Global Indirect Aerosol Effects: A Review

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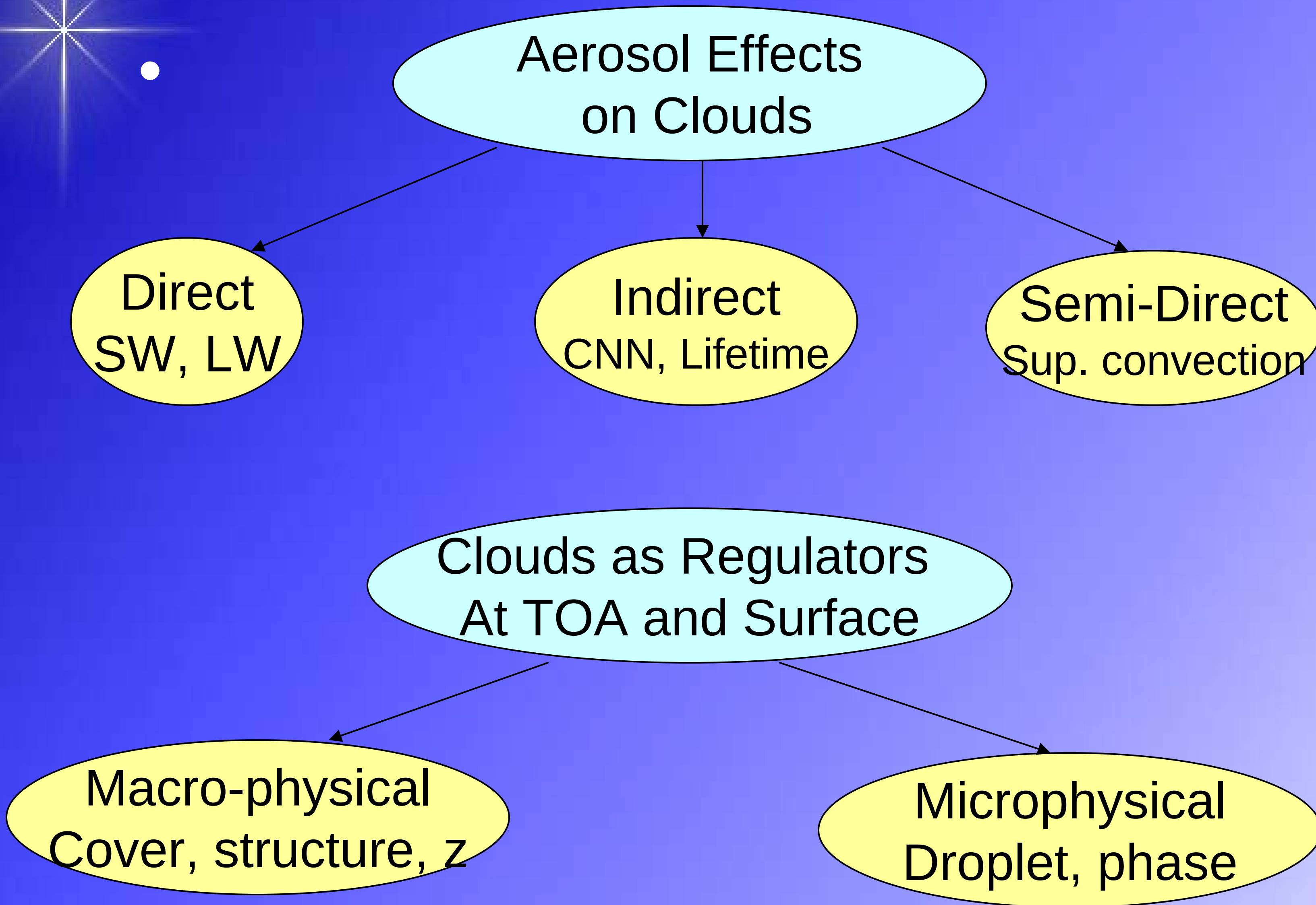
Presentation by Yanping He

1 Introduction



Global Aerosol Effects on Radiation Budget at TOA and Surface

Table 1. Overview of the different aerosol indirect effects and range of the radiative budget perturbation at the top-of-the atmosphere (F_{TOA}) [$W\,m^{-2}$], at the surface (F_{SFC}) and the likely sign of the change in global mean surface precipitation (P) as estimated from Fig. 2 and from the literature cited in the text.

Effect	Cloud type	Description	F_{TOA}	F_{SFC}	P
Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)	All clouds	The more numerous smaller cloud particles reflect more solar radiation	−0.5 to −1.9	similar to F_{TOA}	n/a
Indirect aerosol effect with varying water amounts (cloud lifetime effect)	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	−0.3 to −1.4	similar to F_{TOA}	decrease
Semi-direct effect	All clouds	Absorption of solar radiation by soot may cause evaporation of cloud particles	+0.1 to −0.5	larger than F_{TOA}	decrease
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay the onset of freezing	?	?	increase or decrease
Glaciation indirect effect	Mixed-phase clouds	More ice nuclei increase the precipitation efficiency	?	?	increase
Riming indirect effect	Mixed-phase clouds	Smaller cloud droplets decrease the riming efficiency	?	?	decrease
Surface energy budget effect	All clouds	Increased aerosol and cloud optical thickness decrease the net surface solar radiation	n/a	−1.8 to −4	decrease

2 Aerosol Effects on Water Clouds: Definitions

- Twomey effect (smaller droplet)

The Twomey effect refers to the enhanced reflection of solar radiation due to the more but smaller cloud droplets in a cloud whose liquid water content remains constant (Twomey, 1959).

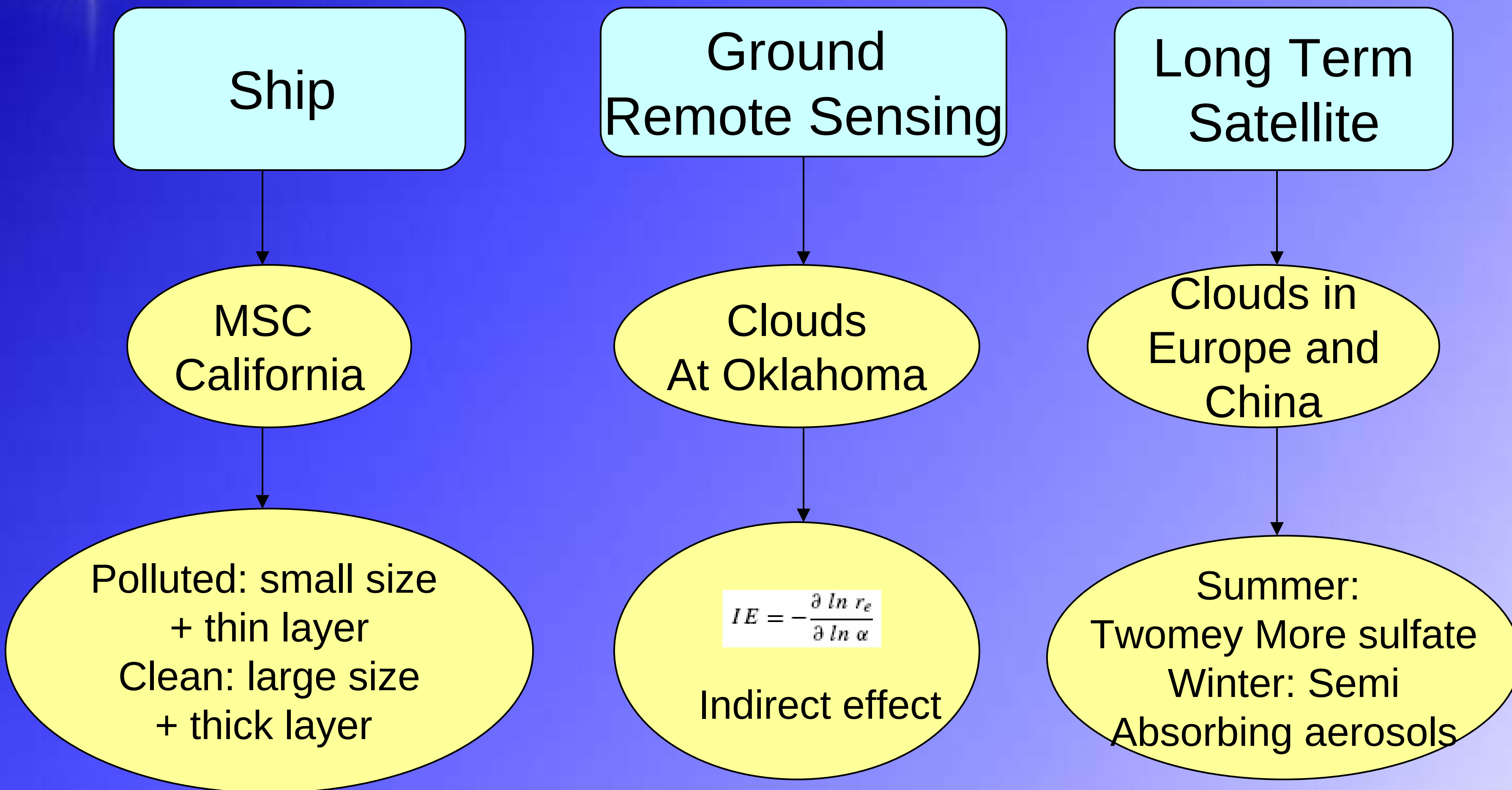
- Second indirect effect (longer lifetime)

The more but smaller cloud droplets reduce the precipitation efficiency and therefore enhance the cloud lifetime and hence the cloud reflectivity, which is referred to as the cloud lifetime or second indirect effect (Albrecht, 1989).

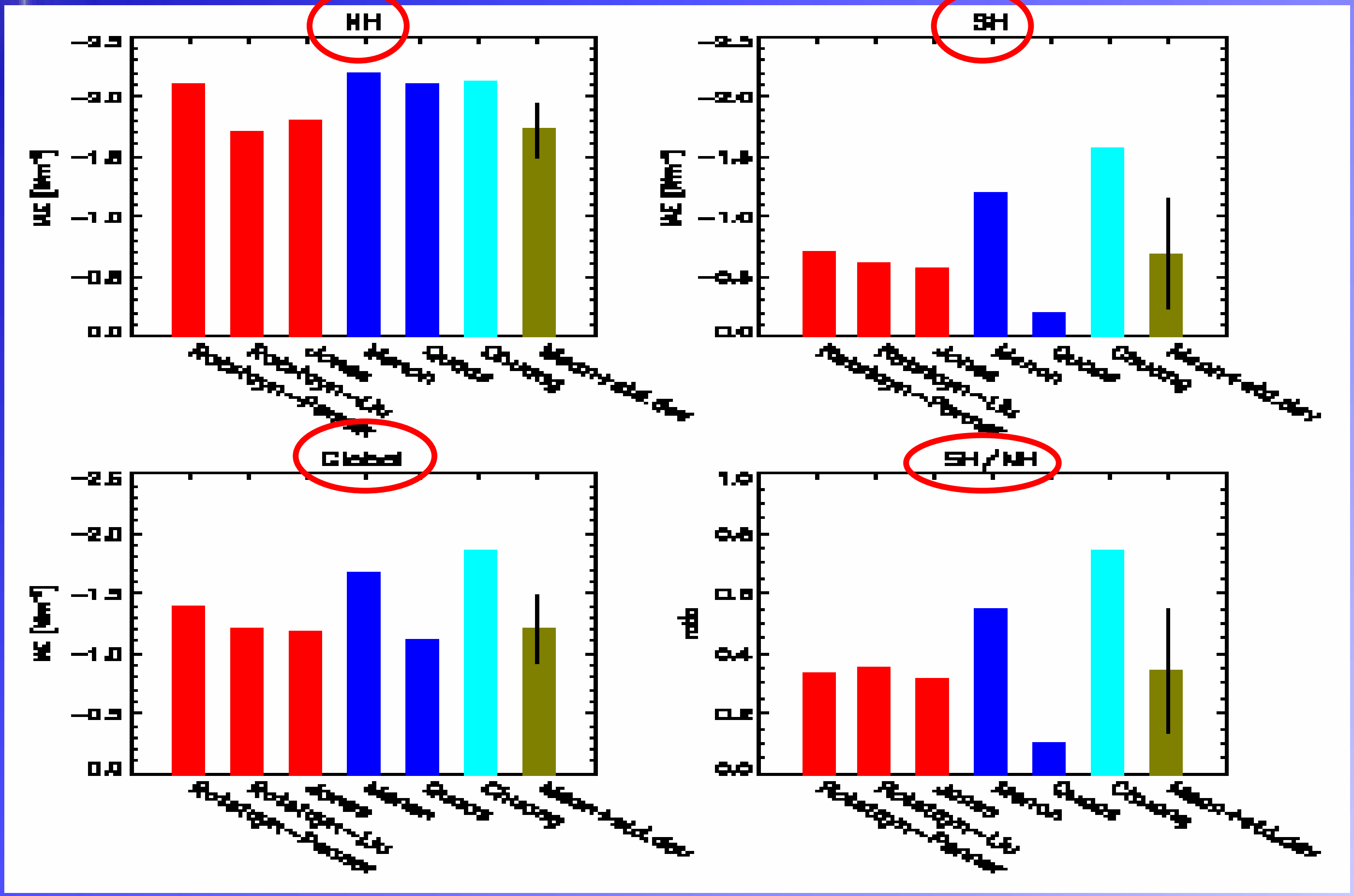
- Semi-direct effect (evaporating droplet)

Absorption of solar radiation by aerosols leads to a heating of the air, which can result in an evaporation of cloud droplets. It is referred to as semi-direct effect (Graßl, 1979; Hansen et al., 1997).

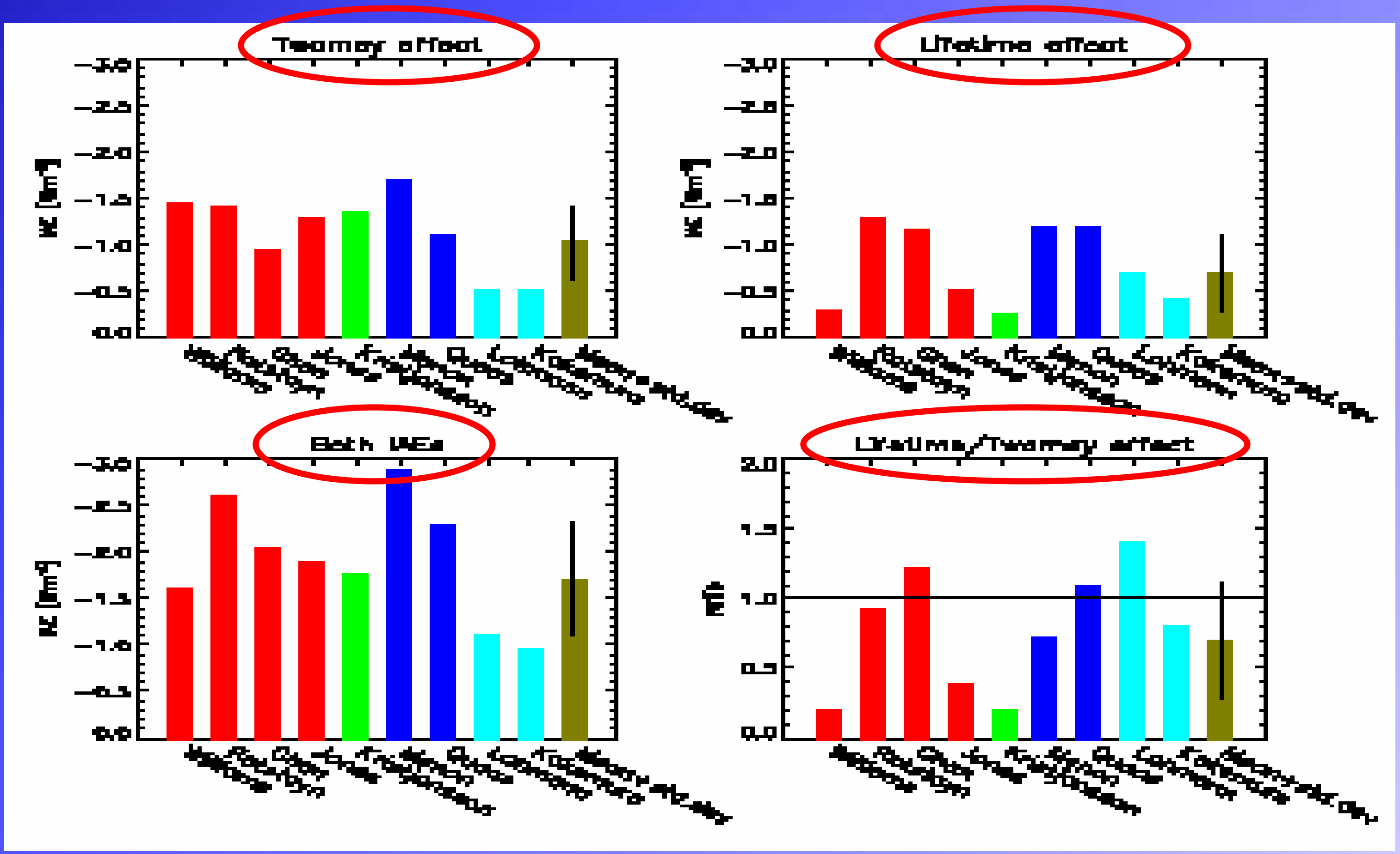
2.1 Evidence of aerosol effects on warm clouds from observation data



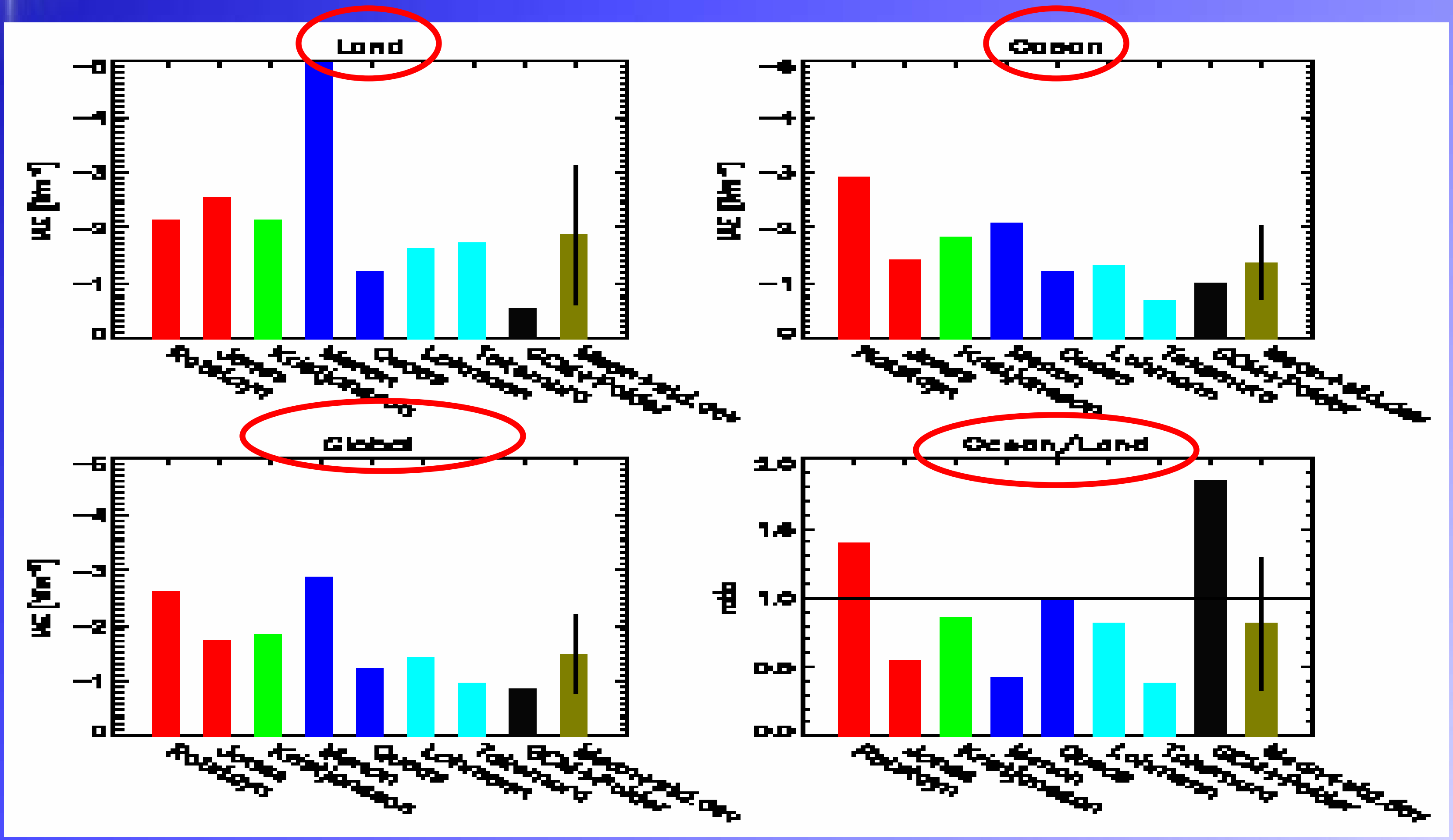
GCM simulated global mean Twomey effect and its contributions



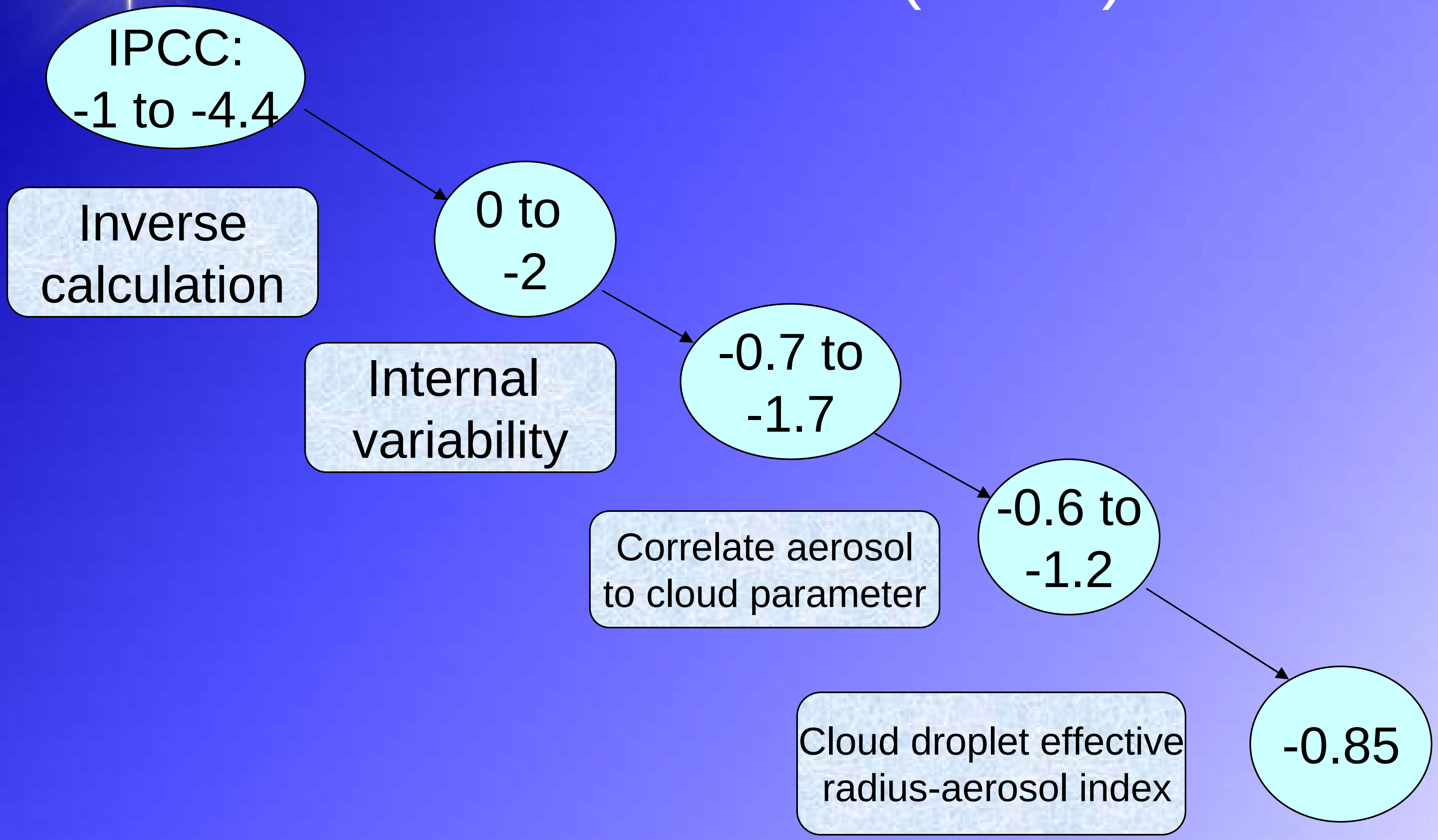
GCM simulated global mean Twomey effect verse Lifetime effect



GCM simulated global mean Twomey effect and Lifetime effect: Land vs. Ocean



Constraints on the estimated global indirect effect (W/m2)



Dispersion Effect and Semi-Direct Aerosol Effect

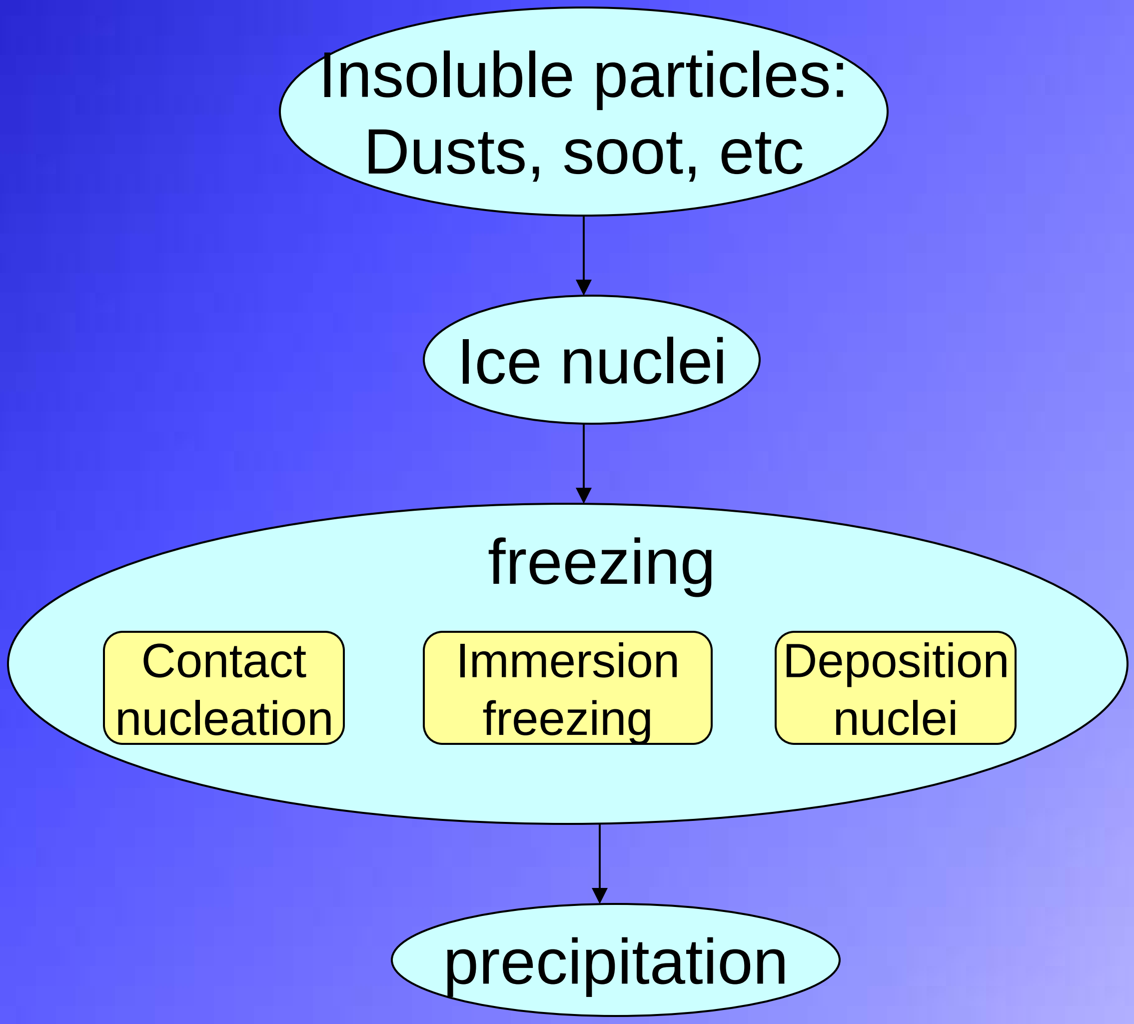
- Dispersion effect

  Liu and Daum (2002) estimated that the magnitude of the Twomey effect can be reduced by 10–80% by including the influence that an increasing number of cloud droplets has on the shape of the cloud droplet spectrum (dispersion effect). Taking this dispersion effect in global climate models into account, this reduction is rather moderate and amounts only to 15–35%

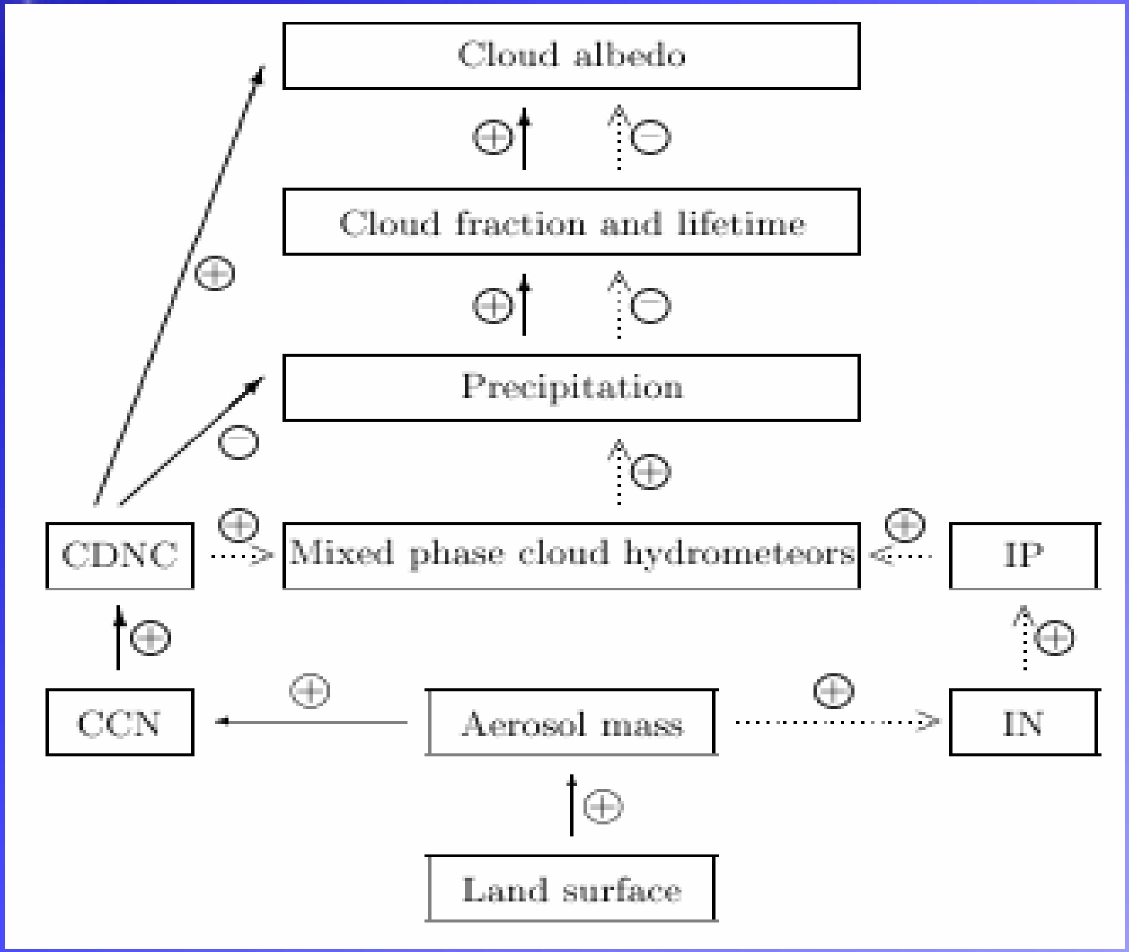
- Semi-Direct effect

  Lohmann and Feichter (2001); Kristj´ansson (2002), and Penner et al. (2003) concluded that the semi-direct effect is only marginally important at the top of the atmosphere in the global mean whereas Jacobson (2002) pointed out that the climatic effect of black carbon is strongly positive.

3: Aerosol Effects on Mixed-Phase Clouds: large-scale mixed-phase clouds

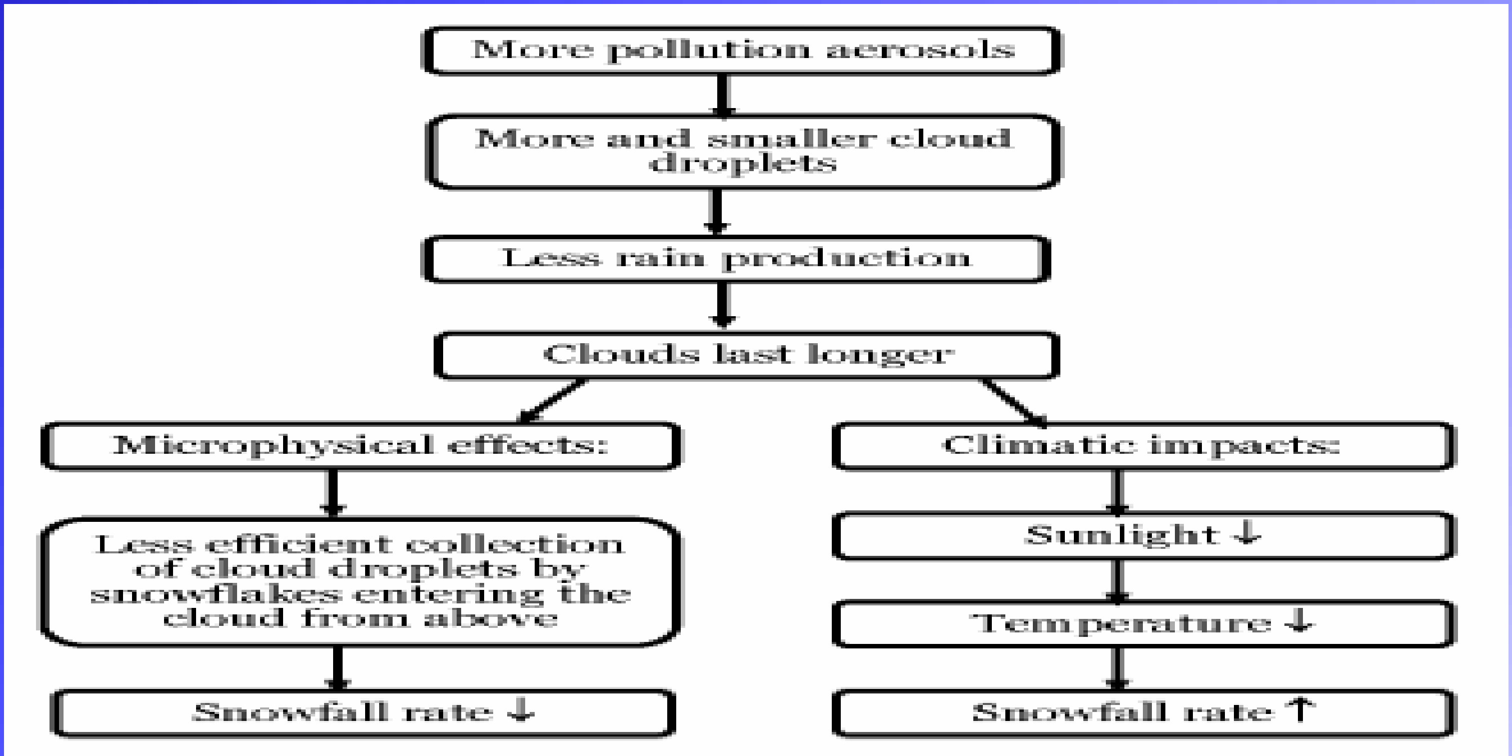


Glaciation indirect effect



Lohmann (2002a) showed that if, in addition to mineral dust, a fraction of the hydrophilic soot aerosol particles is assumed to act as contact ice nuclei at temperatures between 0C and −35C, then increases in aerosol concentration from pre-industrial times to present-day pose a new indirect effect, a "glaciation indirect effect", on clouds as shown in Fig. 4.

3: Aerosol Effects on Mixed-Phase Clouds: Thermodynamic Effect on Deep Convective Clouds



4 Aerosol Effects on Ice Clouds: (1) contrails

The “indirect” effect is due to the impact of an increase in FN (freezing nuclei) in the upper troposphere regions due to particulates from aircraft emissions. These FN act as nuclei for ice crystals which form cirrus clouds.

Supported Observations

(1)Ship observations in the 1980s

(2) surface database in US from 1971 to 1995;

(3) ISCCP 2% per decade over the North Arctic And the winter of North American

GCMs?

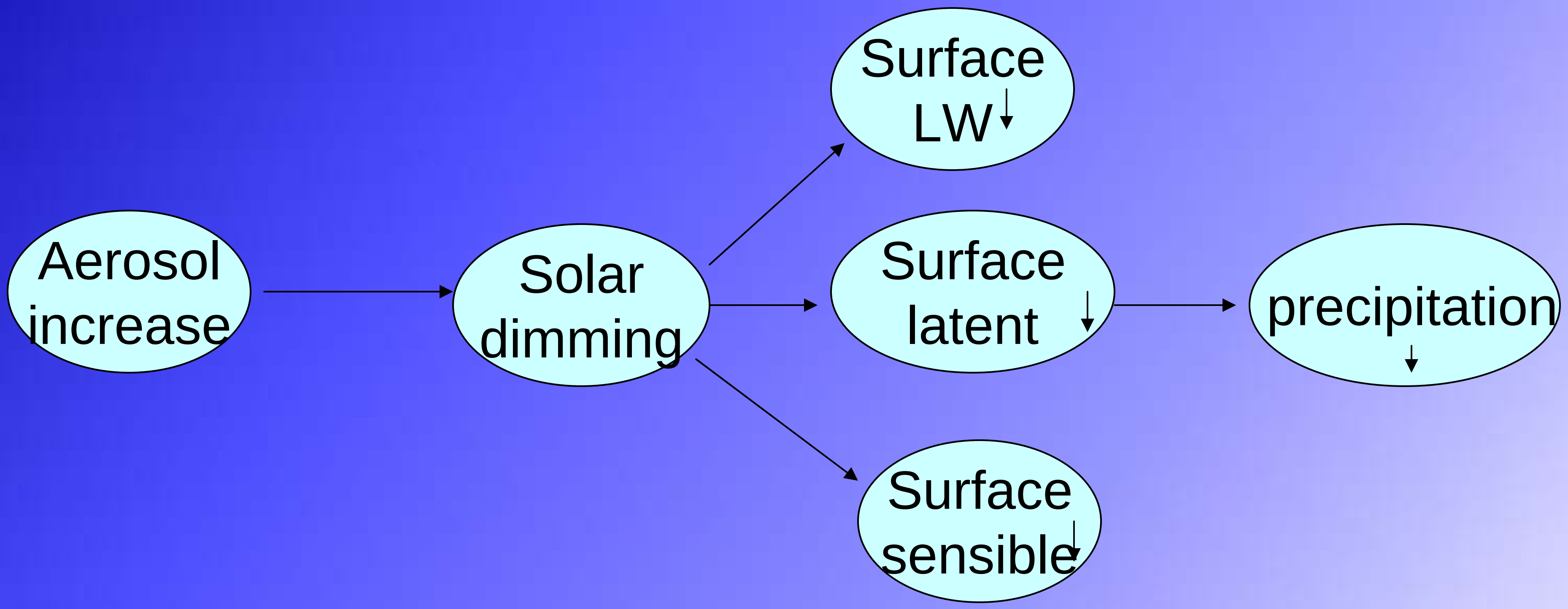
4 Aerosol Effects on Ice Clouds: (2) cirrus clouds

- Twomey effect

- Radiative effect in the infrared.

5 Aerosol Induced Changes of the Surface Energy Budget and Aerosol Effects on Precipitation

$$F_{sw} = F_{lw} + F_l + F_s + F_{cond}$$



6 Aerosol Effects on the Vertical Stability of the Atmosphere

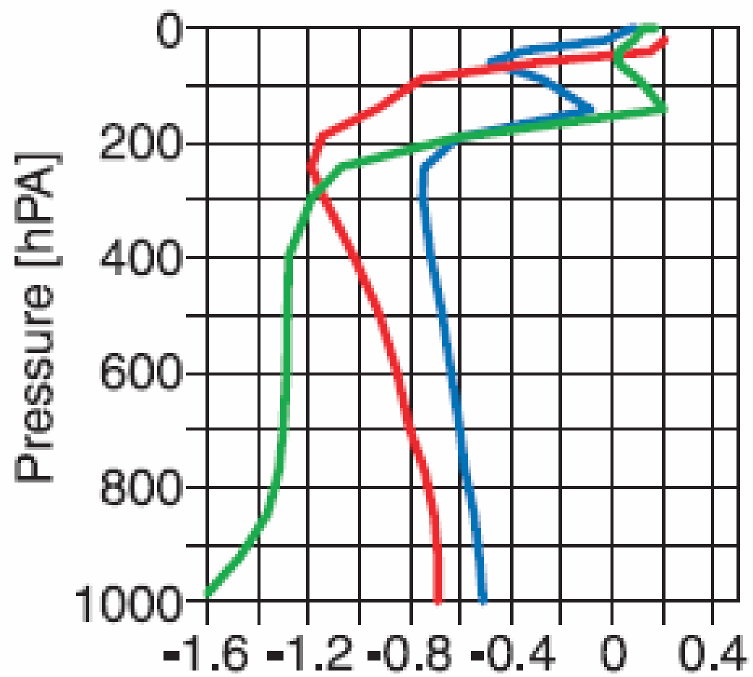


Fig. 6. Changes of the vertical temperature profile due to aerosol effects in K between pre-industrial and present-day conditions: 40° S–40° N (red), 40° N–90° N (green), 40° S–90° S (blue) based on Feichter et al. (2004).

7 Indirect Aerosol Effect-Forcing or Response: Definition of Radiative Forcing

- "The radiative forcing of the surface-troposphere system due to the perturbation in or the introduction of an agent is the change in net irradiance at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with the surface and tropospheric temperatures and state held fixed at the unperturbed values."

Limitations

(1) Holds for long-lived greenhouse gases and direct effects of scattering aerosols;

(2) Breaks down once an absorbing aerosol such as black carbon;

(3) Also precludes all aerosol effects that comprise microphysically induced changes in the water substance.

7 Indirect Aerosol Effect-Forcing: Classical verse New Approaches

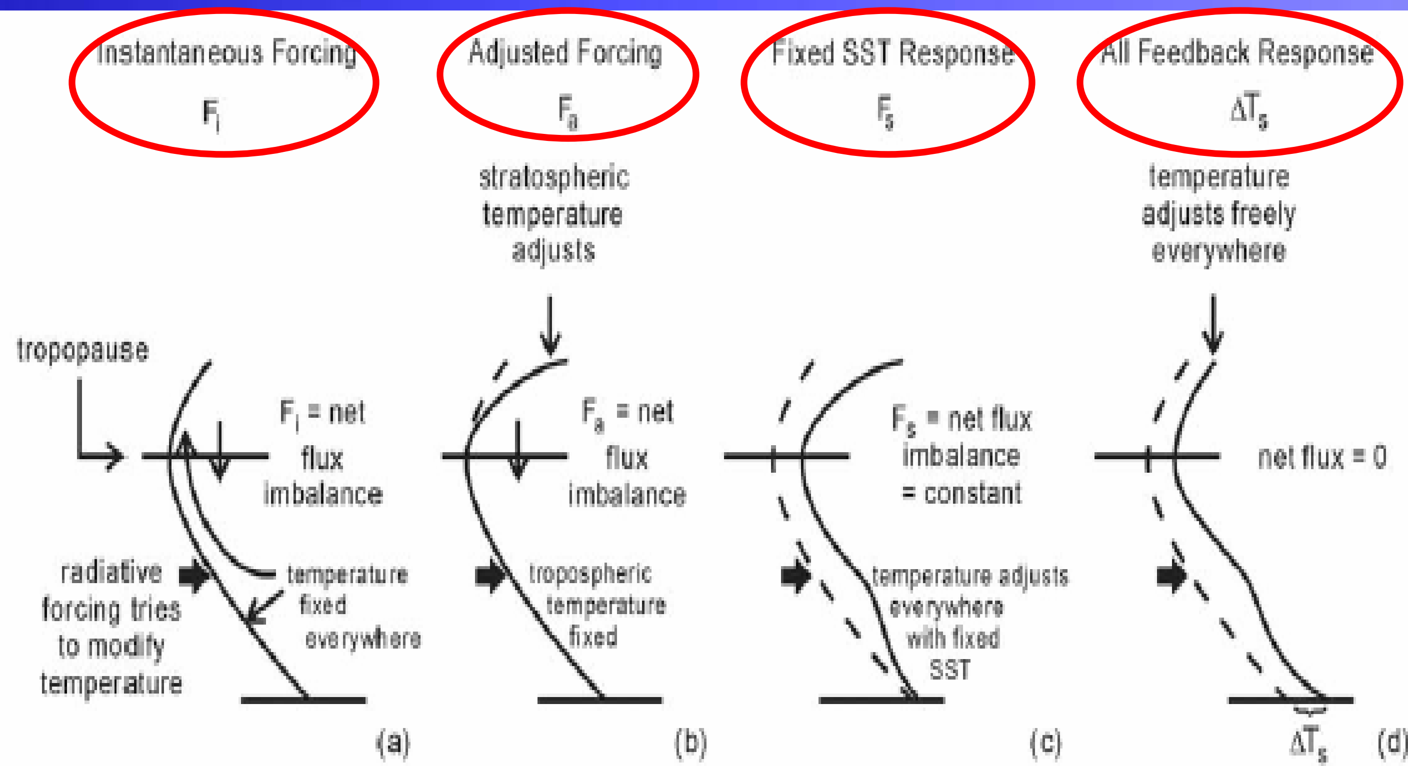


Fig. 7. Cartoon comparing (a) F_i, instantaneous forcing, (b) F_a, adjusted forcing, which allows stratospheric temperature to adjust, (c) F_s, fixed sea surface temperature forcing, which allows atmospheric temperature and land temperature to adjust, and (d) ΔT_s, equilibrium surface air temperature response (with courtesy from Hansen et al., 2002).

Table 2. Instantaneous Forcings F_i ($W m^{-2}$), surface temperature response T_{sfc} (K), climate sensitivities λ ($K m^2 W^{-1}$), efficacies E and effective forcings F_e as defined in the text for different forcing agents and from different coupled equilibrium climate model/mixed-layer ocean simulations (asterisks denote fixed sea surface temperature forcing, WM-GHGs=well mixed greenhouse gases, AP=tropospheric aerosol particles.)

Experiment	F_i	T_{sfc}	λ	E	F_e	Reference
WM-GHGs: 1860–1990	2.12	1.82	0.86	1	2.12	based on Roeckner et al. (1999)
$2\times CO_2$	3.48	3.52	1.01	1	3.48	Rotstayn and Penner (2001)
1880–2000	2.52	1.21	0.48	1	2.52	Hansen et al. (2005)[3]
Direct effect: SO_4	–0.34	–0.24	0.71	0.83	–0.28	based on Roeckner et al. (1999)
SO_4	–0.80	–0.55	0.69	0.68	–0.55	Rotstayn and Penner (2001)
all AP	–0.54*	–0.28	0.52	1.08	–0.58	Hansen et al. (2005)[3]
Twomey effect: SO_4	–0.89	–0.78	0.87	1.01	–0.90	based on Roeckner et al. (1999)
SO_4	–1.35	–1.14	0.84	0.83	–1.12	Rotstayn and Penner (2001)
all AP	–0.77*	–0.38	0.49	1.03	–0.79	Hansen et al. (2005)[3]
Lifetime effect: SO_4	–1.32*	–1.04	0.79	0.78	–1.03	Rotstayn and Penner (2001)
all AP	–1.01*	–0.45	0.45	0.93	–0.94	Hansen et al. (2005)[3]
Total indirect: SO_4	–2.57*	–2.24	0.87	0.86	–2.21	Rotstayn and Penner (2001)
All aerosol effects (direct and indirect	–1.40*	–0.87	0.62	0.72	–1.01	Feichter et al. (2004), F_i from Lohmann and Feichter (2001)
on water clouds)	–2.34*	–1.15	0.49	1.02	–2.40	Hansen et al. (2005)[3]

7.3 Additivity of the different forcing agents

Indirect aerosol forcing and cloud feedback are intimately coupled.

8 Feedbacks of Clouds on Aerosols

- Posivitive feedbacks between sulfate aerosols and the precipitation formation;
- Negative feedbacks between black carbon and the precipitation formation for mixed-phase clouds.

8 Feedbacks of Clouds on Aerosols

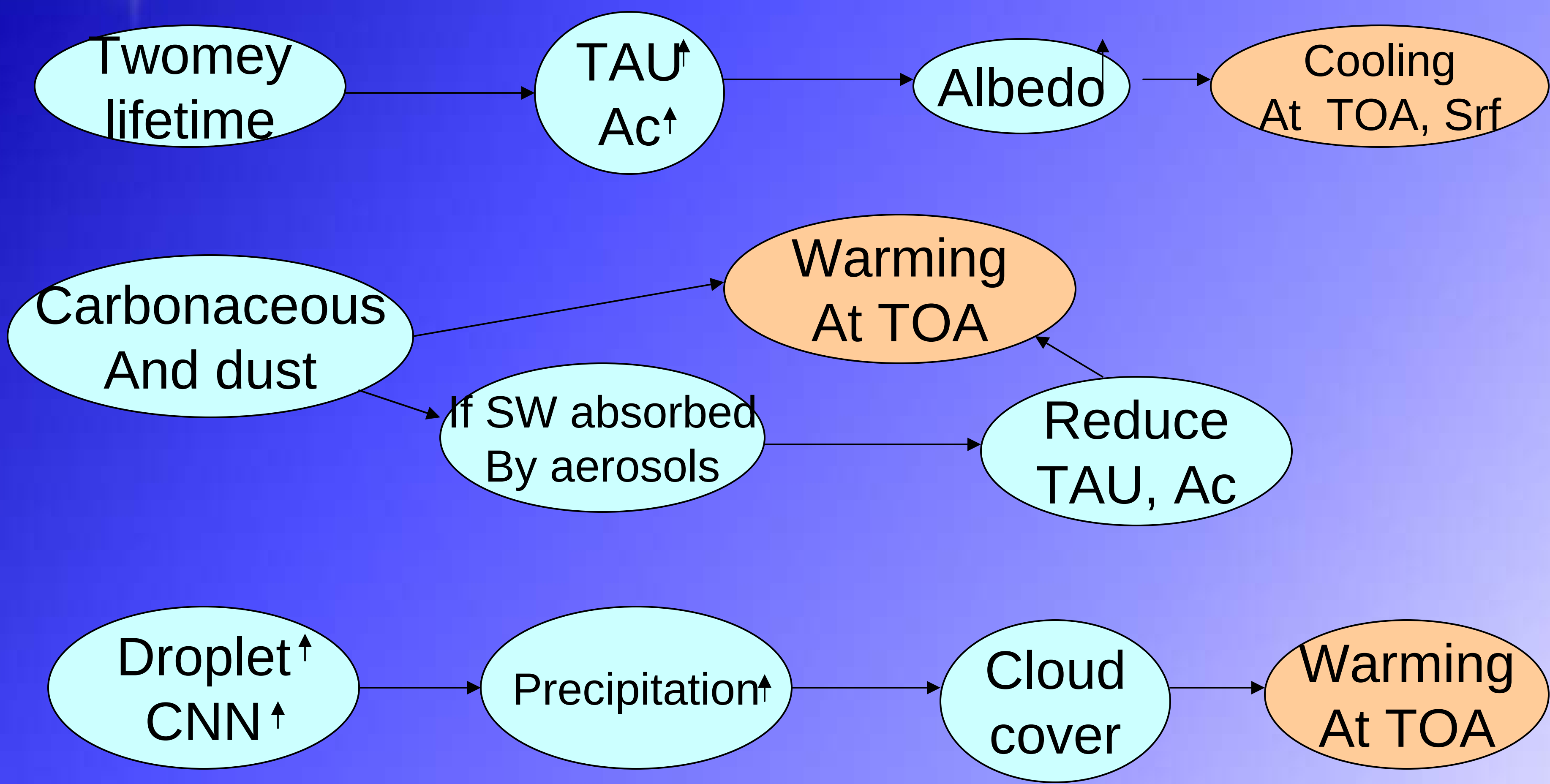
Experiment	ΔT	ΔP	$\Delta P/\Delta T$
present-day aerosol conc., varying GHG conc.	1.3	2.3	1.7
Varying aerosol conc., fixed GHG conc.	–0.9	–3.5	3.9
Varying aerosol and GHG conc.	0.6	–1.1	–1.9

Table 3. Hydrological sensitivity estimated from different pairs of coupled equilibrium ECHAM4 climate model/mixed-layer ocean simulations with an interactive aerosol module.

9 Uncertainties and Needs for Improvements in the Representation of Aerosol Effects on Clouds in Global Climate Models

- Representation of aerosols
- Cloud droplet formation
- Treatment of large-scale clouds
- Treatment of convective clouds
- Subgrid-scale variability and radiative transfer

10 Conclusions (1)
Aerosol radiative effects



10 Conclusions (2)
Aerosol effects on hydrological cycle

- Suppression of drizzle is part of the cloud lifetime effect as being shown most clearly from ship track studies, but GCMS show opposite.
- Aerosols may change the occurrence and frequency of convection and thus could be responsible for droughts and flood simultaneously.
- Aerosols may cause reductions in the net solar radiation reaching the surface; the evaporation could decrease and the hydrological cycle could be expected to slow down.
- The cooling of the Northern Hemisphere causes a southward shift of ITCZ=> Sahelian drought
- Anthropogenic aerosols could influence mixed-phase clouds by retarding the onset of freezing due to their smaller size (thermodynamic process), by acting as ice nuclei in the different freezing modes and hence speeding up the Bergeron-Findeisen process (glaciation effect) and by the reducing the riming process.