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Susceptibility of marine clouds to emission increases – observations and model simulations

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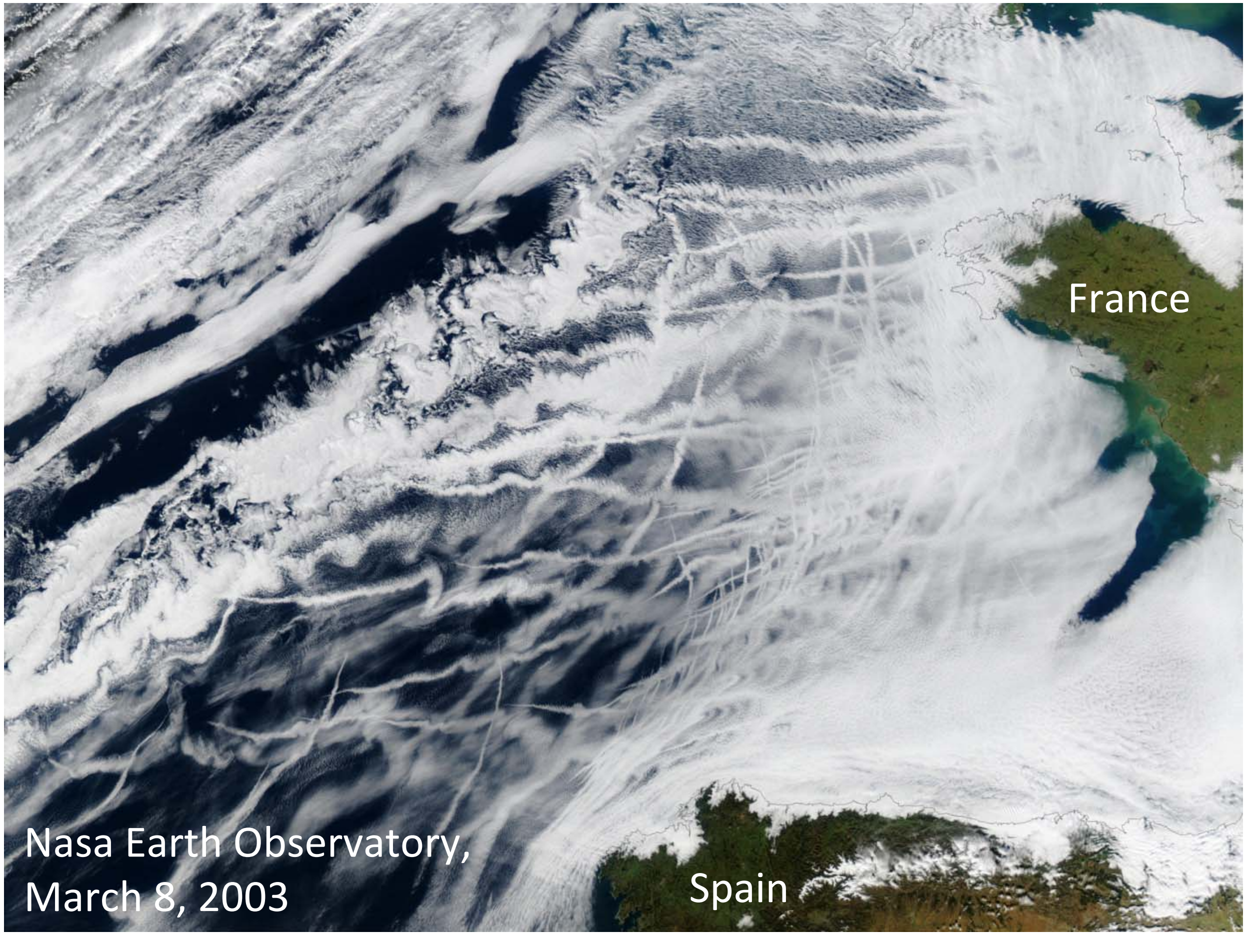
Problem definition



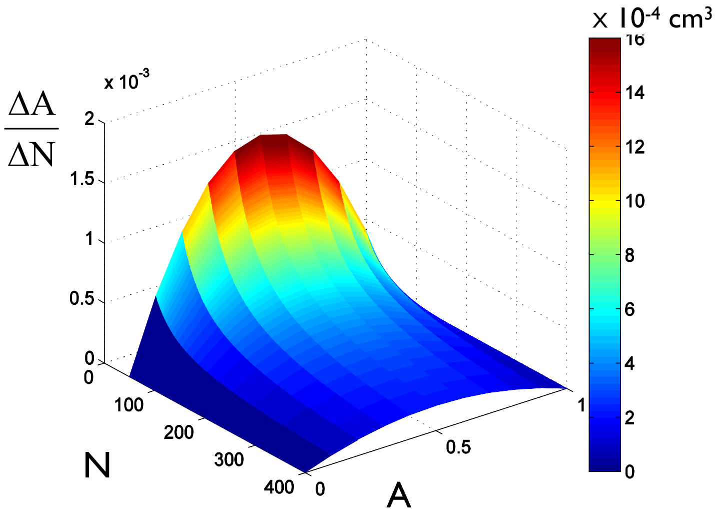
Objectives

- To develop a simple measure of the radiative susceptibility of warm clouds to aerosol-cloud interactions.
- This function can be used for understanding intermodel differences in aerosol indirect effect estimates.
- Validate the developed function through:
  - Calculating the same product based on satellite observations.
  - Simulated sensitivity experiments.

Cloud susceptibility

- Sensitivity of cloud albedo (A) to a given increase in cloud droplet number concentration (N) (*Twomey, 1991*).

$$\frac{\Delta A}{\Delta N} = \frac{A(1-A)}{3N}$$



- Reaches maximum in clean regions (small N) with intermediate albedo (A).

Cloud susceptibility

- Create a normalized susceptibility function, f_{susc}:

$$f_{susc} = \left(\frac{\Delta A}{\Delta N}\right) \Big/ \left(\frac{\Delta A}{\Delta N}\right)_{max} \quad , f_{susc} \in [0,1]$$

- A weighting factor (f_{zen}) accounts for the solar zenith angle, being unity for an overhead sun and zero for sun below the horizon.
- Fraction and frequency of susceptible clouds (f_{cf}) is also important for the total radiative effect of changes in cloud droplet number concentration.

Cloud susceptibility

- The cloud-weighted susceptibility is given by the product of the in-cloud susceptibility function f_{susc}, the solar zenith angle weighting factor (f_{zen}) and the cloud fraction (f_{cf}):

$$f_{c-w\_susc} = f_{susc} \cdot f_{zen} \cdot f_{cf}$$

Model

Norwegian Earth System Model (NorESM)

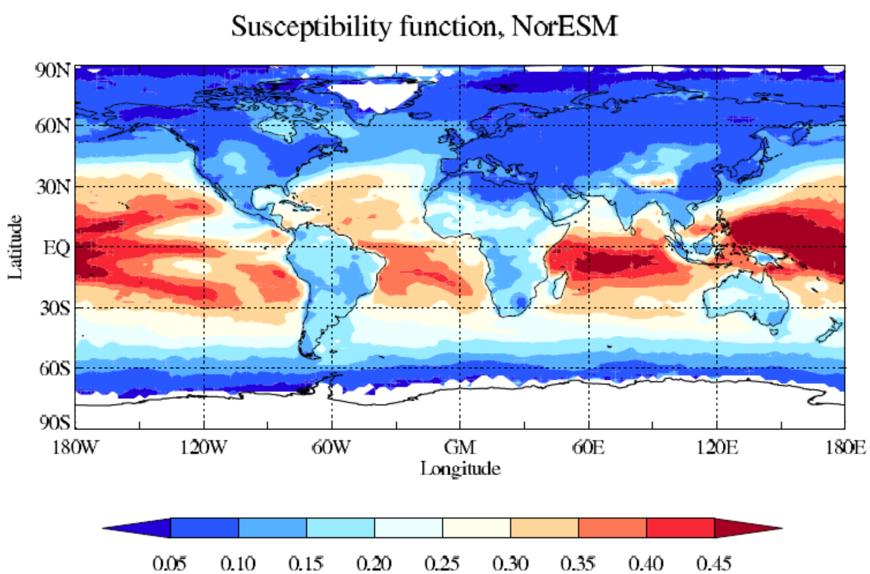
- Based on the NCAR Community Climate System Model version 4 (CCSM4).
- Atmospheric component CAM4-Oslo: Modifications to the treatment of atmospheric chemistry, aerosols, and clouds (e.g. *Seland et al., 2008 and Hoose et al., 2009*).
- New ocean component based on Miami Isopycnal Coordinate Ocean Model (MICOM).

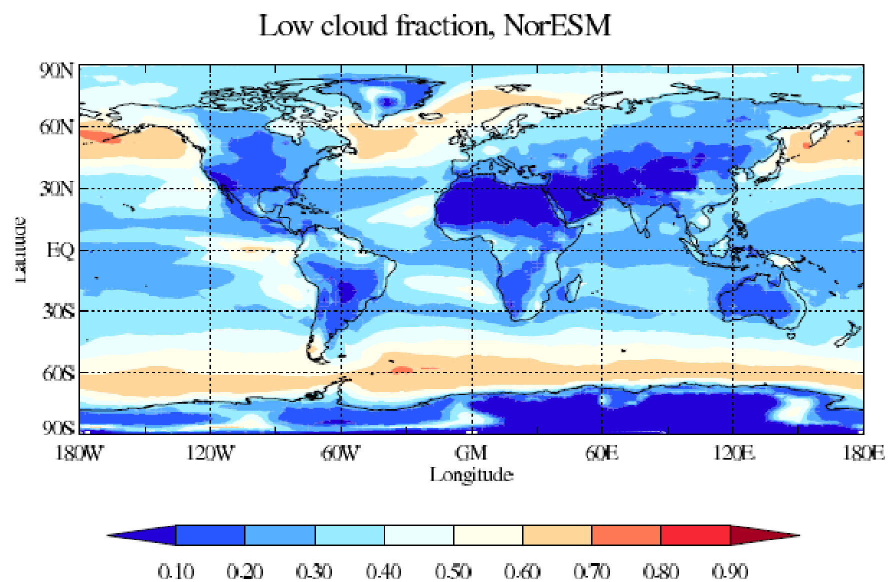
Daily output.

Observational data

- MODIS (MODerate resolution Imager Spectroradiometer) collection 5 data. (τ_{cloud}, r_e, LWP, cloud frac., solar zen.)
- Quaas & Boucher 2003 data set of cloud droplet number concentration:
    - Liquid clouds
    - Adiabatically stratified
    - Constant N in the vertical

NorESM:
Susceptibility (f_{susc}) and low cloud fraction (f_{cf})





- Susceptibility reaches maximum in clean regions (small N) with intermediate albedo.

$$f_{susc} \propto \frac{A(1-A)}{3N}$$

- Fraction of low clouds (> 700 hPa) is large in storm track regions and in stratocumulus regions.

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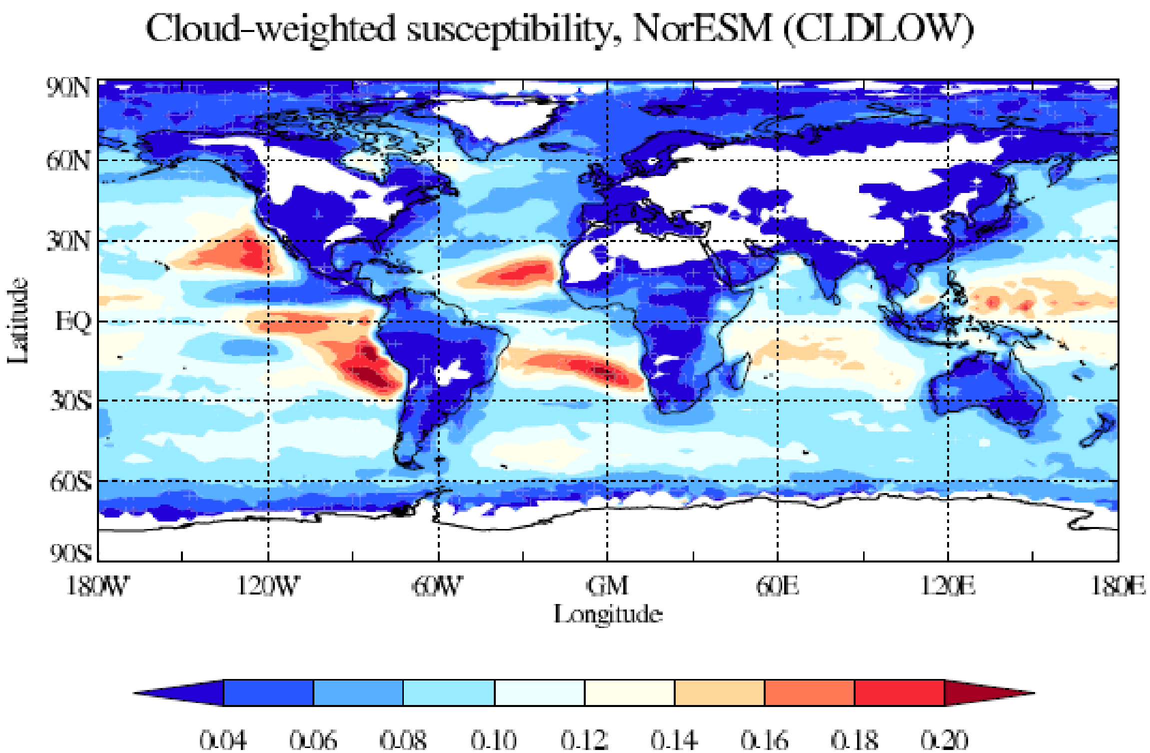
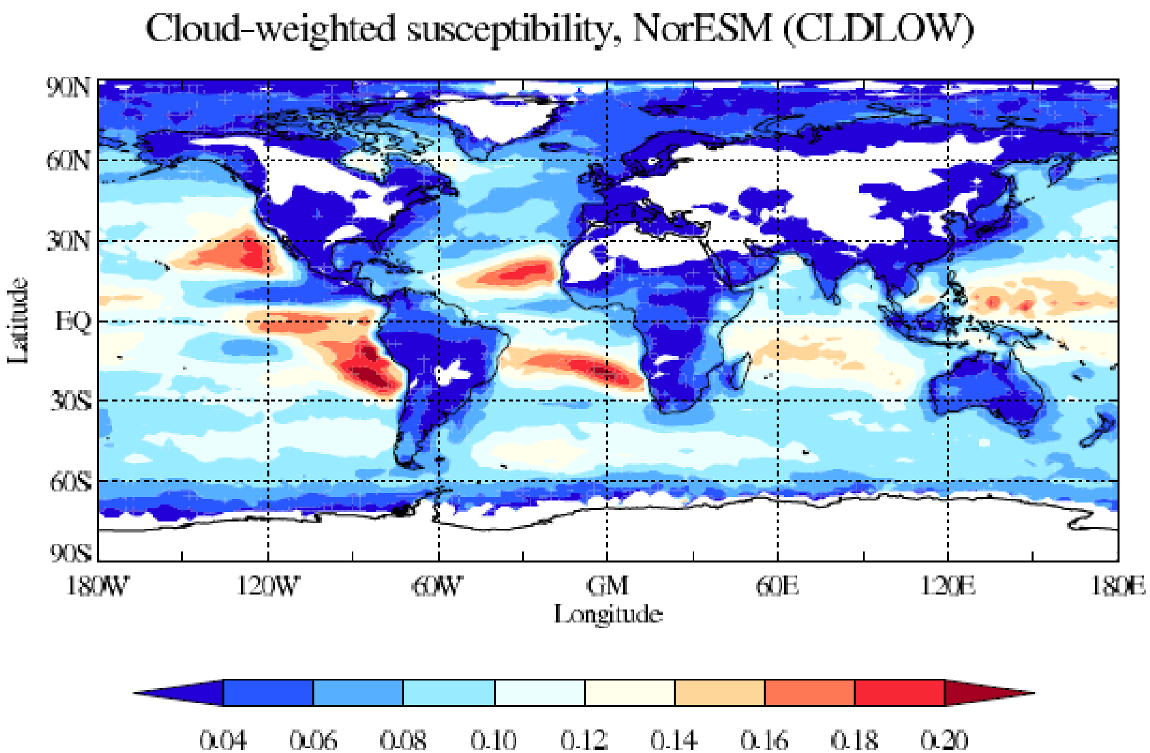
NorESM:
Cloud-weighted susceptibility ($= f_{susc} \cdot f_{zen} \cdot f_{cf}$)



- Dominated by cloud fraction and zenith angle rather than susceptibility.

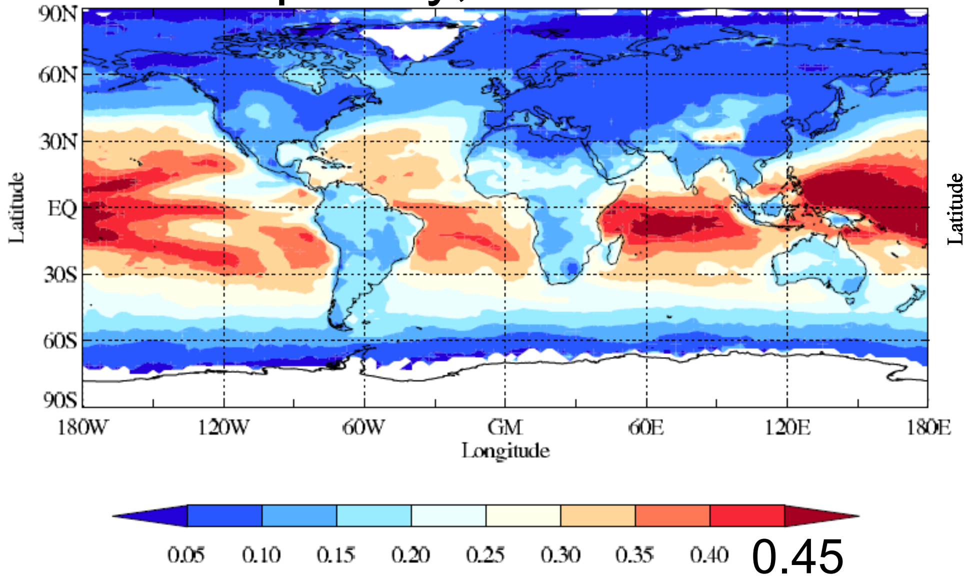
NorESM:
Cloud-weighted susceptibility (= $f_{susc} \cdot f_{zen} \cdot f_{cf}$)



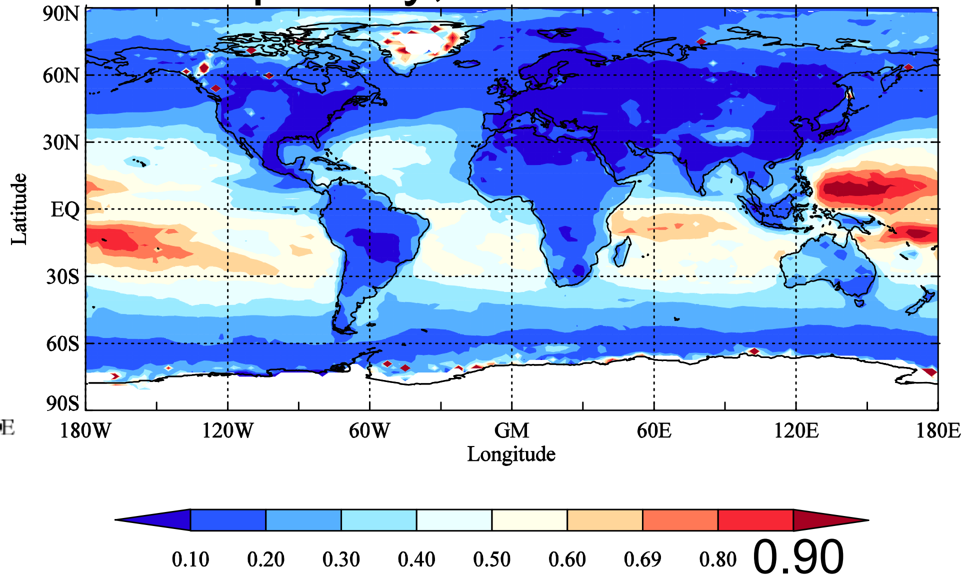
- Areas particularly sensitive droplet number increase include:
  i. The stratocumulus regions off the west coasts of the continents.
  ii. Regions in the Pacific and the Indian Oceans.

NorESM:
Importance of time resolution

Susceptibility, DAILY DATA

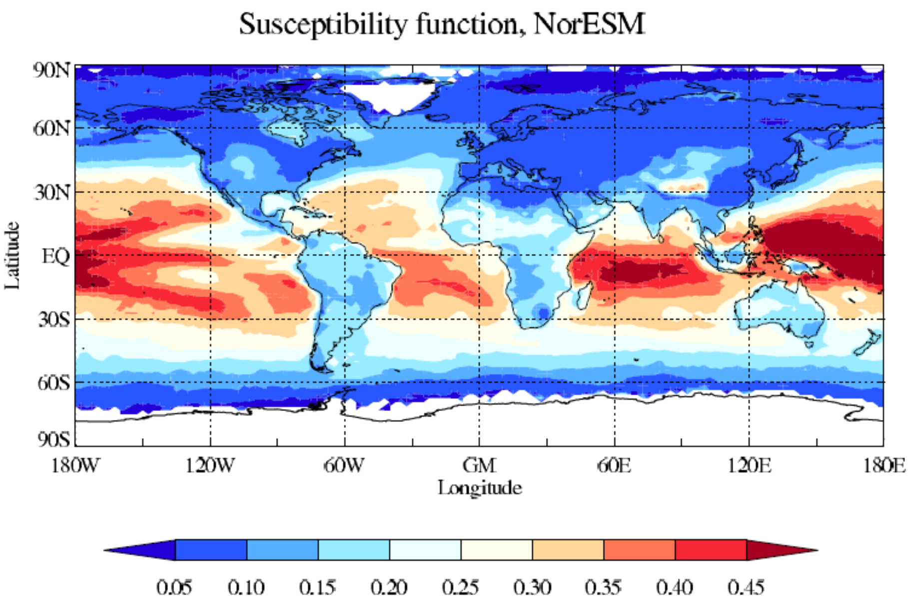


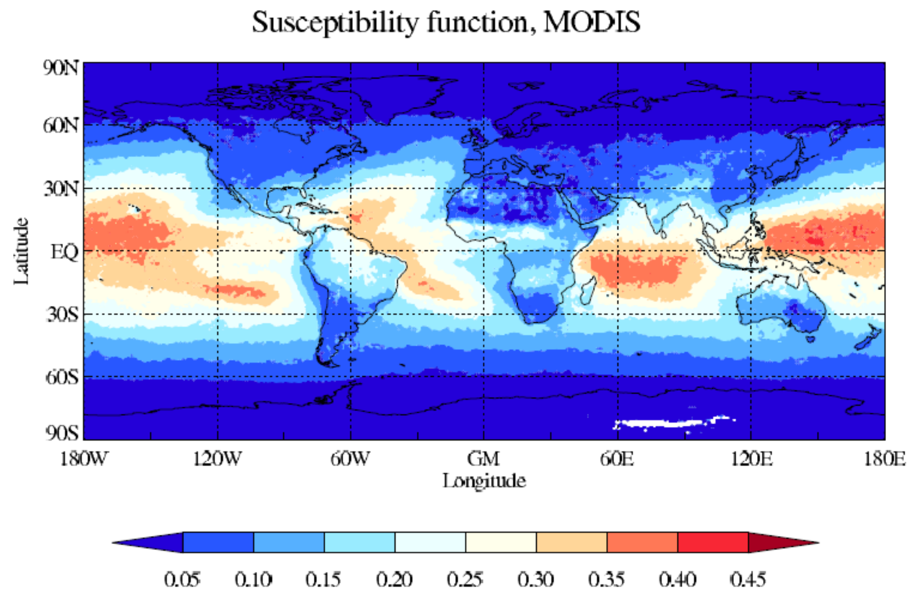
Susceptibility, MONTHLY DATA



- The calculated susceptibility is very sensitive to time resolution, indicating a large spread in cloud properties.
- The same is true when based on satellite observations.

Validation against MODIS:





- Good spatial agreement in general.
- Larger magnitude in NorESM than in MODIS results due to:
  - Lower N in simulations than in the Quaas and Boucher data set.
  - The A from NorESM generally higher and closer to 0.5 than the MODIS cloud albedo.

$$f_{susc} \propto \frac{A(1-A)}{3N}$$

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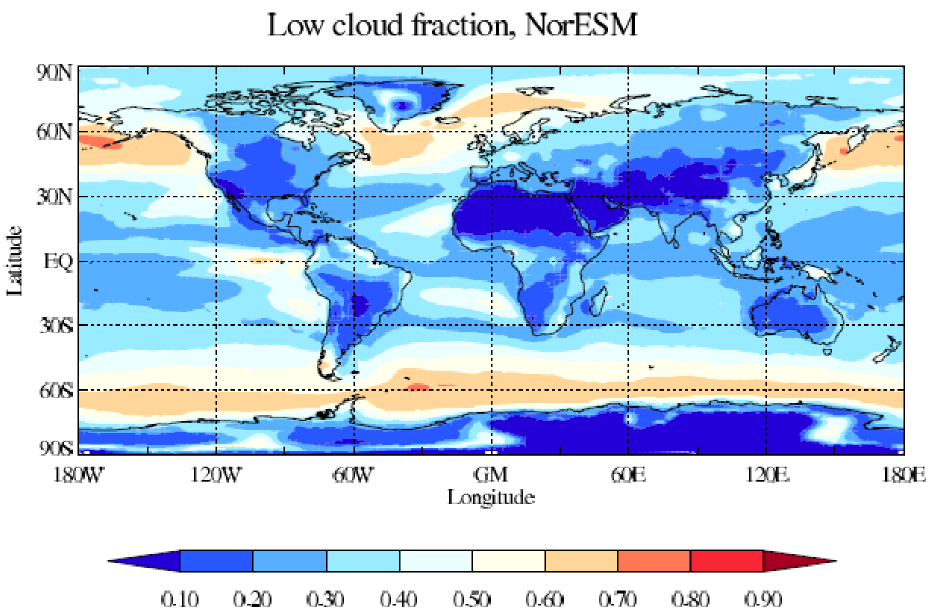
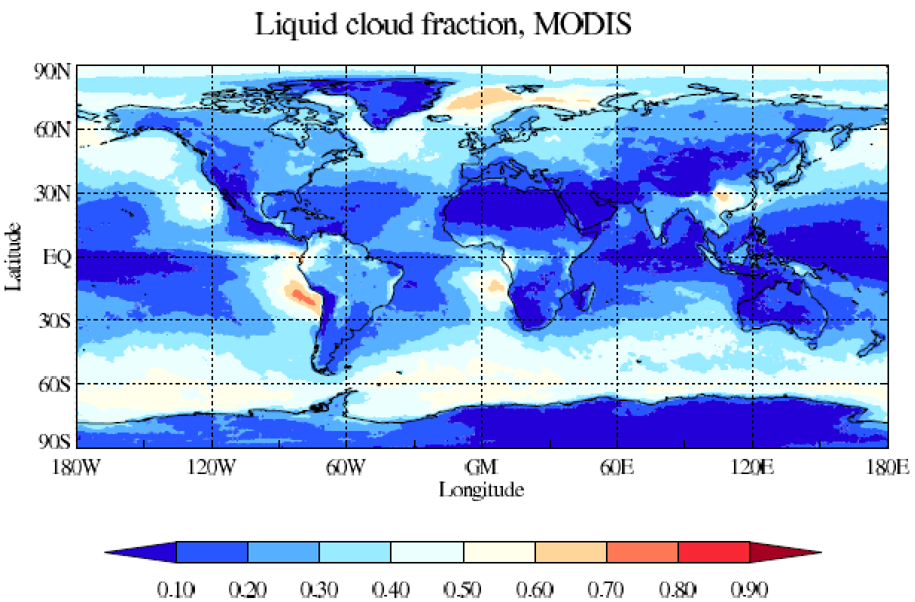
Validation against MODIS:





- NorESM: All clouds up to 700 hPa, including times with overlaying clouds.
- MODIS: Clouds that are only liquid with no overlying clouds.
- The simulated fraction of low clouds is generally higher than the fraction of liquid clouds from MODIS, except in the stratocumulus regions.

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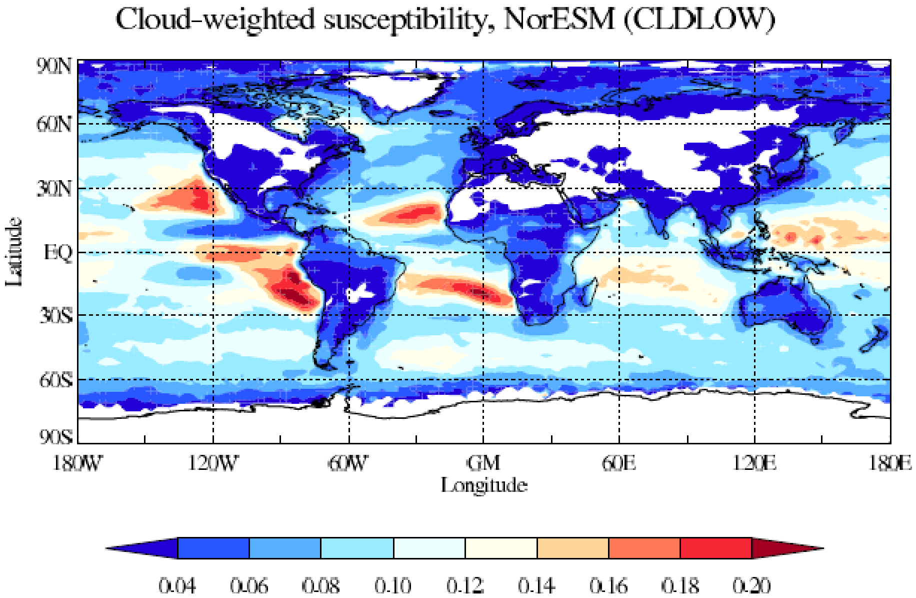
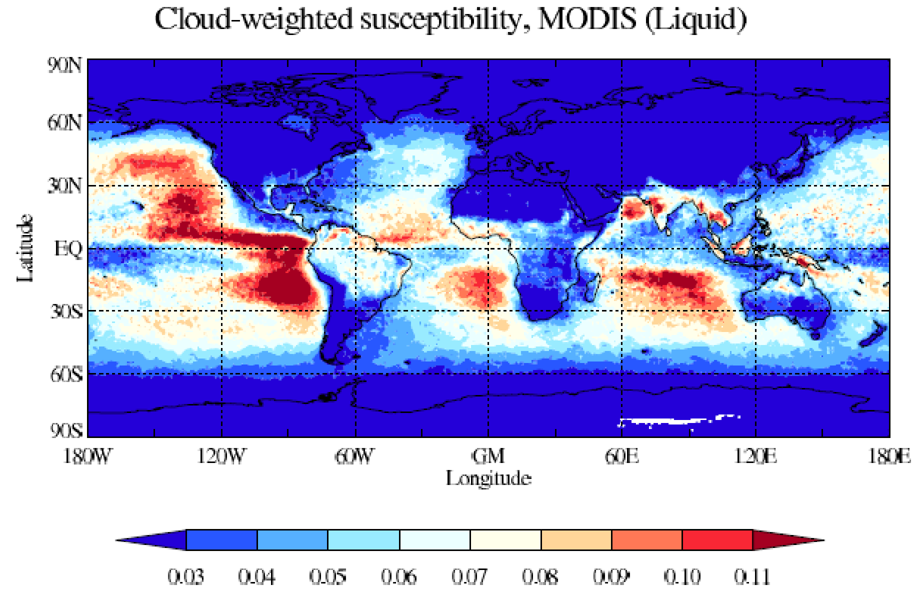
Validation against MODIS:

Please note that color bars differ





- Fair spatial agreement between model and observations.
- Larger magnitude in NorESM than in MODIS results due to:
  - The simulated fraction of low clouds is generally higher than the fraction of liquid clouds from MODIS, except in the stratocumulus regions.
  - Larger magnitude of simulated susceptibility (f_{susc}).

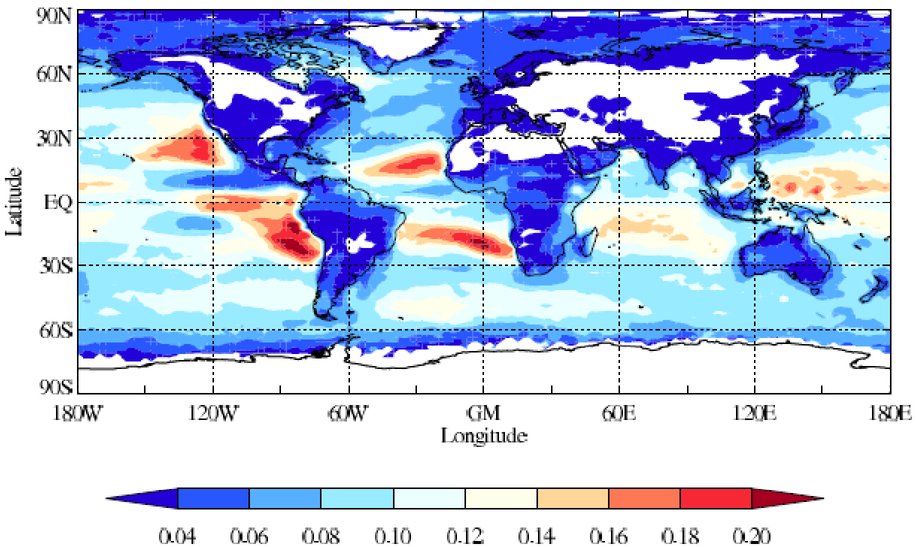
Validation through sensitivity experiment

- Investigate whether areas found to be susceptible experience changes in the radiative balance at TOA with an increased particle number.
- Uniform increase of 10^{-9} kg $m^{-2}s^{-1}$ in the emissions of sea salt over ocean.

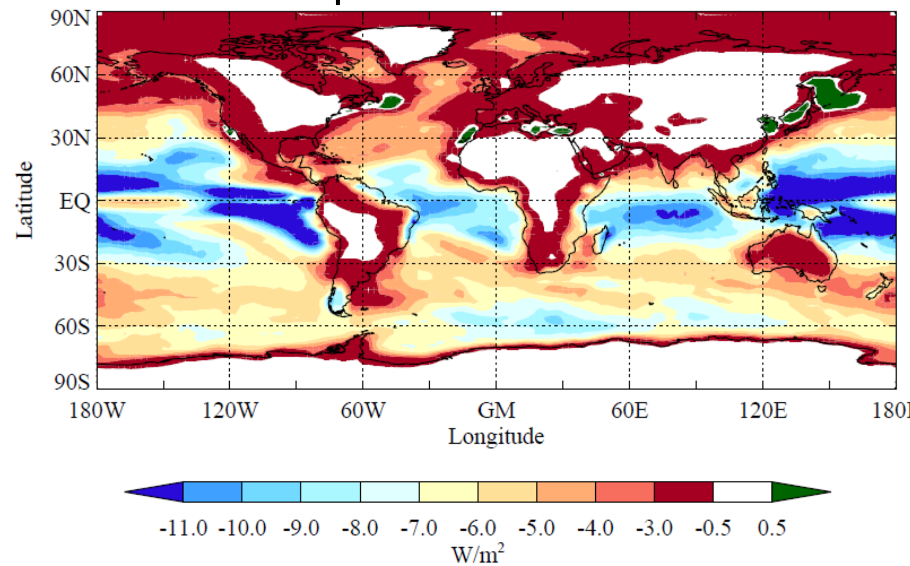
(Modal radius of 0.13 µm, geometric standard deviation of 1.59)

Sensitivity experiment

Cloud weighted susc, NorESM



Change in the column abs solar flux, sens exp.



- The cloud weighted susceptibility function, $f_{c\text{-}w\_susc}$, is a good indicator of the impact of increased CCN concentrations.
- Discrepancies especially large in the mid Pacific.

Conclusions

- Developed a cloud-weighted susceptibility of warm clouds to aerosol-cloud interactions.
- Validation against satellite observations gives an estimate of models' ability to simulate first indirect effect.
- Starting tool for understanding intermodel differences in aerosol indirect effect estimates.
- Likeable for being simple:
  - Post process
  - Variables needed should already be available?

Thank you for your attention!

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References

- Hoose et al. (2009), Constraining cloud droplet number concentration in GCMs suppresses the aerosol indirect effect. *Geophys. Res. Lett.*, 36, doi: 10.1029/2009GL038568
- Quaas, J. and O. Boucher (2005); MODIS_ACDNC Adiabatic Cloud Droplet Number Concentration daily value. World Data Center for Climate. [doi: 10.1594/WDCC/MODIS_CDNC]
- Seland et al. (2008). Aerosol-climate interactions in the CAM-Oslo atmospheric GCM and investigation of associated basic shortcomings. *Tellus*, 60A, 459-491.
- Twomey, S. (1974). Pollution and the planetary albedo, *Atmos. Environ*., 8, 1251-1256
- Twomey, S. (1991). Aerosols, clouds, and radiation. *Atmos. Environ.,* 25**,** 2435–2442

Definition of susceptible areas

$$A \approx \frac{\tau}{\tau + 6.7} \qquad g = 0.85$$

$$A \approx \frac{1}{\mu_s} \frac{a\tau}{\tau + b}$$

$$a = a_0 + a_1 \cdot \ln(r_e) + a_2 \cdot \ln(r_e^{\ 2}) + a_3 \cdot \ln(\frac{1}{\mu_s}) + a_4 \cdot \ln(\frac{1}{\mu_s^{\ 2}})$$

$$a_i = [0.814288, -0.0215277, 0.000377898, -0.837754, 0.327909]$$

$$b = b_0 + b_1 \cdot \ln(r_e) + b_2 \cdot \ln(r_e^{\ 2}) + b_3 \cdot \ln(\frac{1}{\mu_s}) + b_4 \cdot \ln(\frac{1}{\mu_s^{\ 2}})$$

$$b_i = [7.83334, 2.98055, -0.385704, -18.5422, 9.05006]$$

Cloud susceptibility

- $\left(\frac{\Delta A}{\Delta N}\right)_{max}$ based on A = 0.5 and N = 20 cm^{-3} (assumed lower limit)
- $A \approx \frac{\tau}{\tau + 6.7}$ for $g = 0.85$ (*Hobbs, 1993*)

$$f_{c-w\_susc} = \frac{536}{N} \frac{\tau}{(\tau + 6.7)^2}$$

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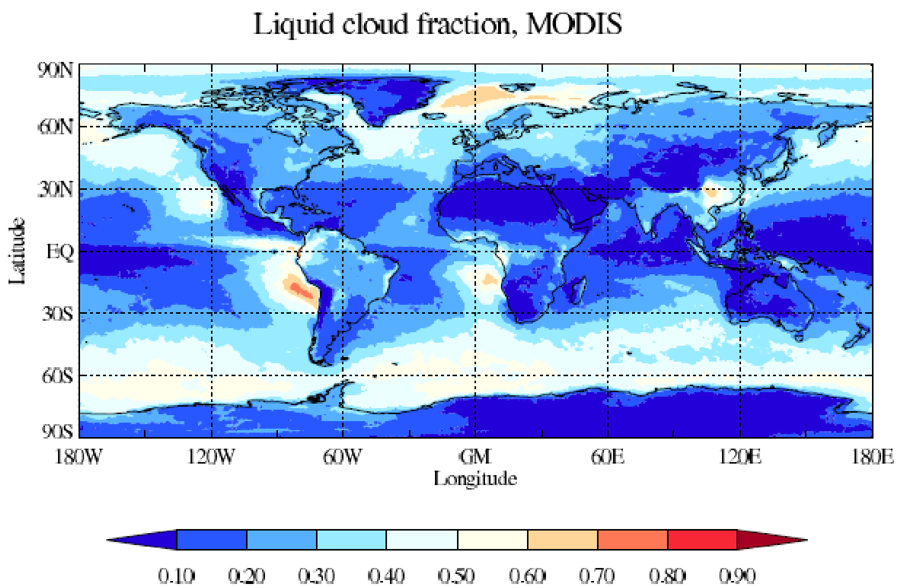
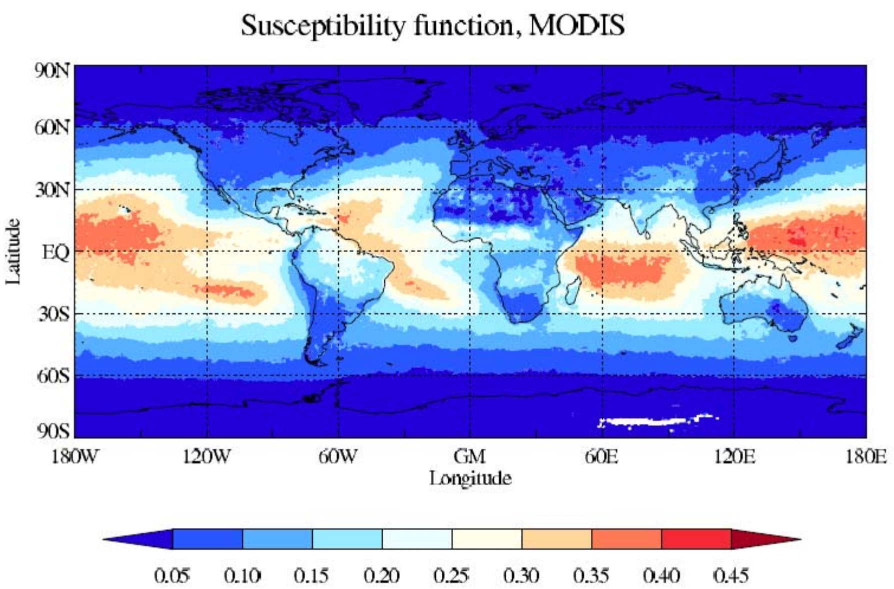
MODIS: Liquid cloud fraction (f_{cf}) and susceptibility (f_{susc})

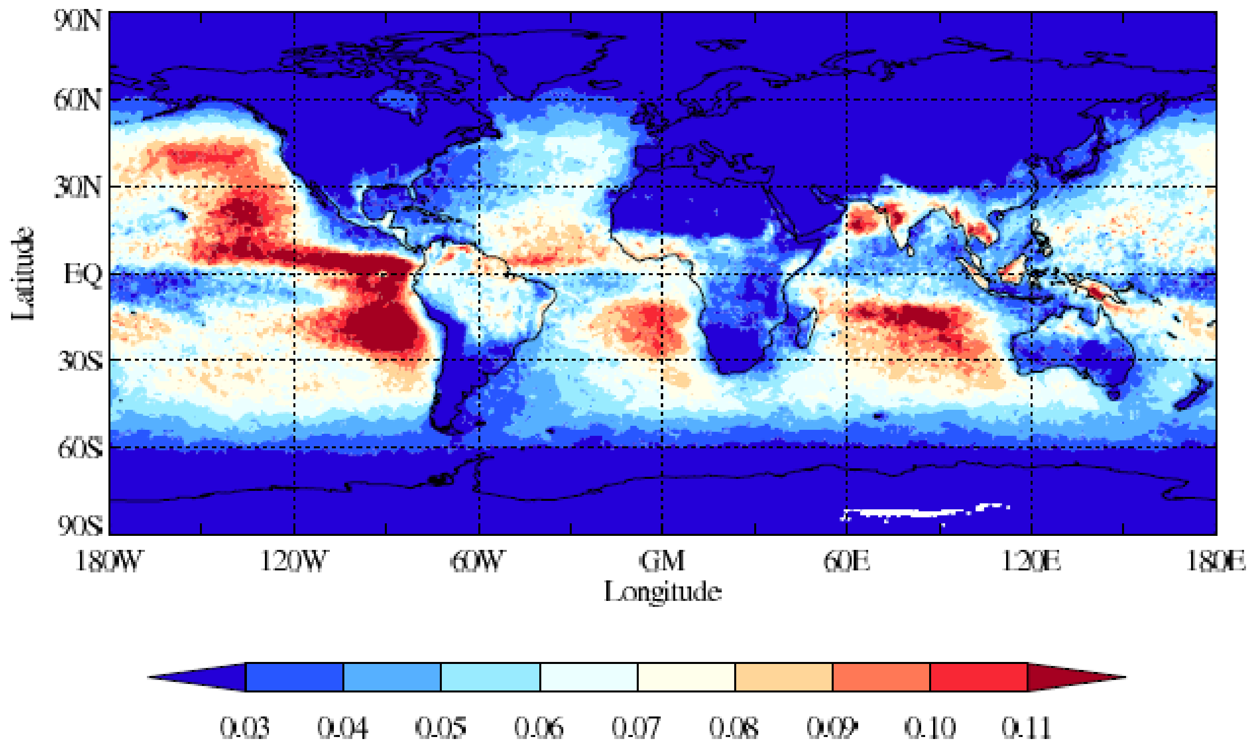




- Fraction of liquid clouds is large in stratocumulus regions and in storm track regions.
- Susceptibility reaches maximum in clean regions (small N) with intermediate albedo.

$$f_{susc} \propto \frac{A(1-A)}{3N}$$

MODIS:
Cloud-weighted suscepbtility (= $f_{susc} \cdot f_{zen} \cdot f_{cf}$)



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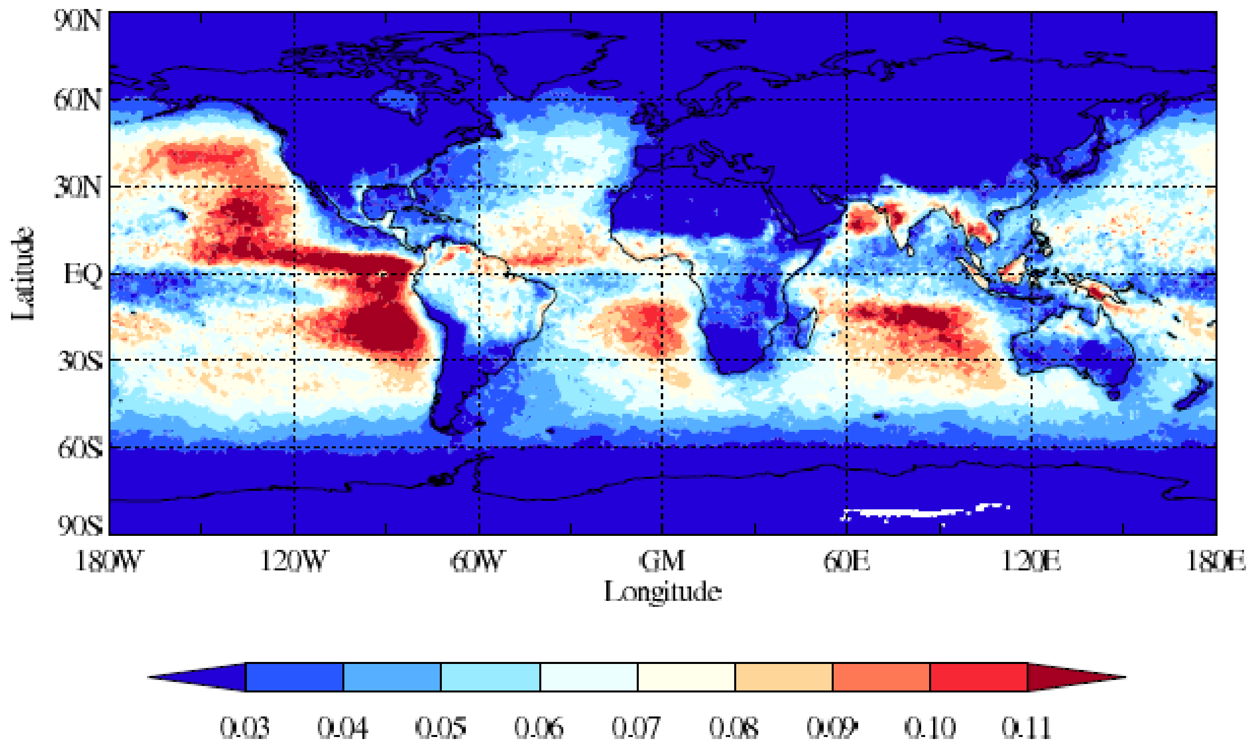
Cloud-weighted suscepbtility (= $f_{susc} \cdot f_{zen} \cdot f_{cf}$)



- Areas particularly sensitive droplet number increase include:
    i. The stratocumulus regions off the west coasts of the continents.
    ii. Large regions in the Pacific and the Indian Oceans.

Summary of the Quaas Boucher CDNC data set

- Cloud droplet number concentration is derived from MODerate Resolution Imager Spectroradiometer (MODIS) data from NASA's Terra platform. The MOD08_D3 daily data (collection 4 processing stream) on a grid of 1x1 degrees is used, which can be downloaded from http://eosdata.gsfc.nasa.gov/daac-bin/MODIS/Data_order.pl.
  From the joint histrogram of cloud optical thickness (COD) and cloud-top droplet effective radius (CDR) for liquid water clouds, CDNC is diagnosed assuming adiabatic clouds.

Maps

Jan - Mar

Apr - Jun

Jul - Sep

Oct - Dec

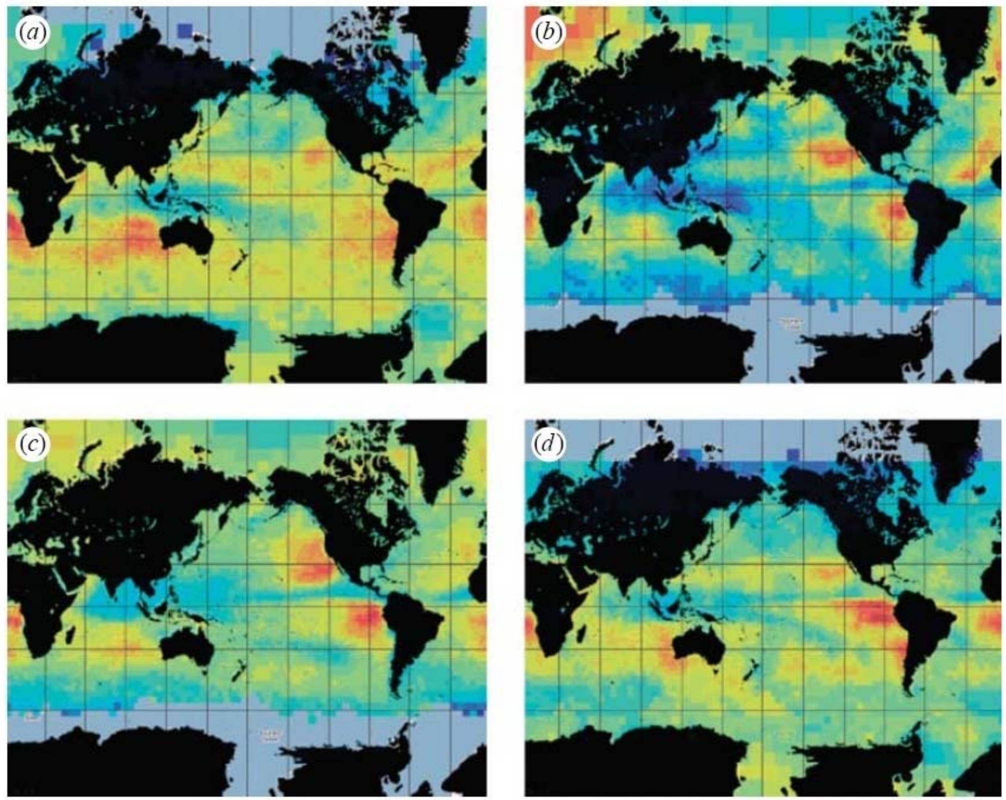


Figure 4. Results of a parameter combination based on a set of selection criteria of sunshine, initial CCN concentration, cloud cover and wind speed for four quarters of 2001 from Sortino (2006). Red is best but yellow is fine. Seasonal migration is indicated. (*a*) January–March, (*b*) April–June, (*c*) July–September and (*d*) October–December.

Salter et al. (2008)

Maps

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

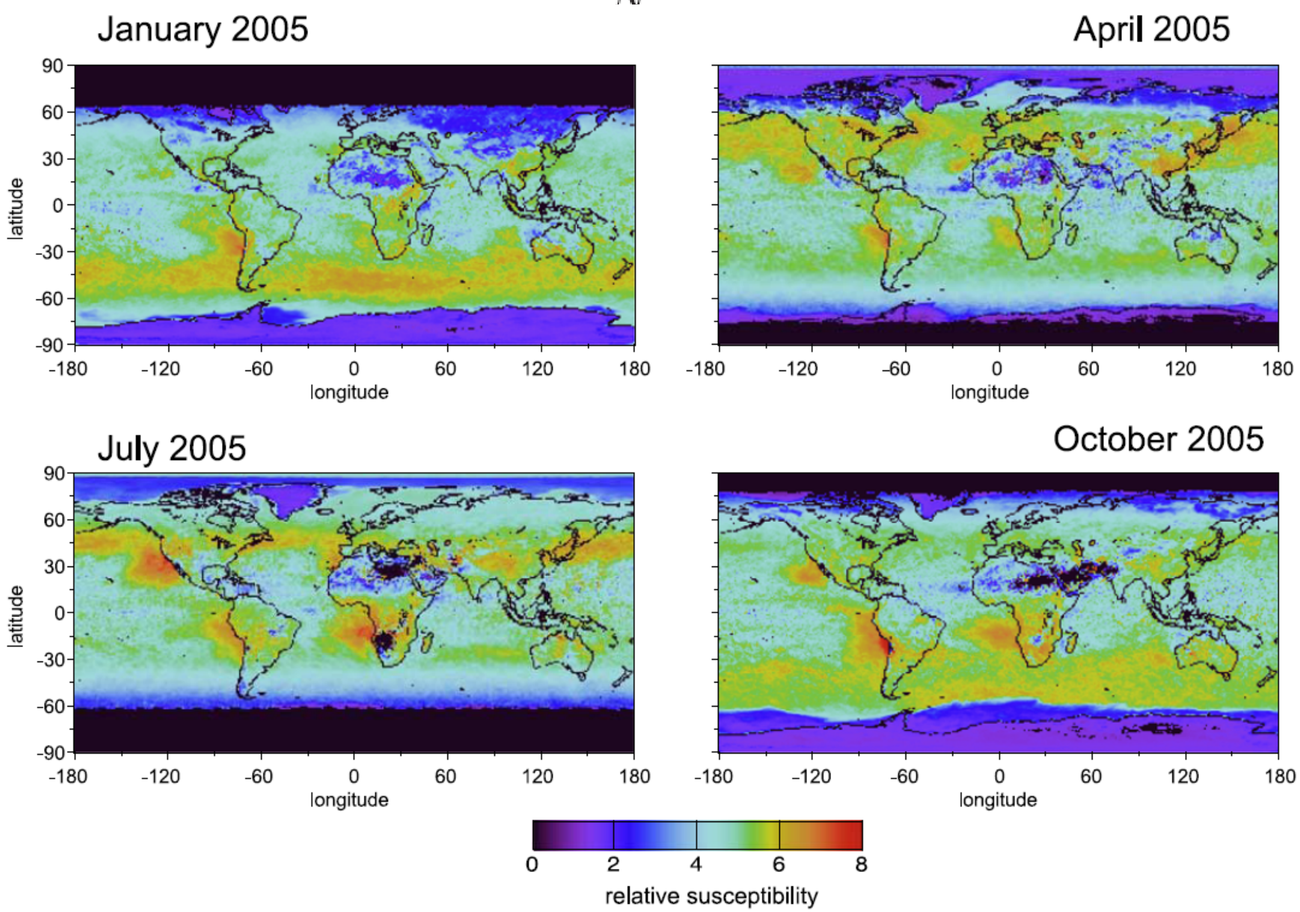


Figure 4b. As in Figure 4a but for relative susceptibility × 1000 ($\Delta N/N$ = 10%).

Oreopoulos & Platnick (2008)