PNWD-SA-9918

What Do We Know About Emissions?

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Workshop on Climate Change Impacts and Integrated Assessment (CCI/IA)
Snowmass, Colorado
July 26, 2012

OUTLINE

Introduction

- Emissions, Inventories, and use by IAMs and others
- Overview of inventory methodology
- Trends and Sectors in Recent Emissions

Uncertainty

- How well do we know emissions?

Observational Verification of Emissions

- Inversions Using Surface and Satellite Observations

Summary

Use of Emission Data

Emission Inventories are produced by governments and independent research organizations

- Guide decision-making regarding health and environmental impacts (focus largely on local to national scale impacts).
- Compliance with local, national, and international regulations.

Integrated Assessment Modelers Use These Data

- To calibrate their models (directly or indirectly)
  - While can, in principle, use emissions factors and build up emissions, IAMs do not have sufficient technological detail to do this for all sectors and substances.
  - Ideally want emissions by fuel and sector, but this is rarely provided.
- Compare past trends to modeled future trends

Issue of Relatively high levels of aggregation in IAMs

- Explicit control technologies and technology differences (stoker vs pulverized; diesel vs petrol; local vs long-distance driving) are often not represented
- Need to assure emission factor consistency across pollutants

Inventory Methodology

The principle is straightforward

$$\text{Emissions} = \sum \text{Emissions\_Factor}_i \bullet \text{Driver}_i$$

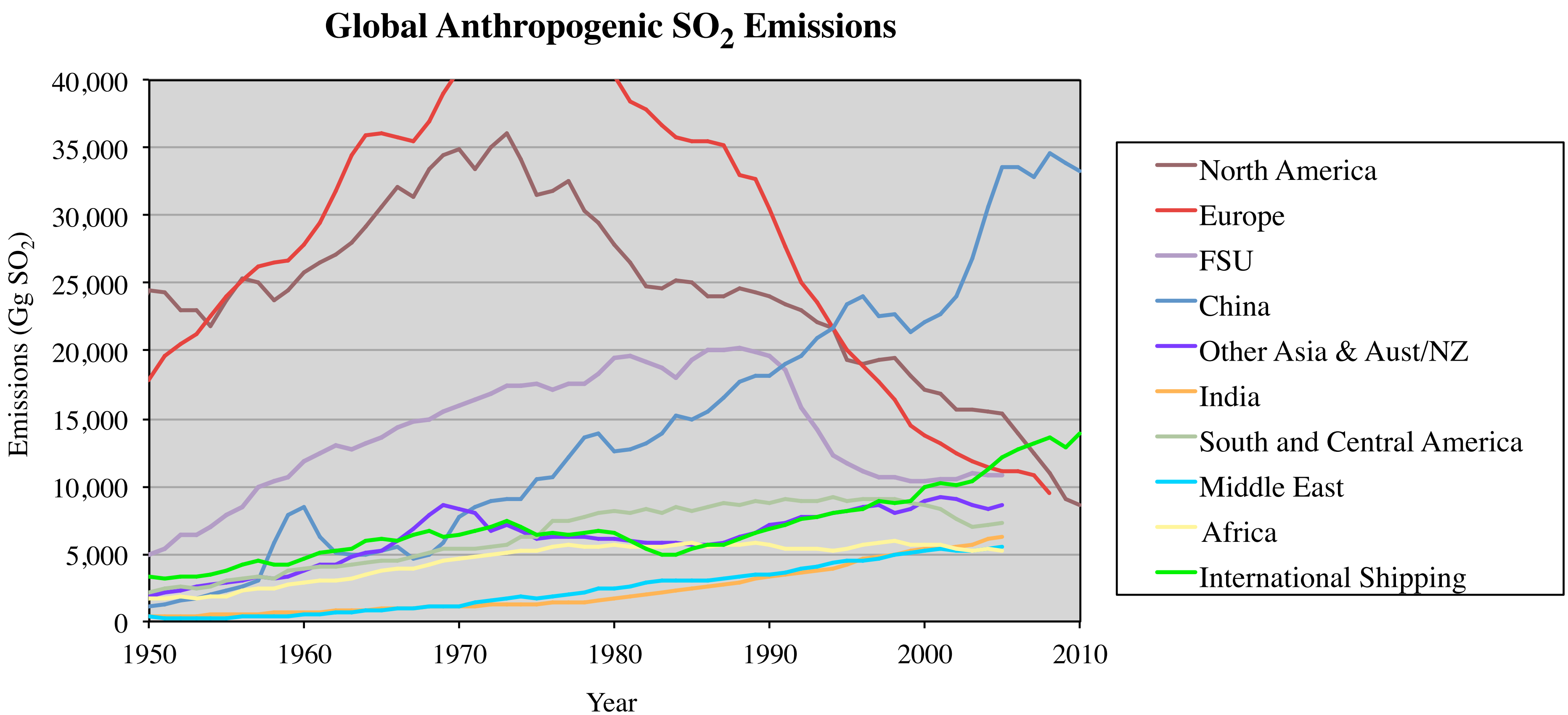
But is labor and data intensive in practice

- Emissions_Factor is really a function of technology type, maintenance, fuel type, operating conditions (load factor/speed), pollution controls, ambient conditions, ….
- Mobile sources are particularly complex.
  - *e.g.*, EPA and US states use the MOVES model for on-road

The approach depends on the source sector

- Point sources (large to small) – sometimes measured, individually reported
- Non-point stationary — residential, commercial
- Road – Depends on vehicle type, speed, maintenance/deterioration, …
- Non-road mobile & engines – poorly understood in general
- Fire events
  - *Important to get emissions correct for a specific year*

Substantial Changes In Emissions Over time

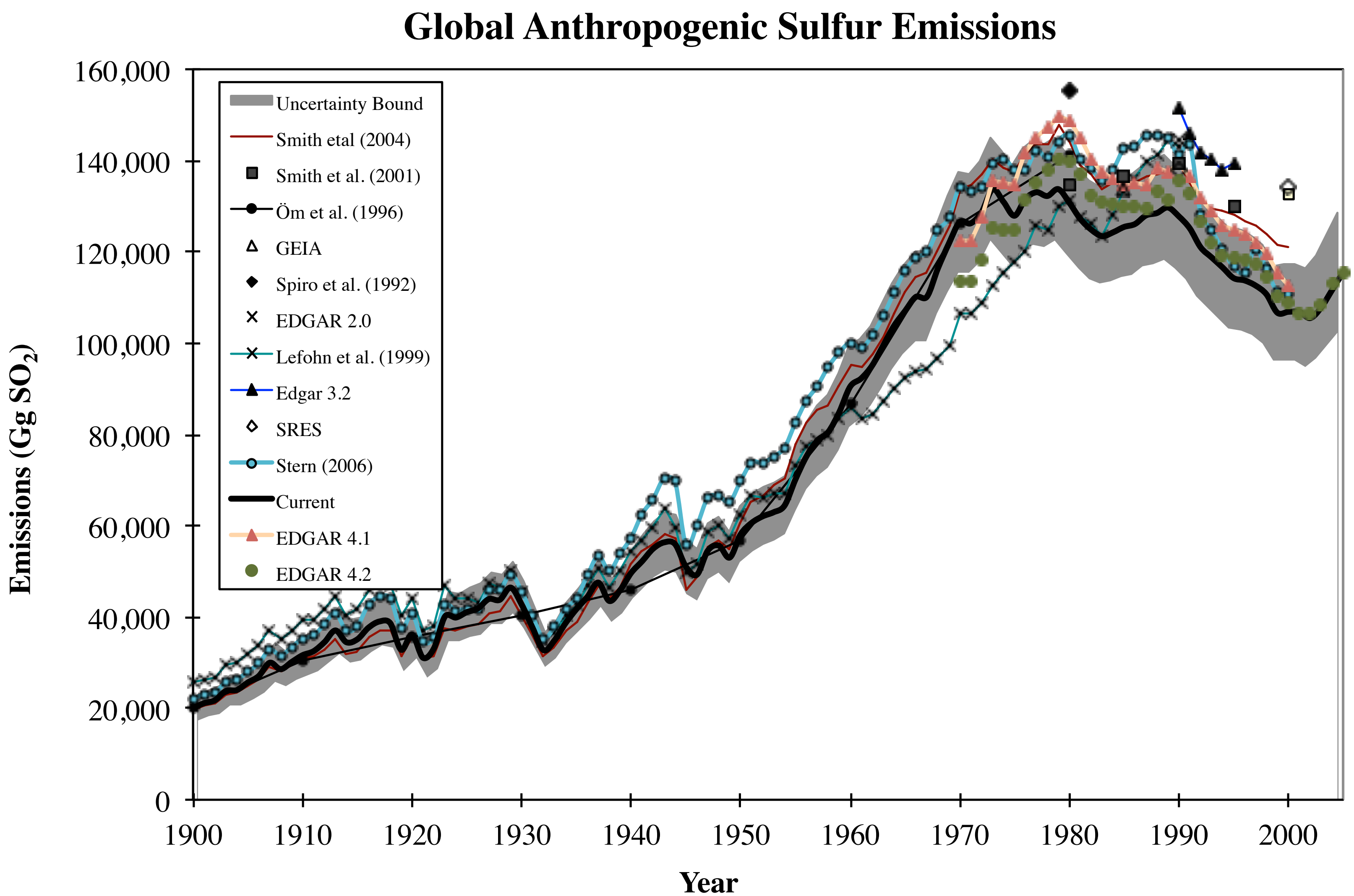


Global SO_2 emissions

- China now plays a dominant role
- Global trends over recent years are not available yet (are working on it…)

Source: Smith et al. (2011), Lu and Streets (2011), EPA, Environment Canada, …

Global SO_2 Emissions Peaked in 1970s



Indications are that this increase was short-lived.

If use points only every decade, might miss some important features!

JGCRI Source: Smith et al. (2011)

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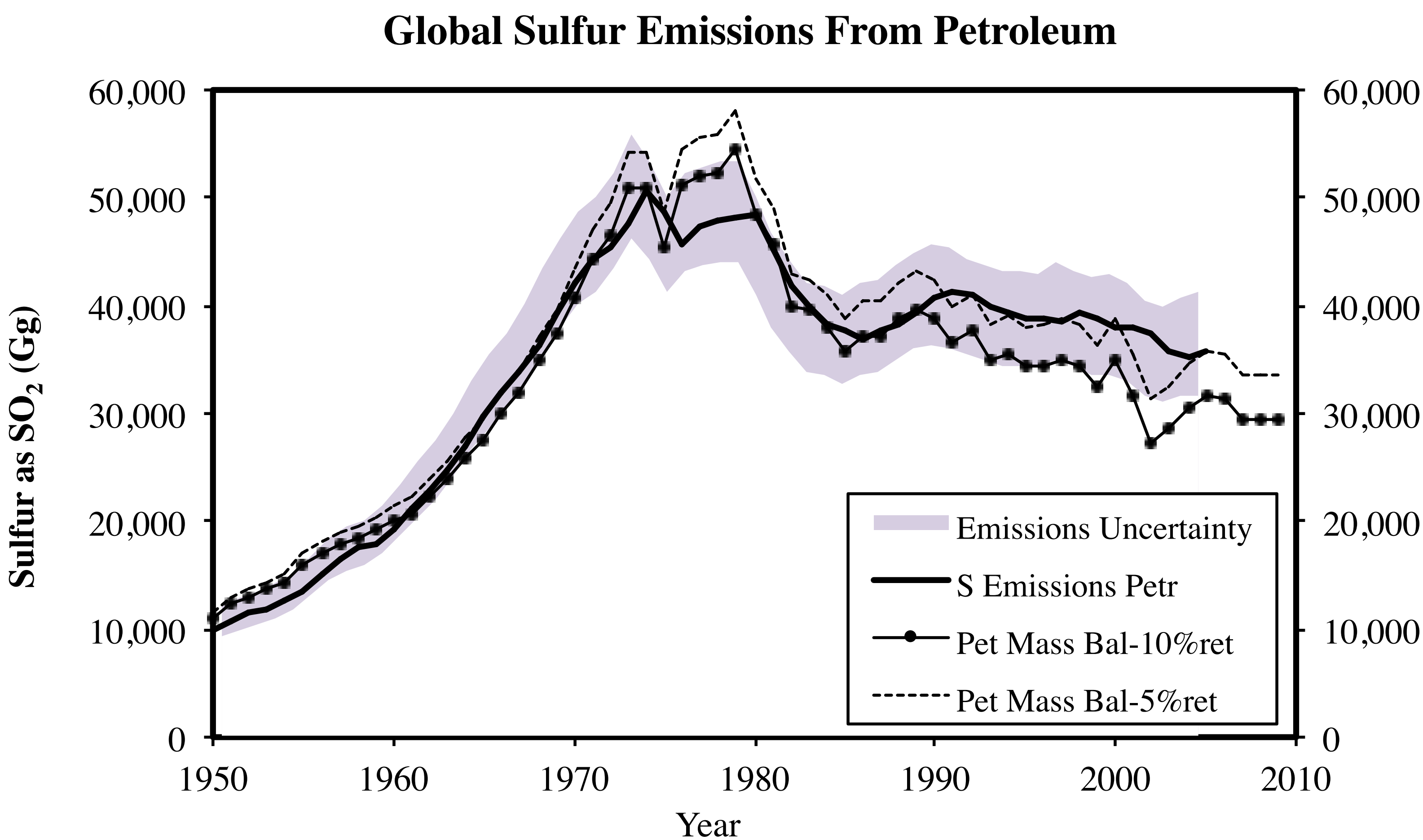
A Top Down Check On Emissions



Global SO_2 emissions from petroleum should equal total sulfur in crude oil minus sulfur taken out in the refinery and sulfur retained in products not combusted (e.g. Bitumen).

Source: Smith et al. (2011), Updated

Issue: Which Sectors Are Important

The importance of sectors depends on the substance:

What IAMs focus on.

	Energy	Industry	Transport	Buildings	Solvents	Agriculture	Ag Wst Brn	Waste
CO2	43%	24%	18%	15%	0%	0%	0%	0%
NOx	27%	18%	41%	10%	0%	2%	1%	0%
SO2	57%	29%	5%	9%	0%	0%	0%	0%
CO	3%	16%	37%	41%	0%	0%	3%	1%
NMVOC	21%	7%	25%	28%	16%	1%	2%	1%
BC	1%	30%	27%	39%	0%	0%	3%	1%
OC	3%	18%	12%	62%	0%	0%	6%	0%
NH3	0%	0%	1%	1%	0%	96%	2%	0%
CH4	26%	0%	0%	5%	0%	46%	1%	23%

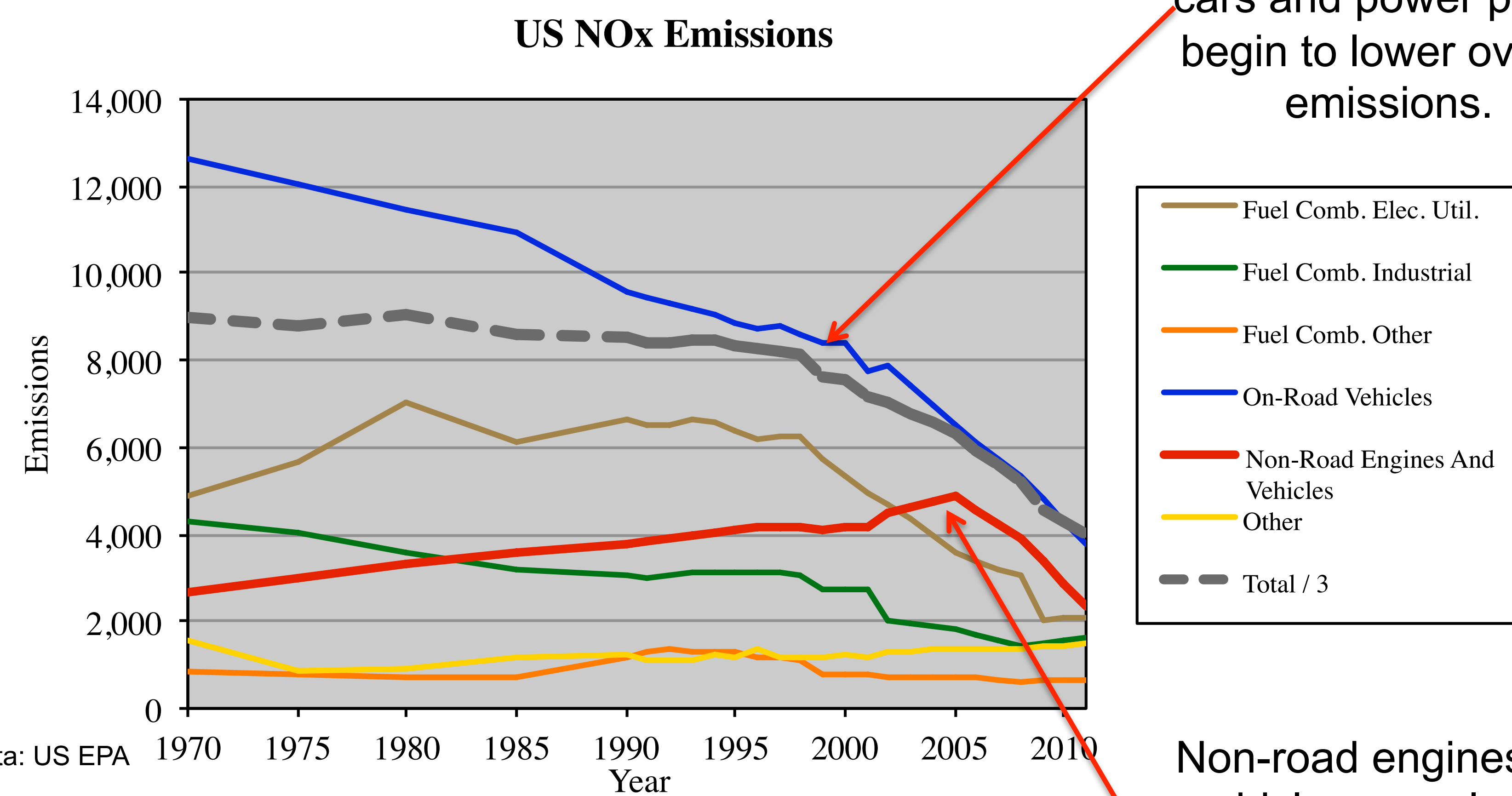
What is important for SLCFs is often different than what is important for GHGs.

- Buildings and transport are particularly important.
- Energy sector, which is a major focus of IAMs, is very important for SO_2, but only moderately or not important for other emissions.

Data: Lamarque, et al. (2010) Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application *Atmospheric Chemistry and Physics* **10** pp. 7017–7039

Issue: Which Sectors Are Important

Increasing controls on cars and power plants begin to lower overall emissions.



Data: US EPA

Non-road engines and vehicles were largely unregulated and became a dominant source!

The non-road sector is complex, data quality is often poor (emissions and fuel consumption).

Is folded into some larger sector in both IAMs and most global inventory data.

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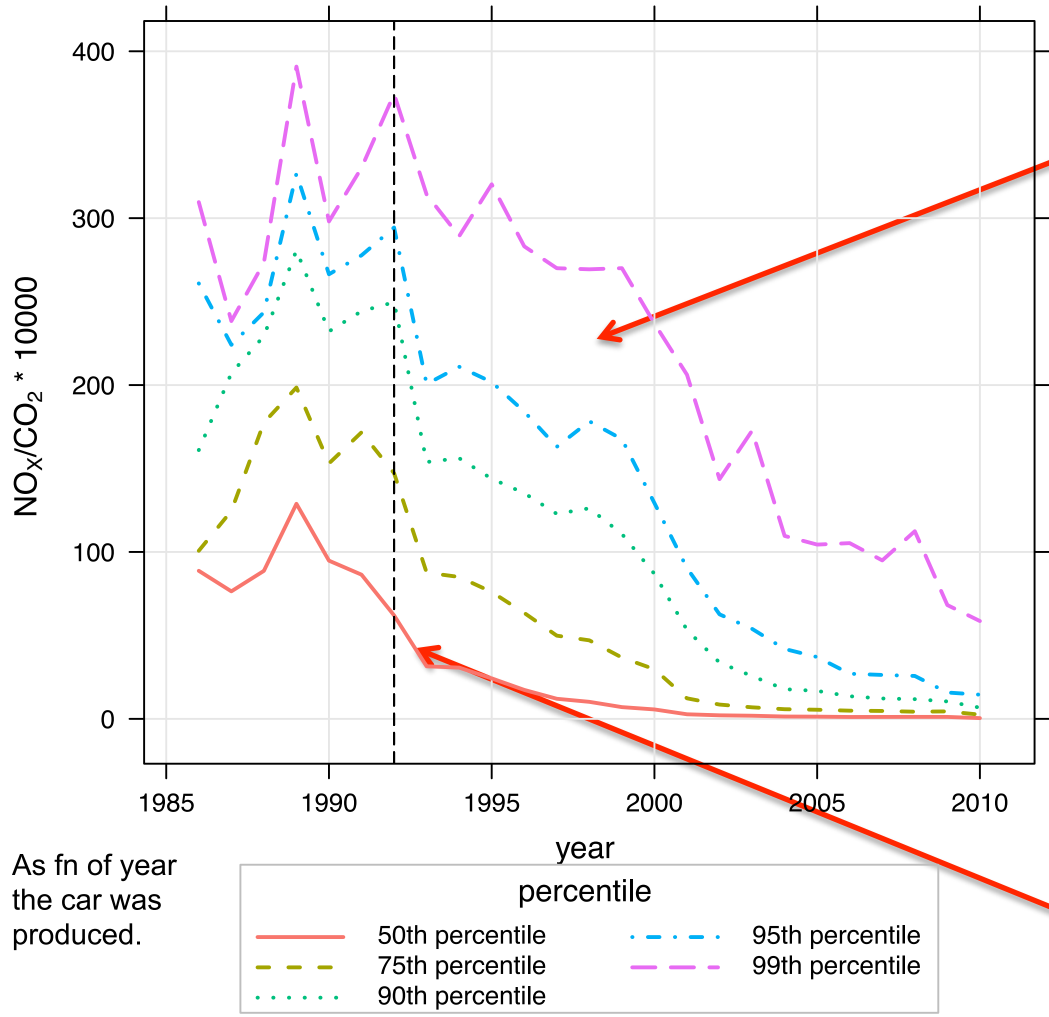
"Superemitters" can be very important

Measurements of NO_x from U.K. Cars



As fn of year the car was produced.

However, a fraction of the vehicles still have high emissions, which can have a large influence on the total.

In an aggregate emissions estimate (e.g., in IAM), need average not median emissions factor!

Impacts both current estimates and future projections.

Median emissions decreased over time, particularly after catalytic converters were introduced

How much of this is super-emitters, and how much driving variation?

 Source: Trends in NOx and NO2 emissions and ambient measurements in the UK (Carslaw etal 2011).

Issue: Inventory Data Lag Observational Data

Activity Data
IEA Energy Balances, FAO Statistics, National Data → **Emissions Factors, Technology Breakout, Emissions Controls, Emission Monitoring** (large sources) → **Emissions Estimate**

The latest global inventory data that could be put together for the RCP scenarios, developed circa 2008/2009, was 2000!

This process contains a number of inherent delays:

1) Detailed activity data (US, IEA, …) typically available after 2–3 years.

   Less detailed data (BP energy, etc.) available after 6 months

2) Also need emission monitoring & control information, fuel standards, technology characteristics. Also ~2–3 years, with data checking and/or peer review.

   This information is aggregated and checked at national level, resulting in national emission reports. And on an ad-hoc basis for developing regions.

3) Some global efforts (e.g. EDGAR, GAINS) performed periodically but not continually.

While, in principle, global emissions estimates could be available after ~2-4 years, in practice comprehensive estimates have generally only been available with a much longer time lag.

Could a community approach speed up data availability?

Frost GJ, et al. (2012) "New Directions: Toward a community emissions approach." *Atmospheric Environment* **51** 333–334

Uncertainty

Uncertainty

All emission inventory data is uncertain, but uncertainty is rarely assessed, and emissions data is often treated as a "known".

When a factor of 2 agreement between models and observations was considered good, this may have been fine. As models and observation improve, emissions uncertainty needs to be explicitly considered.

The source and magnitude of uncertainty varies by substance and source sector.

CO_2	Only small dependence on fuel and combustion conditions
SO_2	Depends primarily on fuel sulfur content and, if present, sulfur removal technology
NO_x, CO, VOCs	Depend on combustion conditions, including number of "super-emitters"
BC, OC	As above, but even more so (physical not chemical limits on formation)

- Emissions from incomplete combustion (NO_x, CO, VOC, BC, OC) and biological processes (CH_4, N_2O, NO_x, NH_3) generally state-dependent and therefore uncertain.
- "Other" sectors are often important, but also often poorly characterized

Approaches To Uncertainty Estimation

Range from the ideal:

uncertainty analysis based on statistical information from measurements, an appropriately designed sampling strategy, including biases, and correlations.

to a simple "expert judgment" of aggregate uncertainty.

The ideal approach is generally not feasible, so what analyses that are done have relied, in large part, on expert judgment combined with formal statistical analysis.

Expert judgment often underestimates uncertainty! (G. Morgan)

Need better quantitative estimates of uncertainty for each component

- Compare different inventory estimates (Granier et al. 2011)
  - *Can gain valuable insights (small differences do not necess. mean small uncertainty!)*
  - *Need to do more to evaluate the sources of these differences*
  - *To do the best job here need detailed emissions (not just by broad sector)*
- Compare with observations
  - *Trends in particular, although biases need to be understood before useful to validate emissions and quantify uncertainty*
  - *Co-emitted pollutants can also be useful. Isotope analysis, etc.*
- Formal uncertainty analysis can underestimate uncertainty if potential systemic biases are not included

Comparison of EPA Inventories: SO_2

Inventory	Data Year 1980	1985	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Coal – Electric Plants														
Trends 1995	0%	0%	0%	0%	0%	0%	0%	-1%	0%					
Trends 1996	0%	0%	1%	0%	0%	0%	0%	0%	0%	-1%				
Trends 1998	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%	-1%	0%		
Trends 2000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
Coal – Industrial Combustion														
Trends 1995	0%	0%	0%	-4%	**-14%**	-3%	-6%	-1%	1%					
Trends 1996	0%	0%	0%	0%	0%	0%	0%	0%	0%	**34%**				
Trends 1998	0%	0%	0%	0%	0%	0%	0%	0%	0%	**12%**	**11%**	**11%**		
Trends 2000	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	**24%**	**29%**
Petroleum (all sectors)														
Trends 1995	-1%	-3%	-1%	**-11%**	0%	-3%	-4%	-9%	**-13%**					
Trends 1996	-1%	-3%	-1%	2%	4%	6%	4%	-3%	-3%	6%				
Trends 1998	-1%	**13%**	**17%**	**19%**	**24%**	**27%**	**25%**	**20%**	**22%**	**28%**	**28%**	**27%**		
Trends 2000	-1%	**13%**	**17%**	**20%**	**24%**	**27%**	**26%**	**20%**	**22%**	**44%**	**44%**	**42%**	**58%**	**64%**
Metals Processing														
Trends 1995	0%	0%	0%	-9%	3%	6%	**11%**	**23%**	**36%**					
Trends 1996	0%	0%	0%	0%	0%	0%	0%	0%	0%	**36%**				
Trends 1998	0%	0%	0%	0%	0%	0%	0%	0%	0%	**10%**	**11%**	10%		
Trends 2000	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**32%**	**31%**
Total														
Trends 1995	0%	0%	0%	-3%	-1%	-1%	-1%	-1%	-2%					
Trends 1996	0%	0%	0%	0%	1%	1%	0%	0%	0%	4%				
Trends 1998	0%	2%	2%	3%	3%	3%	3%	2%	3%	4%	4%	4%		
Trends 2000	0%	2%	2%	3%	3%	3%	3%	2%	3%	6%	6%	6%	**10%**	**11%**

- Measured emissions (*e.g.*, coal power plants) don’t change much
- Significant changes in petroleum emissions
- Most recent 1-3 years are often more uncertain
- **Uncertainty may be larger than shown: no difference not = no uncertainty!**

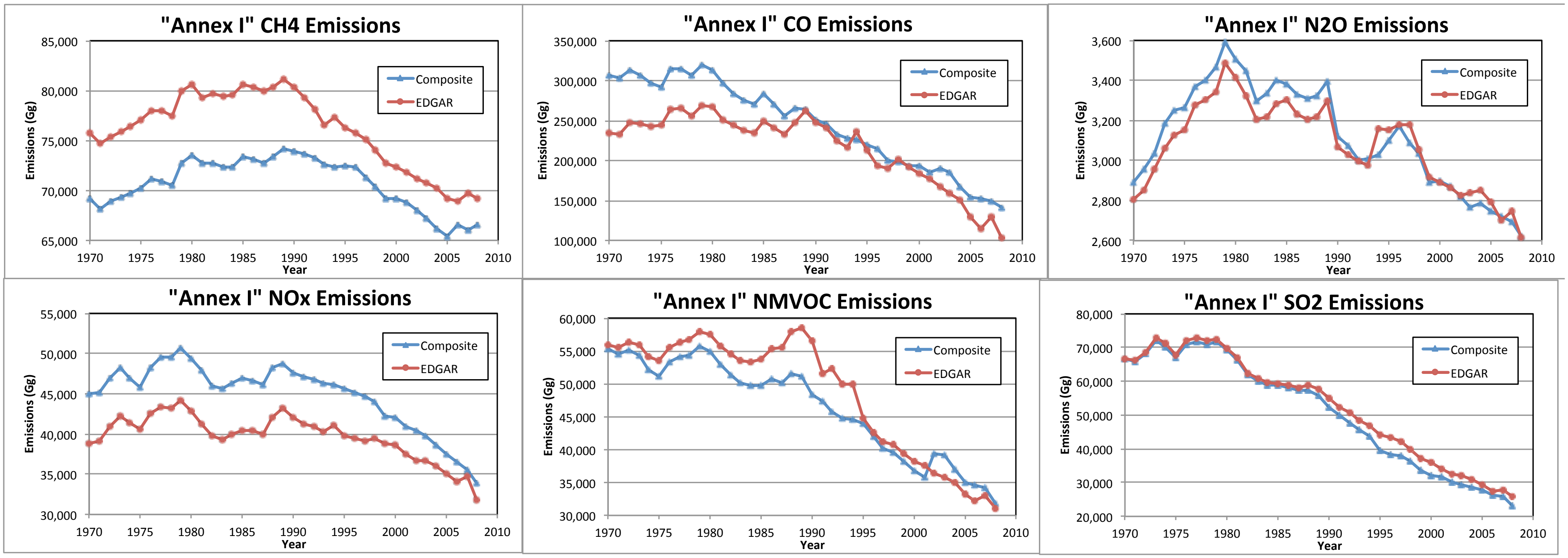
Comparison of EPA Inventories: CO

Inventory	1980	1990	1995	1996	1997	1999	2000	2002	2003	2004	2005	2006
					Data Year							
Combustion												
Trends 1998	0%	0%	0%	**42%**	**25%**							
Trends 2000	0%	0%	0%	0%	0%	**-21%**	-4%					
Trends 2003	0%	0%	0%	0%	0%	0%	0%	####	-8%			
Trends 2006	0%	0%	0%	0%	0%	0%	0%	-8%	-5%	-2%	0%	0%
Process												
Trends 1998	0%	0%	0%	**-29%**	**-29%**							
Trends 2000	0%	0%	0%	10%	9%	**36%**	**75%**					
Trends 2003	0%	0%	0%	0%	0%	0%	0%	**14%**	**21%**			
Trends 2006	0%	0%	0%	0%	0%	0%	0%	0%	3%	7%	**11%**	**11%**
Highway												
Trends 1998	**-46%**	**-48%**	**-35%**	**-32%**	**-32%**							
Trends 2000	**-46%**	**-47%**	**-35%**	**-31%**	**-30%**	**-28%**	**-29%**					
Trends 2003	0%	0%	0%	0%	0%	0%	0%	3%	4%			
Trends 2006	0%	0%	0%	0%	0%	0%	0%	4%	7%	**11%**	**16%**	**19%**
Off-Highway												
Trends 1998	**-13%**	**-15%**	**-15%**	**-17%**	**-14%**							
Trends 2000	**-13%**	**-15%**	**-15%**	**16%**	**18%**	**20%**	**16%**					
Trends 2003	0%	0%	0%	0%	0%	0%	0%	8%	**11%**			
Trends 2006	0%	0%	0%	0%	0%	0%	0%	-1%	4%	9%	**14%**	**21%**
Total												
Trends 1998	**-37%**	**-36%**	**-26%**	**-26%**	**-20%**							
Trends 2000	**-37%**	**-36%**	**-26%**	**-19%**	**-11%**	**-11%**	-4%					
Trends 2003	0%	0%	0%	0%	0%	0%	0%	1%	2%			
Trends 2006	0%	0%	0%	0%	0%	0%	0%	-2%	2%	6%	**10%**	**14%**

- Again, most recent 1-3 years are often more uncertain
- Large change in vehicle emissions for all years. Even more for early years.

EDGAR 4.2 vs Country Inventories

Comparison of a composite dataset based on country inventories (with some extrapolation using EDGAR where data was missing)



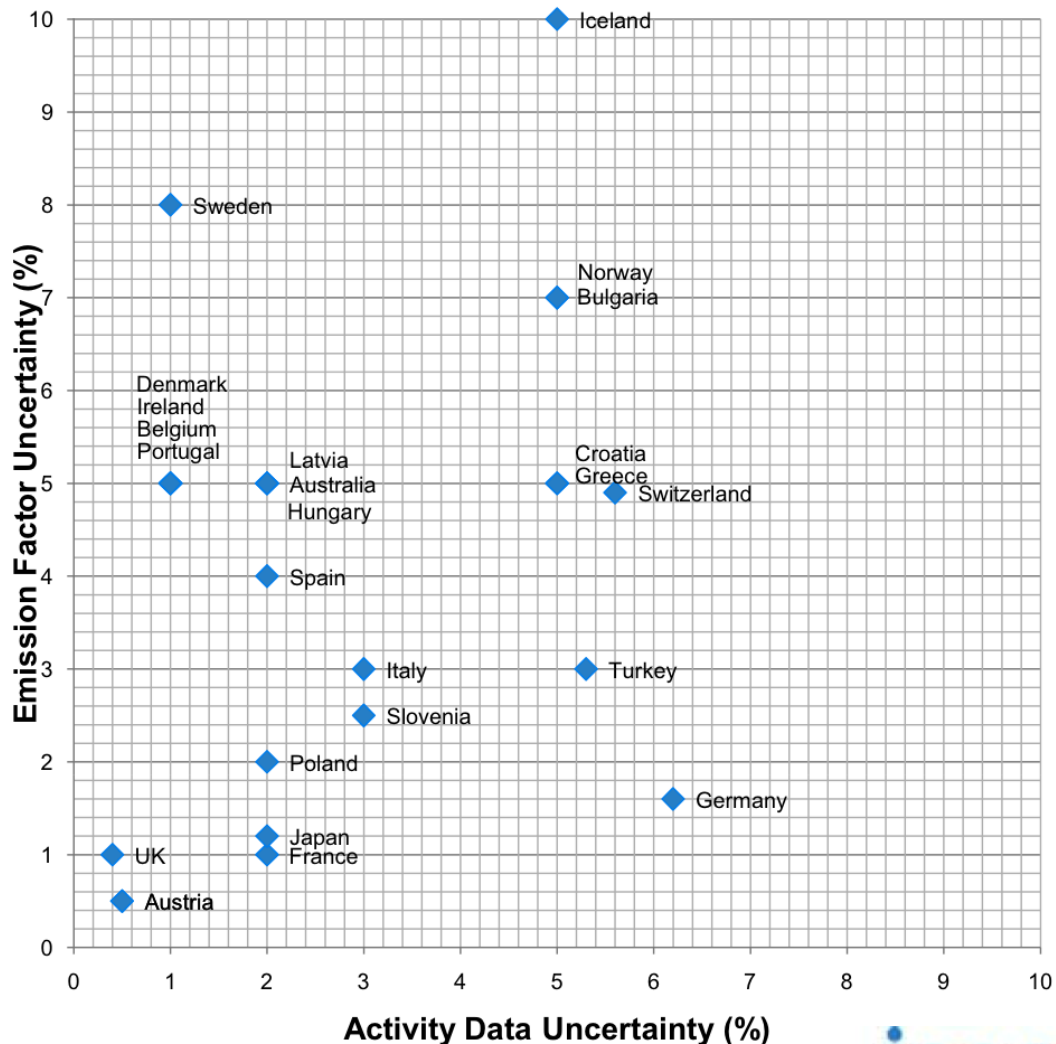
Difference between a global inventory generally using consistent assumptions (EDGAR) and a collection of country-level inventories developed using, presumably, more detailed local data (although, likely, some in-consistent assumptions)

- SO_2 agrees closely with country inventories in this version (calibrated to inventories?).
- General agreement near current day (except for CH_4)
- Some differences in trends

Emissions Uncertainty: Carbon Dioxide

Electrical Power Generation - Solid Fuel

- Data from 2009 submissions to UNFCCC
- Some variability due to differences in national circumstances
  - BUT can that explain all the variation?
- Not all parties report data at this level of detail
- Can we give advice on how to determine data uncertainty in a consistent way and to increase the consistency and transparency of reporting uncertainties?



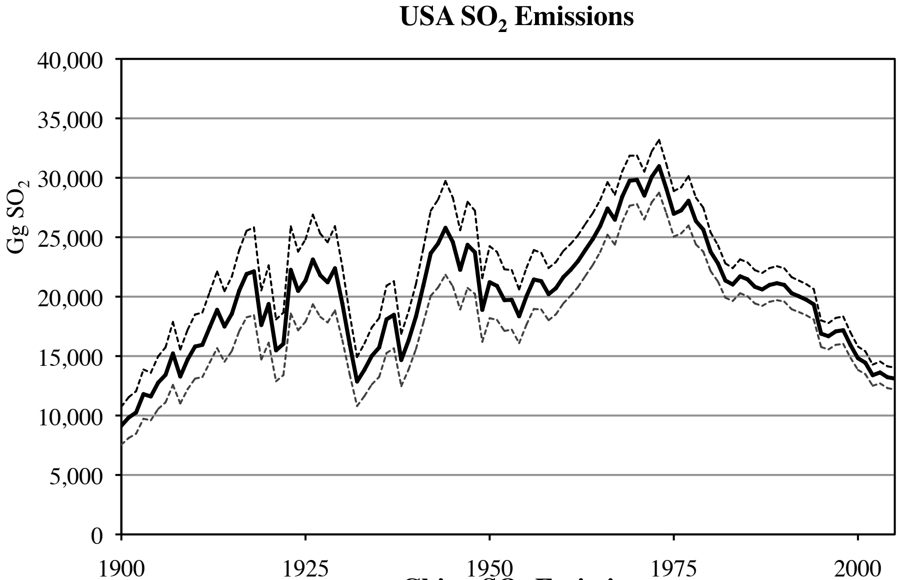
INTERGOVERNMENTAL PANEL ON climate change

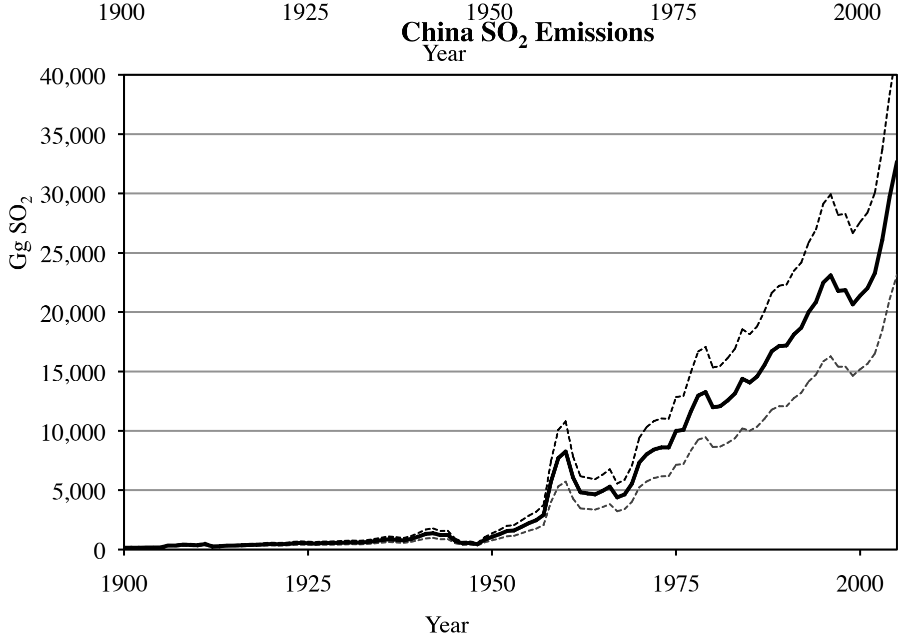
Not clear if uncertainty is consistently estimated

Source: Simon Eggleston IPCC TSU

Emissions Uncertainty: SO_2

Method: Simplified uncertainty analysis at a sector/region level.





Uncertainty in US SO_2 emissions is relatively low

- Uncertainty from independent sources cancel
- Major emissions sources are measured
- Uncertainty was larger In the past

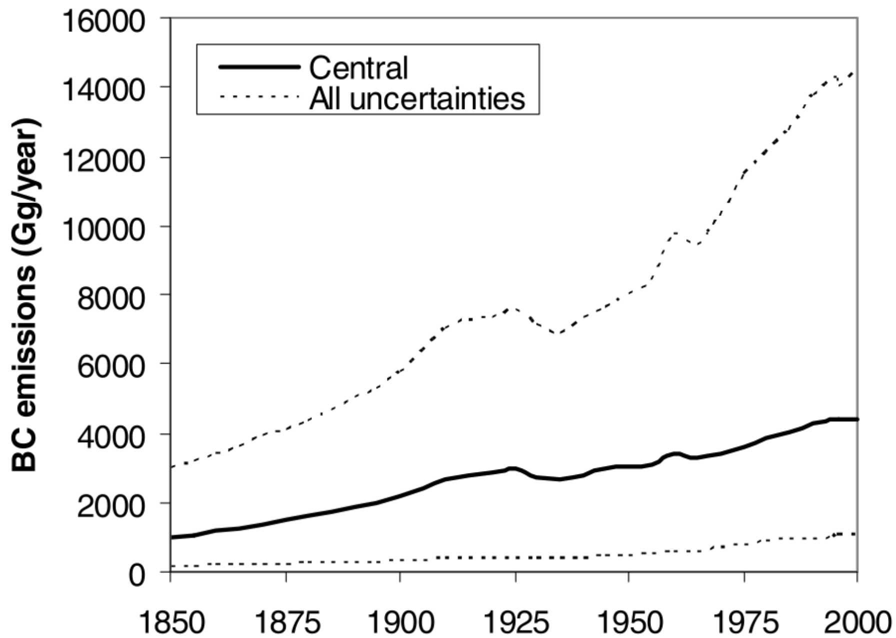
Uncertainty in China SO_2 emissions is fairly large

- Larger uncertainty in driving forces, sulfur content, and ash retention.
- Most emissions from coal combustion, less cancelation in uncertainty across sectors.

 Smith et al. (2011)

Emissions Uncertainty: Black Carbon

Method: Formal uncertainty analysis at a technology & country level.



Uncertainty in BC emissions much larger

- Due to incomplete combustion, inherently more uncertain
- BC fraction of particulate also uncertain
- Uncertainty in major emissions sectors (e.g. cookstoves) potentially correlated across regions
- Emissions from “super-emitters” important and uncertain

 Source: Bond et al. (2007)

Challenges to Better Uncertainty Analysis

- "High uncertainty does not necessarily mean there is potential for improvements in the foreseeable future!"
  - Some uncertainty is here to stay, so need to include this where it is important.
- Complex data and dependency structures and data manipulations (e.g., in national inventories)
- Data combined from multiple sources (many of which may not be willing or able to provide uncertainty information)
- Only some sources of uncertainty quantified (e.g., co-variance in survey data), but many other sources are not quantified
- Limited resources and expertise available
  - How important is uncertainty to agency missions? Not necessarily very important…

Points cribbed from presentation by Blain and Neitzert at the IPCC Expert Meeting on Uncertainty and Validation of Inventory Estimates (March 2010), except for commentary and potential misquotes.

Thoughts On Uncertainty

- Greater focus on uncertainty analysis will often, at first, increase the estimated uncertainty.
- Measurement technology has advanced tremendously, making it possible to gather statistically valid samples for emission factors under real-world conditions.
- Correlations between variables and systemic (non-random) errors are difficult to quantify, but important for a full uncertainty analysis.
- Just because there is an error bar, this does not necessarily mean this is a full estimate of uncertainty! (e.g., showing sampling error only).
- A sophisticated analysis offers little additional information if the basic information going into the analysis is not solid. Often, effort is best spent in improving characterization of uncertainty in fundamental input categories.

- Comparisons with observations can be very useful in pointing to where improvements may need to be made.

Validation Using Observations

Hope for improvement?

Comparison With Observations

Measurements can, in principle, be used along with atmospheric transport (and, where needed, chemistry) modeling to infer the distribution of emissions that best match observations.

Works best for emissions that

- Have minimal: natural sources, atmospheric chemical interactions, small surface sink, and high precision observations of related concentrations.

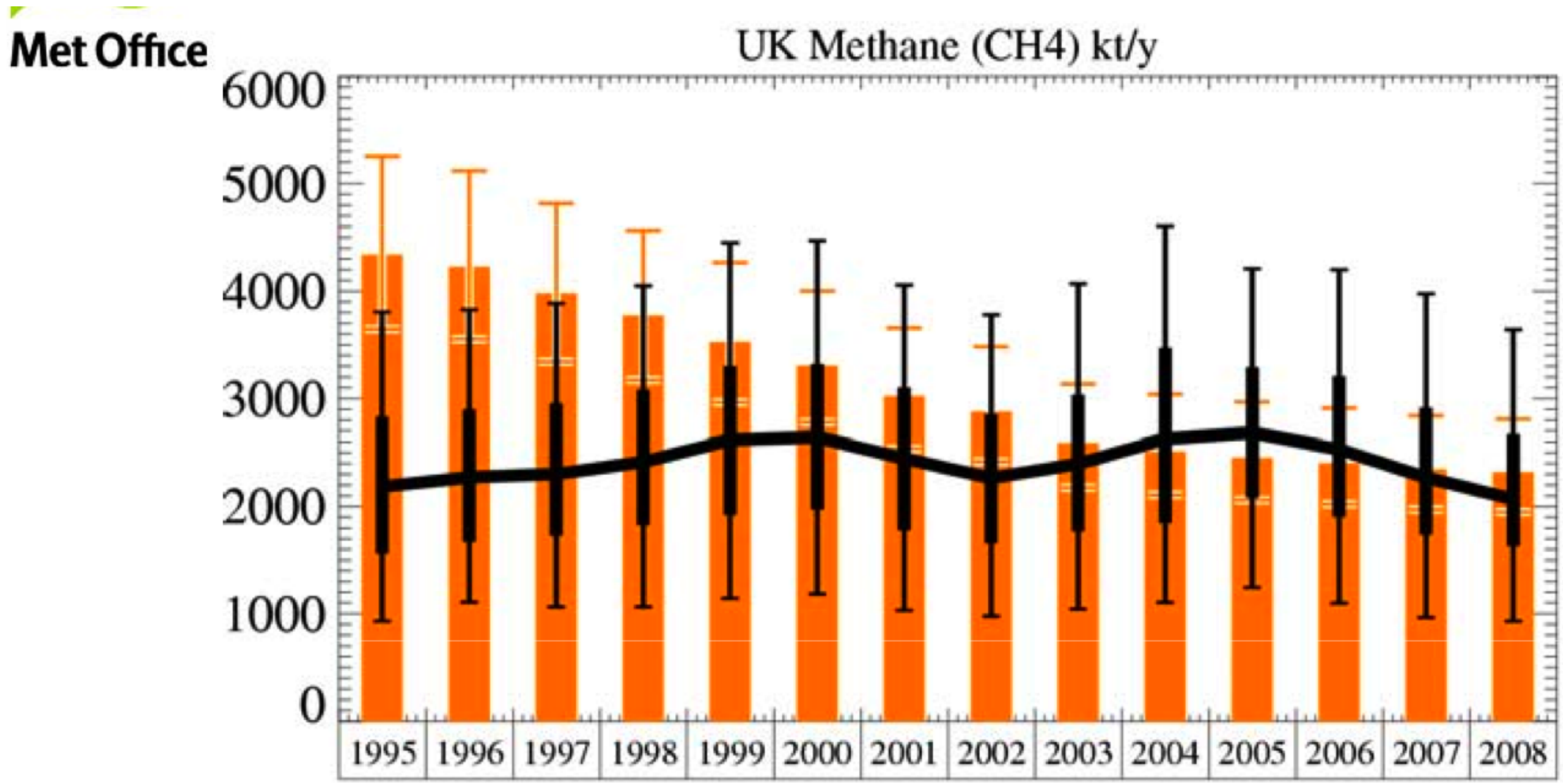
Observations can be from flasks (good detail and precision, lower temporal resolution), continuous measurement (hourly or more), or satellites (better coverage, see column, not concs).

- Best: dense network, high resolution time series, from tall towers (most comparable with model results) and from stations in flat topography.
- Difficult to quantify uncertainty.

Significant research on greenhouse gases

- Motivated, in large part, because current policy instruments are formulated in terms of emissions.
- Some are *relatively* easy (CH_4) while inventory methods are highly in-consistent for others (land-use CO_2).

Emissions Comparison: UK



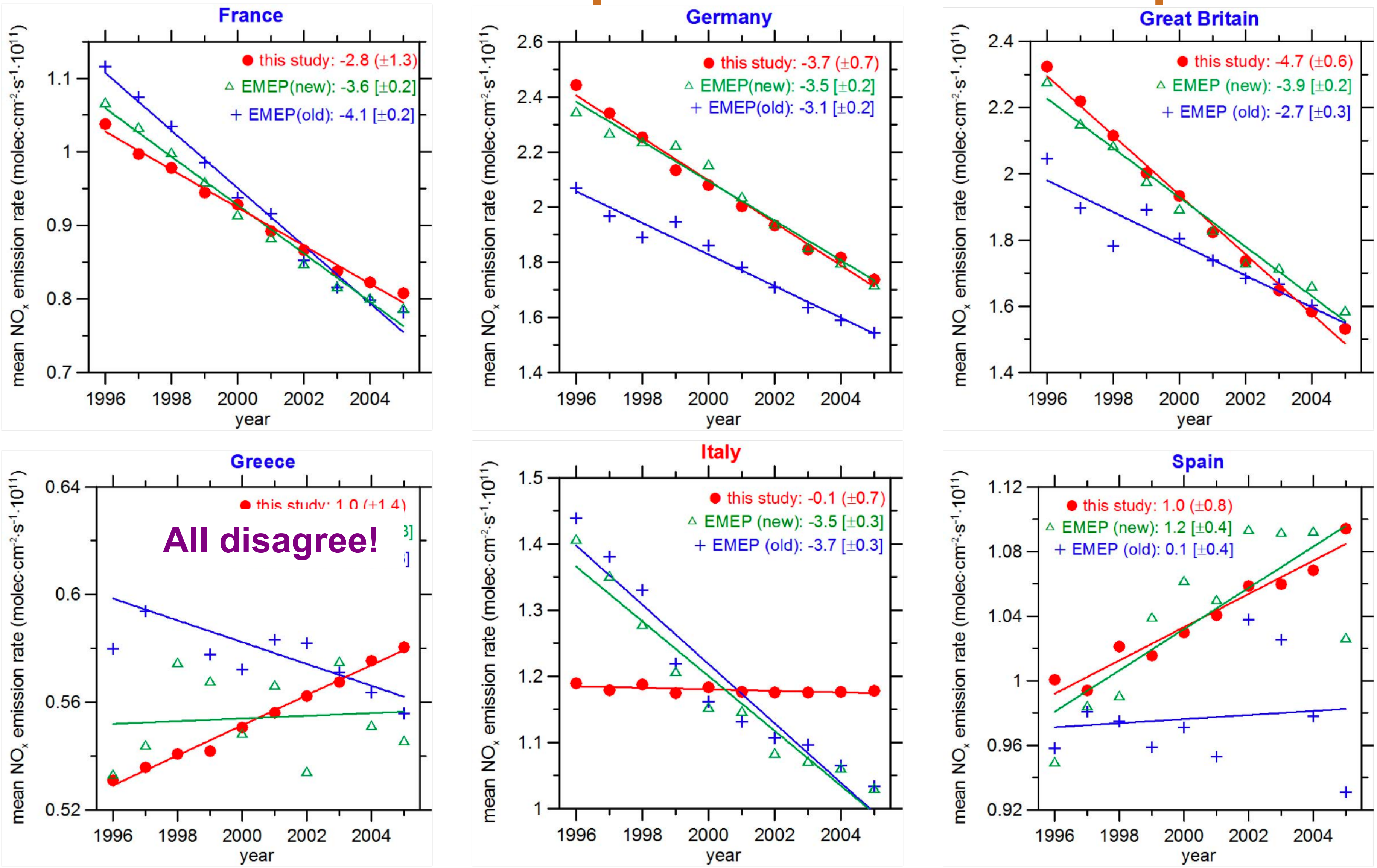
Inversion to match observations → NAME-inversion estimates with uncertainty

Inventory estimates (UNFCCC 2009) (84%-121%)

Atmospheric measurements + models can potentially be used to validate emissions inventories, but uncertainties can still be large

Source: A Manning (2010)

Emissions Comparison: NOx in Europe



Atmospheric & satellite data + models vs emissions inventories

➢ Need uncertainty estimates to evaluate agreement!

JGCRI Source: Konovalov et al. (2008)

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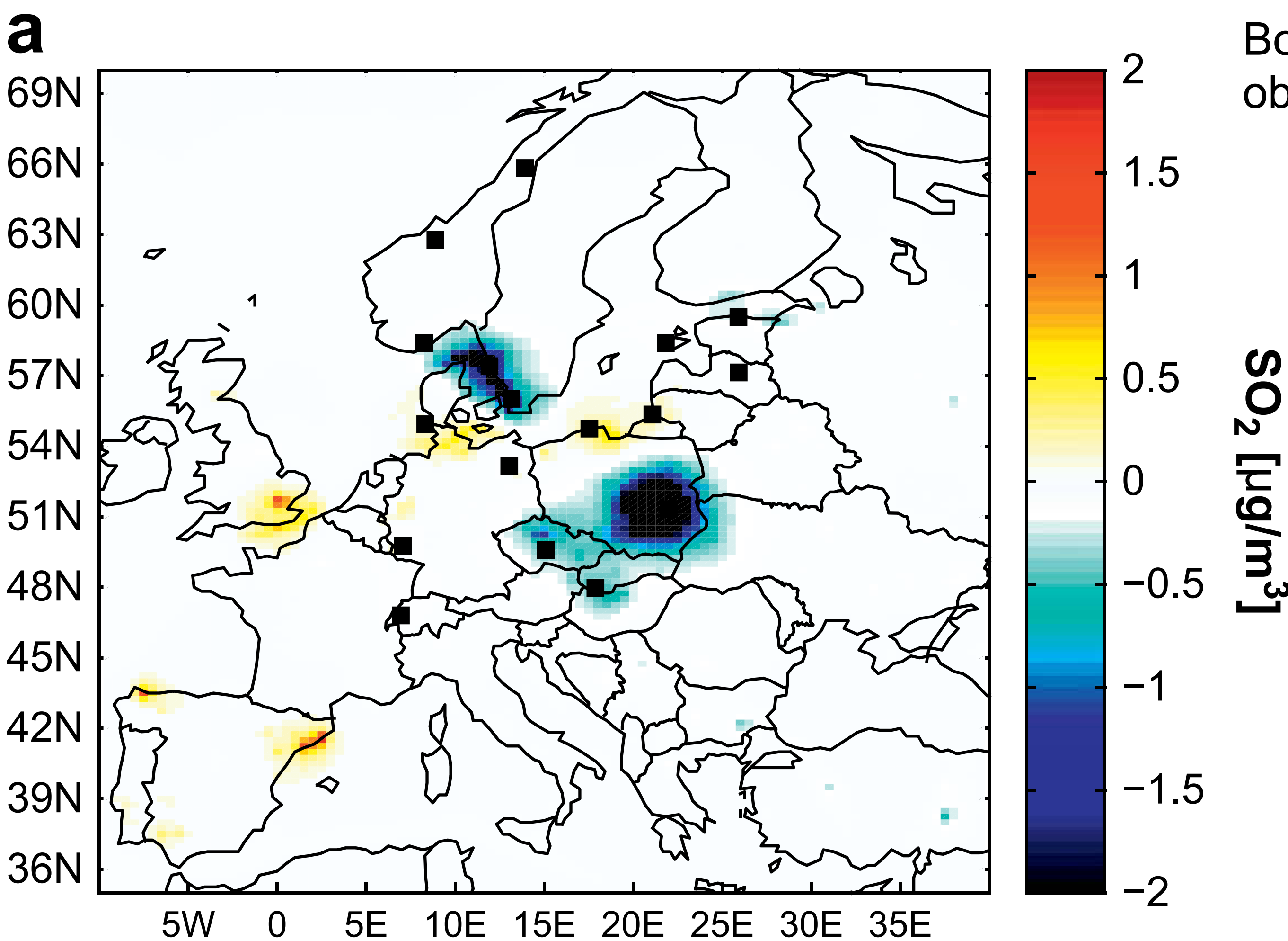
Concentration Comparison: SO_2 in Europe



Boxes are the observation sites.

Note, in all these examples, emissions are inferred – only concentration observations are the target of the assimilation!

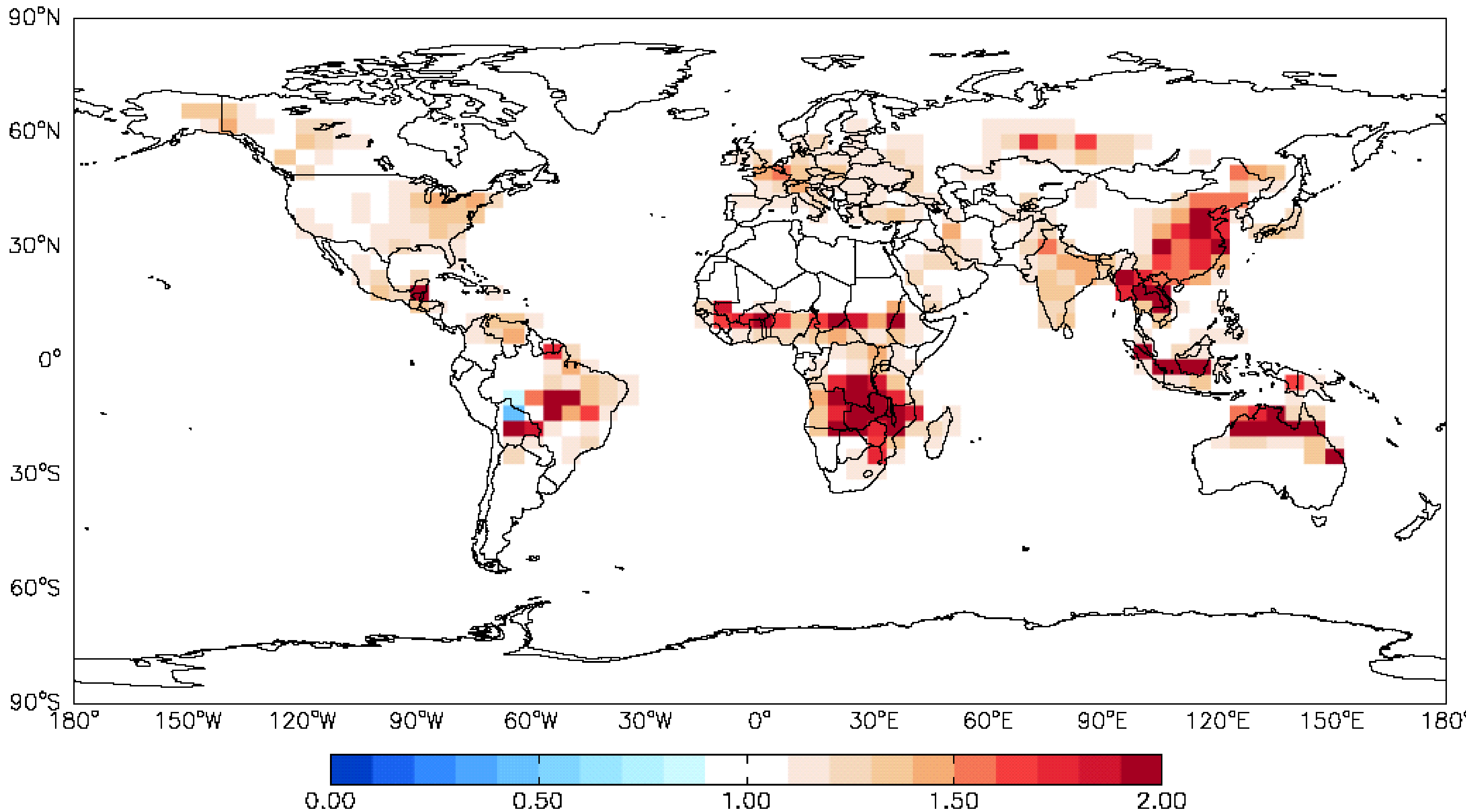
In this exercise, both emissions and the atmospheric conversion rate of SO_2 to SO_4 were adjusted in order to match the observations.

Source: Barbu et al 2008

Emission Comparison: CO

Using multiple satellite datasets

Ratio of inversion estimate to emissions inventory



Suggested that:

- Inventories underestimated emissions
- Inventories underestimate emissions in winter (vehicle cold starts?)

Source: Kopacz etal 2010

Comparison With Observations: Issues

Observations

- Laboratory analysis of flask samples can be more complete. Isotopic data very useful for compounds that contain carbon.
- Ground data is critical for calibration of satellite data.
- Dense observation networks are needed for regional or country-level inversion estimates.
- Satellite data is much more comprehensive, but see a column of the atmosphere, not point emissions. Also can be less sensitive to emissions close to the surface, don't work on cloudy days (bias?), and various other conditions.

Atmospheric Transport

- Large-scale transport models cannot simulate the fine scale detailed transport around measurement stations.
- On a low-wind day, for example, local sources will dominate the signal.
- Detailed dilution and transport, particularly on shorter time scales.

Atmospheric Chemistry

- Adds additional uncertainty, but also provides a mechanism for providing validation of chemistry models as well.

Summary

Inventory Data

- The assumptions made in inventory construction should, ideally, make their way into IAM models.
- Data standards would help with this.
- More timely inventory updates would also help.

Uncertainty

- Emissions estimates are uncertain, some highly so.
- This implies additional uncertainty in future projections.
- Need to consider this in analysis where this uncertainty is important.

Observational validation

- Is relatively new endeavor.
- Can point to areas where inventories might not be correct.

Other

- Did not talk about consistency of gridding!
- If you really want to see more details about global emission inventory production, you can flip through (or even read) the 50 pages (w/ supplement) of Smith et al. (Atmos. Chem. Phys., 11, 1101–1116, 2011), or Bond et al. (2004, 2007).

THE END

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