Arctic Aerosols: Interactions with Clouds and Radiation

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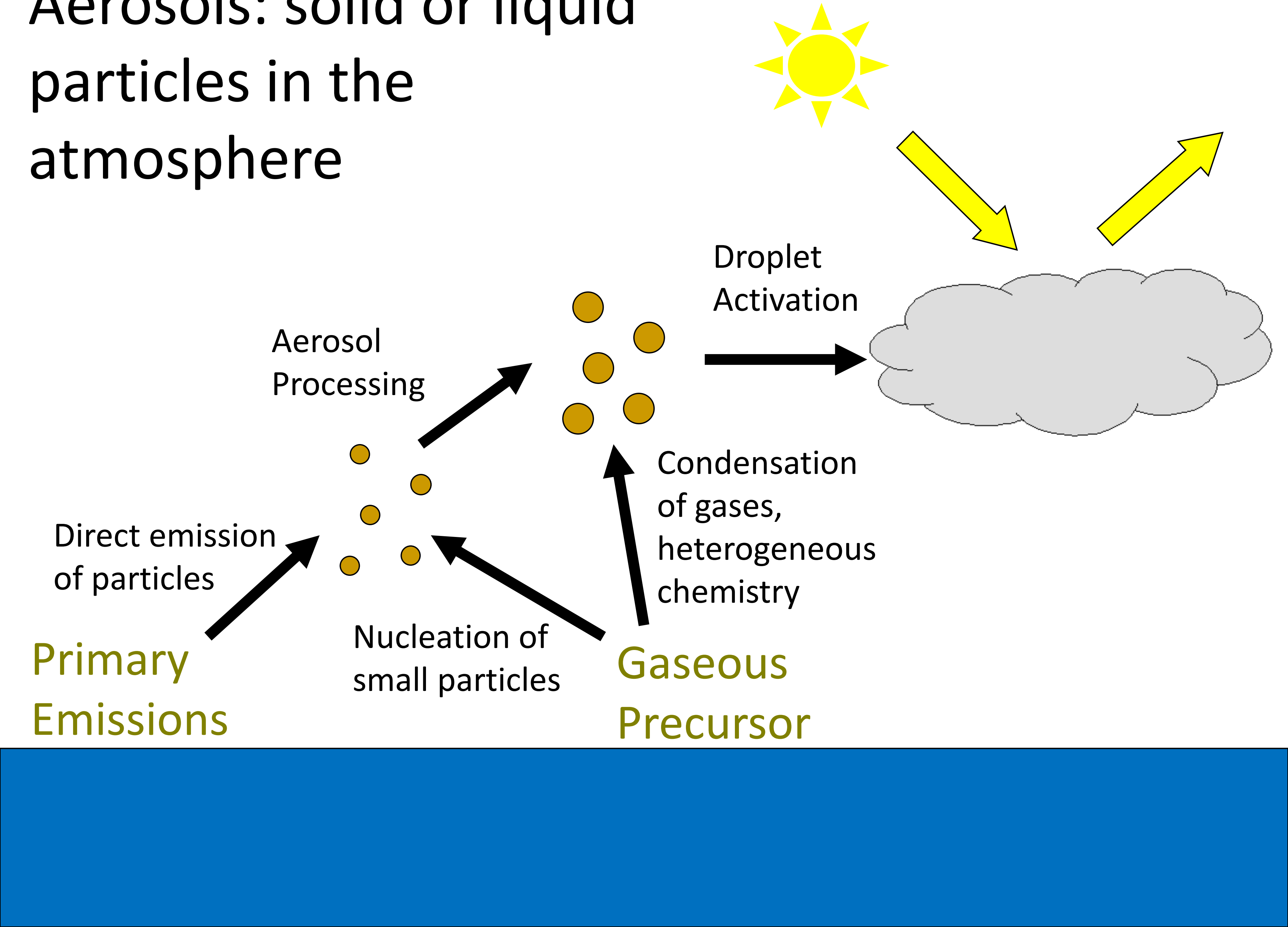
Aerosols: solid or liquid particles in the atmosphere



Droplet Activation

Aerosol Processing

Condensation of gases, heterogeneous chemistry

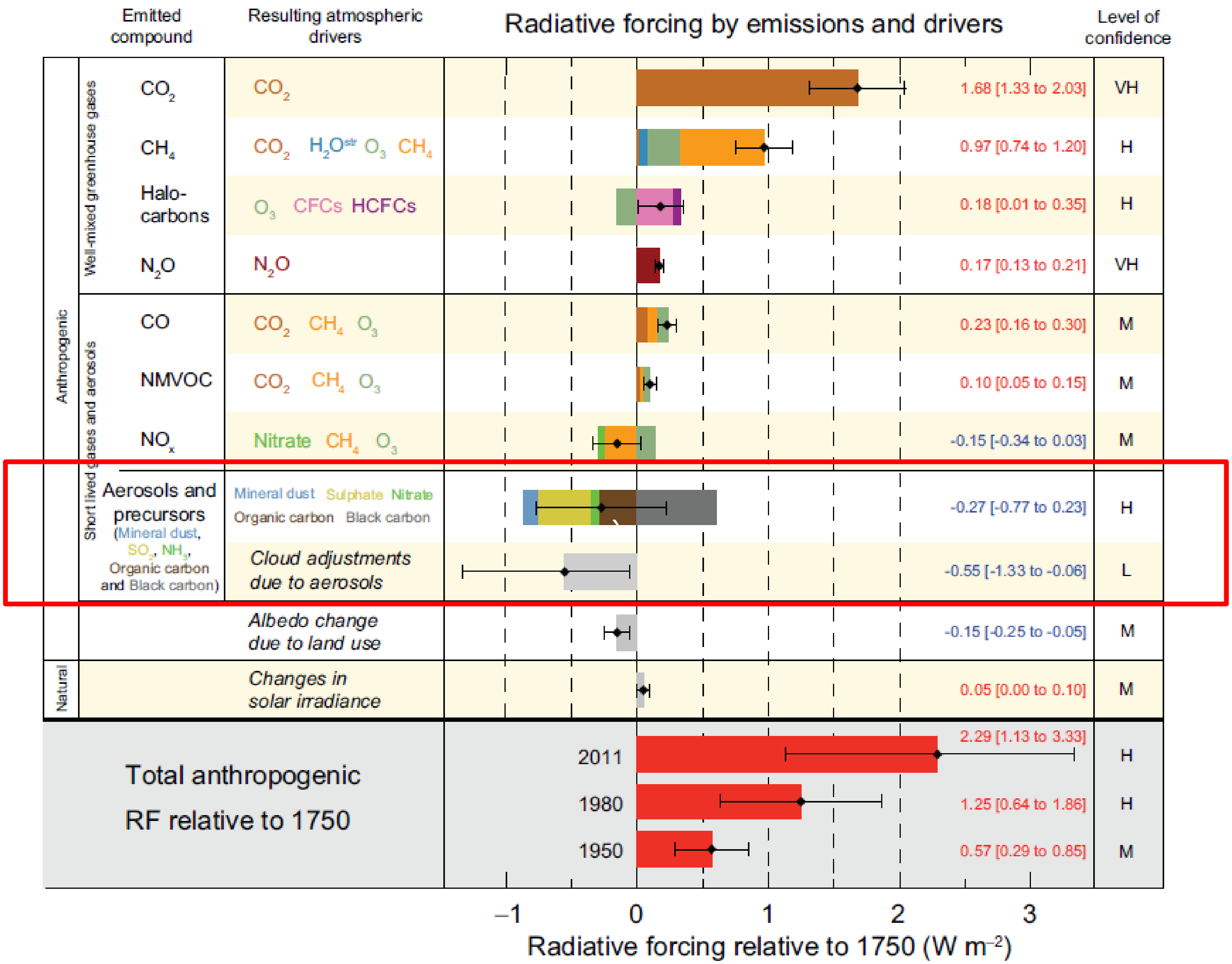
Direct emission of particles

Nucleation of small particles

Primary Emissions

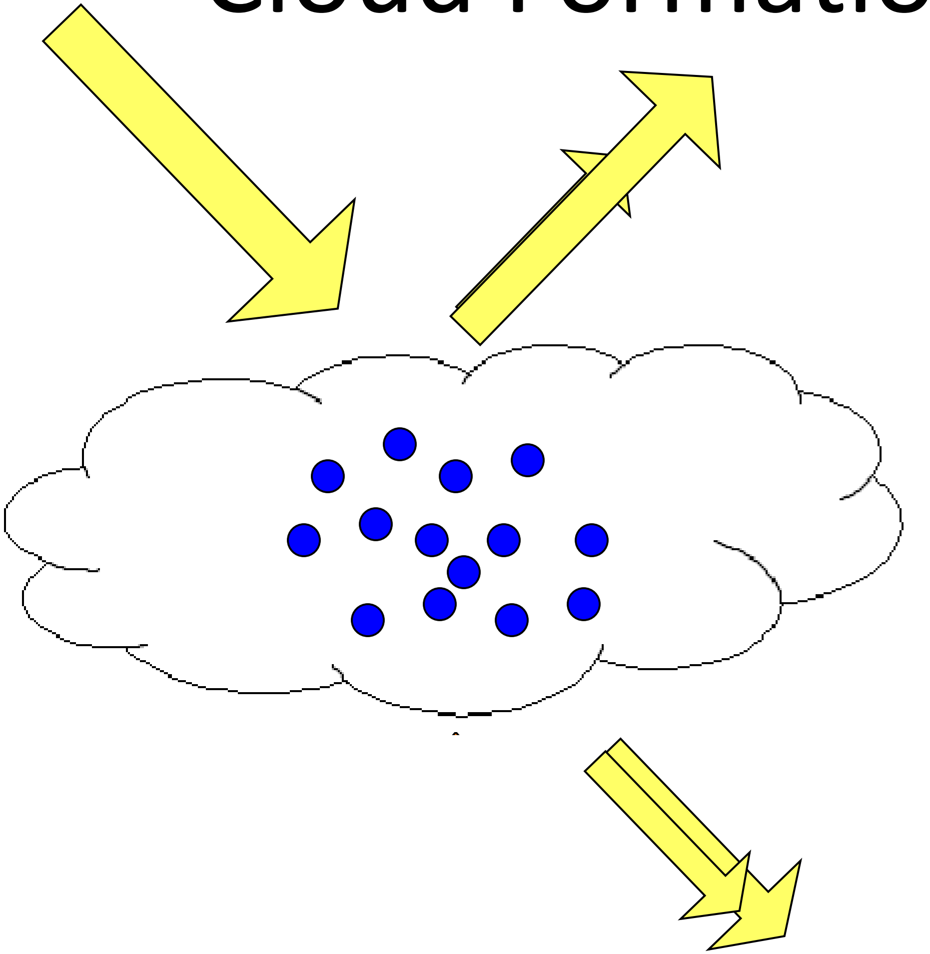
Gaseous Precursor

Uncertainties Due to Aerosols

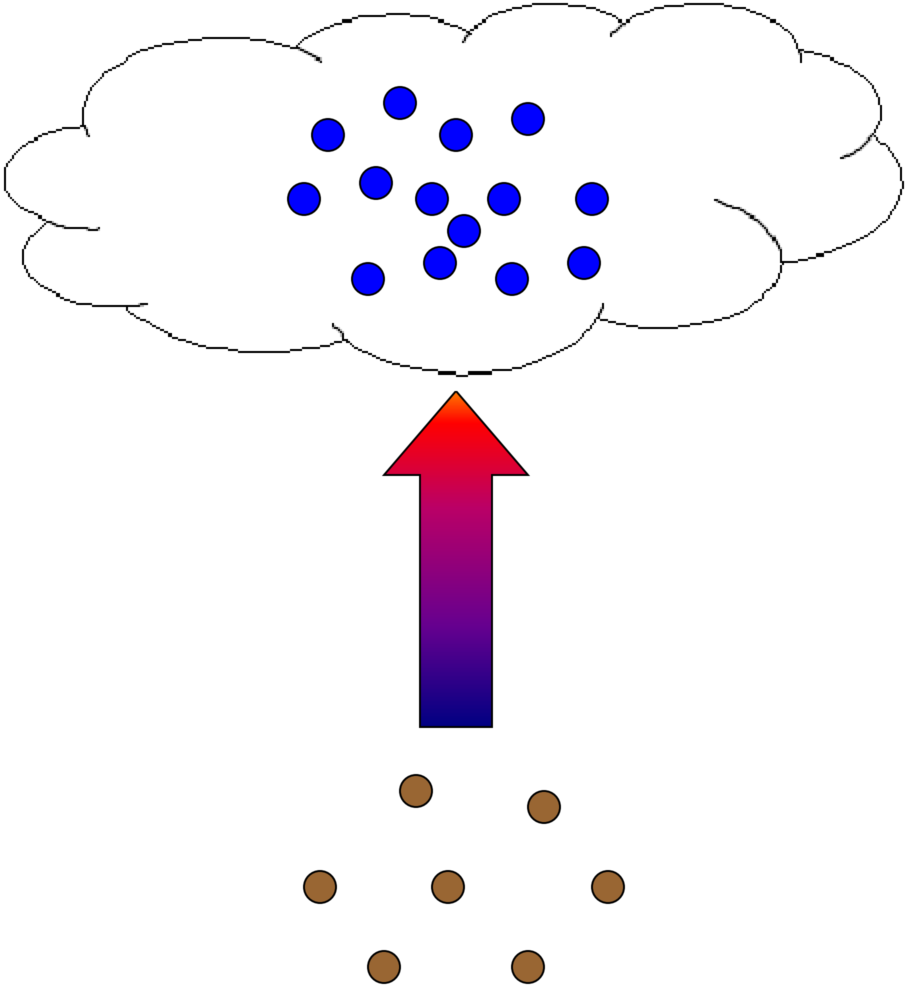


IPCC AR5, 2013

Cloud Formation



Cloud Formation



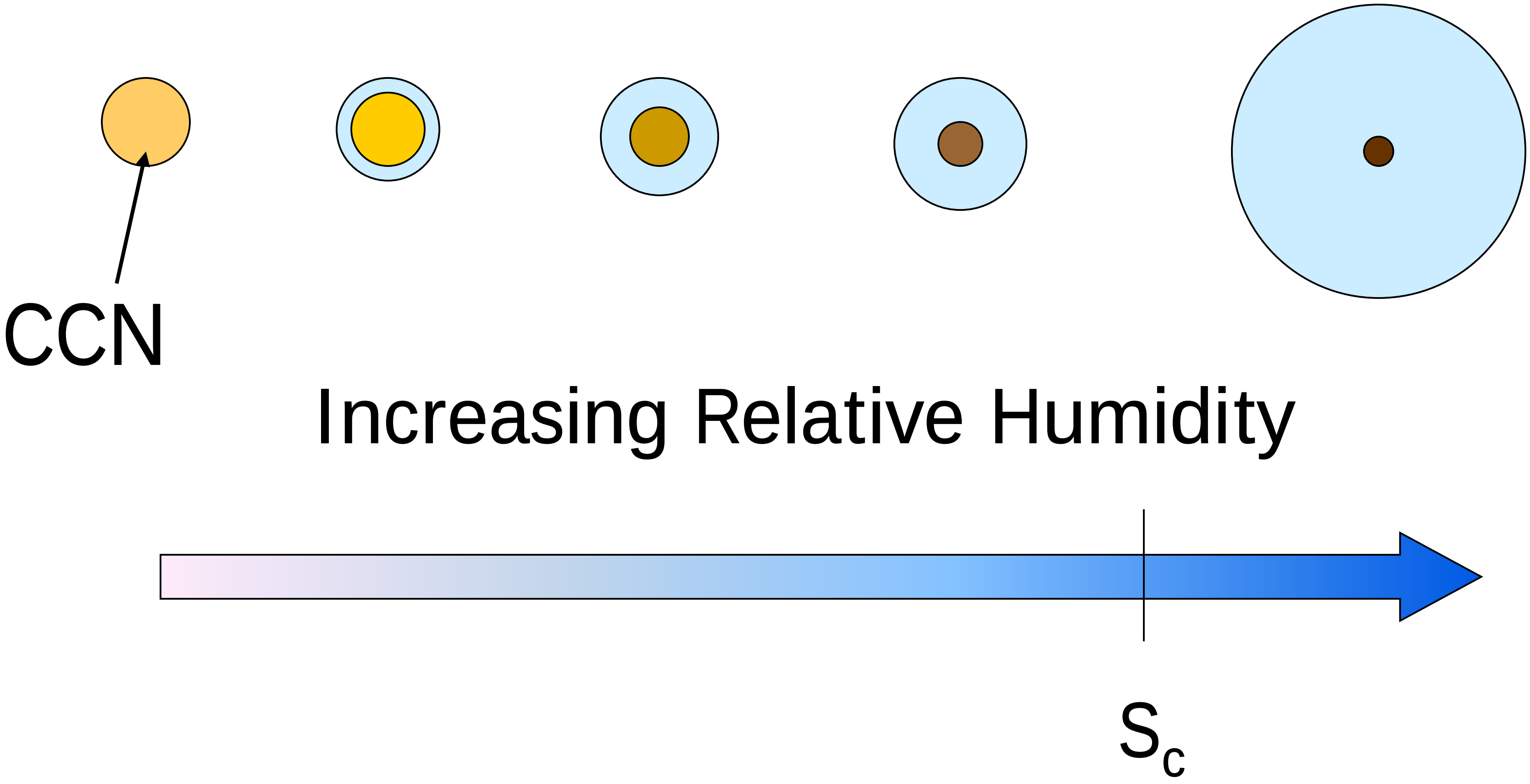
Supersaturation (S)

$$S = \left(\frac{P_{H_2O}}{P^{vap}} - 1 \right) \times 100\%$$

Critical Supersaturation (S_c)

The supersaturation at which a particle will spontaneously activate

Droplet Activation



CCN

Increasing Relative Humidity

S_c

Köhler Equation

$$S = \boxed{\frac{4M_w\sigma_w}{RT\rho_w}\frac{1}{D}} - \boxed{\frac{M_w}{\rho_w}\frac{n_{sol}}{V_{shell}}}$$

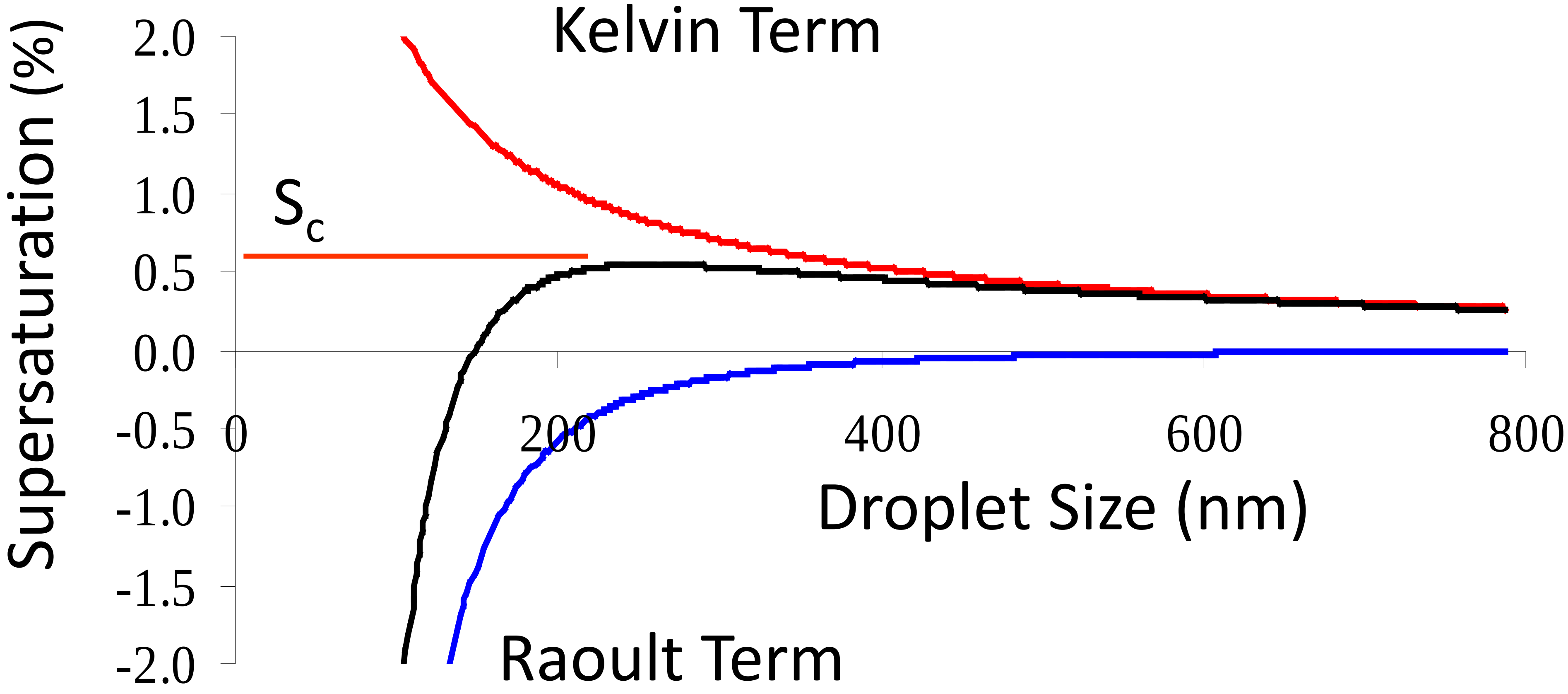
Kelvin Term

curvature increases vapour pressure

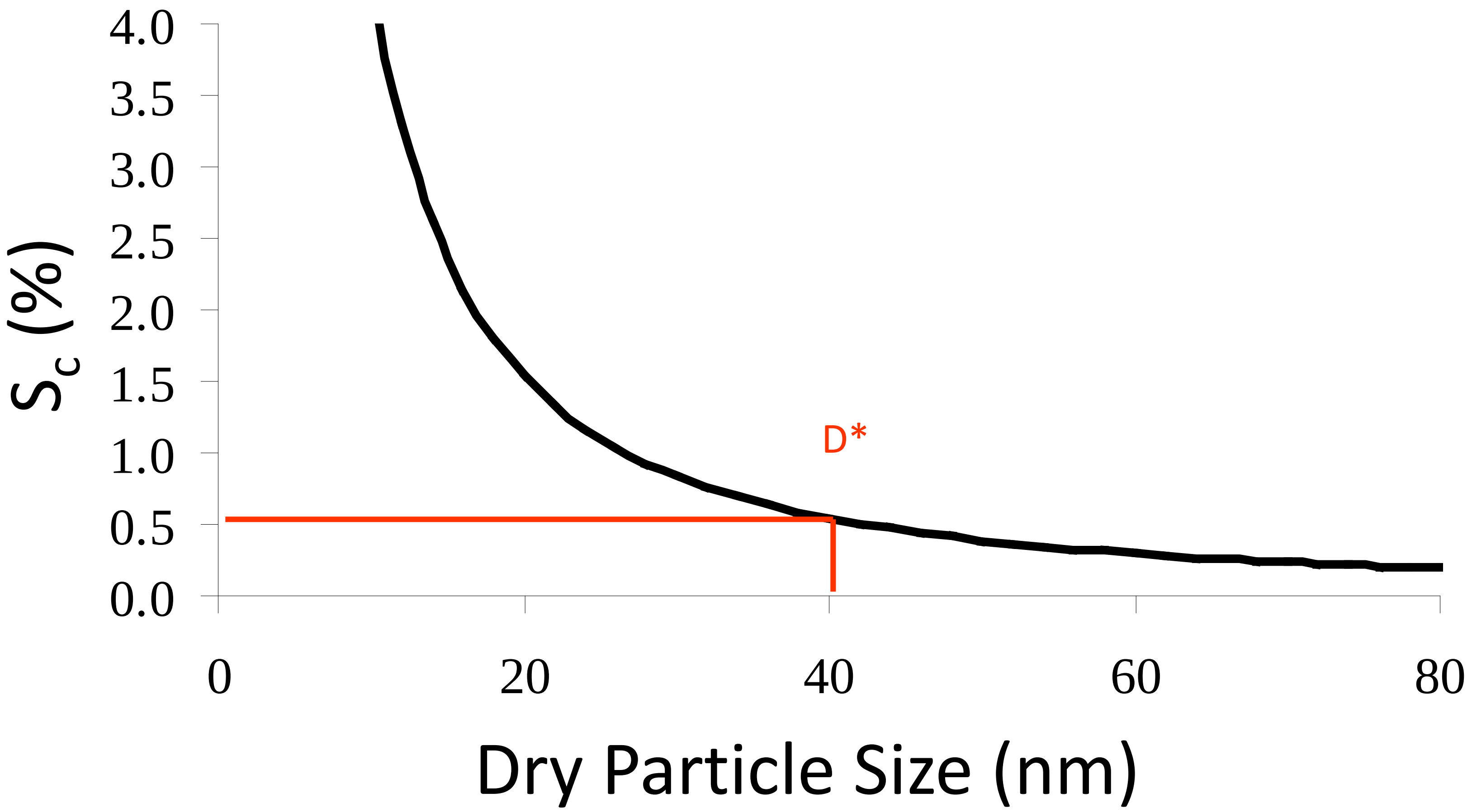
Raoult Term

solutes decrease vapour pressure

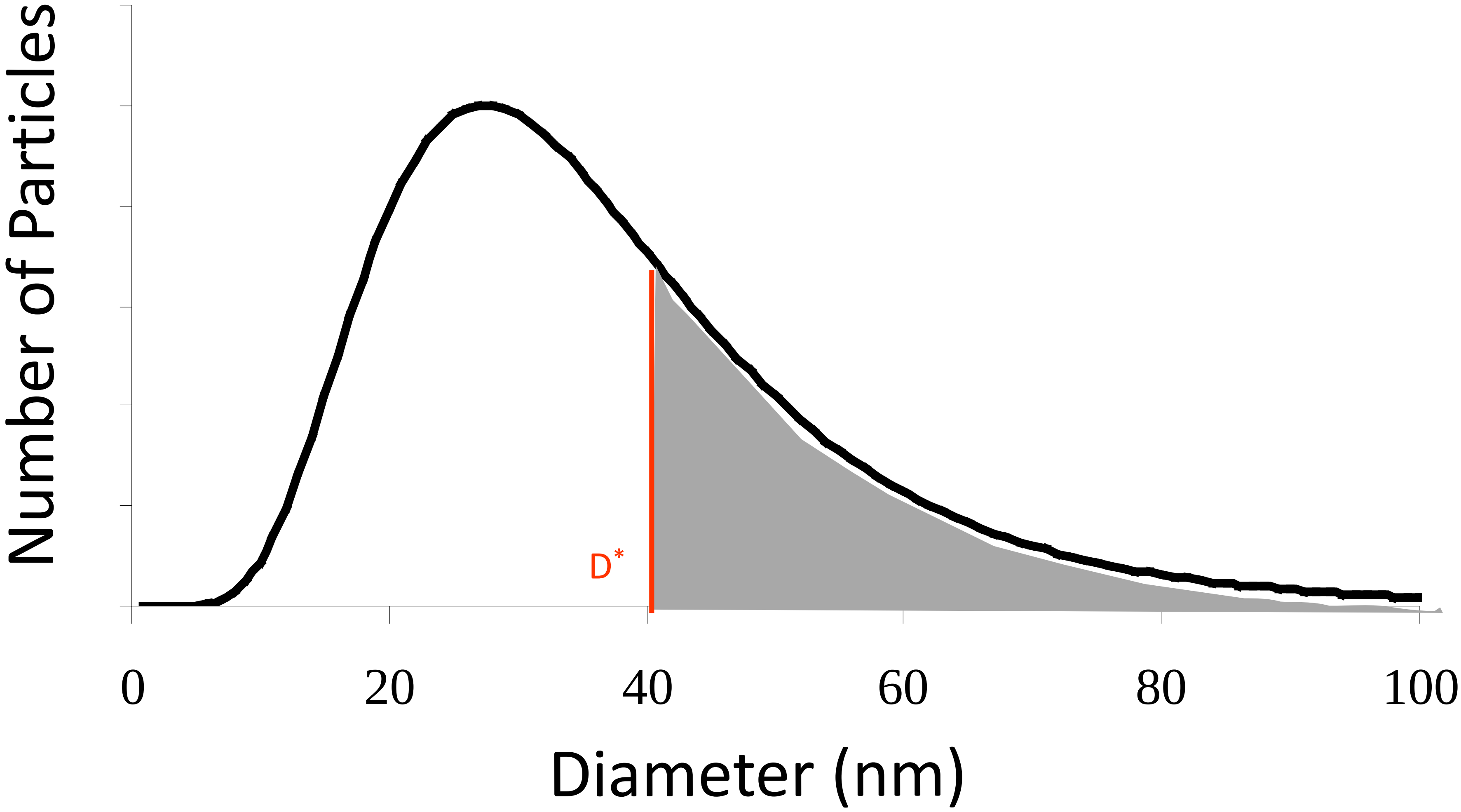
Köhler Curve



Critical Supersaturation and Activation Diameter



Predicted CCN from Size Distribution Data



Background – Köhler Theory

The activation of well-characterized inorganic and organic aerosol can be predicted using Köhler theory.

$$S(D) = \left(1 - \frac{M_w D_d^3}{\rho_w D^3} \sum \frac{\nu_{sol} \phi_{sol} \rho_{sol} \varepsilon_{sol}}{M_{sol}}\right) \exp\left(\frac{4\sigma M_w}{\rho_w RTD}\right)$$

Problem

Ambient aerosol are composed of numerous compounds, especially the organic component.

Simplifying the Köhler Equation

$$S(D) = \left(1 - \frac{M_w D_d^3}{\rho_w D^3} \sum \boxed{\frac{\nu_{sol}\phi_{sol}\rho_{sol}\varepsilon_{sol}}{M_{sol}}}\right) \exp\left(\frac{4\sigma M_w}{\rho_w RTD}\right)$$

Kappa Approach

Petters and Kreidenweis. **2007** *Atmos. Chem. Phys.* 7, 1961

Kappa Approach

- a single hygroscopic parameter (κ) that incorporates
  - solute molecular weight
  - solute density
  - solute non-idealities

$$\kappa_{tot} = \varepsilon_1 \kappa_1 + \varepsilon_2 \kappa_2 + \varepsilon_3 \kappa_3 + \cdots$$

$$\boxed{S(D) = \frac{D^3 - D_d^3}{D^3 - D_d^3(1-\kappa)} \exp\left(\frac{4\sigma M_w}{\rho_w RTD} \right)}$$

Petters and Kreidenweis. **2007** *Atmos. Chem. Phys.* 7, 1961

Kappa Approach

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Ammonium Sulphate	Pinic Acid	Hexadecane
0.61	0.25	<0.00002

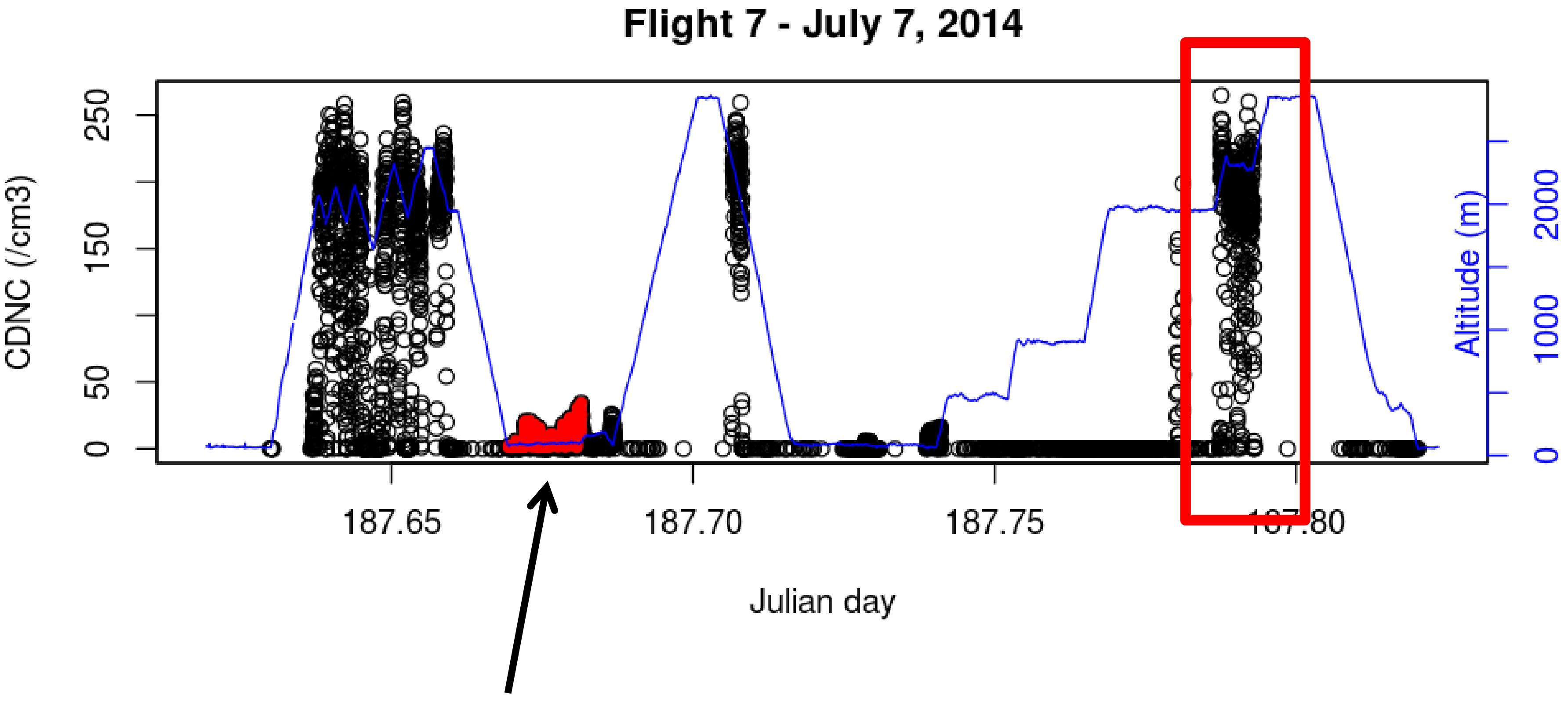
Petters and Kreidenweis. **2007** *Atmos. Chem. Phys.* 7, 1961

Hygroscopicity Parameter of Arctic Aerosol

- Central Arctic, ASCOS: 0.3 – 0.5
  - Martin et al. **2011**, *Atmos Chem Phys*

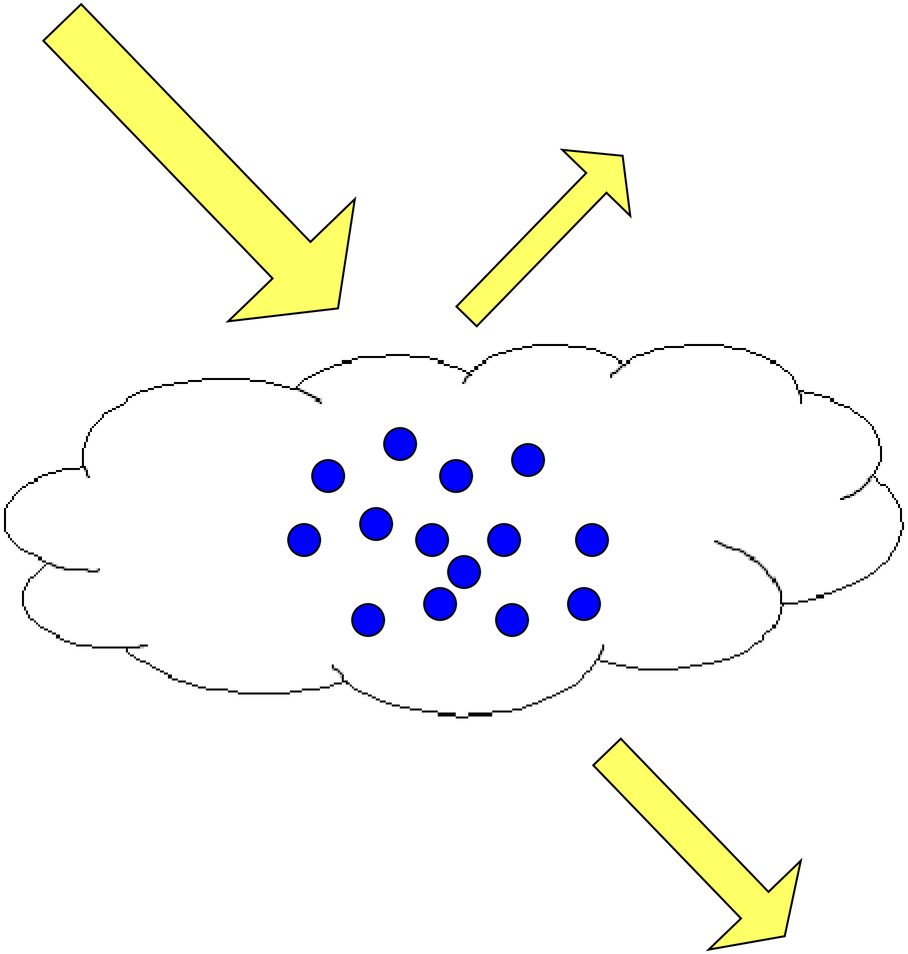
- Canadian Arctic, NETCARE 2014: 0.076
  - Willis et al. **2016**, *Atmos Chem Phys*

Simulating Clouds from NETCARE 2014 Using an Adiabatic Parcel Model

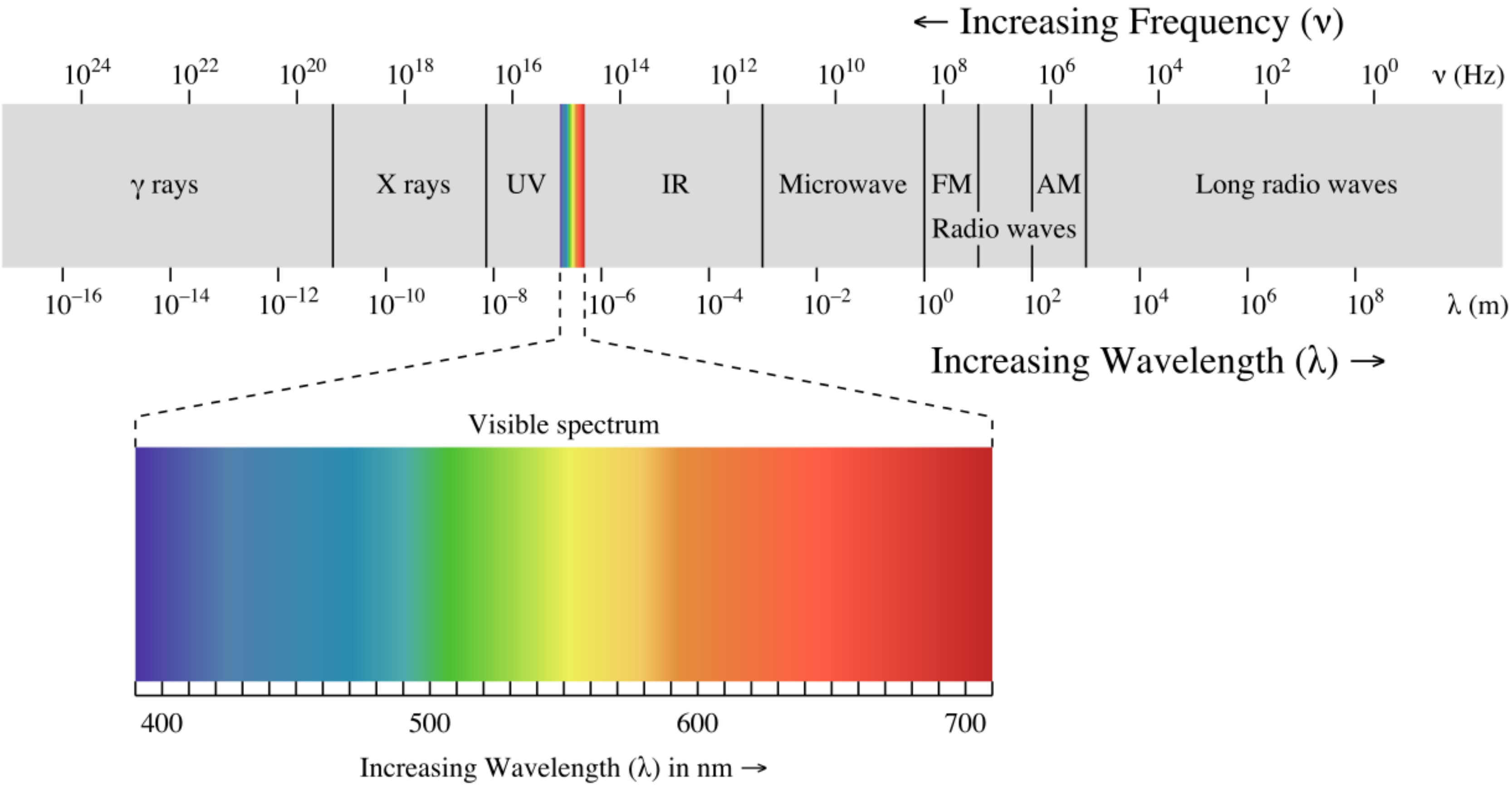


J. Dionne’s Poster

Aerosol and Cloud Scattering

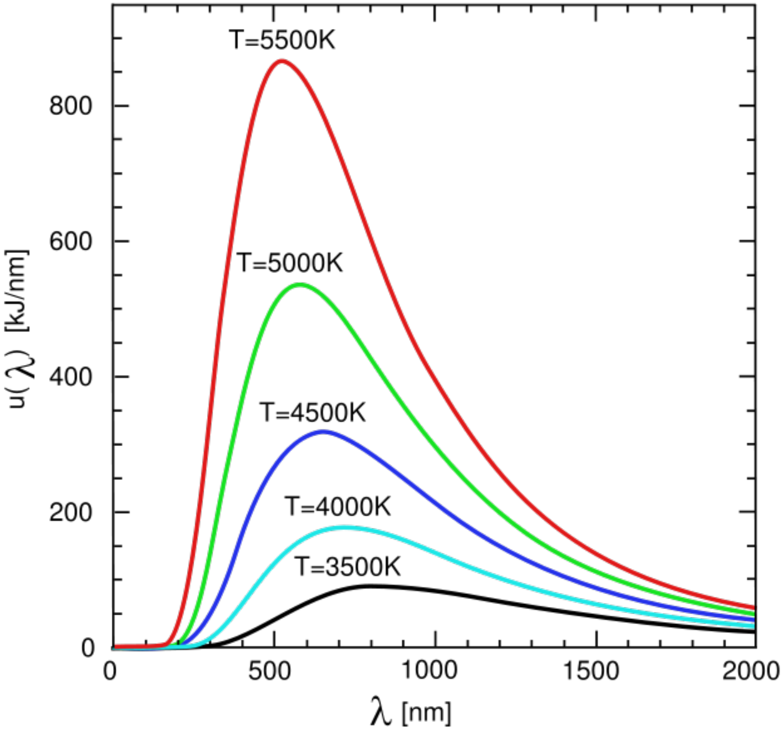


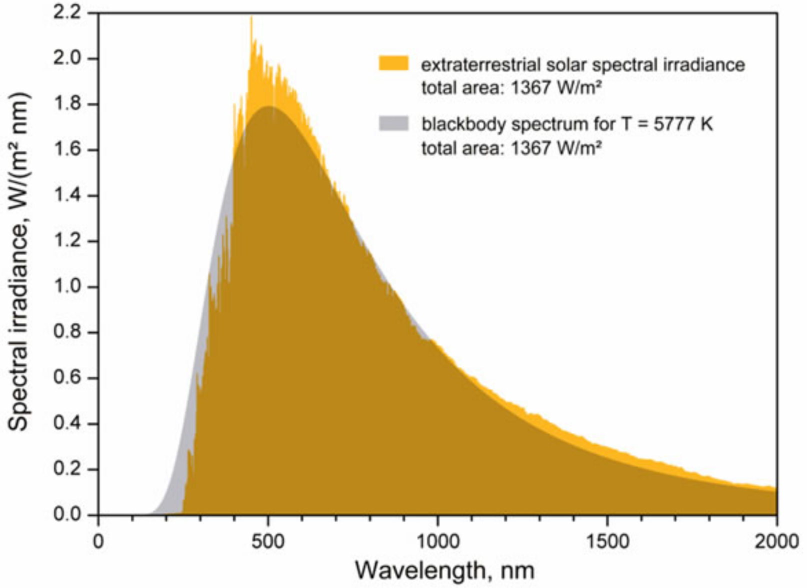
Electromagnetic Spectrum

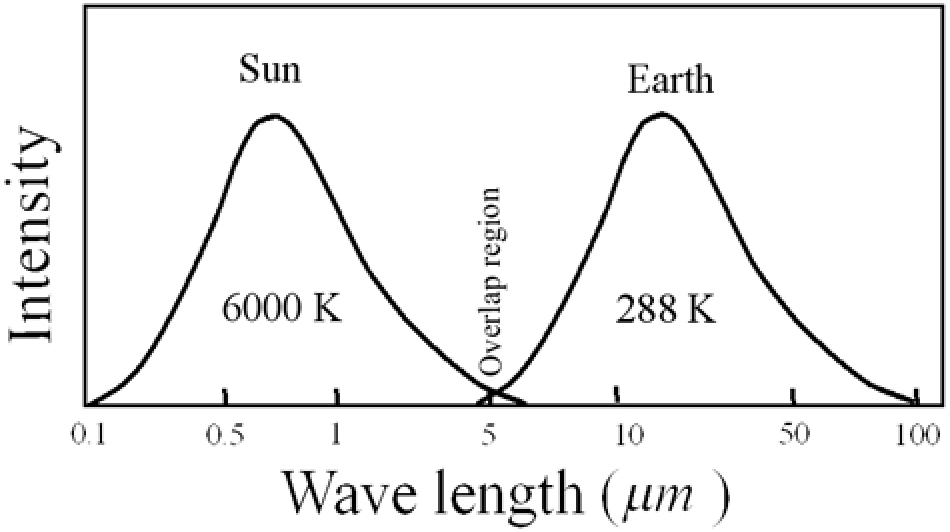


https://commons.wikimedia.org/wiki/File:EM_spectrum.svg

Blackbody Radiation





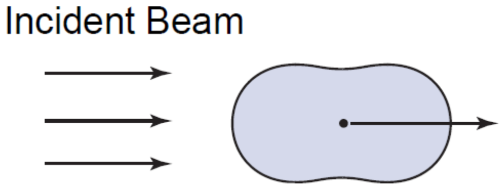


Size Parameter

$$\alpha = \frac{2\pi r}{\lambda}$$

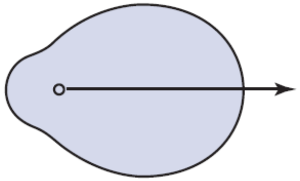
$\alpha \ll 0.2$

Rayleigh Scattering



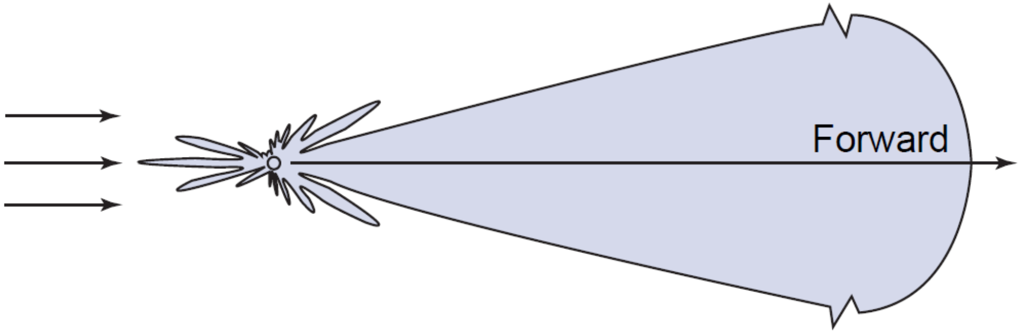
$0.2 \ll \alpha \ll 2000$

Mie Scattering



$2000 \ll \alpha$

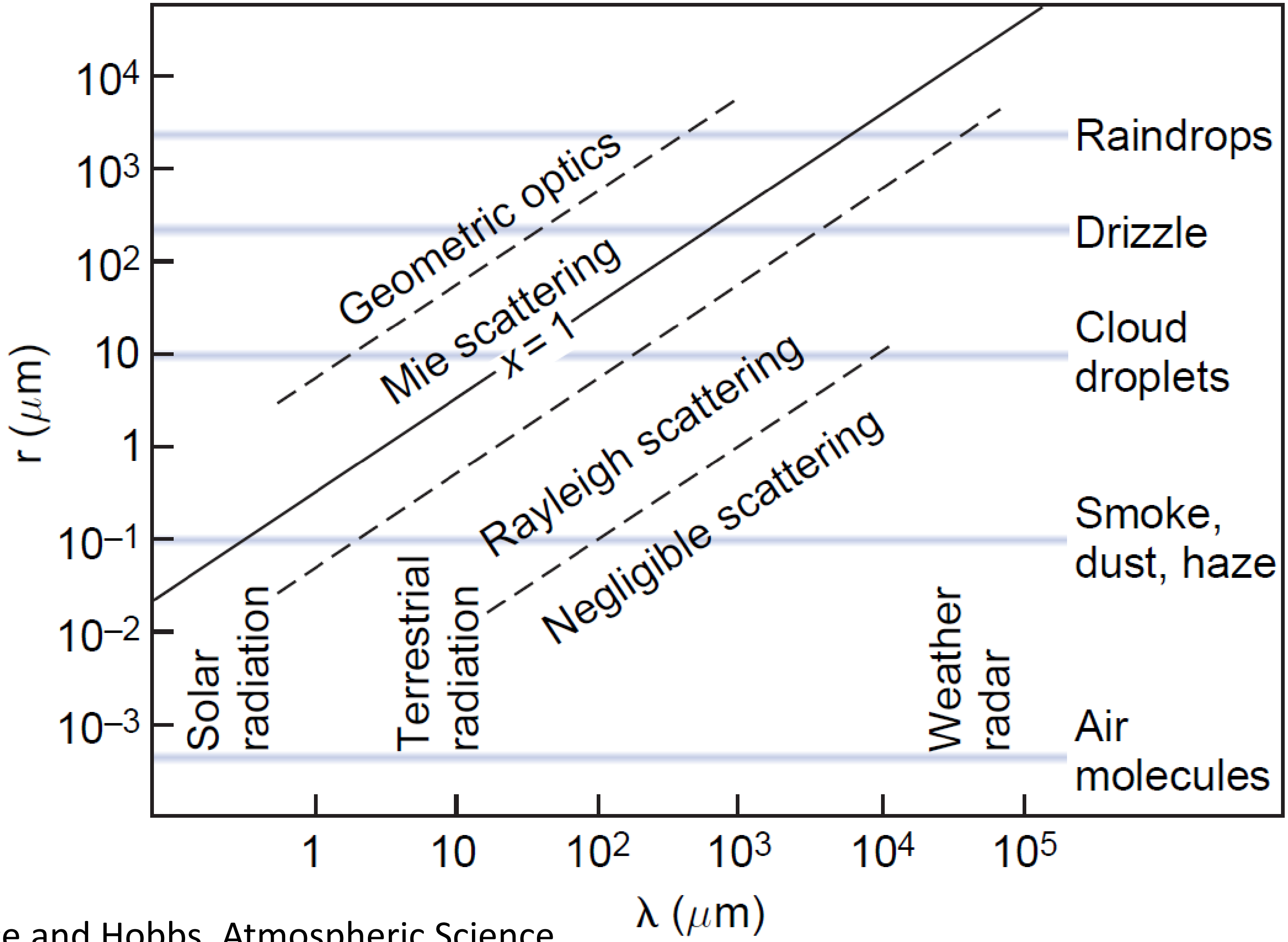
Geometric Optics



Wallace and Hobbs, Atmospheric Science

Scattering

Scattering Regimes



Wallace and Hobbs, Atmospheric Science

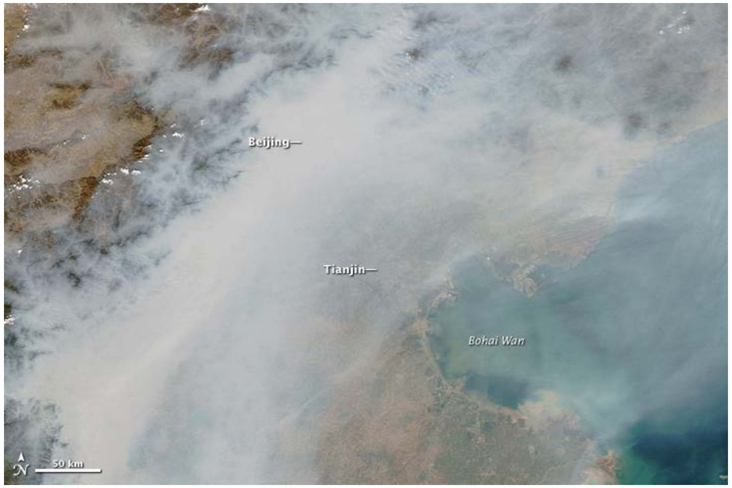
Absorbing Aerosols at the Surface

BC on snow & sea ice: +0.13 W/m^2
Bond et al. **2013**, *JGR*, 118, 5380

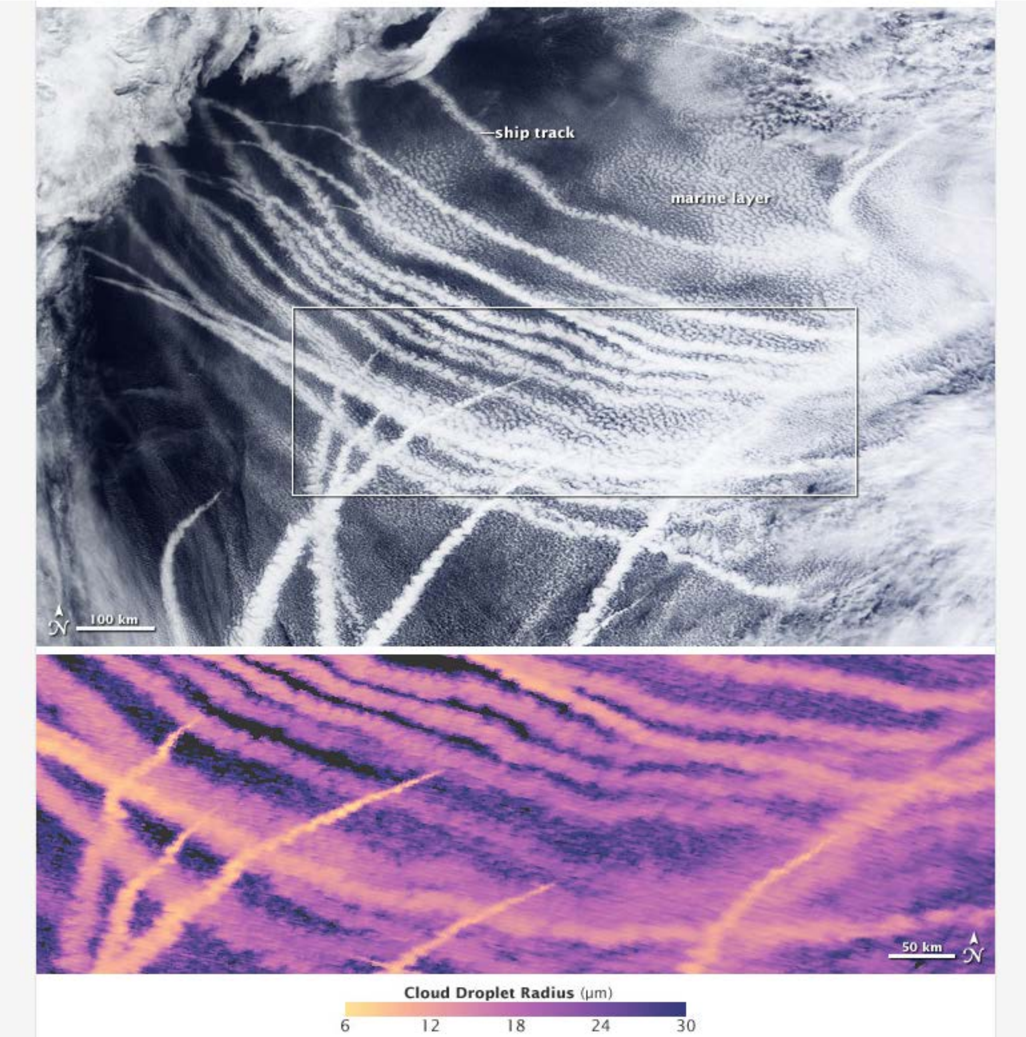
https://earthobservatory.nasa.gov/Features/Aerosols/

Satellite-scale Aerosol Effects

Direct Effects



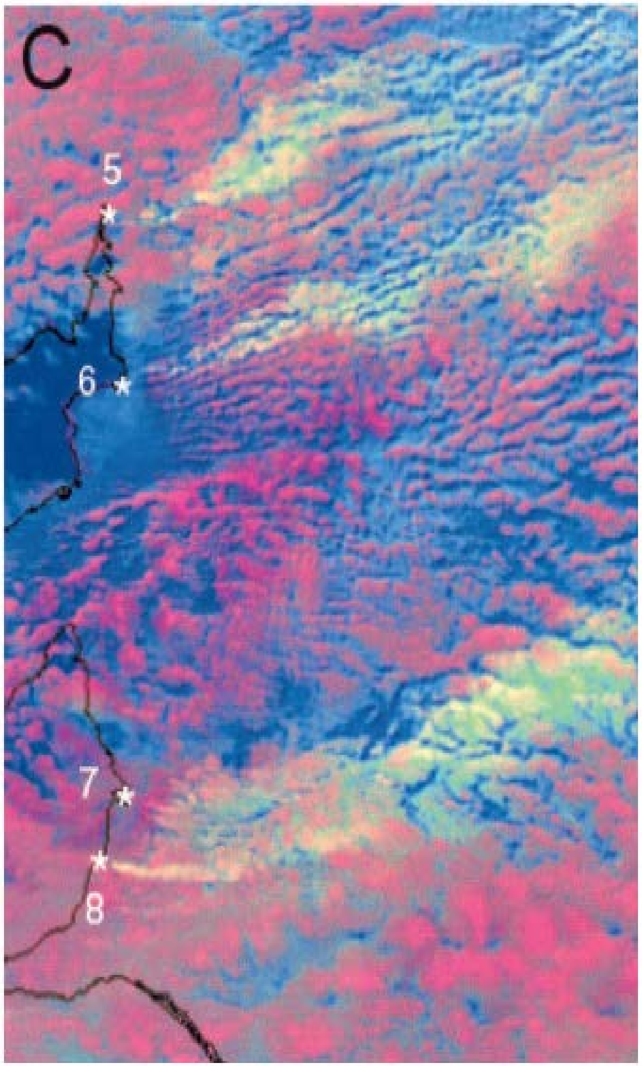
Indirect Effects



https://earthobservatory.nasa.gov/Features/Aerosols/

Anthropogenic Emissions and Clouds

- an increase in particle emission results in
  - first indirect effect
    - smaller cloud droplets
    - more reflective clouds
  - second indirect effect
    - clouds with longer lifetimes
- reduction in radiative forcing



Rosenfeld **2000** *Science*, 287, 1793

Mathematically

$$\tau_c = 2\pi N h r^2$$

$$L = \frac{4}{3}\pi r^3 N \rho_w$$

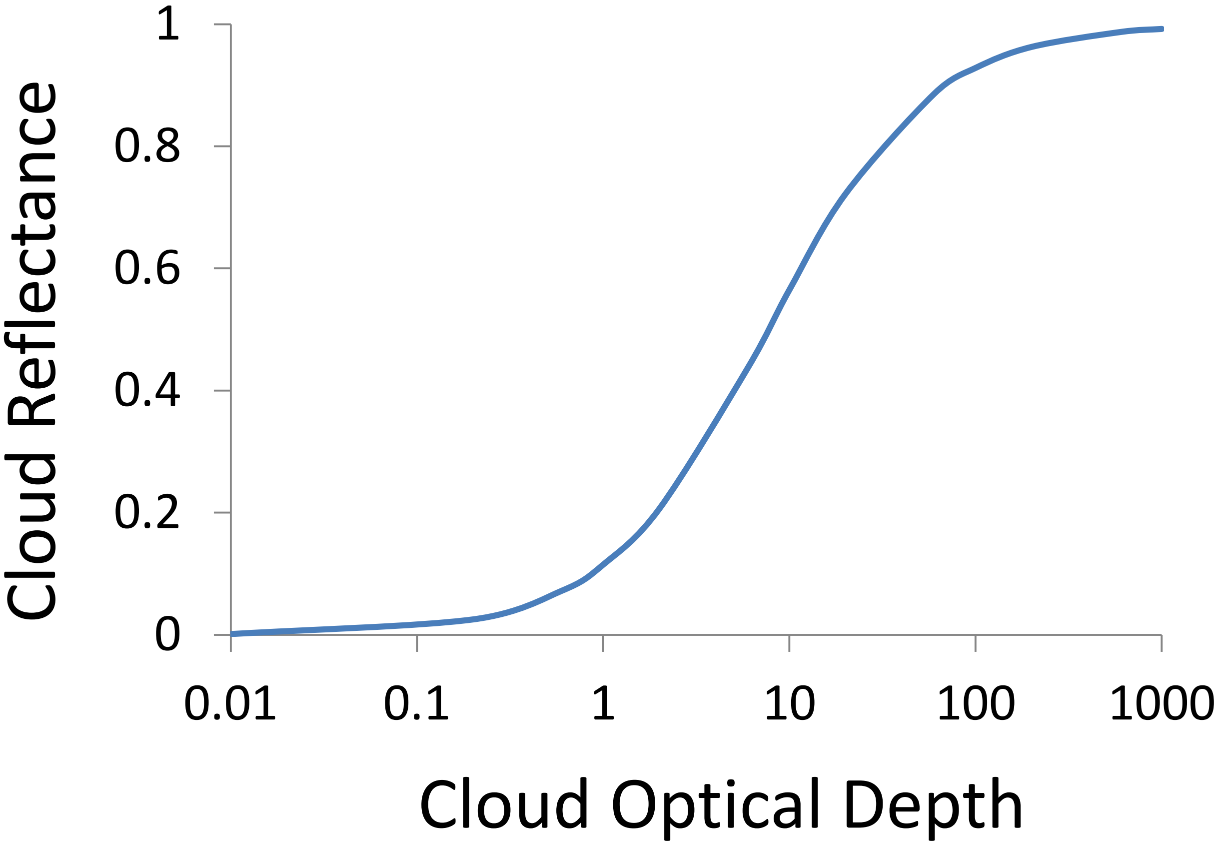
$$\tau_c = \frac{3Lh}{2\rho_w r}$$

$$\tau_c = h\left(\frac{9\pi L^2 N}{2\rho^2{}_{w}}\right)^{1/3}$$

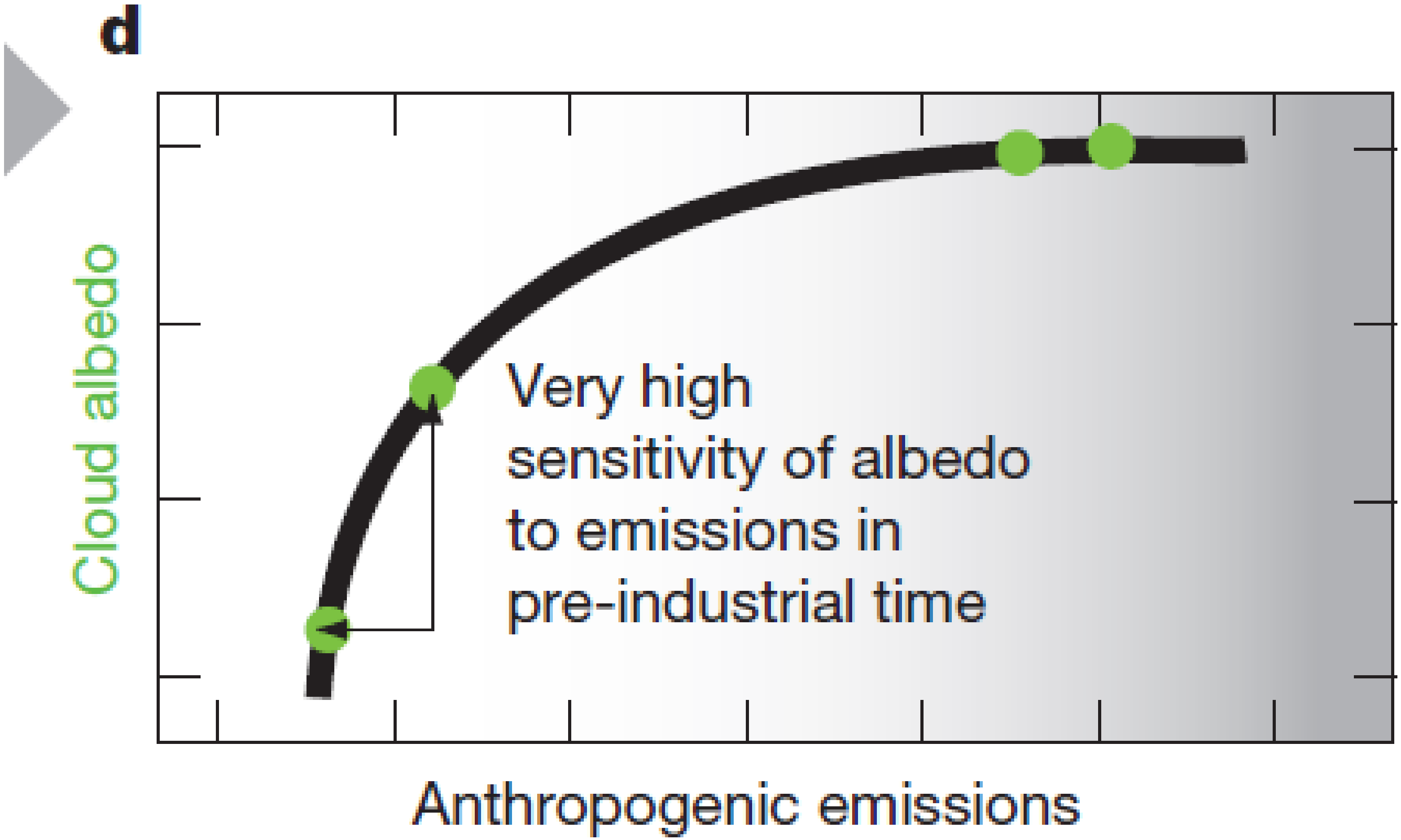
τ = cloud optical depth
N = number of droplets
h = cloud thickness
r = droplet radius
L = liquid water content

Cloud Reflectance

$$\mathrm{R}_c \cong \frac{\tau_c}{\tau_c + 7.7}$$

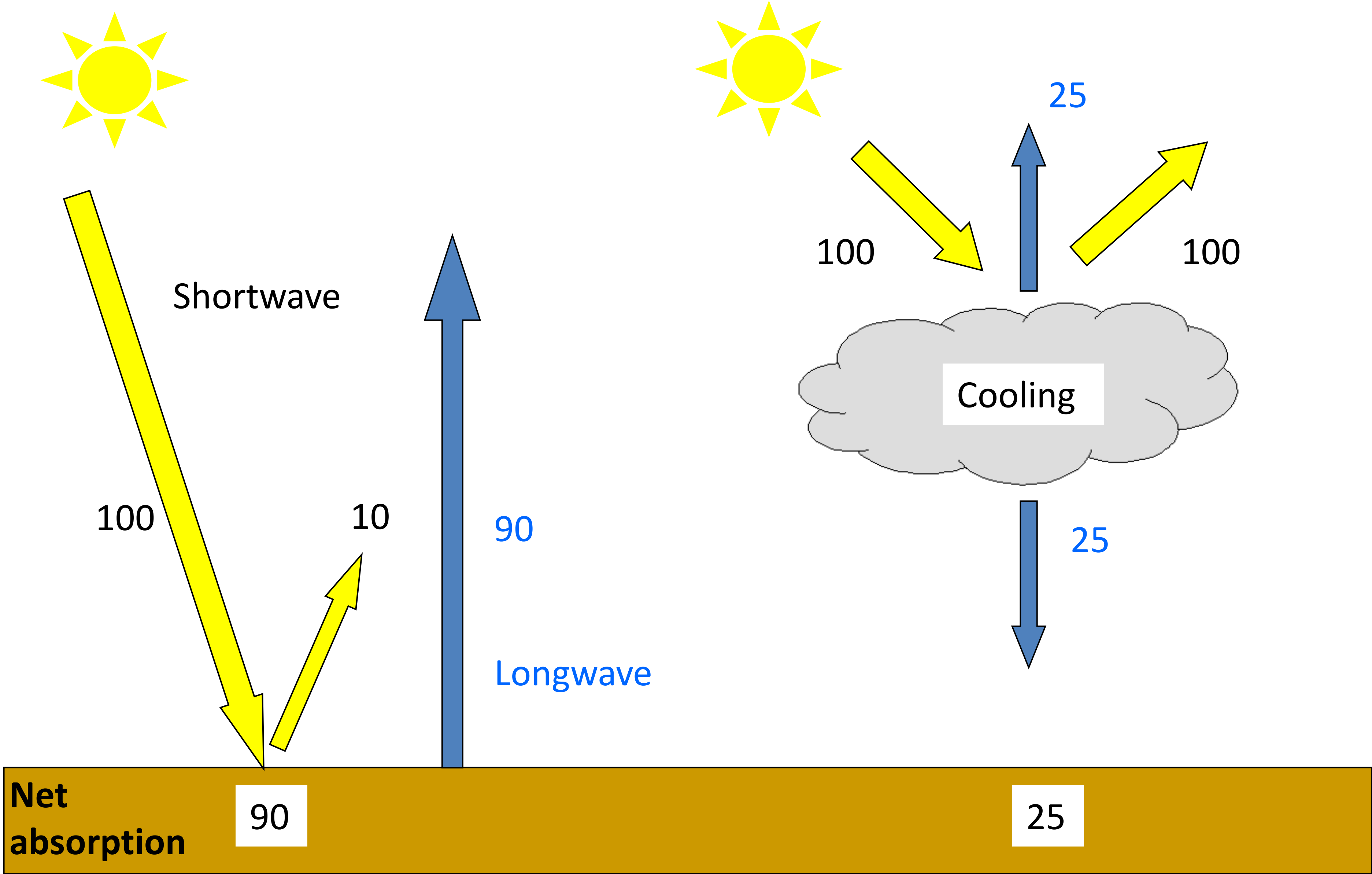


Arctic atmosphere sensitive to aerosol concentrations



Carslaw **2013** *Nature*, 503,67

Clouds Cool: Surface Albedo = 0.1



Shortwave

100

10

90

Longwave

25

100

100

Cooling

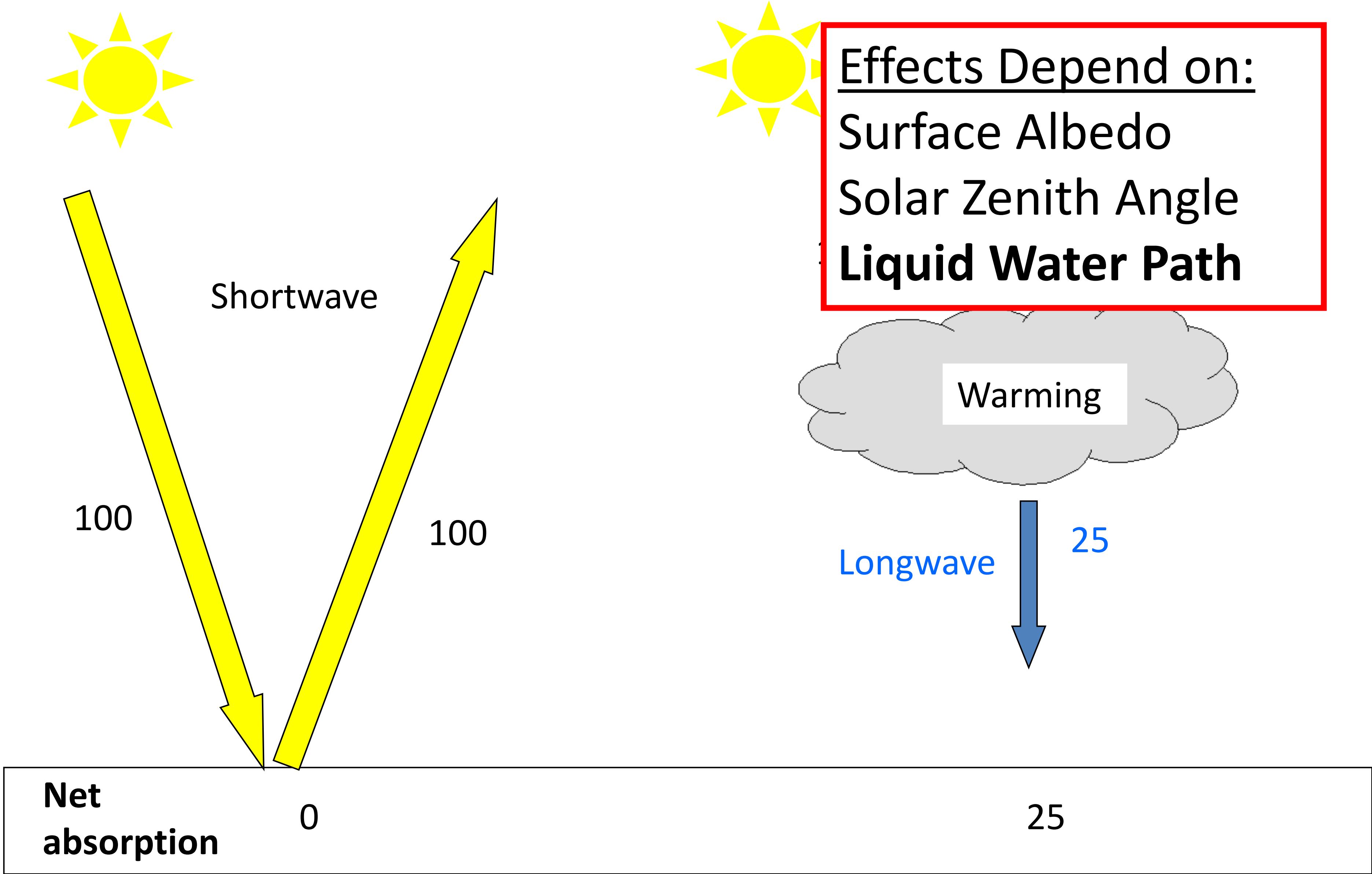
25

Net absorption

90

25

Clouds Warm: Surface Albedo = 1



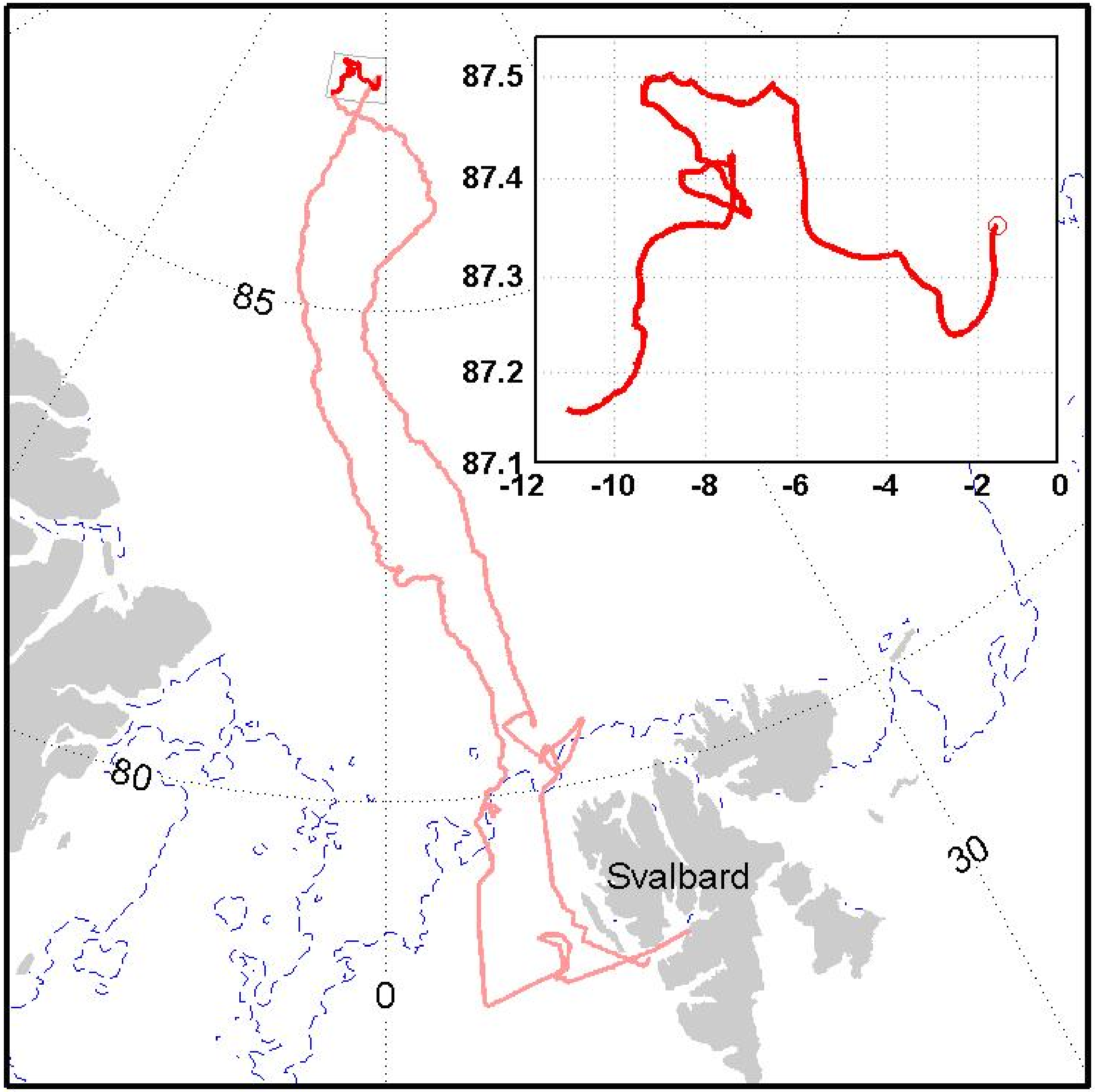
<u>Effects Depend on:</u>

Surface Albedo

Solar Zenith Angle

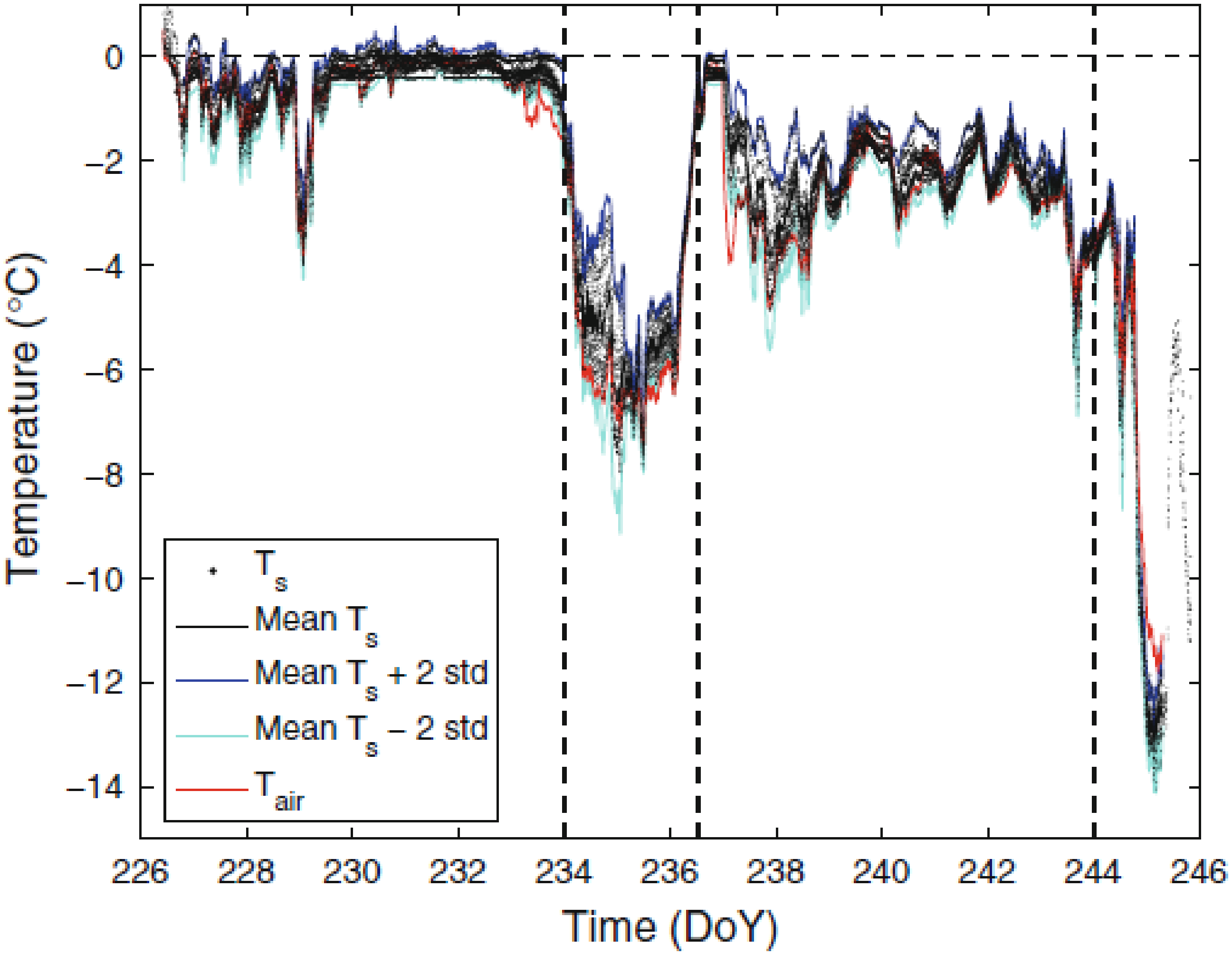
Liquid Water Path

Arctic Summer Cloud and Ocean Study
Aug 1 – Sep 9, 2008



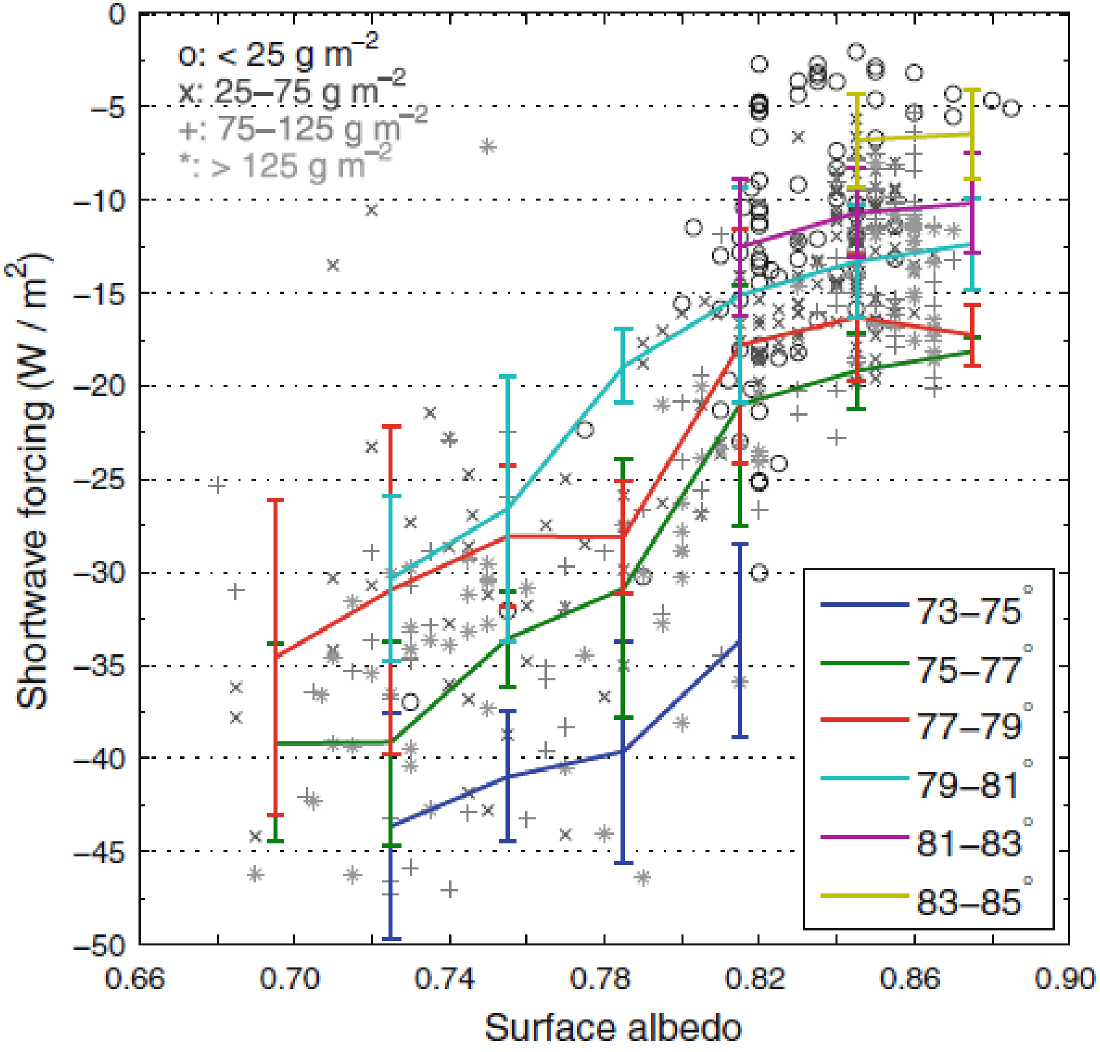
map courtesy of I. Brooks

ASCOS Surface Temperatures



Sedlar et al. **2010** *Climate Dynamics*

Shortwave Forcing Depends on Surface Albedo



Sedlar et al. **2010** *Climate Dynamics*

Longwave Forcing Depends on LWP

Clouds Warm

Clouds Cool

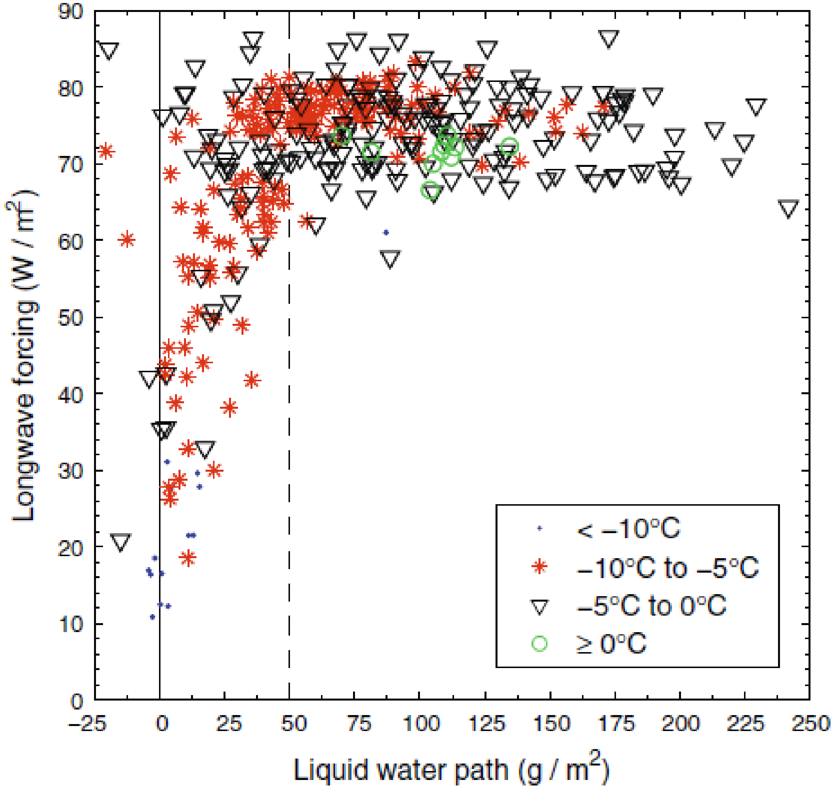


Fig. 11 One-hour LWF (W m^{-2}) as a function of cloud LWP (g m^{-2}), separated by cloud base temperature ranges from <–10 to >0°C. The *solid vertical line* represents the zero LWP line; LWP <0 g m^{-2} are included due to the 25 W m^{-2} uncertainty in the measurement. The *dashed vertical line* marks a LWP of 50 g m^{-2} (see *text*)

Sedlar et al. **2010** *Climate Dynamics*

Radiative effects of Arctic clouds

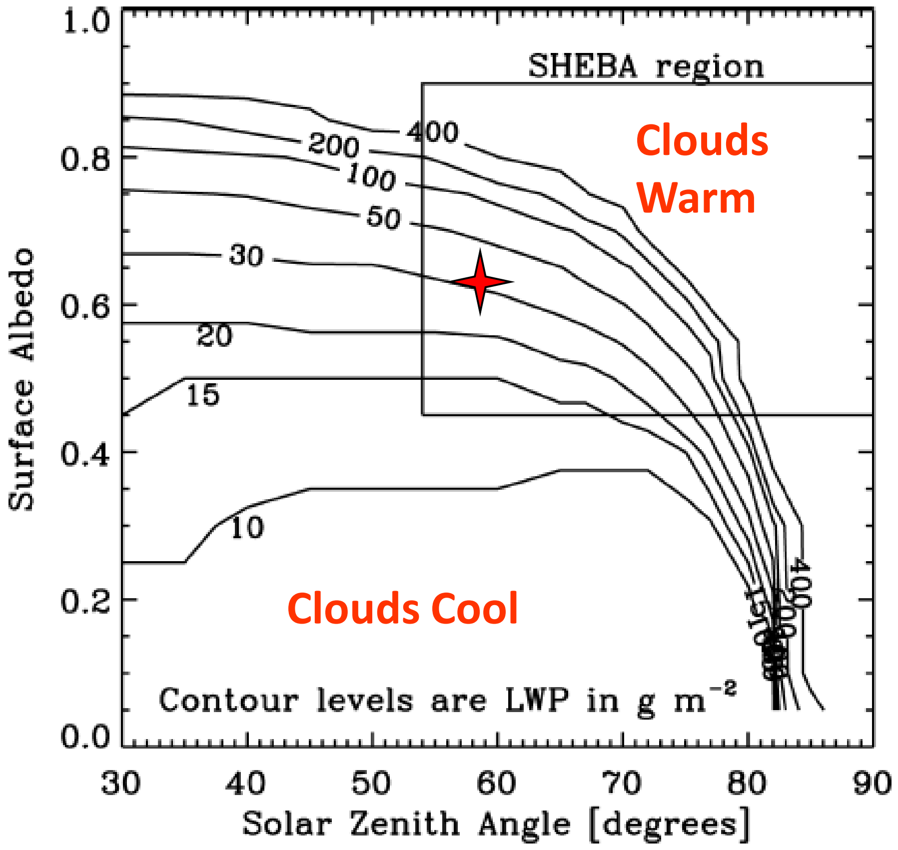


FIG. 7. Contours of the cloud LWP value at which point the SW surface cloud cooling effect becomes dominant over the LW warming effect as a function of θ and α_s. The following parameters are assumed: $T_c = -10°C$, $z_c = 1$ km, $t_{al} = 0.9$, and $t_{as} = 0.75$.

Shupe and Intrieri **2004** *J. Climate*

Summary

- cloud droplet formation depends on aerosol size and composition

- clouds in the Arctic can warm or cool

- radiative forcing of Arctic clouds is dependent on aerosol concentration