Linking Regional Aerosol Emission Changes with Multiple Impact Measures through Direct and Cloud-Related Forcing Estimates

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Organization

- Project overview – Tami Bond
- Size-resolved emission inventory – Dave Streets, reported by Tami Bond
- U.S. regional cloud modeling – Hao He
- Emission-to-forcing measures – Yanju Chen
- Policy-relevant metrics – Praveen Amar, reported by Tami
Project Overview

Or, Why we Did What We Did

(Tami Bond)
The simple view

A dose-response curve for the atmosphere

Forcing

Emission
Bounding-BC lesson

The big uncertainty in BC-rich sources

- **BC** → direct forcing ~ bounded
- **BC** → cloud forcing
  ~ large uncertainties – especially in ice/mixed
- **OC + SO₄** → direct forcing
  ~ small for BC-rich sources
- **OC + SO₄** → cloud forcing
  ~ large and probably negative

*It’s the *indirect* effects of *co-emitted* species that cause big questions about immediate forcing*
Cumulative forcing (add successive categories)

BC forcing positive (+0.33)
Total forcing positive (+0.15)

Bounding-BC Fig 38
Cumulative forcing (add successive categories)

- BC forcing positive (+0.33)
- Total forcing positive (+0.15)

- BC forcing positive (+0.72)
- Total forcing still positive (+0.21)
  but becoming less certainly so, because of cloud uncertainties

Bounding-BC Fig 38
Cumulative forcing (add successive categories)

BC forcing positive (+0.33)
Total forcing positive (+0.15)

BC forcing positive (+0.72)
Total forcing still positive (+0.21)
but becoming less certainly so,
because of cloud uncertainties

BC forcing positive (+1.01)
Total forcing nearly neutral (-0.06)
because of large OC & its cloud forcing
(note: simple sum differs from BC
median produced by Monte Carlo analysis)

Bounding-BC Fig 38
Cumulative forcing (add successive categories)

9

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(note: simple sum differs from BC
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Remainder of aerosol forcing
is in low-BC categories (total -0.95)

Bounding-BC Fig 38
So you got *[some scientific thing]* right. Who cares? Tell me if I should turn this off!

Can you wait 6 months? I have to run my model…
Need a **forcing-to-emission** ratio

*Simple*

\[
Forcing_{\text{source}} = \frac{\text{Forcing}_{\text{modeled}}}{\text{Emission}_{\text{modeled}}} \times \text{Emission}_{\text{source}}
\]
Need a *forcing-to-emission* ratio

**Simple**

\[
\text{Forcing}_{\text{source}} = \frac{\text{Forcing}_{\text{modeled}}}{\text{Emission}_{\text{modeled}}} \times \text{Emission}_{\text{source}}
\]

**Complex**

\[
CF = FC \sum_{i=1}^{I} EF_i \left( \sum_{j=1}^{J} r_{\text{for}c_{i,j}} + \sum_{k=1}^{K} f_{\text{resp}_{i,k}} \right)
\]

Bounding-BC

\[ r_{\text{for}c_{i,j}} = \left. \frac{\partial f_j}{\partial e_i} \right|_{PD} \]
Definition

**Emission-Normalized Forcing** (ENF)

*including*

- **ENDRF** Direct Radiative Forcing
- **ENIRF** Indirect Radiative Forcing

Forcing_{\text{modeled}} \quad \text{approximates this:}

\[ r_{\text{forc},i,j} = \left. \frac{\partial f_j}{\partial e_i} \right|_{PD} \]
Detour: Climate “metrics”

**Normal people think:**
A metric is something you can measure, and report

**The climate policy community says:**
A metric is a well-defined calculation that can be used to *equate* a mass emission of some species to a mass emission of the big bear, CO$_2$
Some climate metrics

Absolute global warming potential → Global warming potential → Global temperature potential

For short-lived species (τ<4 mo), emission-normalized forcing is the **only** model output required to calculate **any** of these metrics.

Other considerations affect the values of emission metrics, but they all come from models of the carbon cycle or Earth’s heat capacity, NOT from models of aerosols.
Complaints against ENF

Forcing is not linear!

You can’t do that for CLOUDS!

It’s different in every REGION.

Anyway none of the model runs were designed for that.
Need: Emission-normalized forcing for both direct forcing and cloud mechanisms.

**Objective 3: Determine functional relationships that express changes in direct and cloud radiative forcing as a function of emission changes in particular locations**
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**Objective 3:** Determine functional relationships that express changes in direct and cloud radiative forcing as a function of emission changes in particular locations

*But wait…*
Relative location of BC and clouds affects direct forcing
It surely also affects *indirect* forcing!!

In this earlier study, we found that the modeled clouds were
Community Atmospher

Note: Also affects semi-direct forcing; see Ban-Weiss et al, Clim Dyn, 2011
Strategy: Compare modeled fields with ISCCP observations

ISCCP = International Satellite Cloud Climatology Project

image: nasa.gov
Need: Confidence in modeled clouds before inferring cloud forcing from a model.

Objective 2: Employ an ensemble of parameterizations in regional-scale models to identify best estimates and uncertainties for fields of direct and cloud-related forcing.
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**Objective 2:** Employ an ensemble of parameterizations in regional-scale models to identify best estimates and uncertainties for fields of direct and cloud-related forcing.
Aerosol effects are size-dependent

Fig. 4. Global mean AIE and ADE [W/m²] values for all size experiments, (S1–4) and the base experiment, BA, for present day conditions.

*Bauer et al.*, ACP, 2010

for carbonaceous aerosols
Need: Knowledge of emission size distributions.

**Objective 1:** Develop size-resolved, speciated emission inventories of aerosols and aerosol precursors
Need: Knowledge of particle size, beginning with emission.

**Objective 1:** Develop size-resolved, speciated emission inventories of aerosols and aerosol precursors

But wait…
YES?!
I’m waiting....
YES?!
I’m waiting……

ALL DONE!
Need: Policy-distilled measures or metrics

**Objective 4:** Iterate emission-to-forcing measures as communication tools between decision makers and climate scientists
Size-Resolved Emission Inventory

Or, Why we Did What We Did

(David Streets, Ekbordin Winijkul, Fang Yan - Ar presented by Tami)
Procedure

PM size distribution from literature [by sector, fuel, and technology]

Parameterize size distribution [lognormal or mixture distribution] (see next slide)

Emission factors by size \((E_{F_{dp}}, \text{ g PM/ kg fuel})\) [Continuous distribution or discrete bins]

Size-resolved PM emission inventory

We already had this

Emission factors \((E_F, \text{ g PM/ kg fuel})\)

Fuel consumption
Parameterizing size distribution

Fit with lognormal distribution…

\[
f (\ln D_p) = \frac{1}{\sqrt{2\pi} \ln \sigma_g} \exp \left[ -\frac{\left( \ln D_p - \ln D_{pg} \right)^2}{2 \ln \sigma_g^2} \right]
\]

…or bimodal distribution

\[
f (x) = w_1 f_1 (x) + w_2 f_2 (x) \quad 0 \leq w \leq 1
\]

Data source: Zhao et al. (2010), AE [Fig.1b, Plant 1#2]
Global size-resolved emission inventory

Size-resolved global emission inventory of primary particulate matter (PM) from energy-related combustion sources
E. Winijkul, F. Yan, Z. Lu, D. G. Streets, T. C. Bond, Y. Zhao
Submitted to Atmos Env, 28 August 2014
Work includes uncertainty and illustrative reduction scenarios

Residential:
Switching from solid fuel to LPG

Industrial:
Baghouses on cement kilns

Winijkul et al., submitted, 2014
Regional Cloud Modeling

Or, Get the Clouds Right

(Hao He, Xin-Zhong Liang – Univ of Maryland)
Modeling Approach

- We used the mesoscale Climate–Weather Research and Forecasting model (CWRF) model.
- Total aerosol field (not just BC) is produced by global models.
- CWRF has alternative parameterizations for cloud properties, aerosol properties, and radiation transfer.

*Purpose: Investigate range of climate forcing in models that agree with observations*
Uncertainty in Cloud-Aerosol-Radiation Modeling

Frequency distribution of TOA radiative flux and CRF averaged over [60ºS, 60ºN] in January 2004 from the CAR ensemble of 960 members

Modeling Approach

- Meteorology: ECWMF ERA interim reanalysis
- Canadian Centre for Climate Modeling and Analysis (CCCMA) radiation scheme

- Model run from 2001 to 2006, with the first year (2001) as spin-up. Average from 2002 to 2006 is presented.
One base case; Five aerosol fields

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Case Name</th>
<th>Temporal Resolution</th>
<th>Aerosol input</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Noaerosol</td>
<td>N/A</td>
<td>Aerosol radiation Off</td>
</tr>
<tr>
<td>2</td>
<td>Default</td>
<td>Monthly</td>
<td>MISR Climatology</td>
</tr>
<tr>
<td>3</td>
<td>NCAR</td>
<td>Monthly</td>
<td>NCAR CAM2 model</td>
</tr>
<tr>
<td>4</td>
<td>GOCART$</td>
<td>Monthly</td>
<td>GOCART model</td>
</tr>
<tr>
<td>5#</td>
<td>CAM5</td>
<td>Monthly</td>
<td>UIUC CAM5 model</td>
</tr>
<tr>
<td>6*</td>
<td>CAM5’</td>
<td>Monthly</td>
<td>UIUC CAM5 model</td>
</tr>
</tbody>
</table>

$ Chin et al 2014; #Assuming all BC and OC are hydrophilic; *Assuming only 85% of BC and OC are hydrophilic
Clear-sky flux: Differences from ISCCP

No aerosol

Default (MISR)

NCAR CAM5

GOCART
Clear-sky flux: Differences from ISCCP

Note the scale. Errors in flux are 10s of W m$^{-2}$. Forcing is < 5 W m$^{-2}$.
Cloudy-sky flux: Differences from ISCCP

- No aerosol
- Default (MISR)
- NCAR CAM5
- GOCART
Comparison between modeled and observed fluxes (average over Continental US)
Error bars are std dev of all grid boxes
Model bias: Difference between CWRF results and ISCCP
Aerosol radiative effects:
Difference between modeled results with & without aerosols
BC and OC partition have substantial impacts on the radiation simulations:
1) Impacts on clear sky flux are uniform.
2) Cloud radiative effects are large ($\pm 5 \text{ W/m}^2$) and regionally dependent, for instance opposite effects are suggested in the southeast US and in the northwest US.
Emission-to-forcing measures

Or, Model Interpretation for Policy Relevance

(Yanju Chen– Univ of Illinois)
Step 1: Test linearity and regionality

- Basis to obtain forcing-per-emission relationship; assumed by emission metrics.

- Direct forcing – *probably* linear

- Cloud forcing – *may be* nonlinear with respect to aerosol concentration (Quaas et al., 2009)

- May vary by region
Experimental Design

- Test linearity between forcing and emission
- Calculate emission-normalized forcing (ENF)
- Apply ENF to calculate forcing in any emission reduction scenario

- Reduce BC from N. America (AM BC)
- Reduce BC from Asia (AS BC)
- Reduce OC from N. America (AM OC)
- Reduce OC from Asia (AS OC)
Model Description and Configuration

- Modified Community Atmosphere Model (CAM5.1)
  - *Three-modal aerosol module (MAM3) (Liu et al., 2012)*
  - *Improved BC spatial and temporal distribution* with modified convective transport and wet removal
  - Tagged BC/OC emission for direct calculation of burden and forcing

- Anthropogenic emissions: from IPCC emission datasets for year 2000 (*Lamarque et al., 2010*).

- Model is configured to run in off-line mode (*Ma et al., 2013*)
  - Model reads in prescribed meteorological fields
  - Model driven by ERA-interim data
  - Semi-direct effect cannot be simulated

- Each simulation is run for 5 years with 2 months for model spin-up.
Need for off-line meteorology

- Perturbation of BC (reducing BC in N. America)
- Variability in total forcing
- Change of climate and meteorology
- Change of burden of other aerosol species

Percentage change of dust burden when reducing BC from N. America from 100% to 50%

- Direct forcing change is caused by **non-BC aerosols** (dust).
- Since cloud-related forcing is inferred from total flux change, it is obscured by dust changes.
- Dust needs to remain in the atmosphere, because it could also affect clouds.
Linearity diagnostic for a single species

\[ R = \frac{F_{100} - F_{50}}{F_{100} - F_0} \]

100% present-day emission → 50% present-day emission

R ≈ 0.5: Forcing is linear in emission.
R < 0.5: Small emission change from present-day produces less forcing change than one would expect

0 emission
Linearity of Global Mean Forcing

2 regions: AM=North America; AS=Asia
Emission-normalized forcing

Bounding-BC values

Indirect forcing, ENIRF: 3-4 times higher in N. America (not saturated)
Reducing same amount of BC/OC in these two regions will result in greatly different cloud change.

Direct radiative forcing, ENDRF:
similar for N. America and Asia
Is cloud forcing visible?

Multi-model study of effects on liquid clouds

Each row is from a different model.

No forcing pattern visible.

Koch et al., ACP 11, 1051, 2011
Regional Location of Indirect Forcing

Example: OC from Asia

* Significant region was statistically determined using paired t-test between IRF0, IRF50 and 0 at significance level $a = 0.1$
Optimum grid box size for testing significance

- Box too small: Each box noisy; few boxes significant
- Box too large: Includes regions with little impact; too few boxes are significant
- $30^\circ \times 30^\circ$ is optimum
- Significant grid boxes equal global mean forcing; the rest are noise
Radiative Forcing in Significant Regions

(a) AMBC reduction

- Only 20-30% of the grid boxes are significant
- Near and downwind of source region

(b) AMOC reduction
Linearity in Significant Regions

- Direct radiative forcing (DRF) is linear in all regions
- Indirect radiative forcing (IRF) is nonlinear in some significant regions, especially for OC
Cause of Nonlinearity

- Nonlinearity occurs when cloud droplets are formed from CCN.
- Formation of droplets is limited, and does not increase as the number of CCN increases.
- Of course, this depends on model parameterization…
Summary – Indirect forcing

- Apparent effect on clouds—ENIRF: N Am OC > N Am BC > Asian OC > Asian BC
- In high-aerosol regions, reducing present-day aerosol has a less-than-linear effect
- Global average forcing can be attributed to a subset (<40%) of significant regions

However, comparison with observations calls modeling of aerosol-cloud effect in North America into question

*Next—Compare global & regional aerosol effect in North America*
Policy-relevant metrics

Or, Get the Story Right

(Praveen Amar, Danielle Meitiv– Clean Air Task Force presented by Tami)
Original goal: Communicate with policy makers to see what metrics they want

<table>
<thead>
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<th>Professional Roles</th>
<th>Number of Interviewees</th>
<th>Percentage of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academic – Climate Policy/Science</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Air Quality Management – State Level</td>
<td>7</td>
<td>20</td>
</tr>
<tr>
<td>Air Quality Management – Federal Level</td>
<td>11</td>
<td>31</td>
</tr>
<tr>
<td>Federal – Climate Policy/Science</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
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<td>9</td>
</tr>
<tr>
<td>NGO – Climate Advocacy</td>
<td>6</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 1. Professional roles and expertise of the interviewees and their percentage of the total pool of interviewees.

“Communicating the science and policy implications of black carbon” – CATF report
Main messages had nothing to do with metrics

- Scientists need understandable ways to communicate black carbon’s effects to non-specialists
  - Even terms like “radiative forcing” and “feedback” are not as straightforward as you think.
- People want to hear about certainty, not uncertainty.
Main messages had nothing to do with metrics

- Equating BC and CO$_2$: Some are wary; in other situations (e.g. California) it’s required.
  - People do not want to think about time horizons. That’s our job.
  - People do not want to think about metrics. Ditto.
- There is not yet a good way to communicate immediacy of forcing changes.
  - Watch this space
Summary of outcomes – easy ones

1: Size-resolved inventory complete.
4: Metrics are up to us. Make it easy.
Summary of outcomes – hard ones

2: The constraint problem: Looking to confirm small changes (forcing) in a large signal (clouds).

3a: Forcing is nearly linear in emission, if regions are treated individually.
   - Average over statistically significant (30x30) boxes.
   - High-aerosol regions have lower indirect forcing per emission. More promising to reduce there.

3b: Cloud models don’t match observations.
   - Reason to doubt emission-to-forcing is not the model’s nonlinear nature, but its inability to match reality.
Done. Questions?
Supplemental slides
Radiative flux in CWRF

We calculated, total radiative flux @ TOA (TOAFlux), clear sky flux @ TOA (CTOAFux) and cloud radiative effect (CldRE) as:

\[ \text{TOAFlux} = SW_{\text{down,TOA}} + LW_{\text{down,TOA}} - SW_{\text{up,TOA}} - LW_{\text{up,TOA}} \]

\[ \text{CTOAFux} = SW_{\text{down,clear}} + LW_{\text{down,clear}} - SW_{\text{up,clear}} - LW_{\text{up,clear}} \]

\[ \text{CldRF} = \text{TOAFlux} - \text{CTOAFux} \]
Selected References


