THE CHALLENGE OF 1‰

per mil

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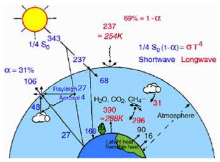
Upton, Long Island, NY

CERES Science Team Meeting
Newport News VA
April 27-29, 2010

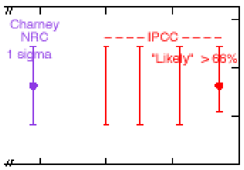
www.ecd.bnl.gov/steve

OVERVIEW

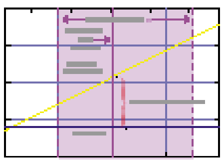

Introductory remarks

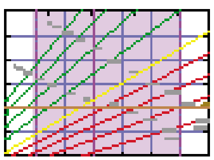


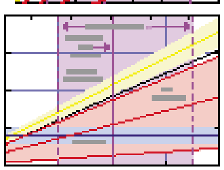
Earth’s energy balance and perturbations

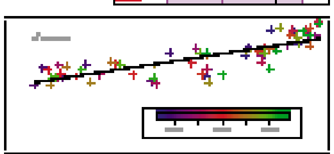


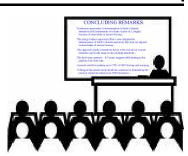
Forcing, response, climate sensitivity


Warming discrepancy and committed warming

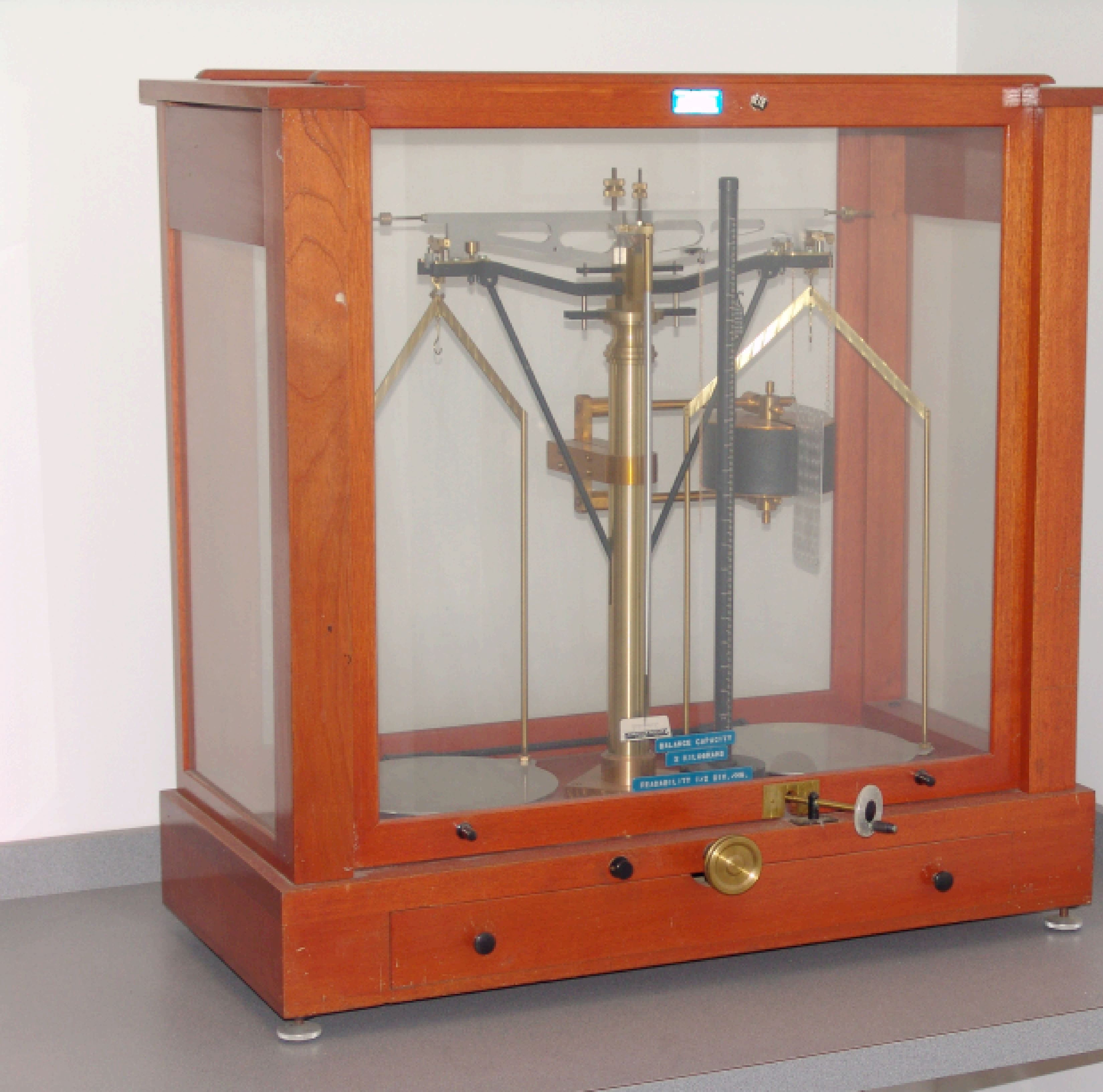

Implications: Allowable future CO_2 emissions


Why hasn’t Earth warmed as much as expected?


Approaches to determining climate sensitivity


Concluding observations

One mill = $0.001



Analytical chemists routinely work to one part in a thousand.

METERING GASOLINE

$0.1 ¢ / \$3.47$
$= 0.3$ ‰

Pricing gasoline to 0.1 cent per gallon implies measurement accuracy of 0.3 ‰.

Equivalent to 1 cubic centimeter in a gallon.

TRENBERTH'S TRAVESTY

From: **Kevin Trenberth** <trenbert@ucar.edu>

Subject: Re: BBC U-turn on climate

Date: Mon, 12 Oct 2009

Hi all

Well I have my own article on where the heck is global warming? We are asking that here in Boulder where we have broken records the past two days for the coldest days on record. We had 4 inches of snow. The high the last 2 days was below 30F and the normal is 69F, and it smashed the previous records for these days by 10F. The low was about 18F and also a record low, well below the previous record low. This is January weather (see the Rockies baseball playoff game was canceled on saturday and then played last night in below freezing weather).

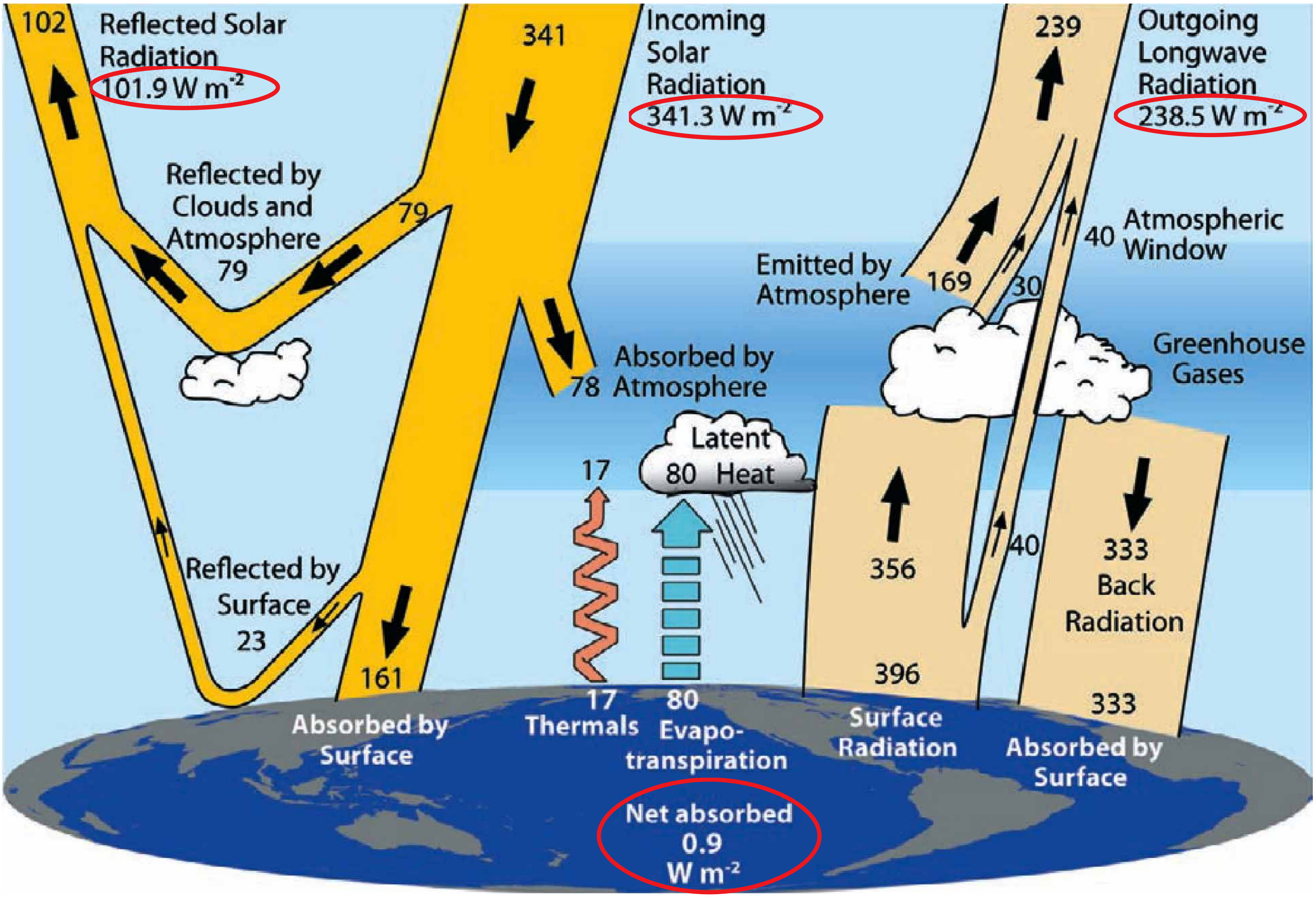
Trenberth, K. E., 2009: **An imperative for climate change planning: tracking Earth's global energy**. *Current Opinion in Environmental Sustainability*, **1**, 19-27, doi:10.1016/j.cosust.2009.06.001

The fact is that we can't account for the lack of warming at the moment and it is a travesty that we can't. The CERES data published in the August BAMS 09 supplement on 2008 shows there should be even more warming: but ***the data are surely wrong. Our observing system is inadequate***.

Kevin

GLOBAL ANNUAL ENERGY BUDGET

Fluxes in $W\ m^{-2}$



Trenberth, Fasullo, Kiehl, BAMS, 2008

$341.3 - (101.9 + 238.5) = 0.9\ W\ m^{-2}$ net imbalance.

NORMAN'S CHALLENGE

From: "Loeb, Norman G. (LARC-E302)" <norman.g.loeb@nasa.gov>
To: "stephen e. schwartz" <ses@bnl.gov>
Date: Sat, 20 Feb 2010 08:08:47 -0600
Subject: Presentation at Spring 2010 CERES Science Team Meeting

Steve,

On the accuracy of net toa imbalance: the actual value is a ~few tenths of a Wm-2, so we need its absolute accuracy to a fraction of that. Even with perfect satellite calibration, I don't think we can realistically get the absolute uncertainty in the net imbalance to much less than 0.5 Wm-2, roughly what I think the uncertainty is from in-situ observations of ocean heat content. . . . The problem is that net imbalance from satellite is determined from the ***difference between two large terms of order 340 Wm-2***.

For the outgoing SW (~100 Wm-2) and outgoing LW (~240 Wm-2) that CERES measures, even 0.2% absolute accuracy doesn't gets us close (sqrt[0.2^2 + 0.48^2] = 0.5 Wm-2). Note that ***we're a long way from 0.2% absolute accuracy today***. . . .

As I've mentioned before, ***the satellite observations are far more precise than they are absolutely accurate***. We therefore can use satellite observations quite effectively at ***monitoring the short and long-term changes in the incoming, outgoing and net TOA radiation***, as well as the associated cloud and aerosol changes (although the latter have sampling challenges due to clouds, as you know). The satellite observations also provide ***great spatial coverage***, and when combined with geostationary data (as is done in CERES), ***temporal coverage***. . . . I see our best hope moving forward is in using long-term satellite observations combined with in-situ ocean heat content measurements.

Regards,

Norman

Concerns over photometric accuracy and over spatial and temporal integration.

Toward Optimal Closure of the Earth's Top-of-Atmosphere Radiation Budget

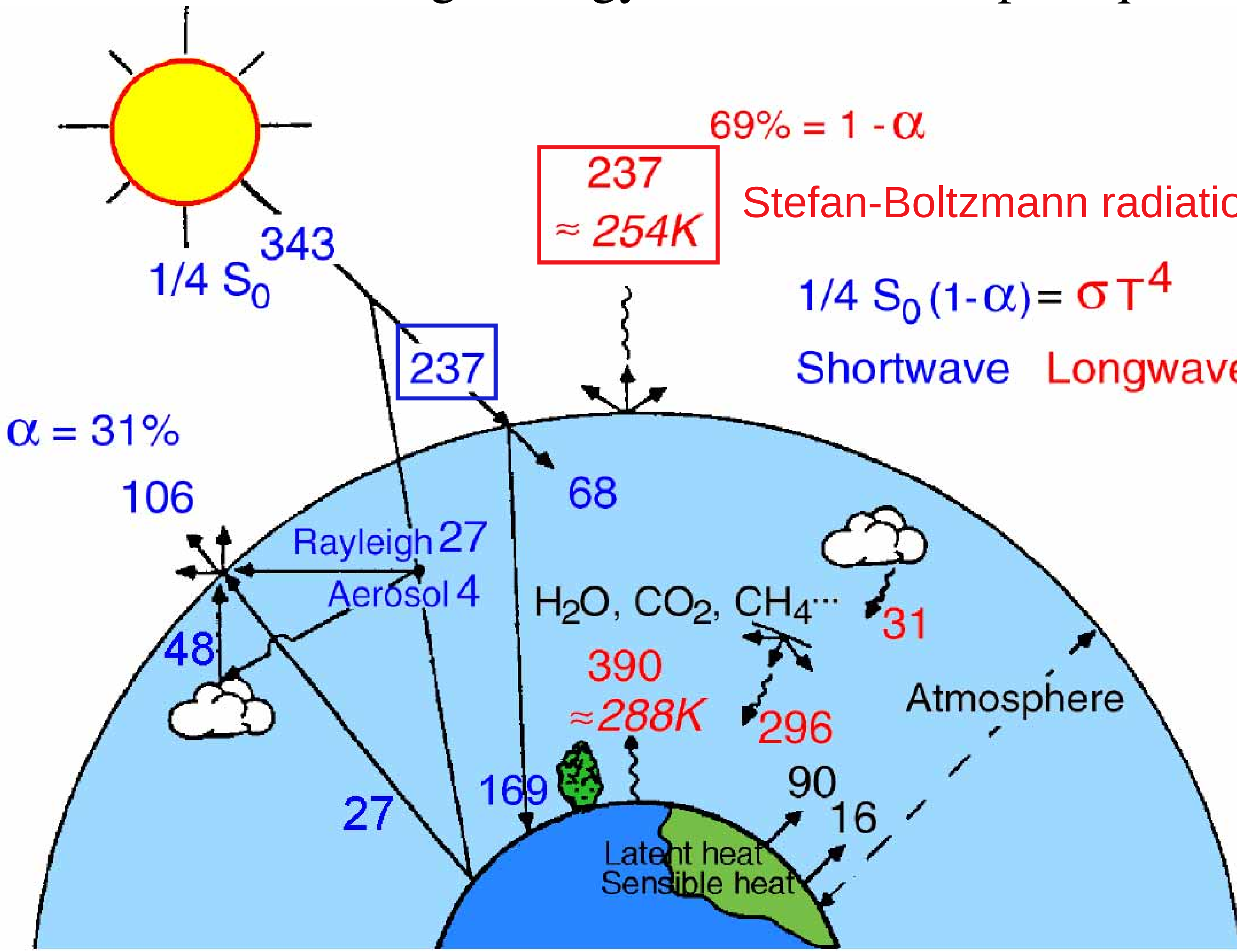
NORMAN G. LOEB,* BRUCE A. WIELICKI,* DAVID R. DOELLING,* G. LOUIS SMITH,+
DENNIS F. KEYES,# SEIJI KATO,* NATIVIDAD MANALO-SMITH,# AND TAKMENG WONG*

ABSTRACT

Despite recent improvements in satellite instrument calibration and the algorithms used to determine reflected solar (SW) and emitted thermal (LW) top-of-atmosphere (TOA) radiative fluxes, a sizeable imbalance persists in the average global net radiation at the TOA from satellite observations. This imbalance is problematic in applications that use earth radiation budget (ERB) data for climate model evaluation, estimate the earth's annual global mean energy budget, and in studies that infer meridional heat transports. This study provides a detailed error analysis of TOA fluxes based on the latest generation of Clouds and the Earth's Radiant Energy System (CERES) gridded monthly mean data products [the monthly TOA/surface averages geostationary (SRBAVG-GEO)] and uses an objective constrainment algorithm to adjust SW and LW TOA fluxes within their range of uncertainty to remove the inconsistency between average global net TOA flux and heat storage in the earth–atmosphere system. The 5-yr global mean CERES net flux from the standard CERES product is 6.5 W m^{-2}, much larger than the best estimate of 0.85 W m^{-2} based on observed ocean heat content data and model simulations. The major sources of uncertainty in the CERES estimate are from instrument calibration (4.2 W m^{-2}) and the assumed value for total solar irradiance (1 W m^{-2}). After adjustment, the global mean CERES SW TOA flux is 99.5 W m^{-2}, corresponding to an albedo of 0.293, and the global mean LW TOA flux is 239.6 W m^{-2}. These values differ markedly from previously published adjusted global means based on the ERB Experiment in which the global mean SW TOA flux is 107 W m^{-2} and the LW TOA flux is 234 W m^{-2}.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

RADIATIVE FORCING

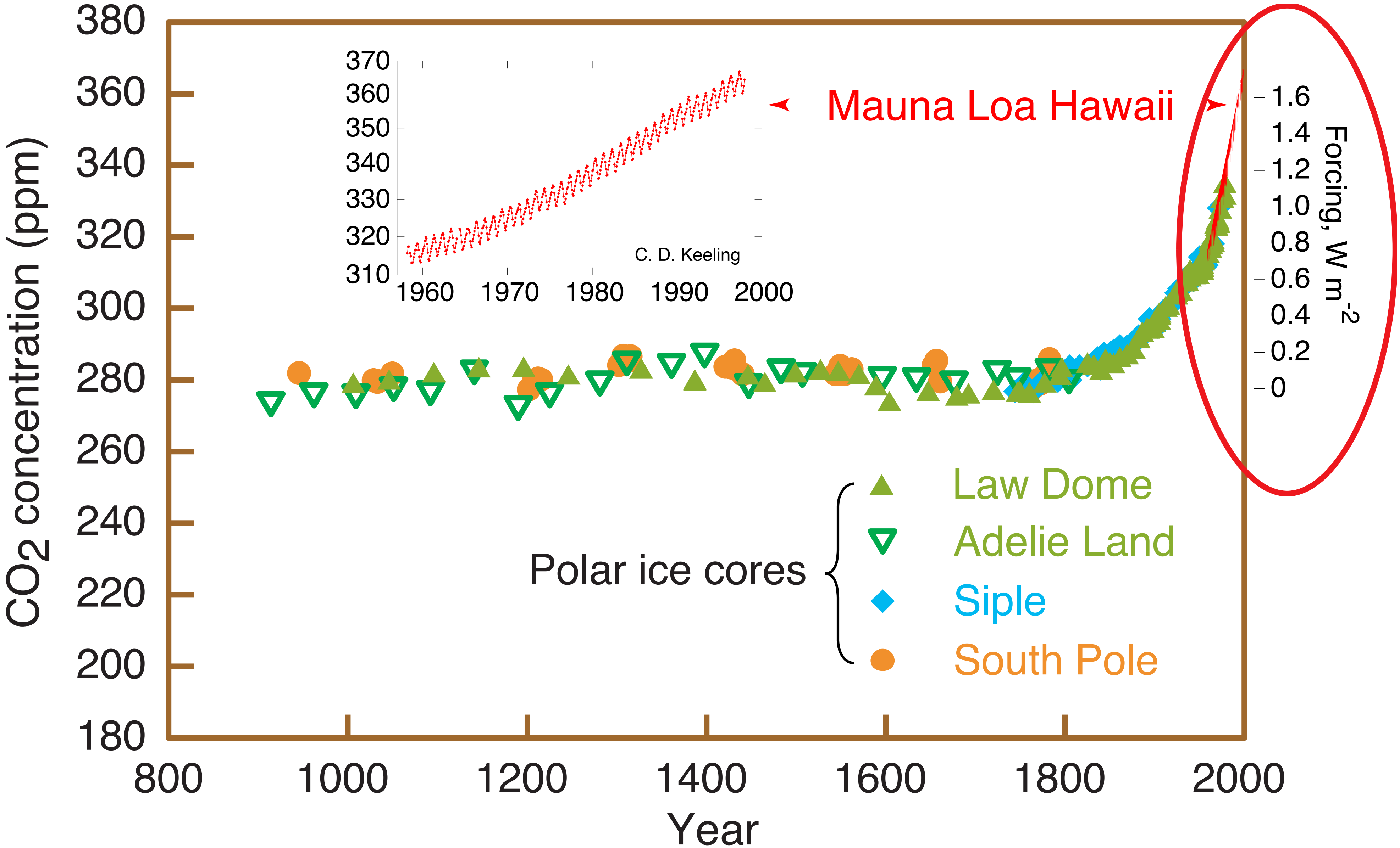
A ***change*** in a radiative flux term in Earth's radiation budget, ΔF, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

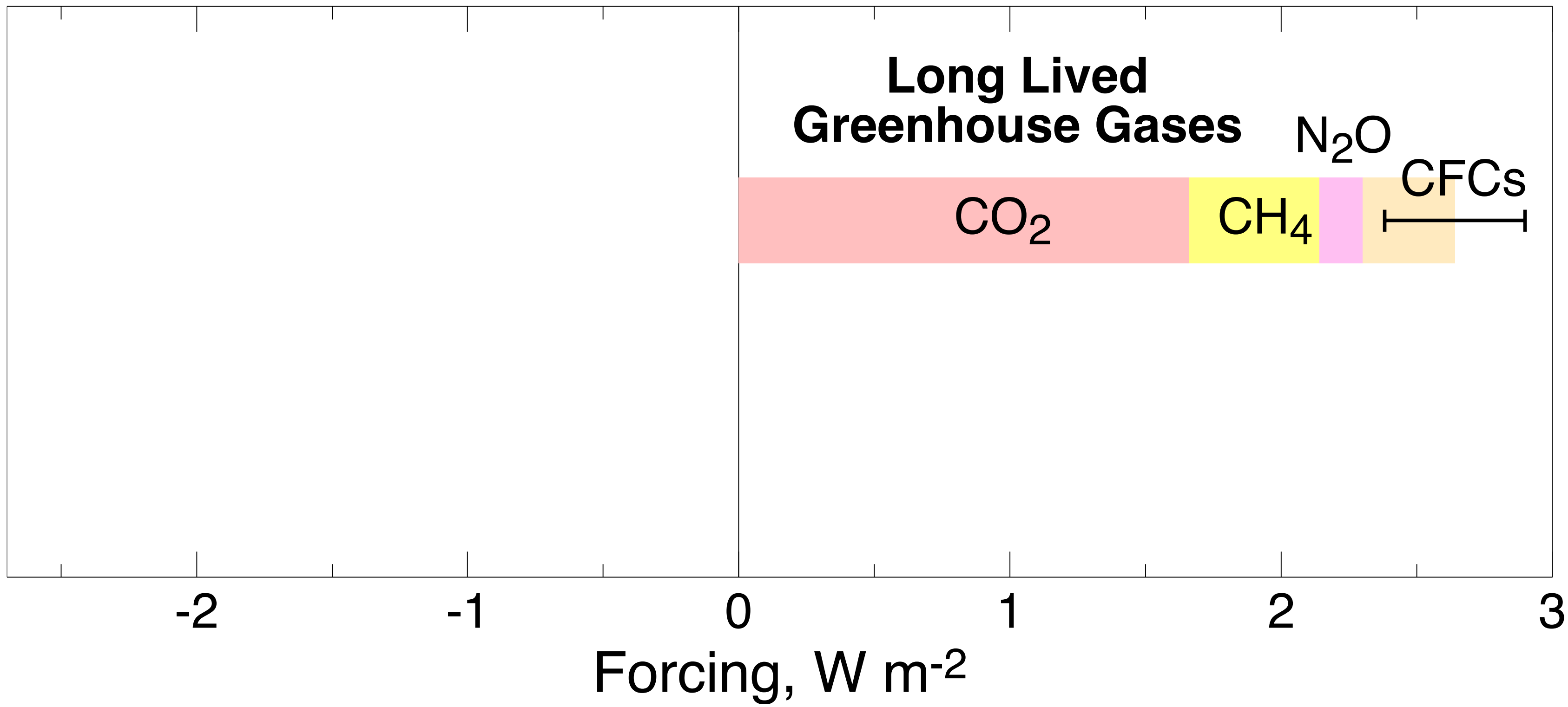
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)

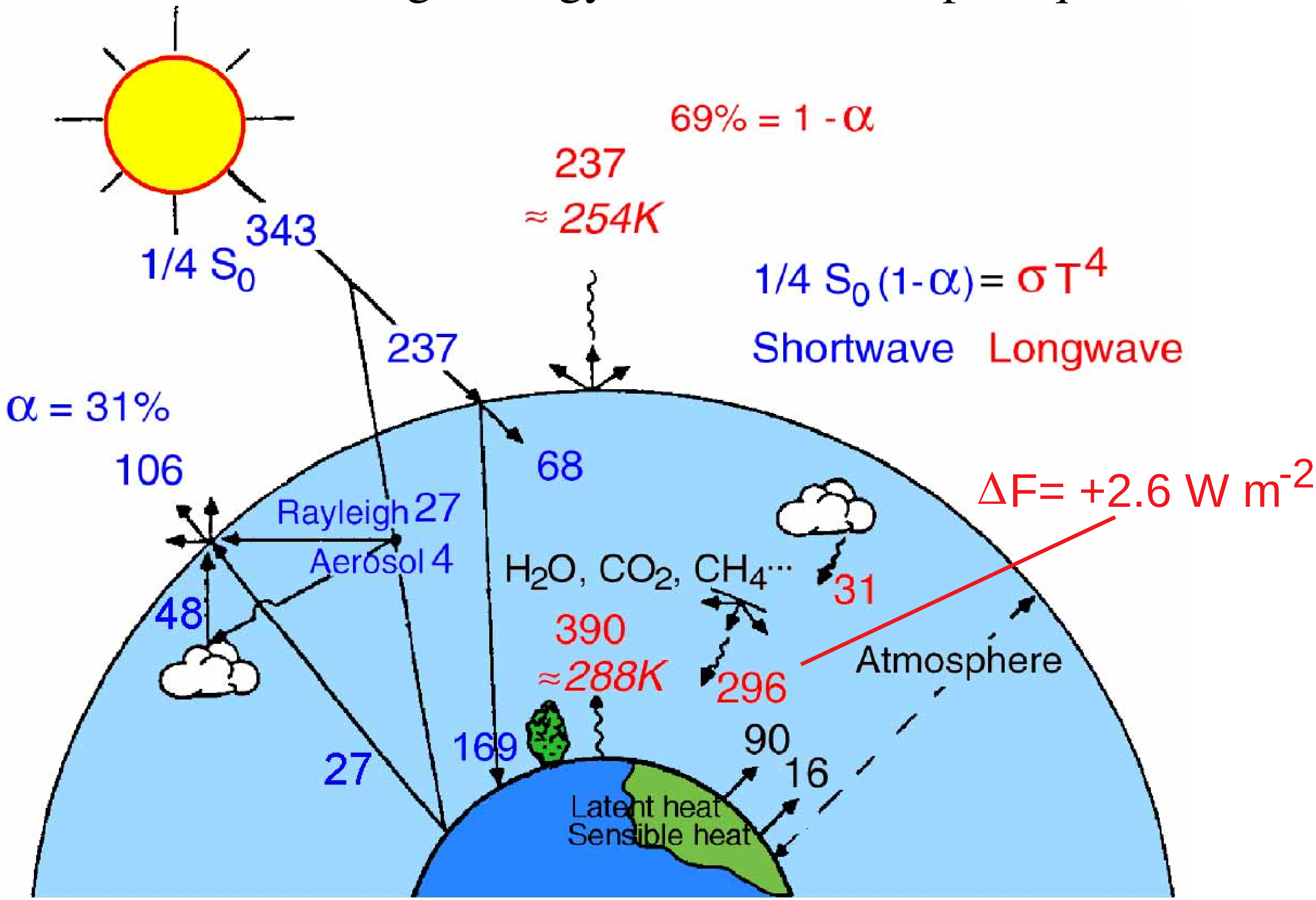


Greenhouse gas forcing is considered accurately known.

Gases are uniformly distributed; radiation transfer is well understood.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

CLIMATE RESPONSE

The ***change*** in global and annual mean temperature, ΔT, K, resulting from a given radiative forcing.

Working hypothesis:

The change in global mean temperature is proportional to the forcing, but independent of its nature and spatial distribution.

$$\Delta T = S\,\Delta F$$

CLIMATE SENSITIVITY

The ***change*** in global and annual mean temperature per unit forcing, S, K/(W m^{-2}),

$$S = \Delta T/\Delta F.$$

Climate sensitivity is not accurately known and is the objective of much current research on climate change.

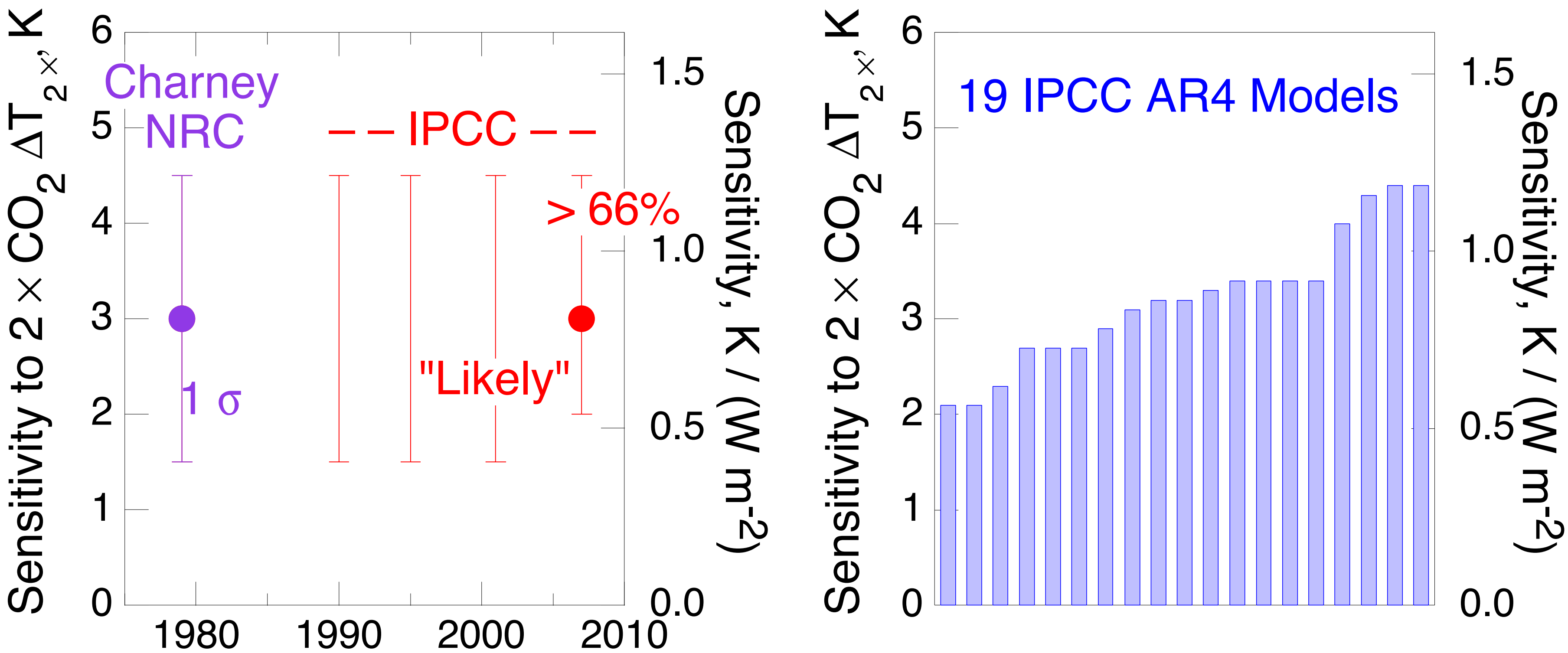
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = S\Delta F_{2\times}$$

$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$

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 $\Delta T_{2\times} = 3$ 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^?

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Robert J. Charlson
University of Washington, Seattle, Washington

Ralph A. Kahn
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Henning Rodhe
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The DOI for this manuscript is doi:10.1175/2009JCLI3461.1

HOW MUCH WARMING IS EXPECTED?

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period

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

IPCC, 2007
Best Estimate

Expected temperature increase:

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

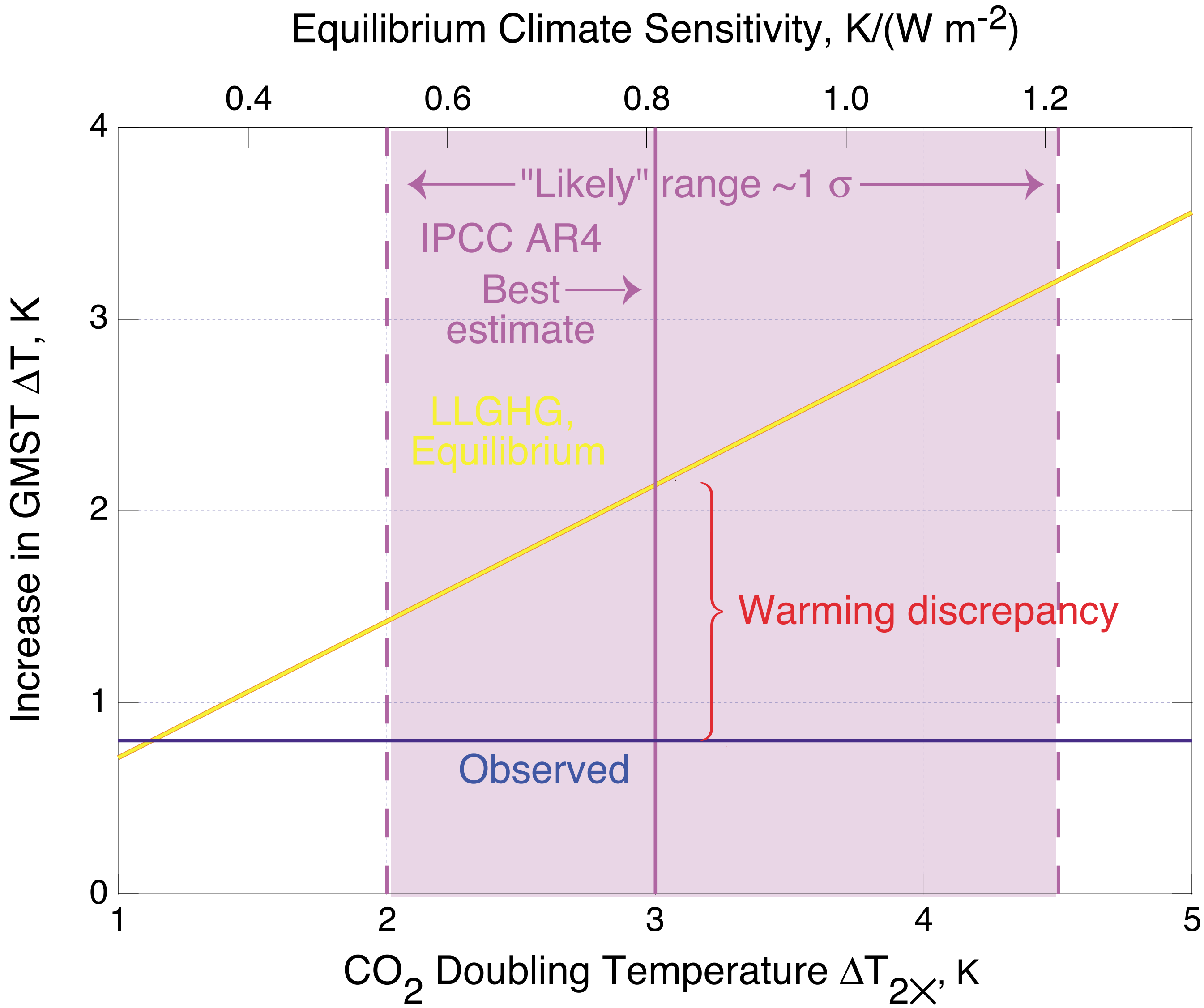
Observed temperature increase:

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

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?

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period

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

Expected temperature increase:

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

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 CO_2 EMISSIONS

How much fossil carbon can be burned and emitted into the atmosphere (as CO_2) without exceeding a given threshold for "dangerous anthropogenic interference" with the climate system?

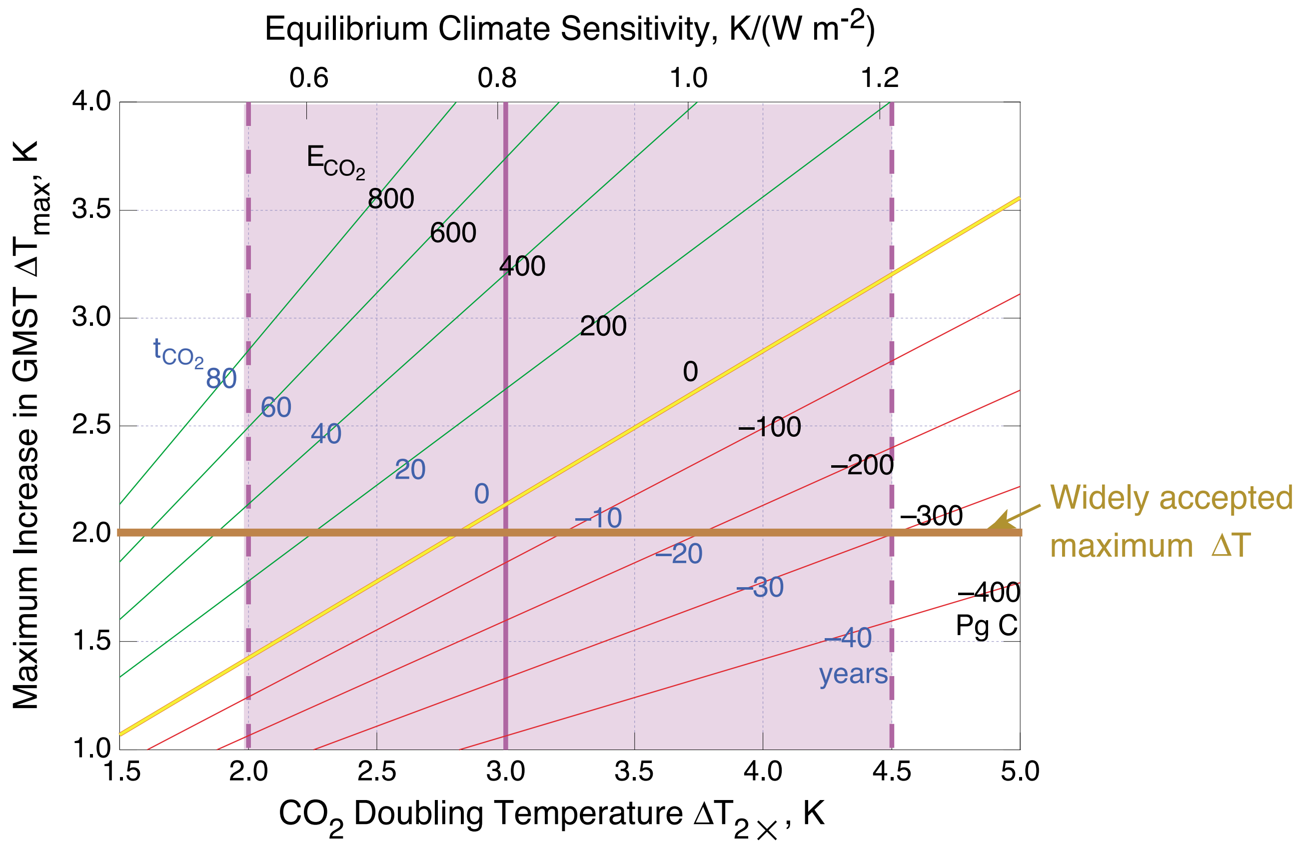
Answer depends on target threshold and climate sensitivity.

Premise of the calculation:

Forcings by LLGHG's only; result expressed as equivalent CO_2.

ALLOWABLE FUTURE CO_2 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.
- Countervailing cooling forcing by aerosols.
- Climate sensitivity lower than current estimates.

CLIMATE RESPONSE TO FORCING

Upon application of a forcing to climate initially at equilibrium

Global heating rate = Forcing – Response

$$N = F - S^{-1}\Delta T_s$$

For positive forcing net downwelling radiation at top of atmosphere immediately increases by the amount of the forcing.

As surface temperature T_s increases, outgoing longwave radiation increases and net downwelling radiation decreases until new equilibrium is reached.

EFFECTIVE FORCING

$$N = F - S^{-1}\Delta T_s$$

In general, not at equilibrium,

$$\Delta T_s = S(F - N)$$

Define ***effective forcing***, $F_{eff} \equiv F - N$

Use of effective forcing permits determination of expected temperature increase ΔT_s as

$$\Delta T_s = SF_{eff}$$

Need to determine net heating rate of Earth, N.

APPROACH TO ACCOUNTING FOR DISEQUILIBRIUM

Determine global heating rate from ***increase in heat content of global ocean***.

Evaluate effective forcing as $F_{\mathrm{eff}} \equiv F - N$.

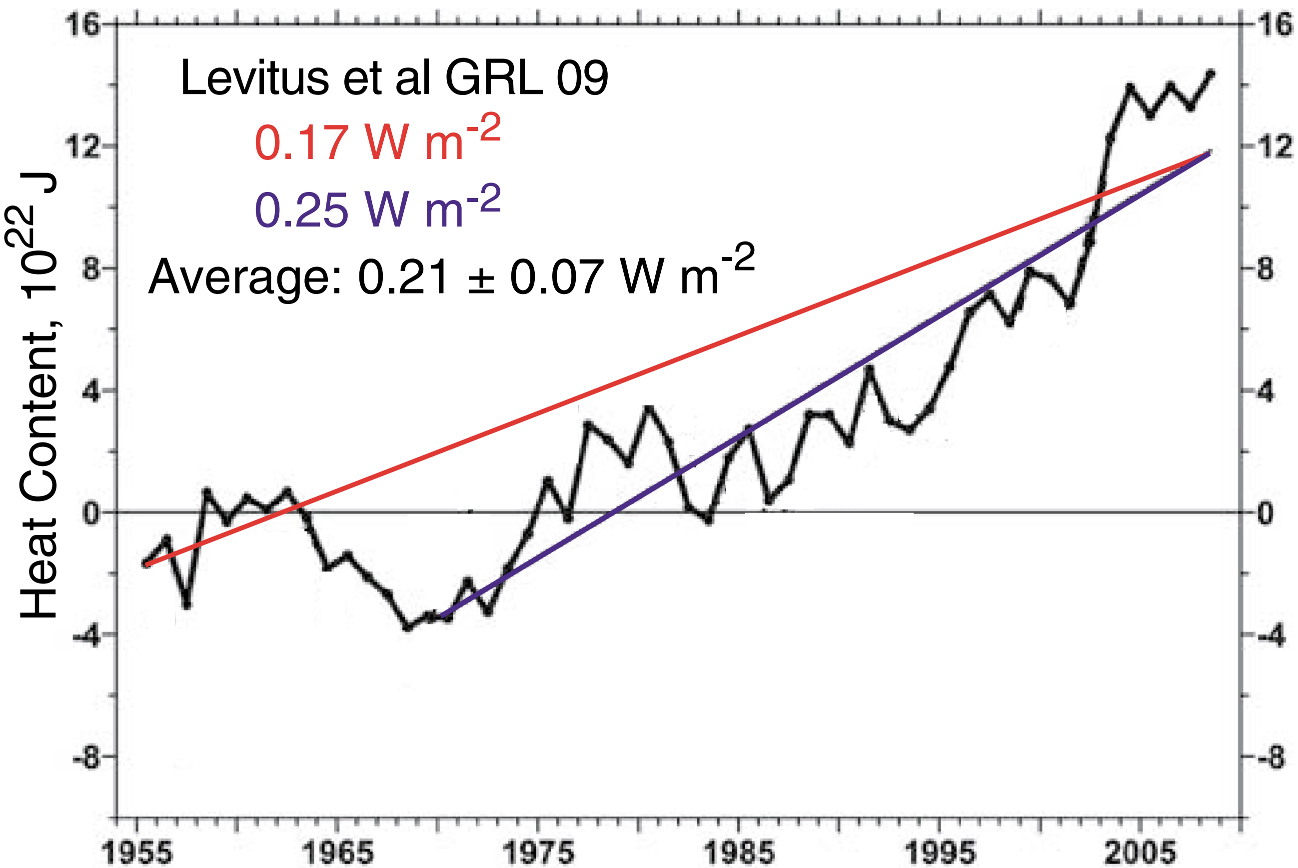
Compare observed ΔT_{s} to that expected for effective forcing.

Need net heating rate accurate to small fraction of the GHG forcing!

Desired but not yet available from satellite measurements.

GLOBAL HEATING RATE FROM OCEAN HEAT CONTENT

Heat content of global ocean – surface to 700 m



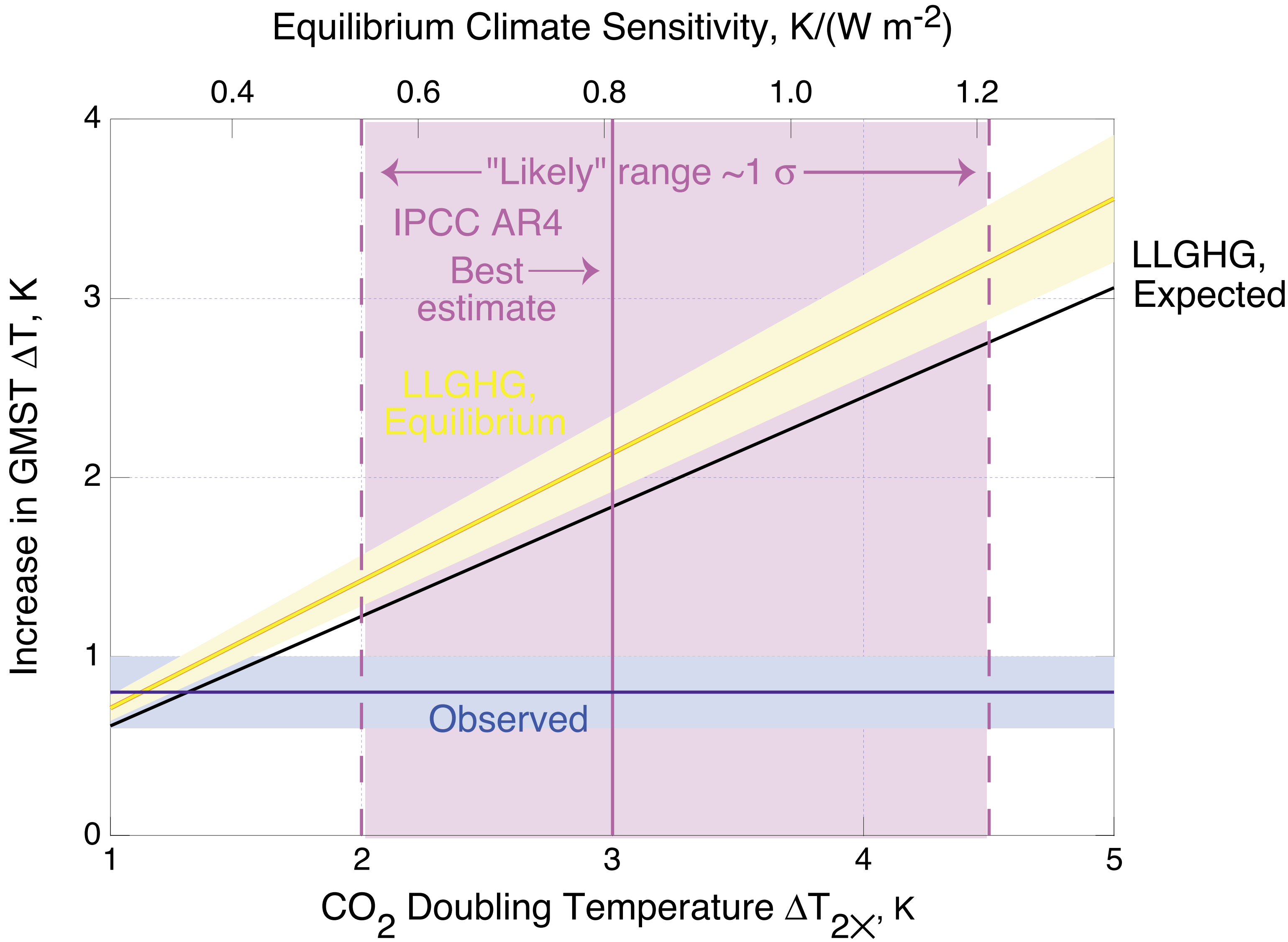
Accounting for heat to 3 km: factor of 1.44.

Accounting for other heat sinks (air, land, melting of ice) factor of 1.19.

Total heating rate 0.37 ± 0.12 W m^{-2}.

EXPECTED INCREASE IN GLOBAL TEMPERATURE

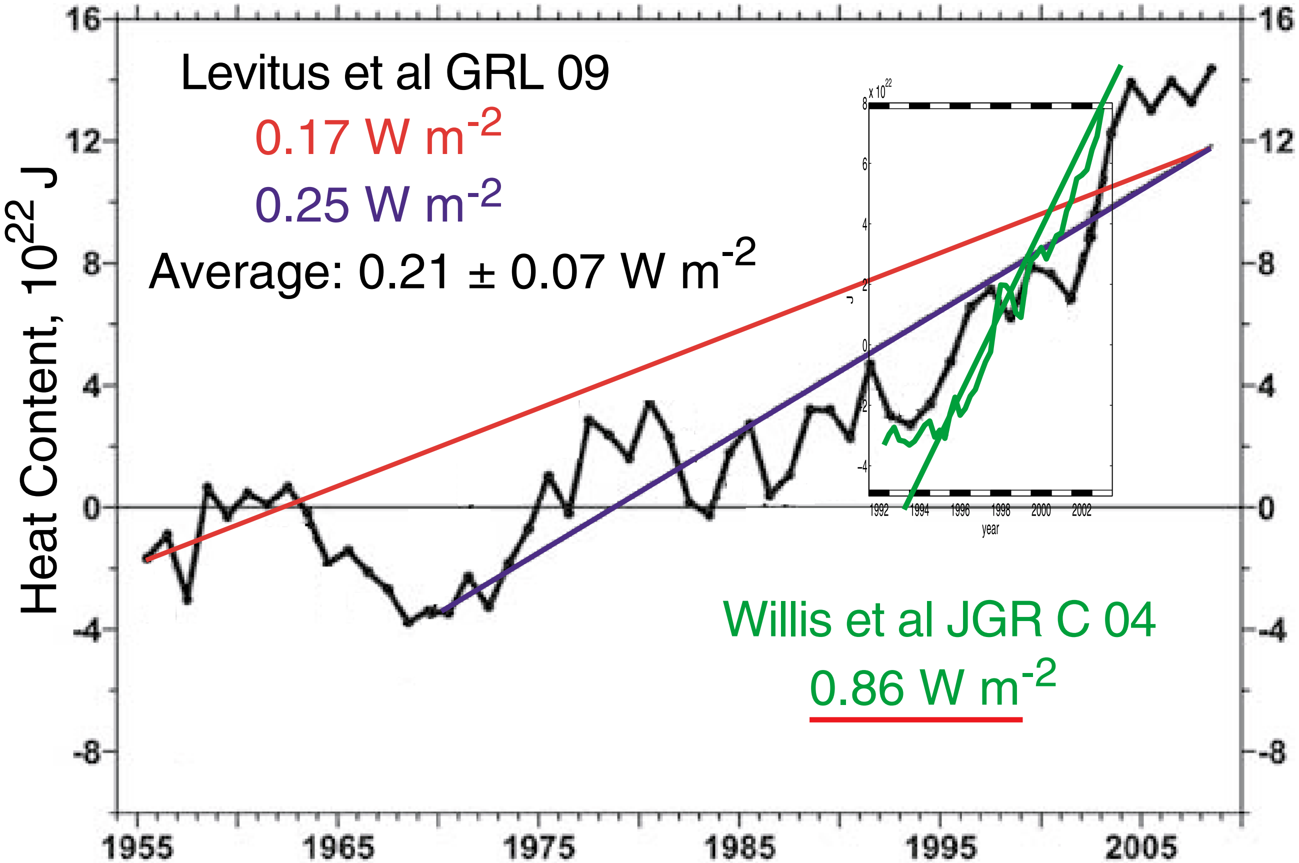
Long-lived GHGs only – Dependence on climate sensitivity



Little of the warming discrepancy can attributed to thermal disequilibrium.

GLOBAL HEATING RATE FROM OCEAN HEAT CONTENT

Heat content of global ocean – surface to 700-750 m

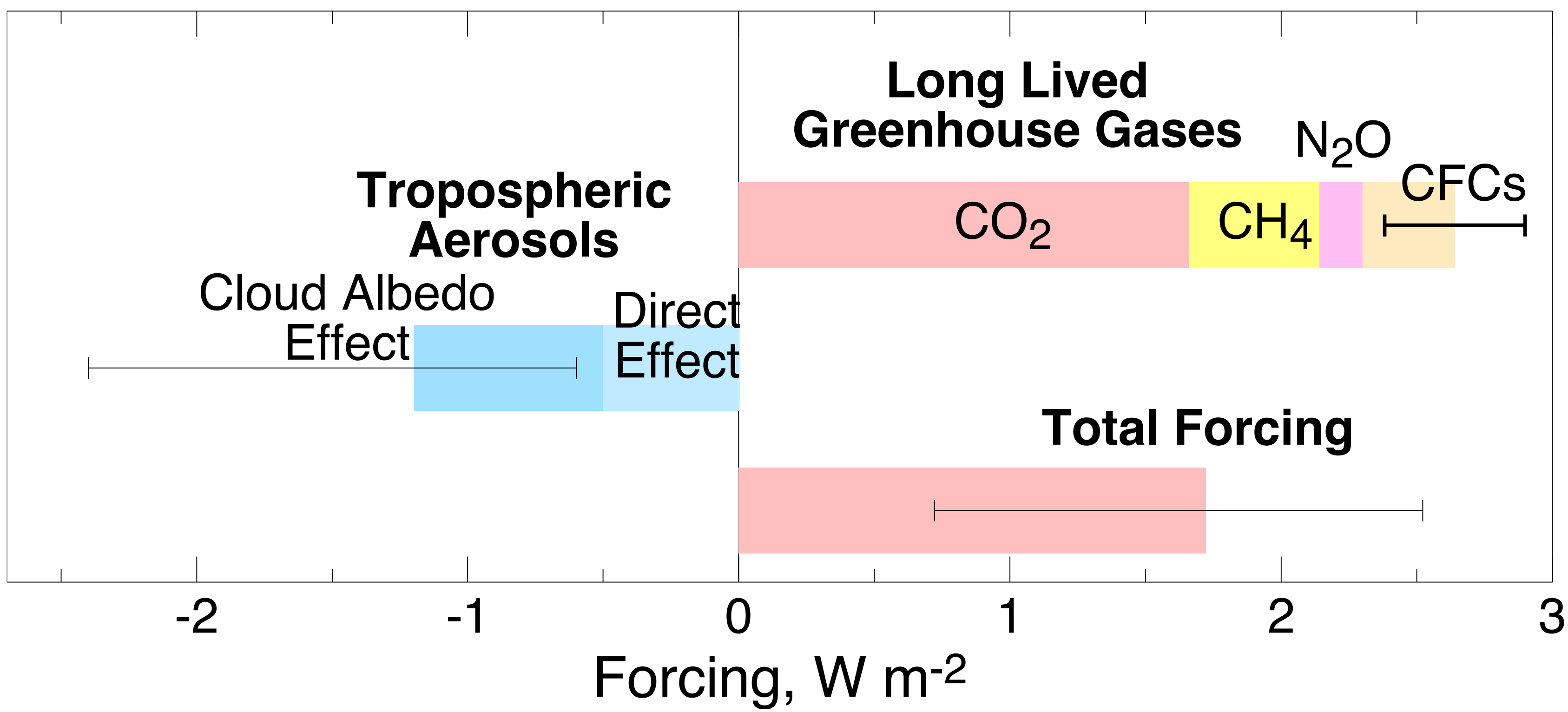


Willis slope is basis of Trenberth *et al*. imbalance.

Heating rate would be even greater if it accounted for deep ocean and other sinks (air, land, melting of ice).

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

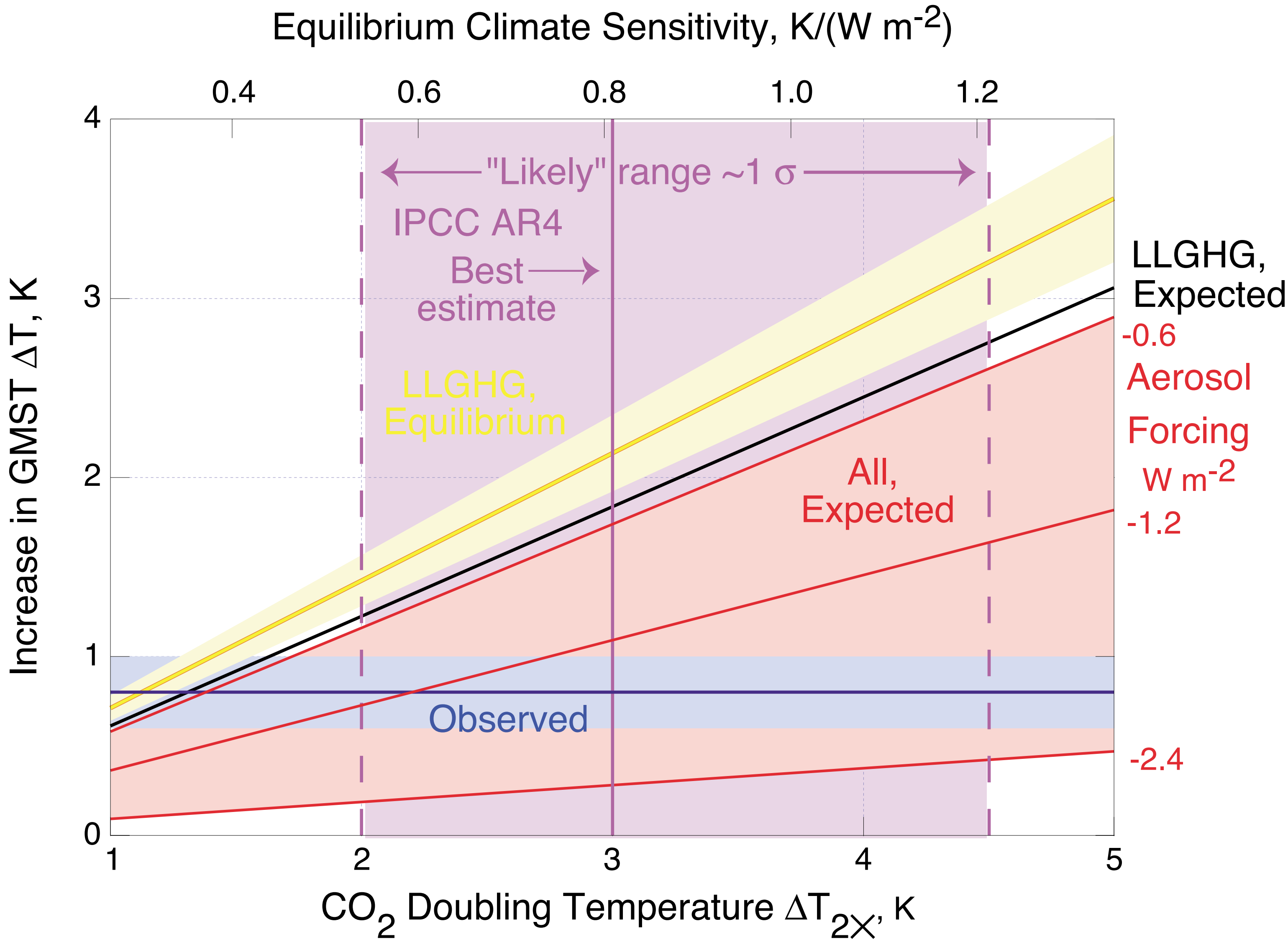
Extracted from IPCC AR4 (2007)



Total forcing includes other anthropogenic and natural (solar) forcings.
Forcing by tropospheric ozone, ~0.35 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.

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

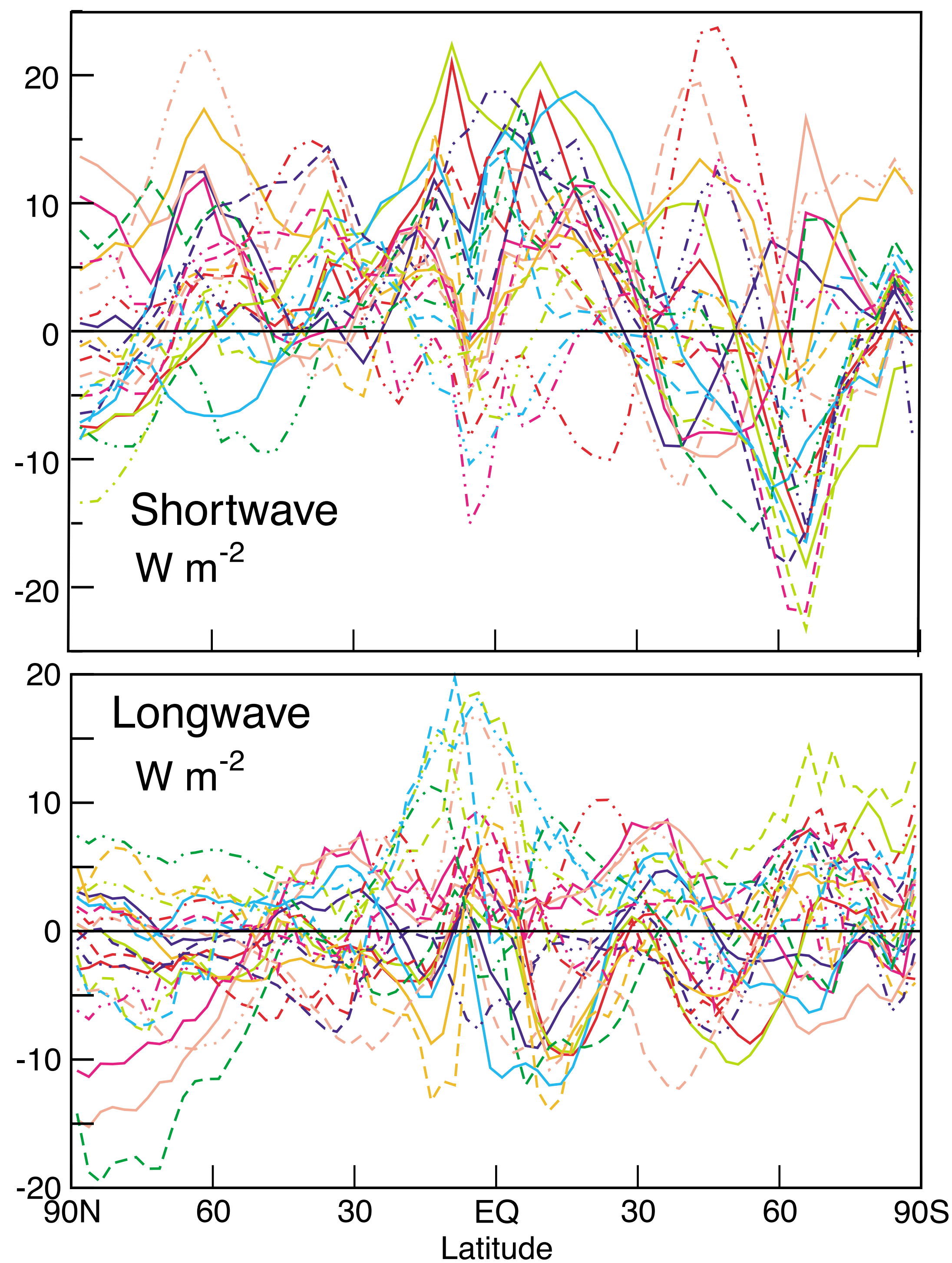
Evaluate by performance on current climate

Evaluate by performance over instrumental record

MODEL ERROR IN UPWELLING TOA IRRADIANCE

Model – ERBE in 23 AR4 Models

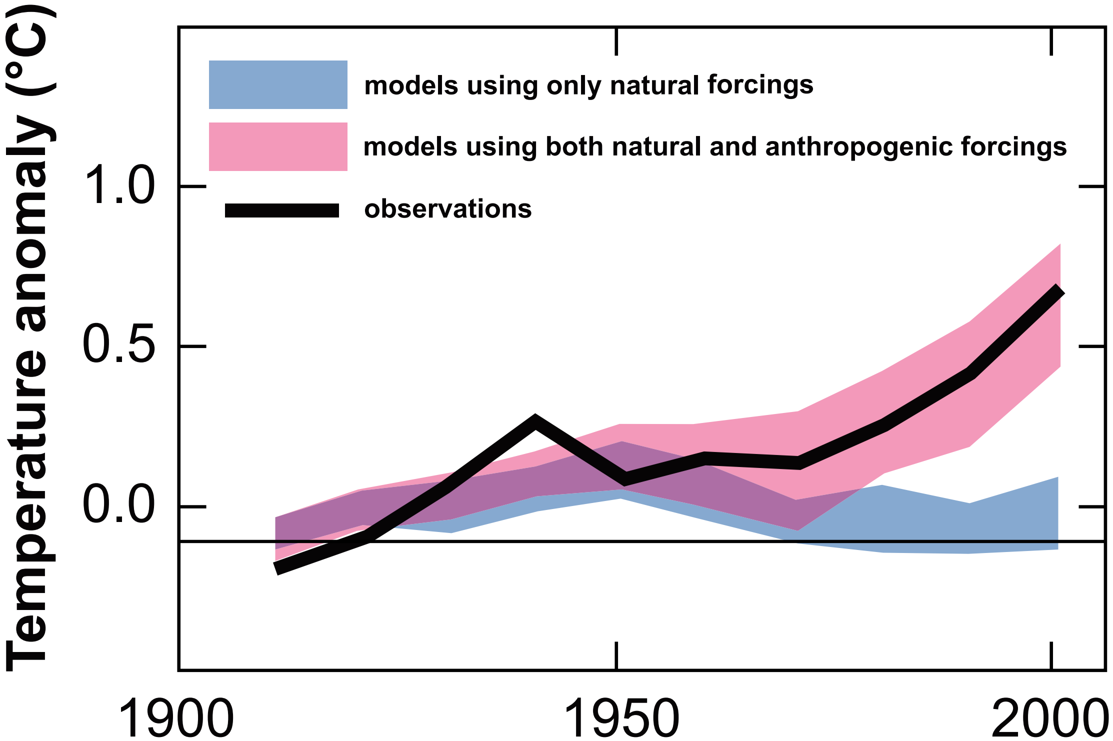
Annual-Zonal Mean for 1985-1989

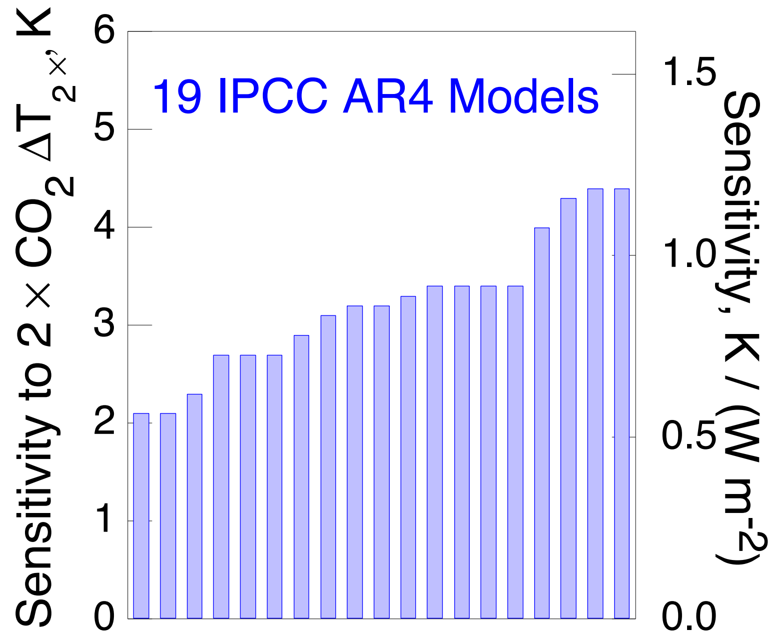


IPCC AR4, Supplement 8, 2007

TOO ROSY A PICTURE?

Ensemble of 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***.

IPCC AR4, 2007

APPROACHES TO DETERMINING CLIMATE SENSITIVITY

Climate models

Evaluate by performance on current climate

Evaluate by performance over instrumental record

Empirical

Paleo: Δ*Temperature*/Δ*Flux*, paleo to present

Instrumental record of temperature and forcing

Sensitivity = *Time constant*/*Heat Capacity*

Satellite measurement: d(*Flux* – *Forcing*)/d*Temperature*

ENERGY BALANCE EQUATION

Global heating rate = Forcing − Response

$$N = F - S^{-1}\Delta T_s$$

Upon rearrangement:

$$F - N = S^{-1}\Delta T_s$$

Suggests plotting $F - N$ vs ΔT_s; slope = S^{-1}.

Concerns:

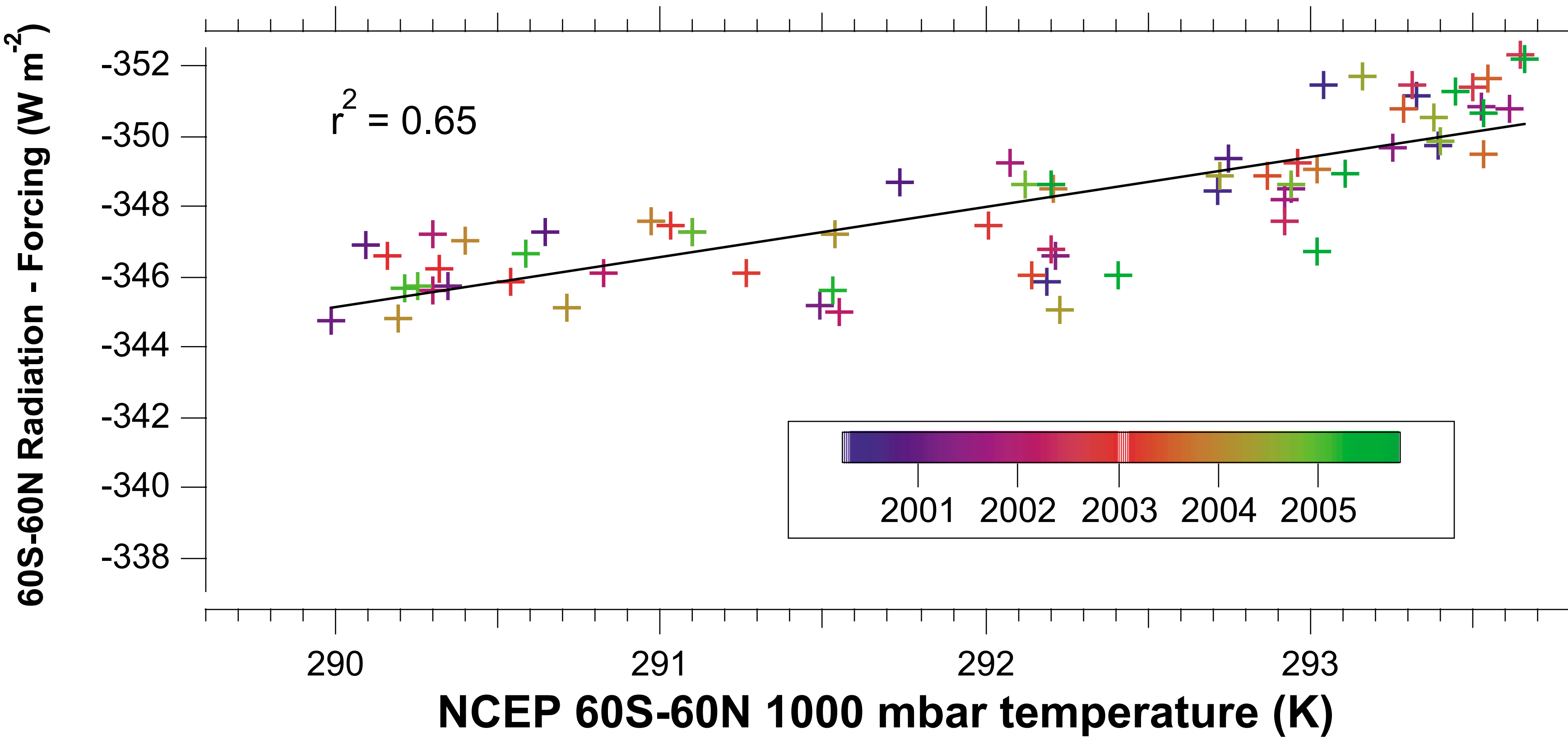
Need to know forcing F.

Need accurate value of heating rate N.

Small range of ΔT_s available to get meaningful slope.

DETERMINATION OF CLIMATE SENSITIVITY

Slope of (Flux – Forcing) vs 60˚N–60˚S Mean Surface Temperature
CERES Monthly Average Total Upwelling TOA Flux
Secular increase in LW GHG forcing



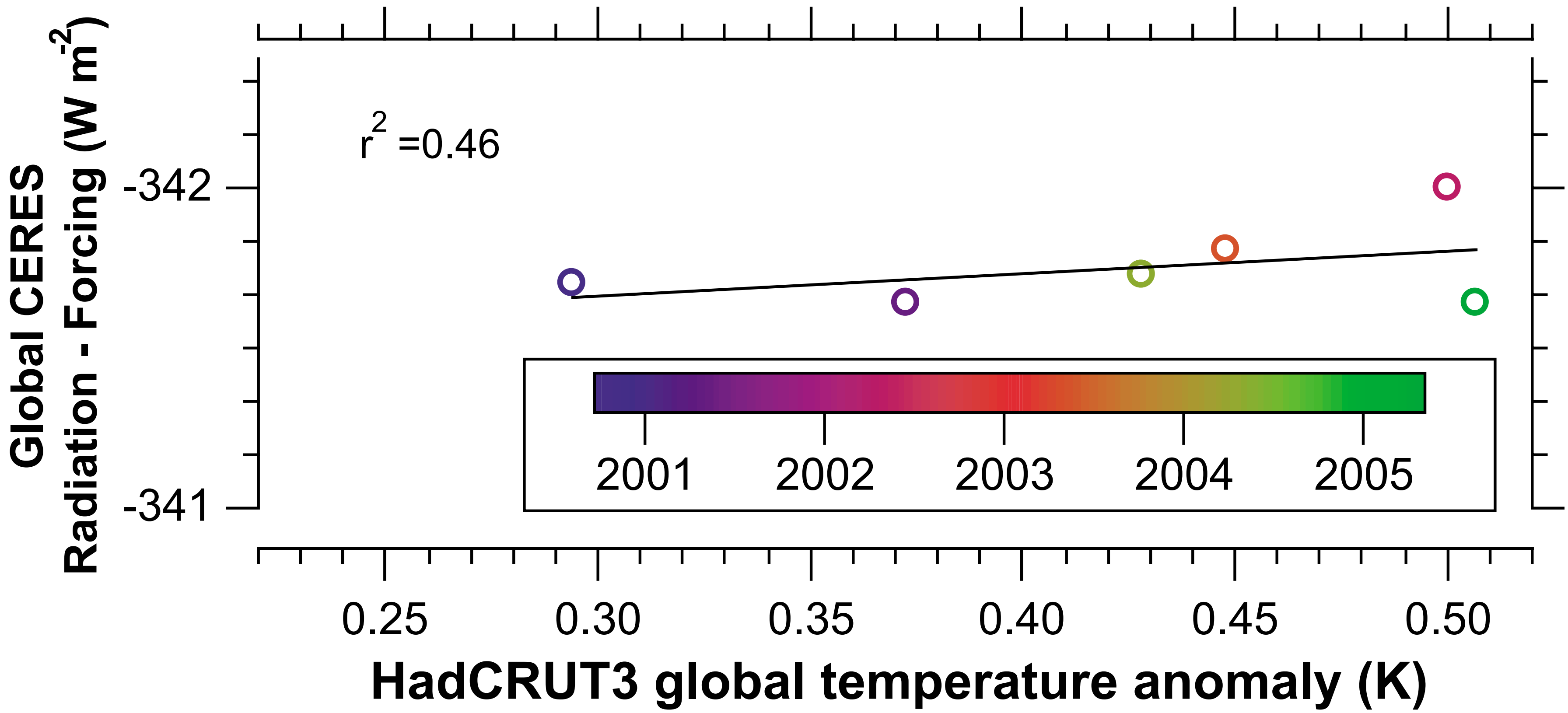
Murphy, Solomon, Portmann, Rosenlof, Forster & Wong, JGR 09

Slope is well defined, leading to precise sensitivity:
$S = 0.70 \pm 0.06$ K/(W m^{-2}); $\Delta T_{2\times} = 2.6 \pm 0.24$ K.

Large temperature span is due to seasonal variation of GMST;
question over applicability to secular temperature change.

DETERMINATION OF CLIMATE SENSITIVITY

Slope of (Flux – Forcing) vs Global Mean Surface Temperature
CERES Annual Average Total Upwelling TOA Flux
Secular increase in LW GHG forcing



Murphy, Solomon, Portmann, Rosenlof, Forster & Wong, JGR 09

Slope is poorly defined, not yielding meaningful sensitivity:
$S^{-1} = 0.69 \pm 0.78$ W m^{-2} K^{-1}; $S = 1.4^{+\infty}_{-0.8}$ K/(W m^{-2}); $\Delta T_{2\times} = 5.4^{+\infty}_{-2.8}$ K.
Cause of interannual variability is not known; might be extended to 2009 to better determine slope.

CONCLUDING OBSERVATIONS

- Accurate knowledge of Earth's climate sensitivity is enormously important to planning the world's energy future.
- Present uncertainty in climate sensitivity does not constrain even the sign of how much more CO_2 can be added to the atmosphere before exceeding any given warming commitment.
- The warming discrepancy is due mainly to climate sensitivity lower than IPCC best estimate and/or offset by aerosol forcing, with little contribution from lack of equilibrium.
- Satellite measurement of Earth's energy imbalance, ***accurate to 1‰***, is essential to determining climate sensitivity.