The combined use of MODIS, CALIPSO and OMI level 2 aerosol products for calculating direct aerosol radiative effects

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Goal: To devise a new, multi-instrument methodology to derive vertical structure of $\Delta F_{\text{aerosol}}(z)$

- Methodology for combining CALIOP, OMI and MODIS data
- Checking consistency of input data
  - Comparison of MODIS and CALIOP-derived AOD
  - Differences in CALIOP V2 and V2.93 (V3 pre-release)
- Inversion methodology & usefulness of lidar backscatter for constraining aerosol radiative properties
- Sensitivity study using synthesized data
- Application to actual data from August 2007
- Conclusions
Motivation: Observation- and model-based estimates of direct aerosol radiative forcing published in IPCC diverge

\[
\text{Mean of Observation-based } \Delta F > \text{Mean of Model-based } \Delta F
\]

Myhre, Science, July 10, 2009

Myhre:
1) Observation-based methods too large
2) Models show great divergence in regional and vertical distribution of DARF.
3) “remaining uncertainty (in DARF) is probably related to the vertical profiles of the aerosols and their location in relation to clouds”.
Goal: To use A-Train aerosol obs to constrain aerosol radiative properties to calculate $\Delta F_{\text{aerosol}}(z)$

Constraints/Input:
- MODIS AOD (7/2 $\lambda$) + $\delta$AOD
- OMI AAOD (388 nm) + $\delta$AAOD
- CALIPSO ext (532, 1064 nm) + $\delta$ext
- CALIPSO back (532, 1064 nm) + $\delta$back

Issues to consider:
- Differences in data quality land/ocean
- Impact of assumptions, e.g., refr. index ($\lambda$), restriction to MODIS modes

MODIS aerosol models:
4 fine and 5 coarse mode distributions define standard deviation and refractive indices of bi-modal log-normal size distribution $\rightarrow$ 20 combinations
Free parameters: $N_{\text{fine}}, N_{\text{coarse}}$

Target: $\Delta F_{\text{aerosol}}(z) + \delta \Delta F_{\text{aerosol}}(z)$

Retrieval:
- ext ($\lambda$, z) + $\delta$ext
- ssa ($\lambda$, z) + $\delta$ssa
- g ($\lambda$, z) + $\delta$g

Rtx code
Aerosol Optical Depth comparisons (CALIOP V2)

- Four months of data: January, April, July and October 2007
- Use CALIPSO 40km-avg. aerosol extinction profiles, and 5km aerosol and cloud layer products
- Find all (up to 4) *instantaneously collocated*, MODIS MYD04_L2 (10x10km) aerosol retrievals traversed by 40km CALIPSO track
- Apply three CALIPSO profile quality criteria:
  1. \( \text{Alt} \_ \text{top} \_ \text{aerosol} > \text{Alt} \_ \text{top} \_ \text{cloud} \)
  2. \( \text{EQC}532\_\text{flag} = 0 \) or 1
  3. Integrated attenuated backscatter @ 532 \( \leq 0.011 \)
- Stratify by MODIS cloud fraction
- Compare CALIPSO Day vs. Night retrievals
- Break down geographically → zonal mean AOD comparisons and representativeness of MODIS obs. along CALIPSO track for ALL MODIS obs.
- Compare zonal means
Calipso old 40km, 2007-08, Ocean only, 3-QC

ModisN = 55158, CalipsoN = 25829, N = 229216
n = 8695

$r^2 = 0.075$

$y = 0.280x + 0.107$

rms = 0.241, 123.9 %
Calipso old 40km, 2007–08, Ocean only, 3–QC, FOC < 0.01

ModisN = 3996, CalipsoN = 25829, N = 229216
n = 1740

$r^2 = 0.485$

$y = 0.850x + 0.015$

rms = 0.111, 72.8%
CALIOP successful AOD retrievals collocated with MODIS-Aqua: V2
August 2007
CALIOP successful AOD retrievals collocated with MODIS-Aqua: V2.93
August 2007

Collocated successful MODIS+OMI+CALIOP:
V2: 5403       V2.93: 17346 (all cloud fractions)
V2: 1399       V2.93: 2398  (cloud fraction<1%)
Calipso V2.93 40km, 2007–08, Ocean only, 3–QC

ModisN = 56030, CalipsoN = 96518, N = 236590
n= 43637

$R^2 = 0.113$

$y = 0.284x + 0.048$

rms = 0.156, 101.9\%
Calipso V2.93 40km, 2007-08, Ocean only, 3-QC, FOC≤0.01

ModisN = 4209, CalipsoN = 96518, N = 236590
n = 3160

$r^2 = 0.425$

$y = 0.493x + 0.024$

rms = 0.115, 81.9%
Calipso V2.93 20km, 2007-08, Ocean only, 3—QC, FOC<0.01

ModisN = 10302, CalipsoN = 165567, N = 458432
n= 7614

$r^2 = 0.415$

$y = 0.515x + 0.017$

$\text{rms} = 0.107, 81.4\%$
Geographical distribution of correlation data, all cloud fractions, V2

<table>
<thead>
<tr>
<th>Latitude</th>
<th>n</th>
<th>(r^2)</th>
<th>y</th>
<th>rms</th>
<th>M aod</th>
<th>C aod</th>
</tr>
</thead>
<tbody>
<tr>
<td>80(^\circ)N</td>
<td>34</td>
<td>0.026</td>
<td>0.157 x + 0.051</td>
<td>0.138, 158.9 %</td>
<td>0.087</td>
<td>0.065</td>
</tr>
<tr>
<td>40(^\circ)N</td>
<td>57</td>
<td>0.051</td>
<td>0.050 x + 0.089</td>
<td>0.519, 150.6 %</td>
<td>0.345</td>
<td>0.107</td>
</tr>
<tr>
<td>0(^\circ)</td>
<td>209</td>
<td>0.008</td>
<td>0.045 x + 0.065</td>
<td>0.313, 158.0 %</td>
<td>0.178</td>
<td>0.076</td>
</tr>
<tr>
<td>40(^\circ)S</td>
<td>236</td>
<td>0.148</td>
<td>-0.19 x + 0.173</td>
<td>0.137, 79.2 %</td>
<td>0.101</td>
<td>0.020</td>
</tr>
<tr>
<td>80(^\circ)S</td>
<td>11</td>
<td>0.005</td>
<td>-0.019 x + 0.040</td>
<td>0.145, 125.4 %</td>
<td>0.116</td>
<td>0.093</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Longitude</th>
<th>n</th>
<th>(r^2)</th>
<th>y</th>
<th>rms</th>
<th>M aod</th>
<th>C aod</th>
</tr>
</thead>
<tbody>
<tr>
<td>180(^\circ)W</td>
<td>839</td>
<td>0.051</td>
<td>0.596 x + 0.063</td>
<td>0.130, 102.2 %</td>
<td>0.128</td>
<td>0.139</td>
</tr>
<tr>
<td>120(^\circ)W</td>
<td>351</td>
<td>0.146</td>
<td>1.298 x + 0.100</td>
<td>0.185, 156.6 %</td>
<td>0.118</td>
<td>0.114</td>
</tr>
<tr>
<td>60(^\circ)W</td>
<td>1181</td>
<td>0.051</td>
<td>0.245 x + 0.085</td>
<td>0.231, 89.9 %</td>
<td>0.193</td>
<td>0.149</td>
</tr>
<tr>
<td>0(^\circ)</td>
<td>963</td>
<td>0.113</td>
<td>0.142 x + 0.134</td>
<td>0.137, 114.6 %</td>
<td>0.137</td>
<td>0.120</td>
</tr>
<tr>
<td>120(^\circ)E</td>
<td>837</td>
<td>0.032</td>
<td>0.454 x + 0.075</td>
<td>0.157, 114.6 %</td>
<td>0.137</td>
<td>0.120</td>
</tr>
<tr>
<td>180(^\circ)E</td>
<td>528</td>
<td>0.053</td>
<td>0.520 x + 0.063</td>
<td>0.120, 114.5 %</td>
<td>0.112</td>
<td>0.121</td>
</tr>
</tbody>
</table>

[Image of map with geographical distribution]
Geographical distribution of correlation data, all cloud fractions, V2.93

Calipso V2.93 40km, AOD scatter info, 2007-08, Ocean Only, 3-QC

Latitude

80°N
n = 388
r = 0.000
y = -0.009 x + 0.054
rms = 0.187, 156.6 %
M aod = 0.119
C aod = 0.053

40°N
n = 219
r = 0.040
y = 0.044 x + 0.060
rms = 0.374, 160.9 %
M aod = 0.232
C aod = 0.070

0°
n = 1422
r = 0.016
y = 0.087 x + 0.060
rms = 0.206, 119.5 %
M aod = 0.172
C aod = 0.075

40°S
n = 728
r = 0.092
y = 0.390 x + 0.021
rms = 0.163, 108.8 %
M aod = 0.150
C aod = 0.079

80°S
n = 51
r = 0.000
y = 0.002 x + 0.027
rms = 0.158, 156.1 %
M aod = 0.101
C aod = 0.027

Longitude

180°W
120°W
60°W
0°
60°E
120°E
180°E

NASA
Zonal mean differences in AOD (550nm) from MODIS and CALIPSO over land and ocean during 4 months in 2007
Comparison of zonal distributions of data density and AOD between V2 and V2.93 (V3, pre-release)
Part 2: Retrieval of aerosol radiative properties from A-Train observations - Methodology

**Constraints/Input:**
- MODIS AOD (7/2 \( \lambda \)) + \( \delta \text{AOD} \)
- OMI AAOD (388 nm) + \( \delta \text{AAOD} \)
- CALIPSO ext (532, 1064 nm) + \( \delta \text{ext} \)
- CALIPSO back (532, 1064 nm) + \( \delta \text{back} \)

**MODIS aerosol models:**
4 fine and 5 coarse mode distributions define standard deviation and refractive indices of bi-modal log-normal size distribution → 20 combinations
Free parameters: \( N_{\text{fine}} \), \( N_{\text{coarse}} \)

**Target:**
\[ \Delta F_{\text{aerosol}}(z) + \delta \Delta F_{\text{aerosol}}(z) \]

**Retrieval:**
- ext (\( \lambda \), \( z \)) + \( \delta \text{ext} \)
- ssa (\( \lambda \), \( z \)) + \( \delta \text{ssa} \)
- g (\( \lambda \), \( z \)) + \( \delta \text{g} \)

Rtx code
Refractive Index of MODIS modes as a function of wavelength
Step 1: Each observable (here AOD 550nm) is consistent with a range of fine/coarse mode particle concentrations for a given fine/coarse mode combination (here fine#1/coarse#5)
Step 2: The totality of all observables is consistent with a smaller range of fine/coarse mode particle concentrations for a given fine/coarse mode combination (here fine#1/coarse#5)
Step 3: For a different fine/coarse mode combination (here fine#3/coarse#6), the observables are consistent with a different range of fine/coarse mode particle concentrations.
Step 4: For all possible fine/coarse mode combinations, the observables are consistent with a different range of fine/coarse mode particle concentrations.
Current choices in retrieval method:

1) Metric

\[ X = \left( \sum_i \log^2 \left( \frac{x_i}{\hat{x}_i} \right) \right)^{1/2} \]

- \( x_i \) : retrieved parameters
- \( \hat{x}_i \) : observables

2) Observables

- \( x_i = \text{AOD } 550\text{nm, AOD } 1240\text{ nm (±0.03±5%)} \) - MODIS
- AAOD 388 nm (±0.03±5%) - OMI
- \( \beta_{532} \) (±10Mm\(^{-1}\)±10%) - CALIOP

3) Use 10% best solutions in context of metric above
Step 5: The best 10% of possible fine/coarse mode combinations & concentrations, define a range of aerosol radiative properties.
Constraints afforded by lidar backscatter retrieval - 1

MODIS AOD (±0.03±5%)
OMI AAOD (±0.03±5%)
No CALIOP $\beta_{532}$
Constraints afforded by lidar backscatter retrieval - 2

MODIS AOD (±0.03±5%)
OMI AAOD (±0.03±5%)
CALIOP $\beta_{532}$ (±20Mm$^{-1}$±10%)
Constraints afforded by lidar backscatter retrieval - 3

MODIS AOD (±0.03±5%)
OMI AAOD (±0.03±5%)
CALIOP $\beta_{532}$ (±10Mm$^{-1}$±10%)
Impact of retrieval uncertainty on instantaneous aerosol DRE

\[ \Delta(\Delta F_{\text{aer}}) = 12 \text{ Wm}^{-2} \]

\[ \Delta(\Delta F_{\text{aer}}) = 18 \text{ Wm}^{-2} \]
<table>
<thead>
<tr>
<th></th>
<th>AOD/SSA</th>
<th>0.8</th>
<th>0.9</th>
<th>0.98</th>
</tr>
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<tbody>
<tr>
<td><strong>EXTINCTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>58.84 +/- 14.88 (30.88/97.62)</td>
<td>49.40 +/- 13.03 (23.98/96.49)</td>
<td>47.53 +/- 13.73 (25.75/93.67)</td>
</tr>
<tr>
<td></td>
<td>input 50.13</td>
<td>input 49.93</td>
<td>input 50.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>201.71 +/- 6.87 (187.96/219.39)</td>
<td>206.81 +/- 20.30 (159.51/256.14)</td>
<td>199.62 +/- 10.33 (172.22/234.64)</td>
</tr>
<tr>
<td></td>
<td>input 199.29</td>
<td>input 200.54</td>
<td>input 200.11</td>
<td></td>
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<tr>
<td></td>
<td>0.7</td>
<td>696.87 +/- 6.23 (689.88/717.68)</td>
<td>708.94 +/- 22.61 (665.50/759.05)</td>
<td>702.61 +/- 23.40 (664.51/762.79)</td>
</tr>
<tr>
<td></td>
<td>input 699.13</td>
<td>input 699.23</td>
<td>input 699.91</td>
<td></td>
</tr>
<tr>
<td><strong>SSA</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.83 +/- 0.05 (0.75/0.94)</td>
<td>0.87 +/- 0.05 (0.75/0.98)</td>
<td>0.97 +/- 0.01 (0.94/0.99)</td>
</tr>
<tr>
<td></td>
<td>input 0.80</td>
<td>input 0.90</td>
<td>input 0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.80 +/- 0.01 (0.77/0.83)</td>
<td>0.90 +/- 0.02 (0.85/0.93)</td>
<td>0.98 +/- 0.00 (0.97/0.98)</td>
</tr>
<tr>
<td></td>
<td>input 0.80</td>
<td>input 0.90</td>
<td>input 0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.80 +/- 0.00 (0.80/0.81)</td>
<td>0.90 +/- 0.00 (0.89/0.91)</td>
<td>0.98 +/- 0.00 (0.98/0.98)</td>
</tr>
<tr>
<td></td>
<td>input 0.80</td>
<td>input 0.90</td>
<td>input 0.98</td>
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</tr>
<tr>
<td><strong>ASYMMETRY</strong></td>
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</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.80 +/- 0.04 (0.62/0.85)</td>
<td>0.76 +/- 0.05 (0.56/0.85)</td>
<td>0.77 +/- 0.03 (0.61/0.80)</td>
</tr>
<tr>
<td></td>
<td>input 0.83</td>
<td>input 0.69</td>
<td>input 0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>0.82 +/- 0.01 (0.79/0.84)</td>
<td>0.74 +/- 0.04 (0.62/0.78)</td>
<td>0.78 +/- 0.01 (0.72/0.79)</td>
</tr>
<tr>
<td></td>
<td>input 0.83</td>
<td>input 0.69</td>
<td>input 0.75</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.83 +/- 0.00 (0.82/0.83)</td>
<td>0.71 +/- 0.02 (0.68/0.73)</td>
<td>0.77 +/- 0.01 (0.73/0.79)</td>
</tr>
<tr>
<td></td>
<td>input 0.82</td>
<td>input 0.69</td>
<td>input 0.75</td>
<td></td>
</tr>
</tbody>
</table>

**Sensitivity:** MODIS AOD (±0.03+5%), OMI AAOD (±0.03+5%), CALIOP $\beta_{532}$ (±10 Mm$^{-1}$±10%)
Example of successful retrieval from actual collocated OMI, MODIS, CALIOP (V2.93) data: Aug. 15, 2007
Conclusions

A. Different cloud screening techniques and assumptions in MODIS, OMI, and CALIPSO have serious implications for the use of collocated data.

B. Monthly AOD comparisons show decent agreement after severe cloud clearing, and regional and zonal averaging. Initial comparisons of CALIOP V2.93 to MODIS-Aqua show increased data density and generally smaller rms differences from 40ºS to 40ºN.

C. A methodology for the retrieval of aerosol radiative properties from MODIS AOD, OMI AAOD and CALIPSO $\beta_{532}$ has been devised.

D. A sensitivity study of current method shows good retrievals for almost all AOD/ssa combinations with AOD greater or equal to 0.2.

E. Next steps:
   1) Test retrieval assumptions (metric, solution space, etc.)
   2) Use CALIOP V3
   3) Constrain OMI AOD retrievals with CALIOP height input
   4) Testing additional constraints afforded by APS
   5) Testing radiative properties against suborbital data
   6) rtx calculations to assess $\delta \Delta F_{aerosol}(z)$
   7) Aerosol DRE above clouds