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
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

Climatic Effects

- Direct Effect
- Indirect Effect
- Semi-direct Effect
Semi-direct Effect

Ackerman et al., 2000

Absorbing aerosols
Untangling aerosol effects on clouds and precipitation in a buffered system

Bjorn Stevens¹,² & Graham Feingold³

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

Global Energy and Water Cycle Experiment (GEWEX)

GEWEX Cloud System Study (GCSS)

- Boundary layer clouds
- Cirrus clouds
- Extra-tropical layer clouds
- Precipitating Convective clouds
- Polar clouds
Clouds and Climate

- 4% increase in low clouds offsets doubling of CO$_2$

- Requires reduction of measurement error of cloud fraction to 1%
Model-simulated Cloud Cover

Source: GEWEX inter-comparison study
Satellite-measured Cloud Cover

From Stubenrauch et al. (2009, GEWEX report)
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
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

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<th>Cloud Fraction</th>
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<td>15m 1.1km</td>
<td>9% 83%</td>
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<tr>
<td>15m 1.1km</td>
<td>8% 32%</td>
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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)

Aerosol Optical Depth (MISR)

Meteorology (NCEP reanalysis data)

70 km × 70 km

λ = slope

17.6 km × 17.6 km
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

Dey et al., GRL, 2011
Relative Distributions of Aerosols and Cloud

Scenario 1

Scenario 2
Cloud Top Height vs. AOD

\[ \text{CTH (m)} \]

- MISR-median CTH
- MISR-90th percentile CTH
- ASTER-median CTH
- ASTER-90th percentile CTH

Ramanathan et al., 2007

Dey et al., 2011
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

Comparison of Technique Bias

Median Bias vs True Cloud Fraction

- $A_e$
- $A_{17}$
- $A_p$
A transition from indirect to semi-direct effect of aerosols on cumulus clouds

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Simple parameterization of cloud properties in terms of aerosols will not hold true
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
MISR flight direction

Stereoscopic parallax

Forward-viewing MISR camera

cloud-top height

apparent cloud position
MISR flight direction

Stereoscopic parallax

Backward-viewing MISR camera

MISR flight direction

cloud-top height

parallax
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.
National Efforts

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

- CTCZ (Continental Tropical Convergence Zone) Campaign
Direct Effect

Extinction = scattering + absorption

Haywood and Boucher, 2000
1\textsuperscript{st} Indirect Effect

\textit{Twomey, 1977}
2nd Indirect Effect

Albrecht, 1989
Aerosol Optical Depth

Ganguly et al., 2009
What do we need?

- Emission Inventory
- Aerosol properties
- Meteorology
- Parameterization of aerosol-cloud relations

Aerosol properties:
1. Aerosol vertical distribution
2. Microphysical processes
3. Mixing State

Meteorology:
1. Microphysical processes
2. Radiative processes
3. Dynamical processes

Cloud Properties:
Grid size

(1) Aerosol vertical distribution
(2) Microphysical processes
(3) Mixing State