Remote Sensing of Aerosols From Satellites:
Why has it been difficult to quantify
Aerosol-Cloud Interactions for climate assessment,
and How can we make Progress?

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Even DARF and Anthropogenic DARF are *NOT* Solved Problems (Yet)

**The global mean radiative forcing of the climate system for the year 2000, relative to 1750**

- **IPCC AR3, 2001** (Pre-EOS)
- **IPCC AR4, 2007** (EOS + ~ 6 years)
Multi-year Annual Average Aerosol Optical Depth from Different Measurements + Synthesis ($S^*$)

From: Kinne et al. ACP 2006
Constraining ARF – The Next Big Challenge

• The next big observational challenge:
  Producing *monthly, global maps of Aerosol Type*

How Good is Good Enough?

*Instantaneous AOD* & *SSA* uncertainty upper bounds for ~1 W/m² TOA DARF accuracy: ~ 0.02

--- For aerosol *indirect effects*, the aerosol type constraint requirements are *more stringent*

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Kinne et al., ACP 2006

Note: These are not yet updated to the CMIP5 (AR5) models

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CCSP - SAP 2.3, 2009
The Current Assessment of Climate Forcing Factors

<table>
<thead>
<tr>
<th>Emitted Compound</th>
<th>Resulting Atmospheric Drivers</th>
<th>Radiative Forcing by Emissions and Drivers</th>
<th>Level of Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{CO}_2 )</td>
<td>( \text{CO}_2 )</td>
<td>1.68 [1.33 to 2.03]</td>
<td>VH</td>
</tr>
<tr>
<td>( \text{CH}_4 )</td>
<td>( \text{CO}_2, \text{H}_2\text{O}^{*}, \text{O}_3, \text{CH}_4 )</td>
<td>0.97 [0.74 to 1.20]</td>
<td>H</td>
</tr>
<tr>
<td>Halo-carbons</td>
<td>( \text{O}_3, \text{CFCs, HCFCs} )</td>
<td>0.18 [0.01 to 0.35]</td>
<td>H</td>
</tr>
<tr>
<td>( \text{N}_2\text{O} )</td>
<td>( \text{N}_2\text{O} )</td>
<td>0.17 [0.13 to 0.21]</td>
<td>VH</td>
</tr>
<tr>
<td>Anthropogenic</td>
<td>( \text{CO}_2, \text{CH}_4, \text{O}_3 )</td>
<td>0.23 [0.16 to 0.30]</td>
<td>M</td>
</tr>
<tr>
<td>( \text{NMVOC} )</td>
<td>( \text{CO}_2, \text{CH}_4, \text{O}_3 )</td>
<td>0.10 [0.05 to 0.15]</td>
<td>M</td>
</tr>
<tr>
<td>( \text{NO}_x )</td>
<td>Nitrate, ( \text{CH}_4, \text{O}_3 )</td>
<td>-0.15 [-0.34 to 0.03]</td>
<td>M</td>
</tr>
<tr>
<td>Aerosols and precursors</td>
<td>Mineral Dust, Sulfate, Nitrate, Organic Carbon, Black Carbon</td>
<td>Cloud Adjustments due to Aerosols</td>
<td>-0.27 [-0.77 to 0.23]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Albedo Change due to Land Use</td>
<td>-0.55 [-1.33 to -0.06]</td>
</tr>
<tr>
<td>Natural</td>
<td>Changes in Solar Irradiance</td>
<td>0.05 [0.00 to 0.10]</td>
<td>M</td>
</tr>
</tbody>
</table>

Global average, & compared to other uncertainties in the models – What about aerosol type?! The next big area to address
Multi-angle Imaging SpectroRadiometer

- Nine CCD push-broom cameras
- Nine view angles at Earth surface: 70.5° forward to 70.5° aft
- Four spectral bands at each angle: 446, 558, 672, 866 nm
- Studies Aerosols, Clouds, & Surface

http://www-misr.jpl.nasa.gov
http://eosweb.larc.nasa.gov
MISR Aerosol Type Discrimination

January 2007

July 2007

Mixture Group

Spherical, non-absorbing

Spherical, absorbing

Non-spherical
Passive-remote-sensing *Aerosol Type* is a *Total-Column-Effective, Categorical* variable!!
For Aerosol-Cloud Interactions – Overall Satellite **Limitations**

- Polar orbiters provide *snapshots only*
- Difficult to probe *cloud base*
- Typically ~100s of meters or poorer *horizontal resolution*
- Passive instruments (imagers) offer little *vertical information*
- Active instruments (e.g., lidar) offer little *spatial coverage*
- Little information about aerosol *particle microphysical properties*
- Bigger issues retrieving aerosols *in the presence of clouds!*
- Cloud property retrievals can be aliased *by the presence of aerosols*
Difficult to retrieve aerosols that are collocated with cloud.

- Cloud-scattered light & cloud “contamination” can affect near-cloud aerosol retrievals.

Rarely can detect aerosol in droplet-formation region below clouds – need cloud & aerosol vertical distributions.

Aerosols smaller than about 0.1 micron diameter look like atmospheric gas molecules – must infer CCN number.

Must deduce aerosol hygroscopicity (composition) from qualitative “type” – size, shape, and SSA constraints.

Environmental (Meteorological) Coupling – Factors can co-vary.

- LWP can decrease as aerosol number concentration increases (also depends on atm. stability).

Many aerosol-cloud interaction time & spatial scales do not match satellite sampling.

Satellites are fairly blunt instruments for studying aerosol-cloud interactions!!
Aerosol Effects on Clouds – ‘Controlled’ Situations

(a) Ship tracks off the coast of California, from AVHRR.
(b) Retrieved $r_c$ and $\tau_c$ differences. [Coakley & Walsh JAS 2002]

- Statically stable conditions
- Fairly uniform stratiform

False-color AVHRR
  - Blue – 11 µm
  - Red – 0.67 µm
  - Green – 3.7 µm

Red indicates large droplets, yellow signifies smaller droplets
[Rosenfeld, Sci. 2000]
Aerosol Effects on Clouds – Correlation Studies

Correlation between AVHRR particle number \( N_a \) (fixed \( r_a \); \( AI = \tau_a \times ANG \)) and cloud droplet \( N_c \) concentrations, for 4 months in 1990;

\( N_a \sim \tau_c; N_a \sim 1/r_c \) in low cloud (yellow) regions

[Feingold et al. JGR 2001] Drop size effect saturates at \( \tau_a \sim 0.4, 0.8 \), depending on conditions (SCAR-B, Brazil)

[Ackerman et al., Sci. 2000] INDOEX – absorbing aerosol can dissipate clouds

Atlantic convective cloud invigoration from MODIS

[Koren et al. GRL 2005]

\( 1/r_c \sim N_c \sim N_a \sim \tau_a \) [Cloud radius effect]

\( r_c \) decrease \( \rightarrow \) early precip. inhibited \( \rightarrow \) higher cloud tops, cloud fraction, glaciation

\( C_f, T_c, \tau_c \) (water clouds) all increase with \( \tau_a \)
The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)

- 15 orbits per day, ~100 m wide sampling *curtain*; averaged to 333 m
- 532 and 1064 nm + polarization (at 532 nm); to ~40 km elevation
- Layer height for AOD $\geq 10^{-2}$; AOD for layers having AOD $\leq 3$
- For low AOD, need the higher S/N of *nighttime*, 532 nm observations

Launched April 2006

<table>
<thead>
<tr>
<th>Vertical Range (km)</th>
<th>Horizontal Resolution (km)</th>
<th>Vertical Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.1 – 40</td>
<td>5</td>
<td>300</td>
</tr>
<tr>
<td>20.2 - 30.1</td>
<td>1.7</td>
<td>180</td>
</tr>
<tr>
<td>8.2 – 20.2</td>
<td>1.</td>
<td>60</td>
</tr>
<tr>
<td>-0.5 – 8.2</td>
<td>0.33</td>
<td>30</td>
</tr>
</tbody>
</table>

Winker et al., JAOT 2009
The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)

Omar et al., JAOT 2009
Changes in geometric perspective with angle

MISR flight direction

Forward-viewing camera

plume height

apparent position

Diner 2003
Changes in geometric perspective with angle

MISR flight direction

Backward-viewing camera

plume height

parallax

Diner 2003
MISR Stereo-Derived Plume Heights
07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39

D. Nelson and the MISR Team, JPL and GSFC
MISR Stereo-Derived **Plume Heights**

07 May 2010 Orbit 55238 Path 216 Blk 40 UT 12:39

**Plume 1**
- Height: $0.25 - 2$ km
- Mode: $< 1$ km

**Plume 2**
- Height: $2.25 - 6$ km
- Mode: $4.8$ km

**Height:** Blue = Wind-corrected
Oregon Fire  Sept 04 2003
Orbit 19753 Blks 53-55 MISR Aerosols V17, Heights V13 (no winds)

Kahn, et al., JGR 2007
CALIPSO nighttime 532 nm backscatter, normalized over 2.99 km. Enhanced aerosol opacity near cloud edge, especially at cloud top and bottom.

Vertically integrated backscatter

- **β_{532}**
- **β_{1064}**

CALIPSO median nighttime 1064/532 nm color ratio. Larger particles near cloud edge, especially at cloud top and bottom.

Detrainment at cloud top??
Hygroscopic growth at cloud bottom??
Collision Coalescence (R↑; N, σ↓)?
Aerosol Properties Near Cloud

Cumulative distance to nearest cloud <3 km

Backscatter & color ratio enhanced to ~15 km

Global data
Sept. – Oct. 2008

Varnai & Marshak, GRL 2011
**AIRS - Temperature & Water Vapor Profiles**

**Temperature Profiles**
Accurate to 1K/km to 30 mb

Ocean, Mid Latitude vs ECMWF

- AIRS Bias
- AIRS RMS

Instrument Spec. Requirement

(T. Hearty/JPL)

**Water Vapor Profiles**
Match Observations 15%/2km

Nauru Island Radiosondes

- AIRS Bias
- AIRS RMS

Radiosonde RMS

(E. Fettler/JPL)

15 km nadir footprint

**Mean Clear Air Precipitable Water**
AIRS data, January 2003

[Map showing clear air precipitable water distribution]
Satellite Capabilities

- Polar orbiting imagers provide **frequent, global coverage**
- Geostationary platforms offer **high temporal resolution**
- Multi-angle imagers offer **aerosol plume height & cloud-top mapping**
- Passive instruments can retrieve total-column **aerosol amount (AOD)**
- Active instruments determine aerosol & some cloud **vertical structure**
- UV imagers and active sensors can retrieve **aerosol above cloud**
- Multi-angle, spectral, polarized imagers obtain **some aerosol type info.**
- Active sensors can obtain **some aerosol type info., day & night**
- Satellite trace-gas retrievals offer **clues about aerosol type**
- Vis-IR imagers can retrieve **cloud phase, r_c, T_c, p_c, \( \tau_c \), \( \alpha_c \), C_p, LWP**

*Need to be creative & Play to the strengths of what satellites offer!!*
Assessing Some Satellite-Retrieval Issues

Partly Filled Pixels

[Coakley & Bretherton JGR 1982]

- Can obtain cloud-fraction for single-layer clouds
- Multi-layered clouds can be identified by distinct $T_b$
- The challenge is selecting a spatial scale for aggregation

Sampling Bias Example

[Rosenfeld & Feingold GRL 2003]

First Indirect Effect: $IE \sim -d \ln r_c / d \ln \tau_a$

AVHRR

$[IE \sim 0.17]$ over ocean (Nakajima et al. 2001)

- Partly filled pixels, surface contributions $\rightarrow r_c$ errors
- Disfavors: thin & broken cloud, especially over land

POLDER (Breon et al., 2002)

$[IE \sim 0.085]$ over ocean; $[IE \sim 0.04]$ over land

- Uses “glory” to get $r_c$ $\rightarrow$
favors more mono-disperse, less turbulent clouds
- Disfavors: thick convective clouds, variable height & $r_c$

Thinner clouds $\rightarrow$
smaller updrafts, less activation, smaller $IE$

So POLDER might produce artificially low regional $IE$
3-D Light Scattering Effects on Remote Sensing

ASTER false-color image
Brazil, 09 August, 2001

Simulated cloud $\rightarrow$ Rayleigh scattered light enhancement vs. $\tau_c$
- Using the image geometry
- For three wavelengths
- For different surf. reflectances ($\alpha_s$)

Refl. in “clear” pixels used for MODIS AOD Retrievals (squares)

Refl. in pixels 3 km away from cloud (ovals) [Wen et al. 2007]
Vertical Structure, and Confounding Meteorology

$r_c$ – Cloud ‘Top’ vs. Cloud Column, & $LTS$

- **TRMM** data, March-May, 2000; 37°N to 37°S
- Vis-IR Radiance Imager (**VIRS**) for $r_c$(top), $\tau_c$
- Microwave Imager (**TMI**) for $r_c$(col), $LWP$ (19, 37GHz)
- Warm clouds only ($T_c > 273$ K)
- VIRS to find cloud-filled TMI pixels
- **AI** from MODIS
- Lower Trop. Stability (**LTS**) from NCEP

- **IE** appears **larger** for $r_c$(col) than $r_c$(top)
- Higher **LTS** and/or **AI** ~ **reduced** $r_c$
  and suppressed rain conditions

- Aerosol effect ~ 50% larger than **LTS** effect
- TMI $LWP$ decreases with reduced $r_c$ → net change in cloud albedo SMALL
  $[d\alpha_c/dLTS \sim 9\%; \text{ LTS effect dominates}]$
Correlation Between AOD from Space and CCN in Remote & Polluted Regions

\[ y = 0.0027x^{0.640} \]
\[ R^2 = 0.88 \]
Using \( \textbf{AI} (= \tau_a \times \text{ANG}) \) to Estimate \textbf{CCN}

Kapustin, Clarke, et al., JGR 2006

- Test Idea: Smaller particles more likely to become CCN; \( \text{Ang} \) is a smaller quantity for larger particles
- ACE-Asia, Trace-P \textit{in situ} field data – CCN proxy
- AI does not work quantitatively in general, but can \textbf{if the data are stratified} by:
  - \( \text{RH} \) in the aerosol layer(s) observed by satellites
  - Aerosol Type (hygroscopicity; pollution, BB, dust)
  - Aerosol Size (\( \text{Ang} \) is not unique for bi-modal dist.)

Practically, in addition to \( \tau_a \) and \( \text{Ang} \), this requires:
  - Vertical \textbf{humidity structure}
  - Height-resolved aerosol type
  - Height-resolved size dist.
    [extrapolated to small sizes(?)]

This study includes enough detail to assess \( \text{AI} \sim N_a \) and \( \text{AI} \sim \text{CCN} \)
Satellite-Derived Proxies for CCN

- OMI NO$_2$ Column
- OMI SO$_2$ Column (mainly near-surface)
- *OMI* UVB (310 nm) Surface noontime irradiance to form secondary sulfate
- *MODIS* AOD [*attempt* to represent the condensation *sink* for nucleation particles]

*These are quantities we can retrieve from satellites, though they are not necessarily the ones we really want*

- Ambiguity in vertical distributions of formation areas and sinks
- Lack of information about diurnal variation from satellites
- The 2-D spatial distribution of proxies compares ~ better with *in situ* observations for S. Africa, except where gas column concentrations are low.
Would you believe the answer if it were a surprise?
MODIS global cloud regimes

CTP vs. TAU Cluster Analysis
(10 “Cloud Regimes”; MOIDS V5.1)

Courtesy of Lazaros Oreopoulos
Precipitation vs AI per CR (50° S to 50° N)

Ocean

Land

Relationship between precipitation & Aerosol Index, stratified by cloud regime (CR) and Land/Ocean

Courtesy of Lazaros Oreopoulos
# Summary

**Observed trends when going from low aerosol index (1Q) to high (3Q)**

<table>
<thead>
<tr>
<th></th>
<th>( \text{CR}_{\text{ice}} ) Land/Ocean (CR 1, 2, 3)</th>
<th>( \text{CR}_{\text{liq}} ) Land/Ocean (CR 6, 7, 8)</th>
<th>( \text{CR}_{10} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precip.</td>
<td>( \uparrow ) ( \downarrow )</td>
<td>-</td>
<td>( \uparrow )</td>
</tr>
<tr>
<td>( C_f )</td>
<td>-</td>
<td>( \uparrow )</td>
<td>( \uparrow )</td>
</tr>
<tr>
<td>CTH</td>
<td>( \uparrow )</td>
<td>( \uparrow )</td>
<td>-</td>
</tr>
<tr>
<td>( \tau_c )</td>
<td>( \uparrow ) ( \downarrow )</td>
<td>( \uparrow )</td>
<td>( \uparrow )</td>
</tr>
<tr>
<td>( r_e )</td>
<td>( \downarrow )</td>
<td>-</td>
<td>( \downarrow )</td>
</tr>
<tr>
<td>PrecipNZ</td>
<td>( \uparrow ) ( \downarrow )</td>
<td>-</td>
<td>( \downarrow )</td>
</tr>
</tbody>
</table>

*red arrow: consistent with invigoration; blue arrow: consistent with 1\(^{\text{st}}\) and 2\(^{\text{nd}}\) indirect effect*

Courtesy of Lazaros Oreopoulos
Satellites

Remote-sensing Analysis
- Retrieval Validation
- Assumption Refinement

CURRENT STATE
- Initial Conditions
- Assimilation

Suborbital
- Targeted chemical & microphysical detail
- Point-location time series

Regional Context

Model Validation
- Parameterizations
- Climate Sensitivity
- Underlying mechanisms

Aerosol-type Predictions; Meteorology; Data integration

Must stratify the global satellite data to treat appropriately situations where different physical mechanisms apply

Adapted from: Kahn, Survey Geophys.
Primary Objectives:

• Interpret and enhance 15+ years of satellite aerosol retrieval products

• Characterize statistically particle properties for major aerosol types globally, to provide detail unobtainable from space, but needed to improve:
  -- Satellite aerosol retrieval algorithms
  -- The translation between satellite-retrieved aerosol optical properties
SAM-CAAM Concept

[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]

• **Dedicated Operational Aircraft** – routine flights, 2-3 x/week, on a continuing basis

• **Sample Aerosol Air Masses** accessible from a given base-of-operations, then move; project science team to determine schedule, possible field campaign participation

• Focus on *in situ measurements required* to characterize particle **Optical Properties**, **Chemical Type**, and **Mass Extinction Efficiency** (MEE)

• **Process Data Routinely** at central site; instrument PIs develop & deliver algorithms, upgrade as needed; data distributed via central web site

• Peer-reviewed Paper identifying **4 Payload Options**, of varying ambition; subsequent selections based on agency buy-in and available resources

SAM-CAAM is feasible because: Unlike aerosol amount, **aerosol microphysical properties tend to be repeatable** from year to year, for a given source in a given season