CLIMATE CHANGE
CERTAINTIES AND UNCERTAINTIES

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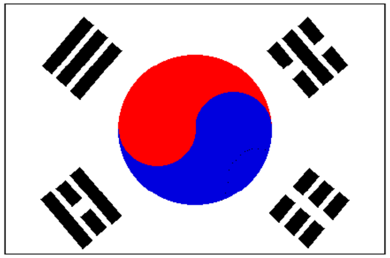
■2008 년 가을 학술대회 발표 프로그램■

Daejon, Republic of Korea
October 23, 2008

http://www.ecd.bnl.gov/steve



KOREAN ATMOSPHERIC SCIENTISTS AT BROOKHAVEN

O-Ung Kwon

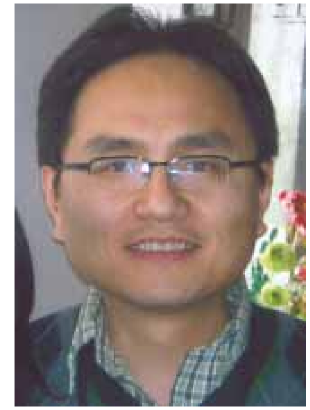
1996-1998

Korea Meteorological Administration

Lim-Seok Chang

2005-2007

Global Environment Research Center



Byung-Gon Kim

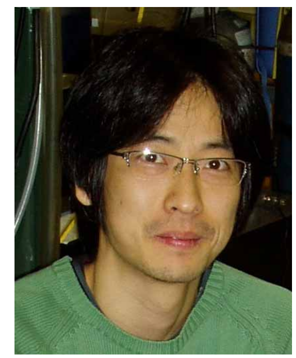
2002-2003 ++

Kangnung University

Jeonghoon Lee

2006-2008

Seoul National University



Seong Soo Yum

2007-2008

Yonsei University

OVERVIEW

Earth's energy balance and perturbations

Contributions to the increase in atmospheric CO_2

Changes in global mean surface temperature

Climate sensitivity – definition, importance, past and current estimates

Climate sensitivity from climate models

Aerosol forcing – uncertainties and implications

Total forcing – uncertainties and implications

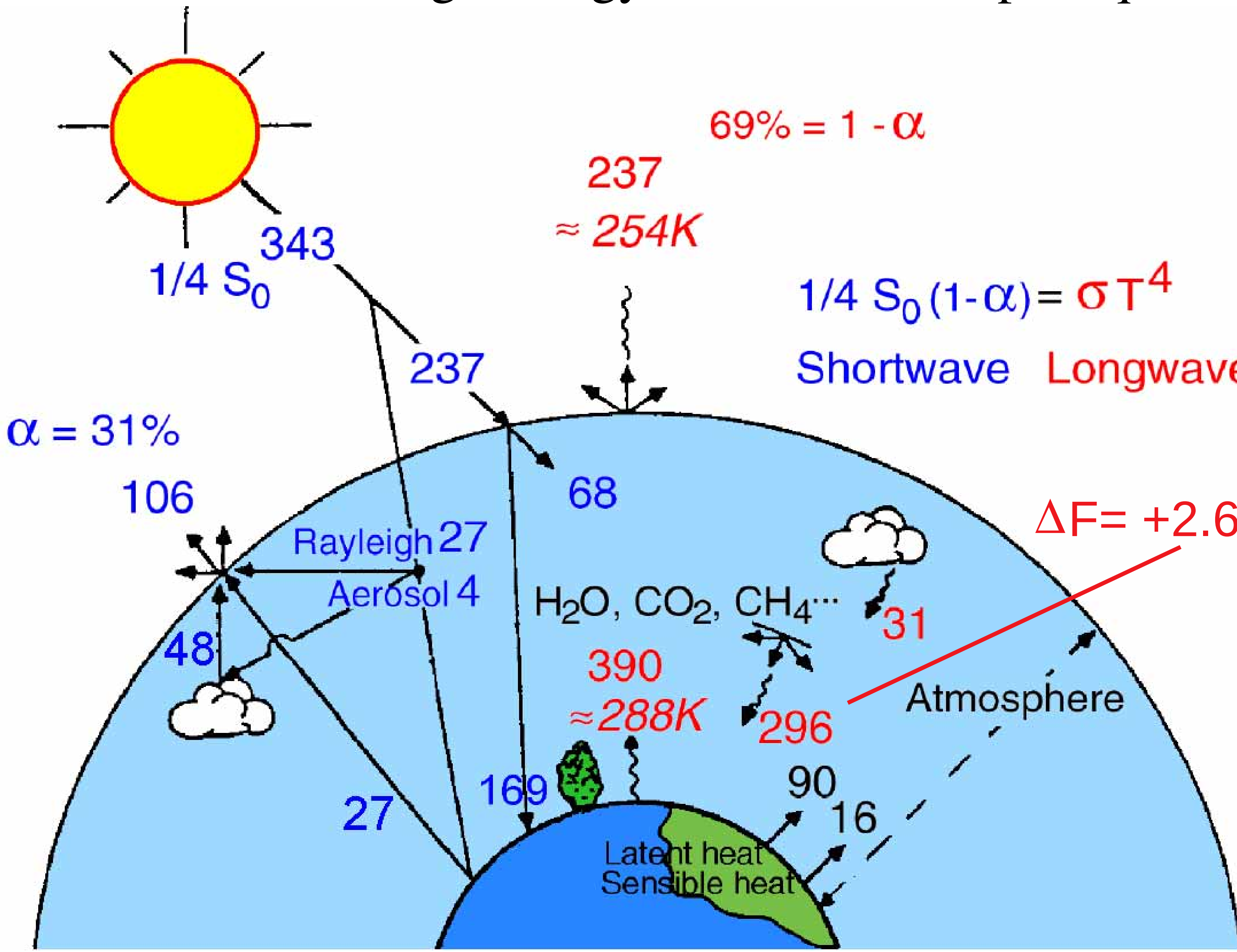
Climate sensitivity – uncertainties and implications

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

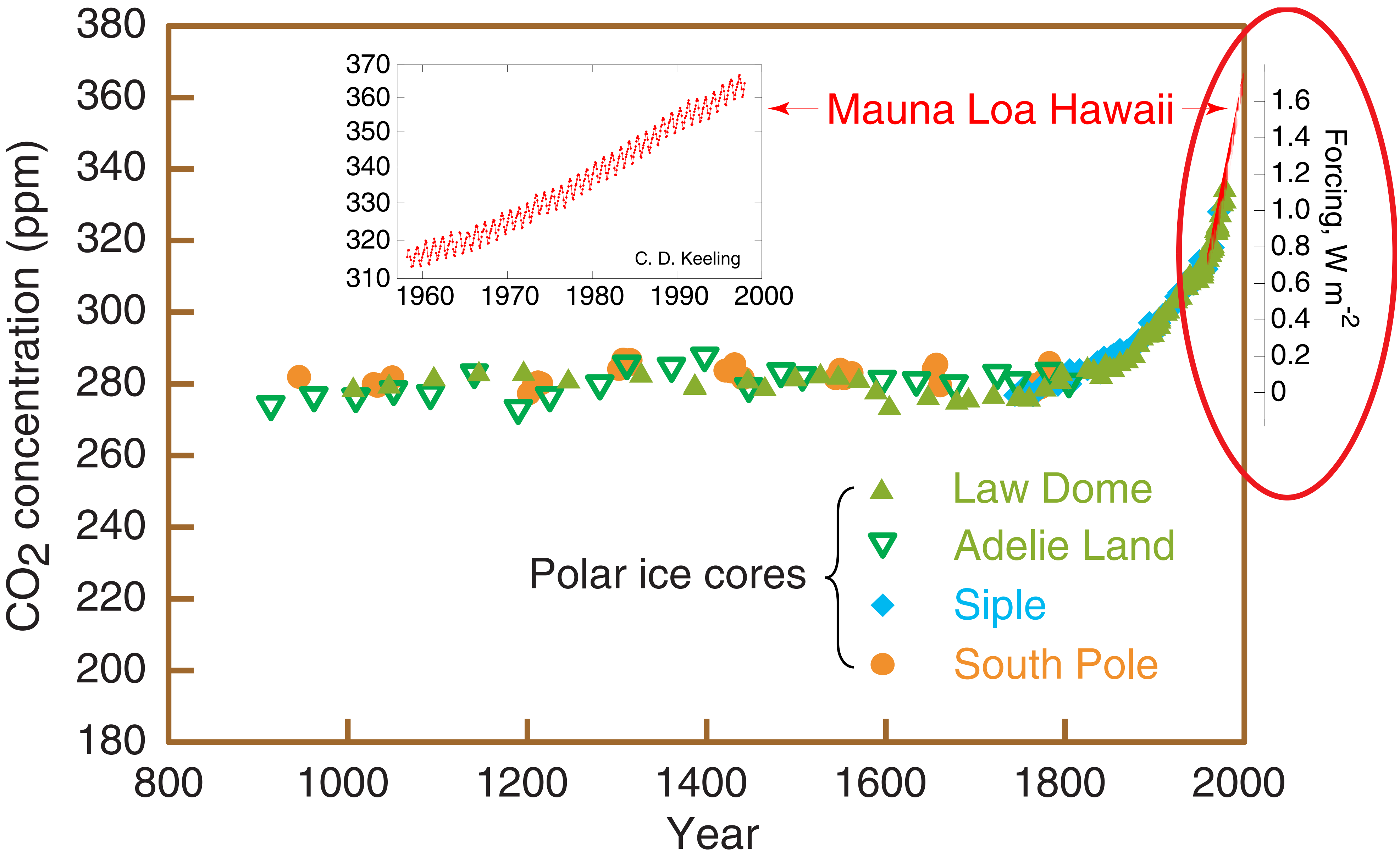
A ***change*** in a radiative flux term in Earth's radiation budget, ΔF, W m^{-2}.

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.

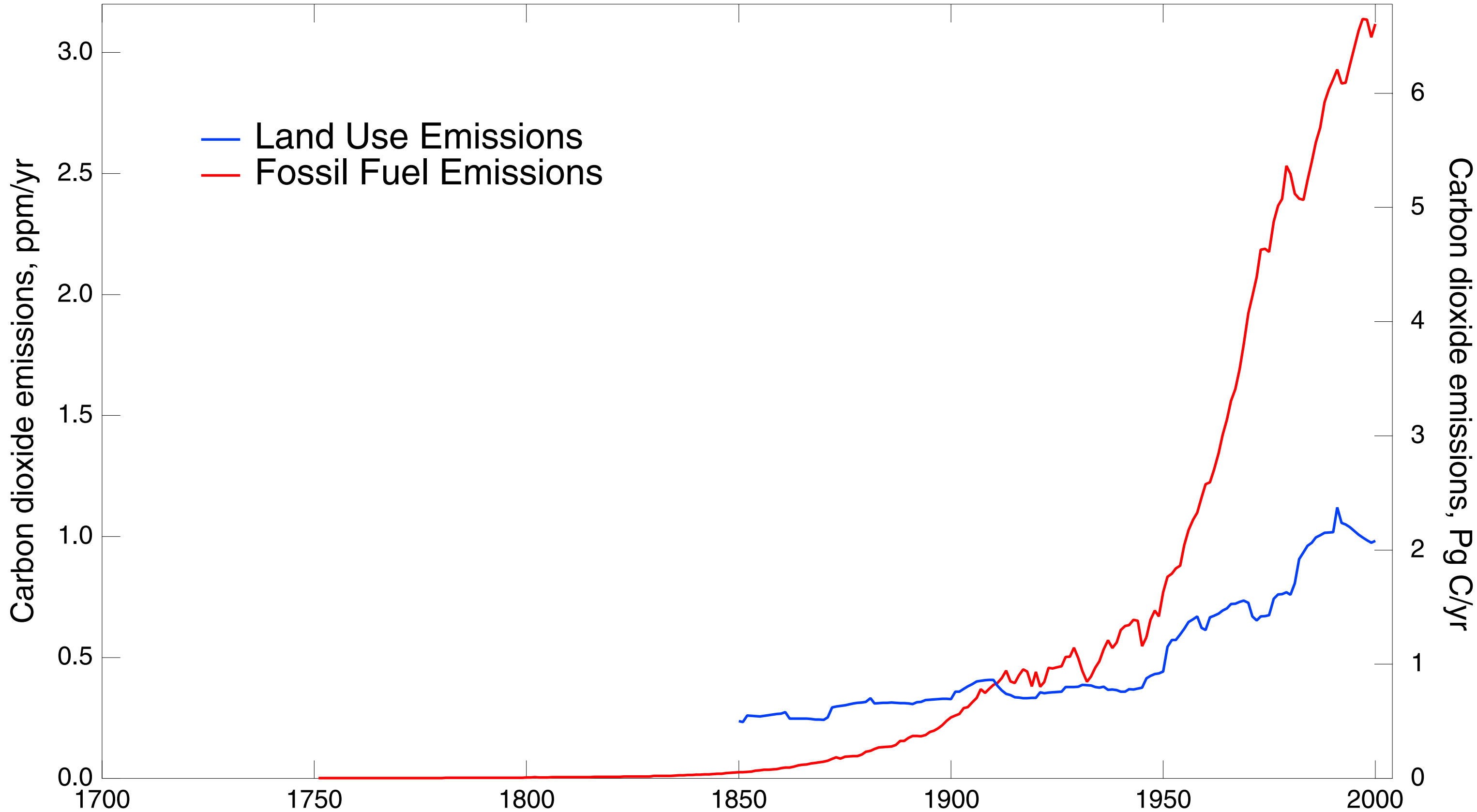
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



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

ATMOSPHERIC CO_2 EMISSIONS

Time series 1700 - 2003



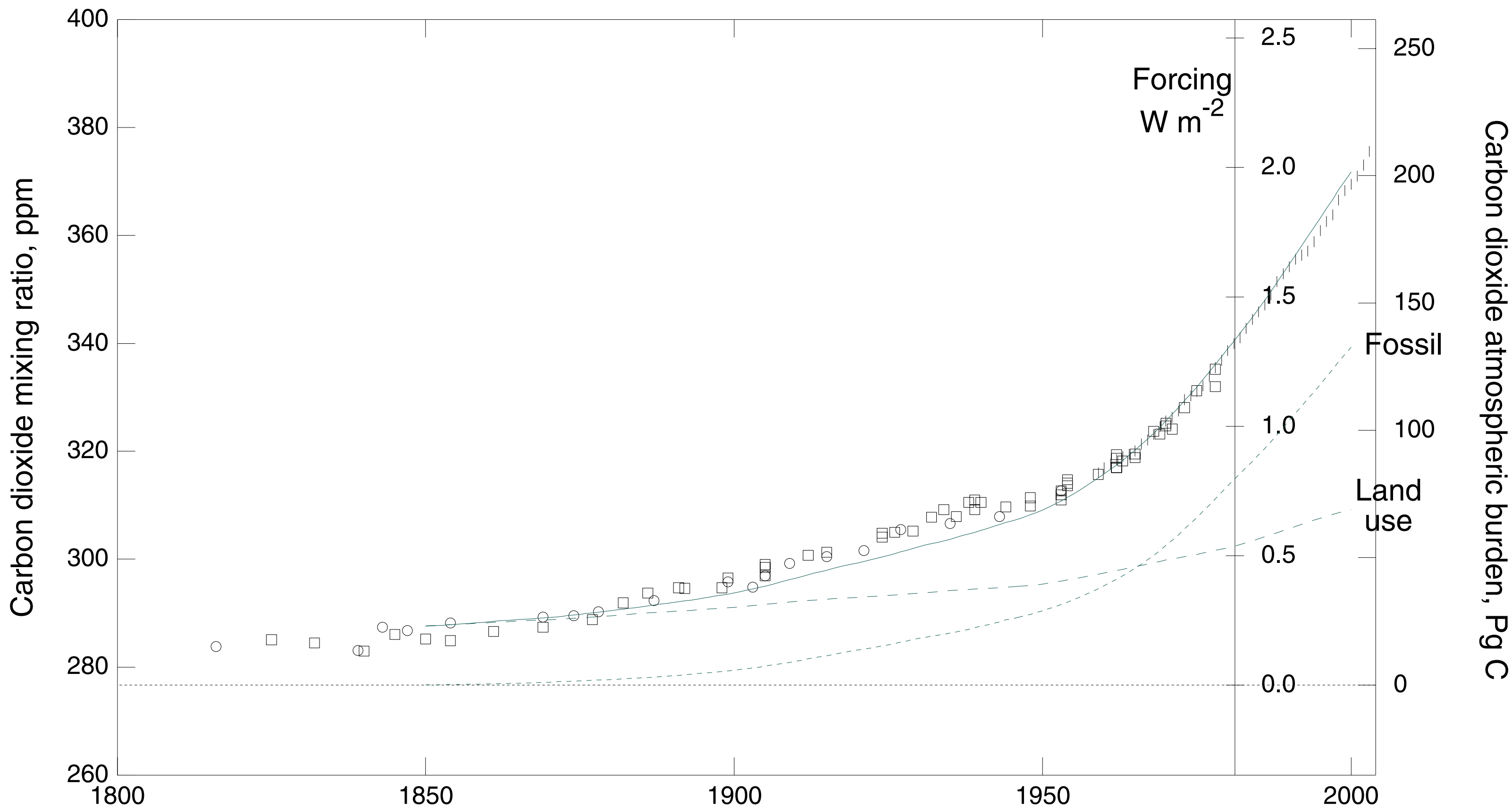
Fossil Fuel - Marland
Land Use - Houghton

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

Subsequently fossil fuel CO_2 has been dominant and rapidly increasing!

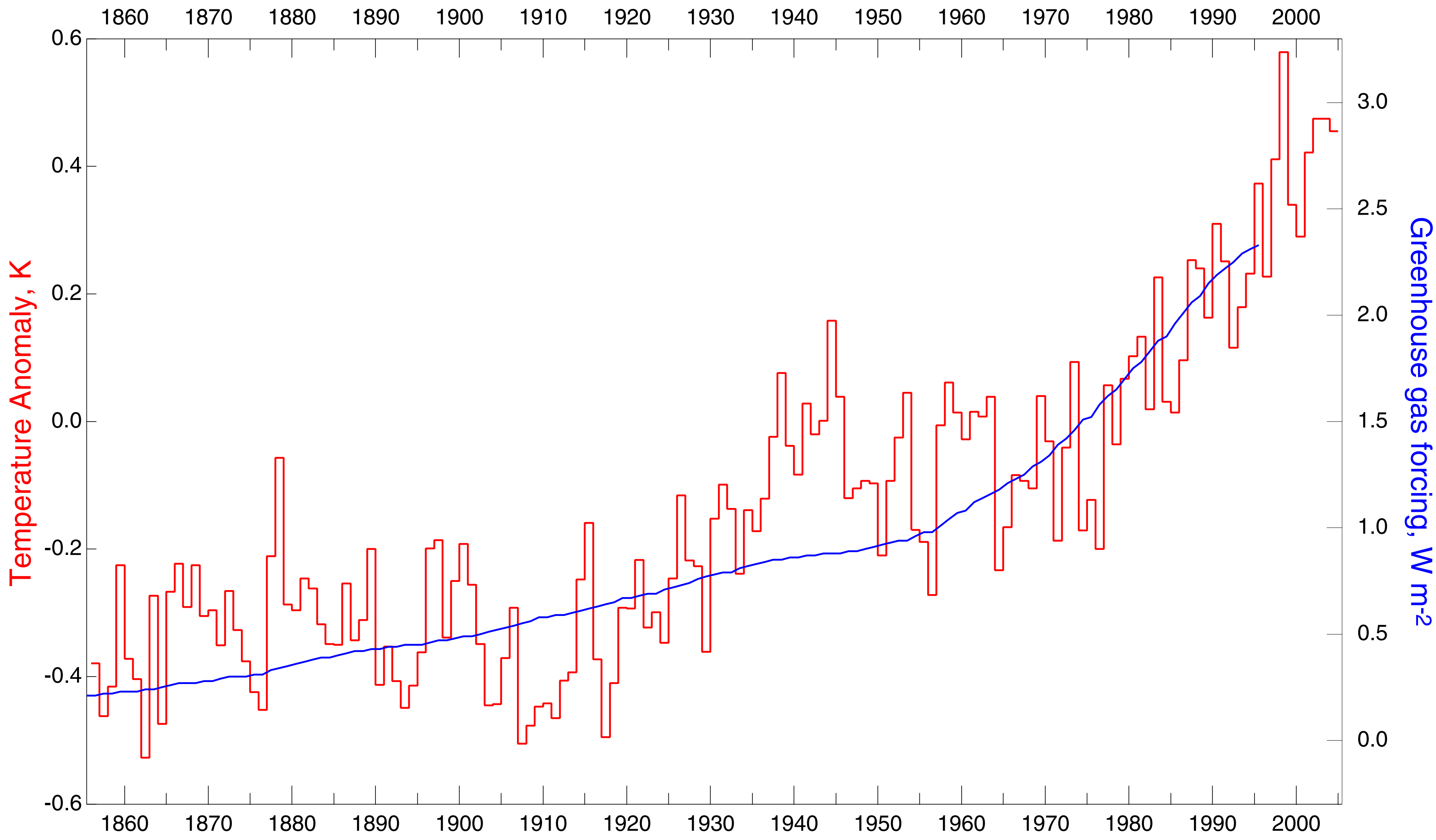
ATTRIBUTION OF ATMOSPHERIC CO_2

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



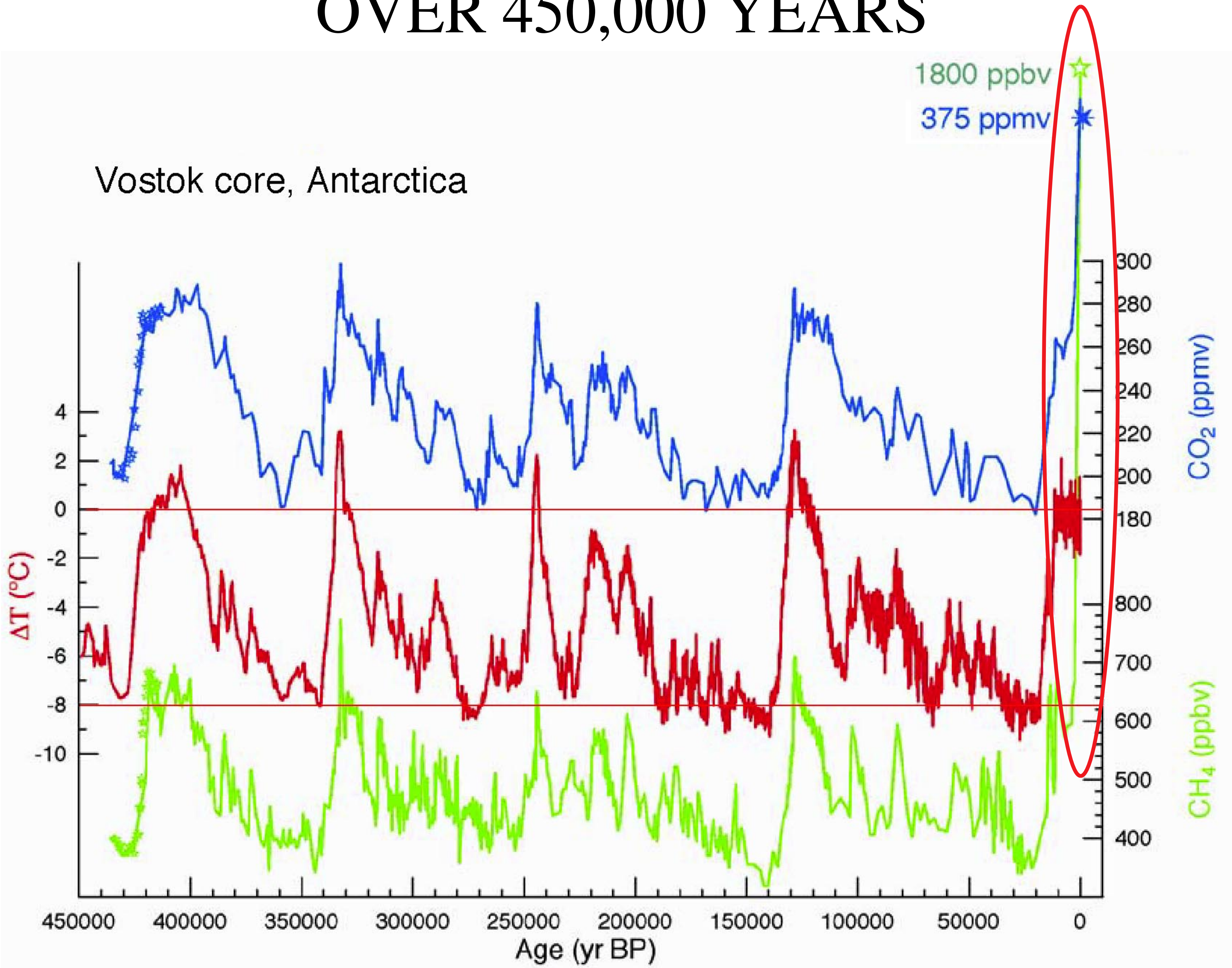
CO_2 from land use emissions – ***not fossil fuel combustion*** – was the dominant contribution to atmospheric CO_2 and forcing over the 20th century.

GREENHOUSE GAS FORCING AND CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004



IPCC, 2001; 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.

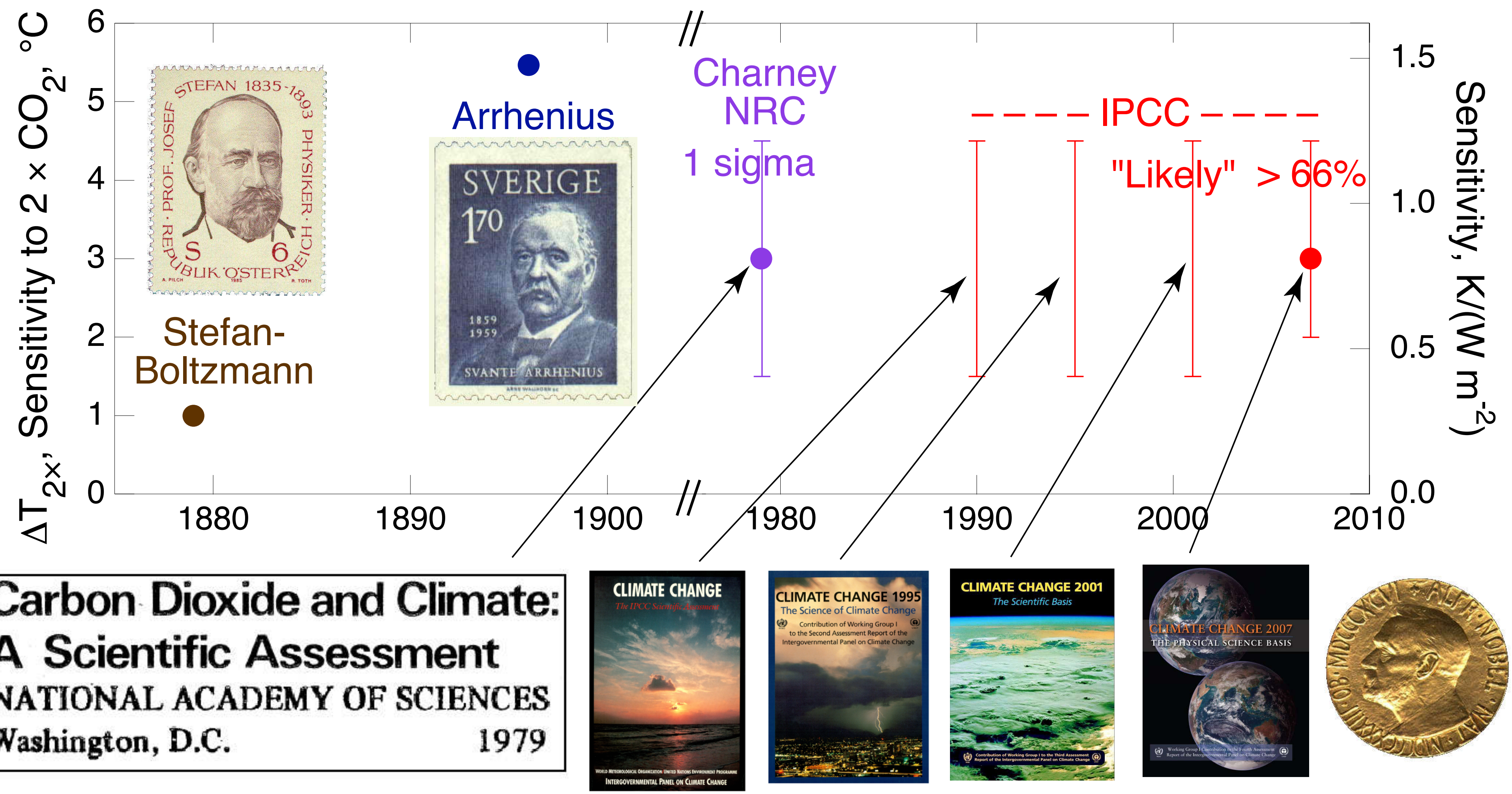
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

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

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

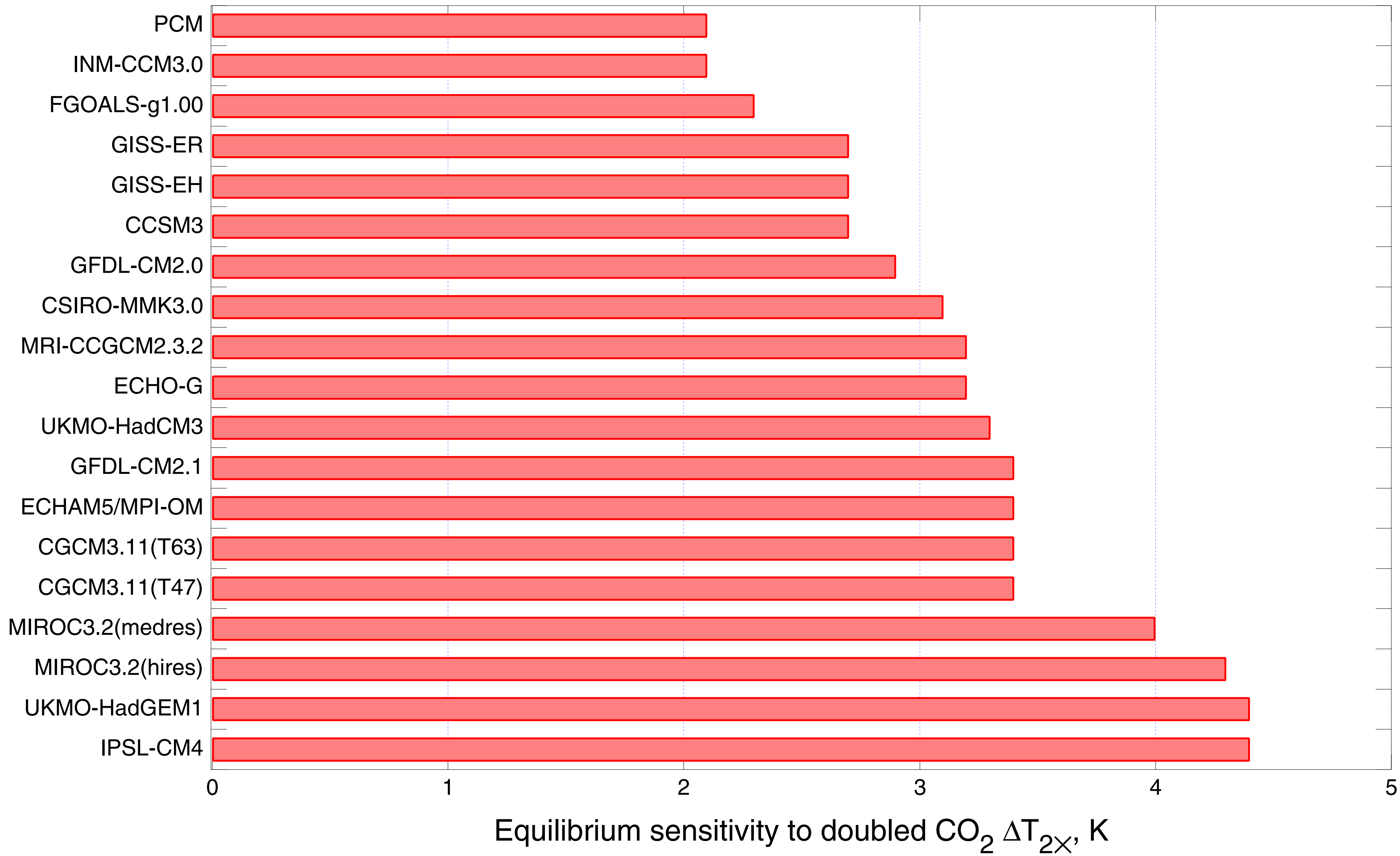
Estimates of central value and uncertainty range from major national and international assessments



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

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

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

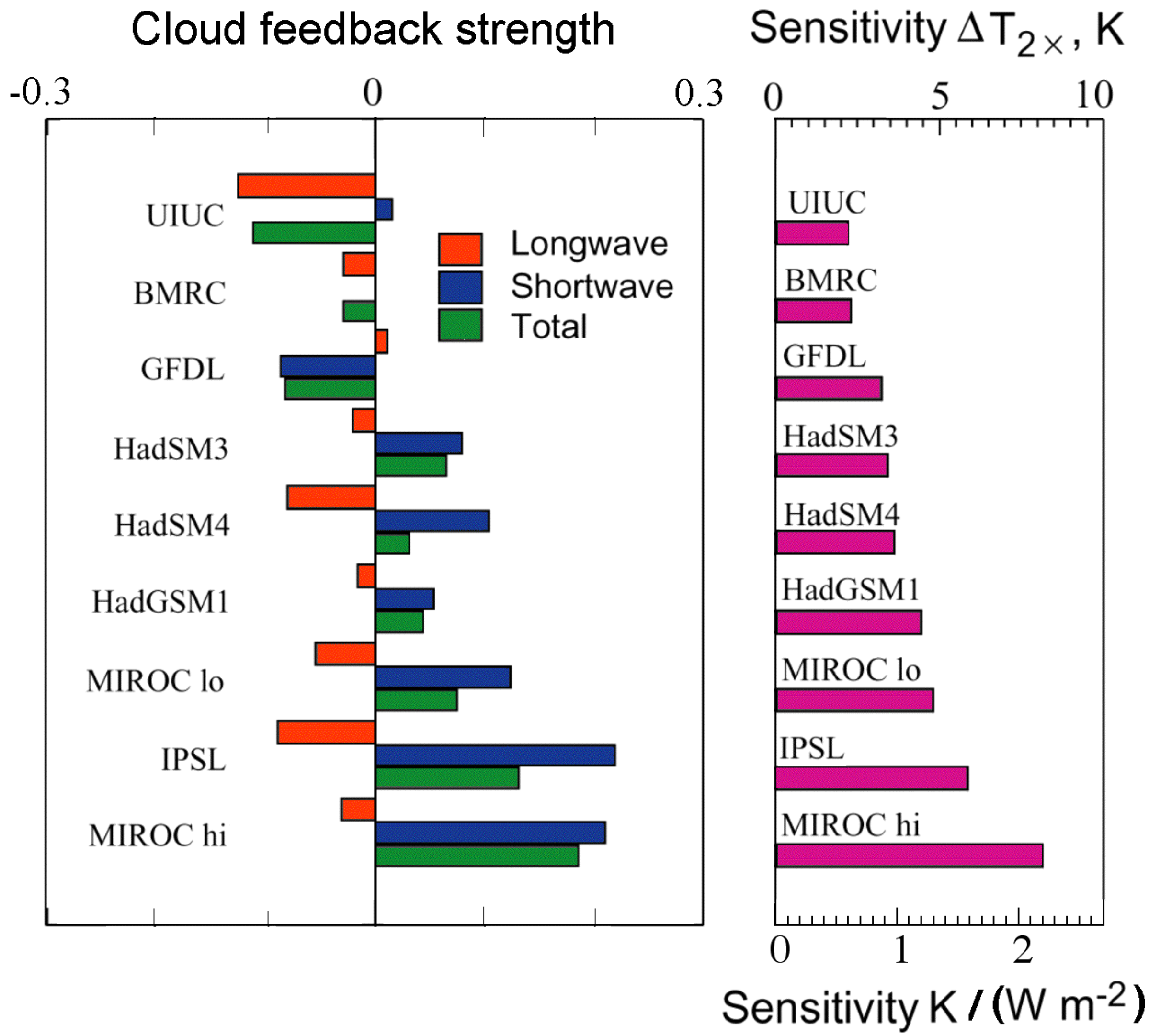
S = Climate sensitivity

S_{SB} = Stefan-Boltzmann sensitivity

$\mathcal{F}$ = feedback strength

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

sum over all feedbacks

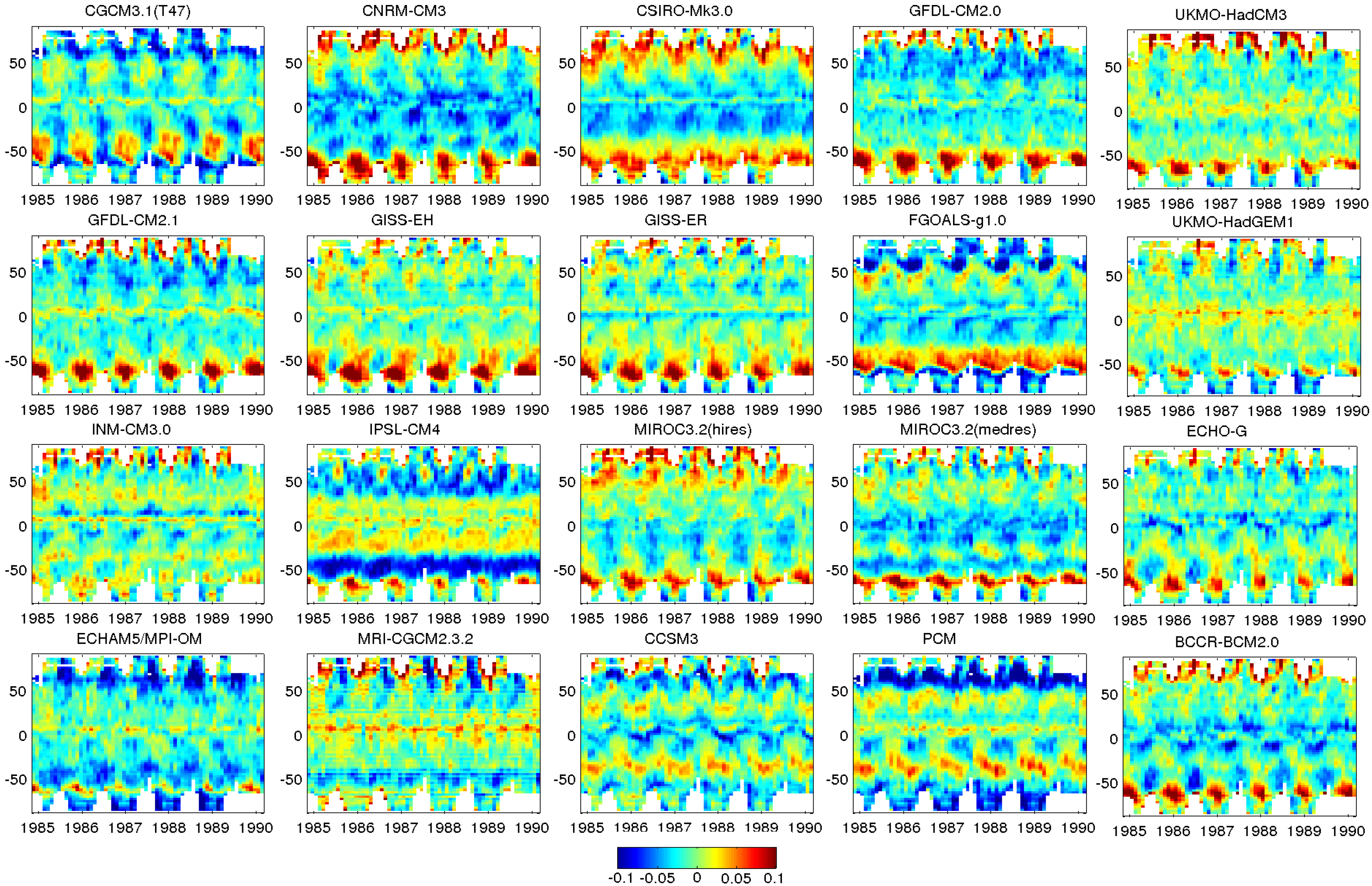


Adapted from Webb et al., Clim. Dyn., 2006

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

ZONAL MONTHLY MEAN ALBEDO

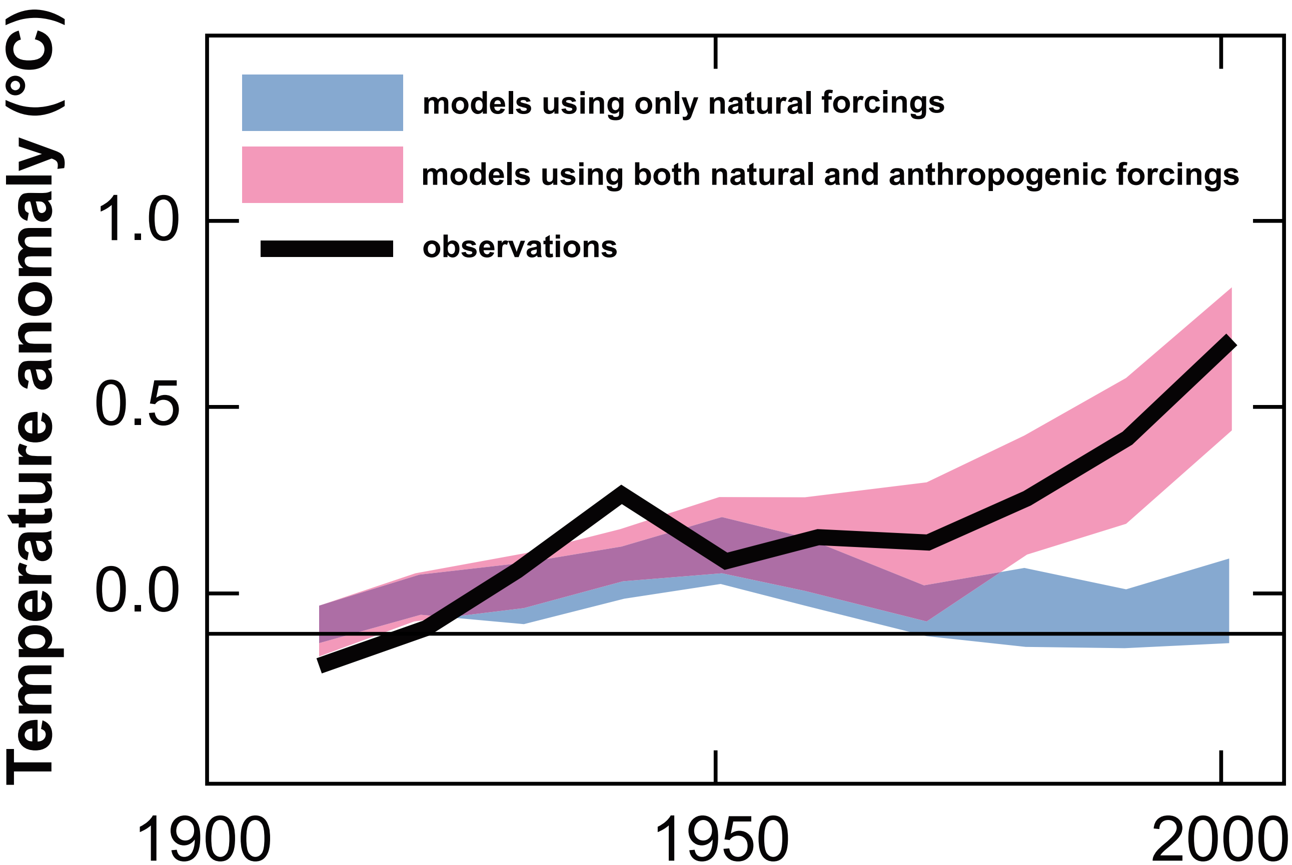
20 GCMs – Difference vs. ERBE Satellite

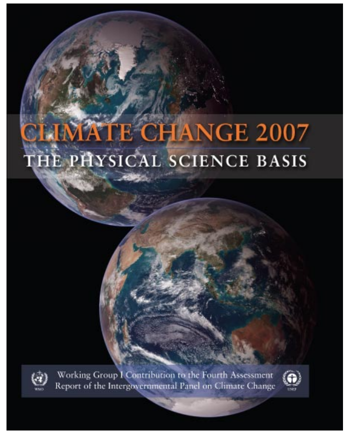


Modified from Bender et al., Tellus, 2006

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



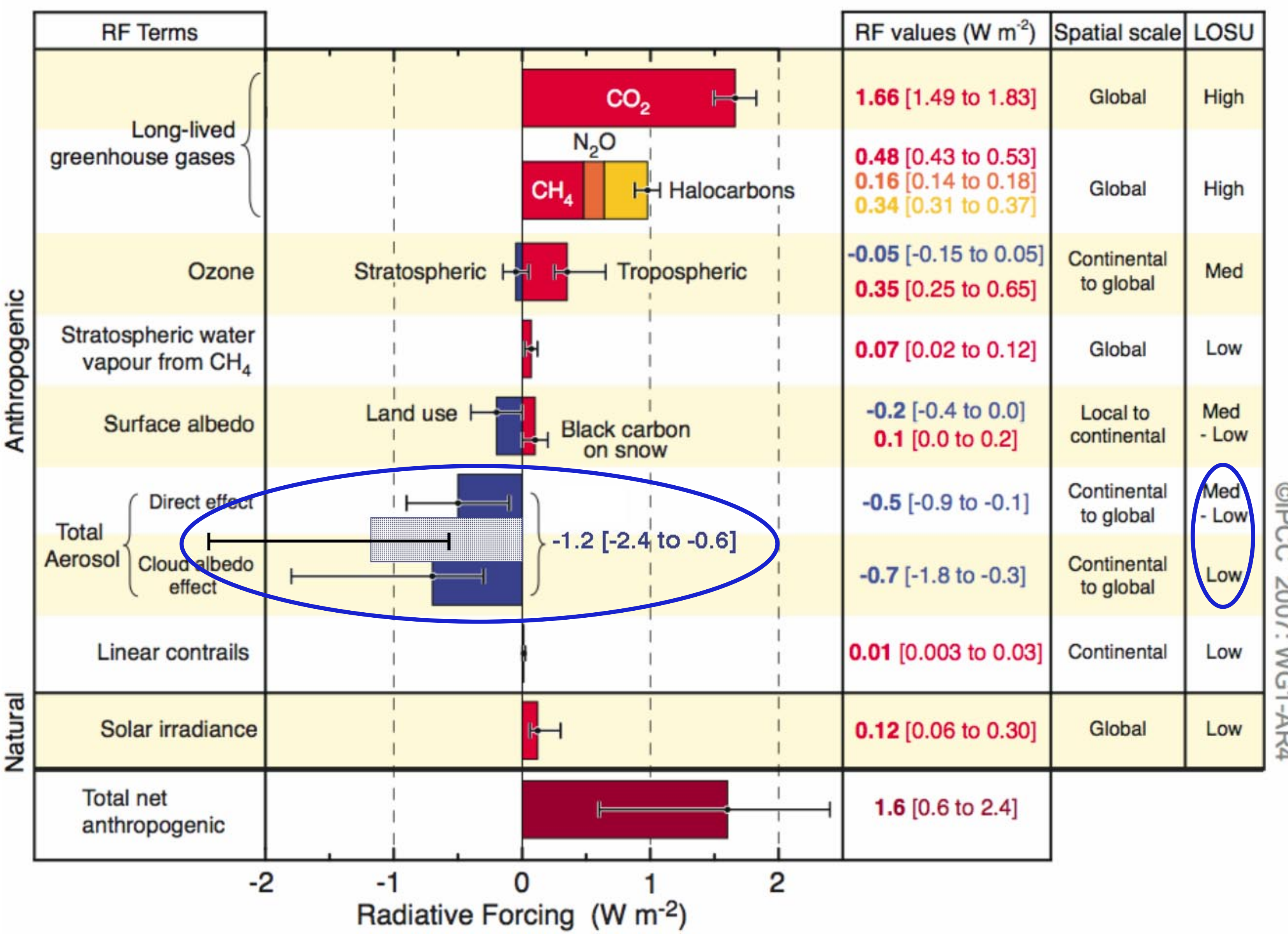


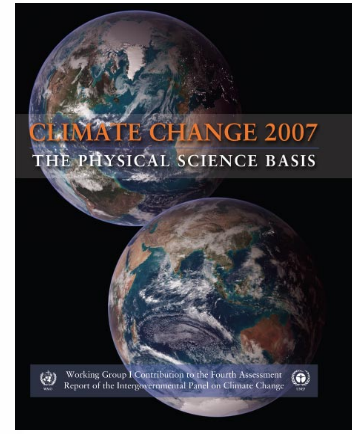
“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

“ These simulations used models with ***different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings***.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

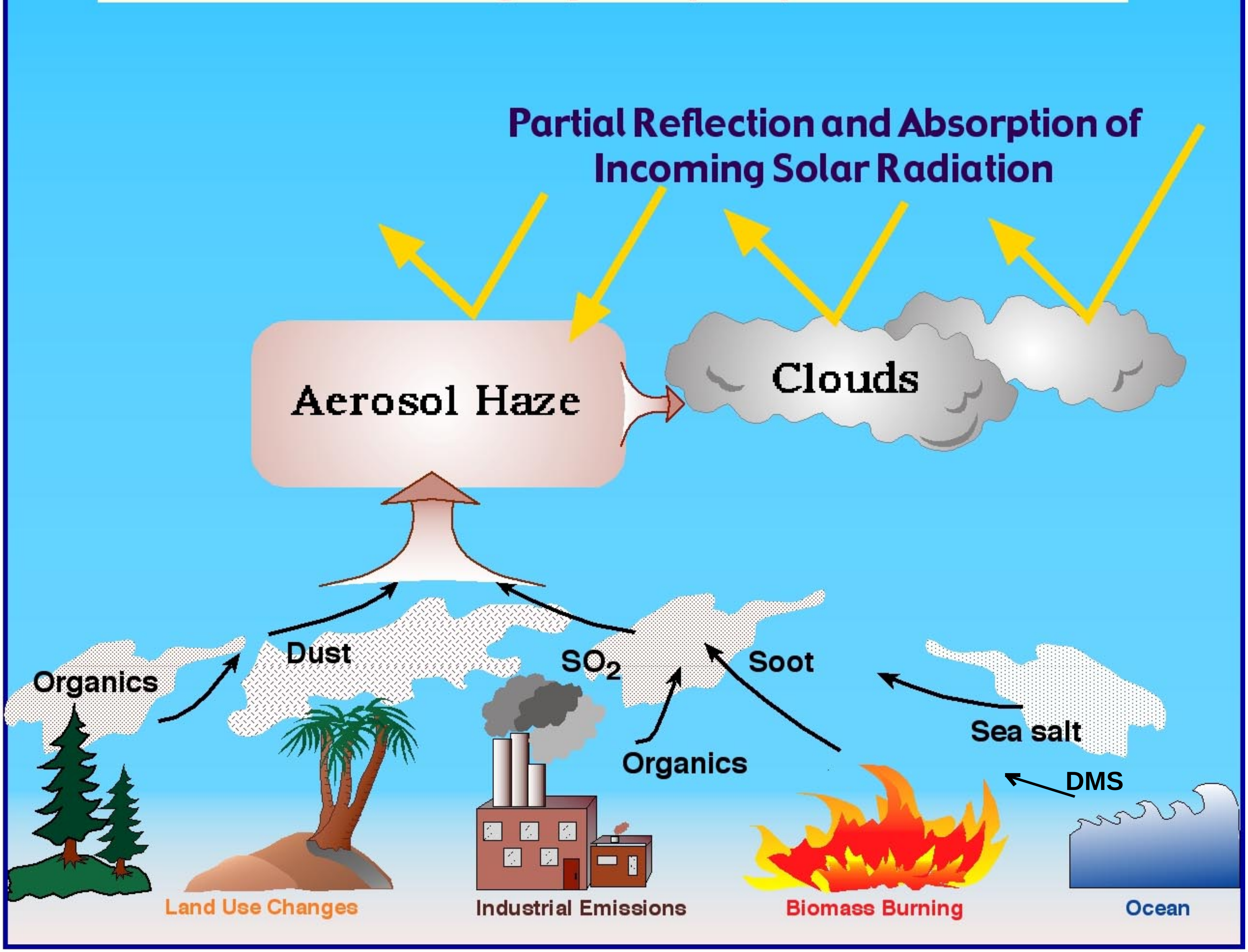
Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)





LOSU denotes level of scientific understanding.

Radiative Forcing by Tropospheric Aerosol

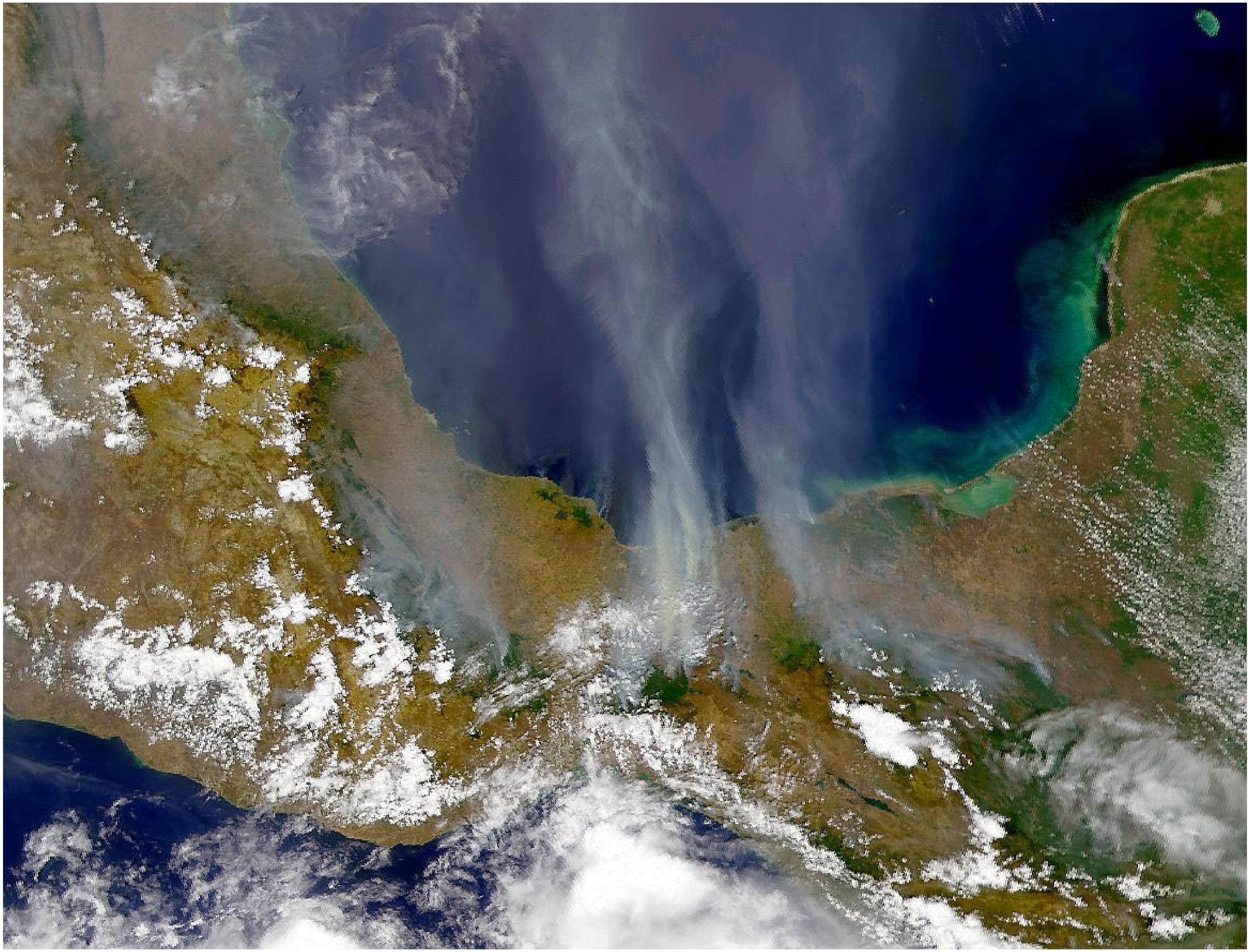


AEROSOL IN SEOUL

View from tower on Nam San Mountain

Upward scattering of light by aerosol exerts a cooling effect on climate.

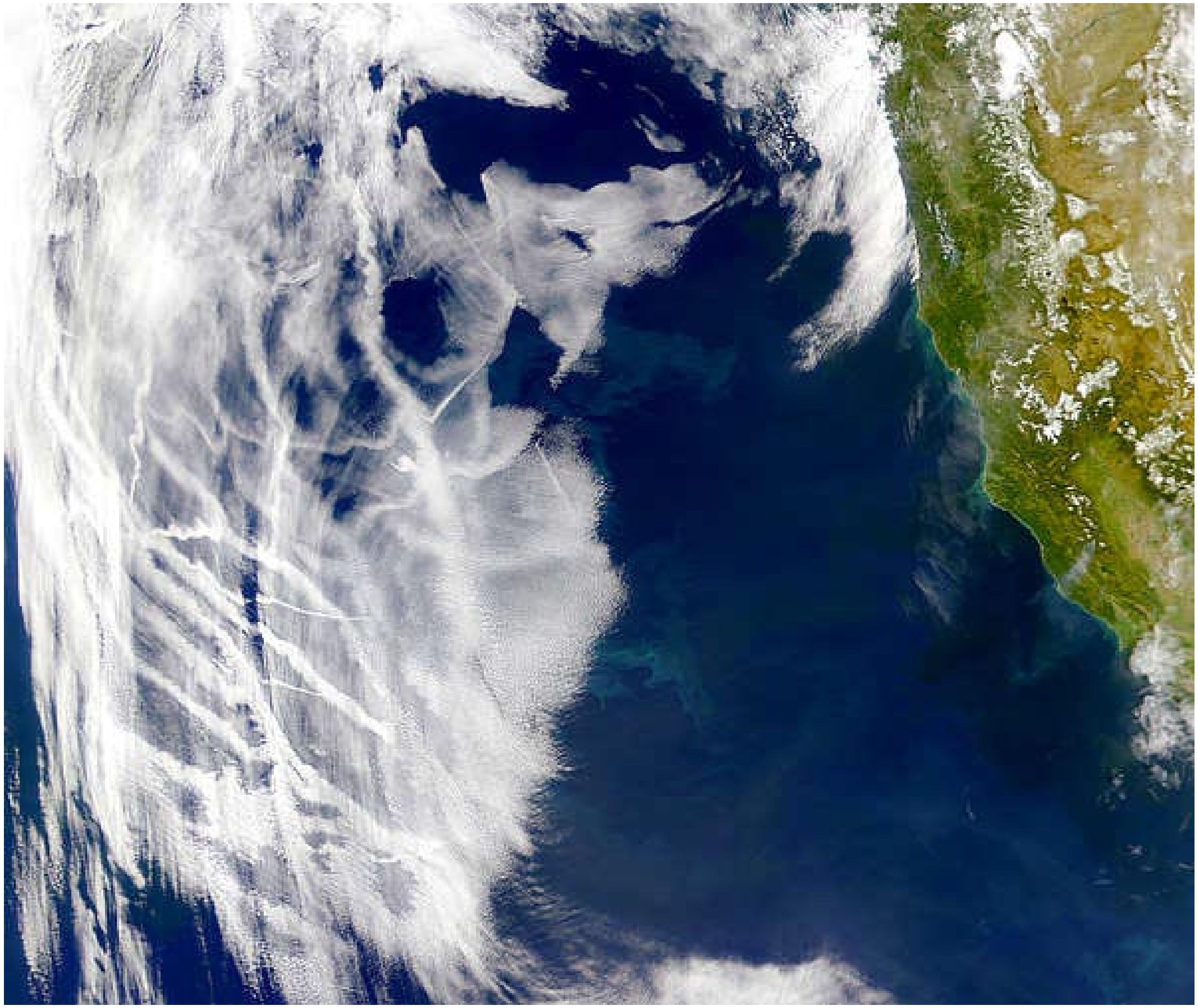
AEROSOLS AS SEEN FROM SPACE



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

CLOUD BRIGHTENING BY SHIP TRACKS

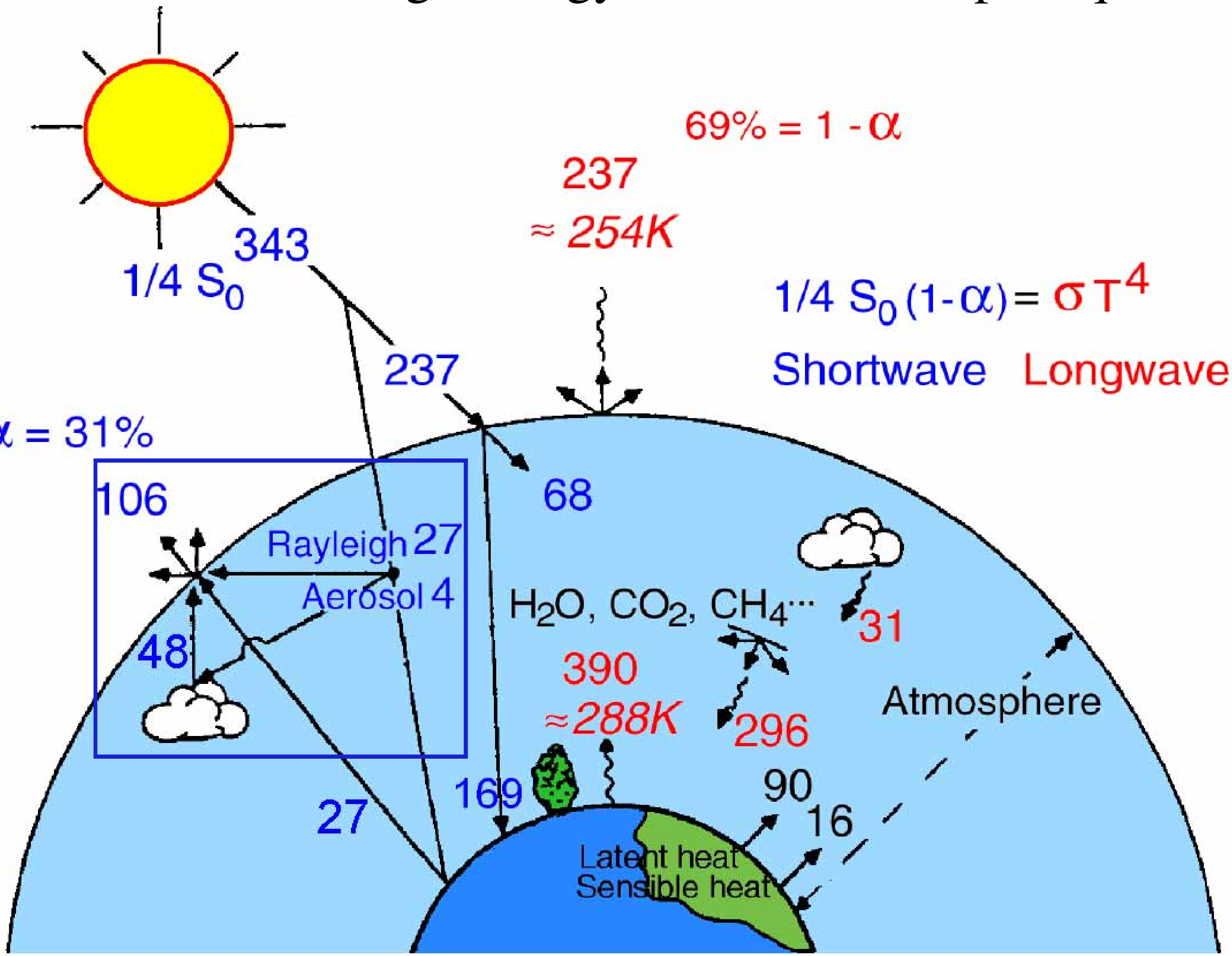
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

GLOBAL ENERGY BALANCE

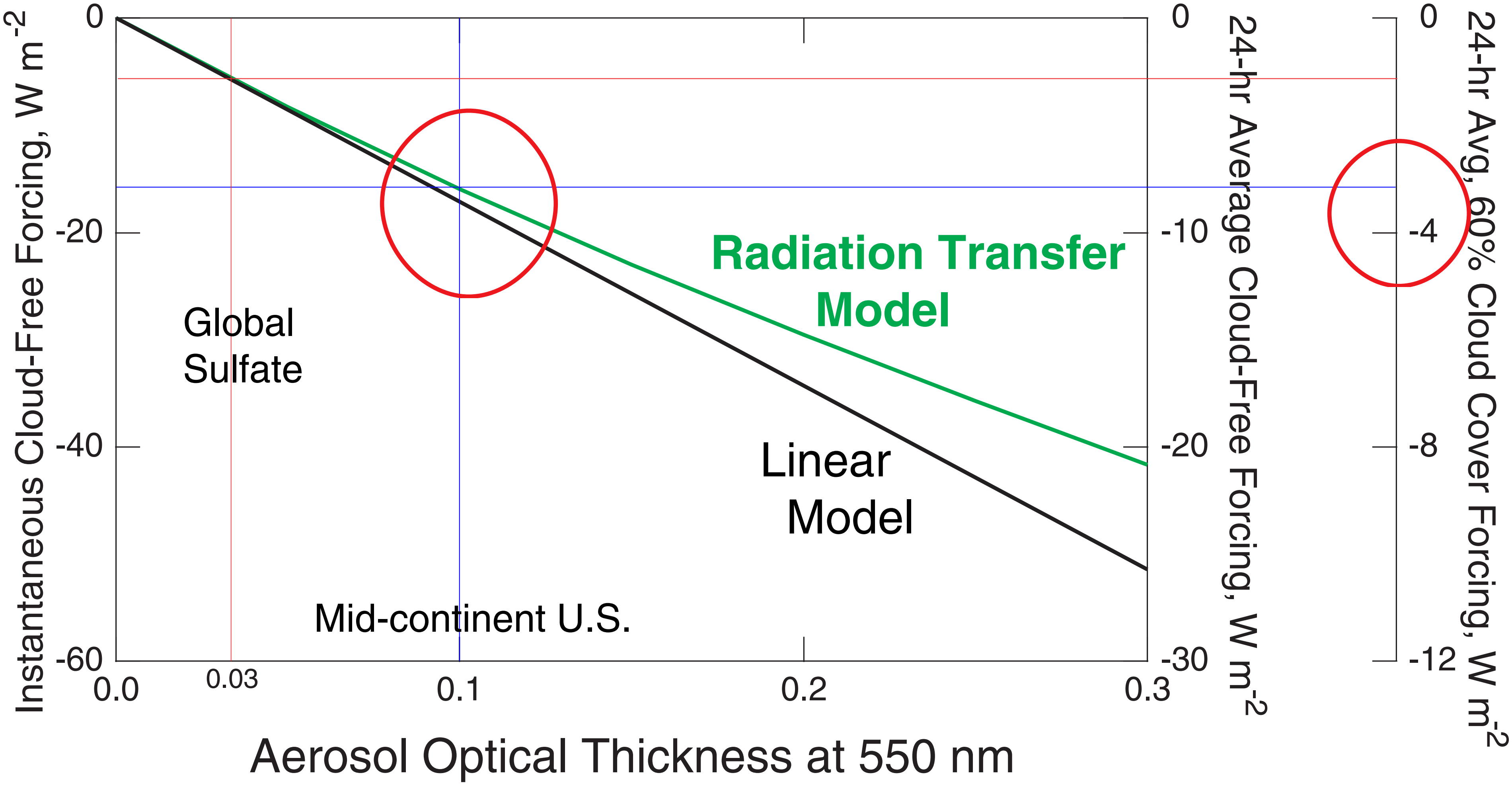
Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

ESTIMATES OF AEROSOL DIRECT FORCING

By linear model and by radiation transfer modeling



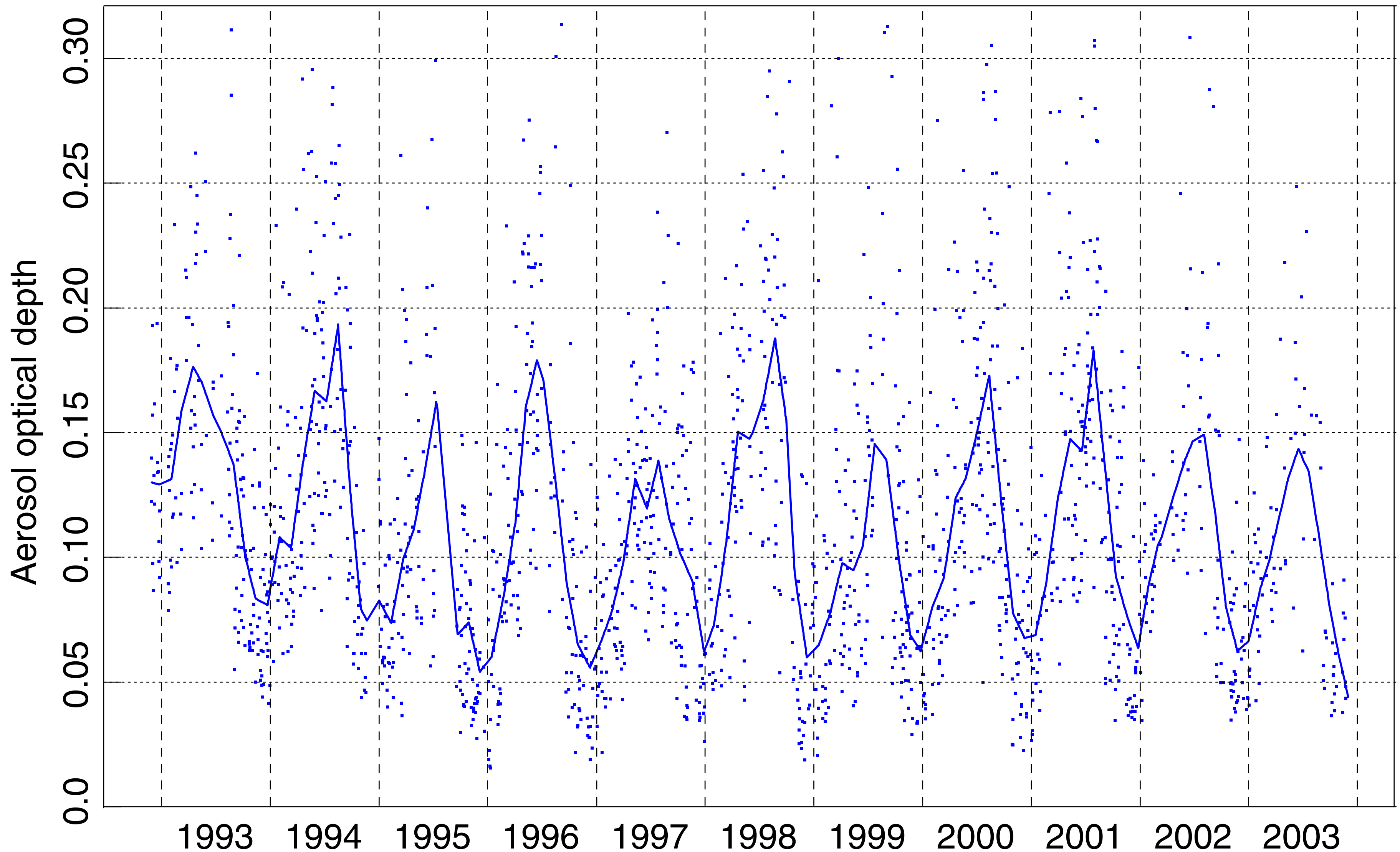
Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling.***

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

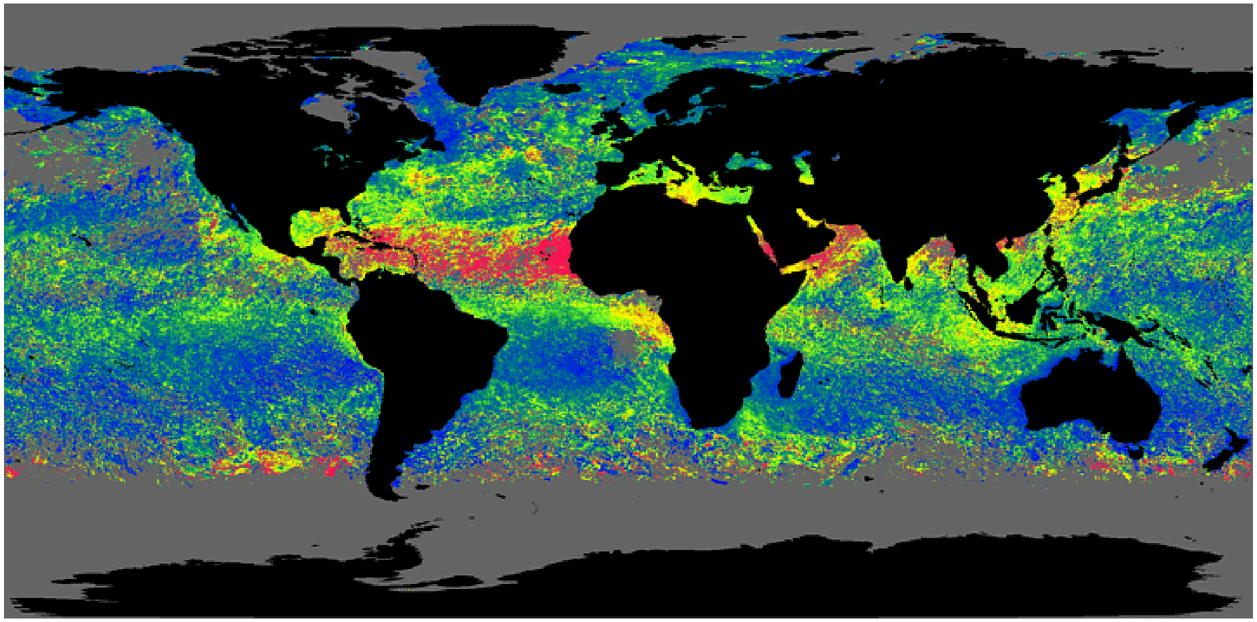
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

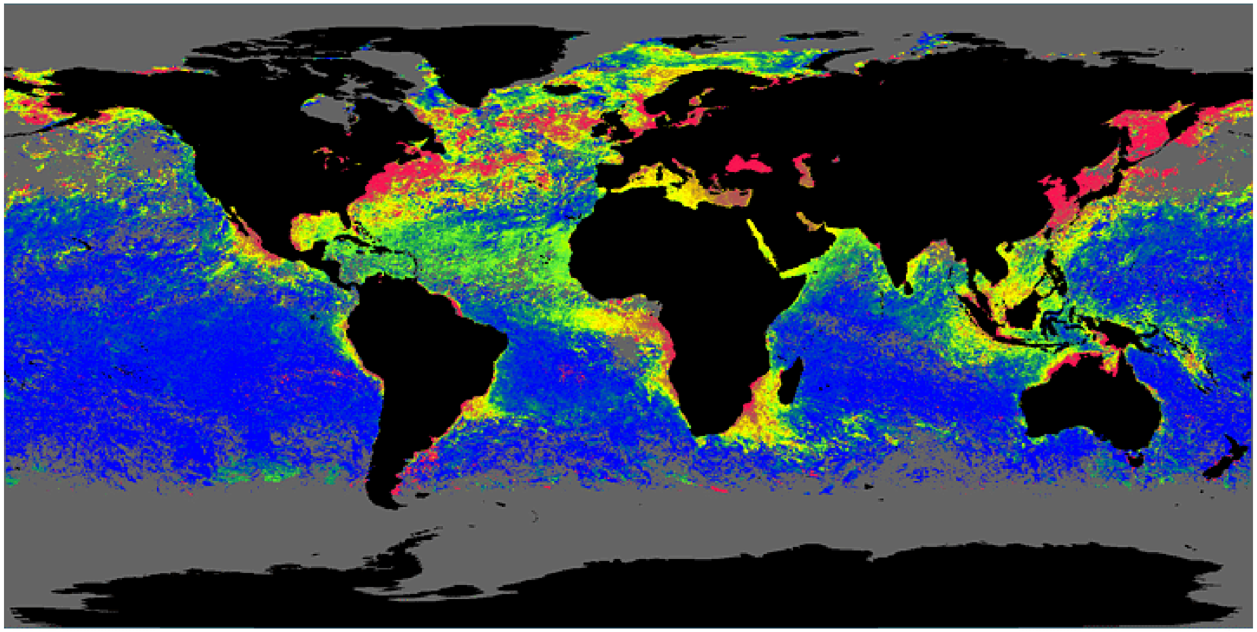
0 — 0.5



Ångström Exponent α

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

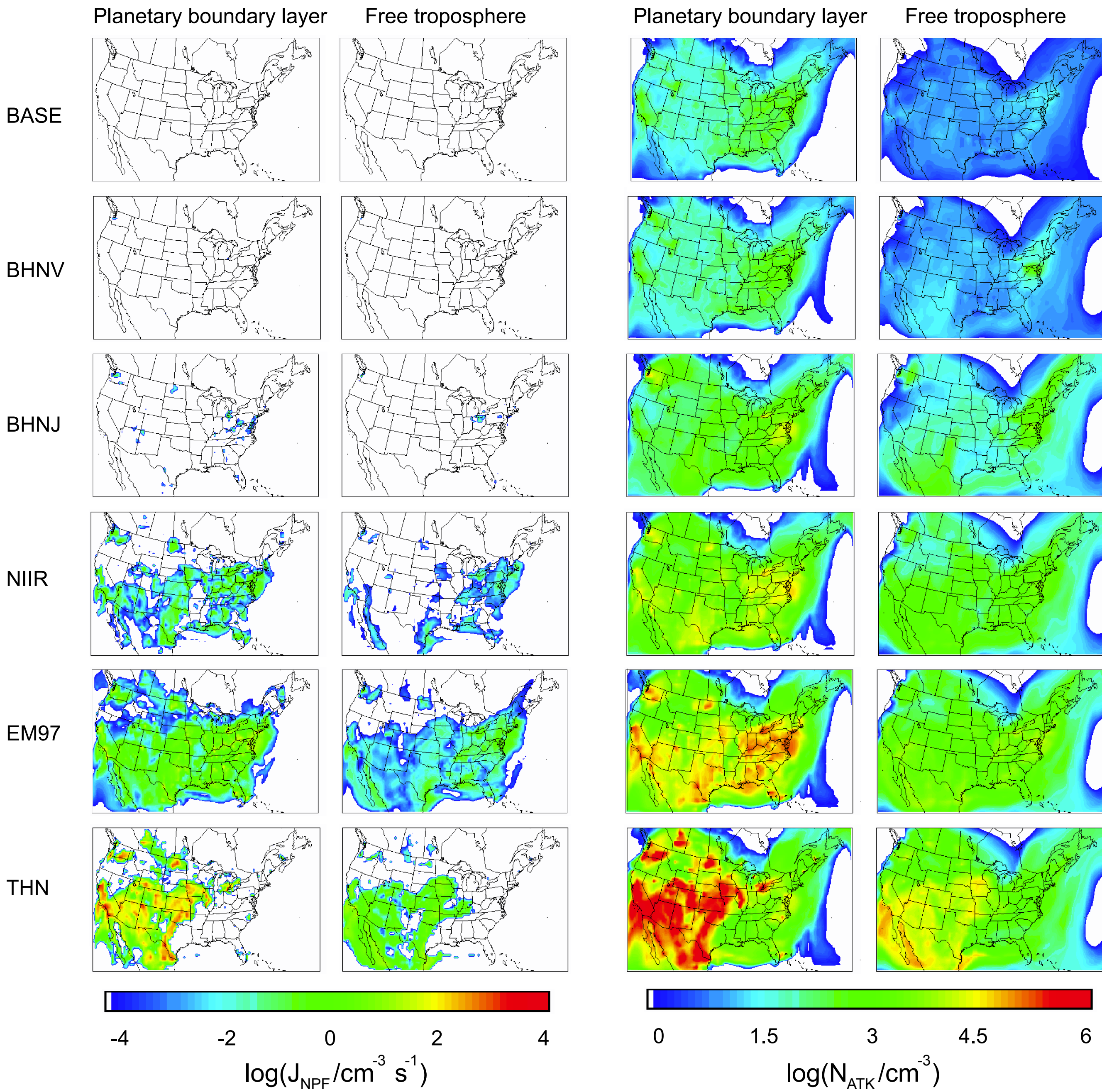
-0.2 Large Particles — 1.2 Small Particles



Small particles are from gas-to-particle conversion.

NEW PARTICLE FORMATION RATE AND AITKEN PARTICLE NUMBER CONCENTRATION

Dependence on formation mechanism



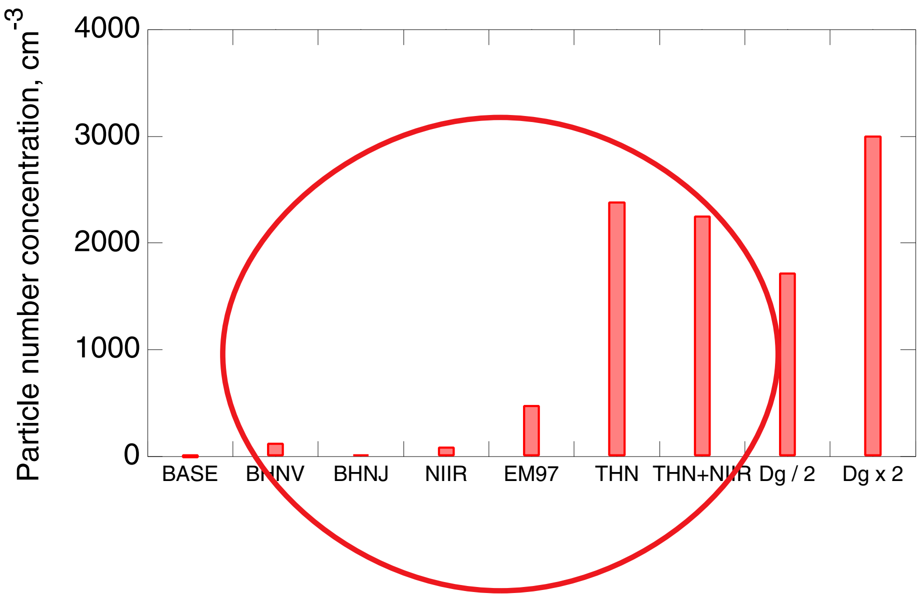
L. S. Chang et al, JGR, 2008, in review

Particle formation rates and particle concentrations depend strongly on NPF mechanism.

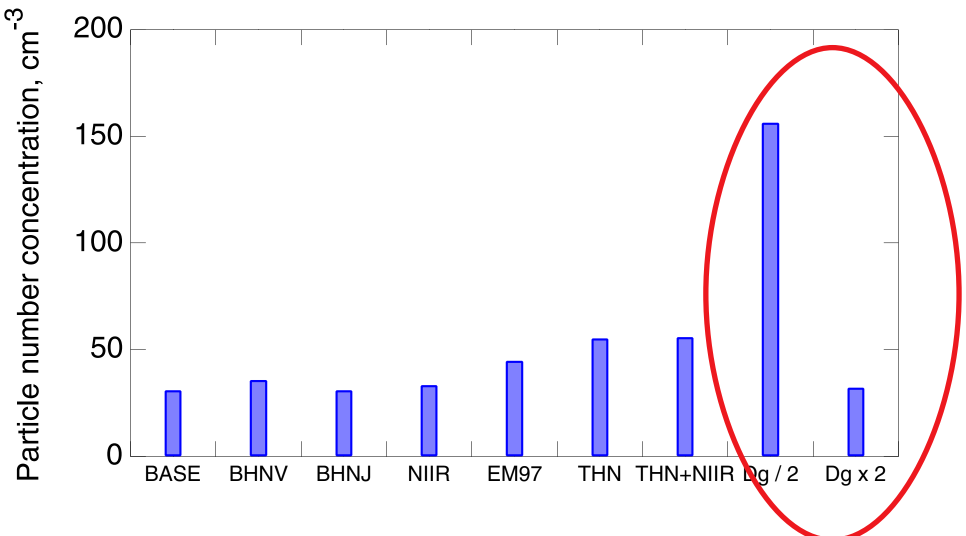
AEROSOL PARTICLE NUMBER CONCENTRATION

Average particle number concentrations North America, July 2004

Aitken mode particles ($D \leq 100$ nm)



Accumulation mode particles ($D \geq 100$ nm)



L.-S. Chang et al., JGR, in review

Strong dependence on new particle formation mechanism

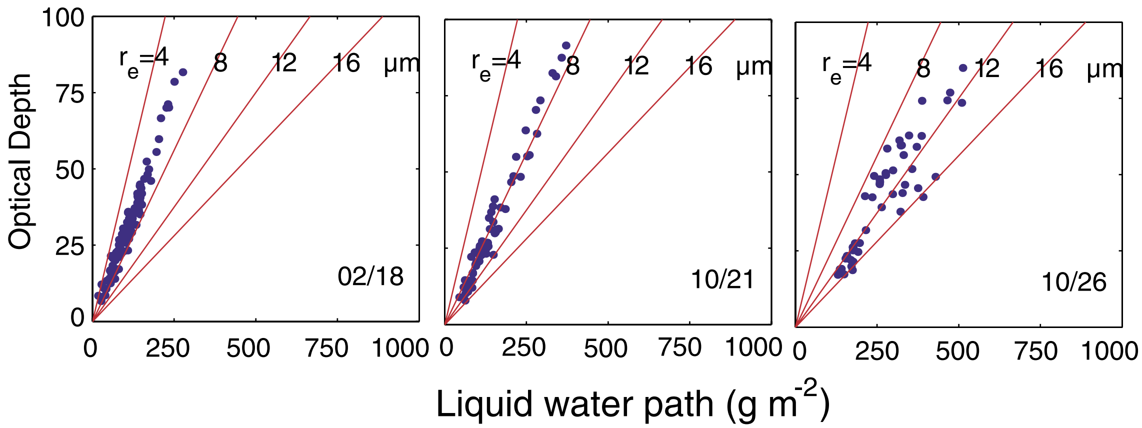
Strong dependence on size of primary emissions

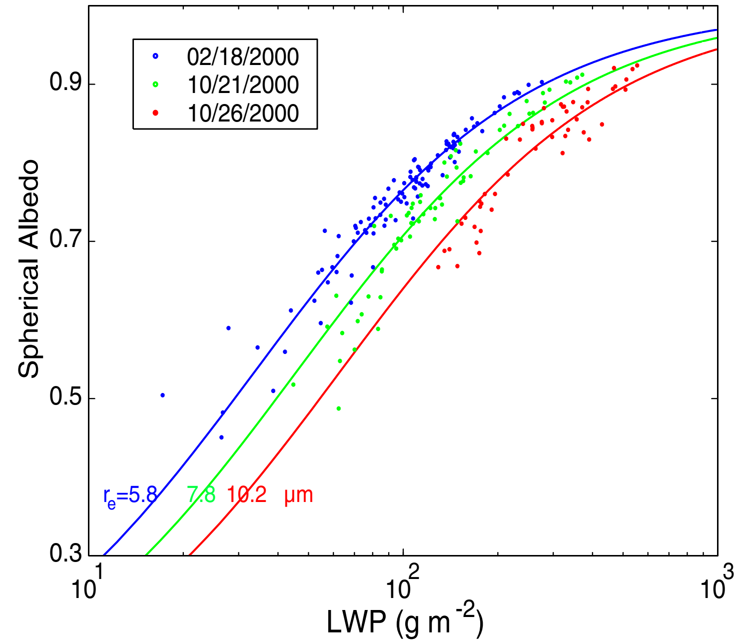
Accurate representation of number concentrations and aerosol indirect effects requires improved knowledge of ***new particle formation rate*** and ***size distributed emissions***.

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.

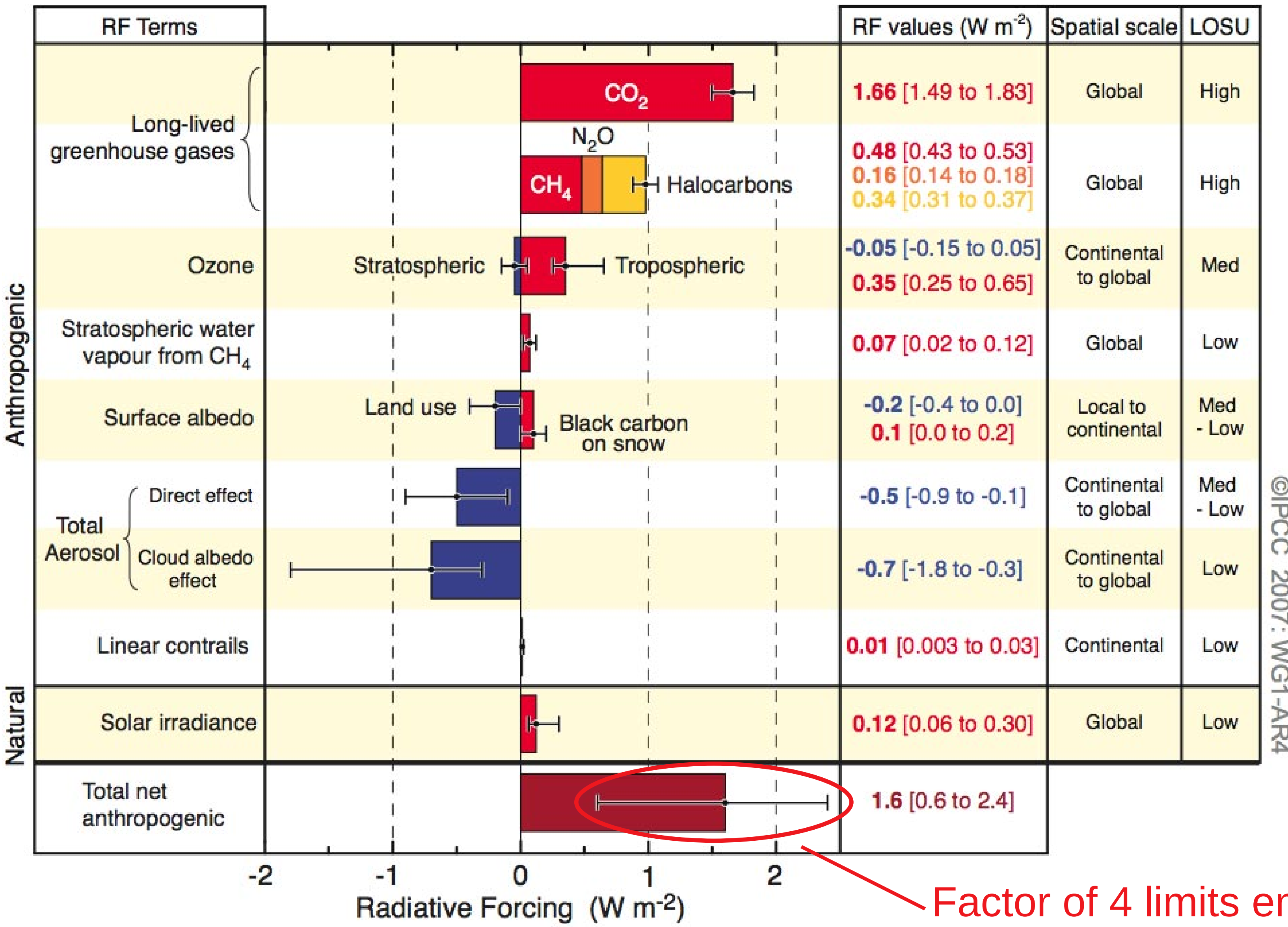
Radiative forcing for solar zenith angle 60° and liquid water path 100 g m^{-2}

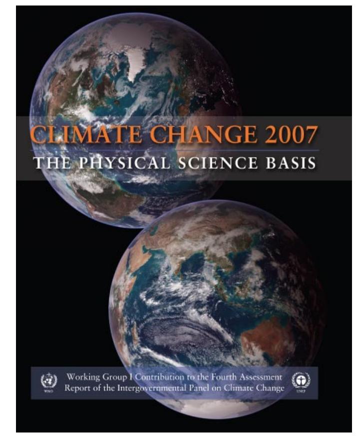
Date, 2000	Effective radius r_e, μm	Optical Depth	Net flux at TOA W m^{-2}	Forcing relative to 10/26, W m^{-2}
10/26	10.2	15.1	293	—
10/21	7.8	20.8	266	27
02/18	5.8	28.3	240	53

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

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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



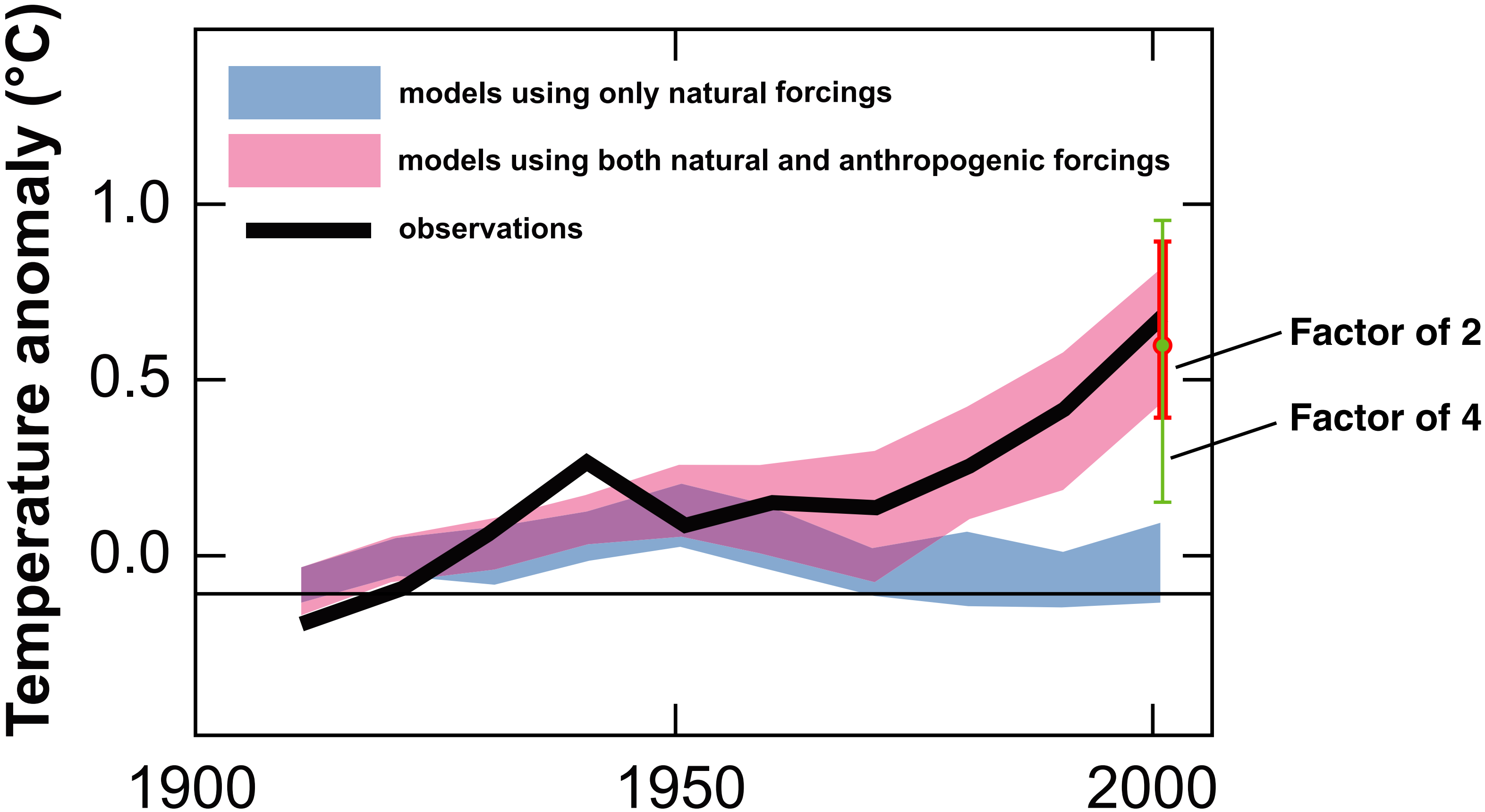


Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



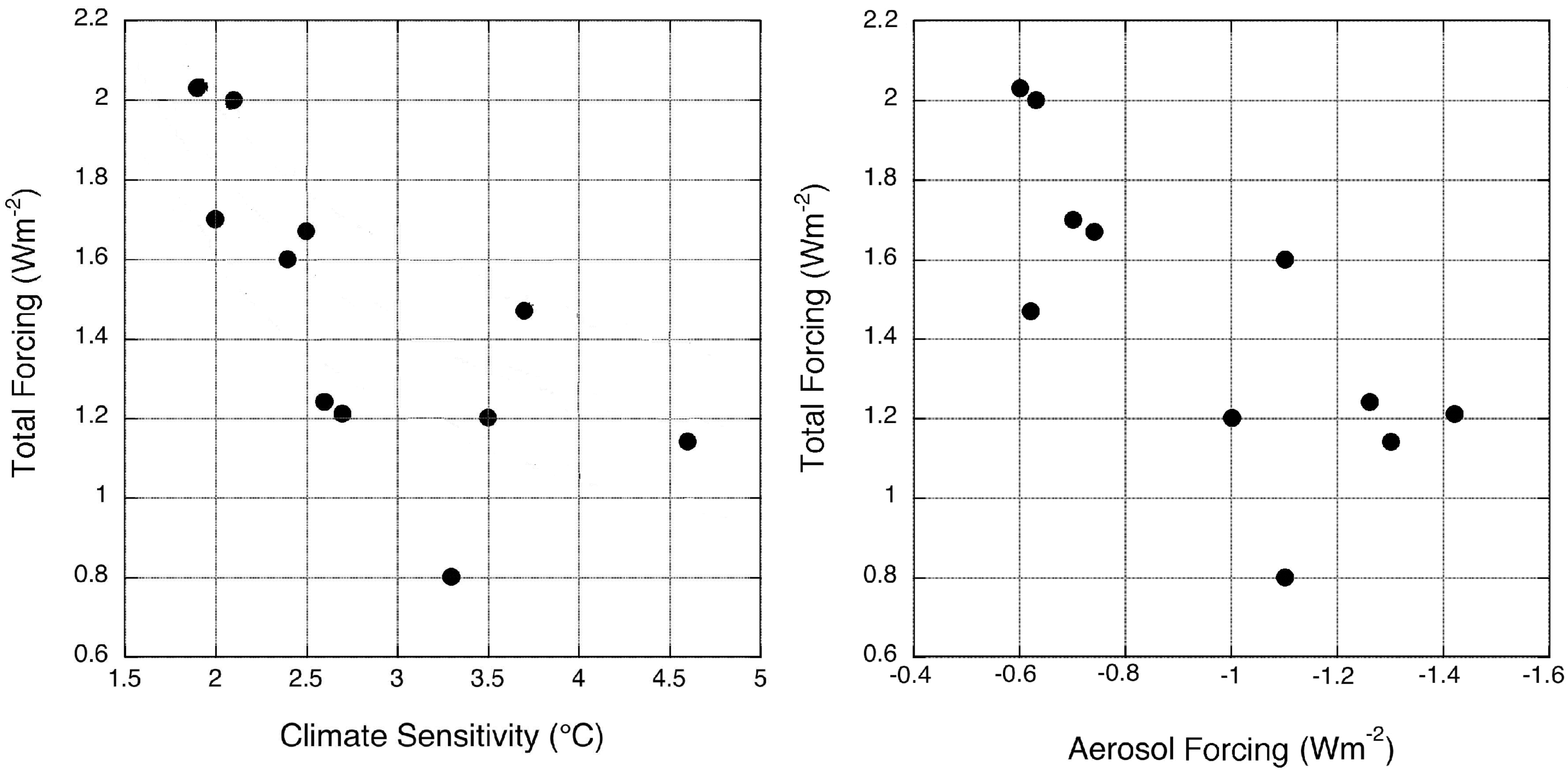
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

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.

RECAPITULATION

Present estimates of Earth's climate sensitivity range over ***at least a factor of 2***.

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 at least a factor of 2.

IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

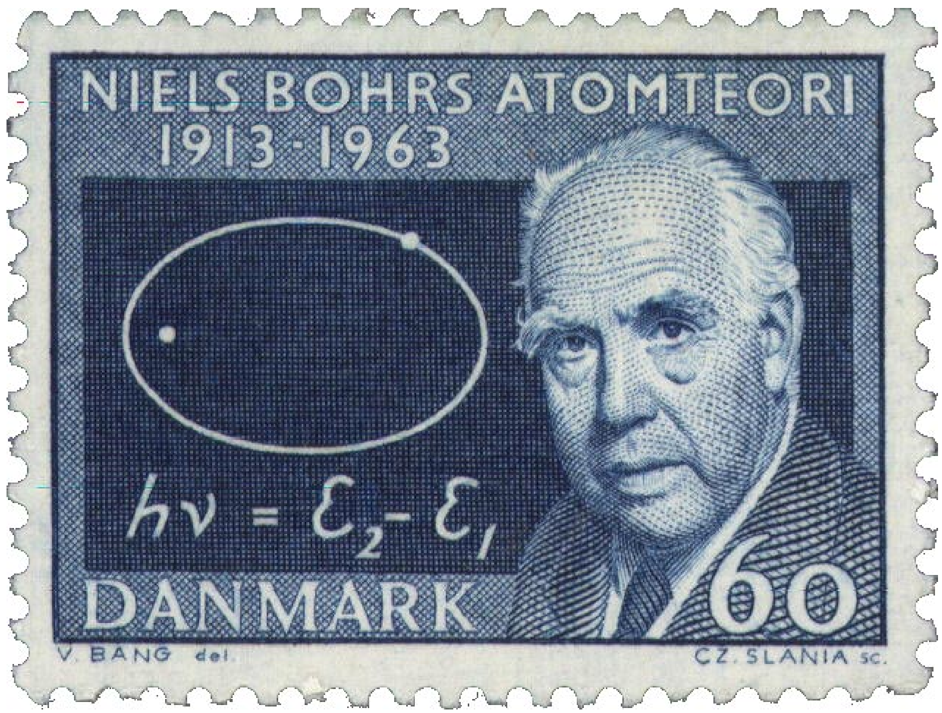
- The lifetime of incremental atmospheric CO_2 is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

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

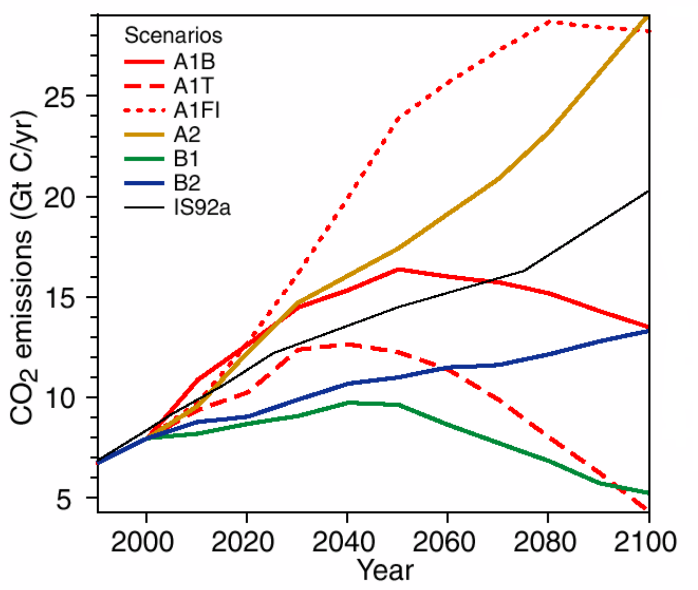
Looking to the Future . . .

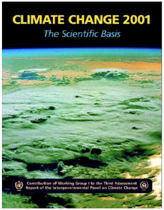
Prediction is difficult, especially about the future.



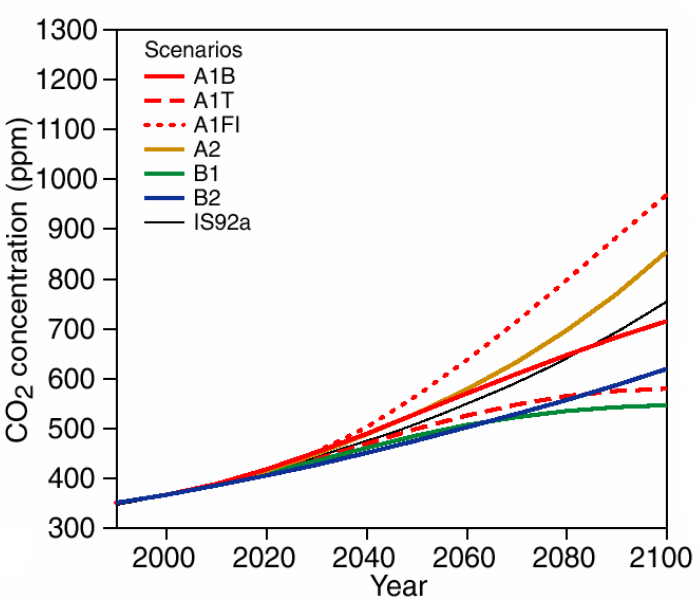
– Niels Bohr

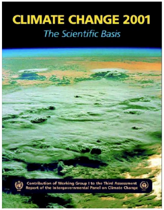
PROJECTIONS OF FUTURE CO2 EMISSIONS



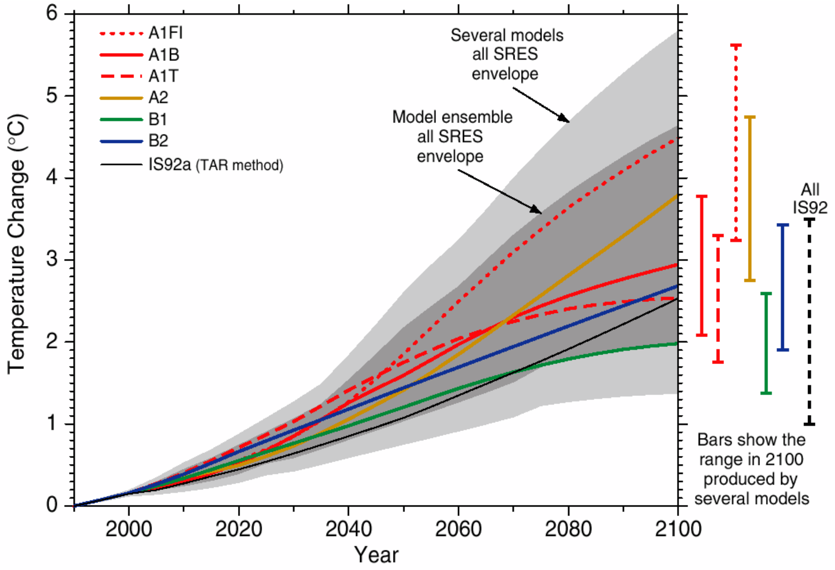


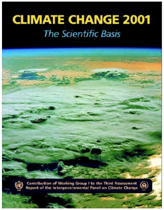
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS





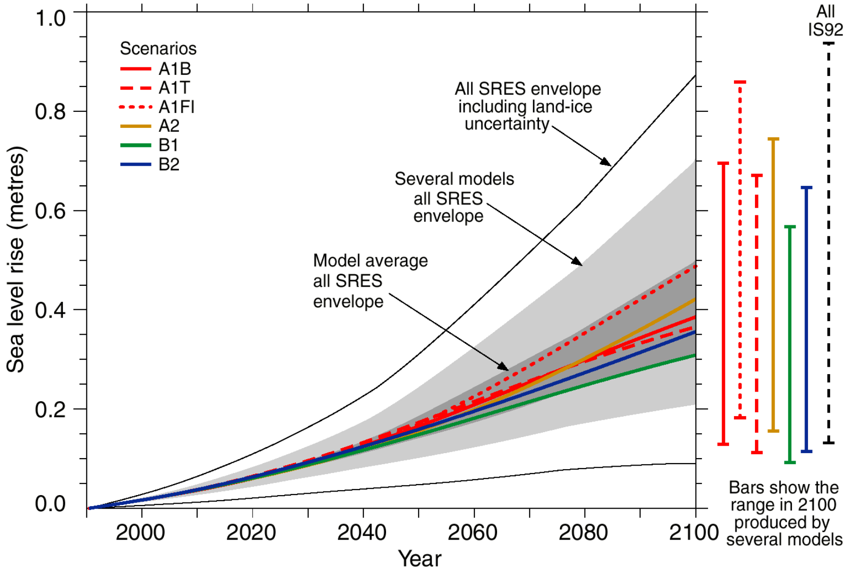
PROJECTIONS OF FUTURE TEMPERATURE CHANGE

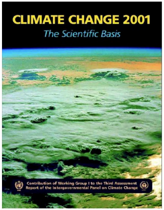




PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only





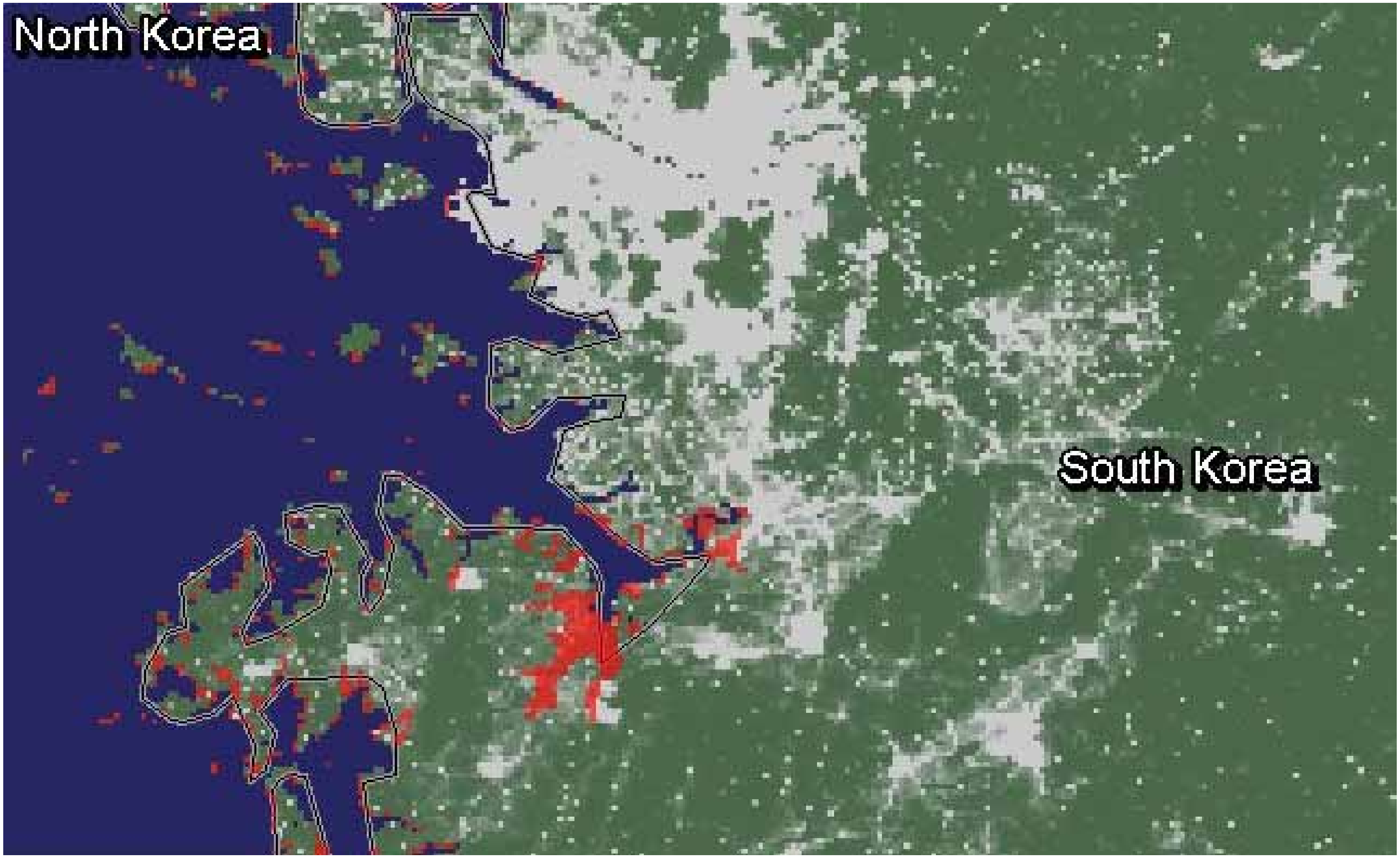
EFFECT OF SEA LEVEL RISE

Population density, current coastline

Weiss and Overpeck, University of Arizona

EFFECT OF SEA LEVEL RISE

Population density, 1 meter sea level rise

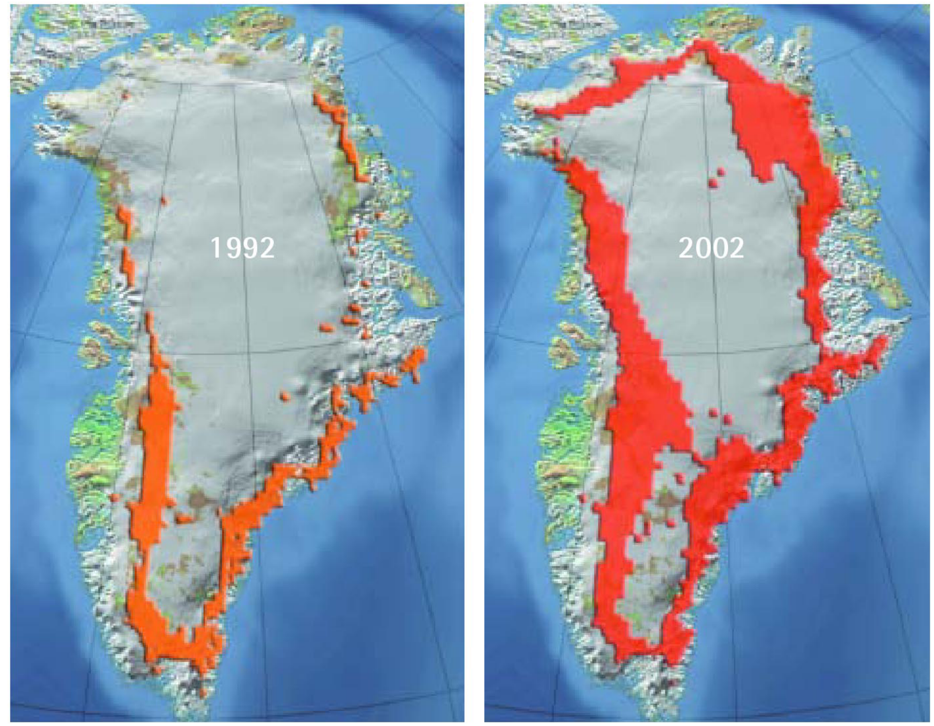


Weiss and Overpeck, University of Arizona

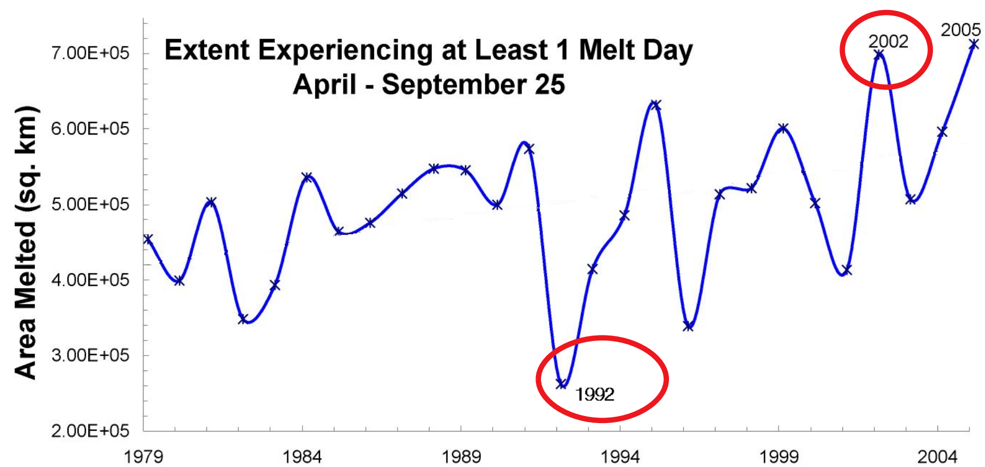
MELTING OF GREENLAND ICE CAP

Satellite determination of extent of glacial melt 1992 vs 2002

NASA



Arctic Climate Impact Assessment, Cambridge, 2004

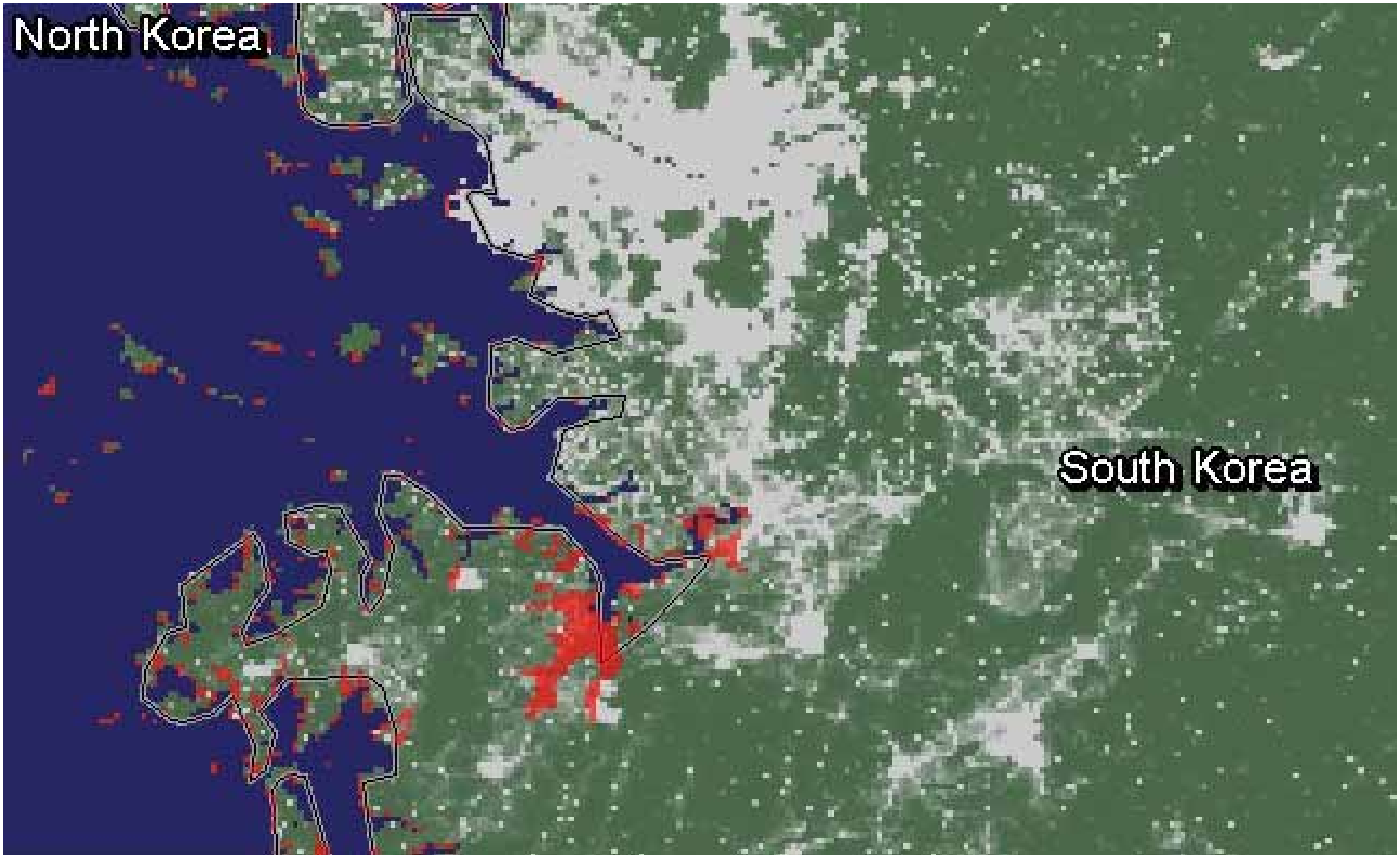


Steffen & Huff , Univ. Colo., 2005

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

EFFECT OF SEA LEVEL RISE

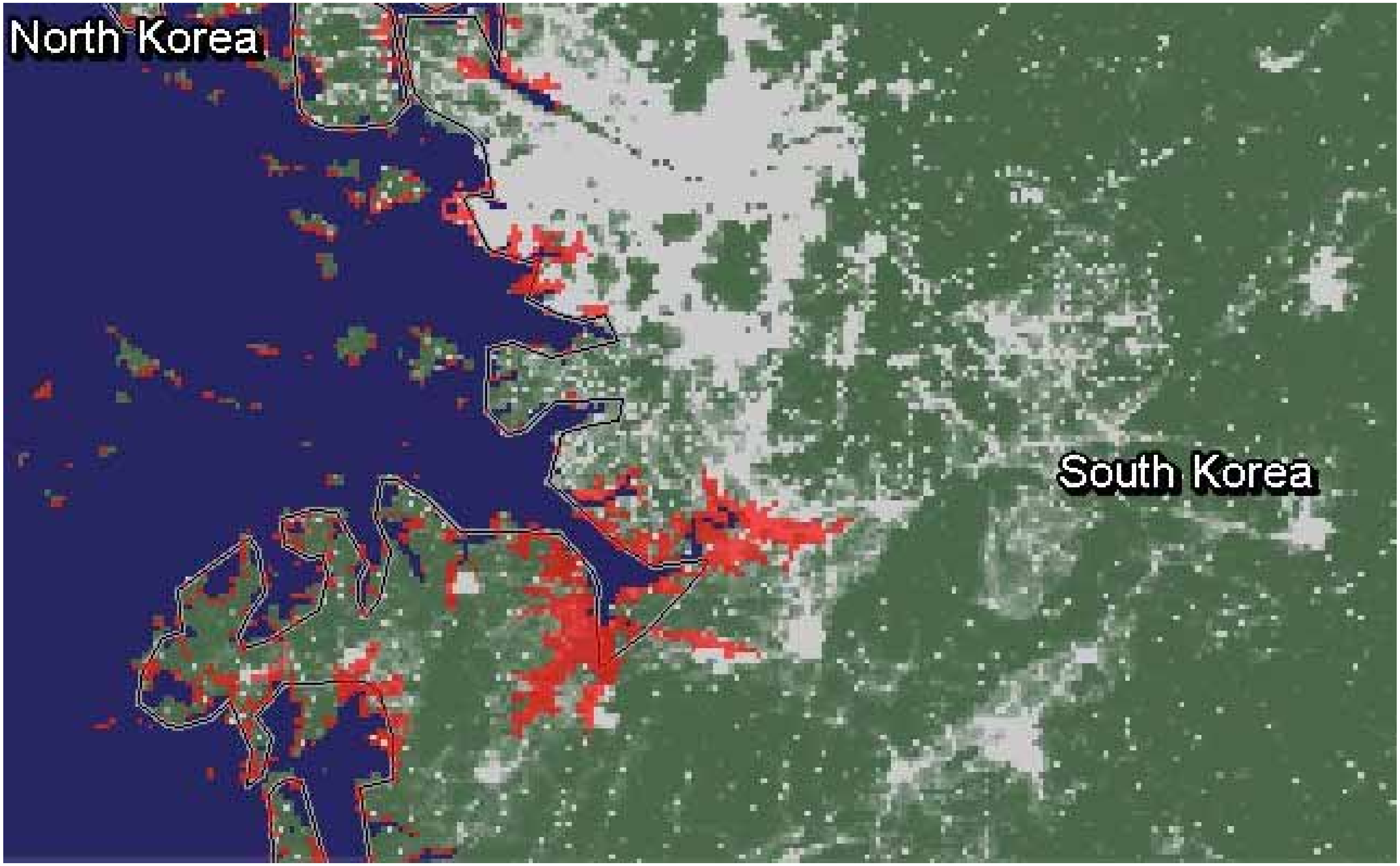
Population density, 1 meter sea level rise



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

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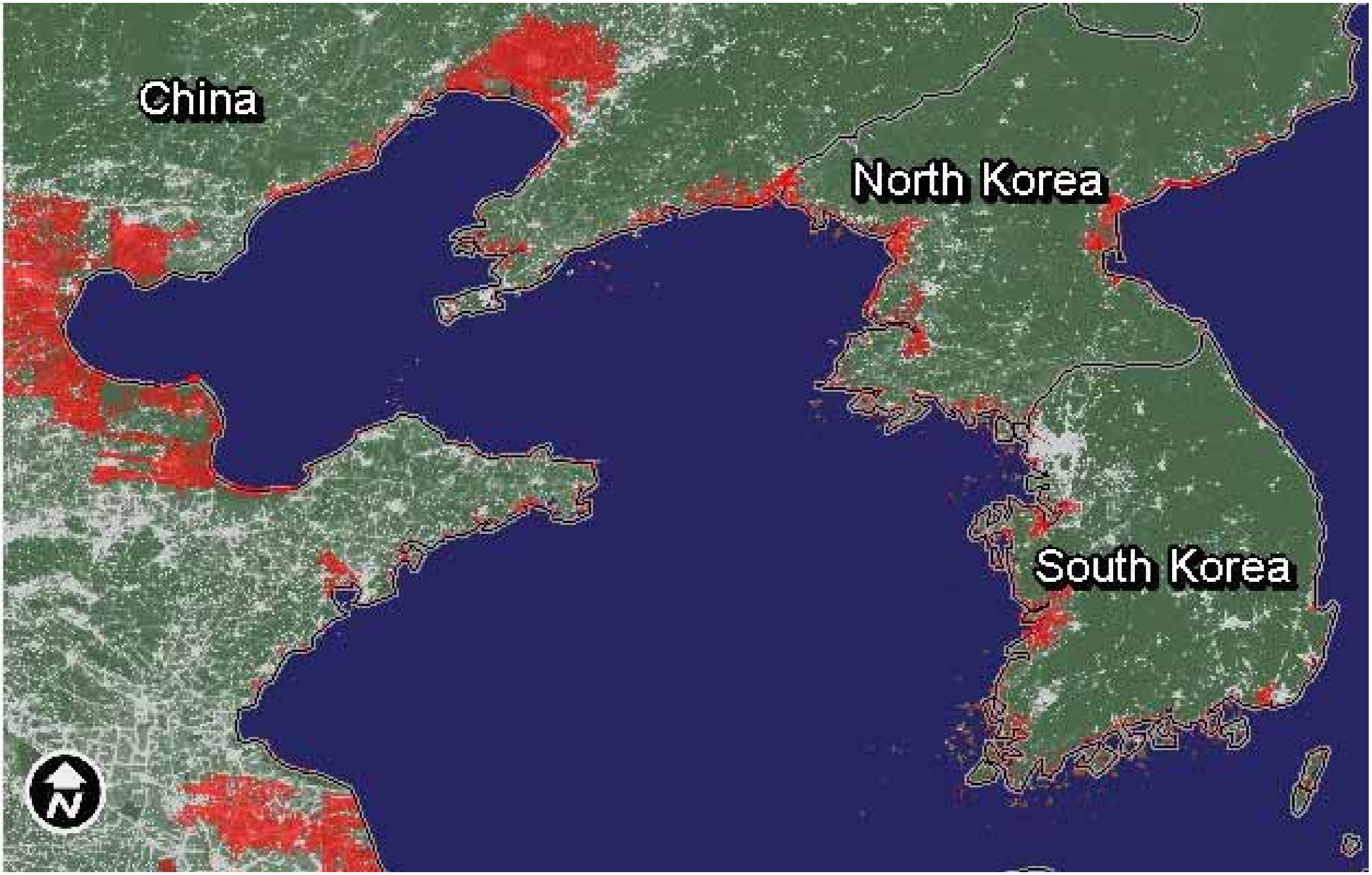

Weiss and Overpeck, University of Arizona

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.