Investigation of Aerosol Indirect Effects on Warm Clouds

Prashant Kumar
11 / 02 / 2008

Indo-Asian Haze transported thousands of kilometers into the equatorial Indian Ocean.
An Introduction - Aerosol Indirect Effect

- Anthropogenic aerosols play a substantial role in changing cloud characteristics
  - By changing the concentration of *Cloud Condensation Nuclei* in the atmosphere. This phenomena is referred to as *Aerosol Indirect Effect*.

1. First Indirect Aerosol Effect or Twomey Effect
2. Second Indirect Aerosol Effect or Cloud Lifetime Effect
3. Semi-Direct Effect
4. Dispersion Effect
5. Thermodynamic Effect
   - Typically have size range: sub-micrometer to micrometer
   - Classified into four broad categories
     1. Sulphates
     3. Dust
     4. Sea Salt
Aerosol Indirect Effect – Hydrological Cycle

- On the surface, there exists a balance between Radiation, Evaporation and Sensible Heat Flux
- 60 – 70 percent of Absorbed Solar Radiation is balanced by Evaporation.
- Mean irradiance decrease between 1958 – 1985 : - 5%
- 1% to 3% decrease per decade in the last four decades
- Reduction in Radiation is balanced by Reduction in Rain Fall.

**SPIN DOWN OF HYDROLOGICAL CYCLE**

Increasing aerosol particle concentration tends to cool climate
Features of high cloud reflectivity embedded in marine stratus clouds, resulting from aerosols emitted by ships.

M. Kulmala: “Nucleation and Atmospheric Aerosols, 1996”
Anthropogenic Indirect Effect: Important

Anthropogenic and natural forcing of the climate for the year 2000, relative to 1750

Global mean radiative forcing (W m⁻²)

- Greenhouse gases
  - Halocarbons
  - N₂O
  - CH₄
  - CO₂
- Tropospheric ozone
- Stratospheric ozone
- Sulphate
- Organic carbon from fossil fuel burning
- Biomass burning
- Black carbon from fossil fuel burning
- Mineral Dust
- Aviation (Contrails, Cirrus)
- Land use (albedo only)
- Solar

The height of a bar indicates a best estimate of the forcing, and the accompanying vertical line a likely range of values. Where no bar is present the vertical line only indicates the range in best estimates with no likelihood.

LEVEL OF SCIENTIFIC UNDERSTANDING

- High
- Medium
- Very low

IPCC (2001)
# Different Aerosols Indirect Effect

<table>
<thead>
<tr>
<th>Effect</th>
<th>Cloud type</th>
<th>Description</th>
<th>$F_{TOA}$</th>
<th>$F_{SFC}$</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indirect aerosol effect for clouds with fixed water amounts (cloud albedo or Twomey effect)</td>
<td>All clouds</td>
<td>The more numerous smaller cloud particles reflect more solar radiation</td>
<td>−0.5 to −1.9</td>
<td>similar to $F_{TOA}$</td>
<td>n/a</td>
</tr>
<tr>
<td>Indirect aerosol effect with varying water amounts (cloud lifetime effect)</td>
<td>All clouds</td>
<td>Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime</td>
<td>−0.3 to −1.4</td>
<td>similar to $F_{TOA}$</td>
<td>decrease</td>
</tr>
<tr>
<td>Semi-direct effect</td>
<td>All clouds</td>
<td>Absorption of solar radiation by soot may cause evaporation of cloud particles</td>
<td>+0.1 to −0.5</td>
<td>larger than $F_{TOA}$</td>
<td>decrease</td>
</tr>
<tr>
<td>Thermodynamic effect</td>
<td>Mixed-phase clouds</td>
<td>Smaller cloud droplets delay the onset of freezing</td>
<td>?</td>
<td>?</td>
<td>increase or decrease</td>
</tr>
<tr>
<td>Glaciation indirect effect</td>
<td>Mixed-phase clouds</td>
<td>More ice nuclei increase the precipitation efficiency</td>
<td>?</td>
<td>?</td>
<td>increase</td>
</tr>
<tr>
<td>Rimming indirect effect</td>
<td>Mixed-phase clouds</td>
<td>Smaller cloud droplets decrease the riming efficiency</td>
<td>?</td>
<td>?</td>
<td>decrease</td>
</tr>
<tr>
<td>Surface energy budget effect</td>
<td>All clouds</td>
<td>Increased aerosol and cloud optical thickness decrease the net surface solar radiation</td>
<td>n/a to −4</td>
<td>−1.8</td>
<td>decrease</td>
</tr>
</tbody>
</table>

Lohmann and Feichter (2005)
A number of Global Circulation Models exist but…

- Limited information about clouds and aerosols
- Aerosol-Cloud interaction are complex. Many processes are poorly represented. eg. Entrainment effects are neglected.
- Empirical relationships between aerosols and cloud droplet number concentration

Hence, ‘NEED’ an improvement to rightly quantify AIE by incorporating the missing links

- Cloud Dynamics: Updraft Velocity, Entrainment, Turbulence
- Aerosol Characteristics: Size, Concentration, Chemical Composition, Morphology
- Cloud Processes: Cloud Droplet Formation, Drizzle and Precipitation, Chemical Rxn
- Meteorological Effects and Physical Interactions

GMI, NASA GISS II, TOMAS, LES, CRM, SCM
Motivation of this presentation

Quantification of Aerosol Indirect Effects


Large-Eddy Simulations of Trade Wind Cumuli: Investigation of Aerosol Indirect Effects

HUIWEN XUE AND GRAHAM FEINGOLD

NOAA/Earth System Research Laboratory, Boulder, Colorado

(Manuscript received 23 August 2005, in final form 21 October 2005)
Framework of Data Presentation

- Description of Model
- Results
- Discussions of Results
- Conclusions

Shallow Low Level Cumulus clouds
**Description of Model Set Up**

LES (Large Eddy Simulation) model:
- Simulations performed with fixed surface sensible heat, latent heat and momentum flux
- Smagorinsky scheme to calculate eddy viscousity and diffusivity
- Lateral boundary cyclic conditions used
- 33 fixed size bin with mass doubling from one bin to the next [radius: 1.5 – 2000 µm]
- Ammonium sulphate, Lognormal Size Distribution, \( r_g = 0.1 \) microns, \( \sigma_g = 1.5 \)
- **Activation, Condensation/Evaporation, Auto-conversion, Sedimentation**
- Solves 72 prognostic Equations simultaneously
- Compares two sets of cases for CLEAN and POLLUTED conditions
- A total of 8 simulations performed for each model set up for 6 hours.
  - First 2 hours: SPINUP TIME → time to stabilize and reach SS
  - Last 4 hours: Analysis Time

**Barbados Oceanographic and Meteorology EXperiment [BOMEX]**
- Solid Lines: Clean Case
- Dashed Lines: Polluted Case

Cloud Fraction (a) and LWP (b, c) approach SS.

Cloud-Top Height (d), Cloud-Base Height (e) and TKE (f) increase

Precipitation (g) is negligible in polluted case

The cloud properties shown here are in quantitative agreement BOMEX study
**Result 2**

TABLE 1. Average cloud properties over the last 4 h of simulations. Numbers in parentheses represent standard deviations. The percentage differences between the clean and polluted cases (polluted − clean) are also shown.

<table>
<thead>
<tr>
<th></th>
<th>Base case</th>
<th>Higher surface flux case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$N_a = 25$ mg$^{-1}$</td>
<td>$N_a = 2000$ mg$^{-1}$</td>
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<tr>
<td>Cloud fraction</td>
<td>0.086 (0.015)</td>
<td>0.069 (0.01)</td>
</tr>
<tr>
<td>LWP_domain (g m$^{-2}$)</td>
<td>8.1 (2.4)</td>
<td>7.0 (2.5)</td>
</tr>
<tr>
<td>LWP_cloud (g m$^{-2}$)</td>
<td>89 (19)</td>
<td>97 (26)</td>
</tr>
<tr>
<td>Cloud top (m)</td>
<td>1192 (92)</td>
<td>1115 (96)</td>
</tr>
<tr>
<td>Cloud base (m)</td>
<td>813 (65)</td>
<td>816 (72)</td>
</tr>
<tr>
<td>TKE (kg s$^{-2}$)</td>
<td>352 (59)</td>
<td>367 (79)</td>
</tr>
<tr>
<td>Cloud depth (m)</td>
<td>379 (50)</td>
<td>299 (39)</td>
</tr>
<tr>
<td>Drop effective radius (μm)</td>
<td>23.4 (3.4)</td>
<td>44.2 (0.14)</td>
</tr>
<tr>
<td>Optical depth</td>
<td>7.2 (1.1)</td>
<td>33.6 (7.4)</td>
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- Increase in cloud optical Depth for Polluted Case: % Diff = 367

- Increase in cloud averaged LWP: % Diff = +8.5

- But decrease in domain average LWP: % Diff = -14
  - This is because cloud fraction ↓ with ↑ aerosol concentration
  - Even though aerosol has distinct influence, this influence is < than dynamical variability
Result 3 – Higher Surface Latent Heat Flux

Investigate the effect of heavily drizzling trade cumulus clouds

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- In general, higher number in cloud variables differences
- In comparison to base run, there is stronger removal of liquid water by drizzle in this simulation.

- Qualitative consistency → Well defined processes and feedbacks
Result 4 – Evaporation & Precipitation Effects

- Solid Lines: Clean Case
- Dashed Lines: Polluted Case

- High concentration of droplets promote both evaporation and precipitation. ↑ in Polluted Case

- Net Evaporation Rate at heights > 1200 m

- Evaporation at cloud top causes cooling and downward motion → ↑ TKE → enhancement of mixing and entrainment due to buoyancy gradients.
Result 5 – Different Simulation Comparisons

- Simulation Set-Up 1: Collision-Coalescence and sedimentation neglected.
- Simulation Set-Up 2: Saturation Adjustment Scheme

  No Collision-Coalescence or Precipitation

  Allows liquid water to condense where supersaturation exists

<table>
<thead>
<tr>
<th>No collision–coalescence or precipitation</th>
<th>$N_a = 25 \text{ mg}^{-1}$</th>
<th>$N_a = 2000 \text{ mg}^{-1}$</th>
<th>Saturation adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud fraction</td>
<td>0.119</td>
<td>0.101</td>
<td>0.097</td>
</tr>
<tr>
<td>LWP_domain (g m$^{-2}$)</td>
<td>14.3</td>
<td>12.6</td>
<td>12.6</td>
</tr>
<tr>
<td>LWP_cloud (g m$^{-2}$)</td>
<td>117</td>
<td>121</td>
<td>128</td>
</tr>
<tr>
<td>Cloud top (m)</td>
<td>1306</td>
<td>1202</td>
<td>1185</td>
</tr>
<tr>
<td>Cloud base (m)</td>
<td>856</td>
<td>854</td>
<td>852</td>
</tr>
<tr>
<td>TKE (kg s$^{-2}$)</td>
<td>566</td>
<td>591</td>
<td>590</td>
</tr>
<tr>
<td>Cloud depth (m)</td>
<td>450</td>
<td>348</td>
<td>333</td>
</tr>
</tbody>
</table>

- Similar qualitative trends
- Results from Saturation Adjustment Scheme are similar to Polluted Simulation
Polluted clouds have stronger updrafts and downdrafts consistent with TKE.

600m below cloud and 2200m above cloud, differences are negligible between polluted and clean cases.

This is due to limited precipitation feedbacks.
Result 7 – Cloud Size & Cloud Depth

Comparison between base (a,c) and higher surface flux cases (b,d)

- Polluted clouds are smaller with lower cloud depth (Dashed Lines)
- Entrainment Model (1998) or Plume Model (2005): Entrainment Rate is inversely proportional to cloud radius.
- Polluted clouds have narrower distribution of cloud depths.
- Polluted clouds are extremely important for shallow cumulus case studies.
Contradicting Results and Studies

- Albrecht (1989) : Focus on stratocumulous clouds vs cumulus cloud in the current study
  1-D turbulence closure model vs LES model
- Kaufmann (2005): ↑ Cloud Fraction and ↑ cloud optical depth over Atlantic.
  Clouds significantly greater than trade cumulus clouds studied
- Norris (2001) : Cloud fraction ↑ and aerosol loading ↑ over the Indian ocean.
  Difficult to quantify both Microphysical and Radiative Effects
- Jiang & Feingold (2006) : Consistent with studies on warm continental cumulus clouds

Microphysical and Dynamical feedbacks in cumulus clouds are important !!

Small and Large clouds have different responses to increasing aerosol concentration !!
Paper 2

Examination of the aerosol indirect effect under contrasting environments during the ACE-2 experiment

H. Guo¹, J. E. Penner¹, M. Herzog², and H. Pawlowska³

¹Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI, USA
²Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, NJ, USA
³Institute of Geophysics, Warsaw University, Warsaw, Poland

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**Funding Organization**

**Geographical Location**
1. Portugal
2. Azores
3. Canary Islands

**Motivation of ACE – 2**
Relate In-Situ Observations To
ATHAM Model Simulations
Case and Model Set Up 1

Case Descriptions:
- Pristine (Clean): 26 June, 1997; Total Aerosol Concentration = 218/cm$^3$
- Polluted: 9 July 1997; Total Aerosol Concentration = 636/cm$^3$
- Size Distributions were obtained using Parameterization developed by Chuang & Penner
- 3 mode Log-Normal Distributions with diameters of 0.05, 0.16 and 0.5µm selected
- Four Different Cases – Sensitivity tests for Aerosol Loading vs Meteorological Conditions

<table>
<thead>
<tr>
<th>Tests</th>
<th>Aerosol loading</th>
<th>Meteorological setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>“CACM”</td>
<td>Clean (26 June)</td>
<td>Clean (26 June)</td>
</tr>
<tr>
<td>“PACM”</td>
<td>Polluted (9 July)</td>
<td>Clean (26 June)</td>
</tr>
<tr>
<td>“CAPM”</td>
<td>Clean (26 June)</td>
<td>Polluted (9 July)</td>
</tr>
<tr>
<td>“PAPM”</td>
<td>Polluted (9 July)</td>
<td>Polluted (9 July)</td>
</tr>
</tbody>
</table>

Choice of Location: Azores High
- Between 25 June & 3 July, Cyclone from Western Europe brought Pristine Marine Air
- Between 4 July & 10 July, High pressure region created an inflow of anthropogenic aerosols
Simulation Setup:

- 3-Dimensional version of ATHAM was applied.
- Time step of 2 sec and results generated every 5 min.
- The model was initialized with data obtained from ECMWF
- Cloud free conditions at the beginning of all simulations
- Temperature and Specific Humidity assumed to be constant with height.
- Horizontal large-scale advection of T and Q obtained from ECMWF data
- Vertical large-scale advection calculated from simulated T and Q profiles
- Simulation start up time: 1800 Local
- Simulation Period: 30 hours
- Spin Up time: First 6 hours
- Data Analysis Time: Last 24 hours
Result 1

**Observations**
- a, b, c: model simulations
- d, e, f: observations
- Similar results for PAPM case
- LWC increases with height
- \( N_d \) remain constant
- \( d_v \) increases with height

- Simulated \( N_d \) is higher that observed \( N_d \) at cloud base: Probe Discrepancy
- \( N_d \) ↓ with cloud height: Entrainment of dry air from cloud top
- Negligible Difference b/w \( d_v \) (c) & adiabatic \( d_v \) (f) with cloud height. But convergence is less for ATHAM than observations.
Result 2 - PDF’s of vertical velocity

Simulated correlated well with observed measurements. Differences < 30% (??)
Result 3 - PDF’s of droplet number concentration

Observations

- Good Correlation at cloud base → Good agreement b/w updraft velocity w
- Slightly poor correlations at cloud top BUT differences < 10% → Possibly due to homogenous mixing in ATHAM model in comparison to real time heterogeneous mixing
Result 4 – CACM vs PACM

Observations
- In-cloud LWP for PACM < CACM
  Difference of 50% at local noon
- CF for CACM > PACM
  Difference of 40% at local noon
- Daily Averaged CF and In-cloud LWP also greater CACM than PAPM

Cloud Liquid Water Content depends both on Precipitation and Entrainment
Result 5 – CAPM vs PAPM

Observations

CF overestimated at night and early morning.

Because:
1. Scale of Grid Resolution
2. Scale of observation
3. Existence of shallow and broken clouds in observations

Entrainment effects are negligible
Sensitivity Tests

COD (Cloud Optical Depth)
- Found to ↑ with ↑ in aerosols
- Approximated by $3\text{LWP}/\beta d_v \rho_w$
- $\beta$ approximated to 1.08
- COD is directly proportional to LWP
- COD is inversely proportional to $d_v$
- A ↓ in $d_v$ with ↑ in aerosol observed
- A ↓ in LWP with ↑ in aerosol observed

Combined Effect: COD increases

Radiative Forcing Estimates for T’AIE
$\Delta F_t(\text{“CM”}) = F_{\text{net}}(\text{“PACM”}) - F_{\text{net}}(\text{“CACM”})$
$\Delta F_t(\text{“PM”}) = F_{\text{net}}(\text{“PAPM”}) - F_{\text{net}}(\text{“CAPM”}).$
Eqn 1 corresponds to AIE for clean base on June 26
Eqn 2 corresponds to AIE for polluted base on July 9

Radiative Forcing Estimates for F’AIE, $\Delta F_1$
Estimated using averaged Nd offline.

Radiative Forcing Estimates for S’AIE, $\Delta F_2$
$\Delta F_2(\text{“CM”}) = \Delta F_t(\text{“CM”}) - \Delta F_1(\text{“CM”})$
$\Delta F_2(\text{“PM”}) = \Delta F_t(\text{“PM”}) - \Delta F_1(\text{“PM”}).$

<table>
<thead>
<tr>
<th></th>
<th>top-of-the-atmosphere (W m$^{-2}$)</th>
<th>surface (W m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta F_t$</td>
<td>$\Delta F_1$</td>
</tr>
<tr>
<td>“CM”</td>
<td>$-8.8$</td>
<td>$-19.5$</td>
</tr>
<tr>
<td>“PM”</td>
<td>$-6.4$</td>
<td>$-6.0$</td>
</tr>
</tbody>
</table>

+ value is obtained because CF and LWP ↓ with ↑ aerosols in both CACM and PACM cases.
Conclusions

- ATHAM model simulations correlate well with observations
- Cloud Fraction and Liquid Water Path decrease when the entrainment due to dry air at cloud top is significant in case of polluted cases.
- Large-scale subsidence correspond to lower entrainment rate which do not suppress the cloud fraction and Liquid Water Path as much.
- Cloud Optical Depth is found to increase in polluted scenarios.
- Magnitude of Second Aerosol Indirect Effect could be either + or –
- BUT Total Aerosol Indirect Effect still tends to be negative.

**Aerosol Loading and Meteorological Conditions both effect**

**Second Aerosol Indirect Effect**
SUMMARY

Development of accurate schemes with appropriate cloud physics that can be used in GCM simulations to relate with in-situ observations for accounting climate changes due to anthropogenic aerosols.

**Annual average indirect forcing**

*Global annual average ~ -1 W/m²*
References


2. IPCC Third Assessment Report: Climate Change 2001


4. Lohmann U. and J. Fletcher, Global indirect aerosol effects: a review. Atmos. Chem. Phys, 5, 715-737, 2005


Class Discussion Topics

Second Aerosol Indirect Effect:
- Do these studies support the mechanism and results of second AIE?
- What additional processes will need to be included in the second indirect effect to give a more realistic description of the impact of aerosols on cloud lifetime?

Similarities or Contradictions:
- Do the findings agree in terms of Cloud Fraction and Cloud Liquid Water?

What is the overall conclusion on how aerosols affect precipitation (drizzle) in low level (cumulus) clouds?