Aerosol Concentration, Size, Hygroscopicity, & MEE, Globally: What do we need to know, and how can we know it?

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**CURRENT STATE**

- **Satellites**
- **Suborbital**
What We Need, Globally

• Aerosol \textbf{AMOUNT} (AOD – 2D)

• Aerosol \textbf{VERTICAL DISTRIBUTION}

• Aerosol “\textbf{TYPE}”
  -- \textbf{Light Absorption} (direct forcing)
  -- \textbf{Hygroscopicity} (interpreting AOD; indirect forcing)
  -- \textbf{Composition}
    (source attribution; μ–physical properties; mass flux)

-- \textbf{Mass Extinction Efficiency} (MEE)
  (measurement ↔ model translation)
### What We Have...
AeroCom Experiment “A” Values

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Mean</th>
<th>Median</th>
<th>Range</th>
<th>Stddev/mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sources (Tg yr⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>179</td>
<td>186</td>
<td>98-232</td>
<td>22%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>11.9</td>
<td>11.3</td>
<td>7.8-19.4</td>
<td>33%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>96.6</td>
<td>96.0</td>
<td>53-138</td>
<td>26%</td>
</tr>
<tr>
<td>Dust</td>
<td>1840</td>
<td>1640</td>
<td>672-4040</td>
<td>49%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>16600</td>
<td>6280</td>
<td>2180-121000</td>
<td>19%</td>
</tr>
<tr>
<td><strong>Removal rate (day⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.2525</td>
<td>0.24</td>
<td>0.19-0.39</td>
<td>18%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>0.15</td>
<td>0.15</td>
<td>0.066-0.19</td>
<td>21%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.16</td>
<td>0.16</td>
<td>0.09-0.23</td>
<td>24%</td>
</tr>
<tr>
<td>Dust</td>
<td>0.31</td>
<td>0.25</td>
<td>0.14-0.79</td>
<td>62%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>5.07</td>
<td>2.50</td>
<td>0.95-35.0</td>
<td>188%</td>
</tr>
<tr>
<td><strong>Lifetime (day)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>4.12</td>
<td>4.13</td>
<td>2.6-5.4</td>
<td>18%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>7.12</td>
<td>6.54</td>
<td>5.3-15</td>
<td>33%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>6.54</td>
<td>6.15</td>
<td>4.3-11</td>
<td>27%</td>
</tr>
<tr>
<td>Dust</td>
<td>4.14</td>
<td>4.04</td>
<td>1.3-7.0</td>
<td>43%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>0.18</td>
<td>0.41</td>
<td>0.03-1.1</td>
<td>58%</td>
</tr>
<tr>
<td><strong>Mass loading (Tg)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>1.99</td>
<td>1.98</td>
<td>0.92-2.70</td>
<td>25%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>0.24</td>
<td>0.21</td>
<td>0.046-0.51</td>
<td>42%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>1.70</td>
<td>1.76</td>
<td>0.46-2.56</td>
<td>37%</td>
</tr>
<tr>
<td>Dust</td>
<td>19.2</td>
<td>20.5</td>
<td>4.5-29.5</td>
<td>40%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>7.52</td>
<td>6.37</td>
<td>2.5-13.2</td>
<td>54%</td>
</tr>
<tr>
<td><strong>MEE at 550 nm (m² g⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>11.3</td>
<td>9.5</td>
<td>4.2-28.3</td>
<td>56%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>9.4</td>
<td>9.2</td>
<td>5.3-18.9</td>
<td>36%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>5.7</td>
<td>5.7</td>
<td>3.7-9.1</td>
<td>26%</td>
</tr>
<tr>
<td>Dust</td>
<td>0.99</td>
<td>0.95</td>
<td>0.46-2.05</td>
<td>45%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>3.0</td>
<td>3.1</td>
<td>0.97-7.5</td>
<td>55%</td>
</tr>
<tr>
<td><strong>AOD at 550 nm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>0.035</td>
<td>0.034</td>
<td>0.015-0.051</td>
<td>33%</td>
</tr>
<tr>
<td>Black carbon</td>
<td>0.004</td>
<td>0.004</td>
<td>0.002-0.009</td>
<td>46%</td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.018</td>
<td>0.019</td>
<td>0.006-0.030</td>
<td>36%</td>
</tr>
<tr>
<td>Dust</td>
<td>0.032</td>
<td>0.033</td>
<td>0.012-0.054</td>
<td>44%</td>
</tr>
<tr>
<td>Sea salt</td>
<td>0.033</td>
<td>0.033</td>
<td>0.02-0.067</td>
<td>42%</td>
</tr>
<tr>
<td><strong>Total AOT at 550 nm</strong></td>
<td>0.124</td>
<td>0.127</td>
<td>0.065-0.151</td>
<td>18%</td>
</tr>
</tbody>
</table>

*Stddev/mean was used as the term “diversity” in Textor et al. 2006.*

**MEE Ranges**

Factors of 3 – 6 or more!

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CCSP 2009 Table 3.2
Mid-Visible AOD
“Dark Target” + “Deep Blue”

MODIS
July 2010
Monthly Average

- Water & some Land
- Globe ~ Every 2 days
- ~ 10:30 AM & 1:30 PM

- Fine/Coarse Ratio
  Over Water + AOD
- Sensitivity to PM10

MODIS Team, NASA Goddard Space Flight Center
Aerosol Sources, Processing, Transports, Sinks: **Lidar + Model**

August 2007 Saharan dust “D” and smoke “S” event mapped by CALIPSO 532 nm backscatter, with superposed model back trajectories and airborne HSRL observations

Piecing together the bigger picture. Consistency requires –

- An understanding of the **mechanisms** governing aerosol evolution
- Adequately constrained **initial & boundary** conditions
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
Changes in geometric perspective with angle

MISR flight direction

Forward-viewing camera

apparent position

plume height

Diner 2003
Changes in geometric perspective with angle

MISR flight direction

Backward-viewing camera

plume height

parallax
**Wildfire Outbreak in Knysna, South Africa**

*MISR* Active Aerosol Plume-Height (AAP) Project 7 June 2017

*Wildfire outbreaks* can generate a significant amount of atmospheric aerosols that can have *regional to global impacts* on Earth’s energy balance and surface temperature. To determine the influence of wildfires, *accurate plume heights* are needed, but are *difficult to obtain in areas of significant cloud cover*. Stereo images from NASA’s Multi-Angle Imaging Spectroradiometer (*MISR*) make it possible to retrieve plume heights using parallax by constraining the smoke plume layer height. When the retrieval height is significantly below the Lifting Condensation Level (*LCL*), the effects of cloud contamination are often reduced.

The *Knysna Wildfire* began the evening of June 6, 2017 and by June 07, consisted of 26 fires. These fires were fanned towards residential areas by strong winds from a cyclone to the west. The towns of Belvidere, Breonton-on-Sea, and Rheenendal were evacuated after news that a family of three passed away in the fire on June 6. The smoke observed by MISR on June 7 was injected at 3+ km. At this height, the aerosols can escape the boundary layer and enter the middle Troposphere, causing enhanced *regional cooling* and increased *long-range aerosol transport*.
Why We Care About *Aerosol Air Mass Type*

*Some applications* of satellite-mapped aerosol type, especially when *combined with* otherwise-constrained, detailed particle properties:

- **Source Attribution**

  - Mapping 3-D *Aerosol Absorption* that mediates impacts on *atmospheric stability structure* and can affect *convection, cloud evolution*, and *larger-scale atmospheric circulation*

- Mapping *Particle Hygroscopicity* required to account for humidity-dependent *particle optical property changes* as well as *particle activation conditions* that initiate cloud formation

- Deducing *Mass Extinction Efficiency* (MEE) distributions, required to *constrain & validate air quality, aerosol-transport*, and *climate model* aerosol mass with remote-sensing-derived particle *optical* properties.

*Aerosol Air Mass Type* derived from remote sensing can provide *2-D and 3-D mapping required* for many of these applications.
Progress Toward a Global Aerosol Type Climatology
CALIPSSO Classification Scheme

\[ \delta - \text{depolarization} \]
\[ \gamma' - \text{layer-integrated attenuated backscatter} \]

Omar et al., JAOT 2009
CALIPSO 6-Grouping Aerosol Type Classification

Omar et al., JAOT 2009
AERONET Aerosol Type 7-Grouping Classification

Four-parameter AERONET-derived classification:
- $EAE_{491,863}$
- $SSA_{491}$
- $RRI_{670}$
- $dSSA_{863-491}$

7 Groupings $SSA_{491}$ vs. Extinction ANG

7 Groupings $RI_{670}$ vs. Extinction ANG

Russell et al. JGR 2014
Single-scattering Phase Functions for **Different Particle Properties**

**Light Absorption**

SSA = scatt / [scatt + absorp]

**Size**

\[ x = 2\pi r / \lambda \]

**Shape**

Kalashnikova & Kahn, JGR 2006

Kahn et al., JGR 1998
Aerosol:
Amount
Size
Shape

Smoke from Mexico -- 02 May 2002

Dust blowing off the Sahara Desert -- 06 February 2004
MISR Aerosol Type Discrimination

January 2007

July 2007

Kahn & Gaitley JGR 2015
MISR Research Algorithm With Self-consistent Ocean Surface Retrieval

MISR An  MISR Df  MISR Chl  MODIS Chl

Limbacher and Kahn AMT 2017
Satellite **Aerosol Type** Summary

- Remote-sensing can provide optical constraints interpreted as particle *Size, Shape, and Indices of Refraction*.

- A *further* interpretative step, entailing additional assumptions, reports particle *Chemical Composition*.

- Remote-sensing *sensitivity to particle properties is much more dependent than AOD on retrieval conditions* (Not straightforward to provide quantitative uncertainty estimates).

- **Validation Data** for aerosol type are *very limited*
  
  -- *Model simulations* and *In Situ measurements* can help.
Adapted from: Kahn, Survey. Geophys.
Primary Objectives:

- Interpret and *enhance* ~17 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 and species-specific aerosol mass and size tracked in aerosol transport & climate models*

[This is currently a *concept-development effort*, not yet a project]
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** (esp. **Light Absorption**), **Composition**, **Hygroscopicity**, and **Mass Extinction Efficiency**

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

- Peer-reviewed paper to 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

*Kahn et al., BAMS 2017*
The **height** at which smoke is injected into the atmosphere affects **how long** it will stay aloft, **how far** it will travel, and **how much of an impact** it will have on air quality downwind, and regional climate. In **northern Iraq**, at least two people have lost their lives, up to 1000 hospitalized, and 200 families evacuated from their homes due to sulfur & smoke pollution.

**Parallax**, the change in apparent plume position relative to the surface, as observed from the NASA Earth Observing System’s Multi-angle Imaging Spectroradiometer (**MISR**) instrument, makes it possible to map the height of **smoke**, **dust**, and **volcanic plumes** near-source, where plume features are visible in the multi-angle views.

*R. Kahn, T. Kucsera / NASA GSFC  
T. Canty, R. Bolt, CJ Vernon / U. Maryland*
Backup Slides
1. AEROSOL PROPERTIES FROM IN SITU MEASUREMENTS & INTEGRATED ANALYSIS

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Required Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EXT          Spectral Extinction</td>
</tr>
<tr>
<td>2</td>
<td>ABS          Spectral Absorption</td>
</tr>
<tr>
<td>3</td>
<td>GRO          Hygroscopic Growth</td>
</tr>
<tr>
<td>4</td>
<td>SIZ          Particle Size</td>
</tr>
<tr>
<td>5</td>
<td>CMP          Particle Type (a composition constraint)</td>
</tr>
<tr>
<td>6</td>
<td>PHA          Single-scattering Phase Function</td>
</tr>
<tr>
<td>7</td>
<td>MEE          Mass Extinction Efficiency</td>
</tr>
<tr>
<td>8</td>
<td>RRI          Real Refractive Index</td>
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</table>
# SAM-CAAM Required Variables

**[Systematic Aircraft Measurements to Characterize Aerosol Air Masses]**

## 2. METEOROLOGICAL CONTEXT

<table>
<thead>
<tr>
<th>Abbrev.</th>
<th>Required Variable</th>
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</thead>
<tbody>
<tr>
<td>9</td>
<td>CO</td>
</tr>
<tr>
<td>10</td>
<td>T; P; RH</td>
</tr>
<tr>
<td>11</td>
<td>LOC</td>
</tr>
</tbody>
</table>

- **9**: Ambient Gases (CO + O₃ + NO₂)
- **10**: Standard Ambient Meteorological Variables
- **11**: Geographic Location

## 3. AMBIENT REMOTE-SENSING CONTEXT

<table>
<thead>
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<th>Abbrev.</th>
<th>Required Variable</th>
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<td>12</td>
<td>A-EXT &amp; A-ABS</td>
</tr>
<tr>
<td>13</td>
<td>A-PHA</td>
</tr>
<tr>
<td>14</td>
<td>A-CLD</td>
</tr>
<tr>
<td>15</td>
<td>HTS</td>
</tr>
</tbody>
</table>

- **12**: Ambient Spectral Extinction & Absorption
- **13**: Ambient Particle Phase Function
- **14**: Ambient Cloud & Large-Particle Size/Type
- **15**: Aerosol Layer Heights

Kahn et al., BAMS 2017