Black carbon: *Climate Effects*

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Thanks to Tami Bond, Jan S. Fuglestvedt , the Bounding-BC team, and IPCC Chapter 7 and 8 writing teams

November 11, 2013

Credits

Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment

T. Bond, S. Doherty, D. Fahey, P. Forster (CLAs), T. Berntsen, B. J. DeAngelo, M. G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P. K. Quinn, M. C. Sarofim, M. G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S. K. Guttikunda, P. K. Hopke, M. Z. Jacobson, J. W. Kaiser, Z. Klimont, U. Lohmann, J. P. Schwarz, D. Shindell, T. Storelvmo, S. G. Warren, C. S. Zender

31 authors, 4 coordinating lead authors, 9 countries represented

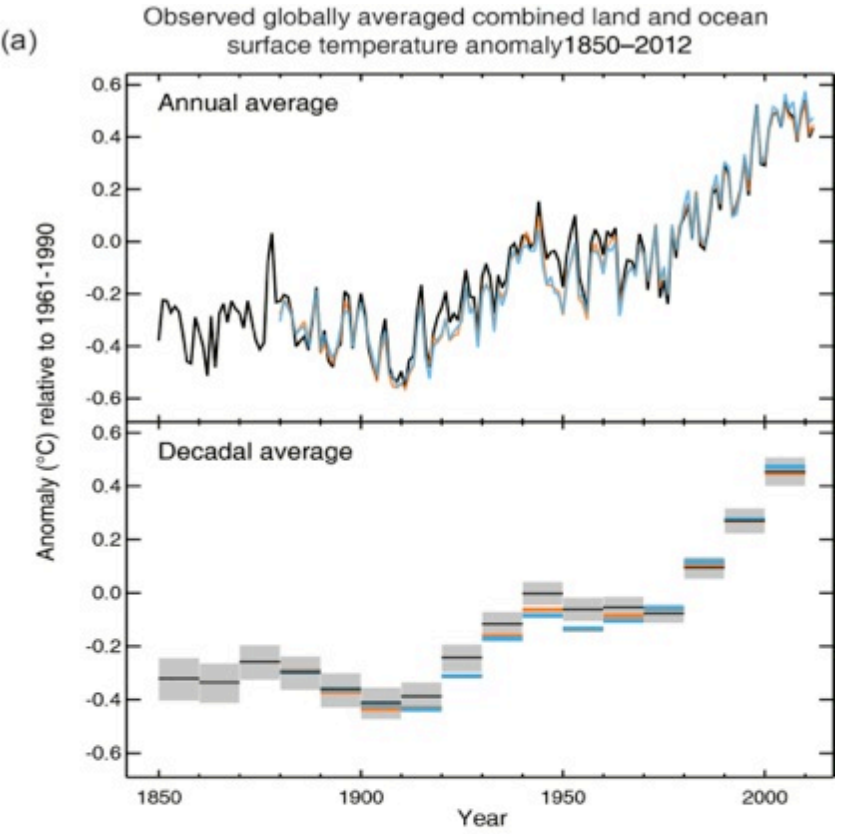
Peer-reviewed paper in JGR-Atmos (177 pgs) (in public domain)

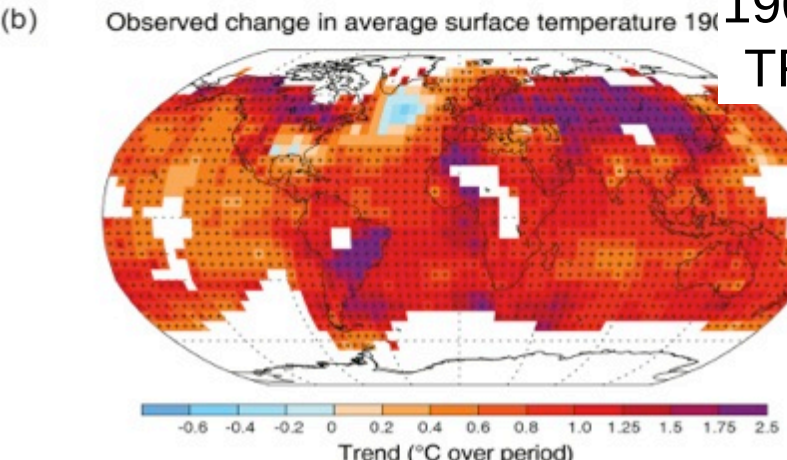
IPCC AR5

Today's talk

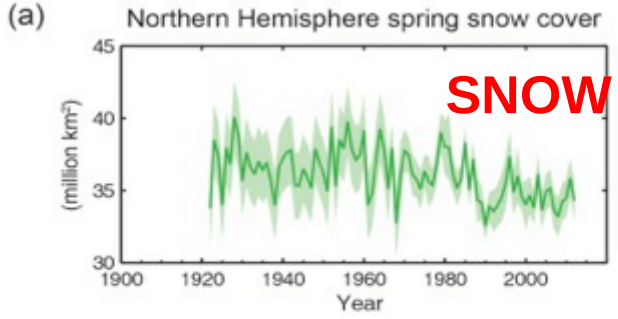
- Contrast Black Carbon (BC) to CO_2
- What is BC?
- Climate effects of BC
- Climate mitigation via BC
- Health vs. climate effects
- Key areas for progress

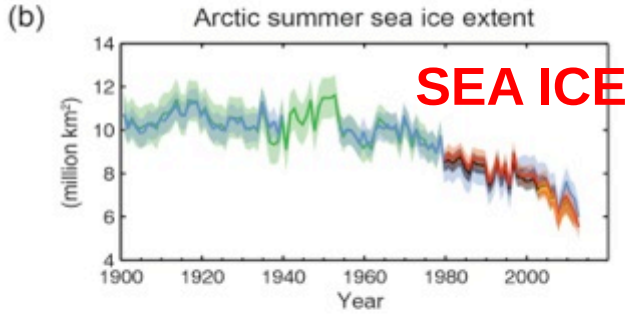
Observations show strong warming trends

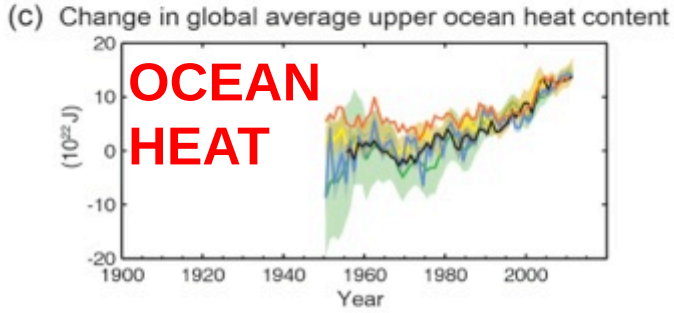


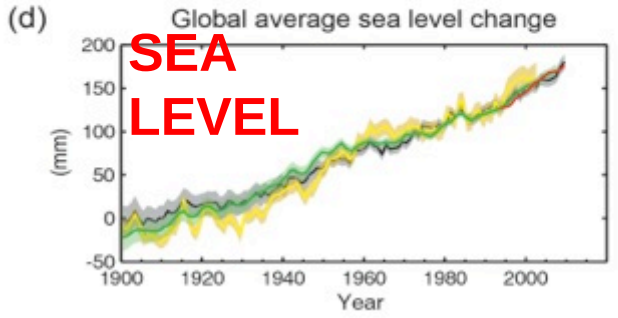


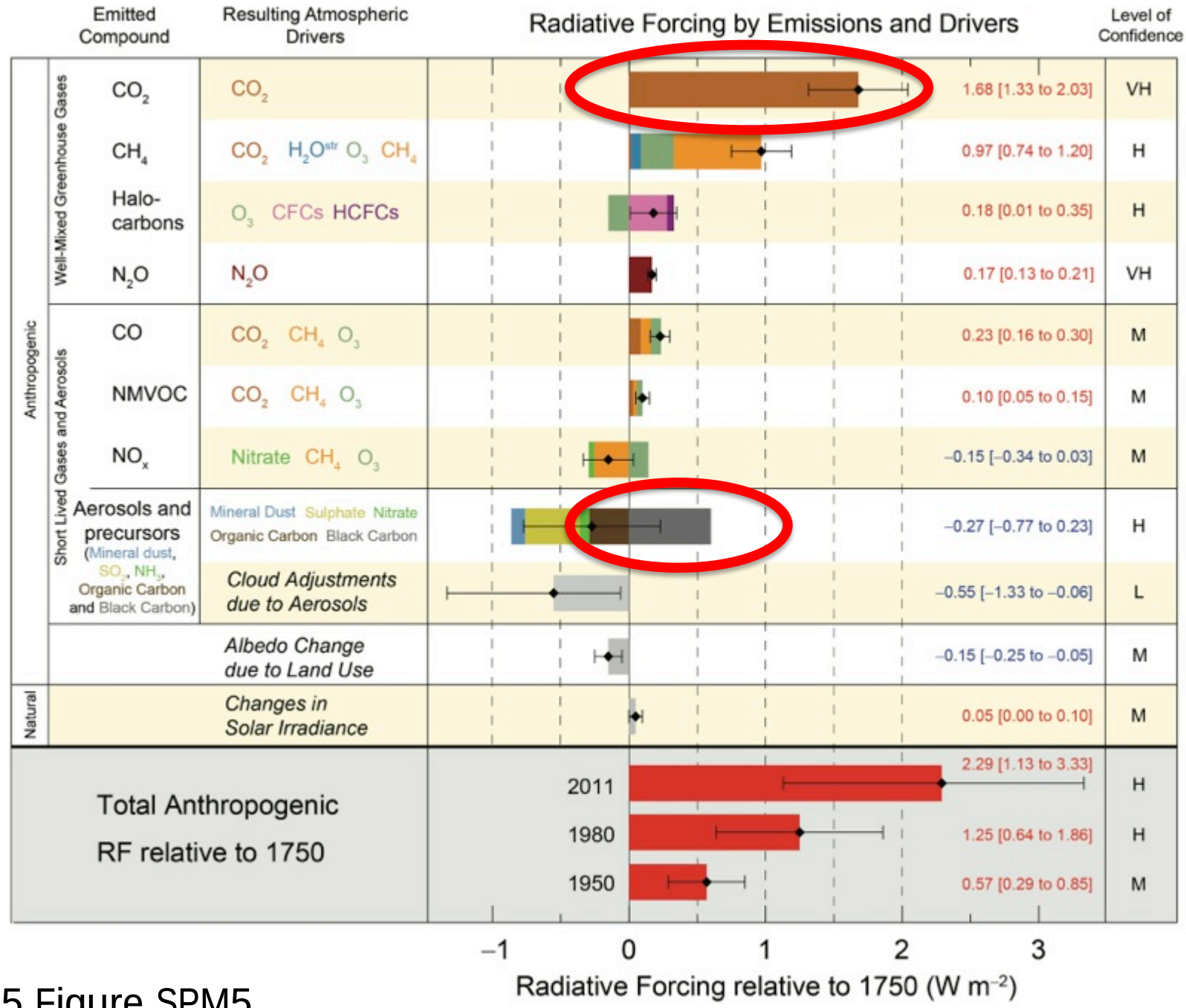
1901-2012
TRENDS











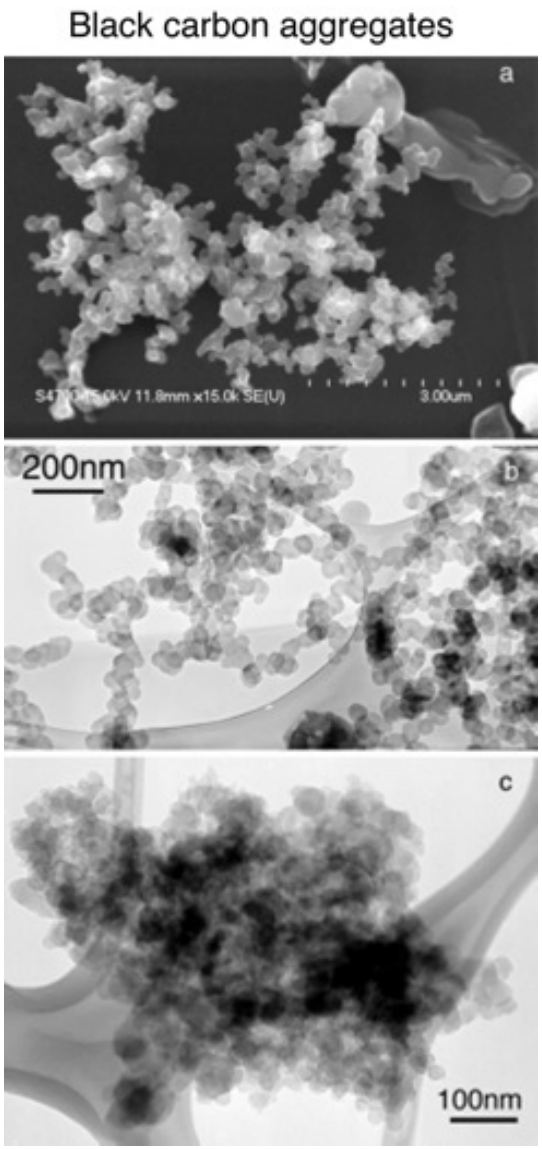
AR5 Figure SPM5

Contrast BC and CO_2

- Technical differences in their climate effects
  - BC affects solar radiation and snow reflectance
- BC short lived in atmosphere
  1. Emissions from different regions/sources have different effectiveness as a GLOBAL climate change agent
  2. Potential for localized climate effects
  3. Mitigation of BC has little effect on long term climate change BUT can have large effect on near term climate
- BC mitigation has direct benefit on air quality

What is Black Carbon?

We know what black carbon is



Unique combination of :

Strong light absorption

Mass absorption cross section of at least 5 m^2g^{-1}, for 550 nm light.

Refractory

Retains basic form at very high temperatures: vaporization temperature near 4000K.

Insoluble

in water and organic solvents

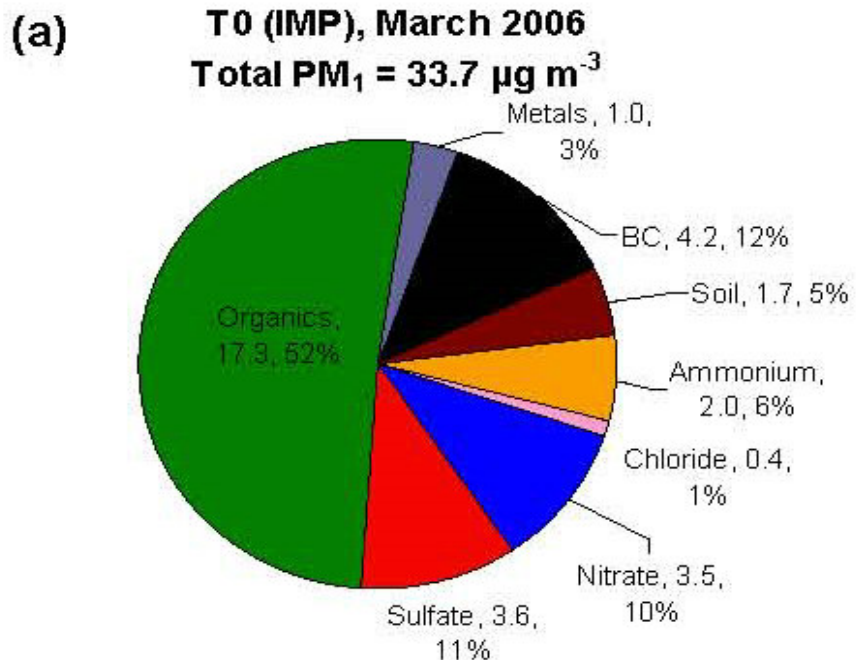
Aggregate

of small carbon spherules

But measurement techniques don't always capture it

Black carbon is a small component of mass

Even in polluted regions



Mass in Mexico City (Aiken *et al.*, Atmos. Chem. Phys. 9, 6633, 2009

Other particle components do not absorb light, or absorb very little.

They COOL the Earth because they reflect light.

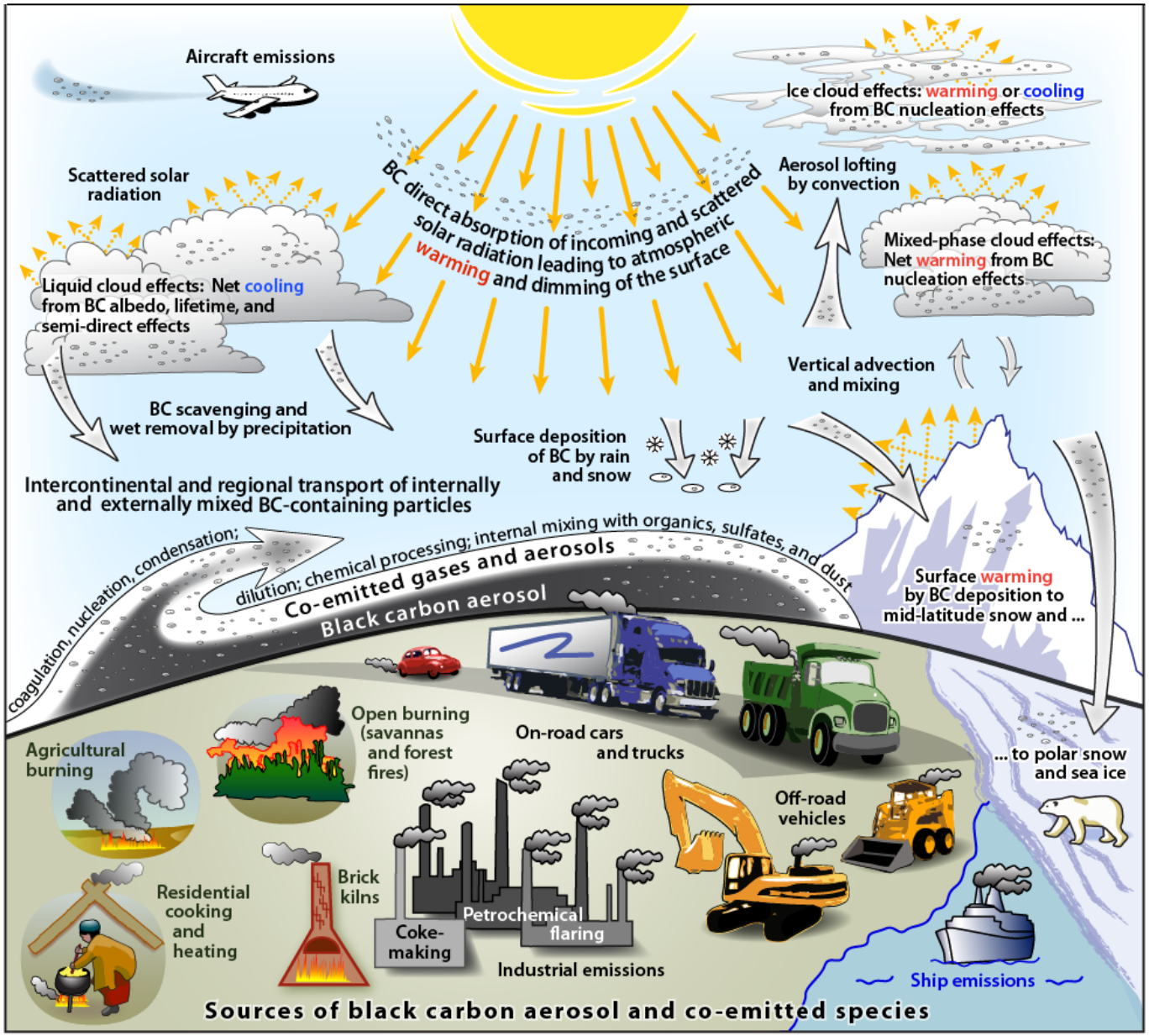
Major components:
sulfate,
organic carbon

this candle is making
black carbon
right here

and this one is making
“organic” carbon…
no flame, no game!

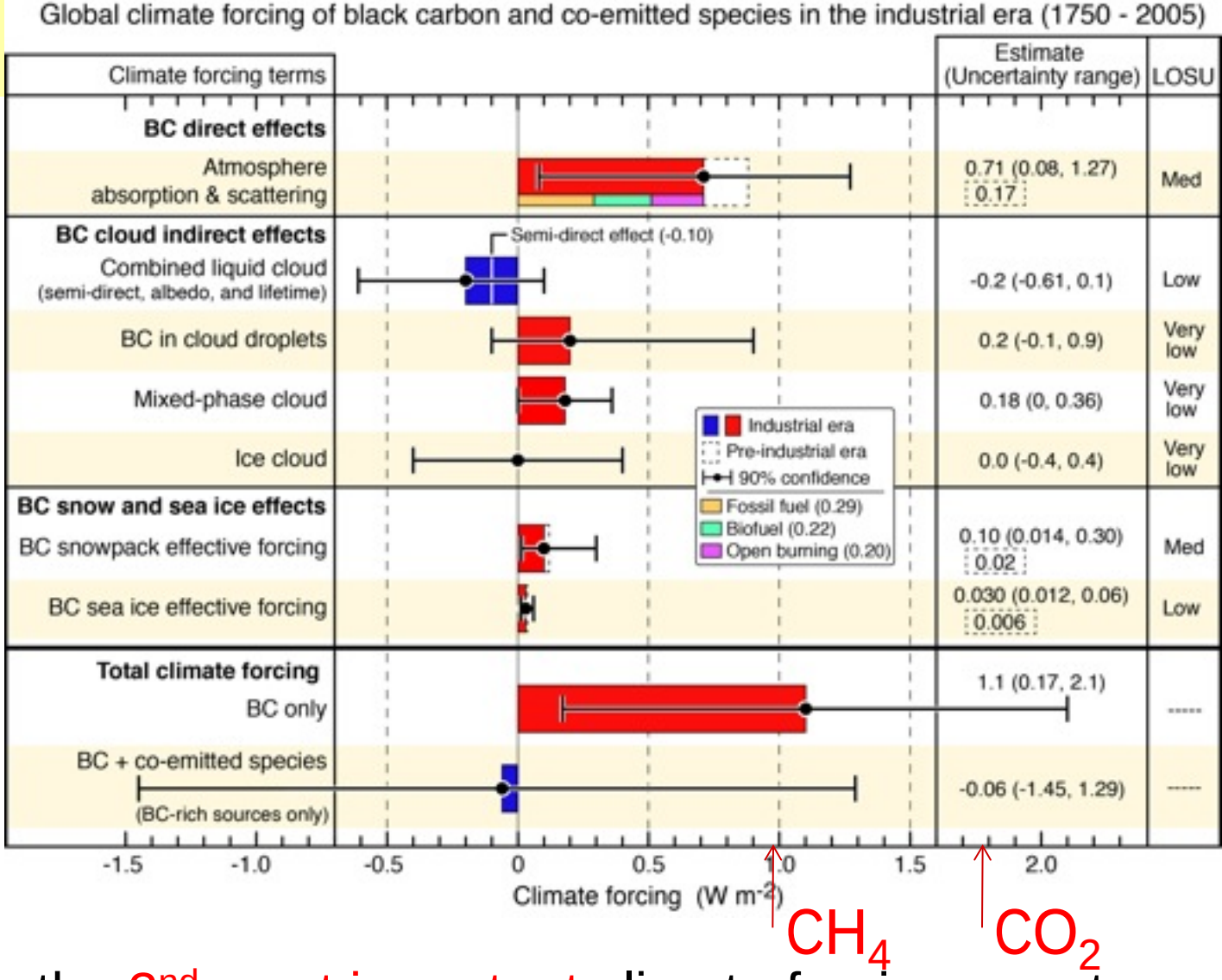
Climate Effects of BC

“Comprehensive” with regard to climate effects

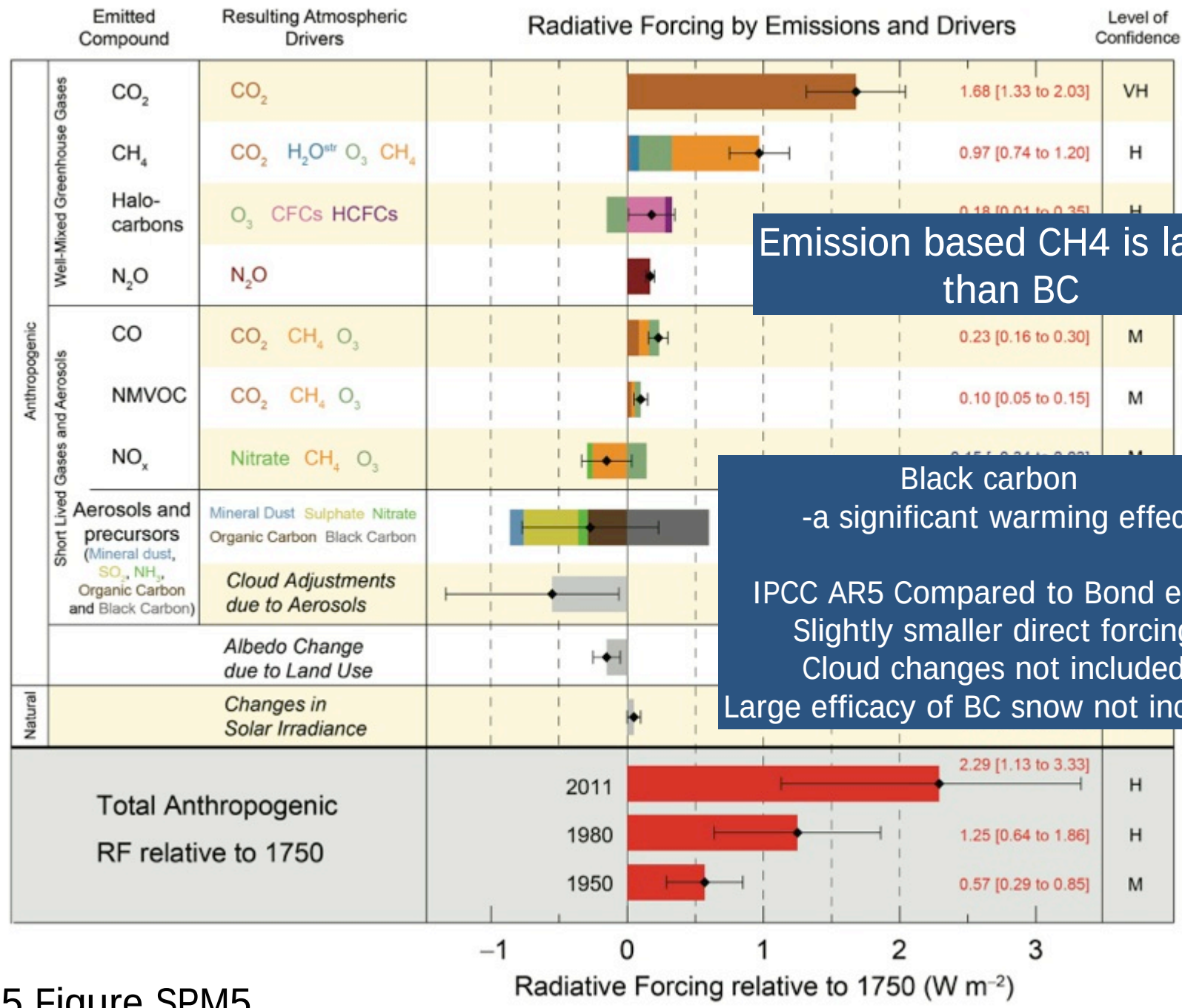


Bond *et al.*, JGR, 2013.

Estimate of black carbon forcing from Bounding-BC



- Black carbon is the 2nd most important climate forcing agent in 2000-2005.
- But, the climate forcing of co-emitted species substantially offsets the radiative forcing of black-carbon emissions alone.



Emission based CH4 is larger than BC

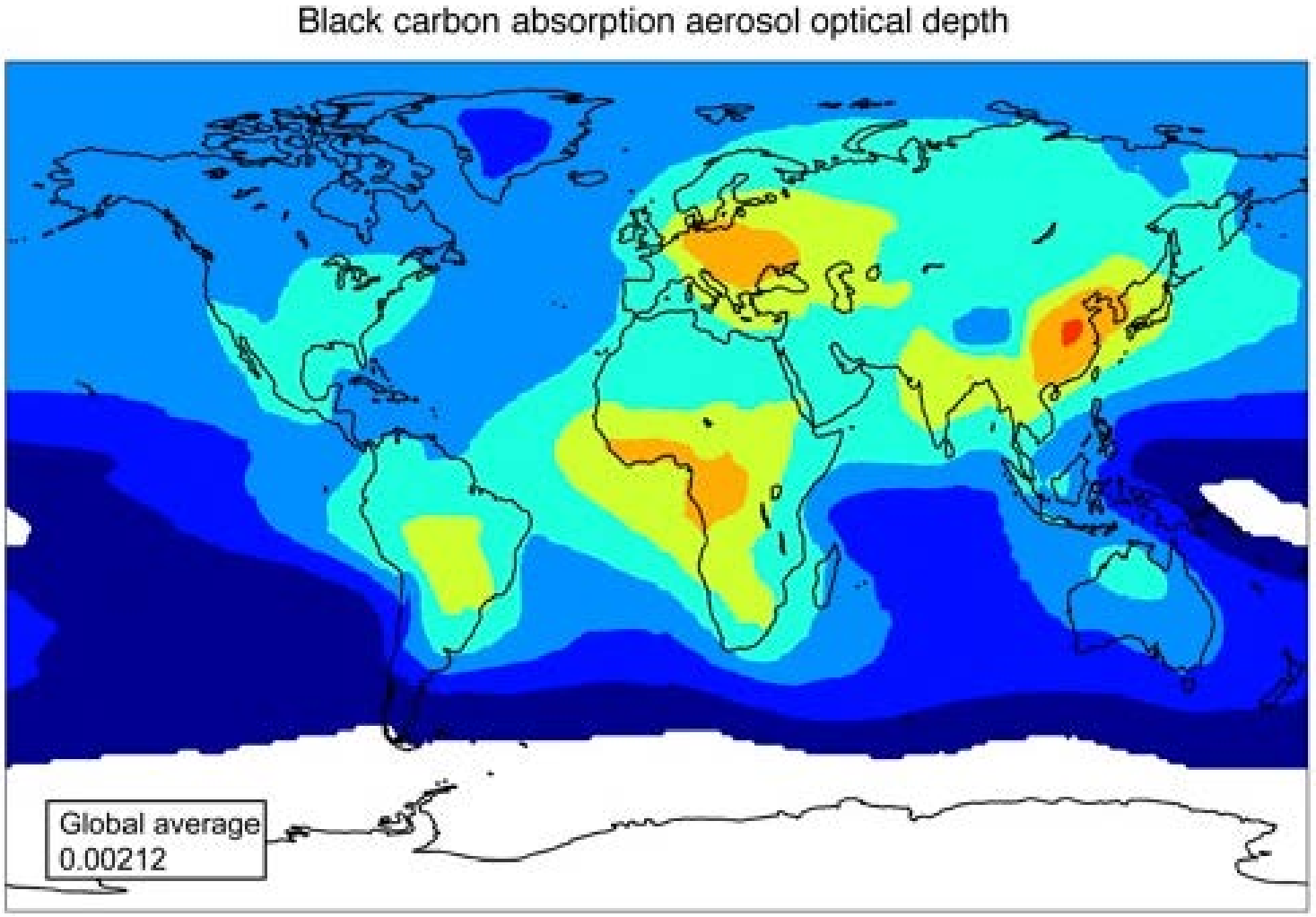
Black carbon
-a significant warming effect

IPCC AR5 Compared to Bond et al:
Slightly smaller direct forcing
Cloud changes not included
Large efficacy of BC snow not included

AR5 Figure SPM5

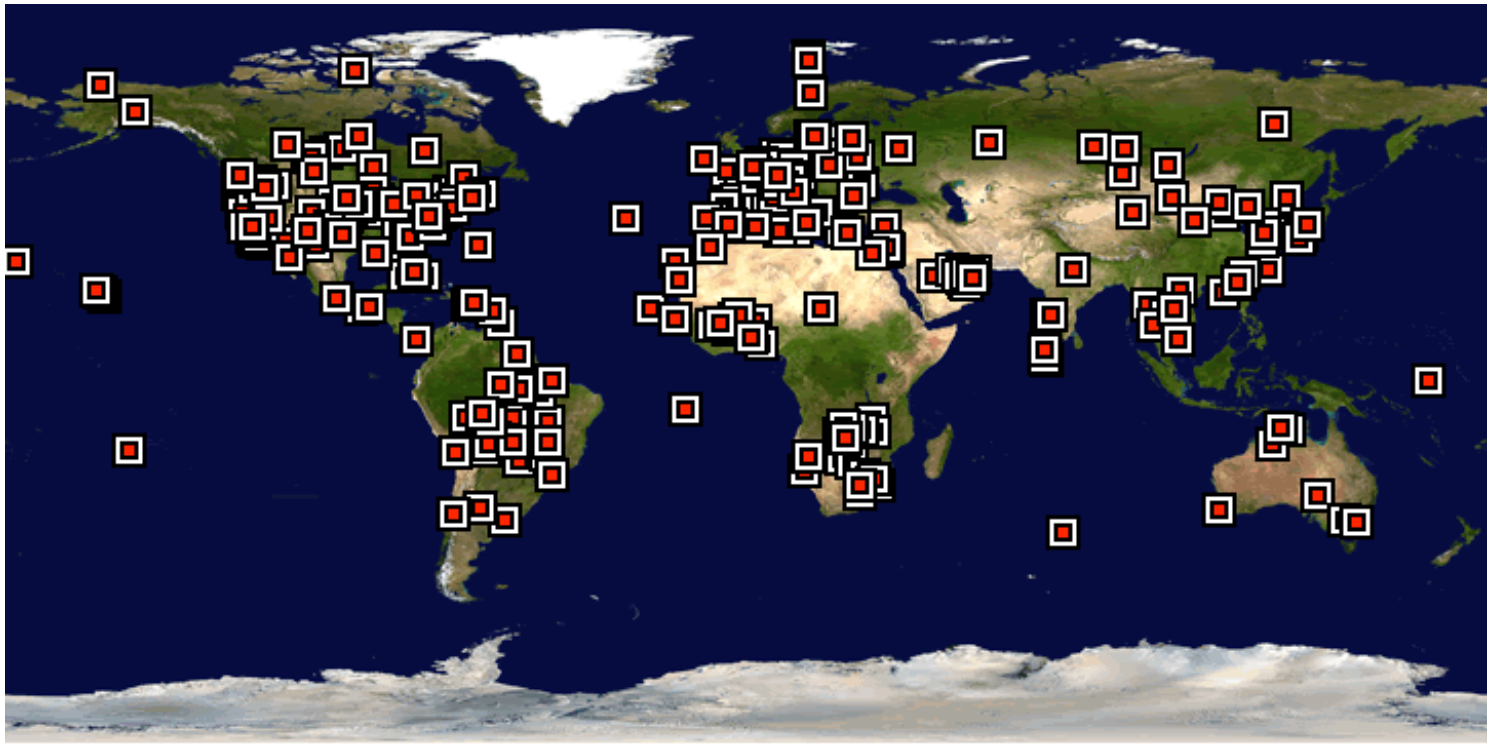
Unlike CO_2, BC is not evenly distributed

- *Need many measurements to constrain distribution*
- *Can't be retrieved from space-borne measurements yet*



Observations key but typically indirect

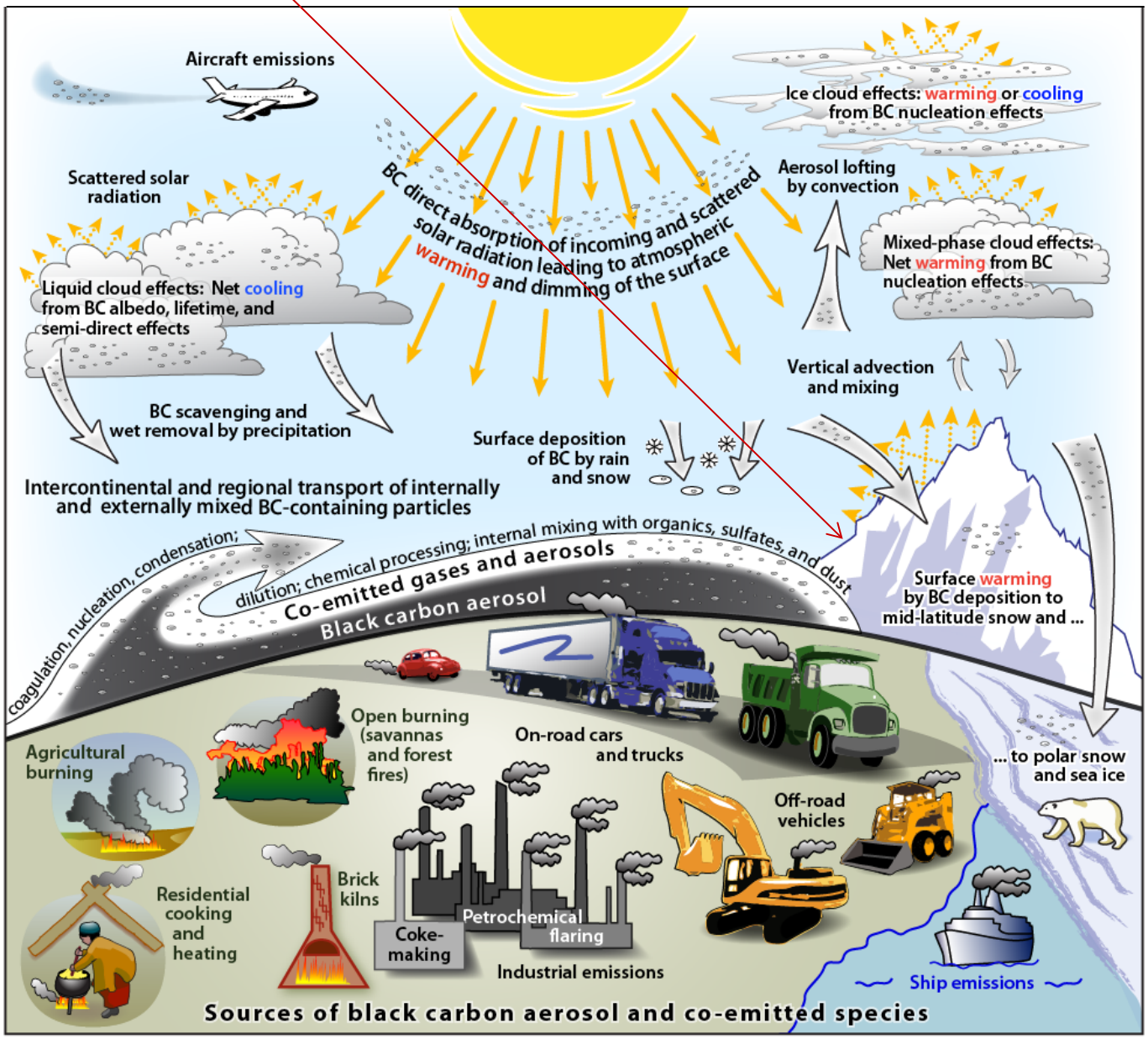
- Based on global network AERONET
- Inferred total absorption from aerosol optical depth and single-scattering albedo
- Both BC and dust absorb light; division is questionable



AERONET sites (Credit: NASA)

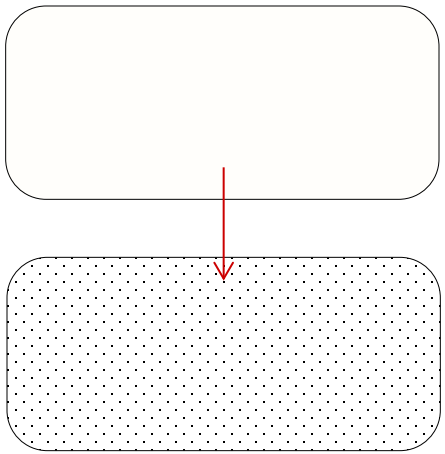
Note limited coverage in some major emitting regions

Snow and ice


Aircraft emissions
Ice cloud effects: warming or cooling from BC nucleation effects
Scattered solar radiation
BC direct absorption of incoming and scattered solar radiation leading to atmospheric warming and dimming of the surface
Aerosol lofting by convection
Mixed-phase cloud effects: Net warming from BC nucleation effects
Liquid cloud effects: Net cooling from BC albedo, lifetime, and semi-direct effects
Vertical advection and mixing
BC scavenging and wet removal by precipitation
Surface deposition of BC by rain and snow
Intercontinental and regional transport of internally and externally mixed BC-containing particles
coagulation, nucleation, condensation; dilution; chemical processing; internal mixing with organics, sulfates, and dust
Co-emitted gases and aerosols
Black carbon aerosol
Surface warming by BC deposition to mid-latitude snow and ...
... to polar snow and sea ice
Open burning (savannas and forest fires)
On-road cars and trucks
Agricultural burning
Off-road vehicles
Brick kilns
Residential cooking and heating
Petrochemical flaring
Coke-making
Industrial emissions
Ship emissions
Sources of black carbon aerosol and co-emitted species

BC deposited on snow has positive forcing

Think of BC as a very small rock.



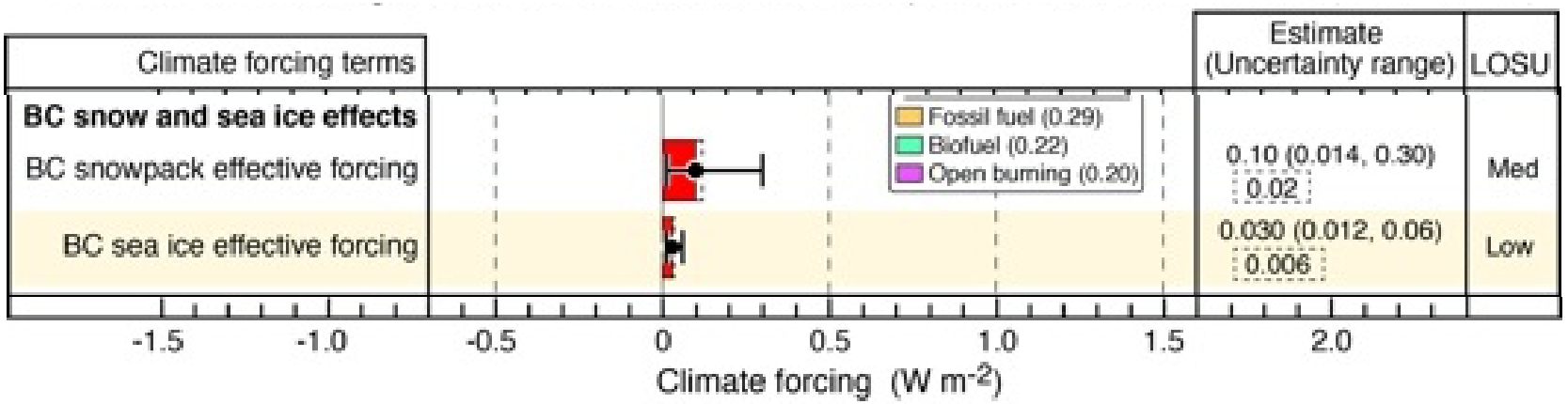
BC reduces snow's reflectivity

Solid takes up heat; heat melts snow (or ice)

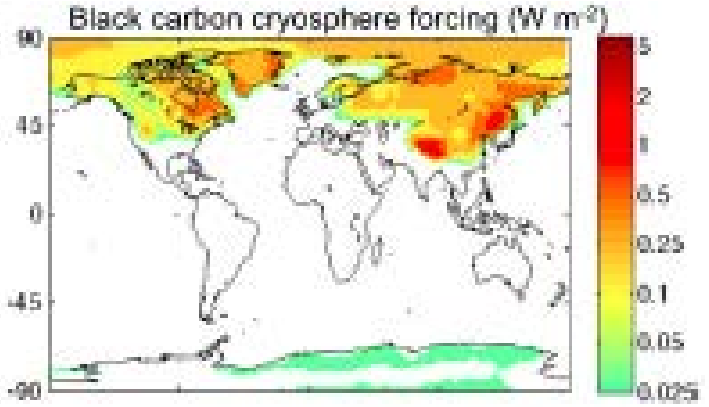
Exposed surface absorbs heat and melts remaining snow

Net result: Effect is greater than just direct forcing

Forcing by BC in snow and ice



- Model results were also scaled to measurements
- Small forcing, but powerful and localized
- 2-4 times stronger affect on global temperature than other forcings

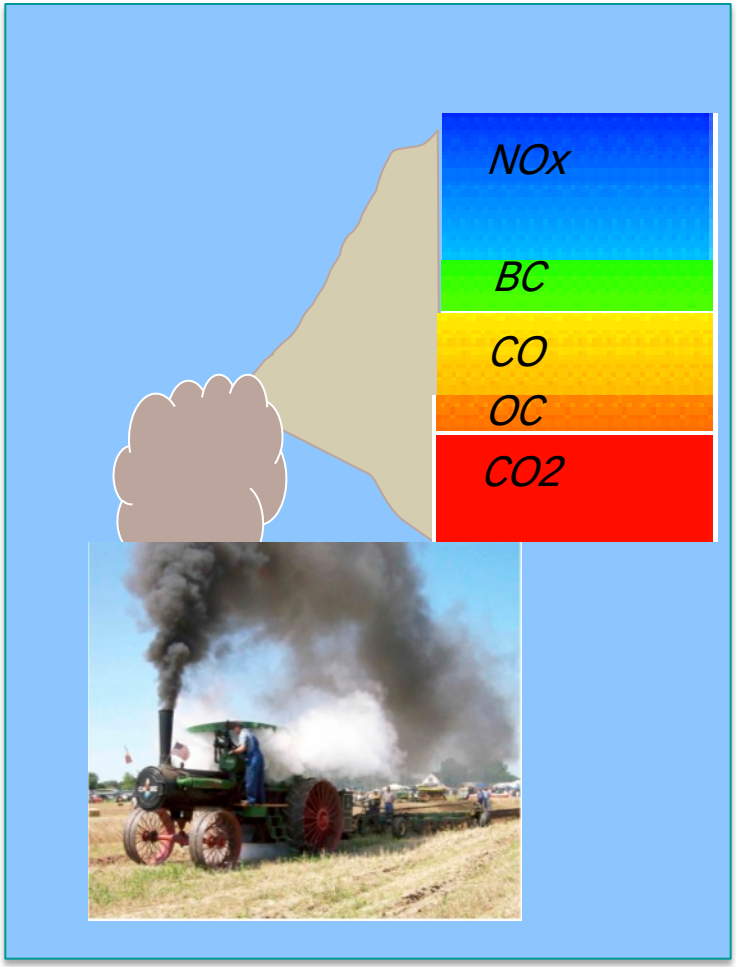


Bond et al., ACP, 2011

Climate Mitigation via BC

BC alone is a an incomplete story

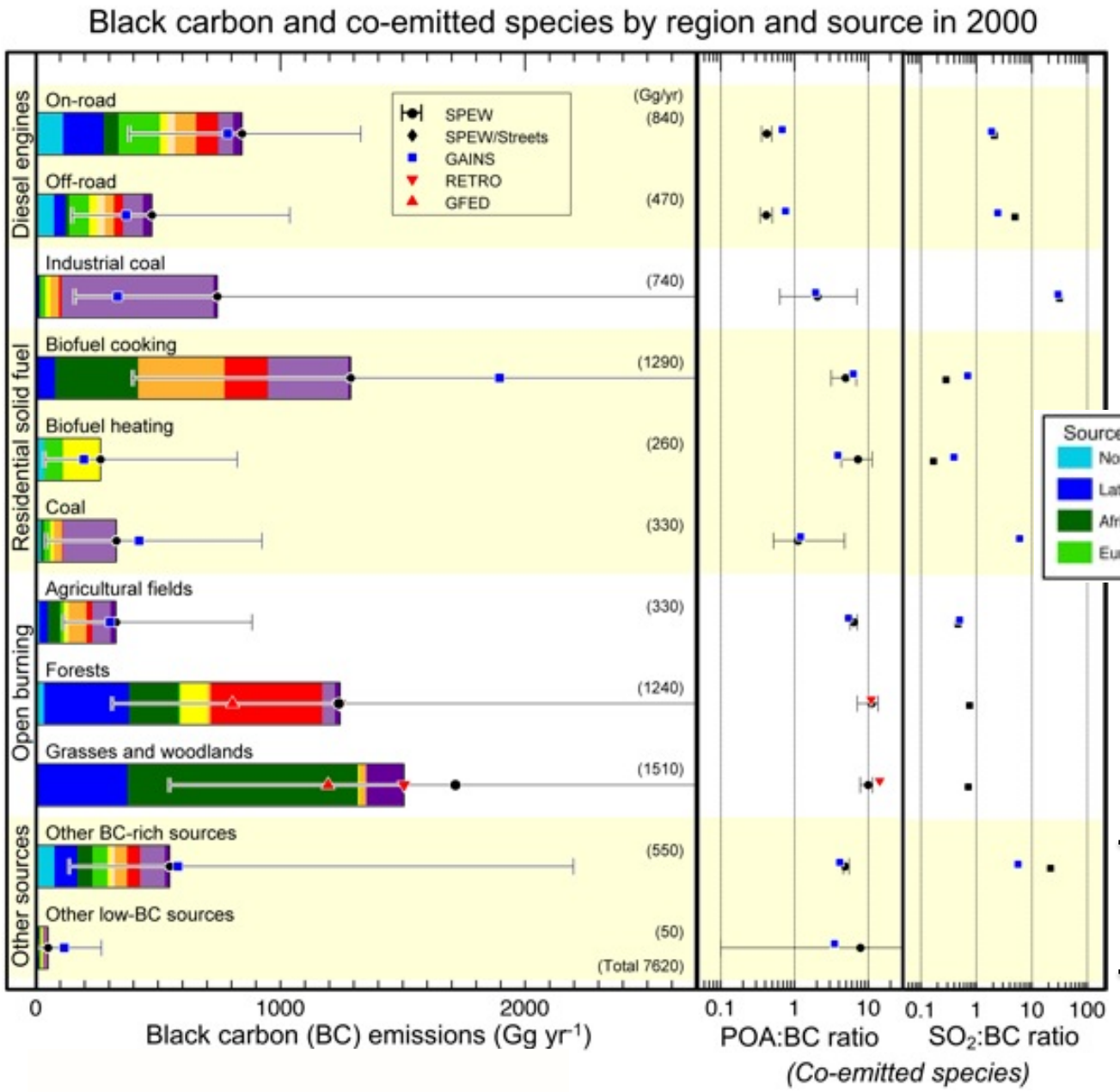
- Sources that emit black carbon also emit other short-lived species * that affect climate
  - Sulfate: COOLING
  - Organic carbon: COOLING
  - Gases: WARMING or COOLING
- Shutting off a source entirely removes all species
- Mitigation actions affect each species differently



* species = chemical species

BC emissions by region & source type

More co-emitted species = Greater likelihood of cooling



Inventories:

SPEW (Speciated Pollutant Emissions Wizard)

GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies)

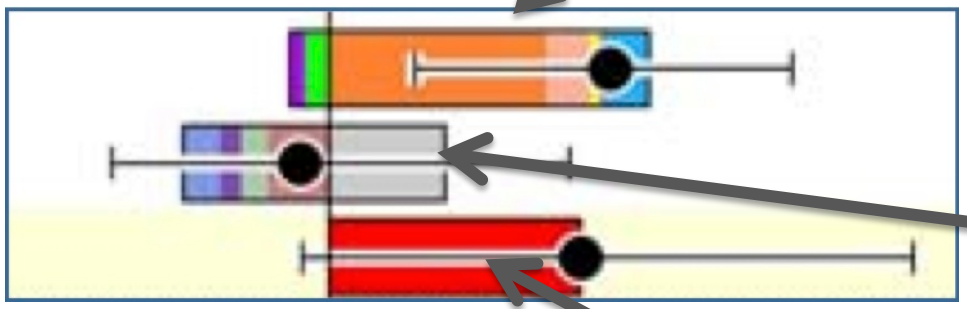
- On-road gasoline engines
- Residential, including diesel generation
- Aviation
- Shipping
- Flaring

Guide to “first-year” forcing graphs

Direct, snow forcing, ozone

High confidence in attribution

- BC atmosphere
- BC snow
- POA atmosphere
- POA snow
- SO_4 atmosphere
- CO on O_3
- NMVOC on O_3
- NO_x on O_3



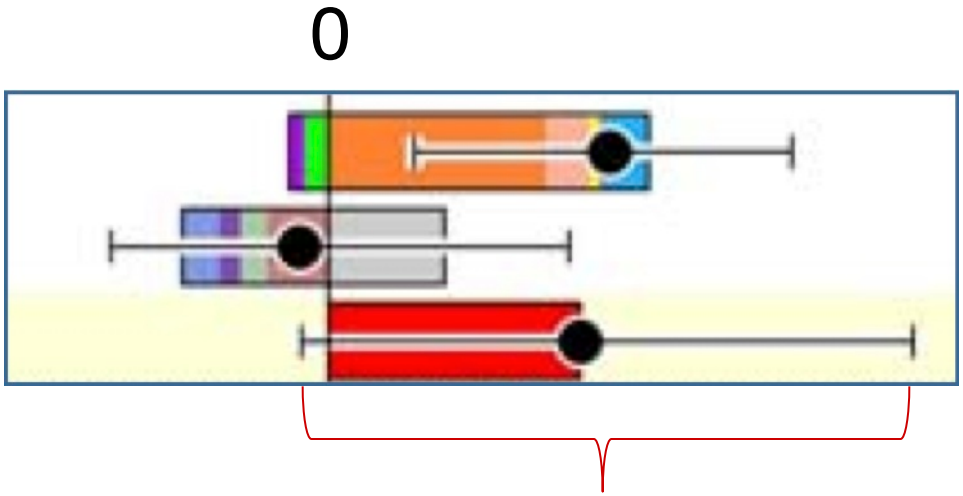
Cloud & Nitrate forcing

Low confidence in attribution

- BC liq clouds
- BC other clouds
- POA clouds
- SO_4 clouds
- NO_x on NO_3

Total

What if the uncertainty crosses zero?



Direct – definitely from this source
Indirect– not sure forcing is from this source

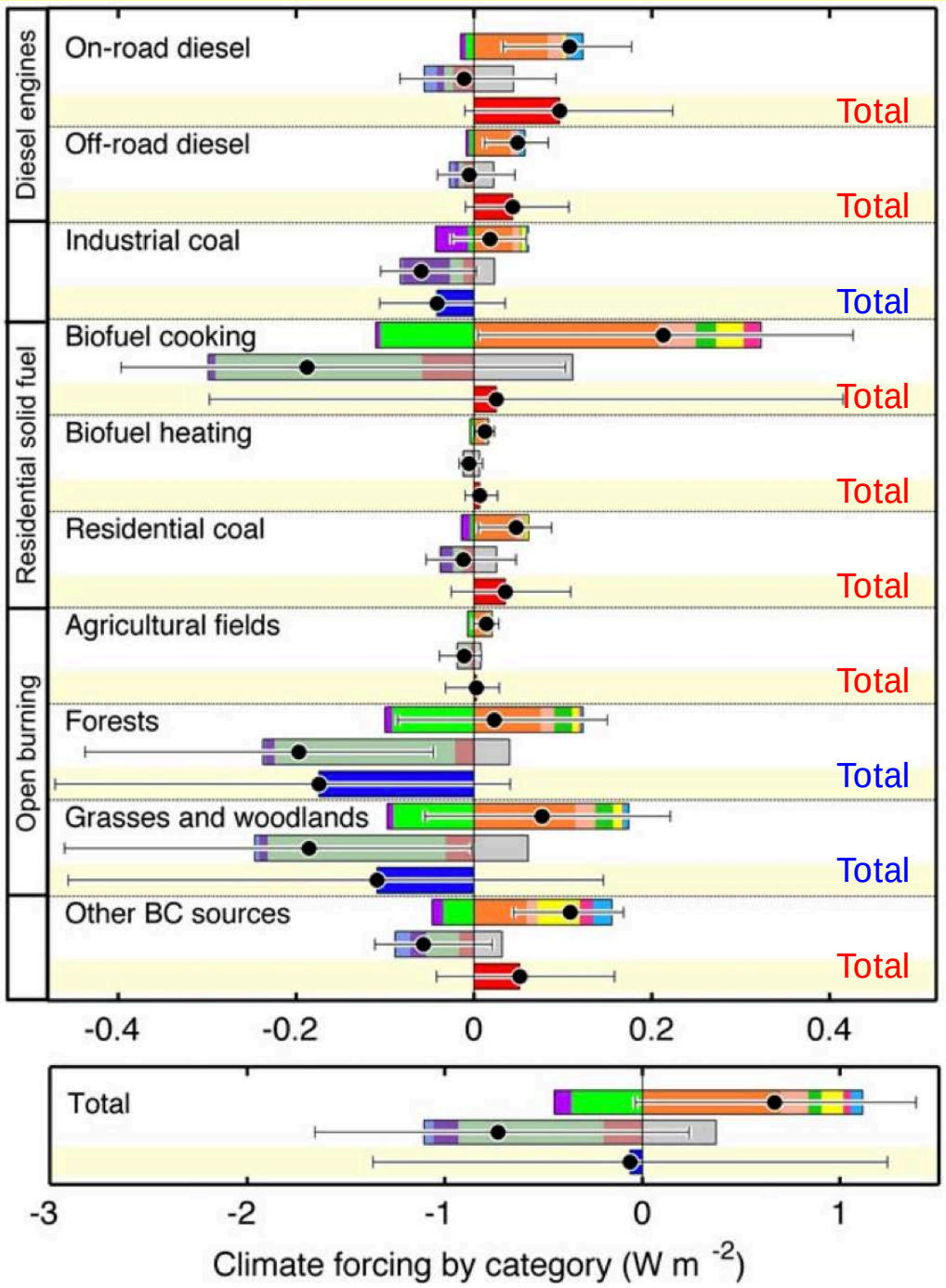
Total

- Best estimate is warming if “Total” bar is red.
- There is some probability that the overall effect of the source is cooling.
  - This probability depends on how much whisker is below zero.
- There is also some probability that the overall effect of the source is much *more* warming than the central estimate.
- Need a risk analysis approach

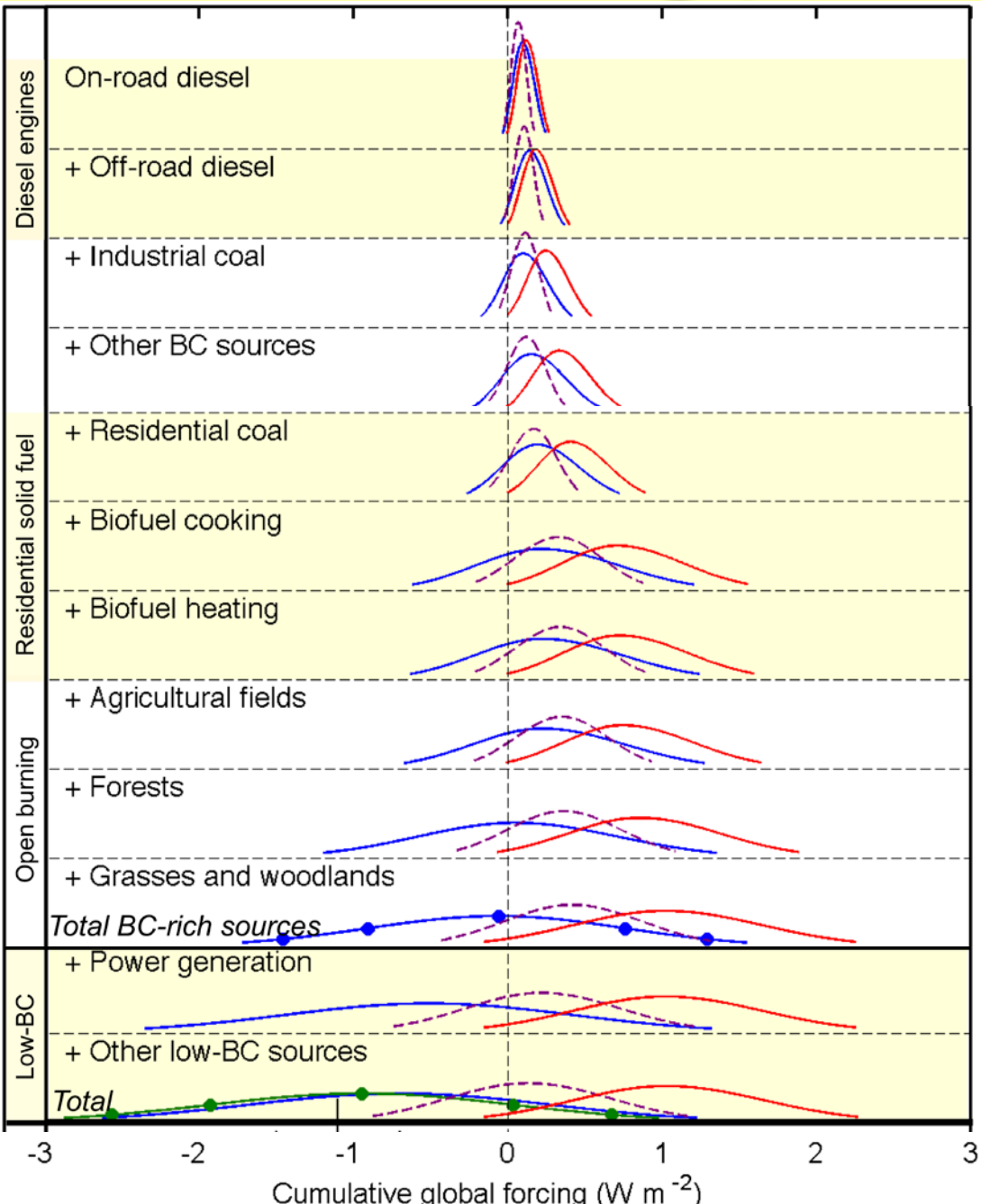
Climate forcing: BC-rich source categories

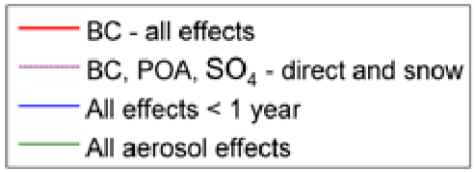
First-year forcing only

- Some categories net positive (red)
- Some net negative (blue)
- Sign is unknown for many categories



Cumulative forcing (add selected categories)





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

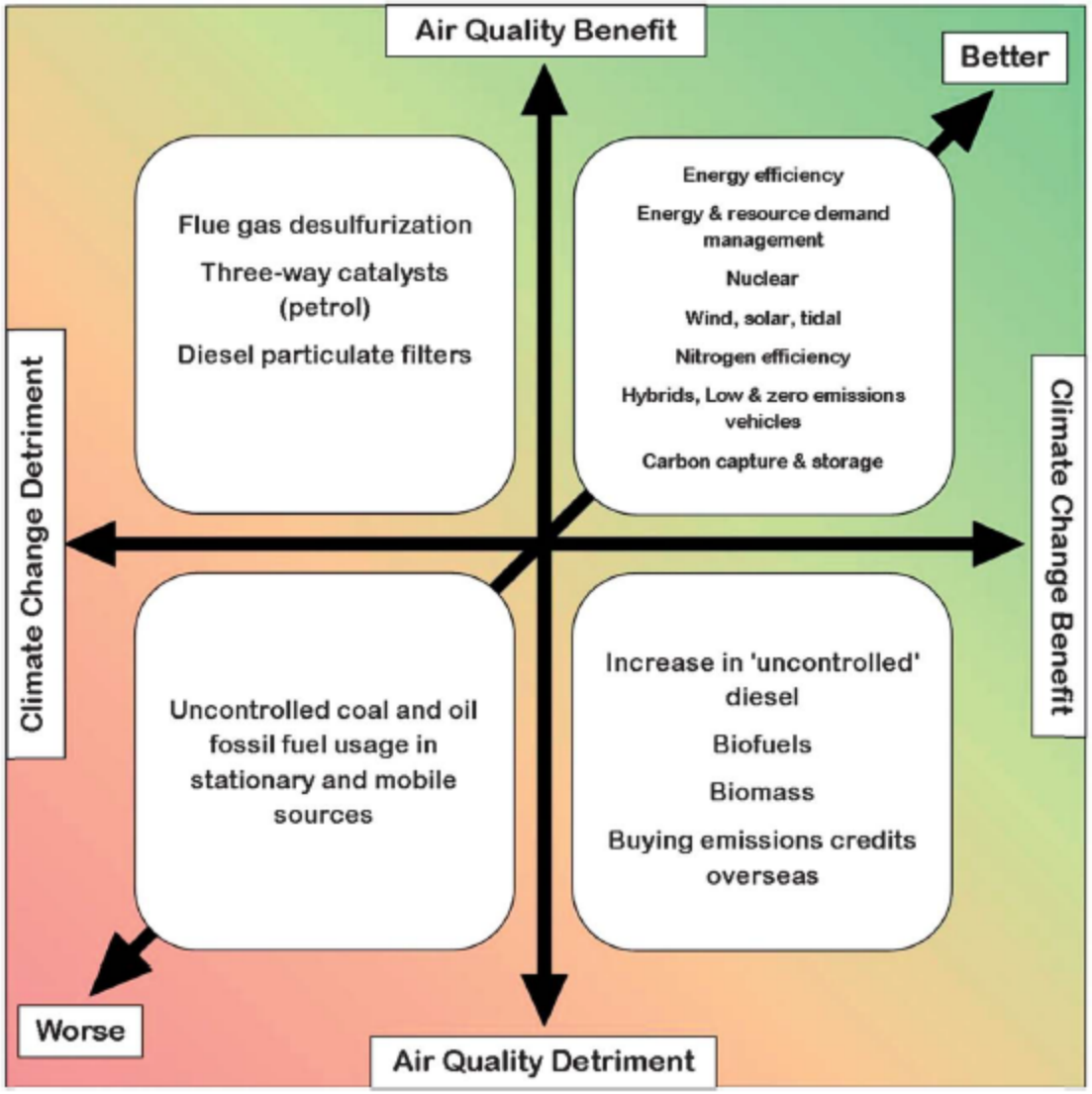
BC forcing positive (+0.72)
Total forcing still positive (+0.21)
although clouds make it less certain

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)*

Remainder of aerosol forcing
is in low-BC categories (total -0.95)

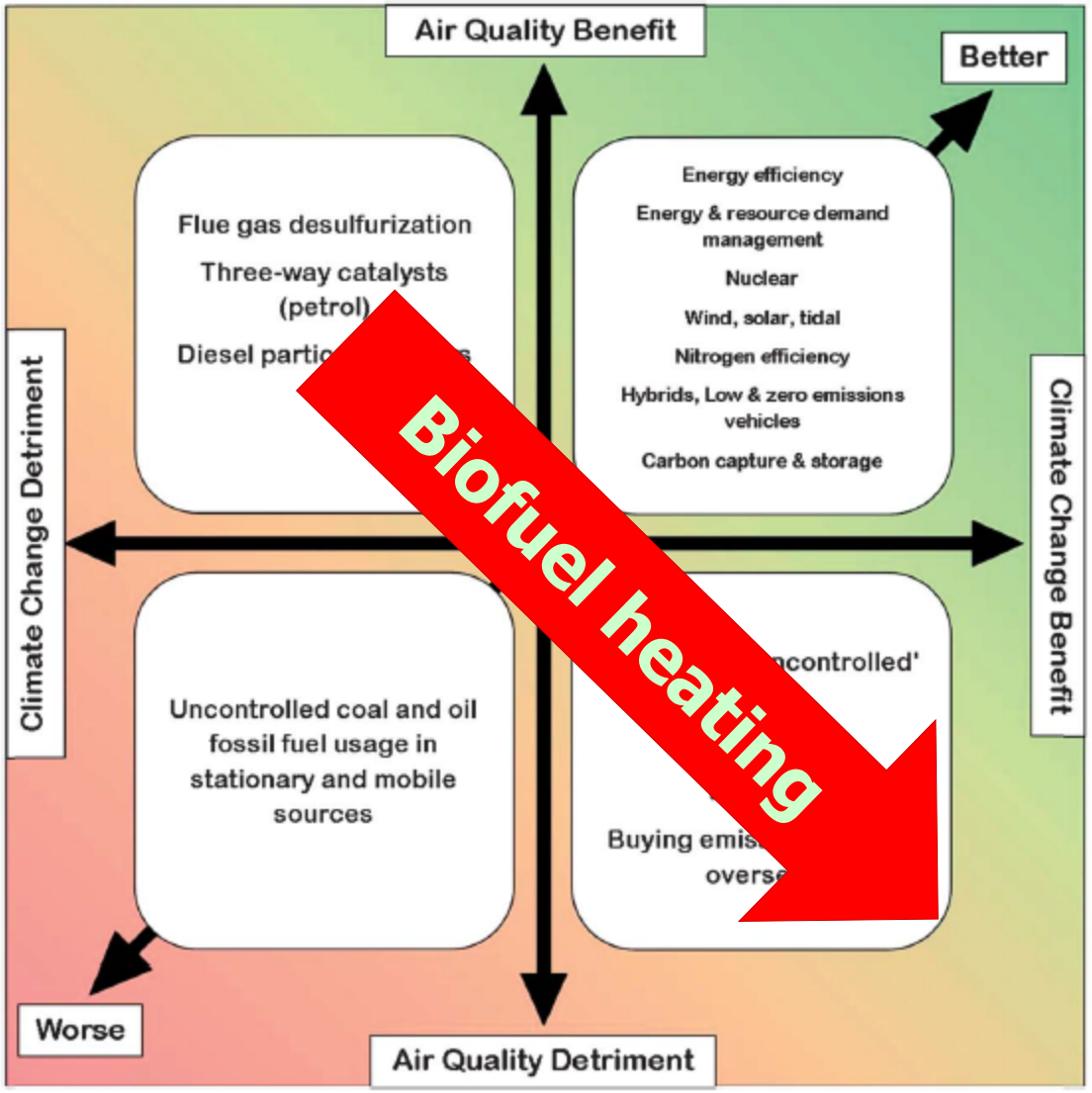
Health vs. Climate Effects of BC

View of trade offs



Schneidemesser and Monks, 2013

View of trade offs



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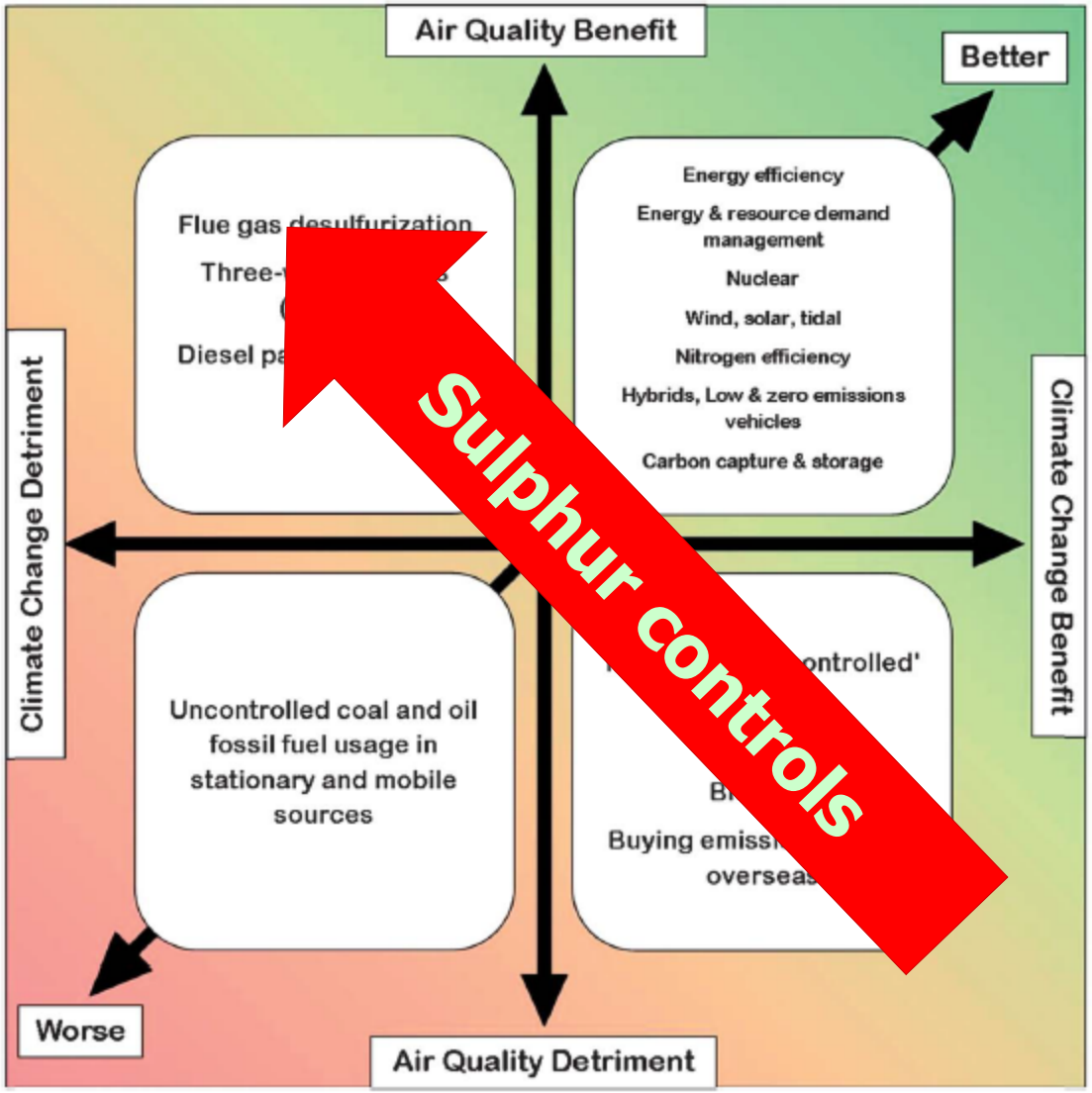
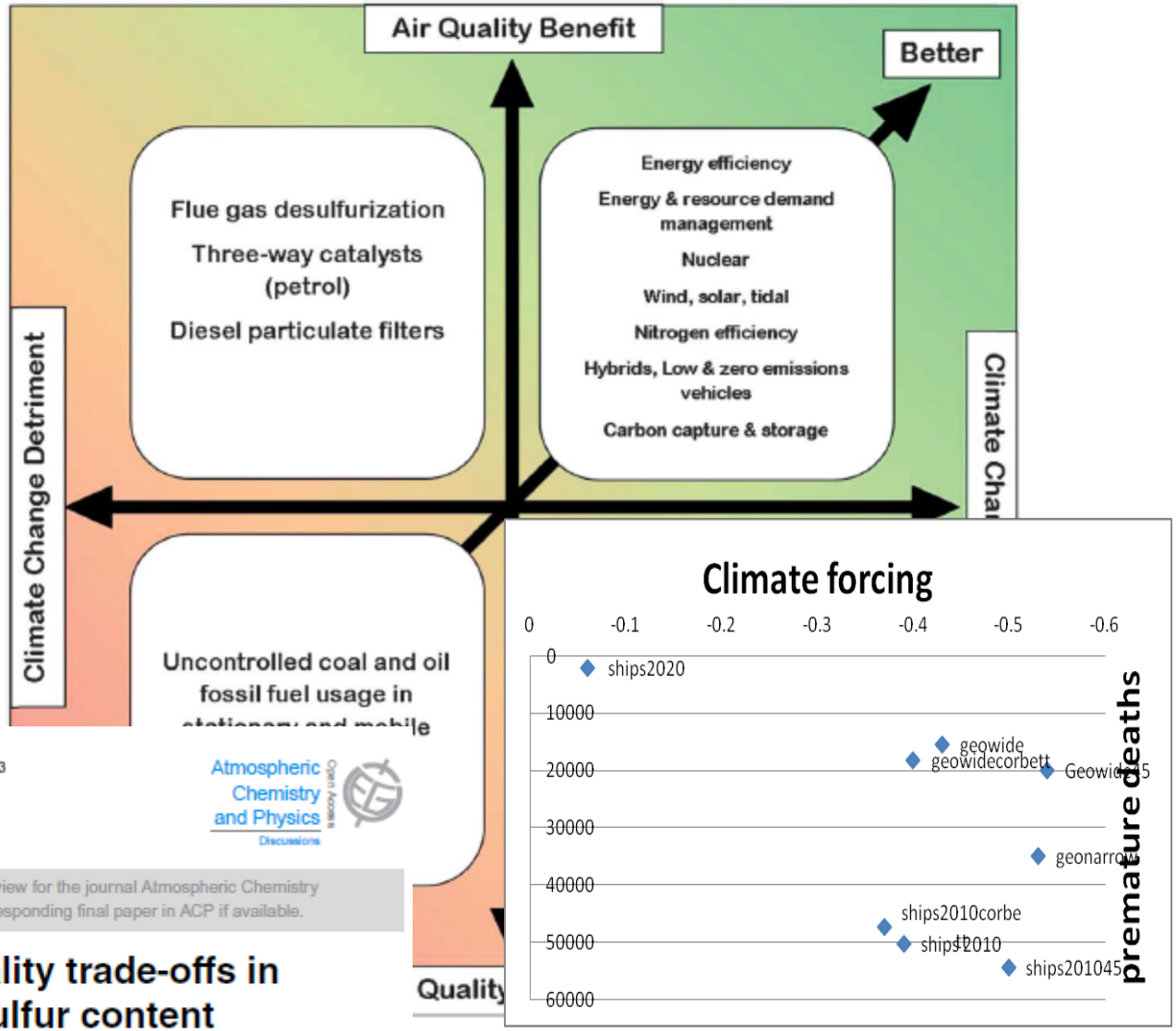
View of trade offs



Schneidemesser and Monks, 2013

View of trade offs



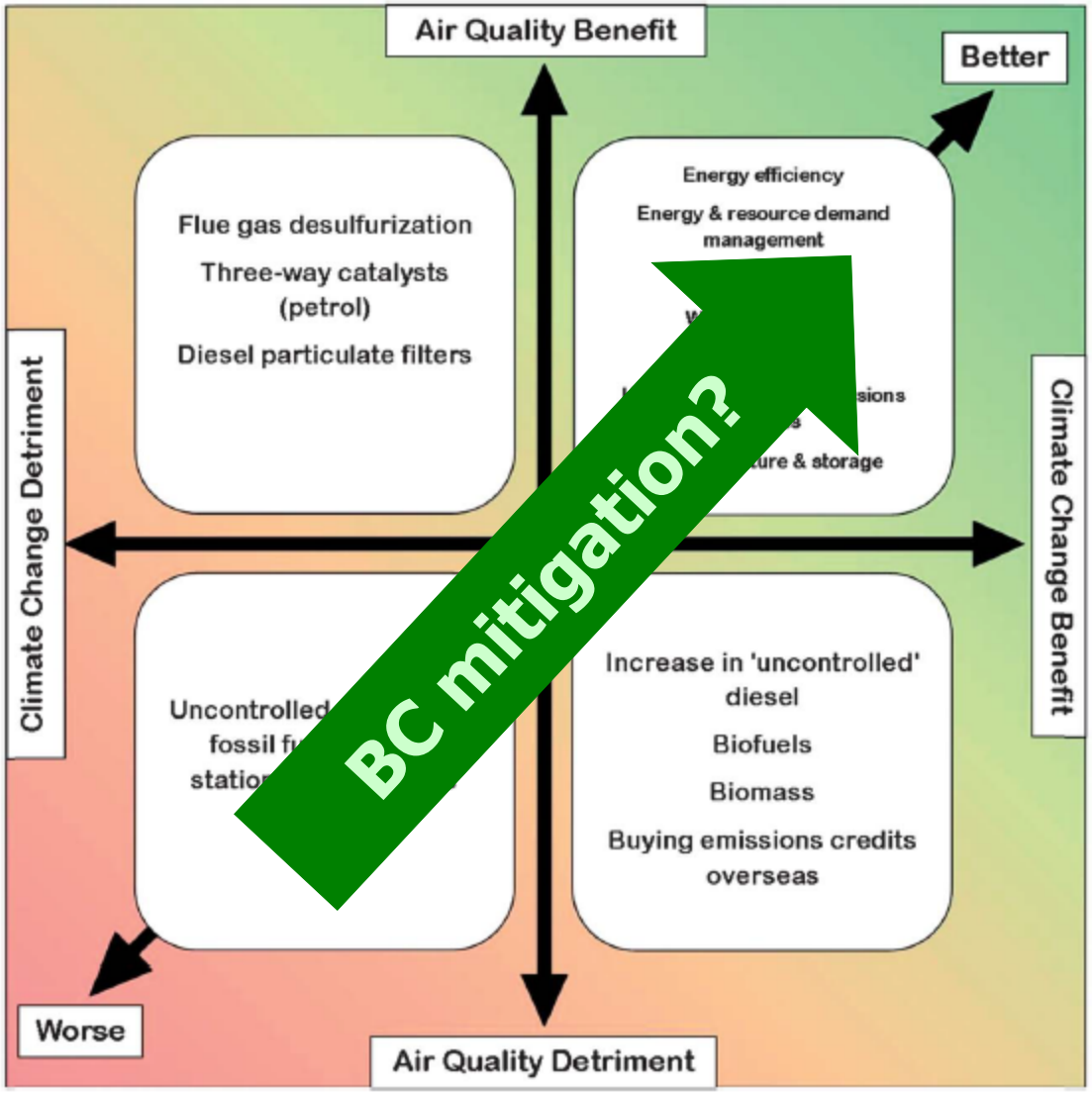
Atmos. Chem. Phys. Discuss., 13, 21989–22024, 2013
www.atmos-chem-phys-discuss.net/13/21989/2013/
doi:10.5194/acpd-13-21989-2013

Atmospheric Chemistry and Physics Discussions

Climate and air quality trade-offs in altering ship fuel sulfur content

A.-I. Partanen[1], A. Laakso[1], A. Schmidt[2], H. Kokkola[1], T. Kuokkanen[3], J.-P. Pietikäinen[4], V.-M. Kerminen[5], K. E. J. Lehtinen[1,6], L. Laakso[4,7], and H. Korhonen[1]

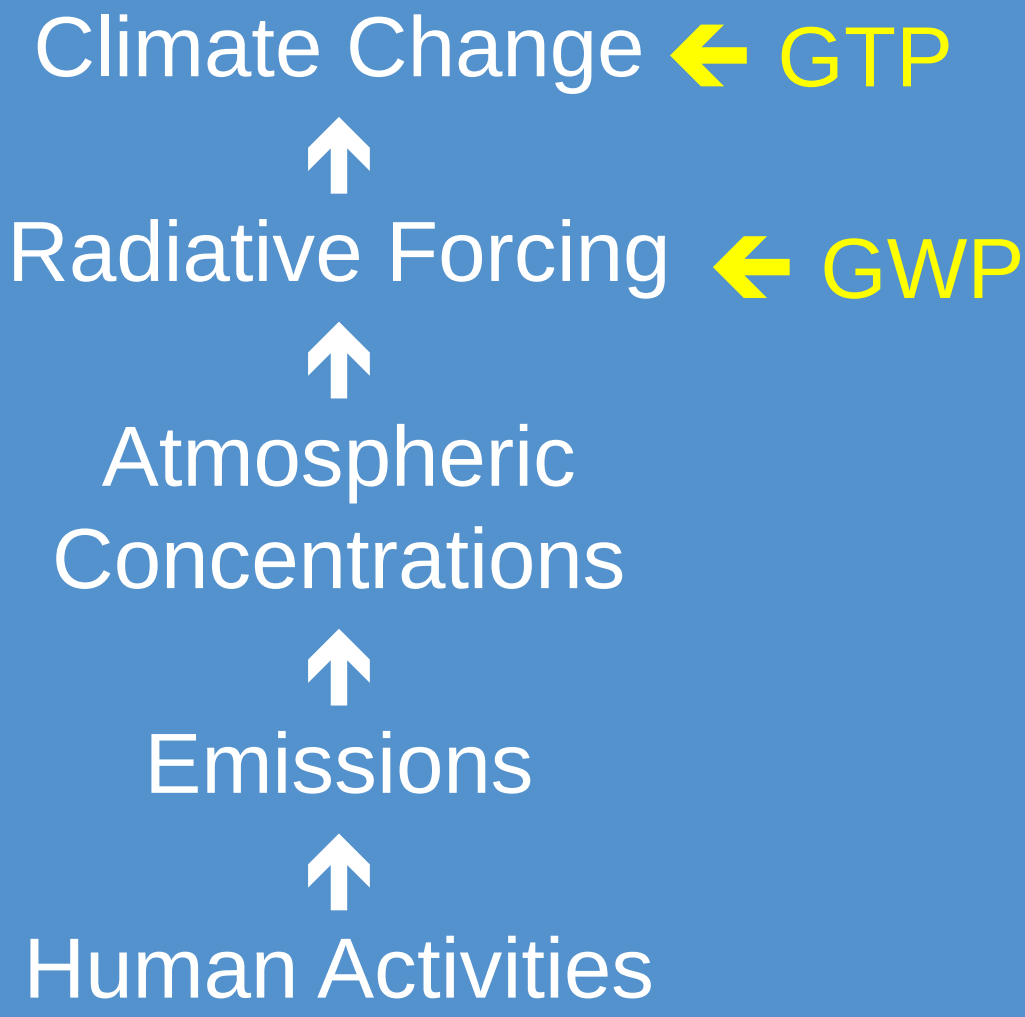
View of trade offs



Schneidemesser and Monks, 2013

Need metrics for axes

- Depends on climate and health policy goals and time horizon
- Climate
  - IPCC AR5 published emission metrics for BC and co emissions: Global Warming Potential, Global Temperature potential (20,50,100 year horizons)
  - Need to decide if things that cool the climate, e.g. SO2 are “good”: may adversely affect rainfall



Totals from Concentrations or Emissions Identical

Present day emissions weighted by metrics

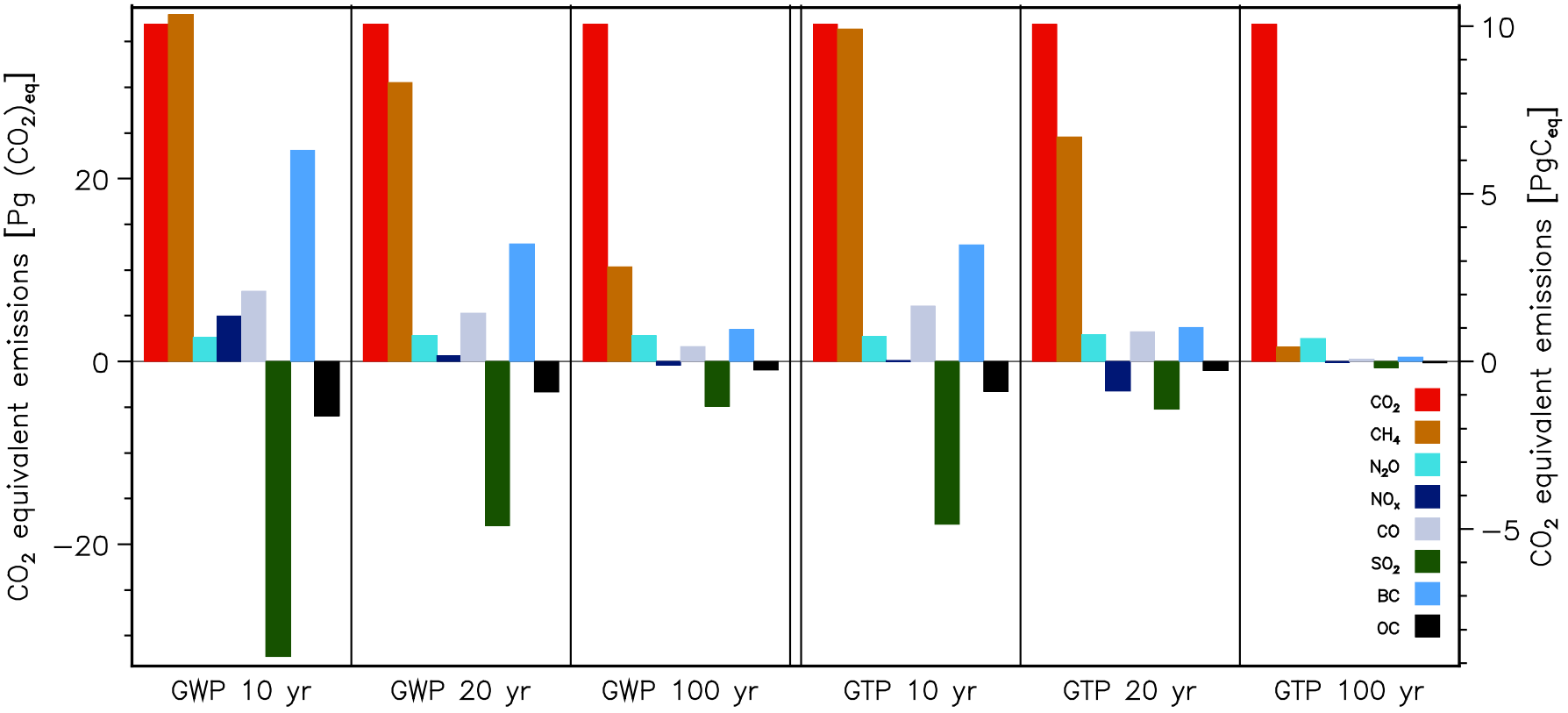
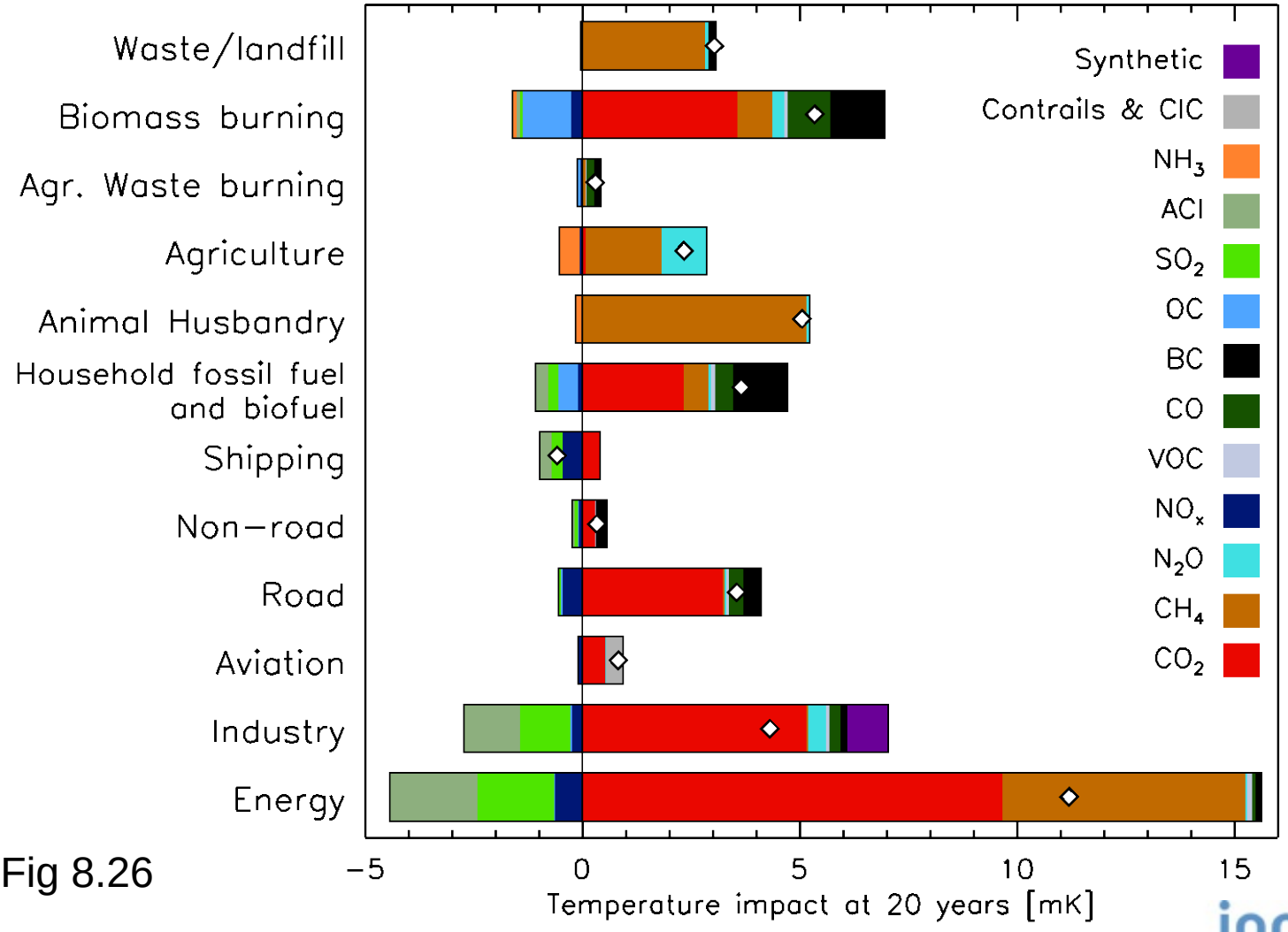


Figure 8.32 AR5

BC from different sectors has significant effect on 20 year temperature change from 2011 emissions (single year)



AR5 Fig 8.26

Need metrics for axes

- Depends on climate and health policy goals and time horizon
- Climate
  - IPCC AR5 published emission metrics for BC and co emissions: Global Warming Potential, Global Temperature potential (20,50,100 year horizons)
  - Need to decide if things that cool the climate, e.g. SO2 are “good”: may adversely affect rainfall
- Several health/air quality metrics exist

Health Metrics

Table 7. Summary of comparison of pooled effects for PM_{10} and BS from time-series studies

Health outcomes	No. of estimates	Percentage change per 10 µg/m3 increase (95% CI)	
		PM_{10}	BS
Mortality			
All causes	7	0.48* (0.18–0.79)	0.68* (0.31–1.06)
CVD	7	0.60* (0.23–0.97)	0.90* (0.40–1.41)
Respiratory diseases	7	0.31 (-0.23–0.86)	0.95 (-0.31–2.22)
Hospital admissions			
All respiratory diseases, elderly people	6	0.70* (0.00–1.40)	-0.06 (-0.53–0.44)
Asthma + chronic obstructive pulmonary disease, elderly people	5	0.86* (0.03–1.70)	0.22 (-0.73–1.18)
Asthma, children	5	0.69 (-0.74–2.14)	1.64* (0.28–3.02)
Asthma, young adults	5	0.77 (-0.05–1.61)	0.52 (-0.51–1.55)
Cardiac, all ages	4	0.51* (0.04–0.98)	1.07* (0.27–1.89)
Cardiac, elderly people	4	0.67* (0.28–1.06)	1.32* (0.28–2.38)
Ischaemic heart disease, elderly people	5	0.68* (0.01–1.36)	1.13* (0.72–1.54)

* $P < 0.05$.

Source: Janssen et al., 2011.

BC likely worse than average PM

Health Metrics: Issues

- How to measure?
- Concentration based, not emission based
- Indoor/outdoor exposure?
- Response functions very poorly known, regionally specific, short and long-term exposure effects

Implications for BC reduction advocates

- Air quality & health always has a win
- Can't reduce BC forcing without affecting co-emissions
- Can find climate "wins"
  - Identify BC-rich categories
  - Identify appropriate sources within category
- BC-rich sources are *most climate-friendly* way to reduce health effects
  - Even if effect is uncertain or neutral!

Key Areas for Progress

Key areas for progress

- Measuring emissions and co-emissions (standardization)
- Measuring concentrations
- Reduce uncertainty in climate effects, especially regional effects
- BC specific health effects

Remember:

- **BC mitigation can only limit near term rate of change; CO_2 cuts needed to keep below 4C or any other target**

EXTRA SLIDES

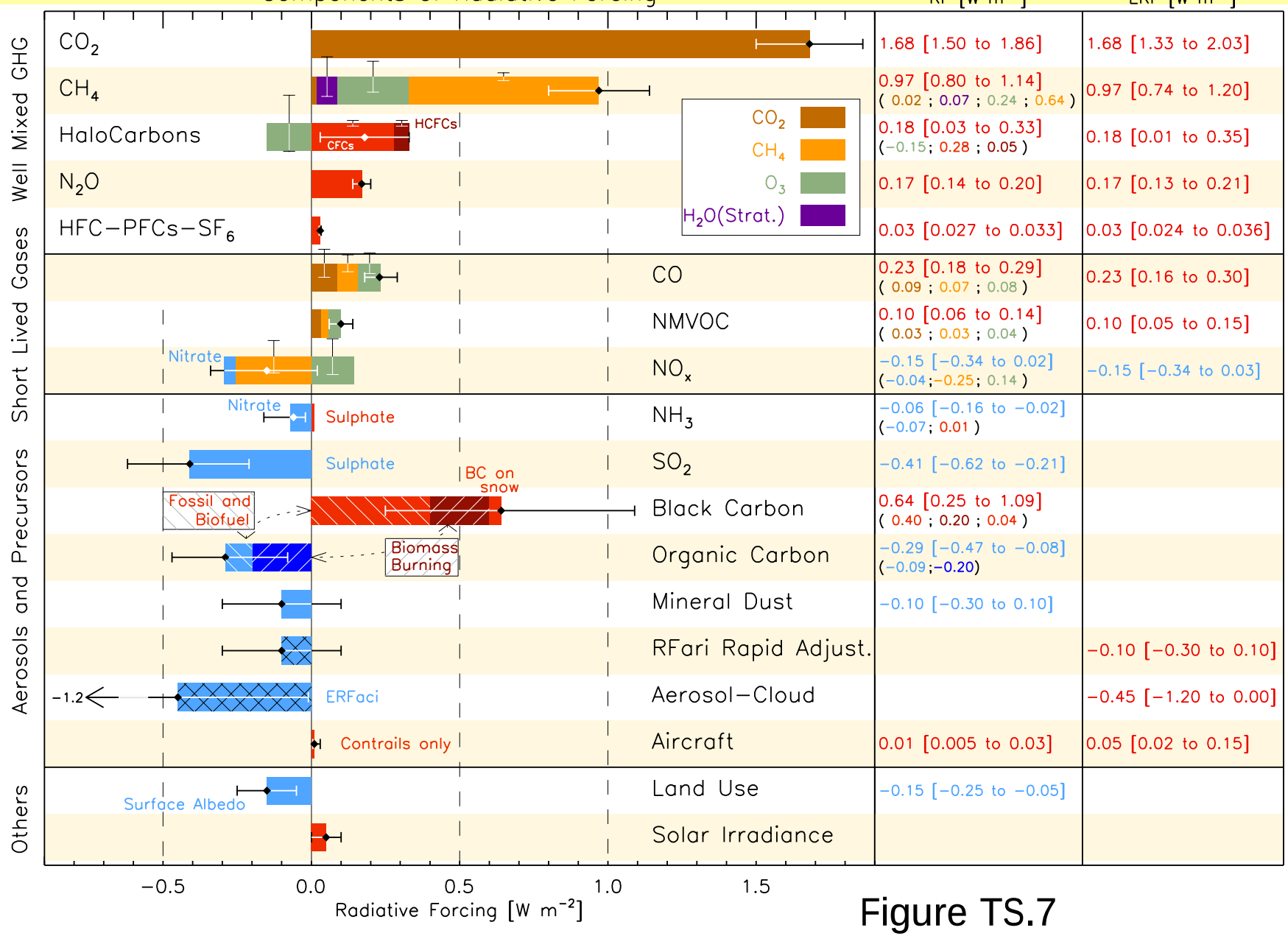

Components of Radiative Forcing
RF [W m⁻²]
ERF [W m⁻²]
Well Mixed GHG
Short Lived Gases
Aerosols and Precursors
Others
CO2
CH4
HaloCarbons
CFCs
HCFCs
N2O
HFC−PFCs−SF6
CO2
CH4
O3
H2O(Strat.)
1.68 [1.50 to 1.86]
1.68 [1.33 to 2.03]
0.97 [0.80 to 1.14]
(0.02 ; 0.07 ; 0.24 ; 0.64)
0.97 [0.74 to 1.20]
0.18 [0.03 to 0.33]
(−0.15; 0.28 ; 0.05)
0.18 [0.01 to 0.35]
0.17 [0.14 to 0.20]
0.17 [0.13 to 0.21]
0.03 [0.027 to 0.033]
0.03 [0.024 to 0.036]
CO
0.23 [0.18 to 0.29]
(0.09 ; 0.07 ; 0.08)
0.23 [0.16 to 0.30]
NMVOC
0.10 [0.06 to 0.14]
(0.03 ; 0.03 ; 0.04)
0.10 [0.05 to 0.15]
Nitrate
NOx
−0.15 [−0.34 to 0.02]
(−0.04;−0.25; 0.14)
−0.15 [−0.34 to 0.03]
Nitrate
Sulphate
NH3
−0.06 [−0.16 to −0.02]
(−0.07; 0.01)
Sulphate
SO2
−0.41 [−0.62 to −0.21]
BC on snow
Fossil and Biofuel
Black Carbon
0.64 [0.25 to 1.09]
(0.40 ; 0.20 ; 0.04)
Biomass Burning
Organic Carbon
−0.29 [−0.47 to −0.08]
(−0.09;−0.20)
Mineral Dust
−0.10 [−0.30 to 0.10]
RFari Rapid Adjust.
−0.10 [−0.30 to 0.10]
−1.2
ERFaci
Aerosol−Cloud
−0.45 [−1.20 to 0.00]
Contrails only
Aircraft
0.01 [0.005 to 0.03]
0.05 [0.02 to 0.15]
Surface Albedo
Land Use
−0.15 [−0.25 to −0.05]
Solar Irradiance
−0.5
0.0
0.5
1.0
1.5
Radiative Forcing [W m⁻²]

Figure TS.7

Policy, but not science, focus on SLCFs

- Lack of adequate scientific foundation for black carbon's role in climate forcing from non-governmental organizations (NGOs).

Ray Minjares (International Council on Clean Transportation); Ellen Baum (Clean Air Task Force); Catherine Witherspoon (Climate Works Foundation); Durwood Zaelke (Institute for Governance and Sustainable Development)

- Required an international assessment given the complexity of BC and the poor state of the existing scientific literature.

iStockPhoto.com

Guiding principles

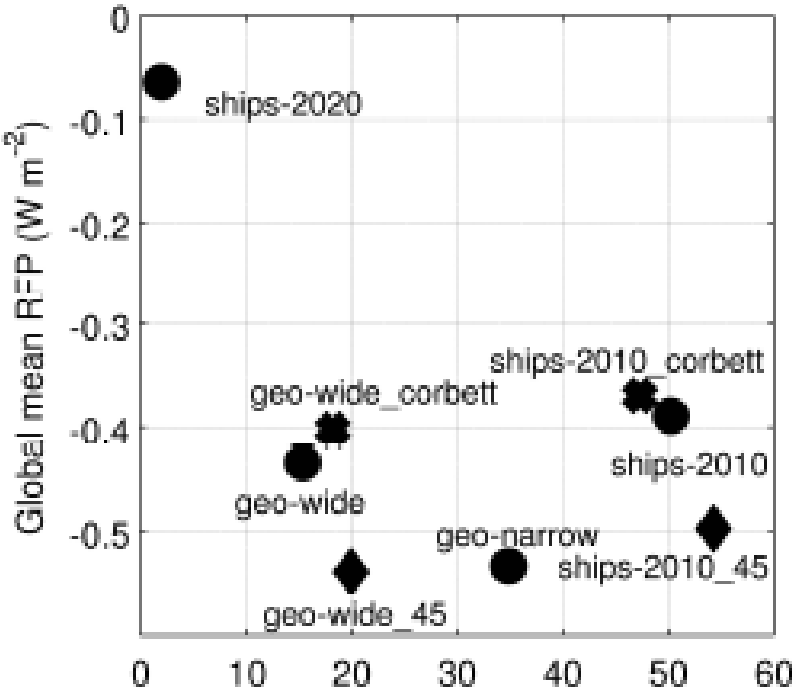
Framework: Provide a framework to discuss and evaluate the role of black carbon in the climate system

Comprehensive: Account for all known effects of BC on climate

Quantitative: Provide best estimate and 90% uncertainty bounds for each effect

Diagnostic: Explain differences in published forcing and impact values

Sulphur from shipping



Atmos. Chem. Phys. Discuss., 13, 21989–22024, 2013
www.atmos-chem-phys-discuss.net/13/21989/2013/
doi:10.5194/acpd-13-21989-2013

Atmospheric Chemistry and Physics Discussions

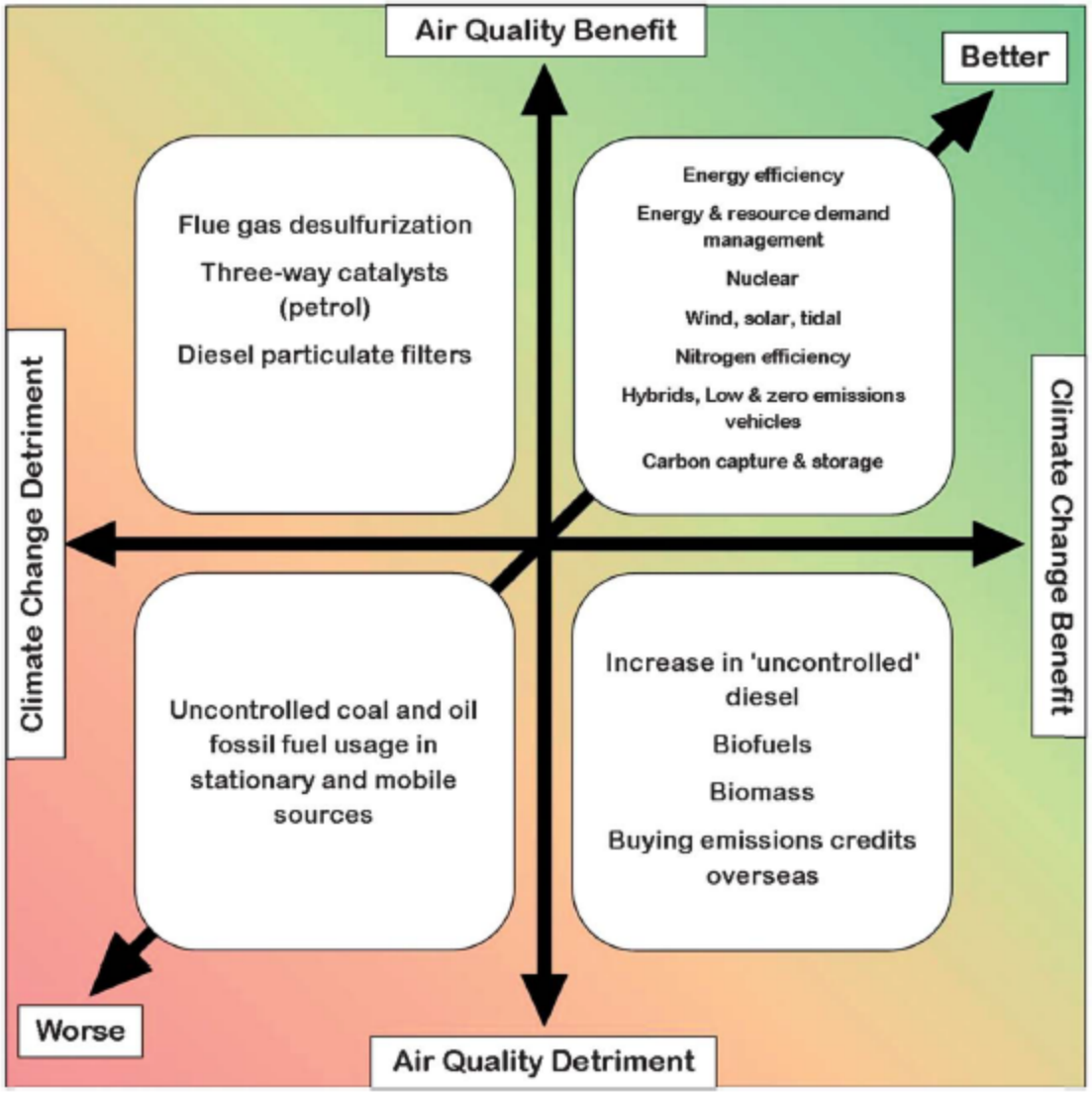
Climate and air quality trade-offs in altering ship fuel sulfur content

A.-I. Partanen[1], A. Laakso[1], A. Schmidt[2], H. Kokkola[1], T. Kuokkanen[3], J.-P. Pietikäinen[4], V.-M. Kerminen[5], K. E. J. Lehtinen[1,6], L. Laakso[4,7], and H. Korhonen[1]

Climate Metrics

1. IPCC AR5 published some emission metrics for BC and co emissions: Global Warming Potential, Global Temperature potential
   - ⇨ Need to choose metric and time horizon for policy
   - ⇨ Unlike Kyoto gases, global response varies with location of emission
   - ⇨ BC emissions are very hard to measure and audit – no standard
   - ⇨ Regional responses may be different
   - ⇨ Need to decide if things that cool the climate, e.g. SO2 are “good”: may adversely affect rainfall

View of trade offs



Schneidemesser and Monks, 2013

Regional dependence: a missing piece in Bounding-BC and IPCC AR5

Bounding-BC and IPCC presented global averages.

Not enough studies to support more analysis

Differences between regional emissions:

- Near-snow: *BC more warming, OC less cooling*
- Cloud effects: probably significant, but unexplored
- Snow forcing: large near snow regions
- Ozone precursors: higher in tropics

Take-home messages

- "Bounding-BC" achievement:
  set up a framework for comprehensive analysis
- Today's understanding:

  BC climate forcing is comparable to methane
- Mitigation:
  - Sources for climate WIN need to be carefully chosen
  - Sources for climate NEUTRAL are BC-rich

BC mitigation can limit near term rate of change; CO2 cuts needed do keep below 4C or any other target

AR5 science implications for urgency and priority (goal dependent)

- **Prevent X°C warming:** cumulative CO2 is what matters (timing less important). BC mitigation can shave off peak (by 0.5 °C if significant CO2 mitigation begins before SLCP cuts.
- **Ameliorate temperature rise out to 2100:** BC cuts can help reduce this but it doesn't matter when they occur (prior to 2090), CO2 mitigation still best way.
- **Prevent rate of change now to give us time to adapt:** BC cuts now are better than CO2 for doing this.
- **Prevent rate of change now to give us time to mitigate CO2: a non sequitur and a whole heap of trouble!**

What is Radiative Forcing?

- Indirect measure of “climate impact”
- Change in energy flux caused by natural and anthropogenic drivers of climate change
- Positive ➔ near-surface warming
- Puts various drivers on common scale