Airborne Particles: What We’ve Learned About Their Role in Climate From Remote Sensing, And Prospects for Future Advances

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Haboob, Khartoum Sudan 2007

Photo Credit: Paul Currion on Flicker
Mt. Etna Eruption 27-30 October 2002
Saharan Dust Plume Tracked Across the Atlantic
05-12 June 1967
ESSA-5 Vidicon Imager

Over Mauritania, Western Sahara, and the eastern Atlantic
7 June 1967

From: Prospero et al.,
Global, Over-Ocean Column Aerosol Amount
July 1989 - June 1991 NOAA AVHRR

Northern Winter

Northern Summer

From: Husar et al., JGR 1997
Mars Dust Storm – Viking Orbiter 1976
Martian Sky – Viking Lander 1, 1976
SeaWiFS – Sahara Dust over Canary Islands  06 March 1998
Even DARF and Anthropogenic DARF are *NOT* Solved Problems (Yet)

**IPCC AR3, 2001**  
*Pre-EOS*

**IPCC AR4, 2007**  
*(EOS + ~ 6 years)*

**FIGURE SPM 2.** Global average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). The net anthropogenic radiative forcing and its range are also shown. These require summing asymmetric uncertainty estimates from the component terms, and cannot be obtained by simple addition. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature. Range for linear contrails does not include other possible effects of aviation on cloudiness. (3.9, Figure 2.20)
Aerosol Contribution to Global Climate Forcing

- Cloud-free, global, Over-ocean, vis, TOA DARF relative to zero aerosol: \(-5.5 \pm 0.2\) W/m\(^2\)
  This is a measurement-based value, with uncertainty based on diversity among estimates (actual uncertainties are probably larger)

- Taking 20\% of aerosol to be anthropogenic, the human-induced component is: \(-1.1 \pm 0.4\) W/m\(^2\)

- Global TOA anthropogenic total ARF relative to pre-industrial: \(-1.3 (-2.2 \text{ to } -0.5)\) W/m\(^2\)
  This is a model-based value, with uncertainty defined as diversity among estimates; (actual uncertainties are probably much larger)

- The models tend to agree on global AOD (as constrained by satellite & surface obs.), but differ on regional-scale AOD, aerosol SSA, and vertical distribution

How Good is “Good Enough”??

From: CCSP - SAP 2.3, 2009
Climate Sensitivity, Aerosols, and Climate Prediction

- **Models are constrained by** historical global mean surface temperature (GMST) change
- Forcing by LL greenhouse gas increase since pre-industrial: \( \sim 2.6 \text{ W/m}^2 \)
- \( \Delta \text{GMST Expected}: \sim 2.1 \text{ K} \); \( \Delta \text{GMST Observed}: \sim 0.8 \text{ K} \)
- **Discrepancy dominated by Aerosol Forcing vs. S** (disequilibrium, natural variation, etc. are less)
- **Model Aerosol Forcing choices compensate for Climate Sensitivity differences** (Kiehl, GRL 2007)

\[ F \times S = \Delta T \]

\( F \) = Effective Forcing  \( S \) = Climate Sensitivity  \( \Delta T \) = Response

From a policy perspective, this bears upon the **urgency of mitigation** efforts
AOD Alone is Not Enough – Even for Direct Aerosol Radiative Forcing

Direct Aerosol Radiative Forcing Efficiency per unit AOD

- Aerosol SSA, Vert. Dist., and Surface Albedo critical, esp. for Surface Forcing
- For Semi-direct Forcing, Aerosol SSA and Vertical Distribution are critical

From: Zhao et al., JGR 2005
Constraining DARF – The Next Big Challenge

- Agreement among models is increasingly good for AOD, given the combined AERONET, MISR, and MODIS constraints

- 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
Aerosols “Indirect” Forcing of Clouds

- **Aerosol Particle Size** Matters
  -- Not easy for remote-sensing techniques to observe the smallest, most numerous CCN
  -- Deducing small-size CCN from larger-particle distribution depends sensitively on ambient RH

- **Aerosol Particle Composition** Probably Matters Too
  -- Remote-sensing not very sensitive to particle chemistry (polarization should help)

- **Location, Location, Location**
  -- Satellite remote-sensing cannot observe aerosol below most clouds; difficult observing aerosol near clouds as well

- **Clouds, Ambient Meteorology** Affect Aerosol Retrievals
The NASA Earth Observing System’s Terra Satellite

First Light: February 24, 2000
MODerate-resolution Imaging Spectroradiometer [MODIS]

- NASA, Terra & Aqua
  - launches 1999, 2001
  - 705 km polar orbits, descending (10:30 a.m.) & ascending (1:30 p.m.)
- Sensor Characteristics
  - 36 spectral bands ranging from 0.41 to 14.385 µm
  - cross-track scan mirror with 2330 km swath width
  - Spatial resolutions:
    - 250 m (bands 1 - 2)
    - 500 m (bands 3 - 7)
    - 1000 m (bands 8 - 36)
  - 2% reflectance calibration accuracy
  - onboard solar diffuser & solar diffuser stability monitor

Improved over AVHRR:
- Calibration
- Spatial Resolution
- Spectral Range & # Bands

MODIS Team, NASA/GSFC
Global, Monthly Average MODIS Aerosol Products
July 2010

Mid-visible Aerosol Optical Depth

Fine-mode Fraction, with AOD encoded as color saturation

From: MODIS Team, NASA GSFC
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
Ten Years of Seasonally Averaged Mid-visible Aerosol Optical Depth from MISR

...includes bright desert dust source regions
Multi-year Annual Average *Aerosol Optical Depth* from Different Measurements + *Synthesis* (S*)

From: Kinne et al. ACP 2006
**Aerosol Source Characterization**
by Combining Measurements and Models

MODIS Fine-mode AOD (550 nm), August 18-30 2000

GoCART Inverse-Model-Retrieved Emissions ($10^7$ kg/day)

From: Dubovik et al., ACP 2008

MODIS July 2006 Siberian Smoke Plume Image + AOD, and 5 GoCART Forward-Model Simulations with different source strengths

From: Petrenko et al., JGR 2012
MISR Aerosol Type Distribution

MISR Version 22, July 2007

Kahn, Gaitley, Garay, et al., JGR 2010
Dust is injected near-surface...

Kahn et al., JGR 2007
Transported Dust Plume
Atlantic, off Mauritania March 4, 2004  Orbit 22399

Transported dust finds elevated layer of relative stability...  
Kahn et al., JGR 2007
MISR Stereo-Derived **Plume Heights**

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

Plume 1

Plume 2
Transported Dust

Polluted Continental Aerosol

Clean maritime and maritime mixed with dust and pollution particles

Seasonally aggregated dust & non-dust vertical extinction profiles over Eastern China for 2007

From: Yu et al., JGR 2010

From: CALIPSO Team, NASA Langley Research Center
Over-Land Aerosol Short-wave Radiative Forcing w/Consistent Data

The slope of:

TOA albedo vs. AOD

For data stratified by:

Surface BHR

Produces:

Spectral aerosol radiative efficiency

\[(d\alpha_{TOA}/d\tau_{mid-vis})\]

Bright surface + dark aerosol = decreasing albedo w/AOD

Depends on aerosol microphysical properties relative to surface albedo

Y. Chen et al. JGR 2009
Aerosol Material Fluxes: Atlantic Dust & Asian Pollution

MODIS AOD & Type
Low AOD, Fine BioBurn, Coarse Dust

NCEP Wind - MODIS AOD Correlation 2.6-5 km; May-October

Dust Transport Estimate (Tg)
May-October (Top) January-April (Bot)
Kaufman et al., JGR 2005

Yu et al., JGR 2008

MODIS AOD & type, Field Campaign aerosol properties & vertical distribution, GEOS model winds;
Compared with GOCART and GMI model Fine-particle mass fluxes
Current MISR & MODIS Mid-Visible AOD Sensitivities

- **MISR**: 0.05 or 20% * AOD overall; better over dark water  
  \[\text{[Kahn et al., 2005; 2010]}\]

- **MODIS**: 0.05 or 20% * AOD over land  
  0.03 or 5% * AOD over dark water  
  \[\text{[Remer et al. 2005; 2008; Levy et al. 2010]}\]

Based on AERONET coincidences (cloud screened by both sensors)

\[\text{Direct Aerosol Radiative Forcing (DARF): Need AOD to } <\sim 0.02\]

\[\text{Particle Properties are Categorical rather than continuous Quantities}\]
Satellites

Remote-sensing Analysis
- Retrieval Validation
- Assumption Refinement

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

Regional Context
- Space-time interpolation,
- DARF & Anthropogenic Component calculation and prediction

CURRENT STATE
- Initial Conditions
- Assimilation

Model Validation
- Parameterizations
- Climate Sensitivity
- Underlying mechanisms

Aerosol-type Predictions
- Frequent, global snapshots;
  aerosol amount & aerosol type maps,
  plume & layer heights

Models
Comparative Planetology and the Atmosphere of Earth

1. **Comparative Planetology** – Discovering how planetary atmospheres are similar, and how they are different, expands our appreciation of Earth itself, by placing specific attributes of our planet into a larger context.
   -- *Radiative and Dynamical Scaling Laws*

2. **Subtle Earth Effects** – Some phenomena in Earth’s atmosphere are of much greater physical importance in the atmospheres of other planets.
   -- *Venus’ Greenhouse; Jupiter’s Magnetosphere*

3. **Data Available Only from Other Planets** – Data of comparable or higher quality relevant to Earth can sometimes be found in other places.
   -- *Inner solar system climate record from Mars (and the Moon?)*

4. **New Ideas** – Inspiration leading to a habit of out-of-the-box thinking…

1989