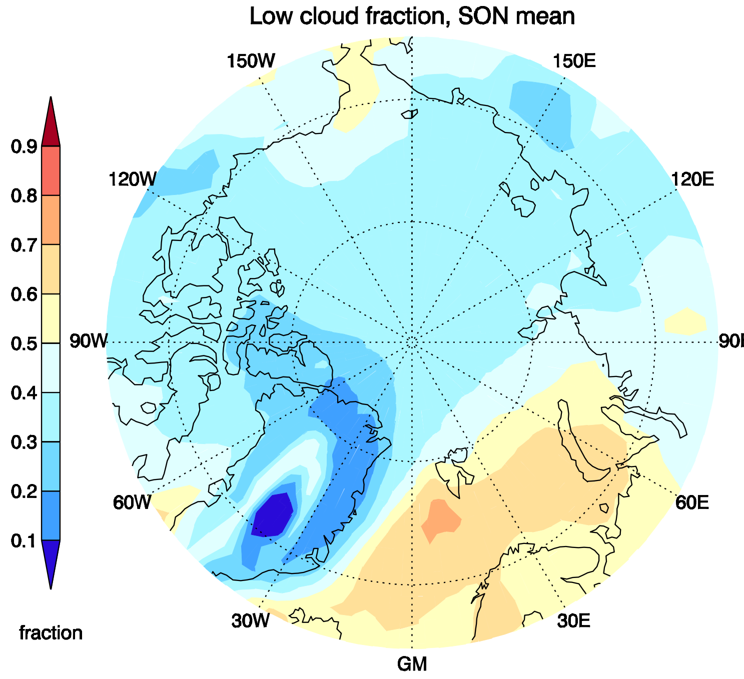
Alterskjær, Kristjánsson, Seland (2011: ACPD, in press)

Low Cloud Cover

June-July-August

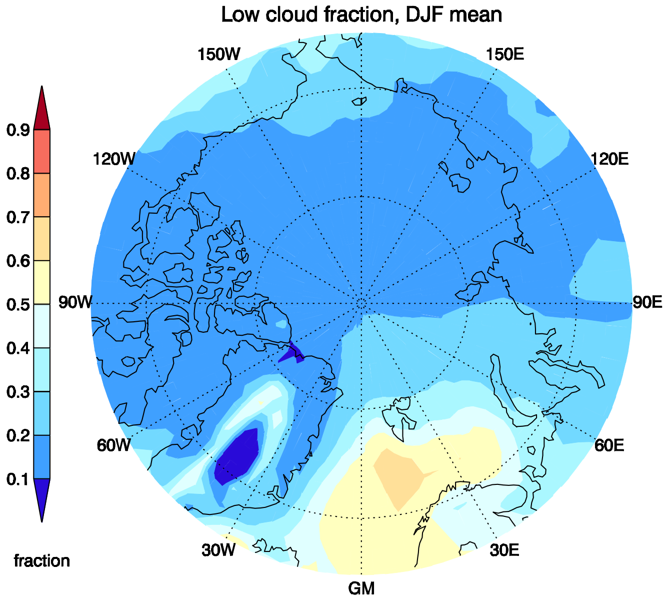


Sep – Oct – Nov

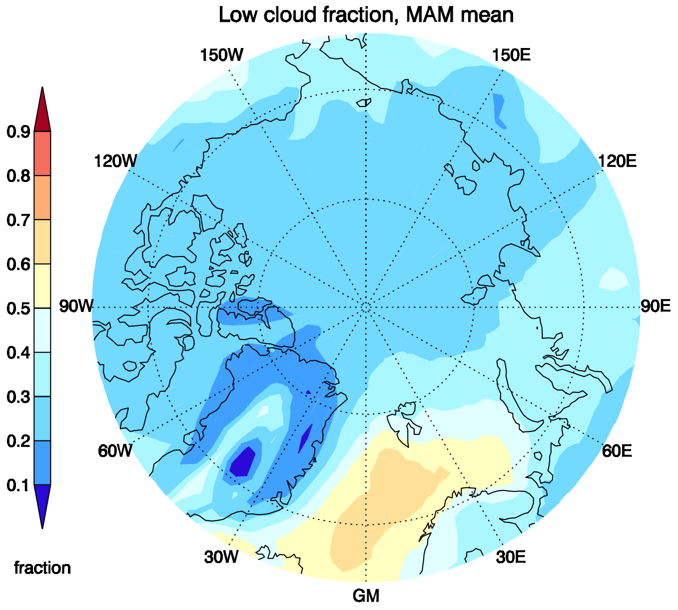


Low Cloud Cover

Dec-Jan-Feb

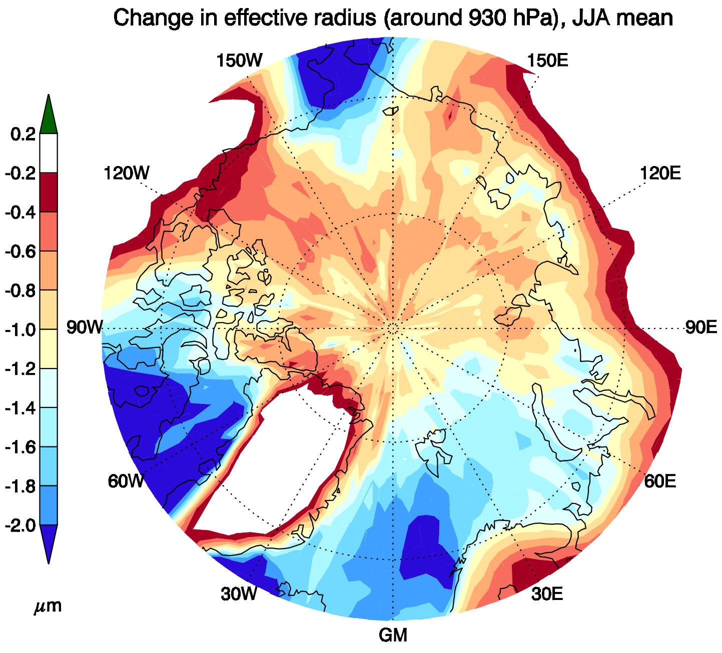


Mar-Apr-May



Change in Cloud Droplet Size

June-July-August



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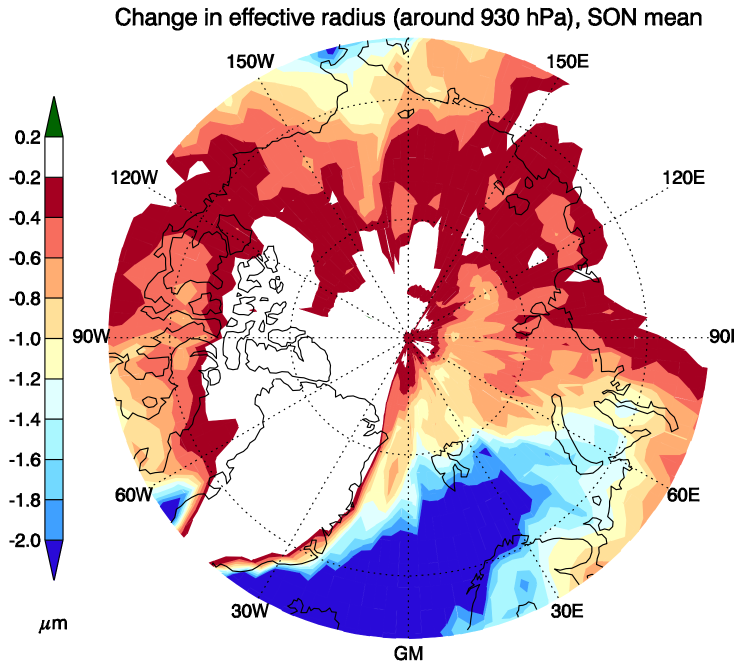
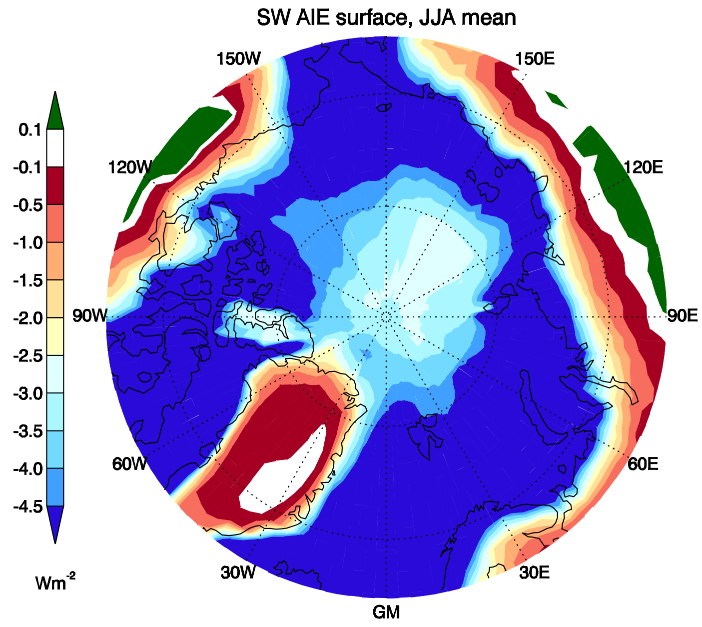
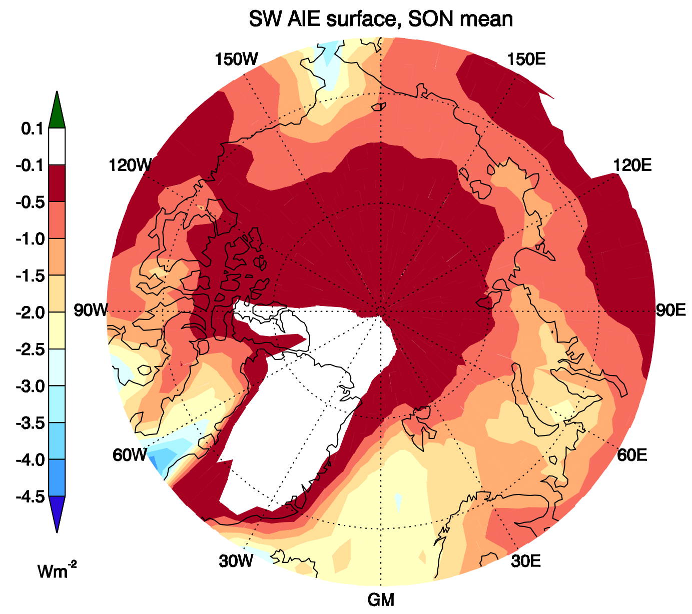


Surface Change in SW Cloud Rad. Forcing

June-July-August

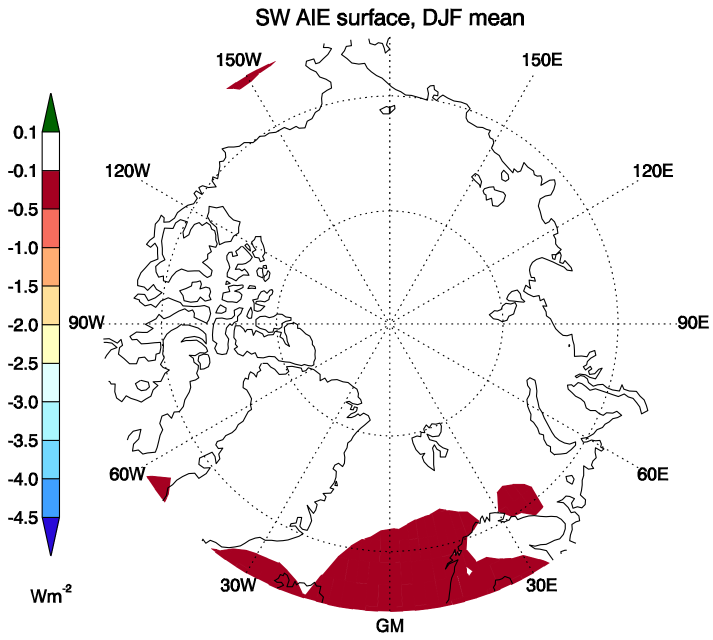


Sep – Oct – Nov

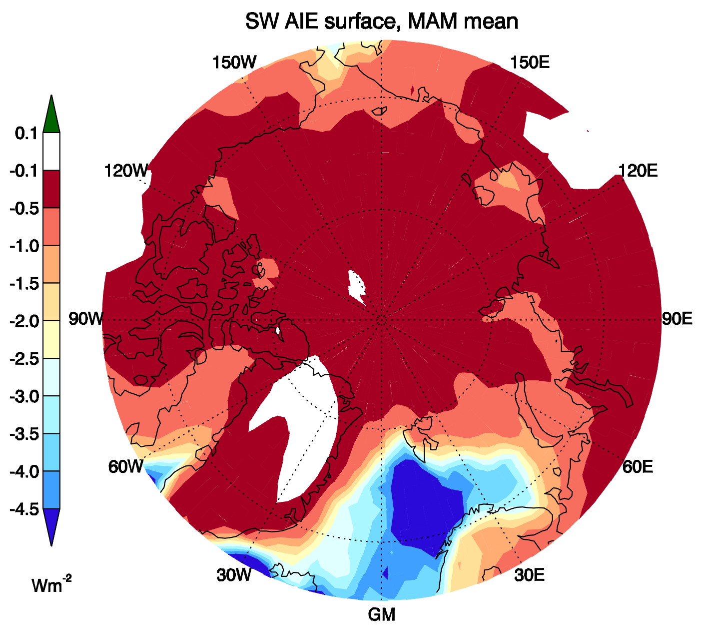


Surface Change in Cloud Rad. Forcing

Dec-Jan-Feb

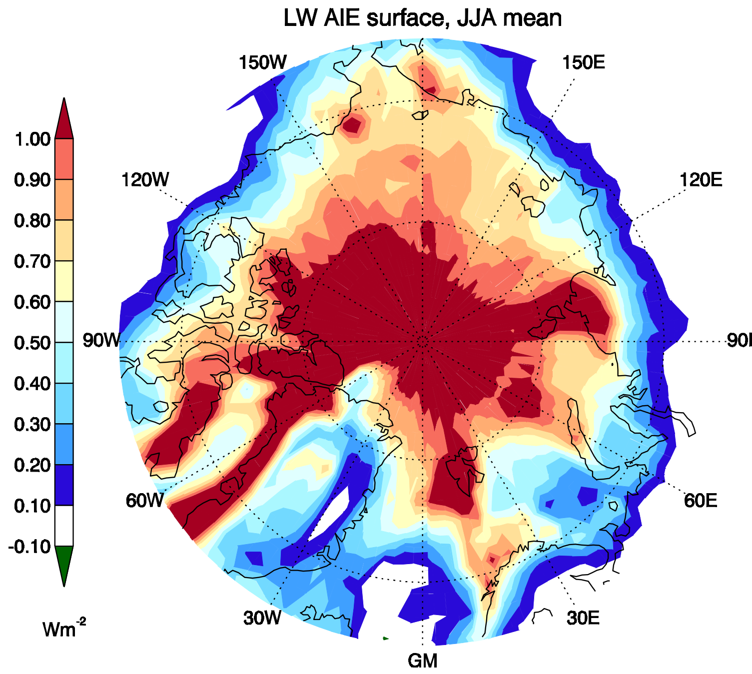


Mar-Apr-May

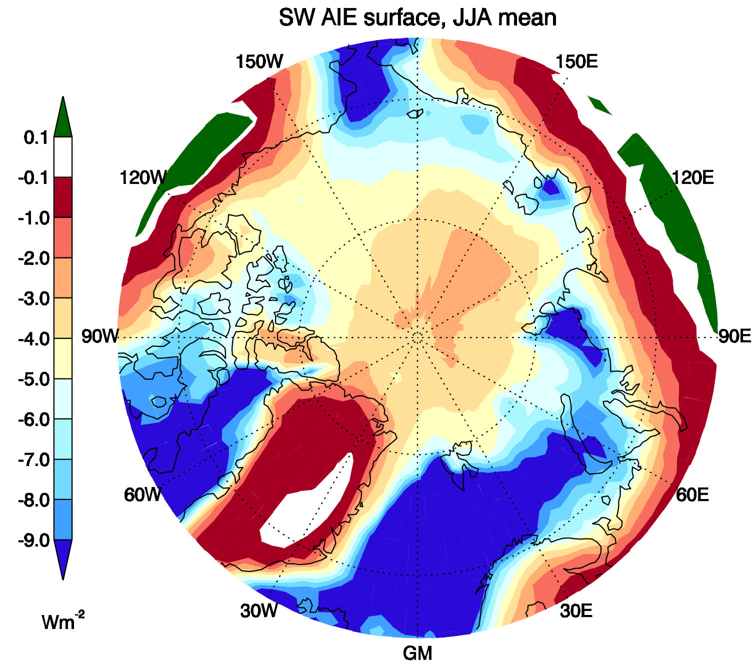


JJA Surface Change in Cloud Radiative Forcing

LW



SW



Note different scales!

Summary and Conclusions

- Geo-engineering of **cirrus clouds** appealing because it operates on thermal-IR radiation directly – but, it has yet to be subjected to comprehensive climate model testing
- Geo-engineering of **marine low clouds** seems promising globally – but there may be side effects
- Geo-engineering of **marine low clouds** might work in the **Arctic** during the **summer**, but thin stratus clouds also have a significant LW component


Thank you!
http://folk.uio.no/jegill