

# Indirect Effects

## *An Historical Perspective*

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# Disclaimer

- Huge amount of material – a complete historical review would take a book (and a group of authors!)
- Apologize for omitting research that someone else holds dear
- Not going to spend a lot of time on satellite remote sensing

# A reminder

- Clouds exist because of dynamical motions, particularly updrafts
- Existence is the first order radiative perturbation
- Moisture availability is the principal driver of cloud optical depth, the second order radiation perturbation
- Microphysics is the third order radiative perturbation

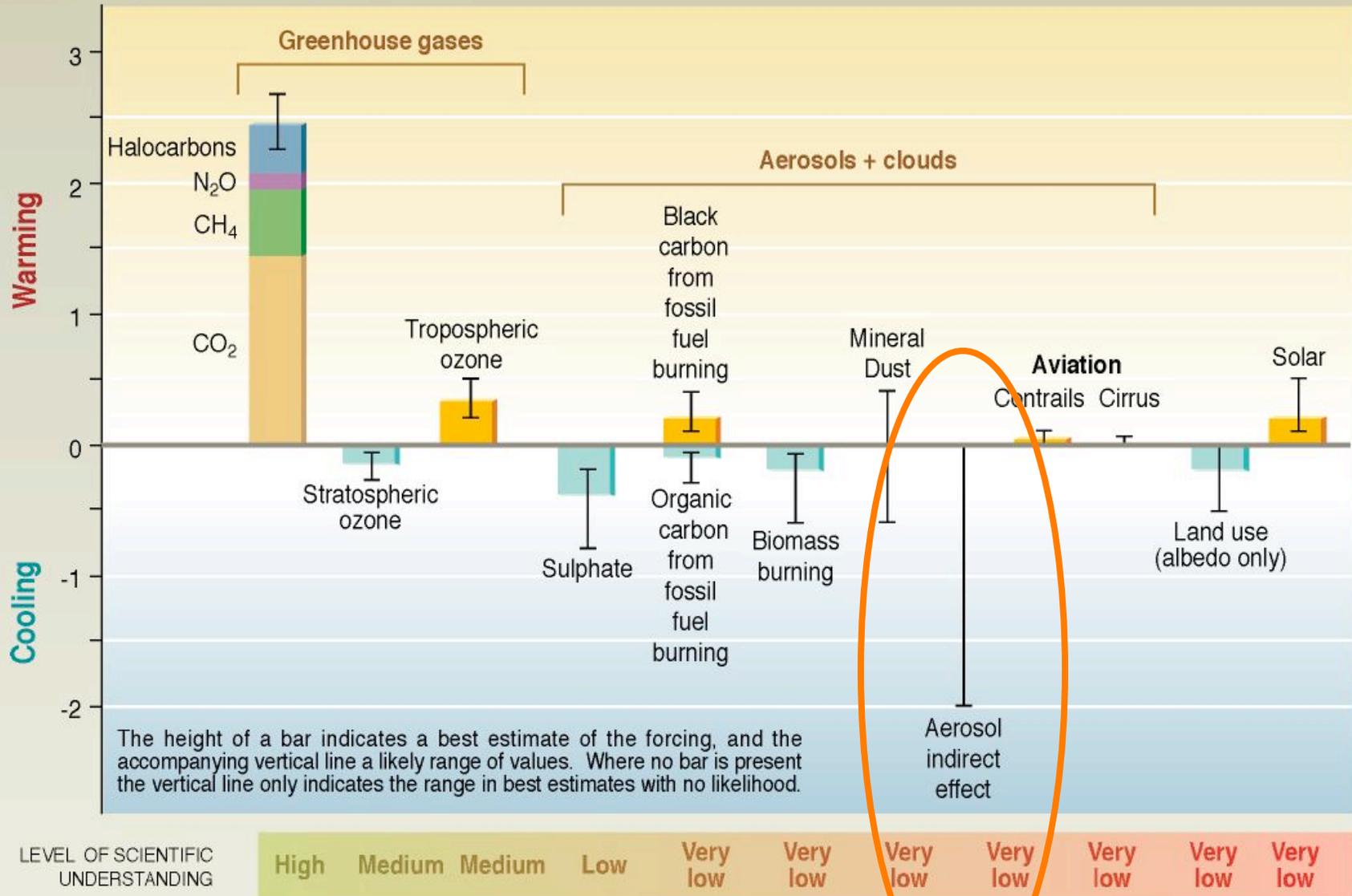
# Joachim Joseph (Tel Aviv University) WMO / IAMAP Meeting, 1983

There is still, in many circles, a general lack of appreciation of the potential importance of aerosols as an agent for climatic change or for acquisition of the necessary data to study the latter. In particular, there is no appreciation of possible direct effects of aerosols on the energy balance or on clouds, on cloud formation and on remote sensing. This final problem can only be ameliorated by showing aerosol effects to be significant and relevant either in nature or in models.

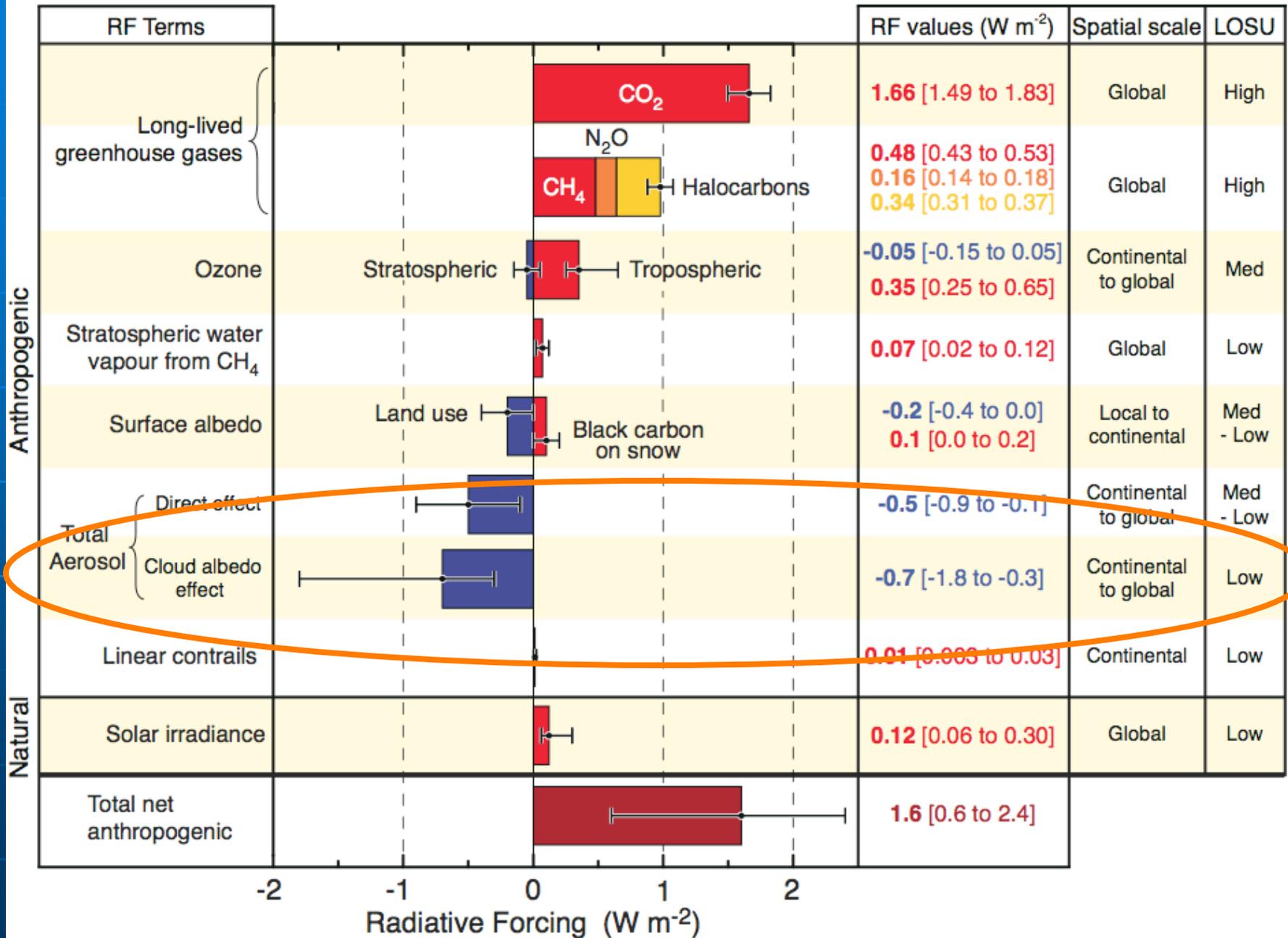
Are we appreciated now?

# Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing ( $Wm^{-2}$ )



# Radiative Forcing Components



# We started (1950 – 1970) with three distinct aerosol communities

- Radiation – climate
  - Direct effects
- Cloud physics
  - Cloud droplet nucleation
  - Cloud seeding
- Atmospheric chemistry
  - Air pollution
  - Health effects

# The beginning

- Inadvertent climate modification – precipitation anomalies downwind of urban areas
  - Stanley Chagnon (Illinois State Water Survey), BAMS, 1968: LaPorte anomaly – identified a precipitation deficit near LaPorte Indiana downwind of Chicago
  - Jack Warner and Sean Twomey (CSIRO) JAM, 1968: Reduction in rainfall associated with smoke from sugarcane fires

# Earl Barrett (NOAA?) IEEE, 1978: Man and Climate: An Overview

Aerosols can also act as modifiers of clouds. The hygroscopic sulfates and other soluble or wettable species act as cloud condensation nuclei (CCN) on which all cloud droplets must form; they may also serve as ice nuclei (IN) which induce supercooled cloud drops to freeze and grow faster as ice crystals ... One would expect to find differences in the statistics of clouds and precipitation in the vicinity of urban particle sources. The well known London "pea-soup" fogs come immediately to mind in this connection. Remarkable decreases in fog density and frequency in London and other British cities took place after the Clean Air Act of 1956 went into effect. Kew Observatory experienced 50 percent more hours of sunshine in winter during the period 1958-1967 as compared with the mean for the climatological epoch 1931-1960

# Earl Barrett (NOAA?) IEEE, 1978: Man and Climate: An Overview

METROMEX (experiment in and around St. Louis):  
... preliminary reports show that rainfall, lightning frequency, and hail attain maxima 15-25-km downwind from the city. Chemical tracers were used to verify the entry of the urban aerosols into convective clouds; these experiments showed that heated and polluted plumes did rise from the city and enter the clouds. Increases in CCN counts inside the clouds of 50-90 percent were measured; clouds affected by these nuclei differed in their drop-size distributions from upwind clouds in just the way predicted by a cloud microphysical model.

## Committee on the Status and Future Directions in U.S Weather Modification Research and Operations, National Research Council, 2003

The Committee concludes that there still is no convincing scientific proof of the efficacy of intentional weather modification efforts. In some instances there are strong indications of induced changes, but this evidence has not been subjected to tests of significance and reproducibility. This does not challenge the scientific basis of weather modification concepts. Rather it is the absence of adequate understanding of critical atmospheric processes that, in turn, lead to a failure in producing predictable, detectable, and verifiable results.

# Conclusion?

- Large sources of pollutants can modify clouds, but effects may be commingled with those from surface heating and moisture changes
- Cloud seeding – deliberate attempts to modify clouds with aerosol – have not been shown to be successful
- What does this say about indirect effects?

# Indirect Aerosol Effects

- **The effect of increasing CCN (the Twomey effect)**

Sean Twomey (U. Arizona) JAS 1977:  
The Influence of Pollution on the Shortwave  
Albedo of Clouds

Pollution may increase or decrease the brightness of clouds depending on the optical thickness of the clouds and the way in which cloud nucleus concentration varies with absorption optical thickness. Plausible assumptions concerning the latter lead to results which suggest that in all but the thickest clouds the pollution increases the albedo. Since most of the earth's cloud cover is in the form of clouds which are not very thick this result suggests that the planetary albedo also will increase with increase of pollution.

# Jim Coakley ( NCAR), Science 1987: Effect of Ship-Stack Effluents on Cloud Reflectivity

The exhaust is a source of cloud-condensation nuclei that increases the number of cloud droplets while reducing droplet size. This reduction in droplet size causes the reflectivity at 3.7 micrometers to be greater than the levels for nearby non-contaminated clouds of similar physical characteristics. The increase in droplet number causes the reflectivity at 0.63 micrometer to be significantly higher for the contaminated clouds despite the likelihood that the exhaust is a source of particles that absorb at visible wavelengths. The effect of aerosols on cloud reflectivity is expected to have a larger influence on the earth's albedo than that due to the direct scattering and absorption of sunlight by the aerosols alone.

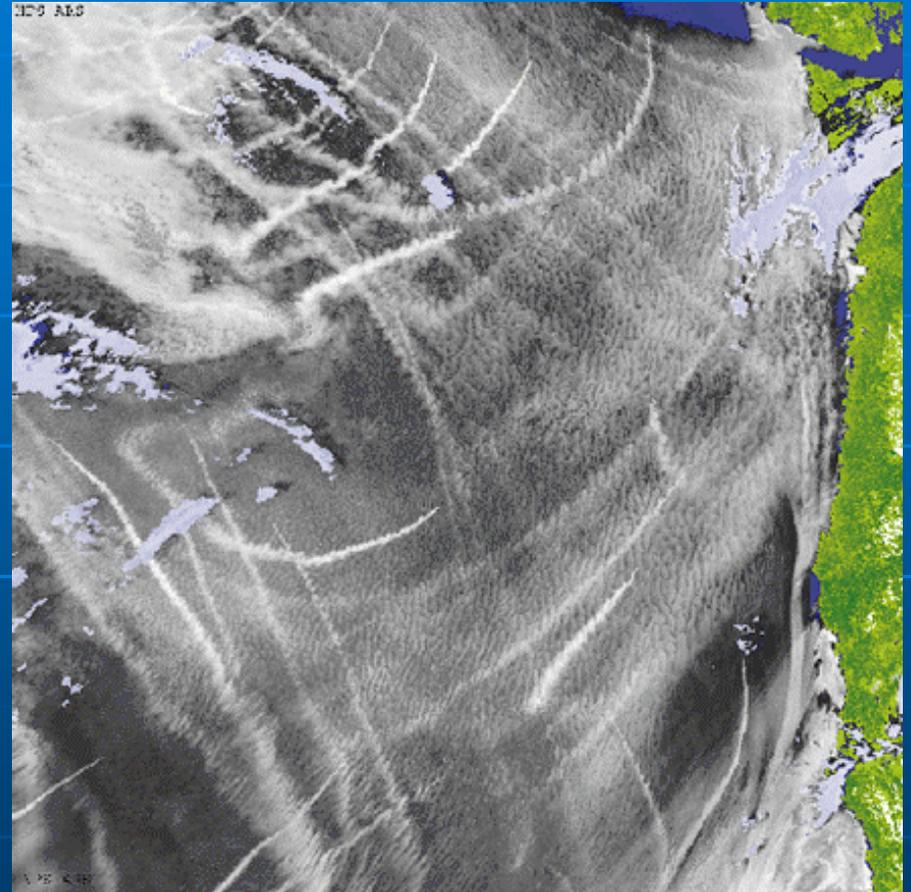


Image from Phil Durkee,  
NPGS

# Further efforts

- Bob Charlson and colleagues: Global sulfate; DMS and CCN
- Mike King and colleagues: Cloud absorption radiometer
- Graham Feingold: Inference of Twomey effect using ARM measurements (also Penner and Dong)
- Andy Ackerman and colleagues (boundary layer cloud modeling – role of environment and entrainment)

# Indirect Aerosol Effects

- The effect of increasing CCN (the Twomey effect)
- **Absorption**

# T. Ackerman and M. Baker (UW), JAM, 1977: Shortwave Radiative Effects of Unactivated Aerosol Particles in Clouds

The energy absorbed by particles within the clouds may be, for realistic concentrations, comparable to the latent heat released and thus may play a significant role in cloud dynamics in some areas.

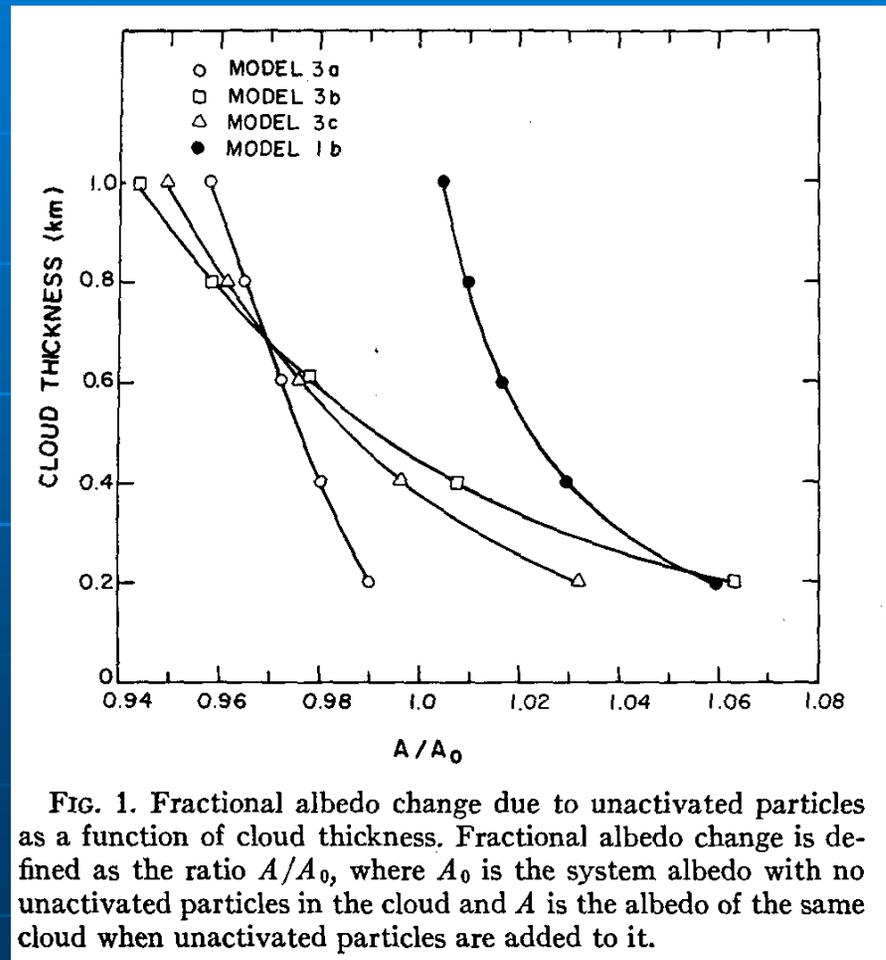


FIG. 1. Fractional albedo change due to unactivated particles as a function of cloud thickness. Fractional albedo change is defined as the ratio  $A/A_0$ , where  $A_0$  is the system albedo with no unactivated particles in the cloud and  $A$  is the albedo of the same cloud when unactivated particles are added to it.

# T. Ackerman and M. Baker (UW), JAM, 1977: Shortwave Radiative Effects of Unactivated Aerosol Particles in Clouds

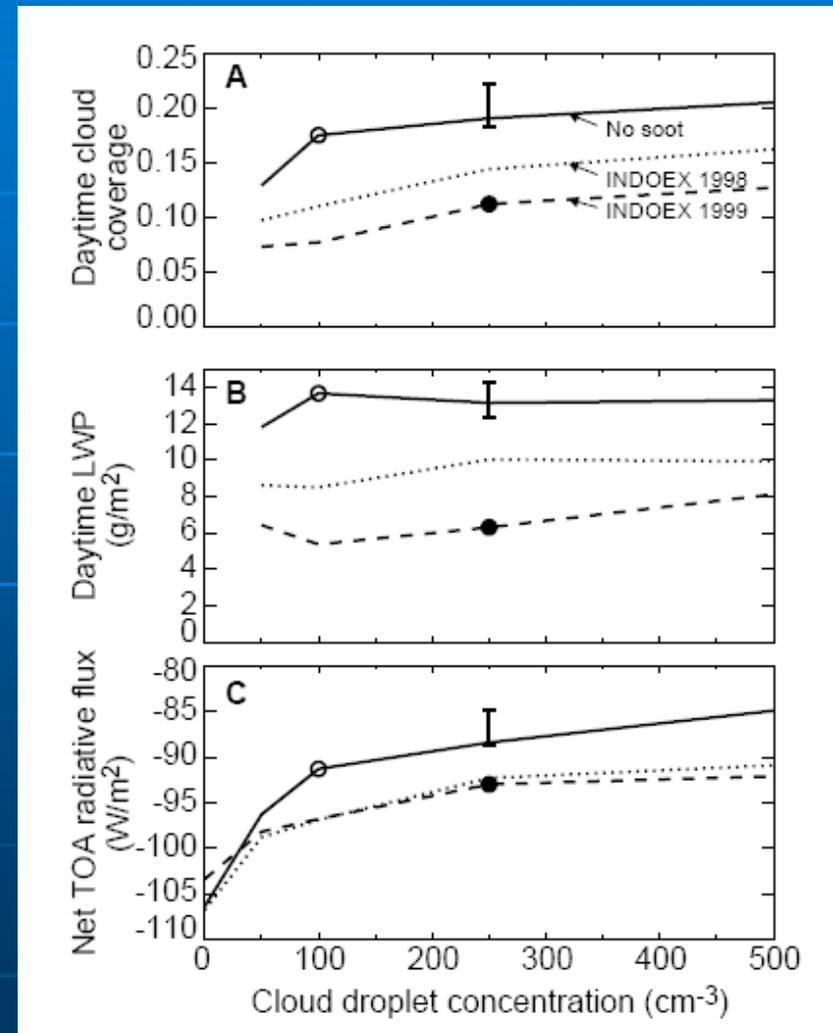
More complete calculations, incorporating spectral variation of the aerosol refractive index, a more realistic model of particle growth within the cloud, and possible effects of deformation of the cloud droplet spectrum by the addition of particles are needed in order to estimate the relative contributions of aerosols, water vapor and the liquid water in the radiation budget of clouds. It would be of interest to sample unactivated particles in clouds and to measure their physical and chemical properties, as well as their vertical distribution within clouds. Such measurements, although difficult to perform, may yield valuable information about possible anthropogenic influence on the radiative properties of stratus clouds.

# Absorption – microphysics

- Carbon in water droplets
  - Maxwell-Garnett mixing rules
  - Concentric spheres (Toon and Ackerman)
  - Carbon floating on water surface and dispersed through droplet (Chylek)

# Andy Ackerman et al. (NASA Ames) Science 2000: Reduction of tropical cloudiness by soot

Our results suggest that the pervasive presence of dark hazes contributed to the scarcity of clouds during INDOEX. It is likely that the lack of clouds was largely due to the dryness of air flowing off the Indian subcontinent, and the soot-effect served to diminish cloud cover even further.



# Indirect Aerosol Effects

- The effect of increasing CCN (the Twomey effect)
- Absorption
- **Cloud lifetime**

# Albrecht (Penn State) Science 1989: Aerosols, Cloud Microphysics, and Fractional Cloudiness

Increases in aerosol concentrations over the oceans may increase the amount of low level cloudiness through a reduction in drizzle – a process that regulates the liquid water content and the energetics of shallow marine clouds. The resulting increase in the global albedo would be in addition to the increase due to enhancement in reflectivity associated with a decrease in droplet size and would contribute to a cooling of the earth's surface.

# Follow-on studies

- Hard to observe lifetime directly but can observe precipitation suppression
- Radke, L. F., J. A. Coakley Jr., and M. D. King, *Science*, 1989: Direct and remote sensing observations of the effects of ships on clouds.
- Rosenfeld, D., *GRL*, 1999: TRMM observed first direct evidence of smoke from forest fires inhibiting rainfall.

And then there are the hundreds of  
articles on aerosol indirect effects

...

# So where are we?

- Twomey effect
  - Well understood and demonstrable
  - Assumes constant LWP => increase in cloud reflectivity
  - Not so clear when complete cloud system is integrated

# So where are we?

## ■ Cloud lifetime

- Only poorly understood
- Complex relationship between environment and cloud dynamics
- Can drive LWC both directions (increase due to reduced precipitation and decrease due to change in subcloud cooling)
- Differences between land and ocean cases

# So where are we?

- Cloud absorption
  - Very uncertain
  - Tends to drive cloud evaporation, but very hard to observe
  - Difficult to separate in-cloud from environmental effects in highly polluted regions

What are the issues?

# Aerosol characteristics

- Size distribution(s)
- Chemical composition by size
- Hygroscopicity
- Geographical distribution

=> if we know these characteristics, can we predict the number of CCN and how that changes with anthropogenic activity?

# Cloud response to CCN

- Supersaturation spectrum of CCN
- Updraft velocity
- Cloud dynamics in general
- Relationship between CCN change and droplet number (or size) is probably non-linear

# Cloud macroscopic properties

- Change in LWP with change in CCN
- Role of absorbing aerosol material
- Increased lifetime (or decreased lifetime)

# Global Model – First effort?

- Charlock and Sellers (U. Arizona) JAS 1980: Aerosol, Cloud Reflectivity and Climate

Present low-level CCN concentrations are about  $1000 \text{ cm}^{-3}$  (low-cloud reflectivity 0.80) over land and about  $100 \text{ cm}^{-3}$  (low-cloud reflectivity 0.65) over water. By doubling the CCN over both land and water, we increase low-cloud reflectivities by about 0.03 and 0.05, respectively. Hence a doubling of CCN would, by this calculation, increase global low-cloud albedo by about 0.045 and reduce surface temperature by  $(0.045)(19.4) \approx 0.9 \text{ K}$ .

# Global Model Estimates - Methodology

- Decide on effect to be parameterized (Twomey effect)
- Implement parameterization at microphysics level (more CCN in polluted areas lower effective radius)
- Run model with new parameterization
- Parameterization produces desired effect (lower effective radius produces higher albedo)
- Evaluate magnitude of effect (model allows for some feedback onto large scale)

TABLE 4. The Global-Mean Annual-Average Indirect Radiative Forcing Due to Aerosols From Different Global Studies

Reference	Aerosol Type	Forcing Estimate, $W m^{-2}$			Remarks
		Cloud Albedo	Cloud Lifetime	Both Effects	
<i>Boucher and Rodhe</i> [1994] <sup>a</sup>	SO <sub>4</sub>			-0.65 to -1.35	(P) use three relationships between SO <sub>4</sub> mass and CCN/CDN concentrations
<i>Chuang et al.</i> [1994]	SO <sub>4</sub>	-0.47			(C) include a parameterization of cloud nucleation processes
<i>Jones et al.</i> [1994]	SO <sub>4</sub>	-1.3			(P) use a relationship between aerosol and droplet number concentrations
<i>Boucher and Lohmann</i> [1995]	SO <sub>4</sub>	-0.5 to -1.4 -0.45 to -1.5			(P) LMD, GCM } use four different relationships between SO <sub>4</sub> and CCN/CDN concentrations (A, B, C, and D) (P) ECHAM }
<i>Jones and Slingo</i> [1996]	SO <sub>4</sub>	-0.3 to -1.5			(P) use two different SO <sub>4</sub> distributions; follow <i>Jones et al.</i> [1994] and <i>Boucher and Lohmann</i> [1995] "D"
<i>Kogan et al.</i> [1996, 1997]	SO <sub>4</sub>	-1.1			use a cloud climatology rather than GCM-simulated clouds
<i>Chuang et al.</i> [1997]	SO <sub>4</sub>	-0.4 to -1.6			(C) include a parameterization of cloud nucleation processes; use a mixture of preexisting aerosols
<i>Feichter et al.</i> [1997]	SO <sub>4</sub>	-0.76			(C) use <i>Boucher and Lohmann</i> [1995] "A" relationship
<i>Jones and Slingo</i> [1997]	SO <sub>4</sub>	-0.55 to -1.50			(P) use two different versions of the Hadley Centre model
<i>Lohmann and Feichter</i> [1997] <sup>a</sup>	SO <sub>4</sub>	-1		-1.4 to -4.8	(C) use <i>Boucher and Lohmann</i> [1995] "A" relationship
<i>Rotstayn</i> [1999] <sup>a</sup>	SO <sub>4</sub>	-1.1 to -1.7	-0.4 to -1.0	-1.6 to -3.2	(P) include a (small) LW radiative forcing
<i>Jones et al.</i> [1999] <sup>a,b</sup>	SO <sub>4</sub>	-0.91	b.e. -0.66	-1.18	(C) include a (small) LW radiative forcing; the two effects add nonlinearly
<i>Kiehl et al.</i> [2000]	SO <sub>4</sub>	-0.40 to -1.78			(C)
<i>Lohmann et al.</i> [2000] <sup>a</sup>	SO <sub>4</sub>			0 to -0.4	(C)
	carb			-0.9 to -1.3	(C) include a parameterization of cloud nucleation
	both		~60%	-1.1 to -1.5	(C)
<i>Ghan et al.</i> [2000a] <sup>a</sup>	SO <sub>4</sub>	~40%	~50%	-1.6 to -3.2 (b.e. -1.7)	(C) include a parameterization of cloud nucleation; predicted aerosol size distribution

Letters P (prescribed) and C (computed) refer to off-line and on-line SO<sub>4</sub> aerosol calculations, respectively; CCN and CDN stand for cloud condensation nuclei and cloud droplet number, respectively. "b.e." stands for best estimate; "carb" stands for carbonaceous aerosols.

<sup>a</sup>The estimate in flux change due to the indirect effect of aerosols was computed as the difference in top-of-atmosphere fluxes between two distinct simulations and therefore does not represent a flux in the strict sense.

<sup>b</sup>Predicts SO<sub>4</sub> concentrations which are too small on average.

# What can we learn from these modeling efforts?

- Sensitivity of climate system to particular indirect effect
- Estimate of range of effect
- Cannot get reliable estimate of coupled effects (at this point)

A few words about ice ...

# Contrails

- Possibility of contrail effects first noted by Walter Orr Roberts in the 1960's

Front page story in *The New York Times* (Sept. 23, 1963). "Until recently, Dr. Roberts explained, cirrus clouds were thought to be more of an effect than a cause of weather conditions. But data from balloon and satellite experiments now suggest... [clouds] may trap enough heat beneath them to affect the weather."

- (from Spencer Weart, AIP)

# Contrails

- Observation: jet contrails sometimes merge together to form an extended thin cirrus deck which modifies radiation field
- Question: would these thin decks occur anyway? How much additional optical depth is provided by jet activity?
- Some satellite (Minnis and colleagues) and aircraft (INCA) observations but difficult to establish causality of human impacts

# Indirect effects on cirrus

- Extremely poorly understood
- Depends on:
  - The relative role of heterogeneous vs. homogeneous nucleation
  - Ability of aerosol particles to act as ice nuclei
  - Available moisture, particularly outside of generating regions

# And finally deep convection ...

- “However there are no quantitative measurements of the impact of the aerosol on deep convective clouds, their propensity to precipitate, the vertical distribution of heating, and the subsequent modulation of circulation systems and rainfall distribution.” (From a statement under preparation by the ACPC Workshop attendees)
- Extremely complex because of dynamics, complex microphysics (including ice) and system energetics

# Indirect Effects Summary

- Many of the outstanding issues were identified in the late 1970's and early 1980's
- Our understanding of these issues has increased dramatically in the last 20 to 30 years
- However, observational evidence is difficult to come by
- The linkage between the issues has become more important
- This complexity is largely responsible for the current uncertainties in evaluating aerosol indirect effects