

# Aerosol-Cloud-Climate Interaction: A Case Study from the Indian Ocean

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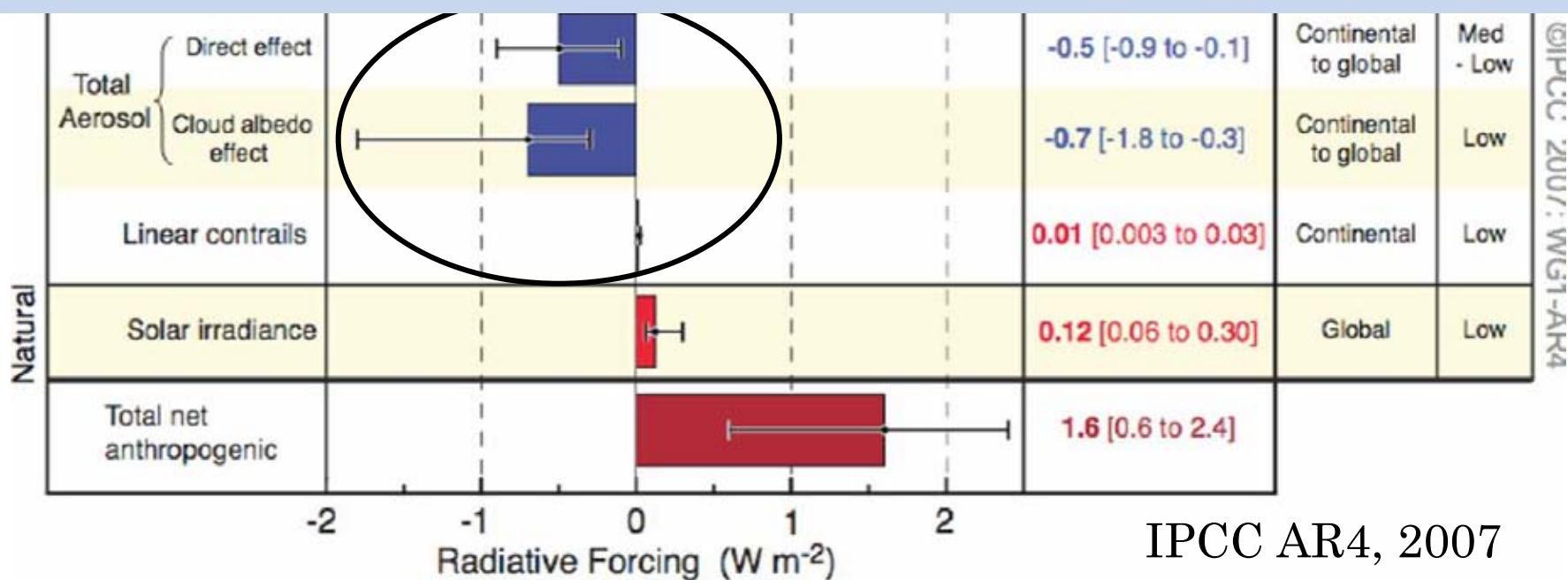
# Content

- ❑ Background and Motivation
- ❑ Case Study – Indian Ocean
- ❑ Challenges Ahead - Discussion

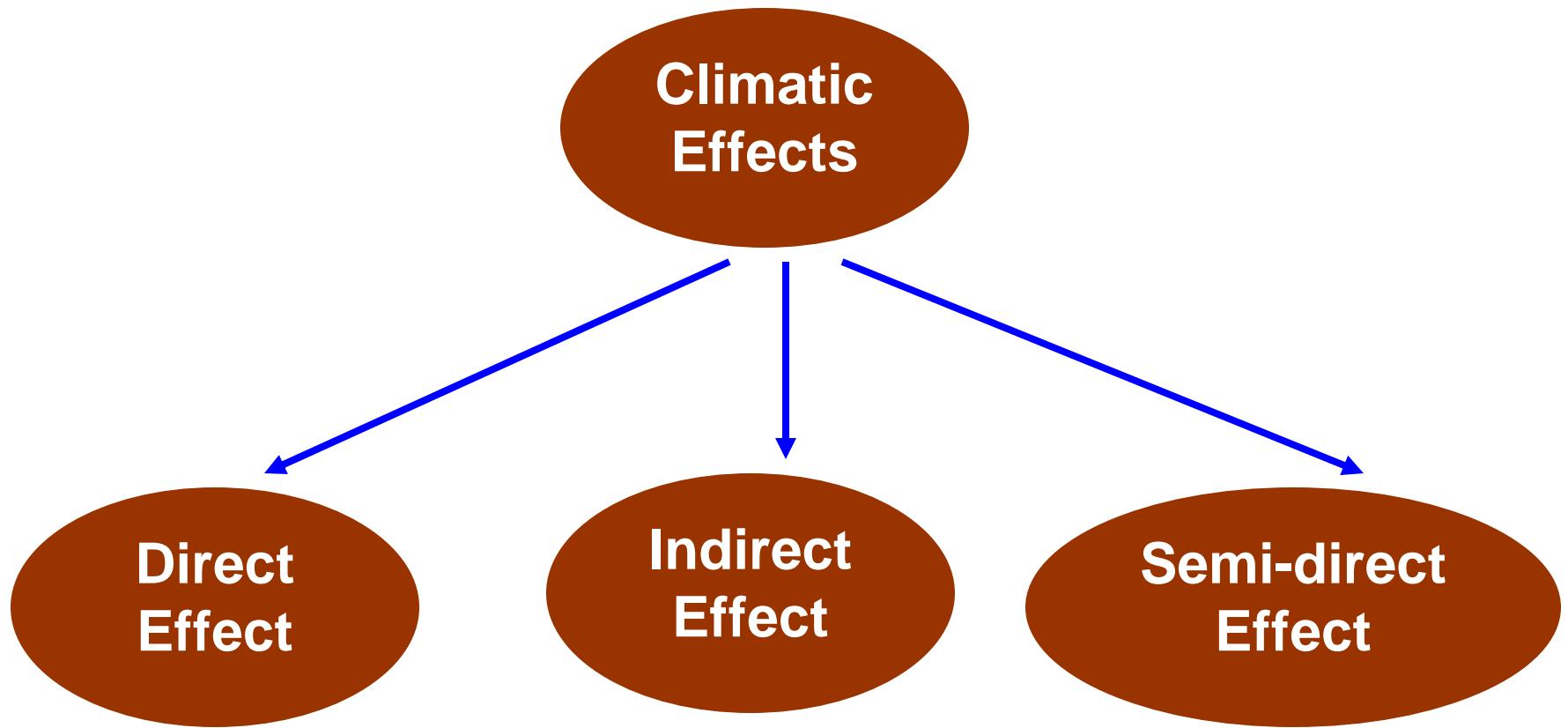
# Radiative Forcing Components

RF Terms	RF values ( $\text{W m}^{-2}$ )	Spatial scale	LOSU
Long-lived CO <sub>2</sub>	1.66 [1.49 to 1.83]	Global	High

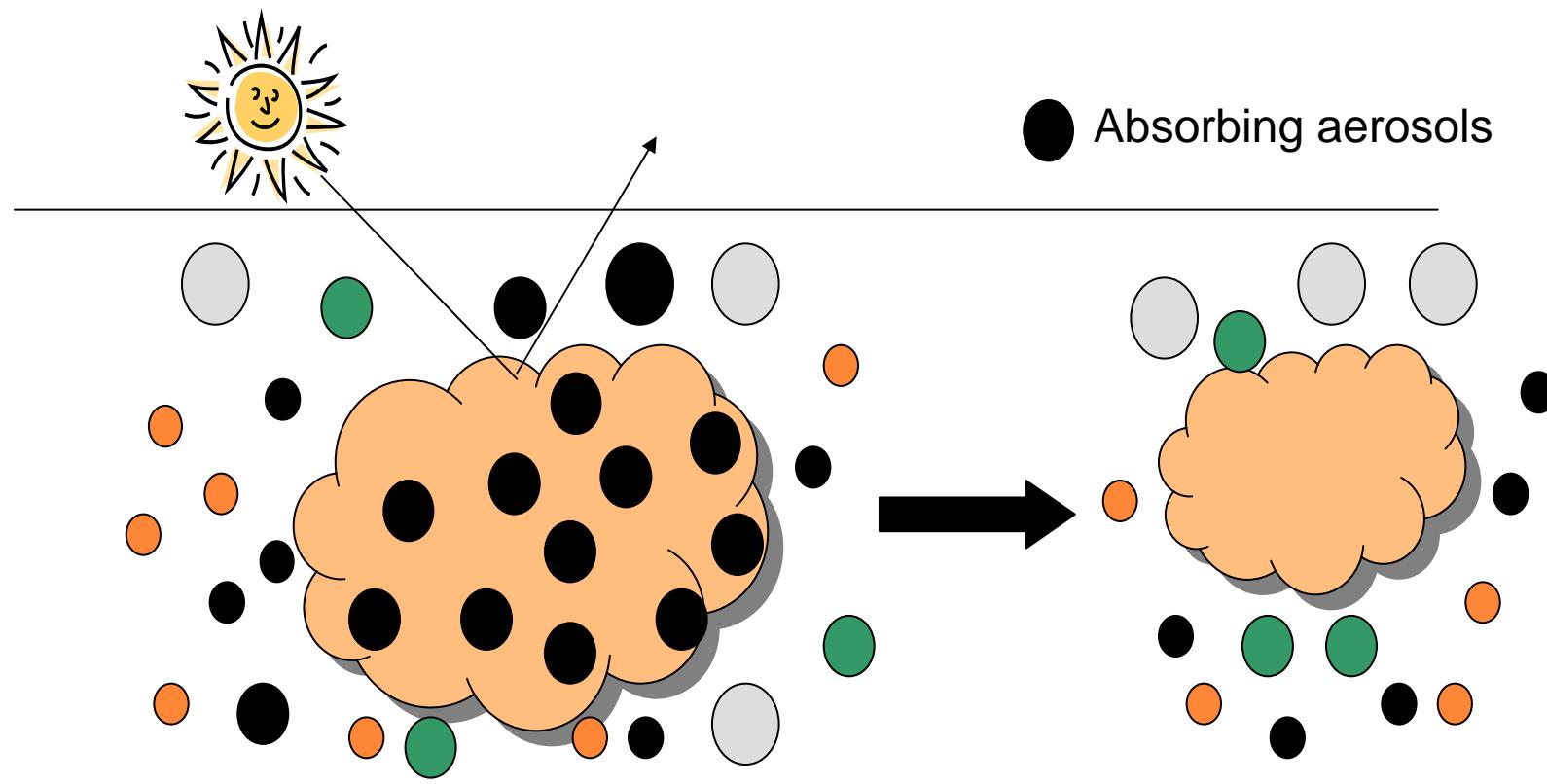
- ❖ Aerosol concentration over India is three times higher than the global mean concentration (Dey and Di Girolamo, JGR, 2010)
- ❖ Aerosols in India amplify greenhouse warming (Ramanathan et al., Nature, 2007)



# Aerosol-Cloud-Climate Conundrum



# Semi-direct Effect



*Ackerman et al., 2000*

## REVIEWS

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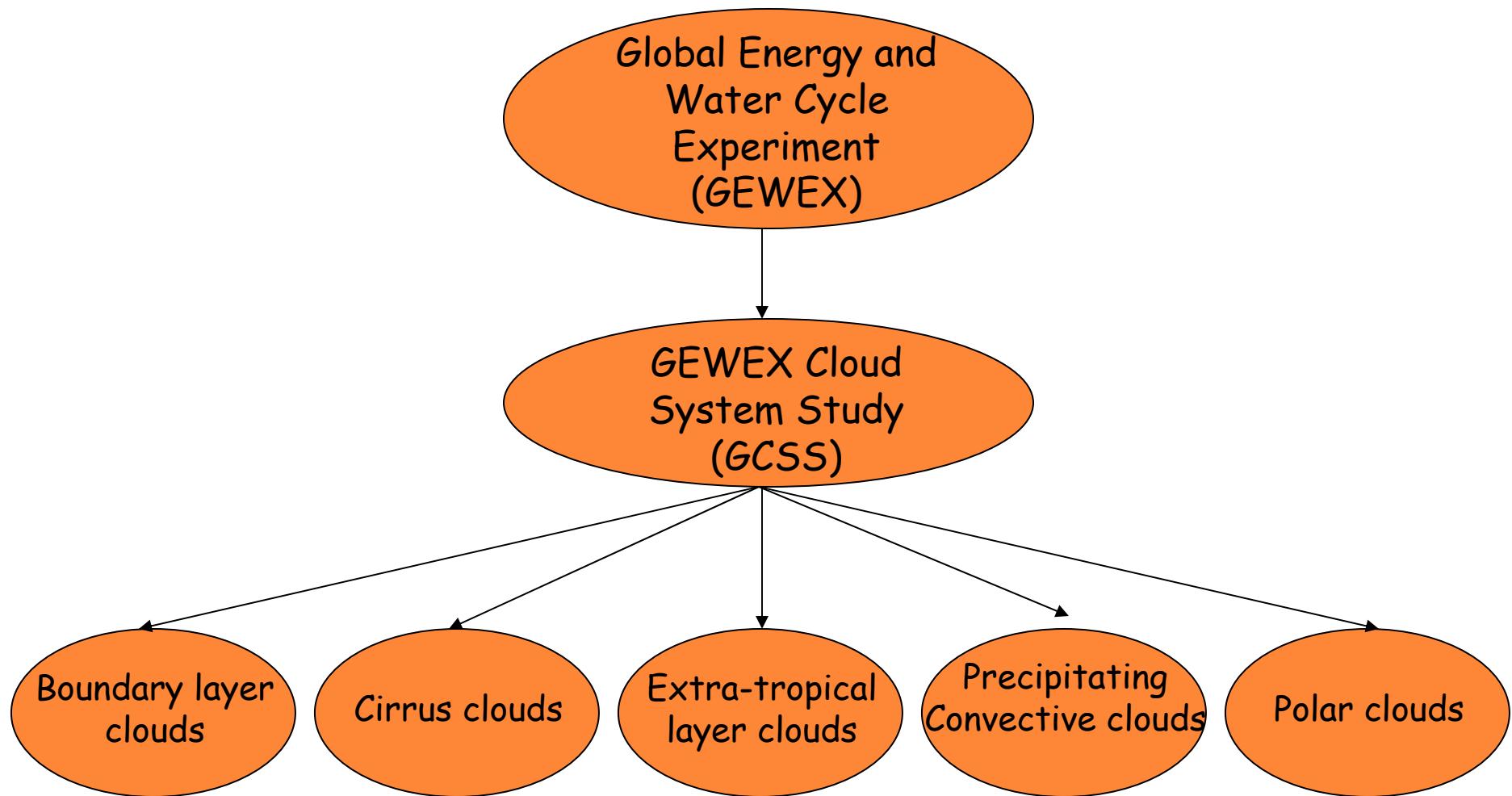
# Untangling aerosol effects on clouds and precipitation in a buffered system

Bjorn Stevens<sup>1,2</sup> & Graham Feingold<sup>3</sup>

It is thought that changes in the concentration of cloud-active aerosol can alter the precipitation efficiency of clouds, thereby changing cloud amount and, hence, the radiative forcing of the climate system. Despite decades of research, it has proved frustratingly difficult to establish climatically meaningful relationships among the aerosol, clouds and precipitation. As a result, the climatic effect of the aerosol remains controversial. We propose that the difficulty in untangling relationships among the aerosol, clouds and precipitation reflects the inadequacy of existing tools and methodologies and a failure to account for processes that buffer cloud and precipitation responses to aerosol perturbations.

- 1. Focus on individual cloud system – Examine aerosol-cloud relationship**
- 2. Develop regime-specific parameterization for large-scale models**

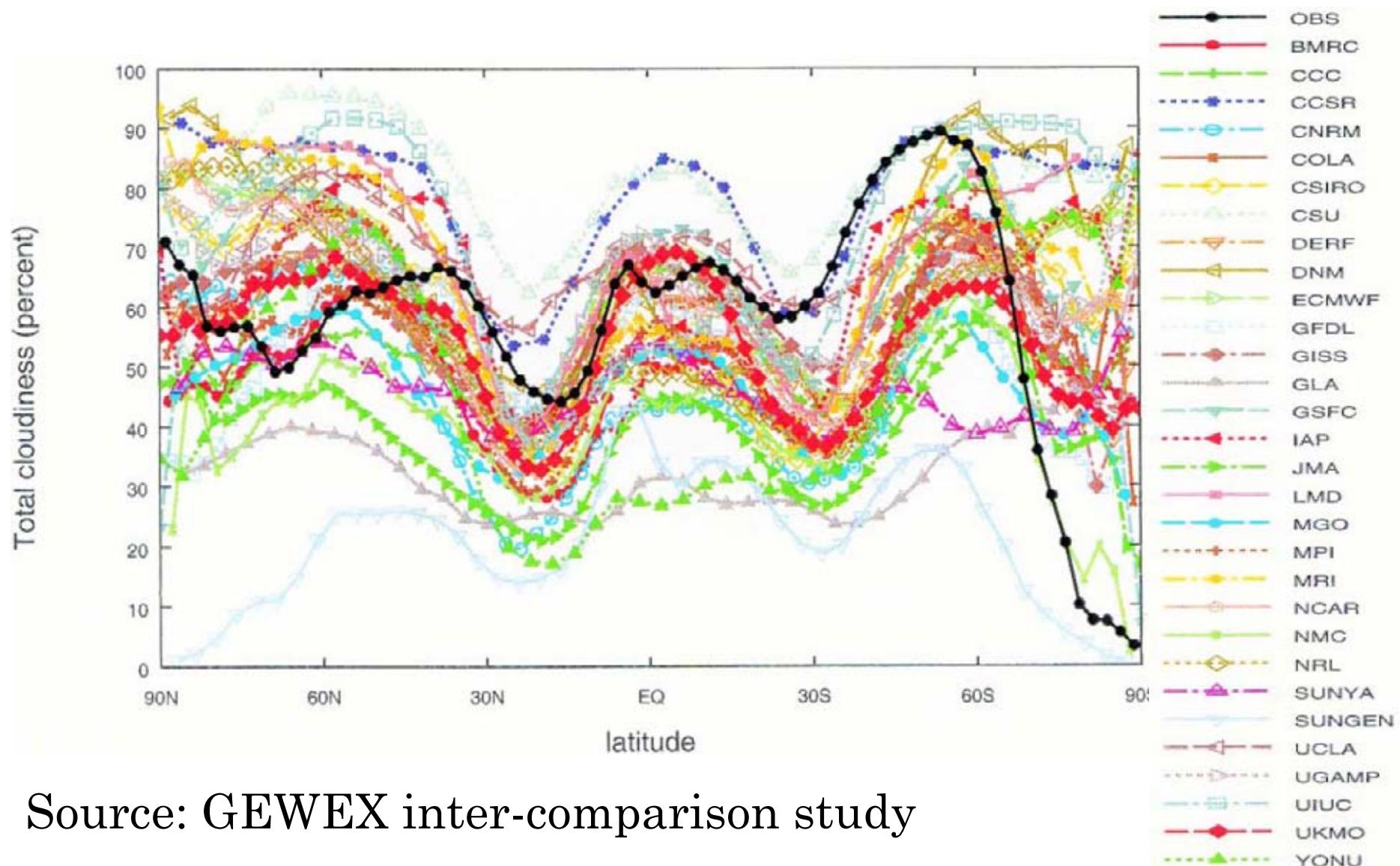
# Global Initiative



# Clouds and Climate

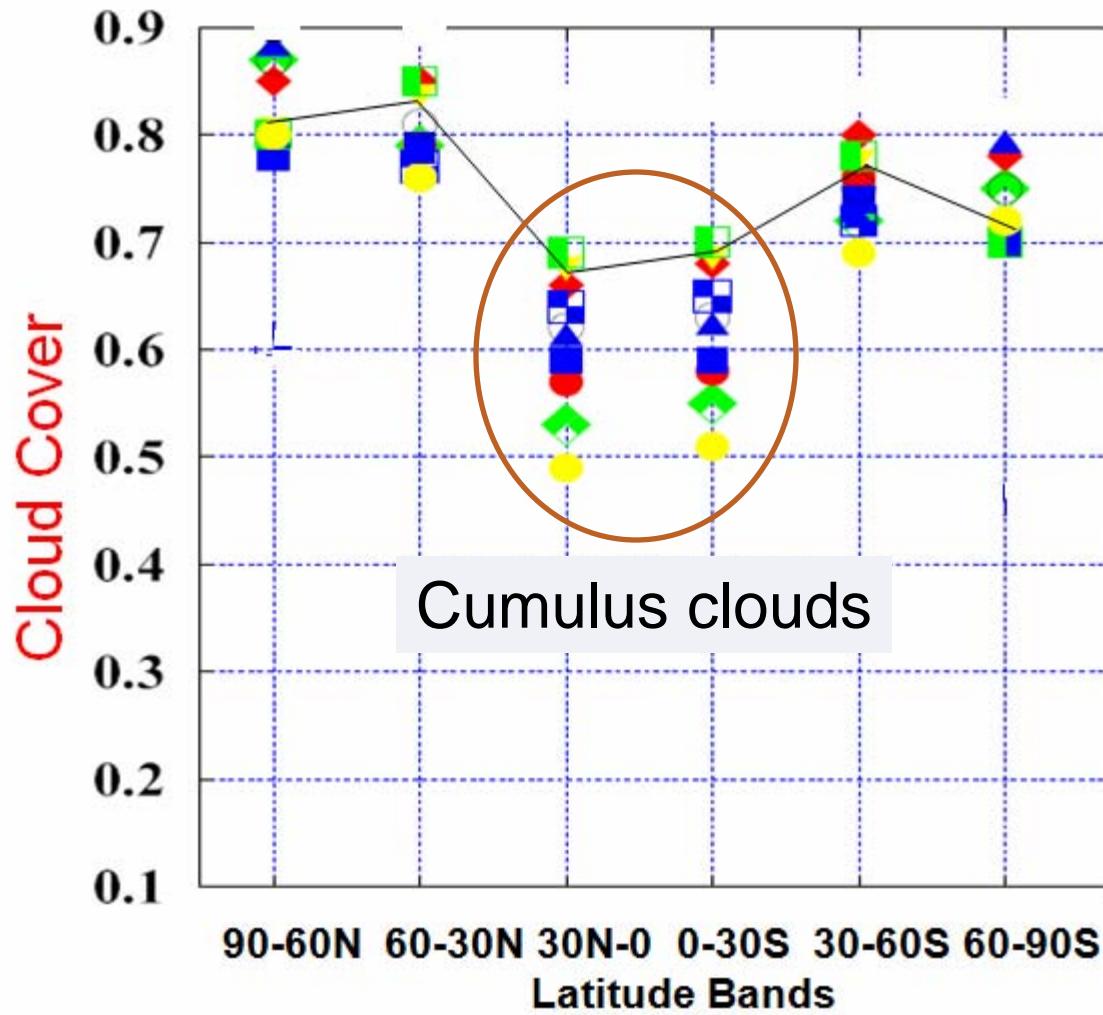
- 4% increase in low clouds offsets doubling of CO<sub>2</sub>
  - A.J. Slingo. 1990. "Sensitivity of Earth's Radiation Budget to changes in low clouds." *Nature*. 343, 49-50.
- Requires reduction of measurement error of cloud fraction to 1%
  - Ohring, G. et al. 2005. "Satellite Instrument Calibration for Measuring Global Climate Change." *Bull. Amer. Met. Soc.*, **86**, 1303-1313.

# Model-simulated Cloud Cover



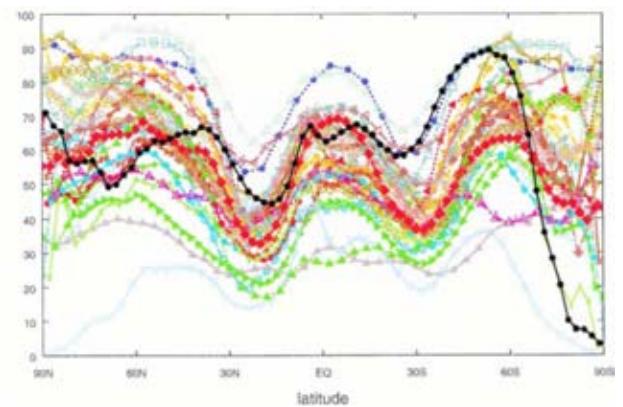
Source: GEWEX inter-comparison study

# Satellite-measured Cloud Cover

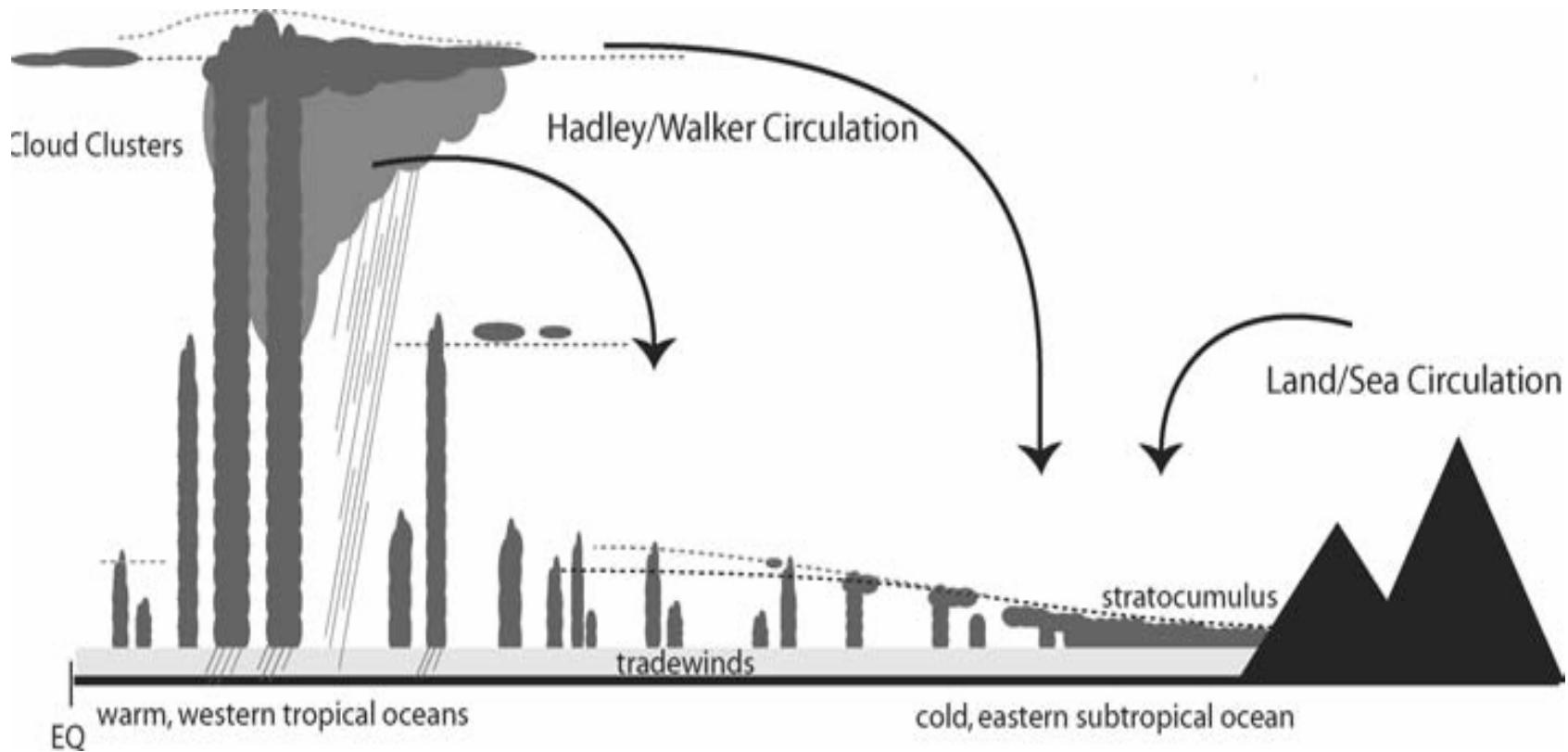


From Stubenrauch et al.  
(2009, GEWEX report)

MODIS-CE AQUA  
AIRS-LMD  
ISCCP  
TOVS-B  
PATMOSX  
MISR  
MODIS-ST AQUA  
POLDER  
ATSR  
GOCCP

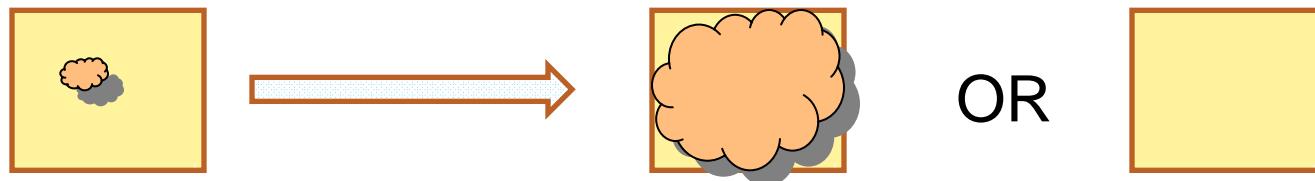


# Cumulus Clouds



- Ubiquitous in tropics – important role in global energy and water budget, act as feeder system in deep convection
- Most poorly represented cloud type in climate models – lack of observational dataset to improve model simulation

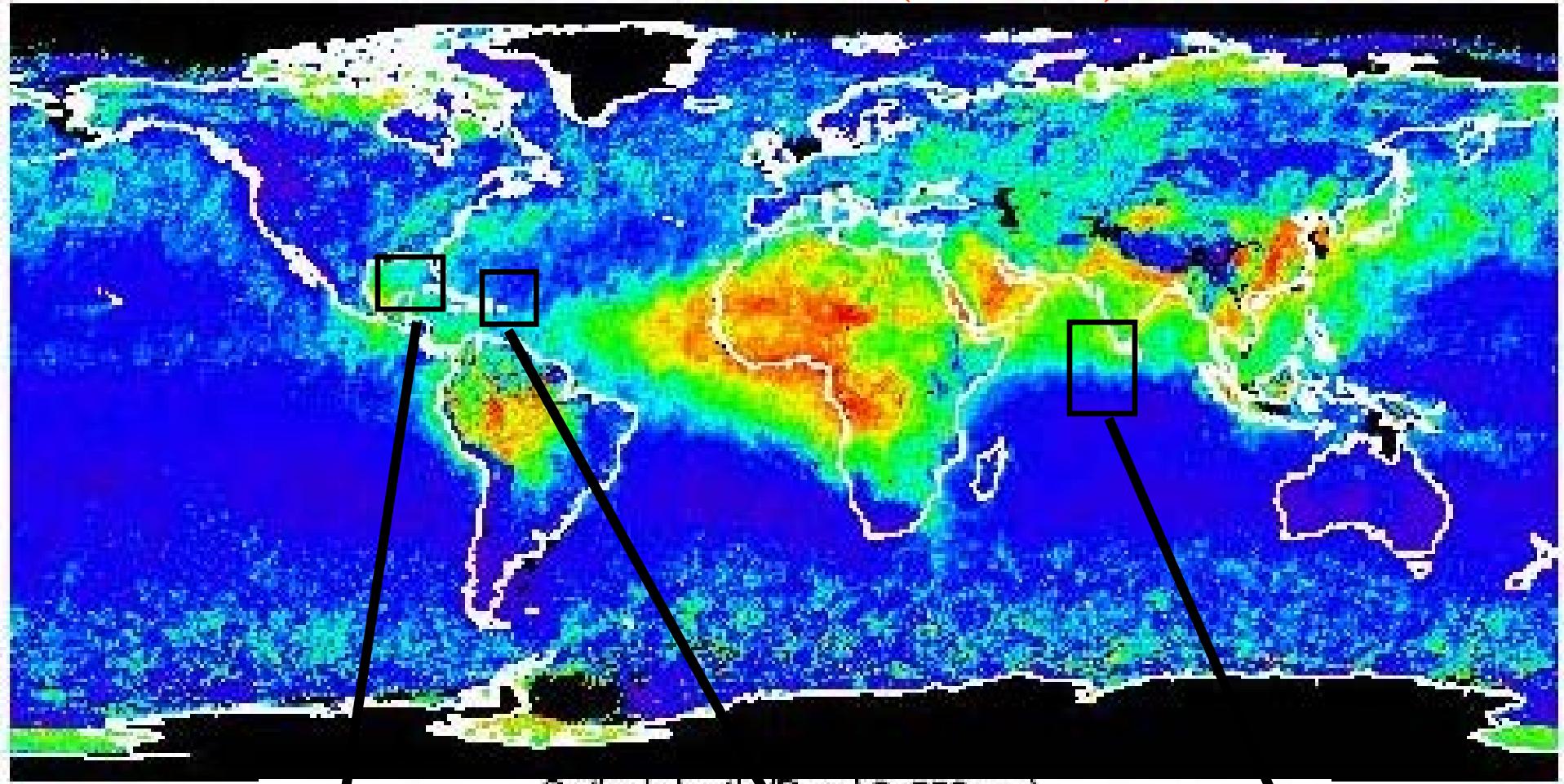
# Scale Effect



We need very high resolution satellite data to address this problem

# Collection of ASTER (15-m resolution) data

Mean AOD from MISR (2000-2008)



Jul 2006 – Sep 2006  
Gulf of Mexico

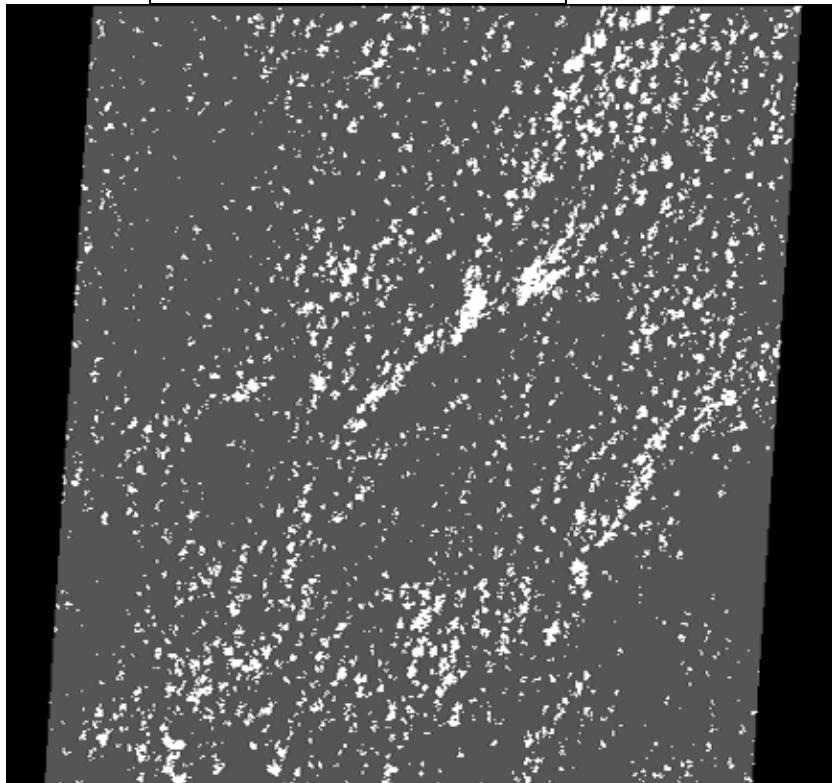
Sep 2004 – Dec 2004  
Tropical western Atlantic  
(RICO)

Nov 2006 – Apr 2007  
Indian Ocean

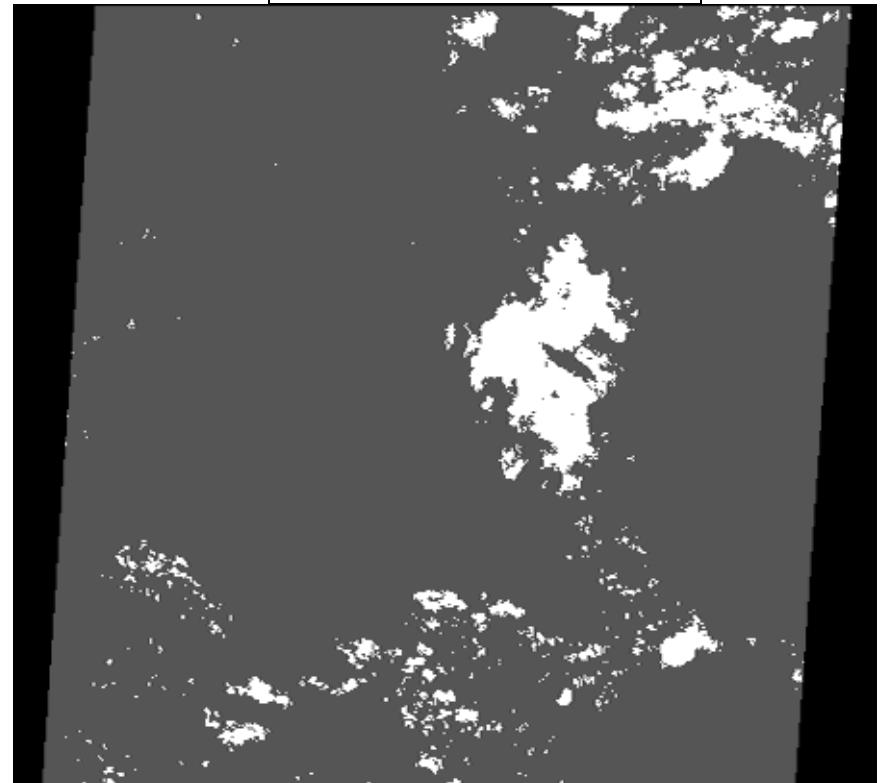


# Resolution Effect

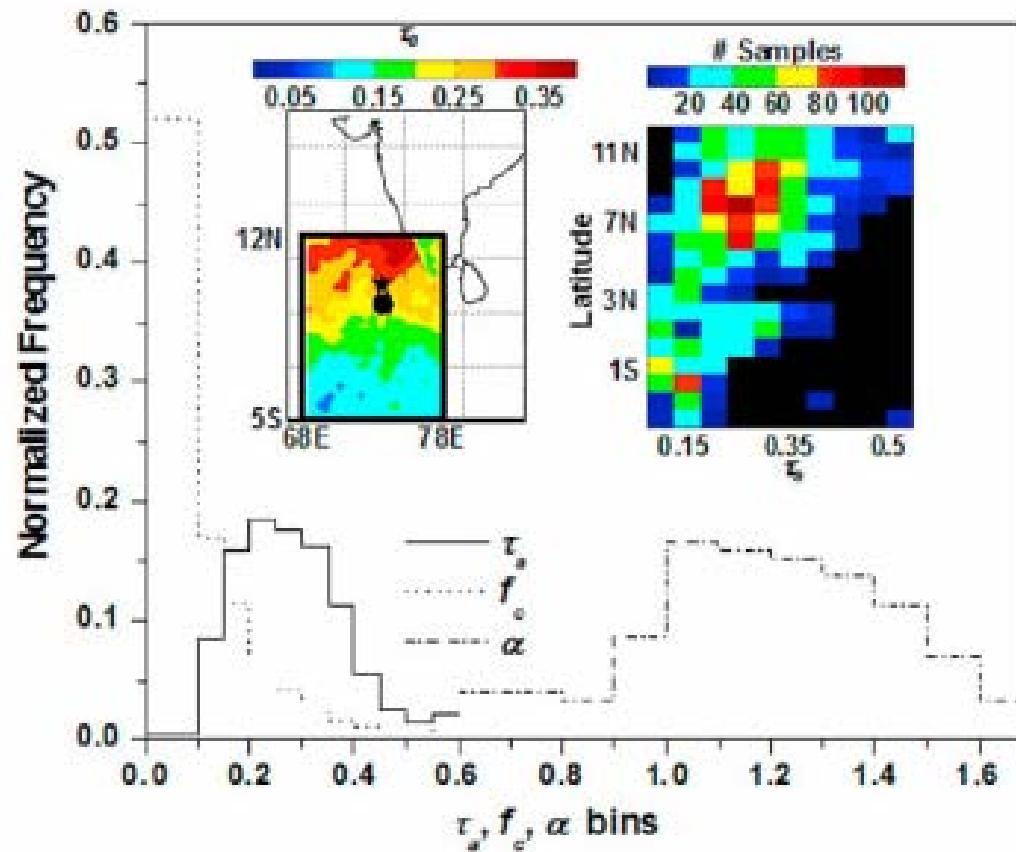
<u>Cloud Fraction</u>	
<u>15m</u>	<u>1.1km</u>
9%	83%



<u>Cloud Fraction</u>	
<u>15m</u>	<u>1.1km</u>
8%	32%



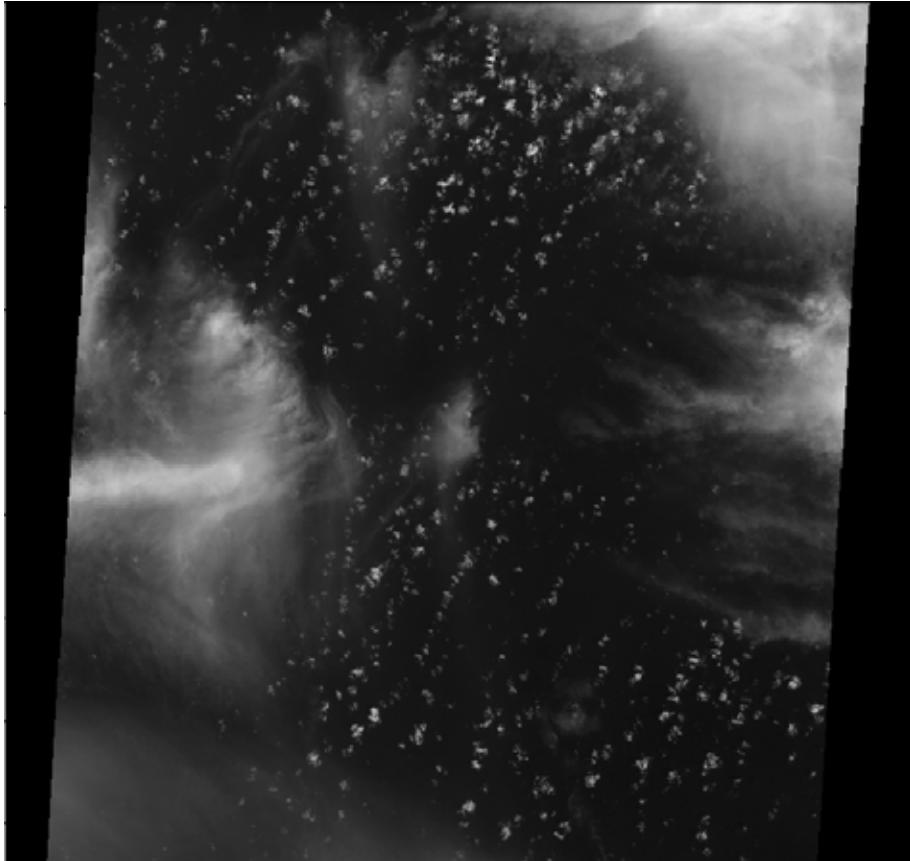
# Case Study over Indian Ocean



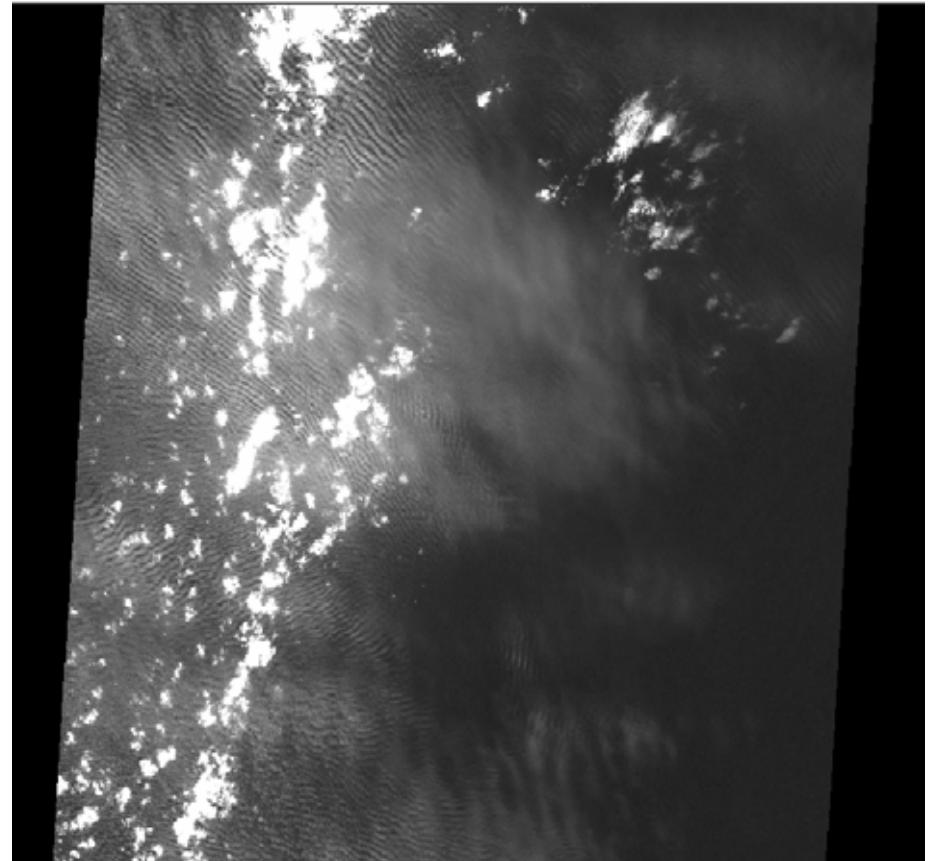
1200 ASTER (15-m) images are collected for the period  
Nov 2006 - Apr 2007

# Potential Problems

Multi-layer clouds

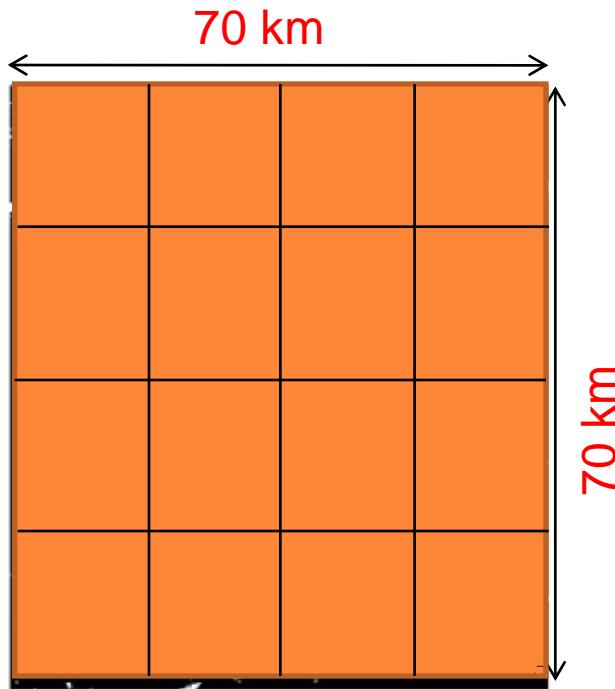


Sun glint

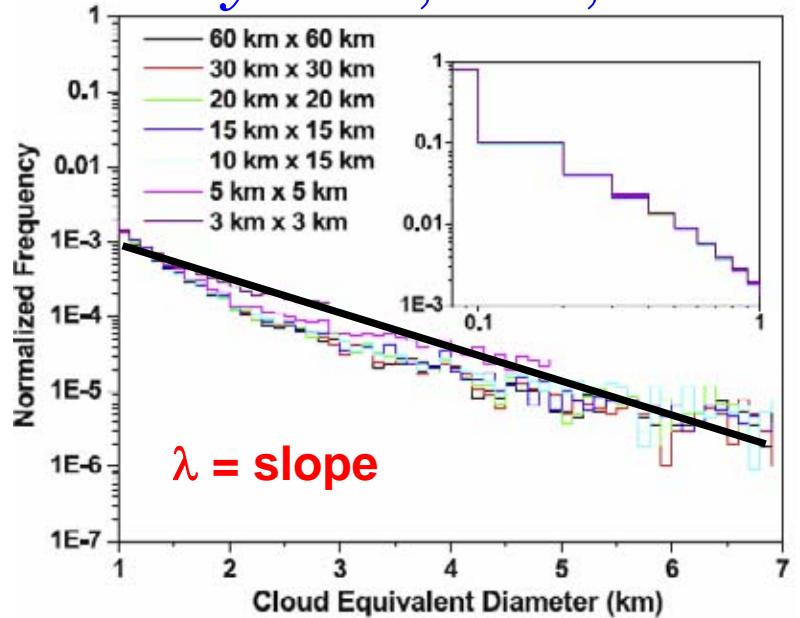


Only 277 ASTER scenes out of 1200 are analyzed  
because these scenes contain only cumulus clouds

# Analysis



Dey et al., JGR, 2008



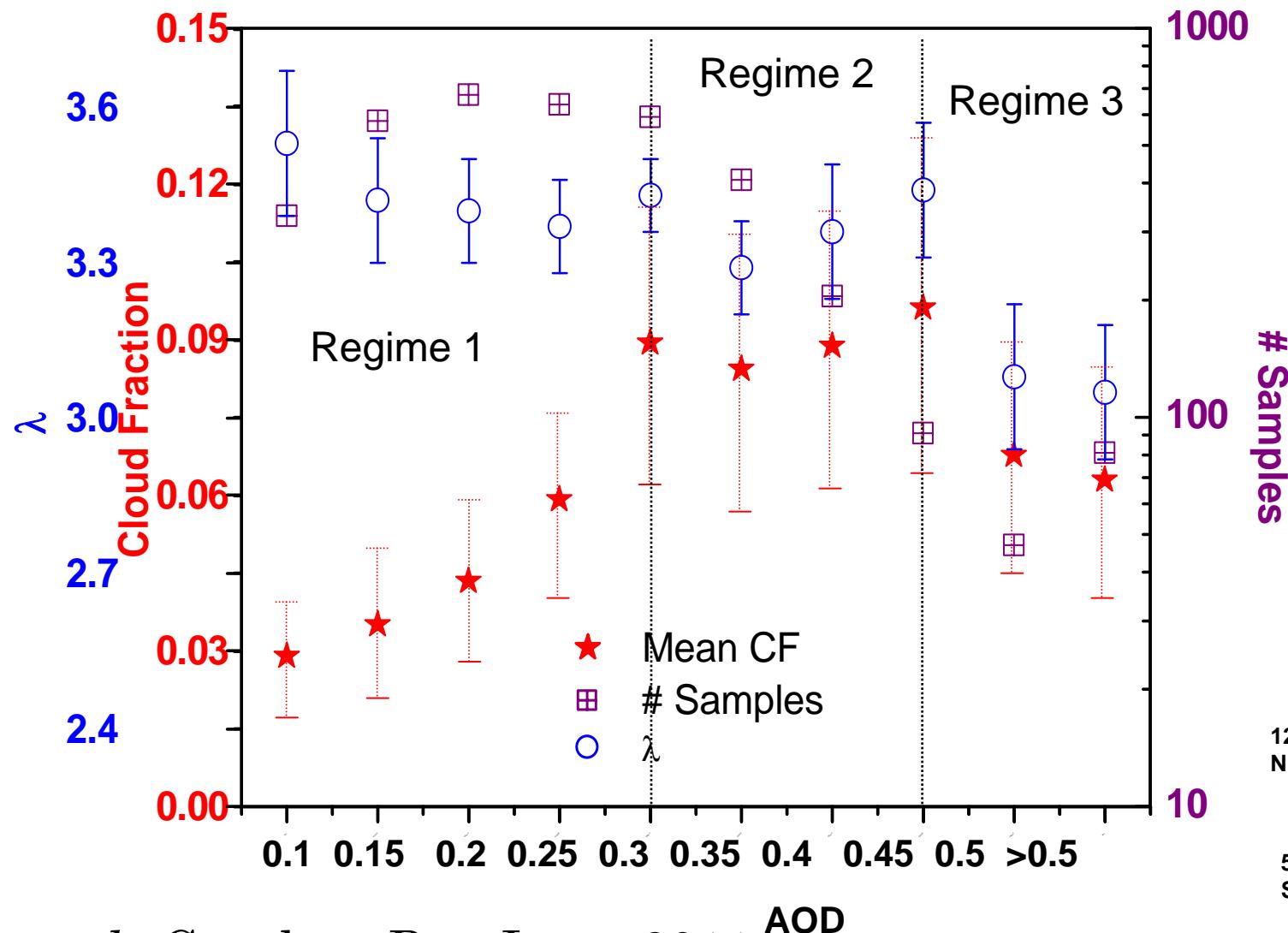
Cloud Fraction, Cloud Size and Top Height Distribution  
(ASTER)

17.6 km × 17.6 km

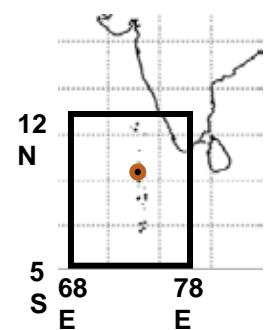
Aerosol Optical Depth  
(MISR)

Meteorology  
(NCEP reanalysis data)

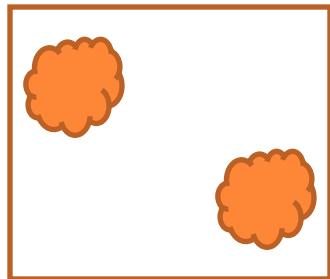
# Cloud Fraction and Cloud Size Distribution vs. AOD



Dey et al., Geophys. Res. Lett., 2011



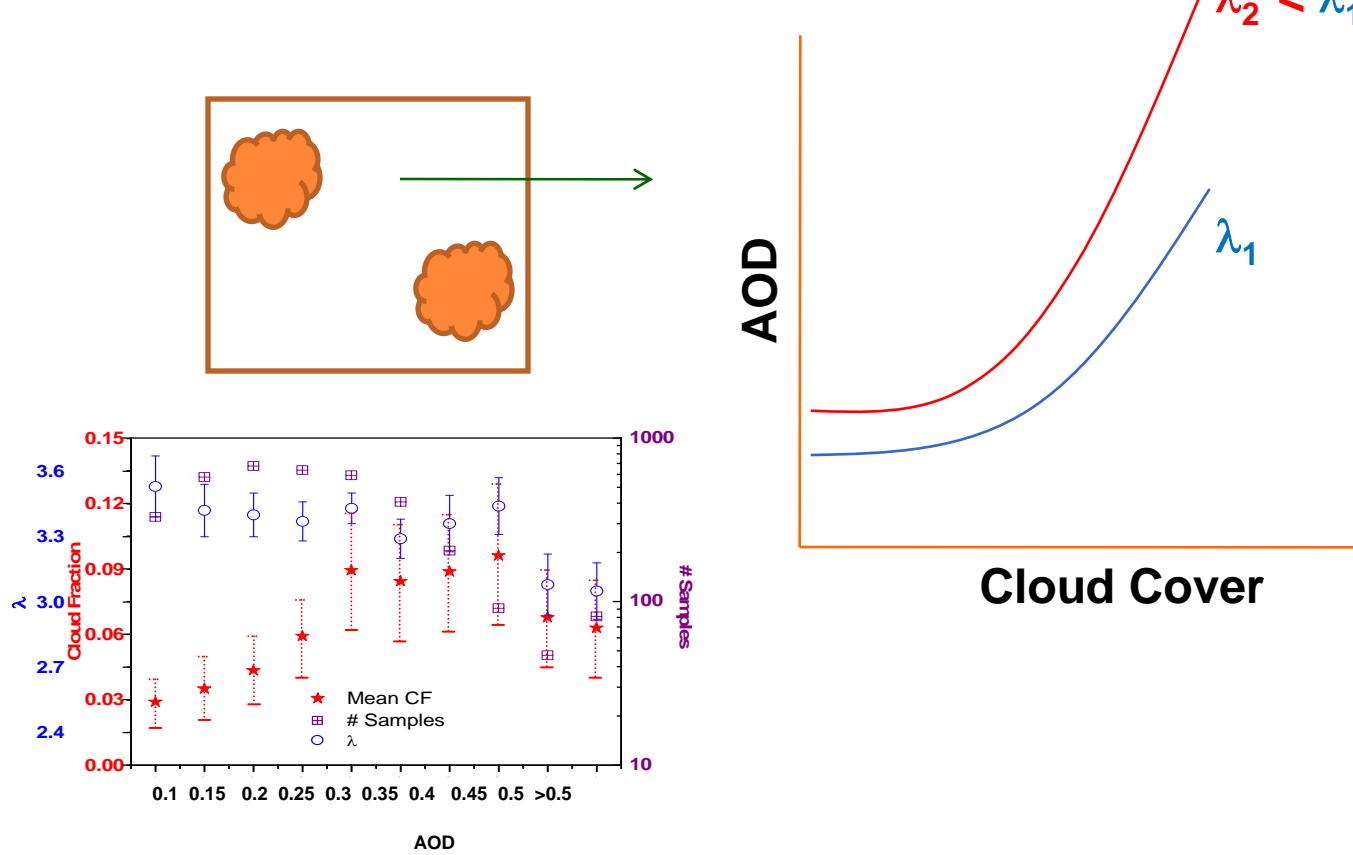
# 1. Direct cloud contamination



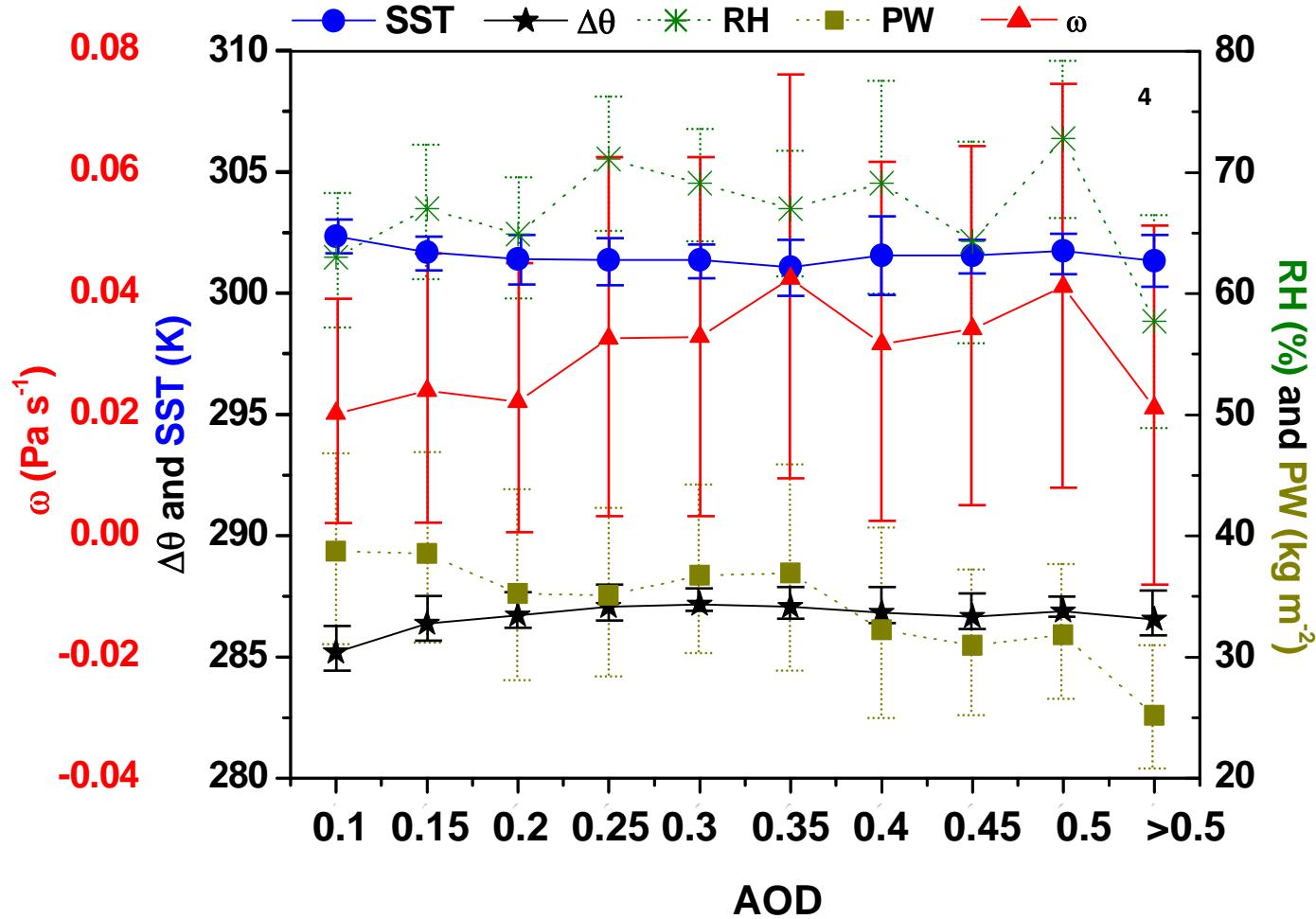
- Only 0.002 bias in AOD due to direct cumulus contamination on MISR AOD retrieval (**Zhao et al., GRL, 2009**)

## 2. 3-D Radiative Effect

- If affects the relation: AOD and AE would have consistently increased with Cloud Fraction (Marshak et al., *JGR*, 2008)

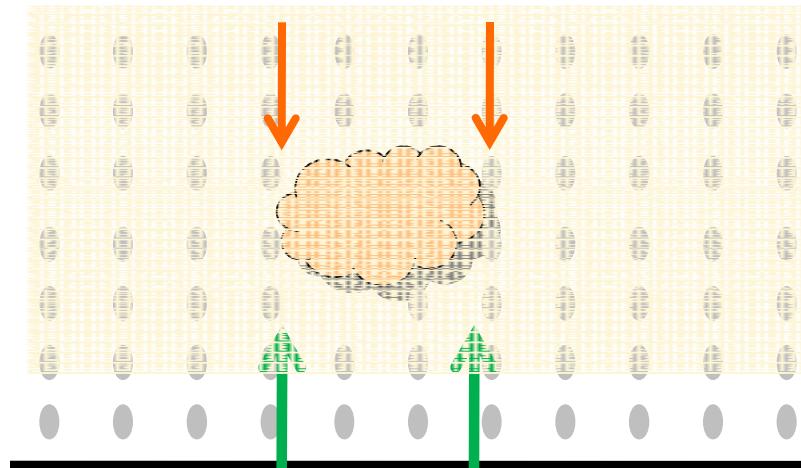


### 3. Effect of Meteorology

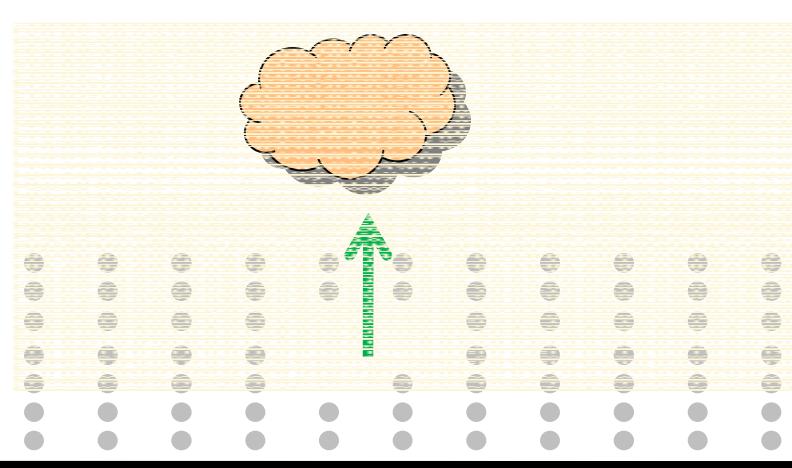


# Relative Distributions of Aerosols and Cloud

Scenario 1

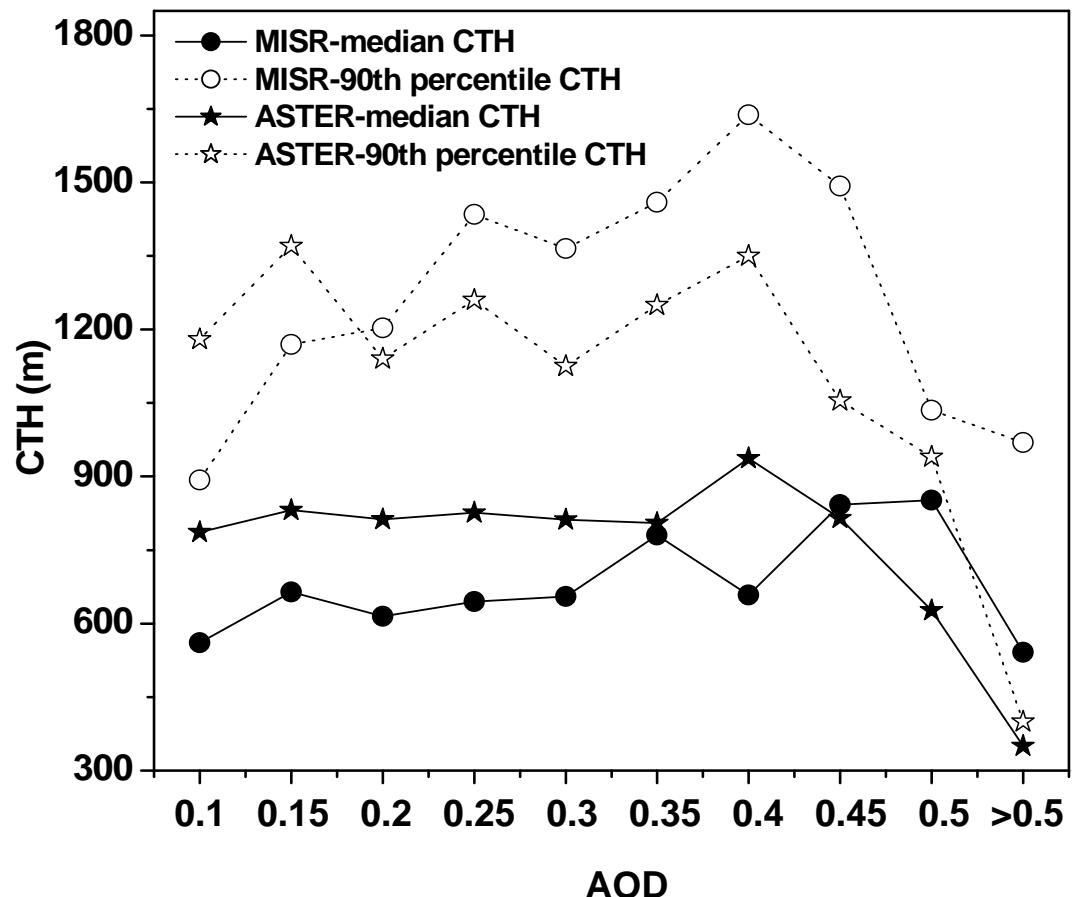


Scenario 2

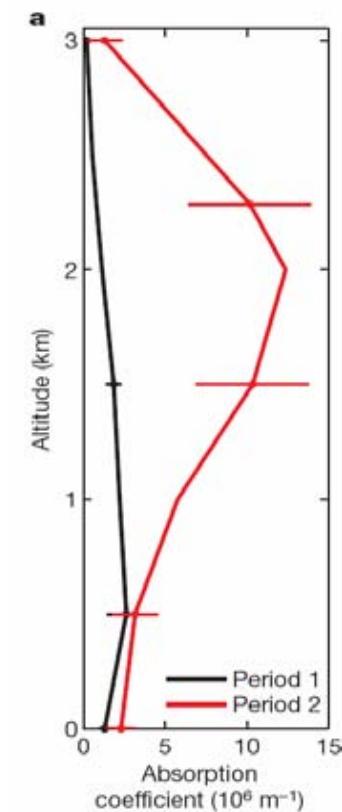


Surface

# Cloud Top Height vs. AOD



Dey et al., 2011

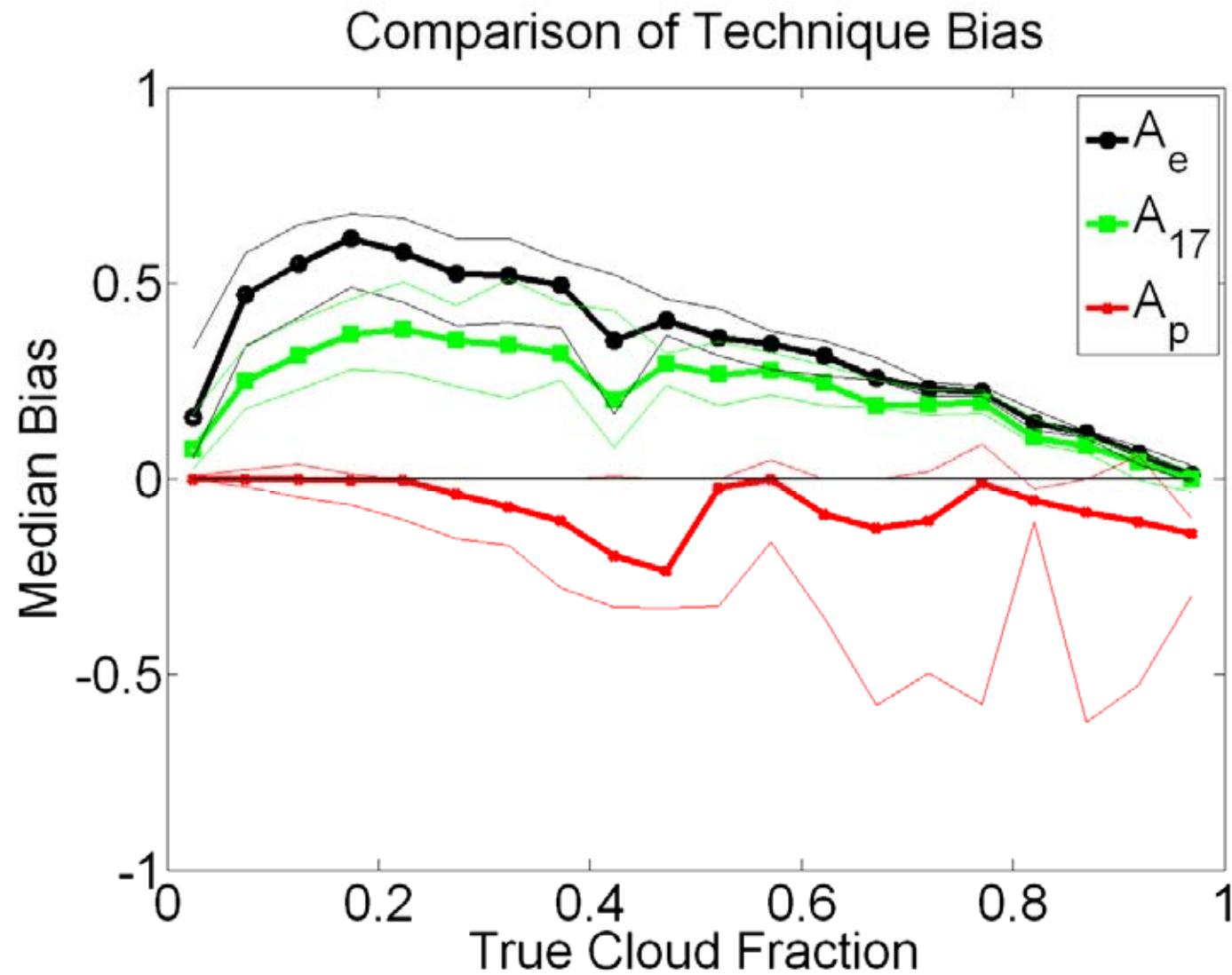


Ramanathan et al., 2007

# Highlights

- ❖ A transition from indirect to semi-direct effect of aerosols on cumulus clouds
- ❖ Observed relationship cannot be explained by meteorology or remote sensing artifacts
- ❖ Regular sensor must be used for multi-year and multi-season coverage
- ❖ Simple parameterization of cloud properties in terms of aerosols will not hold true

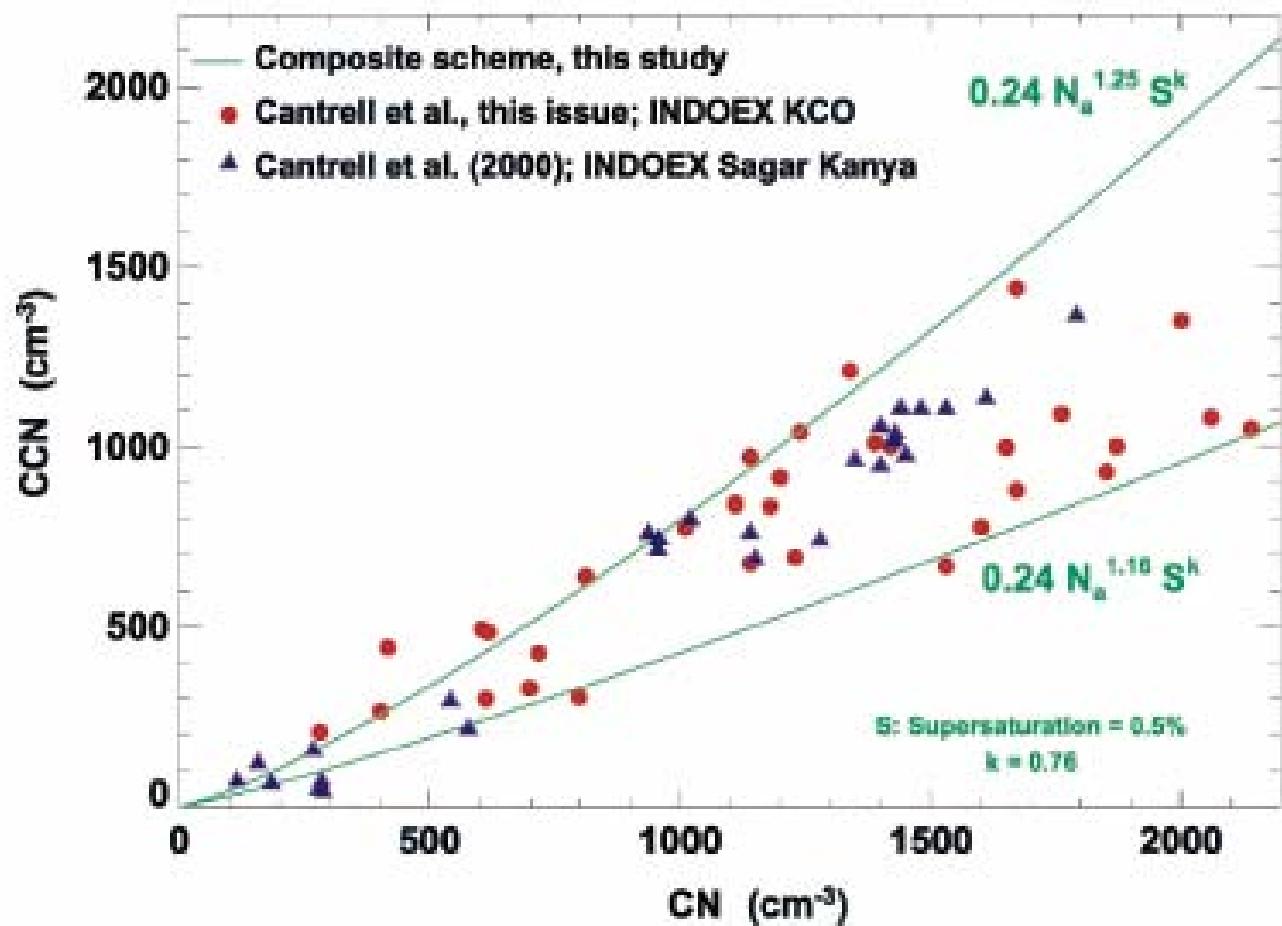
# Correcting CF bias in MISR



# Highlights

- ❖ A transition from indirect to semi-direct effect of aerosols on cumulus clouds
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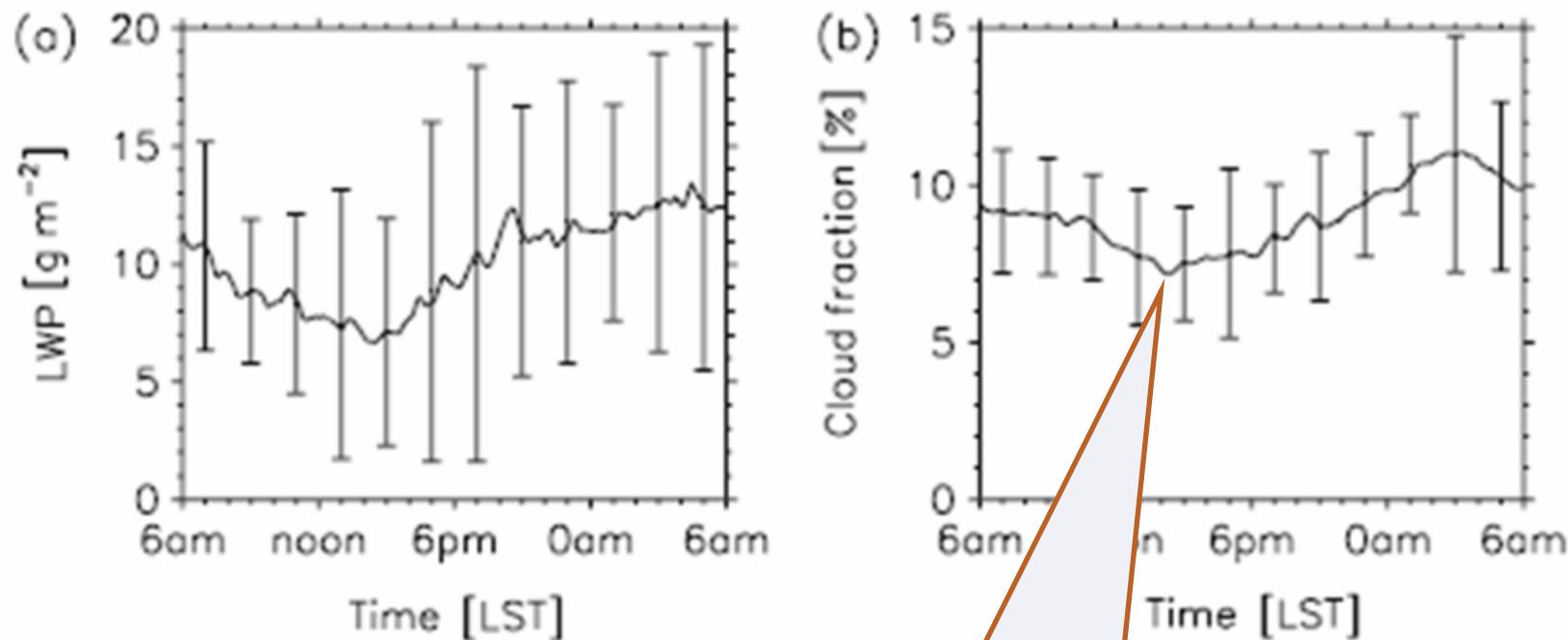
# Parameterization of CCN



*Ramanathan et al., 2001*

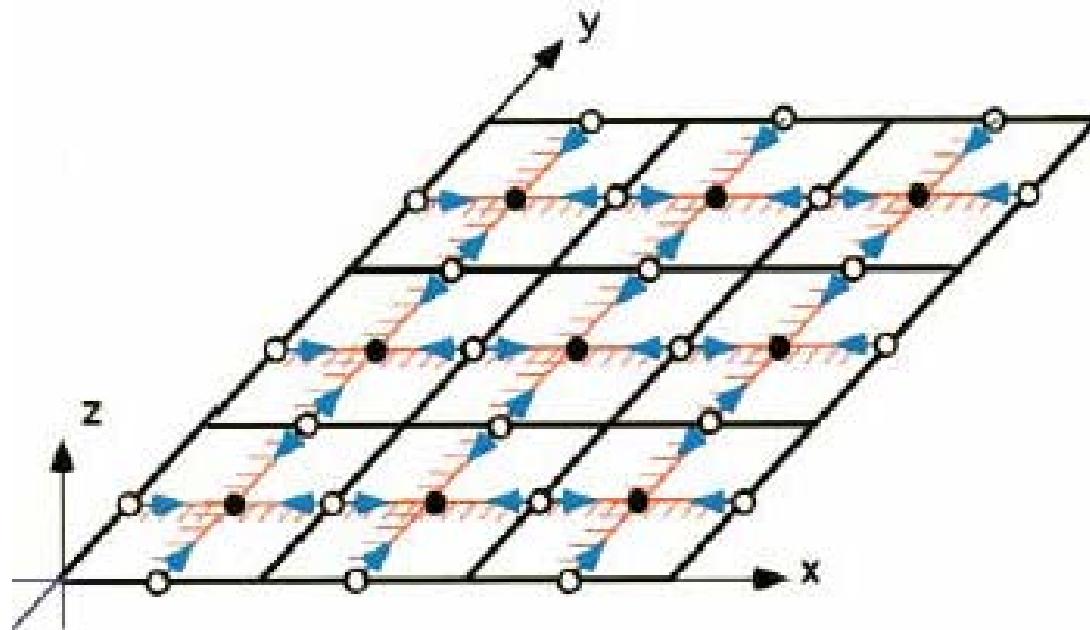
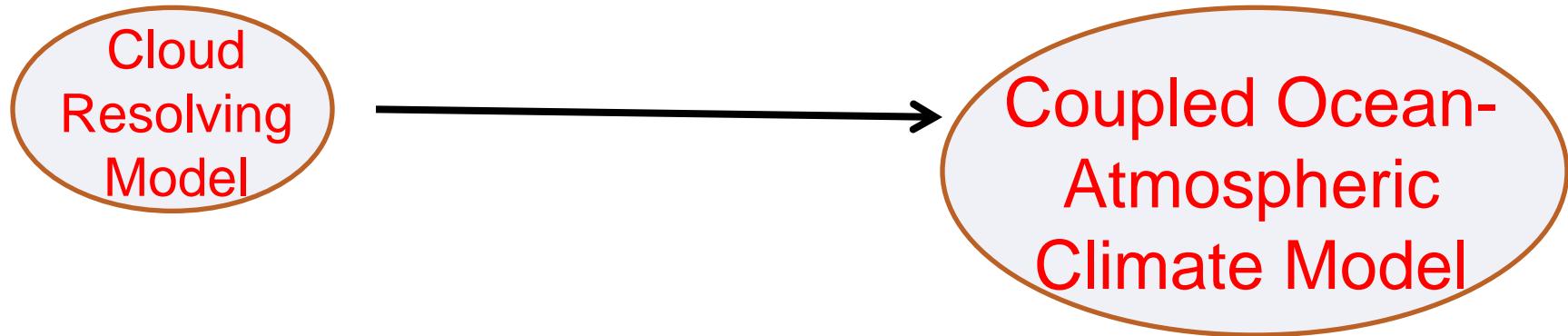
# Include ‘Semi-direct’ effect

- *Wang and McFarquhar (2006; 2008)* – cloud resolving model to understand the ‘semi-direct effect’ on diurnal variations of cloud micro- and macrophysics

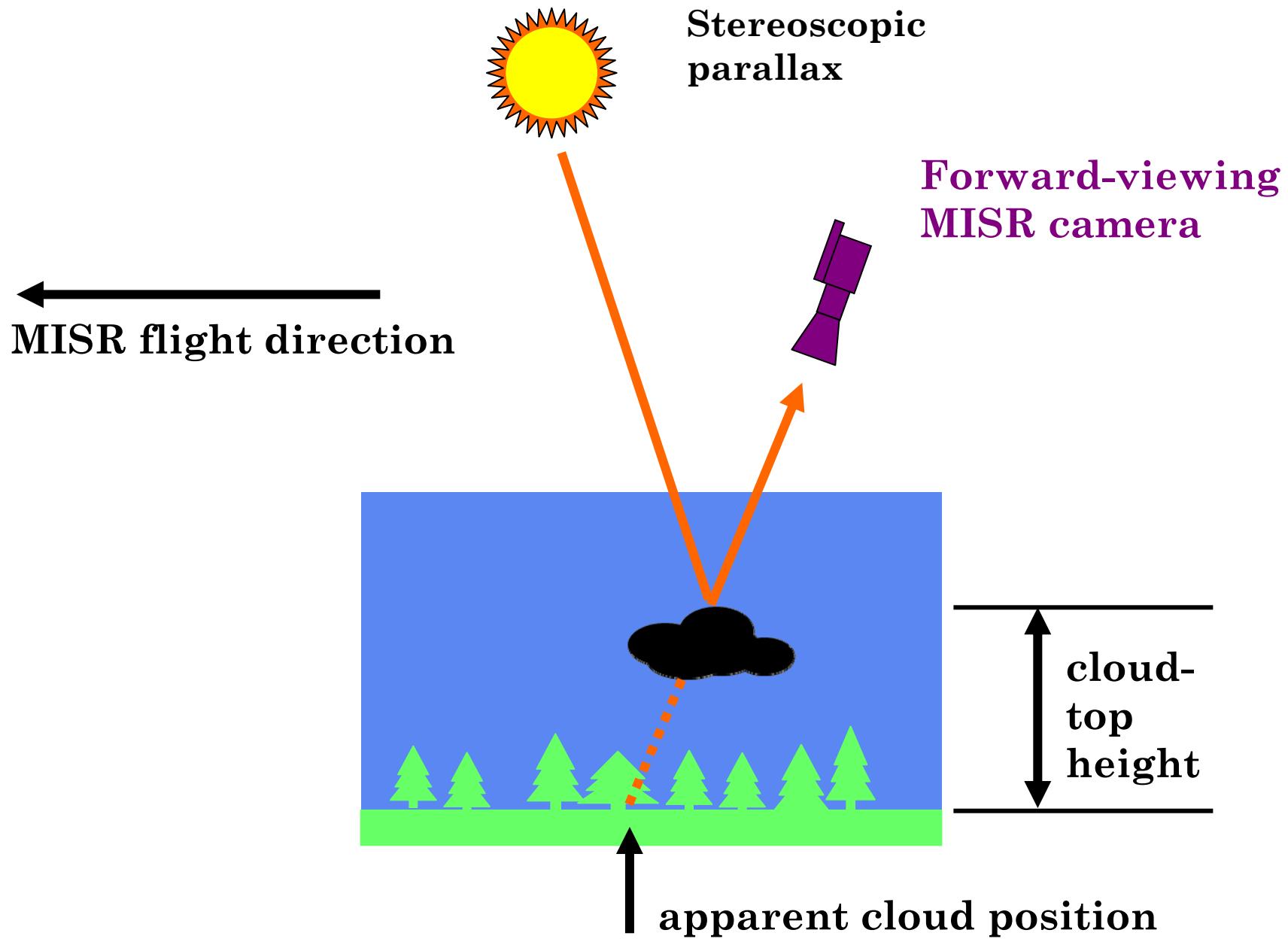


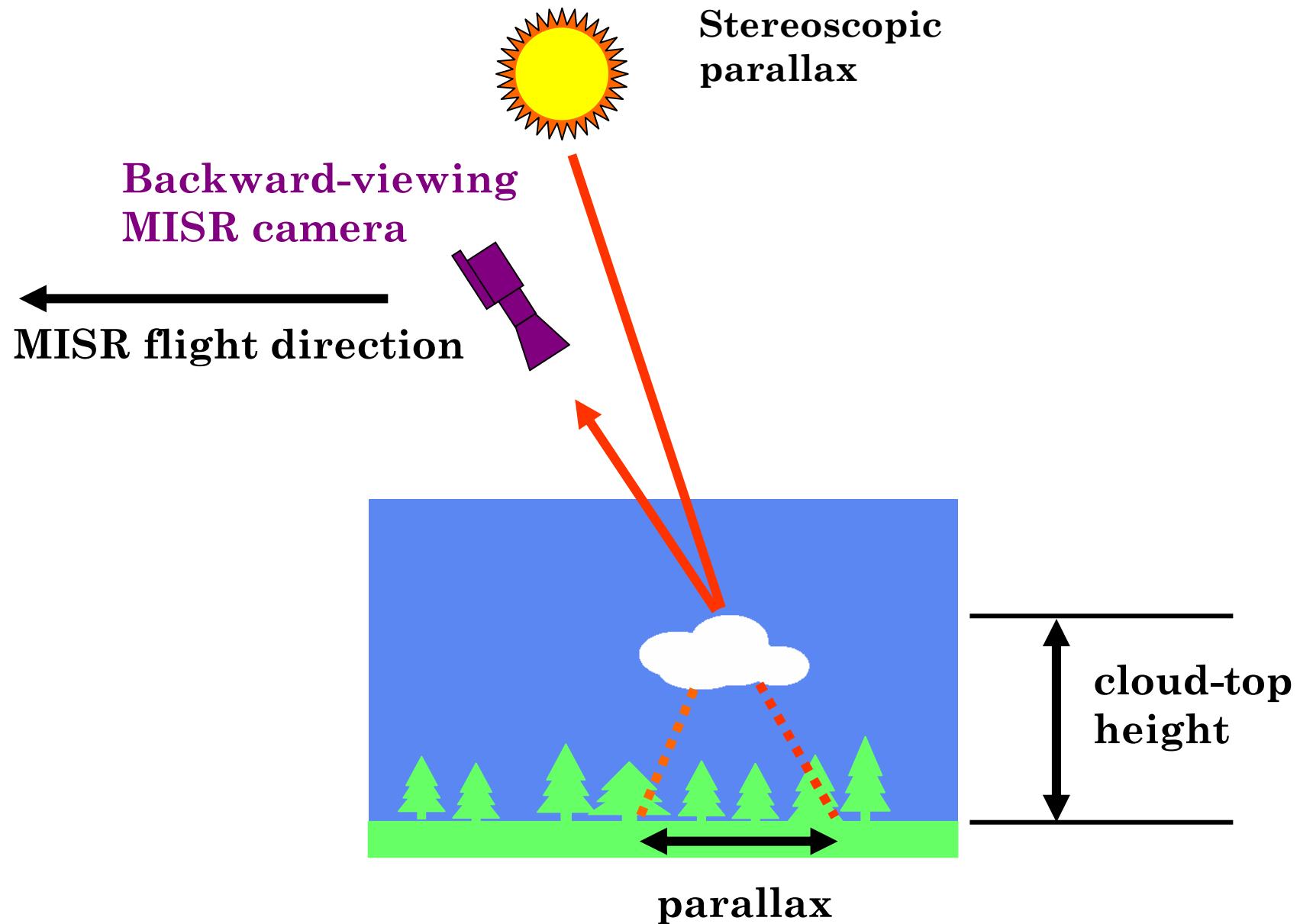
Daytime reduction of  
cloud cover is prominent  
for cumulus dominated  
regime

# Multi-scale Modeling Framework

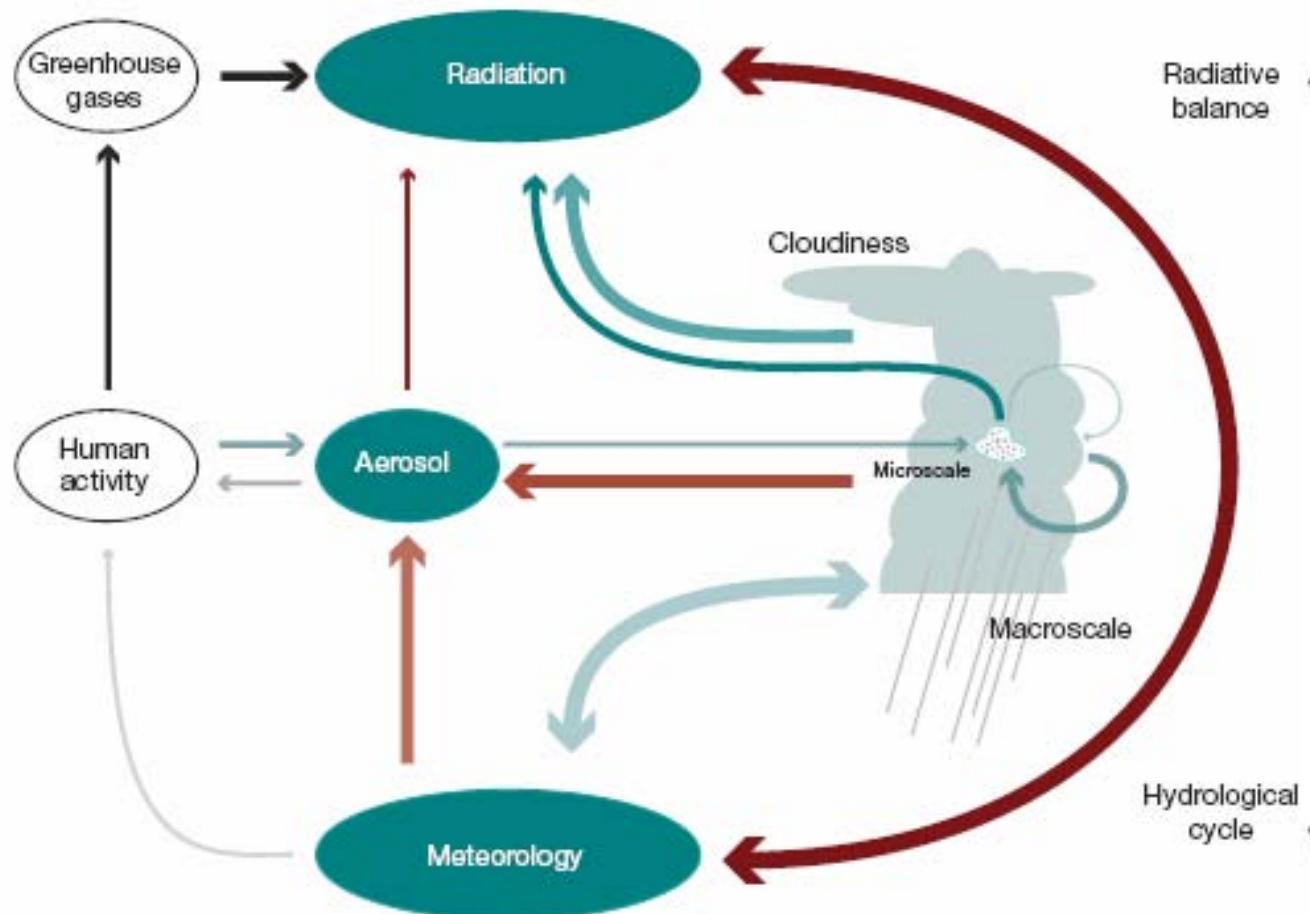


*Randall et al., 2003*





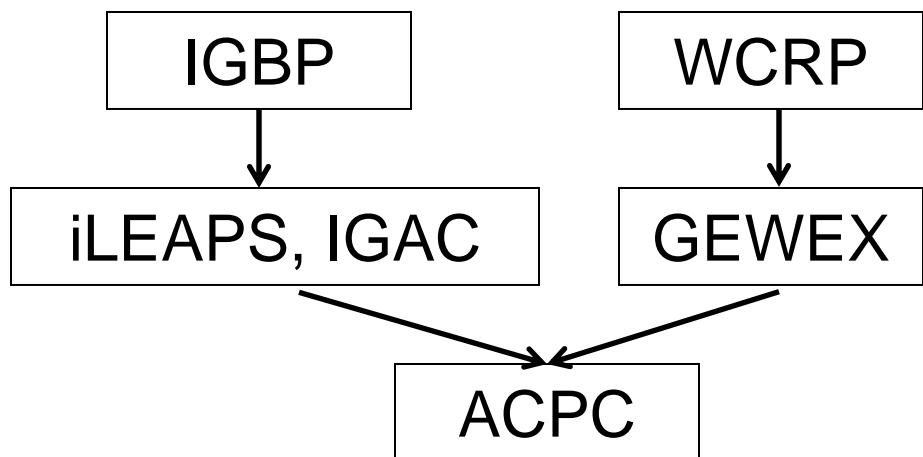
# Why is the problem so difficult to address?



*Stevens and Feingold, 2009*

# Global Efforts

- ☐ Aerosol-Cloud-Precipitation Climate (ACPC)  
Initiative - Integrated research program to investigate the interactions and feedbacks among aerosols, cloud processes, precipitation, and the climate system



<i>IGBP:</i>	<i>International Geosphere-Biosphere Programme</i>
<i>WCRP:</i>	<i>World Climate Research Programme</i>
<i>IGAC:</i>	<i>International Global Atmospheric Chemistry</i>
<i>iLEAPS:</i>	<i>Integrated Land ecosystem-Atmosphere Process Study</i>

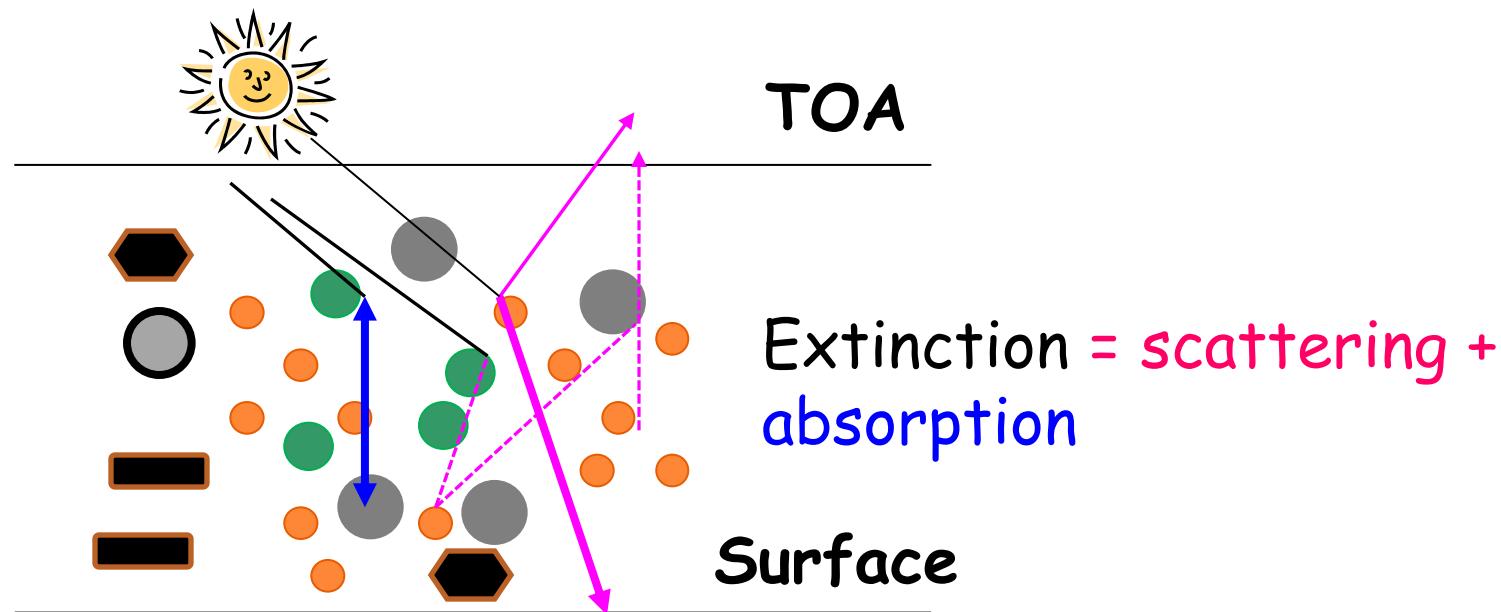
# National Efforts

- CAIPEX (Cloud-Aerosol-Interaction and Precipitation Enhancement Experiment)



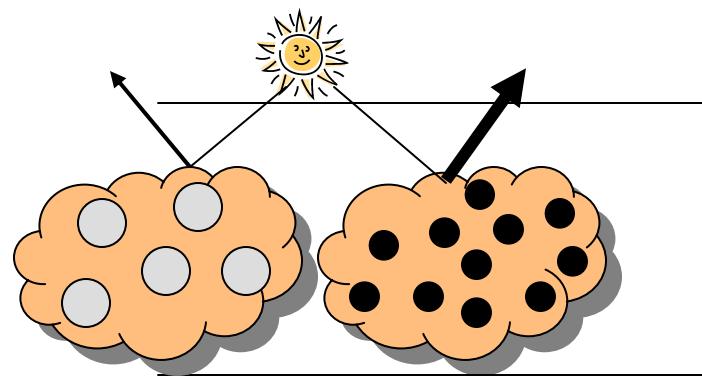
- CTCZ (Continental Tropical Convergence Zone) Campaign

# Direct Effect

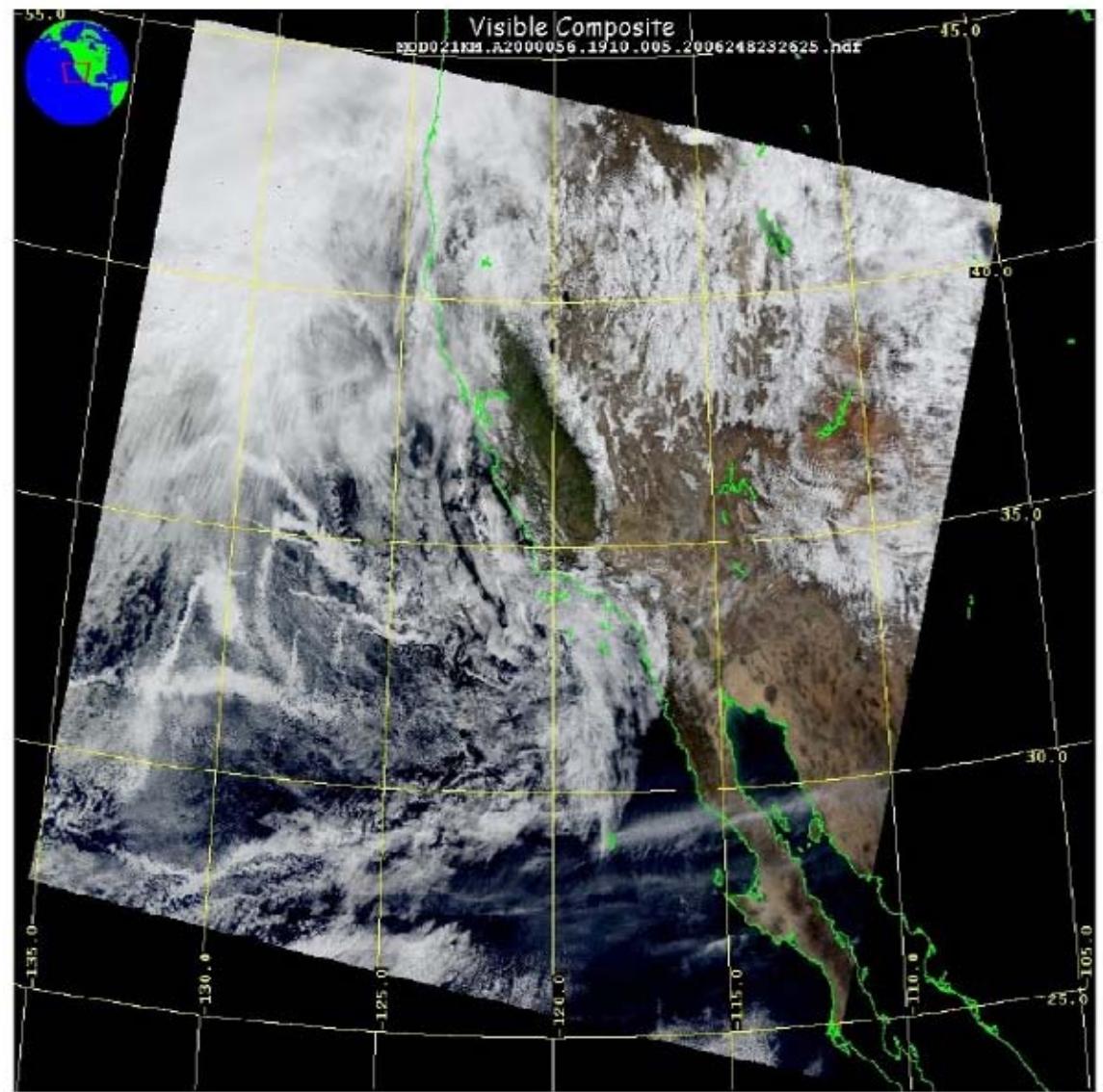


*Haywood and Boucher, 2000*

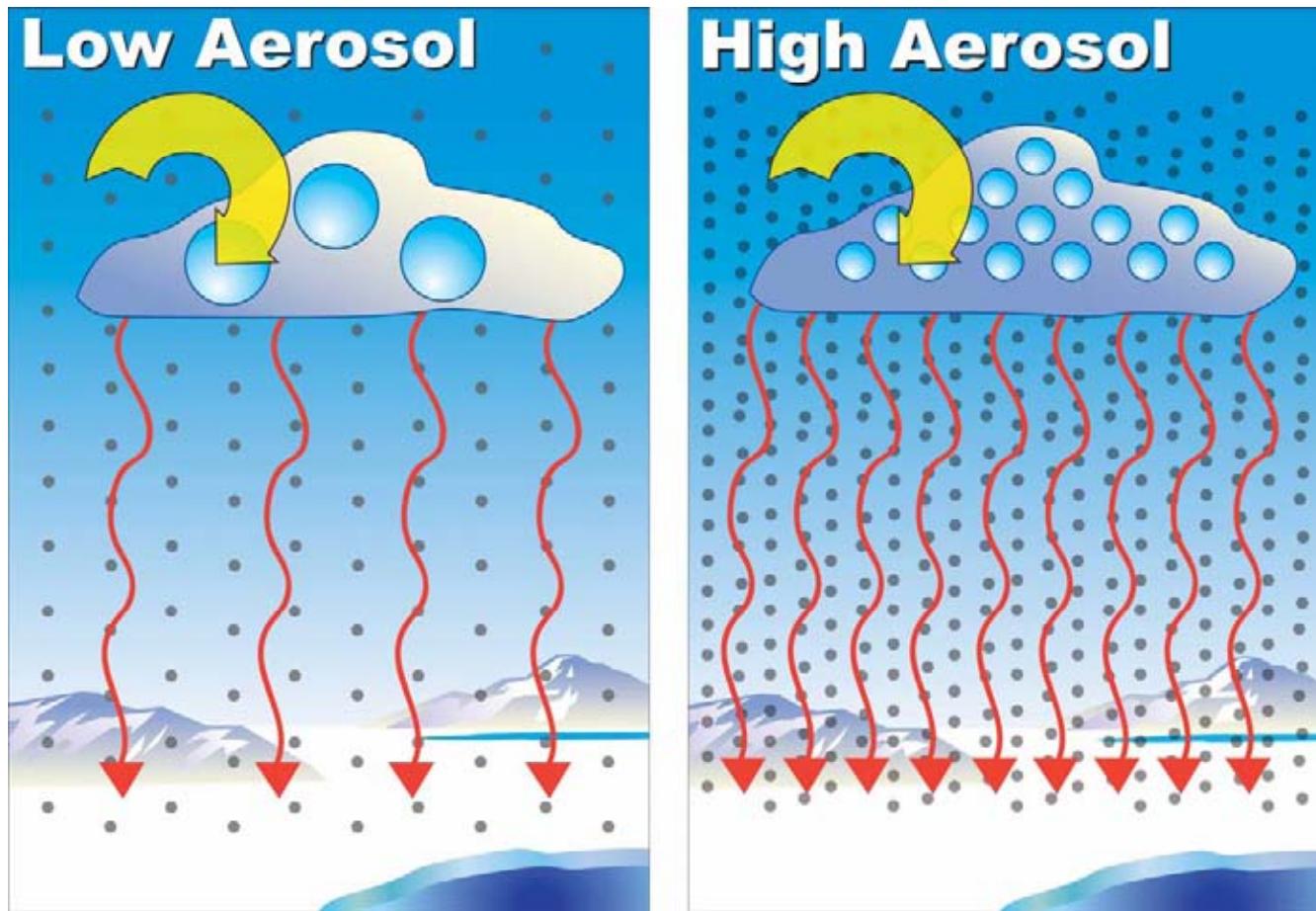
# 1<sup>st</sup> Indirect Effect



*Twomey, 1977*

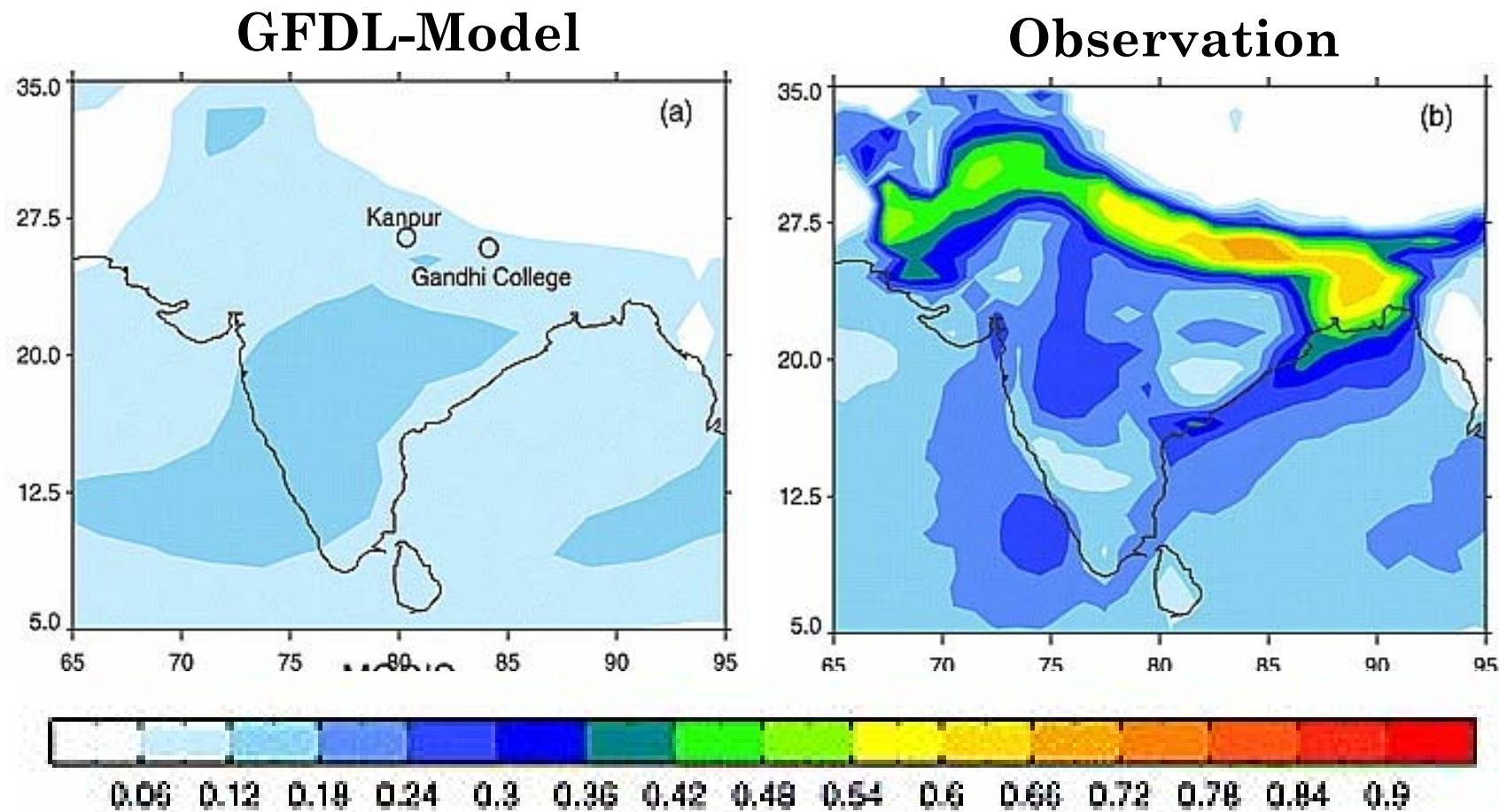


## 2<sup>nd</sup> Indirect Effect



*Albrecht, 1989*

# Aerosol Optical Depth



*Ganguly et al., 2009*

# What do we need?

