Linking Regional Aerosol Emission Changes with Multiple Impact Measures through Direct and Cloud-Related Forcing Estimates

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Argonne National Laboratory

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Clean Air Task Force

Organization

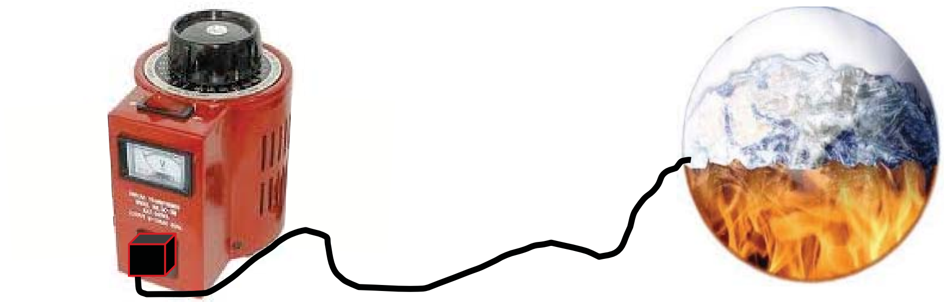
- Project overview – Tami Bond
- Size-resolved emission inventory – Dave Streets, reported by Tami Bond
- U.S. regional cloud modeling – Hao He
- Emission-to-forcing measures – Yanju Chen
- Policy-relevant metrics– Praveen Amar, reported by Tami

Project Overview

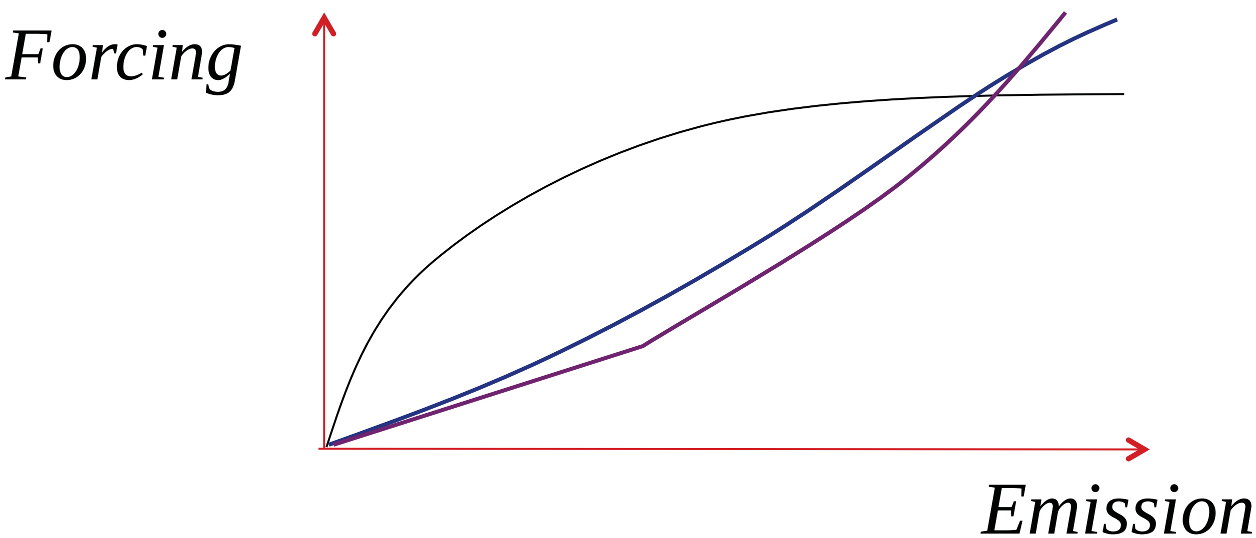
Or, Why we Did What We Did

(Tami Bond)

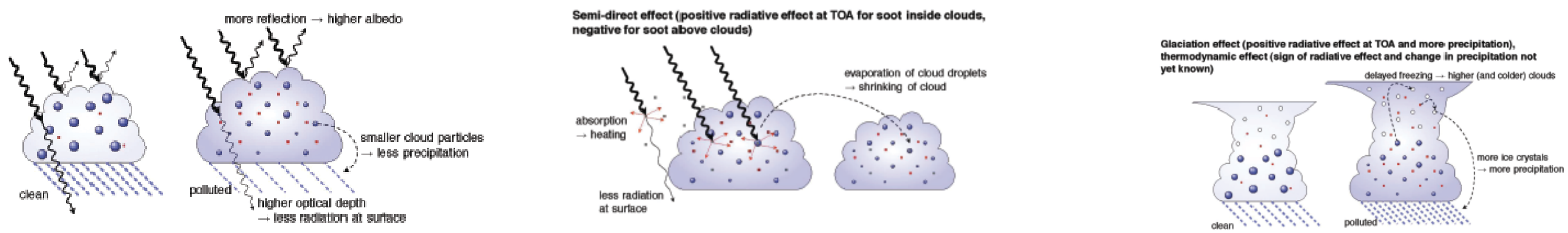
The simple view



A dose-response curve for the atmosphere



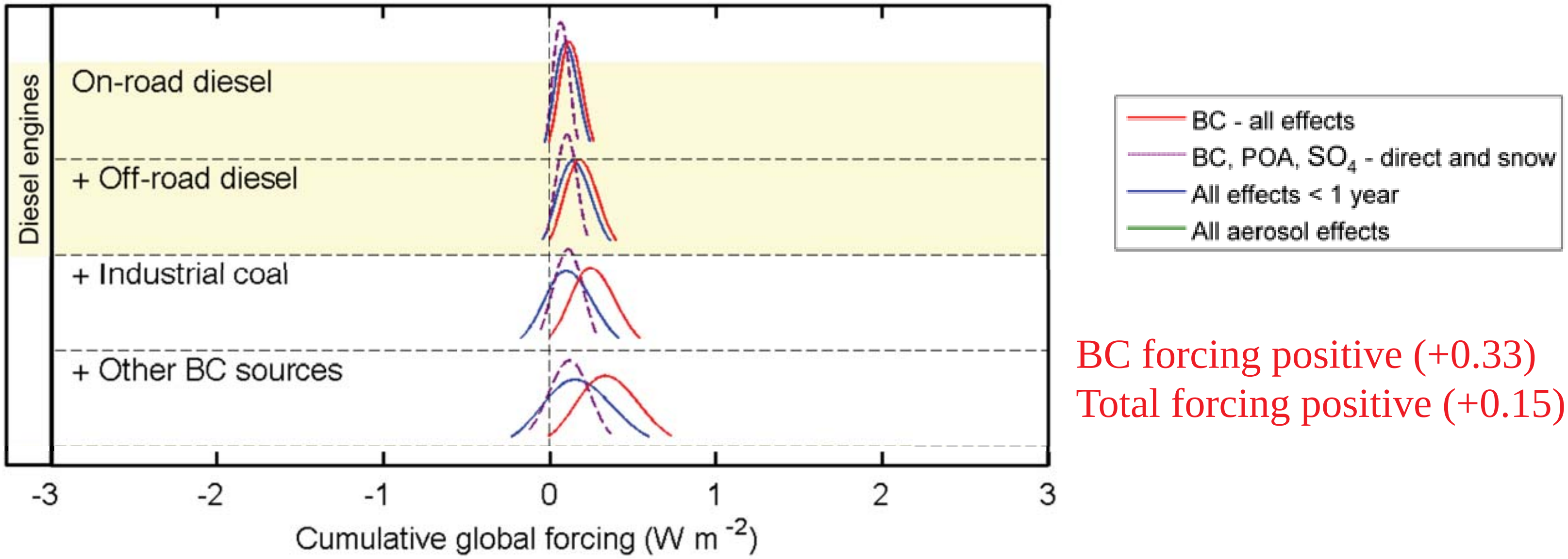
The big uncertainty in BC-rich sources



- BC → direct forcing ~ bounded
- BC → cloud forcing
  ~ large uncertainties – especially in ice/mixed
- OC + SO_4 → direct forcing
  ~ small for BC-rich sources
- OC + SO_4 → cloud forcing
  ~ large and probably negative

It's the indirect effects of co-emitted species that cause big questions about immediate forcing

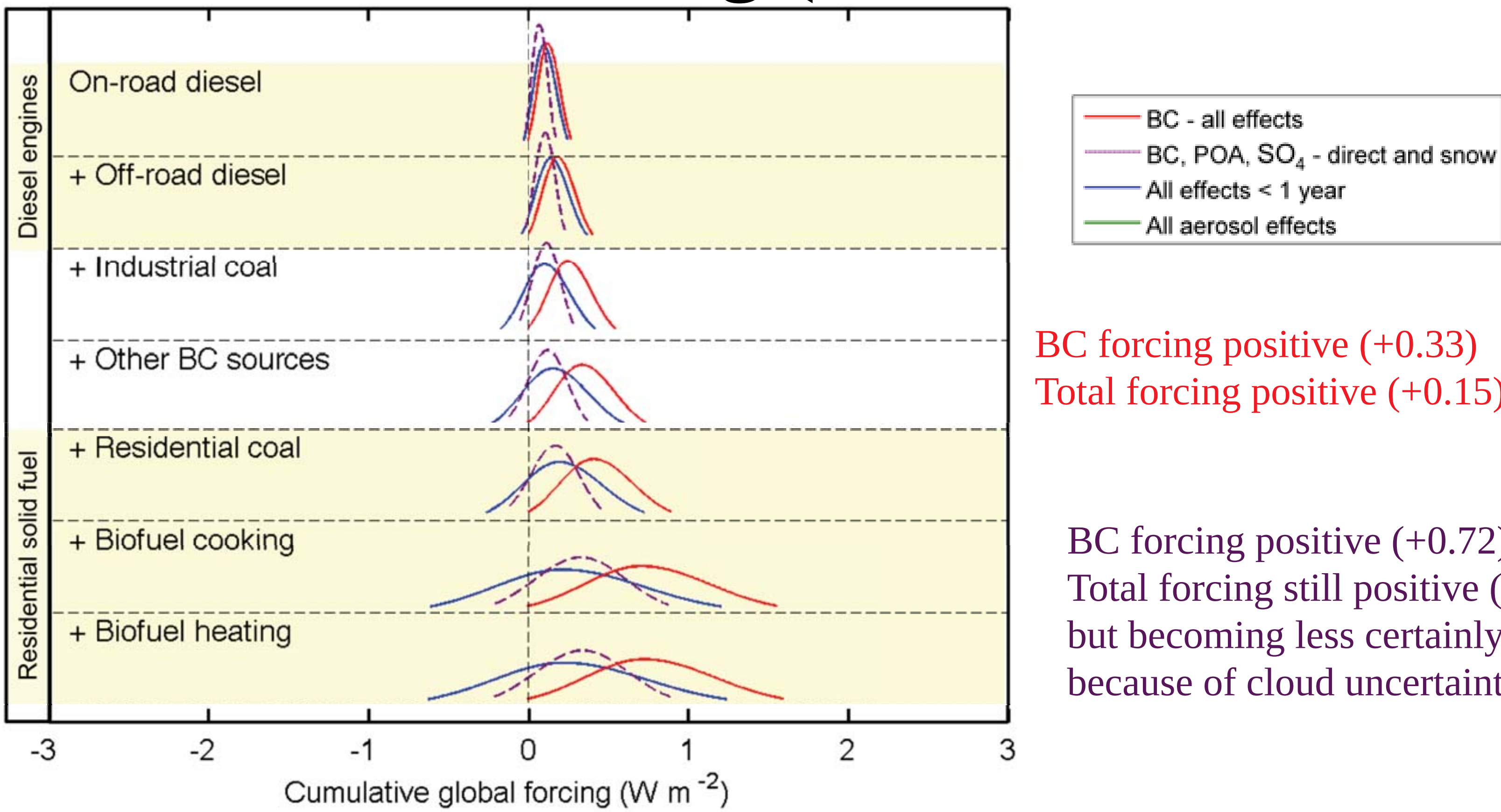
Cumulative forcing (add successive categories)



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

Bounding-BC Fig 38

Cumulative forcing (add successive categories)

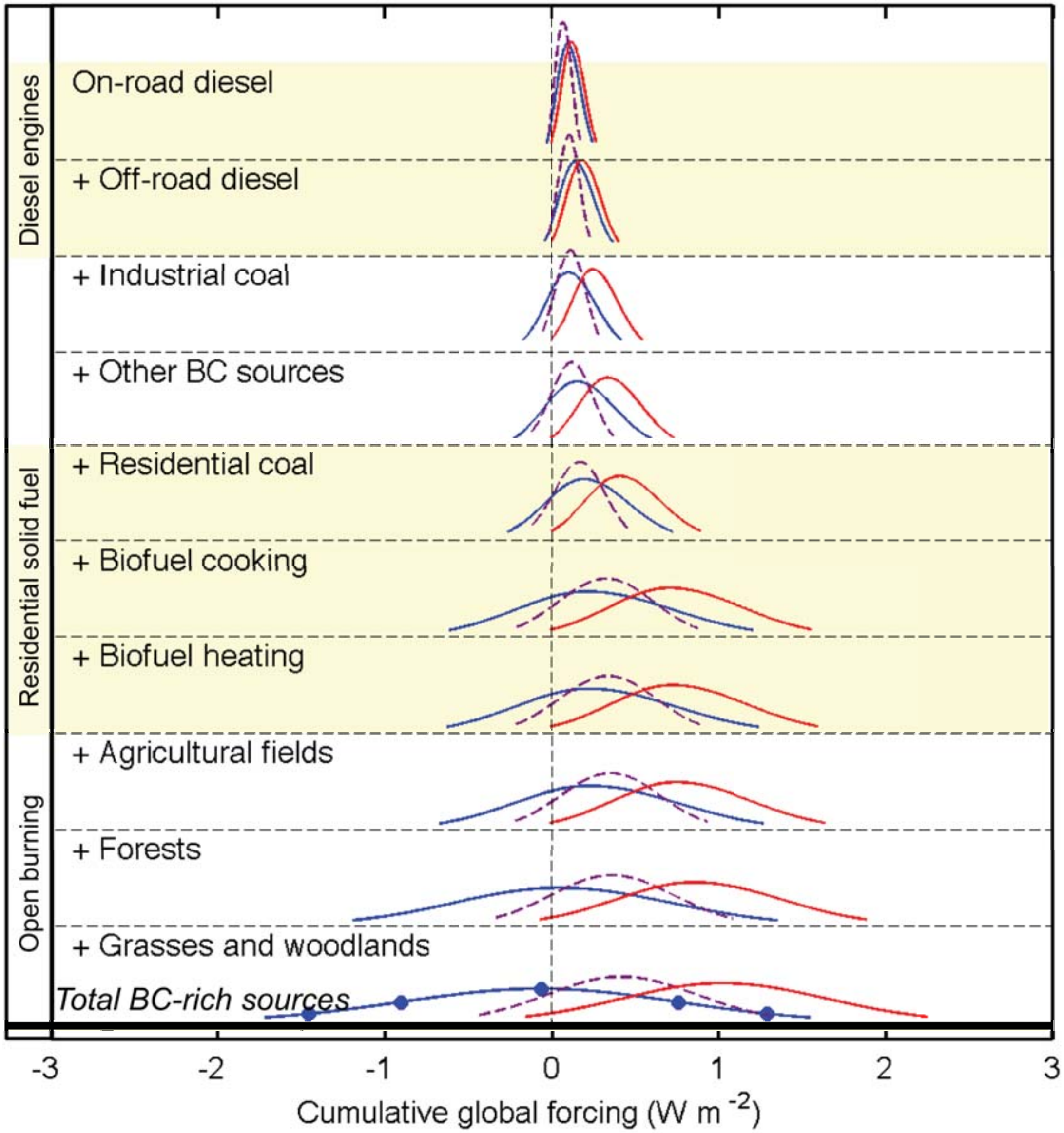


BC forcing positive (+0.33)
Total forcing positive (+0.15)

BC forcing positive (+0.72)
Total forcing still positive (+0.21)
but becoming less certainly so,
because of cloud uncertainties

Bounding-BC Fig 38

Cumulative forcing (add successive categories)



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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)

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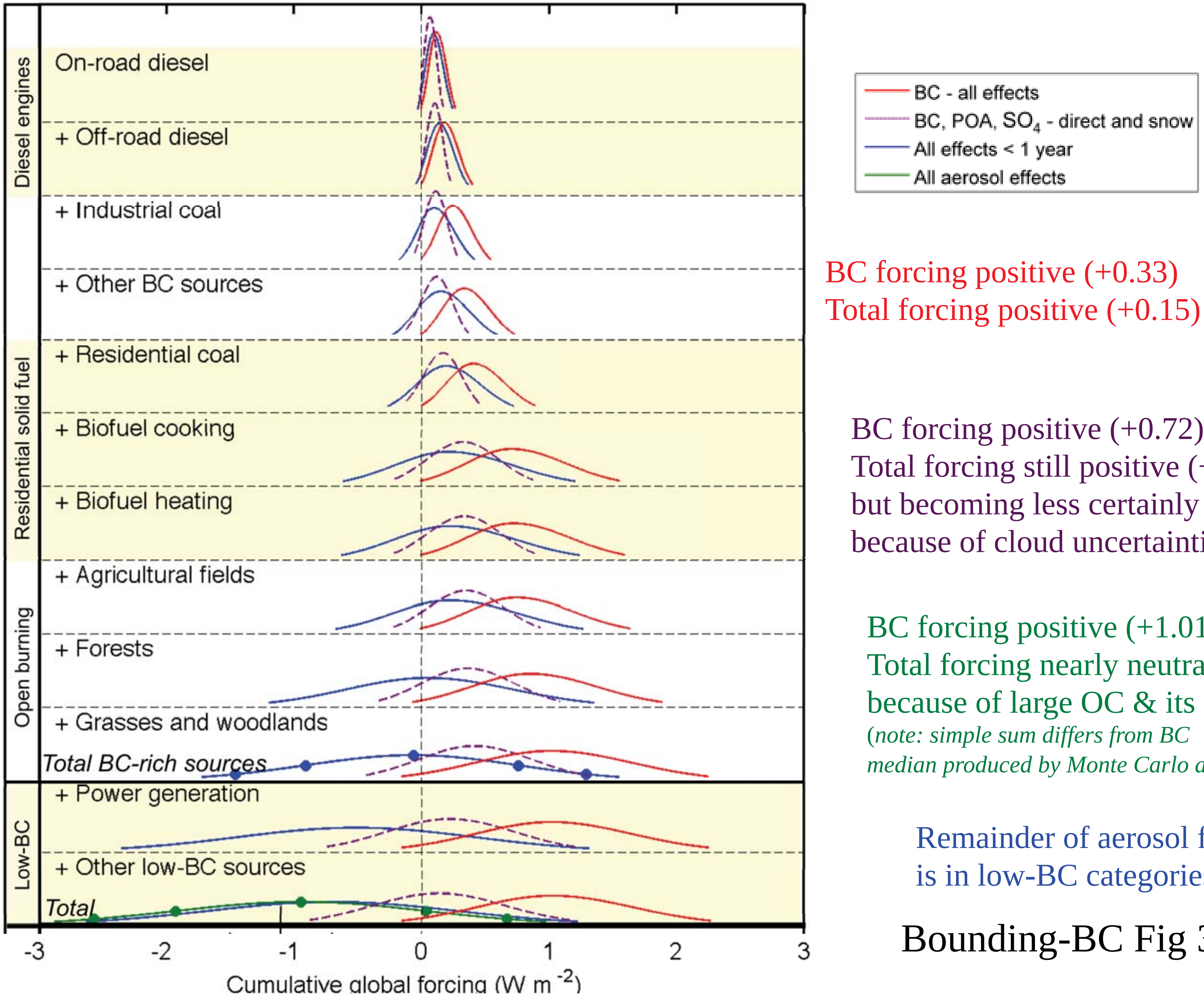
Cumulative forcing (add successive categories)



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(note: simple sum differs from BC median produced by Monte Carlo analysis)

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

Bounding-BC Fig 38

So you got [*some scientific thing*] right. Who cares? Tell me if I should turn this off!

Can you wait 6 months? I have to run my model…

Need a *forcing-to-emission* ratio

Simple

$$\text{Forcing}_{\text{source}} = \frac{\text{Forcing}_{\text{modeled}}}{\text{Emission}_{\text{modeled}}} \times \text{Emission}_{\text{source}}$$

Need a *forcing-to-emission* ratio

Simple

$$\text{Forcing}_{\text{source}} = \frac{\text{Forcing}_{\text{modeled}}}{\text{Emission}_{\text{modeled}}} \text{ x } \text{Emission}_{\text{source}}$$

Complex

$$CF = FC\sum_{i=1}^{I} EF_i \left(\sum_{j=1}^{J} rforc_{i,j} + \sum_{k=1}^{K} fresp_{i,k} \right)$$

Bounding-BC
equation 11.1&1

climate forcing

fuel consumption

emission factor

forcing per emission

response per emission

$$rforc_{i,j} = \left. \frac{\partial f_j}{\partial e_i} \right|_{PD}$$

Definition

Emission-Normalized Forcing (ENF)

including

ENDRF — Direct Radiative

EN IRF — Indirect Radiative

$$\frac{\text{Forcing}_{\text{modeled}}}{\text{Emission}_{\text{modeled}}}$$

approximates this:

$$rforc_{i,j} = \left.\frac{\partial f_j}{\partial e_i}\right|_{PD}$$

Detour: Climate "metrics"

<u>Normal people think:</u>
A metric is something you can measure, and report

<u>The climate policy community says:</u>
A metric is a well-defined calculation that can be used to *equate* a mass emission of some species to a mass emission of the big bear, CO_2

Some climate metrics

Absolute global warming potential

Global warming potential

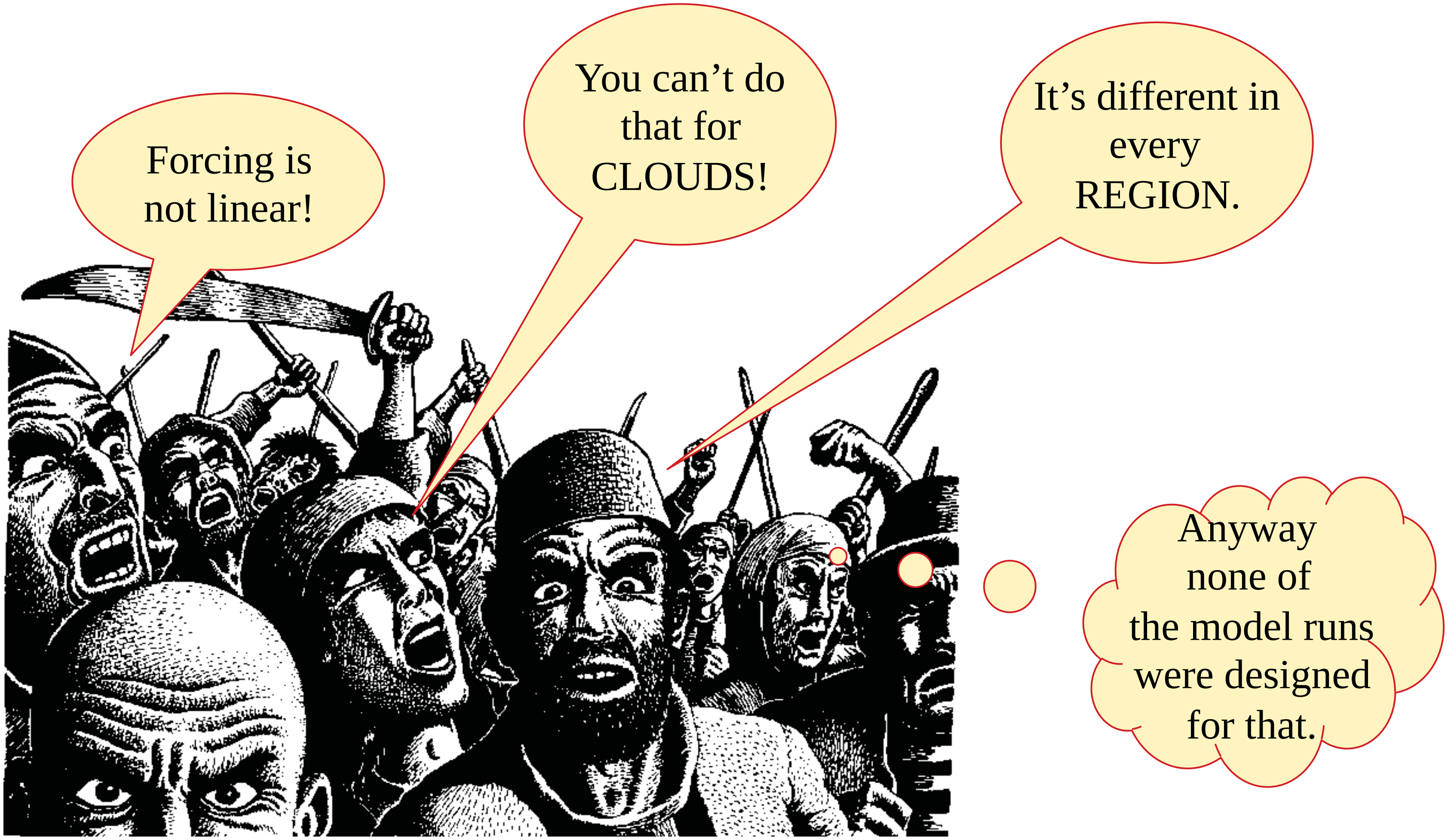
Global temperature potential

ENF

For short-lived species (τ<4 mo), emission-normalized forcing is the *only* model output required to calculate *any* of these metrics.

Other considerations affect the values of emission metrics, but they all come from models of the carbon cycle or Earth' heat capacity, NOT from models of aerosols

Complaints against ENF



Need: Emission-normalized forcing for both direct forcing and cloud mechanisms.

Objective 3: Determine functional relationships that express changes in direct and cloud radiative forcing as a function of emission changes in particular locations

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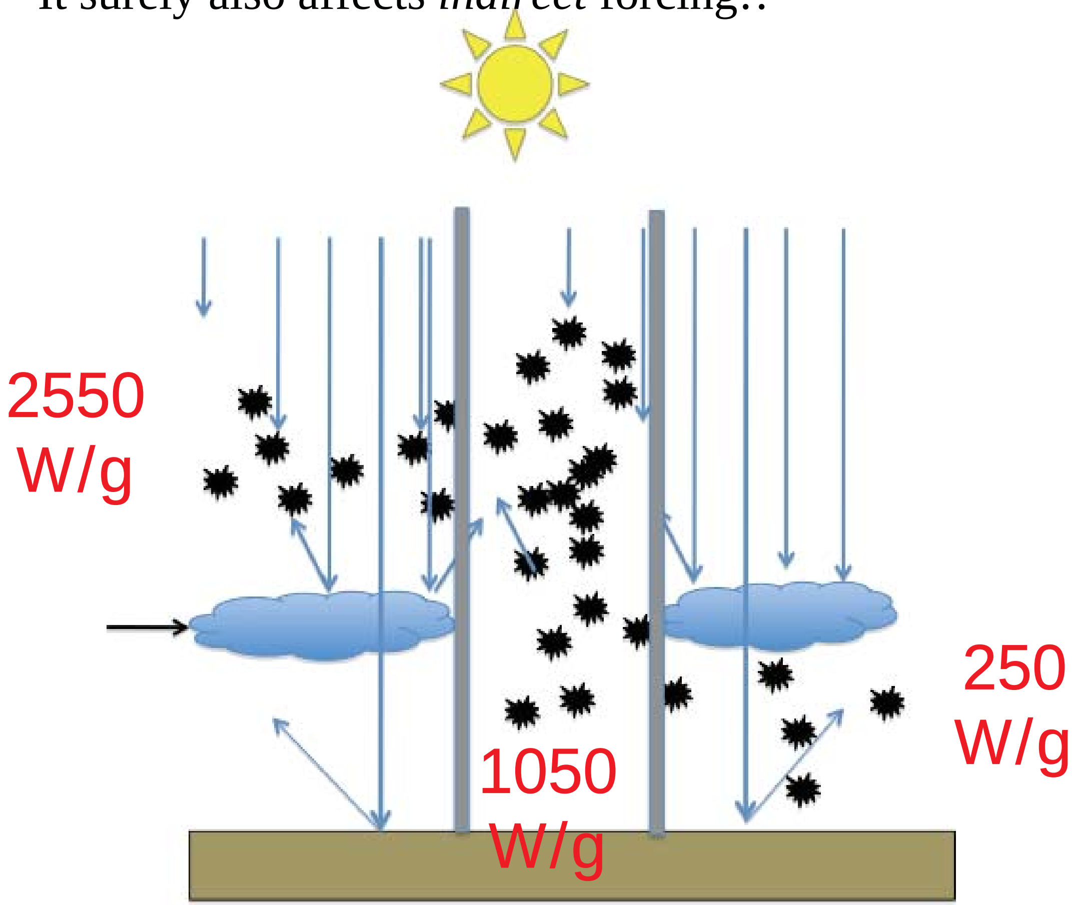
But wait…

Relative location of BC and clouds affects direct forcing

It surely also affects *indirect* forcing!!



Zarzycki & Bond, GRL 2010

In this earlier study, we found that the modeled clouds wer

Community Atmospher

Note: Also affects semi-direct forcing; see Ban-Weiss et al, Clim Dyn, 2011

Strategy: Compare modeled fields with ISCCP observations

ISCCP = International Satellite Cloud Climatology Project

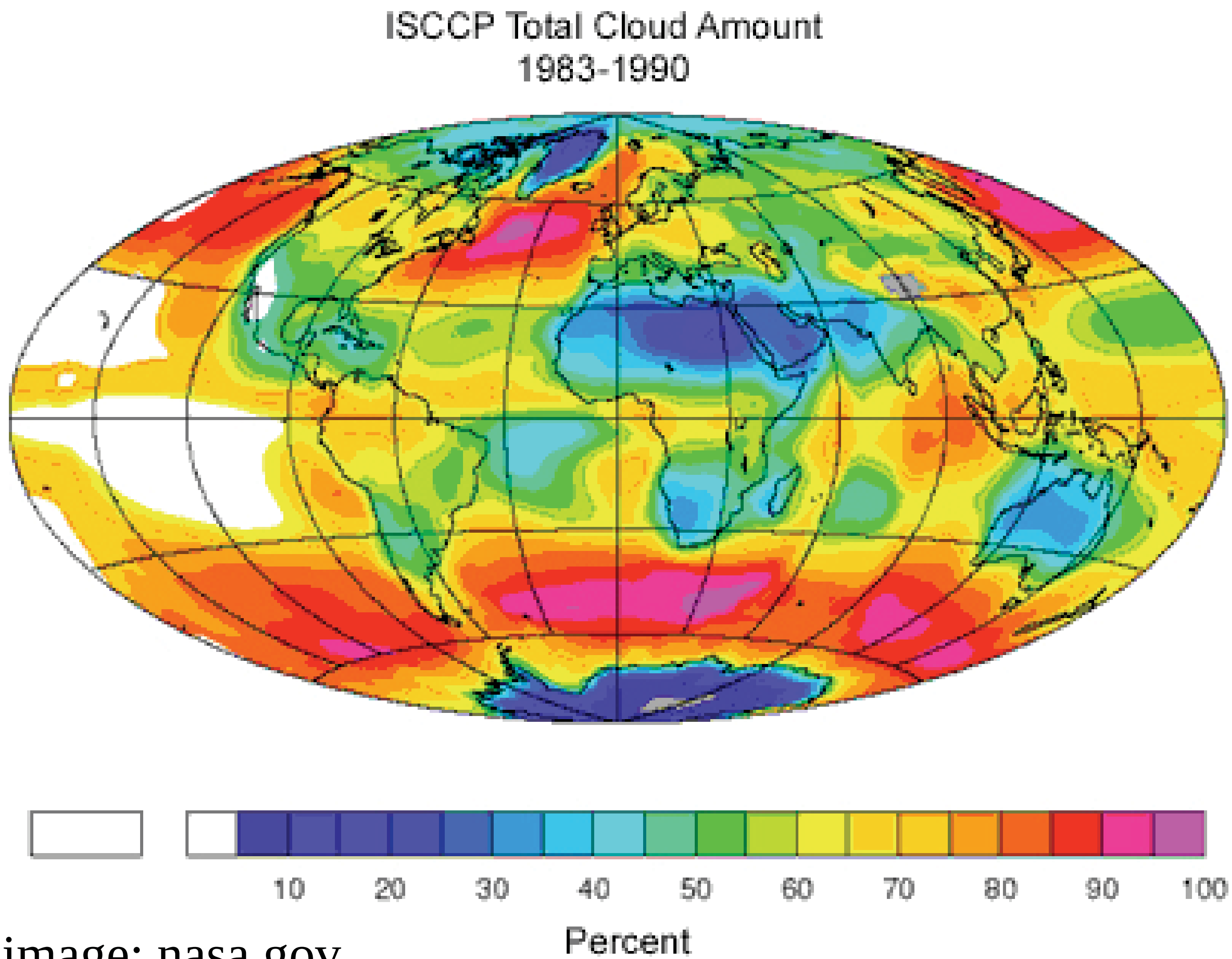


image: nasa.gov

Need: Confidence in modeled clouds before inferring cloud forcing from a model.

Objective 2: Employ an ensemble of parameterizations in regional-scale models to identify best estimates and uncertainties for fields of direct and cloud-related forcing

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Objective 2: Employ an ensemble of parameterizations in regional-scale models to identify best estimates and uncertainties for fields of direct and cloud-related forcing

But wait…

Aerosol effects are size-dependent

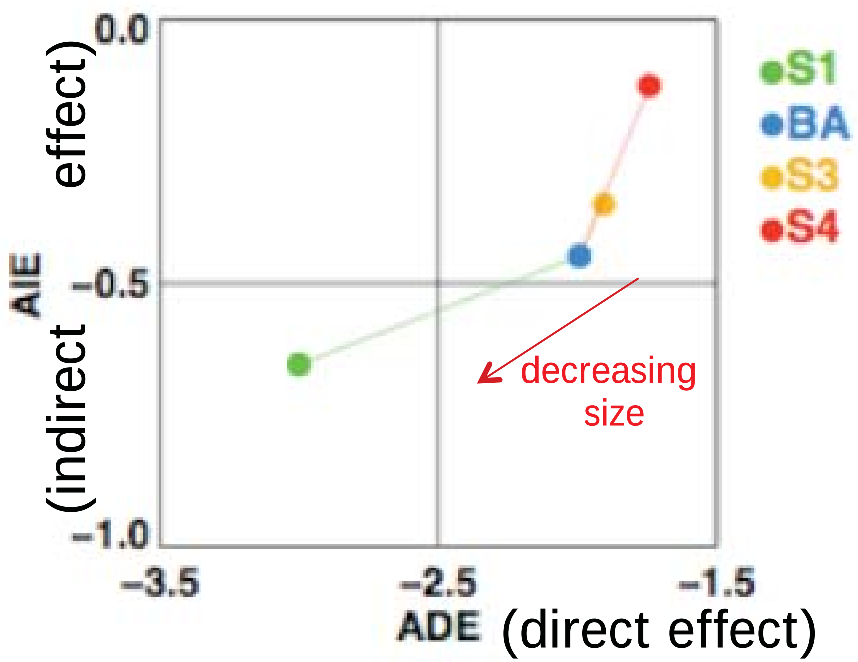


Fig. 4. Global mean AIE and ADE [W/m^2] values for all size experiments, (S1–4) and the base experiment, BA, for present day conditions.

Bauer et al., ACP, 2010
for carbonaceous aerosols

Need: Knowledge of emission size distributions.

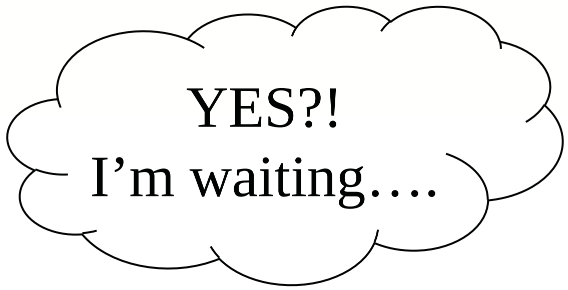
Objective 1: Develop size-resolved, speciated emission inventories of aerosols and aerosol precursors

Need: Knowledge of particle size, beginning with emission.

Objective 1: Develop size-resolved, speciated emission inventories of aerosols and aerosol precursors

But wait…

YES?!
I’m waiting….



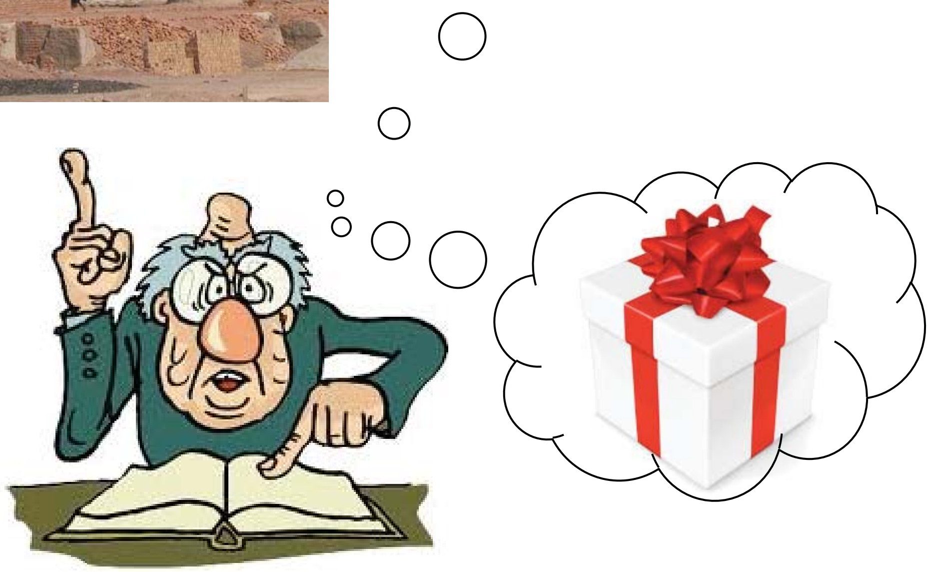


image: gogobambini.com

Need: Policy-distilled measures or metrics

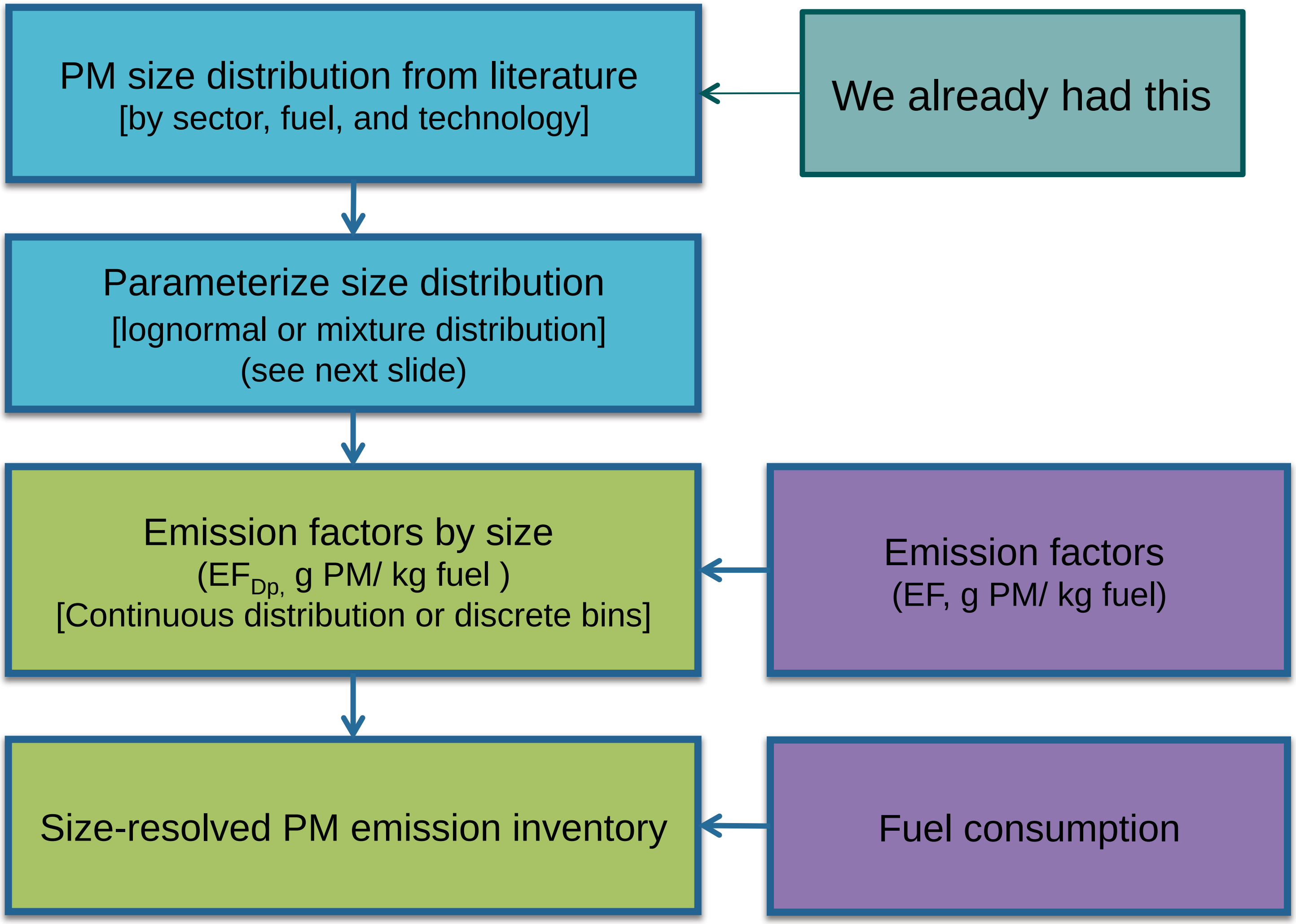
Objective 4: Iterate emission-to-forcing measures as communication tools between decision makers and climate scientists

Size-Resolved Emission Inventory

Or, Why we Did What We Did

(David Streets, Ekbordin Winijkul, Fang Yan - Ar
presented by Tami)

Procedure


PM size distribution from literature
[by sector, fuel, and technology]
We already had this
Parameterize size distribution
[lognormal or mixture distribution]
(see next slide)
Emission factors by size
($EF_{Dp,}$ g PM/ kg fuel)
[Continuous distribution or discrete bins]
Emission factors
(EF, g PM/ kg fuel)
Size-resolved PM emission inventory
Fuel consumption

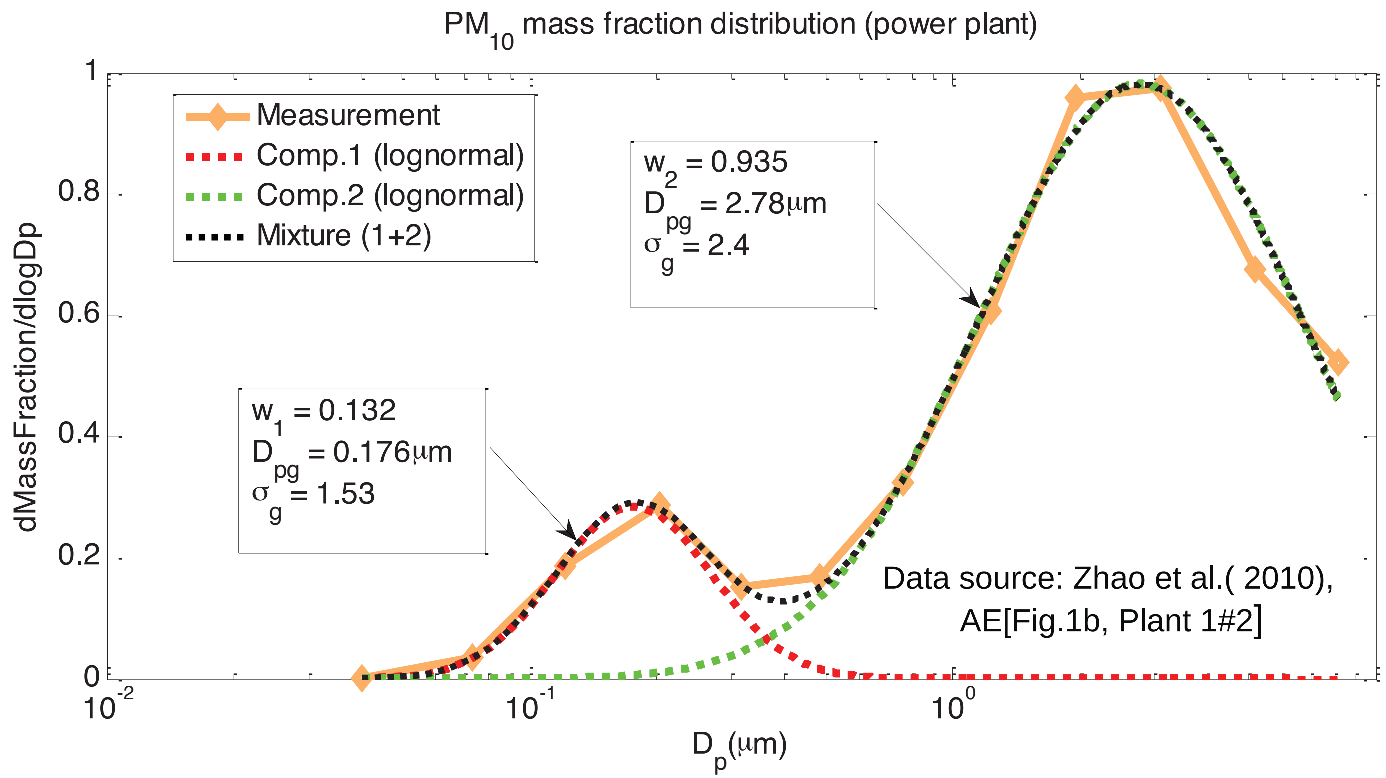
Parameterizing size distribution

Fit with lognormal distribution…

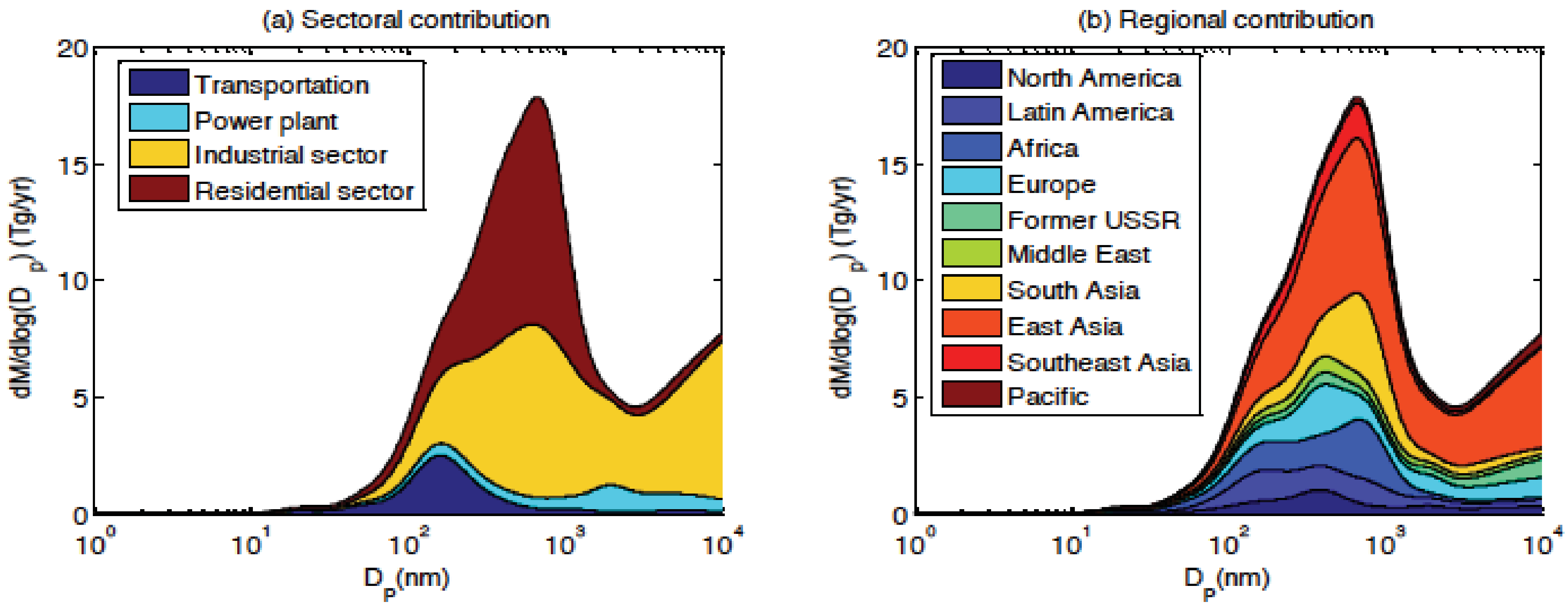
$$f\left(\ln D_p\right) = \frac{1}{\sqrt{2\pi}\ln\sigma_g}\exp\left[-\frac{\left(\ln D_p - \ln \bar{D}_{pg}\right)^2}{2\ln\sigma_g^2}\right]$$

…or bimodal distribution

$$f\left(x\right) = w_1 f_1\left(x\right) + w_2 f_2\left(x\right) \qquad 0 \le w \le 1$$

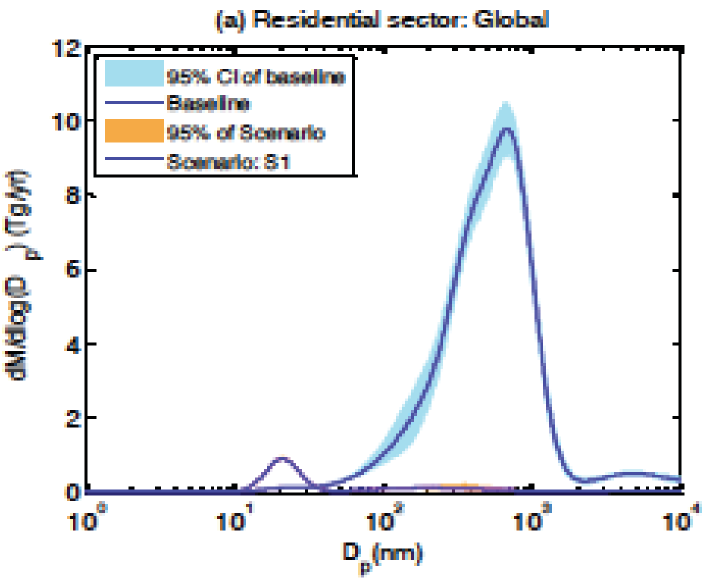


Global size-resolved emission inventory

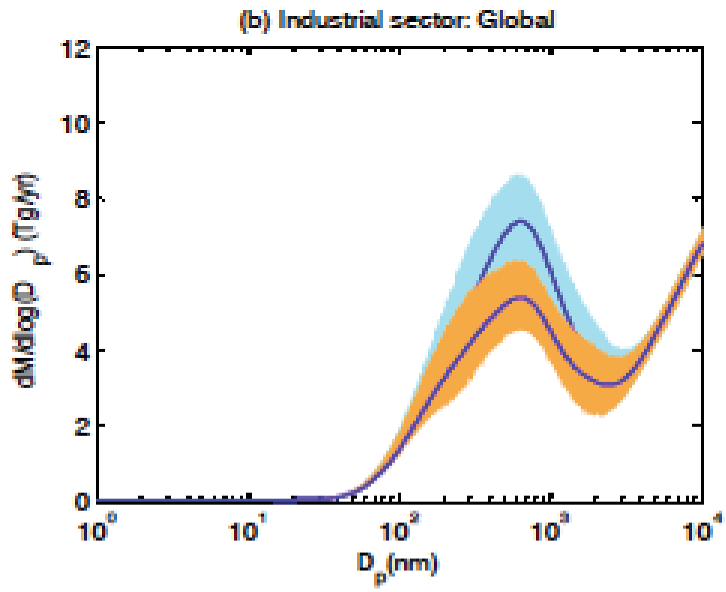


Size-resolved global emission inventory of primary particulate matter (PM) from energy-related combustion sources
E. Winijkul, F. Yan, Z. Lu, D. G. Streets, T. C. Bond, Y. Zhao
Submitted to Atmos Env, 28 August 2014

Work includes uncertainty and illustrative reduction scenarios



Residential:
Switching from
solid fuel to LPG



Industrial:
Baghouses on cement kilns

Winijkul et al., submitted, 2014

Regional Cloud Modeling

Regional Cloud Modeling

Or, Get the Clouds Right

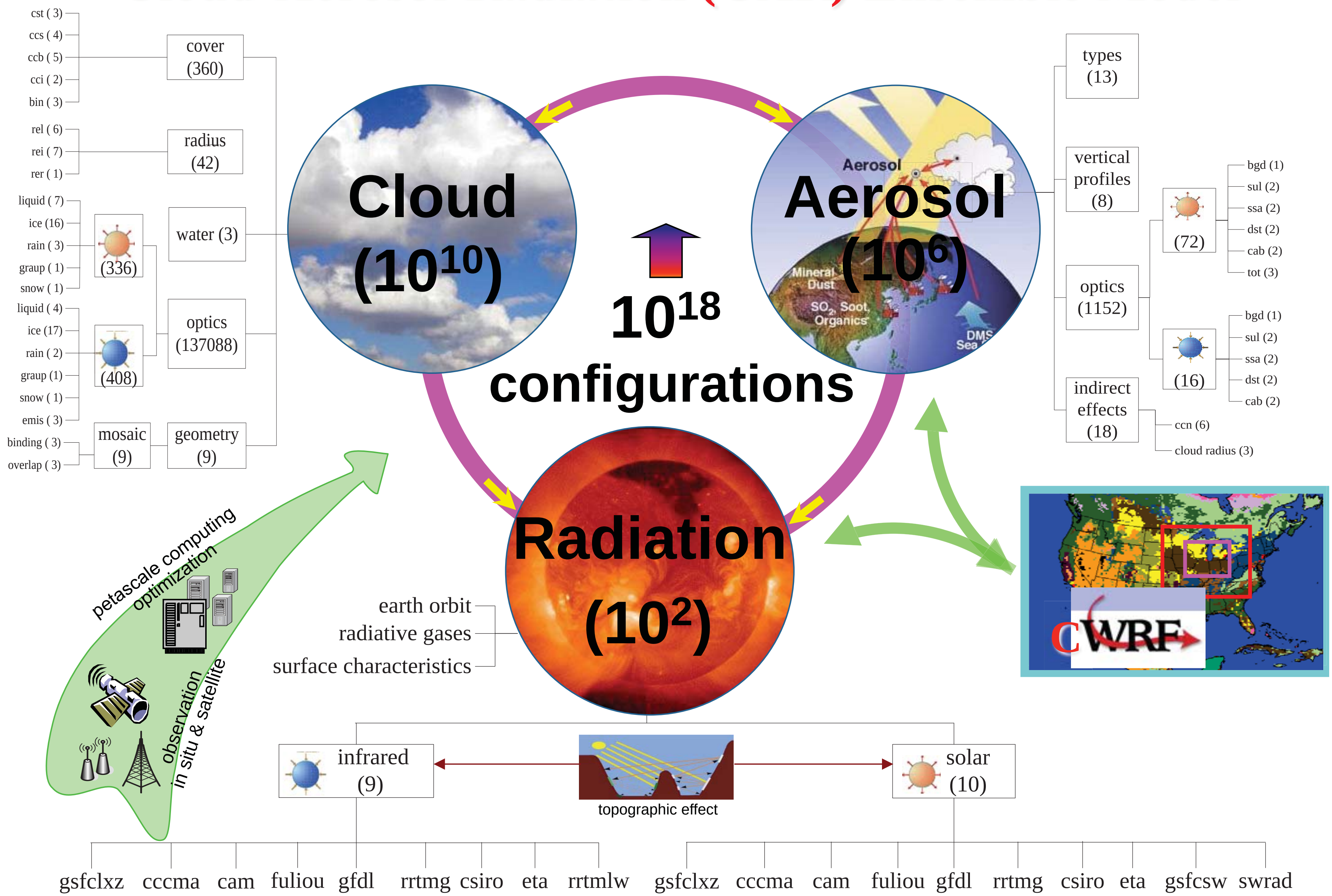
(Hao He, Xin-Zhong Liang – Univ of Maryland)

Modeling Approach

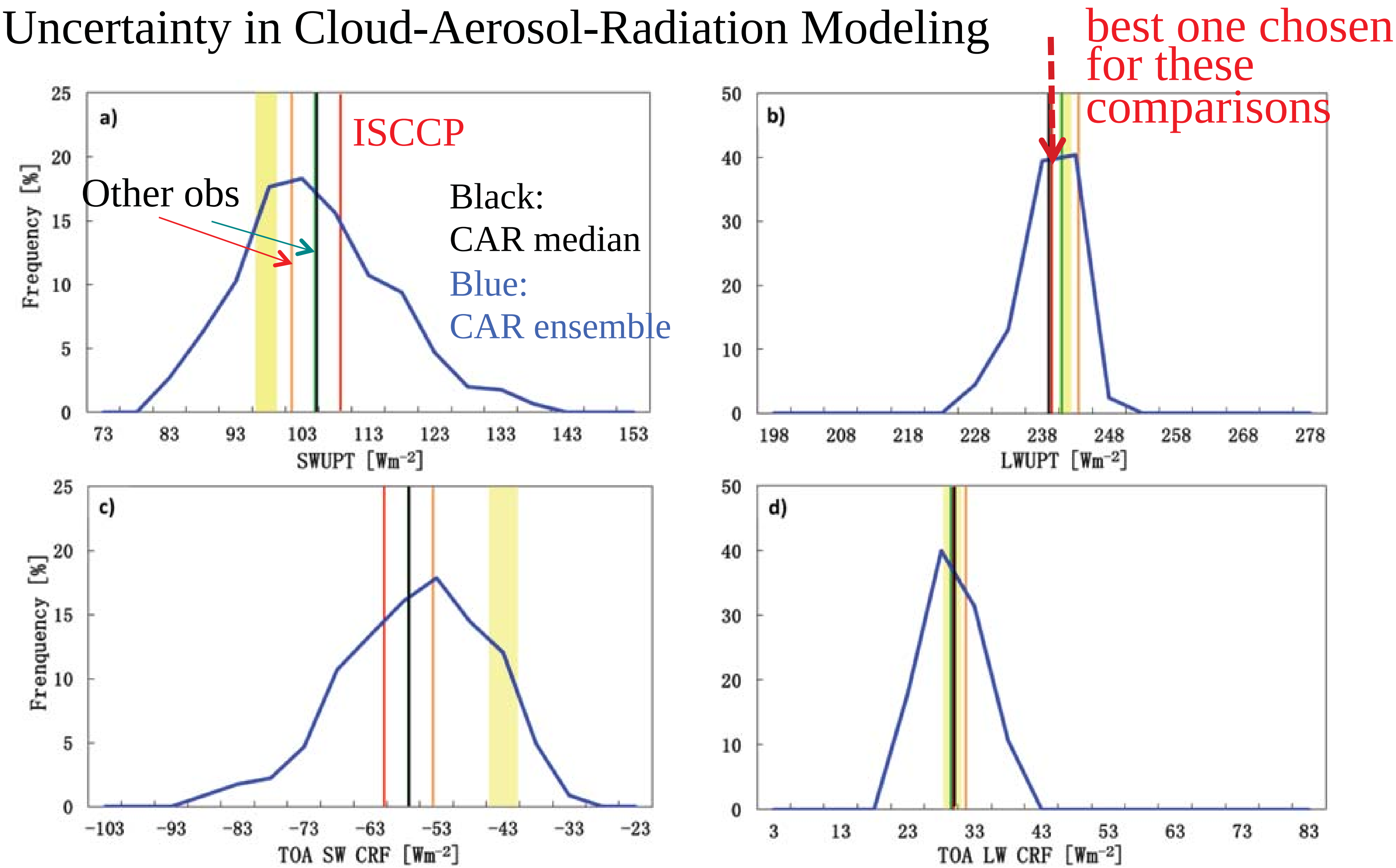
- We used the mesoscale Climate–Weather Research and Forecasting model (CWRF) model.
- Total aerosol field (not just BC) is produced by global models.
- CWRF has alternative parameterizations for cloud properties, aerosol properties, and radiation transfer.

Purpose: Investigate range of climate forcing in models that agree with observations

Cloud-Aerosol-Radiation (CAR) Ensemble Model



Uncertainty in Cloud-Aerosol-Radiation Modeling



Frequency distribution of TOA radiative flux and CRF averaged over [60ºS, 60ºN] in January 2004 from the CAR ensemble of 960 members

Liang, X. Z., and F. Zhang, 2013: The cloud-Aerosol-Radiation (CAR) ensemble modeling system. Atmos. Chem. Phys., ***13, 8335-8364***

Modeling Approach

- Meteorology: ECWMF ERA interim reanalysis
- Canadian Centre for Climate Modeling and Analysis (CCCMA) radiation scheme

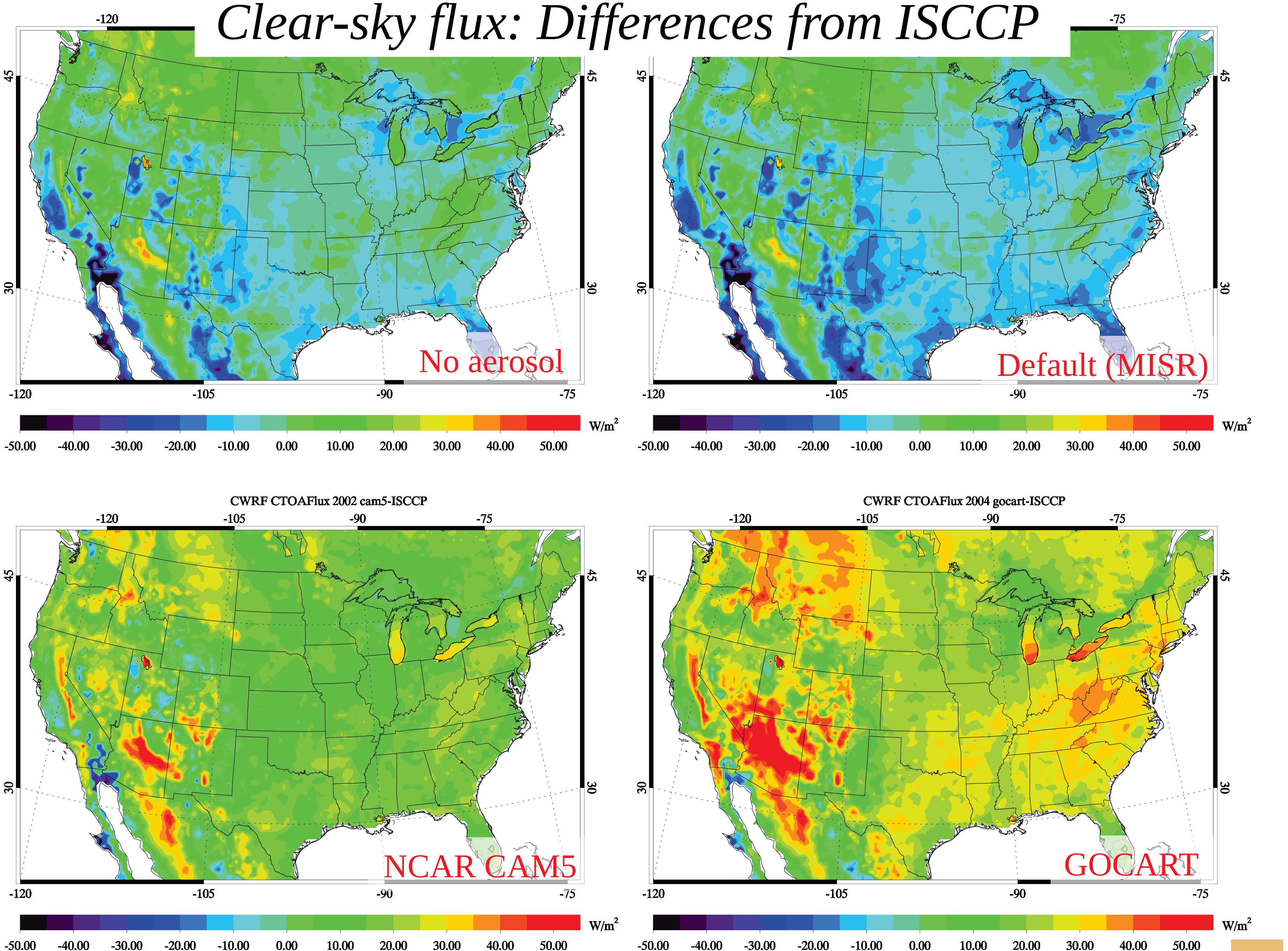
- Model run from 2001 to 2006, with the first year (2001) as spin-up. Average from 2002 to 2006 is presented.

One base case; Five aerosol fields

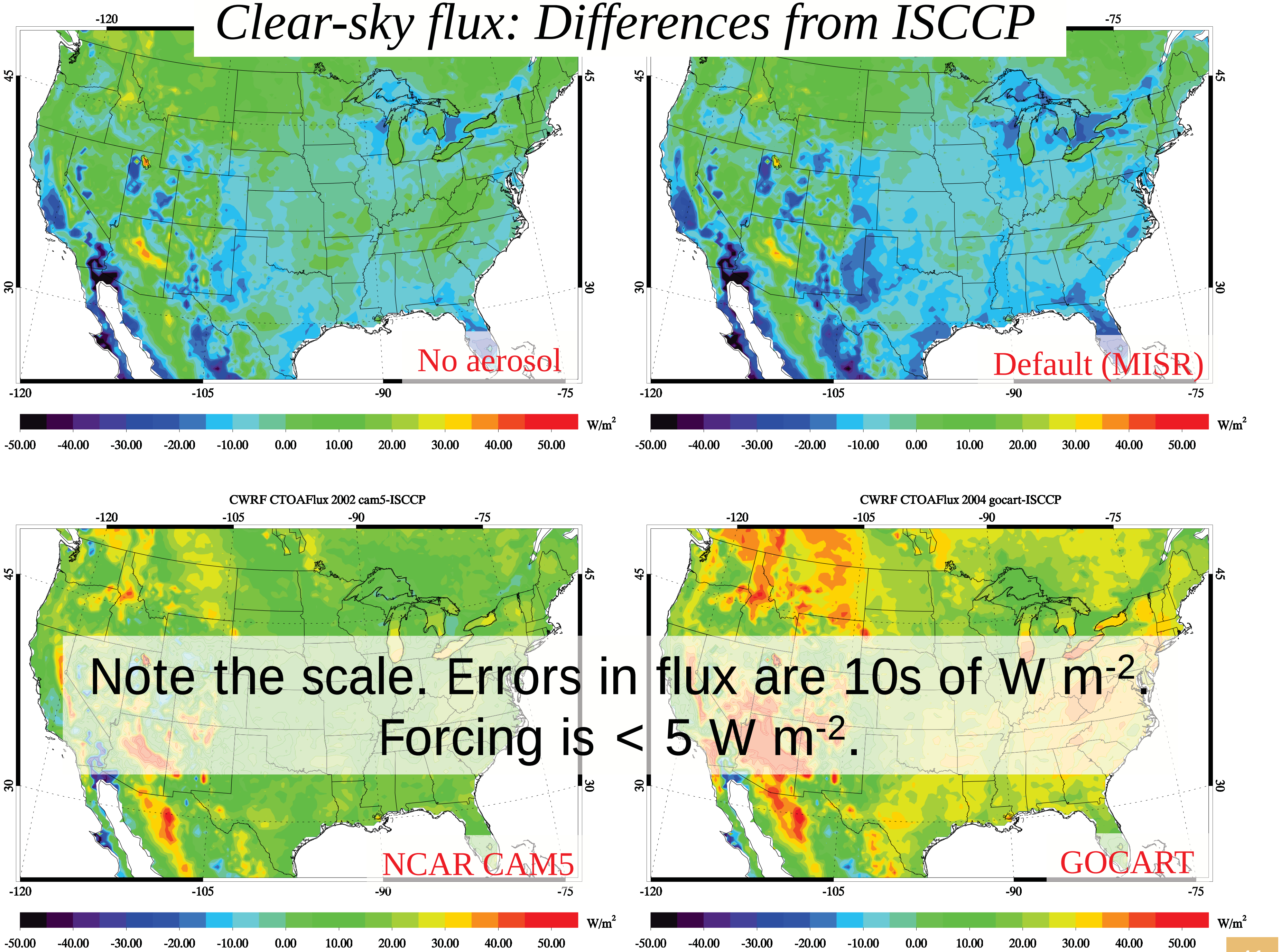
Case No.	Case Name	Temporal Resolution	Aerosol input
1	Noaerosol	N/A	Aerosol radiation Off
2	Default	Monthly	MISR Climatology
3	NCAR	Monthly	NCAR CAM2 model
4	GOCART$	Monthly	GOCART model
5#	CAM5	Monthly	UIUC CAM5 model
6*	CAM5'	Monthly	UIUC CAM5 model

*$ Chin et al 2014; #Assuming all BC and OC are hydrophilic; *Assuming only 85% of BC and OC are hydrophilic*

Clear-sky flux: Differences from ISCCP

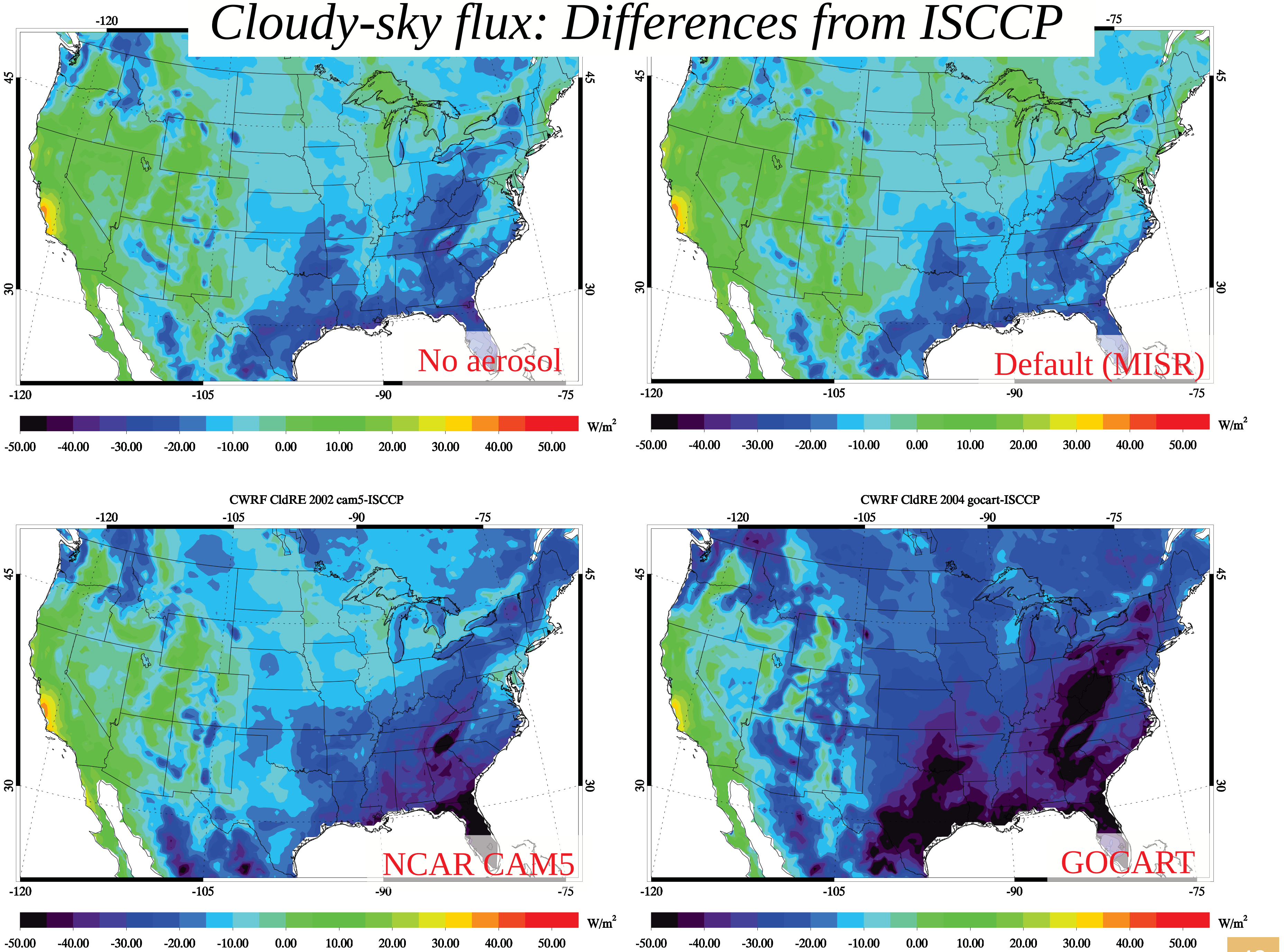


Clear-sky flux: Differences from ISCCP



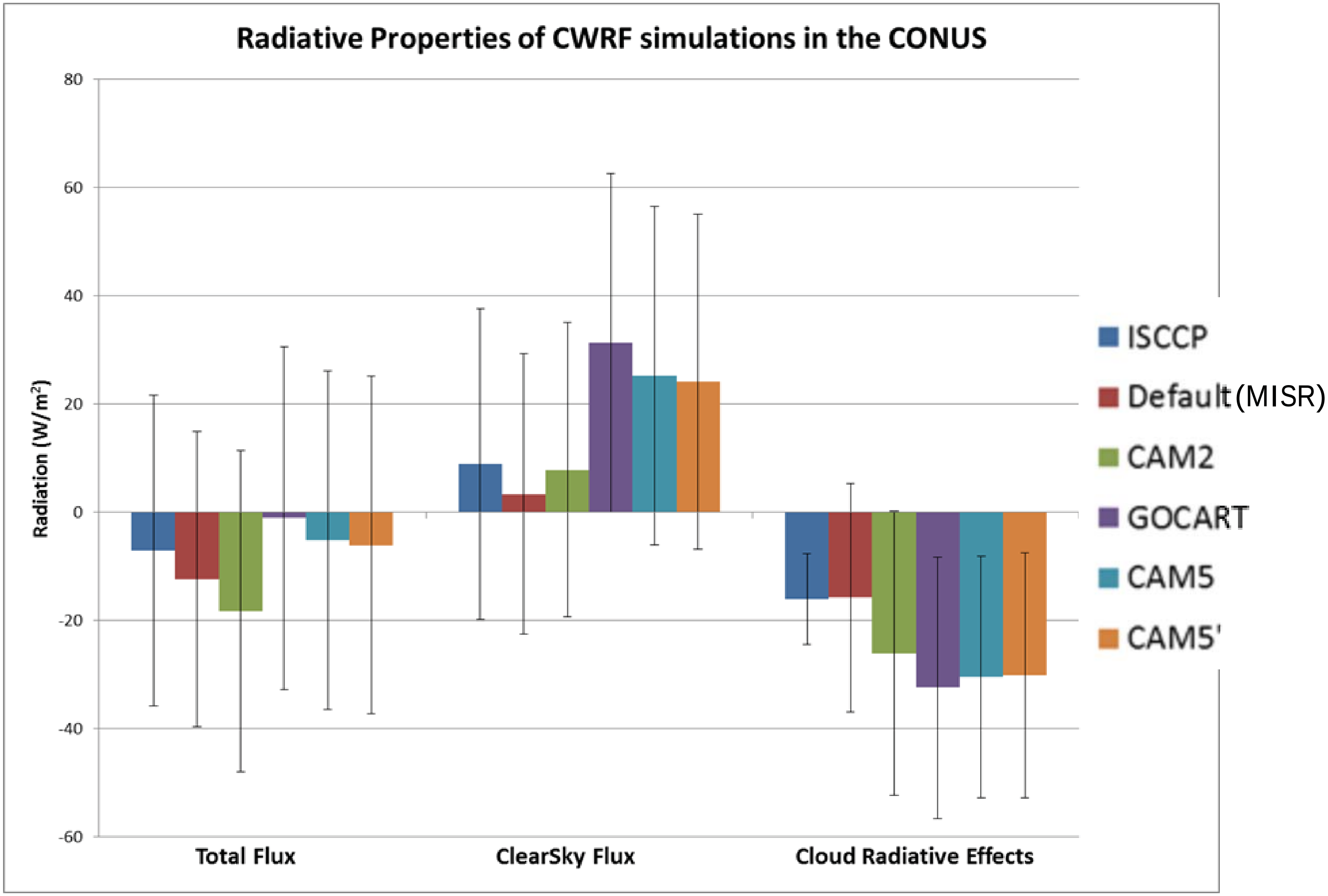
Note the scale. Errors in flux are 10s of W m^{-2}.
Forcing is < 5 W m^{-2}.

Cloudy-sky flux: Differences from ISCCP

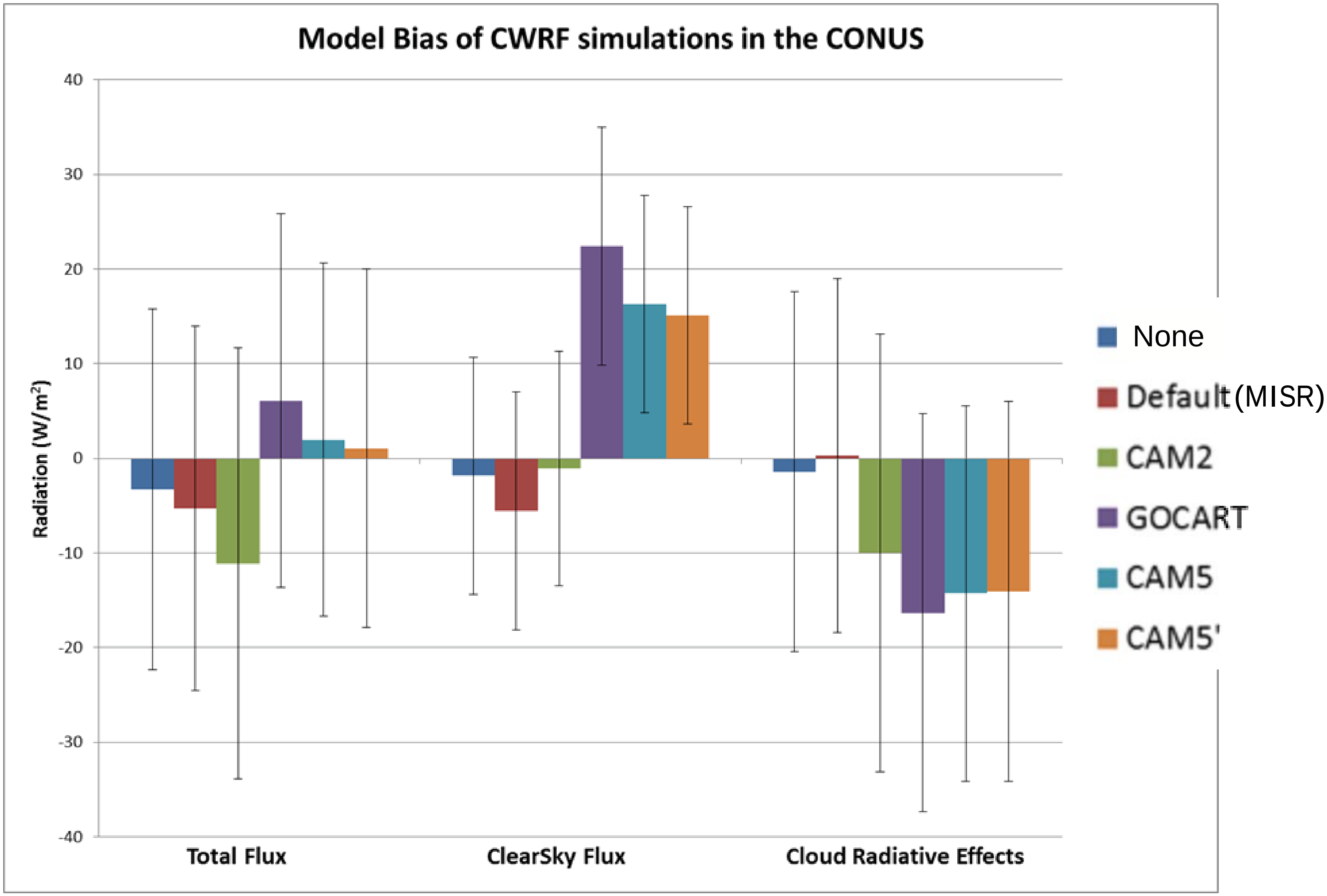


Comparison between modeled and observed fluxes (*average over Continental US)*

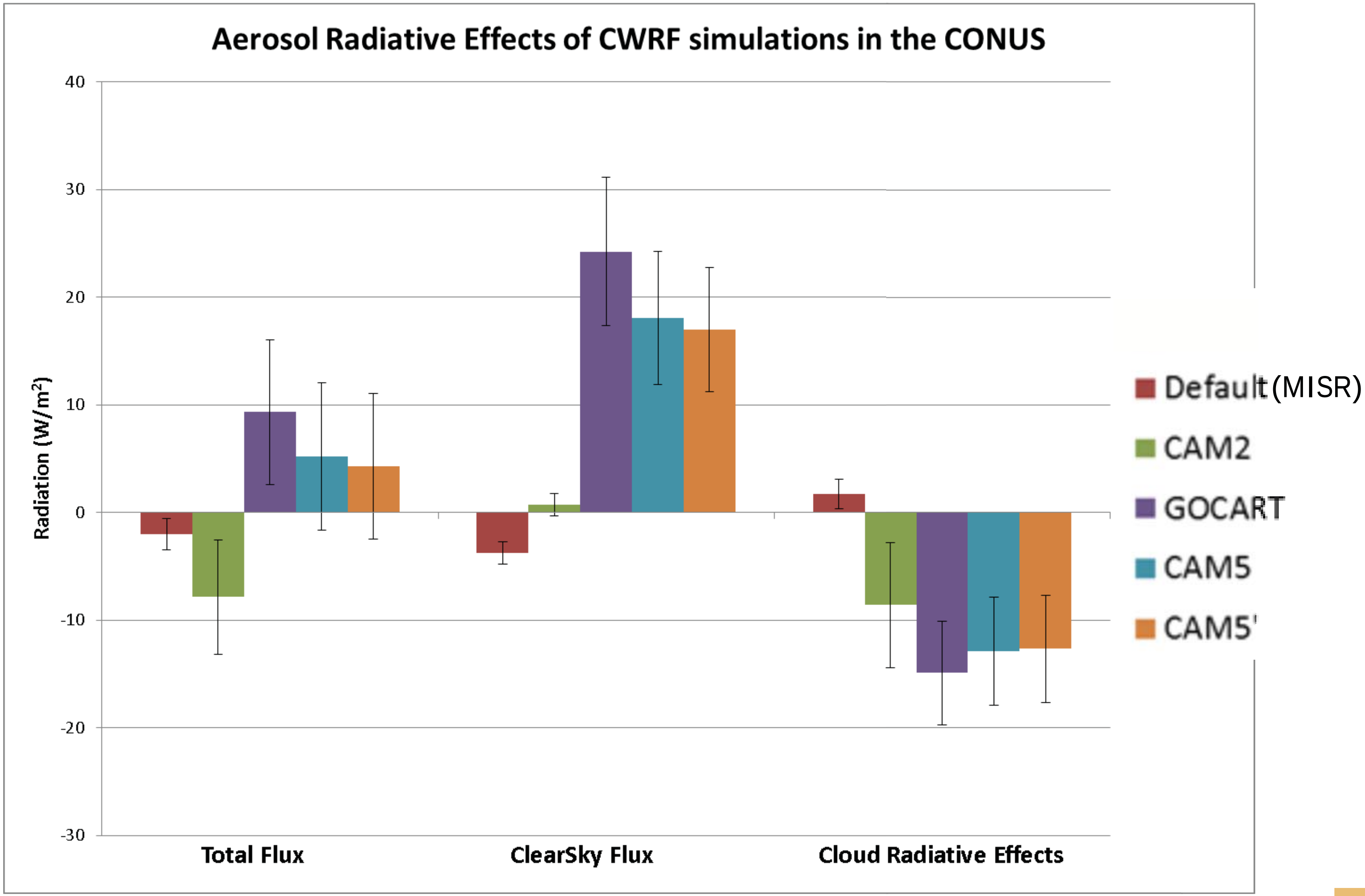
Error bars are std dev of all grid boxes

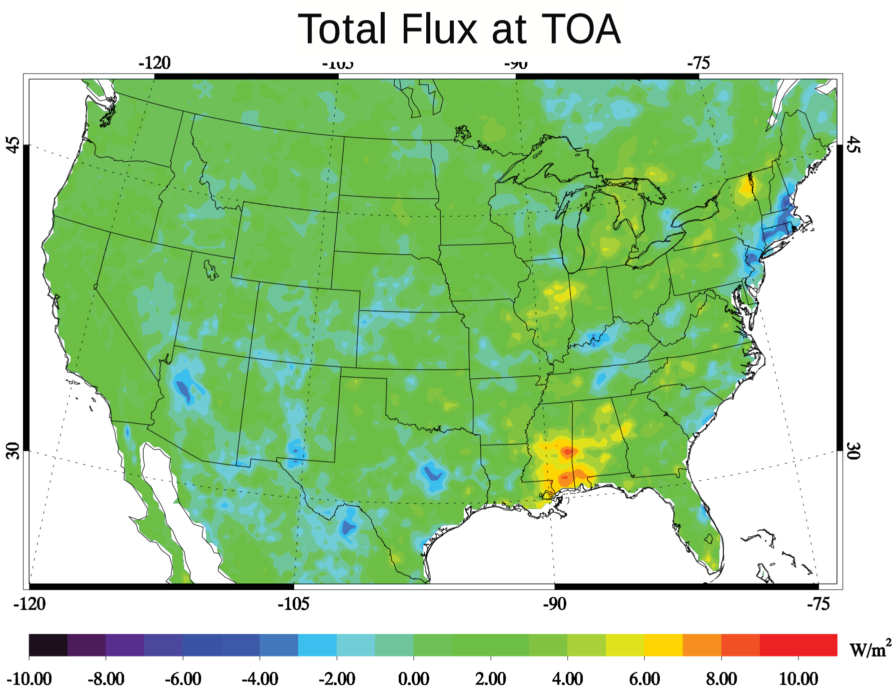


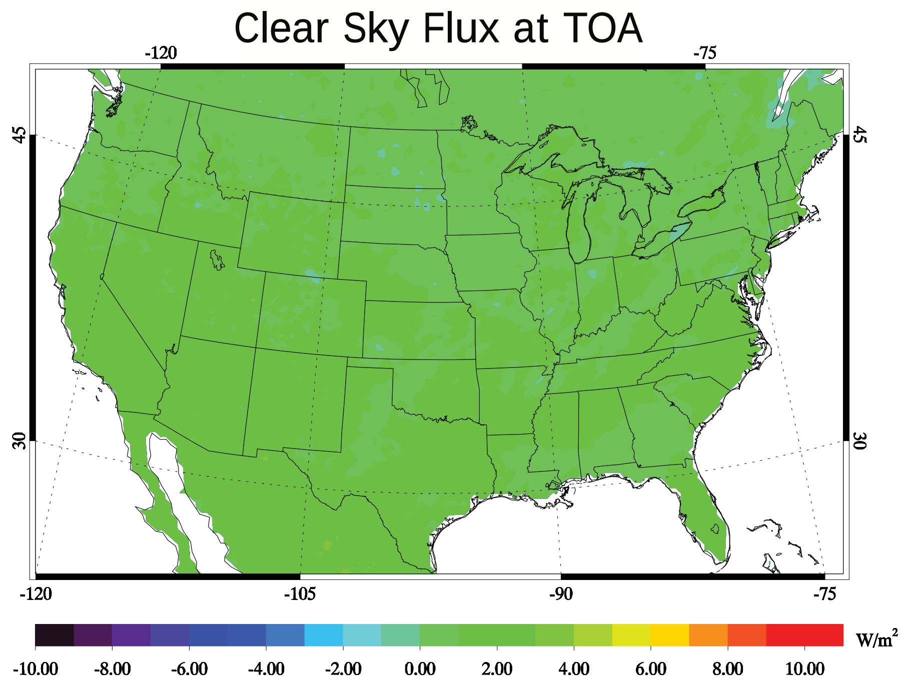
Model bias: Difference between CWRF results and ISCCP

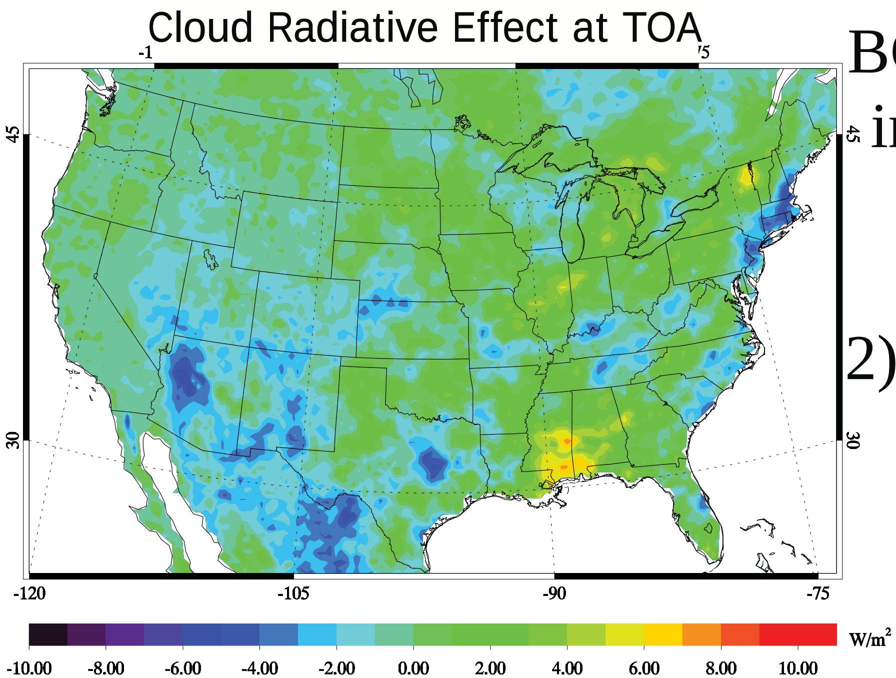


Aerosol radiative effects:
Difference between modeled results with & without aerosols









BC and OC partition have substantial impacts on the radiation simulations

1) Impacts on clear sky flux are uniform

2) Cloud radiative effects are large (± 5 W/m^2) and regionally dependent, for instance opposite effects are suggested in the southeast US and in the northwest US.

Emission-to-forcing measures

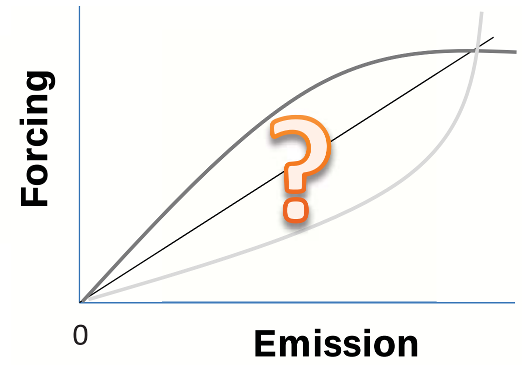
Emission-to-forcing measures

Or, Model Interpretation for Policy Relevance

(Yanju Chen– Univ of Illinois)

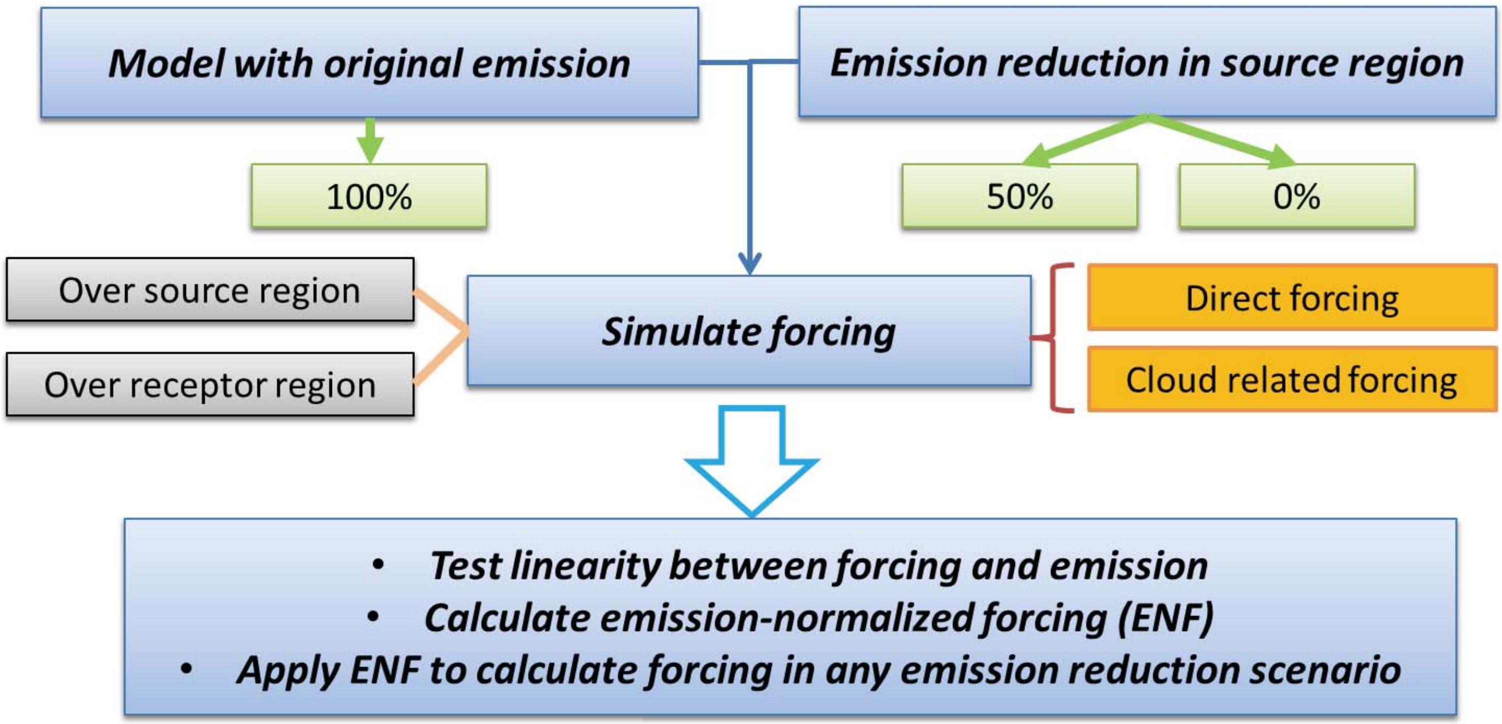
Step 1: Test linearity and regionality

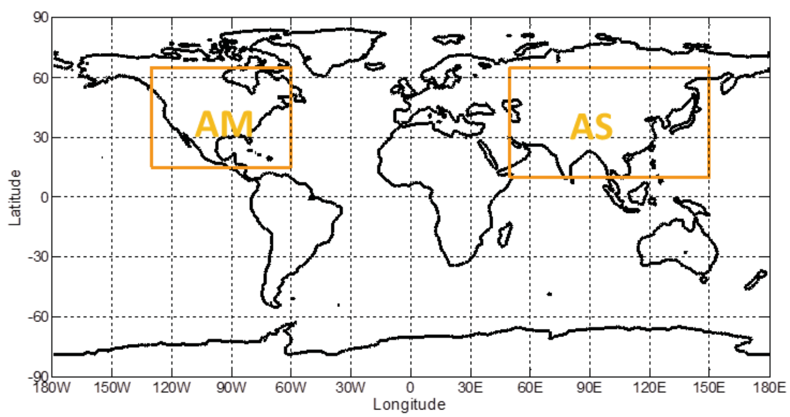
- Basis to obtain forcing-per-emission relationship; assumed by emission metrics.



- Direct forcing – *probably* linear
- Cloud forcing –*may be* nonlinear with respect to aerosol concentration (Quaas et al., 2009)
- May vary by region

Experimental Design



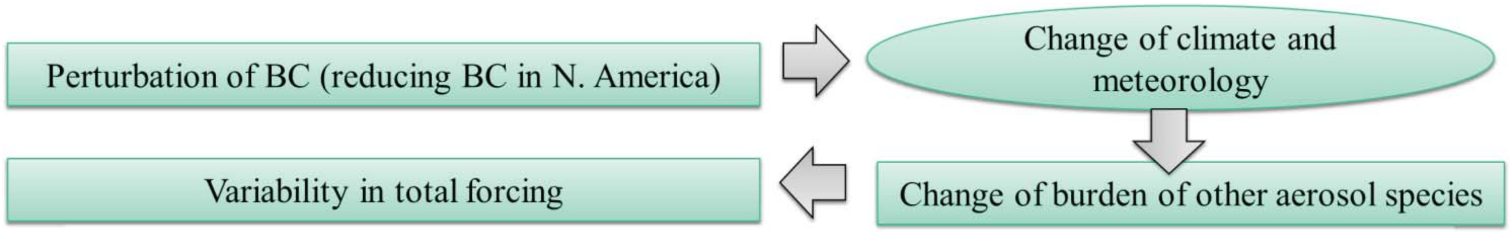


- Reduce BC from N. America (AM BC)
- Reduce BC from Asia (AS BC)
- Reduce OC from N. America (AM OC)
- Reduce OC from Asia (AS OC)

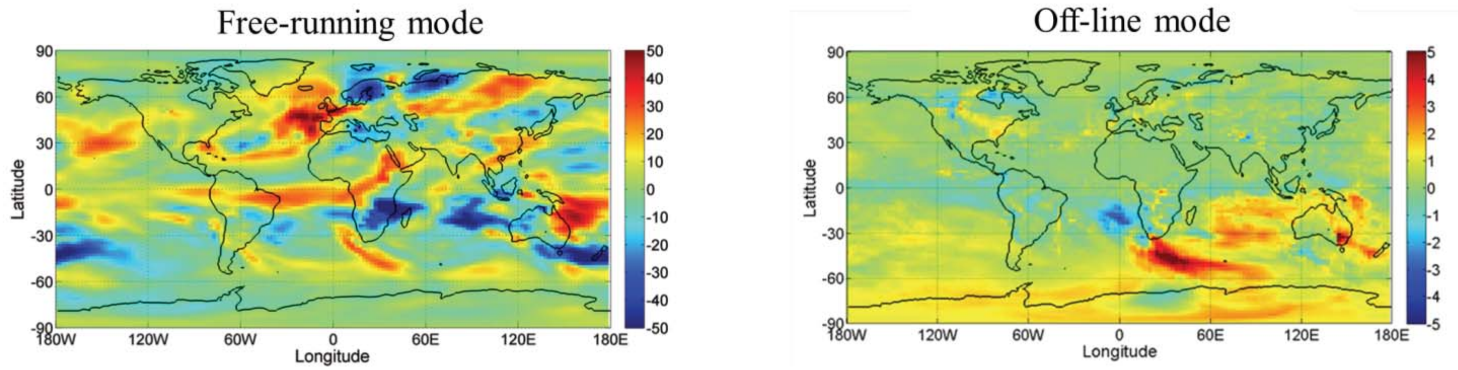
Model Description and Configuration

- Modified Community Atmosphere Model (CAM5.1)
  - ***Three-modal aerosol module (MAM3) (Liu et al., 2012)***
  - ***Improved BC spatial and temporal distribution*** with modified convective transport and wet removal
  - Tagged BC/OC emission for direct calculation of burden and forcing
- Anthropogenic emissions: from IPCC emission datasets for year 2000 (*Lamarque et al.*, *2010*).
- Model is configured to run in off-line mode (*Ma et al*, *2013*)
  - Model reads in prescribed meteorological fields
  - Model driven by ERA-interim data
  - Semi-direct effect cannot be simulated
- Each simulation is run for 5 years with 2 months for model spin-up.

Need for off-line meteorology



Percentage change of dust burden when reducing BC from N. America from 100% to 50%



- Direct forcing change is caused by ***non-BC aerosols*** (dust).
- Since cloud-related forcing is inferred from total flux change, it is obscured by dust changes.
- Dust needs to remain in the atmosphere, because it could also affect clouds.

Linearity diagnostic for a single species

50% present-day emission

100% present-day emission

$$R = \frac{F_{100} - F_{50}}{F_{100} - F_0}$$

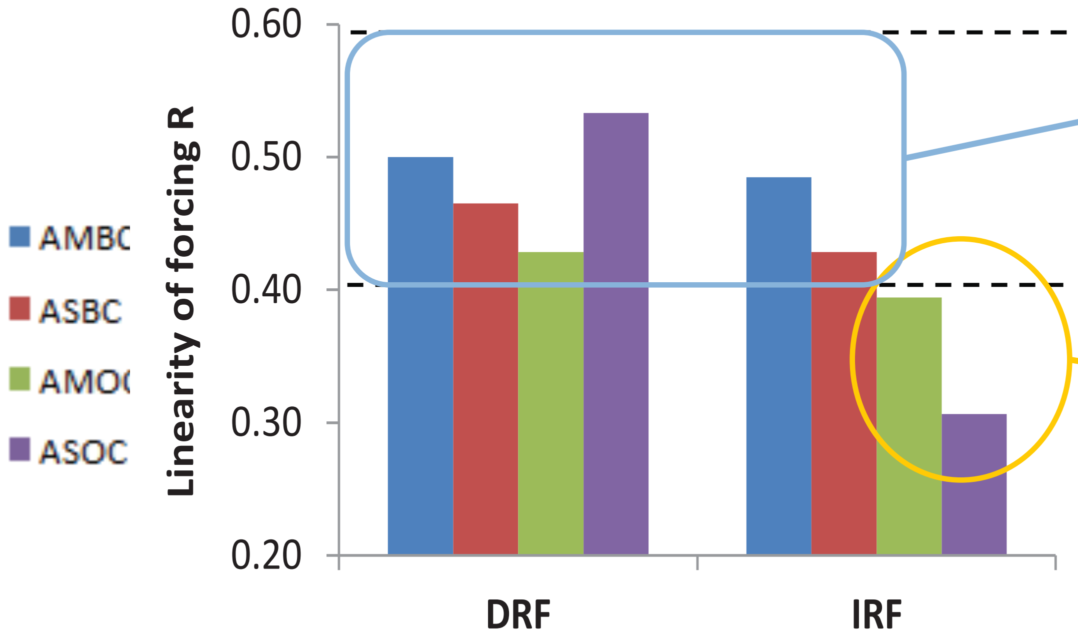
100% present-day emission

0 emission

R≅ 0.5: Forcing is linear in emission.

R< 0.5: Small emission change from present-day produces *less forcing change* than one would expect

Linearity of Global Mean Forcing



Linear for:

Direct forcing by BC

Indirect forcing by BC

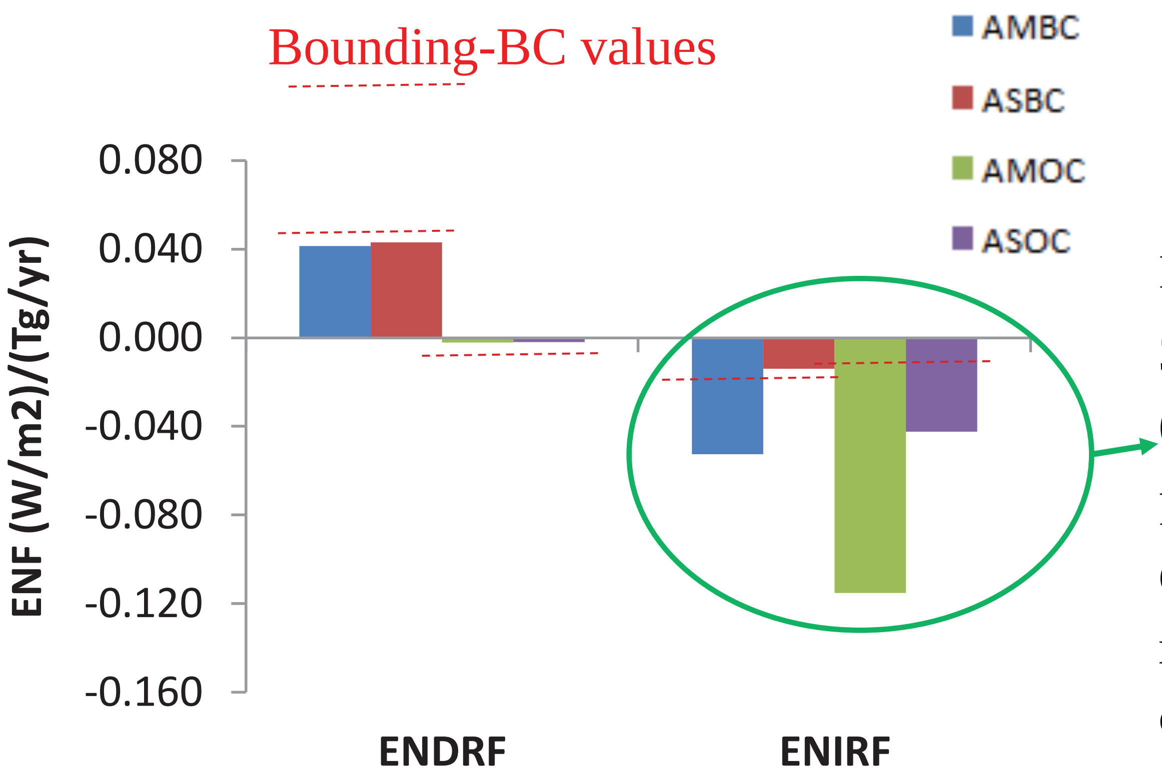
Direct forcing by OC

Sublinear for:

Indirect forcing by OC

2 regions: AM=North America; AS=Asia

Emission-normalized forcing



Indirect forcing, ENIRF:

3-4 times higher in N. America (not saturated)

Reducing same amount of BC/ OC in these two regions will result in greatly different cloud change.

Direct radiative forcing,

ENDRF:

similar for N. America and Asia

54

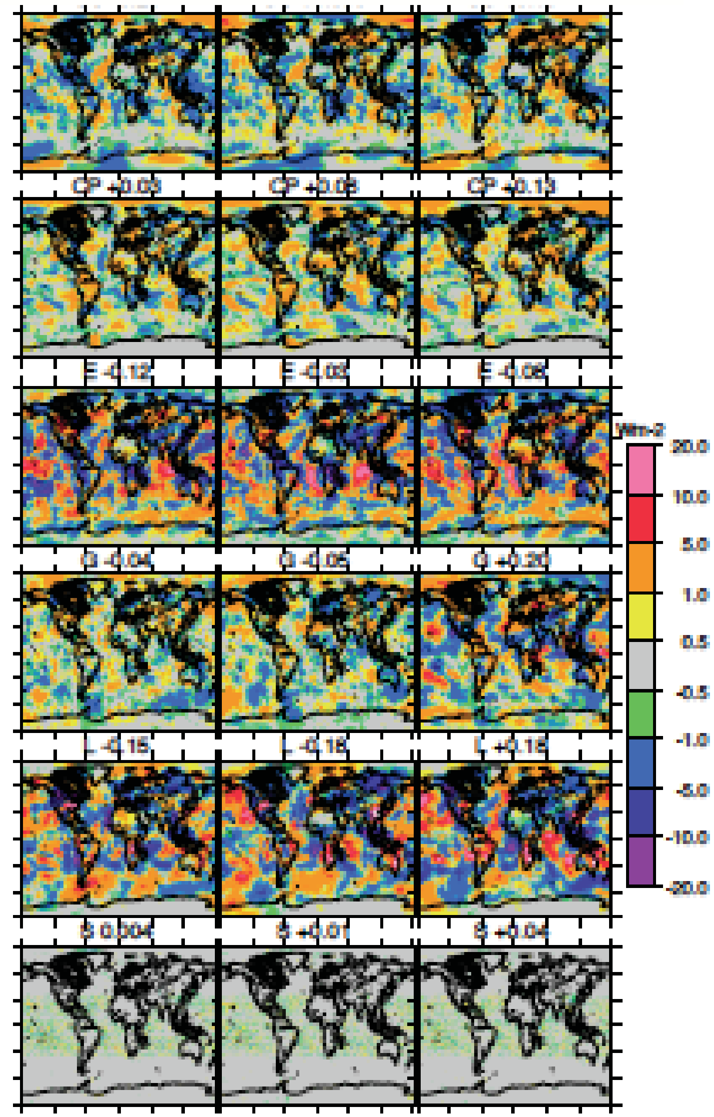
Is cloud forcing visible?

Multi-model study of effects on liquid clouds

Each row is from a different model.

No forcing pattern visible.

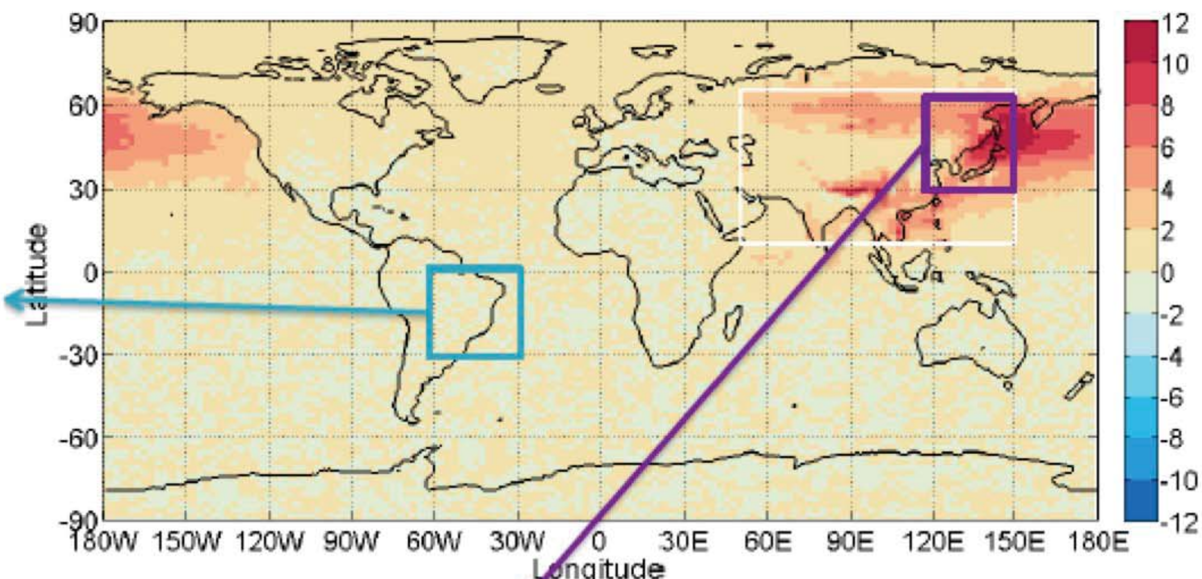
Fossil fuel Diesel Biofuel

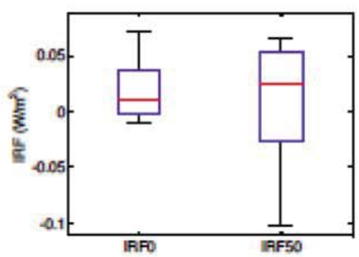


Koch et al., ACP 11, 1051, 2011

Regional Location of Indirect Forcing

Example: OC from Asia

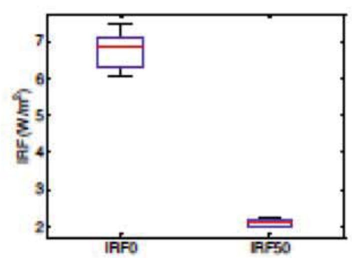




p value = 0.69

IRF0 and IRF50 are NOT significantly different considering interannual variability.

Region with noise



p value = 2.48e-5

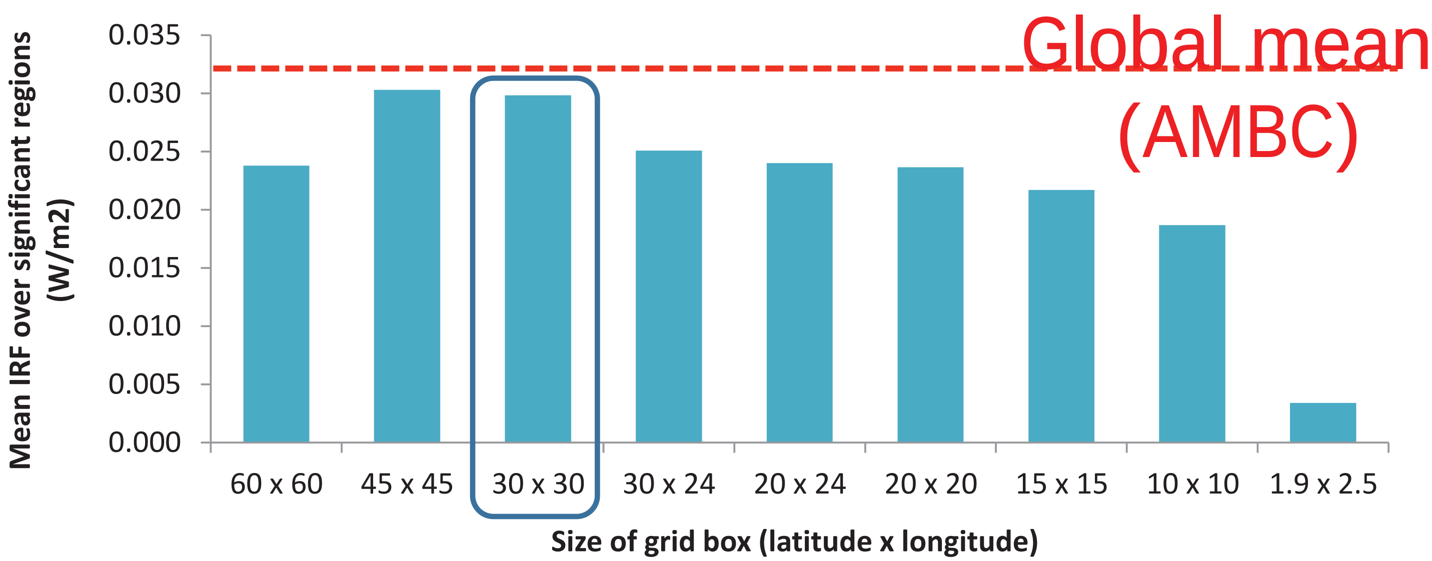
IRF0 and IRF50 ARE significantly different considering interannual variability

Significant region!

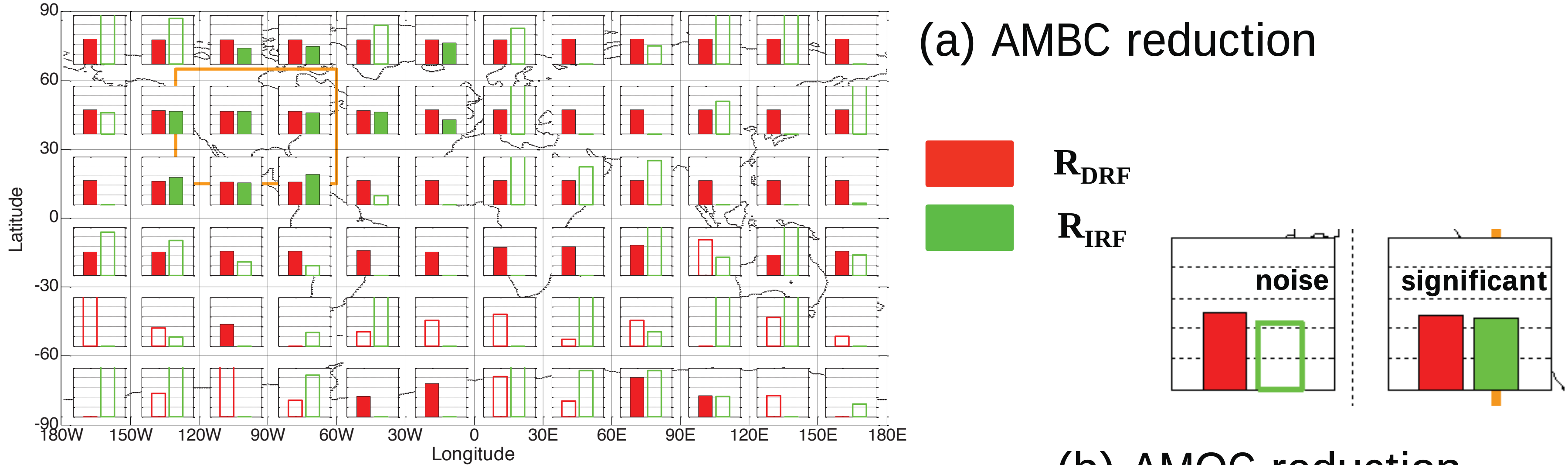
**** Significant region was statistically determined using paired t-test between IRF0, IRF50 and 0 at significance level a = 0.1***

Optimum grid box size for testing significance

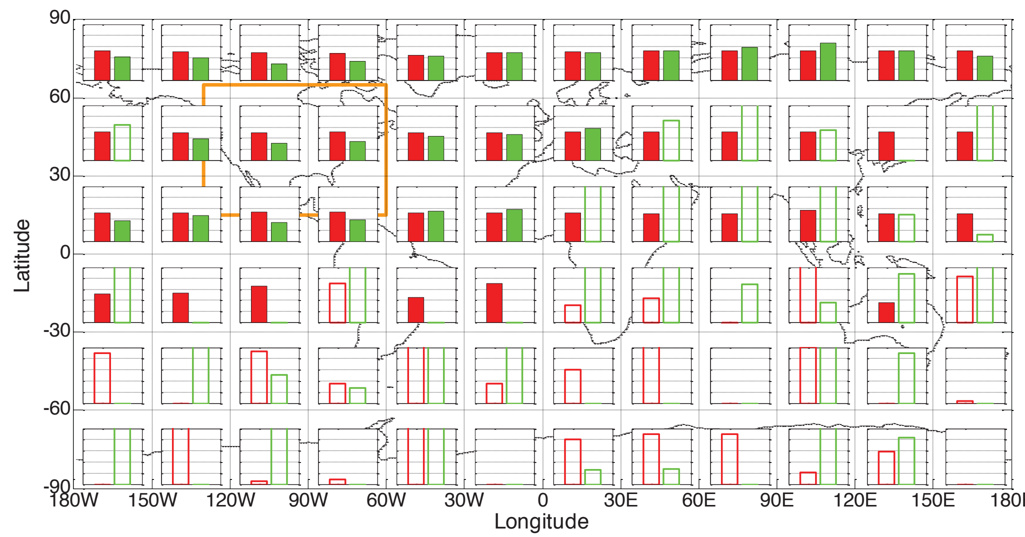
- Box too small: Each box noisy; few boxes significant
- Box too large: Includes regions with little impact; too few boxes are significant
- 30° x 30° is optimum
- Significant grid boxes equal global mean forcing; the rest are noise



Radiative Forcing in Significant Regions

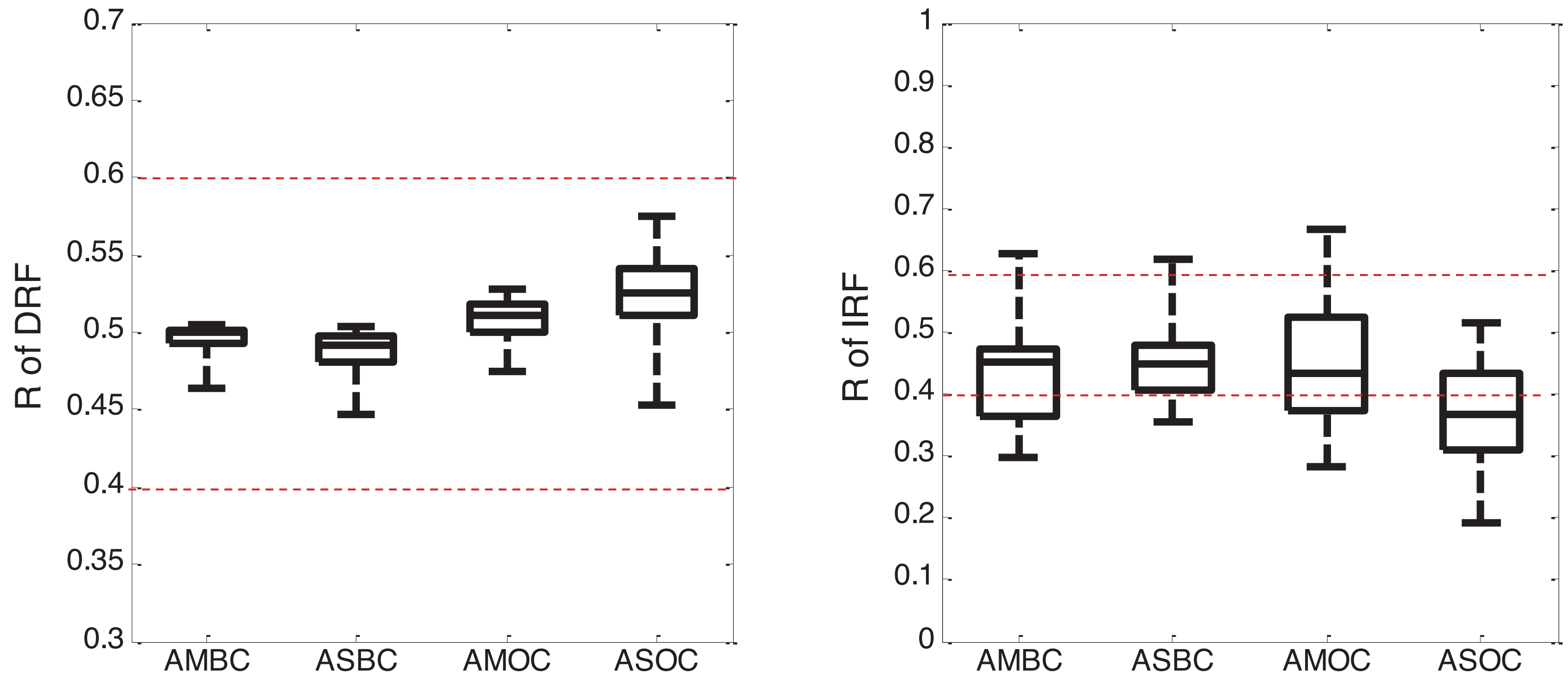


(b) AMOC reduction



- Only 20-30% of the grid boxes are significant
- Near and downwind of source region

Linearity in Significant Regions

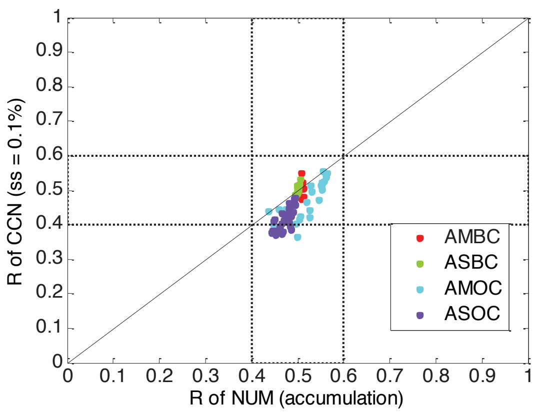


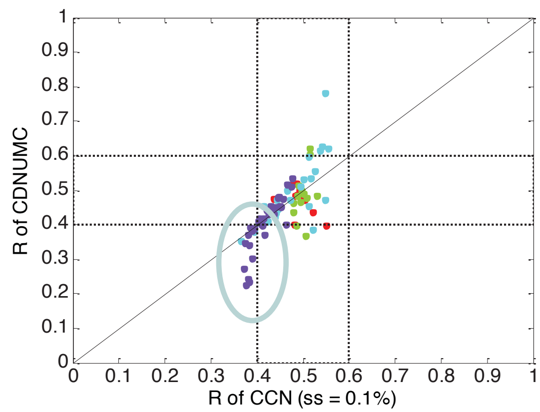
- Direct radiative forcing (DRF) is linear in all regions
- Indirect radiative forcing (IRF) is nonlinear in some significant regions, especially for OC

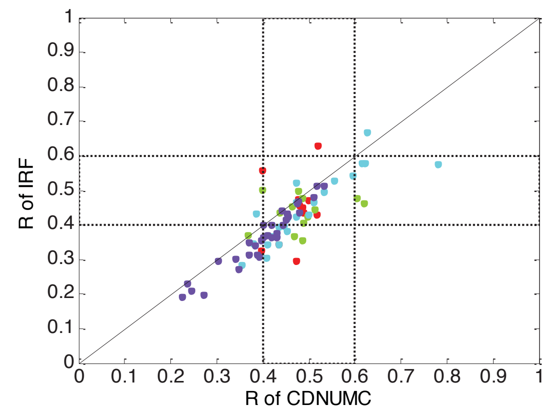
Cause of Nonlinearity

Emission → CN → CCN → droplet (CDNUMC) → IRF

linear **nonlinear** **linear**







- Nonlinearity occurs when cloud droplets are formed from CCN.
- Formation of droplets is limited, and does not increase as the number of CCN increases.
- Of course, this depends on model parameterization…

Summary – Indirect forcing

- Apparent effect on clouds– ENIRF:

N Am OC > N Am BC > Asian OC > Asian BC

- In high-aerosol regions, reducing present-day aerosol has a *less-than-linear* effect
- Global average forcing can be attributed to a subset (<40%) of significant regions

However, comparison with observations calls modeling of aerosol-cloud effect in North America into question

Next– Compare global & regional aerosol effect in North America

Policy-relevant metrics

Or, Get the Story Right

(Praveen Amar, Danielle Meitiv– Clean Air Task Force presented by Tami)

Original goal: Communicate with policy makers to see what metrics they want

Professional Roles	Number of Interviewees	Percentage of Total
Academic – Climate Policy/Science	3	9
Air Quality Management – State Level	7	20
Air Quality Management – Federal Level	11	31
Federal – Climate Policy/Science	5	14
NGO – Air Quality Advocacy	3	9
NGO – Climate Advocacy	6	17

Table 1. Professional roles and expertise of the interviewees and their percentage of the total pool of interviewees.

"Communicating the science and policy implications of black carbon" – CATF report

Main messages had nothing to do with metrics

- Scientists need understandable ways to communicate black carbon’s effects to non-specialists
  - Even terms like “radiative forcing” and “feedback” are not as straightforward as you think.
- People want to hear about certainty, not uncertainty.

Main messages had nothing to do with metrics

- Equating BC and CO_2: Some are wary; in other situations (e.g. California) it's required.
  - People do not want to think about time horizons. That's our job.
  - People do not want to think about metrics. Ditto.
- There is not yet a good way to communicate immediacy of forcing changes.
  - Watch this space

Summary of outcomes – easy ones

1: Size-resolved inventory complete.

4: Metrics are up to us. Make it easy.

Summary of outcomes – hard ones

2: The constraint problem: Looking to confirm small changes (forcing) in a large signal (clouds).

3a: Forcing is nearly linear in emission, if regions are treated individually.

- Average over statistically significant (30x30) boxes.
- High-aerosol regions have lower indirect forcing per emission. More promising to reduce there.

3b: Cloud models don't match observations.

- Reason to doubt emission-to-forcing is not the model's nonlinear nature, but its inability to match reality.

Done. Questions?

Supplemental slides

Radiative flux in CWRF

We calculated, total radiative flux @ TOA (TOAFlux), clear sky flux @ TOA (CTOAFlux) and cloud radiative effect (CldRE) as:

$$TOAFlux = SW_{down,TOA} + LW_{down,TOA} - SW_{up,TOA} - LW_{up,TOA}$$

$$CTOAFlux = SW_{down,TOA,clear} + LW_{down,TOA,clear} - SW_{up,TOA,clear} - LW_{up,TOA,clear}$$

$$CldRF = TOAFlux - CTOAFlux$$

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