

UNCERTAINTY IN CLIMATE SENSITIVITY: CAUSES, CONSEQUENCES, CHALLENGES

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Uncertainty in climate sensitivity: Causes, consequences, challenges

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Fossil fuels supply about 85% of the world's primary energy, and future use would not appear limited by availability of reserves, especially of coal. Rather, future use of fossil fuels will likely be limited by controls on the emission of carbon dioxide into the atmosphere that are agreed to by the nations of the world. The increase in atmospheric CO₂ over the past 200 years, mainly from fossil fuel combustion, is confidently thought to have increased global temperatures and induced other changes in Earth's climate, with the prospect of much more severe consequences from projected future emissions. Limiting such changes in Earth's climate would place major constraints on the combustion of fossil fuels and/or the emission of CO₂ into the atmosphere. Developing effective and cost-effective strategies for limiting CO₂ emissions requires the confident ability to project the changes in climate that would result from a given increase in atmospheric CO₂. However, even the change in global mean surface temperature (GMST), the single most important index of climate change, that would result from a given increase in atmospheric CO₂ remains uncertain to a factor of 2 or more, largely because of uncertainty in Earth's climate sensitivity, the change in GMST per change in radiative flux. This uncertainty in climate sensitivity, which gives rise to a comparable uncertainty in the shared global resource of the amount of fossil fuel that can be burned consonant with a given increase in global mean surface temperature, greatly limits the ability to effectively formulate strategies to limit climate change while meeting the world's future energy requirements. Key limits on determining climate sensitivity are the small change in downwelling longwave irradiance, less than one percent, that would give rise to changes in climate that reach the level of concern, the complexity of cloud processes and the difficulty of representing them in climate models, and limited understanding of the processes that control the radiative influences of atmospheric aerosols. A recent empirical calculation of Earth's climate sensitivity as the quotient of the relaxation time constant of GMST upon the effective heat capacity characterizing climate change on the multidecadal time scale points to a possible alternative approach to determining Earth's climate sensitivity. While improved knowledge of Earth's climate sensitivity is essential to development of optimal energy strategies, even for climate sensitivity at the low end of the range of present estimates, substantial reductions in CO₂ emissions from their present values would be required to avert dangerous anthropogenic interference with the climate system that would otherwise occur well before the end of the present century.

OVERVIEW

Earth 's energy balance and perturbations

Climate sensitivity – definition, past and current estimates

Approaches to determining Earth's climate sensitivity

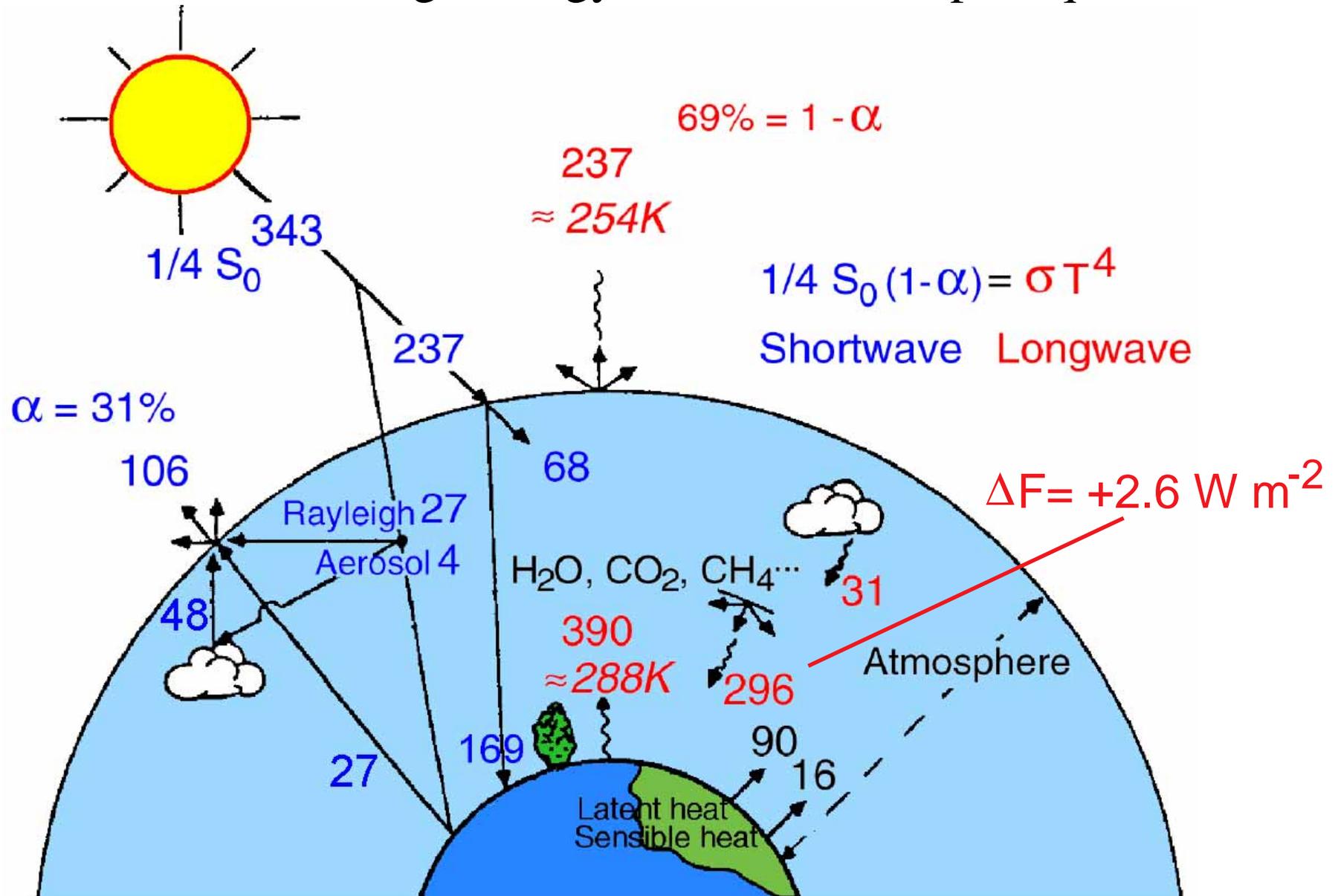
Uncertainty in aerosol forcing and its implications

Looking to the future

Concluding remarks

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

RADIATIVE FORCING

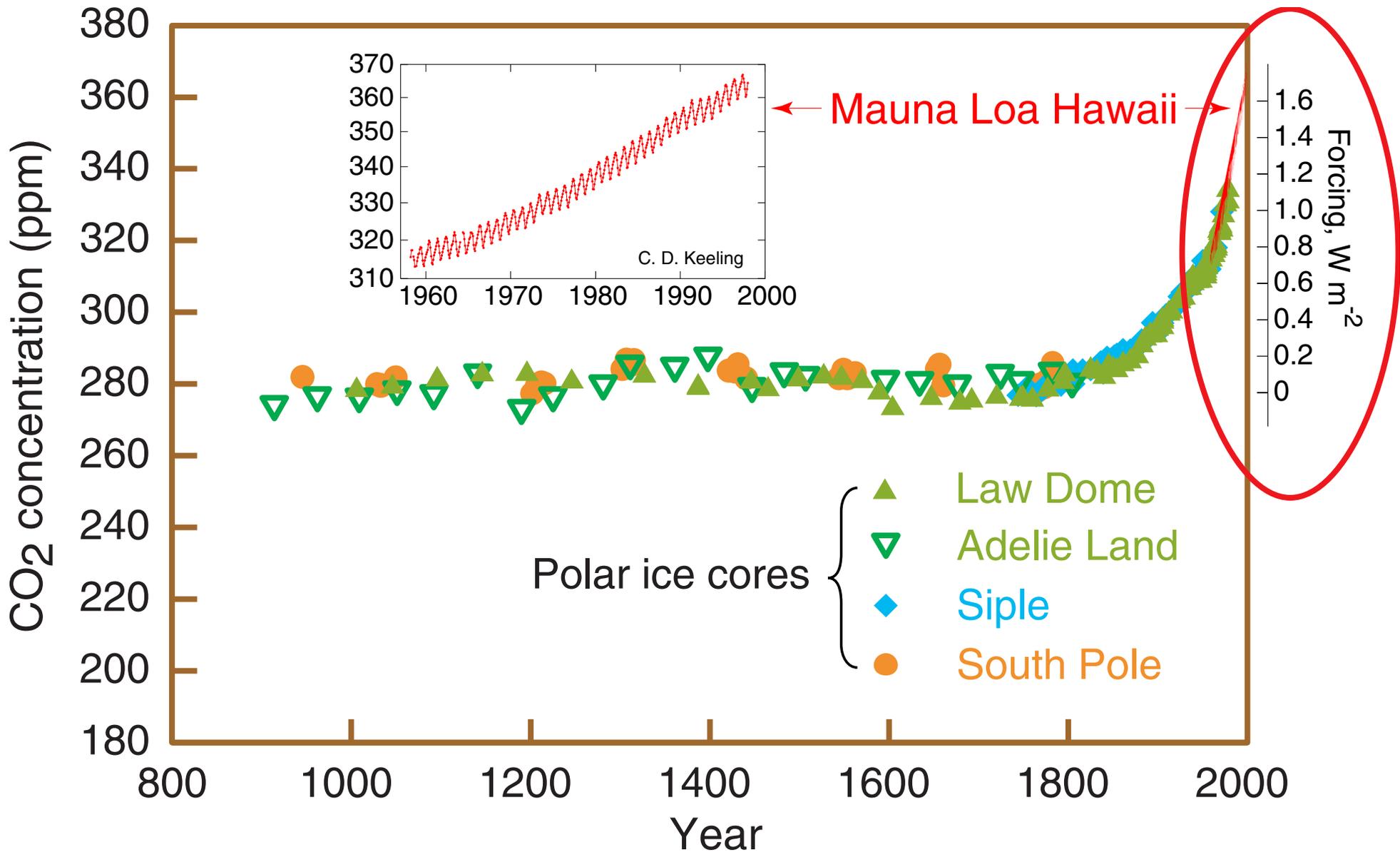
A *change* in a radiative flux term in Earth's radiation budget, ΔF , W m^{-2} .

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

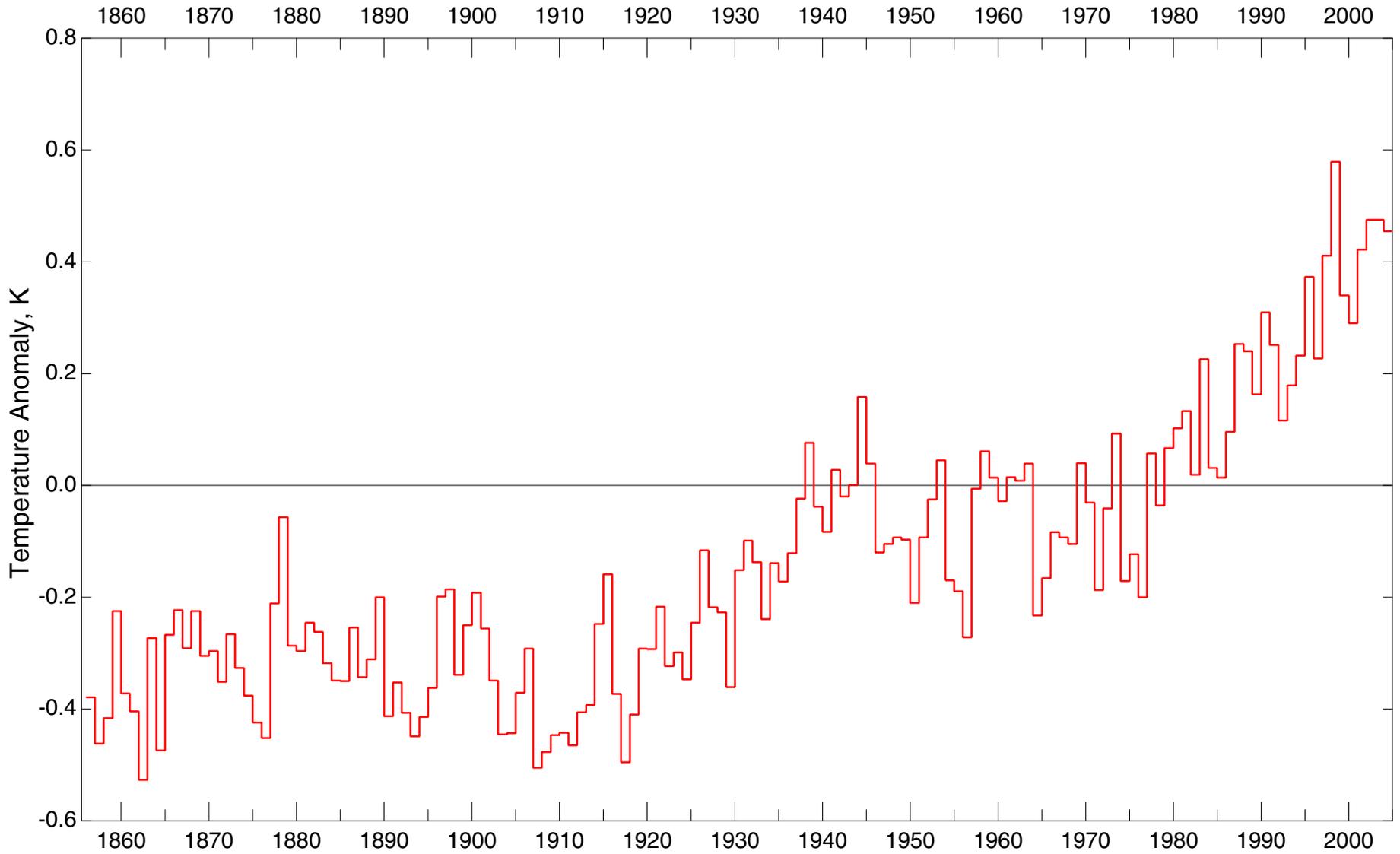
- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



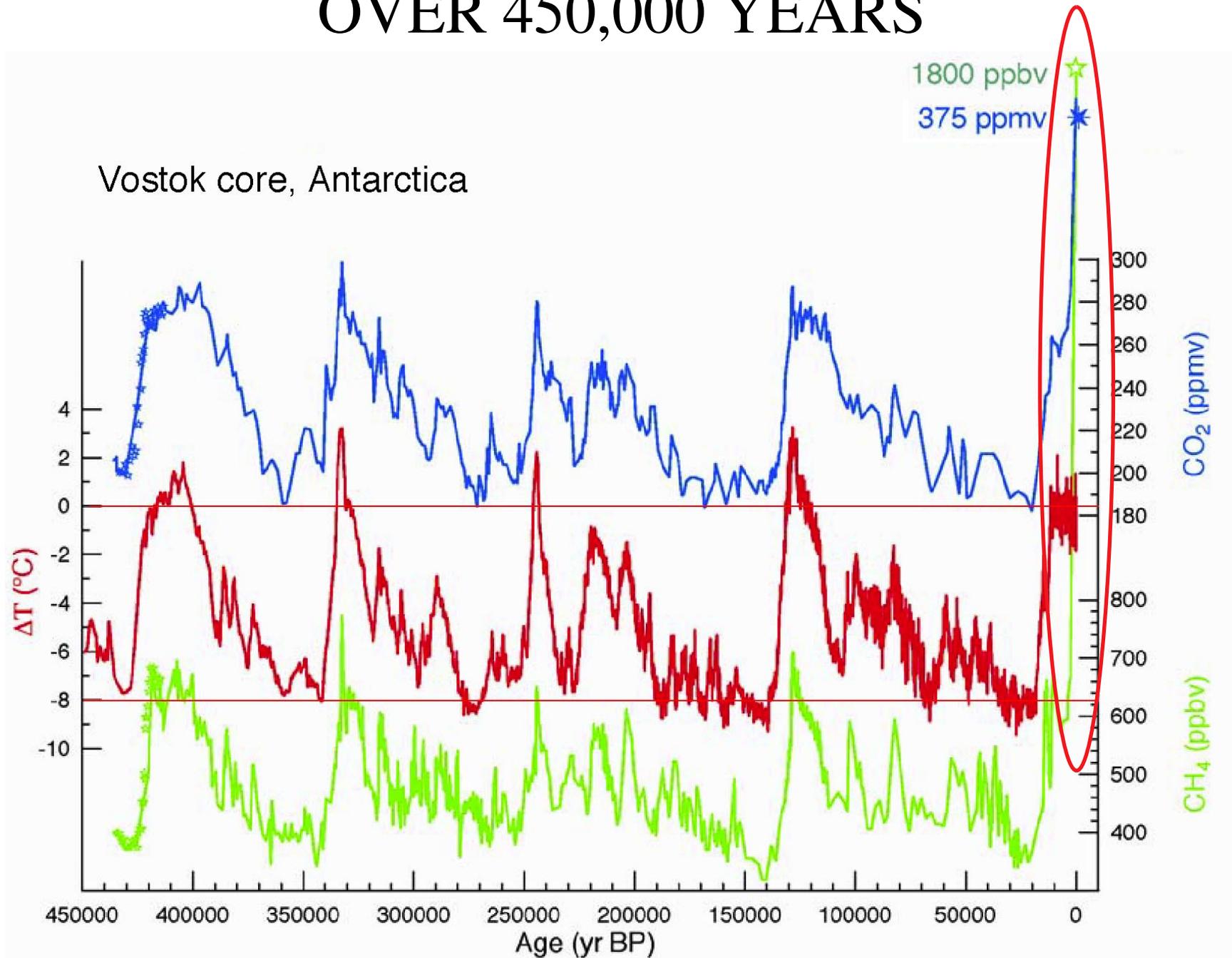
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004



Climate Research Unit, University of East Anglia, UK

GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS



Modified from Petit et al., Nature, 1999

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 , $\text{K}/(\text{W m}^{-2})$,

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

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

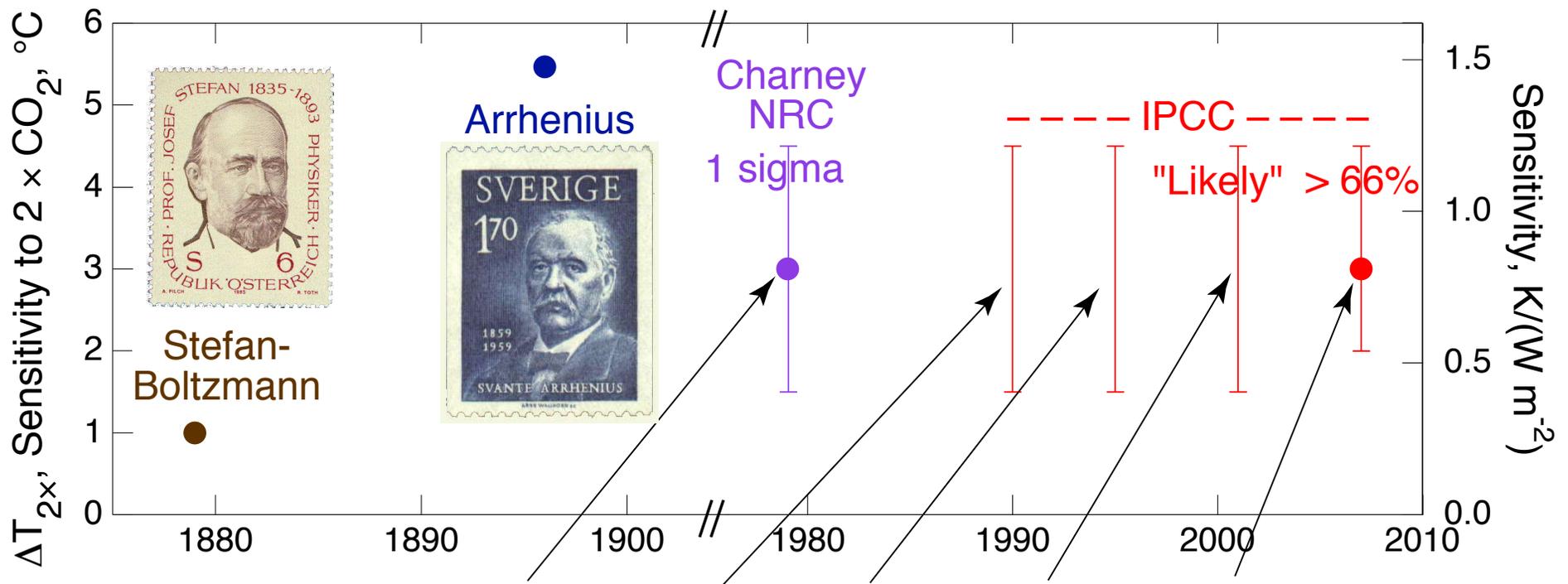
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

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

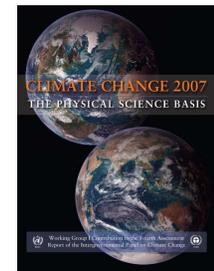
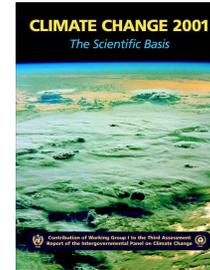
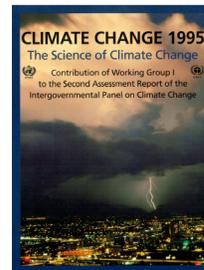
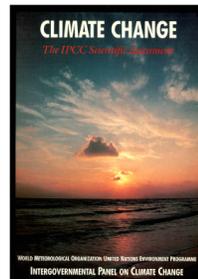
$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments



**Carbon Dioxide and Climate:
A Scientific Assessment**
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1979

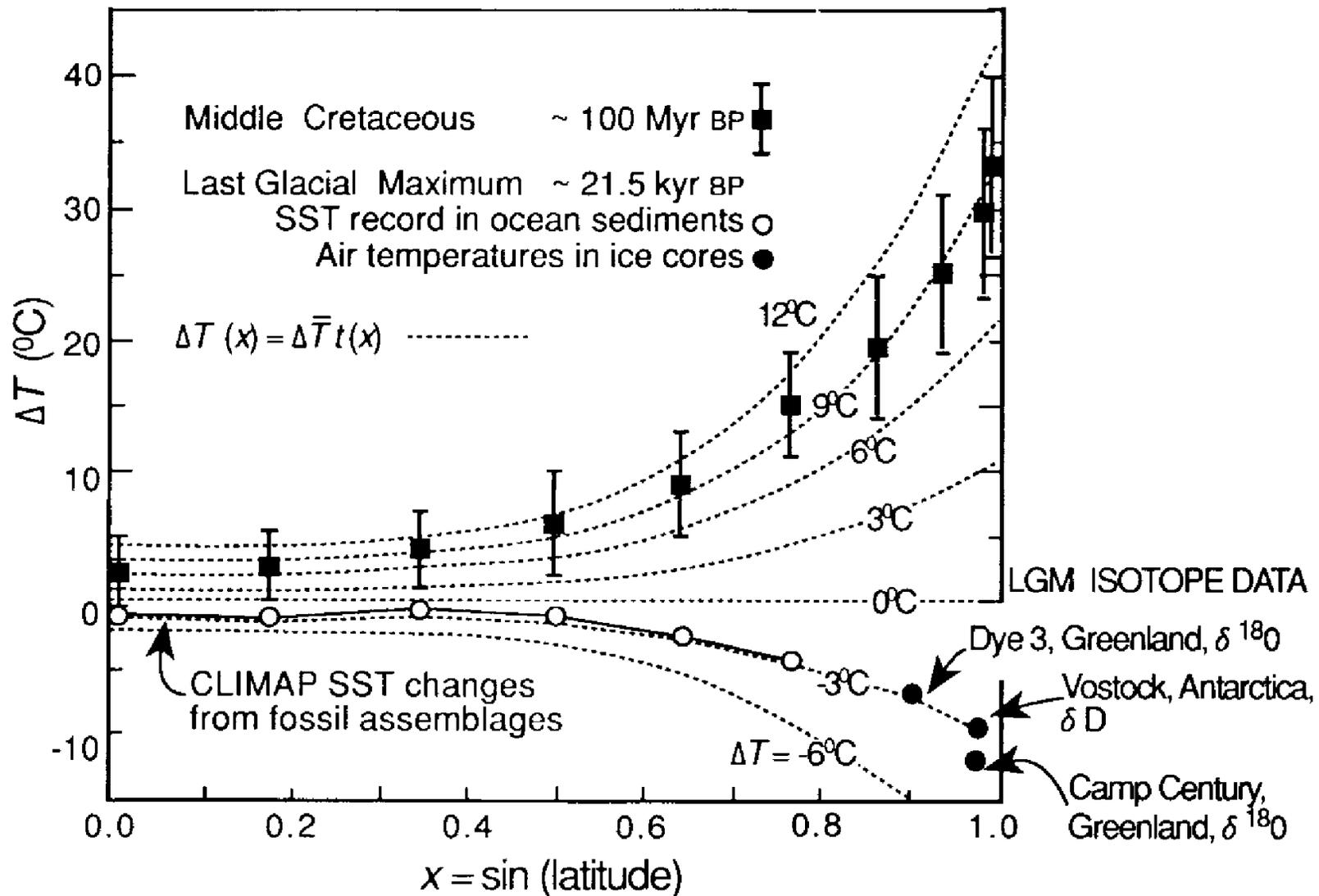


Despite extensive research, climate sensitivity remains *highly uncertain*.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- *Paleoclimate studies*: Forcing and response over time scales from millennial to millions of years.

GLOBAL MEAN TEMPERATURE FROM PALEO DATA



Hoffert & Covey, Nature, 1992

Last Glacial Maximum: $\Delta T = -3$ K; Middle Cretaceous, $\Delta T = +9$ K.

CLIMATE SENSITIVITY FROM PALEO DATA

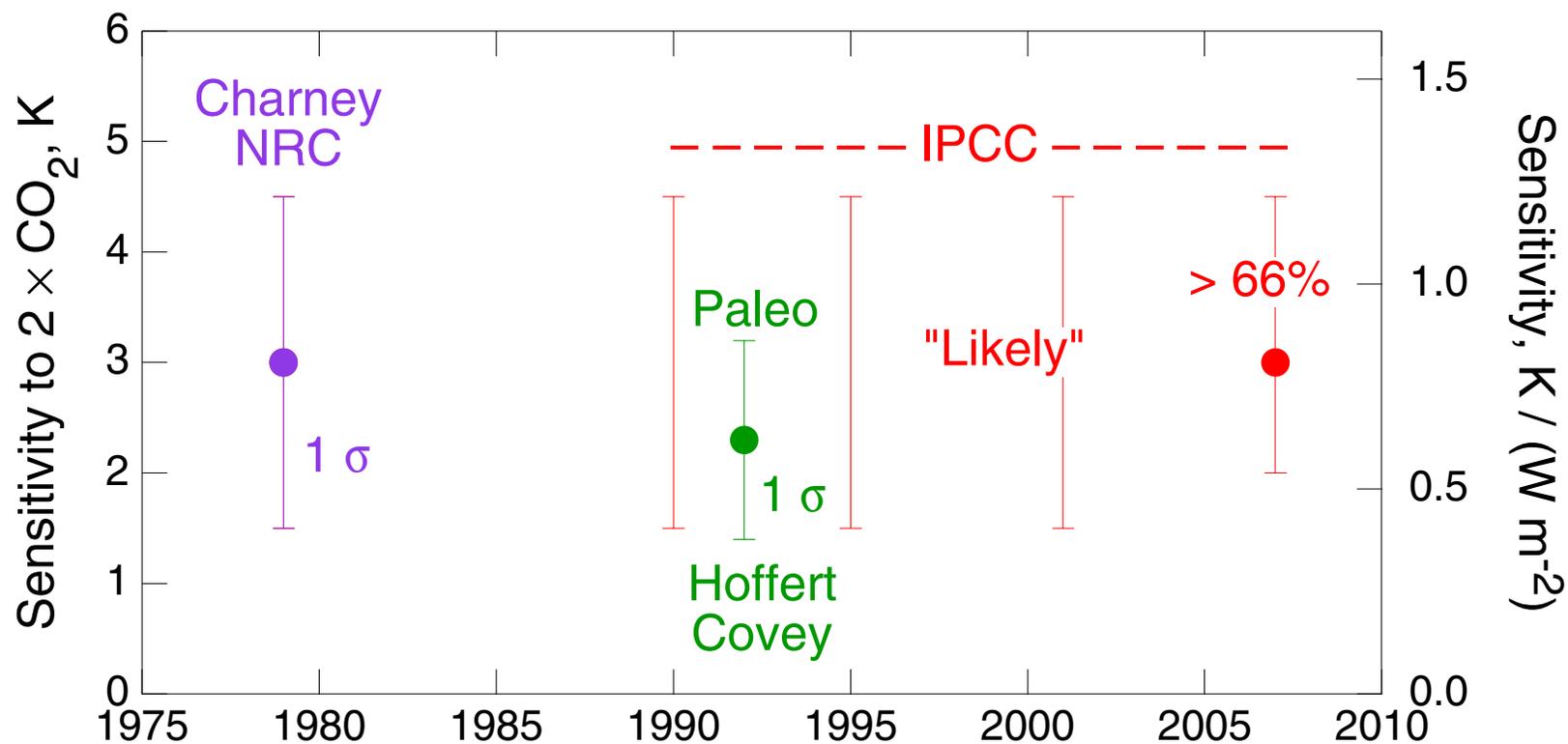
Component	Last Glacial Maximum	Middle Cretaceous
Forcing, W m^{-2}	Value $\pm 1 \sigma$	Value $\pm 1 \sigma$
Sun	0.0 ± 0.2	-1.2 ± 0.2
Albedo	-3.0 ± 0.5	5.8 ± 0.9
Greenhouse	-2.8 ± 0.3	11.1 ± 6.7
Aerosol	-0.9 ± 0.7	
Total ΔF , W m^{-2}	-6.7 ± 0.9	15.7 ± 6.8
ΔT , K	-3.0 ± 0.5	9.0 ± 2.0
S , $\text{K}/(\text{W m}^{-2})$	0.45 ± 0.11	0.57 ± 0.27
$\Delta T_{2\times}$, K ($F_{2\times} = 4.4 \text{ W m}^{-2}$)	2.0 ± 0.5	2.5 ± 1.2

Hoffert & Covey, Nature, 1992

Best estimate $S = 0.51 \pm 0.2 \text{ K}/(\text{W m}^{-2})$; $\Delta T_{2\times} = 2.3 \pm 0.9 \text{ K}$ (1σ).

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from specific approaches and major national and international assessments



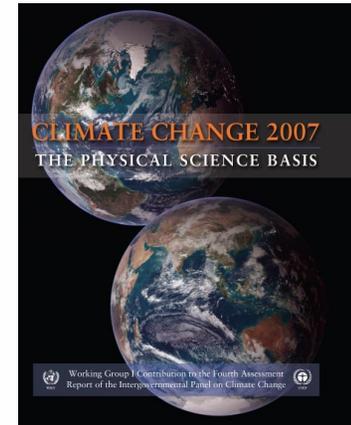
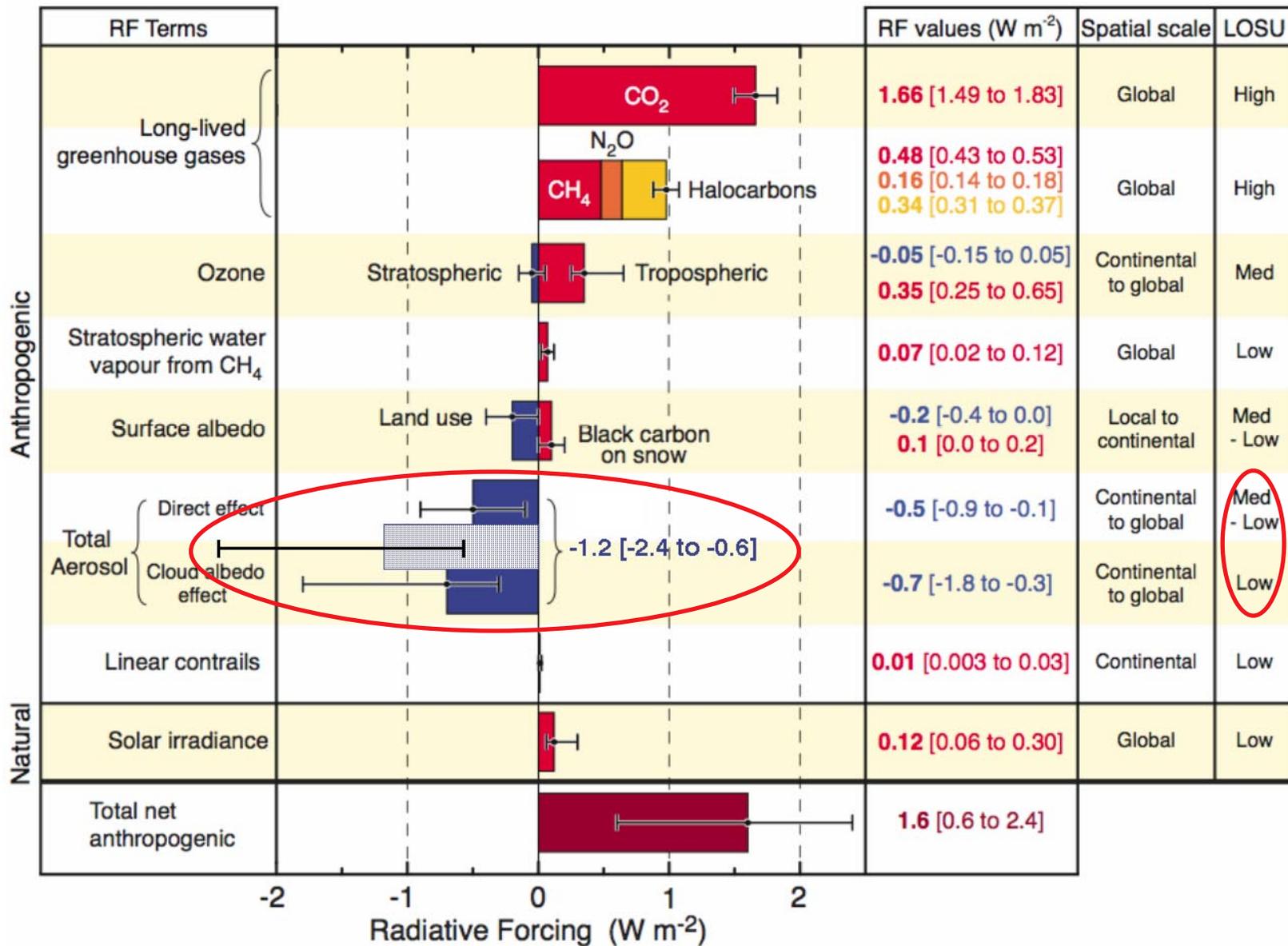
Climate sensitivity from paleo climate has been a major contributor to present assessment of climate sensitivity.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.
- ***Empirical***: Forcing and response over the instrumental record.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

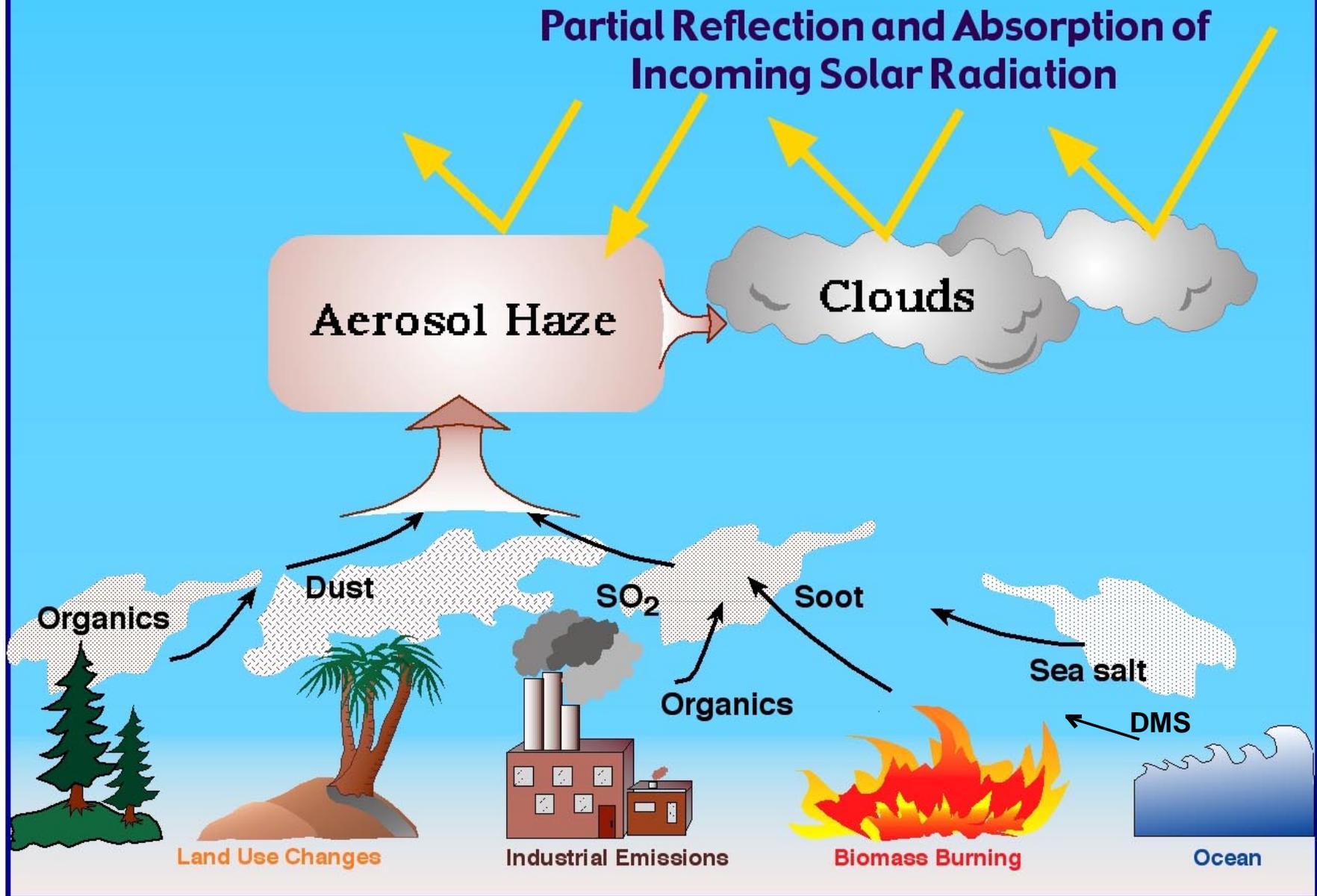
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)



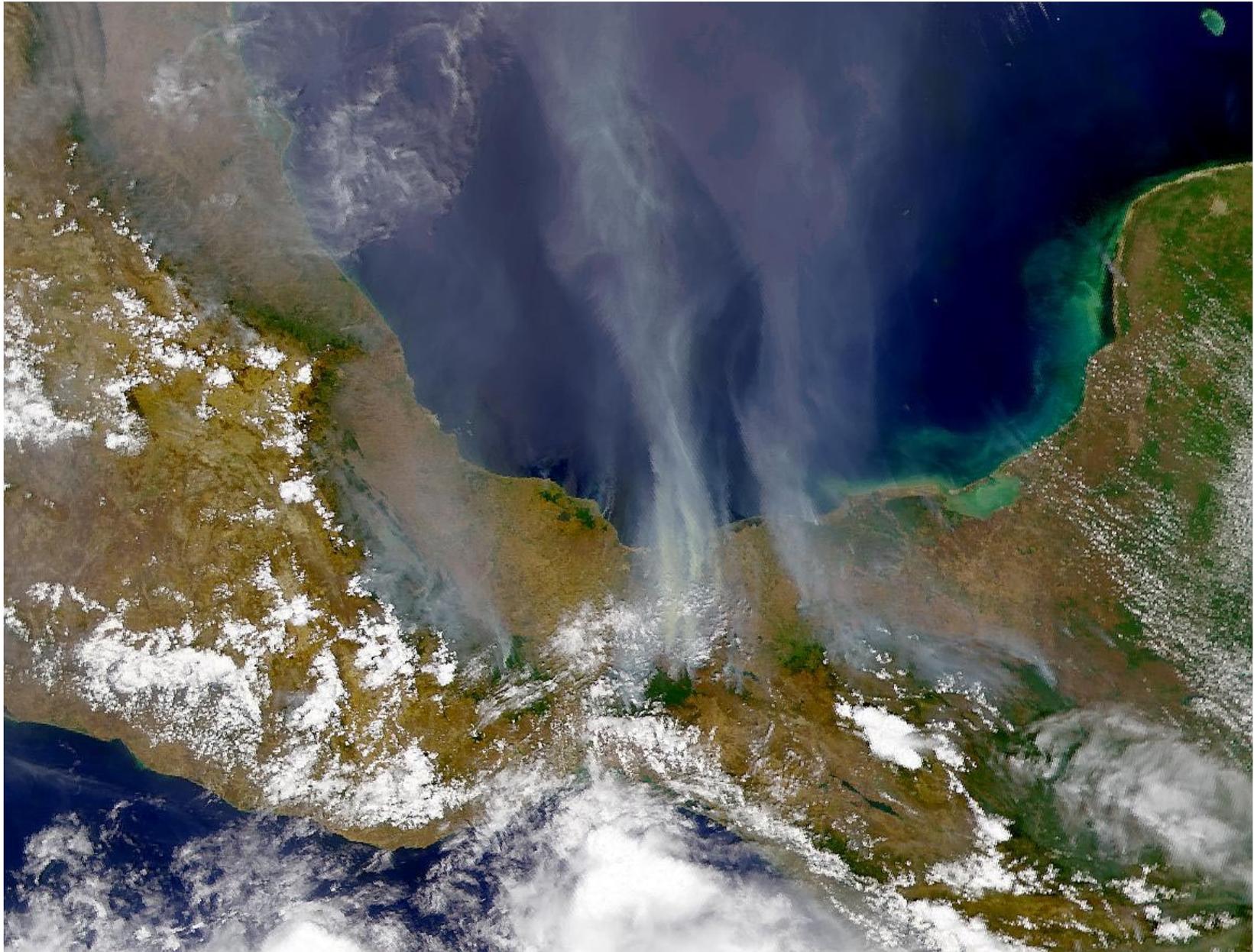
©IPCC 2007: WG1-AR4

LOSU denotes level of scientific understanding.

Radiative Forcing by Tropospheric Aerosol



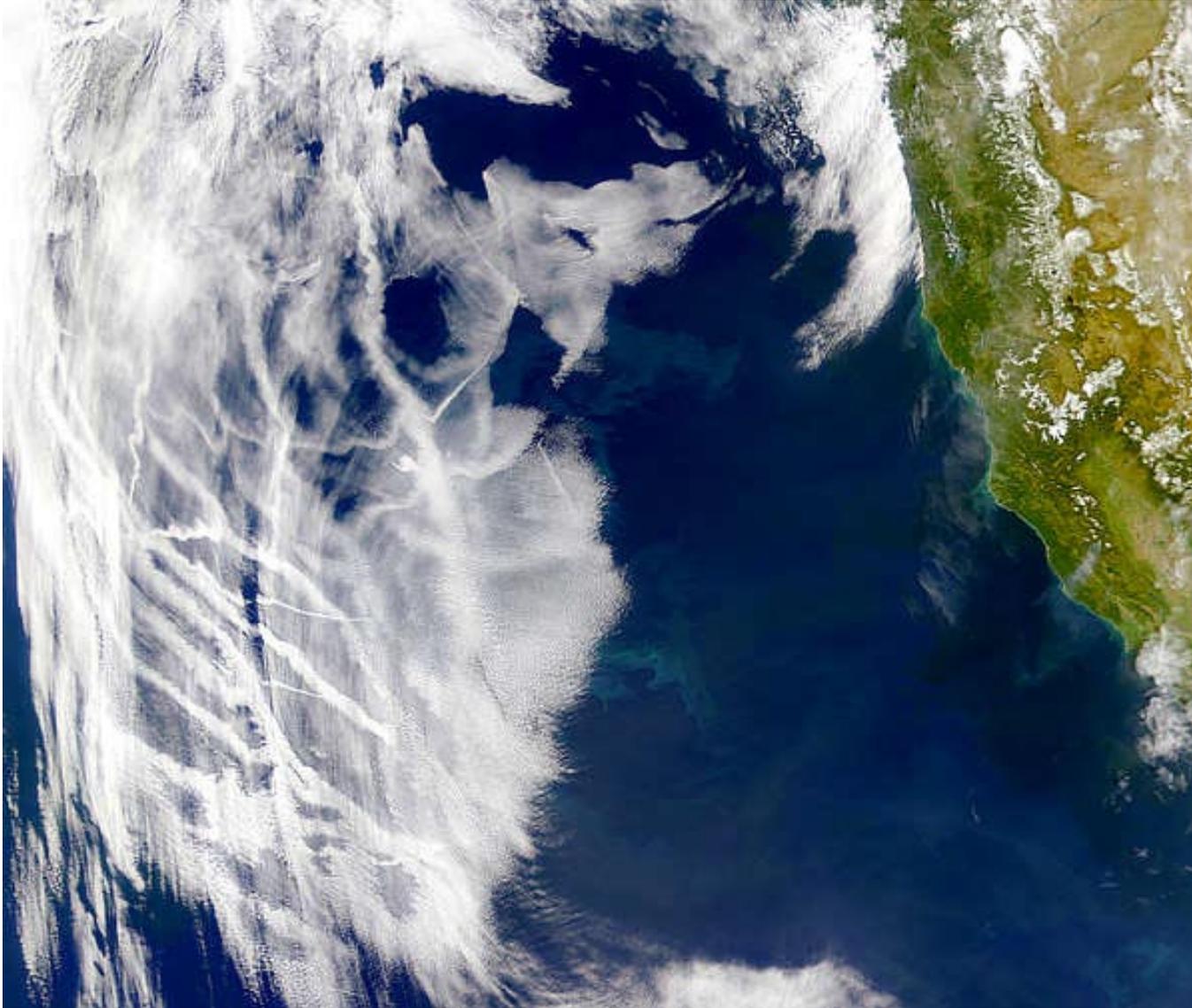
AEROSOLS AS SEEN FROM SPACE



Fire plumes from southern Mexico transported north into Gulf of Mexico.

CLOUD BRIGHTENING BY SHIP TRACKS

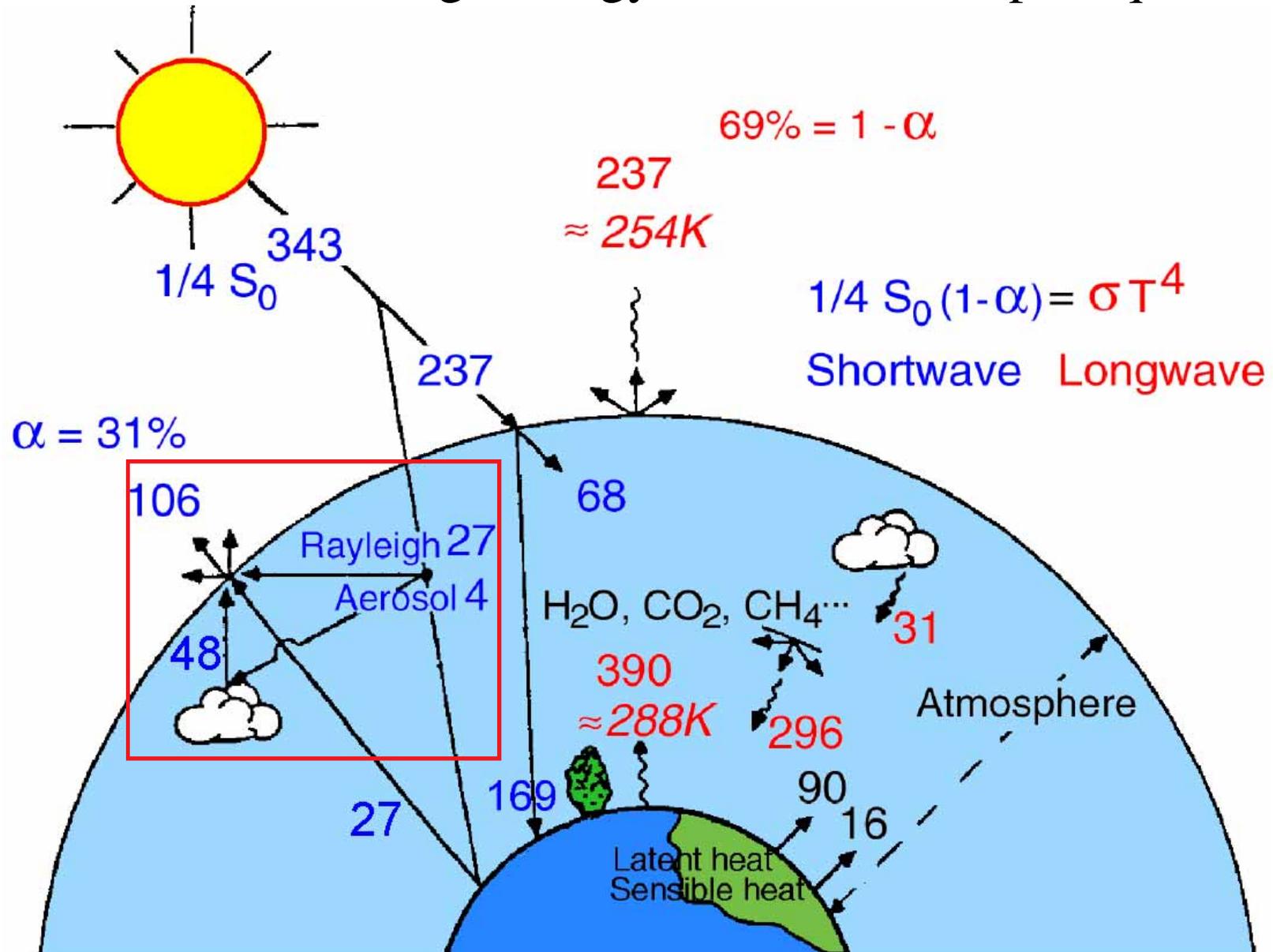
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

GLOBAL ENERGY BALANCE

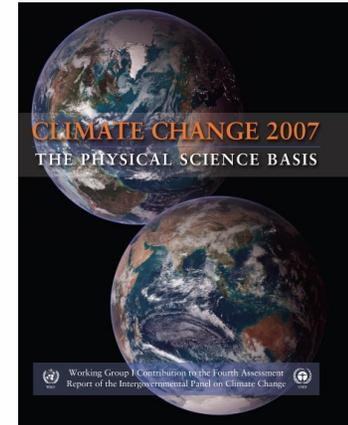
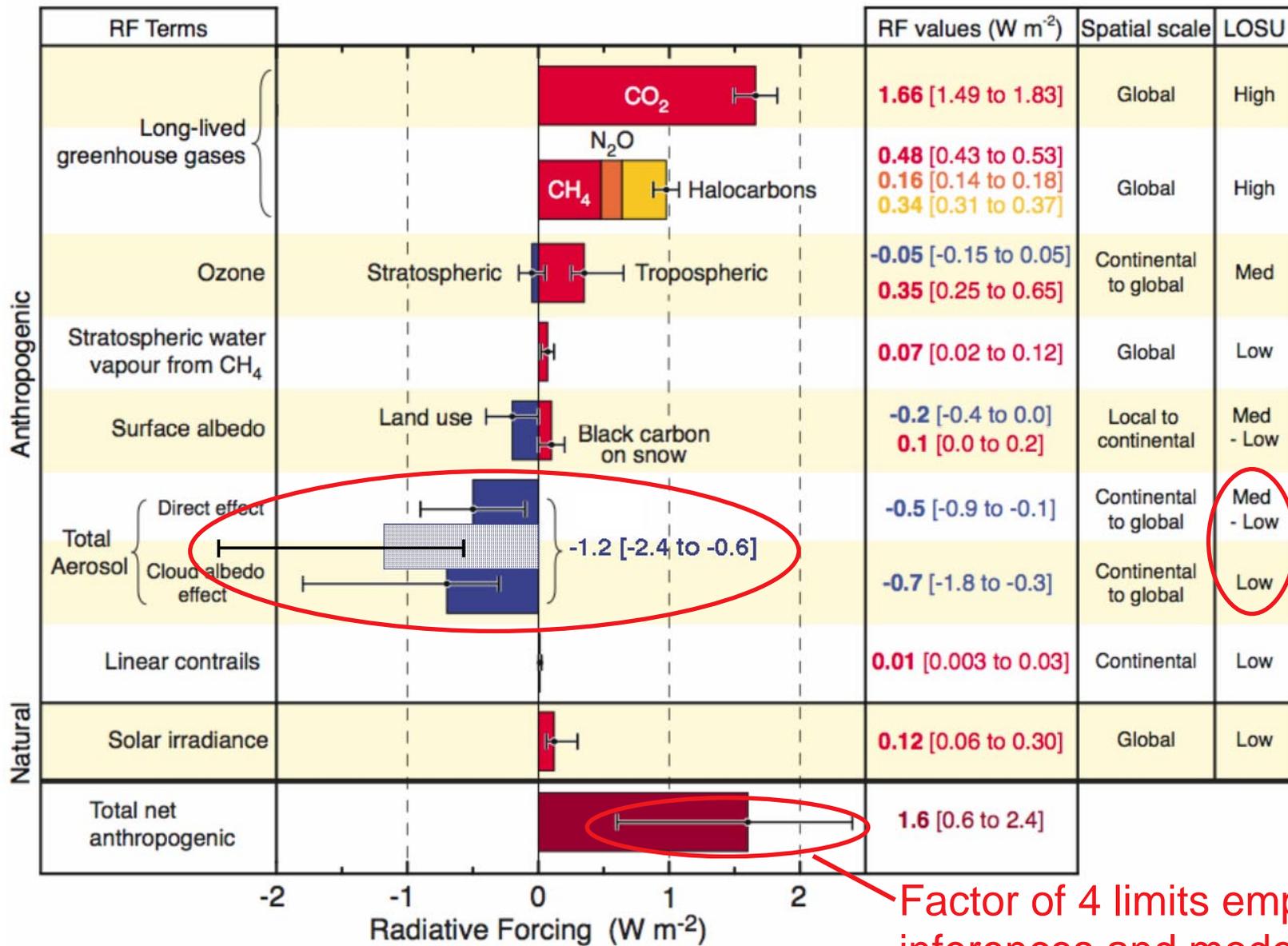
Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)



Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

Uncertainty range: 5 - 95%.

EMPIRICAL DETERMINATION OF CLIMATE SENSITIVITY OVER INDUSTRIAL PERIOD

Sensitivity is temperature change upon forcing accounting for transient heat uptake – *modified from Gregory et al. J. Clim. 2002*

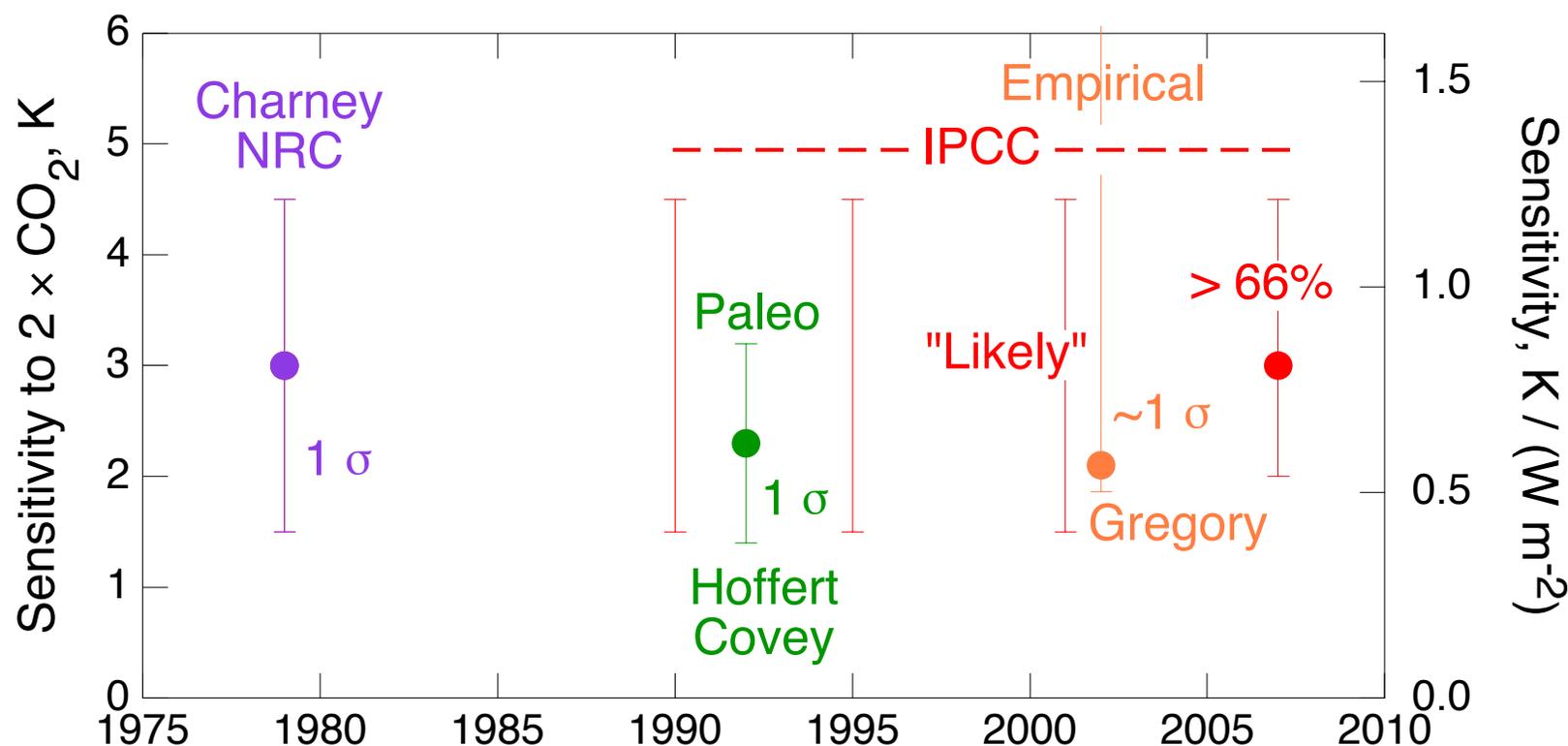
$$S = \frac{\Delta T}{\Delta F - (dH / dt)}$$

Evaluated for 1957-1994 vs. 1861-1900 for $\Delta F_{2\times} = 3.71 \text{ W m}^{-2}$

Symbol	Quantity	Value $\pm 1\sigma$	Unit
ΔT	Temperature change	0.335 ± 0.017	K
ΔF	Forcing	0.35 ± 0.33	W m^{-2}
dH / dt	Planetary heat uptake rate	0.16 ± 0.08	W m^{-2}
S	Climate sensitivity	$0.56^{+2.2}_{-0.07}$	$\text{K}/(\text{W m}^{-2})$
$\Delta T_{2\times}$	ΔT for doubled CO_2	$2.1^{+8}_{-0.24}$	K

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from specific approaches and major national and international assessments



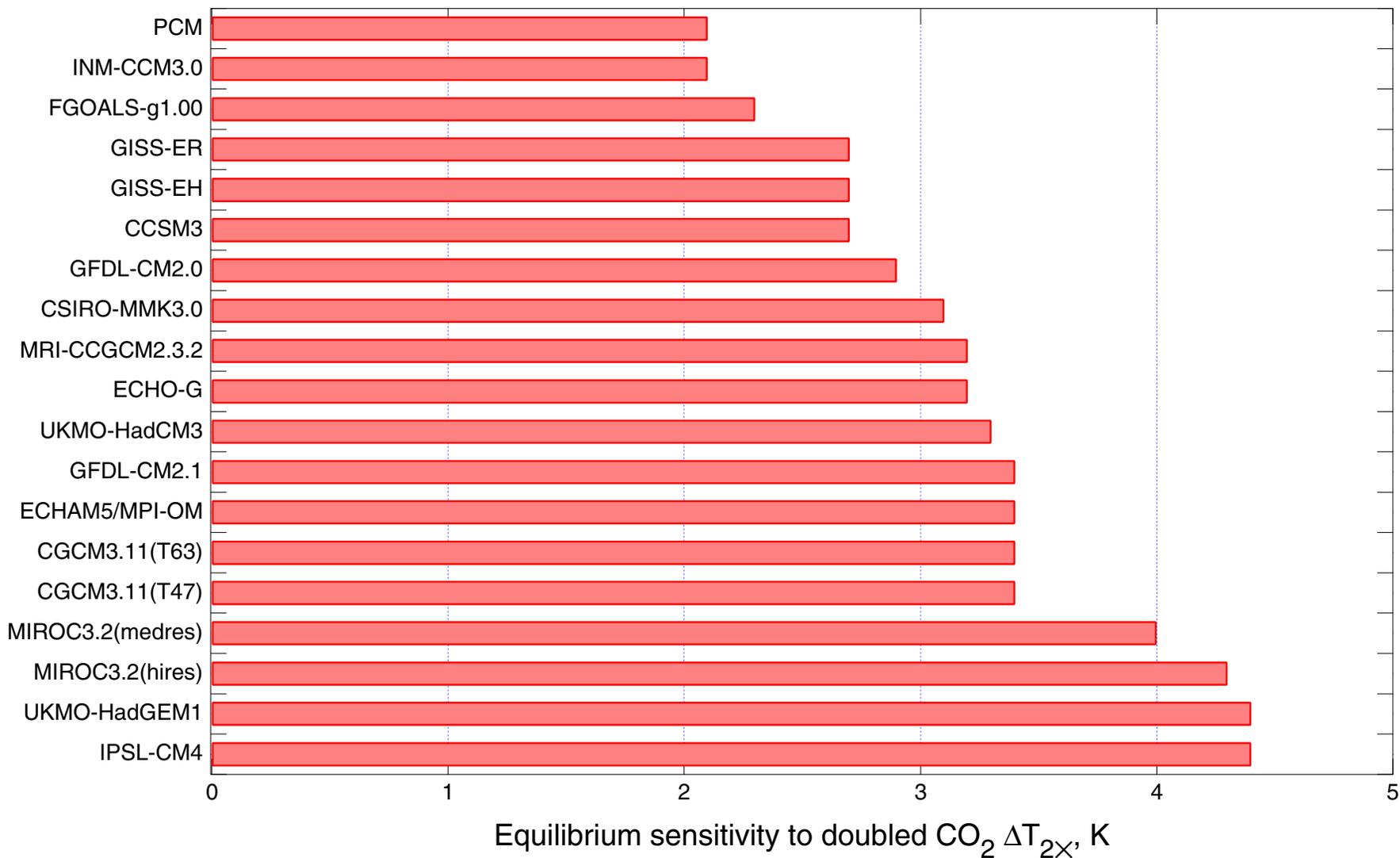
Empirical approach does not greatly constrain sensitivity because of uncertainty in aerosol forcing over the period of instrumental record.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.
- ***Empirical***: Forcing and response over the instrumental record.
- ***Climate modeling***: Understanding the processes that comprise Earth's climate system and representing them in large-scale numerical models.

EQUILIBRIUM SENSITIVITIES IN CURRENT CLIMATE MODELS

20 Models employed in IPCC AR4 simulations



Sensitivity varies by more than a factor of 2.

CLOUD FEEDBACK STRENGTH AND CLIMATE SENSITIVITY IN 9 GCMS

$$S = S_{SB} \frac{1}{1 - \mathcal{F}}$$

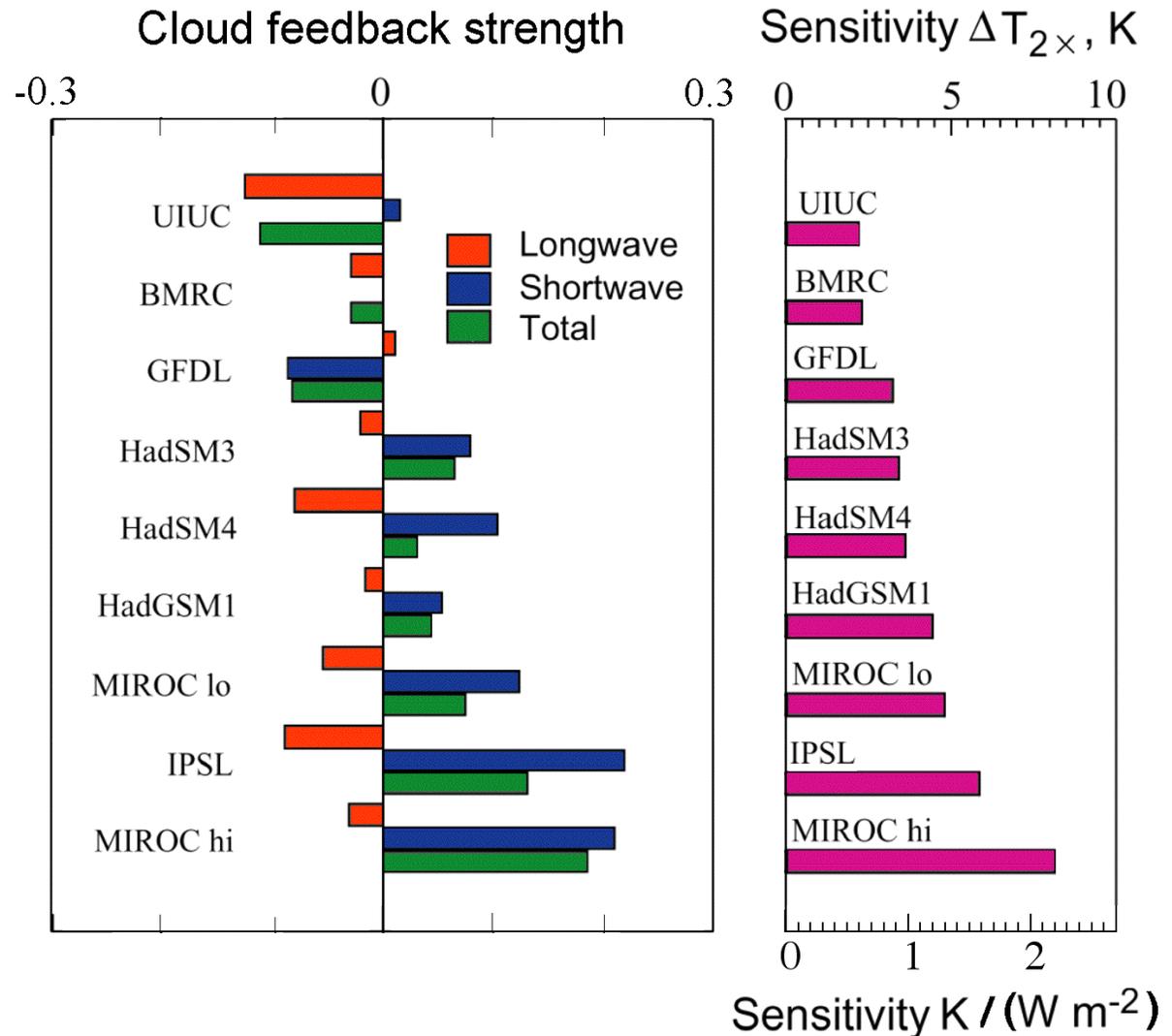
S = Climate sensitivity

S_{SB} = Stefan-Boltzmann sensitivity

\mathcal{F} = feedback strength

$$\mathcal{F} = \sum \mathcal{F}_i$$

sum over all feedbacks

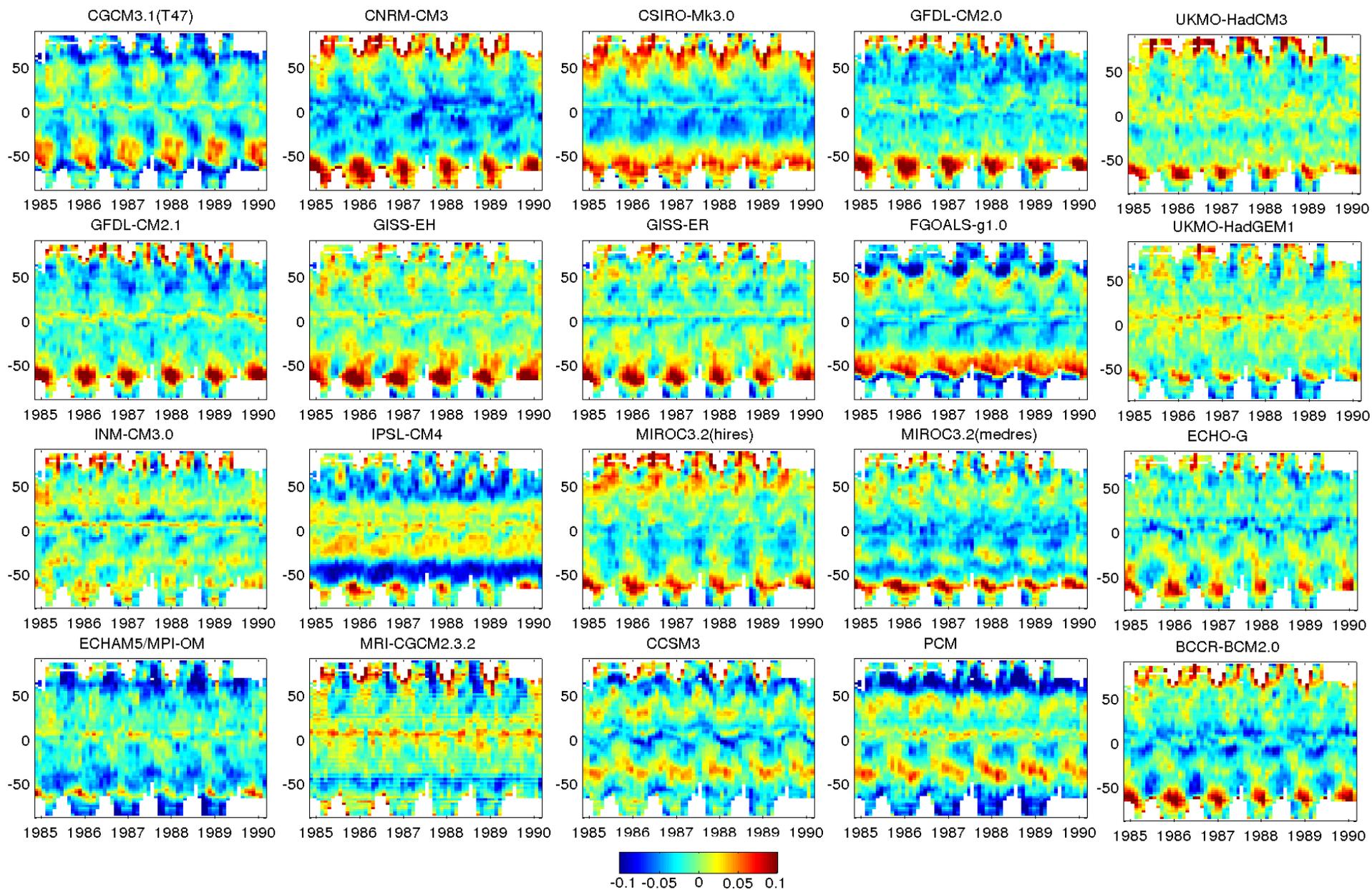


Adapted from Webb et al., *Clim. Dyn.*, 2006

Variation in climate model sensitivity is dominated by variation in cloud feedback strength.

ZONAL MONTHLY MEAN ALBEDO

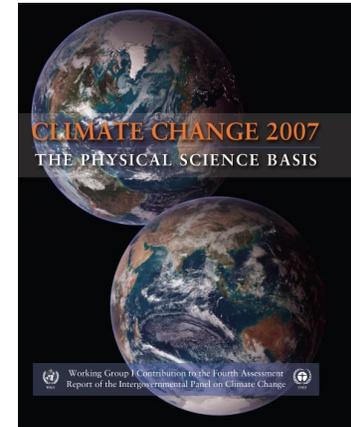
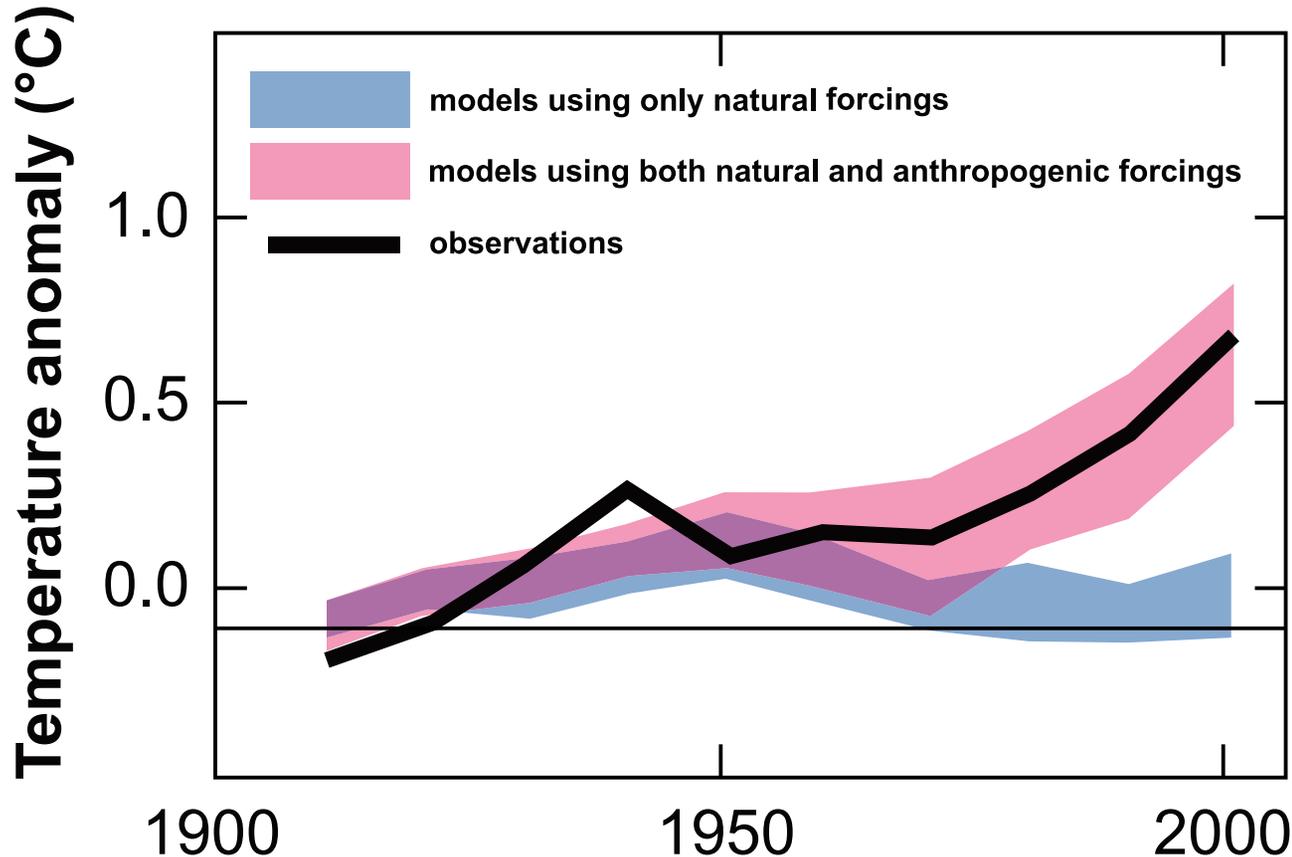
20 GCMs – Difference vs. ERBE Satellite



Modified from Bender et al., Tellus, 2006

TOO ROSY A PICTURE?

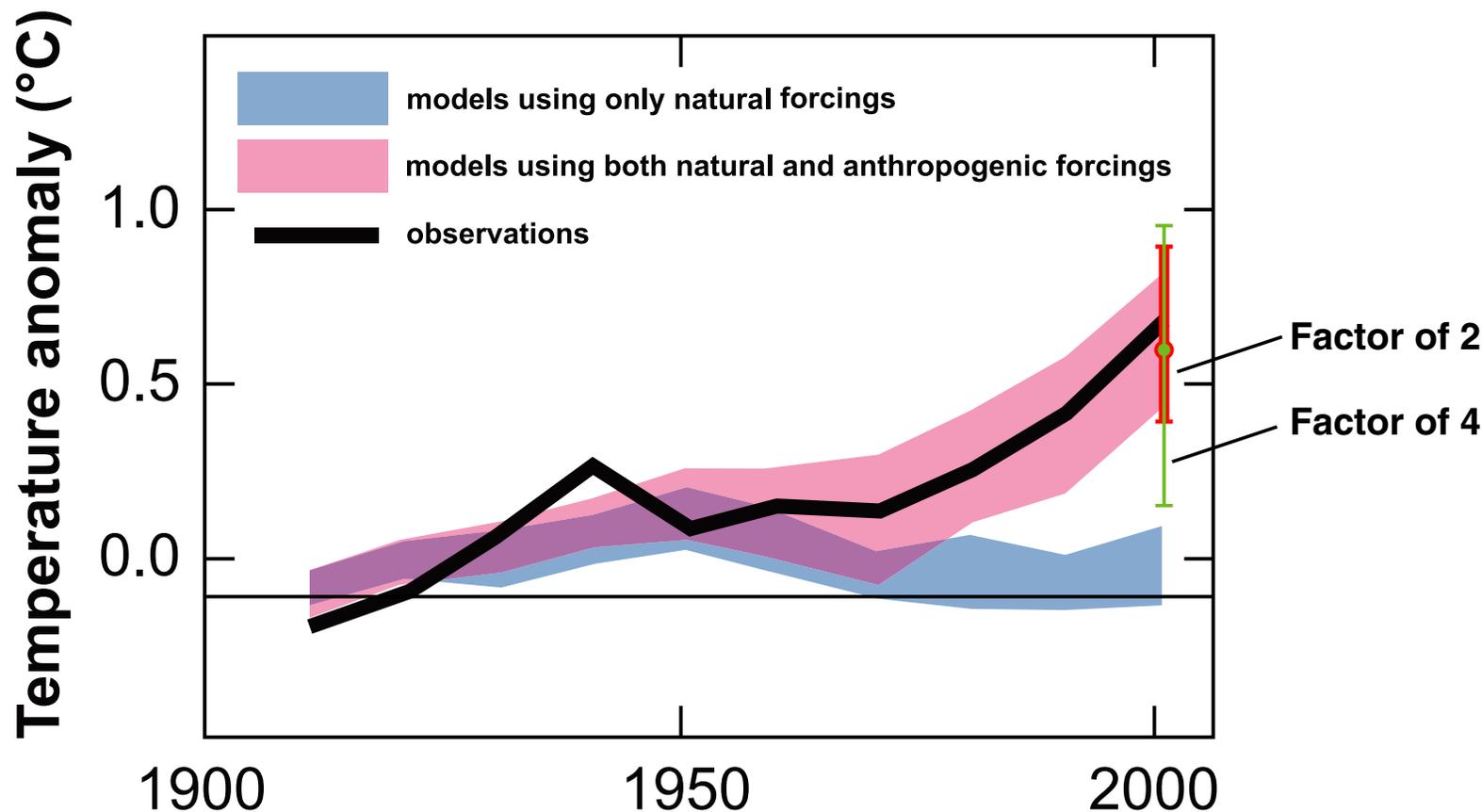
Ensemble of 58 model runs with 14 global climate models



- “ 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*.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

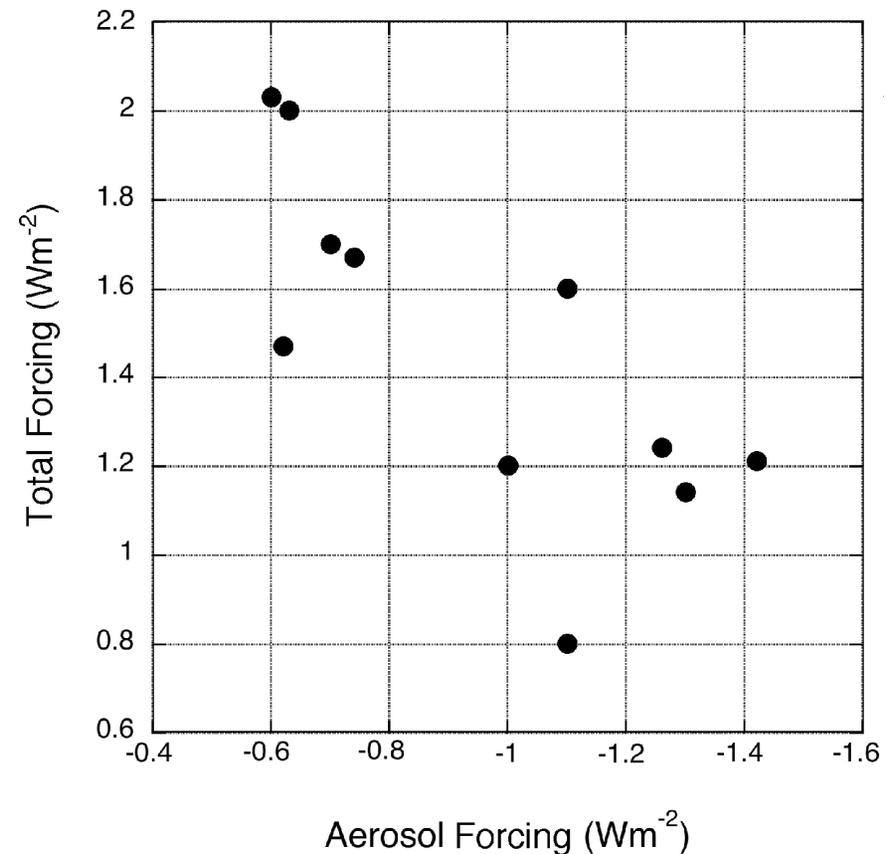
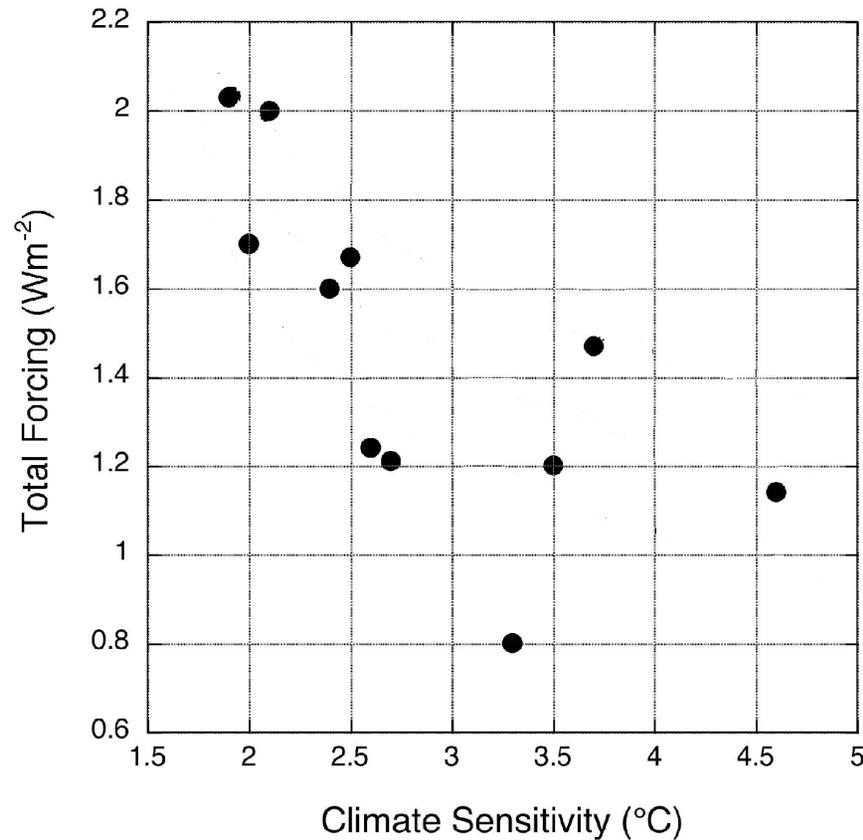
Uncertainty in modeled temperature increase – less than a factor of 2, red – is *well less than uncertainty in forcing* – a factor of 4, green.

The models *did not span the full range of the uncertainty* and/or . . .

The forcings used in the model runs were *anticorrelated with the sensitivities of the models*.

CORRELATION OF AEROSOL FORCING, TOTAL FORCING, AND SENSITIVITY IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis



Modified from Kiehl, GRL, 2007

Climate models with higher sensitivity have lower total forcing.

Total forcing decreases with increasing (negative) aerosol forcing.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.
- ***Empirical***: Forcing and response over the instrumental record.
- ***Climate modeling***: Understanding the processes that comprise Earth's climate system and representing them in large-scale numerical models.
- ***Energy-balance model***: Empirical determination from integral properties of Earth's climate system.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM



$$\text{Global energy balance: } C \frac{dT_s}{dt} = \frac{dH}{dt} = Q - E = \frac{\gamma J_S}{4} - \varepsilon \sigma T_s^4$$

C is heat capacity coupled to climate system on relevant time scale

T_s is global mean surface temperature H is global heat content

Q is absorbed solar energy E is emitted longwave flux

J_S is solar constant γ is planetary co-albedo

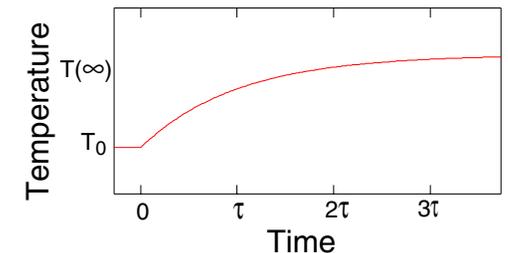
σ is Stefan-Boltzmann constant ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM



Apply step-function forcing: $\Delta F = \Delta(Q - E)$

At “equilibrium” $\Delta T_s(\infty) = S\Delta F$



S is equilibrium climate sensitivity $S = \frac{T_0}{\gamma_0 J_S} f = S_{\text{SB}} f$ Stefan-Boltzmann sensitivity times feedback factor

Time dependence: $\Delta T_s(t) = S\Delta F(1 - e^{-t/\tau})$

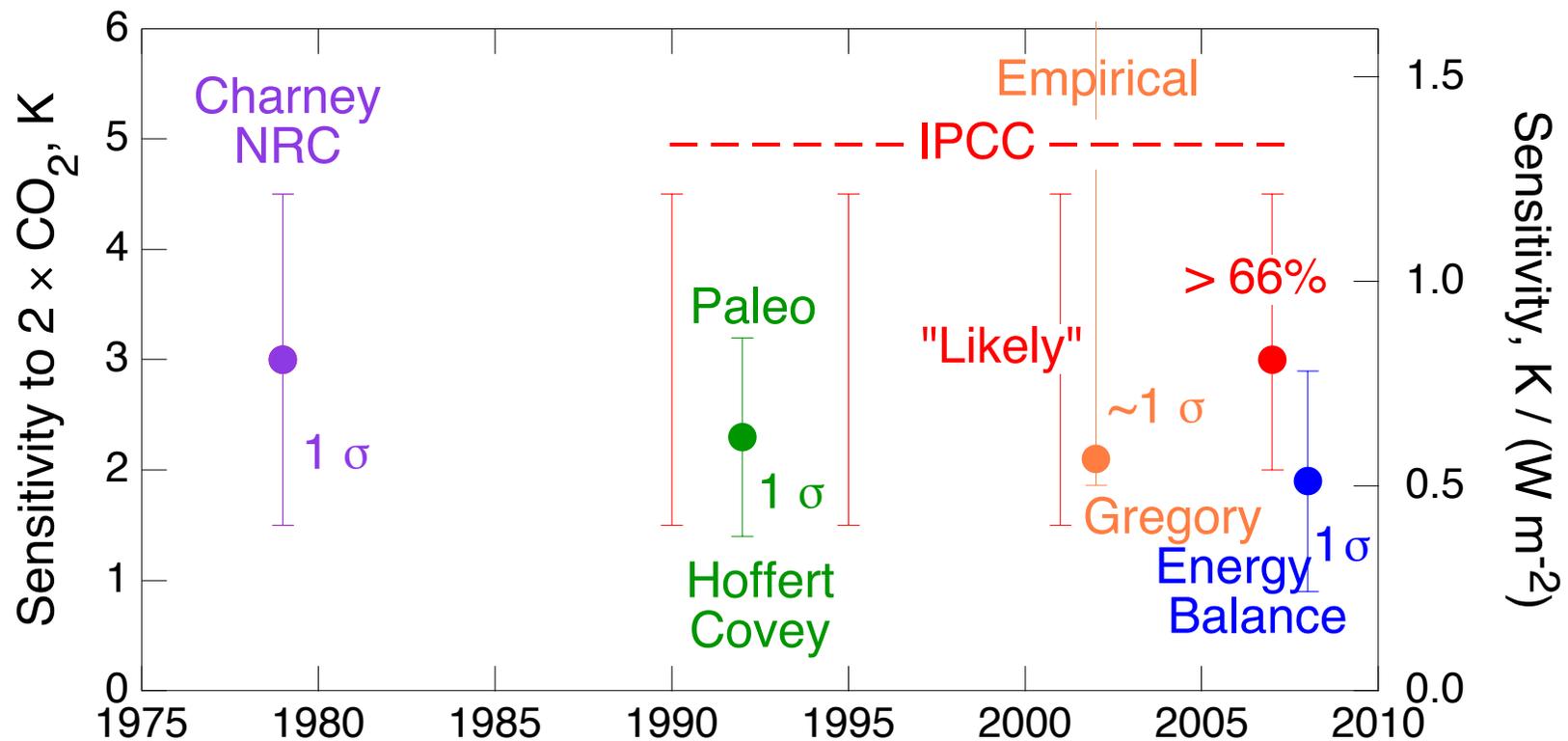
τ is climate system time constant $\tau = CS$ or $S = \tau / C$

One equation in three unknowns!

Approach: Determine C and τ from measurements; calculate sensitivity S .

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from specific approaches and major national and international assessments



Sensitivity obtained in this study overlaps range from climate models, paleo, empirical; seems to rule out $\Delta T_{2x} \gtrsim 3$ K.

RECAPITULATION

Present estimates of Earth's climate sensitivity range over *at least a factor of 3.*

The range of sensitivity in climate models results largely from differing treatment of clouds, resulting in differing cloud feedbacks.

Evaluation of climate models is limited mainly because of *uncertainty in aerosol forcing over the industrial period.*

IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

- Uncertainty in the amount of *incremental atmospheric CO₂* that would result in a given increase in global mean surface temperature.
- Uncertainty in the amount of *fossil fuel carbon* that can be combusted consonant with a given climate effect.

At present this uncertainty is about a factor of 3.

IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

- The lifetime of incremental atmospheric CO₂ is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

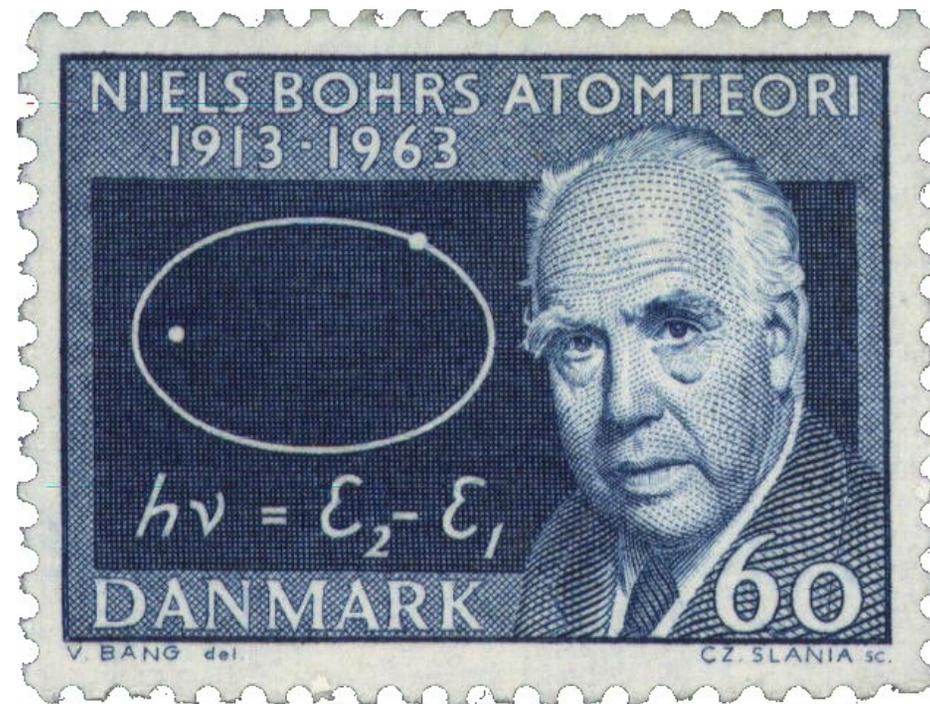
Actions taken today will have long-lasting effects.

Early knowledge of climate sensitivity can result in huge averted costs.

*Looking to the
Future . . .*

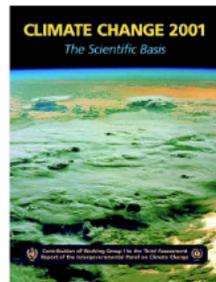
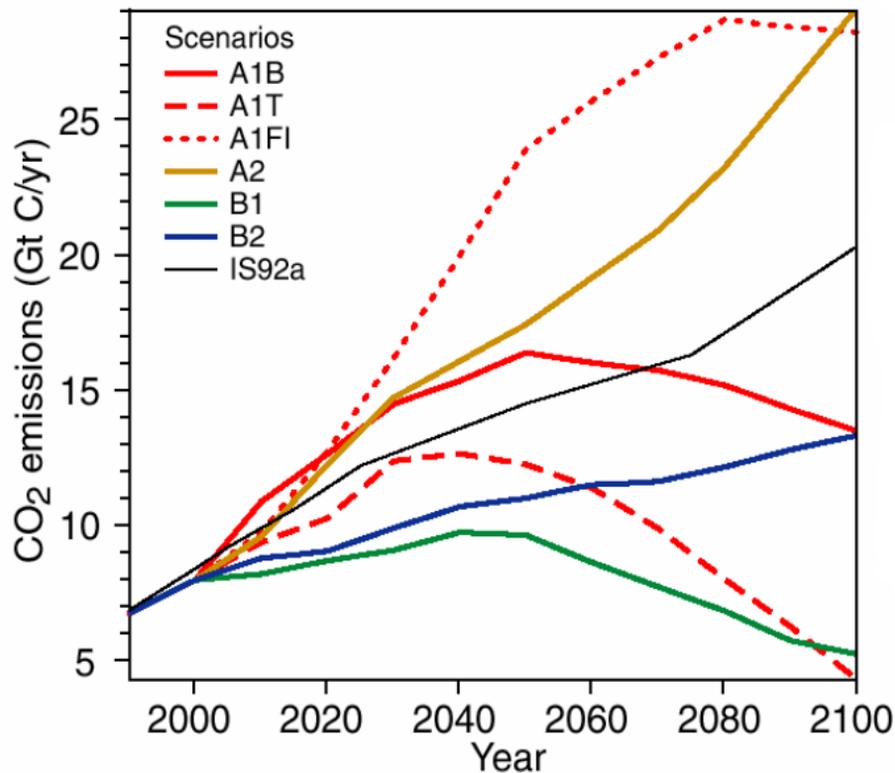


*Prediction is difficult,
especially about the future.*

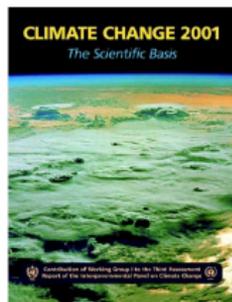
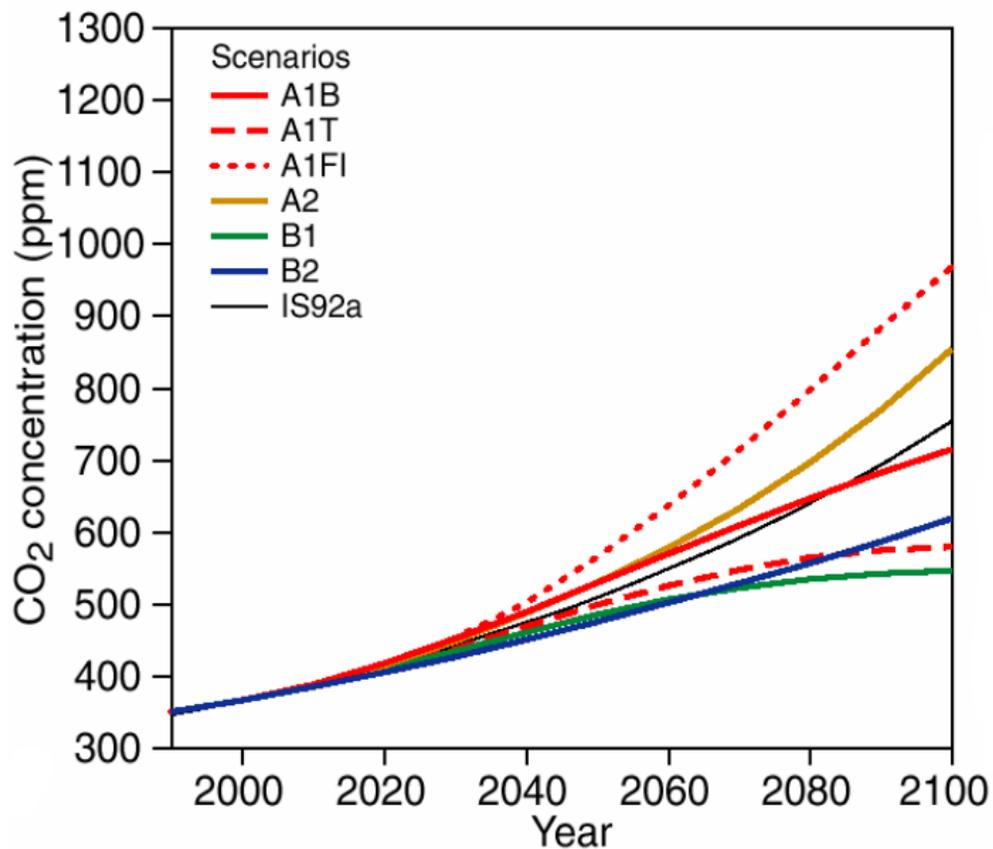


– Niels Bohr

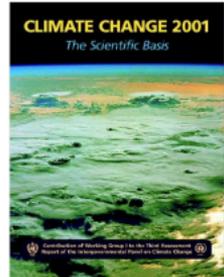
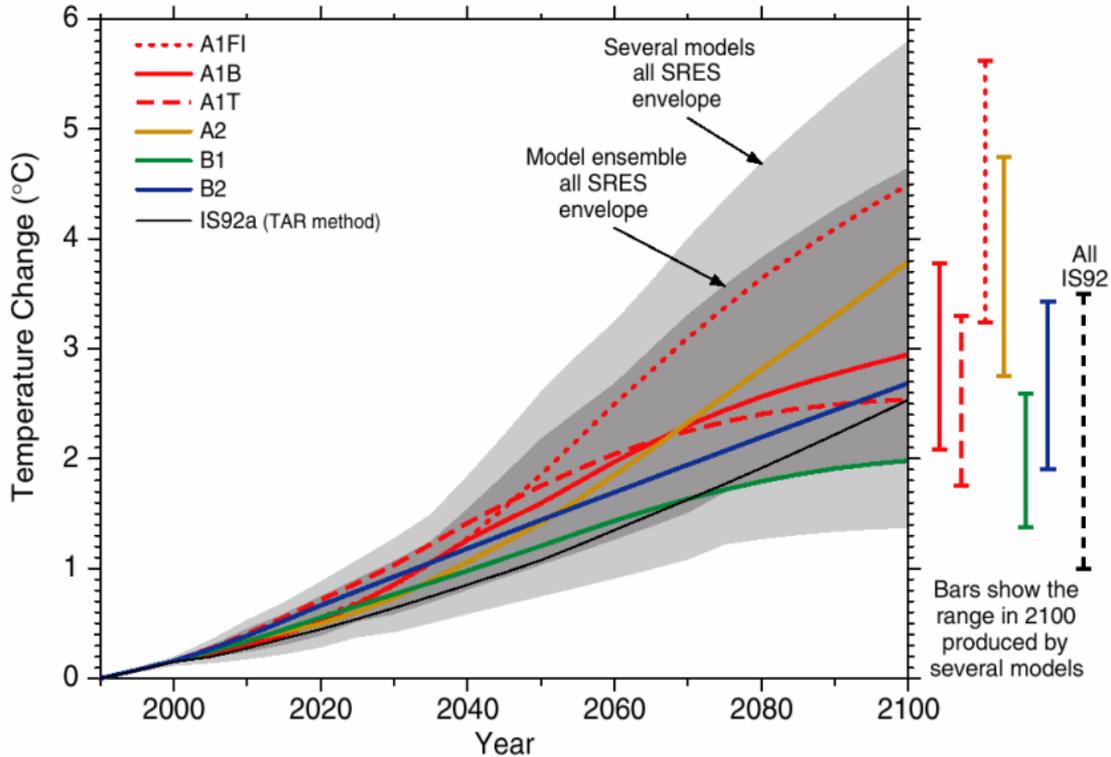
PROJECTIONS OF FUTURE CO₂ EMISSIONS



PROJECTIONS OF FUTURE CO₂ CONCENTRATIONS



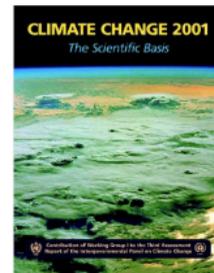
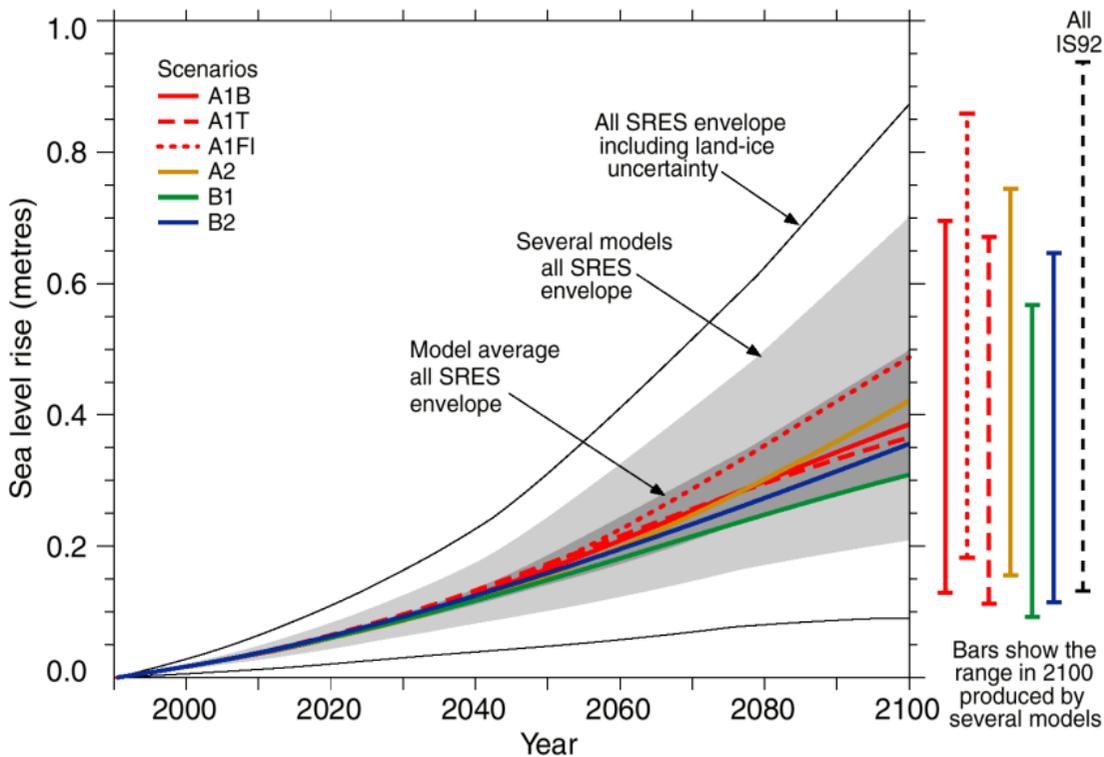
PROJECTIONS OF FUTURE TEMPERATURE CHANGE



Bars show the range in 2100 produced by several models

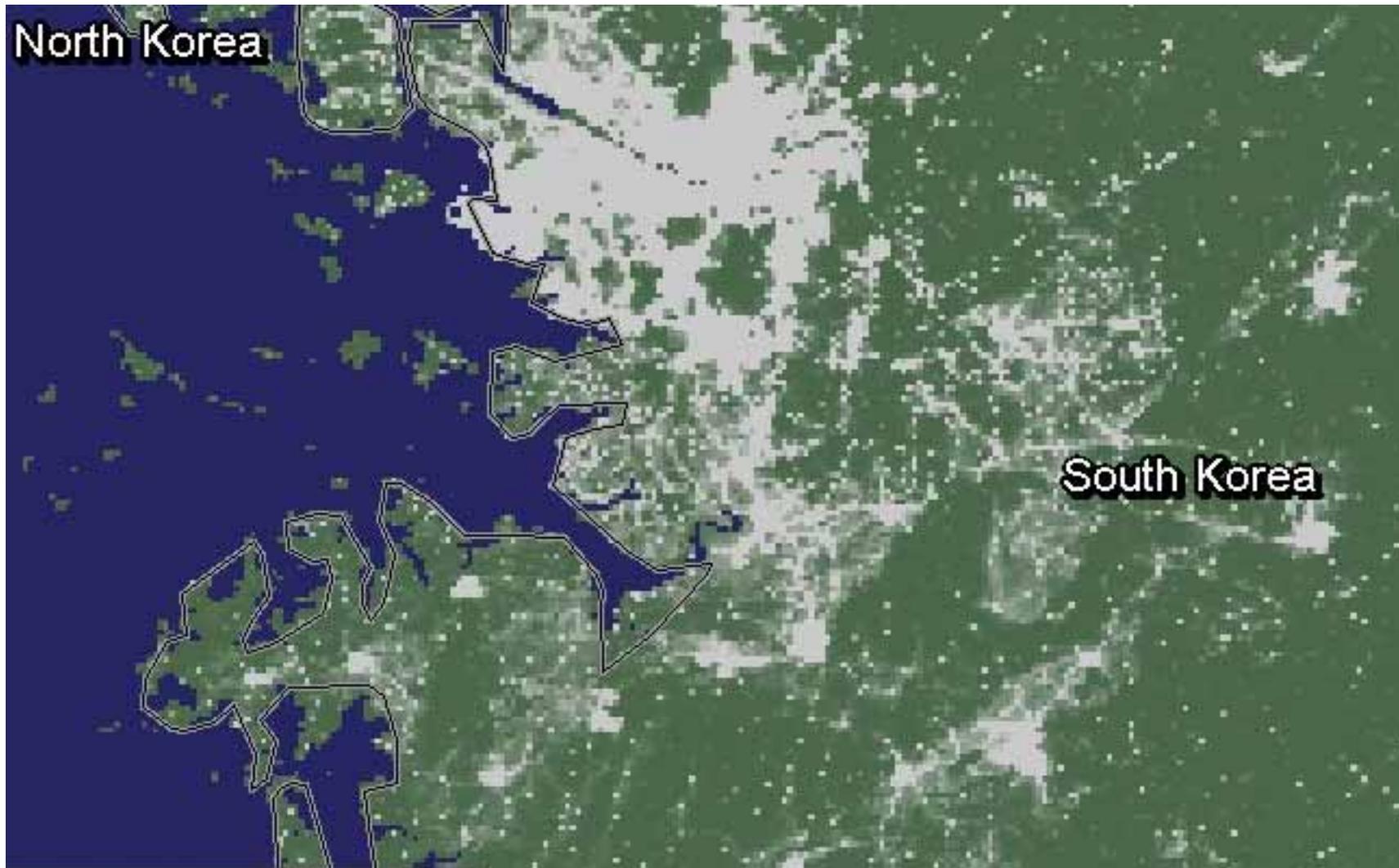
PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only



EFFECT OF SEA LEVEL RISE

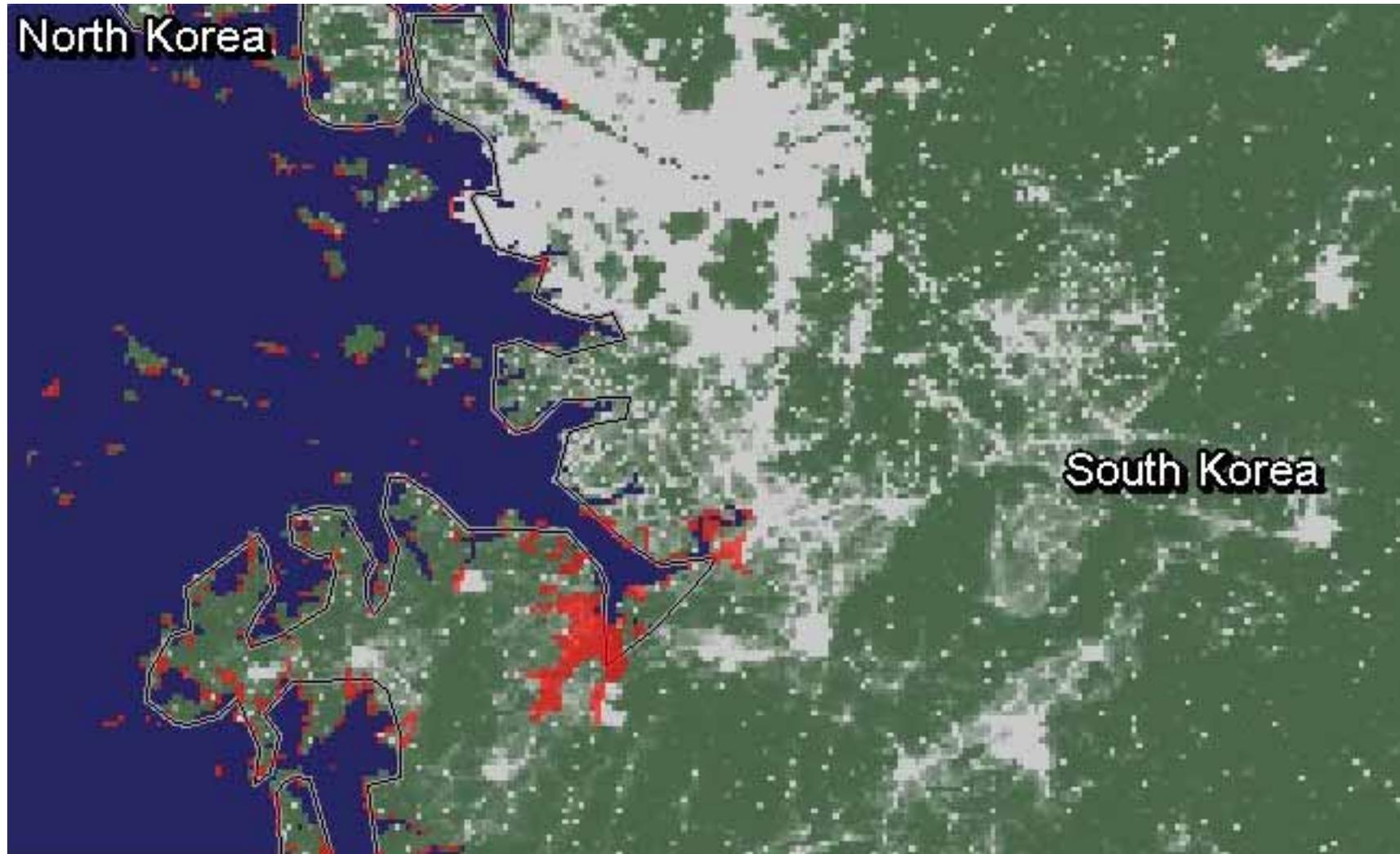
Population density, current coastline



Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

Population density, 1 meter sea level rise



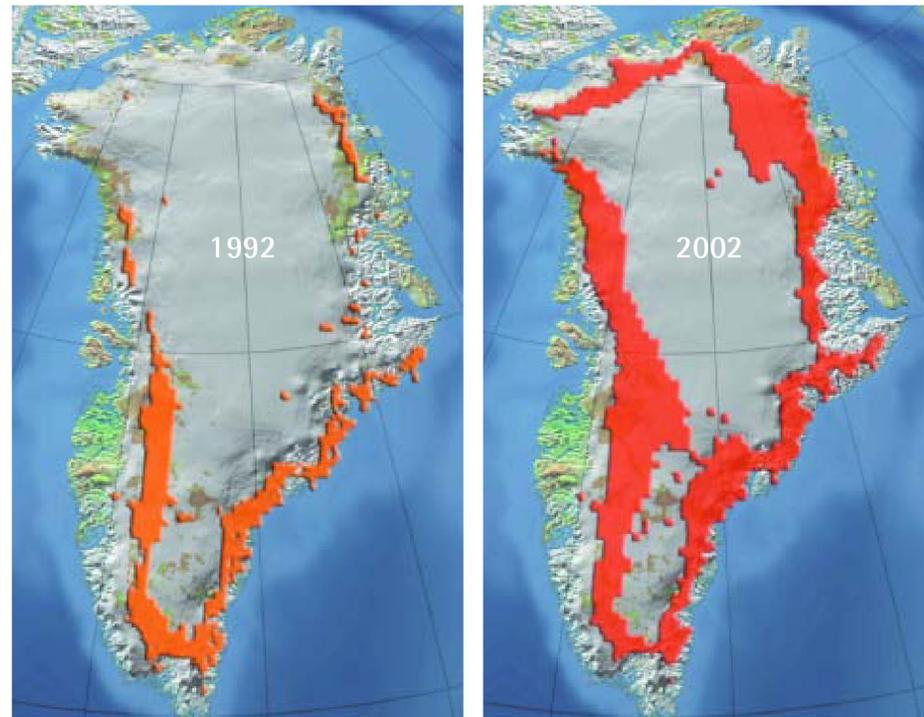
Weiss and Overpeck, University of Arizona

MELTING OF GREENLAND ICE CAP

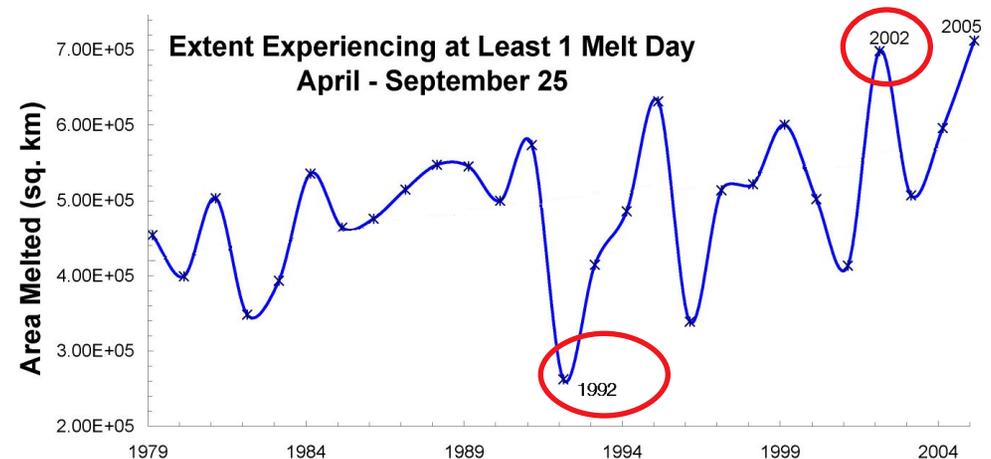
Satellite determination of extent of glacial melt 1992 vs 2002



NASA



Arctic Climate Impact Assessment, Cambridge, 2004

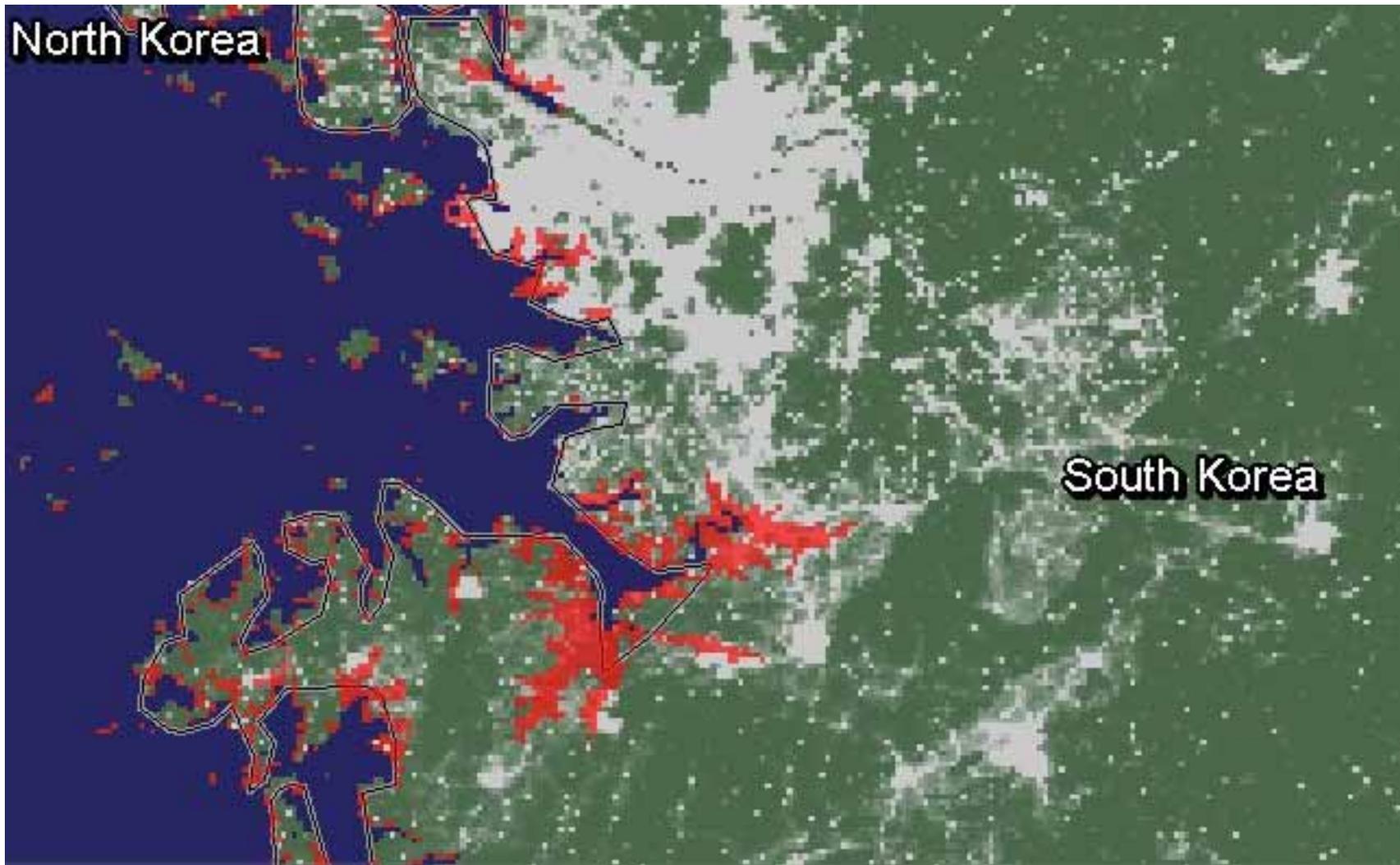


Steffen & Huff, Univ. Colo., 2005

Complete melt of the Greenland ice sheet would raise the level of the global ocean 7 meters.

EFFECT OF SEA LEVEL RISE

Population density, 6 meter sea level rise



Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

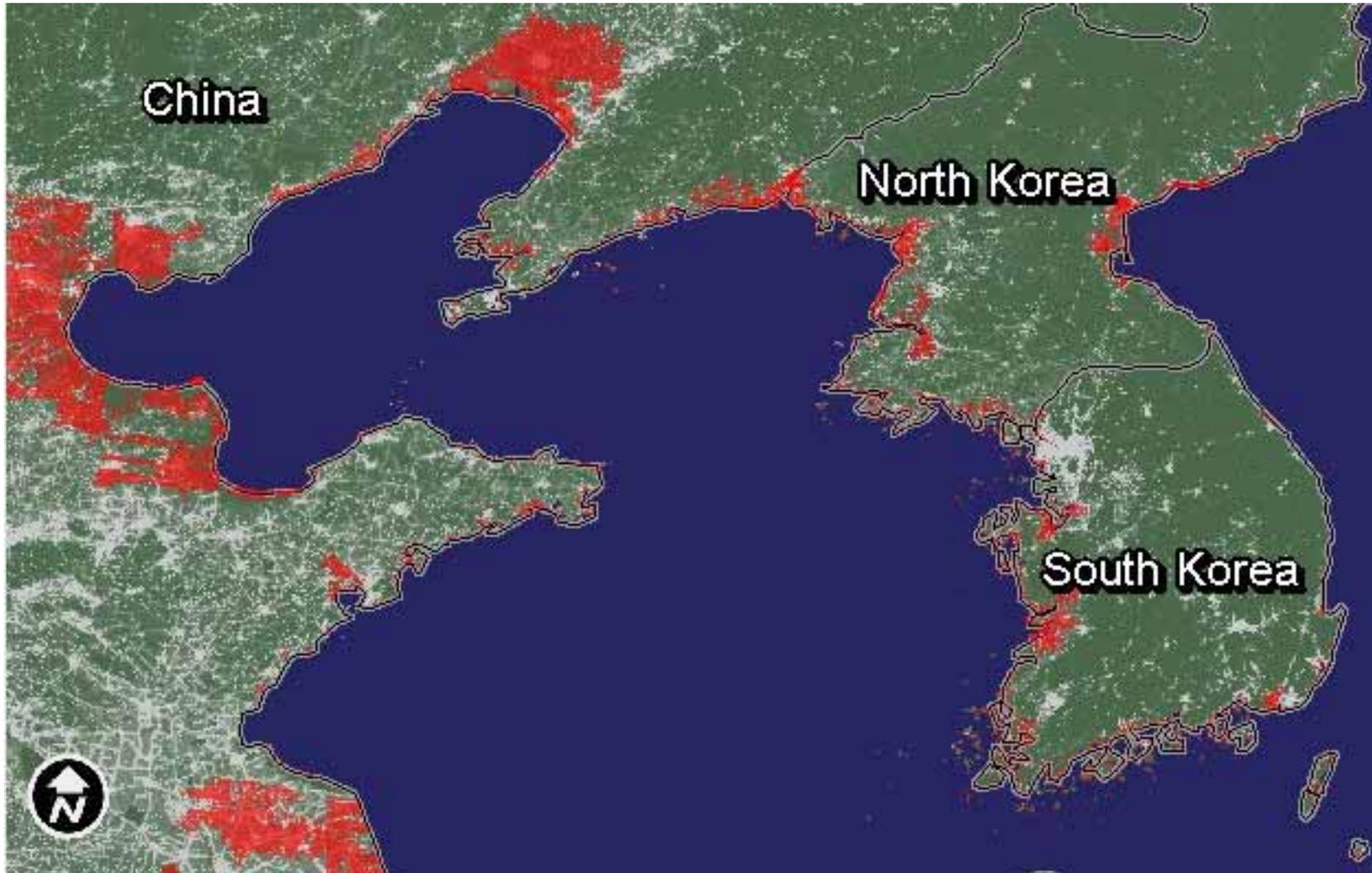
Population density, current coastline



Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

Population density, 6 meter sea level rise



Weiss and Overpeck, University of Arizona

CONCLUDING REMARKS

Atmospheric carbon dioxide will continue to increase absent major changes in the world's energy economy.

The consequences of this increase are not well known but they range from *serious* to *severe* to *catastrophic*.

Present scientific understanding is sufficient to permit “no regrets” decision making.

Research is urgently needed to refine “what if” projections.

Especially important is *reducing uncertainty in climate sensitivity*.

Actions taken (or not taken) today will inevitably affect future generations.