Effects of Black Carbon and CO$_2$ Domes on Climate and Air Quality

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Consequences of Global Change for Air Quality Progress Review
MODIS Aqua Cloud Optical Depth vs. AOD Over Biomass-Burning Region Brazil Sep ‘06

Ten Hoeve, Remer, and Jacobson (2010)
Boomerang Effect: Satellite COD vs. AOD

MODIS, binned by percentile column water vapor 2004-07 for (a) all clouds (b) low clouds → boomerang for all water bins

Calipso Lidar Aug. 12, 2006 → aerosols below/within clouds → boomerang from MODIS

Ten Hoeve, Remer, and Jacobson (2010)
GATOR-GCMOM Model COD vs. AOD
Sep. ‘06

Ten Hoeve, Remer, and Jacobson (2010)
Cloud Microphysical and Chemical Processes

Condensation/deposition of water vapor onto aerosol particles

Coagulation: Aerosol-aerosol  Aerosol-liquid  Aerosol-ice  Aerosol-graupel
       Liquid-liquid  Liquid-ice  Liquid-graupel  Ice-ice
       Ice-graupel  Graupel-graupel

Gas dissolution, aqueous chemistry, hom.-het. freezing, contact freezing

Interstitial aerosol

Dissolved, reacted gas

Liquid

Aerosol-particle core

Ice

Coagulated aerosol particle

Graupel

Shrinkage, precipitation, rainout, and washout

Gas dissolution and aerosol-particle coagulation during precip. (washout)

Rainout of core and existing gas

Cloud evaporation --> interstitial aerosol plus evaporated cores
Absorption Efficiency 12.6-micron cloud drops

DEMA1,2=0.1-, 0.2-micron BC inclusions; Brug=Bruggeman (BC well-mixed); Core/shell=single BC core

MODIS / Model Aerosol Optical Depth

MODIS Avg: 0.28

Model Avg: 0.19

Ten Hoeve, Remer, and Jacobson (2010)
Modeled vs. Aeronet Solar Irradiance at Cuiaba-Miranda, Brazil

Ten Hoeve and Jacobson (2010)
Model vs. Radiosonde Downwind of Biomass Burn, Sep. 2006

Ten Hoeve and Jacobson (2010)
Global Simulations

Simulate the relative effects of controlling fossil-fuel soot (FS), biofuel soot and gases (BSG), and methane on global and Arctic climate and human health.

Simulations run
1) Baseline (all gases, particles from all sources)
2) Time-dependent simulations without FS
3) Time-dependent simulation without FS or BSG
4) Equilibrium climate simulations without methane, CO$_2$. 
Aerosol Size Distributions

Two distributions, each with multiple size bins and components per bin

Ejected fossil-fuel soot (EFFS)
Emission sources: fossil-fuel combustion

Internally-mixed (IM)
Emission sources: biofuel burning, biomass-burning, sea spray, soil dust, road dust, volcanos, pollen, spores, bacteria

Homogeneous nucleation: $\text{H}_2\text{SO}_4-\text{HNO}_3-\text{H}_2\text{O}$ into IM distribution

Coagulation:

- EFFS + EFFS = EFFS
- EFFS + IM = IM
- IM + IM = IM

Growth: Organic matter, $\text{H}_2\text{SO}_4$, $\text{HNO}_3$, $\text{HCl}$, $\text{NH}_3$, $\text{H}_2\text{O}$ grow on both EFFS & IM

Clouds: Both distributions activate size-resolved liquid, ice, graupel clouds
## Fine Fossil-, Bio-fuel Emissions (Tg/yr)

<table>
<thead>
<tr>
<th></th>
<th>Fossil-Fuel</th>
<th>Biofuel</th>
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<tbody>
<tr>
<td>BC</td>
<td>3.2</td>
<td>1.6</td>
</tr>
<tr>
<td>POC</td>
<td>2.4</td>
<td>6.5</td>
</tr>
<tr>
<td>S(VI)</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>Na⁺</td>
<td></td>
<td>0.023</td>
</tr>
<tr>
<td>K⁺ as Na⁺</td>
<td></td>
<td>0.14</td>
</tr>
<tr>
<td>Ca²⁺ as Na⁺</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>Mg²⁺ as Na⁺</td>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>NH₄⁺</td>
<td></td>
<td>0.018</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td></td>
<td>0.16</td>
</tr>
<tr>
<td>Cl⁻</td>
<td></td>
<td>0.30</td>
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<tr>
<td>H₂O-hydrated</td>
<td>calculated</td>
<td>calculated</td>
</tr>
<tr>
<td>H⁺</td>
<td>calculated</td>
<td>calculated</td>
</tr>
</tbody>
</table>

BC/POC from Bond et al. (2004); other emis factors Andreae, Ferek

+ 43 gases
Relative Fossil-Fuel POM, S(VI), BC Emission Size Distributions

Distributions based on fits to EEPS data for vehicles and BC spherule size limits from EST 39, 9486, 2005, except that a coarse mode was added for FF-sources that emit coarse PM (e.g., tire particles, stationary sources).
Despite factor of 20 lower resolution than data, model predicts locations of main features of observed precipitation and, with no flux adjustment, correctly does not produce a double ITCZ as nearly all models at coarse resolution do.
Modeled vs. Measured Cloud Fraction

Data from MODIS
Model calculates lightning by accounting for size-resolved bounceoffs and charge separation in clouds. It predicts nearly the magnitude and the location of the peak observed lightning (Congo) and most locations of lightning.
Modeled vs. Measured Thermal-IR

Data from Kiehl et al., 1998
Modeled vs. Measured 500-hPa Jan Temperature

Data from AIRs
Despite coarse resolution, model captures data features at exact location of data
- Little numerical diffusion of water vapor or energy to stratosphere
Modeled vs. Measured Paired in Space Monthly O$_3$

Data from Logan et al. (1999)

Model predicts the magnitude and altitude of the lower-stratospheric ozone layer
Modeled vs. Measured Sea Ice Area

Model (at 4 x 5 degree resolution) predicts stable sea ice area after only two years of simulation

Data from NASA Team (2009)
Global Cooling Due to Eliminating Anthropogenic CH$_4$, Fossil Soot and Biofuel Soot+Gases (FSBSG) and FS Emissions only
Global Cooling Due to Eliminating Anthropogenic CO$_2$, CH$_4$, FSBSG, and FS Emissions only
Arctic Warming Due to Anth. CH$_4$, Fossil Soot and Biofuel Soot+Gases (FSBSG), & FS

FF+BF soot + BF warm mid & high northern latitudes more than anthropogenic CH$_4$ or FF soot alone
Radiative Forcing Estimates due to 100% Fossil-Fuel Soot (BC+OM) (W/m²)

<table>
<thead>
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<tbody>
<tr>
<td>Indirect forcing</td>
<td>-0.26</td>
<td>-0.26&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Direct forcing</td>
<td>+0.14</td>
<td>+0.25&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Semi-direct effect</td>
<td>0</td>
<td>+0.15&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cloud absorption effect</td>
<td>0</td>
<td>+0.15&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>BC-snow effect</td>
<td>0</td>
<td>+0.05&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Increase in H₂O, CH₄</td>
<td>0</td>
<td>+0.10&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-0.12</strong></td>
<td><strong>+0.44</strong> (Fig. 5g)</td>
</tr>
</tbody>
</table>

<sup>a</sup> Assumed same as Chen et al. upon scaling their result from 50% to 100% soot forcing
<sup>b</sup> From Jacobson (JGR, 2002)
<sup>c</sup> Estimated from Jacobson (JGR, 2010) Hansen et al. 2002 estimate 0.3-0.6 for all BC
<sup>d</sup> Estimated from Jacobson (JGR, 2010)
<sup>e</sup> From IPCC (2007) assuming fossil-fuel BC+OM is ~50% of the total BC-snow effect.
<sup>f</sup> Estimate from increase in water vapor (mostly) and methane from simulations
15-Year, Globally-Averaged Net Solar+Thermal-IR Irradiance Change due to FS and FSBSG

Net irradiance change for FS ~0.44 W/m²
### FF Soot, BC Global Warming Potential

<table>
<thead>
<tr>
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<th>20-yr STRE</th>
<th>100-yr STRE</th>
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<tbody>
<tr>
<td>BC+POC in FS</td>
<td>2400-3800</td>
<td>1200-1900</td>
</tr>
<tr>
<td>BC in FS</td>
<td>4500-7200</td>
<td>2900-4600</td>
</tr>
<tr>
<td>BC+POC in BSG</td>
<td>380-720</td>
<td>190-360</td>
</tr>
<tr>
<td>BC in BSG</td>
<td>2100-4000</td>
<td>1060-2020</td>
</tr>
<tr>
<td>Methane</td>
<td>52-92</td>
<td>29-63</td>
</tr>
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</table>

STRE = Surface Temperature Response per Unit Emission

= Near-surface temperature change after 20 or 100 years per unit continuous emission of X relative to the same for CO₂ (similar to GWP e.g., 20-, 100-yr GWPs for CH₄ are 72, 25).
Contributors to Global Warming

Jacobson (2010, JGR 115, D14209)
Summary

Several factors affect soot’s climate effect aside from indirect effects: cloud absorption, semidirect effect, snow albedo effect, water vapor effect, internal mixing effect.

With these effects, FSBSG soot may be the second-leading cause of global warming behind CO\textsubscript{2} and ahead of CH\textsubscript{4}. FS causes 3 x the warming of BSG, but BSG causes \sim 7x more deaths than FS.

Net global warming (0.7-0.8 K) appears due primarily to gross warming from FF GHGs (2-2.4 K) and FSBSG (0.4-0.7 K) offset by cooling due to non-FSBSG aerosol particles (-1.7 to -2.3 K).

FS and FSBSG may contribute to 13-16% and 17-23% of gross warming from pollutants. Controlling FS, FSBSG may be the fastest and only method of preventing Arctic loss.

www.stanford.edu/group/efmh/jacobson/controlfossilfuel.html
CO$_2$ Domes Over Cities

3-D modeled increases in CO$_2$ due to local emissions for February-April in Los Angeles - numbers in parentheses are population-weighted values.

Change in surface/column CO$_2$ from local CO$_2$ emissions = “CO$_2$ Dome”
Increases in Water Vapor and Temperature Both Increase Ground-Level Ozone in Polluted Air But Not in Background Air

→ California has 6 of the 10 most polluted U.S. cities → Suffers largest impact of higher T, H₂O among states.  

GRL L03809 2008
Feb-Apr L.A. Death Increases Due to CO$_2$ Domes

3-D model results

Additional O$_3$ deaths/yr

Additional PM deaths/yr

Local CO$_2$ emissions increase ozone and PM deaths

PM increases due to

1) increased stability, thus reduced winds and diffusion
2) higher RH thus more gas uptake in aerosols many locations
3) Increased biogenic (not L.A.), evaporative emissions VOCs
Aug-Oct L.A. Deaths From CO$_2$ Dome

3-D model results

Additional O$_3$ deaths/yr

Additional PM$_{2.5}$ deaths/yr

Local CO$_2$ emissions increase ozone and PM deaths
Spatial Correlation Between Increased Local CO$_2$ and Increased O$_3$ (left) & PM$_{2.5}$ (right) in Los Angeles
Changes in California Due to Local CO$_2$

Numbers in parentheses are population-weighted values

- Change in column CO$_2$ “CO$_2$ Domes”
- Increase in surface air temperature
- Increase in column H$_2$O

Local CO$_2$ emissions increase temperatures, water vapor
Additional $O_3$ deaths/yr From CO$_2$ Domes

Increase in surface $O_3$  Additional $O_3$ deaths/yr

Local CO$_2$ emissions increase $O_3$ and $O_3$ deaths
Additional PM deaths/yr From CO$_2$ Domes

Local CO$_2$ emissions increase PM$_{2.5}$ deaths
1-Year Death Inc. Due to CO₂ Domes

Additional ozone deaths/yr

Increase in CO₂ from local emissions

Additional PM deaths/yr

Local CO₂ emissions increase PM₂.₅ and O₃ deaths
Locally-emitted CO$_2$ produces CO$_2$ domes, which increase local ozone and PM$_{2.5}$ premature deaths in California by $\sim$50-100/yr. Thus, reducing locally-emitted CO$_2$ may reduce local air pollution and mortality. If correct, this result contradicts the basis for all previous local air pollution regulation worldwide, which has ignored CO$_2$, thus it provides the basis for controlling CO$_2$ due to its local health impacts.

The result also implies that the main assumption behind “cap and trade” that CO$_2$ impacts are the same regardless of where CO$_2$ is emitted, is incorrect.

Papers:
http://www.stanford.edu/group/efmh/jacobson/Ve.html
http://www.stanford.edu/group/efmh/jacobson/urbanCO2domes.html
Simulation-Averaged Emitted FF-soot BC

BC from FF soot is about half that of BC from FF+BF soot
Internally-Mixed BC From the FF Soot Simulation and from FF+BF Soot Simulation

- Internally-Mixed FF BC
- Internally-Mixed FF+BS BC

BC from FF soot is about half that of BC from FF+BF soot
BC in Snow Due to FF+BF Soot + BF gases and FF Soot Alone

Both FF+BF soot and FF soot increase BC in snow
Surface Albedo Changes Due to FF+BF Soot + BF gases and to FF Soot Alone

Most albedo loss due to FF+BF soot + BF gases is due to FF soot.
AOD Changes Due to FF+BF Soot + BF gases and to FF Soot Alone

- FF+BF soot + BF gases increased AOD more than did FF soot.
Cloud Absorption Due to BC Inclusions in Clouds

Cloud absorption OD change due to FF+BF soot + BF gases

→ FF+BF soot + BF gases increased cloud absorption more than FF soot
Cloud OD Changes Due to FF+BF Soot + BF gases and to FF Soot Alone

Cloud OD change due to FF+BF soot + BF gases

Cloud OD change due to FF soot

FF+BF soot + BF gases increased COD; FF soot decreased COD
Surface Solar Changes Due to FF+BF Soot + BF gases and to FF Soot Alone

- FF+BF soot + BF gases decreased surface solar; FF soot increased it

Surface solar change due to FF+BF soot + BF gases

Surface solar change due to FF soot

→ FF+BF soot + BF gases decreased surface solar; FF soot increased it
Temperature Changes Due to FF+BF Soot + BF gases and to FF Soot Alone

Most temperature inc. due to FF+BF soot + BF gases is due to FF soot

Air temperature change due to FF+BF soot + BF gases

Air temperature change due to FF soot

Most temperature inc. due to FF+BF soot +BF gases is due to FF soot
Changes in PM and Resulting Deaths due to FF+BF soot + BF gases and to FF soot

Deaths due to BF soot+gases ~7 times those due to FF soot