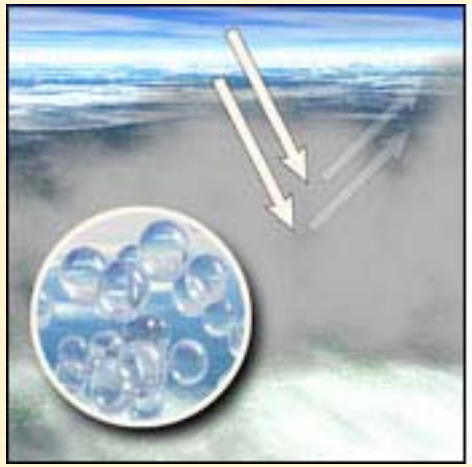
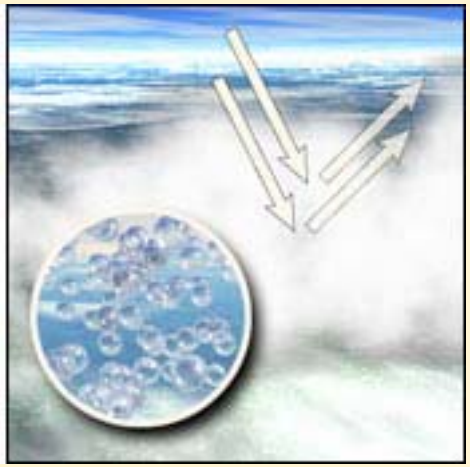
Indirect aerosol forcing and cloud susceptibility

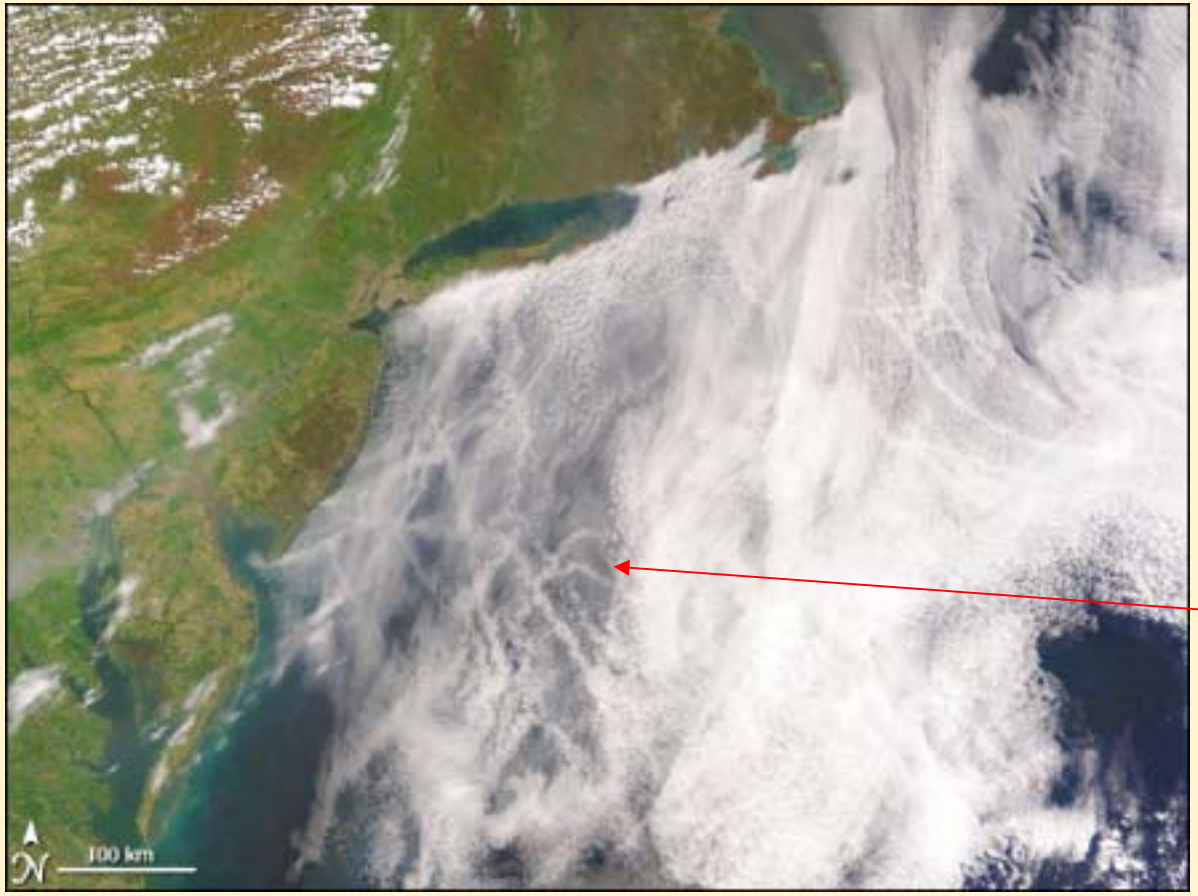
Lazaros Oreopoulos
NASA-GSFC
with contributions from: S. Platnick(GSFC), R. Sotiropoulou (Georgia Tech), A. Nenes (Georgia Tech)

CPWG-AWG Meeting, Lansdowne VA, Nov. 11-13

First indirect aerosol effect (IAE)





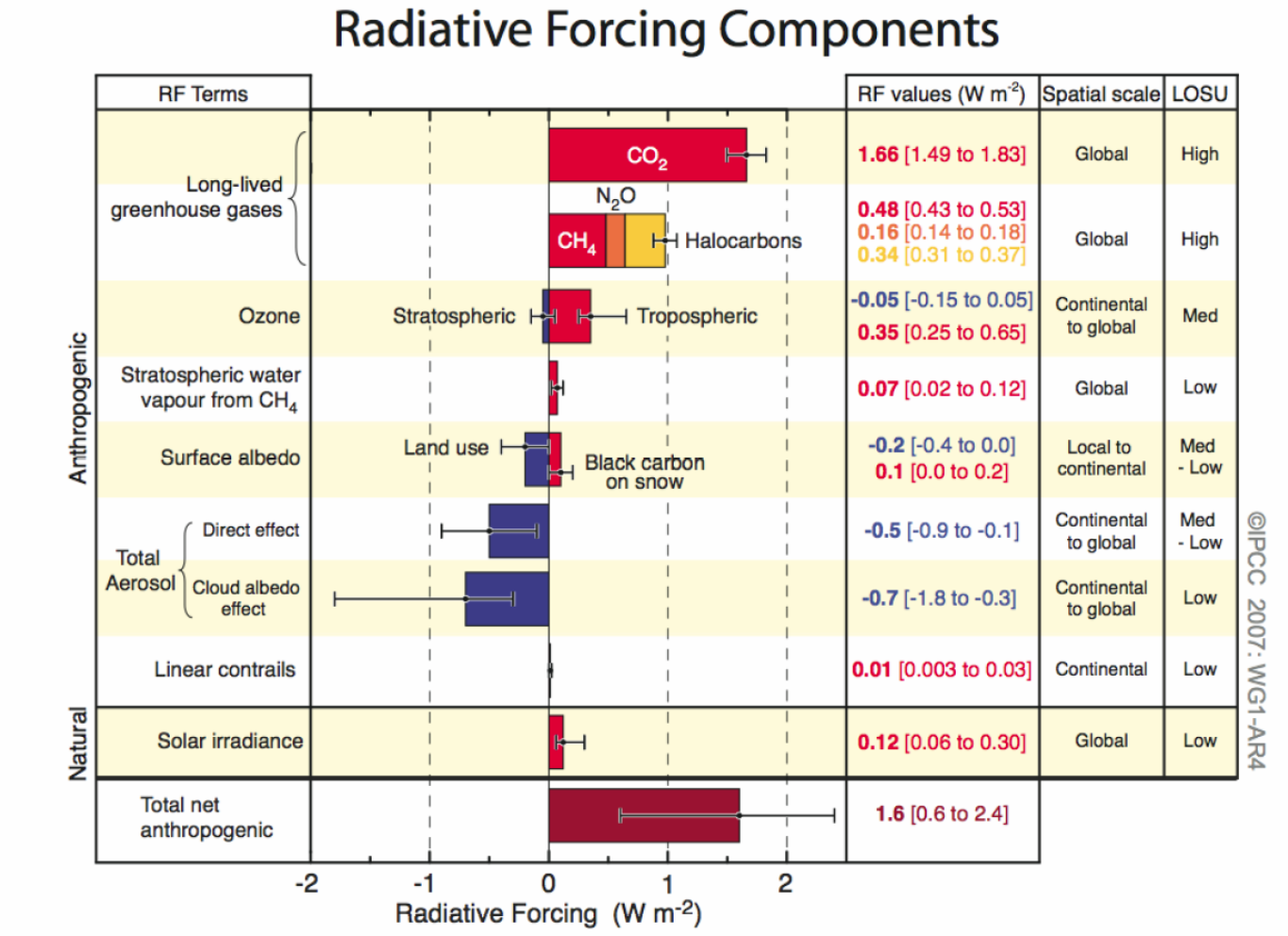


Clouds with the same water, but smaller and more numerous droplets are more reflective ($\tau \approx 3LWP/2\rho r_e$) (aka “Twomey effect”)

Ship tracks off the east coast of USA from Terra, May 2005

A graphic you may have seen before…

$$\Delta RF = RF(2005) - RF(1750)$$



From IPCC 4AR's summary for policymakers (2007)

Global Modeling of IAE (PI-PD)

(Sotiropoulou et al. 2008)

Motivation

- Aerosol-cloud-climate interactions are one of the largest sources of uncertainty in assessments of anthropogenic climate change.
- Much of this uncertainty arises from the approaches used for linking clouds to their precursor aerosol.

Goals of modeling study

- Examine aerosol effects on cloud radiative properties
- Assess the range in aerosol indirect effects from application of different droplet formation schemes, and meteorological fields.
- Express changes in radiative properties in terms of a "forcing" between preindustrial (PI) and present-day (PD) simulations.

Modeling Framework

- NASA Global Modeling Initiative (GMI) CTM
- Aerosol module (Liu et al., 2005) coupled to GMI advection core
- Emissions: SO_2, DMS, BC, OC, mineral dust, and sea salt
- Chemical production of sulfate, gravitational sedimentation, dry deposition, wet scavenging in and below clouds, and hygroscopic growth
- CDNC and effective radius from various schemes
- CLIRAD-SW solar radiative transfer model online to calculate the cloud optical depth (COD) and shortwave (SW) fluxes from the surface layer to the top of the atmosphere (TOA).

Cloud Droplet Number Calculation

- Empirical Correlations:
  - Boucher and Lohmann (BL), 1995
  - Segal and Khain (SK), 2006
- Mechanistic Parameterizations:
  - Abdul-Razzak and Ghan (AG), 2000
  - Fountoukis and Nenes (FN), 2005

Meteorological Fields

- NASA GEOS4 finite volume GCM (FVGCM)
- NASA (former) DAO GEOS1-STRAT (GEOS)
- Goddard Institute for Space Studies II' (GISS)

Simulations Considered

Emission Scenarios

- University of Michigan (Present day, Preindustrial)
- AEROCOM (Present day, Preindustrial)

1st set of simulations

- Liquid Cloud Temperatures: 273 K and above
- Cloud droplet formation schemes: BL, SK, AG, FN

2nd set of simulations

- Liquid Cloud Temperatures :
  263 K over land, 269 K over ocean (GISS GCM scheme)
- Cloud droplet formation schemes: BL, SK, AG, FN

Total Number of Simulations:

$$4 \times 3 \times 2 \times 2 \times 2 = 96$$

N_d scheme — Met field — Threshold T — Emission Case — Emission Inventories

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N_d scheme — Met field — Threshold T — Emission Case — Emission Inventories

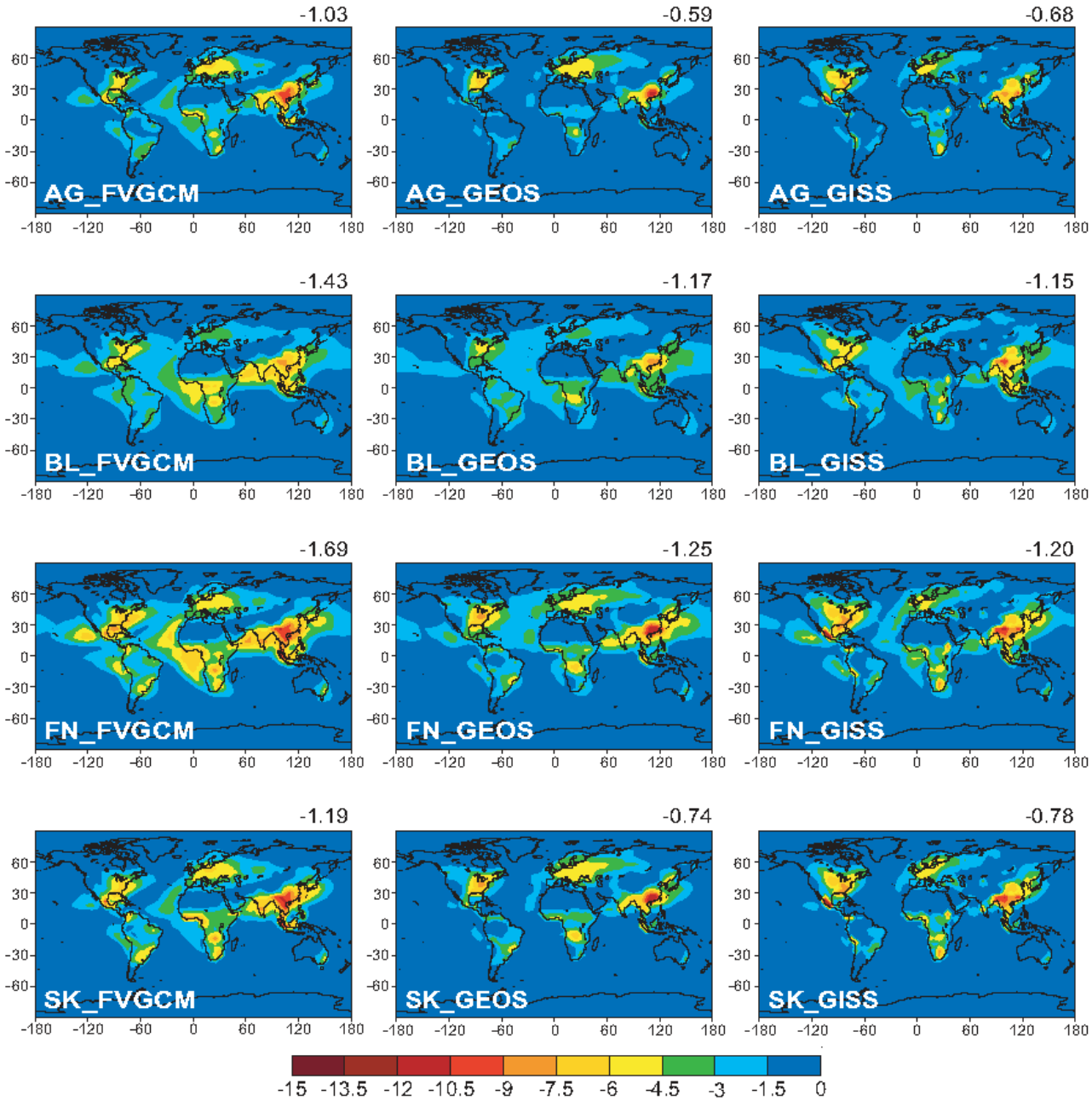
Annual Mean First Indirect Forcing (W m^{-2})

The spatial patterns of indirect forcing follow that of CDNC

Strong horizontal inhomogeneities.

Largest values are predicted over areas with highest amount of anthropogenic sulfur emissions.

Different meteorological datasets contribute 40% variability in globally averaged IF;
results from different cloud droplet formation parameterizations contribute a variability of 60%



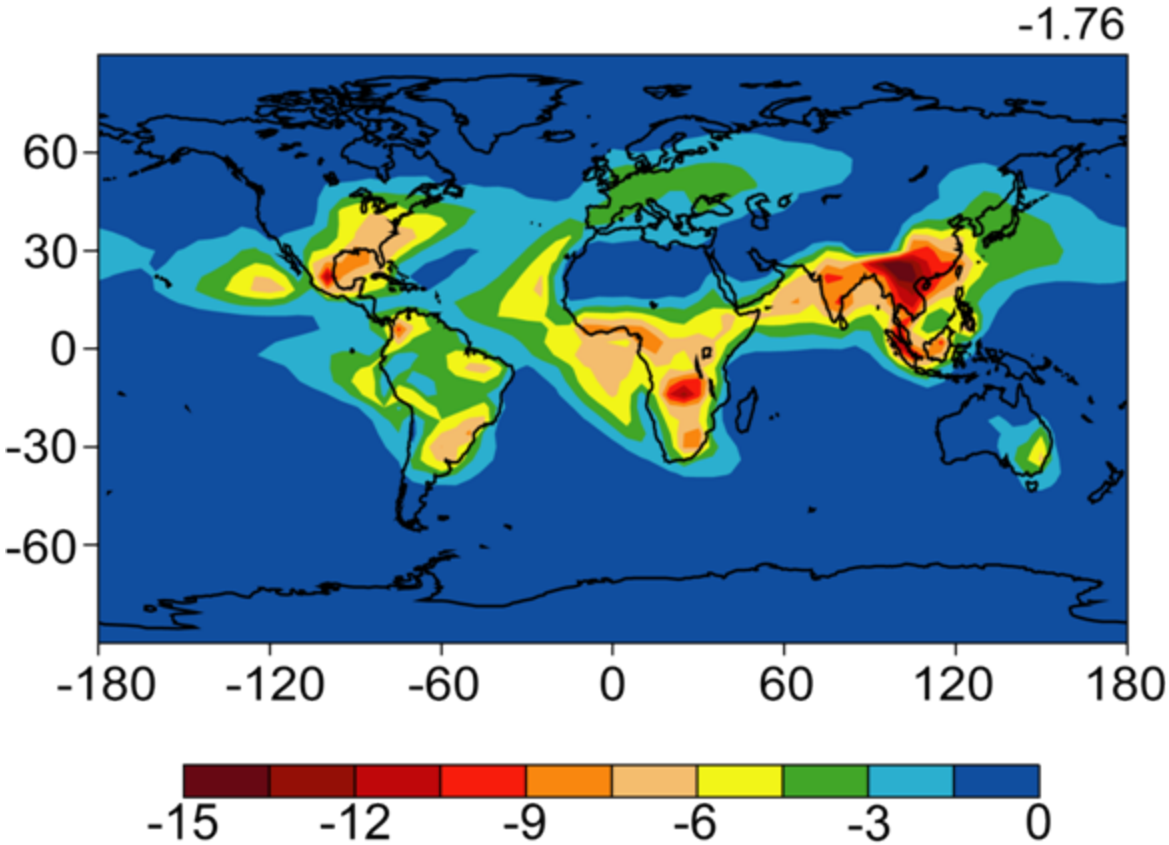
Sotiropoulou et al., JGR, 2008

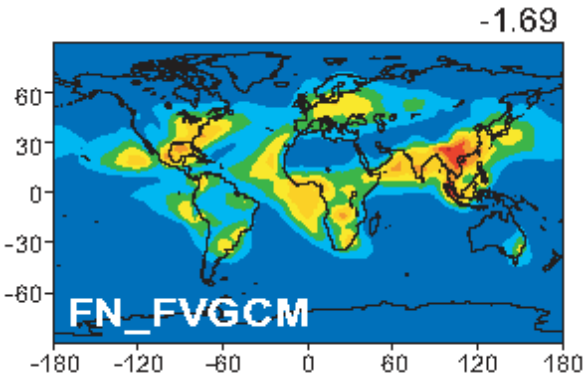
Sensitivity analysis

Conditions:

FN scheme – FVGCM meteorological fields

Ice cloud threshold temperature set to 273K





IF increases by ~ 5%.

This is expected as the contribution of optical depth from cold clouds tends to be small.

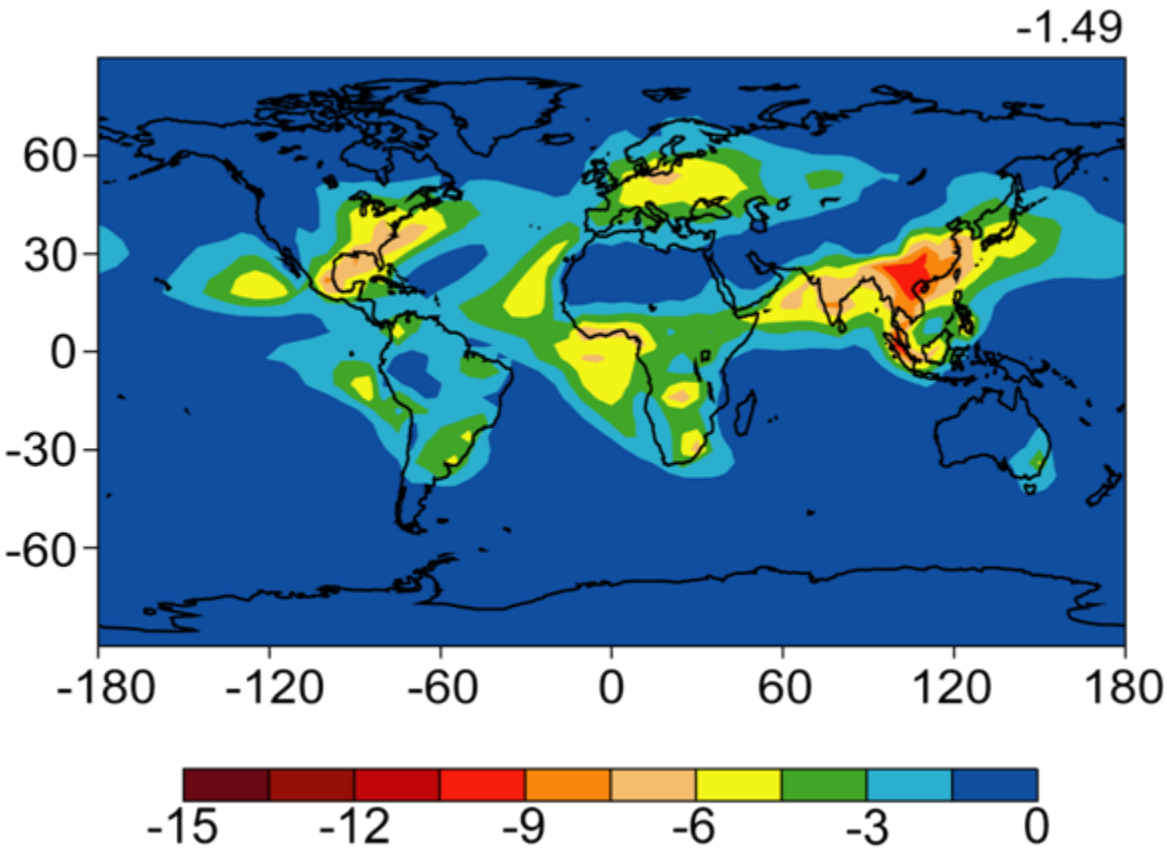
Sotiropoulou et al, 2008

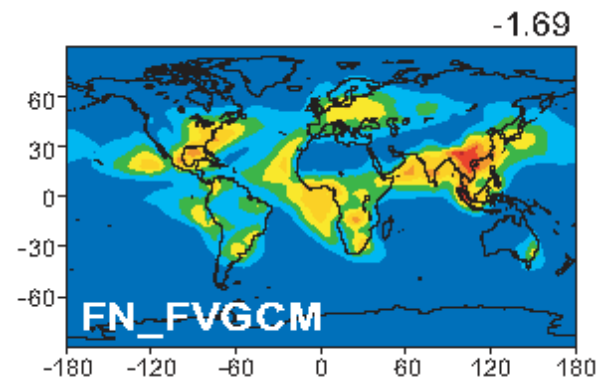
Sensitivity analysis

Conditions:

FN scheme – FVGCM meteorological fields

Updraft velocity set to 0.5 m s^{-1} over land & 0.25 m s^{-1} over ocean.





IF decreases by 0.2W m^{-2}

Largest decrease is noted over the oceanic regions of the NH and the oceanic regions of the SH affected by long range transport of pollution plumes.

Sotiropoulou et al, 2008

Global Assessment of future IE

(Oreopoulos and Platnick 2008)

Susceptibility: What is it and why we want to study it?

- In simple terms: Susceptibility is a cloud radiative sensitivity to a specified change in cloud particle numbers.
- Quantifies the climate impact of well-posed hypothetical cloud modification scenarios, but does not address previous cloud albedo modifications that may have already occurred.
- Usually refers to ***albedo*** susceptibility
- Focus has been warm (liquid) clouds so far
- See Platnick and Twomey (1994) and our two JGR papers in the Kaufman special issue

Formal definitions: absolute and relative susceptibility

$$S_\lambda = \frac{dR_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{dN} = \frac{\partial R_\lambda}{\partial \tau_\lambda}\frac{d\tau_\lambda}{dr_e}\frac{dr_e}{dN} + \frac{\partial R_\lambda}{\partial g_\lambda}\frac{dg_\lambda}{dr_e}\frac{dr_e}{dN} + \frac{\partial R_\lambda}{\partial \varpi_\lambda}\frac{d\varpi_\lambda}{dr_e}\frac{dr_e}{dN}$$

absolute susceptibility + – – – + – + – –

$$S_\lambda^{rel} = \frac{dR_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{\frac{dN}{N}}$$

relative susceptibility

Could also examine other types of perturbations, (e.g., Feingold and Siebert, 2008) :

$$\frac{d\ln R_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{d\ln N} = \frac{\frac{dR_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{R_\lambda}}{\frac{dN}{N}}$$

$$\frac{d\ln R_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{dN} = \frac{\frac{dR_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{R_\lambda}}{dN}$$

Practical considerations (determining Δr_e)

$$N = \frac{3LWC}{4\rho_w \pi r_\upsilon^3} \approx \frac{3LWC}{4\rho_w \pi k r_e^3} \qquad r_\upsilon^3 = \int r^3 n(r)dr \Big/ \int n(r)dr \qquad \tau_{vis} = \frac{3H\,\bar{Q}_{vis} LWC}{4\,\rho_w\, r_e} \approx \frac{3H\,LWC}{2\,\rho_w\, r_e}$$

$k \approx 0.6 - 0.9$

Under adiabatic conditions:

$$N = \frac{1}{2\pi k}\left(\frac{5}{\rho_w \bar{Q}_{vis}}\right)^{1/2} C_w^{1/2}\,\tau_{vis}^{1/2}\, r_e (H)^{-5/2}, \qquad LWC(h) = C_w h$$

impractical, because we don't know C_w or H and don't really retrieve $r_e(H)$!

For constant LWC, k processes:

$$r_e' = r_e\left(\frac{N}{N+\Delta N}\right)^{1/3} \Rightarrow \frac{\Delta r_e}{r_e} = \left(\frac{1}{1+\frac{\Delta N}{N}}\right)^{1/3} - 1 \Rightarrow \frac{\Delta r_e}{r_e} \approx -\frac{1}{3}\frac{\Delta N}{N}$$

, specify $\Delta N/N$ ✓

or:

$$\frac{\Delta r_e}{r_e} = \left(\frac{1}{1+\frac{4\rho_w \pi k r_e^3 \Delta N}{3LWC}}\right)^{1/3} - 1$$

, specify ΔN, LWC ✓

or:

$$\frac{\Delta r_e}{r_e} = \left(\frac{1}{1+\frac{2\rho_w \pi k\, r_e^2 H \Delta N}{\tau_{vis}}}\right)^{1/3} - 1$$

, specify ΔN, H (<u>not used</u>)

Practical considerations

(RT calculation steps)

1) Impose ΔN or $\Delta N/N$ (> 0) ➡ Δr_e (< 0) ➡ $\Delta\tau_i$, Δg_i, $\Delta\varpi_i$ (from radiation code)

Δr_e is determined specifying either:

an absolute change in N (e.g., ΔN = 1 cm^{-3}) ➔ *susceptibility* S
a relative change in N (e.g., $\Delta N/N$ = 10%) ➔ *relative susceptibility* S_{rel}

2) Calculate spectral flux perturbation within RT code

$$\Delta F_i = F_i\left(\tau_i + \Delta\tau_i,\, g_i + \Delta g_i,\, \varpi_i + \Delta\varpi_i\right) - F_i\left(\tau_i, g_i, \varpi_i\right)$$

3) Convert to BB albedo perturbation within RT code:

$$\Delta R = \frac{\sum_i f_i\, F_i^{\uparrow}\left(\tau_i + \Delta\tau_i,\, g_i + \Delta g_i, \varpi_i + \Delta\varpi_i\right)}{\mu_0 F_0^{\downarrow}} - \frac{\sum_i f_i\, F_i^{\uparrow}\left(\tau_i, g_i, \varpi_i\right)}{\mu_0 F_0^{\downarrow}}$$

4) Calculate absolute or relative susceptibility as:

$$S \approx \frac{\Delta R}{\Delta N}, \qquad S^{rel} \approx \Delta R$$

Dominant terms and assumptions

$$S_\lambda = \frac{dR_\lambda(\tau_\lambda, g_\lambda, \varpi_\lambda)}{dN} = \frac{\partial R_\lambda}{\partial \tau_\lambda}\frac{d\tau_\lambda}{dr_e}\frac{dr_e}{dN} + \frac{\partial R_\lambda}{\partial g_\lambda}\frac{dg_\lambda}{dr_e}\frac{dr_e}{dN} + \frac{\partial R_\lambda}{\partial \varpi_\lambda}\frac{d\varpi_\lambda}{dr_e}\frac{dr_e}{dN}$$

$$+ \quad - \quad - \qquad - \quad + \quad - \qquad + \quad - \quad -$$

The first term is dominant (even more for visible wavelengths)

for constant k, LWC, H

$$S_\lambda(1) = \frac{\partial R_\lambda}{\partial \tau_\lambda}\frac{d\tau_\lambda}{dr_e}\frac{dr_e}{dN} = \frac{\tau_\lambda}{3N}\frac{\partial R_\lambda}{\partial \tau_\lambda} = \frac{4\pi\rho_l}{9w}\tau_\lambda\frac{\partial R_\lambda}{\partial \tau_\lambda}k r_e^3 \approx \frac{R_\lambda(1-R_\lambda)}{3N}$$

$$S_\lambda^{rel}(1) = \frac{\partial R_\lambda}{\partial \tau_\lambda}\frac{d\tau_\lambda}{dr_e}\frac{dr_e}{dN}N = \frac{\tau_\lambda}{3}\frac{\partial R_\lambda}{\partial \tau_\lambda} \approx \frac{R_\lambda(1-R_\lambda)}{3}$$

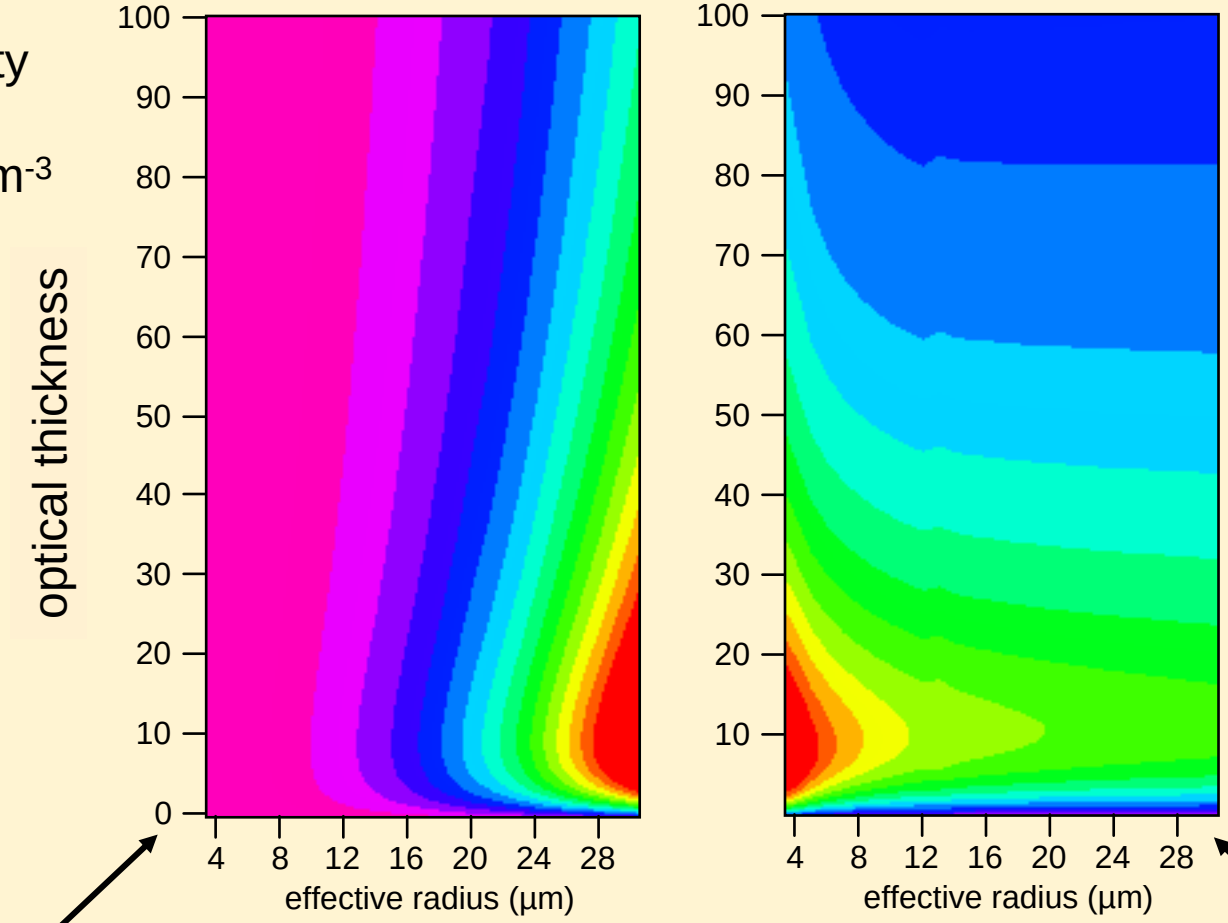
(visible, two-stream, max at R_λ=0.5)

More generally: $$S_\lambda(1) = \frac{\partial R_\lambda}{\partial \tau_\lambda}\frac{d\tau_\lambda}{dr_e}\frac{dr_e}{dN}\left(1 + \frac{d\ln k}{d\ln N} + 2\frac{d\ln LWC}{d\ln N} + 3\frac{d\ln H}{d\ln N}\right)$$

Theoretical susceptibility calculations

(spherical albedo)

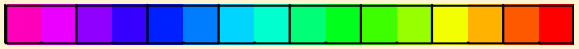
Susceptibility
ΔN=1 cm^{-3}
LWC = 0.3 gm^{-3}



Relative susceptibility
$\Delta N/N$=10%

$$\frac{\Delta R}{\Delta N} \approx \frac{4\pi}{9LWC}\tau\frac{\partial R}{\partial \tau}k^3 r_e^3$$

S: 0 – 20x10^{-3} cm^3

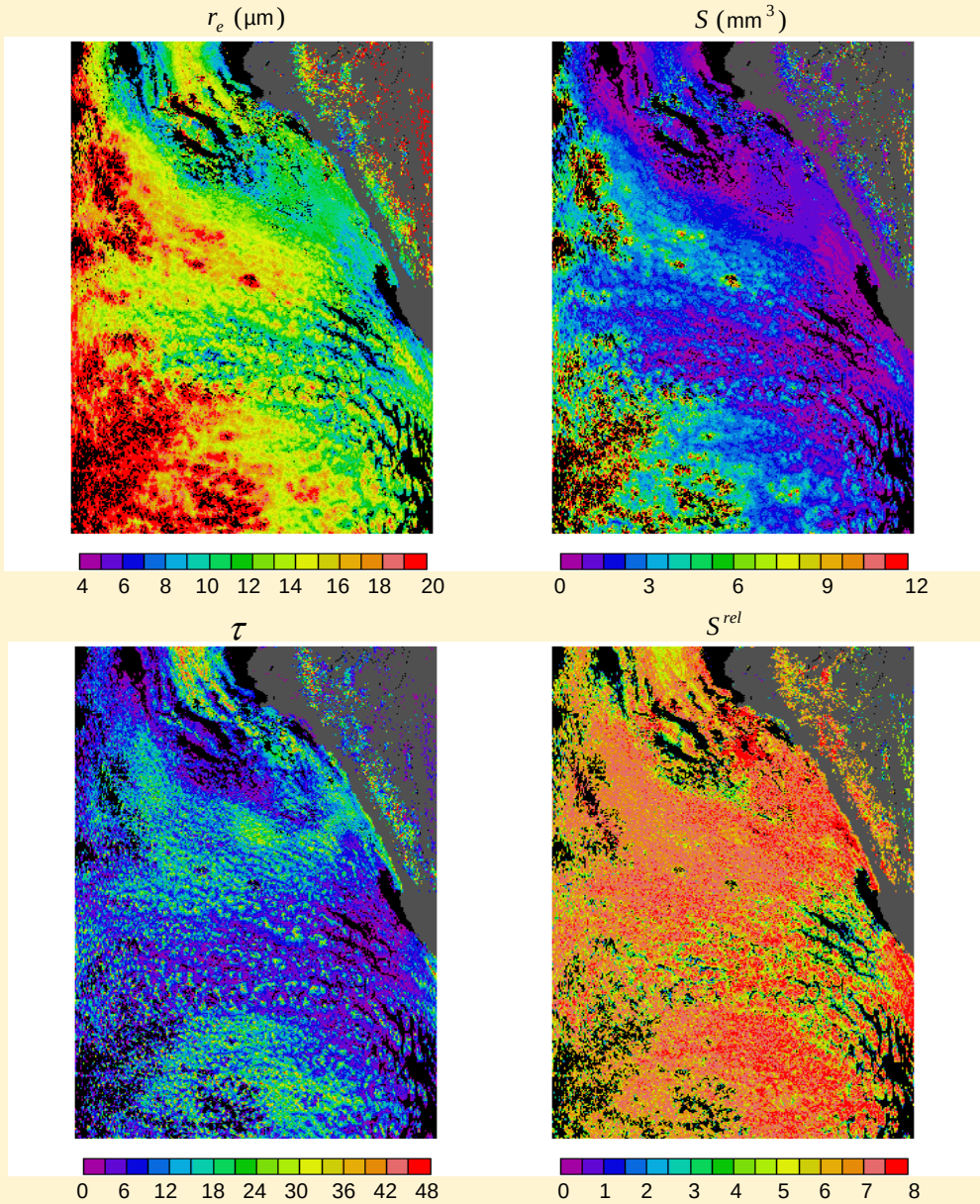


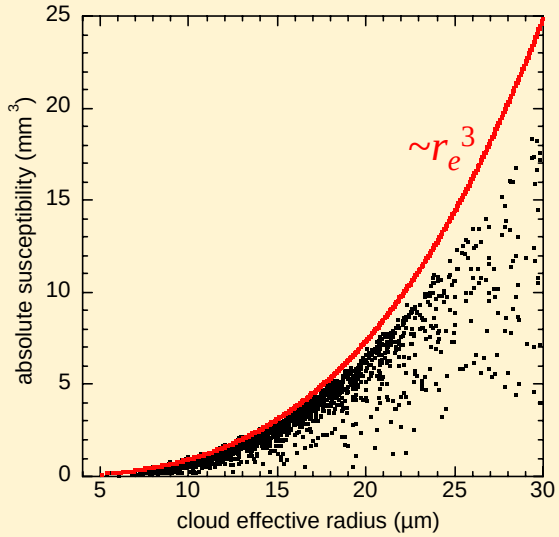
S_{rel}: 0 – 11.5x10^{-3}

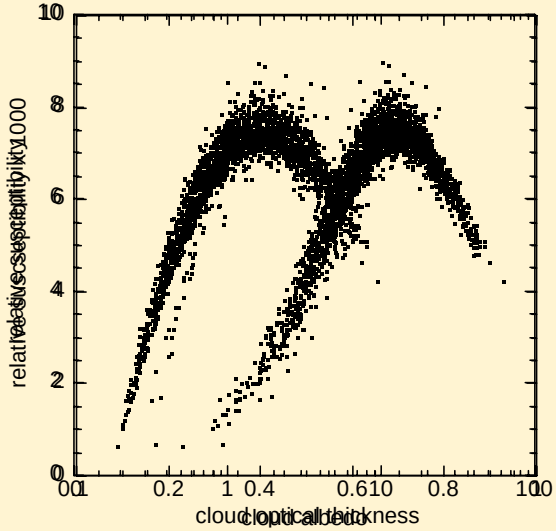
$$\Delta R \approx \frac{1}{3}\tau\frac{\partial R}{\partial \tau}\frac{\Delta N}{N}$$

Each 1x10^{-3} cm^3 corresponds to ~0.7 Wm^{-2}

Application to MODIS granules





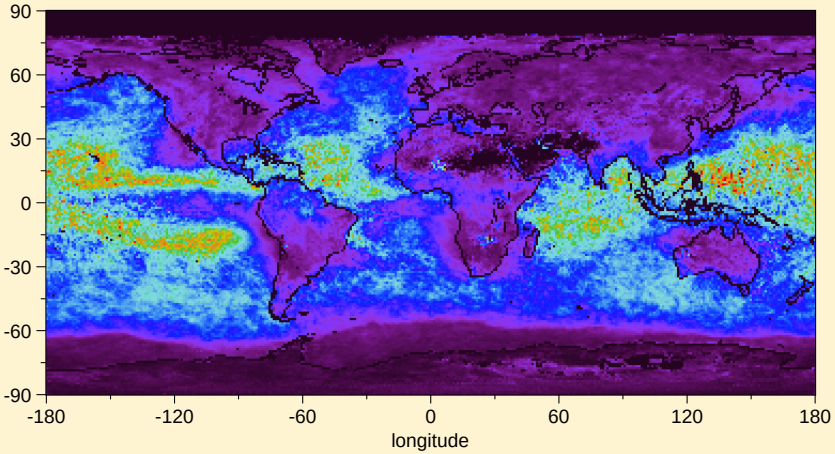


Global cloud albedo susceptibility from MODIS Level-3

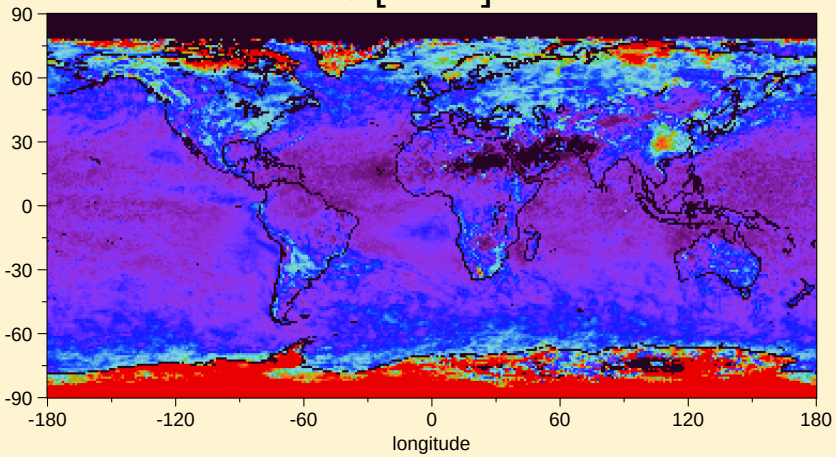
- D3 data provides daily joint τ - r_e histograms at 1°
- Used to calculate broadband unperturbed and perturbed (due to Δr_e changes) albedos; their difference is converted to susceptibility
- The albedos are obtained with the aid of a BB SW RT code
- Atmospheric and surface effects, consistent with retrievals, are included
- Daily susceptibility values are averaged to monthly scales
- Susceptibility has been calculated for four months (January, April, July, October 2005) of Collection 5 Terra and Aqua liquid cloud data
- Oreopoulos and Platnick (2008) (JGR Kaufman special issue)

Susceptibility, ΔN=1 cm^{-3}, LWC=0.3 gm^{-3}, MODIS Terra, Oct. 2005

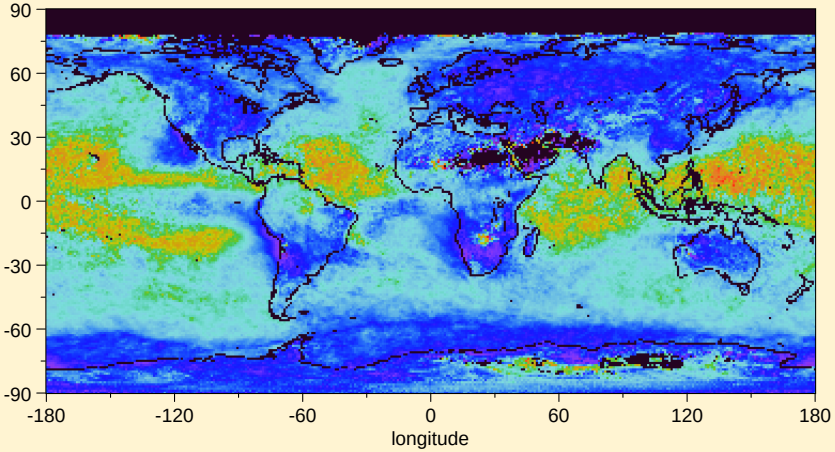
S [0–10 mm^3]



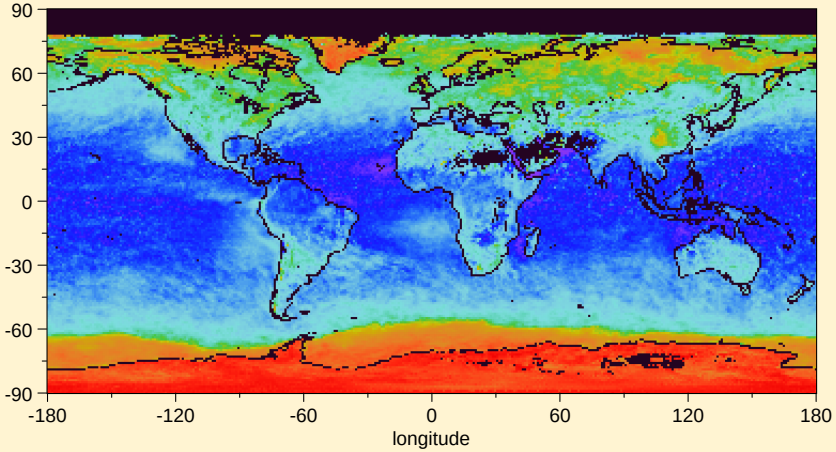
τ [0–50]



r_e [4–28 µm]

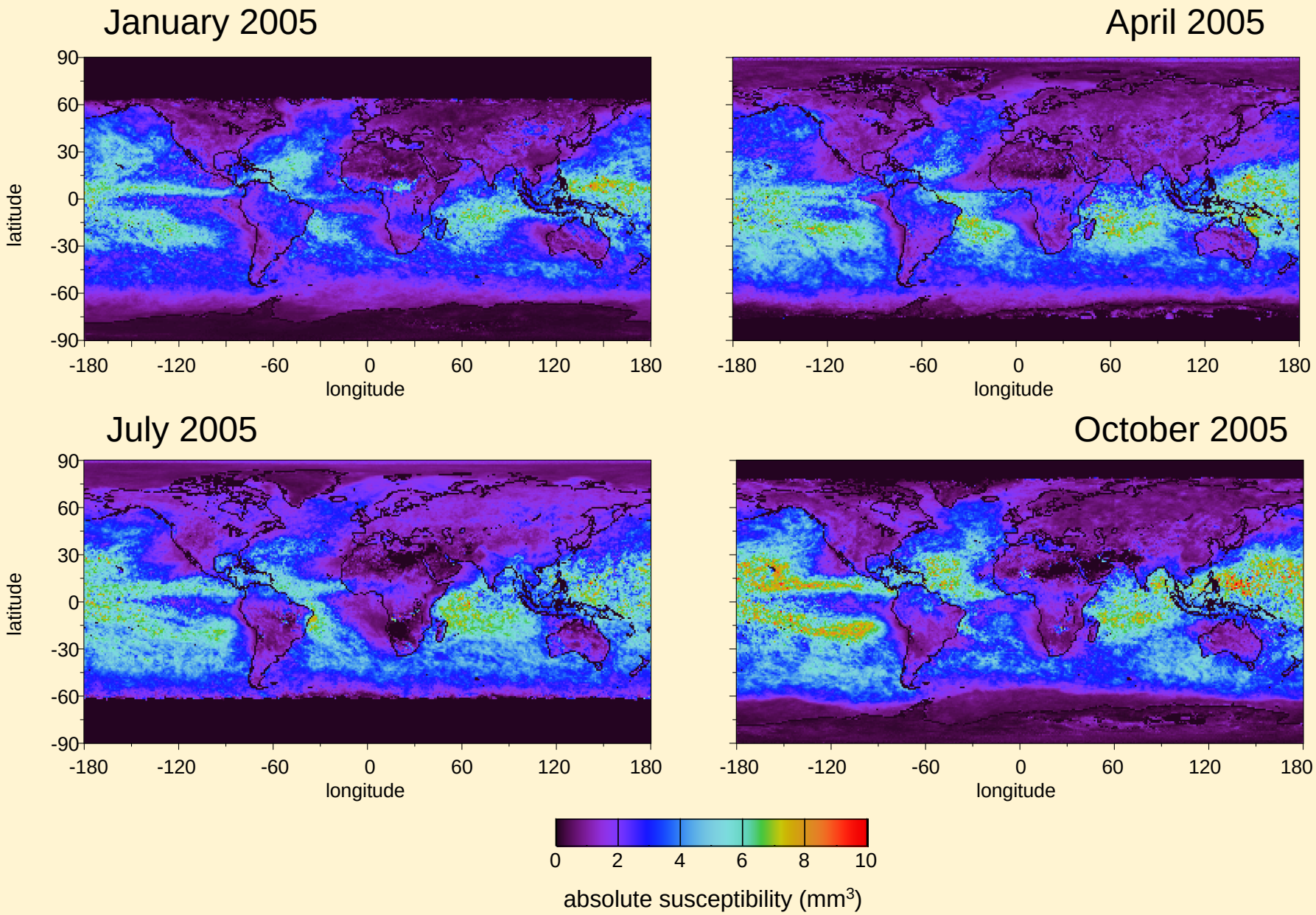


TOA albedo [0–0.8]



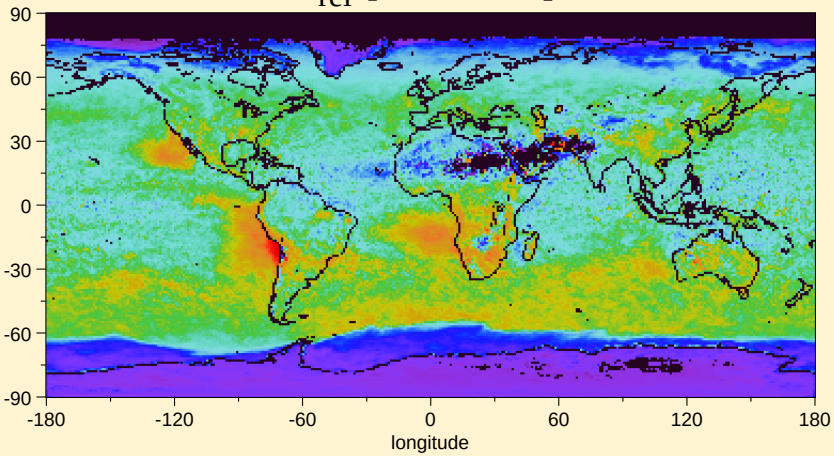
S correlates with r_e

Susceptibility, ΔN=1 cm^{-3}, LWC=0.3 gm^{-3}, MODIS Terra

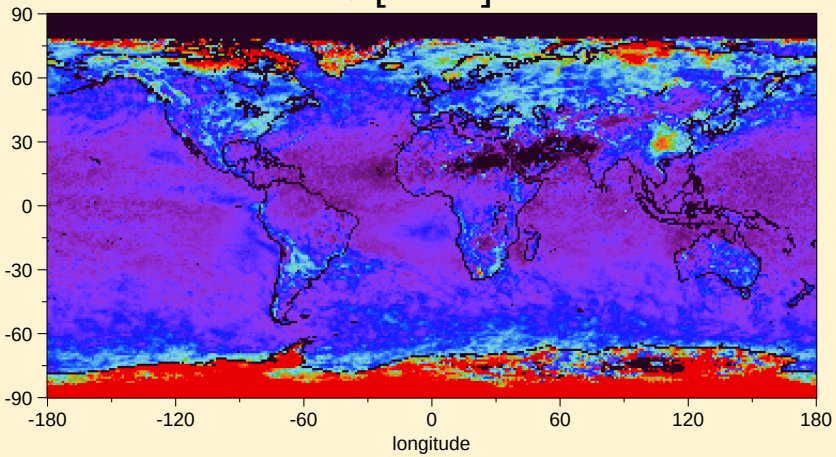


Relative susceptibility, $\Delta N/N$=10%, MODIS Terra, Oct 2005

S_{rel} [0–8x10^{-3}]



τ [0–50]



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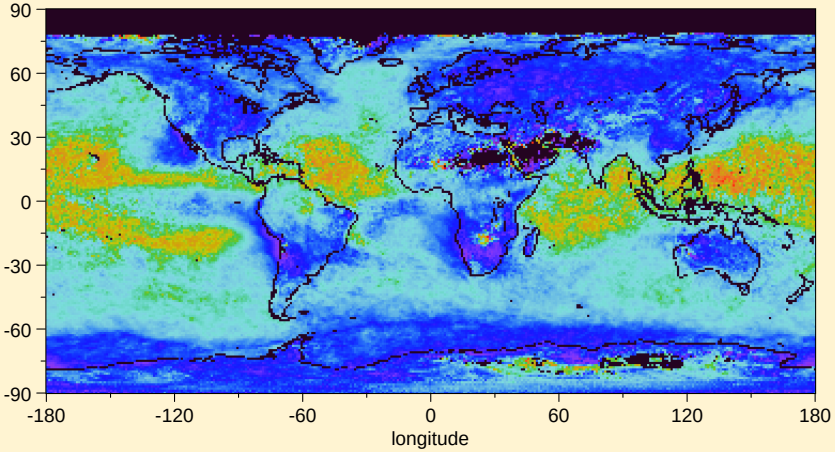

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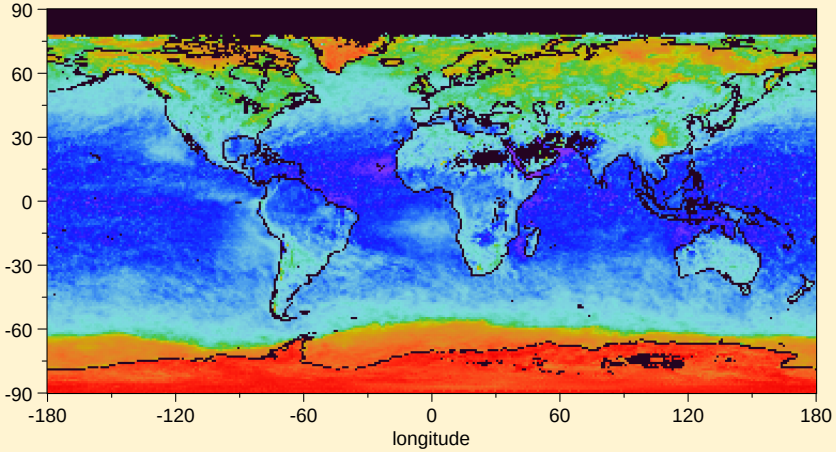
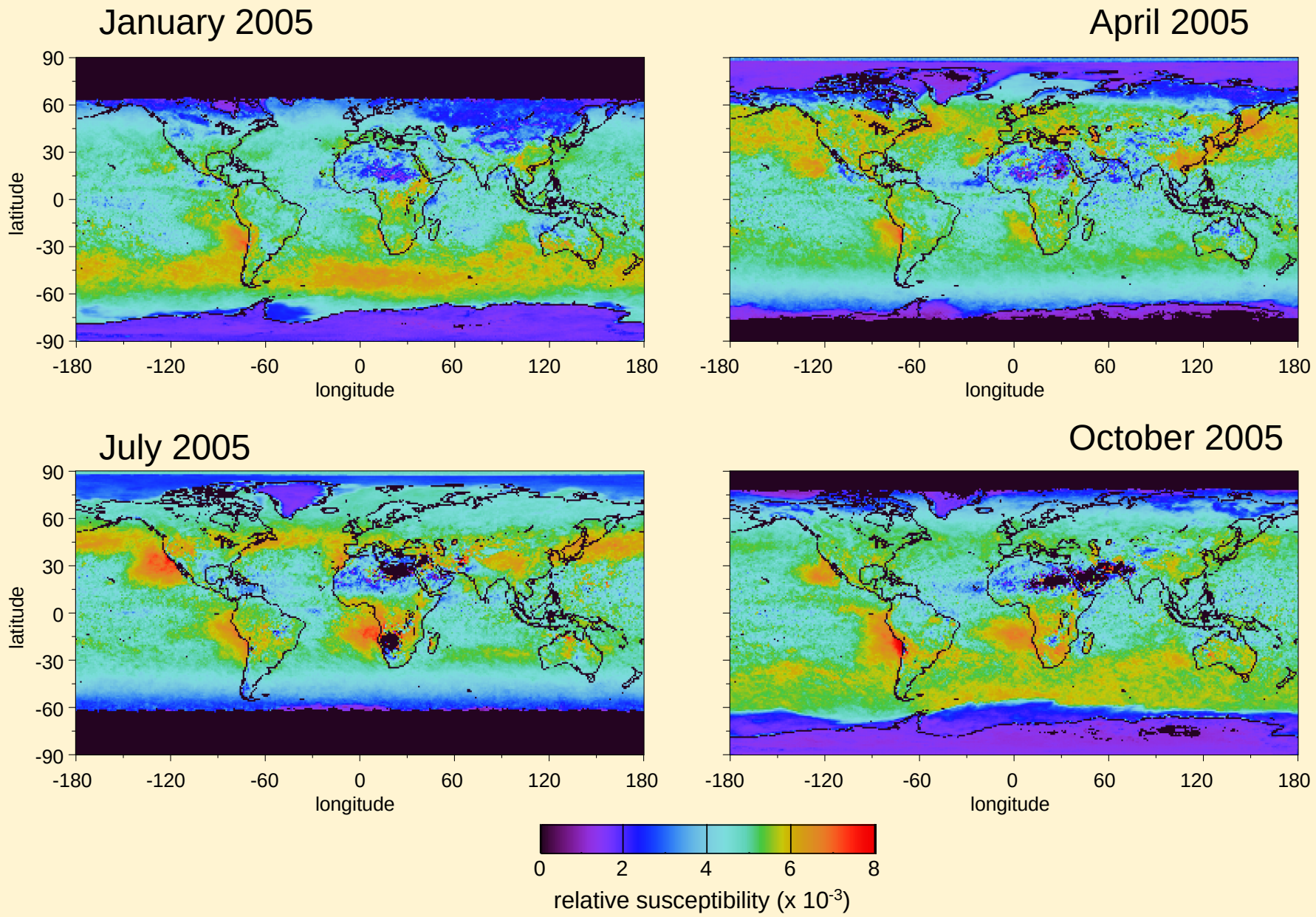
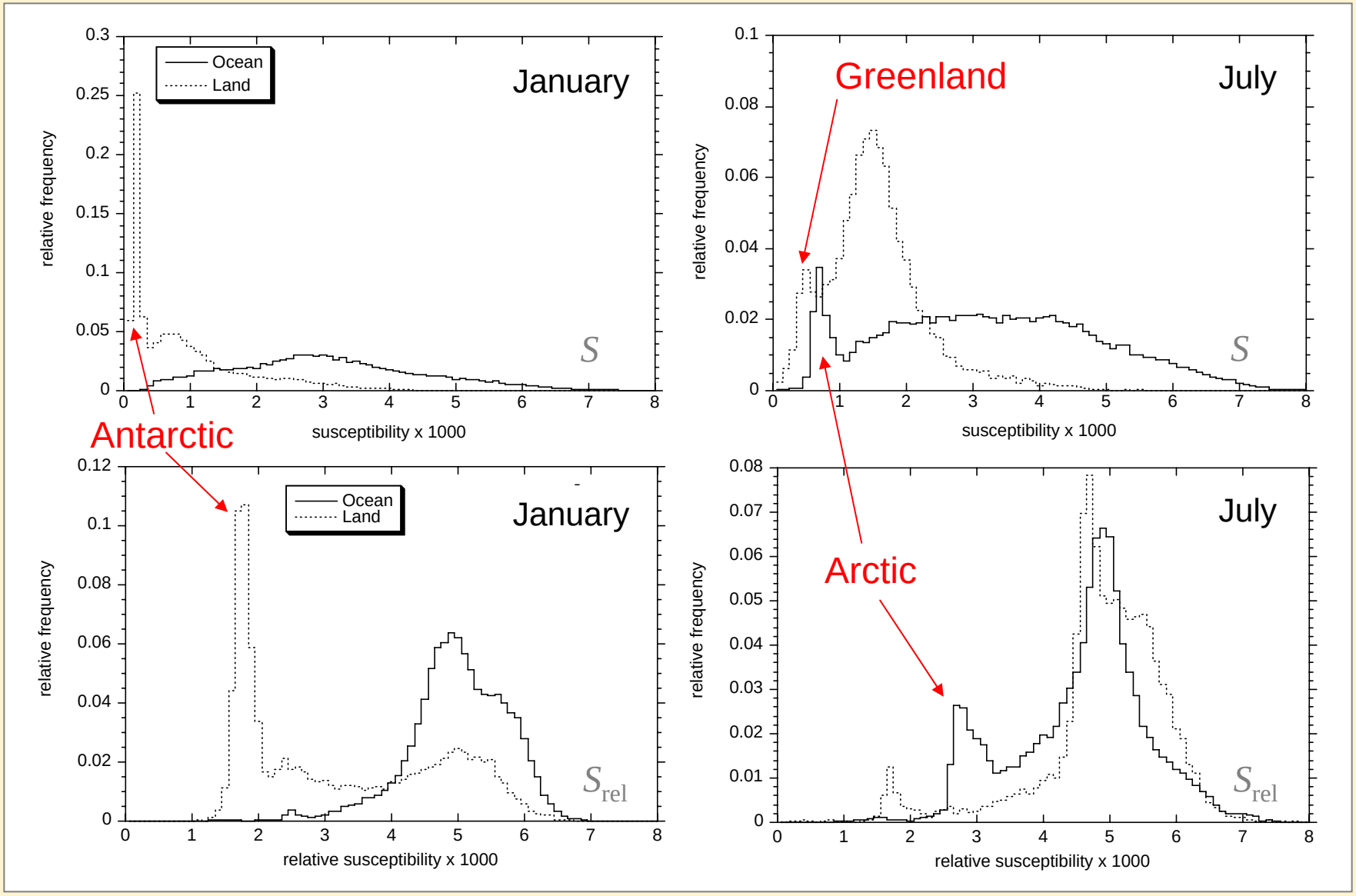


S_{rel} correlates with R_{cld}

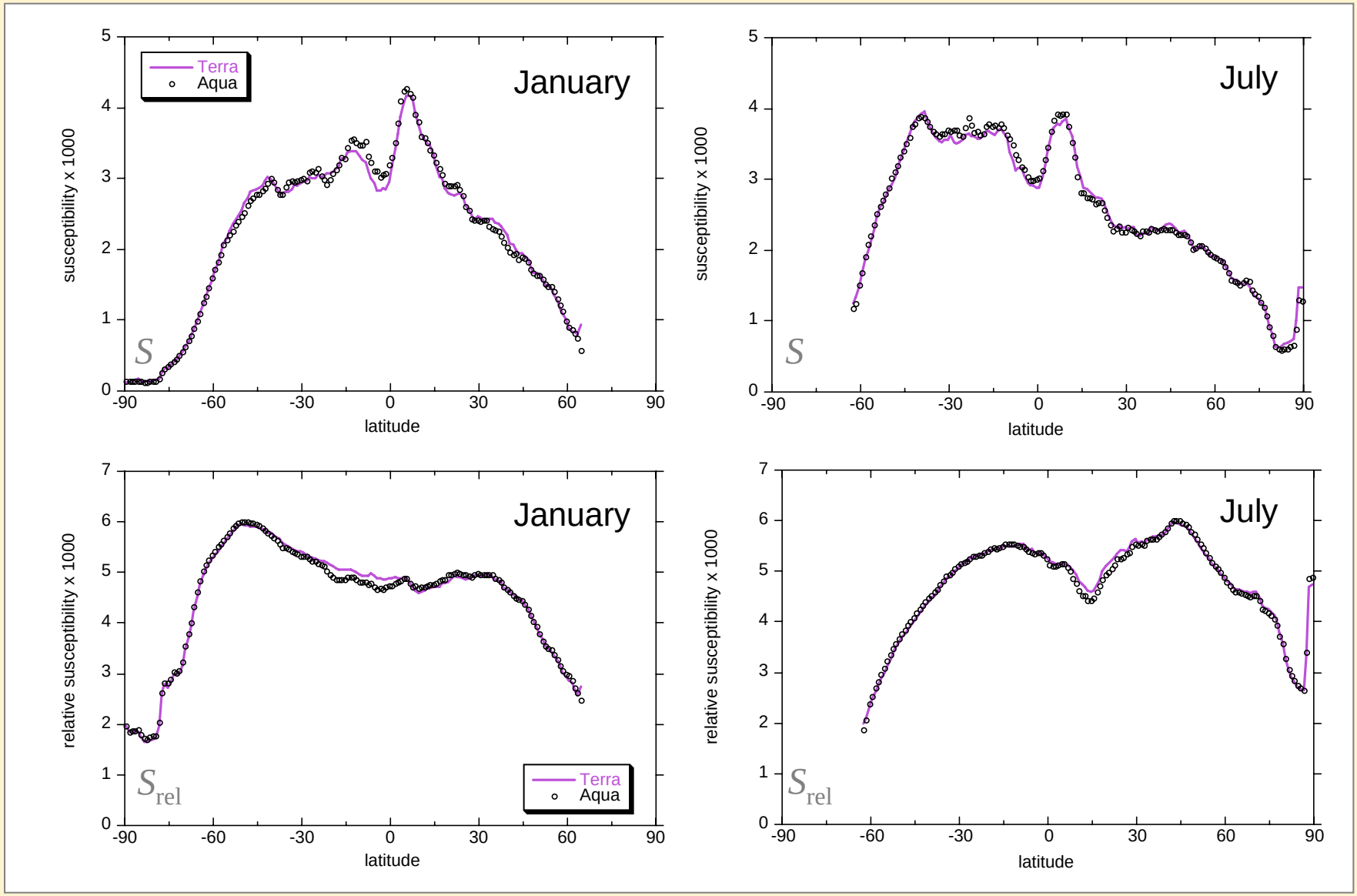
Relative susceptibility, $\Delta N/N$=10%, MODIS Terra



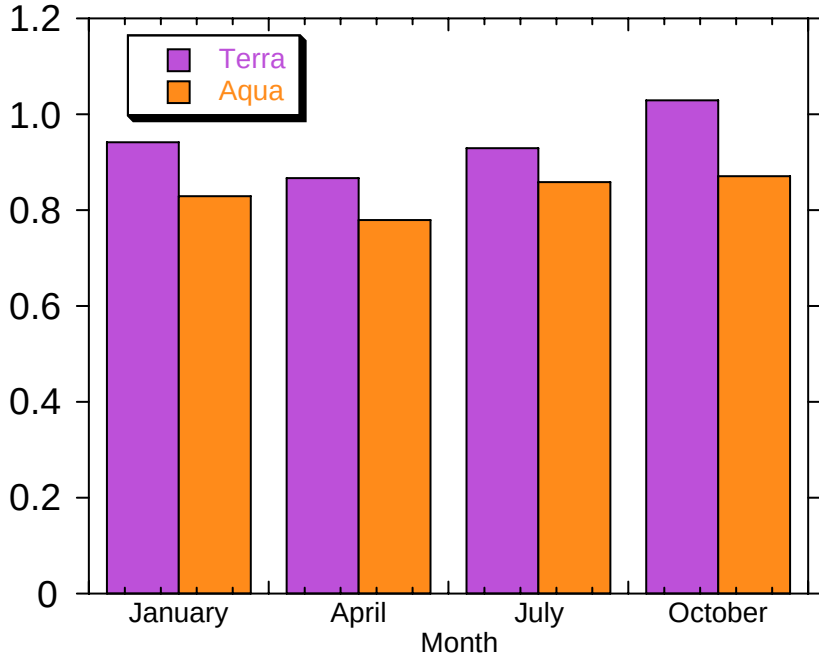
Land-ocean susceptibility contrast (MODIS Terra)



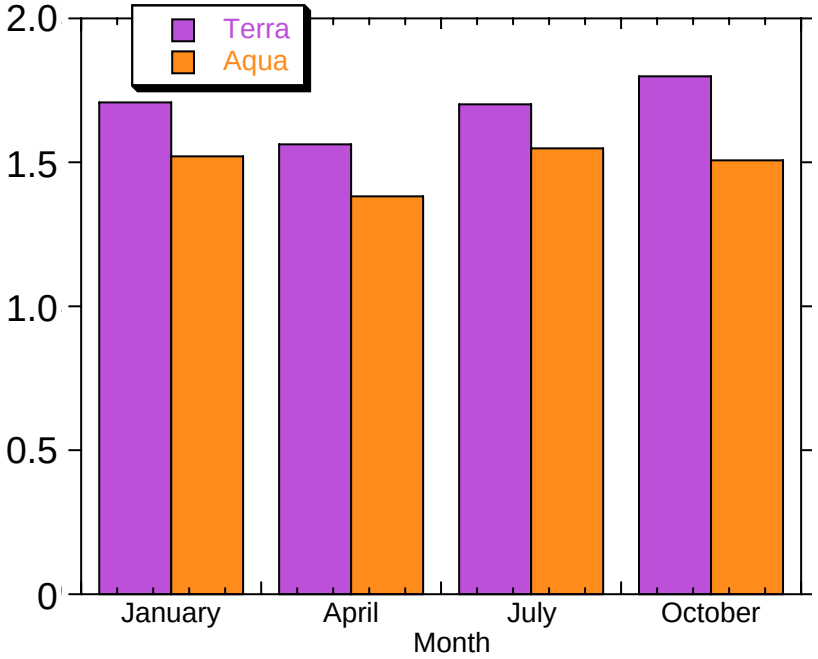
Zonal susceptibility differences MODIS Terra-Aqua



Global Susceptibility Forcing Examples



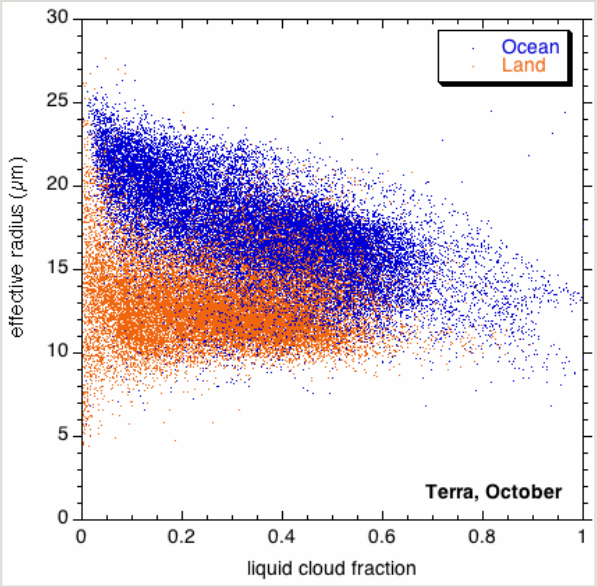
Global TOA flux change for ΔN=1cm^{-3}, LWC=0.3 gm^{-3}

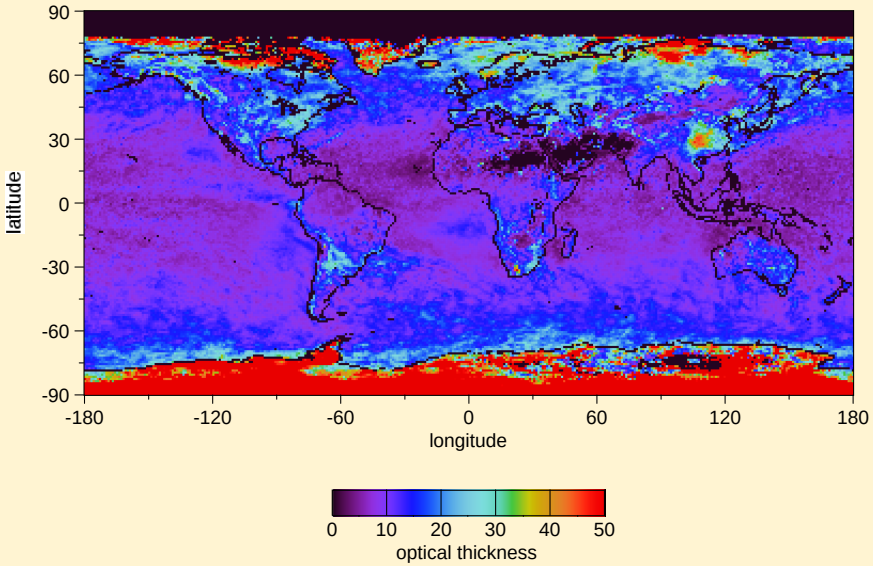


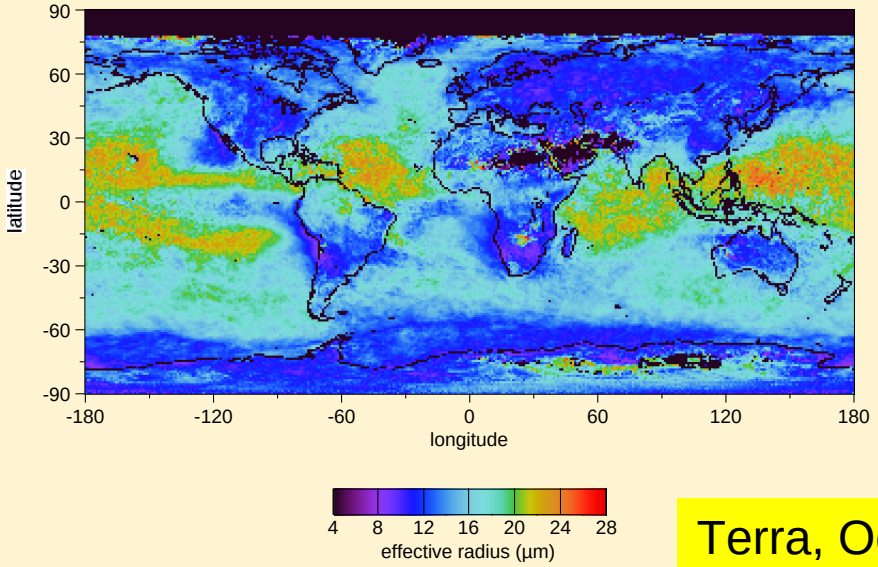
Global TOA flux change for $\Delta N/N$=10%

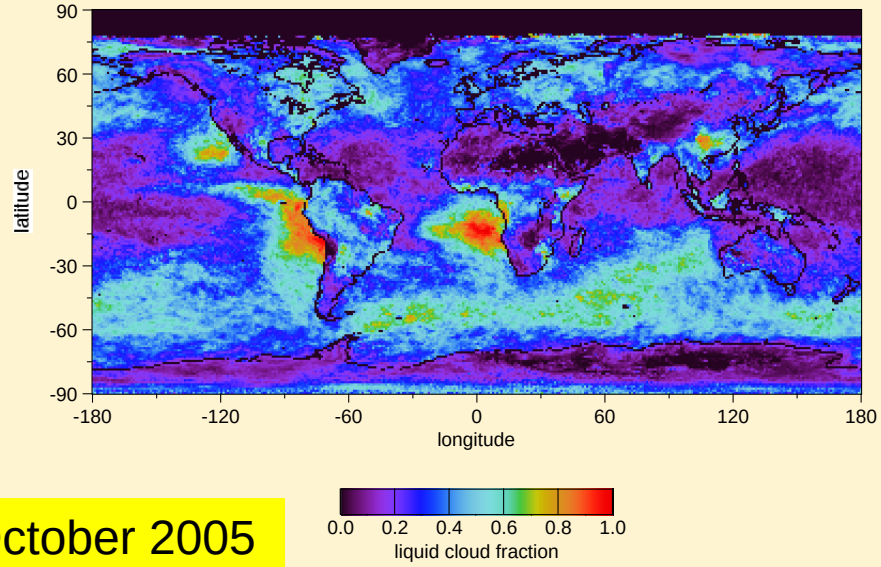
Susceptibility-cloud fraction relations are important!

The impact of cloud fraction









Terra, October 2005

Summary/ARM links

Modeling PI-PD IAE

- GMI global annual indirect forcing: -0.59 to -1.69 W m^{-2}.
- Different metfields lead up to **40%** (global average) variability in indirect forcing calculations. Remaining variability is from droplet parameterizations

Observing cloud sensitivity for future IAE (susceptibility)

- Observationally-based, global studies of broadband TOA liquid water cloud susceptibility are possible with passive cloud retrievals, but depend dramatically on the formalization of the microphysical perturbation
- Provides a higher order validation for GCM cloud fields used in IAE studies
- Global susceptibility results:
  - Significant seasonal variations, consistent with seasonal shifts in cloud patterns and properties, marine clouds are more susceptible than continental clouds
  - Current distribution of liquid clouds as observed from MODIS, yields **~1.5 Wm^{-2}** for a uniform 10% increase in N under constant liquid water content conditions
- ARM cloud susceptibility (ideas?) : LWC, r_e profiles available (e.g., MICROBASE), but CDNC assumed. Field campaigns (RACORO)?