Global Inventories
of carbonaceous aerosols

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Geneva, Switzerland
1. estimating emissions
   a. particular challenges of carbonaceous aerosols
   b. inventory procedure & brief results
   c. major uncertainties
2. a brief history of inventories
   a. present dilemma
3. work on the future (from D. Streets)

not here (and *needed*):
- *secondary anthropogenic* aerosol
- *biogenic* aerosol
BC/OC emission challenge

- **Emission estimation**
  - harder than species with bounded emissions (CO₂, SO₂)
  - similar to process-dependent species (NOₓ, CO)

- **Model validation**
  - harder than well-mixed species (CO₂, CH₄)
  - similar to species with short lifetimes (SO₂/SO₄⁻, CO)

- **Chemistry-optics connection**
  - harder than single species (CO₂, CH₄, even SO₄⁻)

1a. some challenges
Variability in different burning of the same fuel

1a. some challenges
Variability between similar sources

**Response to regulation**

<table>
<thead>
<tr>
<th>Emission rate (g/kg)</th>
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<td>0</td>
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<td>2</td>
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<td>3</td>
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<table>
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<td>1980</td>
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<tr>
<td>1990</td>
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<td>2000</td>
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From Yanowitz et al., 2000

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**Cumulative Distribution of CO Emissions from Passenger Cars in Bangkok**

- Vehicles
- Emissions

From Yanowitz et al., 2000

**Cumulative Distribution of Smoke Opacity for Buses in Bangkok**

- Vehicles
- Emissions

Source: McGregor and others 1994

From Faiz et al., 1996

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1a. some challenges
Diesel engines are constrained to lean equivalence ratios because of the soot limit—the point at which “excessive soot” begins to form [8]. This limit is apparent in the figure for values of φ greater than about 0.6 when engine speed is about 600 RPM. At higher speeds, the acceptable φ is even lower, because the particles have less time to oxidize. The value of EIabs at 800 RPM, φ = 0.6 was greater than 40 m² kg⁻¹.

Figure 7-1. Emission of absorption (left) and mass (right) from Caterpillar engine.

1a. some challenges
emission from one technology
  = fuel use x PM emission factor x characteristics

- activity levels (usually *fuel*)
  - International Energy Agency, United Nations, etc.
- emission factors (vary by fuel/technology)
- characteristics (also vary by fuel/technology)
  - BC fraction
  - Removal by control devices
  - Size (affects optical properties)
- technology divisions
  - division into >100 fuel+technology categories
  - regionally-distinct technology divisions

total emissions = sum over technologies
global sources

Bond, Streets et al., JGR 109, D14203, doi:10.1029/2003JD003697

1b. estimation procedure
Estimating uncertainties

- activity factors
  - high case has larger contribution of polluting activity
- emission factors
  - 1. process differences?
  - 2. assume lognormal
  - 3. estimate expected value & c.i.
  - 4. combine characteristics assuming independence
- EF for fuel/sector
  - combine confidence intervals assuming linear dependence & asymmetric distribution
- sectoral emissions
  - combine c.i. assuming asymmetric distribution & independence
- sectoral energy data
  - each fuel/sector has own uncertainty
- total emissions
  - asymmetric distribution, independence

1b. estimation procedure
uncertainties

- inventory contains full uncertainty propagation (activity estimates, emission factors, etc)
- of course, there are many guesses

<table>
<thead>
<tr>
<th>Sector</th>
<th>N.America</th>
<th>S/C America</th>
<th>Europe</th>
<th>Former USSR</th>
<th>Asia</th>
<th>Africa</th>
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<td>OC</td>
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Uncertainty > 25% of total “contained combustion” emission estimate for region

Uncertainty > 10%

1c. major uncertainties
Open biomass burning

Issues

→ Quantities of vegetative matter burned
→ Emission factors variable with combustion conditions; not represented

Image: CSIRO

1c. major uncertainties
Transport sector

**Issues**

 notoriously on-road

- estimated fleet emission factor (fleet information hard to find for many countries)
- superemitters
- difference between dynamometer measurements & real world

off-road mobile/industrial

- estimated from fraction of fuel used in various sectors
- country treatment of reporting is inconsistent

1c. major uncertainties

Image: www.nada.org
Issues

- limited measurements
  - emission factors/characteristics
  - types of industrial use
  - willingness to be measured

1c. major uncertainties
Domestic biofuel

**Issues**

- **fuel quantities**
  - haven’t been well estimated even by energy sector
  - not just a “developing” country issue (per-capita wood use in U.S. 50% of that in India)

- **emission factors**
  - many sources; difficult to estimate average
  - measurement of aerosol type (BC/OC) most uncertain

1c. major uncertainties
Field measurements higher than lab measurements
(Christoph Roden, UIUC, work in progress)

Mass & speciation information from different sources

1c. major uncertainties
<table>
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<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Description</th>
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<td>Turco</td>
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<td>1993</td>
<td>Penner</td>
<td>Based on fuel use</td>
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<tr>
<td>1996</td>
<td>Cooke &amp; Wilson</td>
<td>Fossil fuel + biofuel</td>
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<td>1996</td>
<td>Lioussse</td>
<td>Biomass/biofuel</td>
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<td>1999</td>
<td>Cooke et al</td>
<td>Emissions different by development level</td>
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<td>2001</td>
<td>Andreae &amp; Merlet</td>
<td>Comprehensive tabulation of biomass emission factors</td>
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<tr>
<td>2004</td>
<td>Bond &amp; Streets</td>
<td>Emissions different by technology</td>
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</table>
A brief history of global inventories

<table>
<thead>
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<th>Year</th>
<th>Authors</th>
<th>Black Carbon</th>
<th>Organic Carbon</th>
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<tbody>
<tr>
<td>1983</td>
<td>Turco</td>
<td>2.6-22</td>
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<tr>
<td>1993</td>
<td>Penner</td>
<td>6.6 FF, 6 BB</td>
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<td>24 (ratios w/sulfur)</td>
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<td>Cooke &amp; Wilson</td>
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<td>Cooke et al</td>
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<td>10 FF</td>
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<td>4.8 BB</td>
<td>36 BB</td>
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<tr>
<td>2004</td>
<td>Bond &amp; Streets</td>
<td>3.0 FF, 5.0 BB/ BF (4.3-22)</td>
<td>2.4 FF, 31 BB/ BF (17-77)</td>
</tr>
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</table>
Why the reduction in FF emissions?

Differences are easily explained.

Coal, power generation (difference 1.5 Tg/yr)
We rely on measured BC fractions (<1%) instead of guesses (25%)

On-road diesel (difference 1 Tg/yr)
We use emission measurements and World Bank studies instead of assuming “developing countries have 5x higher emissions” (15 g/kg average PM emission factor)

Domestic diesel (difference 0.25 Tg/yr; large in Europe)
We do not apply emission factors for internal combustion engines to external-combustion boilers

2. inventory history
The present dilemma

- “corrections” reduced emission estimates from 14 Tg/yr to 8 Tg/yr
- models typically need more BC to match observations... not less!
- measurement techniques may be uncertain...
- ...but probably not enough to explain discrepancy.

2a. inventory dilemma
Forecasting BC and OC emissions

From Bond et al., JGR, 2004

3. future carbonaceous
How fast will control technology improve?

Electrostatic precipitator, high collection efficiency

Cyclone, low collection efficiency

3. future carbonaceous
Representing time trends with S-shaped technology penetration curve

- 1996 current emission factor (Bond/Streets)
- Shape depends on lifetime, build rate, etc.
- “Net” performance in 2030
- “Ultimate” performance

Emission rate (g/kg)

Time (years)

3. future carbonaceous
Technology improvement overwhelms energy growth!

3. future carbonaceous
General decline in all cases

Results suggest we are headed for a world with stable or lower primary aerosol emissions.

3. future carbonaceous
Main message

- Estimating emissions of carbonaceous aerosols has challenges that may go beyond previous IPCC inventories.
- Technology & other practice are important.
- More cooperation and information from local knowledge is needed.