

AEROSOL FORCING, CLIMATE SENSITIVITY, AND ALLOWABLE FUTURE CO₂ EMISSIONS

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Board on

Atmospheric Sciences & Climate

DIVISION ON EARTH & LIFE STUDIES

THE NATIONAL ACADEMIES

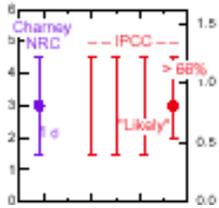
Advisers to the Nation on Science, Engineering, and Medicine

Washington DC
May 4-5, 2010

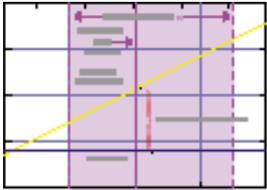
www.ecd.bnl.gov/steve

OVERVIEW

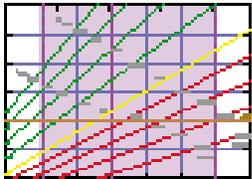
Climate sensitivity



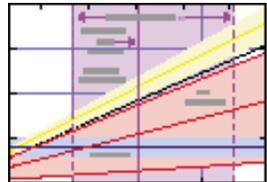
GHG forcing and the warming discrepancy



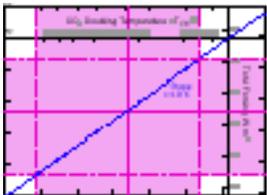
Allowable future CO₂ emissions



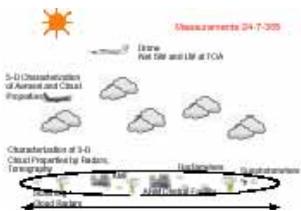
Why hasn't Earth warmed as much as expected?



Approaches to determining climate sensitivity; the need for forcing

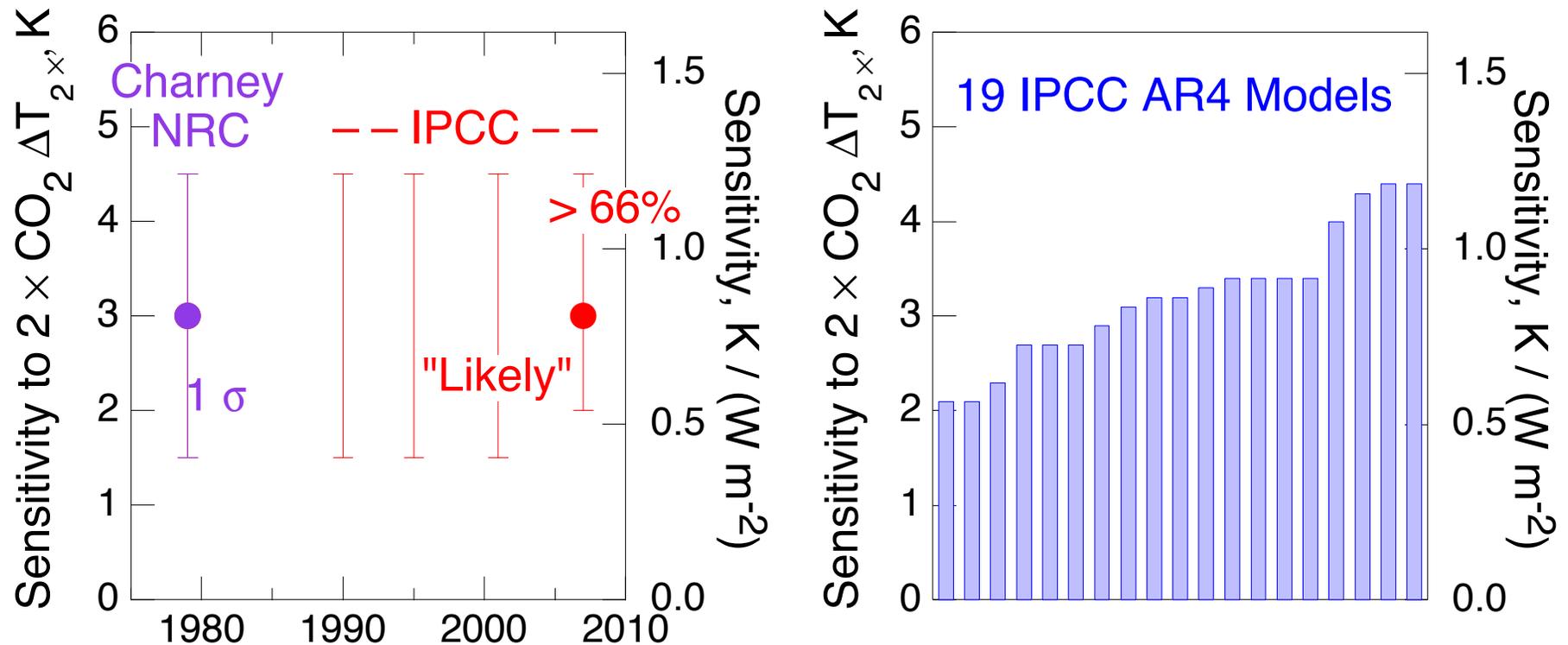


The path forward: Determining aerosol forcings



ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models



Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2 \times} = 3 \text{ K}$, but with substantial uncertainty.

Range of sensitivities of current models roughly coincides with IPCC "likely" range.



AMERICAN
METEOROLOGICAL
SOCIETY

Journal of Climate

EARLY ONLINE RELEASE
From Forcing by Long-Lived Greenhouse Gases
Why Hasn't Earth Warmed as Much as Expected?

Stephen E. Schwartz
Brookhaven National Laboratory, Upton, New York

Robert J. Charlson
University of Washington, Seattle, Washington

Ralph A. Kahn
NASA Goddard Space Flight Center, Greenbelt, Maryland

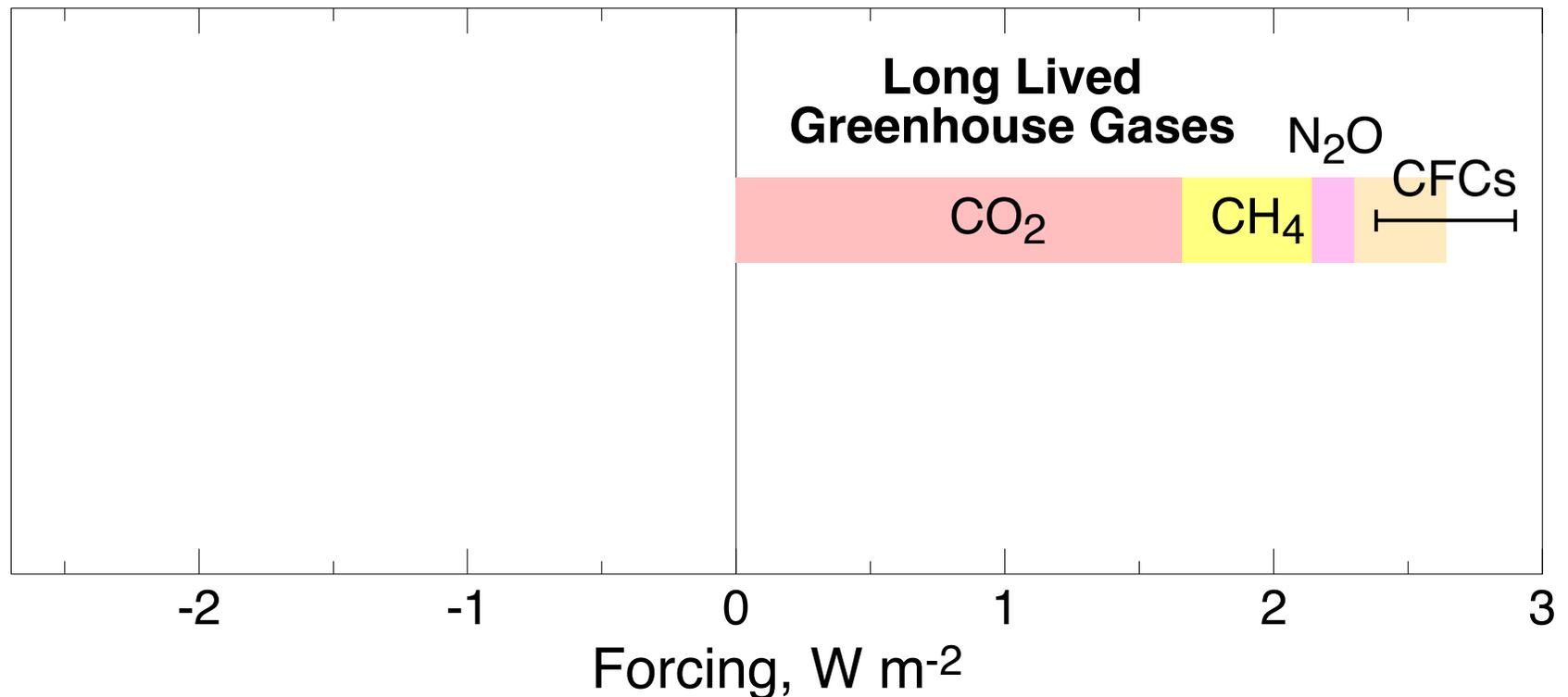
John A. Ogren
NOAA Earth System Research Laboratory, Boulder, Colorado

Henning Rodhe
Department of Meteorology, Stockholm University, Stockholm, Sweden

The DOI for this manuscript is doi:10.1175/2009JCLI3461.1

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

HOW MUCH WARMING IS EXPECTED?

For increases in CO₂, CH₄, N₂O, and CFCs over the industrial period

$$F = 2.6 \text{ W m}^{-2}$$

IPCC, 2007
Best
Estimate

Expected temperature increase:

$$\Delta T_{\text{exp}} = \frac{F}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.6}{3.7} \times 3 \text{ K} = 2.1 \text{ K}$$

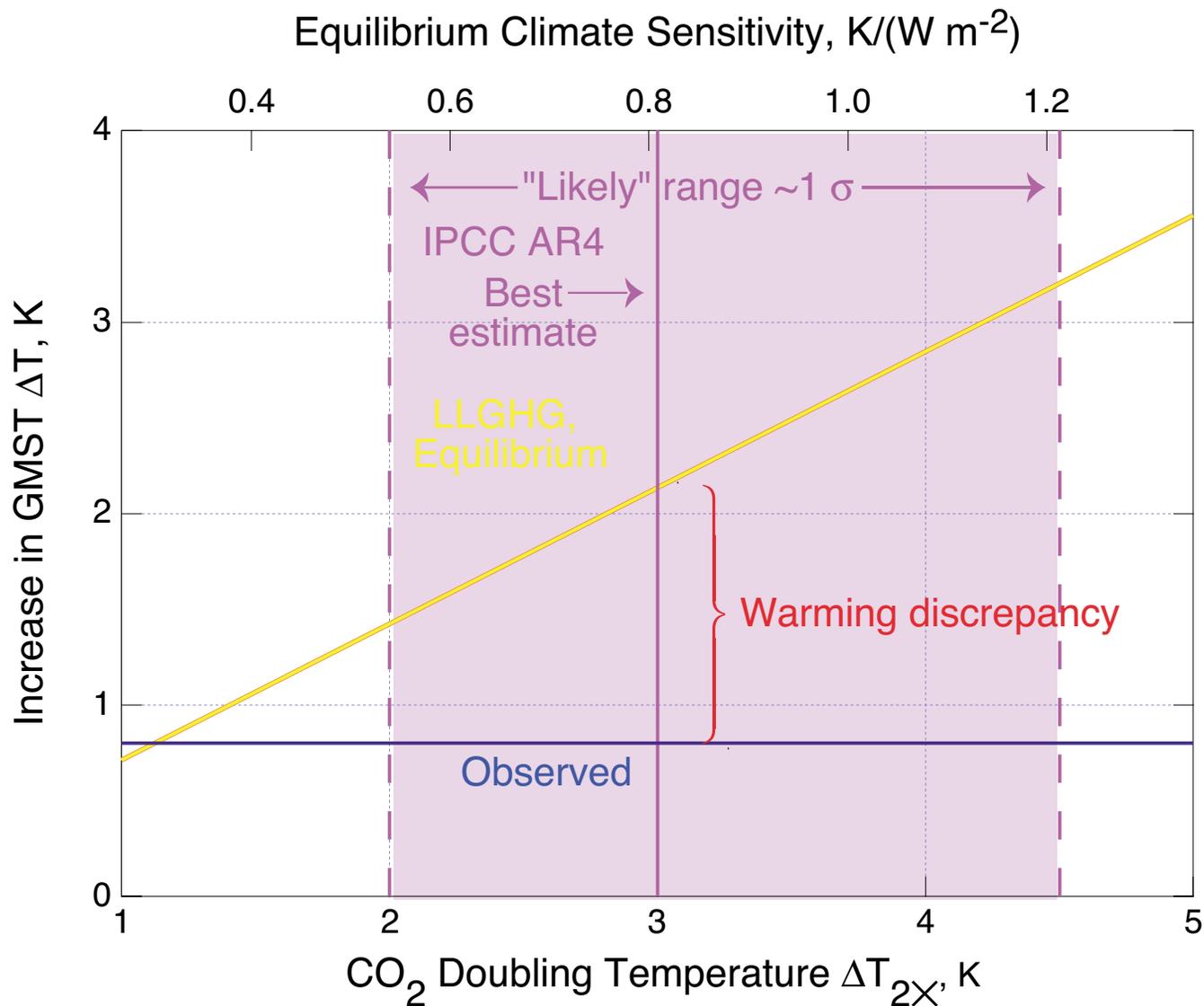
Observed temperature increase:

$$\Delta T_{\text{obs}} = 0.8 \text{ K}$$

Warming
discrepancy

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



This discrepancy holds throughout the IPCC AR4 “likely” range for climate sensitivity.

HOW MUCH WARMING IS EXPECTED?

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Expected temperature increase:

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Committed
warming

Observed temperature increase:

$$\Delta T_{\text{obs}} = 0.8 \text{ K}$$

Because of uncertainty in climate sensitivity the committed warming is likewise uncertain.

IMPLICATIONS

ALLOWABLE FUTURE CO₂ EMISSIONS

How much fossil carbon can be burned and emitted into the atmosphere (as CO₂) without exceeding a given threshold for “dangerous anthropogenic interference” with the climate system?

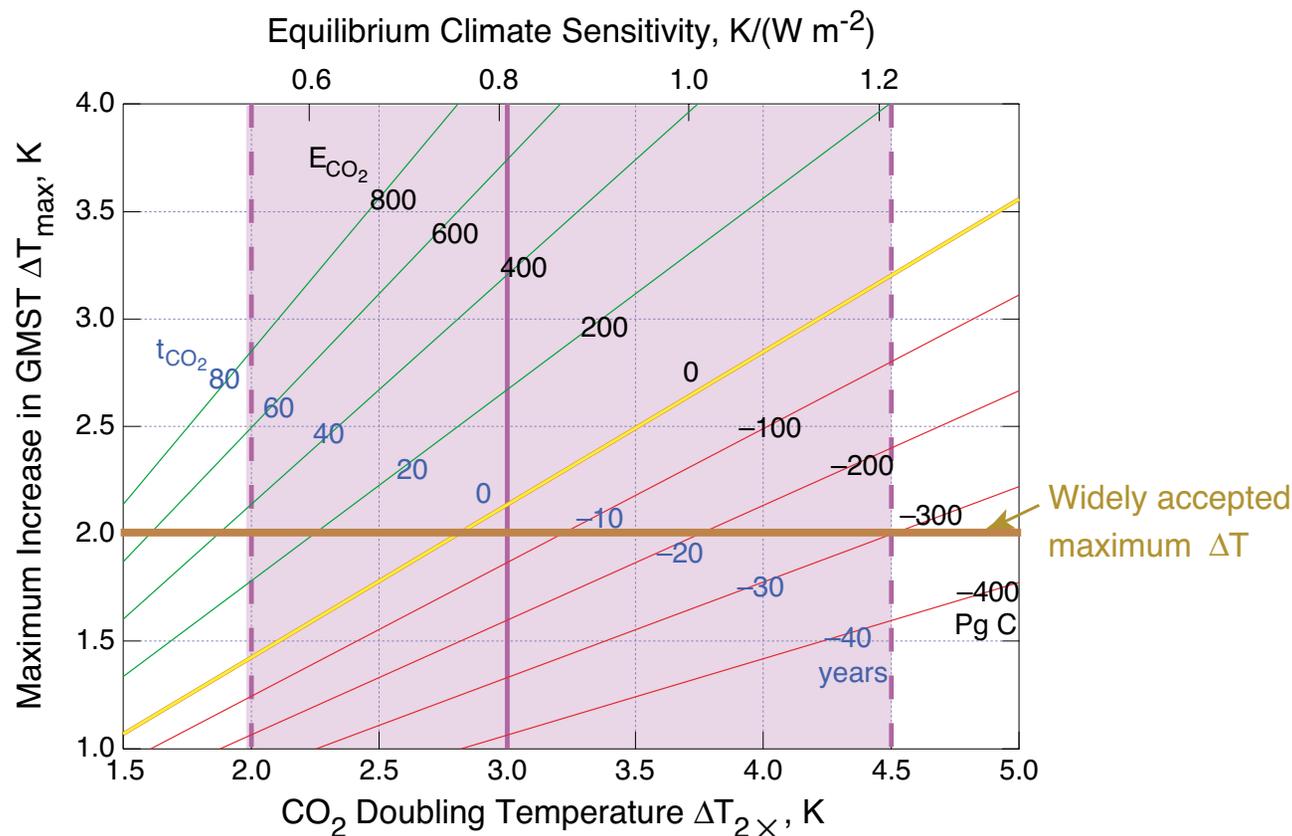
Answer depends on target threshold and climate sensitivity.

Premise of the calculation:

Forcings by LLGHG's only; result expressed as equivalent CO₂.

ALLOWABLE FUTURE CO₂ EMISSIONS

Dependence on climate sensitivity and acceptable increase in temperature relative to preindustrial



For $\Delta T_{\max} = 2$ K . . .

If sensitivity $\Delta T_{2\times}$ is 3 K, *no more emissions*.

If sensitivity $\Delta T_{2\times}$ is 2 K, ~ **30 more years of emissions at present rate**.

If sensitivity $\Delta T_{2\times}$ is 4.5 K, **threshold is exceeded by ~30 years**.

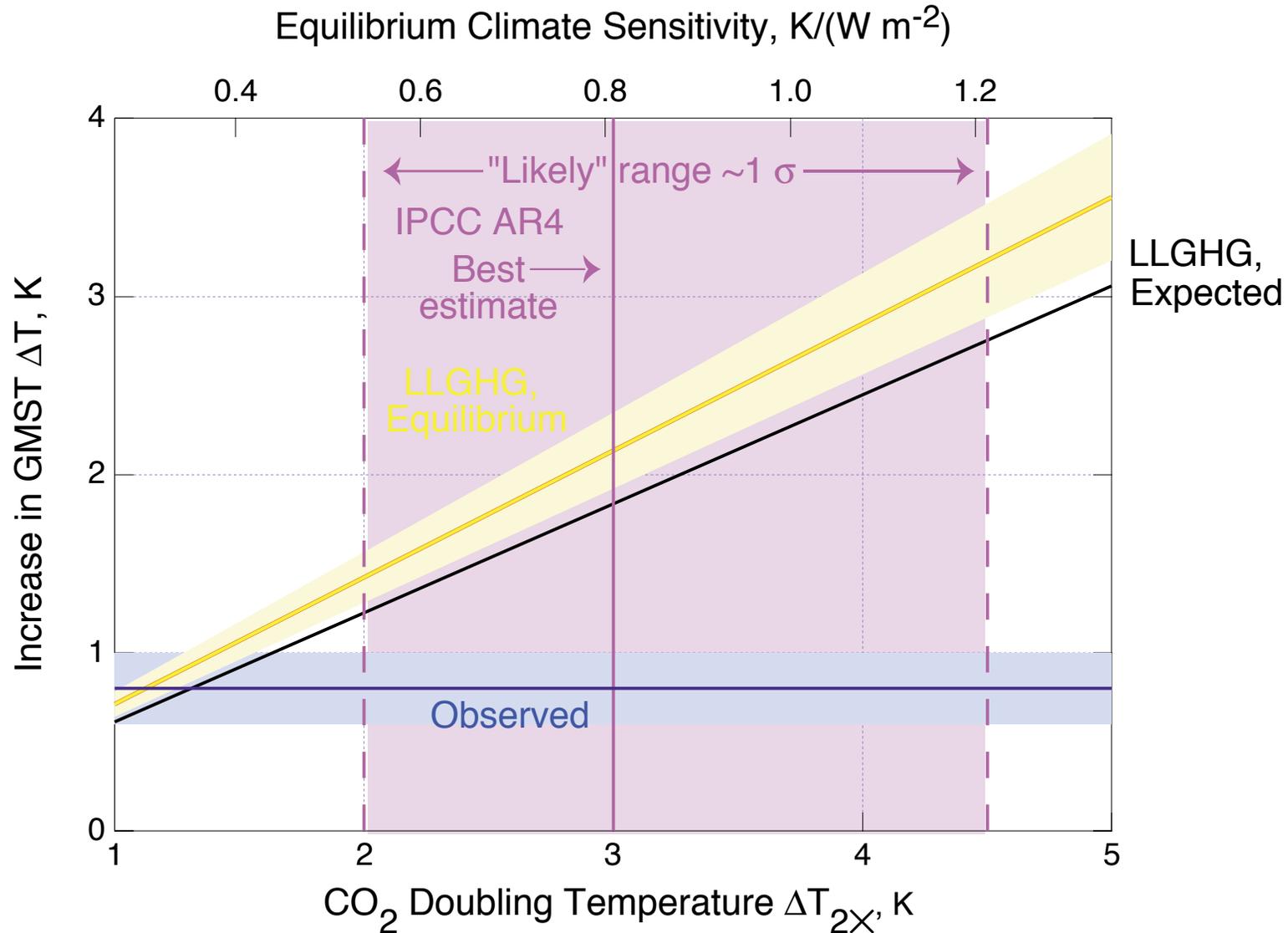
WHY HASN'T THE EARTH CLIMATE WARMED AS MUCH AS EXPECTED?

FROM FORCING BY LONG-LIVED GREENHOUSE GASES?

- ~~Uncertainty in greenhouse gas forcing.~~
- ~~Countervailing natural cooling over the industrial period.~~
- Lag in reaching thermal equilibrium. $\sim 0.4 \text{ W m}^{-2} - 15\%$
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

Long-lived GHGs only – Dependence on climate sensitivity



Little of the warming discrepancy can be attributed to thermal disequilibrium.

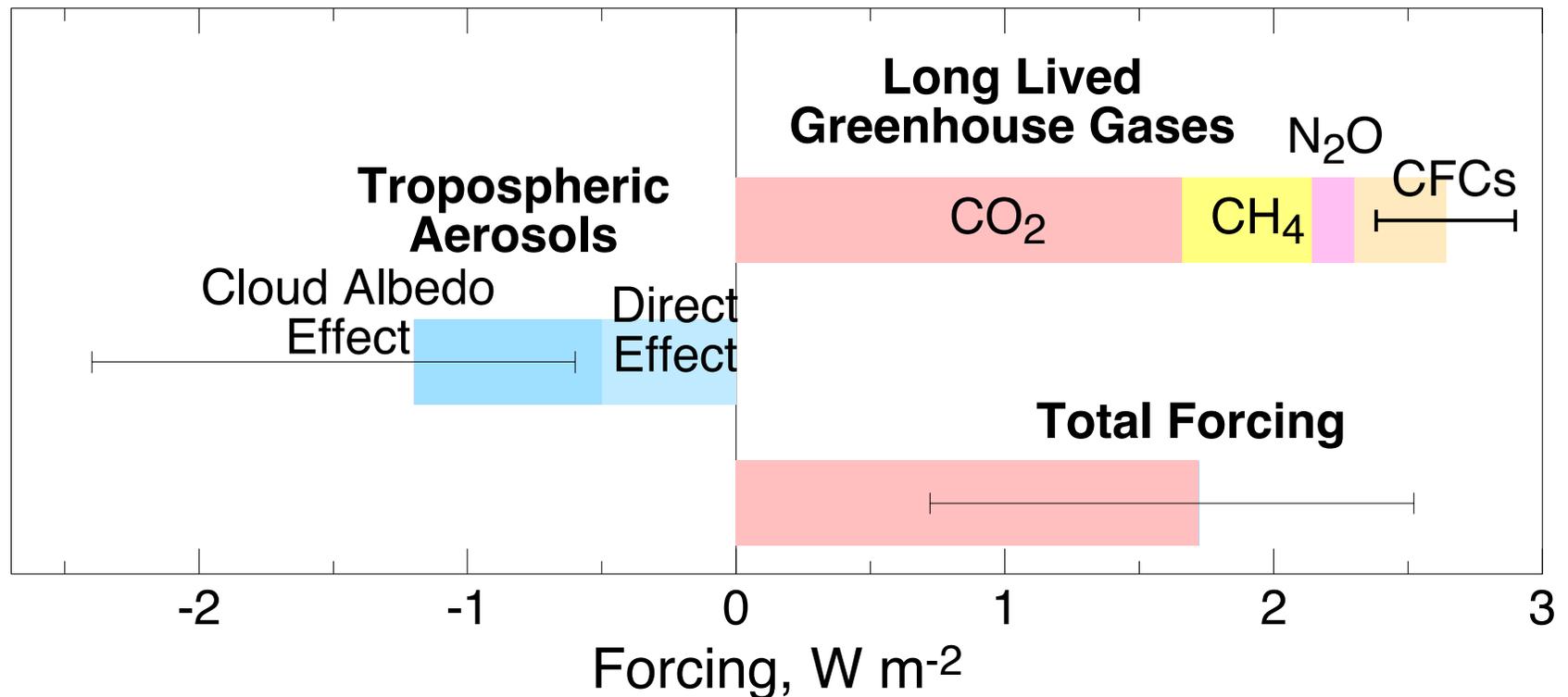
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CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

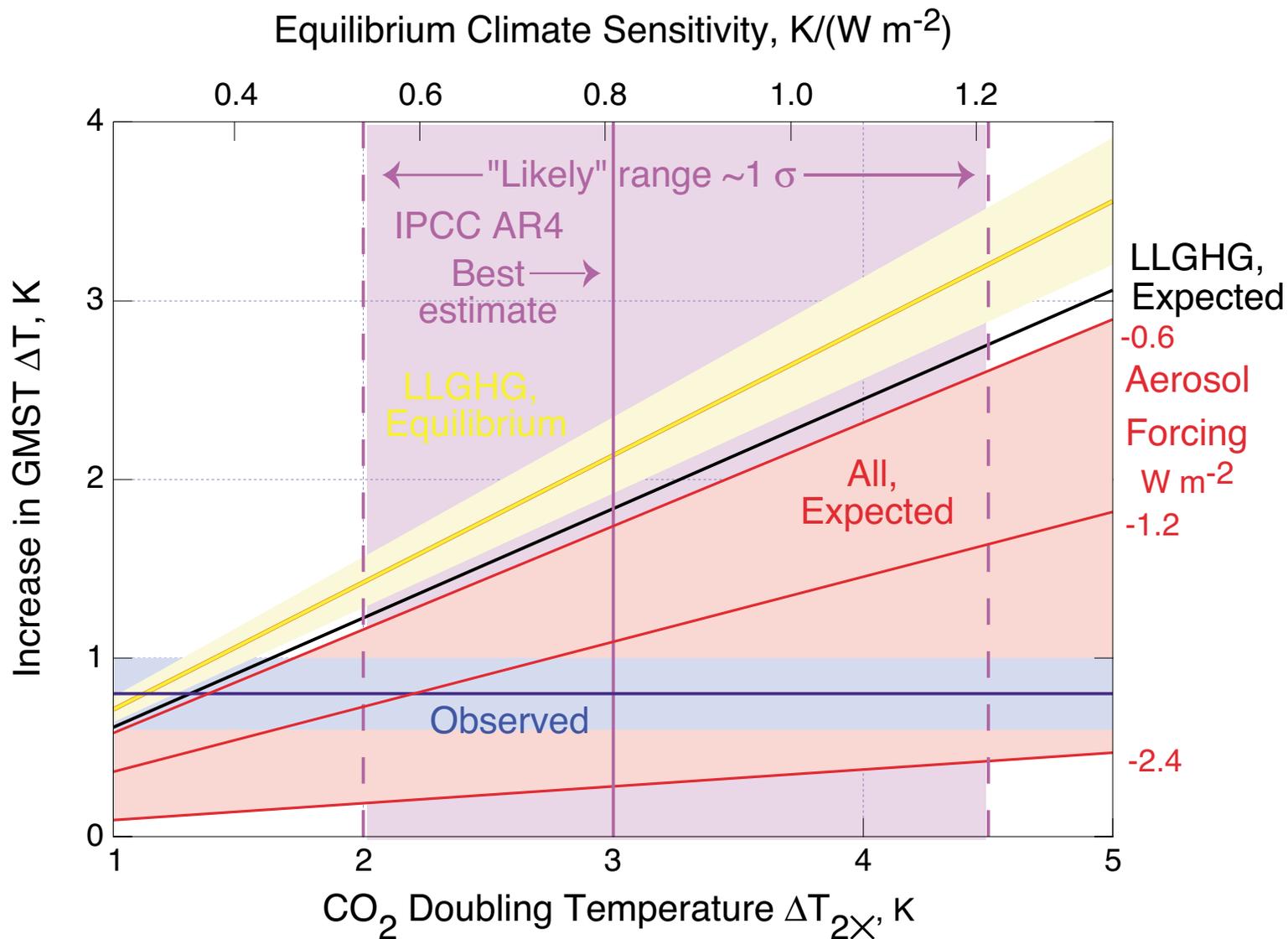
Extracted from IPCC AR4 (2007)



Total forcing includes other anthropogenic and natural (solar) forcings. Forcing by tropospheric ozone, $\sim 0.35 \text{ W m}^{-2}$, is the greatest of these. Uncertainty in aerosol forcing dominates uncertainty in total forcing.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

All forcings – Dependence on climate sensitivity



The warming discrepancy is certainly resolved by countervailing aerosol forcing (within the IPCC range) for virtually any value of sensitivity.

WHY HASN'T THE EARTH CLIMATE WARMED AS MUCH AS EXPECTED?

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APPROACHES TO DETERMINING CLIMATE SENSITIVITY

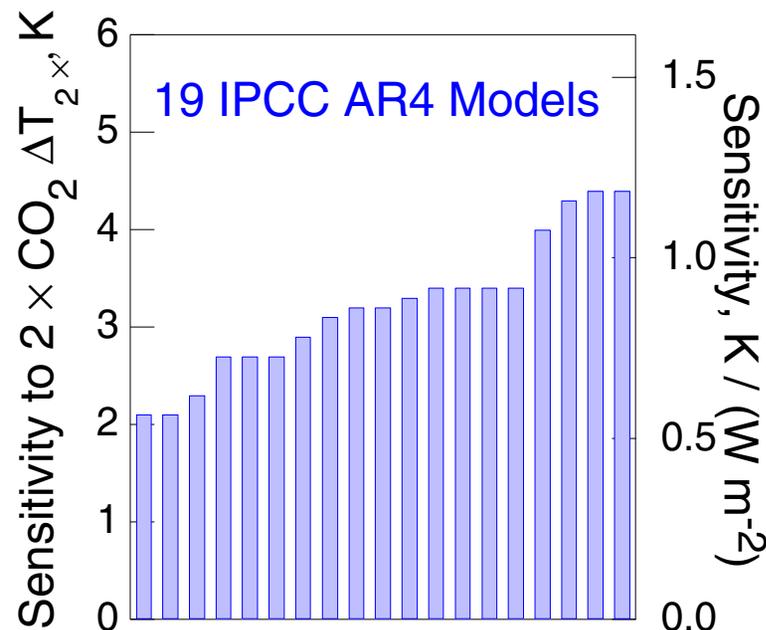
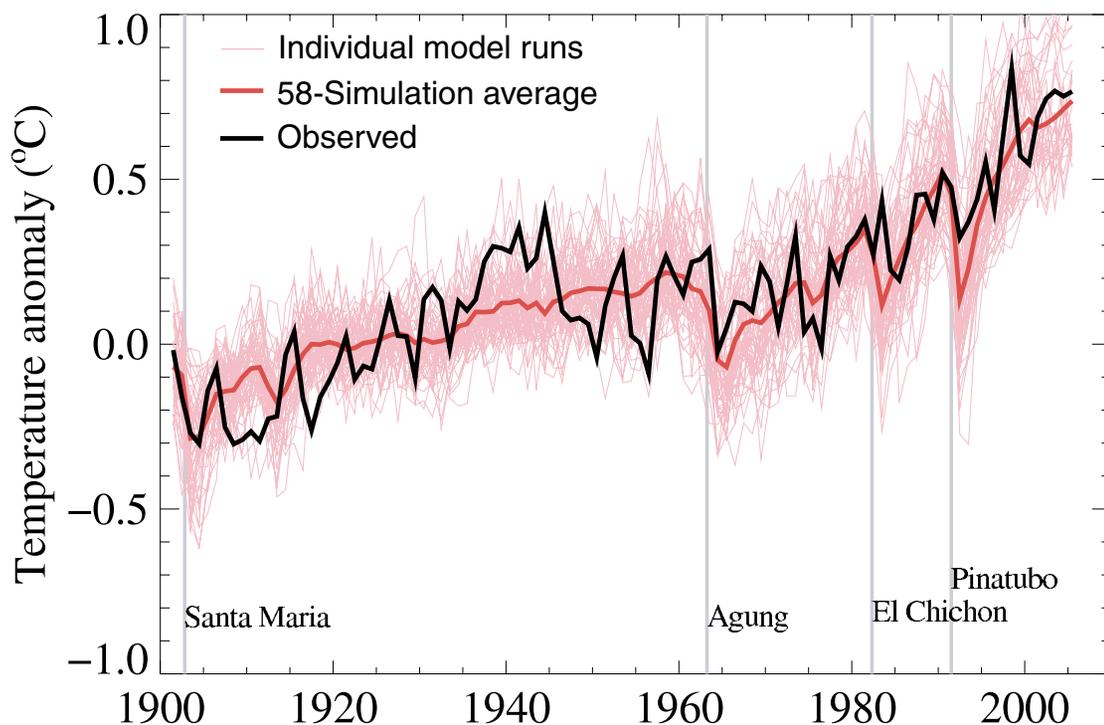
Climate models

Evaluate by performance on current climate

Evaluate by performance over instrumental record

TOO ROSY A PICTURE?

58 model runs with 14 Global Climate Models



- “ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a *consistent explanation of the observed temperature record*.
- “ These simulations used models with *different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings*.

How can this be?

IPCC AR4, 2007

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

Evaluate by performance on current climate

Evaluate by performance over instrumental record

Empirical

Sensitivity = Time constant/Heat Capacity

Paleo: $\Delta Temperature / \Delta Flux$, paleo to present

Instrumental record $\Delta Temperature / (Forcing - Flux)$

Satellite measmt.: $[d(Forcing - Flux) / dTemperature]^{-1}$

CLIMATE MODEL DETERMINATION OF CLIMATE SENSITIVITY

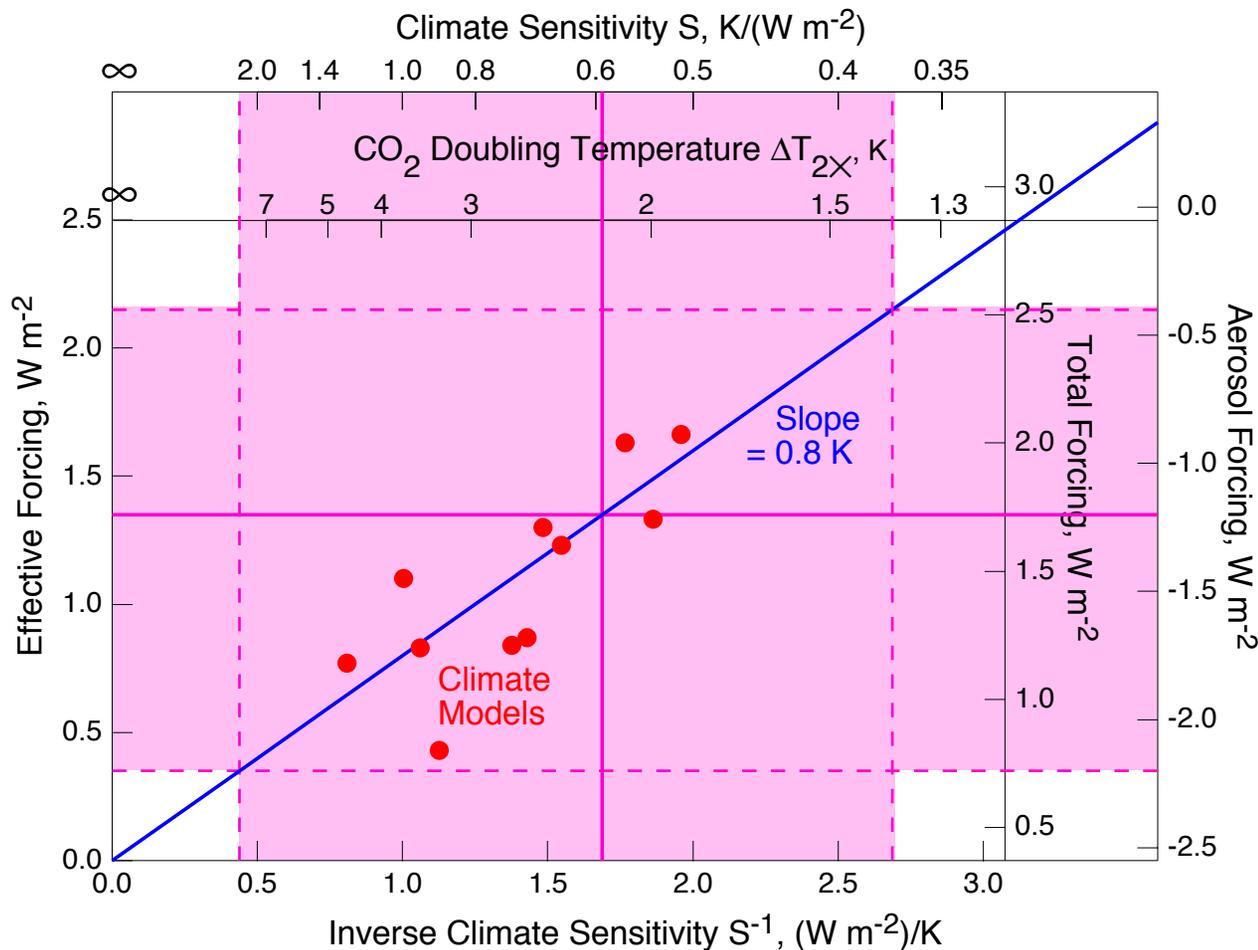
Effect of uncertainty in forcing

$$F_{\text{eff}} = F - H$$

$$\Delta T = S F_{\text{eff}}$$

$$F_{\text{eff}} = \Delta T S^{-1}$$

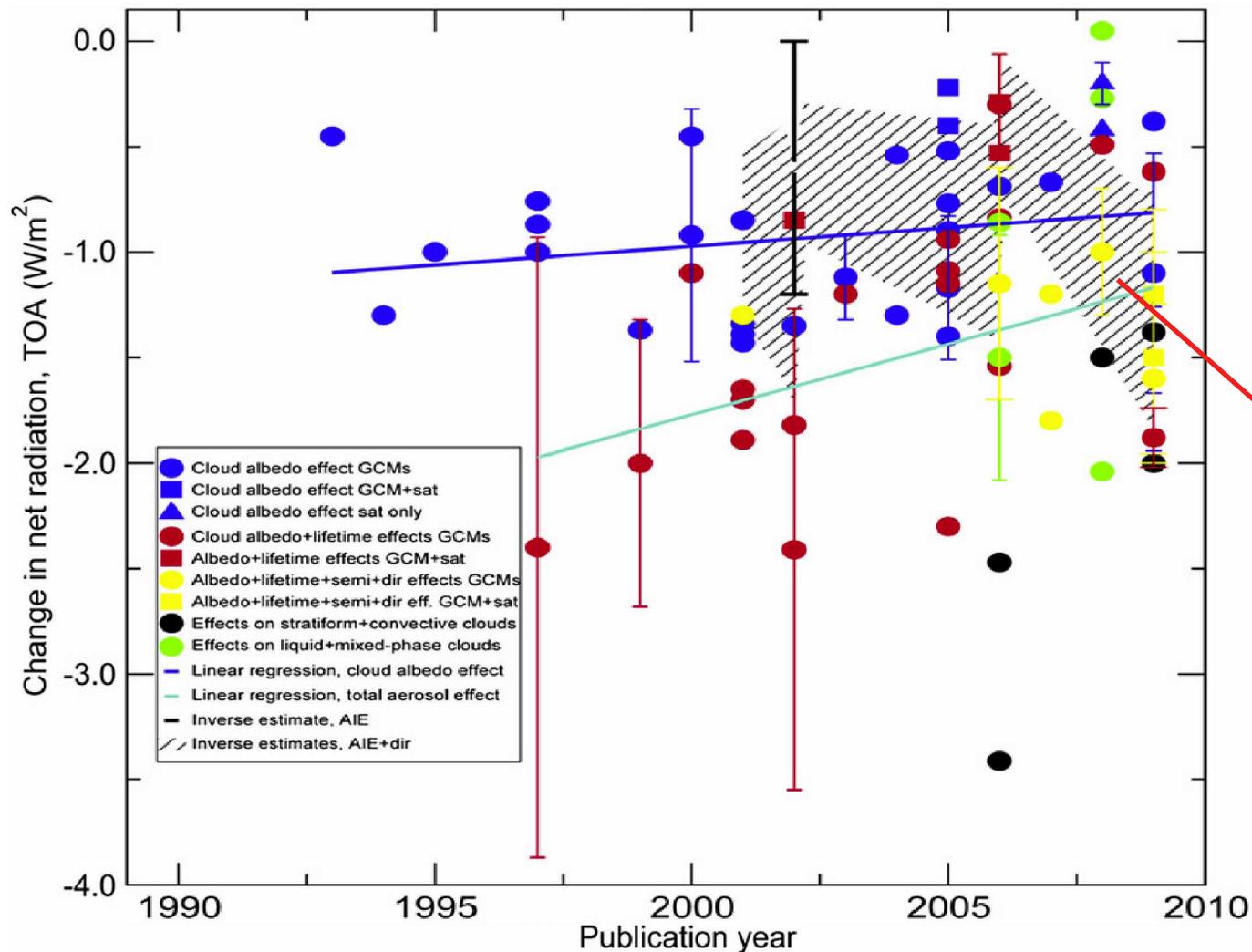
*Model forcings and sensitivities:
Kiehl, GRL, 07*



Uncertainty in aerosol forcing allows climate models with widely differing sensitivities to reproduce temperature increase over industrial period.

PUBLISHED ESTIMATES OF AEROSOL INDIRECT EFFECT

Anthropogenic changes in net radiation at the TOA



Atmospheric composition change: Climate–Chemistry interactions
I.S.A. Isaksen, C. Granier, G. Myhre, T.K. Berntsen, S.B. Dalsøren, M. Gauss,
Z. Klimont, R. Benestad, P. Bousquet, W. Collins, T. Cox, V. Eyring, D. Fowler, S. Fuzzi,
P. Jöckel, P. Laj, U. Lohmann, M. Maione, P. Monks, A.S.H. Prevot, F. Raes, A. Richter,
B. Rognerud, M. Schulz, D. Shindell, D.S. Stevenson, T. Storelvmo, W.-C. Wang,
M. van Weele, M. Wild, D. Wuebbles
Atmospheric Environment (2009)

Estimates are only slowly converging.

THE PATH FORWARD

Determine aerosol forcing with high accuracy.

Multiple approaches are required:

Laboratory studies of aerosol processes.

Field measurements of aerosol processes and properties:
emissions, new particle formation, evolution, size
distributed composition, optical properties, CCN
properties, removal processes . . .

Represent aerosol processes in *chemical transport models*.

Evaluate models by *comparison with observations*.

Satellite measurements for spatial coverage.

Calculate forcings in *chemical transport models and GCMs*.

Measurement based determination of aerosol forcings.

There are
many
aerosol
forcings!

[www.climate-science.gov/
Library/sap/sap2-3](http://www.climate-science.gov/Library/sap/sap2-3)



Atmospheric Aerosol Properties and Climate Impacts

Synthesis and Assessment Product 2.3
Report by the U.S. Climate Change Science Program
and the Subcommittee on Global Change Research

COORDINATING LEAD AUTHOR:
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LEAD AND CONTRIBUTING AUTHORS:
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January 2009

SEVEN DIMENSIONS OF AEROSOL RADIATIVE FORCING

<i>Where we are now</i>		<i>Where we need to be</i>
Direct clear sky	Indirect aerosol effects on clouds	Both
Cloud-free sky	Cloudy sky	All-sky
Shortwave (solar)	Longwave (thermal infrared)	Both
Surface	Top-of-atmosphere	Both
Total aerosol	Natural	Anthropogenic
Instantaneous		Annual
Local		Global

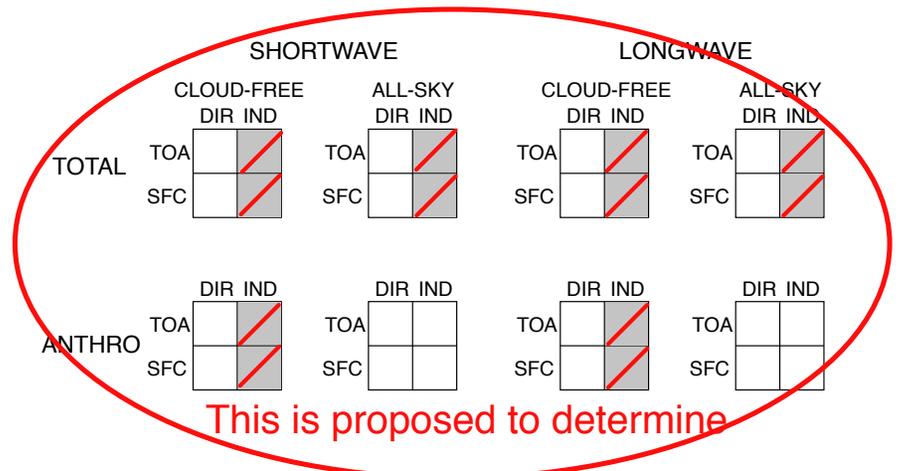
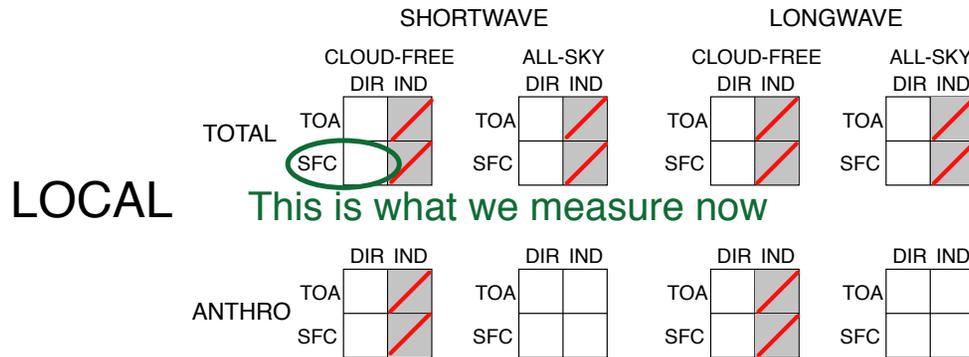
Each aerosol forcing is a *difference* between two fluxes:
perturbed aerosol minus initial aerosol.

Need *measurement-based* determination of aerosol *forcings*.

SEVEN DIMENSIONS OF AEROSOL FORCINGS

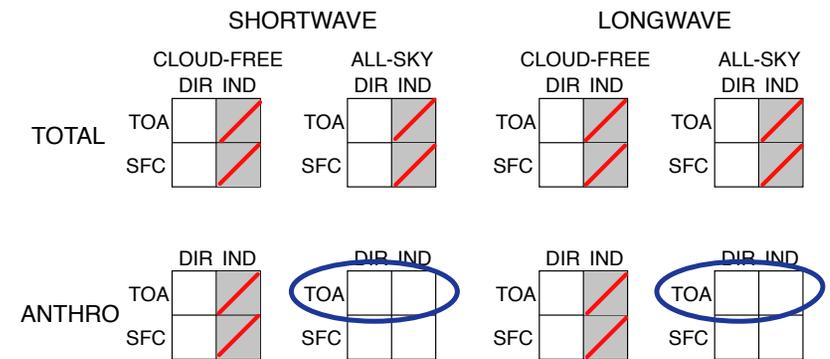
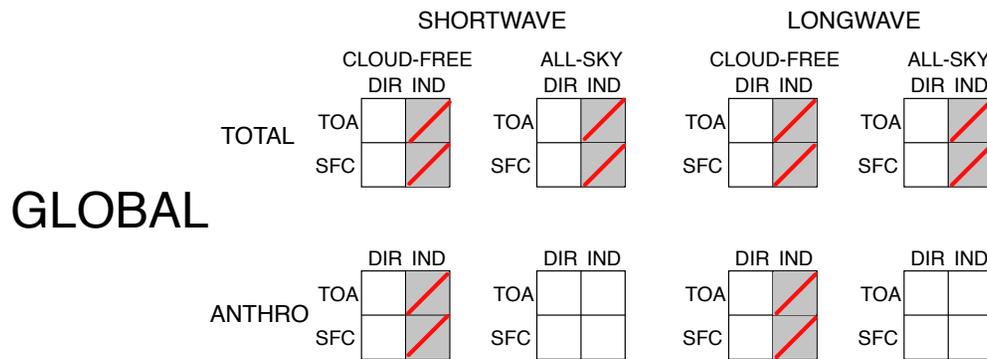
INSTANTANEOUS

24-HOUR TO ANNUAL AVG



INSTANTANEOUS

24-HOUR TO ANNUAL AVG



▧ Denotes that indicated forcing is not defined.

80 Distinct aerosol forcings

DIRECT DETERMINATION OF AEROSOL FORCINGS AT ARM SITES



Measurements 24-7-365



Drone
Net SW and LW at TOA

3-D Characterization
of Aerosol and Cloud
Properties



Characterization of 3-D
Cloud Properties by Radars,
Tomography

