Aerosol – cloud interactions are difficult to study for a variety of reasons.

Will address this theme by way of a specific calculation

Changes in deep convective cloud structure in the tropics due to changes in aerosol

Why is there such a variety of results?
## Radiative Forcing - Uncertainty

### Radiative Forcing of Climate Between 1750 and 2011

<table>
<thead>
<tr>
<th>Forcing agent</th>
<th>Confidence Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well Mixed Greenhouse Gases</td>
<td>Very High</td>
</tr>
<tr>
<td>Other WMOGHGs</td>
<td>Very High</td>
</tr>
<tr>
<td>CH4, NO</td>
<td></td>
</tr>
<tr>
<td>Ozone</td>
<td>High</td>
</tr>
<tr>
<td>Stratospheric</td>
<td>Medium</td>
</tr>
<tr>
<td>Tropospheric</td>
<td>Medium</td>
</tr>
<tr>
<td>Stratospheric water vapour from CH4</td>
<td>AR4 estimates</td>
</tr>
<tr>
<td>Surface Albedo</td>
<td>High/Low</td>
</tr>
<tr>
<td>Land Use</td>
<td></td>
</tr>
<tr>
<td>Black carbon on snow</td>
<td></td>
</tr>
<tr>
<td>Contrails</td>
<td>Medium/Low</td>
</tr>
<tr>
<td>Contrail induced cirrus</td>
<td></td>
</tr>
<tr>
<td>Aerosol-Radiation Interac.</td>
<td>High/Medium</td>
</tr>
<tr>
<td>Aerosol-Cloud Interac.</td>
<td>Low</td>
</tr>
<tr>
<td>Total anthropogenic</td>
<td>Medium</td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**IPCC WG1 AR5-TS**

### Aerosol-Cloud Interactions: Low Confidence Level
More CCN changes liquid droplet, ice, and latent heat release profiles

Rosenfeld et al. (Science, 2008)
Conclusions of Different Signed Outcomes


Cloud top heights *increased* as AODs *increased*

Wall, Zipser, Liu (2014): 14 years of TRMM reflectivity and MODIS Aerosol-index (i.e. AOD x Ångstrom exponent) data

Echo-top heights *decreased* as the aerosol index *increased* over the equatorial Atlantic
Calculations

Calculate changes in *cloud structure* (Ice Water Content, IWC)
Regional basis (12 Tropical regions)
Each Season, 2007 - 2010
Use MODIS Aerosol Optical Depths (AODs)
   Proxy for Cloud Condensation Nuclei (CCN)
Look at Deep Convection, 5 – 15 km altitude range

Bin IWC average profiles (*Altitude*, AOD, Season, Region)

Also calculate the *Shapes* of the IWC average profiles
   Normalize to unity at 5 km

Calculate 100 \( \frac{d \text{IWC}}{d \text{AOD}} \)/ IWC *derivatives*
   % change / 0.1 AOD units

Aggregate regional calculations into Land only, Ocean only, and
Tropical averages
   Profiles of derivatives (2 km vertical steps)
Motivation for Shape Normalization

Bulk Microphysics

(c) $t = 4\text{ hr}$

Bin microphysics

(d) $t = 4\text{ hr}$

ICE - - - Polluted - - - Semi–Polluted - - - Clean

Lebo and Seinfeld, ACP, 2011
A 2D slice samples a *portion* of the 3D cloud field.

July 10, 2010 Example
Geographical Regions
Derivatives are Positive and Negative

Derivatives are for the 5 to 15 km altitude range. Most of the largest derivatives are over India (□ symbols)
Shape Derivatives over Ocean and Land

Exclude India

2 \sigma\text{ error bar}
Tropical Averages

IWC

Shape

Altitude (km)

% per 0.1 AOD

Not significant

Significant (2σ)

5%
Microphysics – Cloud Dynamics – Time

\[ \frac{\partial}{\partial t} \frac{\partial IWC}{\partial AOD} \bigg|_{\text{RH=const}} \]

but \[ \frac{\partial IWC}{\partial \text{RH}} \] and \[ \frac{\partial IWC}{\partial t} \neq 0 \]

Important life-cycle presentation by R. Fu and Sudip Chakraborty
Condensate Loading Term

*Lebo and Seinfeld* (2011): “The aerosol-induced effect is controlled by the balance between latent heating and the increase in condensed water aloft, each having opposing effects on buoyancy.”

\[
\text{Buoyancy} = g \left[ \left( \frac{\theta^*}{\theta_a} \right) + (\kappa-1)\left( \frac{p^*}{p_a} \right) - q_H \right] \quad \text{Houze (2014)}
\]

\(\theta\) virtual potential temperature  
\(a\) ambient value  
\(*\) perturbed value of a parcel  
\(q_H\) condensate loading due to liquid water and ice

Need to consider *changes in the opposing terms*

\[
\left( \frac{\theta^*}{\theta_a} \right) + (\kappa-1)\left( \frac{p^*}{p_a} \right) \quad \text{due to latent heat release}
\]

\(q_H\) due to *condensate loading*
Condensate Loading Term

Cloud resolving model study of aerosol - deep convective cloud development

Figure 8 curves are for different aerosol concentrations (\# / cm\(^3\))

“Changes in latent heating were, on average, an order of magnitude smaller than those in the condensate loading term”

![Figure 8: Diagrams of Buoyancy from Latent Heat and Condensate Loading](image)
Conclusions

The variance of the derivatives is dependent upon the number of profiles used in regional calculations.

For the specific case of equatorial deep convection:

\[ \frac{\partial IWC}{\partial AOD} \] average derivatives are very small if you average over 4 years time.

\[ \frac{\partial IWC}{\partial AOD} \] shape derivatives are statistically significant (%5, 11 – 13 km)

There are a variety of results in the literature since:

a) Aerosol-cloud interactions (for deep convective clouds) are fairly small (the condensate loading term needs greater attention)

b) Equal consideration (and adequate sampling) of microphysical and cloud dynamic variables is needed

c) The time coordinate is important, while many of our experiments are locked into the A-train 1:30 am / pm fixed time