Radiative Forcing Efficiency of a Forest Fire Smoke Plume at the Surface and TOA

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Fourmile Canyon Fire 6 Sept. 2010
Our focus is to compute the Radiative Forcing Efficiency (RFE) of the smoke aerosol at the Surface and Top of Atmosphere (TOA)

\[ \text{RFE} = \Delta \text{Total Net Rad/unit AOD}_{500\text{nm}} \]

Surface, Atmosphere, and TOA

\[ \text{RFE}_{\text{atmos}} = \text{RFE}_{\text{TOA}} - \text{RFE}_{\text{sfc}} \]
Why are case studies like this important?

- Smoke sometimes covers large parts of the globe for several months and can affect climate variability.
- Case studies are useful for validating smoke aerosol parameterizations in models.
- Smoke particles are very small and may not be handled well by generic aerosol parameterizations.
- Rare comprehensive data sets like that on the Fourmile Canyon fire should be exploited.
Plume boundary at 18:18 UTC ~ 2h after fire started
Abundant clear-sky surface measurements throughout the day allowed direct calculation of $RF_{sfc}$.

Net SW (Wm$^{-2}$)

Net LW (Wm$^{-2}$)

Total Net (Wm$^{-2}$)
TOA – not as easy

1. Satellite observations
   - NASA’s Terra and Aqua polar orbiters.
   - First choice CERES broadband imagers
   - Sampling is minimal--1 or 2 passes per day
   - TOA radiative forcing is computed by comparing an aerosol case to a reference case

2. Radiative transfer model
Available Satellite data

1. CERES SW and IR broadband imagers, 20 km resolution at nadir
2. MODIS 36-channel spectral imager, 1 km resolution at nadir

Problems:
• CERES could not resolve the Fourmile plume
• MODIS could, but NASA does not do a narrowband-to-broadband conversion
MODIS Spectral radiance to broadband conversion

Tang et al. [2006], *JGR* used 159,000 MODTRAN runs to produce a linear model that converts the first 7 spectral channel reflectances ($\rho$) to SW broadband reflectance ($r$)

RMS error = 0.01

$$r = b_0 + \rho_1 b_1 + \rho_2 b_2 + \rho_3 b_3 + \rho_4 b_4 + \rho_5 b_5 + \rho_6 b_6 + \rho_7 b_7$$

where:

$$b_i = c_{1i} + \frac{c_{2i}}{1+\exp((1/\cos(VZA)-c_{3i}/c_{4i}))}$$

$$\rho_i = \pi L_i d^2/E_{\omega_i} \cos(SZA)$$

$L_i$ is the measured upwelling radiance for channel i

+ 17 more (3660 – 14385 nm)
Surface AOD measurements at BAO and SURFRAD (TBL)

Background AOD before fire began
NASA Terra MODIS imager
1820 UTC, ~ 2 hours after the fire started
Terra broadband reflectance 6 Sept. 2010, 1820 UTC

RMS=0.01
NASA Aqua MODIS imager
2000 UTC, ~ 3.5 hours after the fire started
Aqua broadband reflectance 6 Sept. 2010, 2000 UTC
Terra broadband TOA SW flux 6 Sept. 2010, 1820 UTC

\[ F = r S_0 \cos(SZA)/d^2 \]
Calculations of SW Radiative Forcing

SW forcing is dominant -- can be 20 times greater than LW forcing

\[\text{Net } SW_{\text{TOA}} = [1361*\cos(SZA)/d^2] – SW_{\text{TOA}}^{\uparrow}\text{ (satellite)}\]

\[RF_{\text{TOA}} = \text{Net } SW_{\text{TOA}}\text{ (plume)} - \text{Net } SW_{\text{TOA}}\text{ (ref. area)}\]

\[RF_{\text{sfc}} = AOD_{500} * RFE_{SW}\text{ (from Stone et al. 2011)}\]

\[RF_{\text{atmos}} = RF_{\text{TOA}} - RF_{\text{sfc}}\]
### RF Results ($\theta \sim 35^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>$\text{AOD}_{500}$</th>
<th>$\text{Sfc} \text{RF}_{sw}$</th>
<th>$\text{TOA} \text{RF}_{sw}$</th>
<th>$\text{Atmos.} \text{RF}_{sw}$</th>
<th>Atmos. heating ($^\circ$K/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SURFRAD</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1820 UTC</td>
<td>0.060 (-1 min.)</td>
<td></td>
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</tr>
<tr>
<td><strong>Terra</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>BAO</td>
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<tr>
<td>1820 UTC</td>
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<td></td>
<td>3.97</td>
<td>(±5%)</td>
<td>(±6%)</td>
<td>(±7.5%)</td>
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<tr>
<td><strong>SURFRAD</strong></td>
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<tr>
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<td>1.36</td>
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<tr>
<td>BAO</td>
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<tr>
<td>2000 UTC</td>
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5°C cooling measured at surface
## RFE Results ($\theta \sim 35^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>$\text{AOD}_{500}$</th>
<th>Sfc $\text{RFE}_{\text{sw}}$</th>
<th>TOA $\text{RFE}_{\text{sw}}$</th>
<th>Atmos. $\text{RFE}_{\text{sw}}$</th>
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<td><strong>SURFRAD</strong></td>
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</tr>
<tr>
<td>1820 UTC</td>
<td>0.060 (-1 min.)</td>
<td>0.057</td>
<td>0 Wm$^{-2}$/AOD</td>
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<tr>
<td><strong>Terra</strong></td>
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<tr>
<td>BAO</td>
<td>3.38</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1820 UTC</td>
<td>3.37</td>
<td>-152 Wm$^{-2}$/AOD</td>
<td>-34 Wm$^{-2}$/AOD</td>
<td>+118 Wm$^{-2}$/AOD</td>
</tr>
<tr>
<td></td>
<td>3.97</td>
<td>(±5%)</td>
<td>(±6%)</td>
<td>(±7.5%)</td>
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<tr>
<td><strong>SURFRAD</strong></td>
<td>1.36</td>
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<td>1.33</td>
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</table>
From JGR, Stone et al. 2008

Sfc albedo = .15
SZA = ~35°

SZA = 50°, From JGR, Stone et al. 2008
Summary

• MODIS SW spectral to broadband conversion algorithm gives reasonable results at TOA

• TOA aerosol radiative forcing computed from MODIS-based broadband SW fluxes consistent with similar empirical and model case study results

Plans

• Model observed surface radiation fluxes with MODTRAN using the actual particle size distribution as measured by CSD, measured spectral albedo, aerosol microphysics, etc.

• Model the TOA SW fluxes at the BAO and SURFRAD locations to validate the satellite-based results and expand TOA calculations to the entire day

• Use MODTRAN to estimate LW TOA radiative forcing of the smoke aerosol
END

Questions?
Smoke plume | Reference area

\[ \text{RF}_{\text{TOA}}(\theta, \alpha) = \text{Net}_{\text{TOA}}^{\text{aerosol}} - \text{Net}_{\text{TOA}}^{\text{Ref.}} \]

\[ \text{RF}_{\text{atmos.}}(\theta, \alpha) = \text{RF}_{\text{TOA}}^{\text{aerosol}} - \text{RF}_{\text{sfc.}}^{\text{aerosol}} \]

\[ \text{RF}_{\text{sfc}}^{\text{aerosol}}(\theta, \alpha) \text{ Measured directly} \]

Net_{sfc}^{\text{aerosol}} S W LW S W

\text{Sfc. albedo } \alpha
Analytic Approximation method of Caracena (1987) used to interpolate to a 0.1 km grid

\[
\langle F_{i,j} \rangle = \frac{\sum_{k=1}^{N} W_{i,j,k} f_k}{N_{i,j}}, \quad \text{Weighted sum}
\]

where: \( N_{i,j} = \sum_{l=1}^{N} W_{i,j,k} \)

Gaussian weights are used: \( W_{i,j,k} = \exp\left\{ \frac{|r_{i,j,k}|^2}{L^2} \right\} \)

To effect three more passes of analyzing and removing residuals, the above equation becomes:

\[
\langle F_{i,j} \rangle^{(4)} = \sum_{k=1}^{N} W_{i,j,k} \left( 4I-6W+4W^2-W^3 \right) f_k \frac{f_i}{N_{i,j}}
\]

where: \( W = \text{crossweight matrix} \)

and: \( I = \text{Identity matrix} \)

Weighted sum with residuals removed in three successive passes
GPS water vapor data

(Courtesy of Seth Gutman)
Radiative Forcing Efficiency \((RFE_x)\) valid for sfc. Albedo of 0.15

\[
\begin{align*}
RFE_{sw} & \quad \text{Wm}^{-2}/\text{AOD}_{500} \\
RFE_{Lw} & \quad \text{Wm}^{-2}/\text{AOD}_{500} \\
RFE_{\text{all wave}} & \quad \text{Wm}^{-2}/\text{AOD}_{500}
\end{align*}
\]

-194 to 0 Wm\(^{-2}\)/AOD\(_{500}\) in the daytime

+10 Wm\(^{-2}\)/AOD\(_{500}\) day and night
Terra coverage 18:18:43 to 18:19:24 UTC (41 sec.)