Opposite indirect effect of aerosols on water and ice clouds: Satellite observations and GCM simulations

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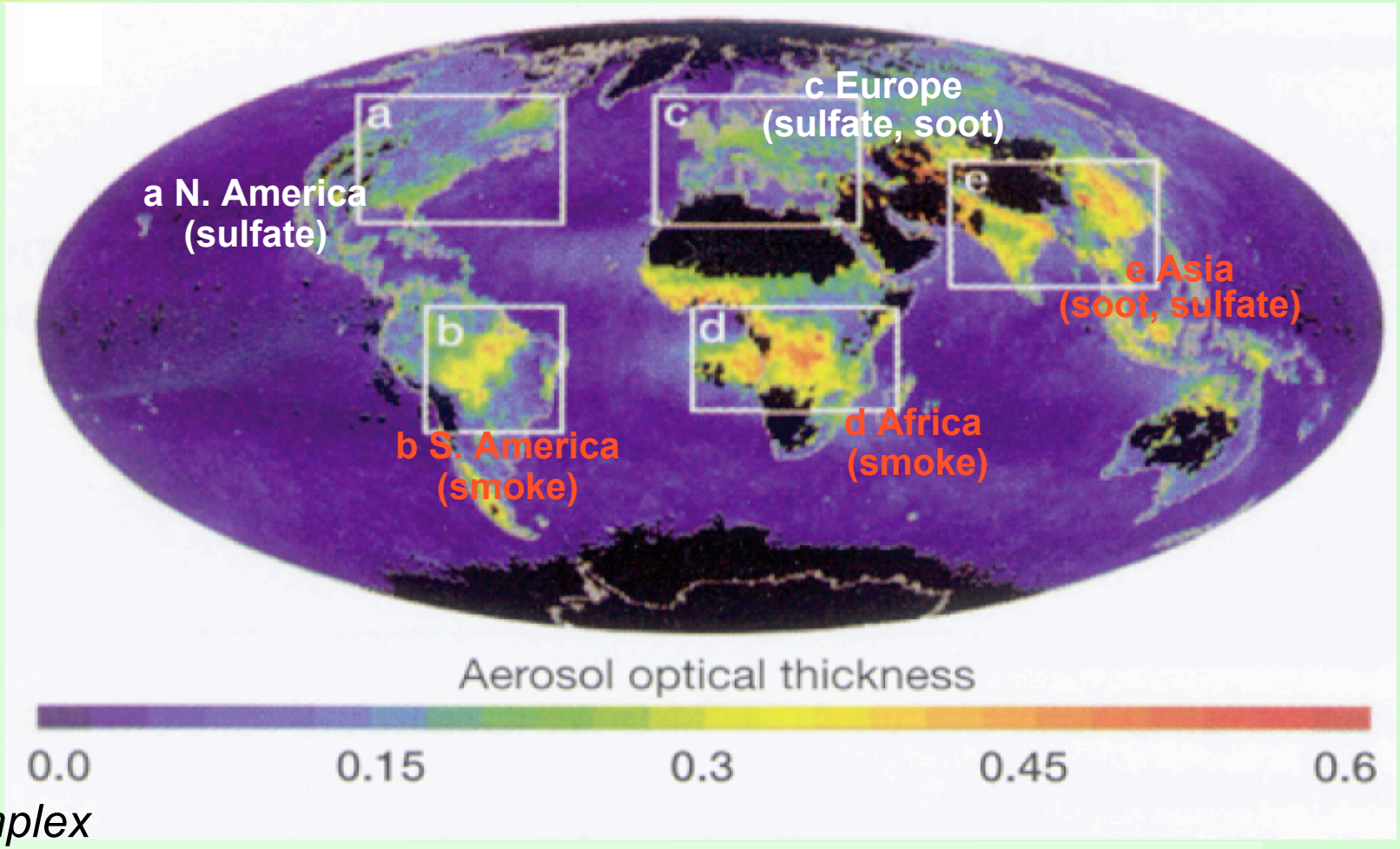
NOAA Boulder CO

OUTLINE: The SE Asian Haze Perturbation

- Strong regional perturbation to study Aerosol-Cloud interactions
  - In situ studies during INDOEX
- MODIS data products (5yrs) over SE Asia available
  - Aerosol optical depth and fine mode fraction
  - Cloud water effective radii
  - Cirrus cloud ice crystal effective radii
- Spatiotemporal correlations amongst AOD, water and ice R_e
- GCM studies: Homogeneous Vs Heterogeneous ice nucleation
- Develop Mechanisms: Correlations to Causality

Global Human Aerosol Pollution: Satellite Image



Complex Climate Impact

$$\iint_{season,latitude,longitude} F\{Asia(soot,sulfate),S.Am.(smoke),N.Am.(sulfate),Europe(sulfate,soot),Africa(smoke)\}$$

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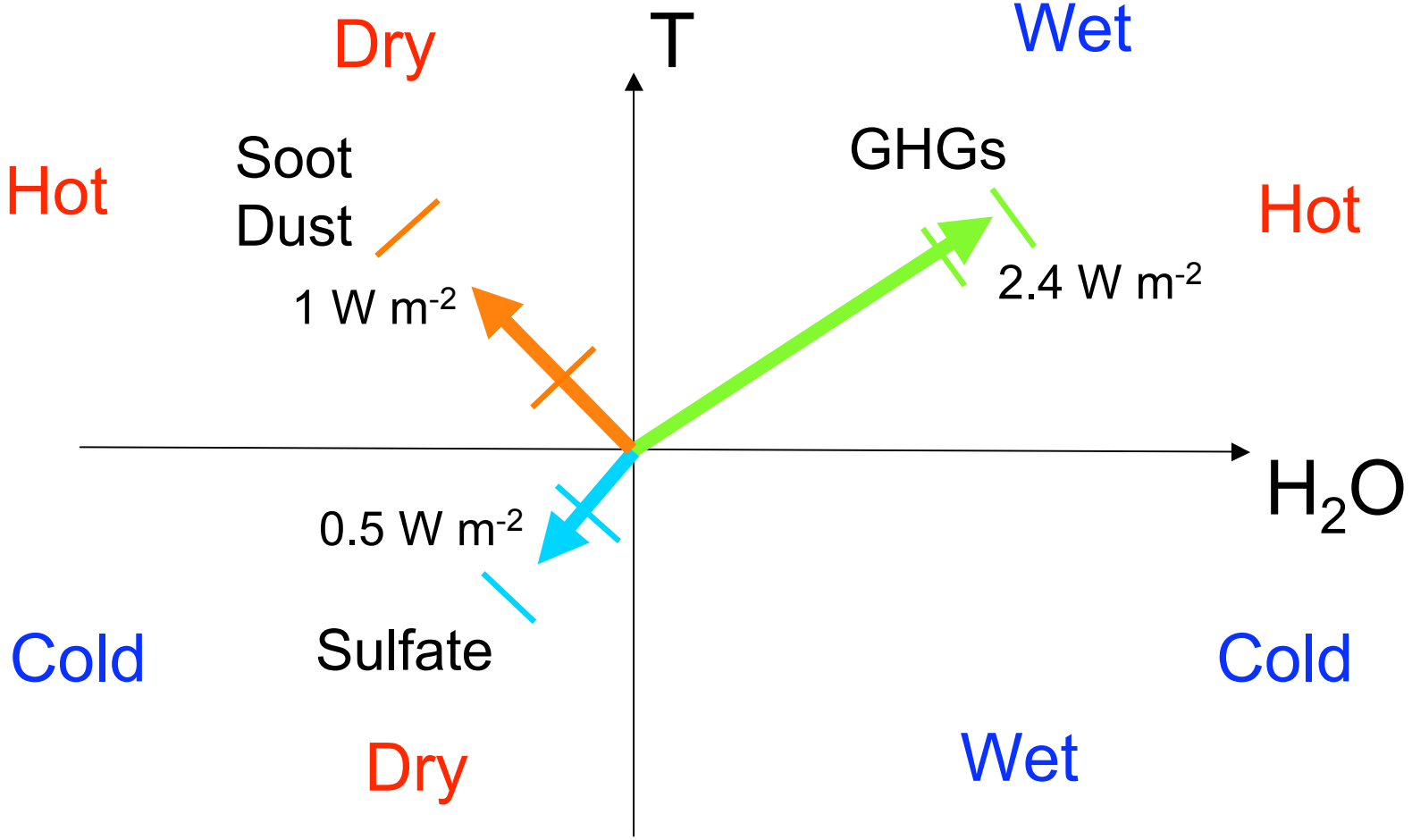
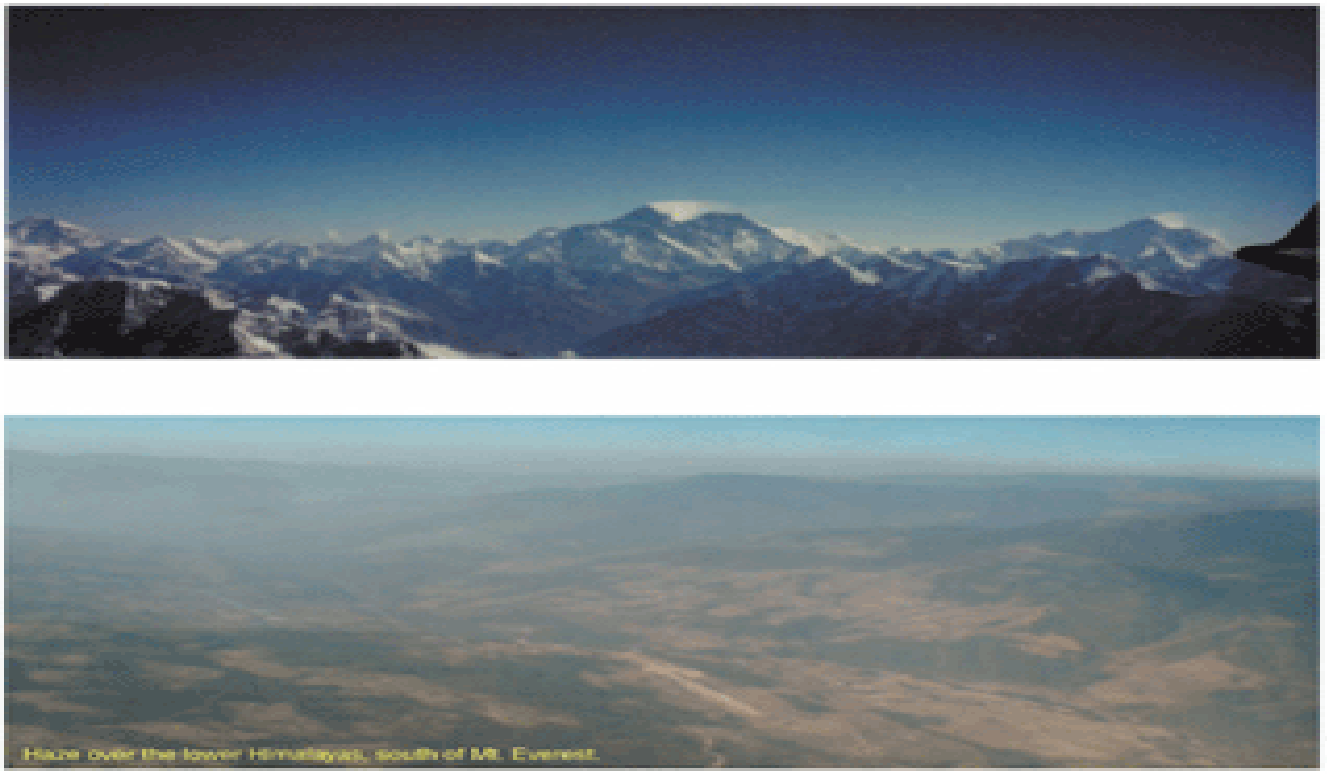
Climatic Effects: Greenhouse Gas and Aerosols



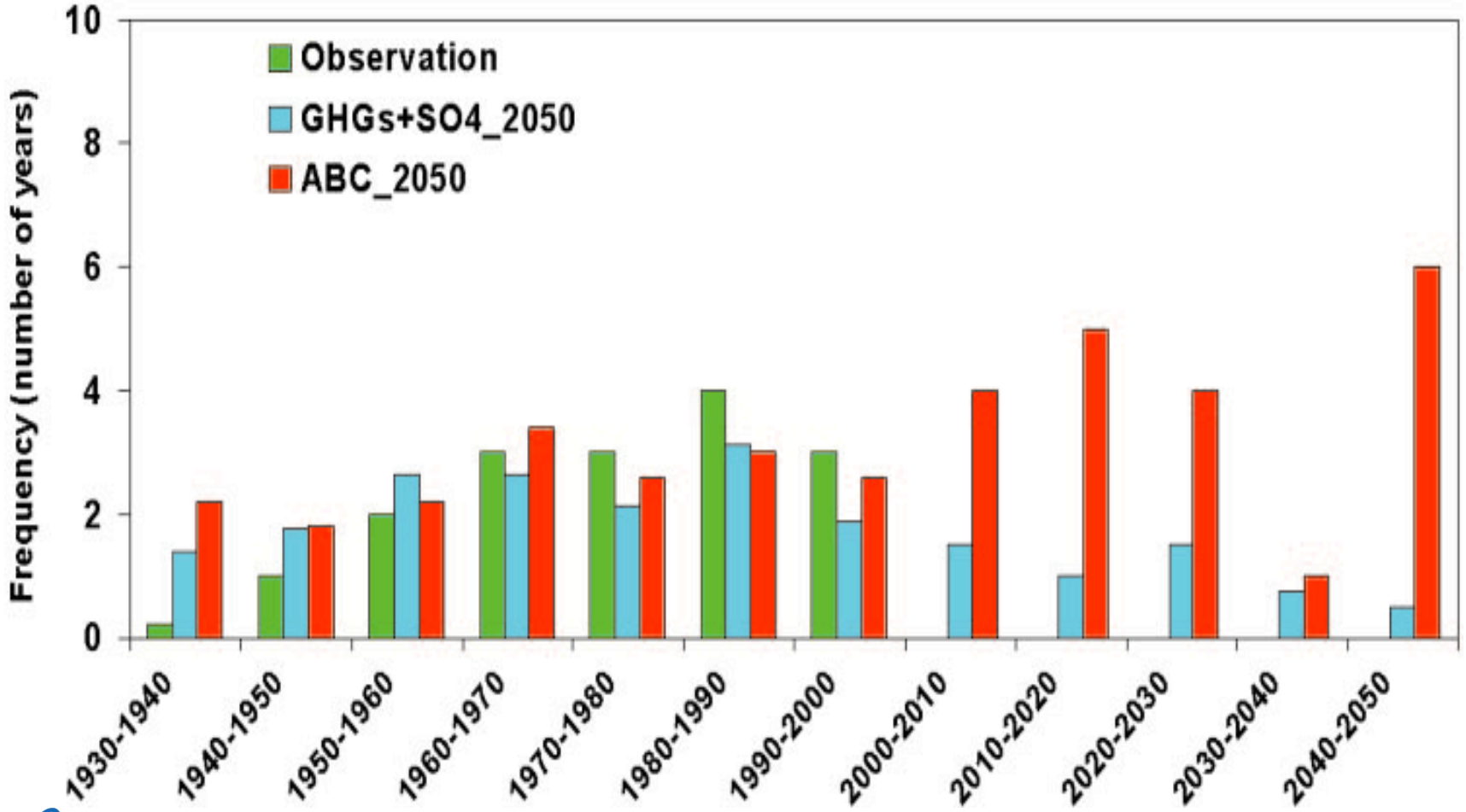
Sensitivity of Climate to Human Forcing?

Asian Brown Haze: Himalayas to Indian Ocean



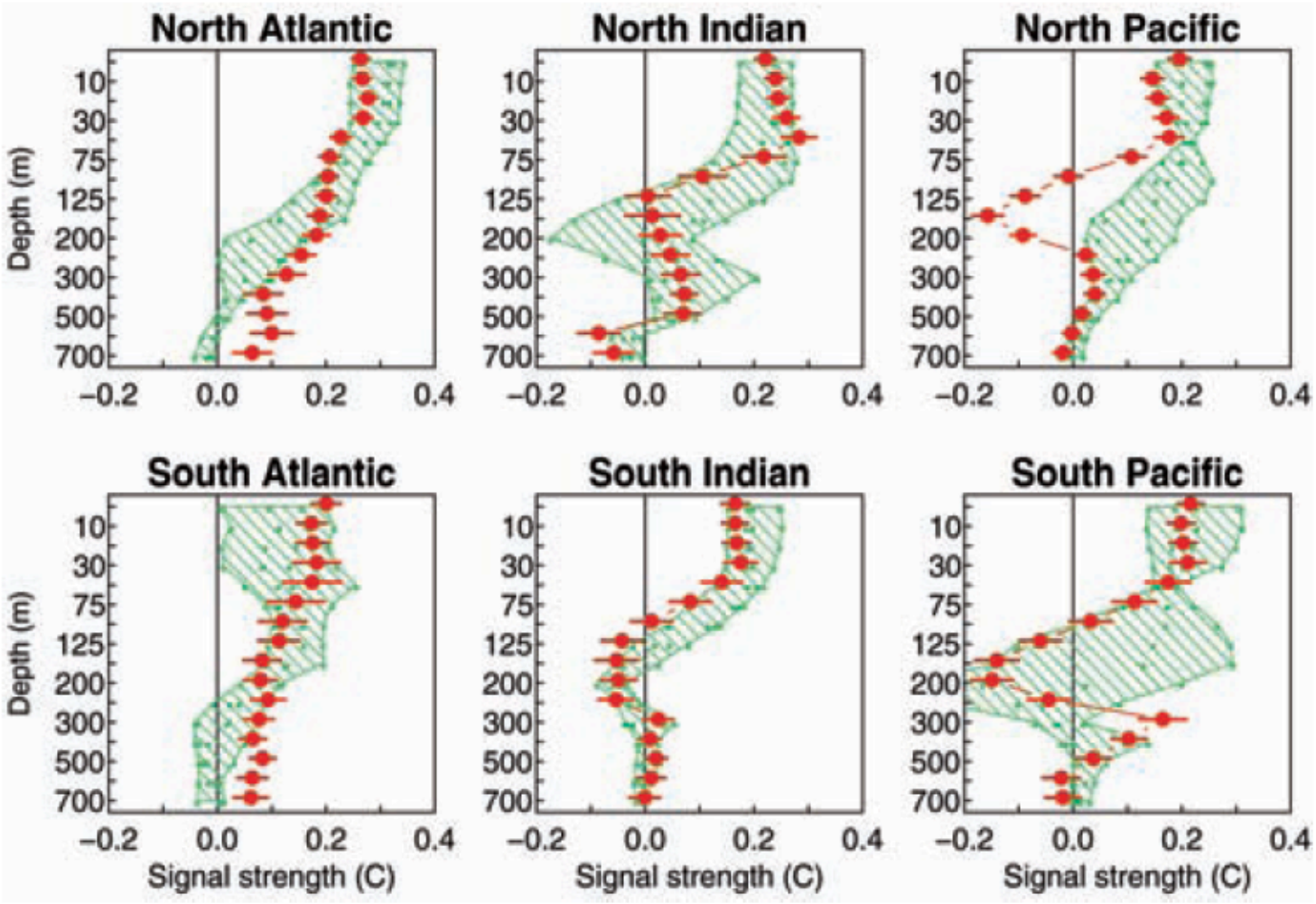
How to absorbing aerosols (black carbon from biomass burning, a 6 fold increase over 1930) impact regional and global environment?

Drought Frequency in India: Observations and Predictions



Ramanathan et al., PNAS, April 12, 2005

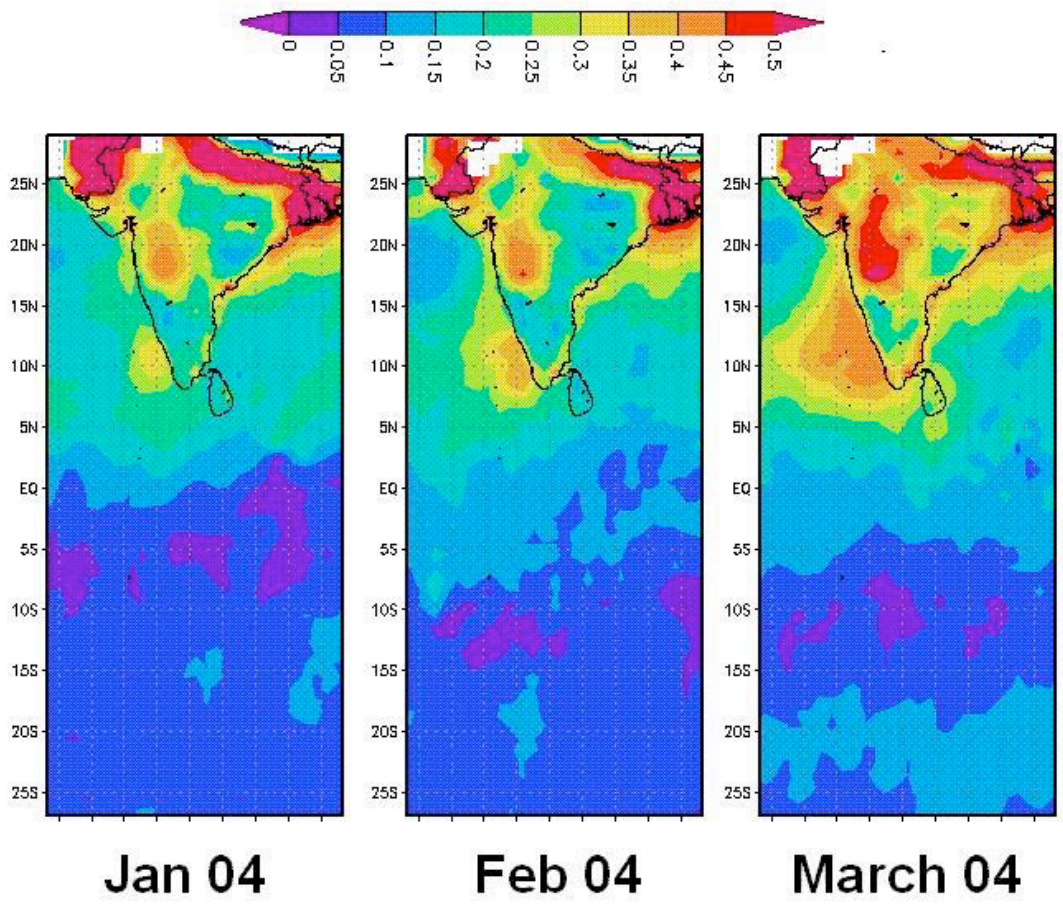
Ocean Thermal Signature: Aerosols vs GHGs



Barnett et al Science July '05

Pollution Over Indian Ocean: Aerosol Optical Depth

MODIS
On Terra



Aerosol Optical Depth

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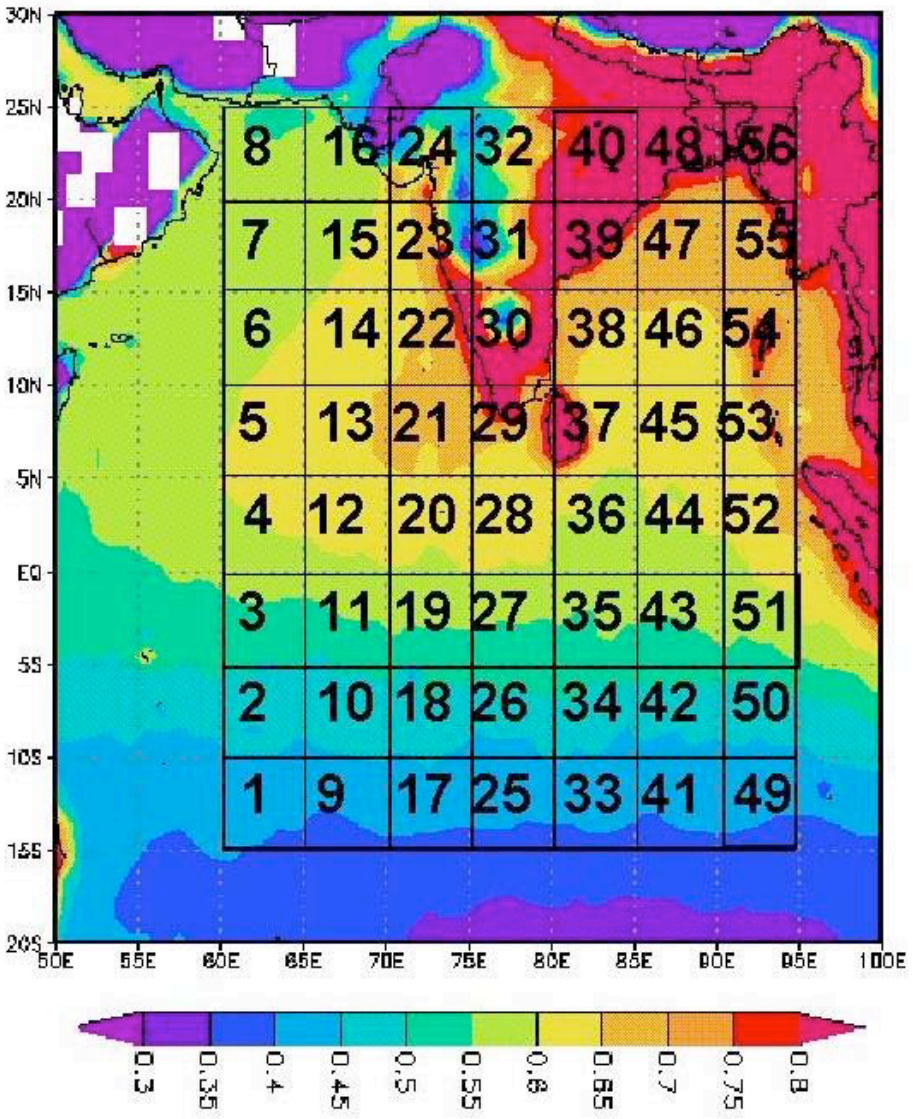
Fine mode fraction AOD (01-05): Spatial Distribution

Dirty

Increasing Pollution

Clean



15°S-25°N
60°E-95°E
Gridded
into 56
5°x5° regions

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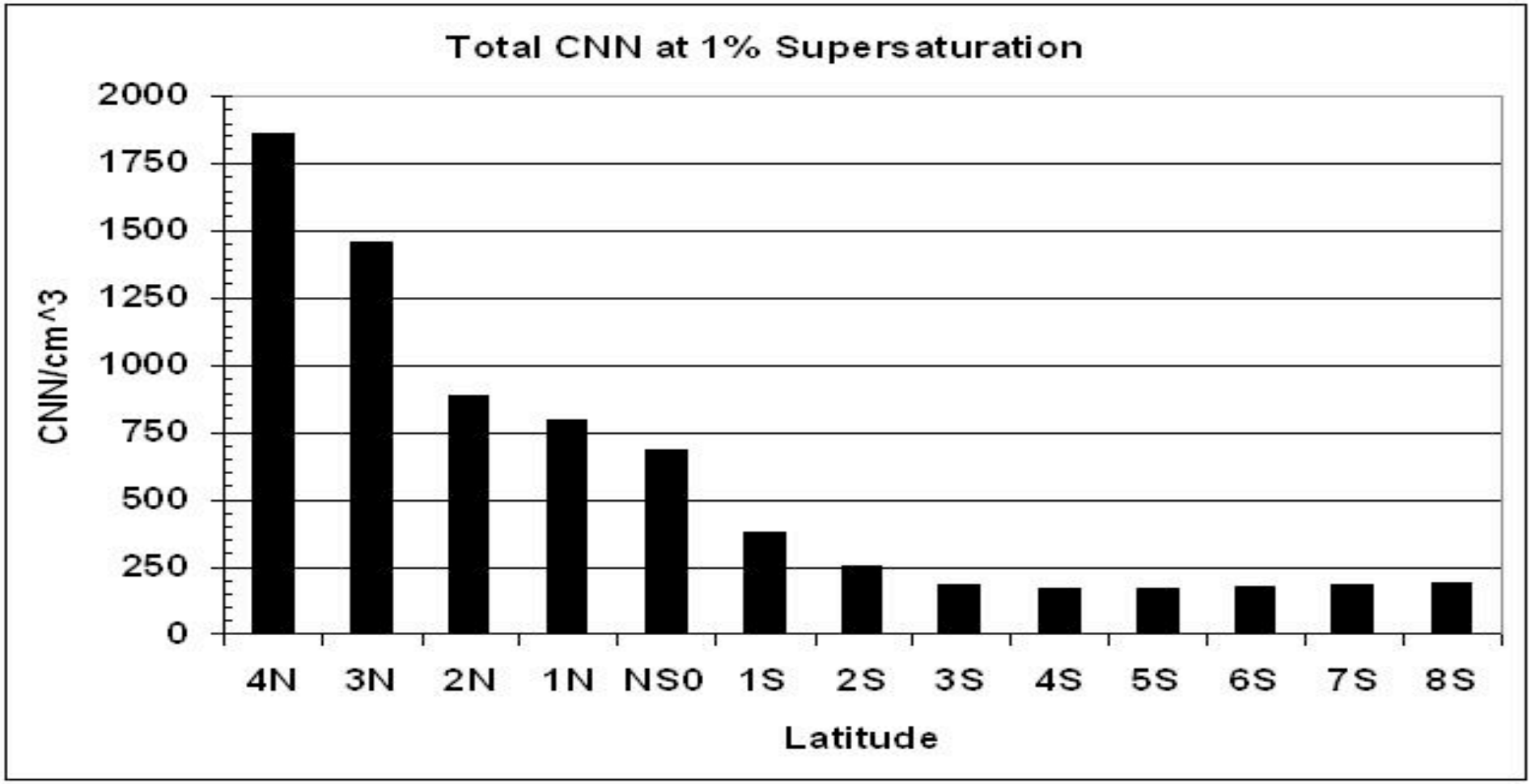
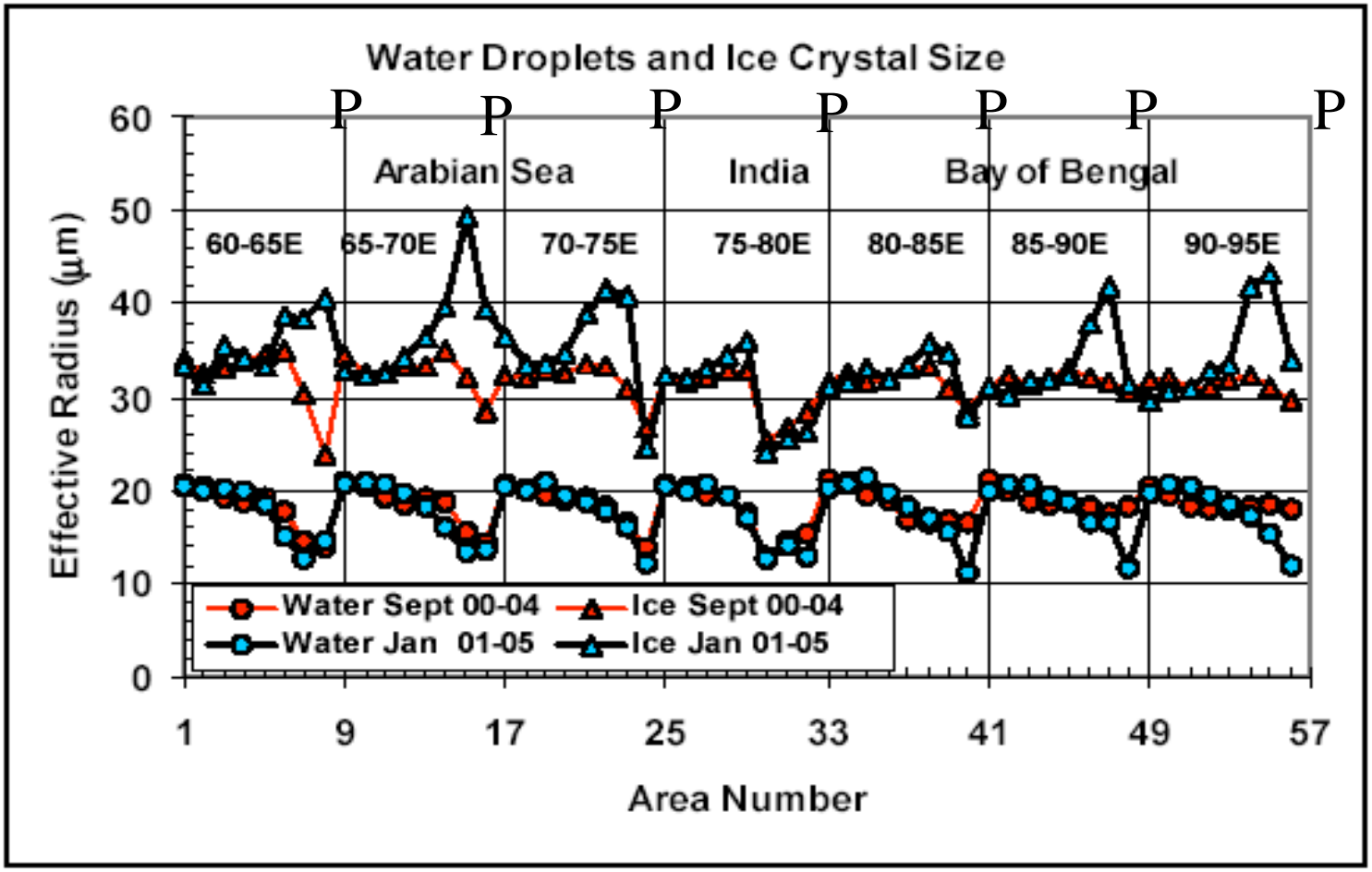
Cloud Condensation Nuclei concentrations over Arabian Sea and South Indian Ocean as a function of latitude (from 8^{o}S to 4^{o}N).



Water and Ice (Sept-Jan): Regional Differences Clean vs Polluted



Ice Ocean
Anticorrelated
Larger in Jan

Water drops
Correlated
Smaller in Jan

15S-15N
is clean
no change

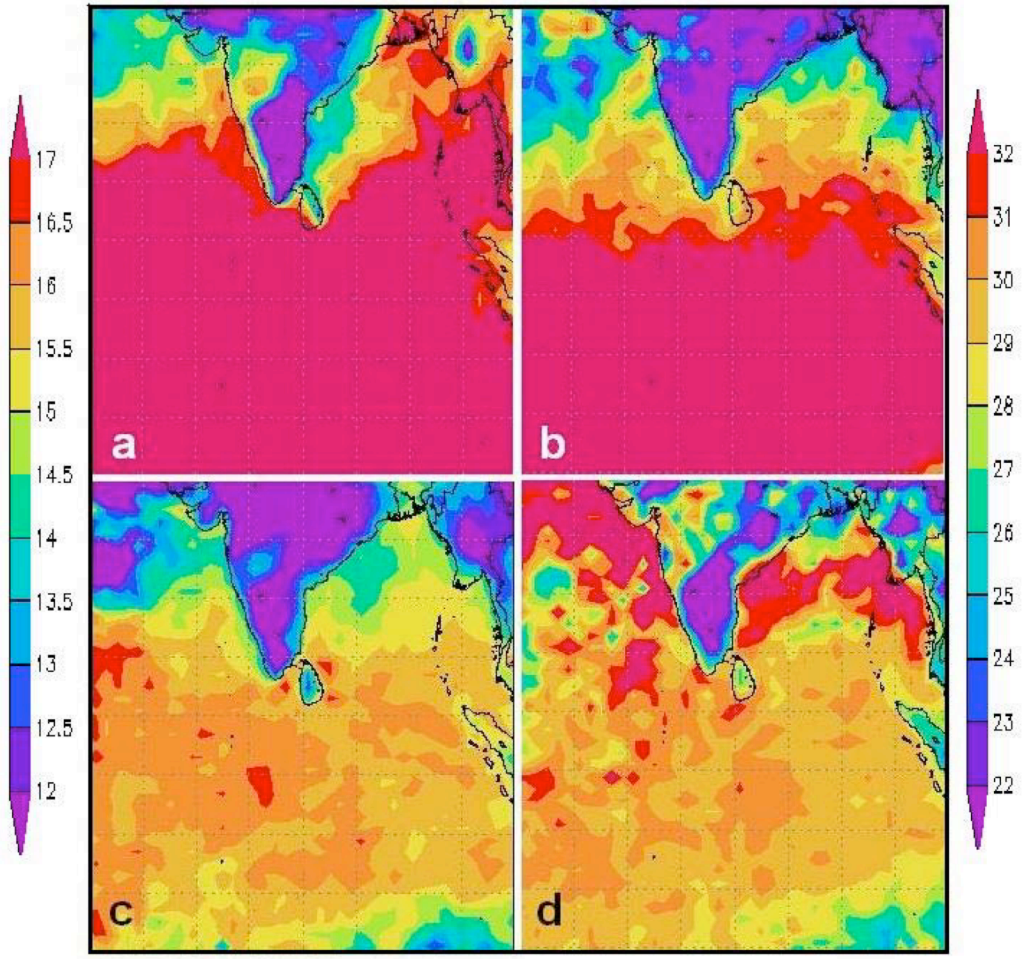
Aerosols can reduce water drop radius (2-10μ) but increase ice crystal size (2-20μ) over ocean

Opposing effects of aerosols on water and cirrus clouds

Summer, Clean, Wet
South-West Winds → Winter, Polluted, Dry
North-East Winds

Cloud drop Effective Radius

Decreases



Ice crystal Effective Radius

Increases

May03-Sept03

Nov03-Mar04

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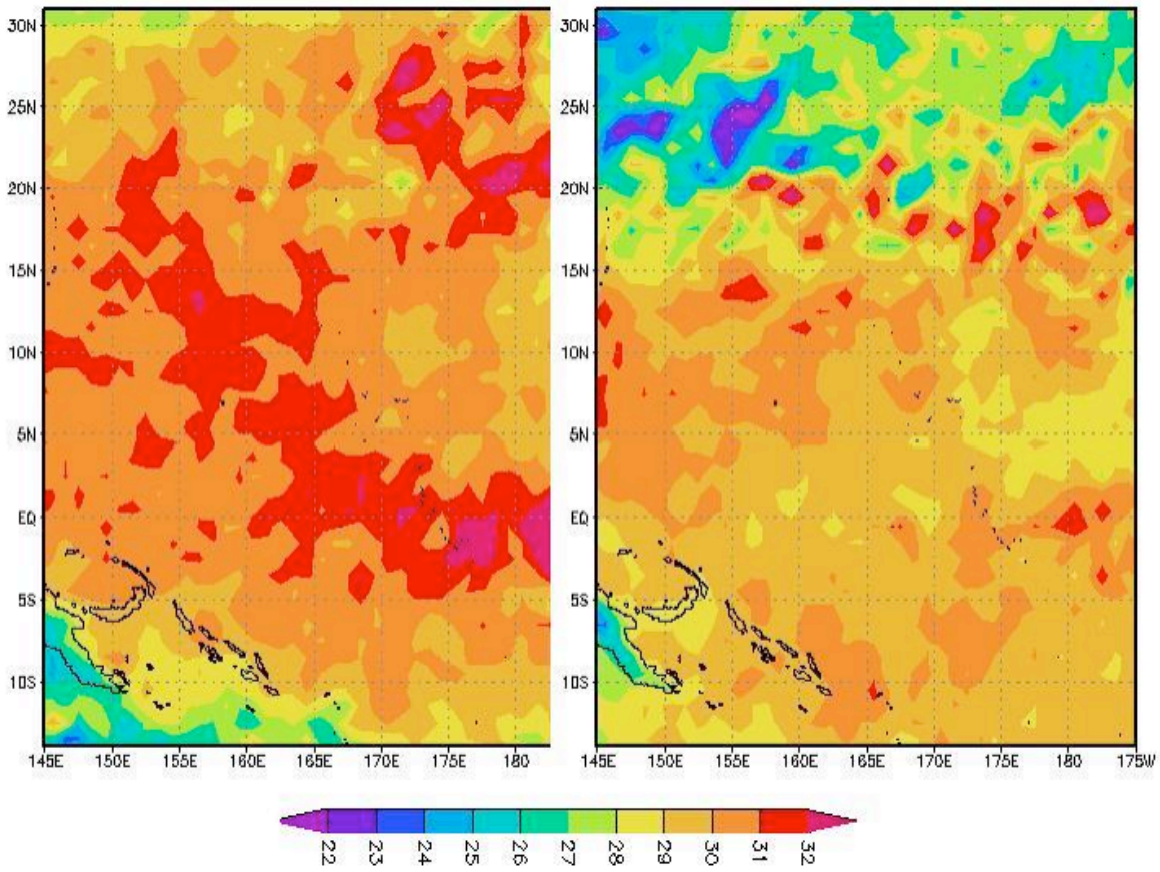
From Correlations towards causality

Mechanism: Natural or Anthropogenic or a mix?

Investigate further with the information we have.

Cirrus Cloud Crystal Size Seasonality: Clean Pacific Ocean

summer ⟶ winter



Smaller ice crystals

Seasonal dynamical state changes are opposite to our observations over Indian Ocean, implicating pollution

Homogeneous vs Heterogeneous Freezing: Critical Supersaturation

Spherical ice cap on insoluble core
Internally mixed with sulfate-water

sulfate

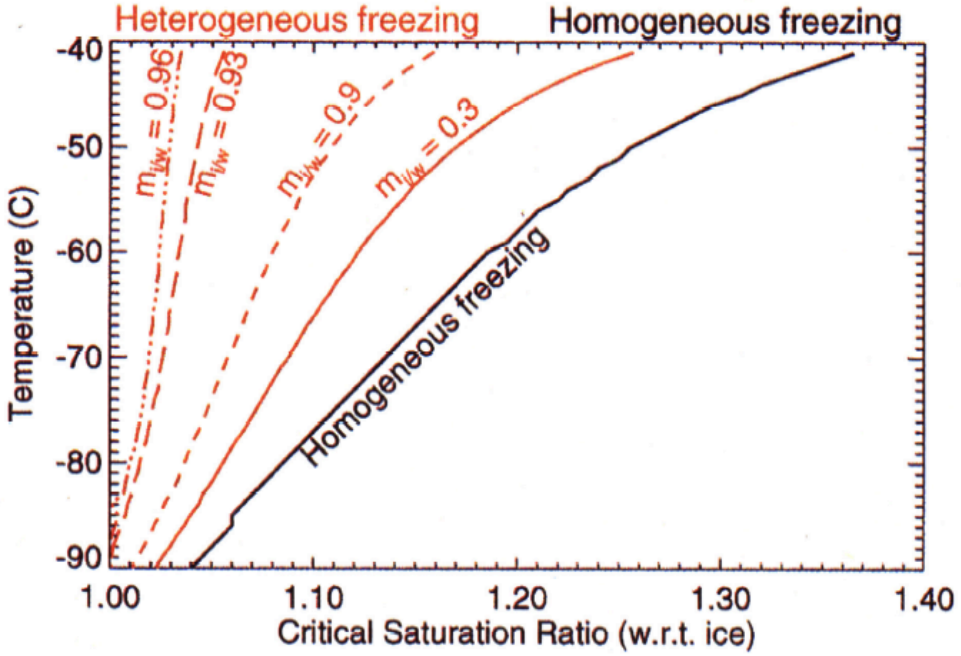


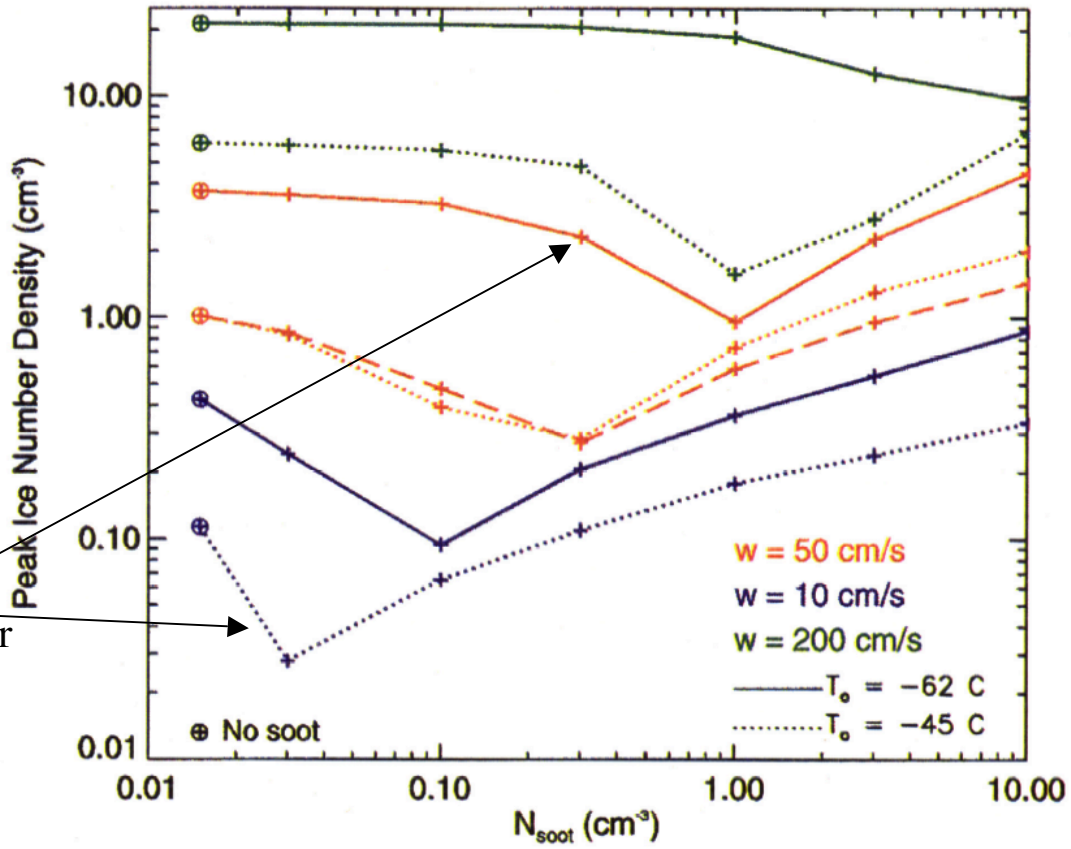
Figure 1. Critical saturation for ice nucleation in 1 second versus temperature for homogeneous freezing and heterogeneous freezing assuming a range of contact parameters. Even with relatively poor heterogeneous freezing nuclei, the critical ice supersaturation required for freezing of aerosols should be substantially reduced.

Fletcher Theory
Contact (Free Energy) Parameter
$m_{i/w} = \cos(\theta)$
$= (\sigma_{N/a} - \sigma_{N/i})/\sigma_{i/a}$

Ice Nucleation on Soot : Aircraft Exhaust and Cirrus Clouds

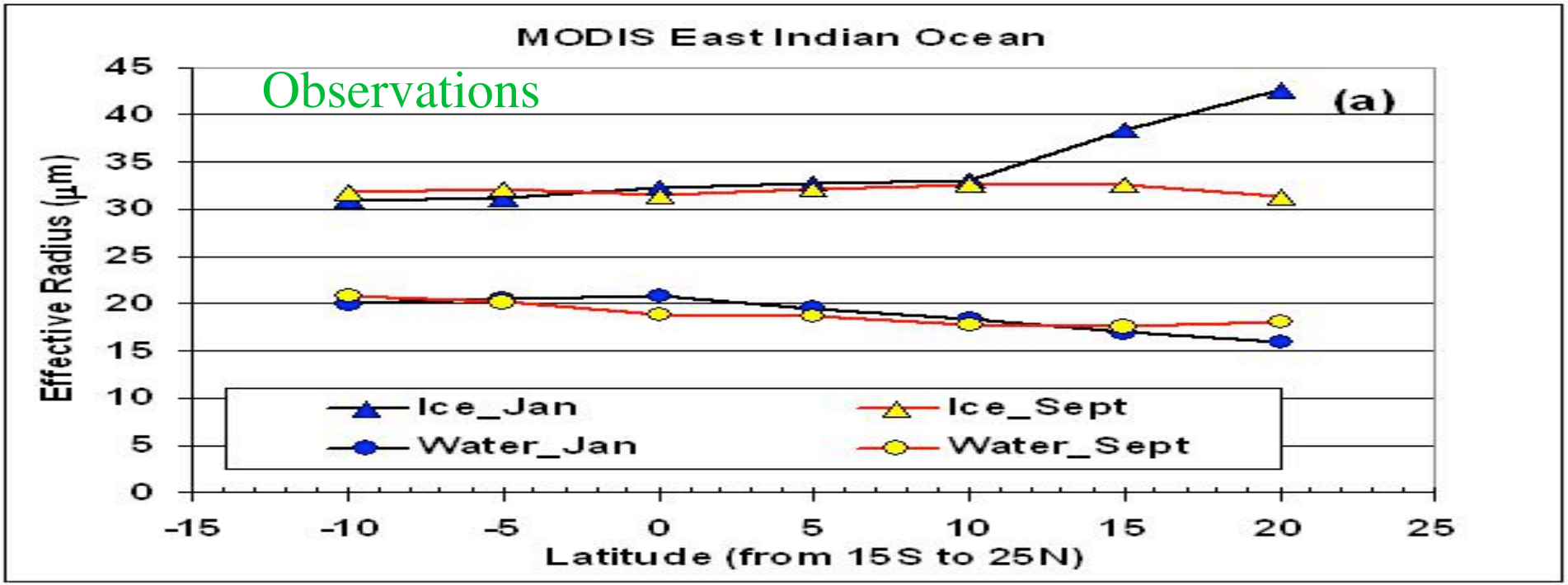
•Soot nucleates fewer ice crystals (at lower supersat. than homo. nucl.) that can grow to large sizes

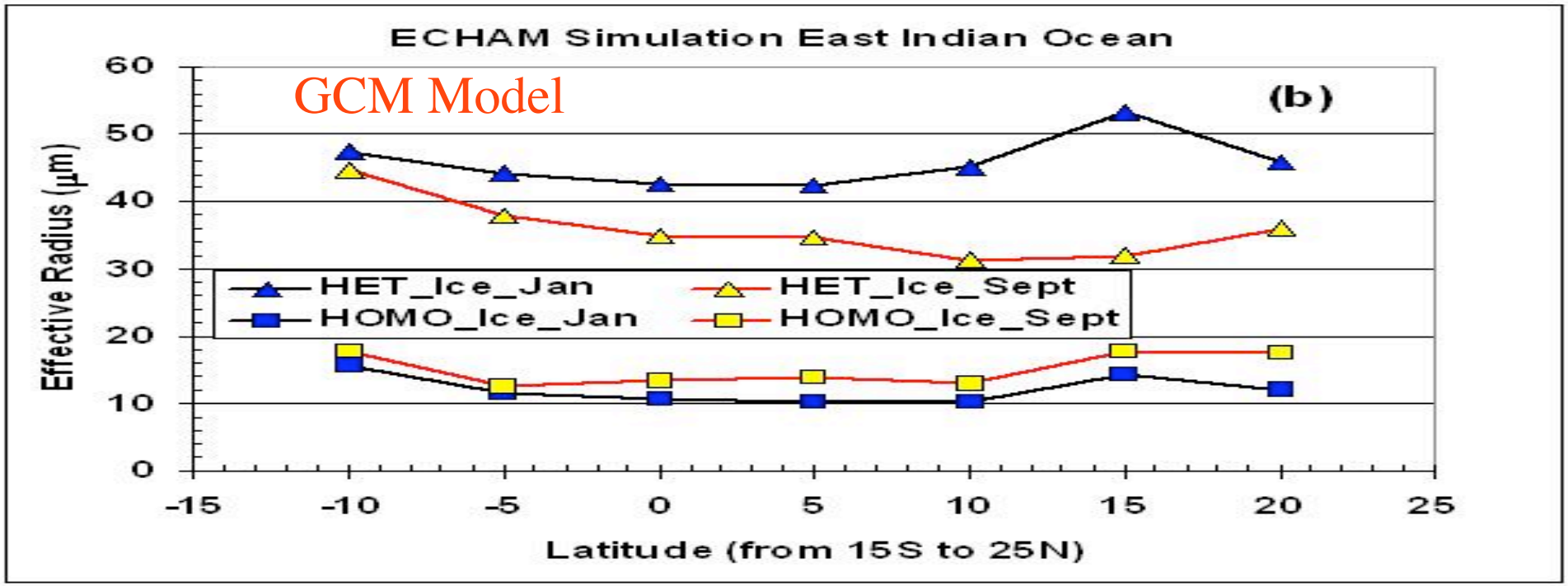
•Most pronounced at warmer temperatures, slower lifting or cooling rates



Jensen & Toon GRL 1997

Figure 4. Peak ice crystal number density versus the initial sulfate/insoluble particle number density. Curves are shown for different updraft velocities, temperatures, and $m_{i/n}$ values.

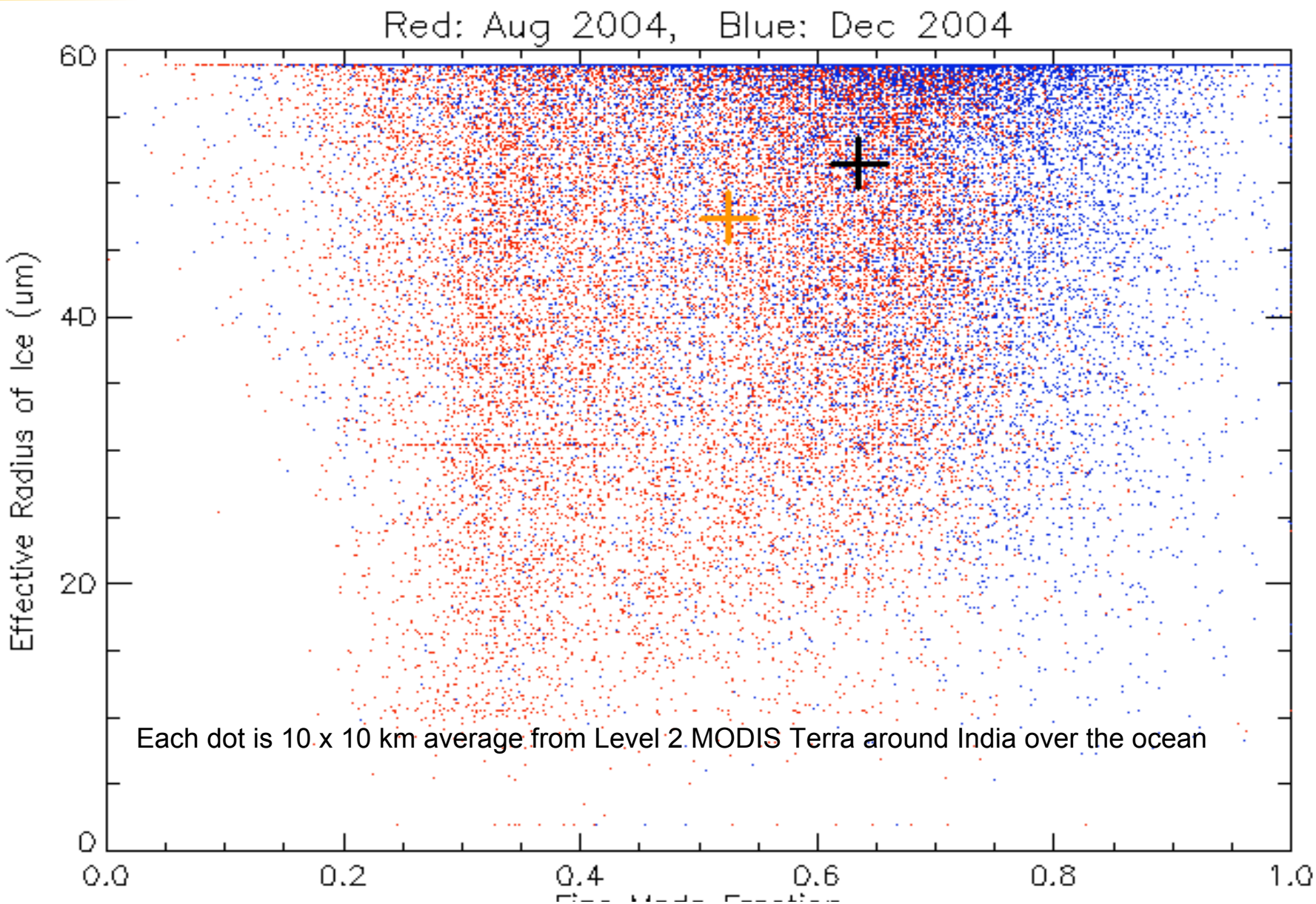

MODIS East Indian Ocean
Observations
(a)
Effective Radius (μm)
45
40
35
30
25
20
15
10
5
0
-15
-10
-5
0
5
10
15
20
25
Latitude (from 15S to 25N)
Ice_Jan
Ice_Sept
Water_Jan
Water_Sept


ECHAM Simulation East Indian Ocean
GCM Model
(b)
Effective Radius (μm)
60
50
40
30
20
10
0
-15
-10
-5
0
5
10
15
20
25
Latitude (from 15S to 25N)
HET_Ice_Jan
HET_Ice_Sept
HOMO_Ice_Jan
HOMO_Ice_Sept

Conclusions

- Discovered aerosol pollution reduces cloud liquid drop size but *surprisingly increases cirrus cloud ice particle size*.
  - Heterogeneous ice nucleation by aerosols possible mechanism.
- Recent Laboratory studies point to some effective ice nuclei
  - Organic Acid Hydrates $(COOH)_2.2H_2O$, produced by cloud processing followed by lofting, seen directly by PALMS reduces IN T by about 3 K
  - Long chain alcohols and testosterone very potent IN
- Cirrus clouds with larger and fewer ice particles should
  - Reflect less solar radiation (warming) but let more IR escape (cooling)
  - ECHAM model suggests cooling dominates, with a forcing of ~ 5 W m^{-2}
- In situ upper tropospheric studies needed to establish causality

Aerosol fine mode-Ice crystal size correlation at high resolution (8000 Images)

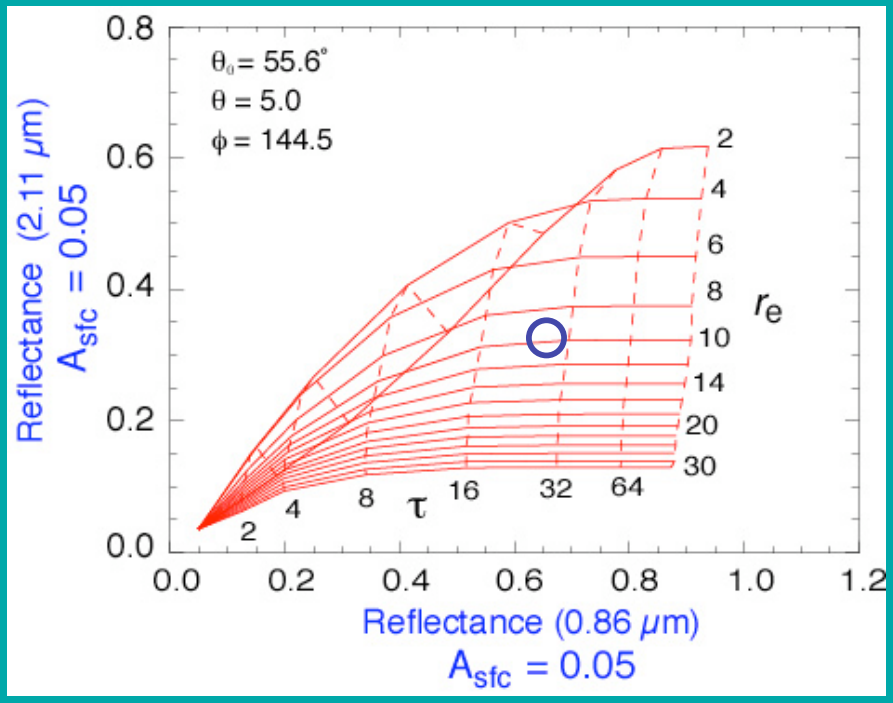


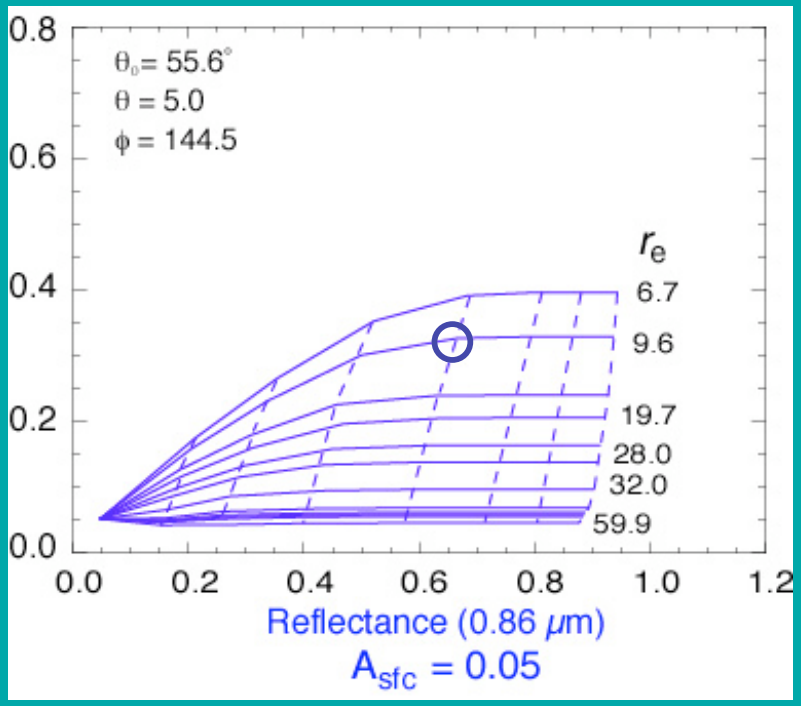
MODIS Channels

Principal Channels

Channel	λ (μm)	Δλ (μm)	Resolution (m)	Atmospheric Purpose
→ 1	0.645	0.050	250	cloud optical thickness over land
2	0.858	0.035	250	cloud optical thickness over ocean
5	1.240	0.020	500	cloud optical thickness over snow & ice
6	1.640	0.025	500	snow/cloud discrimination, thermodynamic phase
→ 7	2.130	0.050	500	cloud effective radius
20	3.750	0.180	1000	cloud effective radius; surface temperature
26	1.375	0.030	1000	thin cirrus detection
29	8.550	0.300	1000	thermodynamic phase
→ 31	11.030	0.500	1000	thermal emission correction; cloud height
32	12.020	0.500	1000	thermodynamic phase
33	13.335	0.300	1000	cloud height

Cloud Optical & Microphysical Retrievals from MODIS





Liquid water cloud
ocean surface

Ice cloud
ocean surface

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From King et al.