Black carbon in Earth's changing atmosphere: Historical and present day climate effects

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Funding acknowledgement:

NASA – MAP Program

DOE – ESM Program

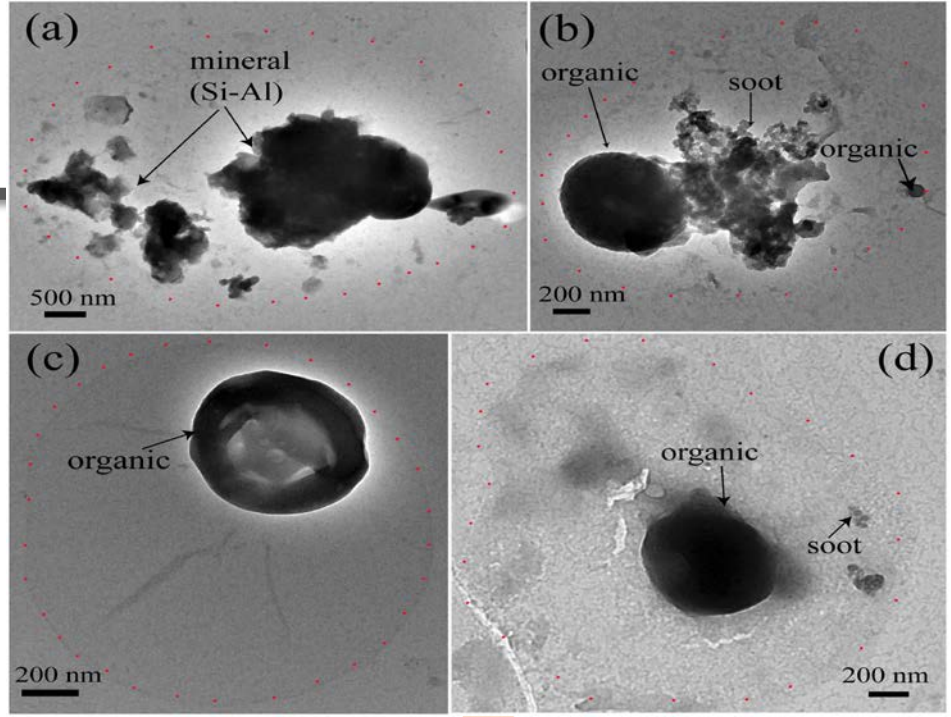
Overview

Part I:
BC climate effects

Climate forcing

Climate impacts of emissions by sector

Feasible emission scenarios



Part II
Historic BC

Ice core records from Antarctica,

Greenland and the Tibetan Plateau

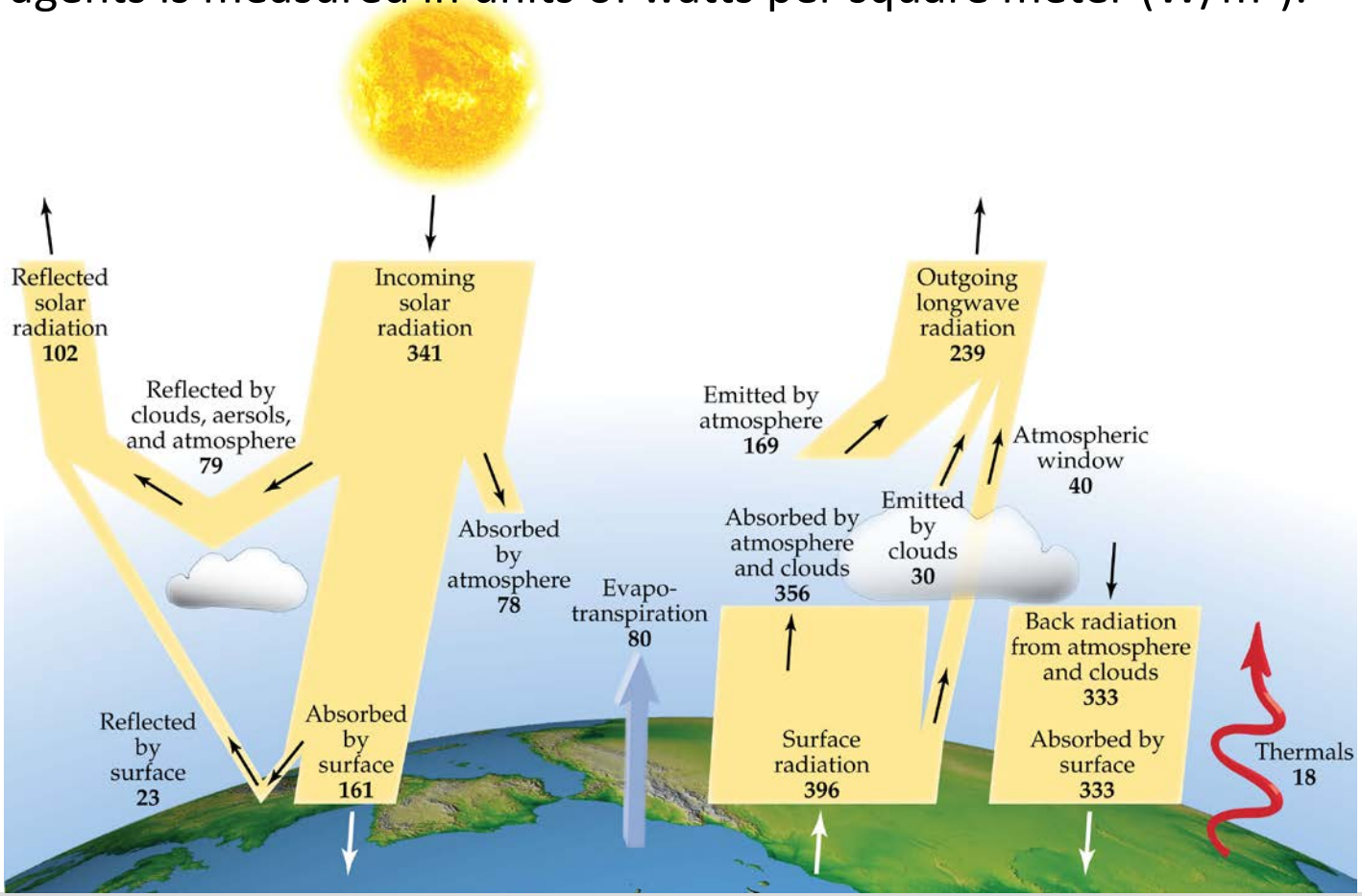
Part I

Unfortunately BC impacts on climate are very complicated

Physically ➔ what is BC? Properties?
Climate ➔ direct and indirect impacts and feedbacks
Sources ➔ Individual sources emit a wide range of chemical species
Time evolution ➔ no monotonous increase since pre-industrial times

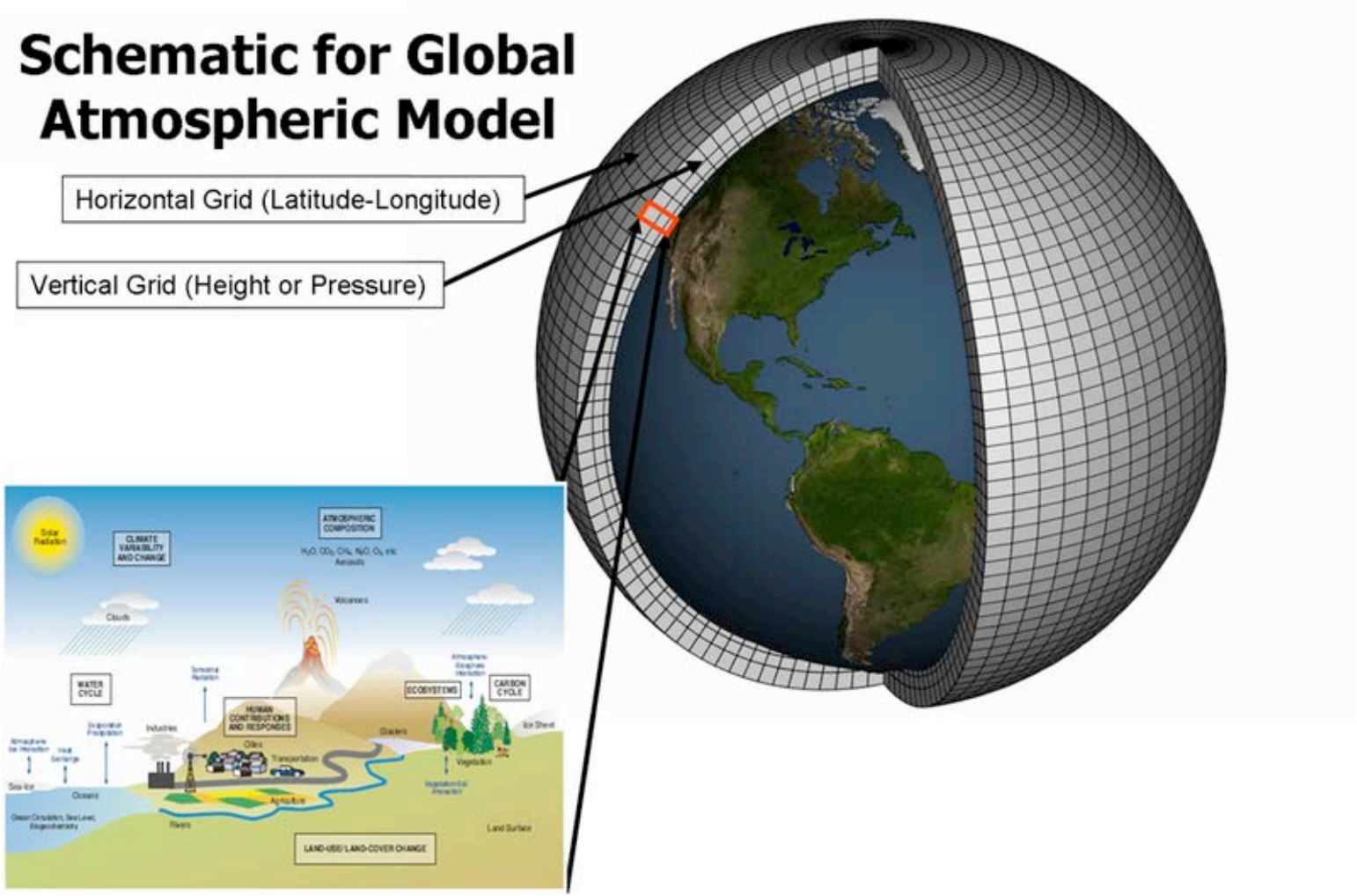
Climate Forcing

Climate forcing can be defined as an imposed perturbation of Earth's energy balance. Energy flows in from the sun (visible wavelengths), and back out again as long-wave infrared (heat) radiation. The common unit of measure for climatic forcing agents is measured in units of watts per square meter (W/m^2).



Climate model : giss-modelE

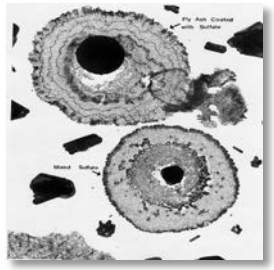
Goddard Institute for Space Studies climate model



Reference: Schmidt et al, 2013: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. J. Climate, in. prep
Bauer S.E. et al, 2008: MATRIX (Multiconfiguration Aerosol TRacker of mIXing state): An aerosol microphysical module for global atmospheric models. Atmos. Chem. Phys.

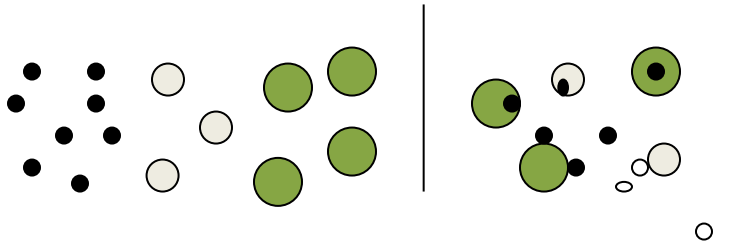
Black Carbon effects considered in the Climate model

Aerosol direct effect: NEGATIVE for aerosols, POSITIVE for BC



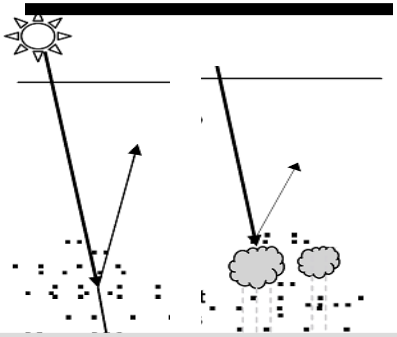
- Absorption and scattering of light by aerosols
- Absorbing particles warm the atmosphere, scattering cools.
- Stronger absorption by coated BC particles

Aerosol indirect effect: NEGATIVE for aerosols and BC



- Aerosol act as CCN (cloud condensation nuclei)
- Change of cloud cover, cloud brightness and cloud lifetime

Aerosol semi-direct effect: POSITIVE or NEGATIVE for aerosols and BC



- Presence of aerosols change thermal structure of Atm.
- Increased aerosol absorption can change clouds
- can lead to increase or decrease in clouds

Aerosol snow-darkening effect: POSITIVE for BC

- Albedo change due to BC deposition on snow and ice

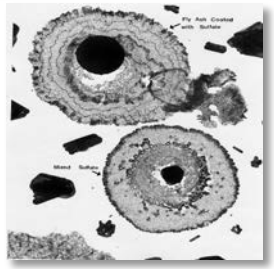
Reference: Bauer, S.E., and S. Menon, 2012: Aerosol direct, indirect, semi-direct and surface albedo effects from sector contributions based on the IPCC AR5 emissions for pre-industrial and present day conditions. J. Geophys. Res.,

Black Carbon effects considered in the Climate model

Aerosol direct effect: NEGATIVE for aerosols, POSITIVE for BC

- o Absorption and scattering of light by aerosols
- o Absorbing particles warms the atmosphere, cooling surfaces.
- o Stronger absorption by coated BC particles

Direct effect



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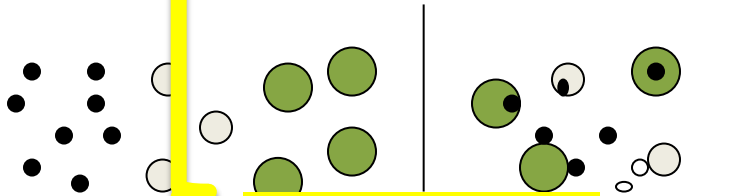
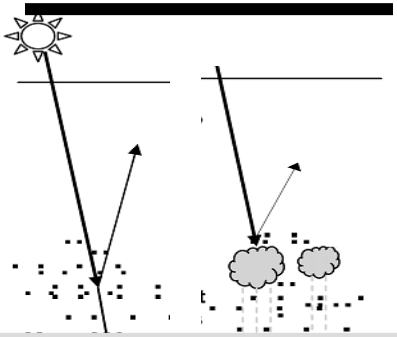


Total effect

Aerosol semi-direct effect: POSITIVE or NEGATIVE for aerosols and BC

Feedback effect

- o Presence of aerosols change thermal structure of Atm.
- o Increased aerosol absorption can change clouds:
- o can lead to increase or decrease in clouds



Aerosol snow-darkening effect: POSITIVE for BC

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A substantial portion of BC emission is natural: Forest and grass fires 42%

BC sources are not a modern phenomena: cooking, land clearing, agricultural burning 20% (bio-fuels only)

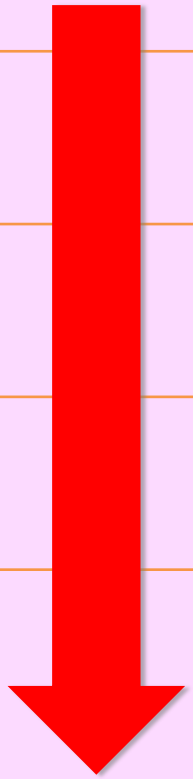
BC emissions from fossil fuel 38%

BC effects are not best estimated by calculating pre-industrial v.s. present day changes

Reference: Bond T et al, 2004: A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion, Journal of Geophysical Research

Defining BC experiments

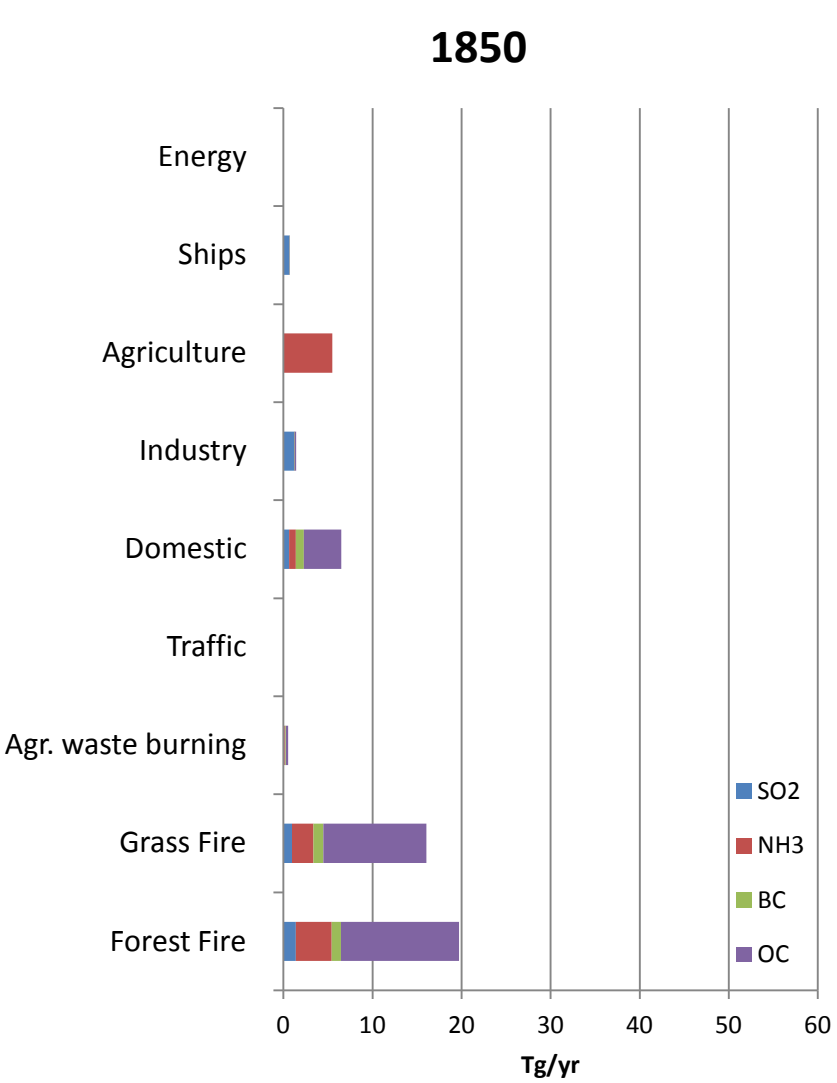
Experiment	Specifics	Representing	Information for Policy makers	Forcing effect
Total BC effect	Removal of all BC	Theoretical experiment		
Anthropogenic BC effect (last IPCC report)	Removal of BC 2000 - 1850	Theoretical experiment		
Human BC effect	Removal of non-forest fire BC sources	Theoretical experiment		
Sector experiments (not BC specific)	Changing a sector / per country	Source sector effects	useful	
Feasible emission reduction experiments	Changing a fraction of a sector/ per region	Policies, Technology improvements	Very useful	

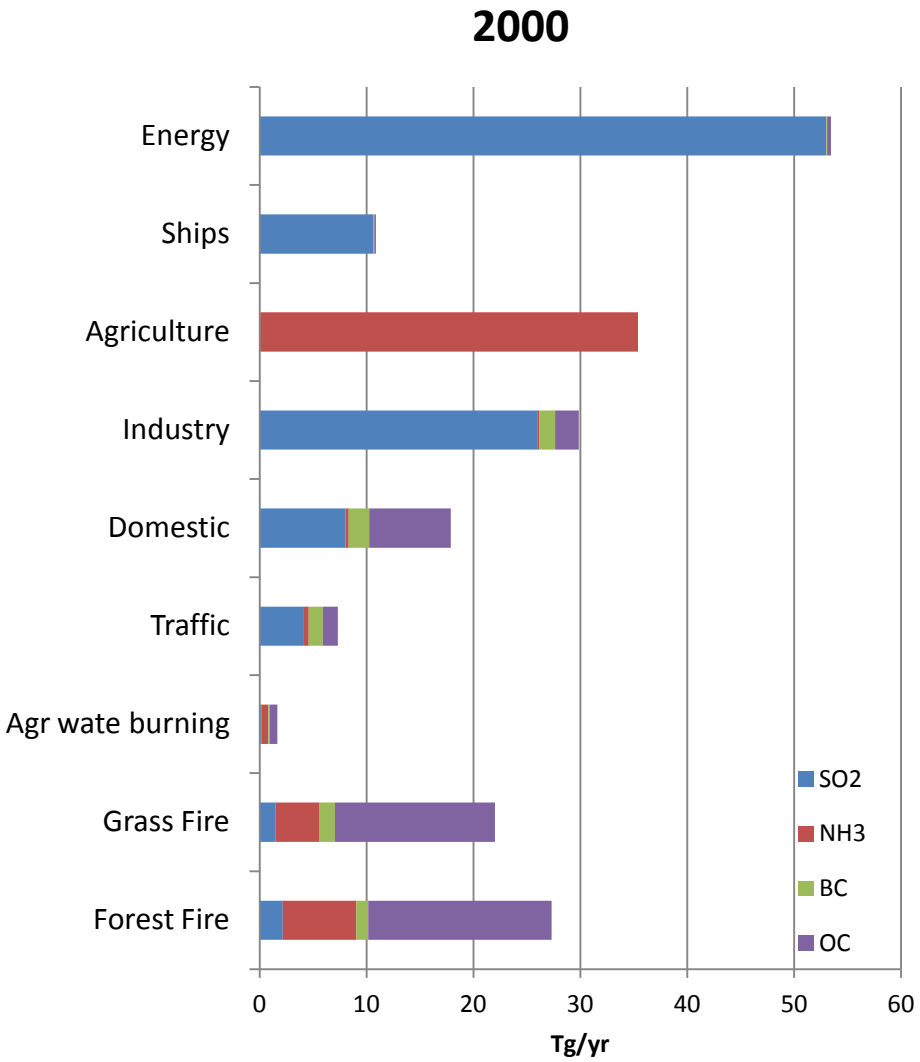


How to get the most robust answer for policy questions?
Multi model (~2-3, but high quality) simulations of identical scenarios, representing realistic and feasible regulations or technology changes.

Sector Experiments

Historical (1850 – 2005) CMIP 5 emissions





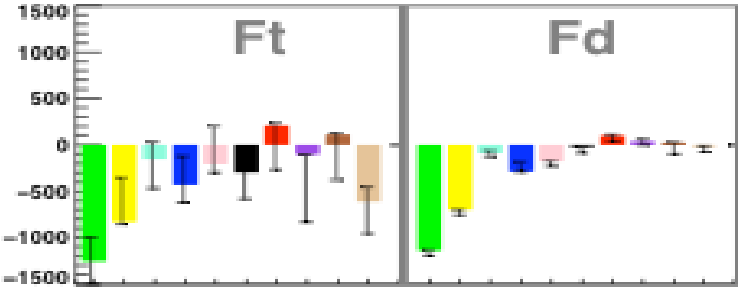
Reference: Lamarque, J.-F. et al., 2010: Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. Atmos. Chem. Phys., 10, 7017-7039, doi:10.5194/acp-10-7017-2010.

Total RF Include. cloud | Direct RF

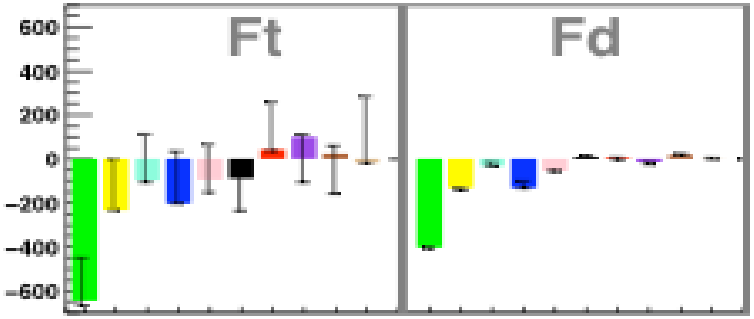
Forcings per emission sector since 1850

mW/m^2

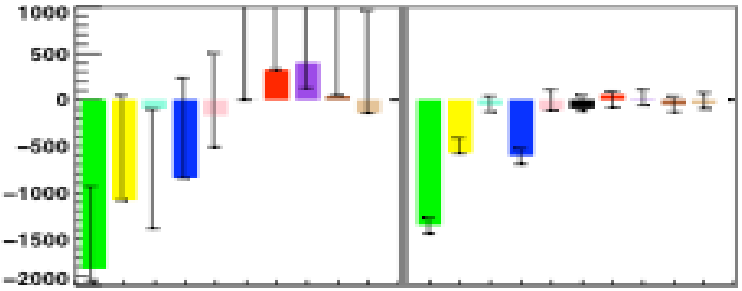
North America



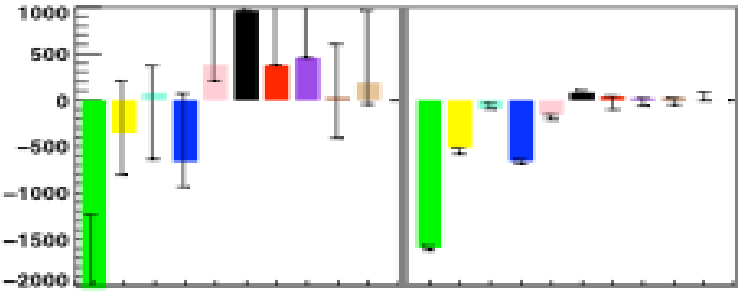
GLOBAL



EUROPE



ASIA



- Global RFs are small, regional RFs can be large!
- **Globe:** Transportation and waste burning only + RF
- **North America**: Transportation only + RF
- **Europe**: Transportation and waste burning are warming
- **Asia**: Domestic emissions dominate +RF (higher BC than in US/EU dom), Industry, Transportation, AWB

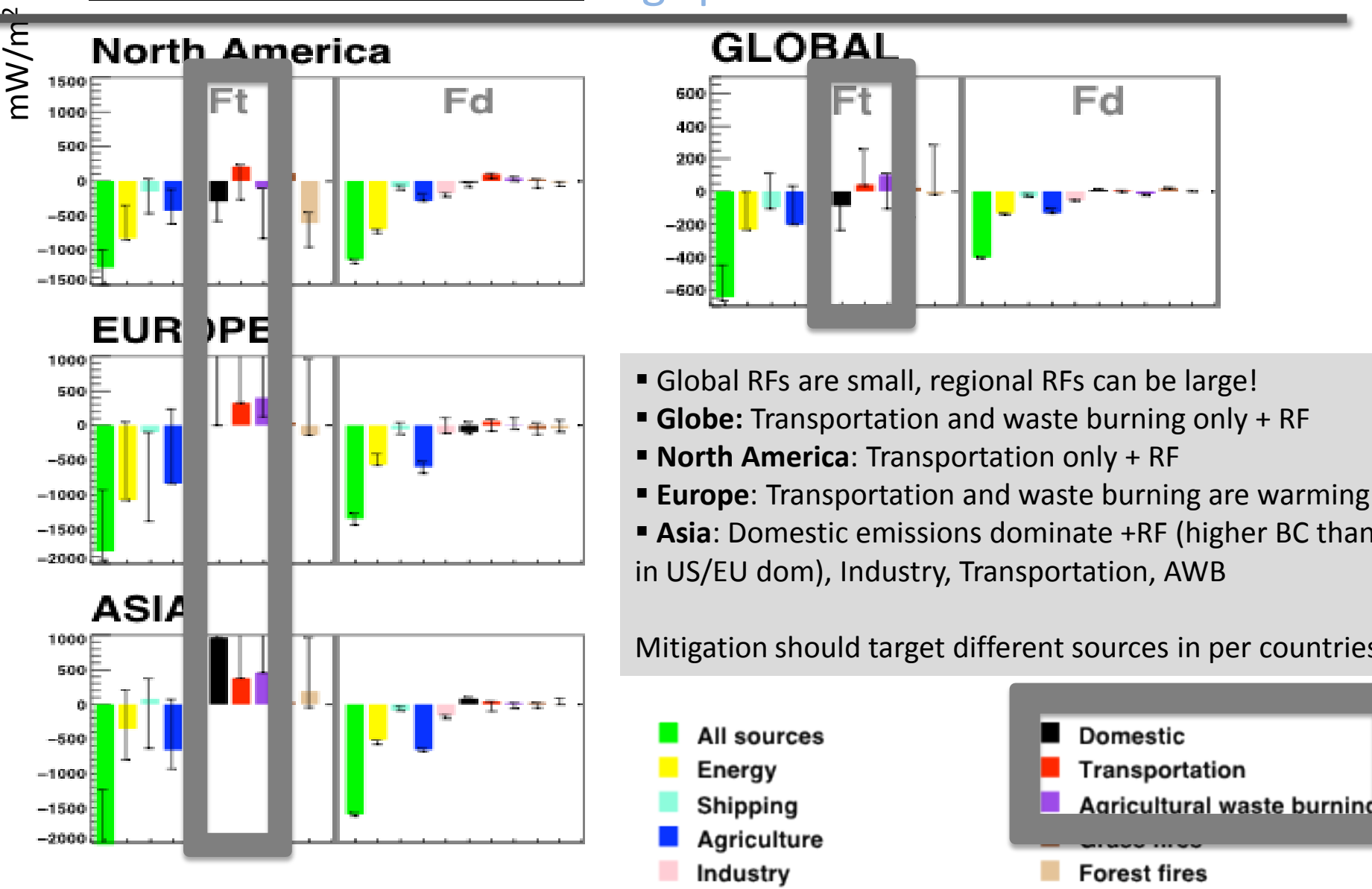
Mitigation should target different sources in per countries

- All sources
- Energy
- Shipping
- Agriculture
- Industry
- Domestic
- Transportation
- Agricultural waste burning
- Grass fires
- Forest fires

Reference: Bauer, S.E., and S. Menon, 2012: Aerosol direct, indirect, semi-direct and surface albedo effects from sector contributions based on the IPCC AR5 emissions for pre-industrial and present day conditions. J. Geophys. Res.,

Total RF Include. cloud | Direct RF

Forcings per emission sector since 1850



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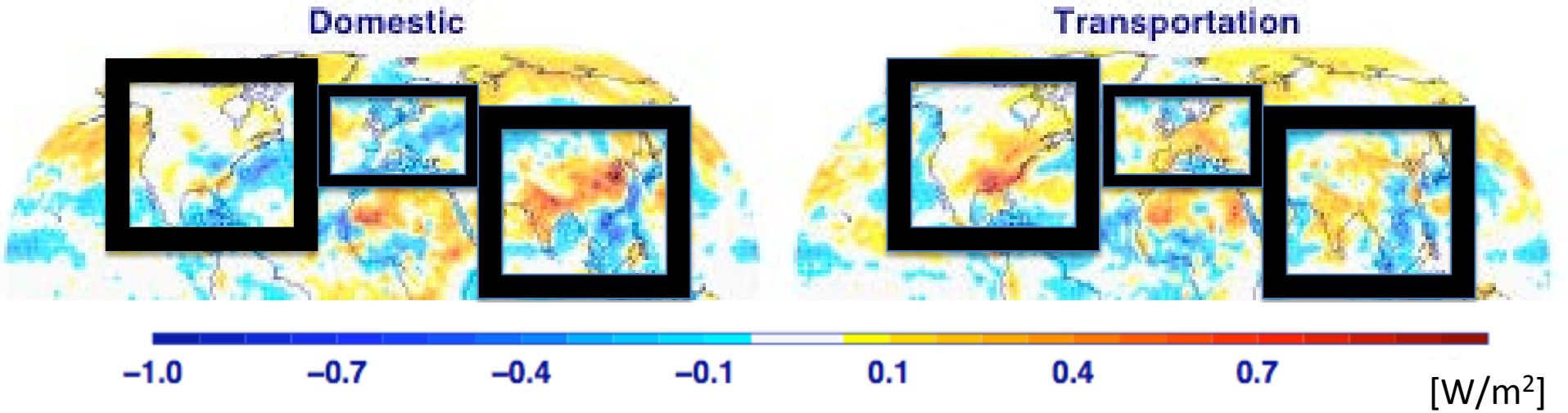
Direct Forcings per emission sector since 1850



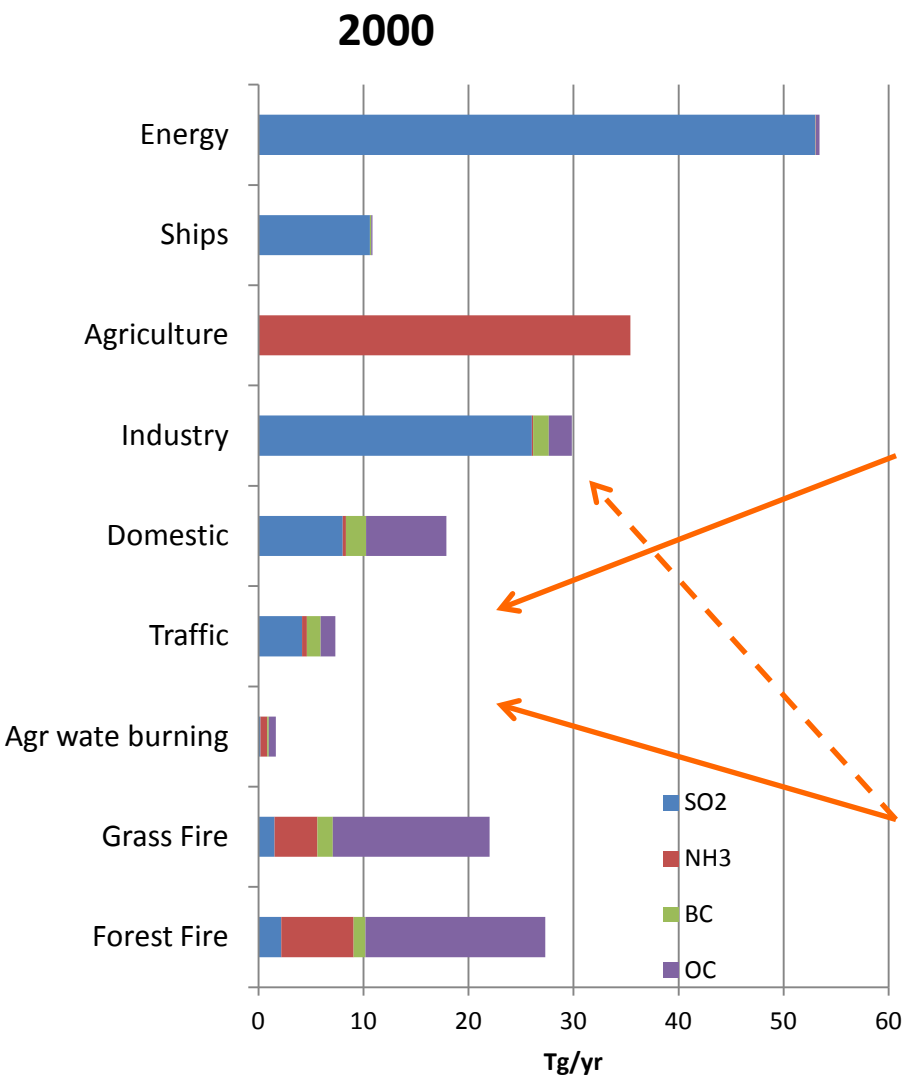
Domestic Sector:
North America, Europe and Asia use very different technology in this sector. Europe, is SO_2 rich, Asia more BC rich.

Transportation sector:
Strongest signal in the US, followed by Europe and India.

Reference: Bauer, S.E., and S. Menon, 2012: Aerosol direct, indirect, semi-direct and surface albedo effects from sector contributions based on the IPCC AR5 emissions for pre-industrial and present day conditions. J. Geophys. Res.,

Feasible Reduction Experiments

Feasible BC mitigation scenarios: Diesel and Bio-fuels burning (domestic)



Scenario: **50% reduction in bio-fuels**

Fossil & bio-fuels: 4.6 Tg BC, 30.9 Tg OC

Fossil & -50% bio-fuels: 3.0 Tg BC, 21.9 Tg OC

Scenario: **No emission from diesel engines**

Fossil & bio-fuels: 4.6 Tg BC, 30.9 Tg OC

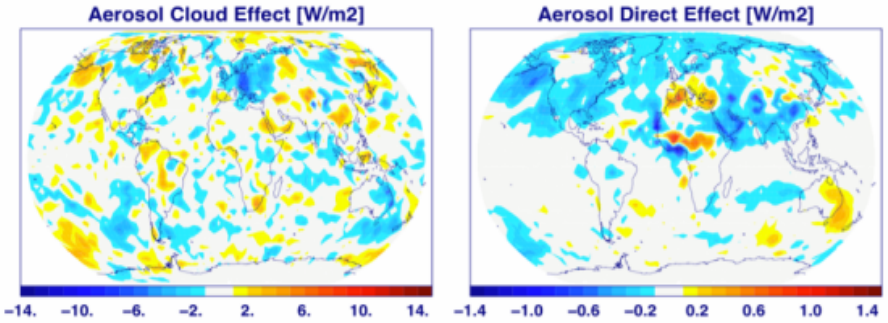
Fossil & bio-fuel w/o diesel: 3.3 TgBC 30.3 Tg OC

Reference: Bauer, S.E., et al, 2010: A global modeling study on carbonaceous aerosol microphysical characteristics and radiative forcing. Atmos. Chem. Phys.

diesel mitigation

Biomass burning:	3.0 Tg BC	34.2 Tg OC	standard emission
Fossil and bio-fuels:	4.6 Tg BC	30.9 Tg OC	
Fossil and bio-fuels:	3.3 Tg BC	30.3 Tg OC	no diesel

Differences between standard emission case and BC reduction:



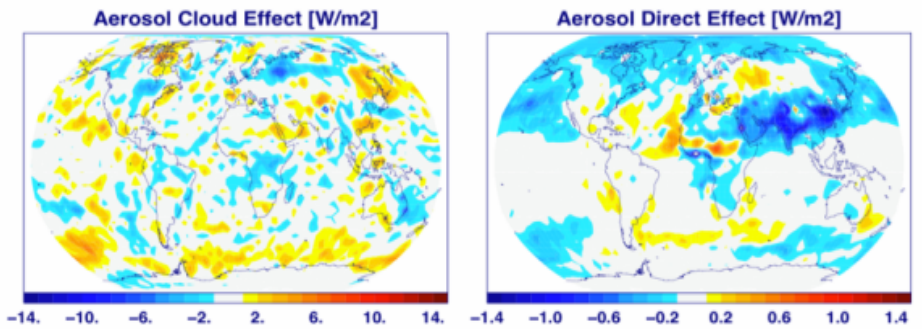
Radiative flux change between standard run and no diesel:

Indirect effect: -0.05 W/m²
Direct effect: -0.05 W/m²
Net Rad. change: -0.10 W/m²

bio-fuel mitigation

Biomass burning:	3.0 Tg BC	34.2 Tg OC	standard emission
Fossil and bio-fuels:	4.6 Tg BC	30.9 Tg OC	
Fossil and bio-fuels:	3.0 Tg BC	21.9 Tg OC	50% Bio-fuel

Differences between standard emission case and BC reduction:



Radiative flux change between standard run and reduced bio-fuel:

Indirect effect: 0.17 W/m²
Direct effect: -0.05 W/m²
Net Rad. change: 0.12 W/m²

DIESEL

- Direct effects similar in both cases.
- Diesel mitigation would have a beneficial effect on climate.
- The global forcing effect is very small.

BIO-FUEL

- Feedback effects lead to overall positive forcing in bio-fuel case due to high amount of organic carbon in bio-fuels.
- Globally, bio-fuel mitigation would not lead to an beneficial effects on climate.

Reference: Bauer, S.E., et al, 2010: A global modeling study on carbonaceous aerosol microphysical characteristics and radiative forcing. Atmos. Chem. Phys.

Part I - Summary

- Design of clever experiments:

  Mitigation experiments have to use sophisticated models because aerosol effects on climate are very complex. The experiments have to consider all important forcing processes (even so many of them are uncertain), and consider all co-emitted species.

  Use of more than one model.

- When discussing BC climate mitigation potentials, we have to look at feasible (not theoretical) emission reduction effects. Most likely those effects on climate will be very small globally, but could have more significant effects locally.

- Aerosols in general have a radiative cooling effect. Black carbon by itself does have a warming effect, however all emission sources emit a complex mixture of chemical species. We have to consider the combined effects.

- Aerosols cause many feedback effects. Mainly through their ability to influence clouds. These feedbacks can have positive and negative forcing effects. The prediction of these feedbacks bear many uncertainties, but they have to be taken into account in the policy discussion.

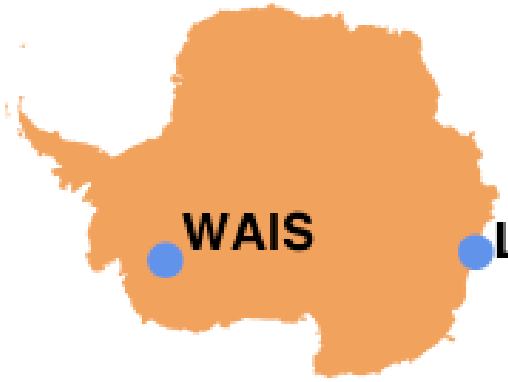
Reference: Bauer, S.E., and S. Menon, 2012: Aerosol direct, indirect, semi-direct and surface albedo effects from sector contributions based on the IPCC AR5 emissions for pre-industrial and present day conditions. J. Geophys. Res.

Bauer, S.E., et al, 2010: A global modeling study on carbonaceous aerosol microphysical characteristics and radiative forcing. Atmos. Chem. Phys.

Part II

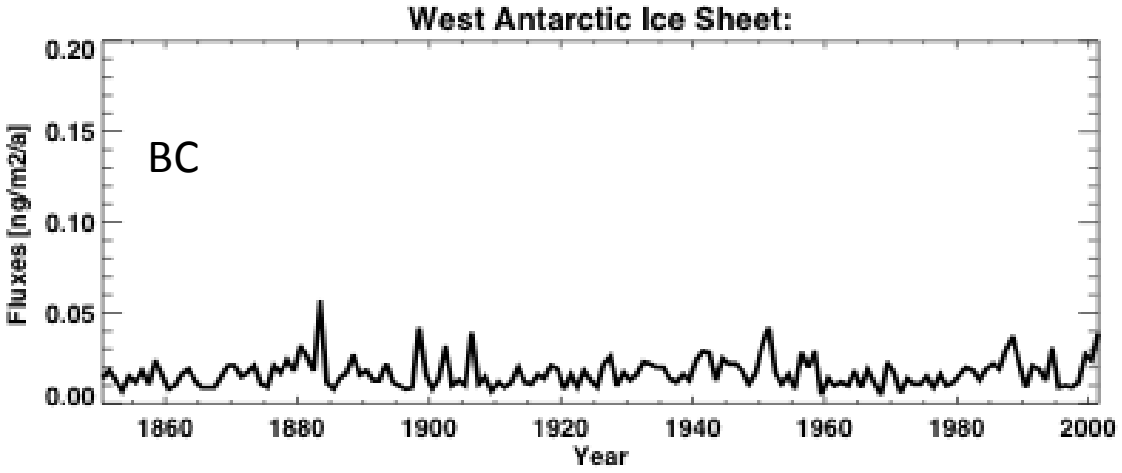
Unfortunately BC impacts on climate are very complicated

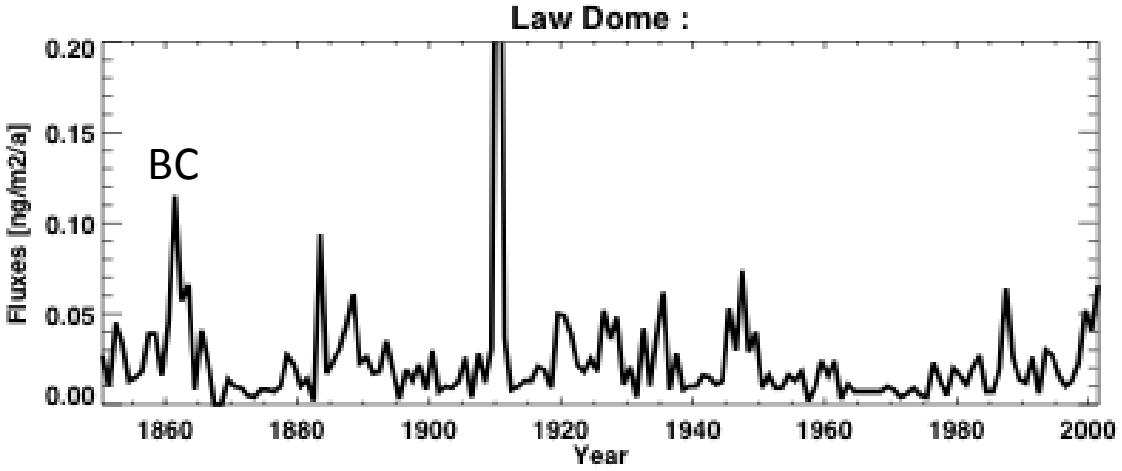
Physically ➔ what is BC? Properties?
Climate ➔ direct and indirect impacts and feedbacks
Sources ➔ Individual sources emit a wide range of chemical species
Time evolution ➔ no monotonous increase since pre-industrial times



- Clean background
- Law Dome exposed to higher BC fluxes
- BC lifetime too short to reach the South Pole

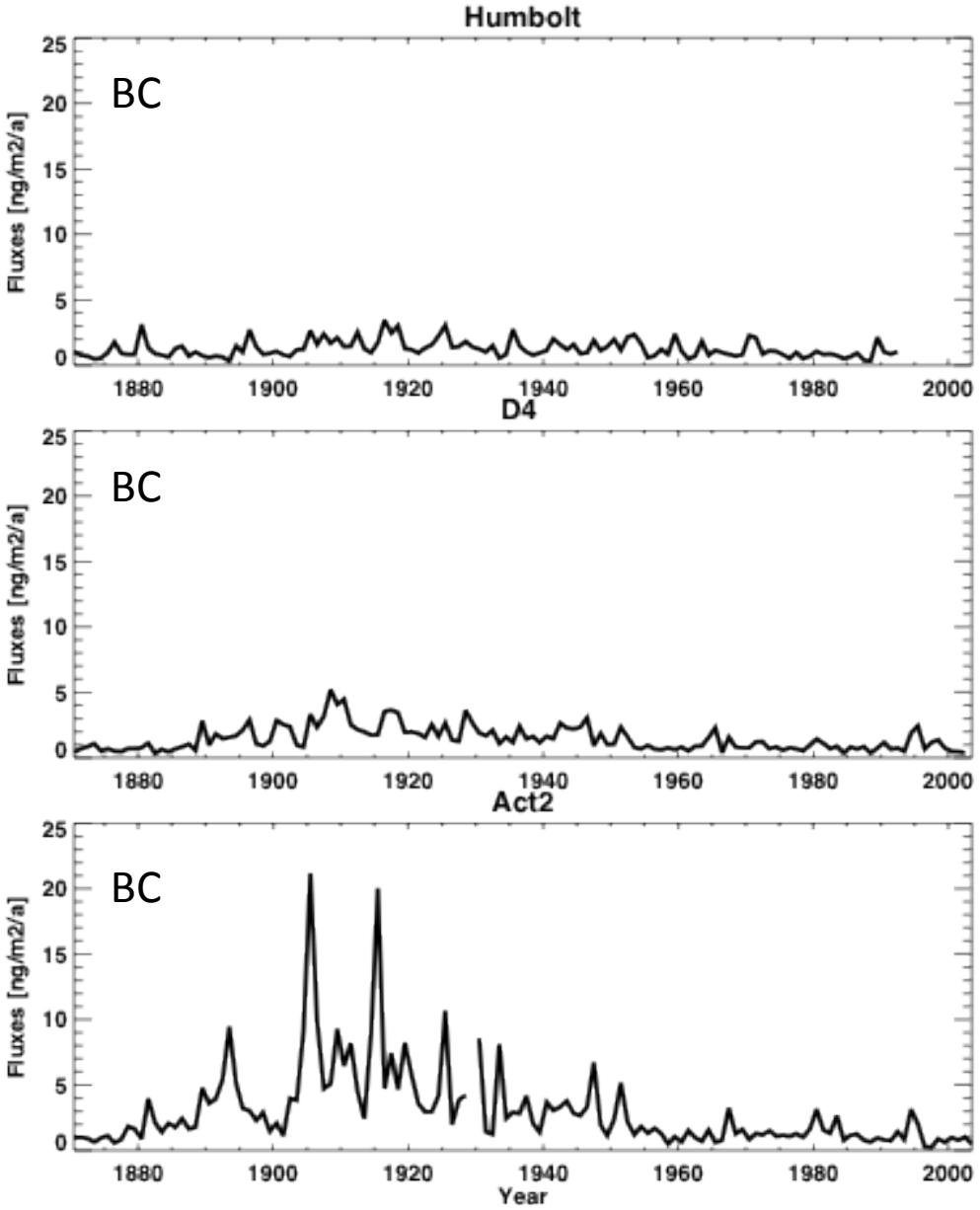

Dr Eric Wolff from the British Antarctic Survey





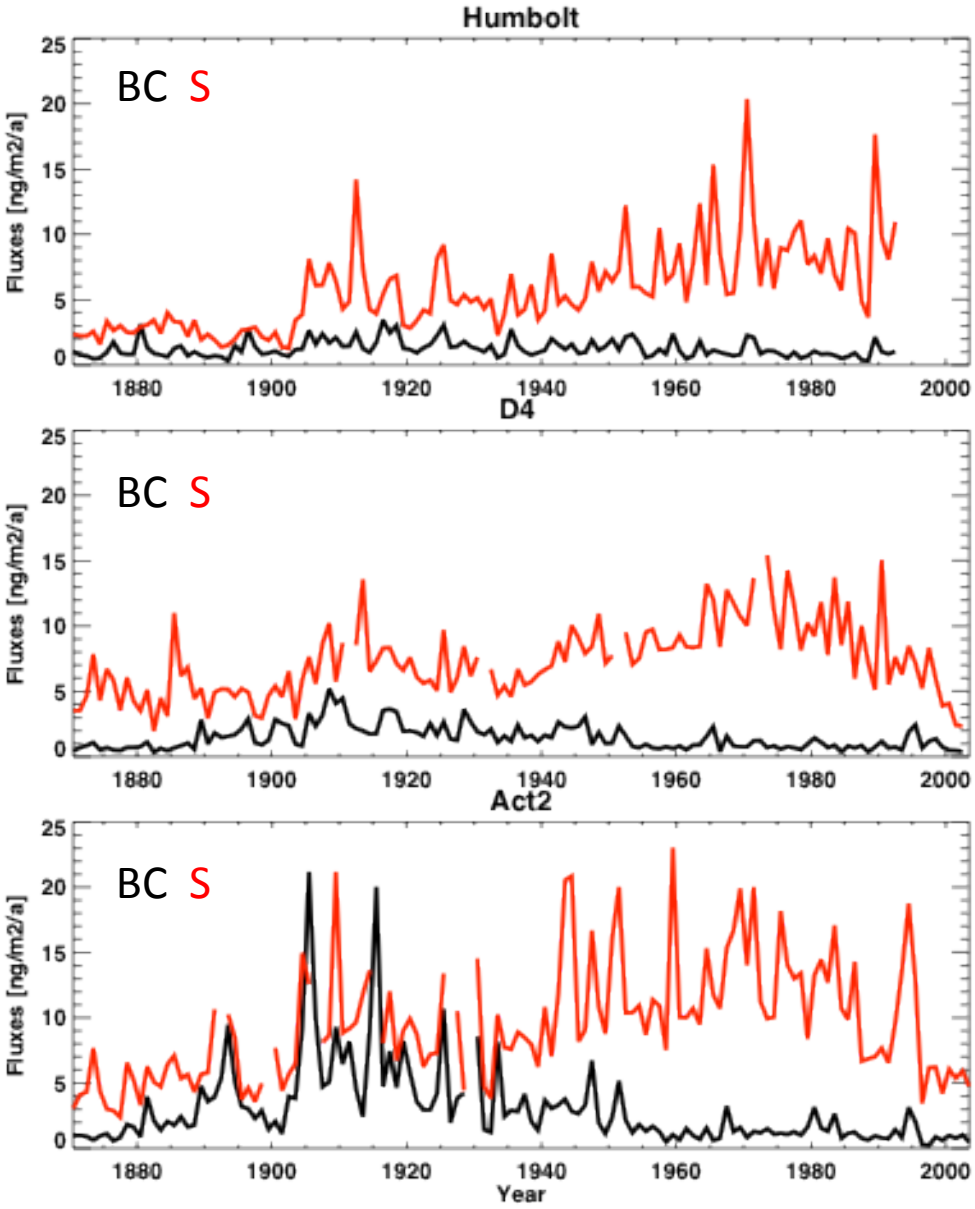
Reference: Bisiaux M.M., et al, 2012: Changes in black carbon deposition to Antarctica from two high-resolution ice core records, 1850 – 2000 AD, Atmospheric Chemistry and Physics

- 10 x higher BC fluxes compared to Antarctic at Humbolt
- Steep North / South gradient
- Highest concentrations in the early 20th century
- Land clearing and wood burning in North America (Europe)



Reference: McConnell, J. R. (2010), New Directions: Historical black carbon and other ice core aerosol records in the Arctic for GCM evaluation, *Atmospheric Environment*, *44*(21–22)

- Sulfur shows clear anthropogenic increase
- Major sulfur dioxide sources are the energy and industry sectors.
- Sulfur dioxide emissions are released by wood burning
- Decrease since 1990



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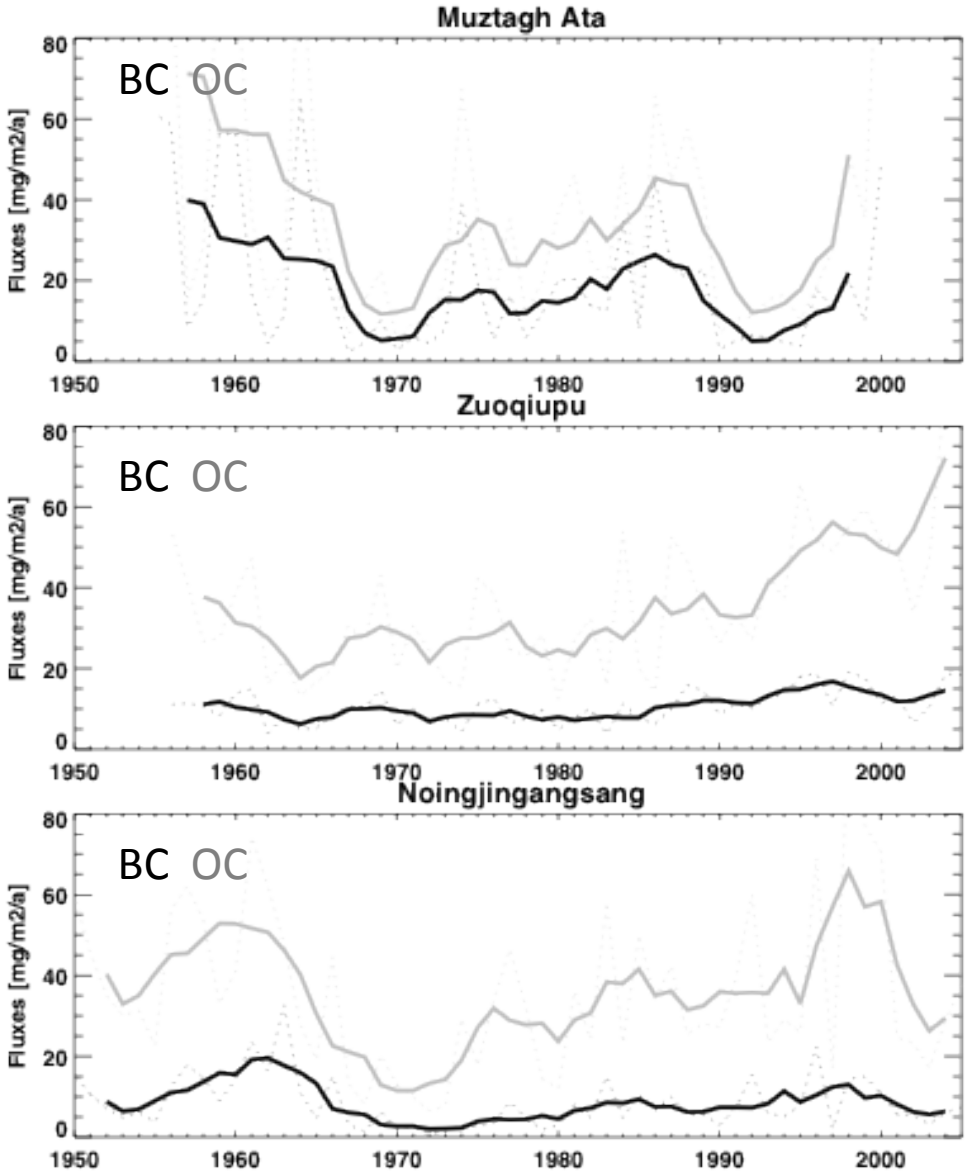
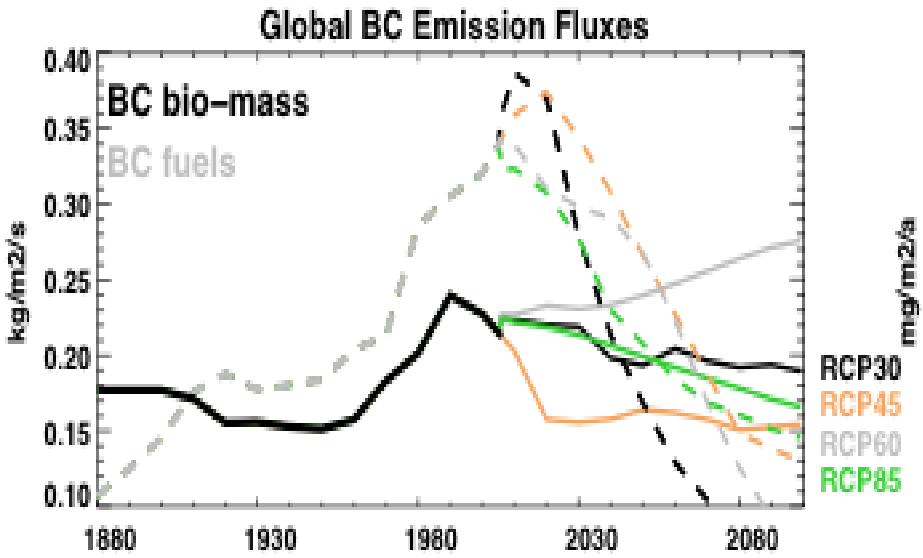
- Himalaya is much more influenced by regional BC sources

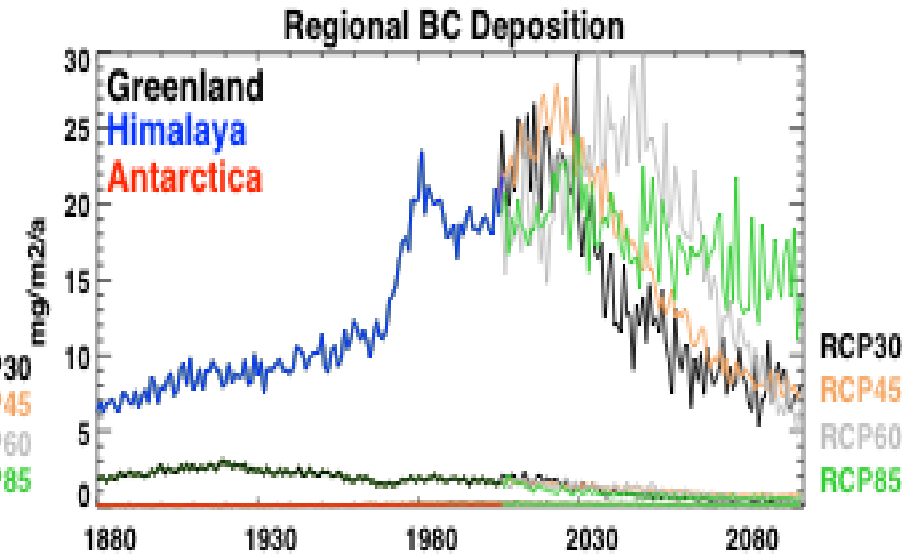
- BC conc. are
~ 10 x than in Greenland
~100x than in Antarctica

- Exposed to wood/coal/fuel burning throughout the century



Reference: Xu B., et al, 2009, Black soot and the survival of Tibetan glaciers, PNAS





GLOBAL BC EMISSION FLUXES & REGIONAL DEPOSITION

Emissions are expected to further increase in the near future (2010 – 2030) leading to increased BC in snow concentrations for a couple of decades in the Himalayas.

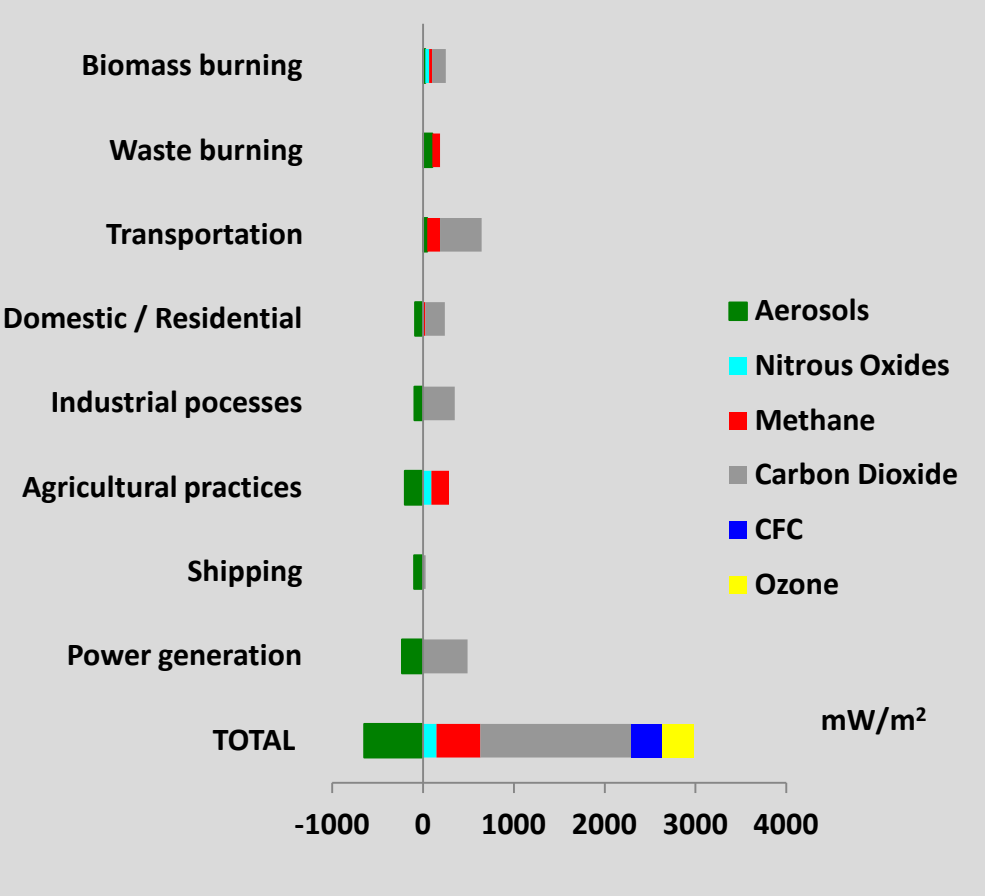
Future BC emission fluxes are predicted to decrease after 2030 in all RCPs, leading to decreased BC deposition in Greenland (ACT2), the Himalayas (Muztagh Ata) and Antarctic (Law Dome).

Part II - Summary

- Ice cores measurements are of tremendous value.
- BC emissions are not a modern phenomena: Aerosol sources (rich on BC) attributed to burning processes have been high during the past century.
- BC aerosols have a limited lifetime (5 days) and therefore are not homogenously distributed over the planet. Antarctica has the lowest background concentrations.
- Historical atmospheric chemistry in Greenland is strongly influenced by land clearing in North America and Europe during the early 20th century.
- The deposition of black carbon on Tibetan glaciers can have a significant impact on the observed rapid glacier retreat. Reduction of BC emissions, in addition to reduced greenhouse gases may be required to avoid further glacier retreat.

Thoughts / perspectives

- Feasible BC mitigation effects on climate are very small globally. Eventually too small to have any positive impacts on climate.
- Regionally, e.g. in Asia, mitigation can be beneficial to climate, especially when reducing domestic and transportation emissions.
- Globally, transportation sector most promising mitigation target, when considering GHG!
- Future aerosol projections assume decreasing **aerosol** emission.



Is this realistic? - if yes: good news for health, but bad news for climate!

Reference: Bauer, S.E., and S. Menon, 2012: Aerosol direct, indirect, semi-direct and surface albedo effects from sector contributions based on the IPCC AR5 emissions for pre-industrial and present day conditions. J. Geophys. Res.,