The Influence of Absorbing Aerosols on Clouds and the Climate

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Absorbing Aerosols in the Atmosphere and in Clouds

- soot ($m = 1.75 + i\,0.44$)
- dust ($m = 1.53 + i\,0.0055$)
- soluble organics ($m = 1.43 + i\,0.0060$) (?)

for comparison:

- sulfate ($m = 1.47 + i\,0.0000001$)

[*d'Almeida et al.*, 1991]

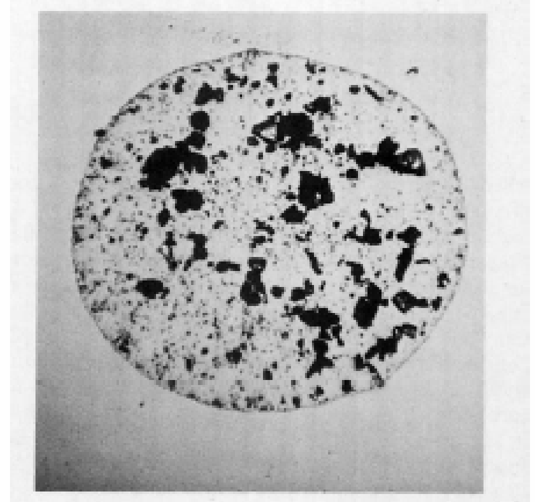
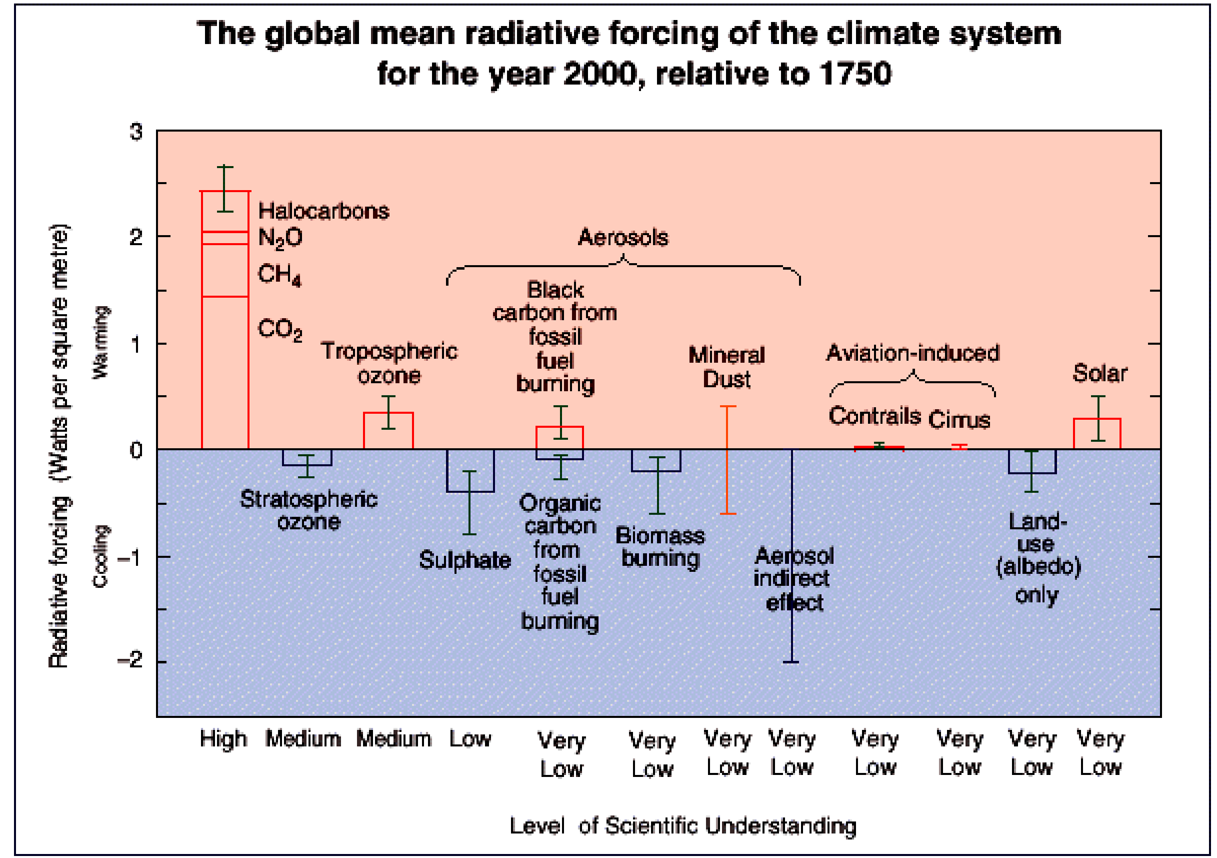


FIG. 2. Raindrop was frozen immediately after the collection. Several hundreds of individual solid particles were found after sublimation of ice.

[*Chýlek et al.*, 1984]

Indirect and Semi-Direct Aerosol Effects

[*IPCC*, Climate Change 2001]



Indirect effect:

Increase the number of aerosols

⇒ Increase the number of drops

⇒ Increase the cloud reflectivity

⇒ Less solar reaches the surface

⇒ Cooling

Semi-direct effect:

Increase absorption in cloud vicinity

⇒ Increase the cloud heating rate

⇒ Drops begin to evaporate

⇒ More solar reaches the surface

⇒ Heating?

Previous Studies in the Context of the Semi-Direct Effect

- Anomalous Absorption
  Kiehl et al. [1995]
- Stratocumulus Dissipation
  Ackerman and Toon [1996], Johnson et al. [2004]
- Forcings and Response
  Hansen et al. [1997]
- Indo-Asian Haze
  Ackerman et al. [2000], Ramanathan et al. [2001] and Chung et al. [2002]
- Semi-Direct Effect
  Cook and Highwood [2004]

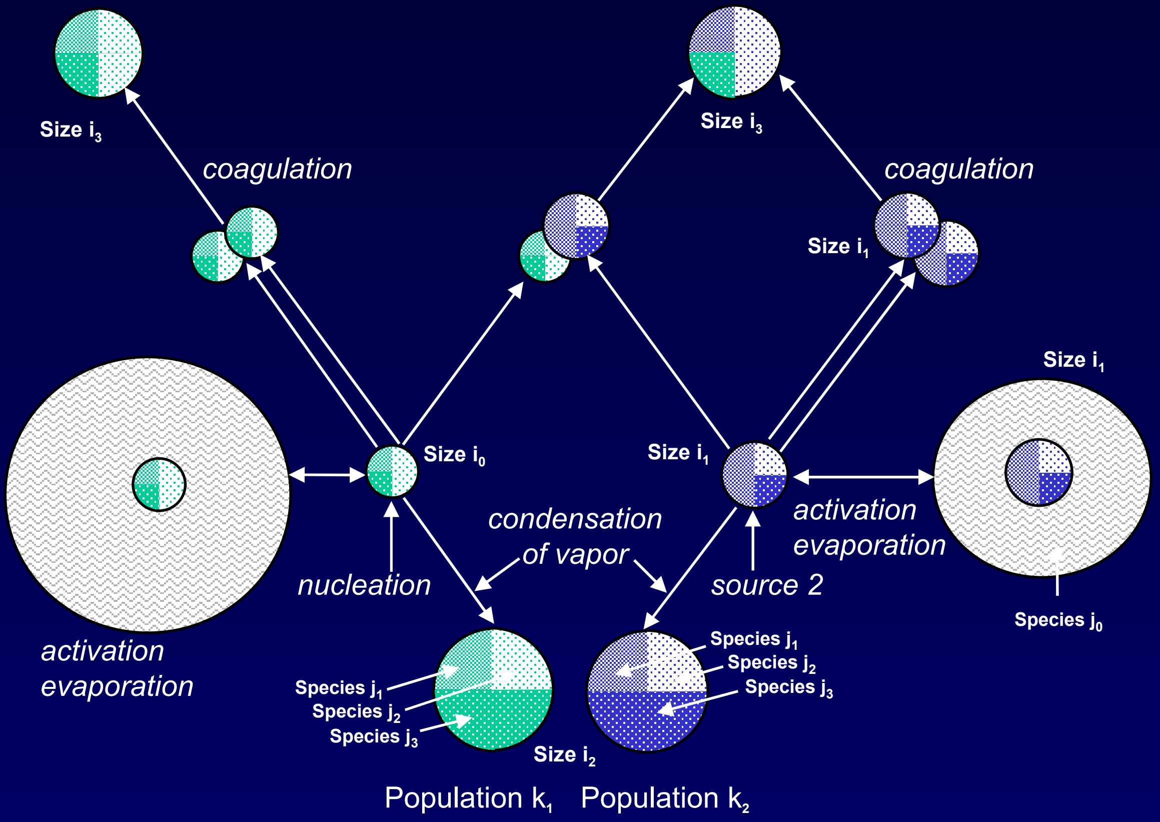
Goals of This Work

- Simulate effect of moderate continental aerosol absorption (not as strong as anomalous absorption or Indo-Asian Haze).
- Simulate the aerosol-cloud microphysics as accurately as possible (Parcel Model).
- Look at the effects of clusters of absorbing aerosols in cloud drops.
- Contrast the effect of holding cloud amount constant (Radiative Convective Model) and allowing cloud amount to vary (General Circulation Model).
- Look at regional responses to global perturbation.

Parcel Model

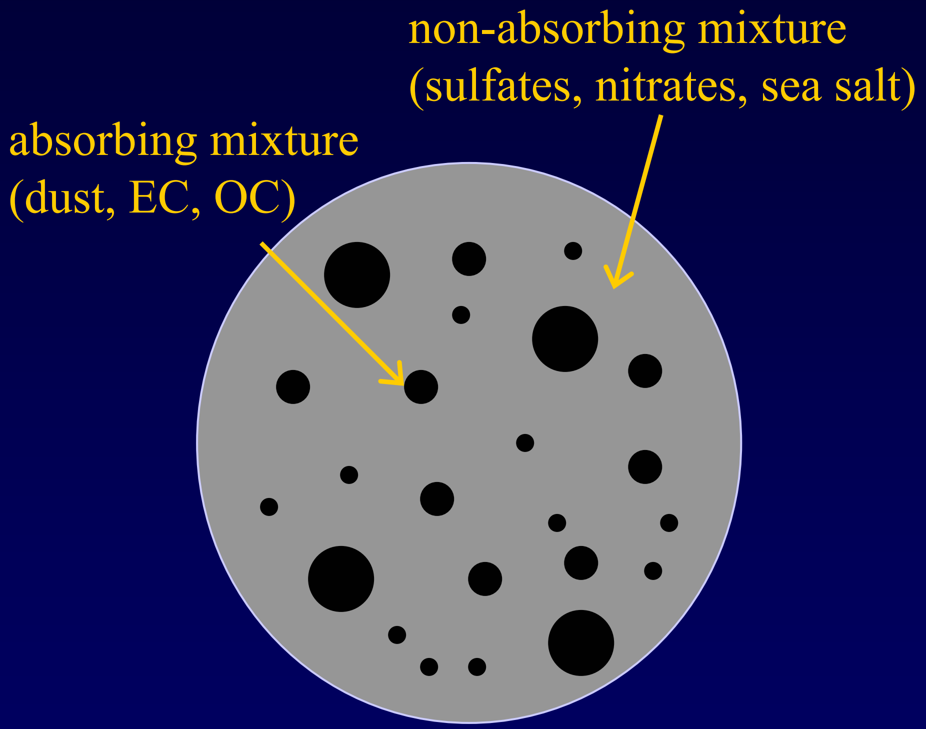
[*Russell and Seinfeld*, 1998]

- processes: condensation, nucleation, activation, coagulation, deposition
- vertical velocity prescribed
- kinetic theory to model condensation rate
- external and internal mixtures are handled explicitly
  - dual moment fixed-sectional method for coagulation and solute growth
  - moving-sectional method for evaporable components



Effective Radiative Properties of a Cloud Drop Containing Particles

- Calculate the effect refractive index:
  - *linear* for non-absorbing species
    - * weighted by volume
  - *Maxwell-Garnett theory* for absorbing species
    - * assumes a random distribution of absorbing inclusions in an otherwise homogeneous matrix
- Calculate the drop single scattering parameters – Mie scattering subroutine [*Bohren and Huffman*, 1983]:
  - input: drop radius, concentration, effect refractive indices
  - output: single scattering parameters
  - integrate over all drops in distribution



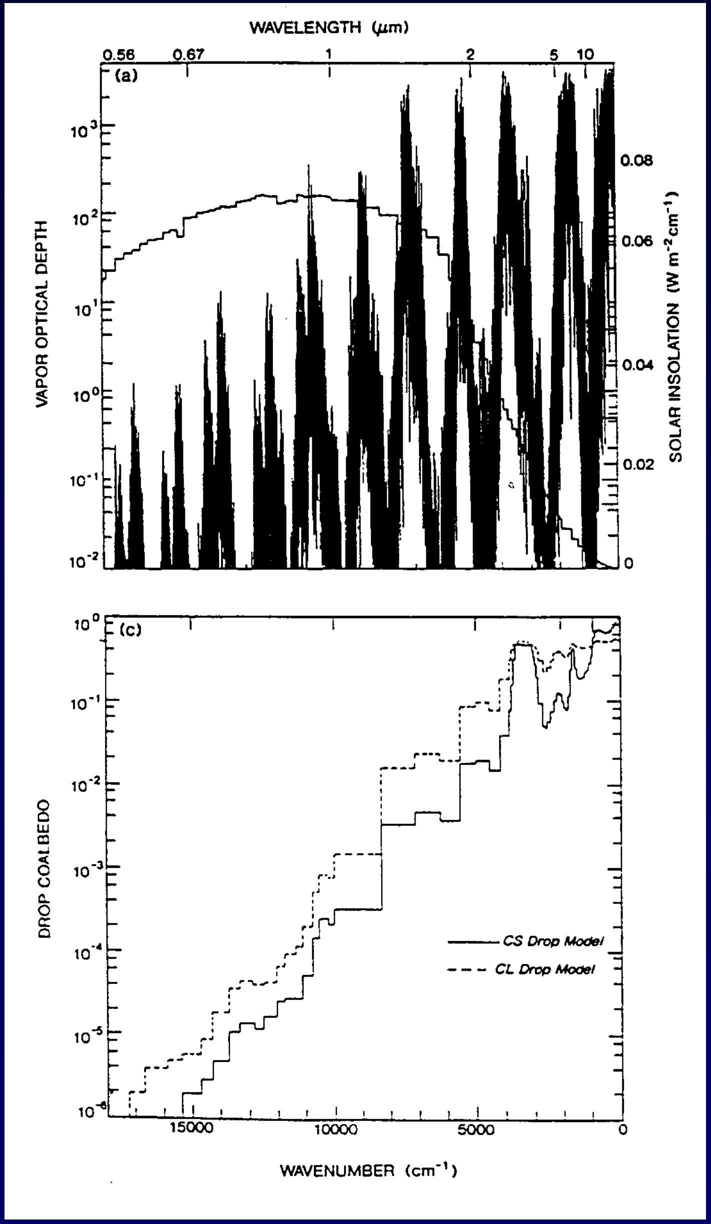
Shortwave Radiation Algorithm (From SKYHI)

[*Freidenreich and Ramaswamy*, 1999]

- 25-band solar parameterization
- particular emphasis on atmospheric absorption
- exponential sum-fit technique for water vapor transmission

$$\overline{T}_{\mathrm{H_2O\ vapor}}(p_0, w) = \sum_n a_n e^{-k_n w}$$

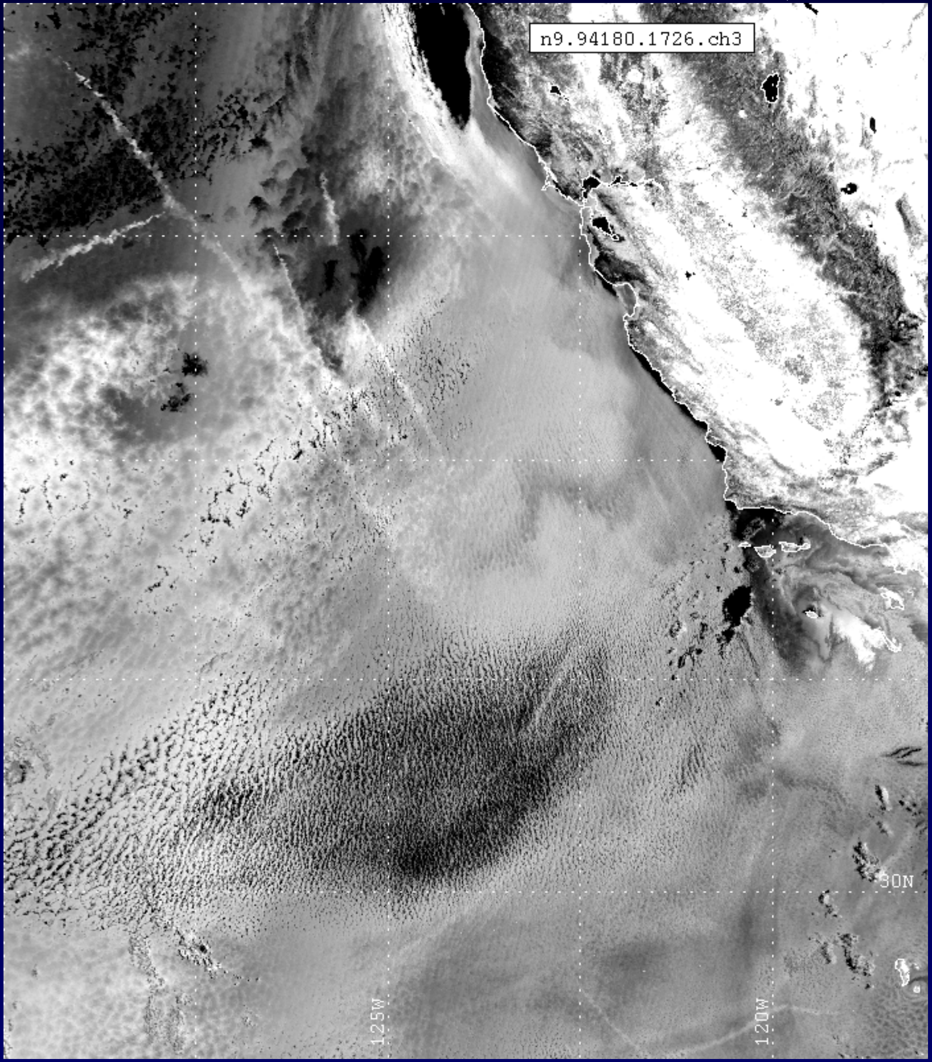
- delta-Eddington method for reflectance and transmittance of scattering layers [*Joseph et al.*, 1976]
- adding method to combine layers [*Ramaswamy and Bowen*, 1994]
- wavelengths of perturbation: 0.2–1.0 μm



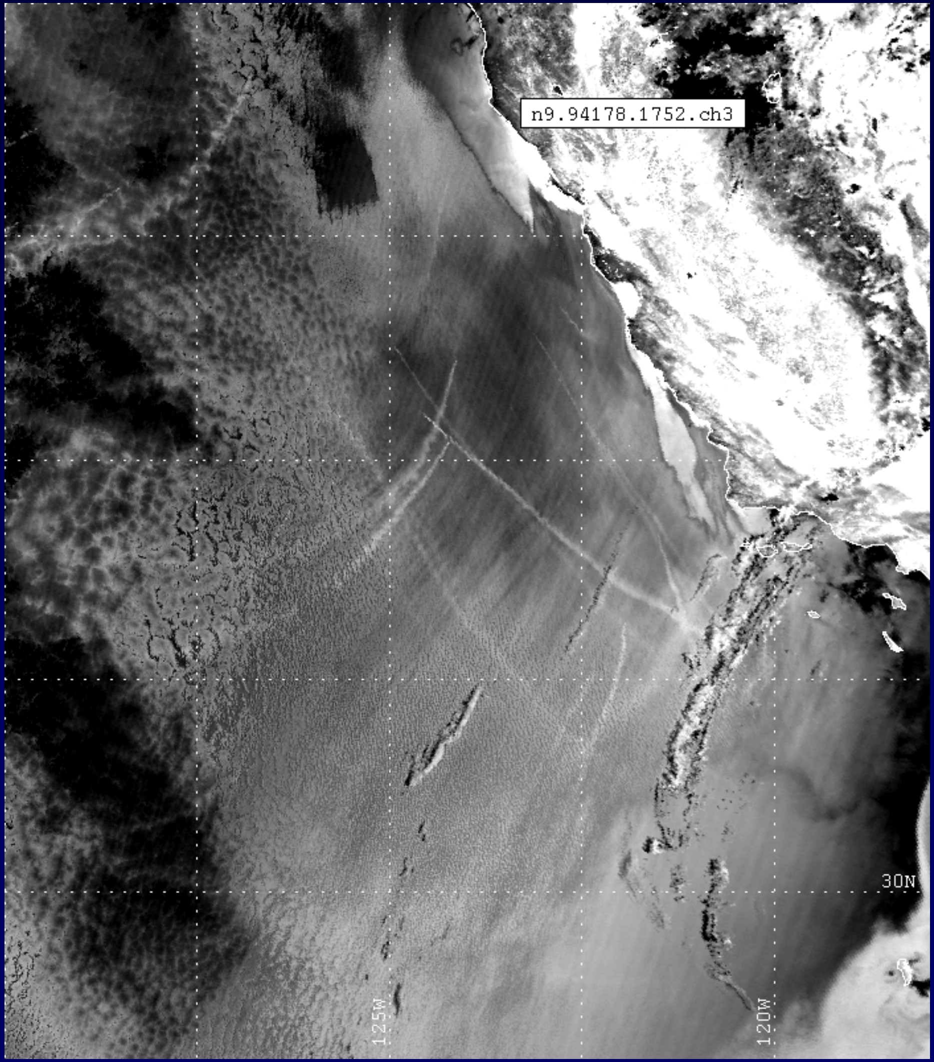
[*Ramaswamy and Freidenreich*, 1998]

Two Case Studies
Monterey Area Ship Track Experiment (MAST), June 1994

clean marine stratocumulus
(JDT180, *Star Livorno*, June 29)



continentally influenced stratocumulus
(JDT178, *Tai He*, June 27)



Parcel Model Results

- clean marine cloud

	Pure Water	All Species
Albedo	0.360	0.361
Absorption, W m^{-2}	39.0	39.0
Transmission	0.623	0.623

- continentally influenced cloud

	Pure Water	All Species
Albedo	0.565	0.556
Absorption, W m^{-2}	41.5	**65.1**
Transmission	0.404	0.389

Change in Visible Cloud Single Scattering Albedo

$$\varpi = \frac{k_{\text{sca}}}{k_{\text{sca}} + k_{\text{abs}}}$$

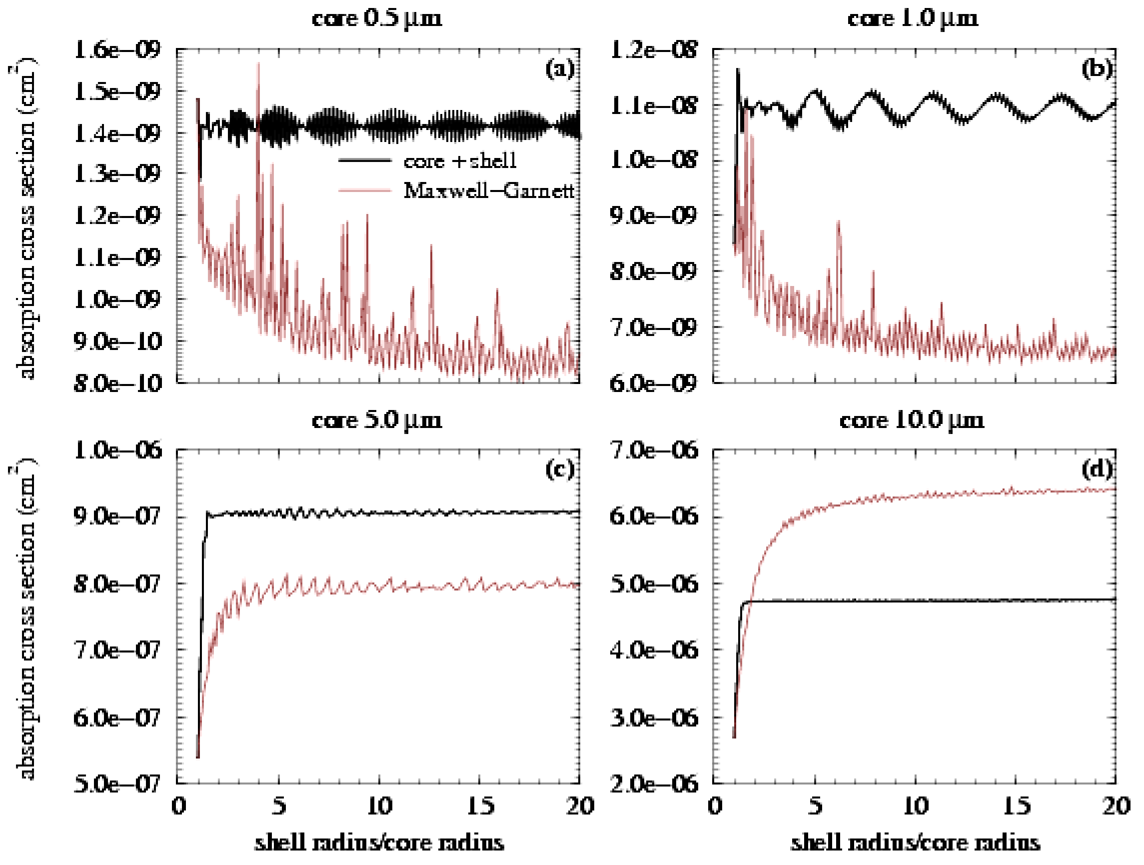
$$\text{marine cloud} : \varpi = 0.999998$$

$$\text{continentally influenced cloud} : \varpi = 0.99$$

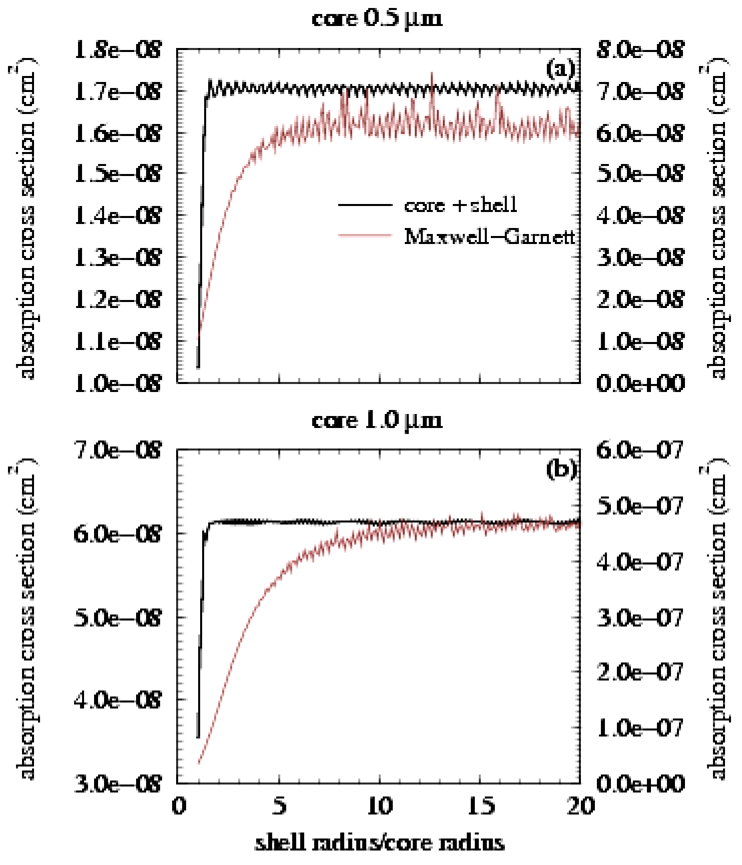
Effects of Clusters of Absorbing Aerosols in Water Drops

[*Erlick and Schlesinger*, in preparation, 2005]

Water/Dust



Water/Soot



$C = \left(F^{\downarrow}_{\text{cloudy}} - F^{\uparrow}_{\text{cloudy}}\right) - \left(F^{\downarrow}_{\text{clear}} - F^{\uparrow}_{\text{clear}}\right)$

Cloud Forcing and Cloud Forcing Ratio

Cloud Forcing:

$$C = \left(F^{\downarrow}_{\text{cloudy}} - F^{\uparrow}_{\text{cloudy}}\right) - \left(F^{\downarrow}_{\text{clear}} - F^{\uparrow}_{\text{clear}}\right)$$

Cloud Forcing Ratio:

$$R = \frac{C(\text{SFC})}{C(\text{TOA})}$$

Cloud Forcing Ratio With 5.0 μm Dust Inclusions

Cloud Optical Depth	*R*, Pure Water Cloud	*R*, Core Plus Shell	*R*, Maxwell-Garnett
Dust Core 5.0 μm, Shell 10.0 μm (f = 0.125)			
1	1.17	5.04	4.87
5	1.15	4.07	4.36
20	1.16	3.61	3.40
41.8	1,16	2.97	2.82
100	1.15	2.32	2.23
Dust Core 5.0 μm, Shell 20.0 μm (f = 0.008)			
1	1.17	3.09	3.03
5	1.15	3.00	2.95
20	1.16	2.74	2.71
41.8	1.16	2.50	2.47
100	1.15	2.15	2.14

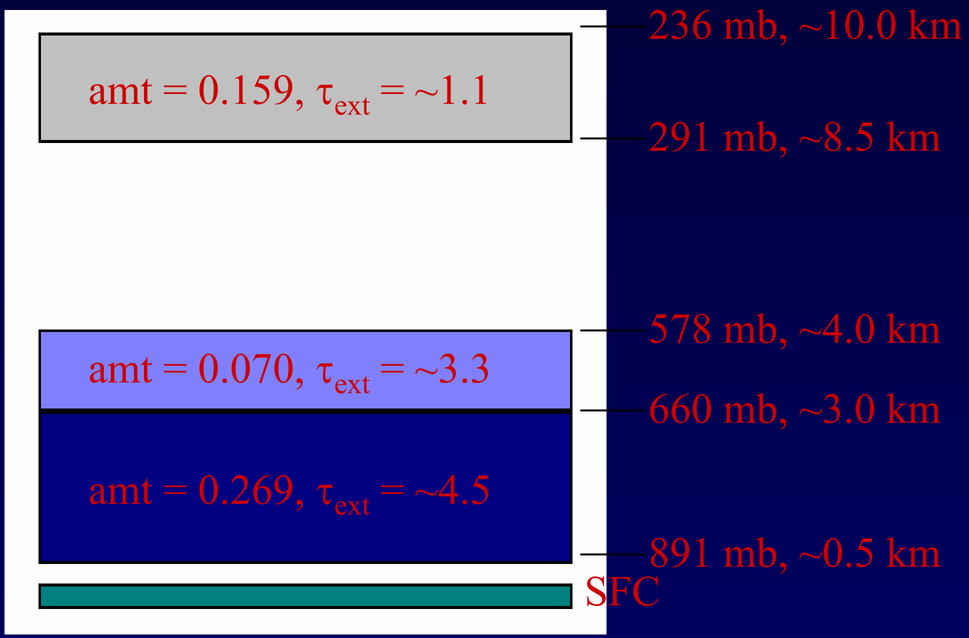
Cloud Forcing Ratio With 0.5 μm Soot Inclusions

Cloud Optical Depth	*R*, Pure Water Cloud	*R*, Core Plus Shell	*R*, Maxwell-Garnett
Soot Core 0.5 μm, Shell 1.0 μm (f = 0.125)			
1	1.17	1.82	2.59
5	1.15	1.40	1.63
20	1.16	1.30	1.42
41.8	1,16	1.27	1.37
100	1.15	1.24	1.31
Soot Core 0.5 μm, Shell 9.0 μm (f = 0.000171)			
1	1.17	1.29	1.69
5	1.15	1.29	1.65
20	1.16	1.27	1.56
41.8	1.16	1.26	1.49
100	1.15	1.24	1.40

Radiative Convective Model

[*Schwarzkopf and Ramaswamy*, GFDL]

mid-latitude summer cloud profile



236 mb, ~10.0 km

amt = 0.159, τ_{ext} = ~1.1

291 mb, ~8.5 km

578 mb, ~4.0 km

amt = 0.070, τ_{ext} = ~3.3

660 mb, ~3.0 km

amt = 0.269, τ_{ext} = ~4.5

891 mb, ~0.5 km

SFC

Radiative Convective Model – Equilibrium Temperature Profile Effects of Absorbing Aerosols Outside of Clouds

- dust: less absorbing ⇒ *cooling* effect
- soot: more absorbing ⇒ *warms* aerosol layer, *cools* surface ⇒ *inversion*
  - * level of inversion depends on vertical distribution of aerosols

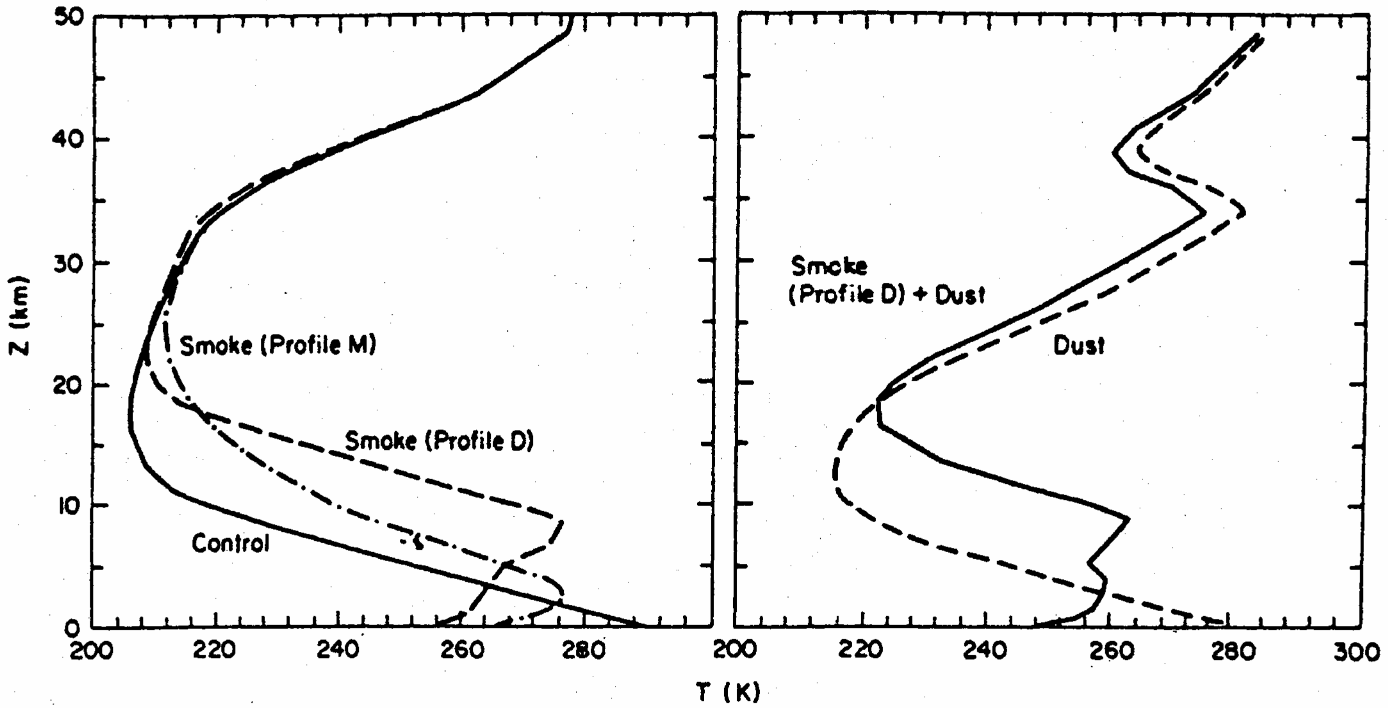


Fig. 17. Perturbations in the thermal structure of the atmosphere after 20 days for (*a*) the unperturbed atmosphere, smoke profile M and smoke profile D, with $r_s^s = 0.26$ μm and $W_{smoke} = 0.5$ g m^{-2}, (*b*) dust aerosols without and with smoke profile D: $r_s^d = 0.26$ μm and $W_{dust} = 0.2$ g m^{-2}.

[*Ramaswamy and Kiehl.*, 1985]

Radiative Convective Model – Equilibrium Temperature Profile
Effects of Clouds Without Absorbing Aerosols

- middle and low clouds mostly reflect ⇒ *cooling* effect
- high clouds transmit solar but are heated by surface emission ⇒ *warming* effect

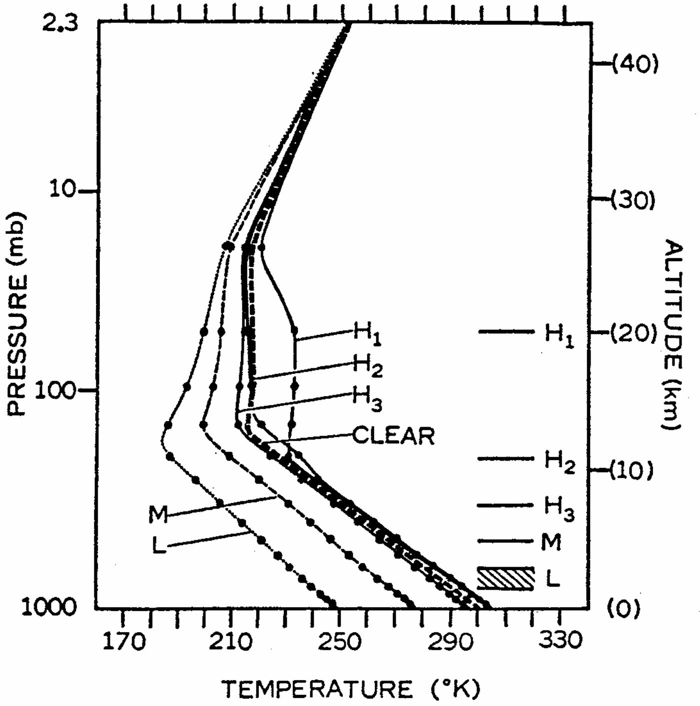
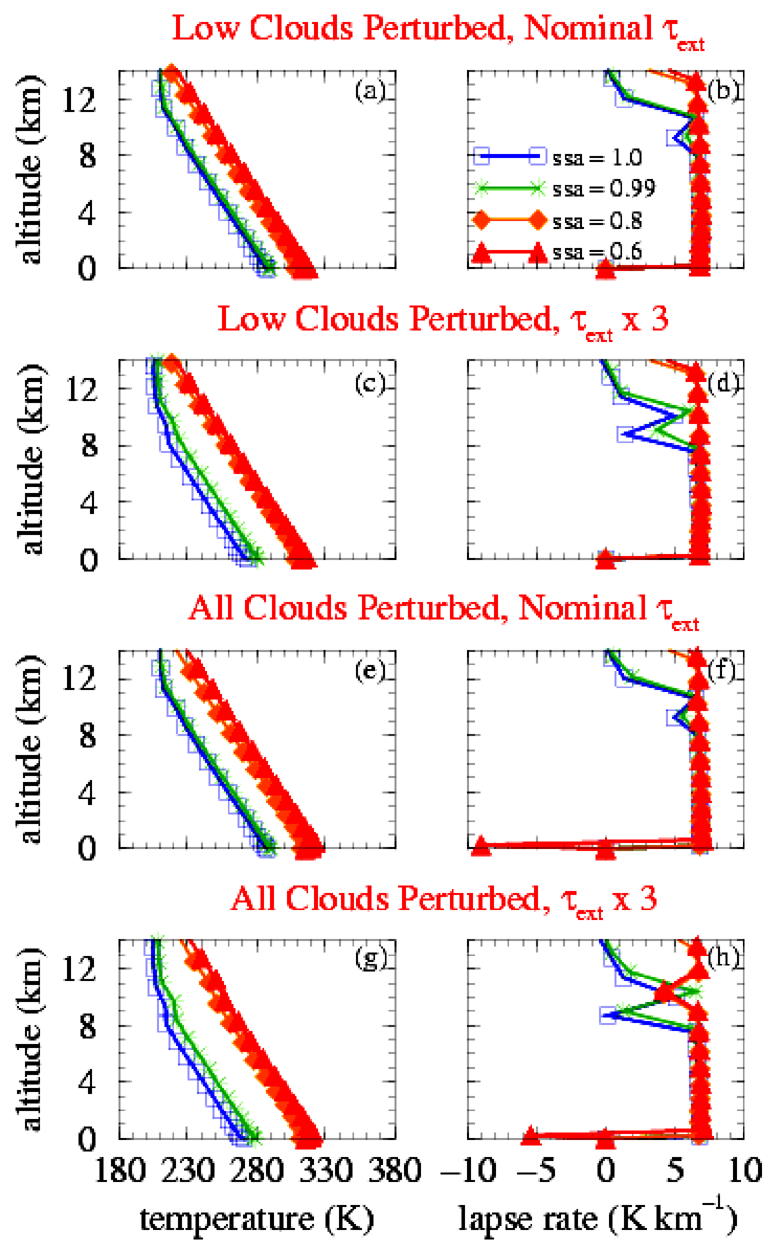


FIG. 7a. Thermal equilibrium of various atmospheres with clouds (the critical lapse rate for convective adjustment is 6.5 deg km^{-1}). On the right hand side of the figure the height of overcast clouds used for each computation is shown, H_1, H_2, and H_3 denoting high clouds, M and L denoting middle and low clouds. As a reference, the equilibrium curve of the clear atmosphere is shown by a thick dashed line.

[*Manabe and Strickler*, 1964]

Radiative Convective Model – Equilibrium Temperature Profile

Effects of Clouds Containing Absorbing Aerosols



aerosols in low clouds only

- increase in absorption *warms* the troposphere and surface, *stabilizes* the troposphere
- *no inversion*

aerosols in all clouds

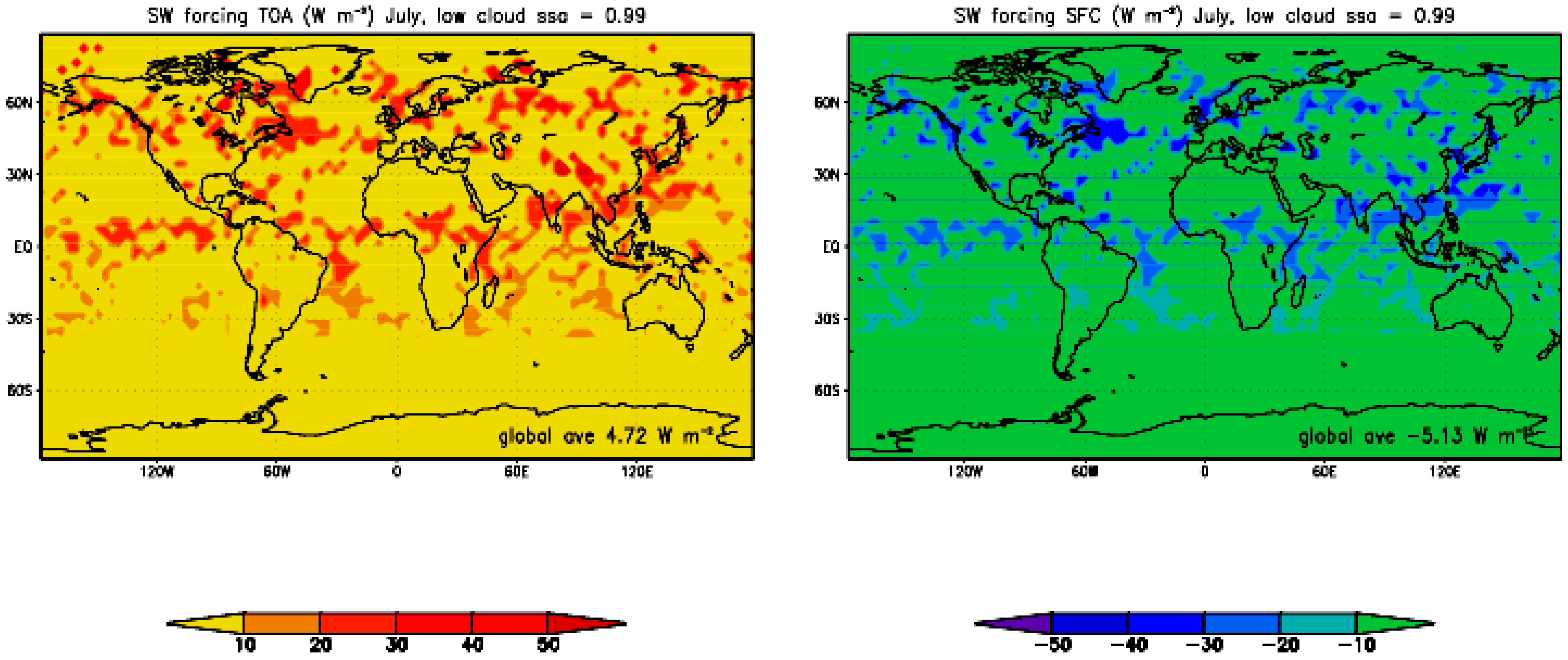
- increase in absorption *warms* the troposphere and surface, *stabilizes* the troposphere
- *inversion* for ssa ≤ 0.6 (not realistic)

General Circulation Model (SKYHI)

[*Hamilton et al.*, 1995; *Schwarzkopf and Ramaswamy*, 1999]

- 40-level finite difference grid
- 3.0° x 3.6° latitude-longitude resolution
- predicted clouds [*Wetherald and Manabe*, 1988]
  - a layer is fully cloud covered when $RH > 100\%$
  - low clouds: 680–1000 mb, $\tau_{\mathrm{ext}} \sim 12$, $r_{\mathrm{eff}} = 10\ \mu\mathrm{m}$
  - middle clouds: 440–680 mb, $\tau_{\mathrm{ext}} \sim 3$, $r_{\mathrm{eff}} = 10\ \mu\mathrm{m}$
  - high clouds: 10–440 mb, $\tau_{\mathrm{ext}} \sim 1$, $r_{\mathrm{eff}} = 10\ \mu\mathrm{m}$
- Slingo parameterization for cloud radiative properties [*Slingo*, 1989]
- fixed SST's
- shortwave radiation as described earlier
- longwave radiation [*Schwarzkopf and Ramaswamy*, 1999]
  - simplified exchange approximation method for IR radiative transfer [*Schwarzkopf and Fels*, 1991]
  - gaseous absorption approximated over 8 spectral bands

Shortwave Forcing = Instantaneous $\left(F^{\downarrow}_{\text{pert}} - F^{\uparrow}_{\text{pert}}\right) - \left(F^{\downarrow}_{\text{cont}} - F^{\uparrow}_{\text{cont}}\right)$

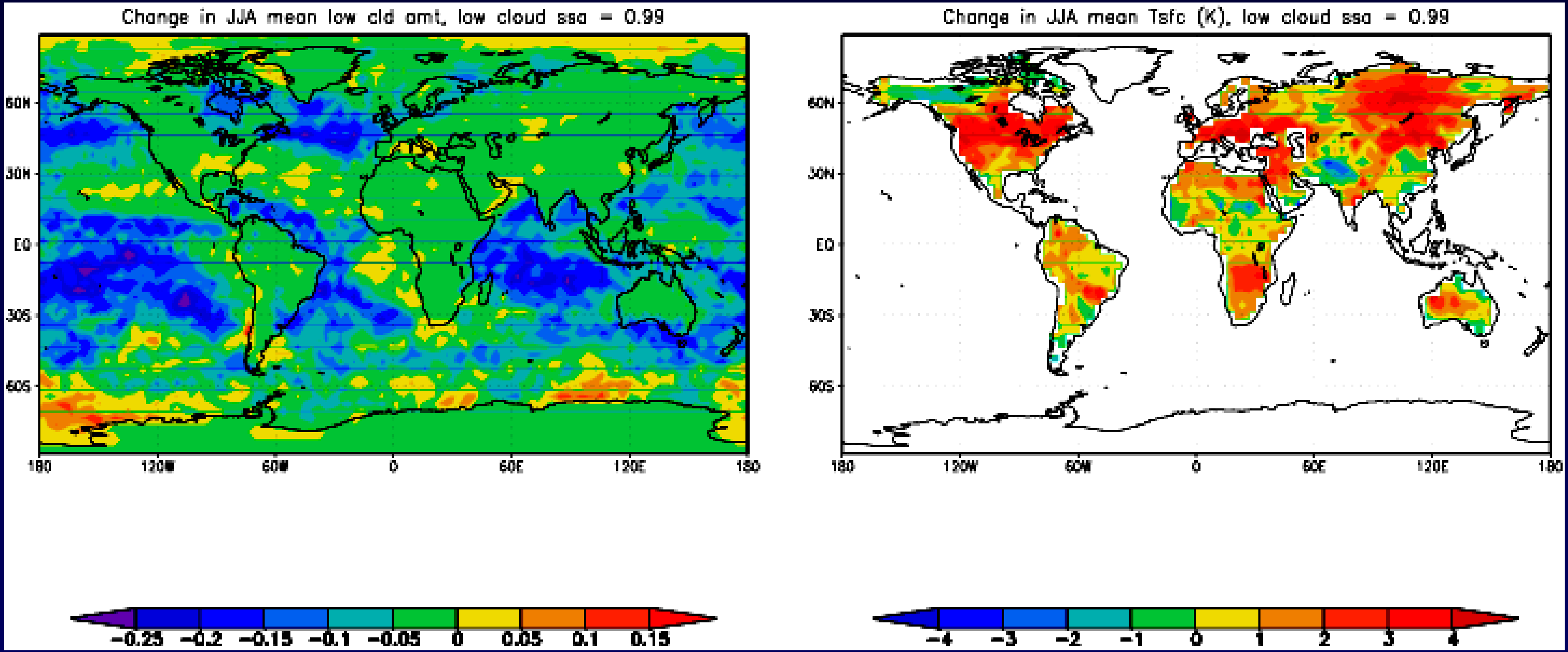


SW forcing TOA ($W\ m^{-2}$) July, low cloud ssa = 0.99

SW forcing SFC ($W\ m^{-2}$) July, low cloud ssa = 0.99

- *less* upward flux at TOA
- *less* downward flux at SFC

Changes in Cloud Amount and Surface Temperature

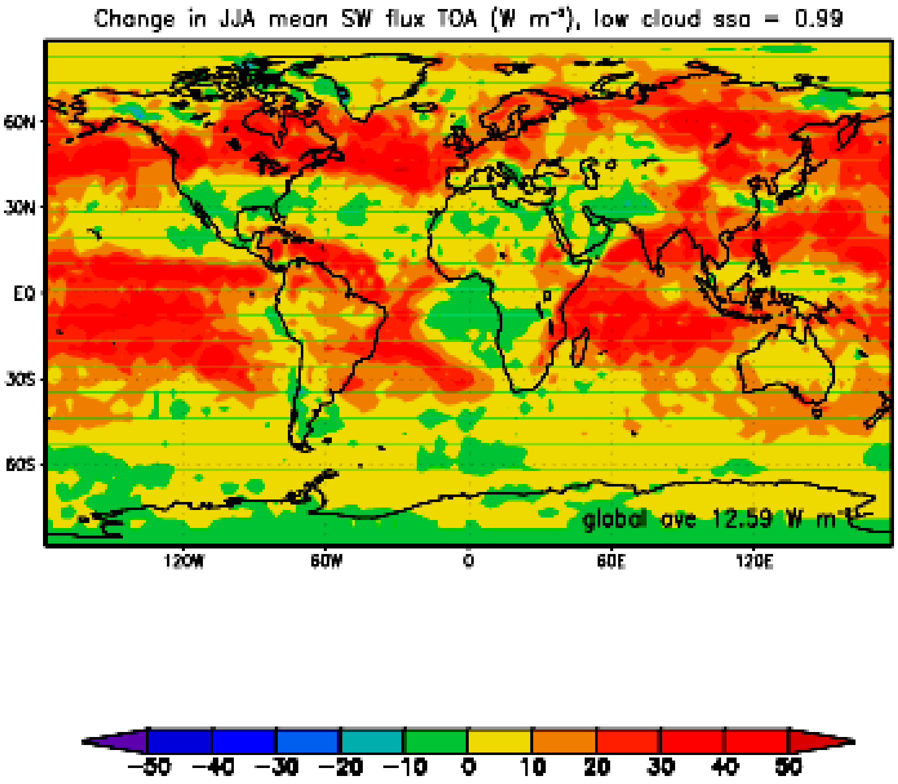


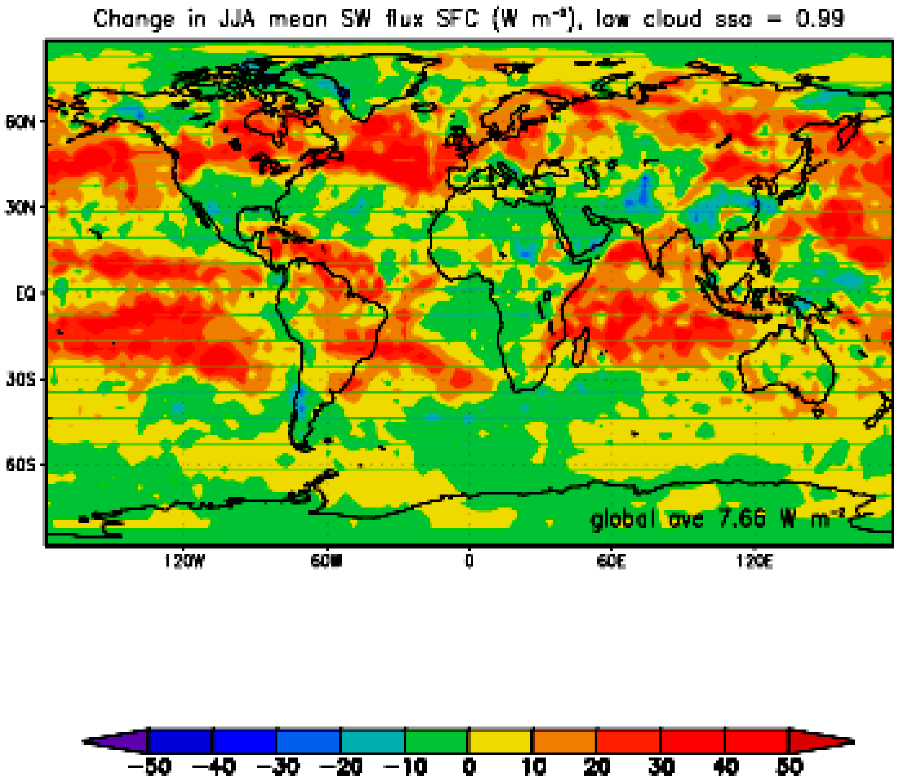
Change in JJA mean low cld amt, low cloud ssa = 0.99

Change in JJA mean Tsfc (K), low cloud ssa = 0.99

- *decrease* in low cloud amount
- *increase* in land surface temperature (heating + dissipation)

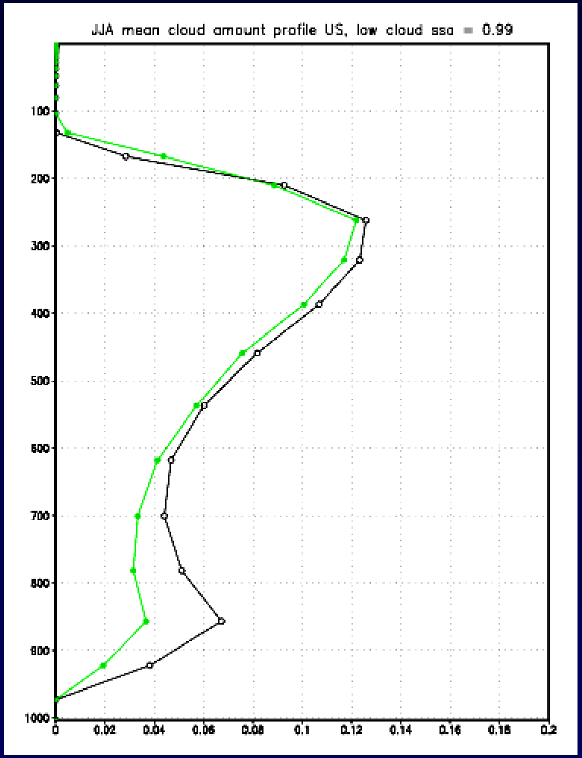
Change in Equilibrium Shortwave Flux

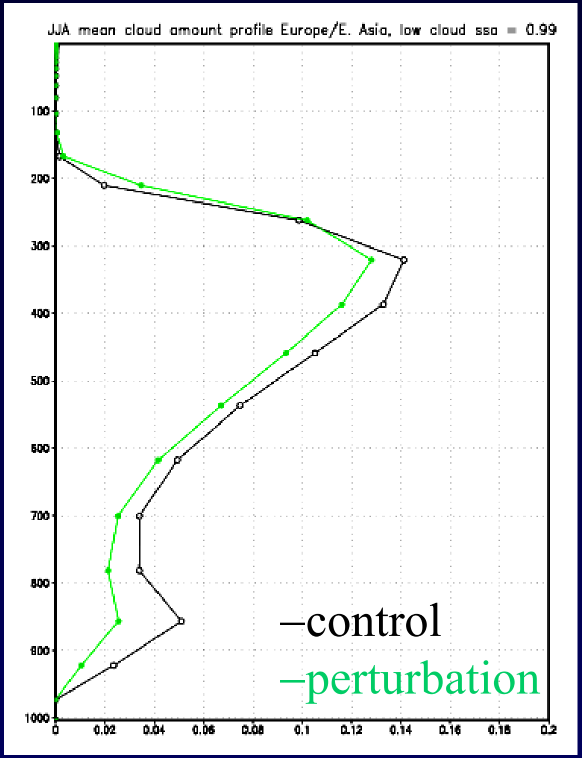

Change in JJA mean SW flux TOA ($\mathrm{W\ m^{-2}}$), low cloud ssa = 0.99


Change in JJA mean SW flux SFC ($\mathrm{W\ m^{-2}}$), low cloud ssa = 0.99

- existing low clouds absorb + *less* low clouds: *even less* upward flux at TOA, *more* downward flux at SFC (change in sign!)
- SW flux TOA increases more than SW flux SFC ⇒ net input to the system ⇒ the system warms

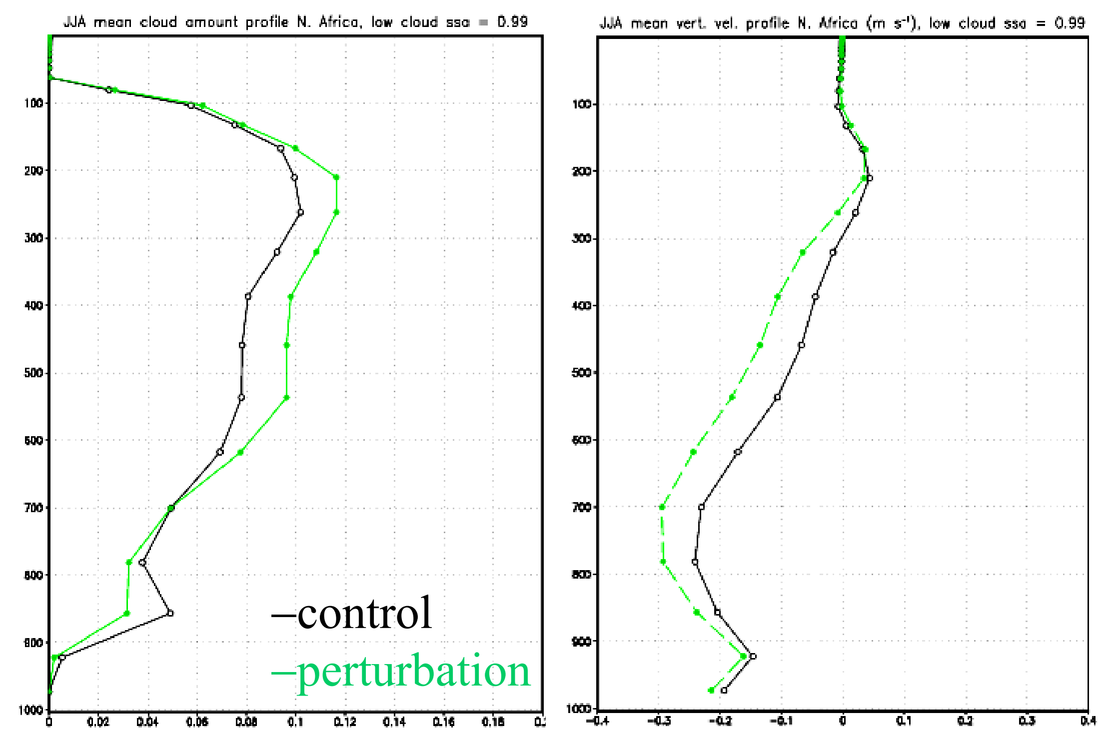
Regional Differences in JJA Response: U.S. and Europe/E. Asia





- *decrease* in low and high cloud amounts
- *increase* in sw flux to surface
- *warming* of lower troposphere (despite the decrease in cloud amount – similar to biomass burning clouds [*Rosenfeld et al.*, 2002]) and surface
- *increase* in tropospheric water vapor
- *increase* in stability (lower troposphere warms more than surface)
- *decrease* in precipitation, soil moisture

Regional Differences in JJA Response:
N. Africa



- *decrease* in low cloud amount, *increase* in high cloud amounts (overall *increase*)
- *decrease* in sw flux to surface
- *warming* of lower troposphere and surface
- *increase* in tropospheric water vapor
- *decrease* in stability near surface (surface warms more than lower troposphere)
- *increase* in precipitation, latent heat flux from surface, soil moisture, evaporation and sublimation from surface

Significance of Change in Land Surface Temperature

	Global Mean	United States	Europe/ E. Asia	N. Africa
Control, K	293.86	298.14	196.81	302.70
*Weighted std. dev. control, *K*	1.49	4.26	2.56	2.16
Perturbation, *K*	295.10	300.46	299.02	303.38
*Weighted std. dev. perturbation, *K*	1.06	3.19	1.96	1.56
*Weighted mean T-value (T-test)	3.53	2.24	3.51	1.32
Degrees of freedom	52	52	52	52
Level of confidence, %	99.95	97.5	99.95	90

* weighted by land area

Significance of Change in Low Cloud Amount

	Global Mean	United States	Europe/ E. Asia	N. Africa
Control	0.18	0.038	0.025	0.0063
*Weighted std. dev. control	0.018	0.047	0.023	0.012
Perturbation	0.12	0.020	0.011	0.0035
*Weighted std. dev. perturbation	0.0072	0.018	0.0077	0.0049
*Weighted mean T-value (T-test)	17.68	2.04	3.30	1.20
Degrees of freedom	52	52	52	52
Level of confidence, %	99.95	97.5	99.5	>75,<90

* weighted by land area

Effects Not Taken Into Account

- variation of SST:

  warming of ocean surface ⇒ increase in evaporation ⇒ increase in high cloud amount [*Cook and Highwood*, 2004] ⇒ increase in global precipitation [*Folland et al.*, 2001; *Ramanathan et al.*, 2001]

- aerosol-cloud microphysics:

  indirect effect competes with semi-direct effect ⇒ increase in total cloud amount [*Lohmann and Feichter*, 2001]

Summary

- Dust and soot in clouds may significantly reduce the cloud single scattering albedo and increase the solar cloud forcing ratio.
- Clusters of dust and soot inside cloud drops can have a particularly large effect.
- Globally, absorption of solar radiation by clouds causes a *warming* of the surface, *stabilization* of the lower troposphere, and a *decrease* in precipitation.
- Regionally, results may vary. In the United States and Europe/E. Asia horizontal heat flux is more efficient, while in N. Africa there is a distinct local (vertical) balance [*Chen and Ramaswamy*, 1995].