EARTH'S CLIMATE SENSITIVITY WHAT IT MEANS AND WHAT IT MEANS TO US

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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 CO_2 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 CO_2 into the atmosphere. Developing effective and cost-effective strategies for limiting CO_2 emissions requires the confident ability to project the changes in climate that would result from a given increase in atmospheric CO_2. 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 CO_2 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 CO_2 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

Radiative forcing of climate change

Climate ***response***

Climate ***sensitivity*** – definition, importance, past and current estimates

Climate sensitivity from ***paleoclimate***

Empirical determination of climate sensitivity from temperature change over the instrumental record

Aerosol forcing – uncertainty and implications

Climate sensitivity from ***climate models***

Climate sensitivity from whole-earth ***energy-balance models***

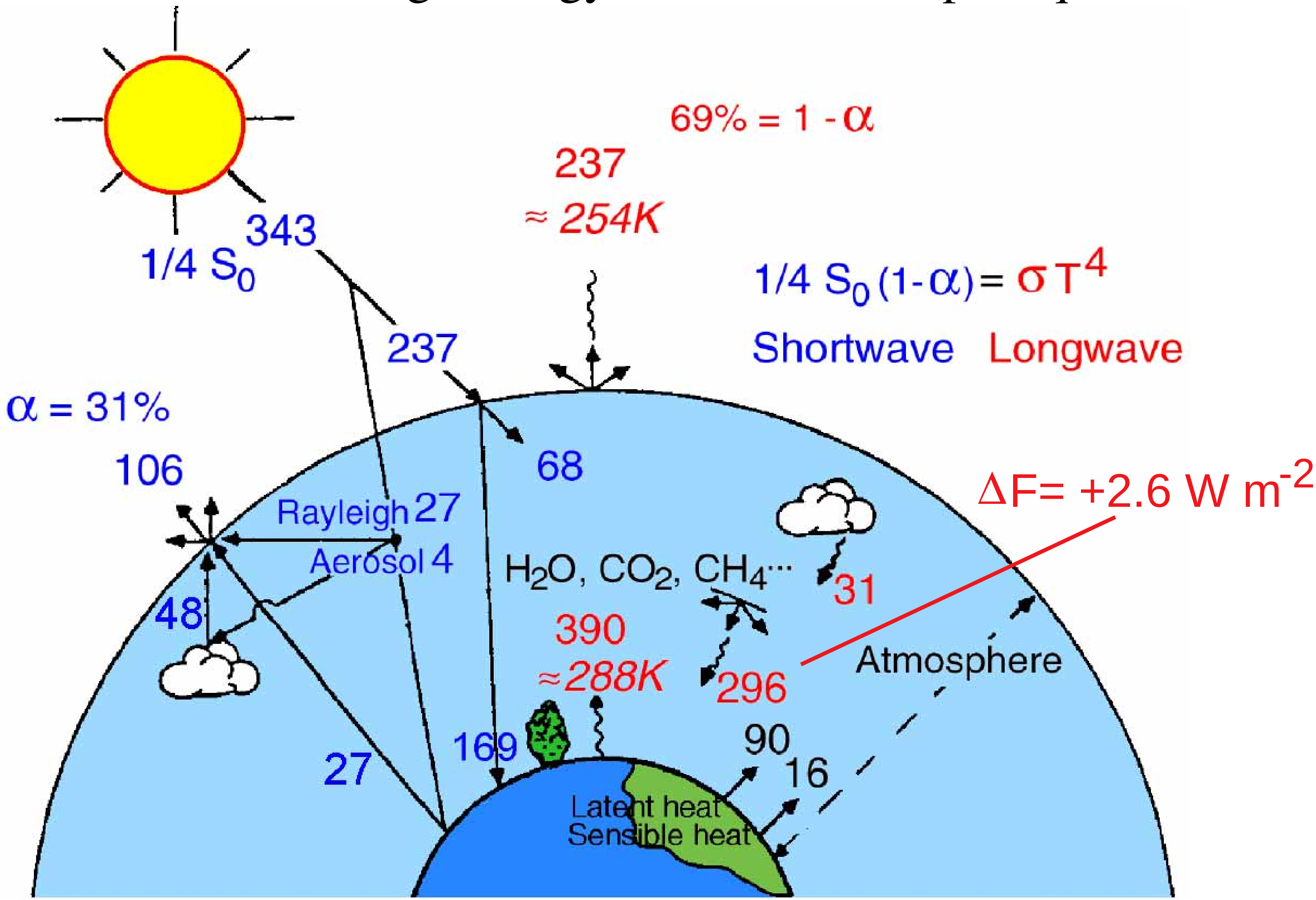
Implications of uncertainty in climate sensitivity

Looking to the future

Concluding remarks

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



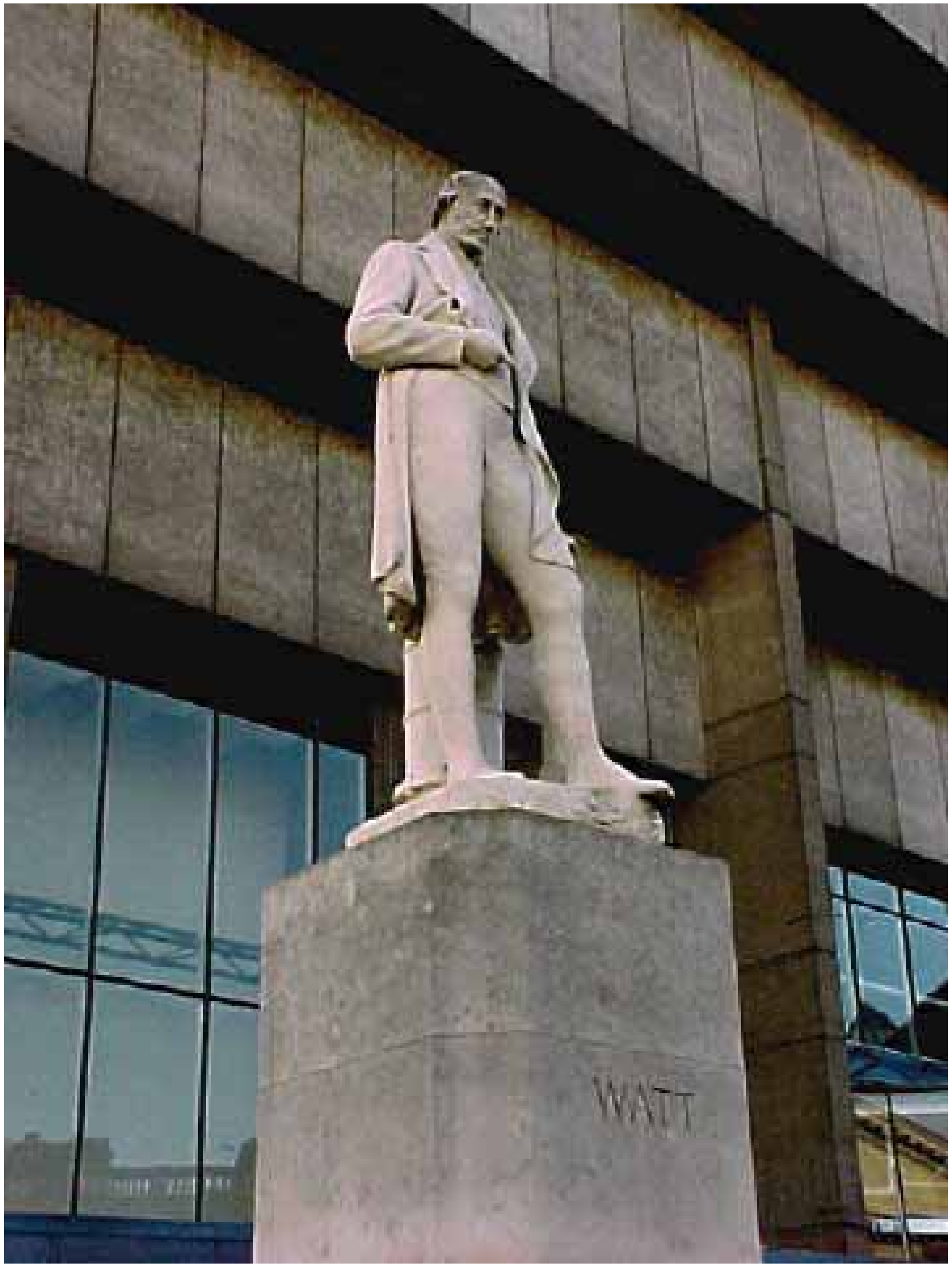
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

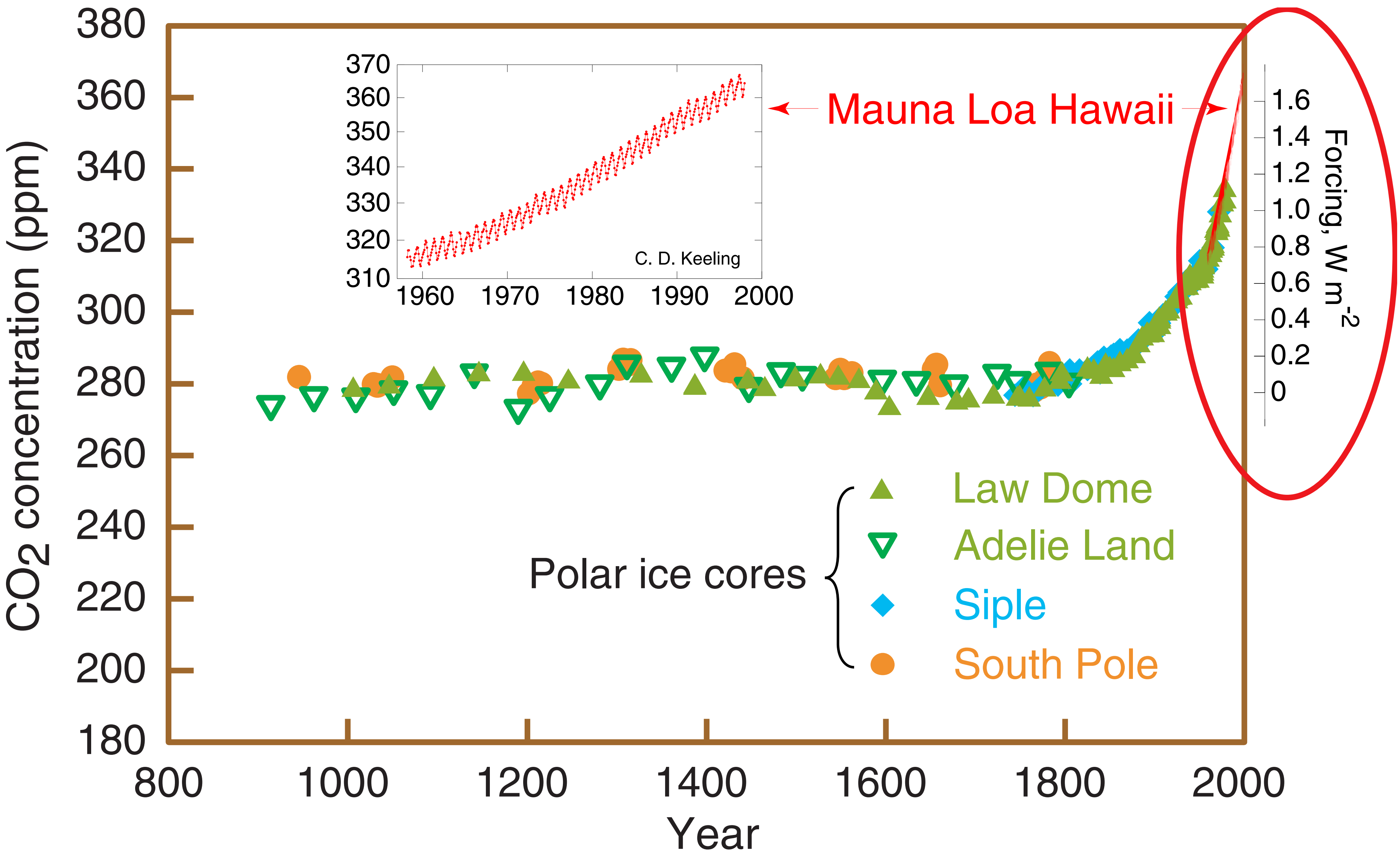
Power per area

Energy per time per area

Unit:
Watt per square meter
W m^{-2}



ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

RADIATIVE FORCING

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

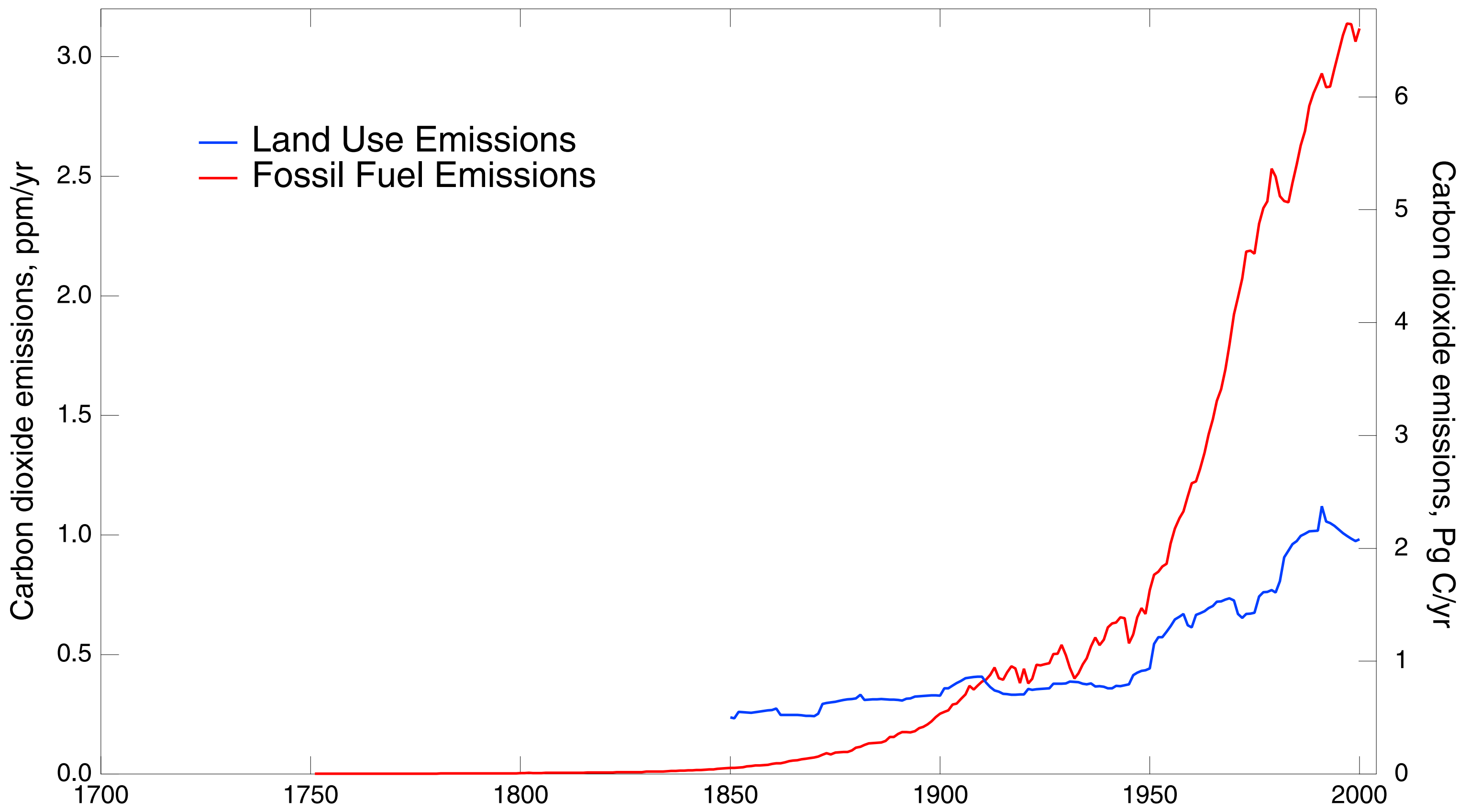
Working hypothesis:

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 CO_2 EMISSIONS

Time series 1700 - 2003



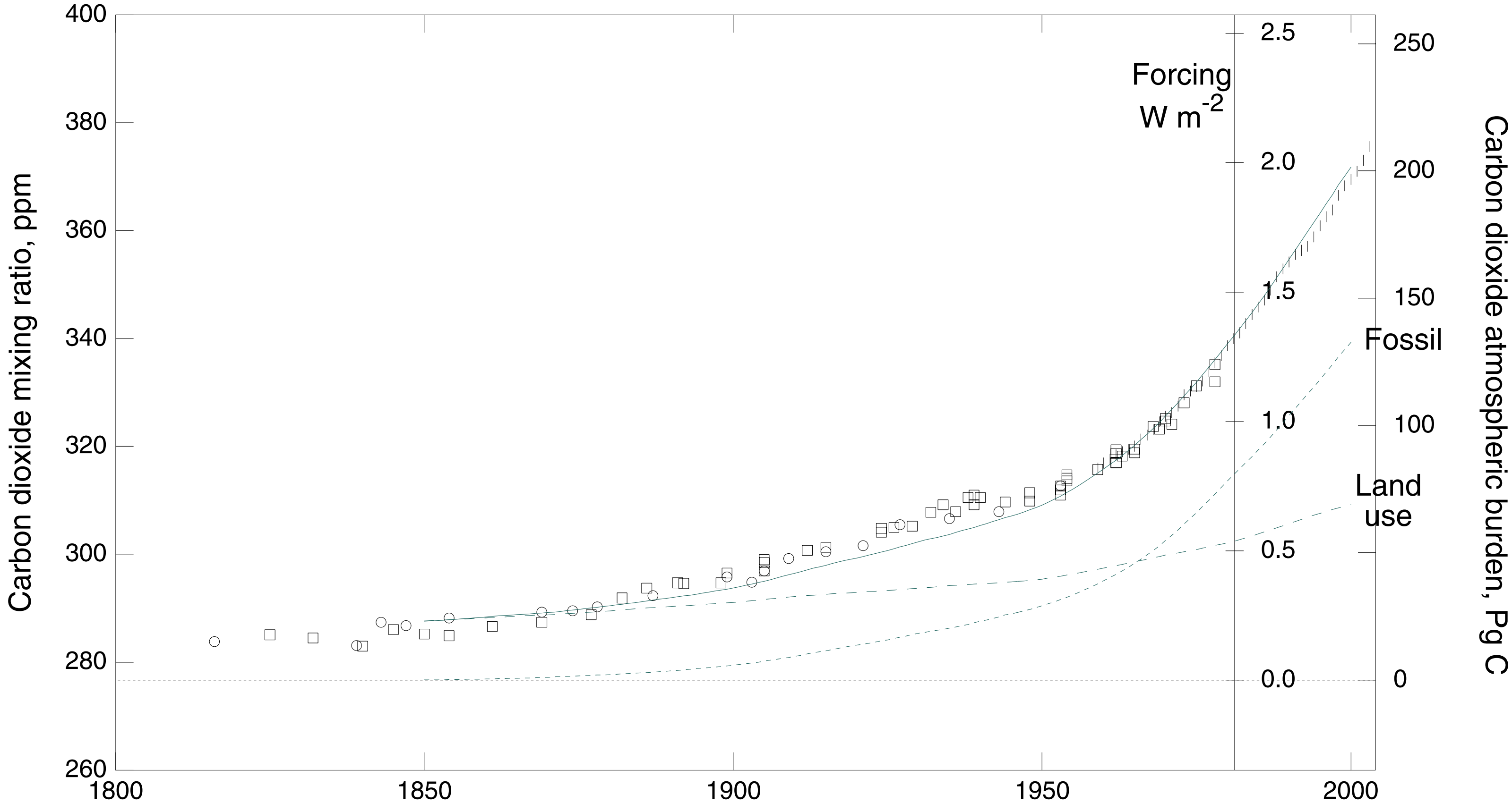
Fossil Fuel - Marland
Land Use - Houghton

Prior to 1910 CO_2 emissions from land use changes were dominant.

Subsequently fossil fuel CO_2 has been dominant and rapidly increasing!

ATTRIBUTION OF ATMOSPHERIC CO_2

Comparison of CO_2 ***mixing ratio and forcing*** from fossil fuel combustion and land use changes



CO_2 from land use emissions – ***not fossil fuel combustion*** – was the dominant contribution to atmospheric CO_2 and forcing over the 20th century.

CLIMATE RESPONSE

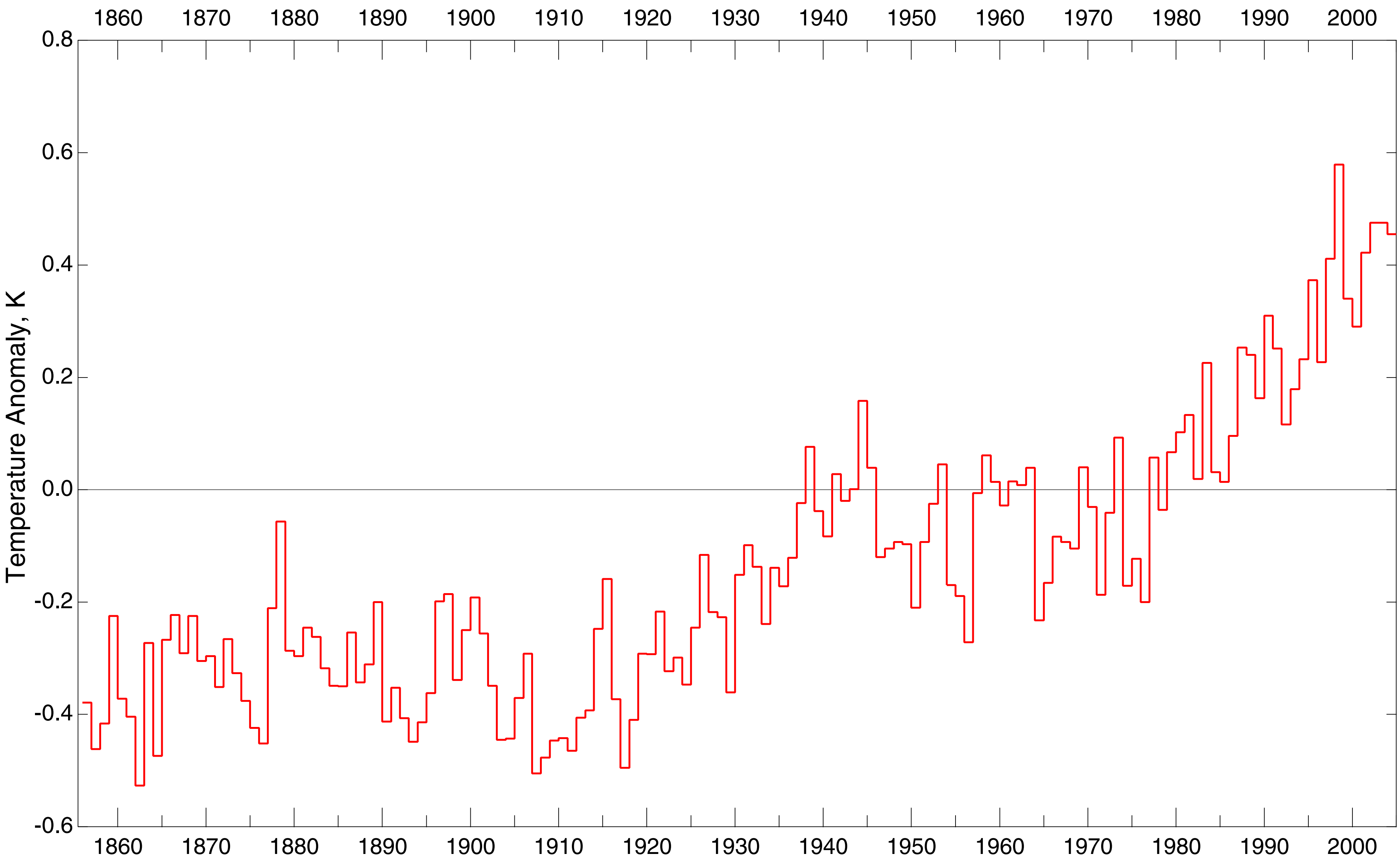
The ***change*** in global and annual mean temperature, ΔT, K, resulting from a given radiative forcing.

Working hypothesis:

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

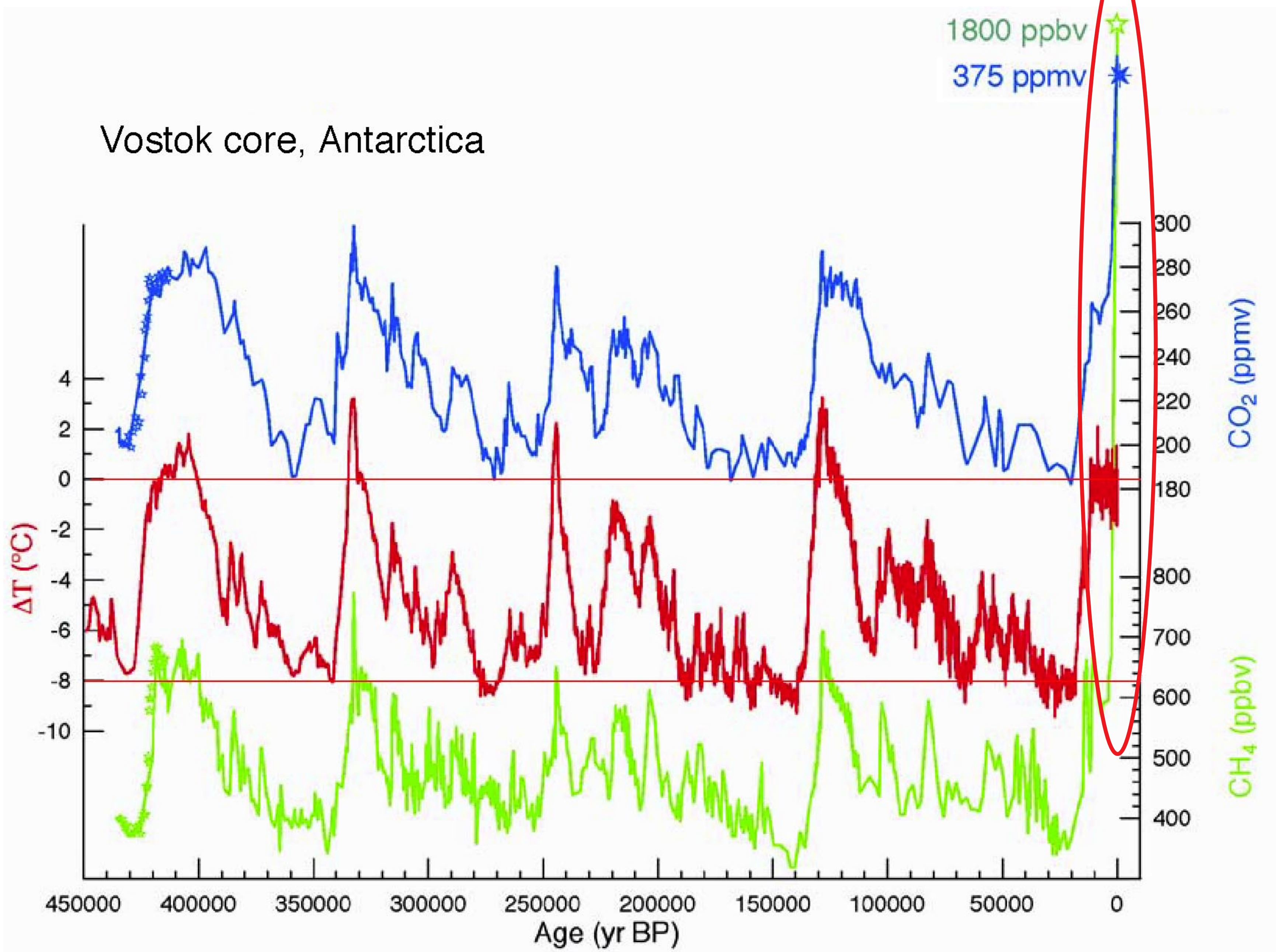
$$\Delta T = S\,\Delta F$$

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 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 known and is the objective of much current research on climate change.

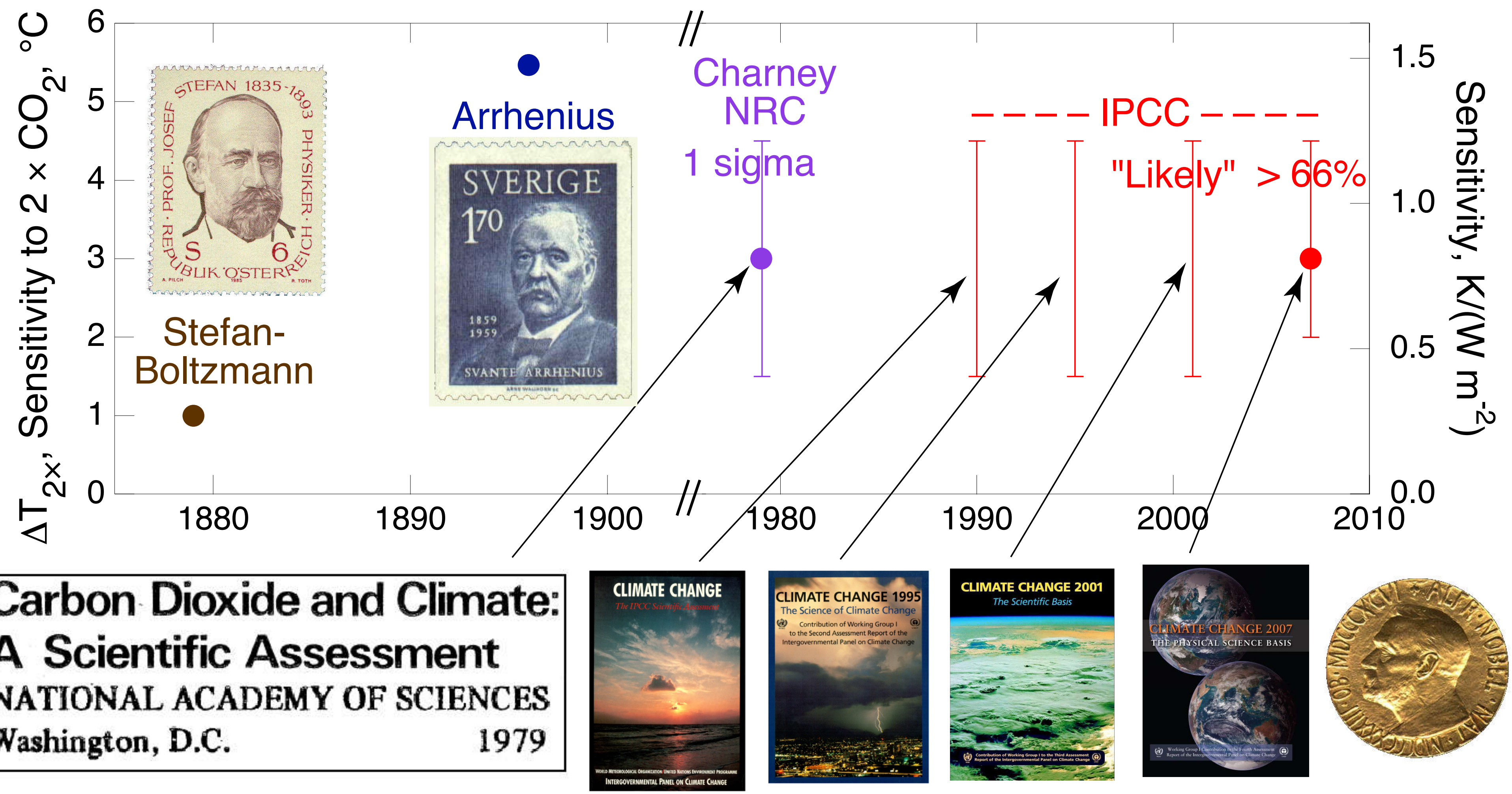
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

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

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

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

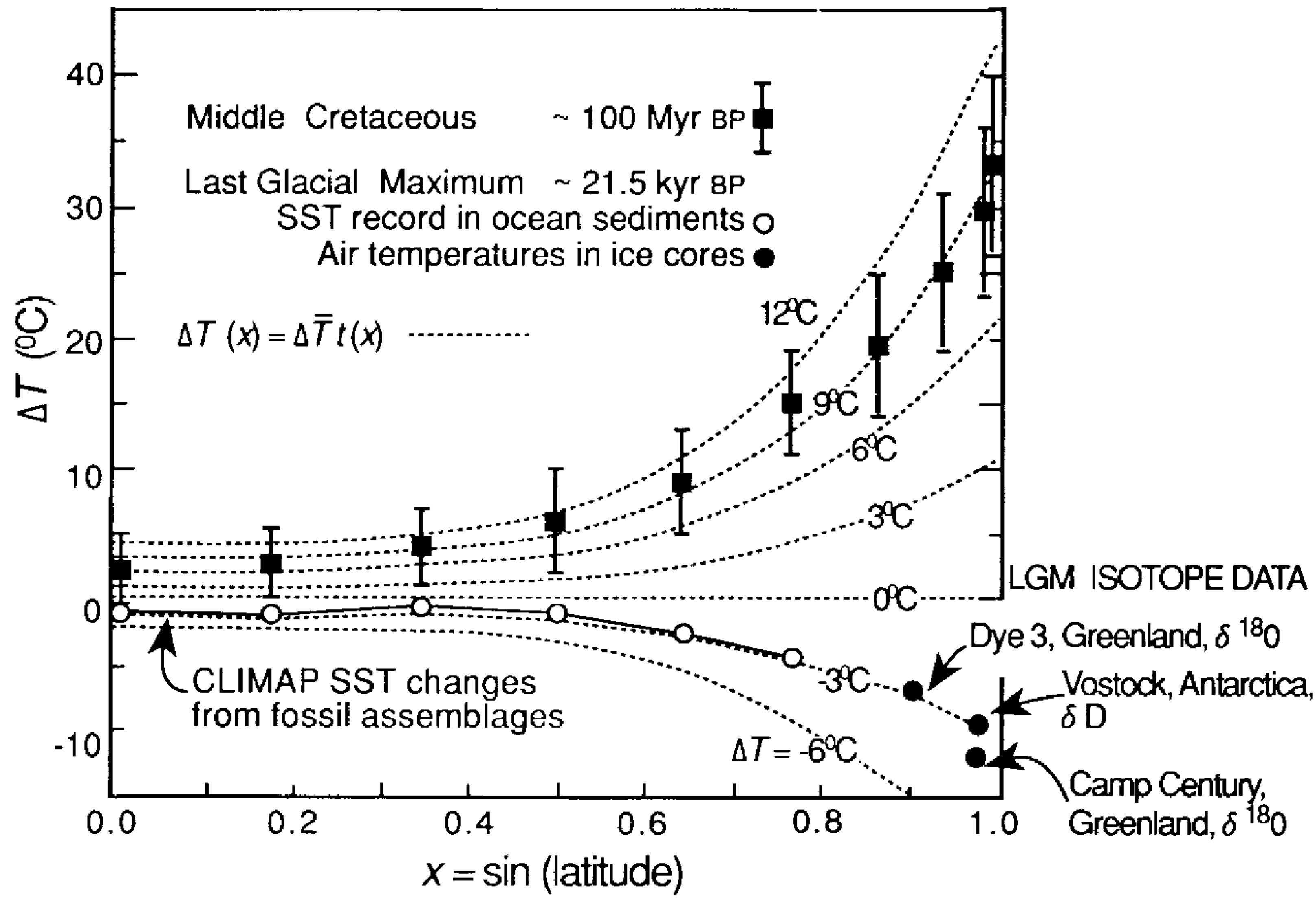


Despite extensive research, climate sensitivity remains ***highly uncertain***.

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: ΔT = -3 K; Middle Cretaceous, ΔT = +9 K.

CLIMATE SENSITIVITY FROM PALEO DATA

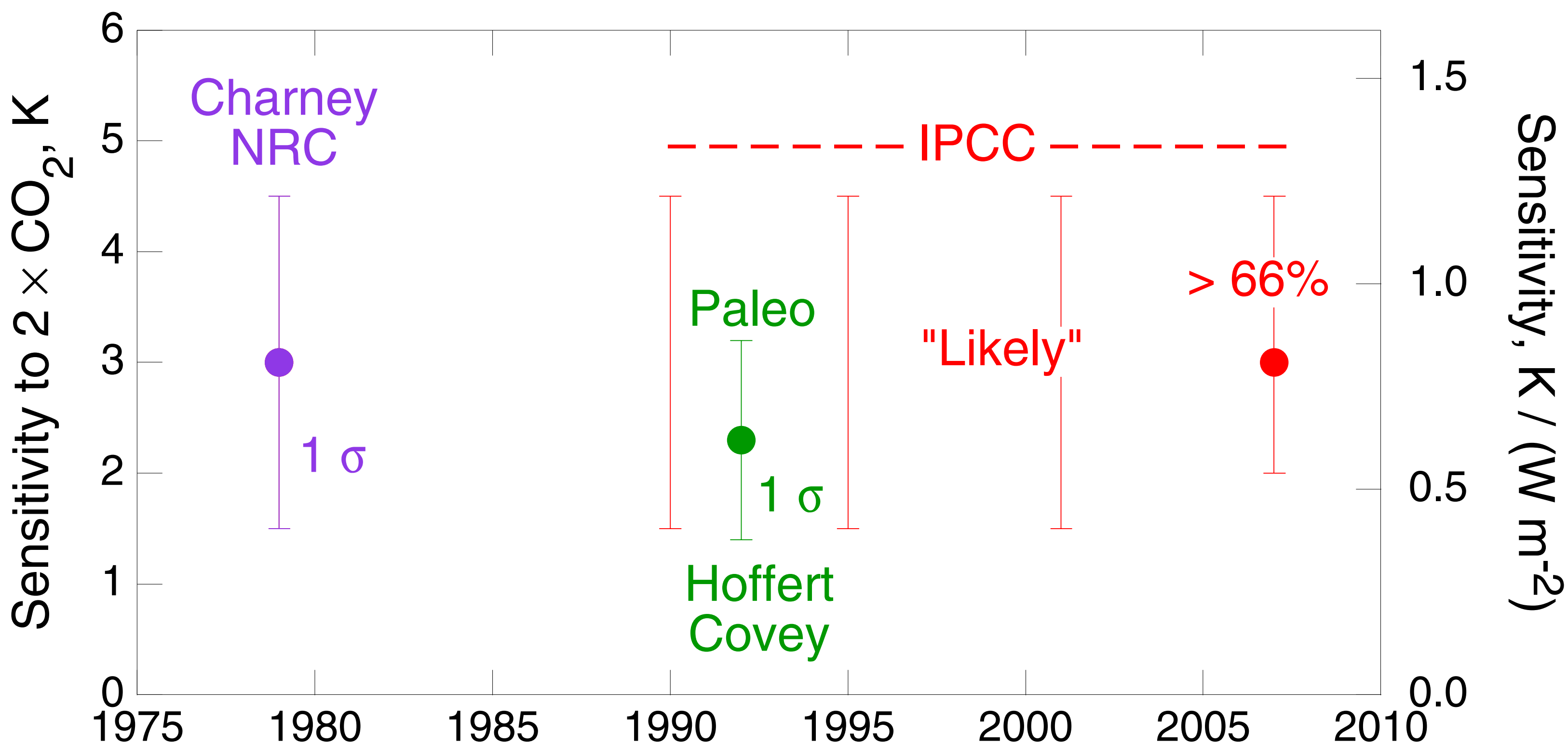
Component	Last Glacial Maximum	Middle Cretaceous
Forcing, W m^{-2}	Value ± 1 σ	Value ± 1 σ
Sun	0.0 ± 0.2	-1.2 ± 0.2
Albedo	-3.0 ± 0.5	5.8 ± 0.9
Greenhouse	-2.8 ± 0.3	11.1 ± 6.7
Aerosol	-0.9 ± 0.7	
Total ΔF, W m^{-2}	-6.7 ± 0.9	15.7 ± 6.8
ΔT, K	-3.0 ± 0.5	9.0 ± 2.0
S, K/(W m^{-2})	0.45 ± 0.11	0.57 ± 0.27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

Hoffert & Covey, Nature, 1992

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

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.

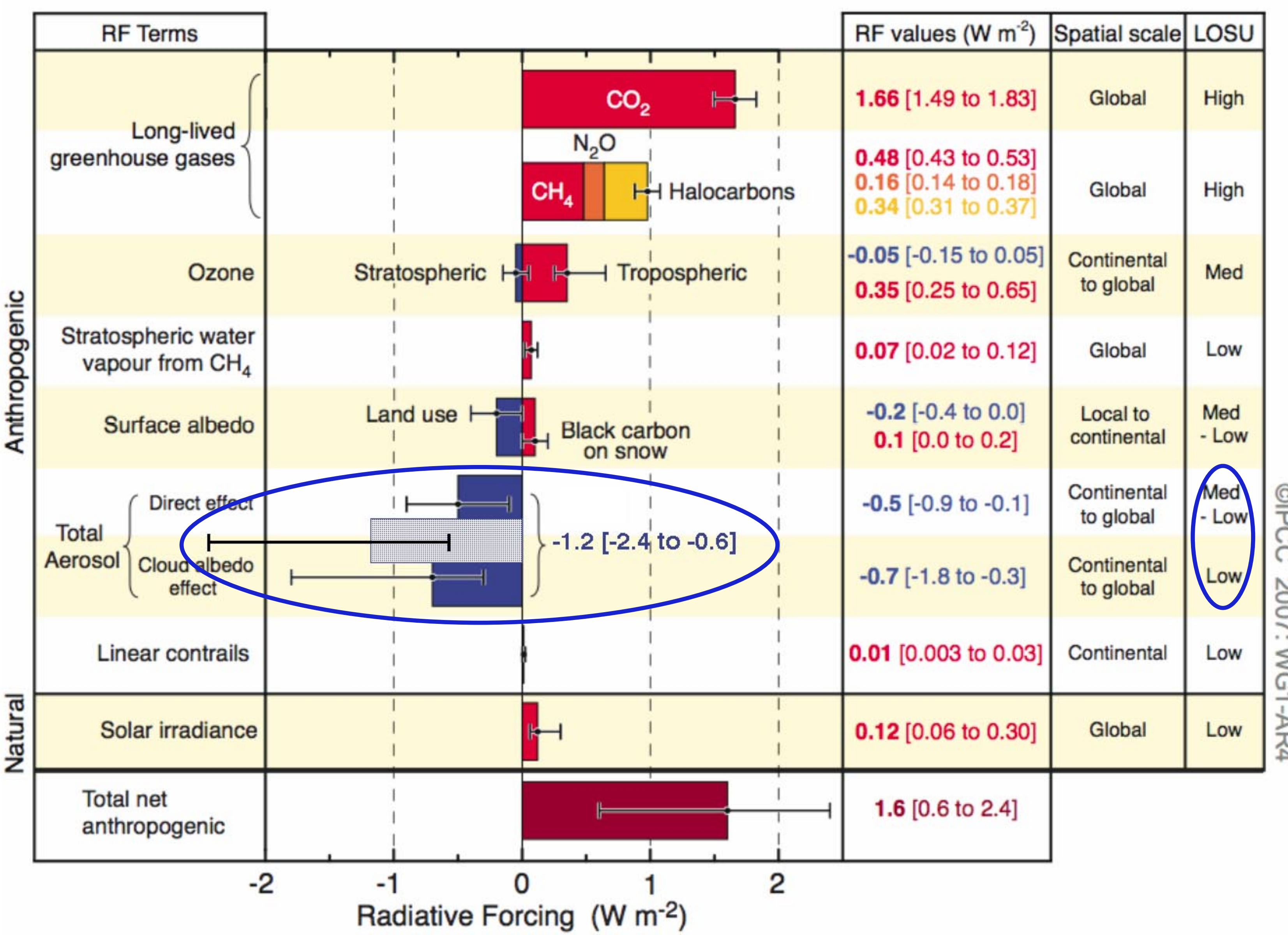
KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

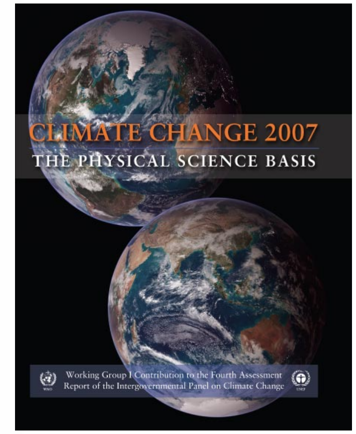
- ***Paleoclimate studies***: Forcing and response over time scales from millennial to millions of years.

- ***Empirical***: Forcing and response over the instrumental record.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

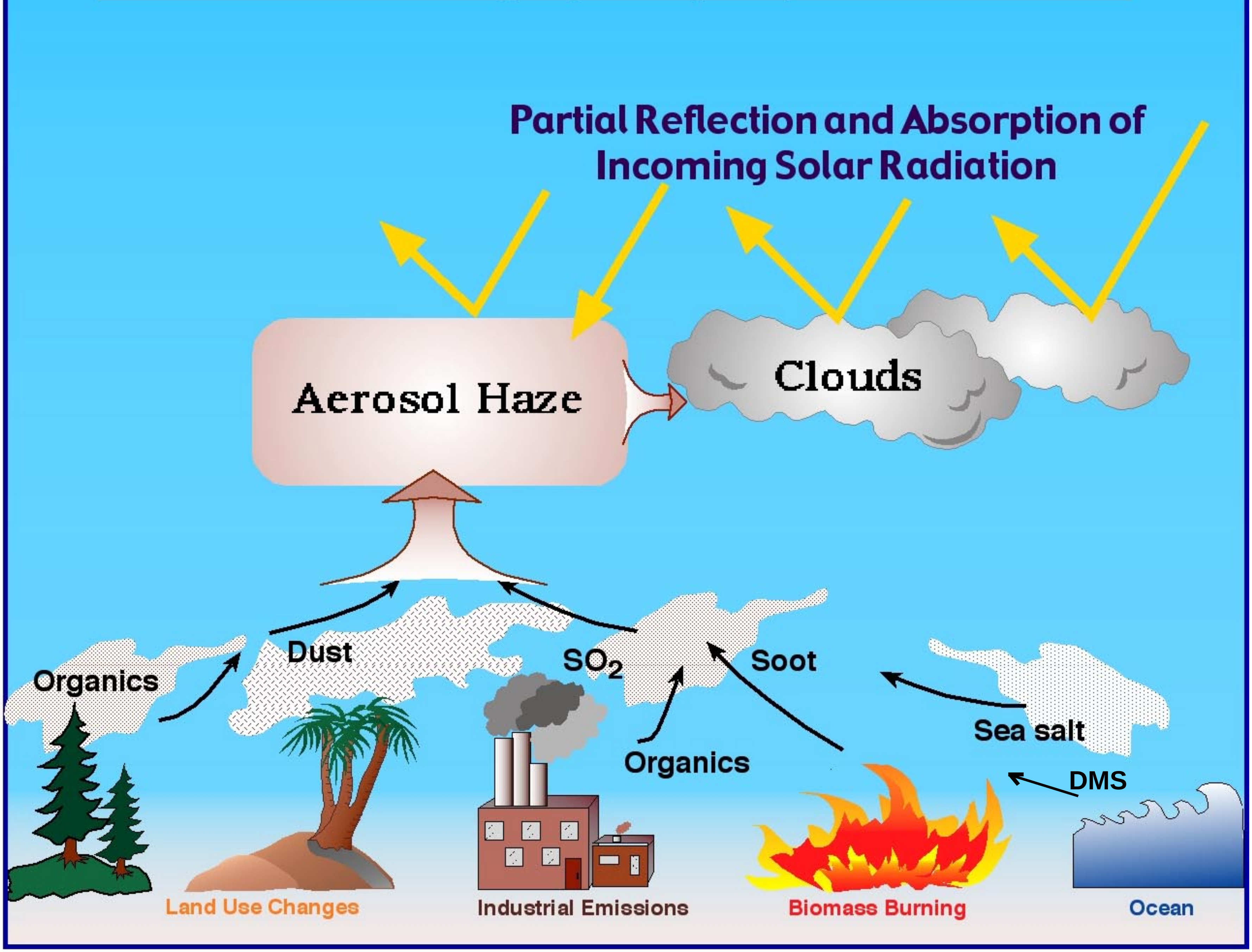
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)



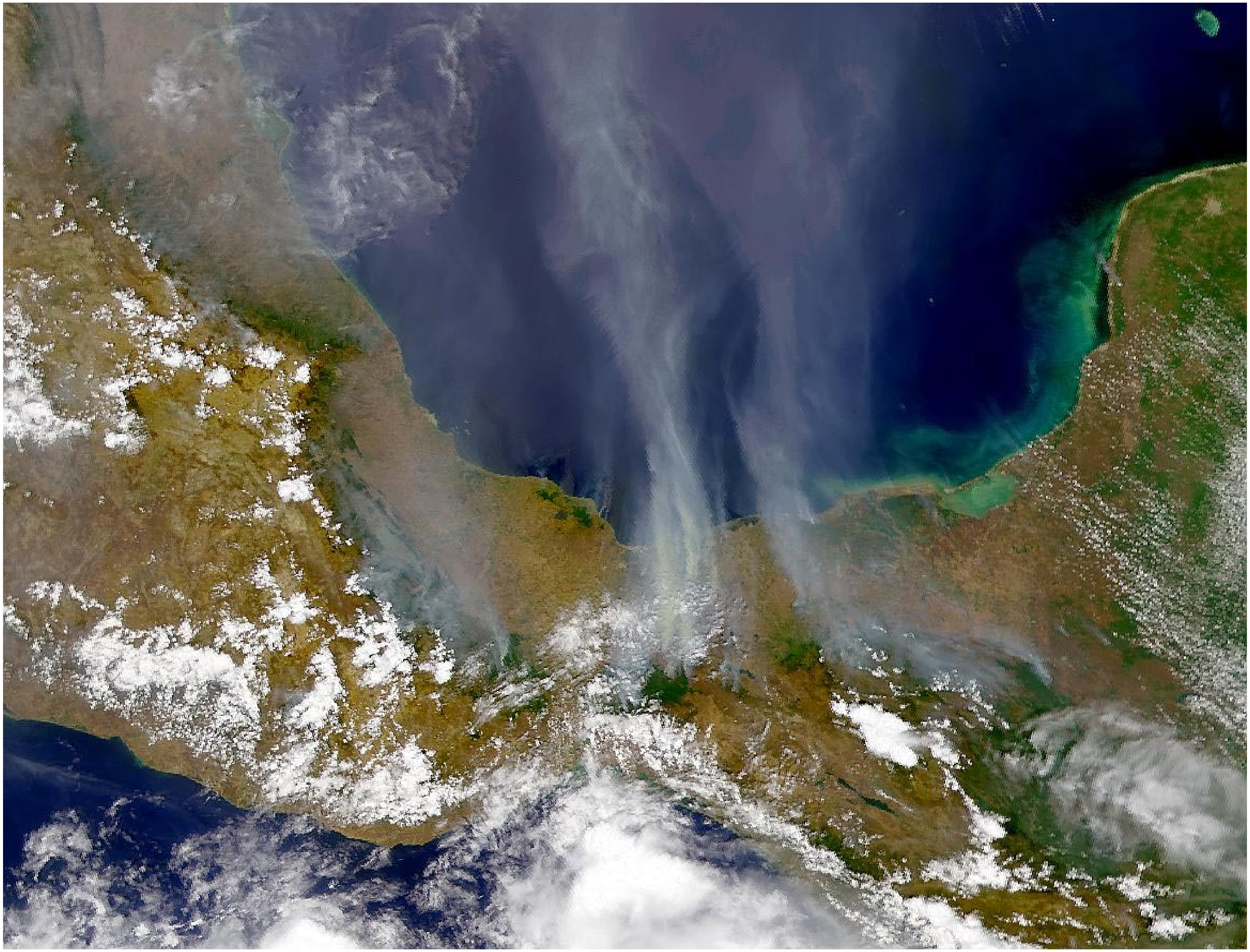


LOSU denotes level of scientific understanding.

Radiative Forcing by Tropospheric Aerosol



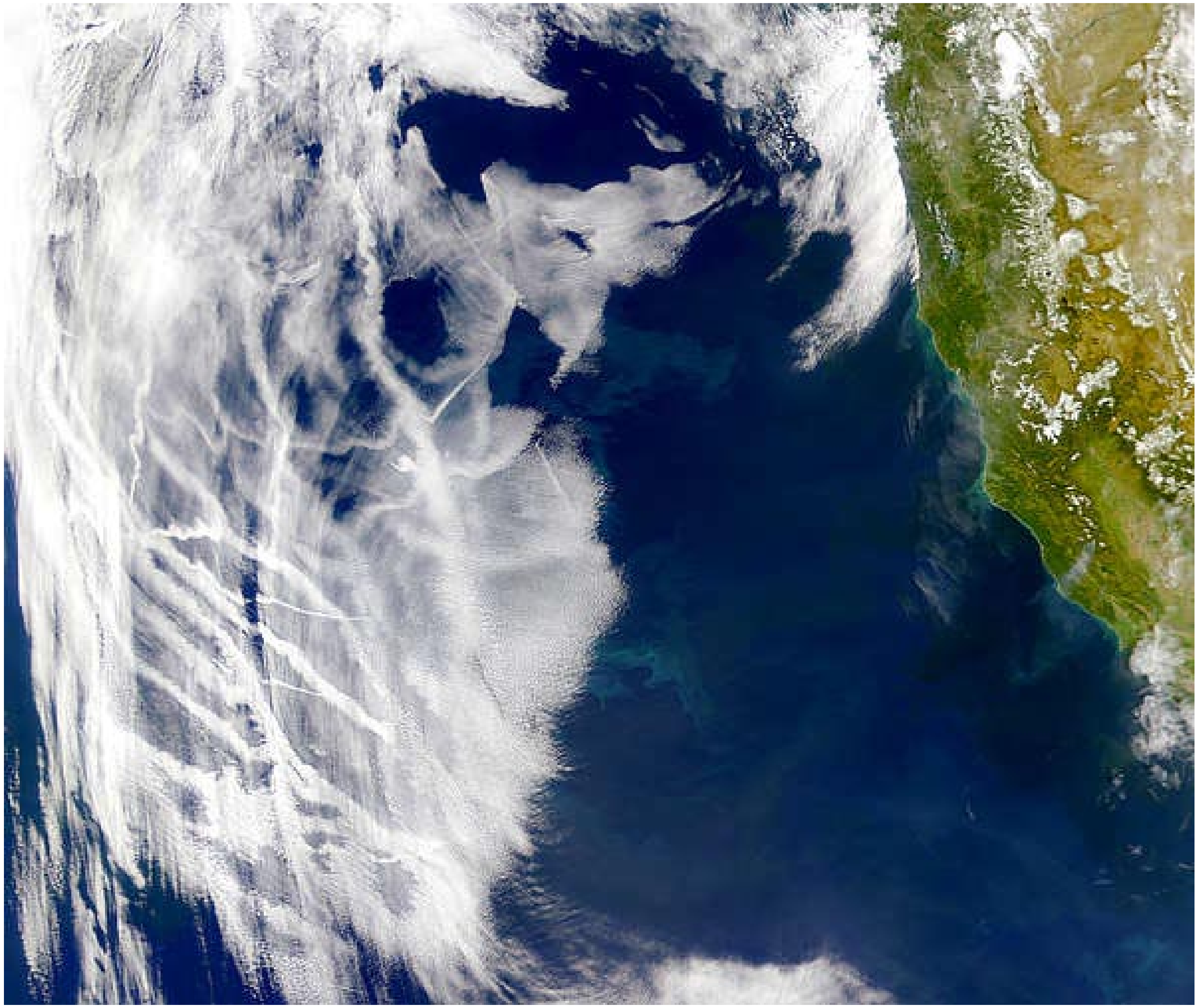
AEROSOLS AS SEEN FROM SPACE



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

CLOUD BRIGHTENING BY SHIP TRACKS

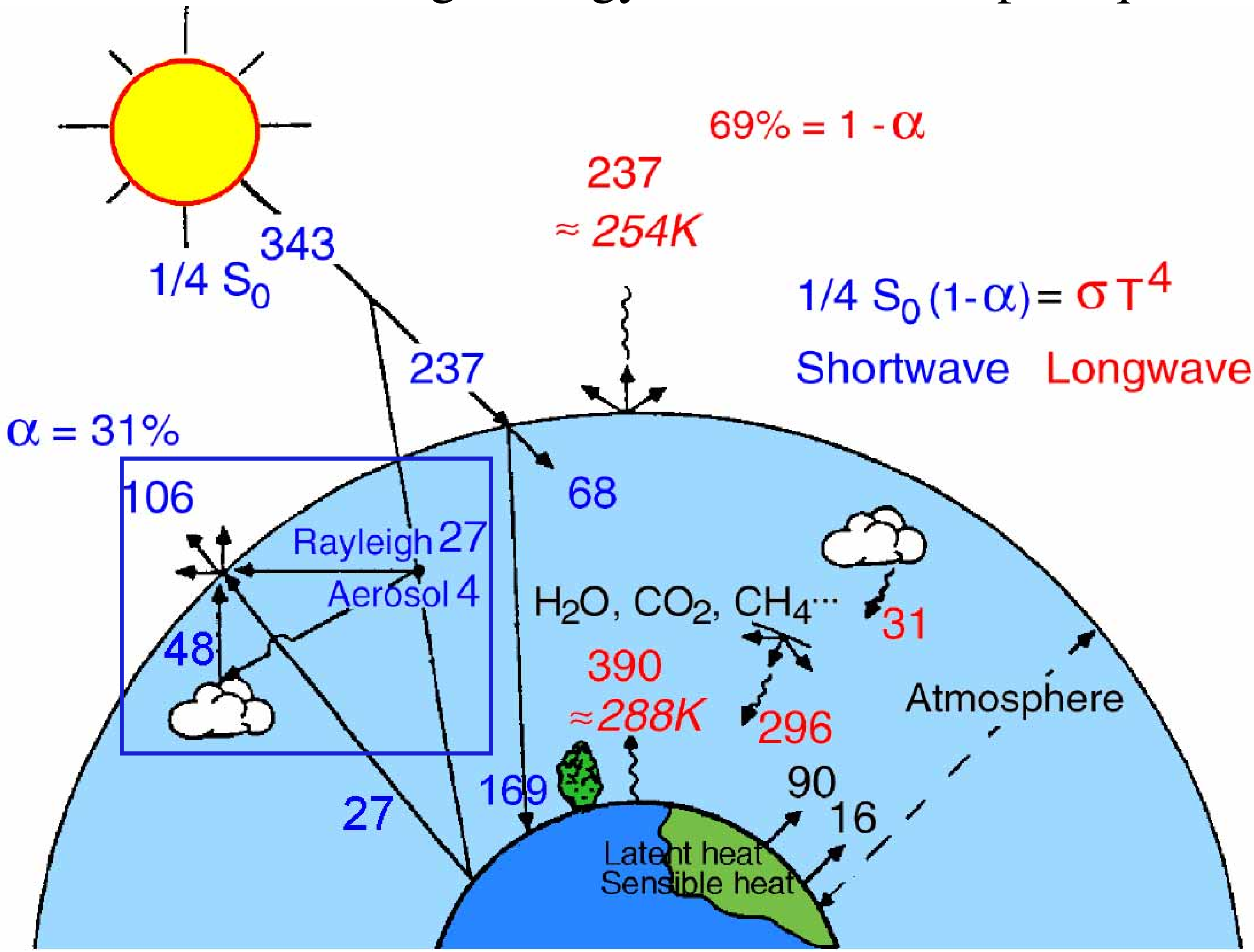
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

GLOBAL ENERGY BALANCE

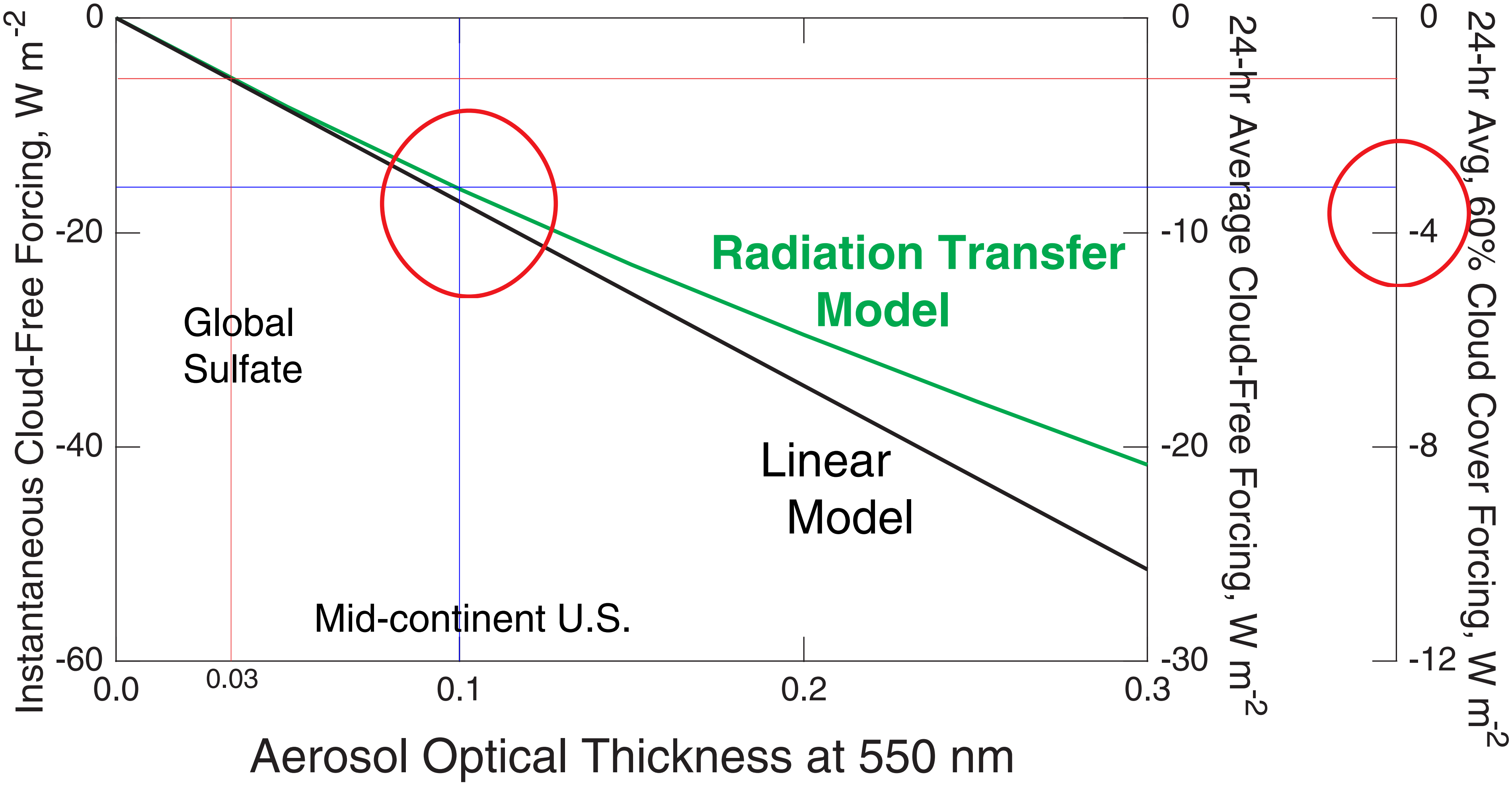
Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

ESTIMATES OF AEROSOL DIRECT FORCING

By linear model and by radiation transfer modeling



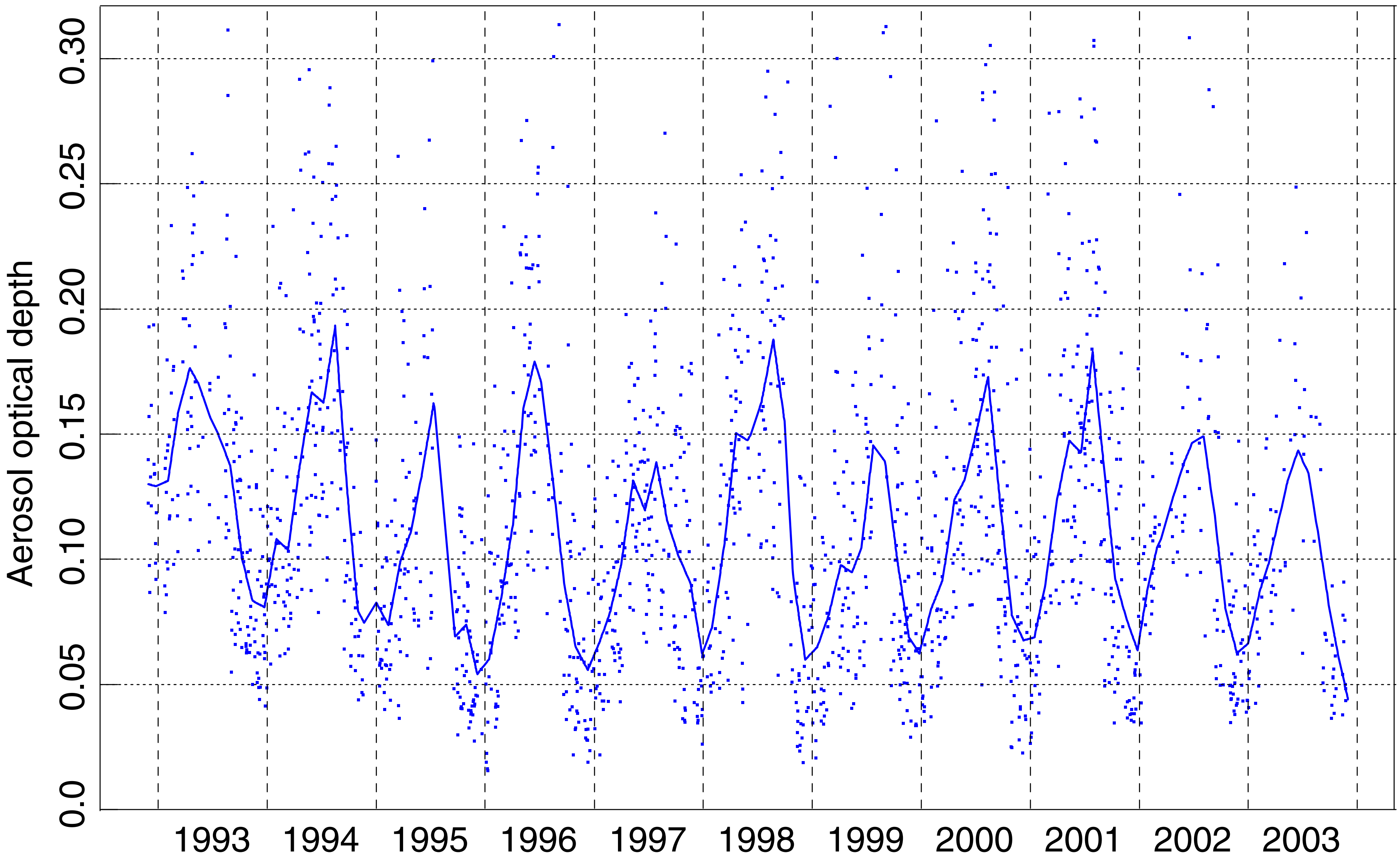
Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling***.

In ***continental U. S.*** typical aerosol optical thickness is 0.1: ***3 W m^{-2} cooling***.

AEROSOL OPTICAL DEPTH

Determined by sunphotometry

North central Oklahoma - Daily average at 500 nm



J. Michalsky et al., JGR, 2001

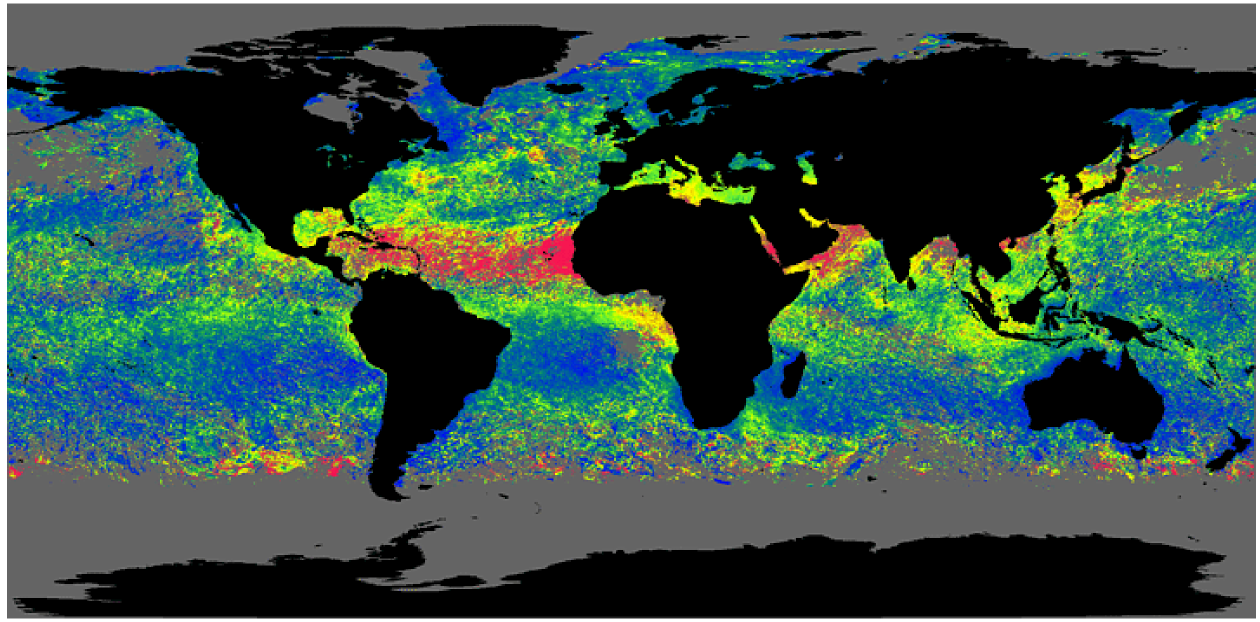
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

0 0.5



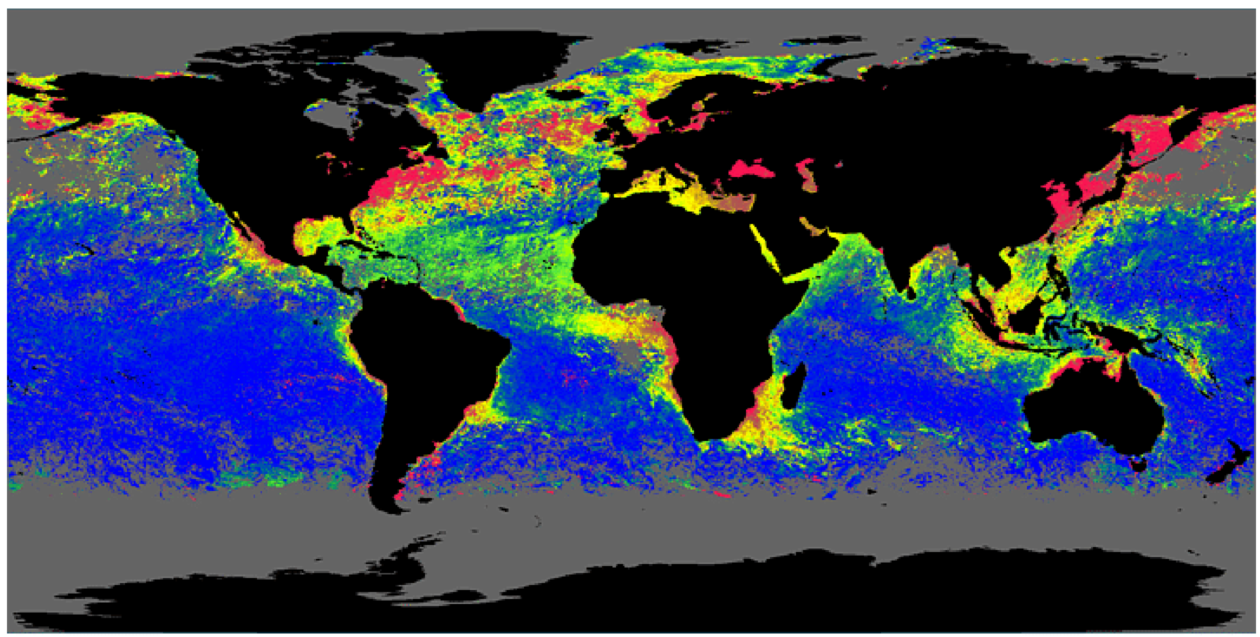
Ångström Exponent α

$$\alpha = -d \ln \tau / d \ln \lambda$$

-0.2 1.2

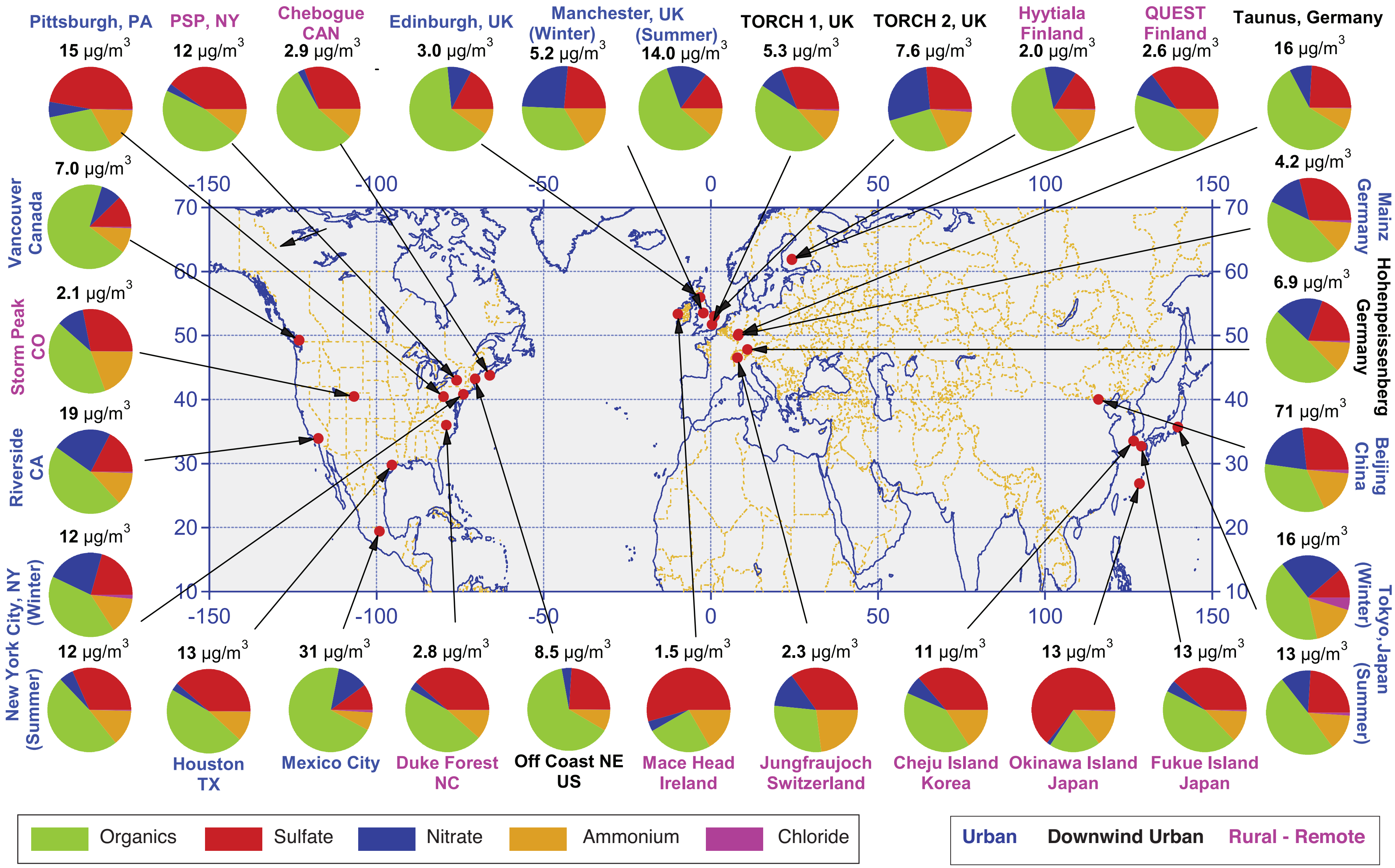
Large Particles — Small Particles

Small particles are from gas-to-particle conversion.



DOMINANCE OF ORGANIC AEROSOL

Measurements by aerosol mass spectrometer

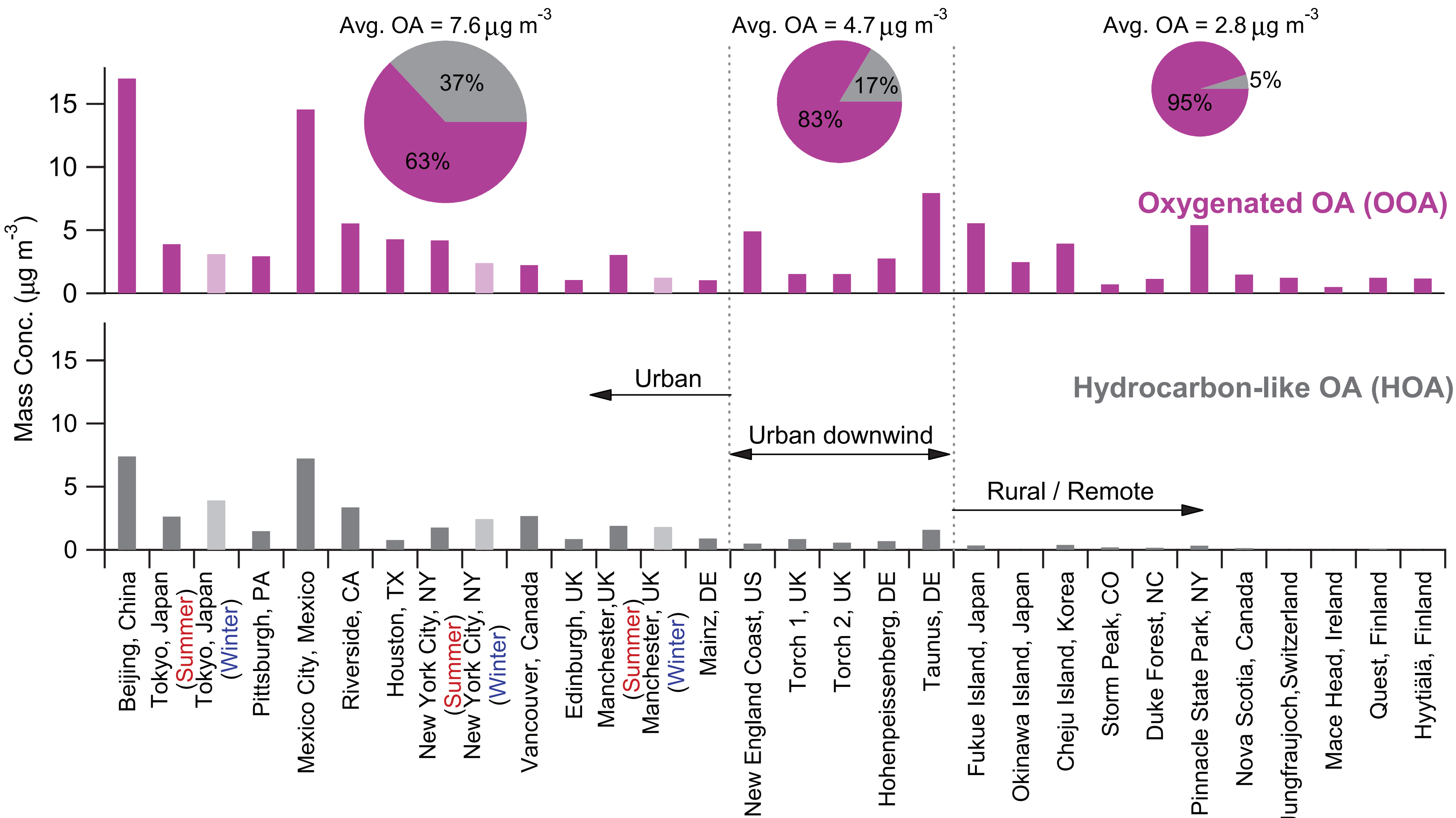


Zhang et al., GRL, 2007

Organic aerosol is major or dominant species throughout the anthropogenically influenced Northern Hemisphere.

HOA AND OOA BY LOCATION TYPE

Area of pie scaled to organic aerosol concentration



Zhang et al., GRL, 2007

OOA fraction increases with increasing distance from urban sources.

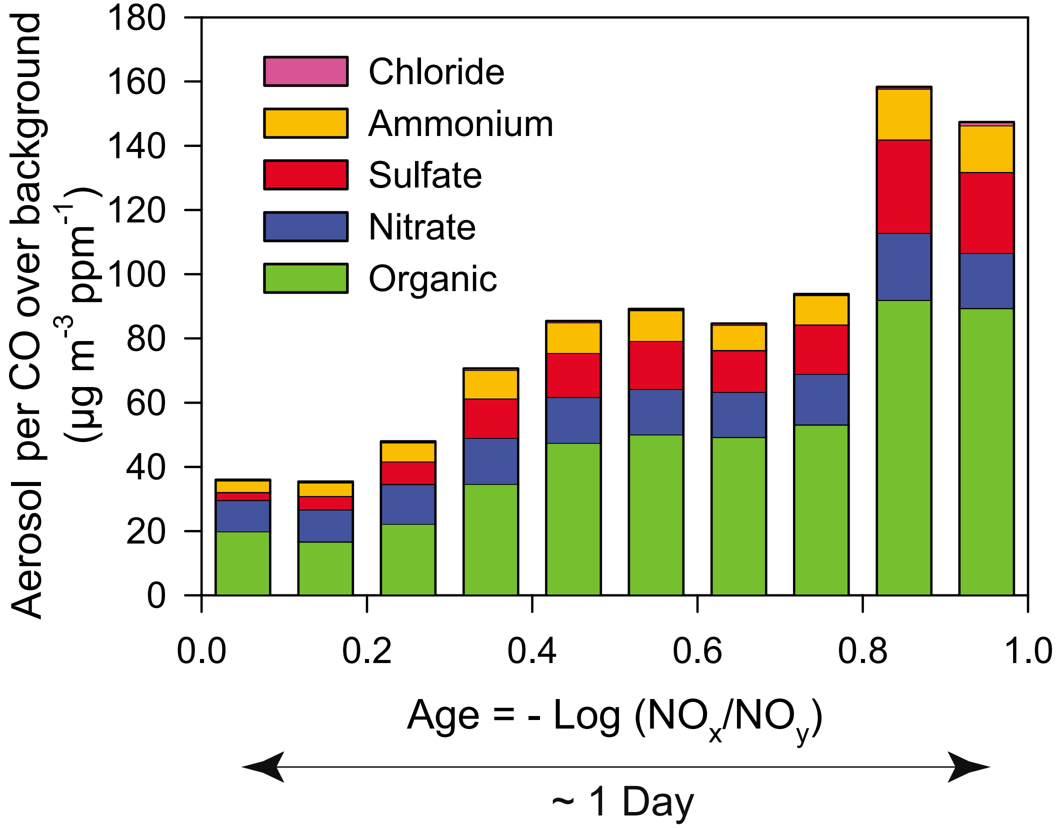
AEROSOL IN MEXICO CITY BASIN

AEROSOL IN MEXICO CITY BASIN

Mexico City is a wonderful place to study aerosol properties and evolution.

SECONDARY AEROSOL PRODUCTION

Eight aircraft flights above and downwind of Mexico City, March 2006



Kleinman et al, ACP, 2008

Parcel photochemical age measured using $-\mathrm{Log}(NO_x/NO_y)$ as clock.

Aerosol normalized to CO above background to account for dilution.

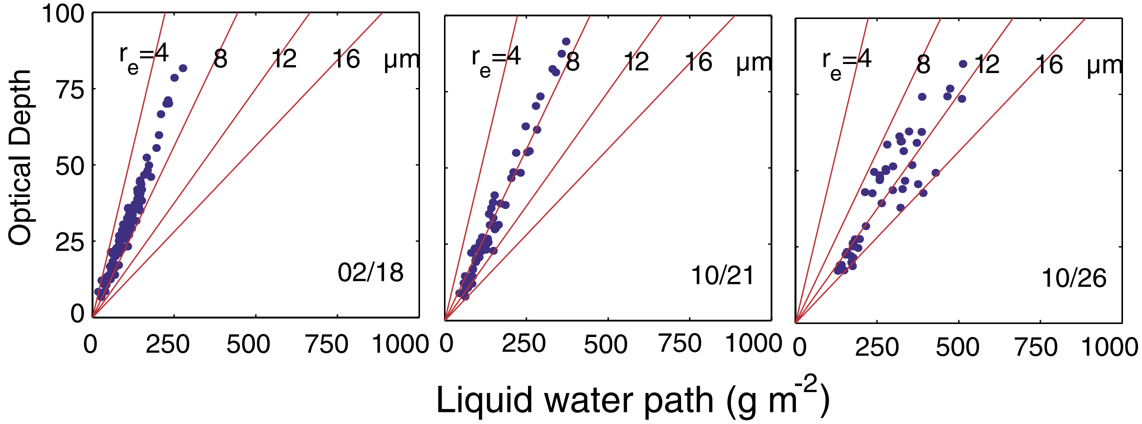
Fivefold increase in organic aerosol.

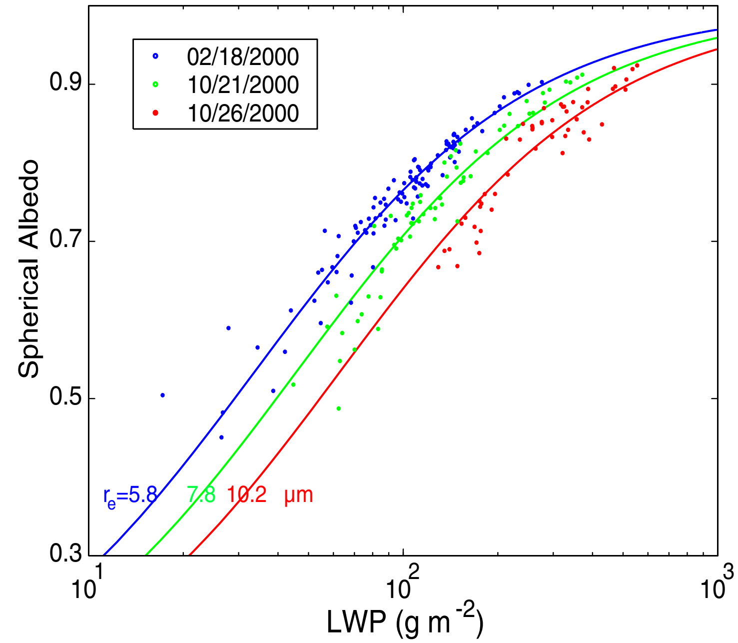
Measured increase in organic aerosol exceeds modeled based on laboratory experiments and measured volatile organic carbon ***tenfold***.

CLOUD ALBEDO AND FORCING CALCULATED FROM MEASURED EFFECTIVE RADIUS AND LIQUID WATER PATH

North Central Oklahoma

Effective radius determined from slope of Optical depth vs. Liquid water path





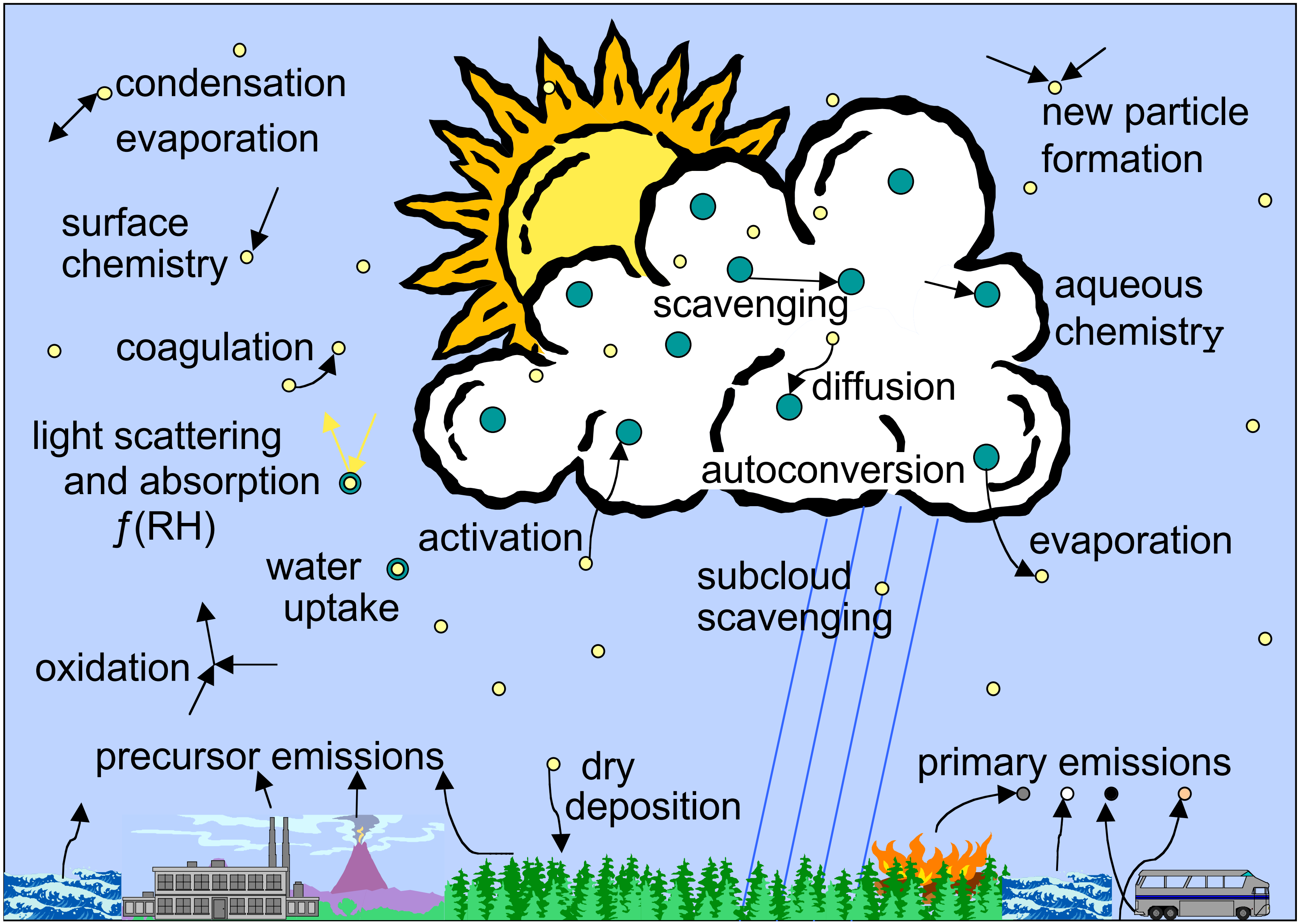
Cloud albedo is calculated for observed data and for average effective radius for each day. Forcing is calculated for indicated conditions relative to October 26.

Radiative forcing for solar zenith angle 60° and liquid water path 100 g m^{-2}

Date, 2000	Effective radius r_e, μm	Optical Depth	Net flux at TOA W m^{-2}	Forcing relative to 10/26, W m^{-2}
10/26	10.2	15.1	293	—
10/21	7.8	20.8	266	27
02/18	5.8	28.3	240	53

Kim, Schwartz, Miller, and Min, JGR, 2003

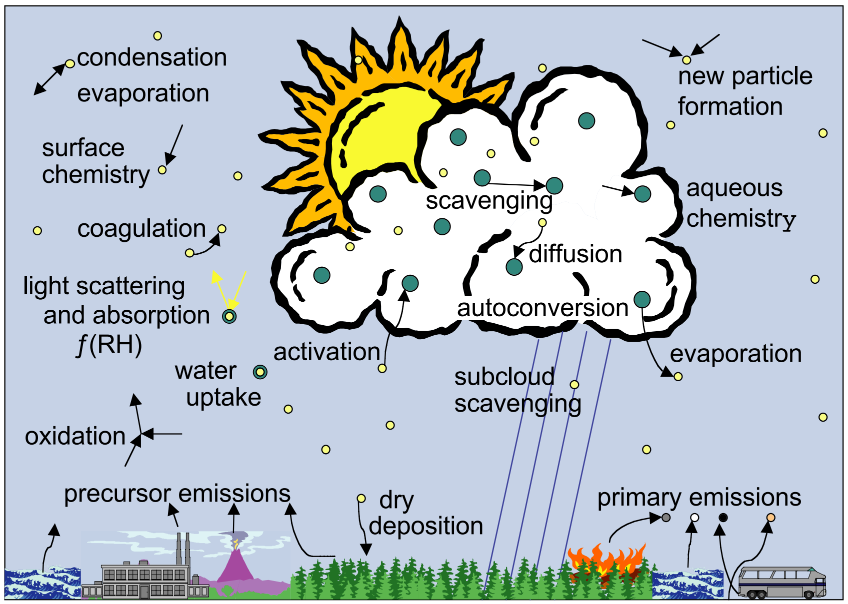
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS



Ghan and Schwartz, Bull. Amer. Meterol. Soc., 2007

APPROACH TO DETERMINE AEROSOL FORCING

Numerical simulation of physical processes



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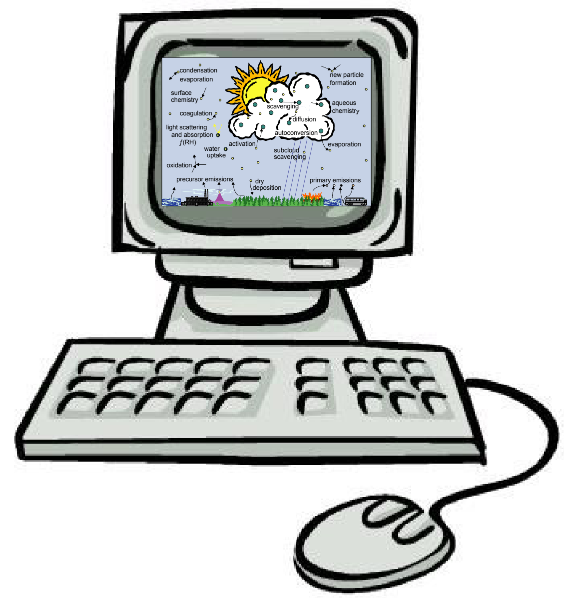
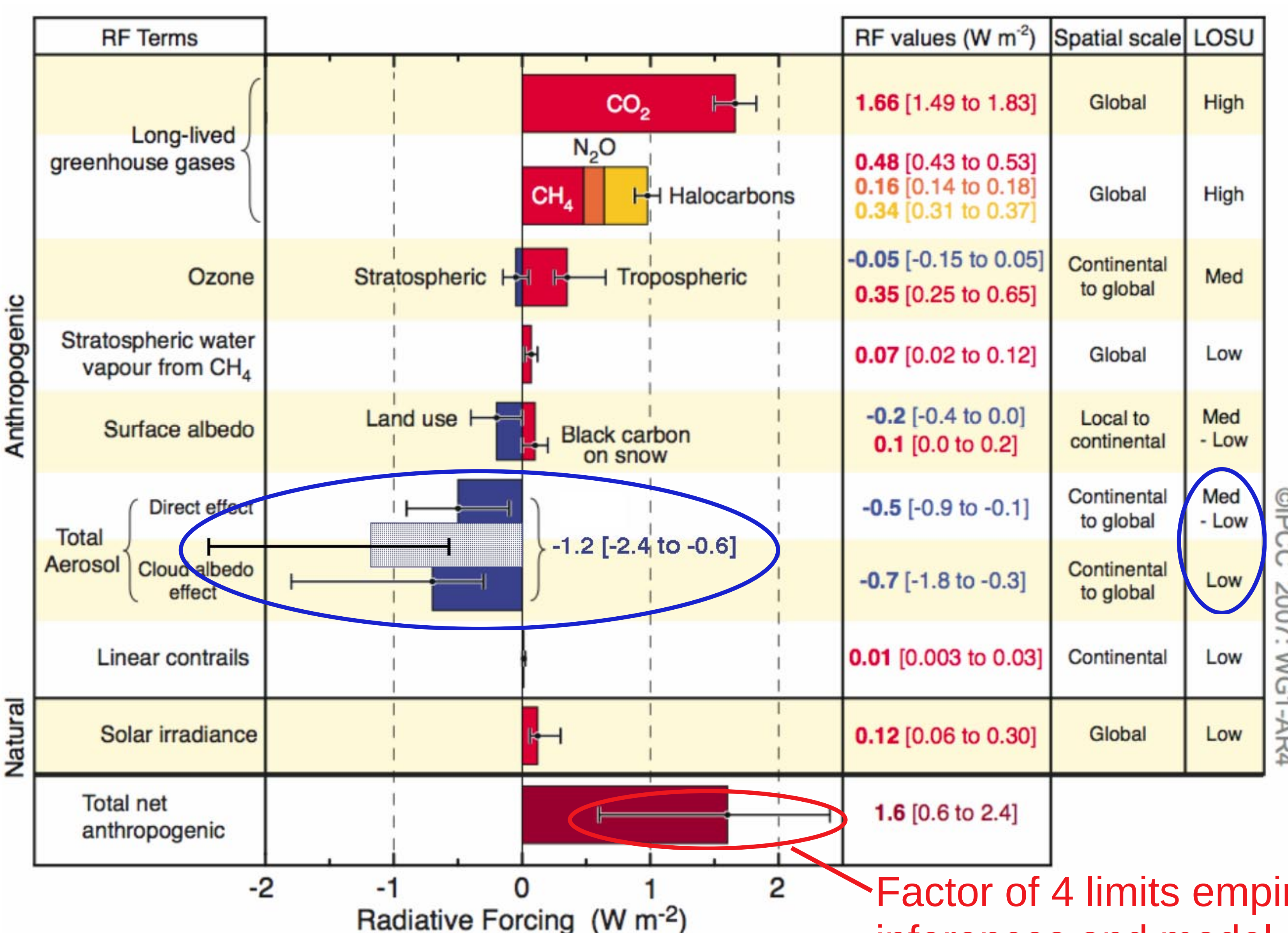


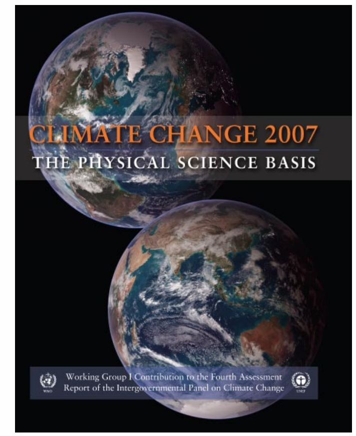
Isomorphism of processes to computer code

Modeling aerosol processes requires understanding these processes, developing and testing their numerical representations, and incorporating these representations in global scale models.

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*

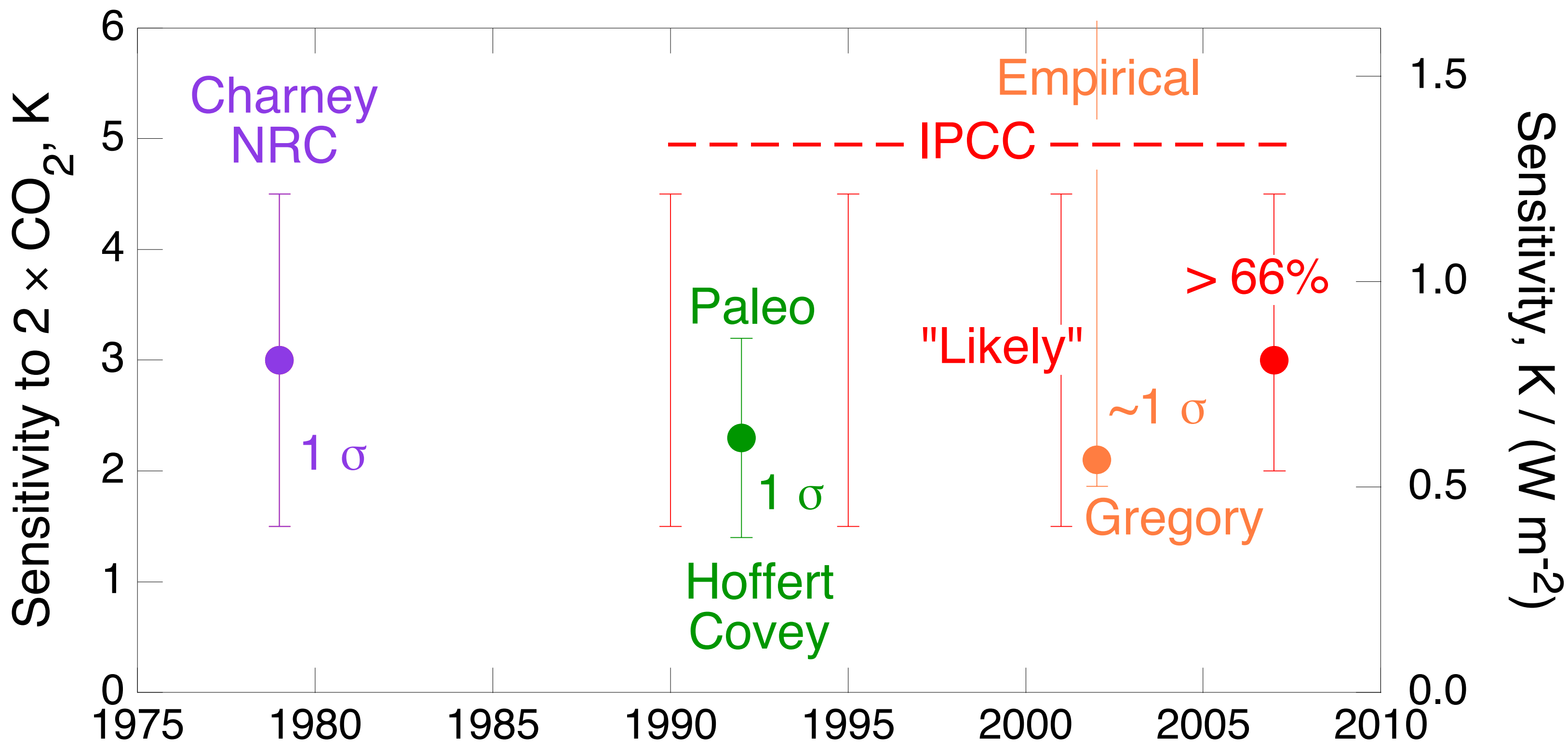
$$S = \frac{\Delta T}{\Delta F - (dH/dt)}$$

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

Symbol	Quantity	Value ± 1σ	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	$0.56^{+>2.2}_{-0.07}$	K/(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.
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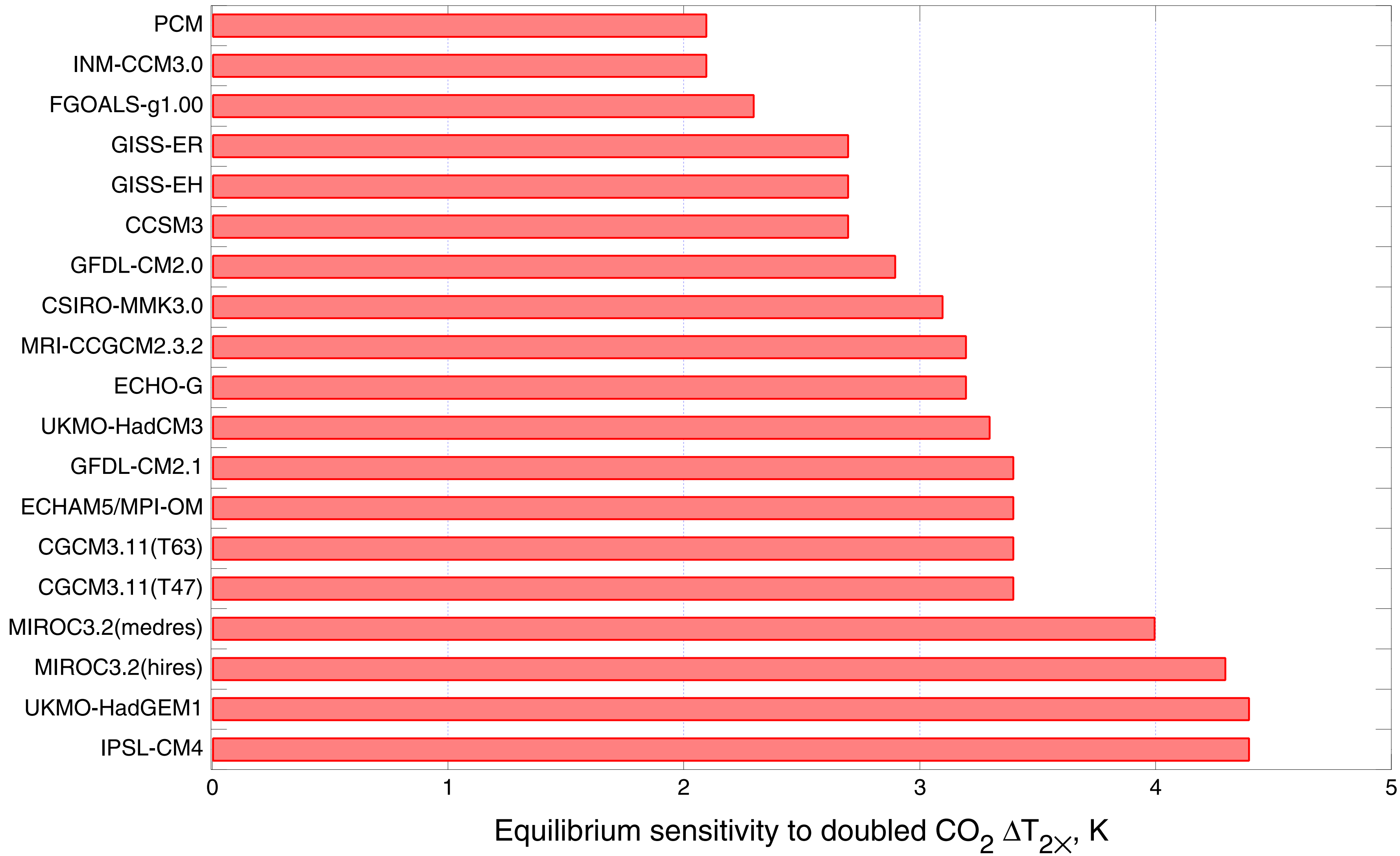
EQUILIBRIUM SENSITIVITIES IN CURRENT CLIMATE MODELS

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

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

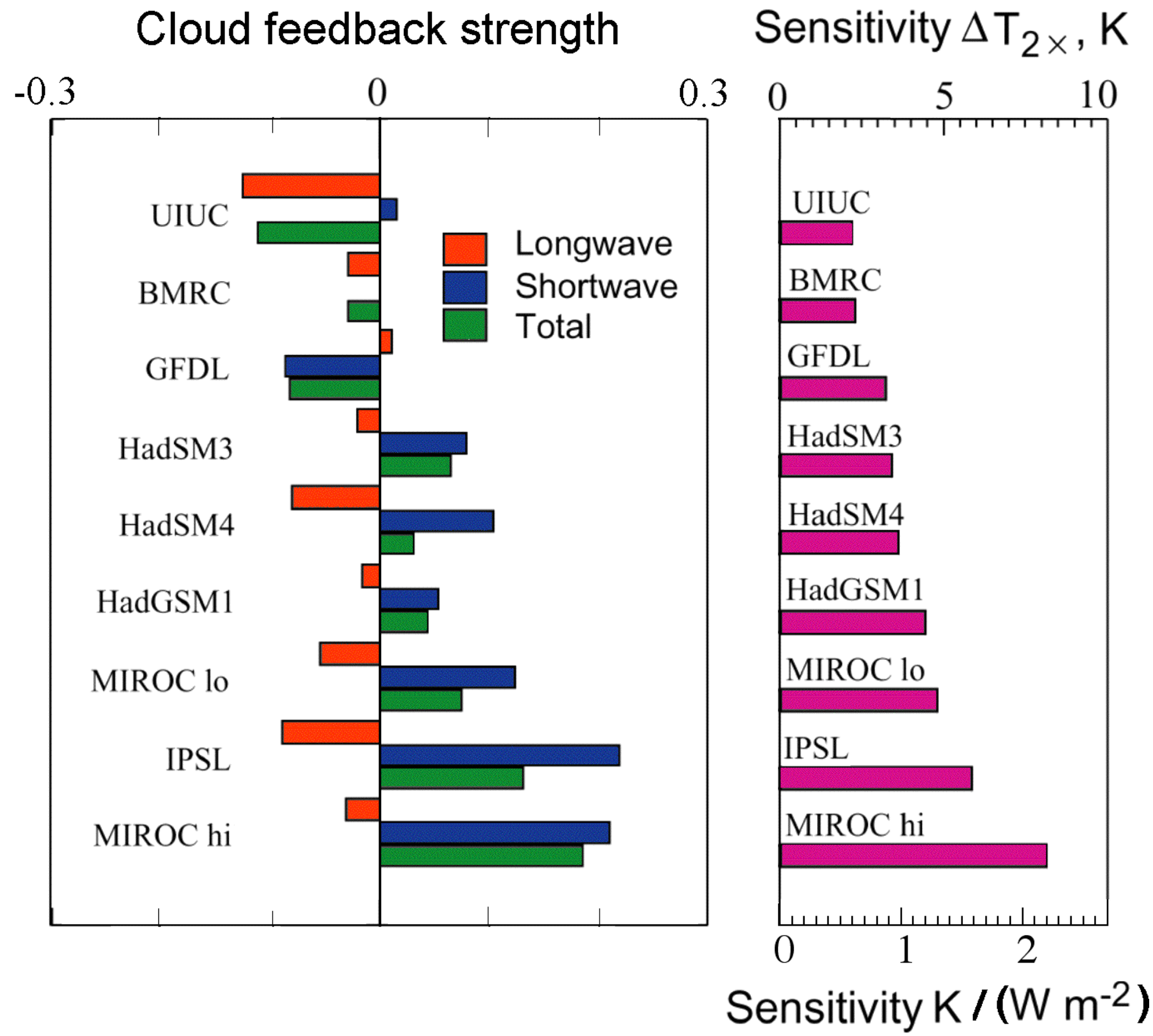
S = Climate sensitivity

S_{SB} = Stefan-Boltzmann sensitivity

$\mathcal{F}$ = feedback strength

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

sum over all feedbacks

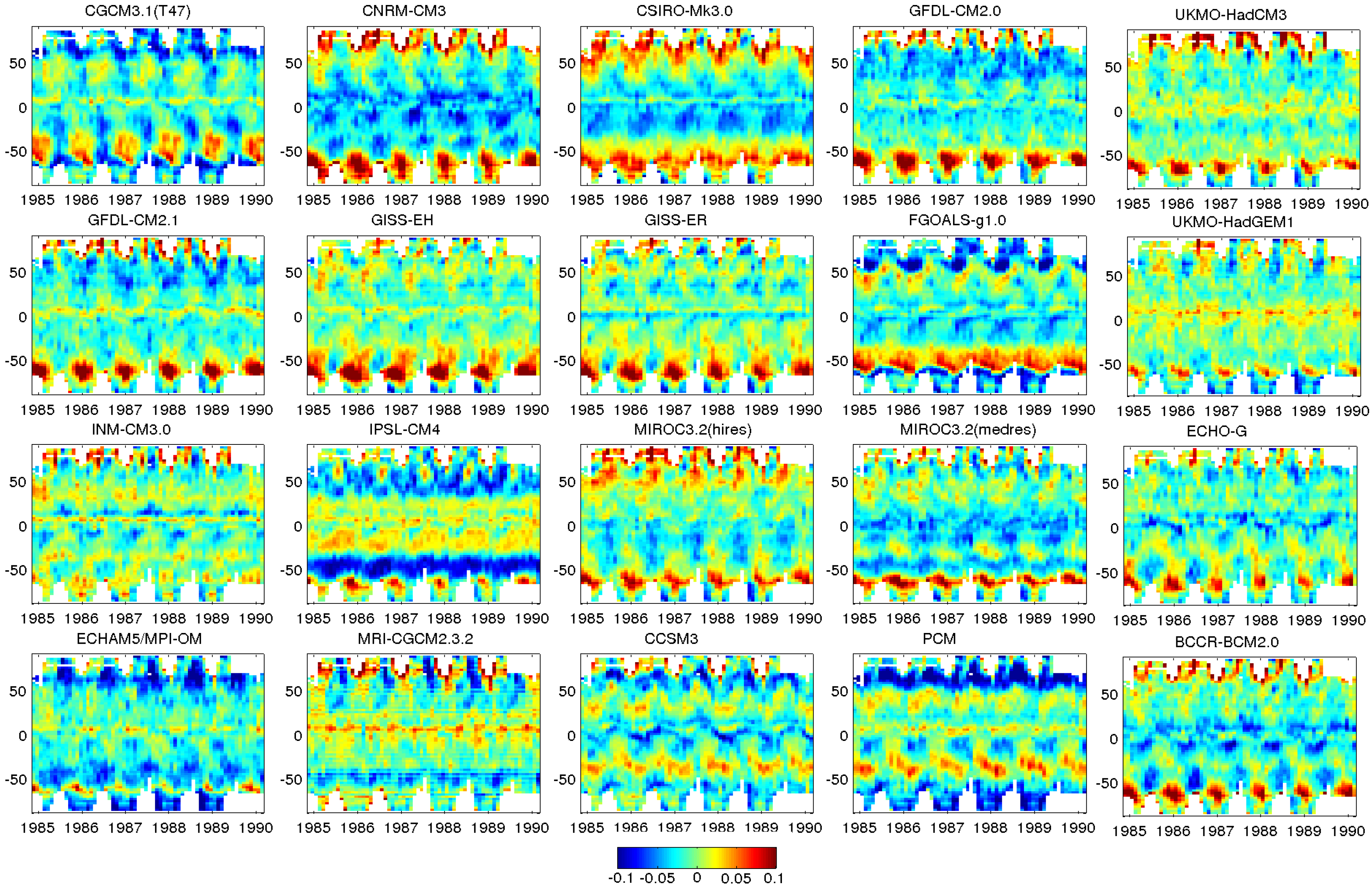


Adapted from Webb et al., Clim. Dyn., 2006

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

ZONAL MONTHLY MEAN ALBEDO

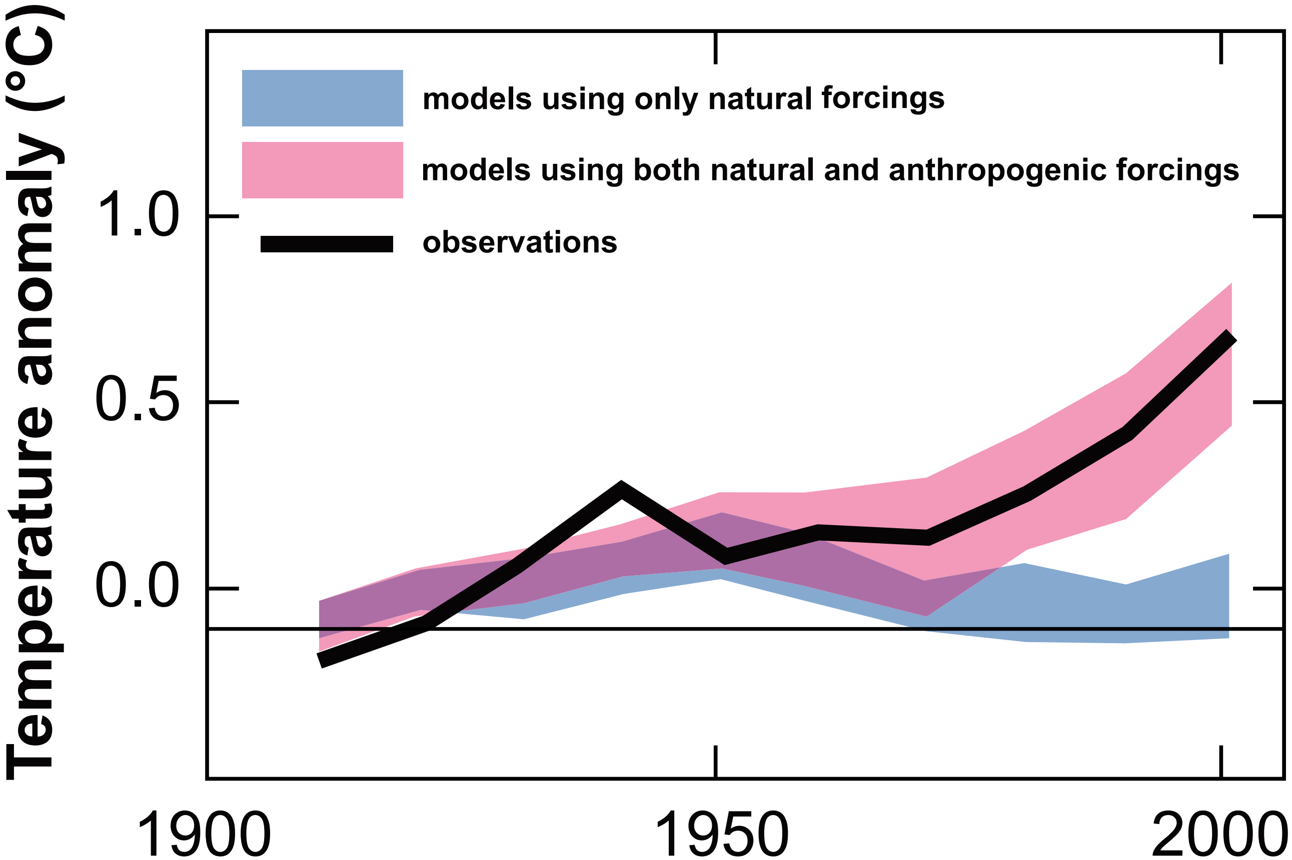
20 GCMs – Difference vs. ERBE Satellite

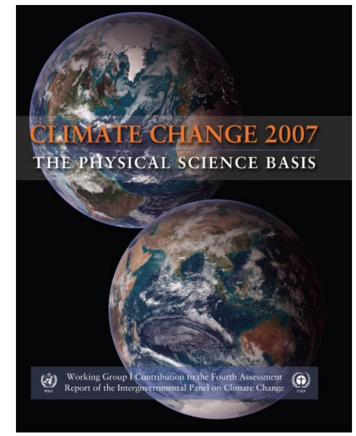


Modified from Bender et al., Tellus, 2006

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



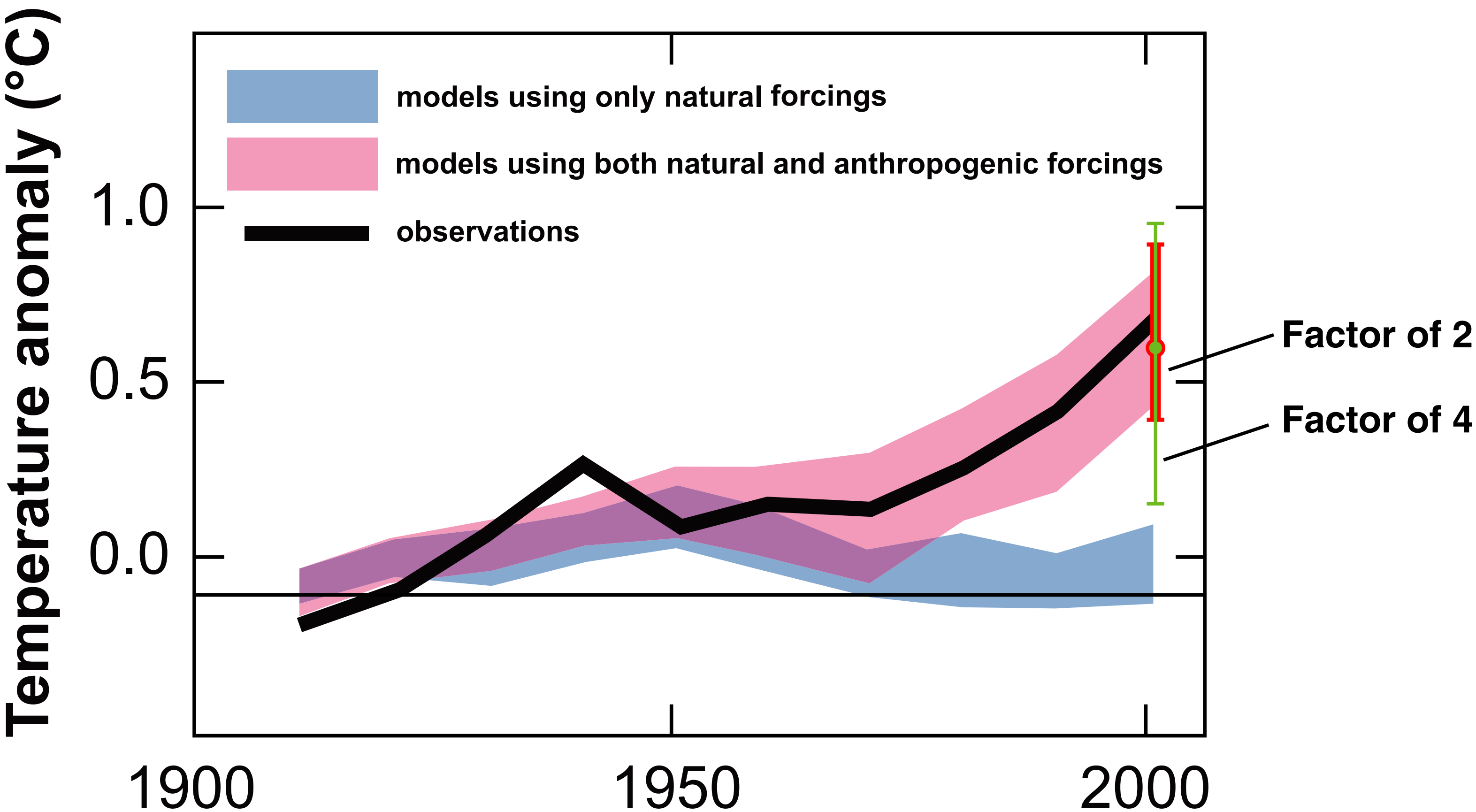


“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

“ 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



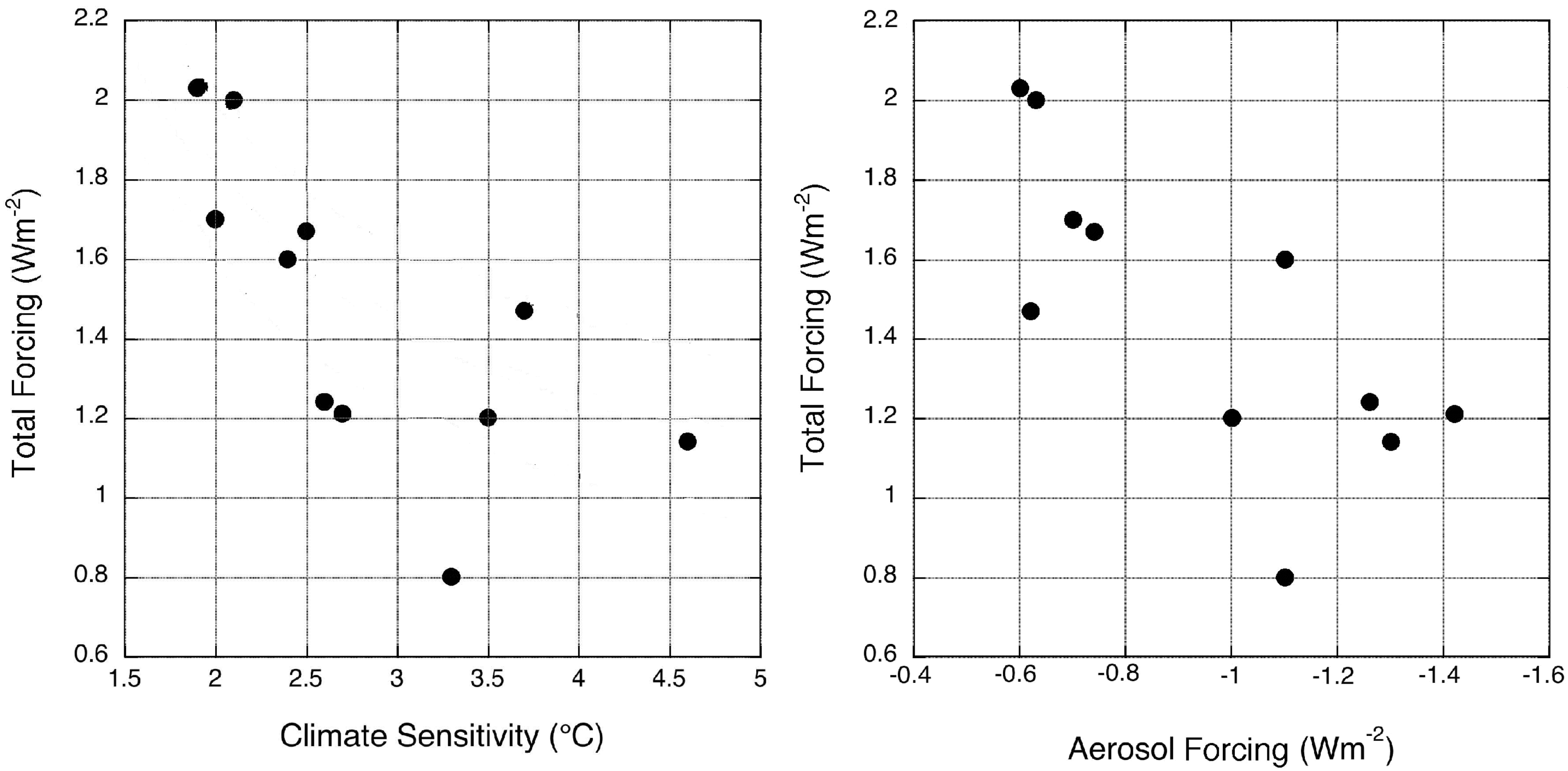
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

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

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

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

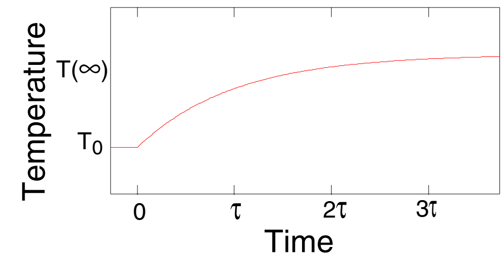
γ is planetary co-albedo

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 $S = \frac{T_0}{\gamma_0 J_S} f = S_{SB} f$ Stefan-Boltzmann senstivity 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*.

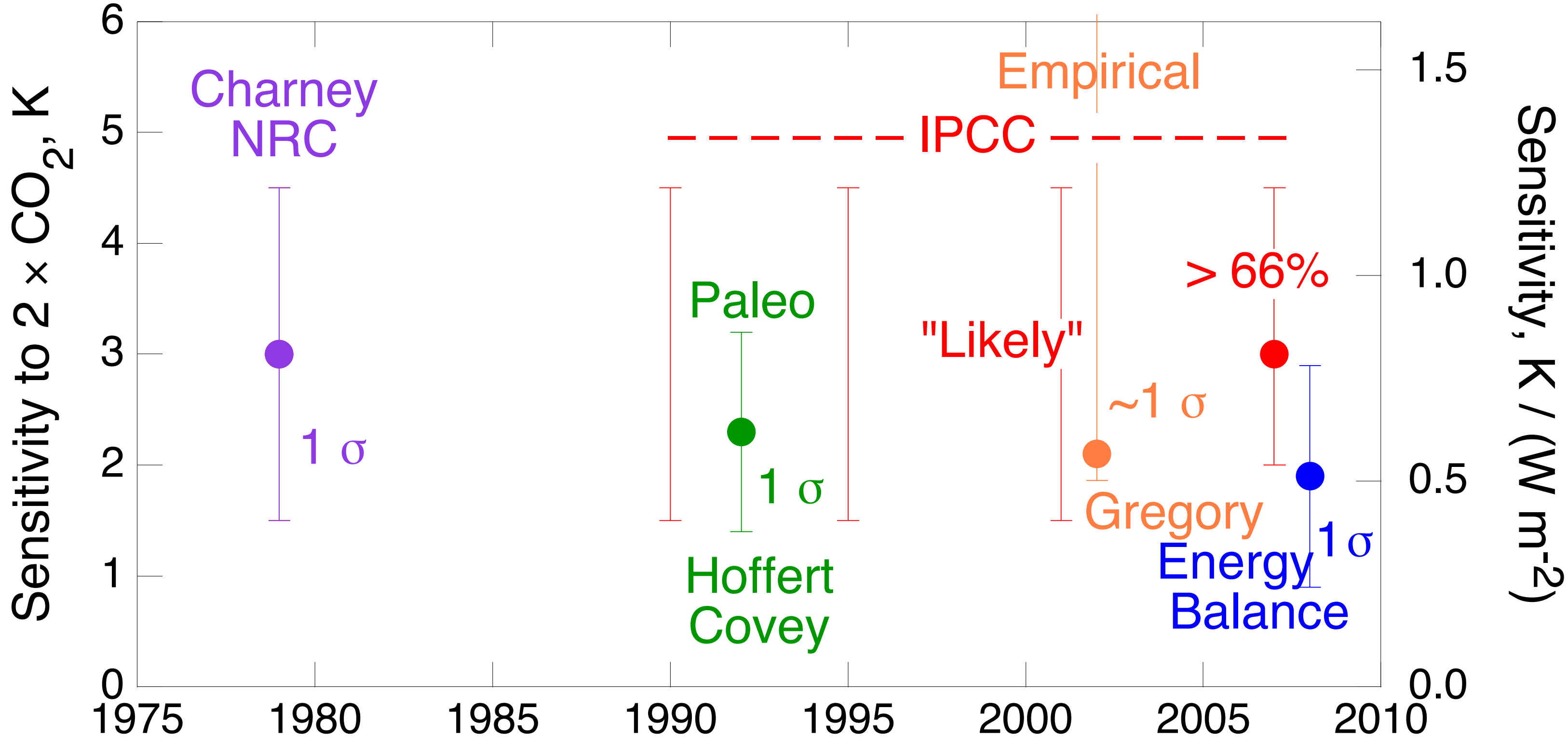
EVALUATION OF SENSITIVITY AND FORCINGS

Quantity	Unit	Value	1 σ
Effective global heat capacity C	W yr m^{-2} K^{-1}	**17**	**7**
Effective climate system time constant τ	yr	**8.5**	**2.5**
Equilibrium climate sensitivity $S = \tau / C$	K/(W m^{-2})	**0.51**	**0.26**
Feedback factor f	–	**1.7**	
Equilibrium temperature increase for $2 \times CO_2$, $\Delta T_{2\times}$	K	**1.9**	**1.0**

Schwartz, JGR, 2007-2008

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 $\Delta T_{2\times} \gtrsim 3$ 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*** **CO_2** 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

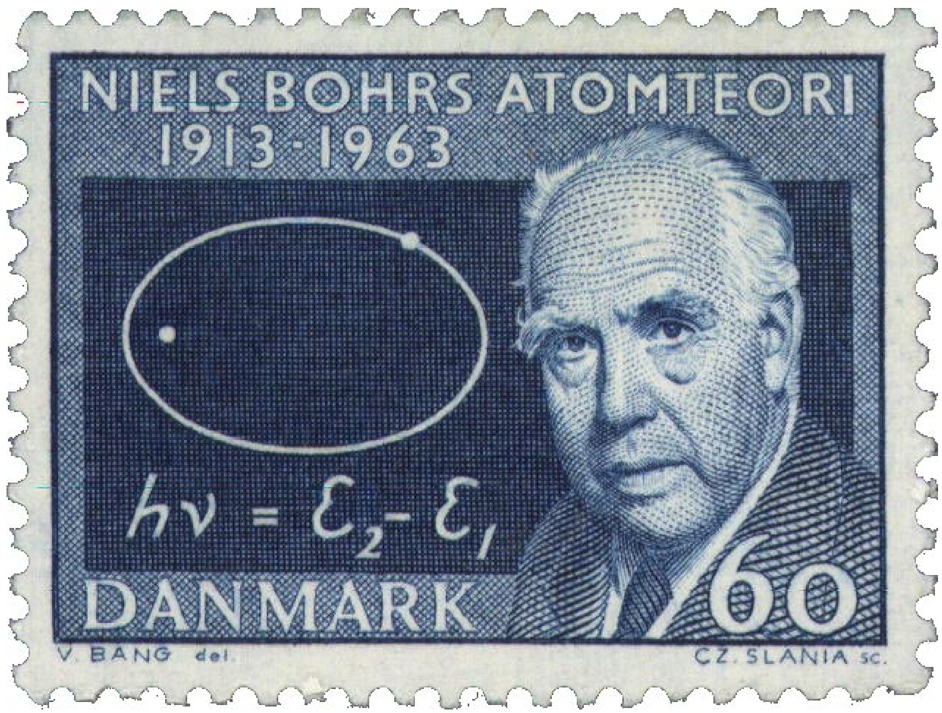
- The lifetime of incremental atmospheric CO_2 is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

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

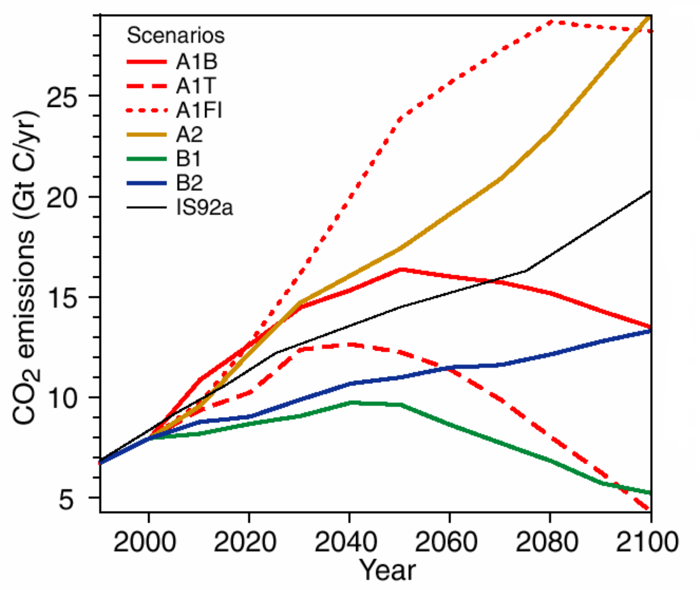
Looking to the Future . . .

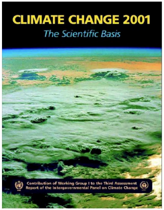
Prediction is difficult,
especially about the future.



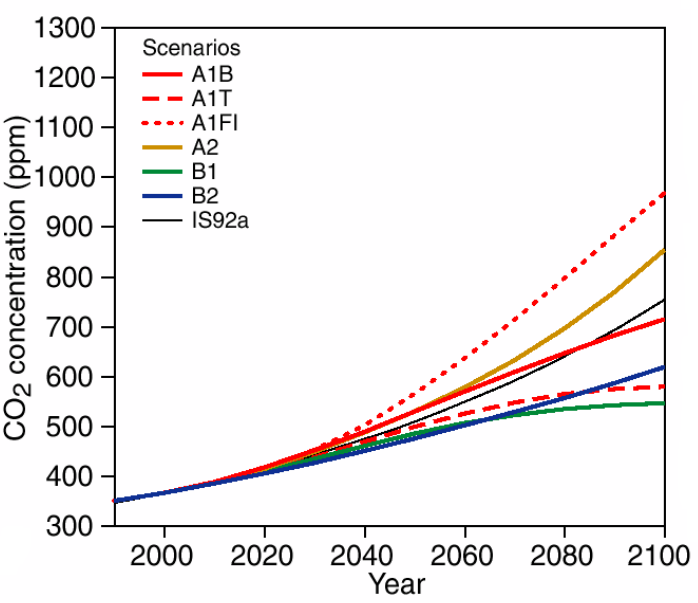
– Niels Bohr

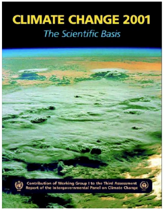
PROJECTIONS OF FUTURE CO2 EMISSIONS



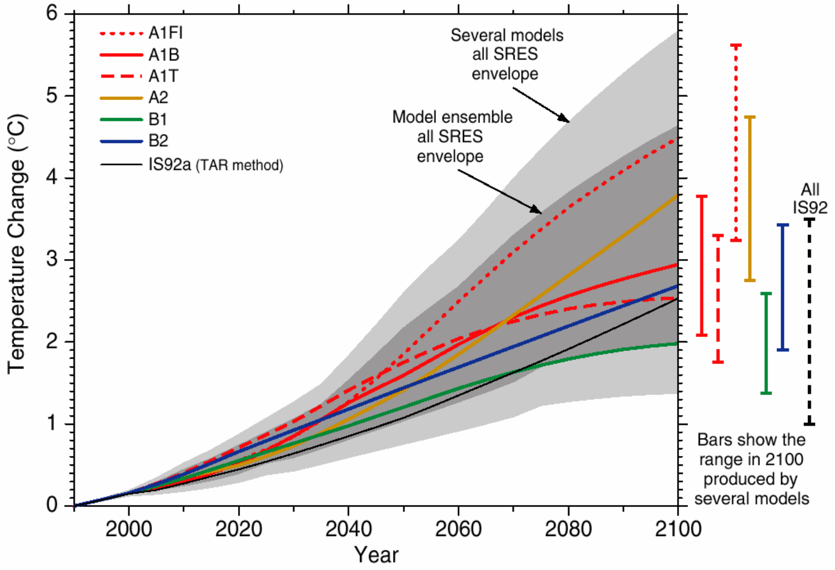


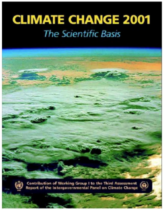
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS





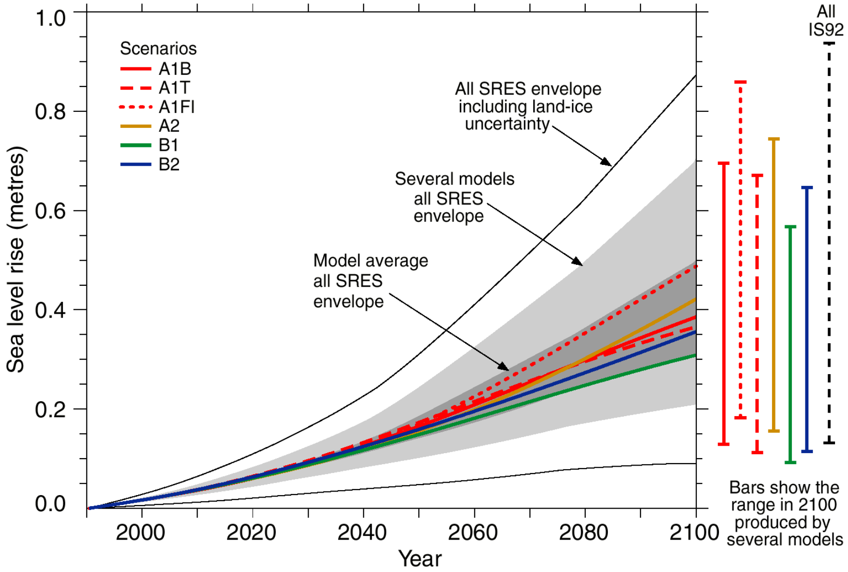
PROJECTIONS OF FUTURE TEMPERATURE CHANGE

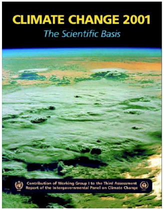




PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only





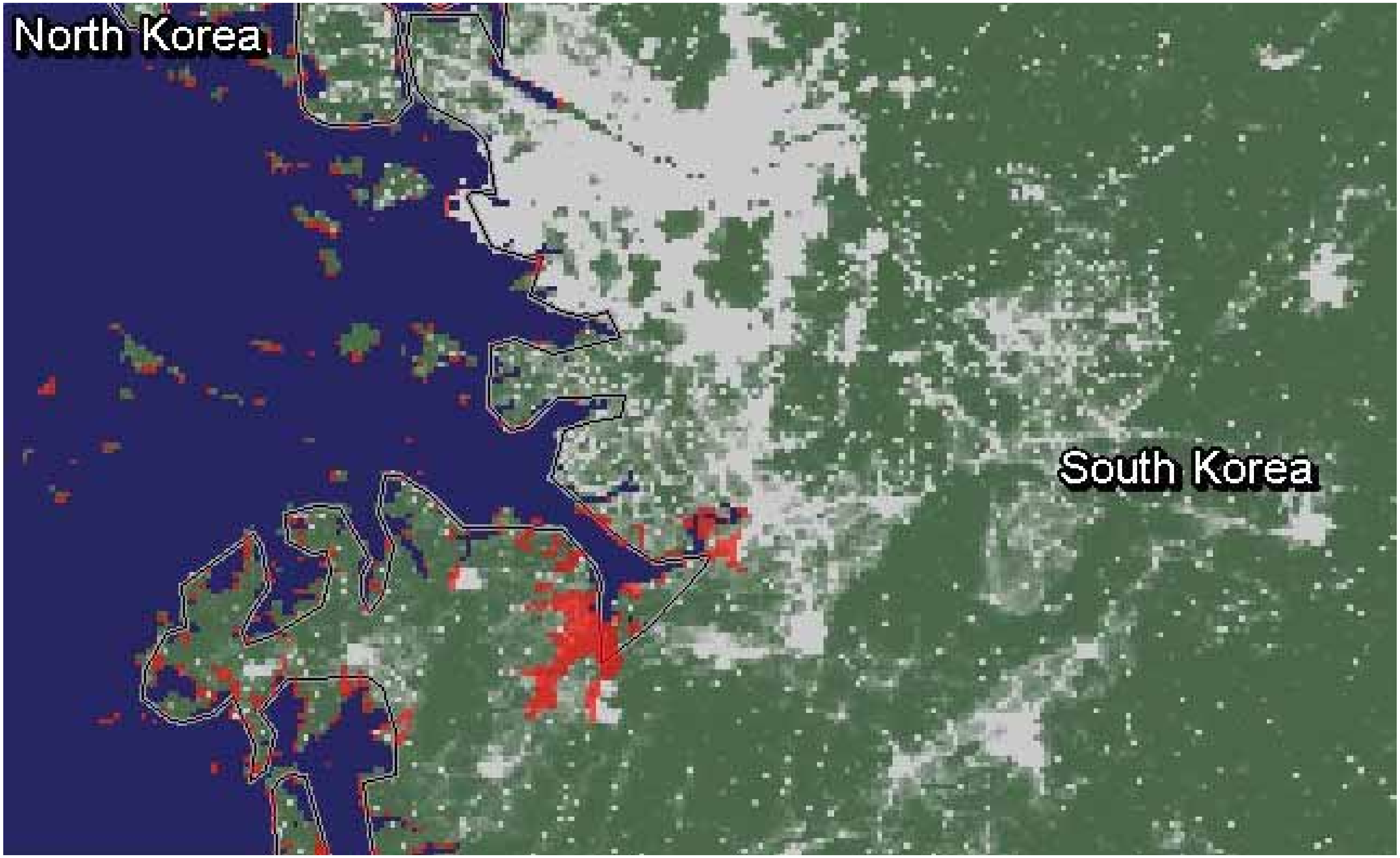
EFFECT OF SEA LEVEL RISE

Population density, current coastline

Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

Population density, 1 meter sea level rise

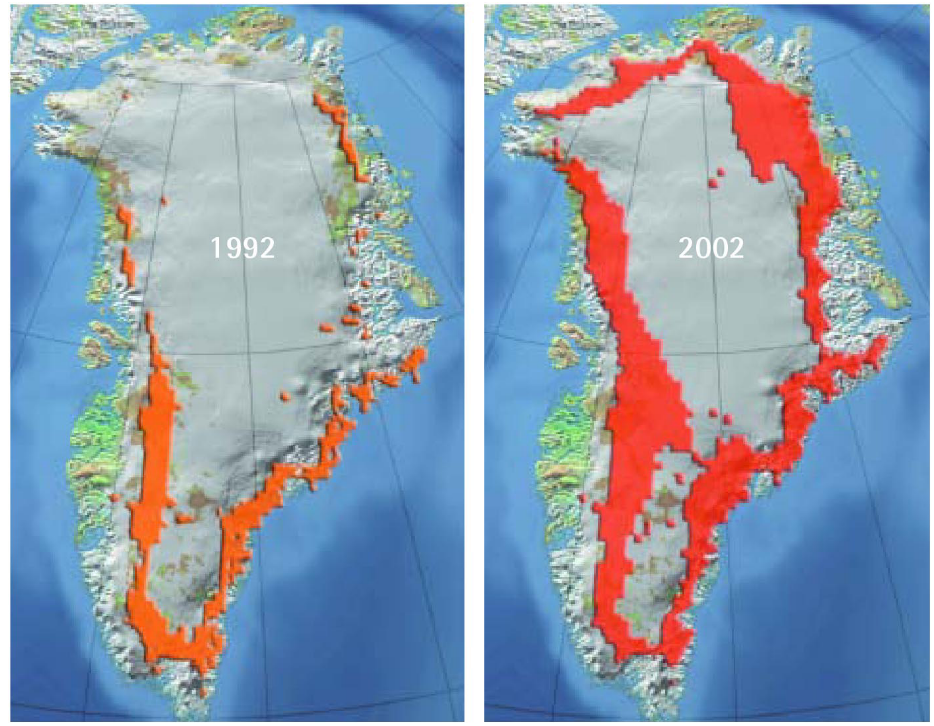


Weiss and Overpeck, University of Arizona

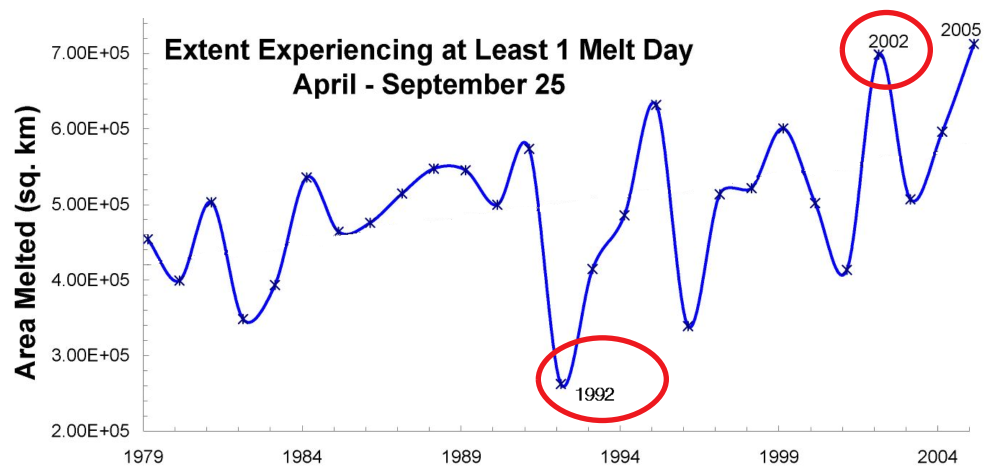
MELTING OF GREENLAND ICE CAP

Satellite determination of extent of glacial melt 1992 vs 2002

NASA



Arctic Climate Impact Assessment, Cambridge, 2004

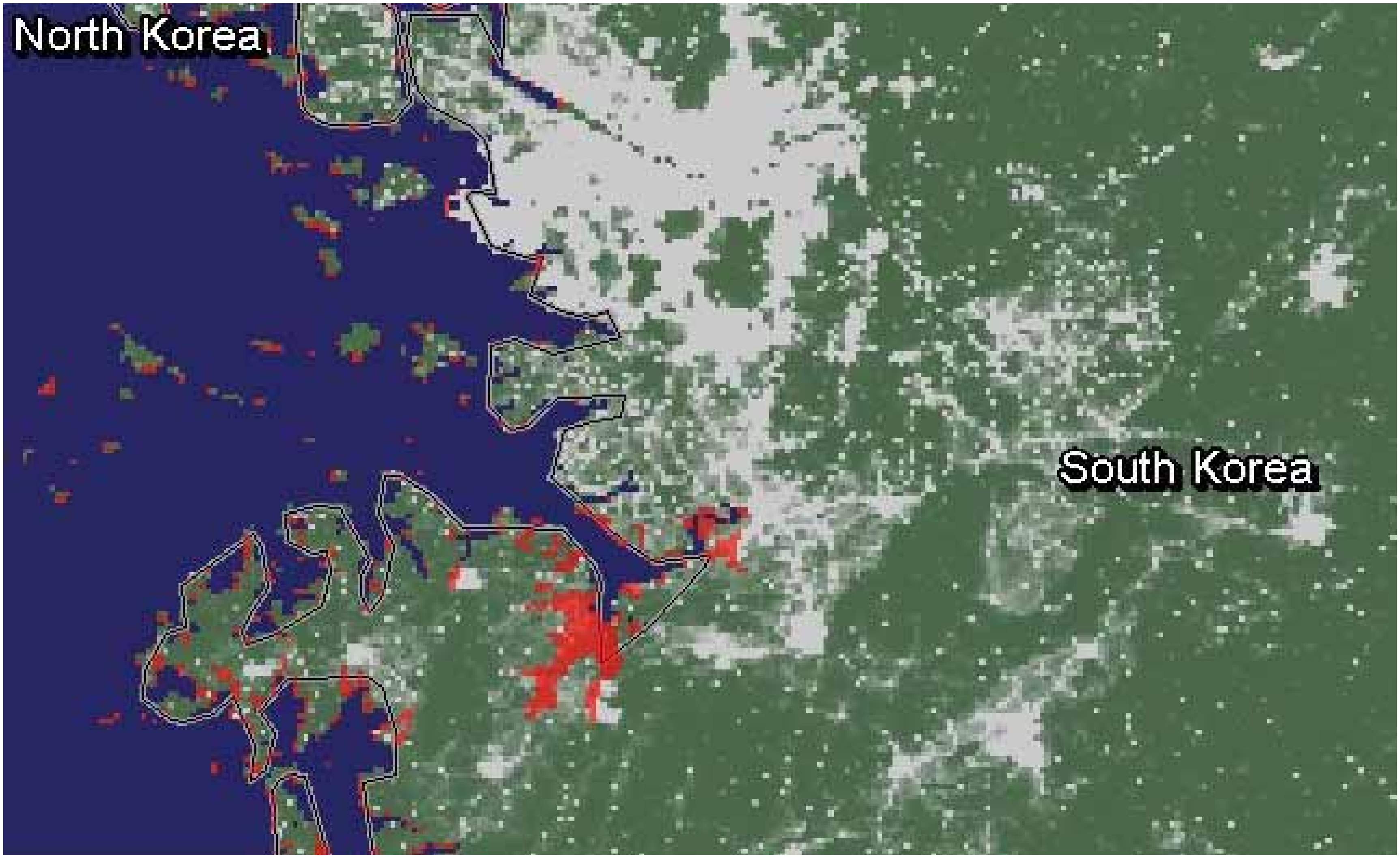


Steffen & Huff , Univ. Colo., 2005

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

EFFECT OF SEA LEVEL RISE

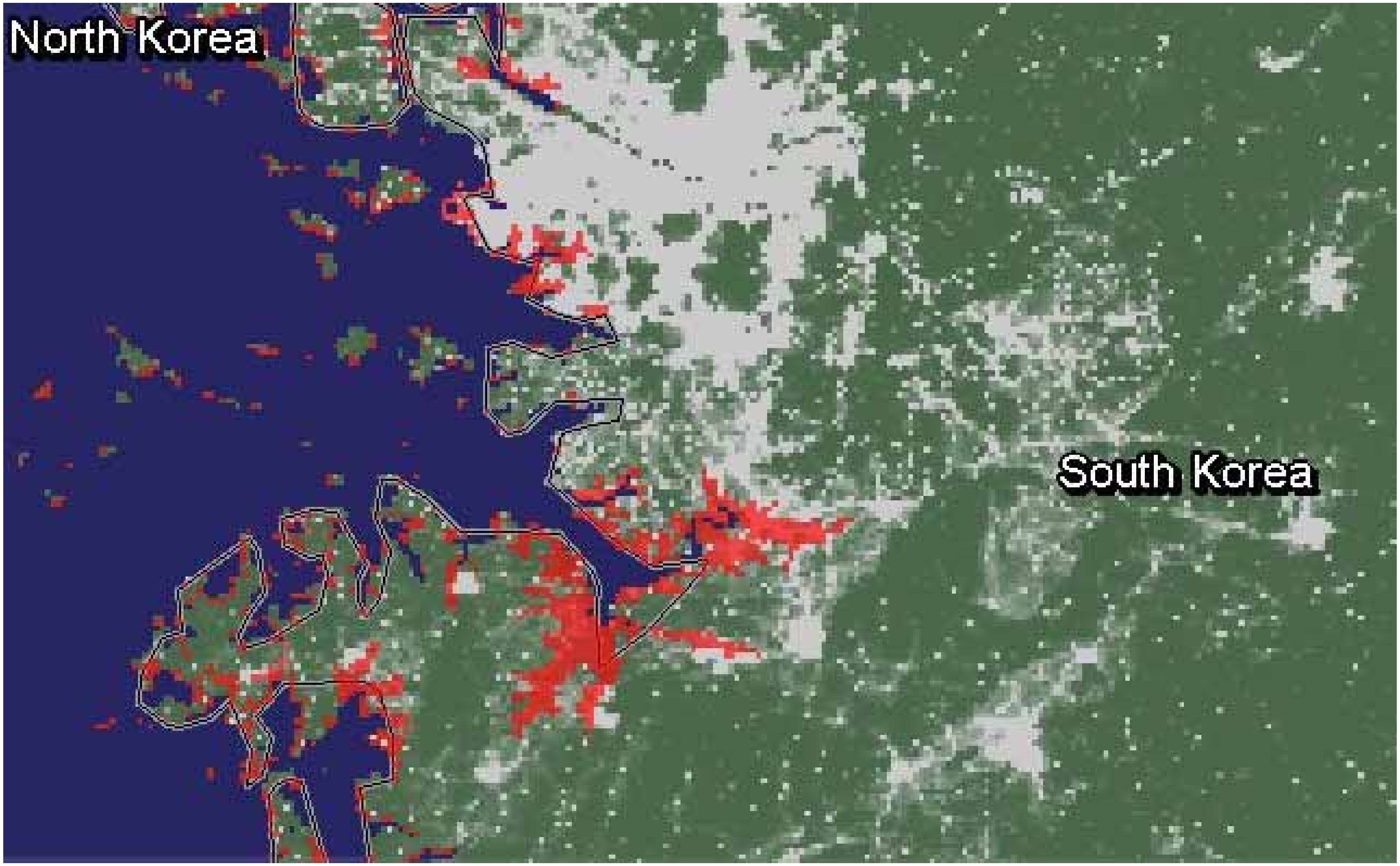
Population density, 1 meter sea level rise



Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

Population density, 6 meter sea level rise



Weiss and Overpeck, University of Arizona

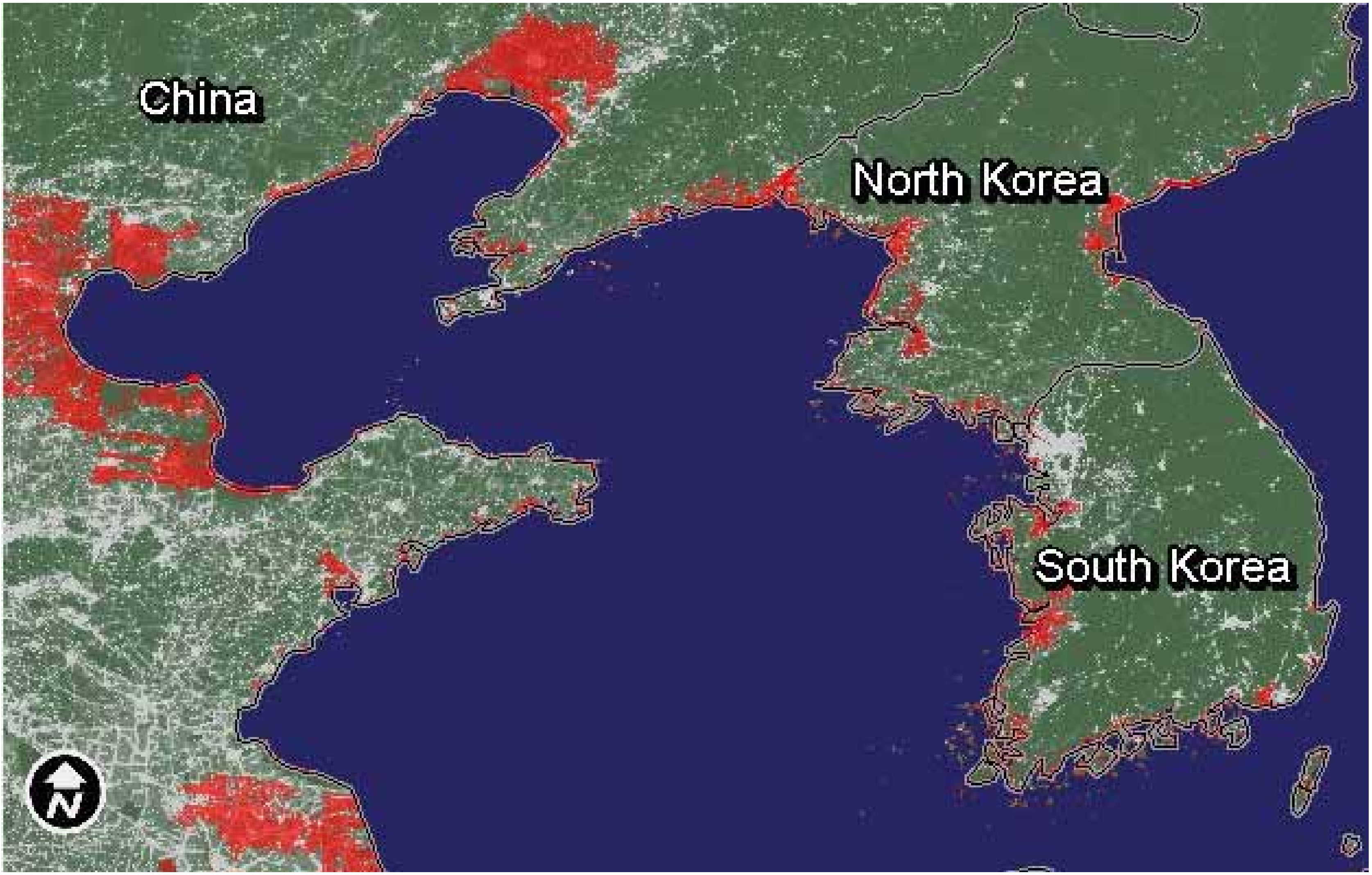
EFFECT OF SEA LEVEL RISE

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.