Dust Emission Optimization with Satellite Remote Sensing: Application to CLAEERO

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The sign of the dust forcing is still unknown.
Motivation

Motivated by Wielicki et al. (2013, BAMS):

- CLARREO enables two new approaches to climate analysis:
  - benchmark spectral fingerprinting
  - reference inter-calibration

- CLARREO measures with high spectral resolution over 95% of the spectrum of Earth’s thermal emitted radiation (200–2000 cm$^{-1}$ or 5–50-$\mu$m wavelength) and solar reflected radiation (350–2300 nm) for the first time.

- Spectral fingerprint linearity has been shown for both IR and SW.

We like to ask the question:

- To what extent does the long-term variability of dust emissions manifest first-order changes in large-scale general circulation that can be possibly recovered from the satellite-based spectral climate?

- Across what temporal and spatial scales are these features evident in spectral climate data?
In shortwave, spectrally flat; In infrared, negative slope in BT in 820-920 cm\(^{-1}\) (12.2 -10.87 µm). We think dust can be best characterized by using SW (UV+blue in particular) + IR. CALERRO is well suited for this.
UNified & Linearized Vector Radiative Transfer Model (UNL-VRTM)

INPUT

- Atmospheric profile
- Aerosol Size and Refractive indices
- Sensor Configuration

FORWARD CALCULATIONS

- Rayleigh scattering and gas absorption (HITRAN)
- Aerosol scattering (linearized Mie and linearized Tmatrix)
- Surface Bi-Directional Reflectance Function (BRDF)

ANALYSIS

- Linearized Radiative Transfer (VLIDORT)
- Optimization and diagnosis analysis


Unique feature of UNL-VRTM – Gas Absorption

Note: \( \text{SO}_2 \) and \( \text{NO}_2 \) emissions have changed in the past 3-4 decades because of (a) Clean-air policies in Europe and US, and (b) fast-growing economy in Asia and other developing regions.
Unique feature of UNL-VRTM – fully linearized for Jacobian calculations

Calculation of Jacobians of any Stokes parameter $\xi$ with respect to any aerosol parameter $x$ (such as size parameter) proceeds according to

$$x \frac{\partial \xi}{\partial x} = x \left[ \frac{\partial \xi}{\partial \tau_L} \frac{\partial \xi}{\partial \omega_L} \left\langle \frac{\partial \xi}{\partial B^j_L} \right\rangle_{j=0,J} \right] \begin{bmatrix} \frac{\partial \tau_L}{\partial x} & \frac{\partial \omega_L}{\partial x} & \left\langle \frac{\partial B^j_L}{\partial x} \right\rangle_{j=0,J} \end{bmatrix}^T$$

Linearized VRTM code  Linearized Mie code

Analytic Jacobian  Finite Difference Derived Jacobian
Validation
Pure Rayleigh-Scattering Atmosphere

(a) $A_s = 0$, Isotropic
$A_s = 0$, Anisotropic
$A_s = 0.25$, Anisotropic

(b) Rayleigh
$A = 0$
$A = 0.25$
Observed

(c) UNL-VRTM $I$

(d) Coulson et al. (1960) $Q$

(e) $U$
Validation
Atmosphere with aerosols

<table>
<thead>
<tr>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
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<tbody>
<tr>
<td>( I \times 10^{-1} )</td>
<td>( Q \times 10^{-2} )</td>
<td>( U \times 10^{-2} )</td>
<td></td>
<td></td>
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<tr>
<td>Garcia and Siewert, 1989</td>
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<tr>
<th>(f) Relative Difference</th>
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<tr>
<td>Average</td>
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<tr>
<td>( I )</td>
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<tr>
<td>( Q )</td>
</tr>
<tr>
<td>( U )</td>
</tr>
<tr>
<td>( V )</td>
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<tr>
<td>( DOLP )</td>
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</tbody>
</table>
Hyper-spectral simulation of dust effect in IR including sensitivity of BT to dust particle size and layer height.

Top: simulated brightness temperature in 9 – 14 μm for various atmospheric conditions. Bottom: corresponding Jacobians with respect to dust height, size, and AOD. Unless labeled otherwise, rg = 0.5 μm, h_peak = 3.0 km, AOD = 2.0 at 0.55 μm
The adjoint provides receptor→source relationship.

\[ E \frac{\partial C}{\partial E} \]

UNL-VRTM provides:

\[ C \frac{\partial I}{\partial C} \]

So, GEOS-Chem adjoint and UNL-VRTM together provide a powerful tool to examine the information content of aerosol parameter and aerosol source function in the satellite measurements.
Forward calculation of synthetic data

(a) A clear-sky RGB image in the TEMPO’s viewing geometry, (b) Jacobians of TOA intensity in blue w.r.t. AOD, (c) differences of Jacobians between blue and red, and (d) DFS for AOD retrievals.
Use reflectance to optimize dust emission
2-step approach

1. AOD RETRIEVAL

\[ \tau = \tau + \frac{\partial \rho}{\partial \tau} \times \Delta \rho \]

scale the aerosol mass

2. GEOS-CHEM ADJOINT TO ESTIMATE EMISSION

\[ \rho_{\text{MODIS}} = \frac{\rho_{\text{GEOS-chem}}}{\text{MODIS/Terra, MODIS/Aqua}} \]

\[ \text{Keep same dark cloud-free pixels as MOD04.} \]

\[ \rho_{\text{MODIS}} = \rho_{\text{GEOS-chem}} \]

AOT(\tau) and 3D aerosol mass

VLIDORT (Spurr, 2006) surface reflectance algorithm (Drury, 2008)

Reflectance \( \rho_{\text{GEOS-chem}} \) & Jacobian \( \frac{\partial \rho}{\partial \tau} \)

MODIS/Terra, MODIS/Aqua

Levy et al. (2007)

MOD04, MYD04

Reflectance \( \rho_{\text{MODIS}} \)
Can we use reflectance to constrain dust parameterization?

Inputs: Wind speed, friction velocity \((u_*)\), soil texture and moisture, Land surface properties

Ideal threshold wind friction \(v\): 
\[ u_* = f(D_0, \rho_p) \]

Real threshold wind friction \(v\) affected by drag partition (turned off) and moisture inhabitation:
\[ u_*(\theta, z_{0,m}) = u_* \cdot f(\theta) \cdot f(z_{0,m}) \]

Horizontal saltation flux:
\[
Q_s(u_*; u_*) = \begin{cases} 
\frac{C_k \rho_a}{g} u_*^3 \left(1 - \frac{u_*}{u_*}ight) \left(1 + \frac{u_*}{u_*}ight)^2, & \text{if } u_* > u_* \\
0, & \text{if } u_* \leq u_*
\end{cases}
\]

Vertical entrainment flux:
\[
F_{d,j} = T_0 f_{\text{bare}} S \alpha Q_s \sum_{i=1}^3 M_{i,j}
\]

- \(f_{\text{bare}}\) Fraction of bare soil
- \(S\) Soil “erodibility” (GOCART)
- \(\alpha\) Sand blasting efficiency factor (Fixed)
- \(M_{i,j}\) Mass fraction of transport bin \(j\) from parent soil mode \(i\)

Zender et al [2003]
Iversen and White [1982]
Marticorena and Bergametti [1995]
Fairlie et al [2007]
Adjoint Implementations

- Gradients of emission flux with respect to $S'$ and $u_{*t}$:

$$\frac{\partial F_d}{\partial S'} = f_{\text{bare}} \int_{u_{*t}}^{u_{*\text{max}}} Q_s(u_{*t}; u_*) p(u_*) du_*$$

$$\frac{\partial F_d}{\partial u_{*t}} = f_{\text{bare}} S' \int_{u_{*t}}^{u_{*\text{max}}} \frac{\partial Q_s(u_{*t}; u_*)}{\partial u_{*t}} p(u_*) du_*$$

$$\frac{\partial Q_s(u_{*t}; u_*)}{\partial u_{*t}} = \frac{c_K \rho_a}{g} u_3 \left[ \frac{1}{u_*} - \frac{2u_{*t}}{u_*^2} - \frac{3u_{*t}^2}{u_*^3} \right]$$

- Adjoint gradient verification:
Optimization Results with MODIS-DB AODs (June 2008)
CLARREO reference inter-calibration for GEO can further help use of GEO to constrain aerosol emissions.


GEO constellation for AQ have been endorsed by various international protocols and conventions (IGACO, GEO, WMO GAW).
## Funded tropospheric chemistry mission parameters (as of 5/2014)

<table>
<thead>
<tr>
<th></th>
<th>Europe Sentinel 4</th>
<th>USA TEMPO</th>
<th>Korea GEMS</th>
<th>Europe Sentinel 5 Precursor TROPOMI</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Orbit</strong></td>
<td>Geostationary</td>
<td>Geostationary</td>
<td>Geostationary</td>
<td>Low-Earth</td>
</tr>
<tr>
<td><strong>Domain</strong></td>
<td>Europe and surrounding</td>
<td>North America</td>
<td>Asia-Pacific</td>
<td>Global</td>
</tr>
<tr>
<td><strong>Revisit</strong></td>
<td>1 hour</td>
<td>1 hour</td>
<td>1 hour</td>
<td>1 day</td>
</tr>
<tr>
<td><strong>Payload</strong></td>
<td>UV-Vis-NIR 305-500, 750-775 nm</td>
<td>UV-Vis 290-490, 540-740 nm</td>
<td>UV-Vis 300-500 nm</td>
<td>UV-Vis-NIR-SWIR 270-500, 675-775, 2305-2385 nm</td>
</tr>
<tr>
<td><strong>Products</strong></td>
<td>O₃, NO₂, SO₂, HCHO, AAI, AOD, height-resolved aerosol</td>
<td>O₃, trop. O₃, 0-2km O₃, NO₂, HCHO, SO₂, CH₂OCHO, AOD, AAI</td>
<td>O₃, NO₂, SO₂, HCHO, AOD</td>
<td>O₃, NO₂, SO₂, HCHO, AAI, AOD, height-resolved aerosol, CO, CH₄</td>
</tr>
<tr>
<td><strong>Spatial Sampling</strong></td>
<td>8 km x 8 km at 45N</td>
<td>2.1 km N/S x 4.7 km E/W @35N</td>
<td>3.5 km N/S x 8 km E/W @38N</td>
<td>7 km x 7 km nadir</td>
</tr>
<tr>
<td><strong>Nominal product resolution</strong></td>
<td>8.9 km N/S x 11.7 km E/W @40N</td>
<td>8.4 km N/S x 4.7 km E/W or better @35N (with 100W orbit)</td>
<td>7 km N/S x 8 km E/W @38N (gas), 3.5 km N/S x 8 km E/W @38N (aerosol)</td>
<td>7 km x 7 km nadir</td>
</tr>
<tr>
<td><strong>Notes</strong></td>
<td>Two instruments in sequence on MTG-S; use TIR sounder on MTG-S (expected sensitivity to O₃ and CO). Synergy with imager on MTG-I w.r.t. aerosol and clouds.</td>
<td>GEO-CAPE precursor or initial component of GEO-CAPE. Synergy with GOES-R/S ABI w.r.t. aerosol and clouds.</td>
<td>Synergy with AMI and GOCI-2 instruments w.r.t. aerosol and clouds.</td>
<td>In formation with S-NPP for synergy w.r.t. clouds and O₃.</td>
</tr>
</tbody>
</table>
USA TEMPO mission

PI: Kelly Chance, Smithsonian Astrophysical Observatory
Deputy PI: Xiong Liu, Smithsonian Astrophysical Observatory
Instrument Development: Ball Aerospace
Instrument Project Manager: Wendy Pennington, NASA LaRC
Mission Project Manager: Alan Little, NASA LaRC
Project Scientist: Dave Flittner, LaRC; Deputy PS: Jay Al-Saadi, LaRC
Other Institutions: NASA GSFC (led by Scott Janz), NOAA, EPA, NCAR, Harvard, UC Berkeley, St. Louis U, U Alabama Huntsville, U Nebraska
International collaboration: Korea, ESA/Eumetsat, Canada, Mexico
Selected Nov. 2012 through NASA’s first Earth Venture Instrument solicitation
TEMPO Spectral Range

- Albedo \( \left( \frac{\Pi}{\mu_0 \times \text{irradiance}} \right) \)
- Wavelength (nm)
- Temple, fully cloudy
- Sahara Desert
- Vegetation red edge
- Clear ocean albedo

Key Absorbing Species:
- \( O_3 \)
- \( O_3 \)
- \( NO_2 \)
- \( O_2-H_2O \)
- \( O_2-O_2 \)
- \( H_2O \)
- \( H_2O \)

Temple absorption bands and \( O_3 \) peaks are highlighted.
Another example: using spectral information to constrain particle size in the dust emission

Pseudo AOD in the red box will be used to constrain dust emissions
OSSE Design

<table>
<thead>
<tr>
<th></th>
<th>DA 1</th>
<th>DA 2</th>
<th>DA 3</th>
<th>DA 4</th>
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</thead>
<tbody>
<tr>
<td>Band</td>
<td>553 nm</td>
<td>1243 nm</td>
<td>2219 nm</td>
<td>553, 1243, and 2219 nm</td>
</tr>
</tbody>
</table>

- Pseudo AOD observations have been removed when cloud fraction is larger than 0.2

- In every data assimilation (DA) experiment, two cases are conducted
  - Case A: Pseudo AOD is provided once a day (simulating polar satellite)
  - Case B: Pseudo AOD is provided 8 times a day (simulating geostationary satellite)
Results

(a) NR
(b) Prio - NR
(c) Posterior – NR LEO
(d) Posterior – NR GEO
Top-Down vs. Bottom-Up estimate of aerosol emission

**Bottom-up emission estimate**
- Usually has a 2~3 yr lag
- Often seasonal or annual
- Point or area average
- Chemically speciated
- Lack of constraint on emission above the surface

**Top-down emission estimate**
- Has the potential for near real time
- Daily (polar-orbiting) or higher (geo.)
- Globally with high spatial resolution
- Trace gases, & optical thickness
- Reflecting the columnar mass, and thus 1st order of emission
Next steps

• One-step approach to use averaged reflectance to optimize dust emission and compare the results with two-step approach.

• Explore both short-wave and long-wave spectral information to constrain dust emission
  – Real data from GOME, SCIAMACHY, AIRS, and IASI.
  – Synthetic data from GEOS-Chem + UNL-VRTM

• Dust feedback will be analyzed by using FIM-Chem.

• Climate model output of dust concentration is needed.
Thank you.
Forcing of each aerosol component

Table 8.4 | Global and annual mean RF (W m⁻²) due to aerosol–radiation interaction between 1750 and 2011 of seven aerosol components for AR5. Values and uncertainties from SAR, TAR, AR4 and AR5 are provided when available. Note that for SAR, TAR and AR4 the end year is somewhat different than for AR5 with 1993, 1998 and 2005, respectively.

<table>
<thead>
<tr>
<th></th>
<th>SAR</th>
<th>TAR</th>
<th>AR4</th>
<th>AR5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphate aerosol</td>
<td>−0.40 (−0.80 to −0.20)</td>
<td>−0.40 (−0.80 to −0.20)</td>
<td>−0.40 (−0.60 to −0.20)</td>
<td>−0.40 (−0.60 to −0.20)</td>
</tr>
<tr>
<td>Black carbon aerosol</td>
<td>+0.10 (+0.03 to +0.30)</td>
<td>+0.20 (+0.10 to +0.40)</td>
<td>+0.20 (+0.05 to +0.35)</td>
<td>+0.40 (+0.05 to +0.80)</td>
</tr>
<tr>
<td>from fossil fuel and biofuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary organic aerosol</td>
<td>Not estimated</td>
<td>−0.10 (−0.30 to −0.03)</td>
<td>−0.05 (0.00 to −0.10)</td>
<td>−0.09 (−0.16 to −0.03)</td>
</tr>
<tr>
<td>from fossil fuel and biofuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biomass burning</td>
<td>−0.20 (−0.60 to −0.07)</td>
<td>−0.20 (−0.60 to −0.07)</td>
<td>+0.03 (−0.09 to +0.15)</td>
<td>−0.0 (−0.20 to +0.20)</td>
</tr>
<tr>
<td>Secondary organic aerosol</td>
<td>Not estimated</td>
<td>Not estimated</td>
<td>Not estimated</td>
<td>−0.03 (−0.27 to +0.20)</td>
</tr>
<tr>
<td>Nitrate</td>
<td>Not estimated</td>
<td>Not estimated</td>
<td>−0.10 (−0.20 to 0.00)</td>
<td>−0.11 (−0.30 to −0.03)</td>
</tr>
<tr>
<td>Dust</td>
<td>Not estimated</td>
<td>−0.60 to +0.40</td>
<td>−0.10 (−0.30 to +0.10)</td>
<td>−0.10 (−0.30 to +0.10)</td>
</tr>
<tr>
<td>Total</td>
<td>Not estimated</td>
<td>Not estimated</td>
<td>−0.50 (−0.90 to −0.10)</td>
<td>−0.35 (−0.85 to +0.15)</td>
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</table>
Retrieve-then-average vs. Average-then-retrieve?

The Jacobians of monthly-averaged normalized radiances (e.g., reflectance) with respect to AOD can be obtained from hourly outputs:

\[
\frac{\partial (R_1 + R_2 + \cdots) / N}{\partial \tau_{\text{avg}}} = \frac{1}{N} \left[ \frac{\partial R_1}{\partial \tau_1} \frac{\partial \tau_1}{\partial \tau_{\text{avg}}} + \frac{\partial R_2}{\partial \tau_2} \frac{\partial \tau_2}{\partial \tau_{\text{avg}}} + \cdots \right]
\]

because \( \tau_{\text{avg}} = (\tau_1 + \tau_2 + \cdots) / N \), we have \( \partial \tau_1 / \partial \tau_{\text{avg}} = N \). With similar derivations, we obtain:

**Spectral fingerprint linearity**

\[
\frac{\partial (R_1 + R_2 + \cdots) / N}{\partial \tau_{\text{avg}}} = \frac{\partial R_1}{\partial \tau_1} + \frac{\partial R_2}{\partial \tau_2} + \cdots
\]

Since each term on the right-hand side of the above equation is readily computed with our simulator (UNL-VRTM + GEOS-Chem), the left-hand of this equation can be readily obtained. Similarly, we can show that

\[
\frac{\partial (R_1 + R_2 + \cdots) / N}{\partial \omega_{\text{avg}}} = \frac{\partial R_1}{\partial \omega_1} \frac{\tau_{\text{avg}}}{\tau_1} + \frac{\partial R_2}{\partial \omega_2} \frac{\tau_{\text{avg}}}{\tau_2} + \cdots
\]

Thus, through the chain rule, we can derive Jacobians of reflectance to other aerosol properties (such as particle size and height) by using what we computed on the daily basis, which will then be used to derive DFS. This DFS (e.g., from the mean of reflectance) will then be compared with averages of instantaneous DFS.

**This will answer if average-then-retrieve gives mean state of emission.**