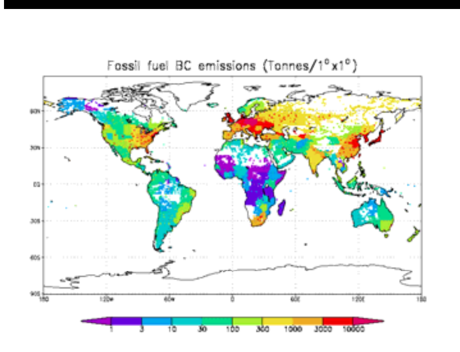
Black Carbon as a Short-Lived Climate Forcer: A profile of Emission Sources and Co-Emitted Pollutants



Tesh Rao and Joseph Somers
Office of Air and Radiation
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EPA Emissions Inventory Conference
San Antonio, TX

SLCF Science

- Emerging evidence that aerosol particles, and especially the BC component is a potent source of human-induced warming
- Unlike CO_2, which can remain in atmosphere for centuries, BC has a very short life span (days-to-weeks before deposition and removal)
- Thus, if we can reduce BC emissions now, it would help blunt warming almost instantly and help offset some of the effects felt by LLGHGs like CO_2
- Slowing atmospheric build up of CO_2 the most important long-term strategy for combating climate change
- However, recent research points to the fact that shorter-lived pollutants, including BC, CH_4, and tropospheric O_3 maybe collectively responsible for as much Temperature impact as CO_2, especially in receptor regions like the Arctic
- BC has global, regional, AND local effects. Regional effects may be the ones to focus initial mitigation efforts on.

BC is the shortest-lived of all the SLCFs

- Small dark particles that remain after incomplete combustion of fossil fuel or biomass
- BC warms primarily by absorbing solar radiation
- In areas covered with snow and ice, deposition of BC darkens the surface, increasing absorption
- BC also has health impacts since it is a component of $PM_{2.5}$
- BC is always co-emitted with a range of other pollutants during combustion, with the most important being OC
- Much of OC is likely “cooling.” However “Brown Carbon” is light-absorbing and is part of the OC spectrum.
- The ratio of BC/OC emissions for a given source is a potentially important metric when talking climate mitigation

Black carbon is different in a number of ways from GHGs

- Definitional uncertainties and lack of standardized measurement techniques
- Short-lived in atmosphere (not well mixed like GHGs)
- Location matters more (e.g., proximity to Arctic can lead to additional effects)
- Causes precipitation, “dimming”, and snow albedo effects not directly associated with GHGs
- Co-emitted with other aerosols including organic carbon which has cooling effects (different sectors have different BC:OC ratios)
- Number and size of particles can matter (not just mass); aging processes in the atmosphere
- Estimates of common metric ‘radiative forcing’ more uncertain compared to well-mixed GHGs

Given all of this mounting evidence on BC…

- Congress has required EPA to conduct a comprehensive study on BC, due April 2011
  - An inventory of major sources of BC
  - An assessment of the impacts of BC on global and regional climate
  - An assessment of potential metrics for quantifying the climactic effects of BC emissions…comparisons to CO_2
  - An identification of the most cost-effective approaches to reduce BC emissions
  - An analysis of the climactic effects and other environmental and public health benefits of those approaches
    - To fulfill this charge, EPA has conducted an intensive effort to compile, assess, and summarize available scientific information on the current and future impacts of BC, and to evaluate the potential costs and benefits of pursuing additional BC mitigation efforts to protect climate, public health, and the environment. The results are presented in the *Report to Congress on Black Carbon*.

Presentation Today…

- Focus of this presentation will be on the inventory portions of the report, as well as general inventory-related issues that are not necessarily part of the RtC
  - Only recently has black carbon science received more attention at EPA, including inventory issues
  - Which sources are dominant emitters of BC globally and domestically?
  - What are the spatial distributions of BC emissions?
  - How much OC do major source categories and major emitters of EC emit? What are characteristic OC:EC ratios?
  - Future areas of focus

Report to Congress Outline

Chapter	1	BLACK CARBON AS A CLIMATE POLLUTANT
Chapter	2	AMBIENT CONCENTRATIONS AND EMISSIONS OF BLACK CARBON
Chapter	3	GLOBAL AND REGIONAL CLIMATE IMPACTS OF BLACK CARBON
Chapter	4	MITIGATION APPROPACHES FOR REDUCING GLOBAL EMISSIONS OF BLACK CARBON
	4.1	Mobile Source Mitigation
	4.2	Stationary Source Mitigation
	4.3	Residential Heating and Cooking Mitigation
	4.4	Open Biomass Burning
	4.5	Cost-Effective Mitigation Options: Analytic Synthesis
Chapter	5	BENEFITS OF MITIGATING BLACK CARBON
	5.1	Climate Benefits of Black Carbon Mitigation
	5.2	Public Health Benefits of Black Carbon Mitigation
	5.3	Other Environmental Benefits of Black Carbon Mitigation
	5.4	Summary of Benefits of Reducing Black Carbon

How do we estimate BC in our inventories?

- “BC” inventories are calculated mathematically from $PM_{2.5}$ inventories, which are estimated in the NEI using a “bottom-up” approach
  - For the purposes of this discussion, “BC” and “EC” will be used interchangeably. Most measurements in the US are EC.
- These calculations divide the direct carbonaceous particle emissions from the $PM_{2.5}$ inventory into two categories: EC and OC.
  - By tracking only EC, current inventories fail to account for the portion of primary OC emissions that is light absorbing
  - This likely means current domestic (and international) inventories systematically underestimate total LAC; however, the magnitude of this gap has not been adequately quantified to date.
- Currently, emissions of EC and other PM constituents (OC, nitrates, sulfates, crustal material) are <u>not</u> directly reported as part of the NEI.
  - Chemical speciation of PM2.5 in the inventories is done via the emissions modeling process
  - EC emissions for most sources are estimated by matching $PM_{2.5}$ emissions from the NEI for those sources to source-specific EC speciation profiles from the “SPECIATE” database
    - The one exception is on-road mobile sources, for which EC emissions are estimated directly through OTAQ models
  - Since EC estimates are developed via modeling inventories, we generally have estimates for every year.

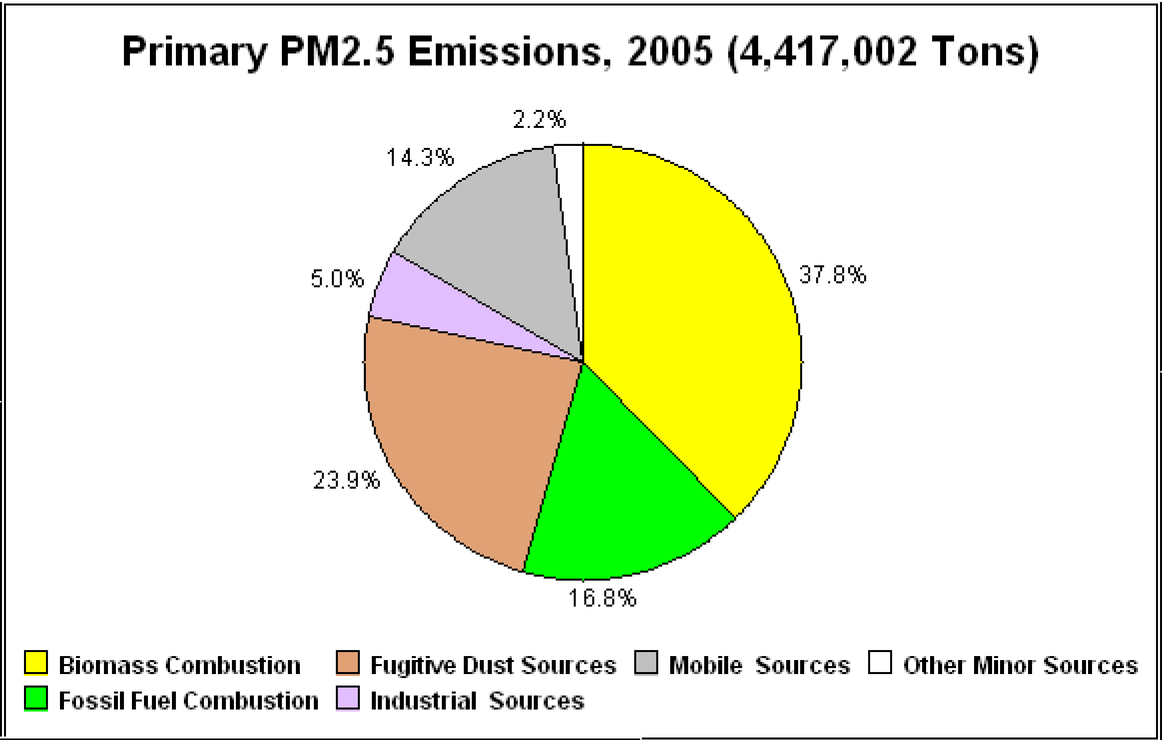
Domestic Emissions

2005 U.S. Tons of EC by “Mega” Source Categories

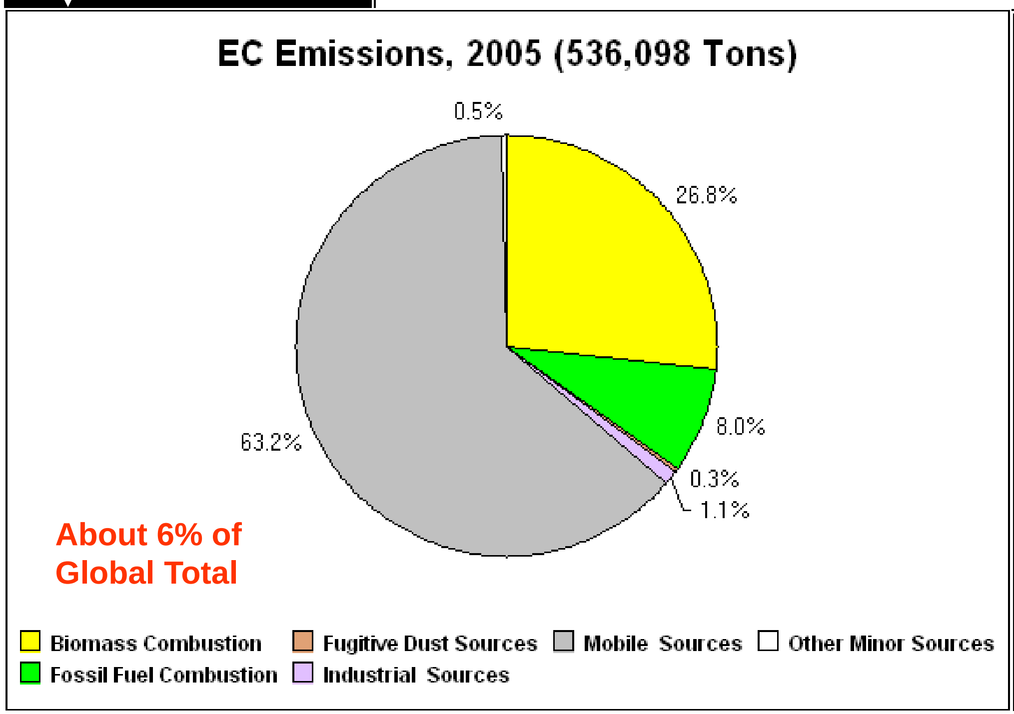
"Mega" Source Category	$PM_{2.5}$	EC	OC	EC/OC	EC/PM2.5
Biomass Combustion	1,668,395	143,902	775,724	0.19	0.09
Fossil Fuel Combustion	740,335	43,049	48,888	0.88	0.06
Fugitive Dust Sources	1,056,877	1,609	46,221	0.03	0.00
Industrial Sources	219,460	6,083	16,232	0.37	0.03
Mobile Sources	633,222	338,930	204,855	1.65	0.54
Other Minor Sources	98,714	2,525	16,640	0.15	0.03
Totals:	**4,417,002 (4,007 Gg)**	**536,098 (486 Gg)**	**1,108,560 (1,006Gg)**	**0.48**	**0.12**

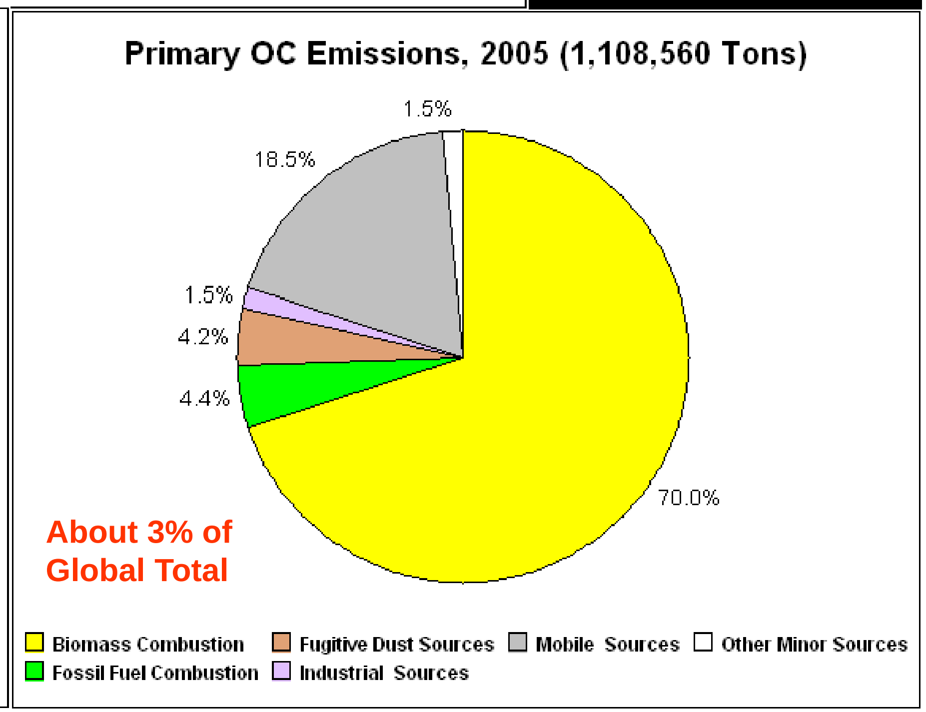
- Mobile Sources and Biomass Burning comprise ~90% of EC in the US
- Mobile Sources PM2.5 is mostly carbon, not so for other categories
- Highest EC/OC ratio for mobile sources; biomass emissions show very low EC/OC
- In these inventories, ~12% of PM2.5 is EC, about 25% of PM2.5 is OC (ambient data shows EC to be between 5-12% of PM2.5 mass)

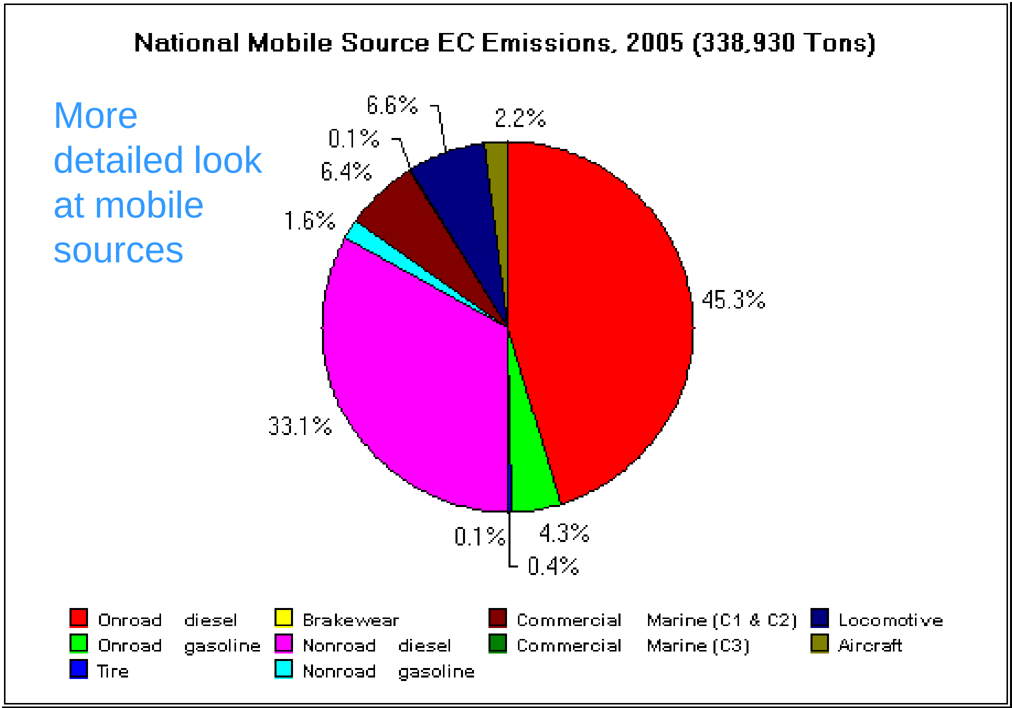
- EC inventory dominated by Mobile Source Emissions



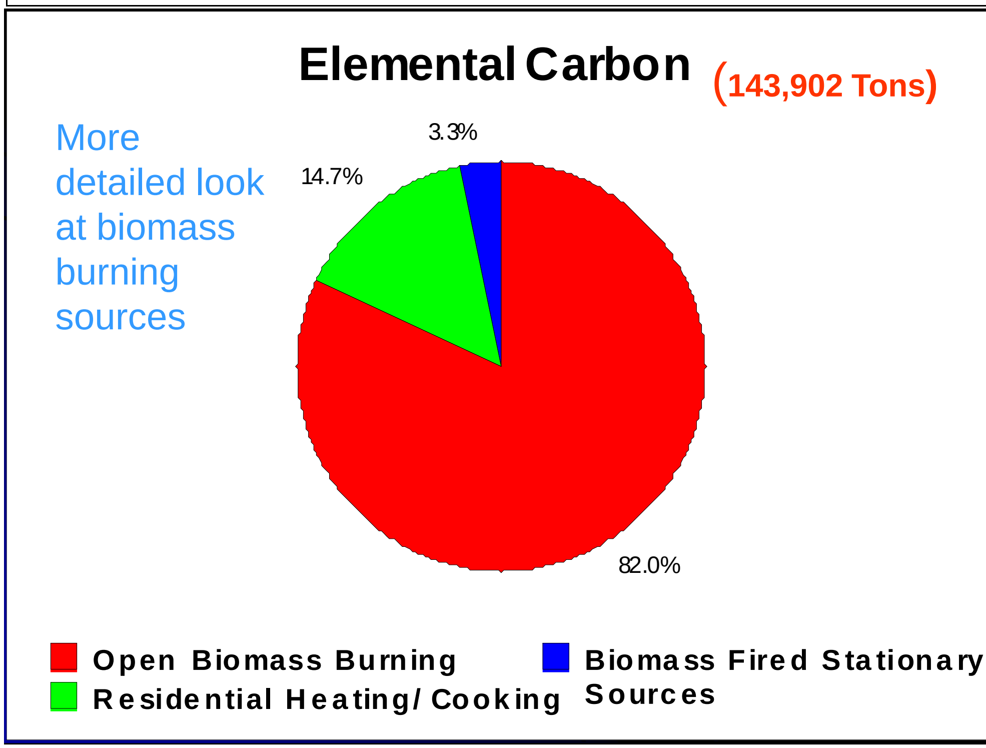
- OC inventory dominated by Burning



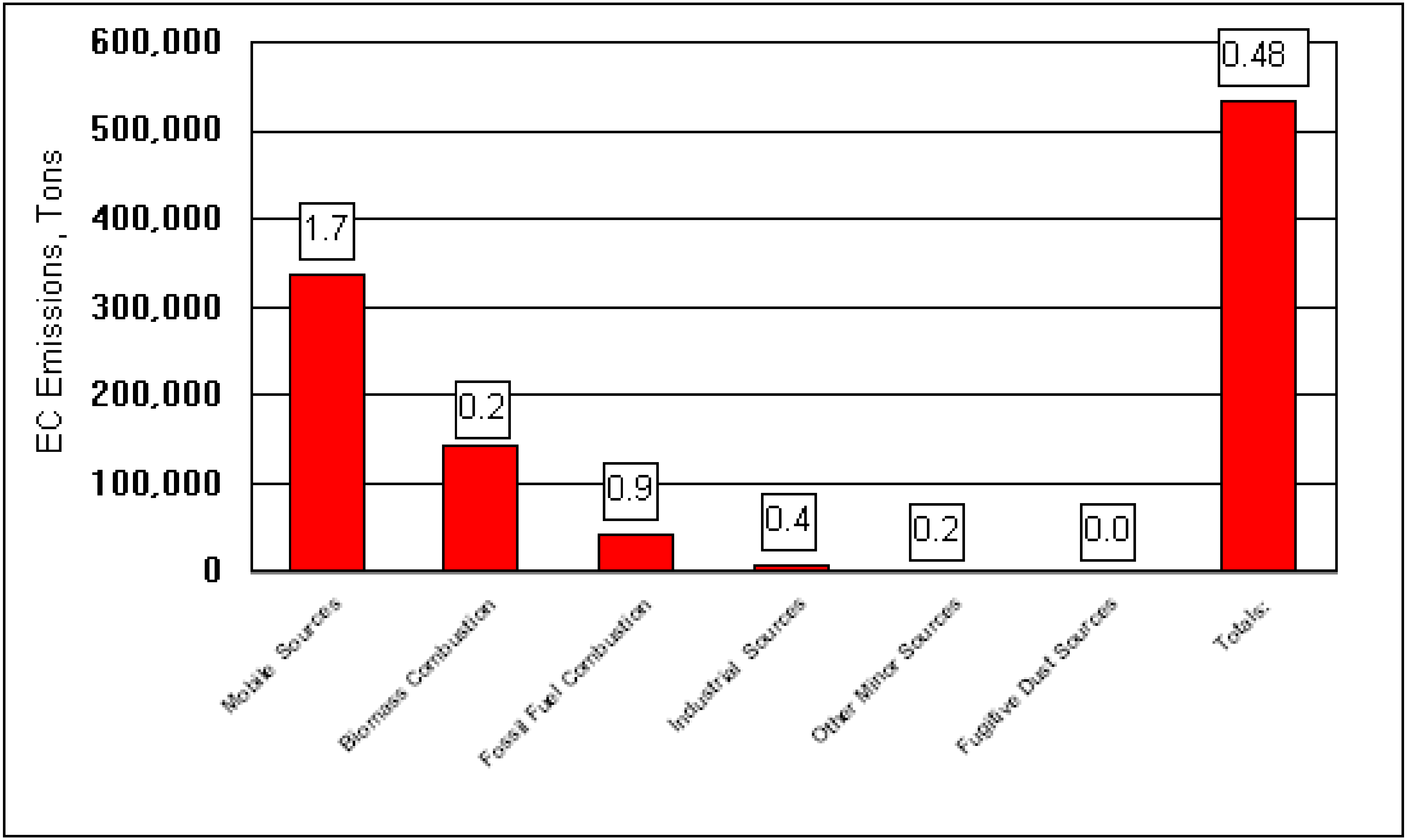




- Mobile Source EC inventory dominated by diesel sources in 2005 (nearly 90%)
- Some categories based on limited amount of EC speciation information
- In the future, diesel emissions will be reduced making other categories stand out

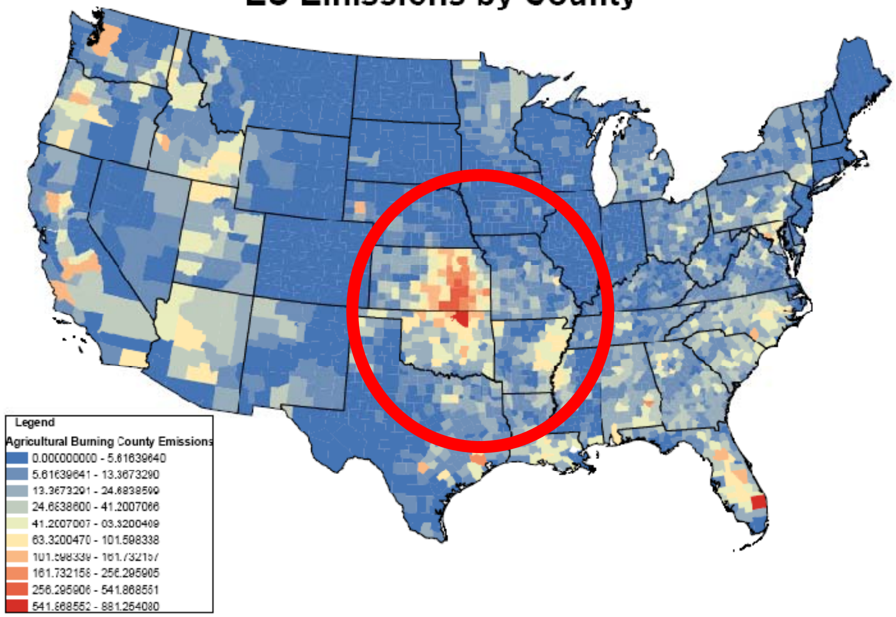


- All burning categories have lots of OC, making them questionable mitigation targets for climate purposes
- OC from burning could have significant amounts of light-absorbing brown carbon
- Open burning (ag, Rx, and wildfires) dominate US EC inventory
- Some of burning is very seasonal
- In future years, fires are expected to make up much larger percentage of BC inventories

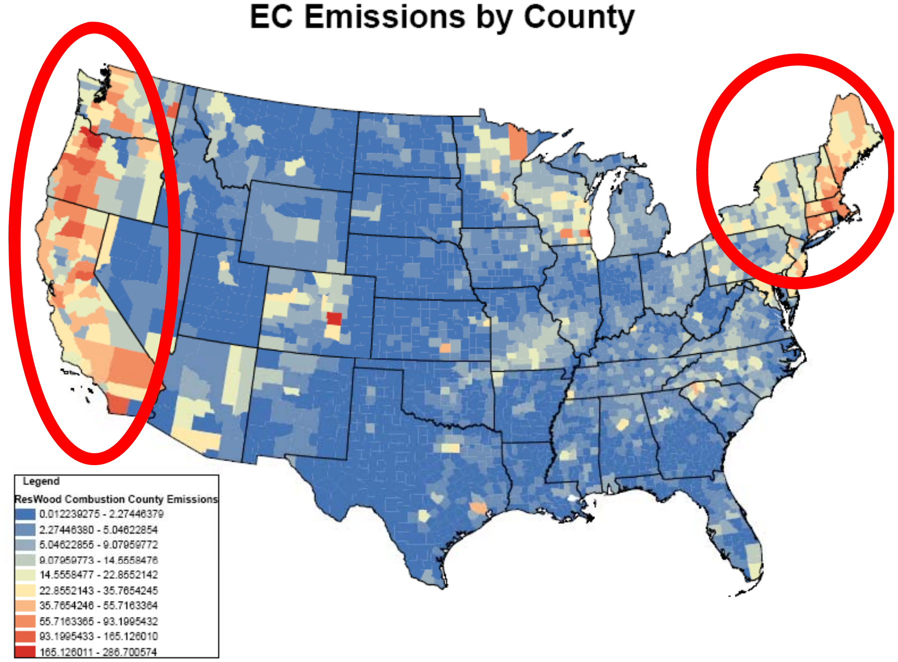


- The EC/OC ratio is often used to rank sources for climate mitigation purposes
  - For health purposes, this ratio is not as meaningful (all chemical constituents of PM2.5 cause HEs)
  - In areas like the Arctic, this ratio is also less useful
- Mobile sources (diesel) are the only category that show more EC than OC emissions

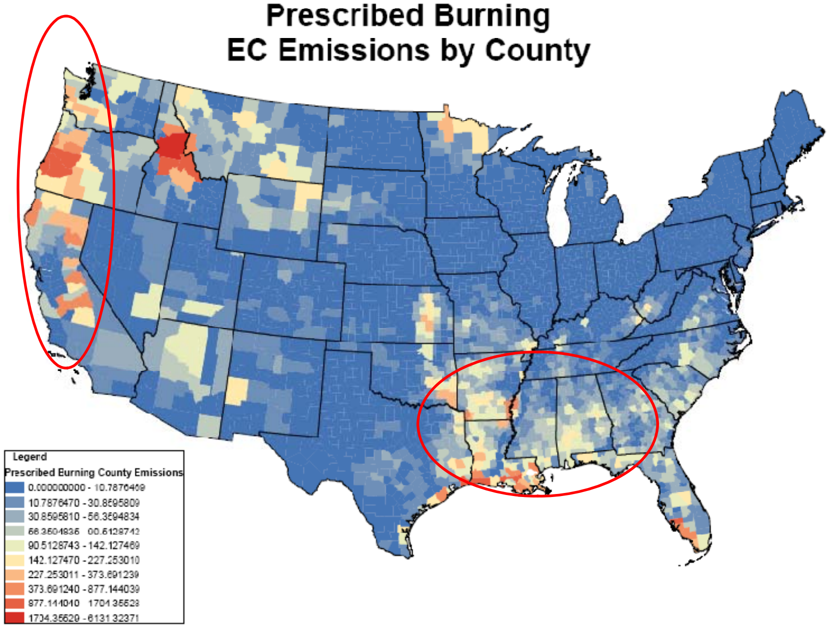
Agricultural Burning
EC Emissions by County



Residential Wood Combustion
EC Emissions by County

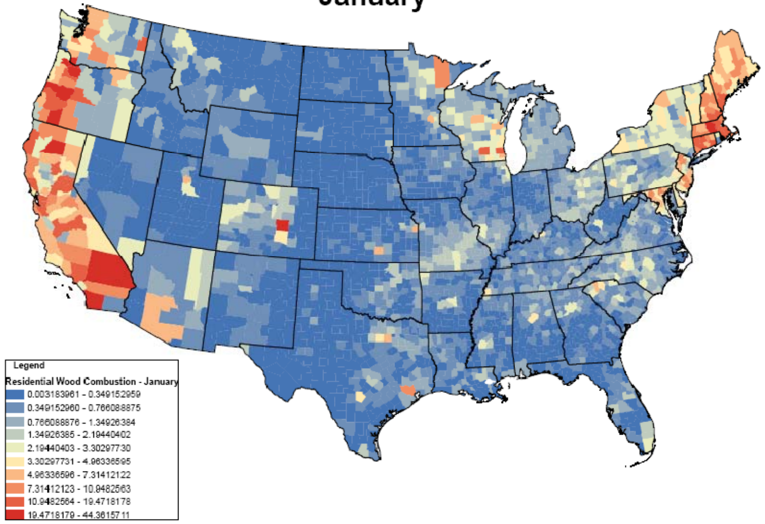


Prescribed Burning
EC Emissions by County

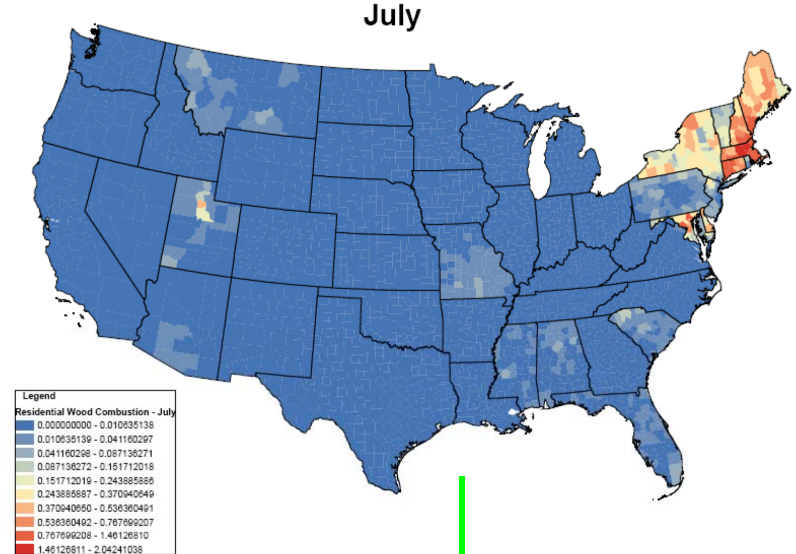


- County based EC emission estimates allow for looking at spatial distributions.
- Burning estimates show clear spatial patterns in these maps based on 2005 emissions
- Overall, about 70% of EC emissions are found in urbanized counties. Some categories contribute more in urban areas than others.

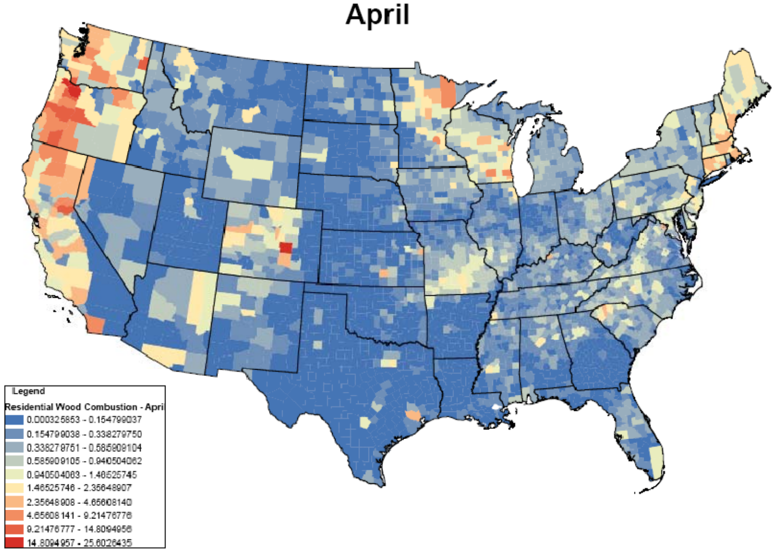
Residential Wood Combustion
EC Emissions by County
January



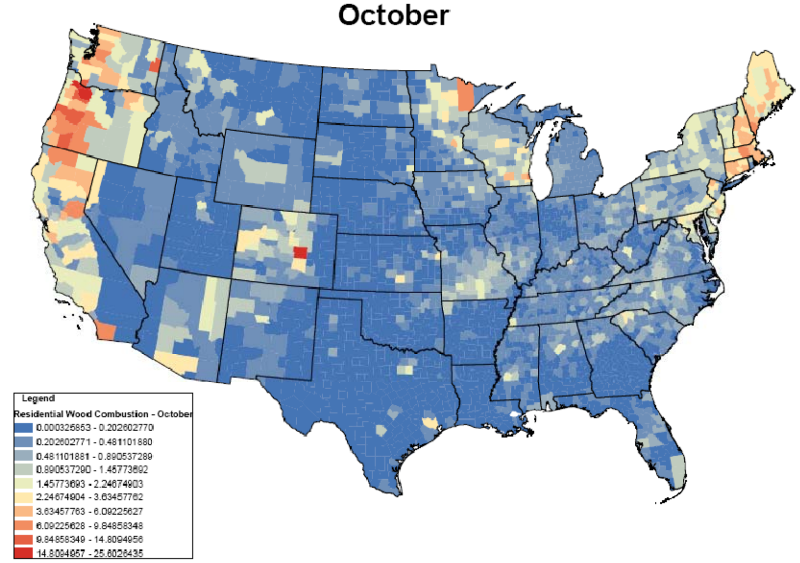
Residential Wood Combustion
EC Emissions by County
July

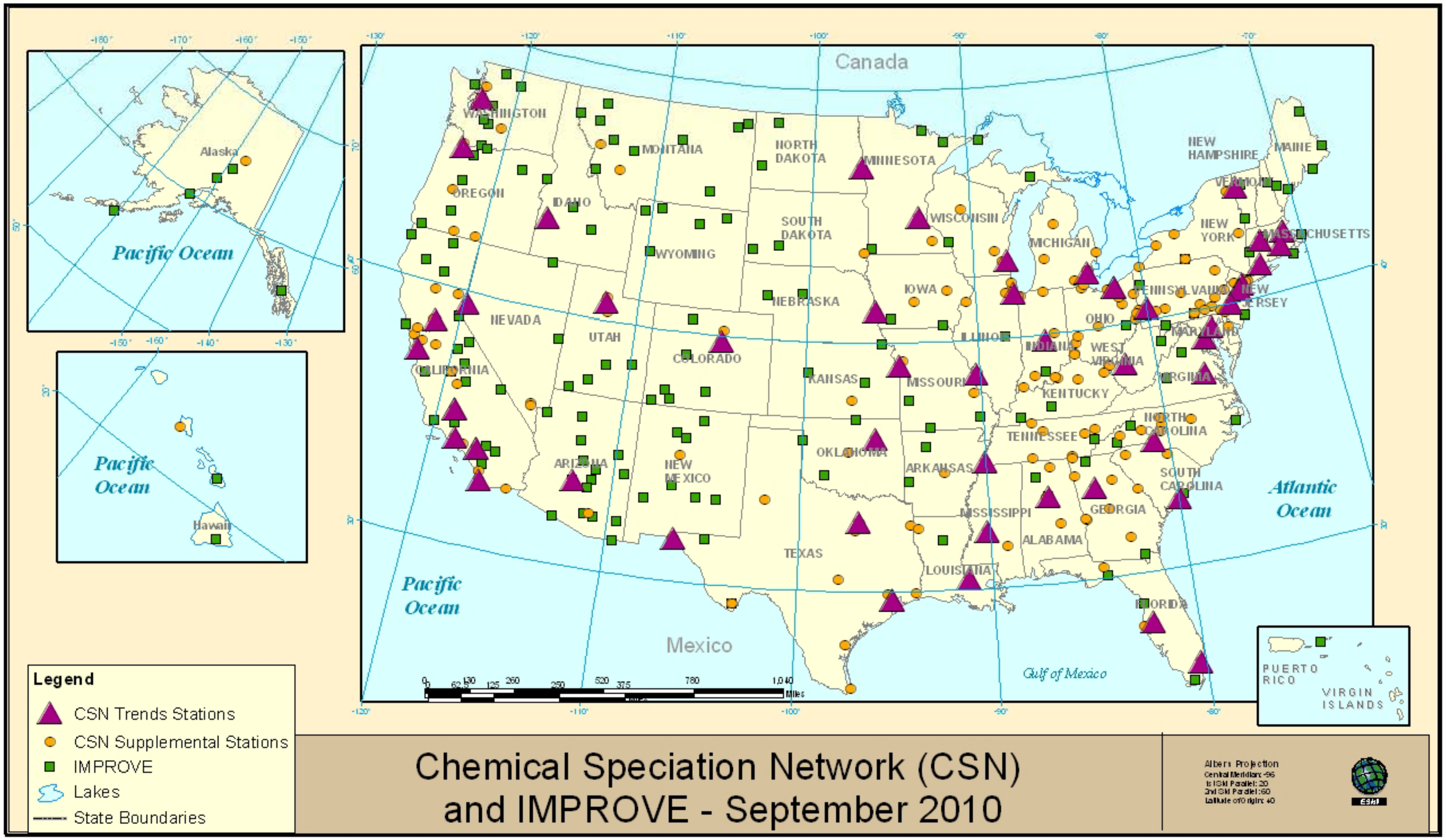


Residential Wood Combustion
EC Emissions by County
April

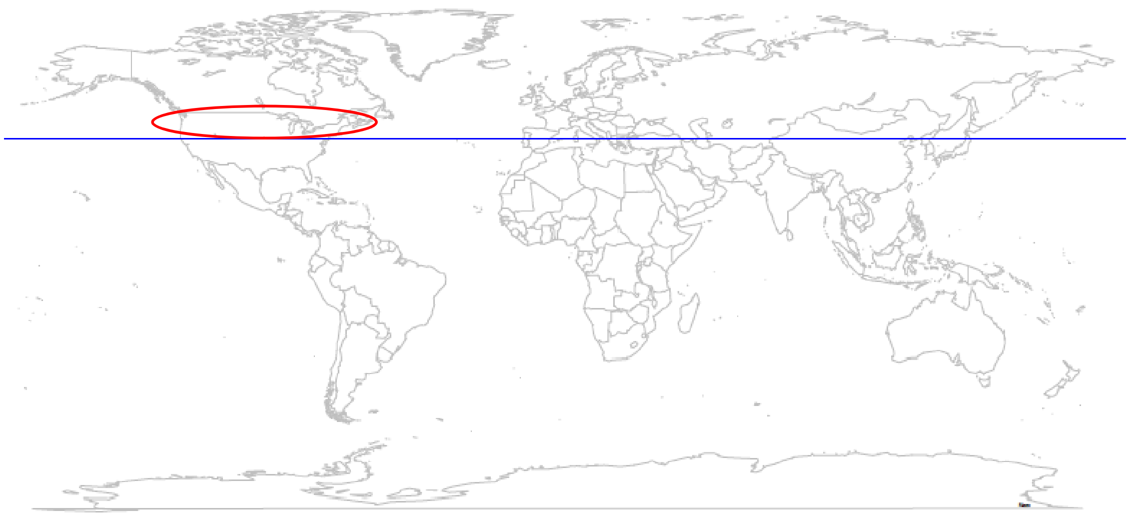


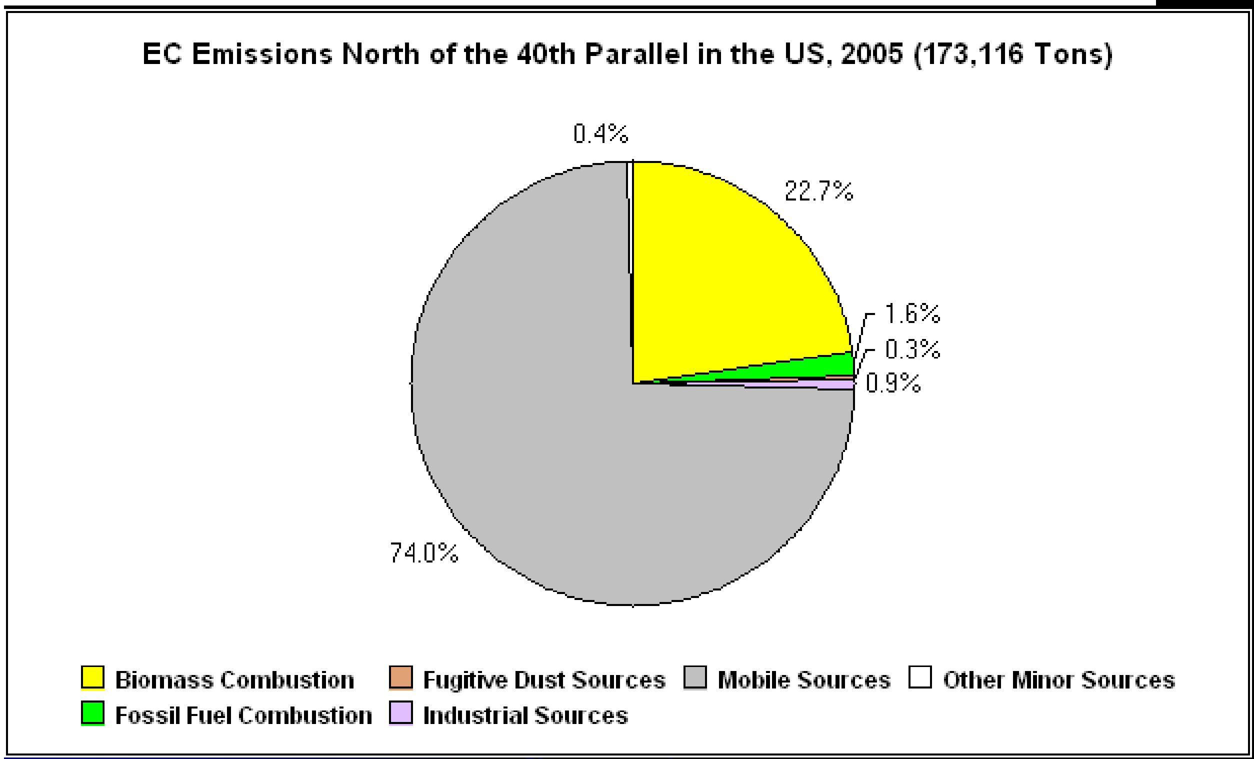
Residential Wood Combustion
EC Emissions by County
October



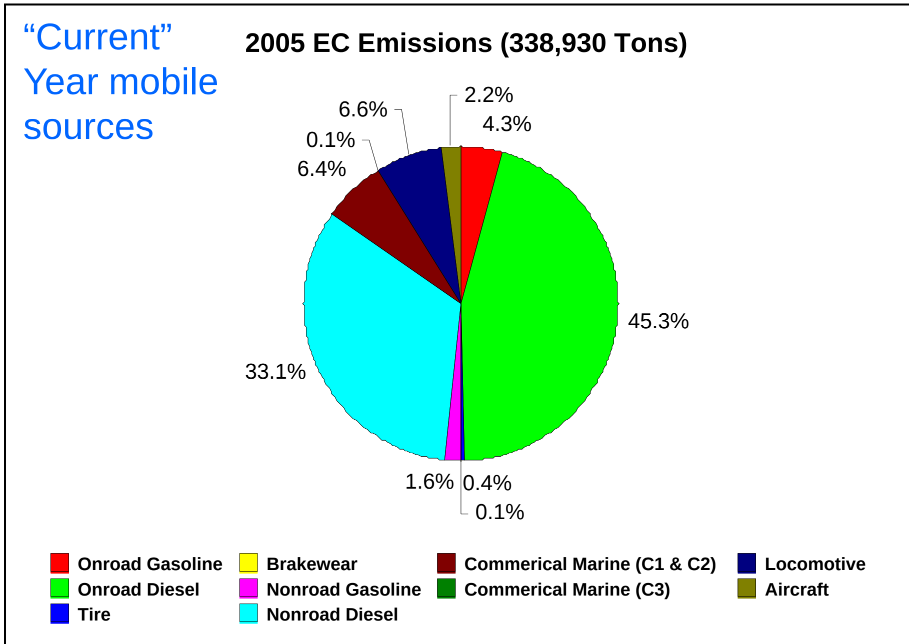


- We have over 300 urban/rural monitors that measure EC in the ambient air
- We are currently trying use these data for time-series analysis as well as in conjunction with emissions data to QA the EC inventory and better characterize sources that emit EC.

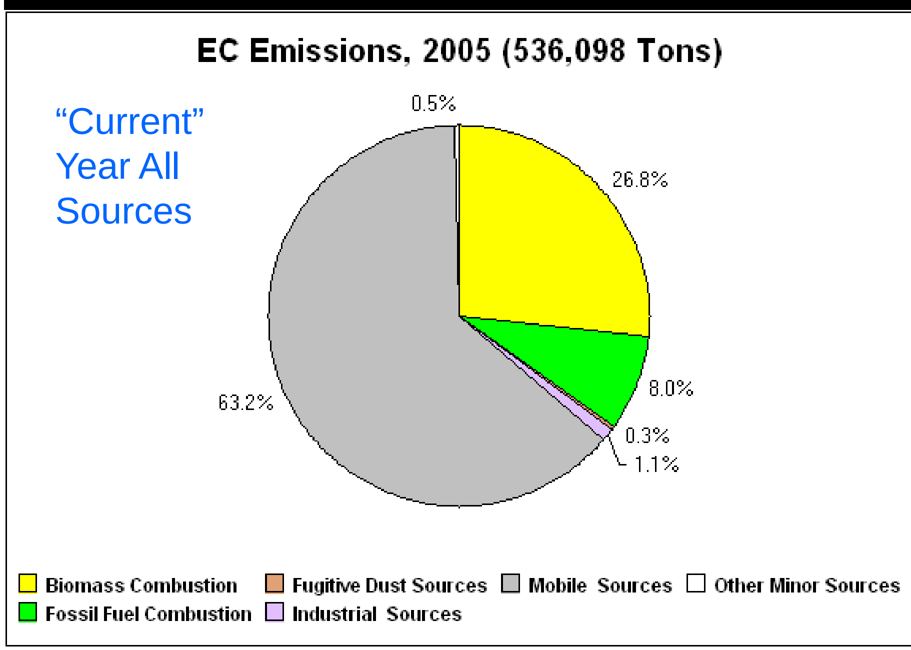


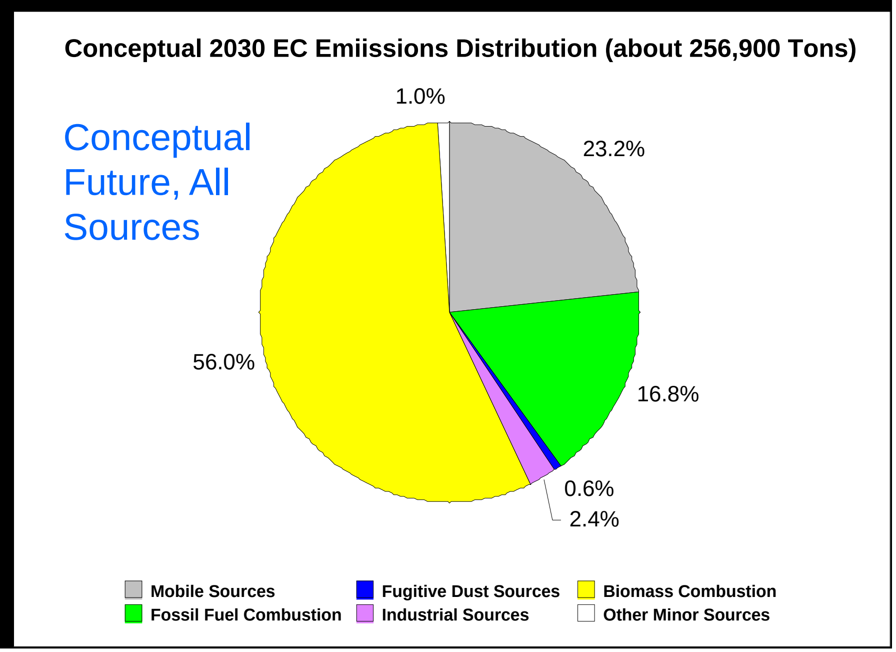


- Deposition of BC onto snow and ice in the Arctic causes warming and melting of the ice. {OC also has “warming” effects in these areas…)
- Emissions north of the 40th parallel have been shown to particularly effect Arctic/Greenland impacts
- In the US, there are about 1180 counties (about 38% of total) north of the 40th parallel.
- When arrayed against the national EC emissions piechart, this graph shows mobile sources to have even more of a contribution to EC emissions north of 40 in the United States.



- Diesel mobile sources dominate current EC inventories…
- Mobile Source diesel regulations significantly reduce EC emissions from those categories as we move into future (numbers will be available in RtC)
- Bottom chart is conceptual depiction of how 2030 EC may look based on expected mobile source reductions.
- All other categories' emissions kept at 2005 levels.

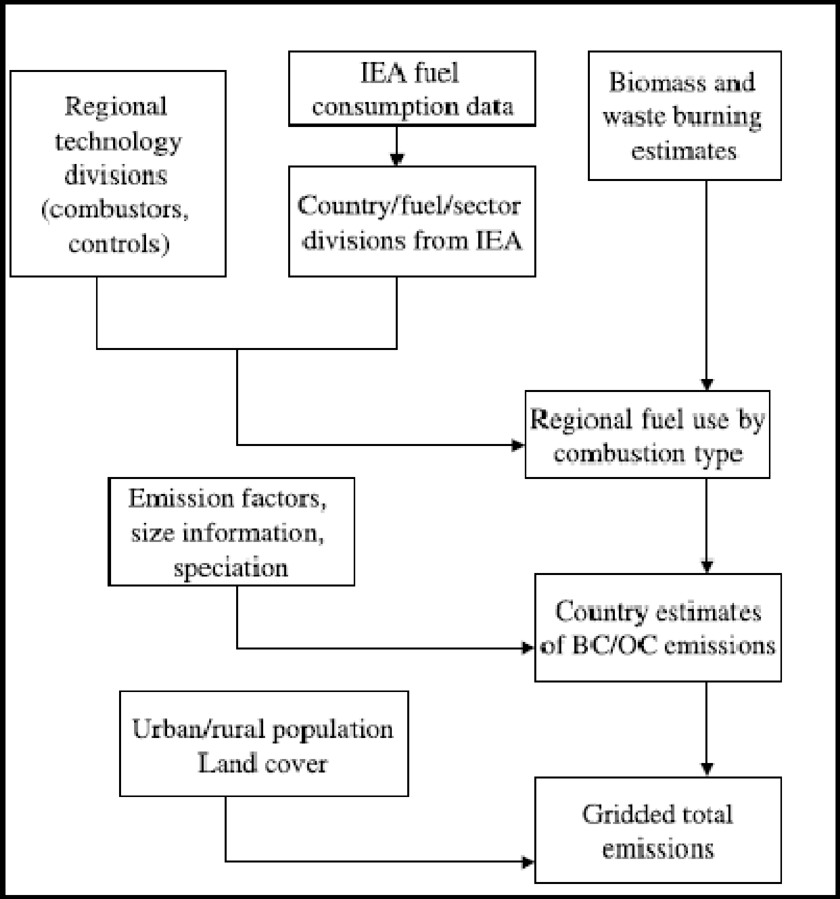


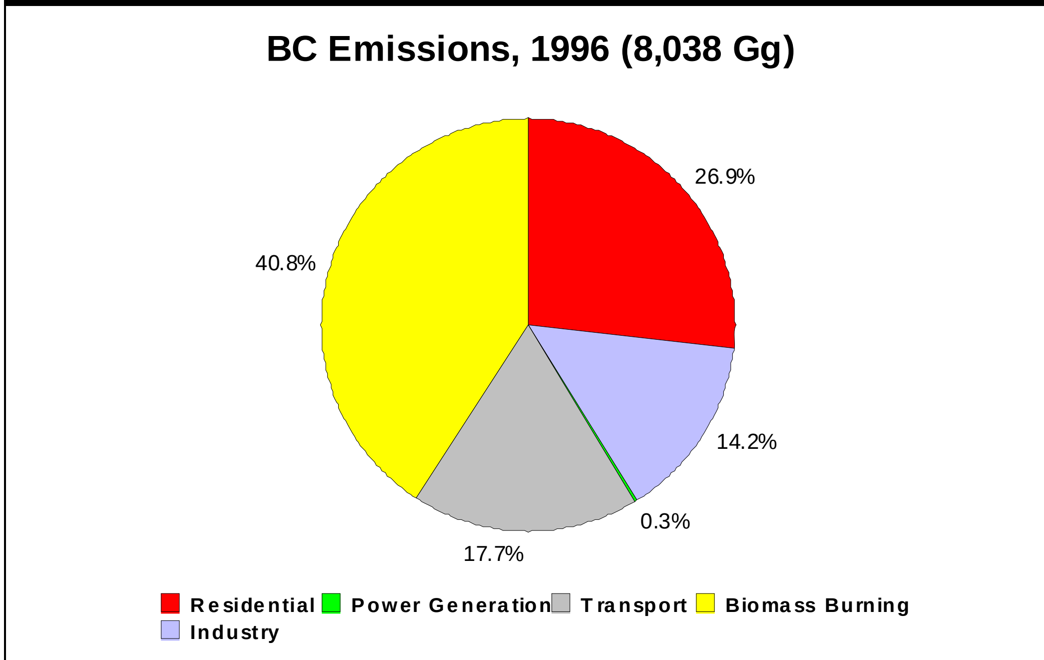


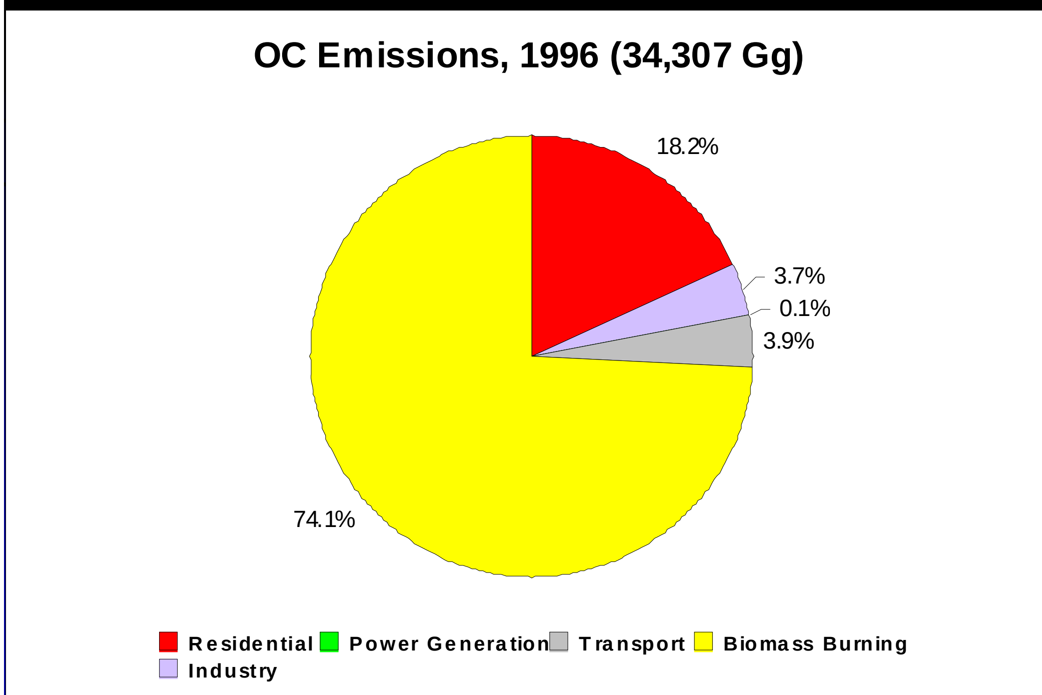
Global Emissions

Global BC/OC Methods

- Relying completely on literature for global characterizations
- Relying on Streets, Bond paper(s) for most of the information on global BC/OC emissions
- Combining fuel composition data and assumptions of combustion technologies and emissions controls
- Similar to earlier work done in the literature (Klimont, 2002).
- Emissions for a fuel/sector combination are calculated as an aggregate of the contributions of all technologies within that sector.
- The total emissions for each country, in turn, are the sum across all fuel/sector combinations
- These are “sub micron” inventories…inventories in PM2.5 range maybe 10-15% higher
- See Bond et al. 2004 for more information…



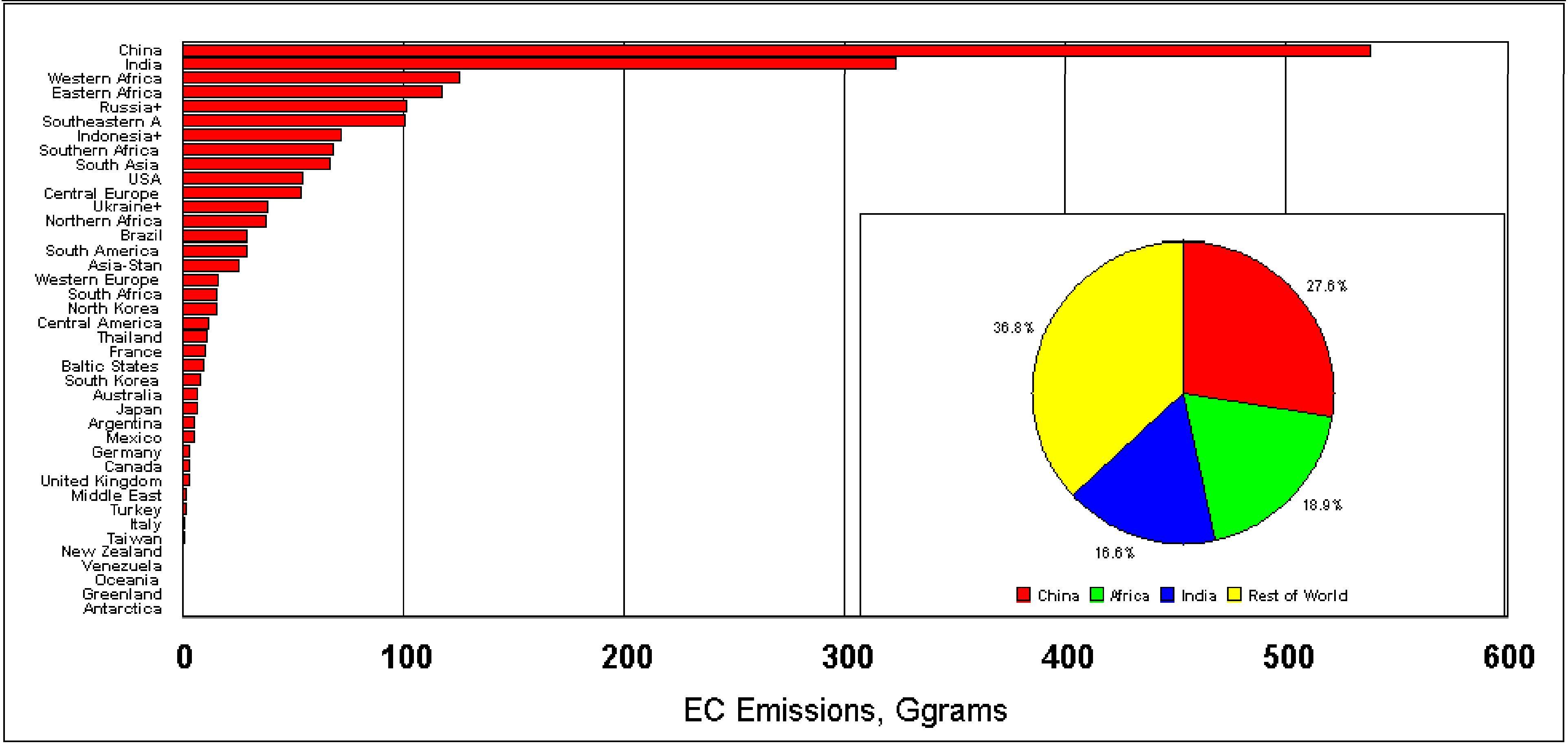


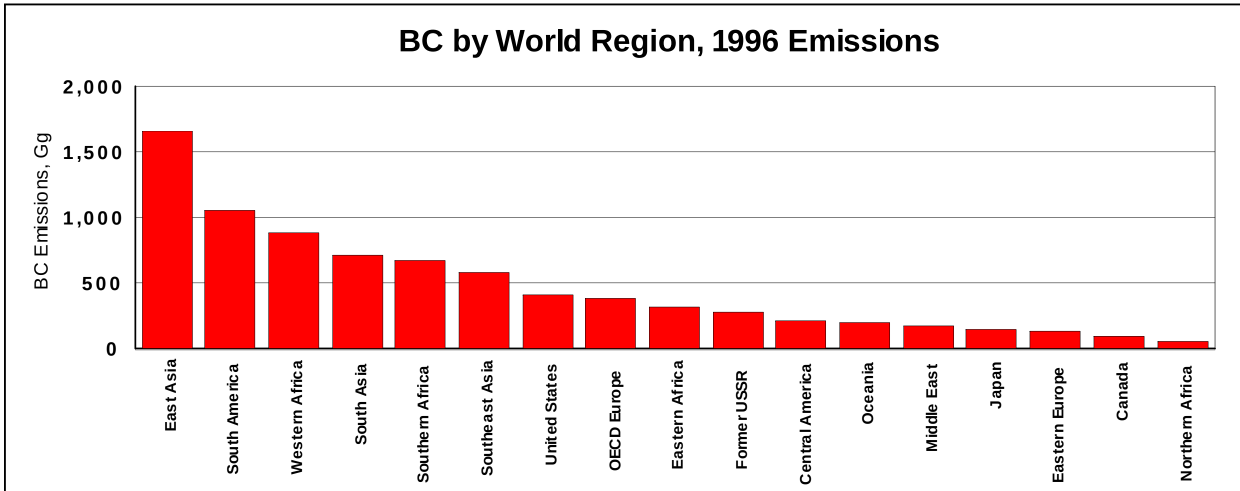


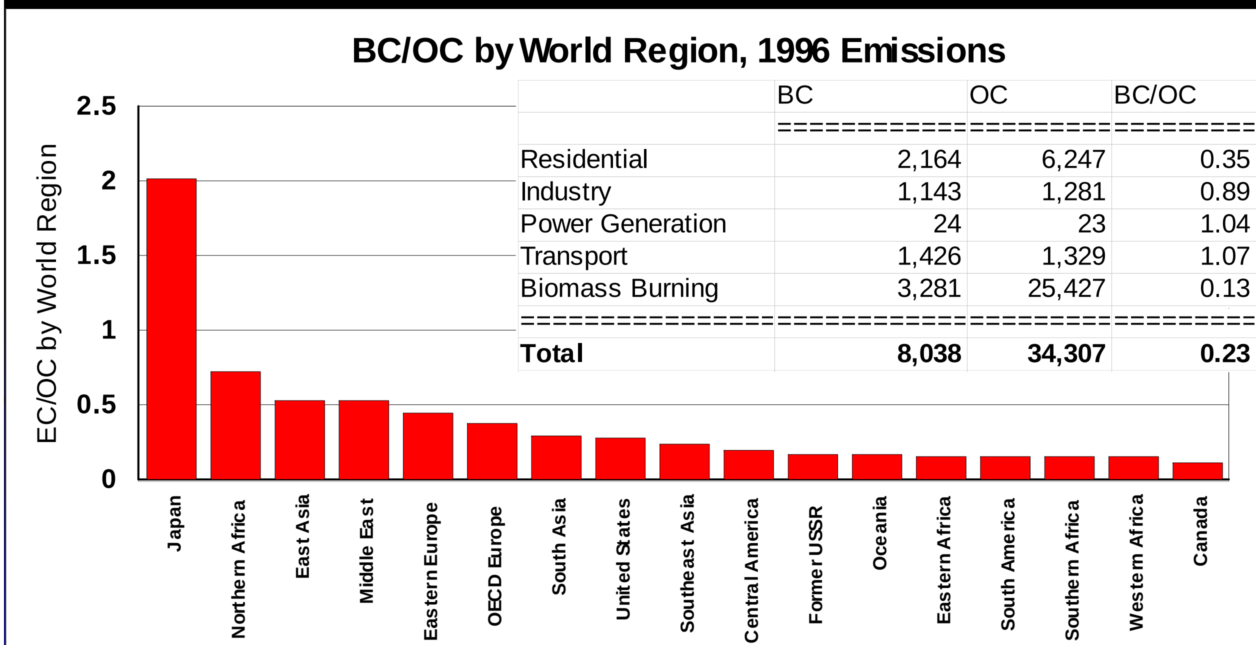
- Globally, biomass burning and residential sources make more than 2/3rds of the total BC. Biomass burning contributes to nearly 3/4th of total global OC emissions.
- Global OC emissions are about 4 times higher than EC emissions (OC:EC in EPA inventories is about 2:1)
- There are uncertainties in these emission estimates. Studies indicate that emissions estimates from all sources maybe off by a factor of 2, on average. For specific nations and sectors, inventories maybe considerably more uncertain.
- Note that these estimates are for year 1996 while domestic emissions are for year 2005
- All global inventory information in RtC comes directly from peer-reviewed literature

Streets, D. G., Bond, T. C., Lee, T., and Jang, C.: On the future of carbonaceous aerosol emissions, J. Geophys. Res., 109, doi:10.1029/2004JD004902

- One of the very important contributors to BC emissions in developing countries is the residential sector. This sector contributes 27% of EC emissions globally.
- In developing countries, most of these emissions come from cookstoves (for which there is a separate mitigation section in RtC). In the US, it is likely heating contributes more to this sector than cooking
- Cookstoves burn different fuels, but all produce thick clouds of soot that coat houses, cause human health problems, leads to mortality, and damages glaciers thosands of miles away.
- China, India, and Africa contribute nearly 2/3rds of total BC emissions from this key global sector.

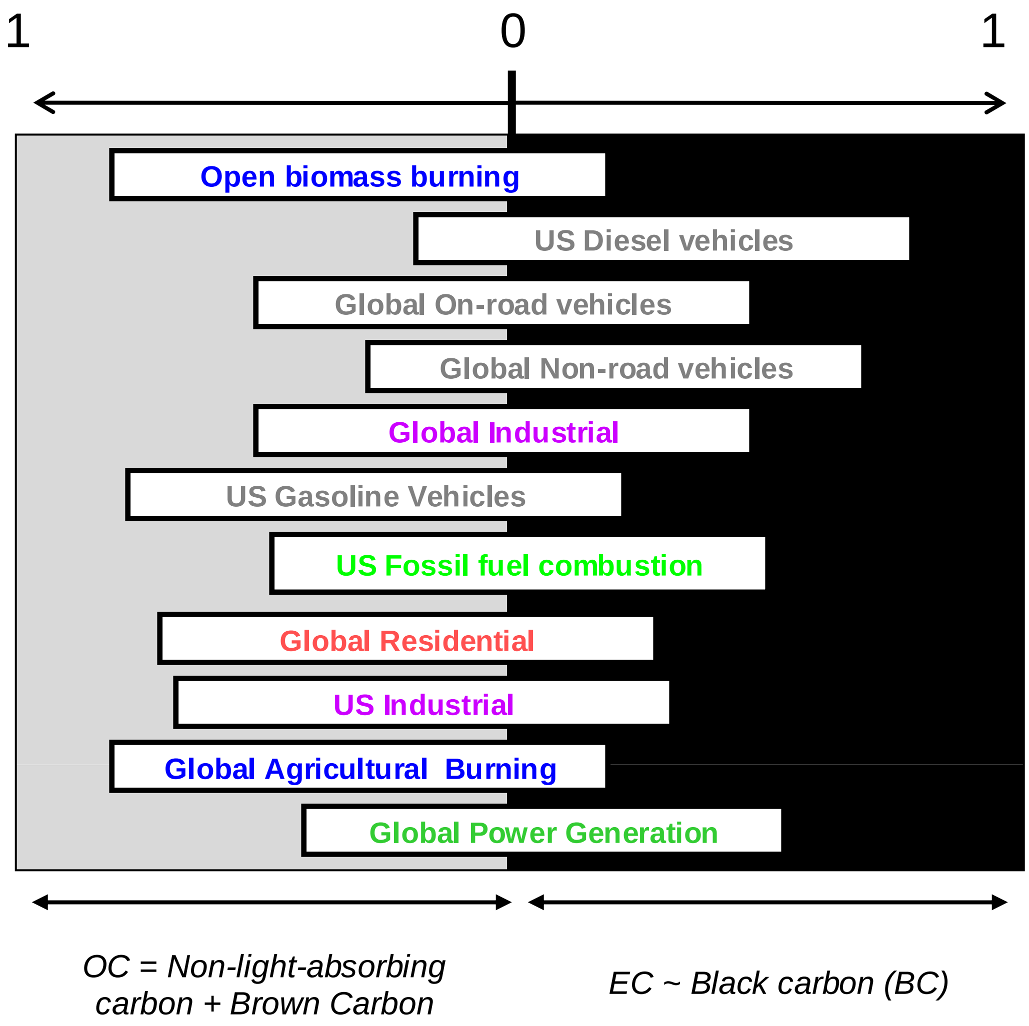






	BC	OC	BC/OC
	==========	==========	==========
Residential	2,164	6,247	0.35
Industry	1,143	1,281	0.89
Power Generation	24	23	1.04
Transport	1,426	1,329	1.07
Biomass Burning	3,281	25,427	0.13
==========	==========	==========	==========
Total	**8,038**	**34,307**	**0.23**

- Regionality is important: Asia, Africa, and Latin America contribute more than 75% of EC emissions. Asian emissions contribute regionally to Himalayan ice/snow melt.
- South America and Africa are biggest contributors to EC from biomass burning sources.
- Like in the US, EC emissions from OECD Europe, Middle East, and Japan are limited, and come mainly from transportation sector
- Like in the US, transport has more BC than OC emissions
- It is also interesting that Japan, on whole, is estimated to have more BC than OC emission



Estimated Annual Emissions

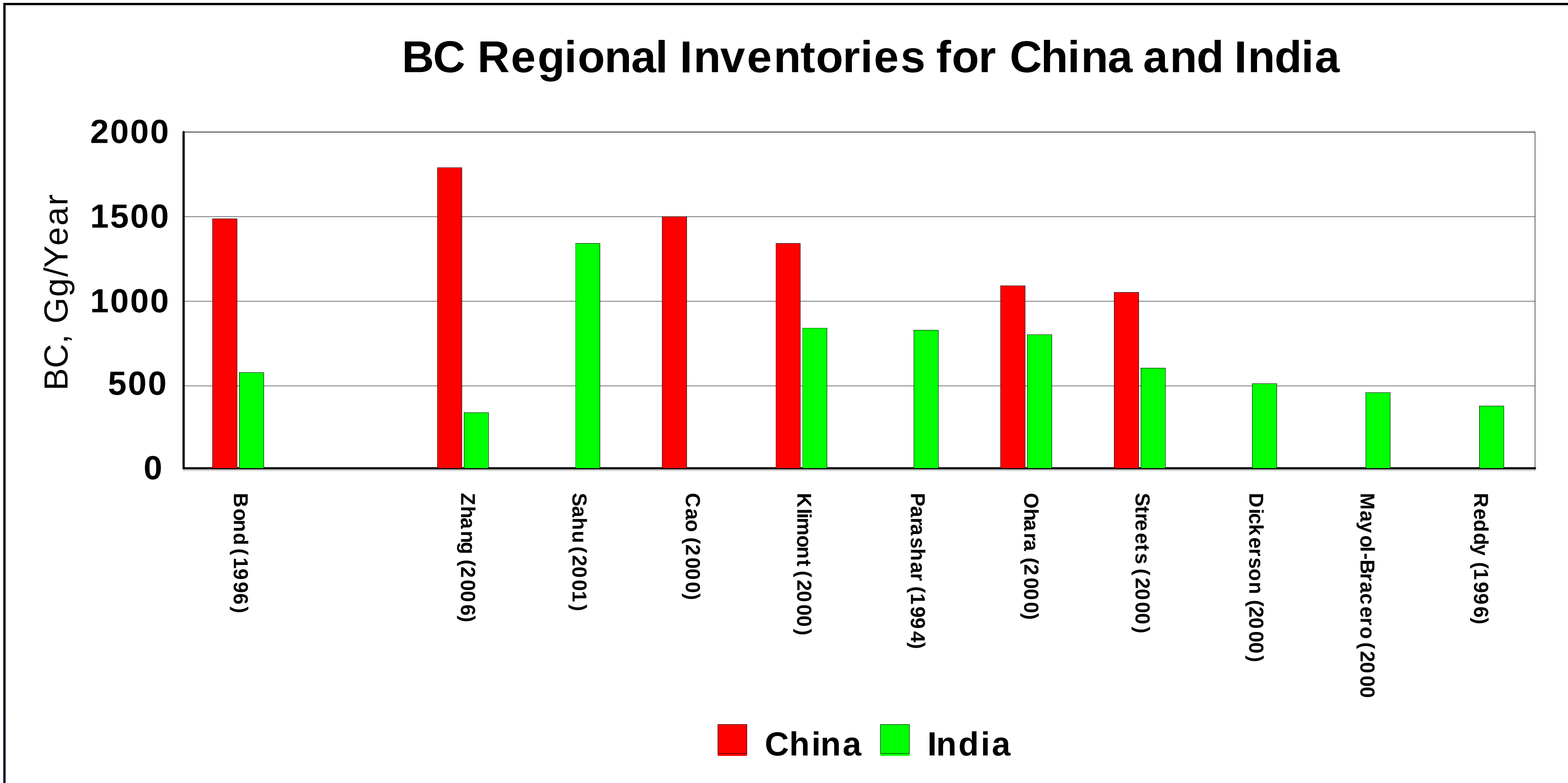
Source	US (2005)	Global (1996)
Open biomass burning	566	28,234
US Diesel vehicles	180	
Global On-road vehicles		2,113
Global Non-road vehicles		867
Global Industrial		2,424
US Gasoline Vehicles	67	
US Fossil fuel combustion	83	
Global Residential		8,411
US Industrial	20	
Global Agricultural Burning		17
Global Power Generation		47

EC + OC (Gigagrams)

--Global and Domestic Sources arrayed by their contribution to OC and EC Emissions

--BC:OC ratios favored in some sectors. Total carbon emissions highest for burning categories

RtC, Chapter 1, Hemming, Frank, et al.



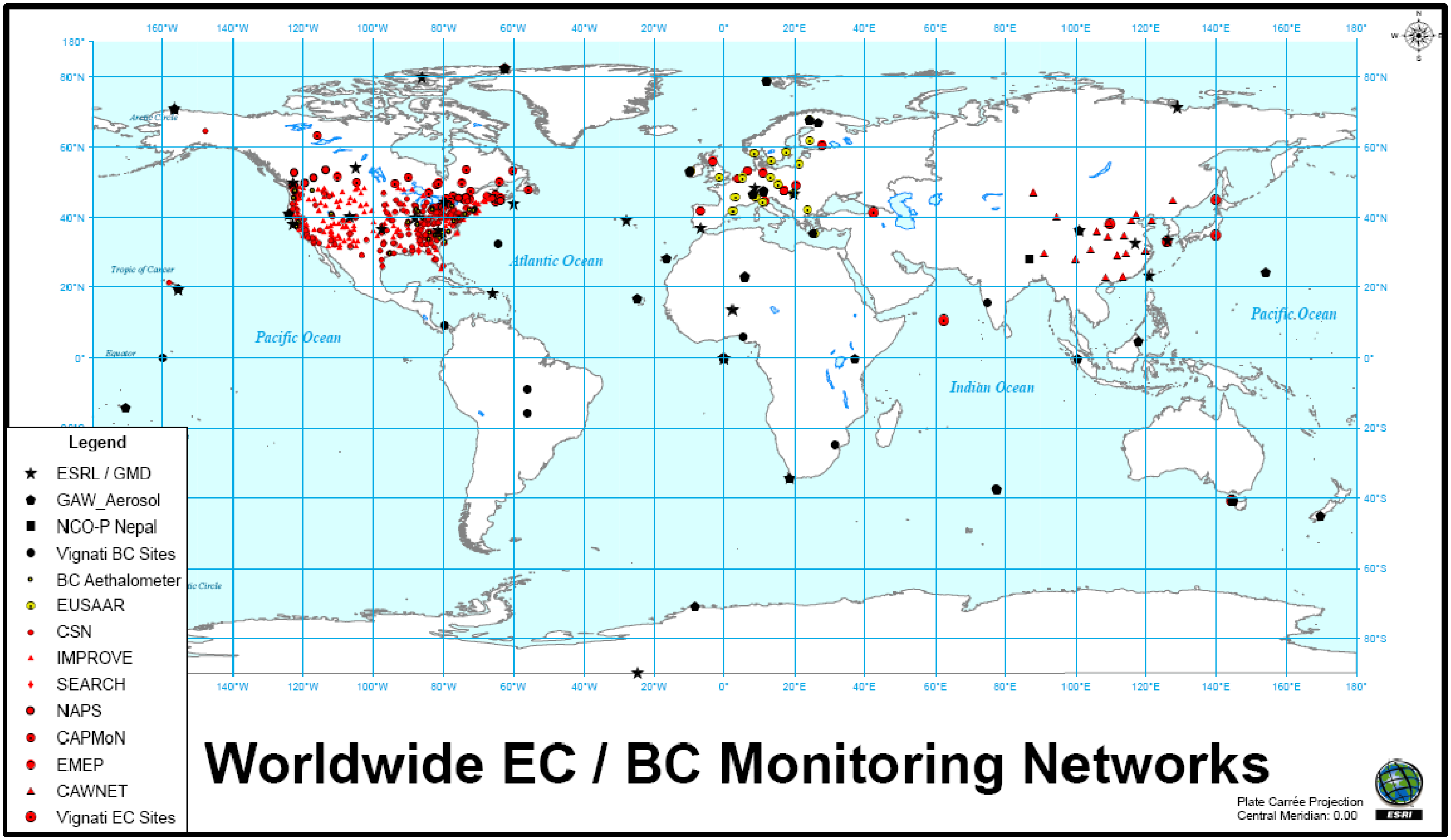
- Regional inventories can address specificity of sectors better than global inventories, but methods can be different
- China/India parts of global inventories compare reasonably well with regional estimates (within error bounds)…
- We need to encourage more regional inventory development efforts, globally

From various literature sources

	Bond et al (Unpublished Numbers)				US EPA, 2005 (as in Section 2.2)			
	BC	OC	BC/OC	% BC of Total	EC	OC	EC/OC	% EC of Total
	==========	==========	==========	==========	==========	==========	==========	==========
Agriculture Burning	3,330	15,932	0.2	1%	51,411	183,099	0.3	10%
Industry	15,854	119,350	0.1	3%	6,083	16,232	0.4	1%
Open Burning	66,593	911,213	0.1	13%	66,601	322,110	0.2	13%
Power Generation	3,109	2,117	1.5	1%	41,436	45,373	0.9	8%
Residential Biofuel	35,932	198,677	0.2	7%	23,282	220,409	0.1	4%
Residential Coal	21,918	17,685	1.2	4%	634	1,187	0.5	0%
Residential Other	3,539	3,451	1.0	1%	979	2,327	0.4	0%
Road Transport	232,999	141,411	1.6	47%	169,660	109,461	1.5	32%
Off-Road Transport (Nonroad)	110,717	76,053	1.5	22%	169,270	95,394	1.8	32%
Totals:	**493,991**	**1,485,889**	**0.3**	**100%**	**529,356**	**995,592**	**0.5**	**100%**

- US Emissions compared to US part of Bond EC and OC inventories
- EPA EC emission estimates are, in sum, are about 7% higher
- However, some sectors don't match well (Ag burning, for example)
- US part of global inventories show much more OC than we estimate in EPA inventories (impacts OC:EC ratios, for example)
- Similar very preliminary comparisons between EPA and IIASA BC inventories for US show EPA estimates to be much higher (x2)
- Comparison issue(s) needs to be explored further (which inventories are used to represent regions in global models, what the sensitivities are, etc.)

Future work includes better understanding global methods for estimating emissions…



- We have some global EC (in red) and BC (in black) monitoring data to work with
- Obtainable data shows highest concentrations exist in China/India.
- Can explore how ambient measurements compare with global inventories…have begun to do some of that with RtC work…lots of measurement types of issues to work out…

Chapter 2, RtC, Frank, Tikvart, et al.

Closing Remarks

- BC is a powerful warming agent…BC is the most strongly light-absorbing from of carbon per unit mass. Other types of combustion particles also absorb light…brown carbon, for example, which is a type of organic carbon.
- Relative amounts of BC, BrC, and NLAC important for climate; health effects associated with direct PM2.5 emissions depend on total ambient mass of all constituents
- Emissions of BC in N/A and Europe have been declining over time. Globally, emissions and ambient concentrations are highest in Asia, LA, and Africa.
  - China and India account for about 35% of total
  - US accounts for only about 6% of emissions in 2005, and this percentage is expected to decline through 2030.
  - In general, BC is concentrated in urban areas, where populations are largest and many people are exposed
  - Sources of EC in US are mobile sources (63%), open and contained biomass combustion (27%), and fossil-fuel combustion (about 8%).
- BC has substantial impacts on climate
- Once emitted, BC stays in the atm for a very short time (up to weeks only). BC's impacts on climate thus are more pronounced at local to regional scales compared to long lived GHGs. Short lifetime makes it difficult to compare SLCFs with LLGHGs via metrics like GWP…
- Mitigation opportunities for BC vary substantially between the US and other countries, in part due to differences in key sources and existing controls…
- Methane and tropospheric ozone are also SLCFs

Future Work…Related to Domestic Inventories…

- Improve BC emission estimates from some sectors, some processes
  - PM composition from nonroad gasoline, aircraft, commercial marine
  - Characteristics of high-emitting vehicles
  - Mobile source emissions at lower temperatures, effects of future technologies
  - Biomass emissions from different types of fires burning different fuels
- Investigate further temporal behavior of sources to better account for seasonality and time-of-day patterns
- Particle size distributions, sulfate and OC size distributions, dust inventories, Fe content, and optical properties
- Investigate BC:EC relationships; look more closely at brown carbon---measurements, sources, etc

Future Work---Global inventories

- Understand methods used to estimate emissions
- Agreement on consistent measurement methods
- Better characterization of small emission sources that have high BC EFs
- Better engagement of international scientists, governments, and regulatory agencies in collaborations of technology assessments
- Innovative ways to assess regional emission rates and emissions:
  - Use of Source Apportionment type tools
  - Use of ambient and remote sensing data, as well as model output
- Better understand uncertainties in emission estimates, by region and sector.

There are other BC assessments on-going that also report global inventory information…

Acknowledgements

- Lots of people are working on the RtC
  - OAQPS, OTAQ, ORD, OAP, others
- Specific to emission portions
  - OTAQ (Joe Somers, Chad Bailey, Harvey Michaels, Penny Carey)
  - OAQPS (Rich Mason, Marc Houyoux, Adam Reff, Neil Frank, Brooke Hemming, Joe Tikvart, James Hemby, Erika Sasser, …)
  - Lots of people from outside (Bond, Streets, Novakov, Husain, Ito, etc.)

Thanks for your Attention!

Questions? Comments?

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