Microphysical-macrophysical interactions

or

Why microphysics matters

Optical properties of liquid clouds

Cloud albedo $\alpha \approx \tau/(\tau+7)$

$$\tau = 3\,LWP/\,r_e$$

LWP is *macro* physical property

- determined largely by meteorological context

r_e is a *micro* physical property

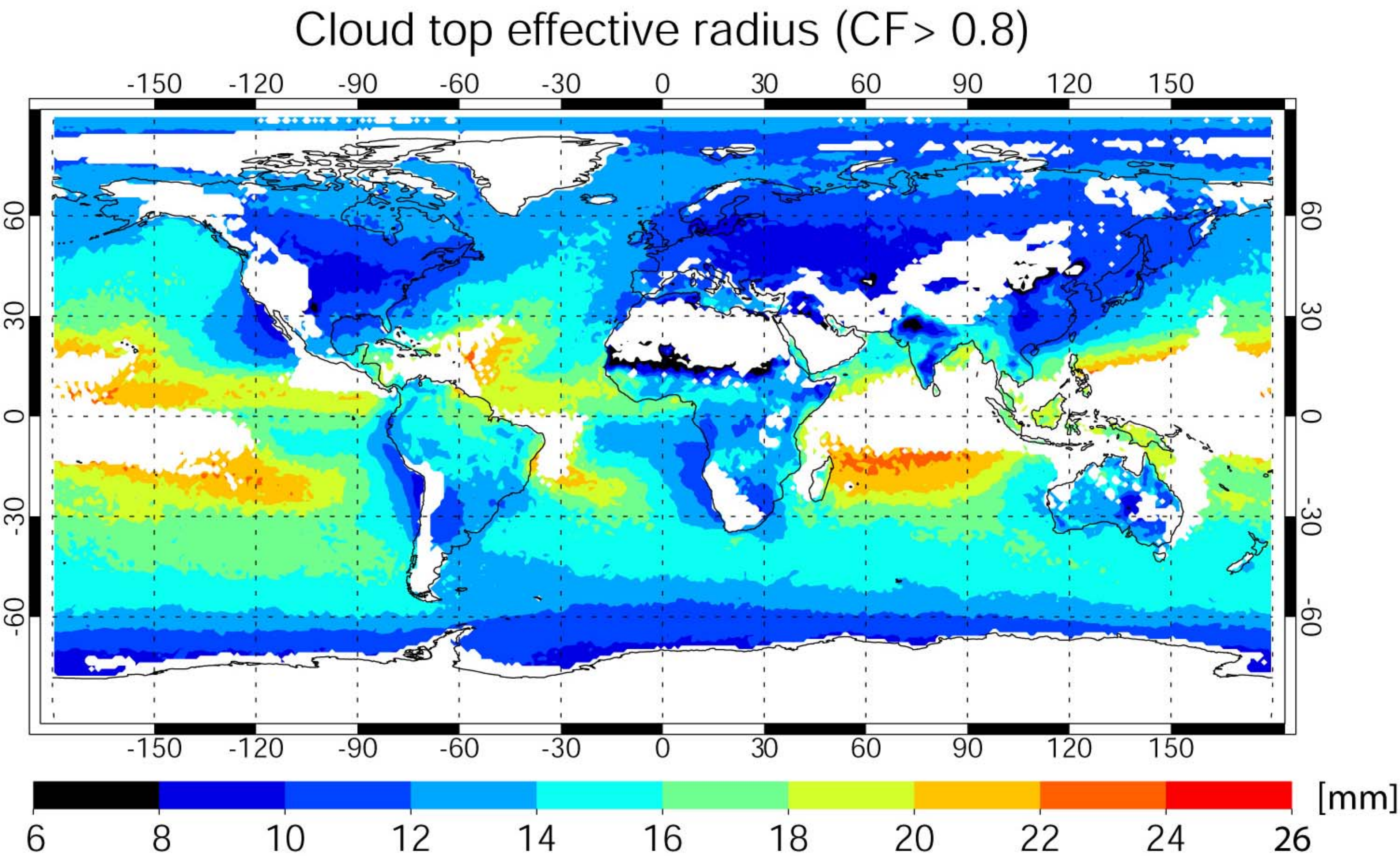
- determined largely by properties of cloud condensation nuclei

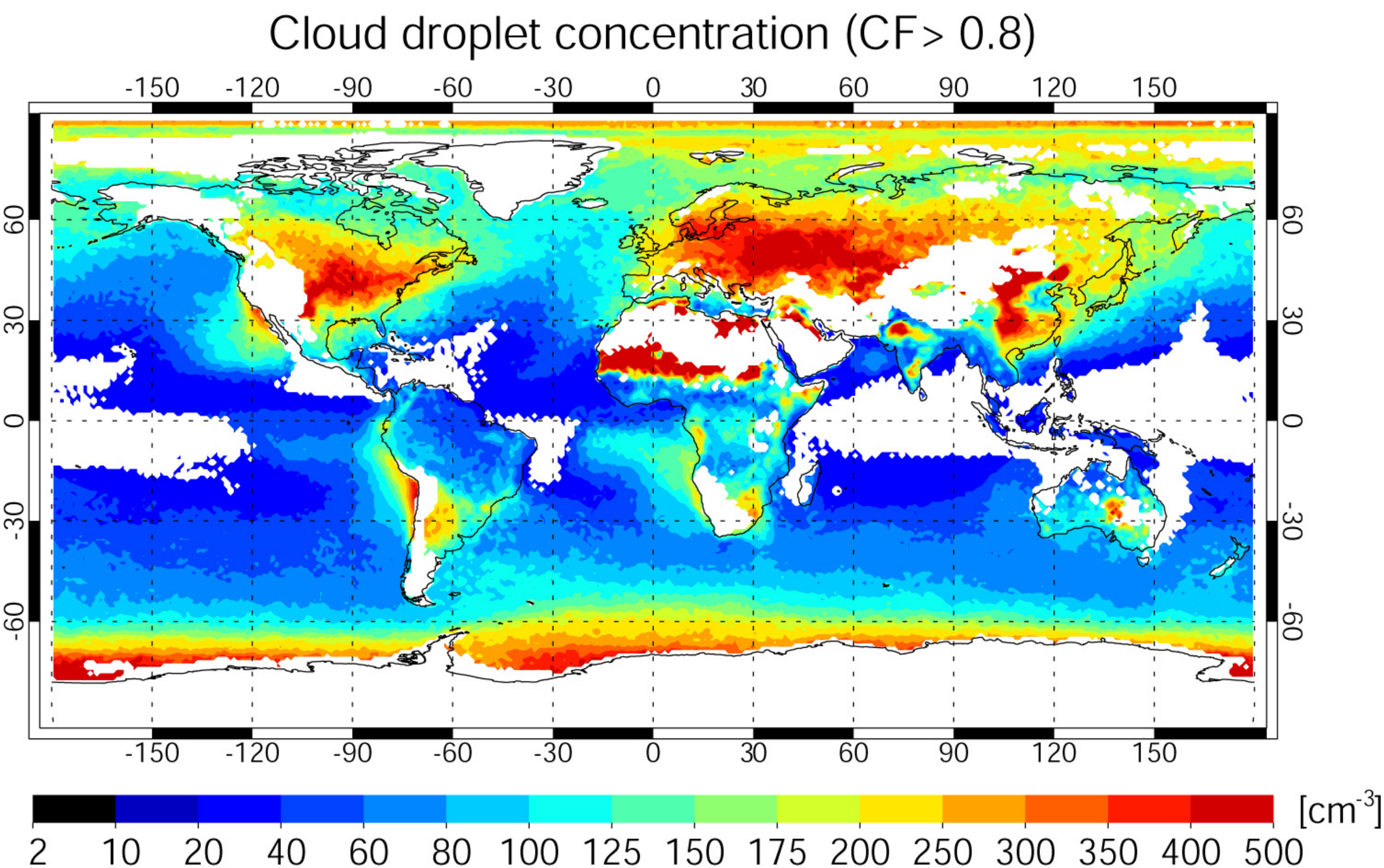
Optical properties of liquid clouds

What determines r_e ?

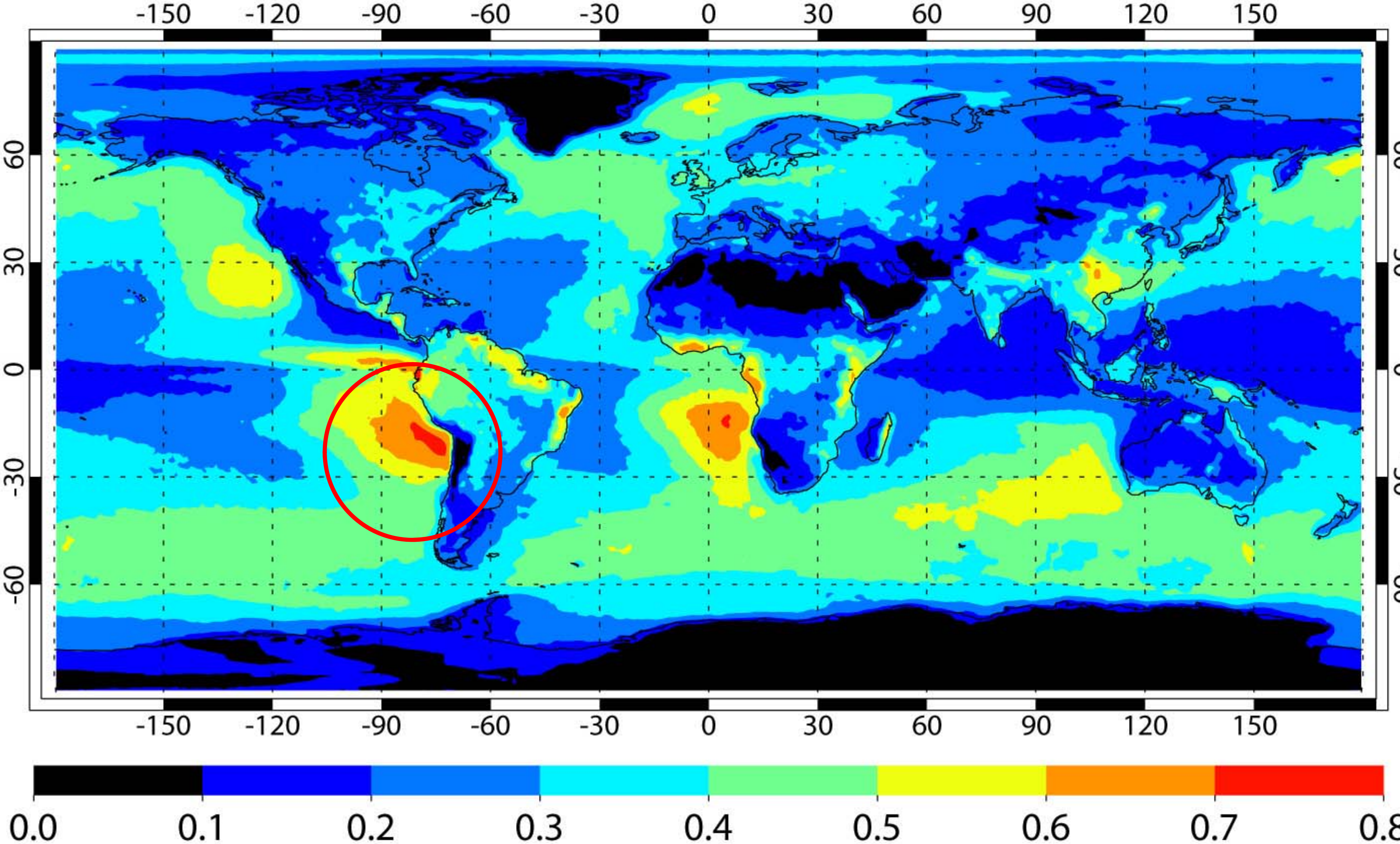
$$r_e \approx (3 LWC / 4 \pi \rho N)^{1/3}$$

for warm layer clouds N dominates
(N can vary from 10-2000 cm^{-3} while *LWC* varies from 0.2-1 g m^{-3})

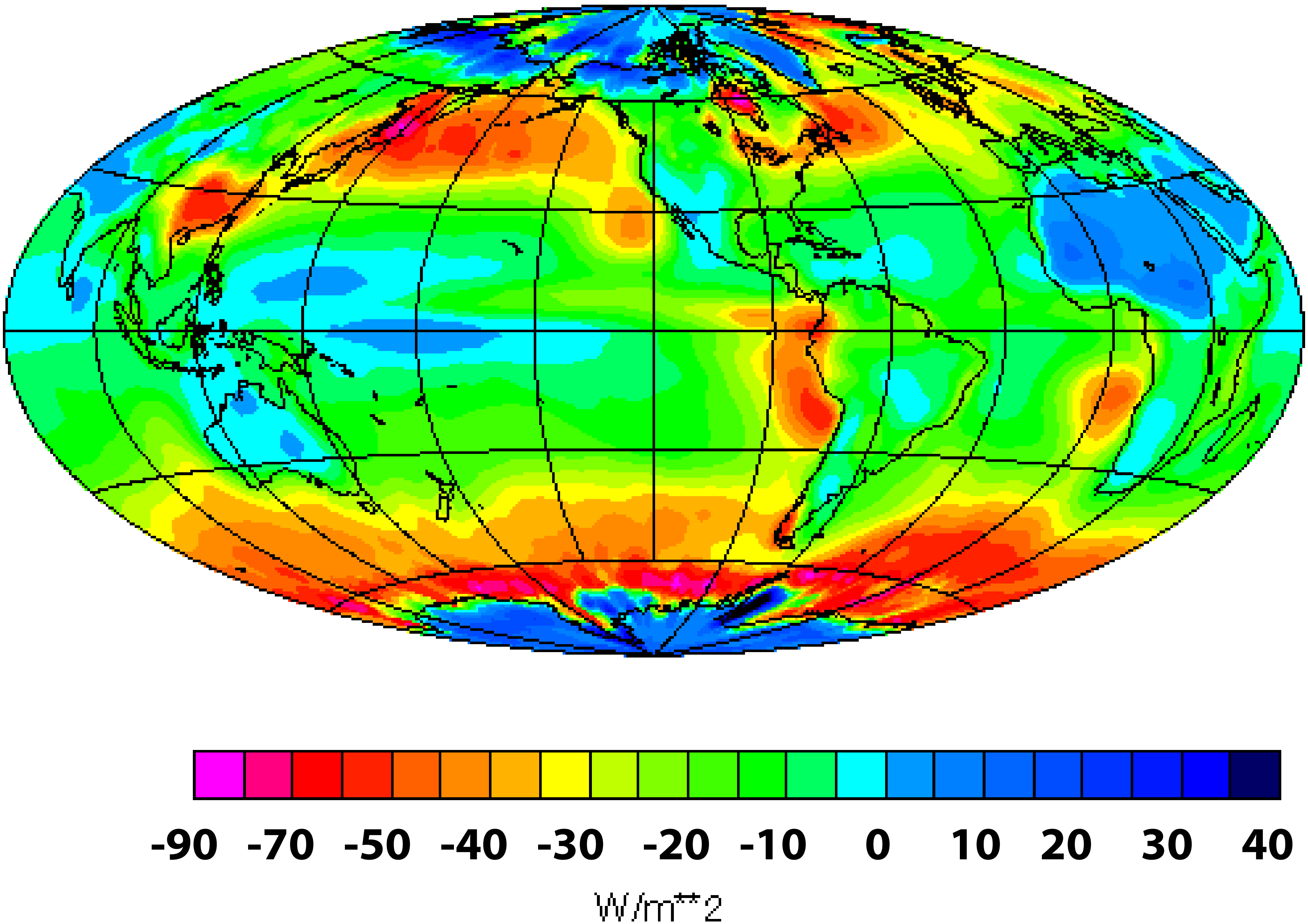

Cloud top effective radius (CF> 0.8)
-150
-120
-90
-60
-30
0
30
60
90
120
150
60
30
0
-30
-60
6
8
10
12
14
16
18
20
22
24
26
[mm]


Cloud droplet concentration (CF> 0.8)
-150 -120 -90 -60 -30 0 30 60 90 120 150
60 30 0 -30 -60
[cm^{-3}]
2 10 20 40 60 80 100 125 150 175 200 250 300 350 400 500

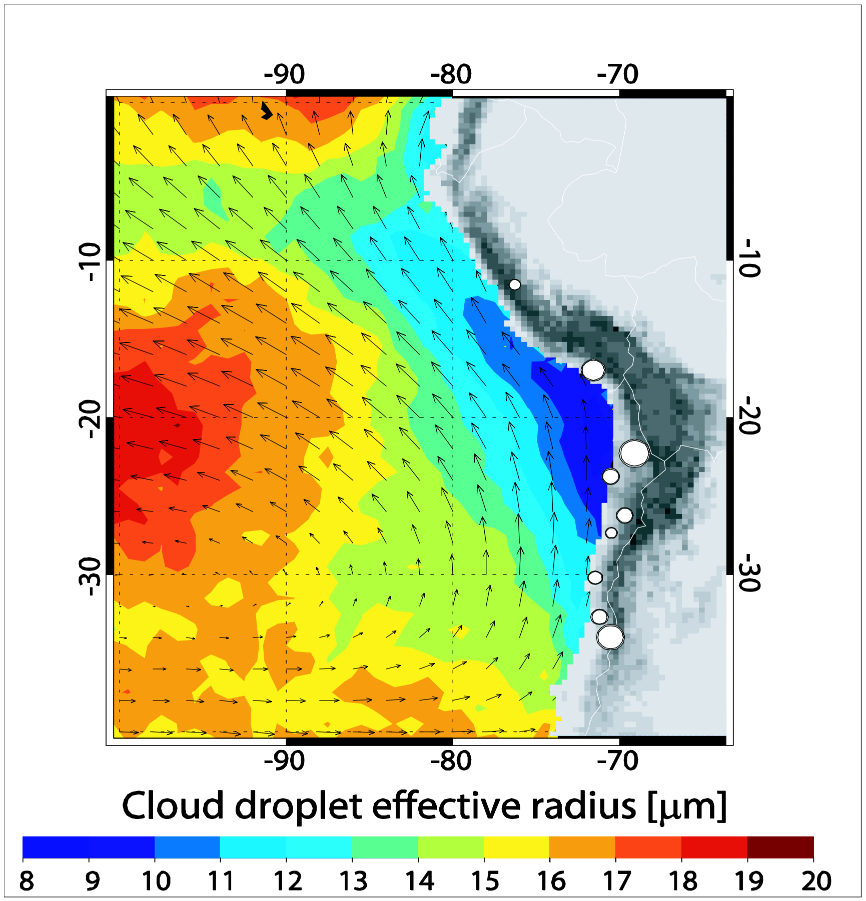
Warm cloud fractional coverage

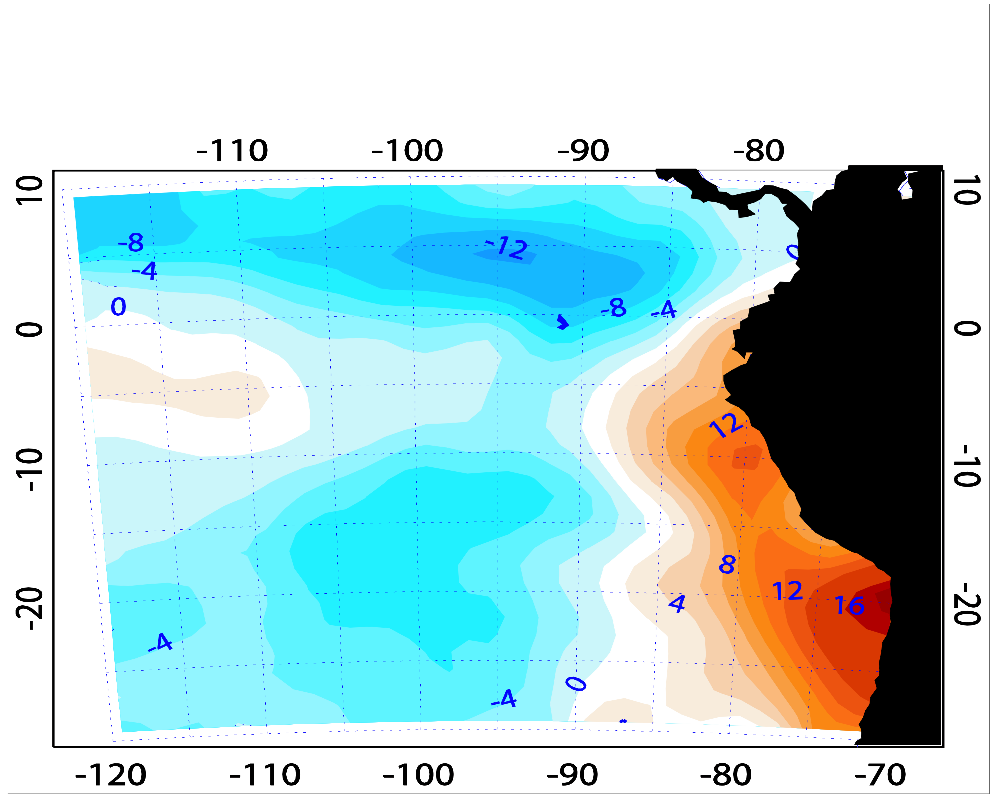


Net cloud radiative effect from ERBE



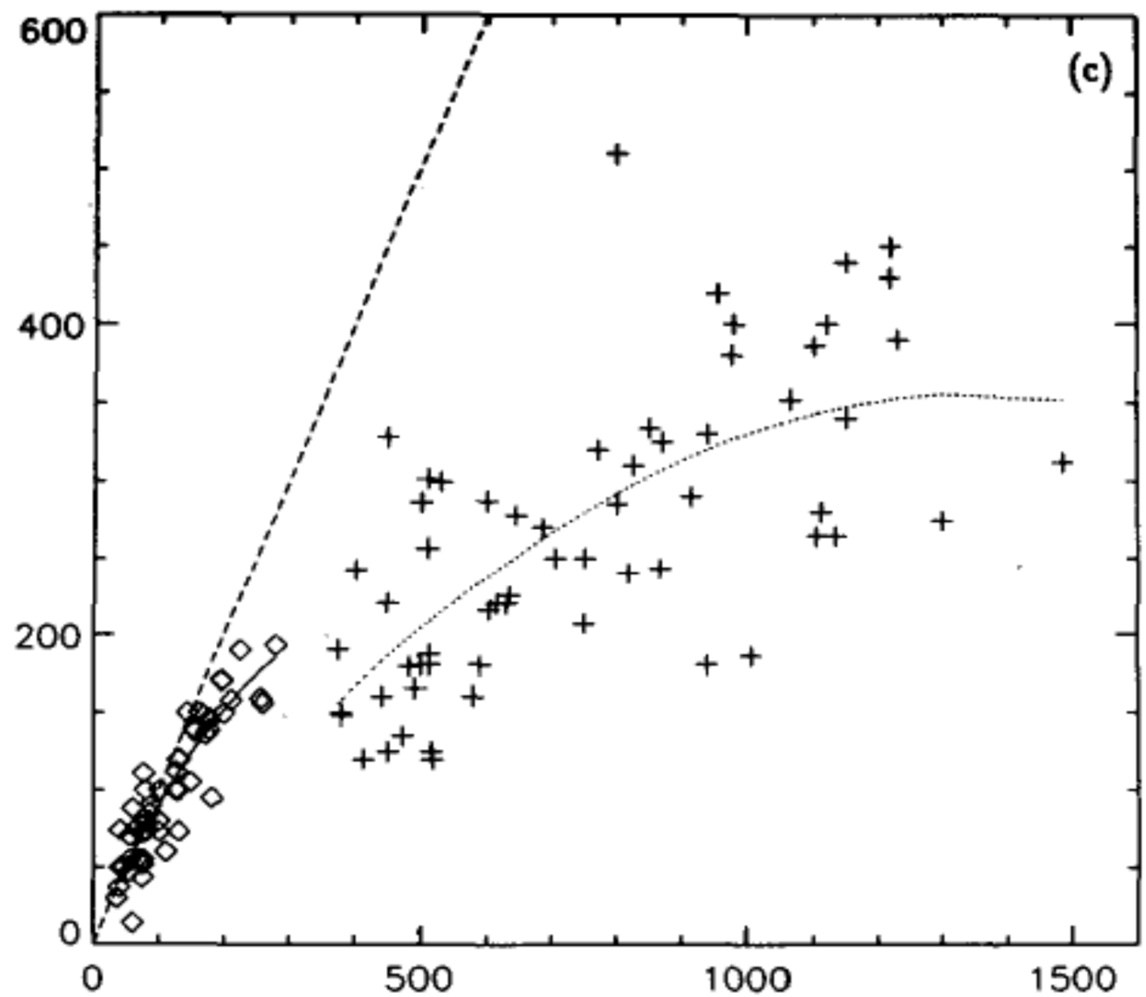
Microphysics and radiation budget





Error in TOA net radiation in assuming no microphysical variability (constant *N*)

What determines *N* in warm clouds?



Cloud droplet concentration [cm^{-3}]

Aerosol concentration (r>0.1 micron) [cm^{-3}]

The Twomey Effect

a.k.a *first aerosol indirect effect*

Increase N

$\Rightarrow$ decrease r_e

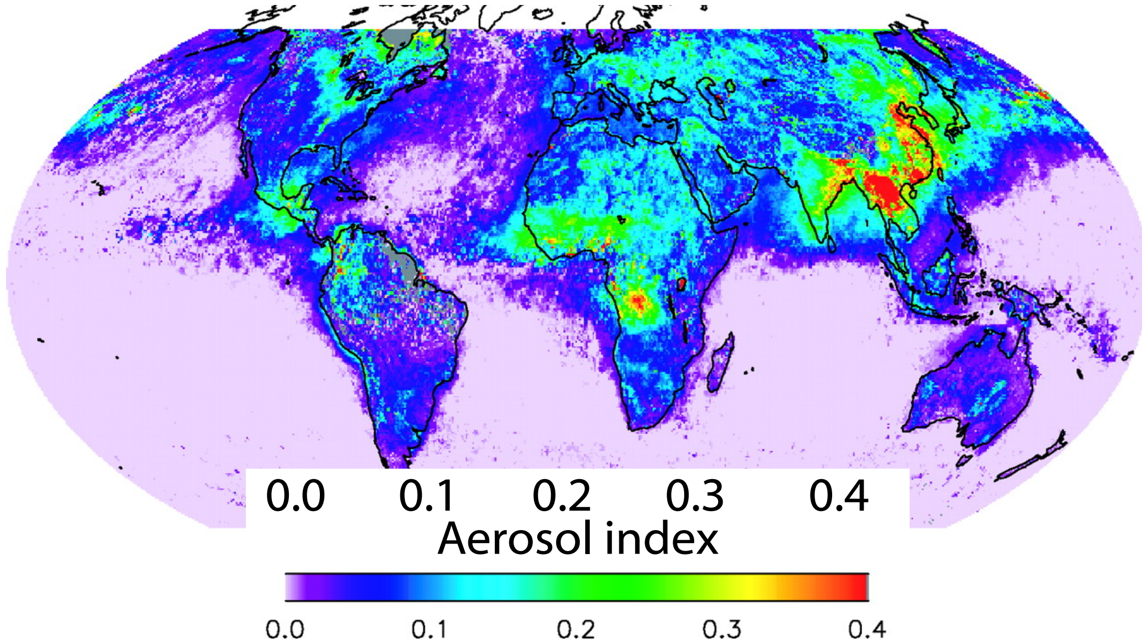
$\Rightarrow$ increase τ (for constant *LWP*)

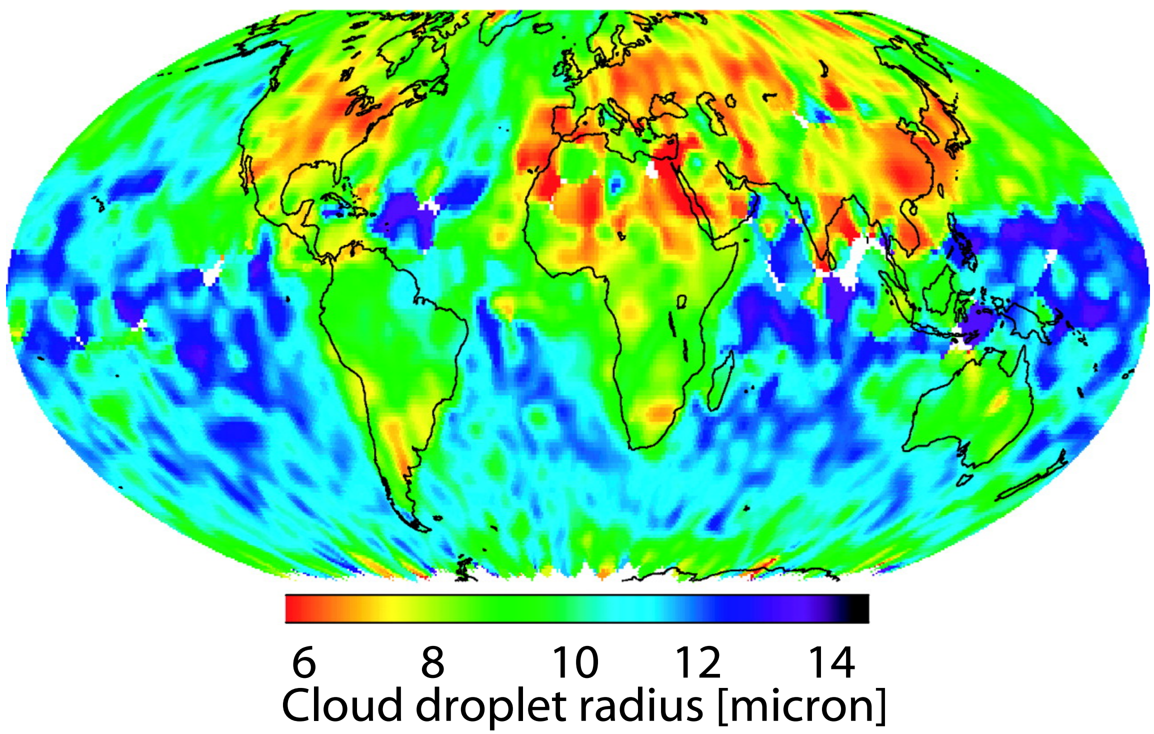
$\Rightarrow$ increased albedo

$$\alpha \approx \tau/(\tau+7)$$

$$\tau = 3\,LWP/\,r_e$$

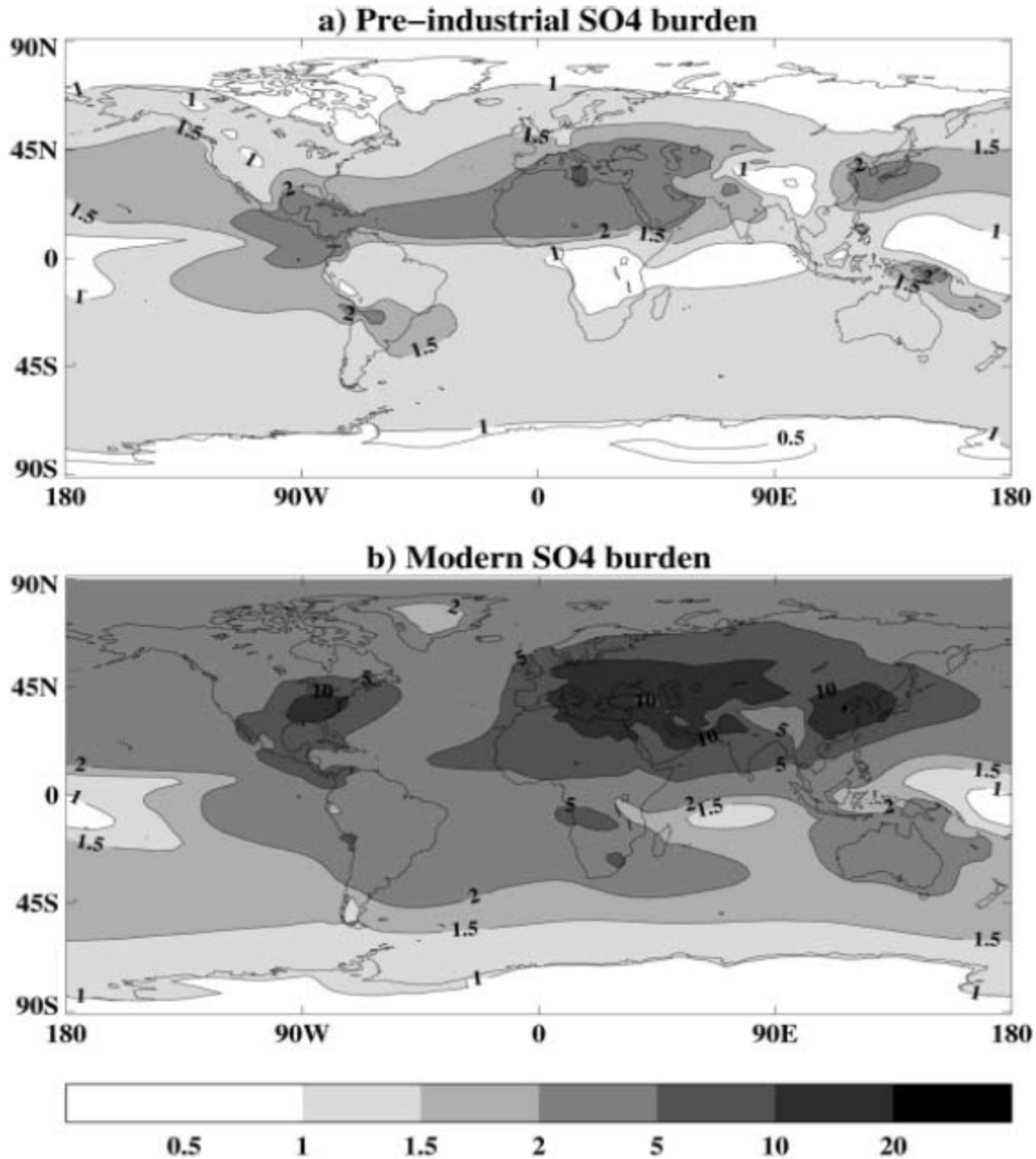
Aerosol loading and cloud droplet effective radius





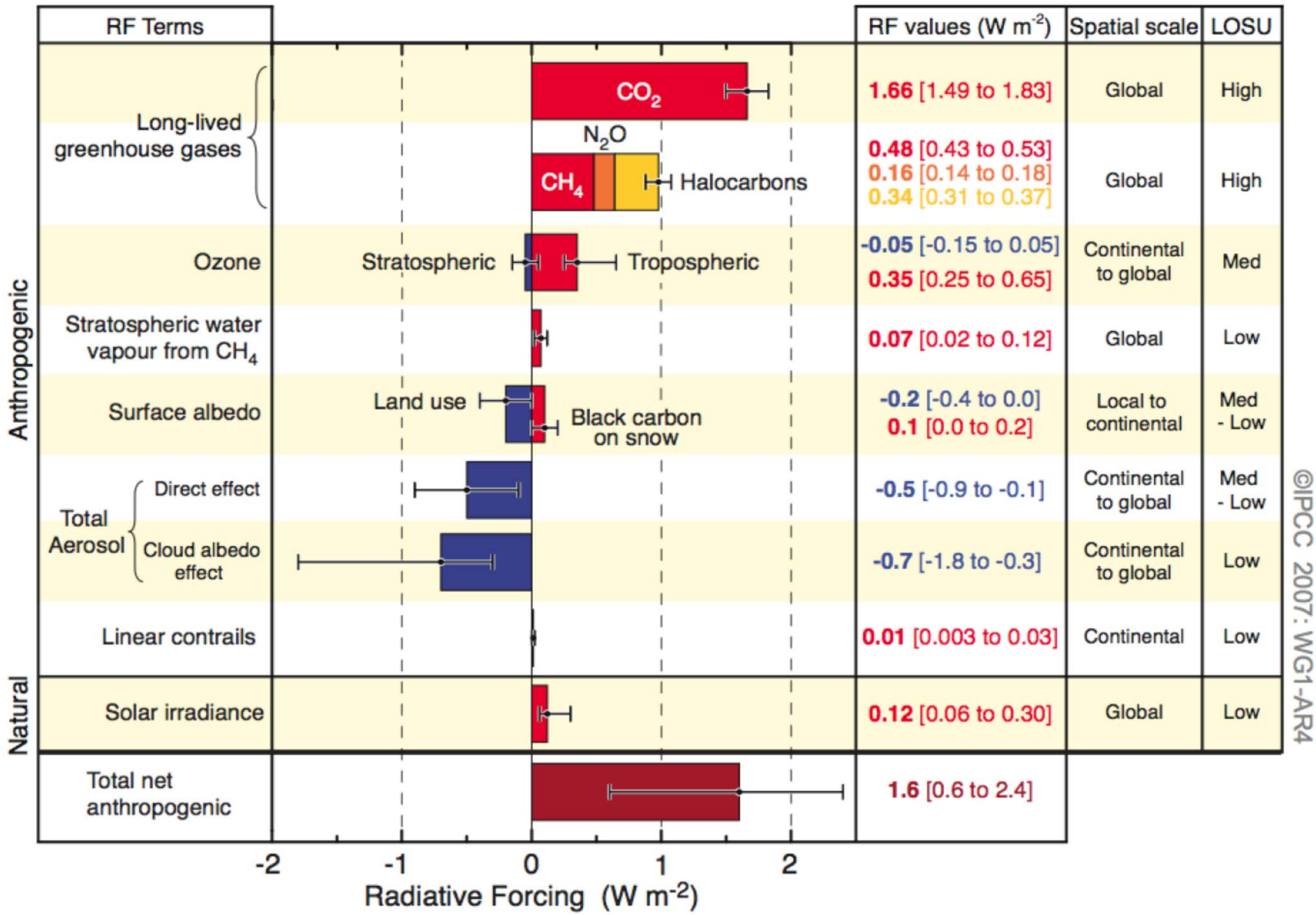
from Breon et al. 2002, *Science*, 295**, 834-838**

Fig. 1a, b Column-integrated annual mean sulfate burden (mg(SO_4) m^{-2}) in the BOTH experiments: **a** with pre-industrial sulfur emissions; **b** with modern (1985) sulfur emissions



Williams et al. (2001)

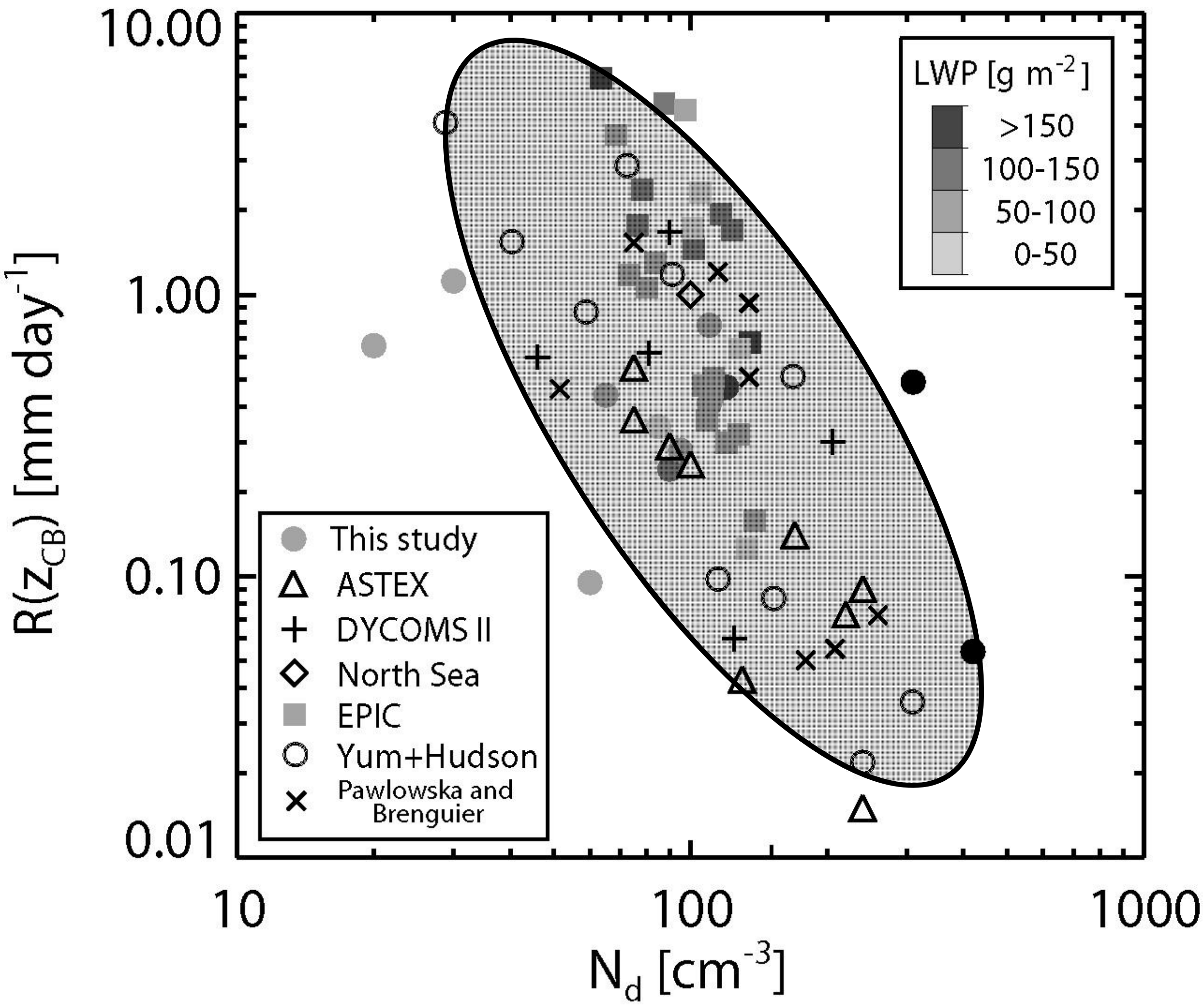
Radiative Forcing Components



Cloud droplet size also impacts precipitation formation

- Terminal speed of falling droplets increases strongly with size
- Collection "efficiency" also increases with drop size
  - smaller drops tend to follow flow field around impinging larger ones, whereas larger ones are collected
- Initial production of precipitation is more efficient in clouds with larger droplets (lower *N*, for a given LWC)

Summary of drizzle observations in stratiform warm clouds from field programs



However, what about feedbacks?

Increase N

$\Rightarrow$ decrease r_e

$\Rightarrow$ decreasing collision coalescence

$\Rightarrow$ decrease precipitation

$\Rightarrow$ reduced LWC sink

$\Rightarrow$ increase cloud LWC

$\Rightarrow$ increase τ

$\Rightarrow$ increased albedo

Albrecht effect
a.k.a "second aerosol indirect effect"

Increase precip. ⇒ decrease cloud cover

Albrecht 1989

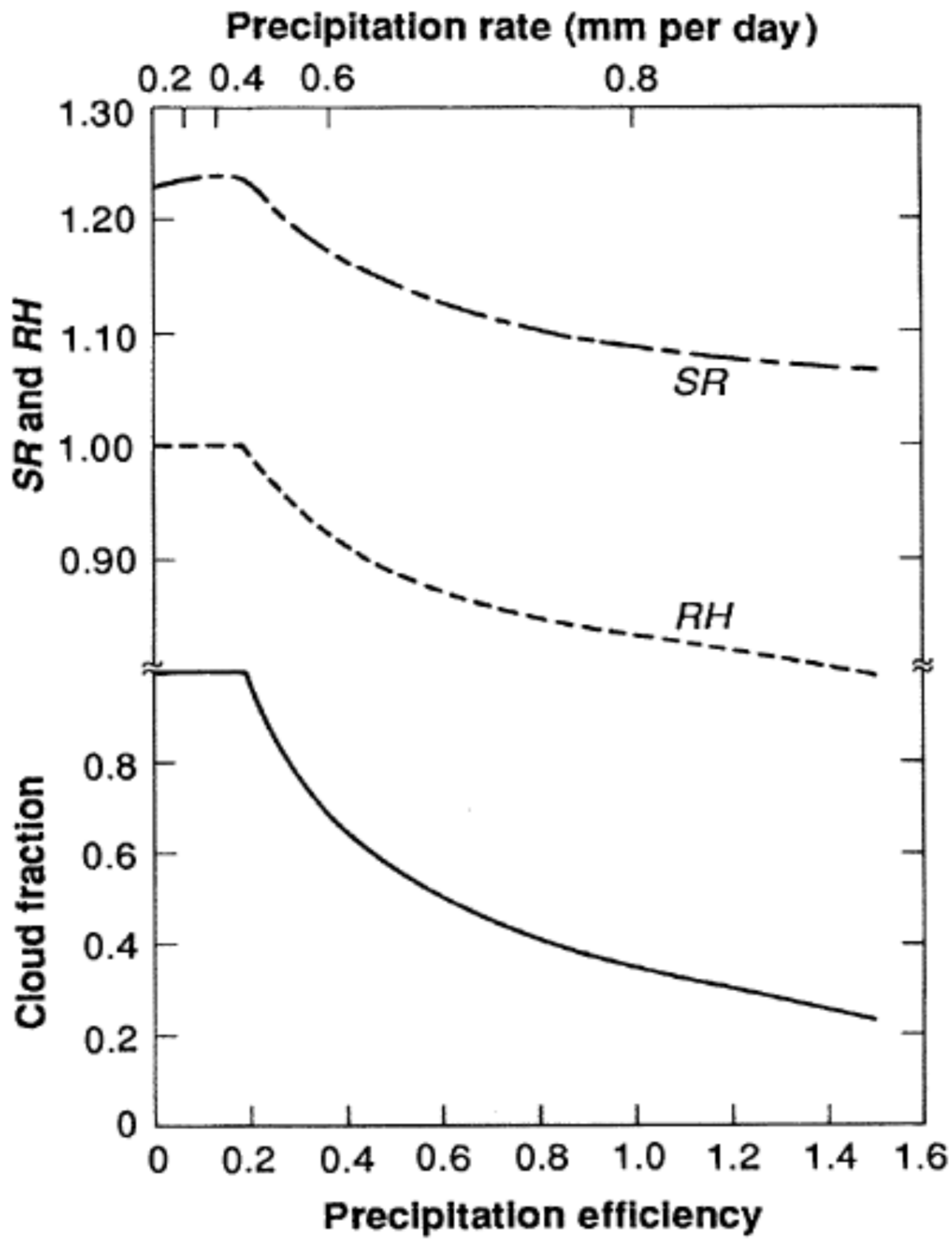
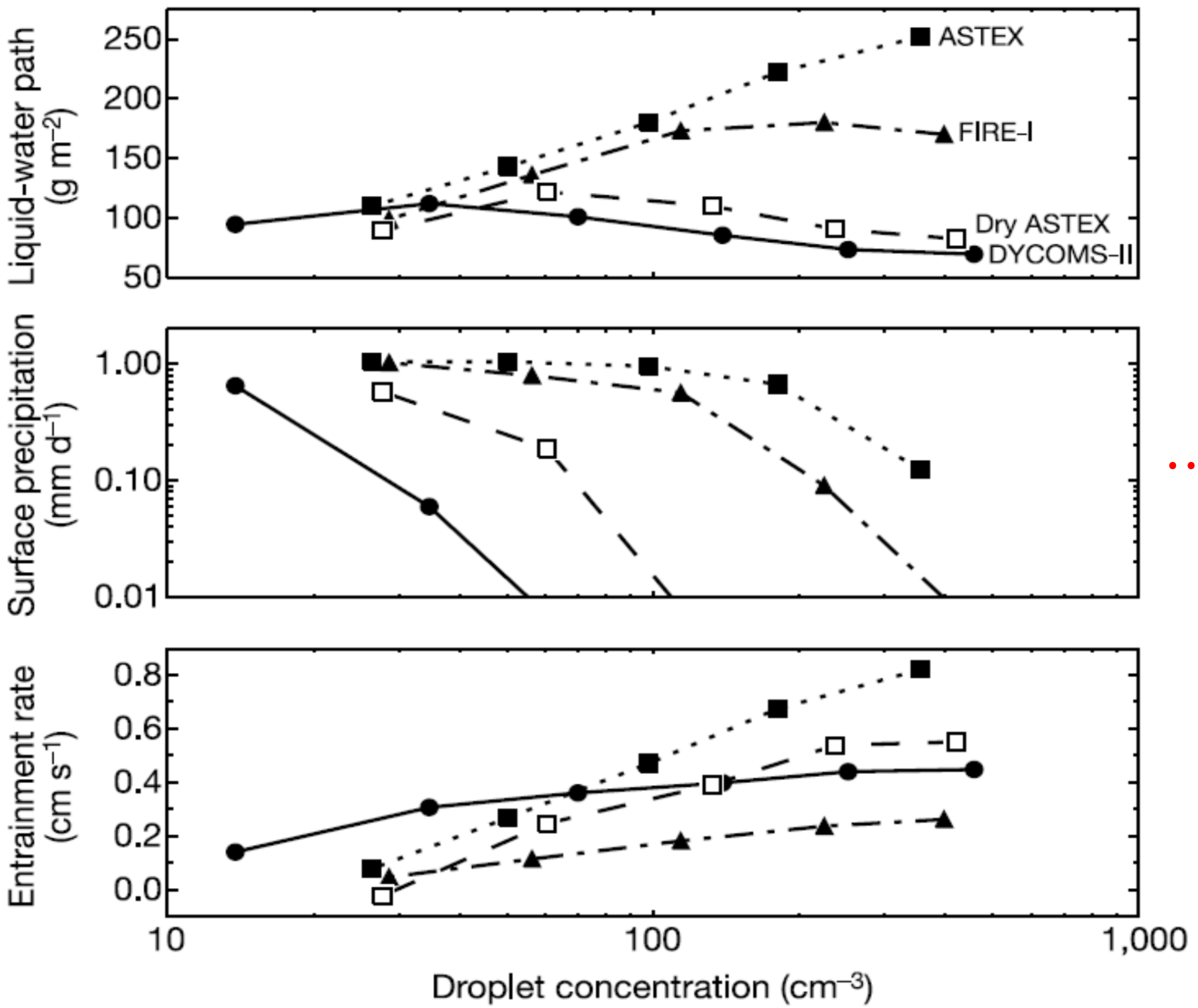


Fig. 4. The dependence of fractional cloudiness, *RH*, and *SR* for different specifications of a precipitation efficiency factor. The removal of water by precipitation processes in the parameterized convective elements by the model is assumed to be $(dl_c/dz)_{\mathrm{PRECIP}} = -a \cdot l_c$ where z is height, l_c is the cloud liquid water, and a is the precipitation efficiency factor in units of per kilometer. A zero efficiency factor is no drizzle production and a value of $a = 1$ corresponds to a decrease in the cloud liquid water (for no condensation) by $1/e$ over a cloud depth of 1 km. Solutions are for the conditions described in Fig. 3 with a sea-surface temperature of 26°C and D_o of $5 \times 10^{-6}\ \mathrm{s}^{-1}$.

Increasing N in a more sophisticated model



reduced precip. *decreases* LWP ! ….sometimes

Ackerman et al. (2004)

Clouds containing the ice phase

Importance of microphysics for orographic precipitation distribution

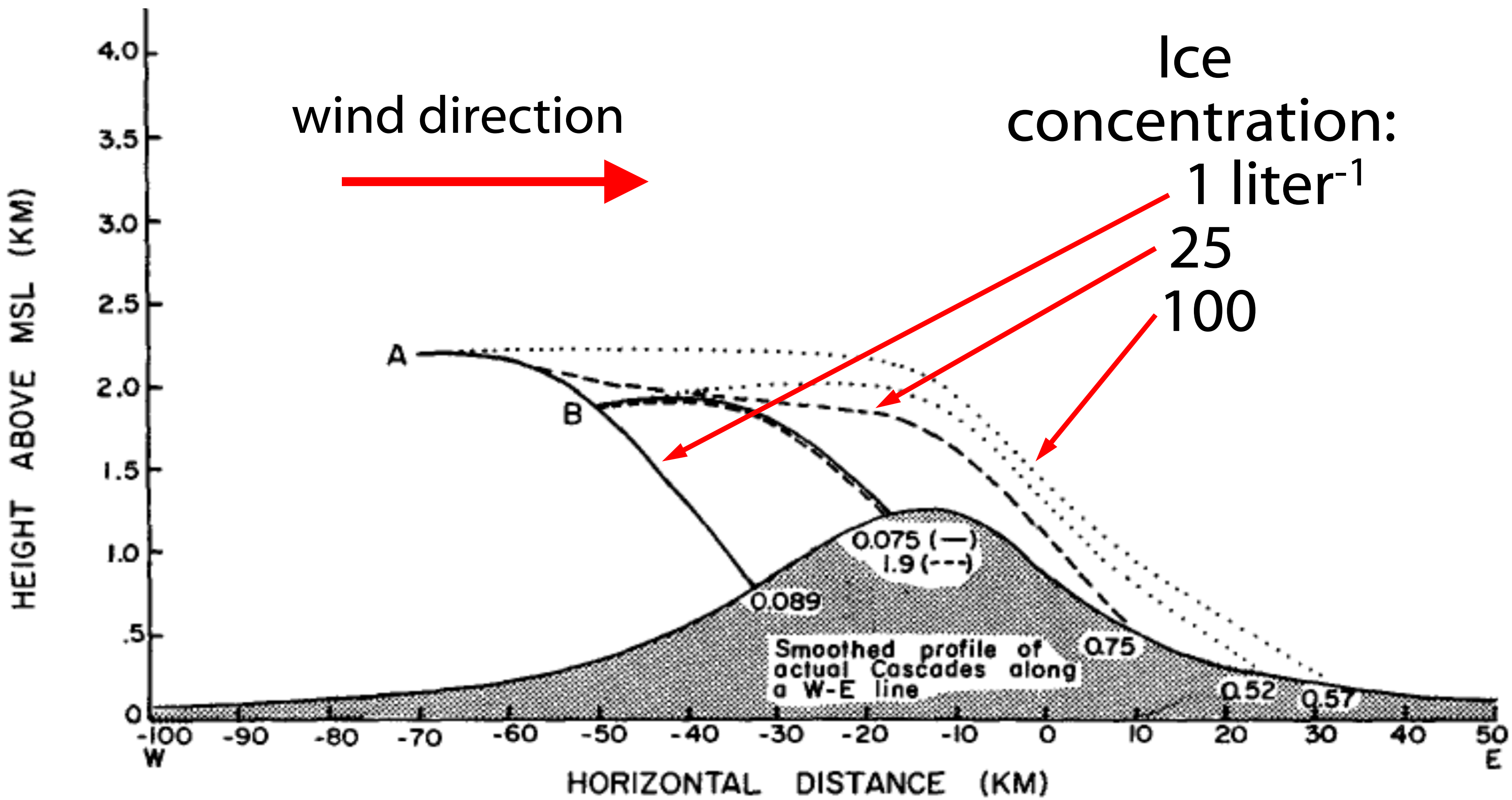
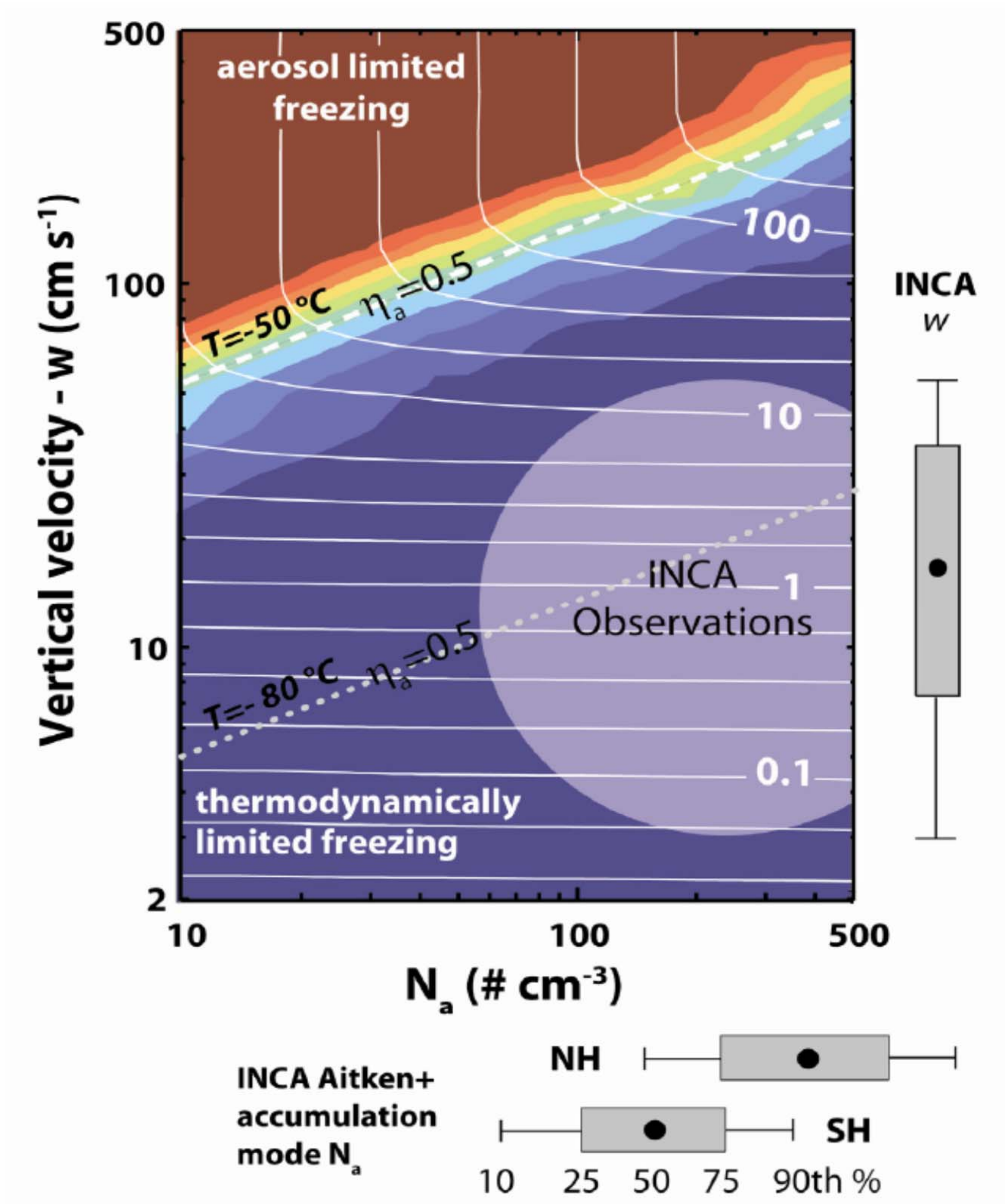
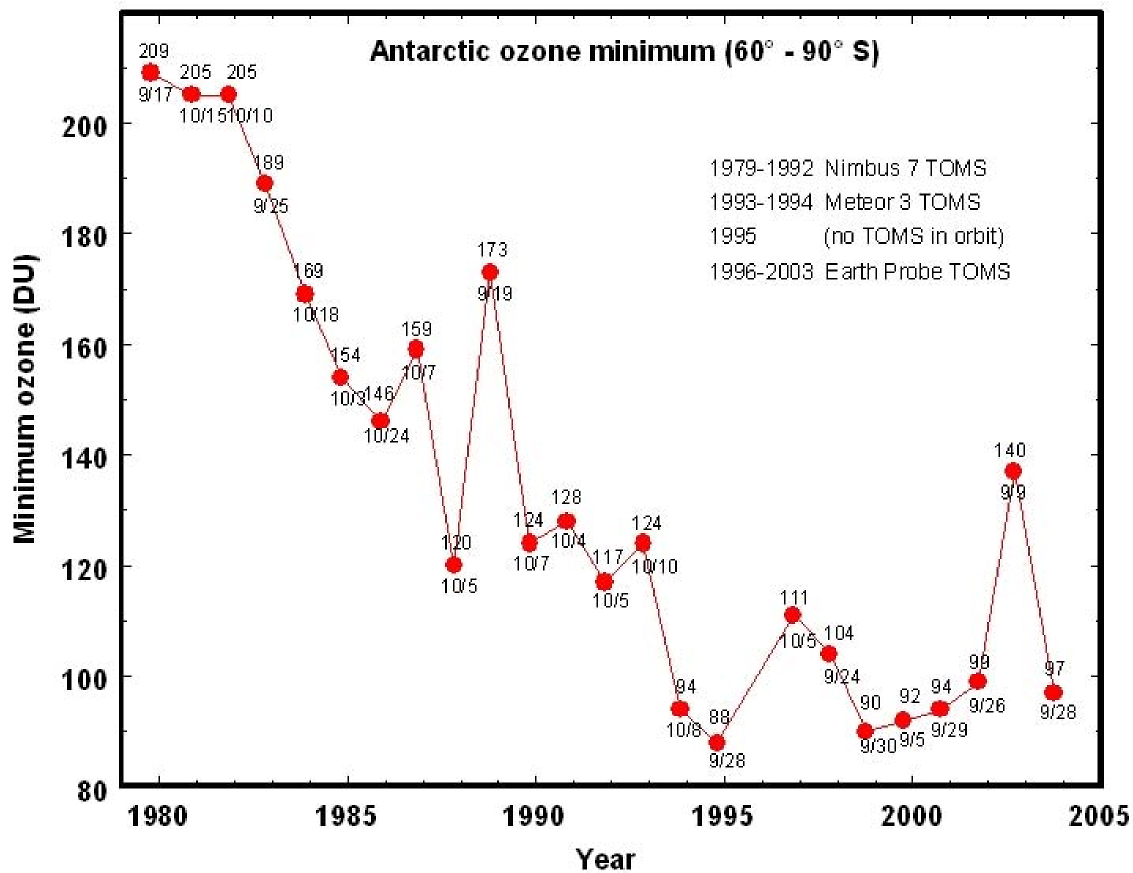


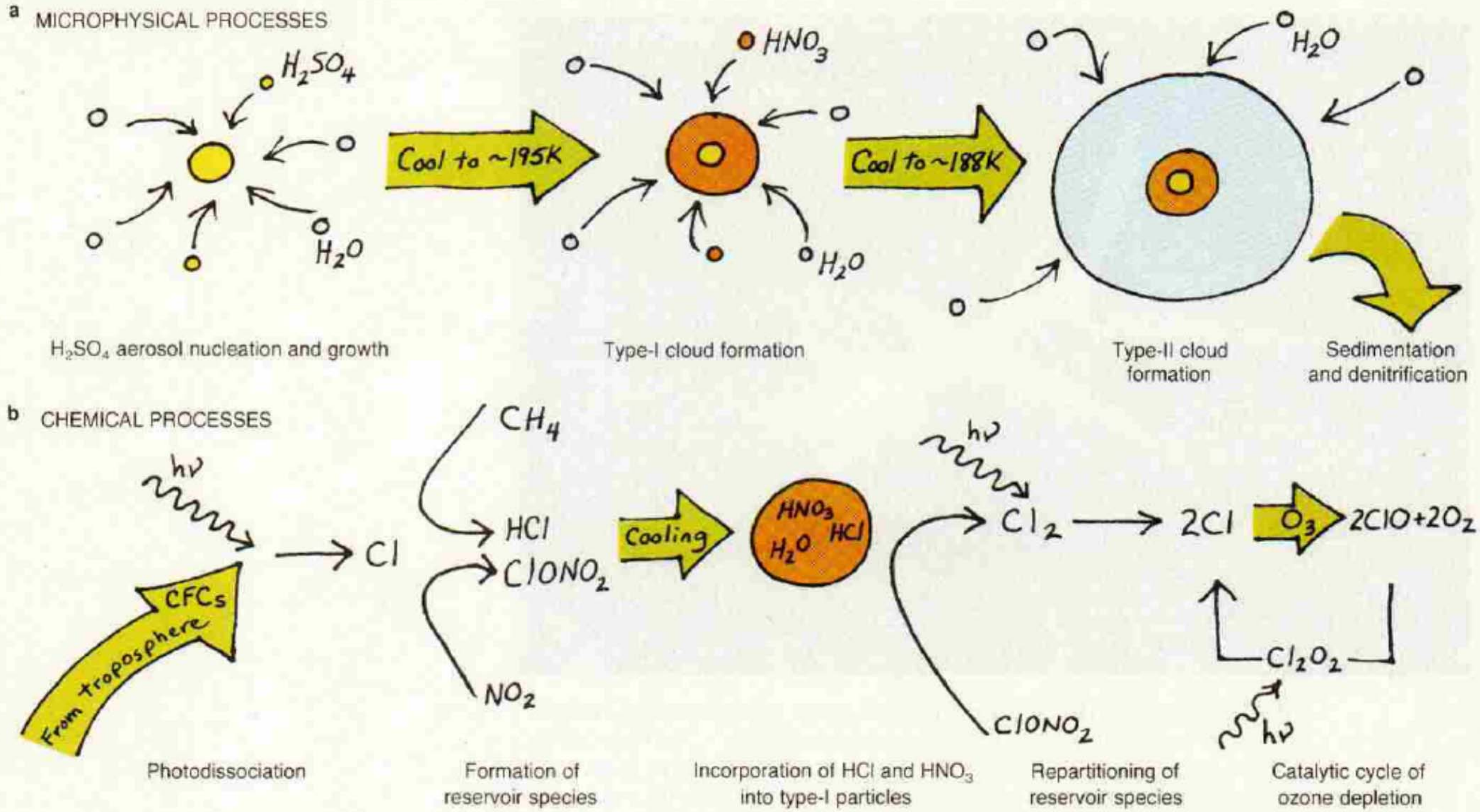
FIG. 2. Calculated trajectories for precipitation particles originating at A and B and growing by deposition and riming over the Cascade Mountains in a westerly airstream for the following specified concentrations (liter^{-1}) of ice particles: 1 (solid line), 25 (dashed line), 100 (dotted line). The number at the end point of each trajectory is the total mass (mg) of precipitation which reaches the ground at that point originating in a volume of 1 liter at the starting point of the trajectory.



Homogeneous freezing sensitivity to aerosol concentration

Polar stratospheric clouds (PSC) and ozone depletion





Cloud particles may contribute to ozone destruction by depleting the stratosphere of nitrogen compounds and providing sites for heterogeneous reactions. **a:** Frozen sulfate particles in the stratosphere seed the heterogeneous nucleation of nitric acid particles. When the temperature drops to about 188 K, water-ice particles form. These particles can grow quite large and, through gravitational sedimentation, fall from the stratosphere. **b:** Chlorofluorocarbons photodissociate to form highly reactive chlorine. Chlorine can react with nitrogen compounds and methane to form less reactive "reservoir species." Sedimentation of the cloud particles denitrifies the polar stratosphere, eliminating this sink for reactive chlorine. Reactions of reservoir species reintroduce reactive chlorine, which at high levels enters a nonlinear catalytic cycle that destroys ozone. **Figure 5**

Hamill and Toon 1991

Indirect effect ratio R_{IE}

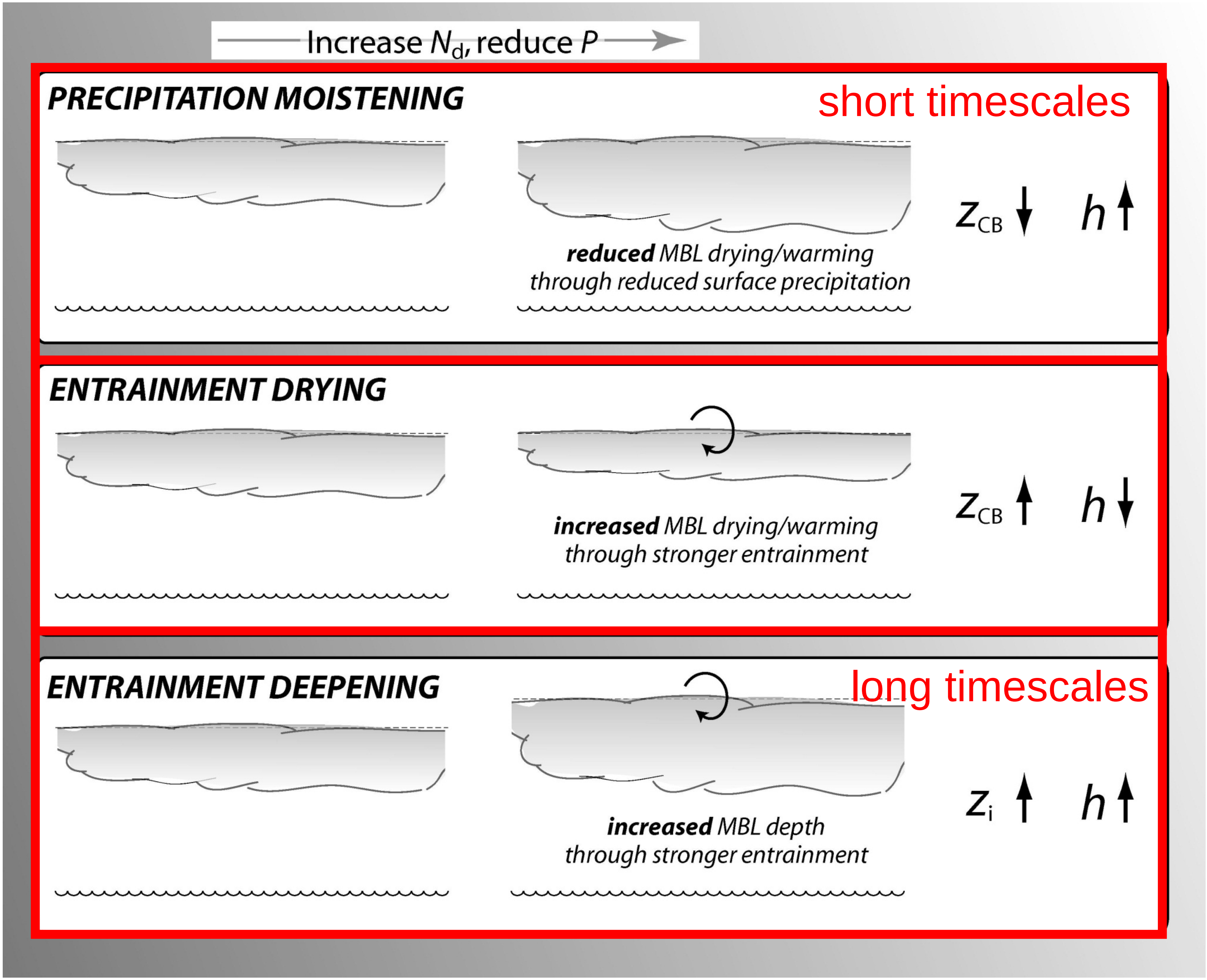
$$\frac{d\ln\tau}{d\ln N_d} = \underbrace{\left(\frac{\partial\ln\tau}{\partial\ln N_d}\right)_{LWP}} + \underbrace{\left(\frac{\partial\ln\tau}{\partial\ln LWP}\right)_{N_d}\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)_{\mathrm{ext}}}$$

For adiabatic cloud layers, $\tau \propto N_d^{1/3}\, LWP^{5/6}$

$$\frac{d\ln\tau}{d\ln N_d} = \frac{1}{3} + \frac{5}{6}\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)_{\mathrm{ext}}$$

$$\boxed{R_{IE} = \frac{5}{2}\left(\frac{\partial\ln LWP}{\partial\ln N_d}\right)_{\mathrm{ext}}}$$

Relative strength of the Albrecht effect compared with Twomey



Increase N_d, reduce P
PRECIPITATION MOISTENING
short timescales
reduced MBL drying/warming through reduced surface precipitation
z_{CB} ↓ h ↑
ENTRAINMENT DRYING
increased MBL drying/warming through stronger entrainment
z_{CB} ↑ h ↓
ENTRAINMENT DEEPENING
long timescales
increased MBL depth through stronger entrainment
z_i ↑ h ↑

Albrecht effect can enhance <u>or</u> cancel the Twomey effect