Feedbacks between Climate and Fire Emissions

Christine Wiedinmyer
National Center for Atmospheric Research

SERDP Partners in Environmental Technology
Technical Symposium & Workshop
November 29, 2011

Tech Session 1A:
Role of Fire in the Carbon Cycle under Climate Change
Fires emit significant amounts of trace gases and particulate matter to the atmosphere. These emissions include greenhouse gases, such as CO2 and methane, reactive gases that include a suite of non-methane organic compounds, and various particulate species, including black and organic carbon. Quantifying these emissions and constraining our understanding of their impacts on the atmosphere continues to be an on-going challenge. Recent advances in measurement techniques, remote sensing observations and modeling tools have enabled much better constraints on these processes, yet, large uncertainties remain. There are feedbacks between the fire and climate systems that can control the emissions from fires. Further, once in the atmosphere, fire emissions not only impact atmospheric composition and air quality, but can also influence the climate system in various ways. For example, particulate matter emitted to the atmosphere from fires can have direct radiative effects that can influence local meteorology, as well as processes that control atmospheric chemistry. This talk will address the various emissions from fires to the atmosphere and their controls, including climatic controls. The impacts of fires on the climate system will also be highlighted and the results from recent studies presented.
FEEDBACKS BETWEEN CLIMATE AND FIRE EMISSIONS

DR. CHRISTINE WIEDINMYER
National Center for Atmospheric Research
3090 Center Green Drive
Boulder, CO  80301
(303) 497-1414
christin@ucar.edu

Fires emit significant amounts of trace gases and particulate matter to the atmosphere. These emissions include greenhouse gases, such as CO₂ and methane, reactive gases that include a suite of non-methane organic compounds, and various particulate species, including black and organic carbon. Quantifying these emissions and constraining our understanding of their impacts on the atmosphere continues to be an on-going challenge. Recent advances in measurement techniques, remote sensing observations and modeling tools have enabled much better constraints on these processes, yet, large uncertainties remain. There are feedbacks between the fire and climate systems that can control the emissions from fires. Further, once in the atmosphere, fire emissions not only impact atmospheric composition and air quality, but can also influence the climate system in various ways. For example, particulate matter emitted to the atmosphere from fires can have direct radiative effects that can influence local meteorology, as well as processes that control atmospheric chemistry. This talk will address the various emissions from fires to the atmosphere and their controls, including climatic controls. The impacts of fires on the climate system will also be highlighted and the results from recent studies presented.
1. Long-lived GHG emissions

2. Short-lived climate forcers: particles

3. Ozone production

4. Change in surface properties
Fires Impacts on the Climate System

1. Emission of long lived greenhouse gases
   - $\text{CO}_2$
     ~ 6-7 Pg $\text{CO}_2$ annually released to atmosphere from open burning
   - $\text{N}_2\text{O}$
   - $\text{CH}_4$
2007 Global CO$_2$ emissions

**Total:**

38 Pg CO$_2$

*Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement

*Source*: Carbon Dioxide Information Analysis Center, Environmental Sciences Division, Oak Ridge National Laboratory, Tennessee, U.S.
CO$_2$ Emissions from open fires across the U.S.

Note: temporal & spatial variability

Wiedinmyer and Neff, CBM, 2007

Black lines represent monthly CO$_2$ emissions from fossil fuel combustion (U.S. Energy Information Administration)
Fires Impacts on the Climate System

1. Emission of long lived greenhouse gases
   - $\text{CO}_2$
     - $\sim 6-7$ Pg CO$_2$ annually released to atmosphere from open burning
   - $\text{N}_2\text{O}$
   - $\text{CH}_4$

2. Direct emission of short-lived climate forcers
   - Black Carbon
   - Particulate organic matter

3. Production of tropospheric ozone and secondary organic particulate matter
## Emissions from Fires

<table>
<thead>
<tr>
<th>Carbon Dioxide (CO₂)</th>
<th>Ethanol (CH₃CH₂OH)</th>
<th>Hydrogen Cyanide (HCN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>Methanol (CH₃OH)</td>
<td>Methyl Nitrate (CH₃ONO₂)</td>
</tr>
<tr>
<td>Nitrous Oxide (N₂O)</td>
<td>Phenol (C₆H₅OH)</td>
<td>Ethyl Nitrate (C₂H₅NO₃)</td>
</tr>
<tr>
<td><strong>Carbon Monoxide (CO)</strong></td>
<td>Formaldehyde (HCHO)</td>
<td>Ammonia (NH₃)</td>
</tr>
<tr>
<td>Acetylene (C₂H₂)</td>
<td>Glycolaldehyde (C₂H₄O₂)</td>
<td>Hydrogen (H₂)</td>
</tr>
<tr>
<td>Ethylene (C₂H₄)</td>
<td>Acetaldehyde (CH₃CHO)</td>
<td>Sulfur Dioxide (SO₂)</td>
</tr>
<tr>
<td>Ethane (C₂H₆)</td>
<td>Acrolein (C₃H₄O)</td>
<td>Nitrous Acid (HONO)</td>
</tr>
<tr>
<td>Propadiene (C₃H₄)</td>
<td>Furaldehydes</td>
<td>Nitrogen Oxides (NOₓ as NO)</td>
</tr>
<tr>
<td>Propylene (C₃H₆)</td>
<td>Propanal (C₃H₆O)</td>
<td></td>
</tr>
<tr>
<td>Propyne (C₃H₄)</td>
<td>Acetone (C₃H₆O)</td>
<td></td>
</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>Methyl Vinyl Ether (C₃H₆O)</td>
<td></td>
</tr>
<tr>
<td>n-Butane (C₄H₁₀)</td>
<td>Methacrolein (C₄H₆O)</td>
<td></td>
</tr>
<tr>
<td>1-Butene (C₄H₈)</td>
<td>Crotonaldehyde (C₄H₆O)</td>
<td></td>
</tr>
<tr>
<td>1,3-Butadiene (C₄H₆)</td>
<td>2,3-Butanedione (C₄H₆O₂)</td>
<td></td>
</tr>
<tr>
<td>n-Pentane (C₅H₁₂)</td>
<td>Furan (C₄H₄O)</td>
<td></td>
</tr>
<tr>
<td>3-Methyl-1-Butene (C₅H₁₀)</td>
<td>3-Methylfuran (C₅H₆O)</td>
<td></td>
</tr>
<tr>
<td>Isoprene (C₅H₈)</td>
<td>Formic Acid (HCOOH)</td>
<td></td>
</tr>
<tr>
<td>Cyclopentane (C₅H₁₀)</td>
<td>Acetic Acid (CH₃COOH)</td>
<td></td>
</tr>
<tr>
<td>n-Hexane (C₆H₁₄)</td>
<td><strong>Methyl Bromide (CH₃Br)</strong></td>
<td></td>
</tr>
<tr>
<td>Heptane (C₇H₁₆)</td>
<td><strong>Methyl Iodide (CH₃I)</strong></td>
<td></td>
</tr>
<tr>
<td>Benzene (C₆H₆)</td>
<td><strong>Trichloromethane (CHCl₃)</strong></td>
<td></td>
</tr>
<tr>
<td>Toluene (C₆H₅CH₃)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xylenes (C₈H₁₀)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethylbenzene (C₈H₁₀)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,3,5-Trimethylbenzene (C₉H₁₂)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>α-Pinene (C₁₀H₁₈)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Particulate Carbon**
- PM₂.₅
- PM₁₀

**Total Suspended Particulate (TSP)**
- Black Carbon (BC)
- Organic Carbon (OC)
- Oxylate (C₂O₄)
- Nitrate (NO₃)
- Phosphate (PO₄)
- Sulfate (SO₄)
- Ammonium (NH₄)
- Cl
- Ca
- Mg
- Na
- K
Global Trace Gas Emissions Estimates

**NO$_2$**

- Anthro
- Biogenic
- Fires

**CO**

**NMOC**

Yokelson et al., ACP, 2008

EDGARFT2000
Yan et al., GBC, 2005
Guenther et al., 1995; 2006; pers. comm.
GFEDv2 (van der Werf et al., 2006)
Andreae and Merlet, GBC, 2001
Global Particulate Matter Emissions

Organic Particulate Matter

Black Carbon

Andreae and Rosenfeld, *Earth Science Reviews*, 2008
Emission Estimates in the U.S.

Fine Particulate Matter ($PM_{2.5}$) Emissions from Fires in Western U.S.

- Annual Anthropogenic $PM_{2.5}$ emissions for 2005
Atmospheric Impacts of Emissions
Violations in $O_3$ health standards in rural areas happened three times more likely because of pollution from the wildfires.
Particles:
- Black Carbon
- Organic Carbon
- Secondary Organic Particles
- Particulate Matter
- Precipitation
- Trace Gases
- Ozone
Radiative Forcing of Particulate Carbon

Total Black Carbon and Particulate Organic Matter Top of the Atmosphere (TOA) forcing

Bond et al., ACP, 2011
Regional Climate Feedbacks from Fires

Equatorial Asia

Reduced Precipitation

Reductions in Net Shortwave Radiation →
(a) SST cooling
(b) Land surface cooling

Black Carbon Absorption →
(a) Tropospheric Heating
(b) Reduced latent heating

Biomass Burning Particulate Emissions

During El Nino- drought and increased fire emissions

Tosca et al., ACP, 2010
Regional Climate Feedbacks from Fires

INHIBIT PRECIPITATION

INCREASE # CLOUD DROPS

DECREASE IN DROP SIZE

INCREASE CCN

SMOKE

(e.g., Andreae et al., 2004; Rosenfeld 1999)
Regional feedbacks to weather and chemistry

Use coupled weather-chemistry model to investigate the feedbacks between the fire emissions, weather, and chemistry

Jiang, Wiedinmyer and Carlton, *in preparation*
Regional feedbacks to weather and chemistry

- Inclusion of fire particulate emissions:
  - Reduction in shortwave radiation
  - Reduction in surface temperature
  - Change in PBL height
  - Decreases in atmospheric water vapor mixing ratio
  - Change ozone concentrations

Fire emissions have regional climate impacts:
- Meteorology and chemistry
- Local and regional effects
- Short-lived impacts

Jiang, Wiedinmyer, and Carlton, in preparation
Fires Impacts on the Climate System

1. Emission of long lived greenhouse gases
   - $\text{CO}_2$
     $\sim 6-7 \text{ Pg CO}_2$ annually released to atmosphere from open burning
   - $\text{N}_2\text{O}$
   - $\text{CH}_4$

2. Emission of short-lived climate forcers
   - Black Carbon
   - Particulate organic matter

3. Production of tropospheric ozone and secondary organic particulate matter

4. Changes in land surface properties
   - Black carbon on snow
   - Albedo
Radiative Forcing of Black Carbon on Snow

Bond et al., ACP, 2011
Fire impacts on climate: Land Cover Change

Post Fire Impacts:
- Surface temperature
- Vegetation production
- Albedo

Impact of fire disturbance on land surface energy and carbon balances. In the summer of 2002, the Biscuit Fire in Oregon destroyed 2000 km² of temperate evergreen forests (left). A Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image taken on 28 July 2003 (middle) shows land surface radiometric temperatures of 46° to 50°C in the area burned the summer before, whereas temperatures in the adjacent unburned forests range from 27° to 32°C. Annual vegetation production measured from MODIS (4) (right) was 20 to 60% lower in the burned area in 2003 to 2004 than before the wildfire.

Running, Science, 2008
Concluding Remarks

- Emissions from open biomass burning are substantial – at global and regional scales.

- Fires can have many impacts on the regional and global climate system:
  - Highly non-linear
  - Impacts occur on various time scales

- Our range in understanding of the emissions and their feedbacks remains large.
Acknowledgements

Bob Yokelson, Sheryl Akagi (University of Montana)
Gavin McMeeking (Colorado State University)
Matthew Hurteau (Penn State University)
Anthony Westerling (Univ. of California-Merced)
Annmarie Carlton (Rutgers University)
Xiaoyan Jiang (Los Alamos National Lab/NCAR)
Louisa Emmons, Gabi Pfister (NCAR)
Jason Neff (University of Colorado)
Carbon Emissions from fire

Source: Andreae and Merlet, GBC, 2001; IPCC, 2007; Bond et al., ACP, 2011
Aerosol effects

Figure 2.10. Schematic diagram showing the various radiative mechanisms associated with cloud effects that have been identified as significant in relation to aerosols (modified from Haywood and Boucher, 2000). The small black dots represent aerosol particles; the larger open circles cloud droplets. Straight lines represent the incident and reflected solar radiation, and wavy lines represent terrestrial radiation. The filled white circles indicate cloud droplet number concentration (CDNC). The unperturbed cloud contains larger cloud drops as only natural aerosols are available as cloud condensation nuclei, while the perturbed cloud contains a greater number of smaller cloud drops as both natural and anthropogenic aerosols are available as cloud condensation nuclei (CCN). The vertical grey dashes represent rainfall, and LWC refers to the liquid water content.
Estimated contribution of fire associated with deforestation to changes in radiative forcing

Bowman et al., *Science*, 2009
Emissions from Fires: Global Warming Potential

Andreae and Merlet, GBC, 2001; IPCC, 2007; Bond et al., ACP, 2011
Models to Predict Emissions from Fires

• Fire-Specific Models
  – Biscuit Fire (Campbell et al., 2007)

• Regional Models
  – North America (Wiedinmyer et al., AE, 2006)
  – Asia (Song et al., ERL, 2010)
  – Western Africa (Liousse et al., 2010)
  – Western U.S. (Urbanski, ACPD, 2011)

• Global Models
  – GFED (van der Werf et al., AC&P, 2010)
  – FINN (Wiedinmyer et al., GMD, 2011)
Estimating Emissions from Fires

\[ \text{Emission}_i = f(ef_i, \text{Biomass Burned}) \]

**Emission Factor**
- Vegetation
  - Type
  - Condition
- Fire
  - Intensity

**Biomass Burned**
- Vegetation
  - Type
  - Condition
  - Density
  - Loading
- Fire
  - Intensity
  - Duration
### Global Emissions from Open Biomass Burning

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>7590</td>
<td>7723</td>
<td>7275</td>
<td>6433</td>
<td>6886</td>
</tr>
<tr>
<td>CH₄</td>
<td>18</td>
<td>20</td>
<td>18</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>CO</td>
<td>375</td>
<td>400</td>
<td>372</td>
<td>330</td>
<td>347</td>
</tr>
<tr>
<td>NMOC</td>
<td>81</td>
<td>92</td>
<td>81</td>
<td>71</td>
<td>75</td>
</tr>
<tr>
<td>NO</td>
<td>13</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>SO₂</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>OC</td>
<td>23</td>
<td>24</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>BC</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

* Emissions in Tg year⁻¹

Wiedinmyer et al., *GMD*, 2011