The Use of Satellite-Measured Aerosol Optical Depth to Constrain Biomass Burning Emissions Source Strength in the Global Model GOCART

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Purpose of this study: Constrain BB emissions source strength

BB emissions in aerosol models are supplied by external emission inventories. Many BB emission inventories have been developed.

- Estimated amounts of BB emissions are different in different inventories.

Satellite observations are crucial to validate emissions on a global scale.

- Satellite snapshot provides instantaneous constraint on a source strength.

Presented results have been published

Outline

Motivation & Review of BB emission estimates

- Estimating BB emissions (2 approaches)
- Comparison of emission options and their individual components

Critical tests of emission options

- Evaluating BB emission options by comparing GOCART model output with satellite observations
- Quantitative relationship between BB aerosol emissions and aerosol optical depth (AOD)

Implications for model parameterization

- Future work towards improving BB emissions for global models
Estimating BB emissions:
1. Burned area-based approach

\[ M_i = A \times B \times C \times F_i \]

- \( M_i \) – mass of emitted gas/aerosol species \( j \) (g)
- \( A \) – burned area (m\(^2\))
- \( B \) – fuel density (kg/m\(^2\))
- \( C \) – combustion completeness (unitless fraction)
- \( F_i \) – species-specific emission factor;
  \( (g_i / \text{kgDM}) \);
  \( j \) = e.g., BC, OC, SO\(_2\)

Effective fuel load (a.k.a. “fuel consumption”)

Dry Mass burned (DM)

Method adapted from Seiler and Crutzen (1979 in Climatic Change)
Burned area estimates for 2006

- Higher Leaf Area Index (trees) → mod1 BA > MCD45
- Lower LAI (shrubs, grasses) → MCD45 > mod1
- Croplands is exception: mod1 > MCD45 > GFED3
- GFED3 resembles MCD45 in many regions

More detailed comparisons are by Roy et al. (2008, RSE), van der Werf et al. (2010, ACP)
Effective fuel load, a.k.a. fuel consumption \((B \times C)\) estimates

- **CCI**, max fuel 6.0 kg/m^2
- **CCm**, max fuel 12.3 kg/m^2
- **CCh**, max fuel 25.4 kg/m^2

**Carbon Consumption database** CC\([l/m/h]\) from Weather and Ecosystem-Based Fire Emissions (WEB-FE)

- Low fire severity
- Medium
- High

**Global Land Cover (GLC) dataset**

- GLC, max fuel 8.9 kg/m^2
- GFED3, max fuel 313.8 kg/m^2

- **GFED3**

- **Largest absolute values and largest differences are in the forested areas**
- **Grass/shrubs** differences not so large, but most burning happens in Africa, Latin America, Australia
### Emission factors ($F_i$)

#### 1. Standard GOCART configuration
(Chin et al., 2007)

- $F_{BC} = 1.00 \text{ g/kgDM}$
- $F_{OC} = 8.00 \text{ g/kgDM}$
- $F_{SO2} = 1.12 \text{ g/kgDM}$

#### 2. GLC (Liousse et al., 2003, 2010)

<table>
<thead>
<tr>
<th>GLC code</th>
<th>GLC vegetation type description</th>
<th>Biomass density, kg/m²</th>
<th>Burning efficiency</th>
<th>$F_{BC}$, g(BC)/kg(DM)</th>
<th>$F_{OC}$, g(OC)/kg(DM)</th>
<th>$F_{SO2}$, g(SO2)/kg(DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tree Cover broadleaved evergreen</td>
<td>23.35</td>
<td>0.25</td>
<td>0.70</td>
<td>6.40</td>
<td>0.57</td>
</tr>
<tr>
<td>2</td>
<td>Tree Cover narrowleaved deciduous closed</td>
<td>20.00</td>
<td>0.25</td>
<td>0.60</td>
<td>6.00</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>Tree Cover broadleaved deciduous open</td>
<td>3.30</td>
<td>0.40</td>
<td>0.62</td>
<td>4.00</td>
<td>0.35</td>
</tr>
<tr>
<td>4</td>
<td>Tree Cover needle-leaved evergreen</td>
<td>36.70</td>
<td>0.25</td>
<td>0.60</td>
<td>6.00</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>Tree Cover needle-leaved deciduous</td>
<td>18.90</td>
<td>0.25</td>
<td>0.60</td>
<td>6.00</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>Tree Cover mixed leaf type</td>
<td>14.00</td>
<td>0.25</td>
<td>0.60</td>
<td>6.01</td>
<td>0.99</td>
</tr>
<tr>
<td>7</td>
<td>Tree Cover regularly flooded fresh water</td>
<td>27.00</td>
<td>0.25</td>
<td>0.70</td>
<td>5.00</td>
<td>0.57</td>
</tr>
<tr>
<td>8</td>
<td>Tree Cover regularly flooded saline water</td>
<td>14.00</td>
<td>0.60</td>
<td>0.65</td>
<td>5.15</td>
<td>0.46</td>
</tr>
<tr>
<td>9</td>
<td>Mosaic: Tree Cover / Other natural vegetation</td>
<td>10.00</td>
<td>0.35</td>
<td>0.61</td>
<td>5.00</td>
<td>0.68</td>
</tr>
<tr>
<td>10</td>
<td>Tree cover, burnt</td>
<td>0</td>
<td>0.35</td>
<td>0.61</td>
<td>5.00</td>
<td>0.68</td>
</tr>
<tr>
<td>11</td>
<td>Shrub Cover closed-open evergreen</td>
<td>1.25</td>
<td>0.90</td>
<td>0.62</td>
<td>4.00</td>
<td>0.35</td>
</tr>
<tr>
<td>12</td>
<td>Shrub Cover closed-open deciduous</td>
<td>3.30</td>
<td>0.40</td>
<td>0.62</td>
<td>4.00</td>
<td>0.35</td>
</tr>
<tr>
<td>13</td>
<td>Herbaceous Cover closed-open</td>
<td>1.43</td>
<td>0.90</td>
<td>0.62</td>
<td>4.00</td>
<td>0.35</td>
</tr>
<tr>
<td>14</td>
<td>Sparse herbaceous or sparse shrub cover</td>
<td>0.90</td>
<td>0.60</td>
<td>0.67</td>
<td>3.11</td>
<td>0.37</td>
</tr>
<tr>
<td>15</td>
<td>Regularly flooded shrub and/or herbaceous cover</td>
<td>0</td>
<td>0.35</td>
<td>0.67</td>
<td>3.11</td>
<td>0.37</td>
</tr>
<tr>
<td>16</td>
<td>Cultivated and managed areas</td>
<td>0.44</td>
<td>0.60</td>
<td>0.73</td>
<td>2.10</td>
<td>0.40</td>
</tr>
<tr>
<td>17</td>
<td>Mosaic: Cropland / Tree Cover / Other natural v.</td>
<td>1.10</td>
<td>0.80</td>
<td>0.64</td>
<td>3.64</td>
<td>0.36</td>
</tr>
<tr>
<td>18</td>
<td>Mosaic: Cropland / Shrub and/or grass cover</td>
<td>1.00</td>
<td>0.75</td>
<td>0.65</td>
<td>3.35</td>
<td>0.37</td>
</tr>
</tbody>
</table>

#### 3. GFED3 (van der Werf, 2010)

<table>
<thead>
<tr>
<th></th>
<th>Deforestation</th>
<th>Savanna and Grassland</th>
<th>Woodland</th>
<th>Extratropical forest</th>
<th>Agricultural waste burning</th>
<th>Peat fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC</td>
<td>4.30</td>
<td>3.21</td>
<td>3.76</td>
<td>9.14</td>
<td>3.71</td>
<td>4.30</td>
</tr>
<tr>
<td>BC</td>
<td>0.57</td>
<td>0.46</td>
<td>0.52</td>
<td>0.56</td>
<td>0.48</td>
<td>0.57</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.71</td>
<td>0.37</td>
<td>0.54</td>
<td>1.00</td>
<td>0.40</td>
<td>0.71</td>
</tr>
</tbody>
</table>
Estimating BB emissions:

2. Fire Radiative Power (FRP) - based approach

\[ E_j = c_{\text{region}_j} \times FRP \]

- \( E_j \): emission rate of gas/aerosol species \( j \) (g/sec)
- \( c_{\text{region}_j} \): region- and species-specific conversion factor
- \( FRP \): MODIS-measured Fire Radiative Power (MJ/s)

(Kaufman et al., 1996; Ichoku and Kaufman, 2005; Wooster et al., 2003, 2005)

Quick Fire Emissions Dataset (QFED2)

- Developed at NASA’s Global Modeling and Assimilation Office for GEOS-5 model
- Uses GFED3 emissions and MODIS AOD as parameters to derive \( c_{\text{region}_j} \)

(Darmenov and da Silva, 2012, manuscript in preparation)
Global total BC estimates for 2006

Vegetation types from Global Land Cover (GLC) dataset

1. Tree cover, broadleaved, evergreen
2. Tree cover, broadleaved, deciduous, closed
3. Tree cover, broadleaved, open
4. Tree cover, needle-leaved, evergreen
5. Tree cover, needle-leaved, deciduous
6. Tree cover mixed leaf type
7. Tree cover, regularly flooded, fresh water
8. Tree cover, regularly flooded, saline water
9. Mosaic: tree cover / other natural vegetation
10. Undefined
11. Shrub cover, closed-open, evergreen
12. Shrub cover, closed-open, deciduous
13. Herbaceous cover, closed-open
14. Sparse herbaceous or sparse shrub cover
15. Regularly flooded shrub and/or herbaceous cover
16. Cultivated and managed areas
17. Mosaic: Cropland/Tree cover/other natural veg
18. Cropland/Shrub and/or grass cover

Black Carbon Emissions, kg

\[ F_i \rightarrow B^*C \rightarrow A \rightarrow \text{fire counts-based} \]

Combined A, Ready-to-use emissions

FRP-based
Goddard Chemistry Aerosol Radiation and Transport (GOCART) model

- Global aerosol model

- Resolution: 1°(lat) x 1.25°(lon) x 30 vert. layers

- Meteorological fields from Goddard Earth Observing System Data Assimilation System (GEOS DAS) version 4

- 3-hourly output

- Emissions include: dust, sea salt, anthropogenic, sulfate & precursors, BB emissions

- BB emissions are input from external inventories
GOCART runs with 13 introduced emission options

- **Study period**: June 2006-June 2007 (+3 months spin-up)

- **13 emission options** are used as BB emissions in separate GOCART runs

- FRP-based QFED inventory uses MODIS AOD as a calibration dataset during development → will not compare to MODIS AOD
124 studied fire cases in 2006-2007

Background colors are Vegetation types from Global Land Cover (GLC) dataset.
Sample Case
Russia
2004-07-20
AOD vs. emissions

Background-dominated regime

BB-dominated regime
Plume dispersion

Side view

Top view

Low wind speed

High wind speed
The equation $Y = a + bX$ is used to model the relationship between the average GOCART AOD within the plume and the OC+BC daily-integrated fire emission in kg per km$^2$.

- $X$ is the OC+BC daily-integrated fire emission in kg per km$^2$.
- $Y$ is the average GOCART AOD within the plume.
- $a$ (related to the background aerosol loading) and $b$ (related to the plume environment) are wind-regime-dependent regional fit coefficients.

Fit is performed for 3+ data points above the emissions cutoff (~10 kg/km$^2$/day usually) in each wind speed category.
Limitations of using MODIS AOD to constrain BB emissions source strength

- We assume that AOD under- or overestimation is mostly a result of emissions deficit or excess, and errors in aerosol removal and optical properties are smaller.

- Total AOD provides poor constraint in heavily polluted environments or for thin plumes (background-dominated regime).

- Only one year of BB has been explored. Interannual variability and different burning regimes are needed to refine the method. + more cases in Alaska during stronger burning year.

- Coarse spatial resolution of the model, the method is insensitive to small variations in AOD during averaging and aerosol concentration changes.

- MODIS AOD product brings a set of its own limitations (omitting retrievals in thick plume cores, in cloudy scenes, omissions and biases above bright surfaces).
Expand the dataset of test cases to account for inter-annual variability of biomass burning and add cases to BB regions where too little burning was detected in 2006-2007 (Alaska)

- Severe vs. “regular” fires
- Consider plume height w.r.t. PBL (use MISR plume height climatology)

Improve the MODIS AOD validation dataset by developing a multi-sensor correction procedure in the regions of known bias [Levy et al. 2010; Hyer et al., 2011]

Define the criteria, develop and test an approach to merge the best-performing BB emission inventories for different regions

Estimate the role of the model configuration on the BB emissions-AOD relationship and subsequent analysis
AeroCom contribution

- Estimate the role of the model configuration on the BB emissions-AOD relationship and subsequent analysis (..test the emissions-AOD relationship in other models ..)

- **Suggested runs (2008):**
  - Standard model run with no BB emissions
  - Standard model run with your own emissions
  - Standard model run with provided new BB emissions, your emission injection height (EIH)
  - Standard model run with prescribed new emissions, prescribed EIH

- **Desired output:** daily
  - 3D: AOD, concentration, winds, Temperature, pressure
  - 2D: emissions (BC, OC, SO$_2$, other)
Background-dominated regions

China 2007-05-29

India 2006-10-15
Plume heights check (want to see most in PBL)

Stereo Heights of MISR pixels (km above terrain)

Region A

Clouds

Region B

MISR = Multiangle Imaging Spectroradiometer

CALIPSO = satellite with spaceborne lidar

Aerosol possibly above BL
Part 1 summary

- We have a representative set of commonly used BB aerosol emission estimates based on different approaches, but yielding a broad range of estimated emission amounts.
- Choice of burned area dataset has the greatest effect (up to an order of magnitude) on resultant emission estimates difference; emission factor or fuel consumption – contribute factor of 2-3 difference each.

Part 2

- Critically test performance of each emission option in the model: compare GOCART-simulated Aerosol Optical Depth (AOD) with satellite-measured smoke AOD.
Part 2 summary

- Regional analysis of emission inventories and their performance is essential
- AOD-emissions relationship forms 2 regimes: background-dominated, and BB-dominated
- In BB-dominated regime, wind speed defines the AOD-emissions relationship

Part 3

- Future work: Apply the current method to improve BB emission estimates for the global models