A satellite perspective of the influence of aerosol on cloud systems

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Picture taken by the Apollo-Soyuz crew (first joint U.S. /Soviet space flight) July 16\textsuperscript{th} 1976 at an Altitude: 174 km; source, Porch et al. (1990)
Take home messages:
-The cloud albedo response to aerosol is the result of an aggregation of processes that tend to buffer each other
– the net effect is more directly determined by the response of the water budget of clouds to aerosol.
The adjustments of models enhance the initial "Twomey" effect.
The adjustments as observed by satellites reduce the effect.
Modeled inter-annual variability of globally averaged fluxes is (on average) 4 times the observed global variability, Source Stephens et al., ‘The albedo of Earth’, Rev Geophys, 2014
1) Warm cloud microphysics from satellite

- Twomey, 1969; ‘Theory’
- Twomey & Cocks, 1982’s first demonstration from aircraft
- Nakajima & King, 1990; streamlined LUT algorithm
- Han et al., 1994; first global maps

Visible reflectance \( (R_1) \) is a function a combination of parameters, i.e. \( R \rightarrow (1-g)\tau \)

Near-IR reflection \( (R_2) \) is a function of optical depth \( \tau \) and the scattering albedo \( \omega \)- the latter is a function of particle size \( r_e \).

Measurements of reflection at two wavelengths returns \( \tau \) and \( r_e \) assuming \( g \)

\[
\frac{LWP}{2} \rightarrow r_e \\
LWP \rightarrow \frac{2}{3} r_e
\]

Implicit, \( r > \lambda \)
20+ year conundrum

These satellite estimates have variable biases when compared to aircraft measurements.
This matters because the strategy for testing aerosol-cloud indirect effects in global models has largely been framed around introducing particle size changes.
Conundrum resolved when particle size and radar reflectivity matched

The evolution from cloud water to drizzle to rain evident in the radar profiles also reflected in the MODIS particle sizes @2.1 but not 3.7

The conundrum and its solution is discussed in Nakajima et al., 2010a,b

......or so we claim!!!!!!
Aerosol from satellite - Implicit, $r \sim \lambda$

The $\tau$ wavelength differential provides bulk information on aerosol size –
- ‘Fine mode’- MODIS, Kaufman, 2005
- Aerosol exponent (turbidity) $\alpha$
  \[ A_l = \tau \times \alpha \] (Nakajima et al., 2001)

Alternatively - use of assimilated aerosol data in place of satellite data – L’Ecuyer at al., 2010, Chen et al., 2013.
Breon et al. (2002), *Science*

\[ r_e \text{ reduction with increasing aerosol} = \text{‘Twomey’ effect} \]
Almost all studies of this type are merely correlations, failing to isolate the Twomey effect (fixed LWP) from other effects. Almost all studies of this type, as well as field experiments supposedly aimed at addressing indirect effects, provide no information about albedo and its change.
A-Train Ship Track Database

CALIOP - Lidar cloud top heights
CloudSat Radar- precipitation occurrence, reflectivity
MODIS particle sizes, LWP, Al
AMSRE LWP
CERES albedo

Period: June 2006 – December 2009

total: 1448
Open cells: 16% increase in cloud top height, large changes in LWP

Closed cells: no change in cloud top height, modest decreases in LWP

Christensen and Stephens (2011)
The buffering of cloud albedo

- Differences in liquid water path primarily determine the sign and strength of the cloud albedo response.
- Humidity above cloud tops is responsible for the differences in LWP.
- E-PEACE results are in good agreement with A-train observations.
The sensitivity of LWP to AI is a function of stability regime:

a) Stable regimes -> insensitive (slight decreases in LWP)
b) Unstable regimes -> increasing sensitivity
c) The stability dependent LWP response of clouds should be included in GCM parameterization schemes

Lebsock et al 2008 find a similar behavior in warm non precipitating clouds globally.

Both AMSR-E and MODIS exhibit the same behaviour.
1. $\tau_{cld}$ and albedo response in precipitating clouds is dominated by the water path effect
2. POP decreased by $\sim5\%$ in dirty air regardless of LWP
A further look at warm rain

1) Nucleation
   \( N_c = f(N_\alpha, \text{species}, w) \)

2) Condensational Growth
   \( S = g(w, N_c) \)

3) Efficacy of Coalescence
   \( E_c = E_c(r, R) \)

\[
\frac{d \ln Z_e}{d} = -\frac{E_c}{6}
\]

Suzuki et al. (JAS 2010)

Photo courtesy Bjorn Stevens
A-Train

$R_e = 5-10\, \mu m$

$R_e = 10-15\, \mu m$

$R_e = 15-20\, \mu m$

$R_e = 20-25\, \mu m$

Suzuki et al., 2011
Evaluation of cloud tuning: Implication for climate prediction

- Autoconversion radius threshold ($r_{crit}$) strongly modulates the indirect effect.
- Larger $r_{crit}$ produces less drizzle and more cloud water.
- A-Train observations indicate a larger value of $r_{crit}$ than used
  - Causes aerosol indirect effect to be excessively large compared to A-train observations [e.g., Lebsock et al. (2008), Quaas et al. (2008)].

Source: Golaz et al. (2013) & Suzuki et al. (2013)
Speculative: Mixed phase and Ice clouds
Aerosol-precipitation effects and the wintertime Arctic Temperature
Sulphur Sources and AVHRR Arctic (Wintertime)

Active Aleutian volcanoes emit large amount of sulphur in the lower
troposphere. This is a strong indication that $SO_2 - SO_4$ sources are affecting
surface temperatures trends shown in AVHRR.

Blanchet et al., 2010
Dehydration-(reverse)Greenhouse Feedback (DGF)

Clouds forming on acidic ice nuclei precipitate more effectively, dehydrate the air, reduce greenhouse effect and cool the surface.

Thin Ice Clouds type 2

- Slow Cooling Process
- Acid Aerosols
- Less H₂O vapour
- Colder

Thin Ice Clouds type 1

- Reduced Greenhouse
- Reduced Greenhouse
- Adiabatic cooling and IR lost
- Low Acid Aerosols
- Hydrophilic
- Increased Greenhouse
- Warmer

Cold Ice and Snow Surface
In this environment clouds look different.

January 19, 2007

Radar – Lidar DGF Signature

Thin Ice Cloud type 1
- low [aerosol] (pristine),
- small crystals
- slow sedimentation

DGF
- Deep
- PBL

No DGF

Thin Ice Cloud type 2
- high [aerosols] (acidic),
- large ice crystals
- and fast sedimentation

Blanchet, 2010
Speculative 3) Convective storm invigoration by aerosol

More aerosol => Suppressed drop collection => more cloud water lofted => more freezing and release of latent heat and eventually more precipitation
CloudSat married with assimilated aerosol data from GEMS shows evidence for convective invigoration. The Polluted – clean reflectivity differences indicate storms reach higher, and possess more ice mass (higher reflectivity values) and produce heavier precipitation.
Unprecedented satellite capabilities offer glimpses of the complex buffering processes inherent in the aerosol-cloud system.

Observed indirect radiative effects are typically weaker than modeled effects due to buffering by precipitation and the environment. These effects in the net are determined by net changes to water budgets of clouds systems.

GCM aerosol indirect effects in warm clouds appear to be too sensitive to autoconversion schemes used (at least in one model).

Higher model resolution will not guarantee improved representation of aerosol effects.

Aerosol effects in cold clouds is not understood & satellite observations are scant. Aerosol influences on wintertime polar clouds may significantly influence the water budget of the Arctic atmosphere.

Aerosol effects on convection remain speculative.

Perhaps the more important influence of aerosol on clouds is on precipitation rather than cloud albedo.
A-Train results

1. CloudSat
   - Precipitation Flag
   - Cloud reflectivity

2. MODIS
   - Cloud effective radius
   - Cloud LWP
   - Aerosol Index
   - Cloud Fraction

3. AMSR-E
   - Cloud LWP
   - Water Vapor

4. CERES
   - Cloud Albedo

5. CALIPSO
   - Cloud top height, CALIOP
Buffering by the Environment

- 4 years of data
- Over 5 million carefully screened retrievals (single layer low-level warm phase cloud detected by CALIPSO, CloudSat, and MODIS).
- Aerosol properties are averaged over 1° regions.
- 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).

Where on Earth do we see this effect?

Co-variability of LTS and RH_ft buffer the liquid water path response to increasing aerosol concentration.

**LTS**: Lower Troposphere Stability \( (LTS = \Theta_{700mb} - \Theta_{surface}) \)

**RH_{ft}**: Free-troposphere Humidity (relative humidity above cloud top)

**LWP**: Liquid Water Path (MODIS)

**AI**: Aerosol Index (MODIS)
- Predominant regions of Sc exist in dry and stable airmasses.
- Optical depth response in these regions is weakly negative.
- Effect of buffering precludes strong indirect effects in these regions.
- Implications for geoengineering.
- Chen et al., 2013.
\[ \frac{LWP}{LWP} = \frac{r_e}{r_e} \mu \]

\[ CDR = r_e \]

\[ b = \frac{d \log (y)}{d \log (Na)} \]

Nakajima and Shultz, 2009
Convective invigoration

Total buoyancy term, plotted as a difference from the clean run, follows a similar trend as the mean updraft

\[ B = g \left( \frac{\theta'}{\theta_0} \right) - gq_c \]
Convective invigoration

- Average updraft decreases through a large portion of the cloud depth
- Average updraft is determined by a balance between latent heating and condensate loading – both are affected by increased aerosol concentrations
- Average updraft increases in the lower levels due to both decreases in drag from condensate loading and increases in latent heat from changes in condensation and rain evaporation
Production of rain

In polluted DCCs:

- Warm rain production decreases dramatically
- Melting of hail doesn’t change significantly
- Ice collection by rain decreases
- Total rain production decreases
- Decrease is dominated by change in warm rain production
- Ice phase production of rain becomes more important
- Sinks of rain also decrease because there are fewer and larger rain drops
Backup
i) Wintertime storms
iii) Pollutants Lifted in Cold Regions

Simulated NARCM

Observed CALIPSO
iv) Pollution inhibits nucleation

Manmade acid coating of natural dust

Ice crystal nucleation on acid coated aerosols

Ref.: Bigg, 1980

Ref.: Bertram, 2008

In Laboratory
Allan Bertram at UBC

Flow cell coupled to microscope

RH$_i$ = 135%
Ship Tracks: a prominent manifestation of the aerosol indirect effect

Twomey Effect

Fewer larger drops → more smaller drops

class reservoir of CCN

Twomey Effect

Lower albedo
Higher albedo

Δτ = \frac{ΔLWP}{LWP} - \frac{ΔR_e}{R_e} \propto \frac{Δ\alpha}{\alpha}

τ: cloud optical thickness
LWP: liquid water path
R_e: effective radius
A: cloud albedo
Buffering Processes

Lifetime Effect

macrophysically different clouds

more efficient precipitation
→ more cloud water depletion
→ less cloud cover/longevity

less efficient precipitation
→ less cloud water depletion
→ more cloud cover/longevity
→ thicker clouds

Cloud water path response

$\Delta LWP = 0$  Twomey effect: (Twomey, 1974)
$\Delta LWP > 0$  Lifetime effect: (Albrecht, 1989)

$\tau = \frac{\Delta LWP}{LWP} - \frac{\Delta R_e}{R_e} \propto \frac{\Delta \alpha}{\alpha}$

$\tau$: cloud optical thickness
$LWP$: liquid water path
$R_e$: effective radius
$\alpha$: cloud albedo
Buffering Processes

Entrainment Effect

- weak cloud top entrainment → less LWP depletion
- stronger cloud top entrainment → more LWP depletion

other factors:
- absorbing aerosol (Koren et al. 2008)
- giant CCN (Feingold et al. 1999)
- mesoscale circulation (Wang et al, 2009)
- cloud layer coupling to surface moisture (Wood 2007)

Cloud water path response

$\Delta \text{LWP} = 0 \quad \text{Twomey effect (Twomey, 1974)}$

$\Delta \text{LWP} > 0 \quad \text{Lifetime effect (Albrecht, 1989)}$

$\Delta \text{LWP} < 0 \quad \text{Entrainment effect (Ackerman et al, 2004)}$

$\frac{\Delta \tau}{\tau} = \frac{\Delta \text{LWP}}{\text{LWP}} - \frac{\Delta R_e}{R_e} \propto \frac{\Delta \alpha}{\alpha}$

- $\Delta \tau$: change in cloud optical thickness
- $\Delta \text{LWP}$: change in liquid water path
- $\Delta R_e$: change in effective radius
- $\Delta \alpha$: change in cloud albedo

$\tau$: cloud optical thickness
LWP: liquid water path
$R_e$: effective radius
$\alpha$: cloud albedo
Buffering by Precipitation

*aerosol suppressing* drizzle in ship track

February 3rd, 2008 at 2145 UTC

- CALIPSO Lidar Backscatter
- CloudSat Radar Reflectivity

**Age ≈ 4hrs**

**Classified: Closed Cell**

**Scan direction**

**Region 100 km**

**Calipso Orbit**

**250 m MODIS: 0.64 μm**

**950 m MODIS: 2.1 μm**
Buffering by Precipitation

*aerosol enhancing drizzle in ship track*

Ship track is ≈1000 km in length

Age ≈ 11hrs

Classified: Open Cell

Light drizzle

Heavy drizzle

Light drizzle

January 11th, 2007 at 2210 UTC
Processes?: Correlation between $r_e$ and $\tau_c$

Fig. 1. Scatter plot between effective particle radius and optical thickness obtained from satellite observation over FIRE (upper) and ASTEX (lower) regions (cited from Nakajima and Nakajima 1995)

1. non-drizzling stage
2. drizzling stage
3. evaporating stage

Nakajima and Nakajima (JAS 1995)
Buffering by Precipitation

- Strong evidence of aerosol affecting drizzle rates.
- Response is regime dependent:
  - strong suppression in closed cells
  - enhancement in open cells
- Increased liquid water paths are rarely observed when drizzle rates are suppressed by pollution.
  - Contradicts the lifetime effect hypothesis (Albrecht, 1989).
  - Suggests buffering by precipitation is critical in regulating cloud water path and albedo.

How does precipitation influence climate models response to increasing aerosol?
Understanding the behavior of microphysics scheme

Single-Column Model that mimics NICAM-SPRINTARS cloud microphysics

\[
\frac{(q_c(z))}{t} = \frac{q_c(z)}{t} + \frac{q_{adb}(z)}{t} \quad (q_r(z))
\]

\(q_c\): cloud water content

Kessler

\[\frac{(q_r(z))}{t} = +\frac{q_c(z)}{t}\]

\(q_{adb}\): adiabatic value

Rain formation parameterizations

Auto-conversion:

Berry ('67)

\[\tau_{aut} = \mu N_c \left( \frac{a}{a} \right)^{0.56} = \text{const.}\]

Accretion:

\[\tau_{acc} = \mu N_c \left( \frac{a}{a} \right)^{0.56} = \text{const.}\]

\(\tau_{aut}\): spontaneous evaporation of cloud droplets

\(\tau_{acc}\): accretion of supercooled cloud droplets to rain drops

\(\mu\): representation of the lifetime effect

\(N_a\): Aerosol Index

\(N_{a,c,max}\): maximum number of aerosol particles per cubic centimeter

\(N_c\): number of cloud droplets per cubic centimeter

\(a\): Aerosol Index

\(f\): representation of the lifetime effect

\(N_a\sim N_a^{0.7}\)

\(N_c\sim N_a^{0.56}\)

\(N_{a,c,max} = (400 \text{ cm}^{-3})^{0.8}\)
Sensitivity of effective radius to aerosol is relatively independent of stability

Value of sensitivity parameter in good agreement with literature (Breon [2002], Matsui [2004])

\[ \text{Sensitivity} = \frac{\log(r_e)}{\log(\text{AI})} = 0.07 \]

This parameter forms the basis of GCM parameterizations of the 1st indirect effect

- Sensitivity of effective radius to aerosol is relatively independent of stability
- Value of sensitivity parameter in good agreement with literature (Breon [2002], Matsui [2004])
The water path effect for precipitating clouds dominates the radius effect in the albedo response of these clouds.
Buffering by Precipitation

*aerosol enhancing* drizzle in ship track

Ship track is \( \approx 1000 \text{ km in length} \)

Age \( \approx 11 \text{ hrs} \)

Classified: Open Cell

Light drizzle

Heavy drizzle

Light drizzle

January 11\textsuperscript{th}, 2007 at 2210 UTC
A-Train data.

1. **CloudSat**
   - Precipitation Flag
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   - Cloud top height, CALIOP
Rapid & sustained cooling of airmass

Process #1: Dynamics
DT ≈ -10 to -20°C
Time scale: ~ 1 day

Process #2: Direct IR
DT ≈ -16 to +10°C
Time scale: 1 to 5 days

Process #3: Indirect IR
DT ≈ -5 to -10°C
Time scale: 1 to 2 weeks

Total Cooling ≈ -30 to -50°C