LWP Control on Cloud Albedo and the Aerosol Indirect Effect

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many thanks to:
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David Neubauer
John Seinfeld
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Aerosol Indirect Effect: **Warm Cloud**

- **Unperturbed warm cloud**
- **Increased CCN cloud albedo effect**
  - Twomey (1974)
- **Drizzle suppression lifetime effect**
  - Albrecht (1989)
- **Enhanced entrainment**
  - Ackerman et al. (2004)
- **Increased CCN aggregate indirect effect**

\[
\Delta \tau = \frac{-\Delta R_e}{R_e} + \frac{\Delta LWP}{LWP} \propto \frac{\Delta \alpha}{\alpha}
\]

- **\( \tau \):** cloud optical thickness
- **LWP:** liquid water path
- **\( R_e \):** effective radius
- **\( \alpha \):** cloud albedo
Aerosol Indirect Effect: **Warm Cloud**

- **Warm Cloud Top**
- **Increased CCN**
- **Cloud Albedo Effect**
- **Constant LWC**
- **Twomey (1974)**
- **Drizzle Suppression**
- **Lifetime Effect**
- **Increased LWC**
- **Albrecht (1989)**

**Cold Cloud Top**

- **Increased IN**
- **Glaciation Indirect Effect**
- **Constant CCN**
- **Lohmann (2002)**

**Cold Cloud Top**

- **Increased CCN**
- **Riming Indirect Effect**
- **Increased IN**
- **Borys et al. (2003)**

- **Aggregate Indirect Effect**

- **Opposite Responses**

**Surface**

- **Enhanced Entrainment**
- **Decreased LWC**
- **Ackerman et al. (2004)**

- **Instantaneous Change**

- **ΔA_ship track = ???**

**Liquid Water Path Susceptibility**

- **ΔLWP**

**Products →**

- **Cloud properties & aerosol-cloud feedbacks are poorly parameterized in GCMs.**
- **The recipe for progress lies in improving our understanding of physical processes and in better representing these processes in models.**

Quass et al. (2009)
A-Train Ship Track Database

**CALIPSO** – lidar cloud top height
**CloudSat** – radar reflectivity, precipitation occurrence/intensity
**MODIS** – particle size, optical depth, liquid water path, cloud albedo

Period: June 2006 – December 2009

Total: 1250
- Warm: 1101 (T > 0°C)
- Cold: 149 (T < 0°C)
Evidence of Cloud Deepening

Open cells: 16% increase in cloud top height

Closed cells: no change in cloud top height

Christensen and Stephens (2011)
Cloud Type Classification

- Stratocumulus cloud type classification: *visual inspection (subjective approach)*.
- Dominant types: closed, open, mixed/unclassifiable, no MCC
- Subtype: none, rolled, wavy, POC, streets
Cloud Type Identification

Rolled Stratocumulus

Visible: 0.64 μm

Year: 2006 Julian day: 204 time: 2145 UTC

NIR: 3.7 μm

Ship Track
Cloud Type Identification

Wavy Stratocumulus

Year: 2006 Julian day: 175 time: 0055 UTC

Visible: 0.64 μm

NIR: 3.7 μm

Ship tracks
Cloud Type Identification:

- Wavy Stratocumulus

Year: 2006  Julian day: 175  Time: 0055 UTC

Visible Wavelength: 0.64 μm

- Ship tracks

Year: 2007  Julian day: 031  Time: 2150 UTC

Visible Wavelength: 0.64 μm

Collapsed Boundary Layer

Type 1 ship tracks

radiatively inactive (collapsed layer)

radiatively active

visible: 0.64 μm
250 m resolution
Ship track observations of a reduced shortwave aerosol indirect effect in mixed-phase clouds

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Christensen et al. (2014), GRL
Ship Track Identification

1. Locate ship track
   - MODIS: 2.1 μm
   - Region 100 km²
   - CAUFSO Orbit
   - February 3rd, 2008 at 2145 UTC

2. Automated Pixel Identification (based on Segrin et al. 2007)
   - Classified: Closed Cell

3. Cloud type classification
Ship Track Identification

1. Locate ship track

2. Cloud type classification

3. Automated pixel identification

4. Construct along track segment

Ship pixels have smaller cloud droplets than the nearby unpolluted control pixels.
5. Collocate CALIOP to MODIS

![Lidar Backscatter](image1)

6. Collocate CloudSat to MODIS

![Radar Reflectivity](image2)

*Drizzle rates are lighter in polluted pixels compared to nearby unpolluted clouds.

Rain rate (2C-Column-Precip)
Con1 = 0.19 mm/day
Ship = 0.08 mm/day
Con2 = 0.19 mm/day
Case Study: Enhanced Precipitation in Ship Track

January 11th, 2007 at 2210 UTC

Ship track is ≈1000 km in length
Age ≈ 11hrs

Light drizzle
Heavy drizzle
Light drizzle

Lidar Backscatter

Radar Reflectivity

Z_e (dBZ)
0 10
-30
-20
-10
0
-12.2 (10.8)
-2.6 (9.8)
-12.9 (6.8)

Height (m)

Distance (km)

Con 1
Ship
Con 2

Height (m)

Distance (km)

0 30 60 90 120
• Larger effective radii are found in open cell clouds (deficient in cloud nuclei).
• Increased aerosol burden from the ship decrease the size of cloud droplets.

• Fractional change in effective radius:
  
  **Closed cells:** -18%  
  **Open cells:** -22%
Does aerosol suppress precipitation and cause liquid water path to increase?
Does decreased drizzle allow Liquid Water Path (LWP) to increase?
(as suggested by Albrecht, [1989], and many others...)

Answer: rarely, in less then 10% of ship track cases.
→ suggests importance of entrainment and other boundary layer mixing processes in regulating the aerosol-liquid water path response.

How often is rainfall suppressed?
Answer: 72% of the time

Closed Cells: 85% & Open Cells: 50%

Liquid water path differences:
Closed Cells: $\Delta LWP = -11.8 (1.5)$ g m$^{-2}$
Open Cells: $\Delta LWP = +25.0 (5.6)$ g m$^{-2}$

To what extent is cloud albedo affected by these processes?

Christensen and Stephens (2012)
Changes in liquid water path primarily determine the sign and strength of the cloud albedo response.

Twomey regime accounts for ~30% of cases:
- Criteria: i.e., macrophysically similar clouds (ΔLWP & ΔH < 5%)

E-PEACE field campaign results are in good agreement with A-train observations.

**A:** Cloud albedo (derived from BUGSRAD radiation code)

**LWP:** Liquid water path

source: Chen et al. (2012)
Free-troposphere humidity is critical

- Cloud top entrainment/drying effect becomes more pronounced as the relative humidity in the free troposphere decreases.
- Cloud albedo effect is reduced as the free troposphere humidity decreases.
- Moisture averaged between 850 and 700 hPa using ECMWF-AUX.

Do we see evidence for this effect on regional/global scales?
Global A-Train Observations

- Under moist and stable condition, LWP enhances with AI.

- Entrainment/drying effect is largest in dry and unstable conditions.
  - Consistent with ship track assessment and the LES simulations performed by Ackerman et al. (2004) & Chen et al. (2011).

- Co-variability of LTS and RH\textsubscript{ft} buffer the liquid water path response to increasing aerosol concentration.

Liquid Water Path Response

- LTS: Lower Troposphere Stability (LTS = \( \Theta_{700\text{mb}} - \Theta_{\text{surface}} \))
- RH\textsubscript{ft}: Free-troposphere Humidity (relative humidity above cloud top)
- LWP: Liquid Water Path (MODIS)
- AI: Aerosol Index (MODIS)

How does precipitation influence the strength of the aerosol indirect effect?
**Cloud response under different environments**

| Moist/dry: RH above cloud top higher/lower than 40%.
Stable/Unstable: LTS ($\Theta_{700\text{mb}} - \Theta_{sfc}$) larger/lower than 17K. |
|---|

- **Non-raining** clouds: LWP decreases with AI.
  **Raining** clouds: LWP increases with AI; cloud albedo increases more.
- Under **moist free troposphere**: LWP increases more for raining clouds, and decreases less for non-raining clouds.
- Under **moist/unstable** environment, cloud albedo increases most.
Drizzling vs. Non-drizzling marine warm clouds

With drizzle

LWP increase

less precipitation

Aerosol

Non/light drizzle

LWP decrease

entrainment
drying

Aerosol

Source: Jean Chen
Statistical relationships between aerosol and cloud properties

\[
\frac{d \ln (R_c)}{d \ln \text{AI}} = -0.1
\]

**Data**
- Aerosol index: product of aerosol optical depth and angstrom exponent is a proxy for cloud condensation nuclei.
- Aerosol-cloud pairs gridded into $1^\circ \times 1^\circ$ regions.
- Each region contains $\sim 40,000$ data L2 cloud-aerosol data points.
- Aerosol (ATSR) properties are paired to 1-km cloud pixels through nearest neighbor method.

How do these observations vary with meteorology?
**Aerosol-Cloud Interactions**

Cloud Water Path Sensitivity Satellite-Model Comparisons

JJA 2008; 60S° – 60° N (Ocean only)

**Satellite:** AATSR

**Model:** ECHAM6 HAM 2

Global mean sensitivity ($\frac{d\ln LWP}{d\ln AI}$) by cloud regime

**Main result**

- LWP sensitivity to increasing aerosols is significantly larger in the ECHAM6 model compared to AATSR observations.

- Model derived aerosol indirect forcing is more than two times larger than satellite data (IPCC, 2013).

- Feedbacks that reduce the LWP sensitivity (e.g., entrainment) are poorly parameterized in model simulated clouds which may explain the significant difference between model and satellite observations.
Global Aerosol Indirect Forcing

**Indirect Forcing Estimates:**
- Intrinsic = $-0.49 \pm 0.33 \text{ W/m}^2$
- Extrinsic = $-0.46 \pm 0.31 \text{ W/m}^2$

**Summary**
- Environmental condition and cloud type exert strong controls on the aerosol indirect effect sensitivity at both local (e.g., ship tracks) and global scales.
- *For observational studies:* it’s imperative to isolate aerosol indirect effects by environmental conditions and, improve cloud albedo, aerosol, precipitation rate, and infrared sounding retrievals.
- *For modeling studies:* feedbacks involving entrainment, drizzle, and surface coupling should be incorporated into GCM’s to improve estimates of the aerosol indirect forcing.

**Formulas:**
\[
\frac{dC_{sw}}{d \ln(\text{AI})} = \left[ \frac{\frac{dA_{clr}}{d \ln(\text{AI})} - \frac{dA_{cld}}{d \ln(\text{AI})}}{c_{m}} \right] \cdot \frac{d\text{cf}}{d \ln(\text{AI})} + \frac{(A_{clr} - A_{cld})}{c_{m}} \frac{dcf}{d \ln(\text{AI})} \cdot F_{c}\]

- $C_{sw}$: Shortwave Cloud Forcing (CERES)
- $A_{clr}$: clear-sky albedo (CERES)
- $A_{cld}$: cloudy sky albedo (CERES)
- $c_{m}$: annual mean marine warm cloud coverage
- $c_{f}$: cloud cover fraction over CERES footprint
- AI: Aerosol index (MODIS)

Chen et al. (2014), Nat. Geosci.