CLIMATE CHANGE

CERTAINTIES AND UNCERTAINTIES

Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

Upton, New York

Lindseth Lecture

Cornell University

College of Engineering

Sibley School of Mechanical and Aerospace Engineering

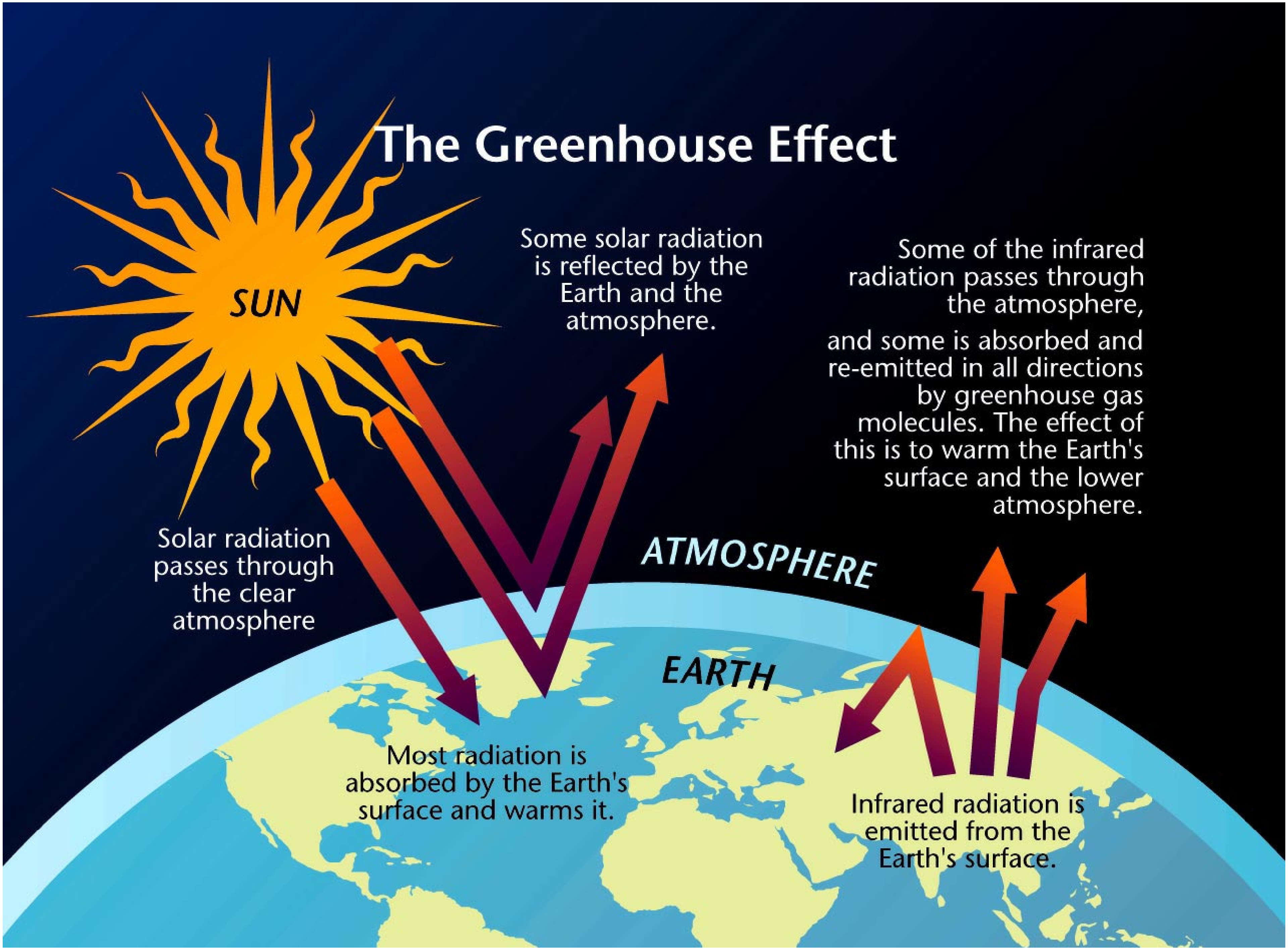
Ithaca, New York

20 November 2007

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

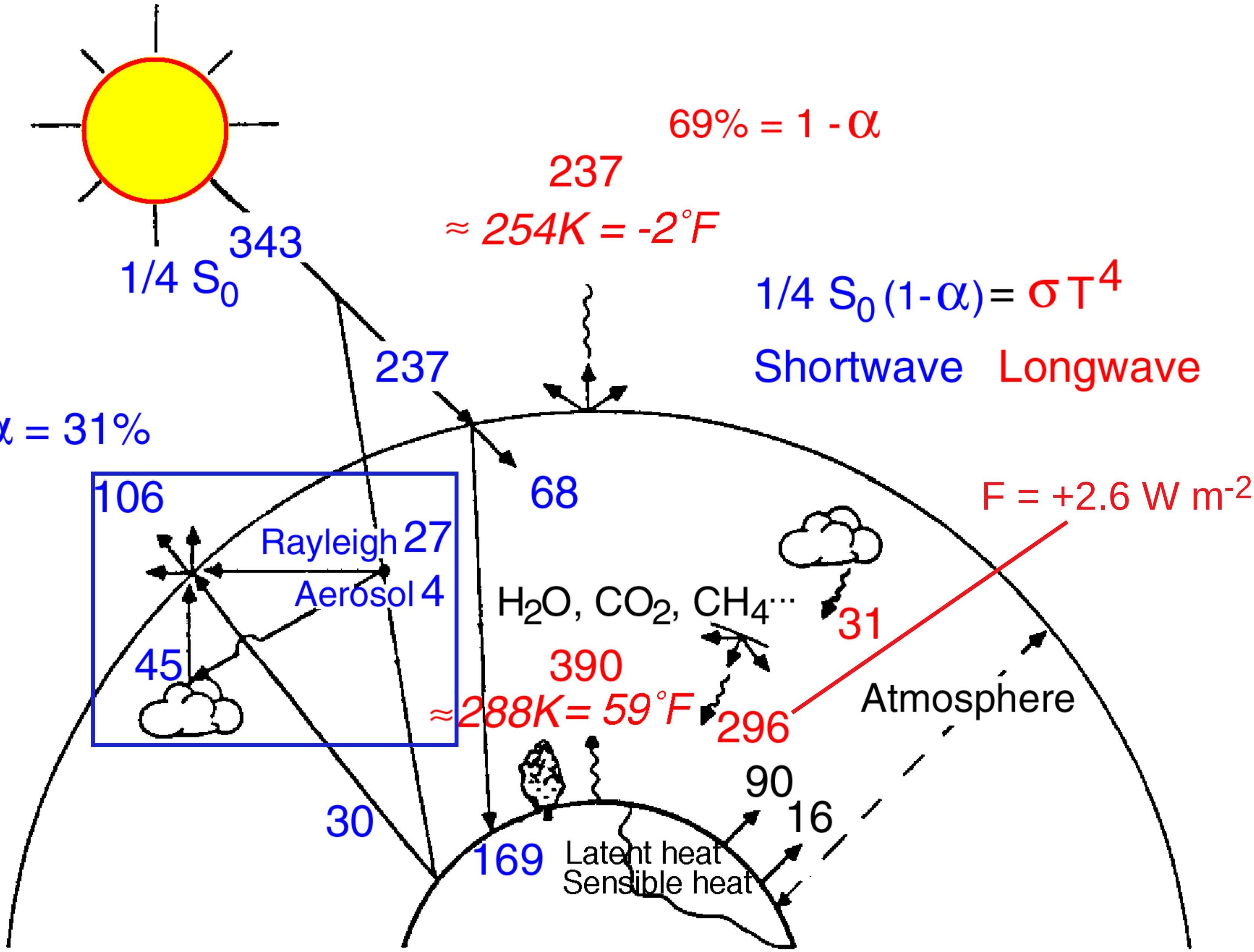
OUTLINE

- Earth's energy balance
  - Perturbations
  - Carbon dioxide
- Climate forcing and response
  - Earth's climate sensitivity
- Influence of aerosols
- Uncertainty in climate forcing and its implications
- Looking to the future
- Concluding remarks


The Greenhouse Effect
SUN
Some solar radiation is reflected by the Earth and the atmosphere.
Some of the infrared radiation passes through the atmosphere,
and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Solar radiation passes through the clear atmosphere
ATMOSPHERE
EARTH
Most radiation is absorbed by the Earth's surface and warms it.
Infrared radiation is emitted from the Earth's surface.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



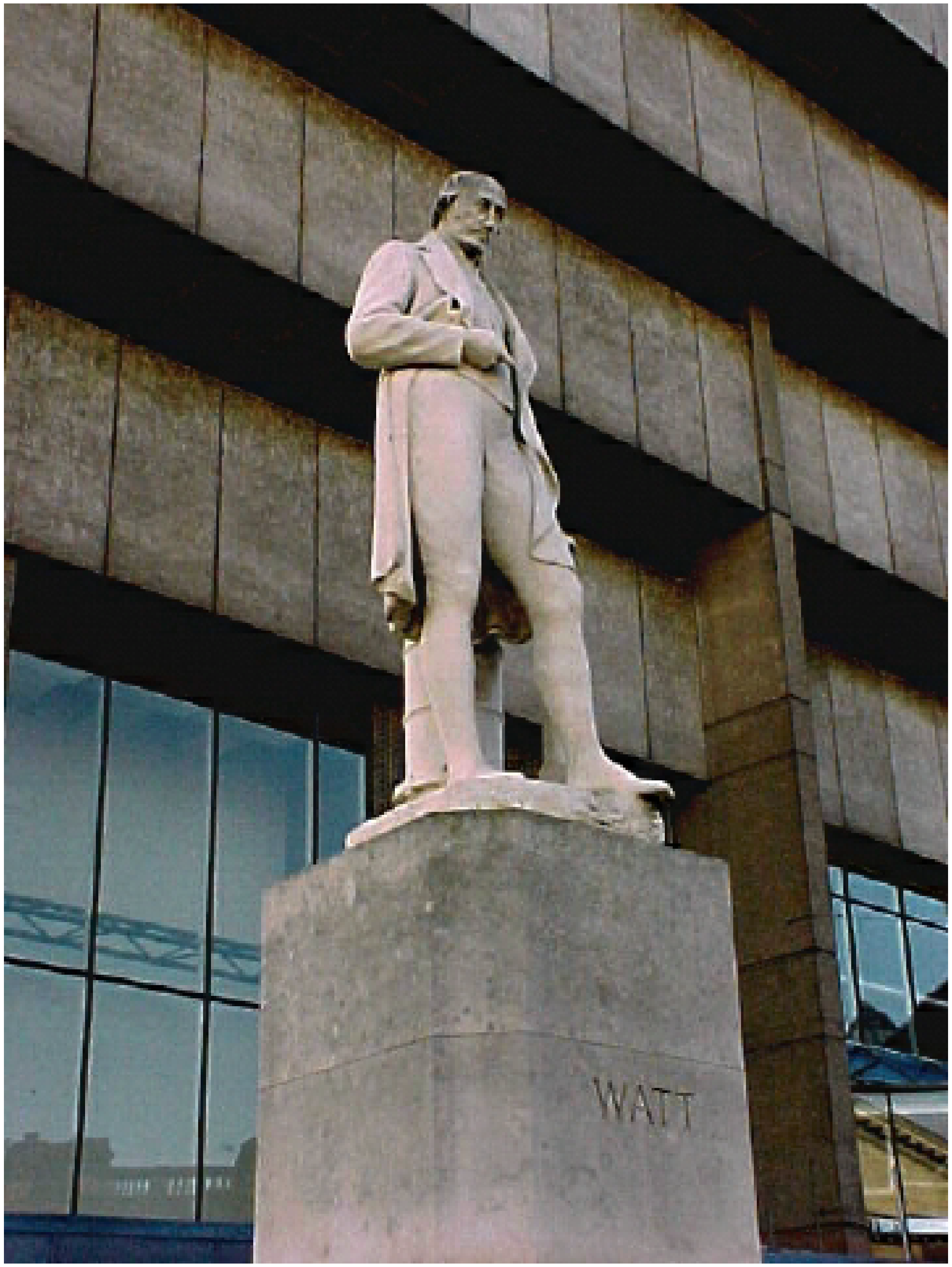
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

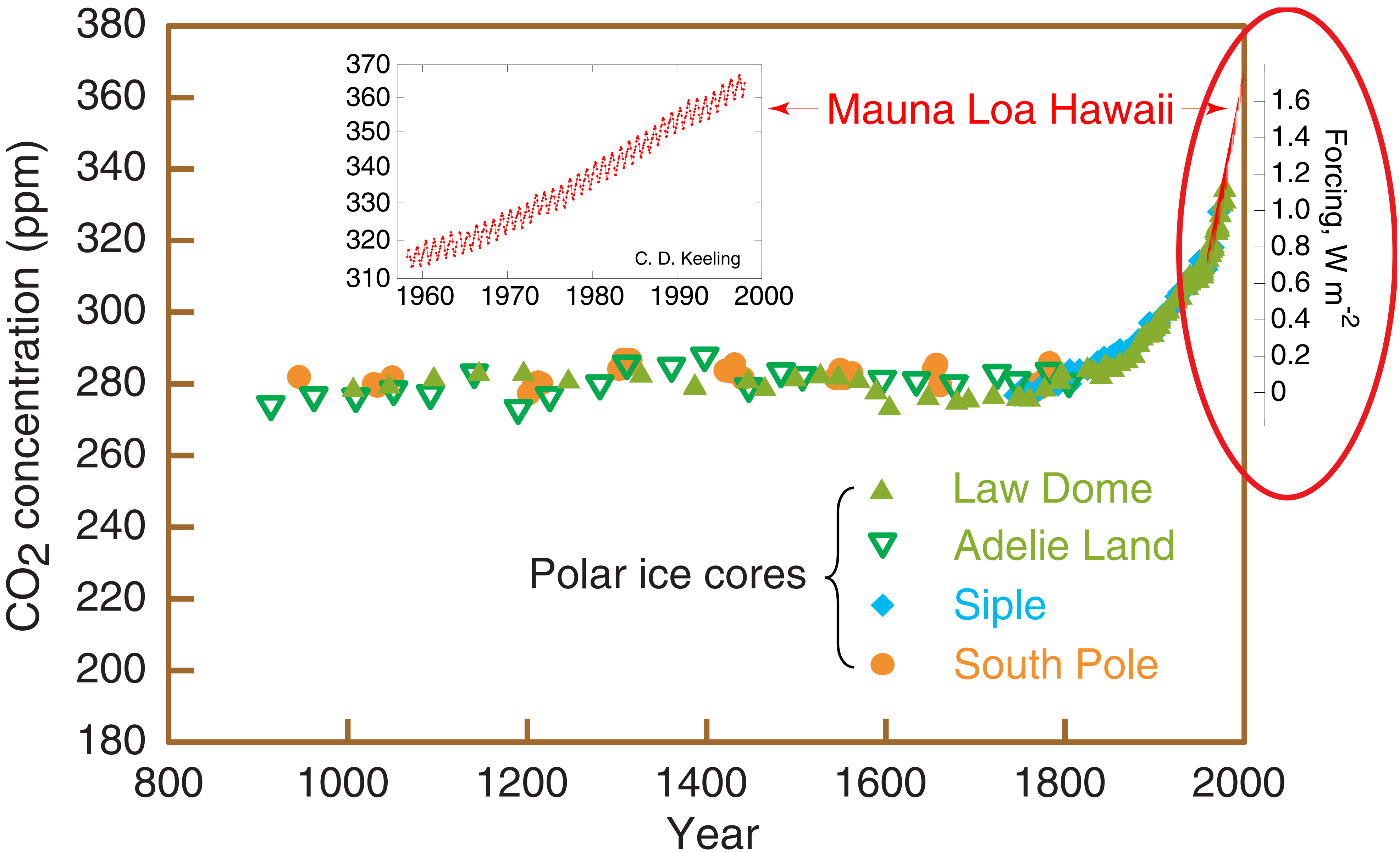
Energy per area per time

Power 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:

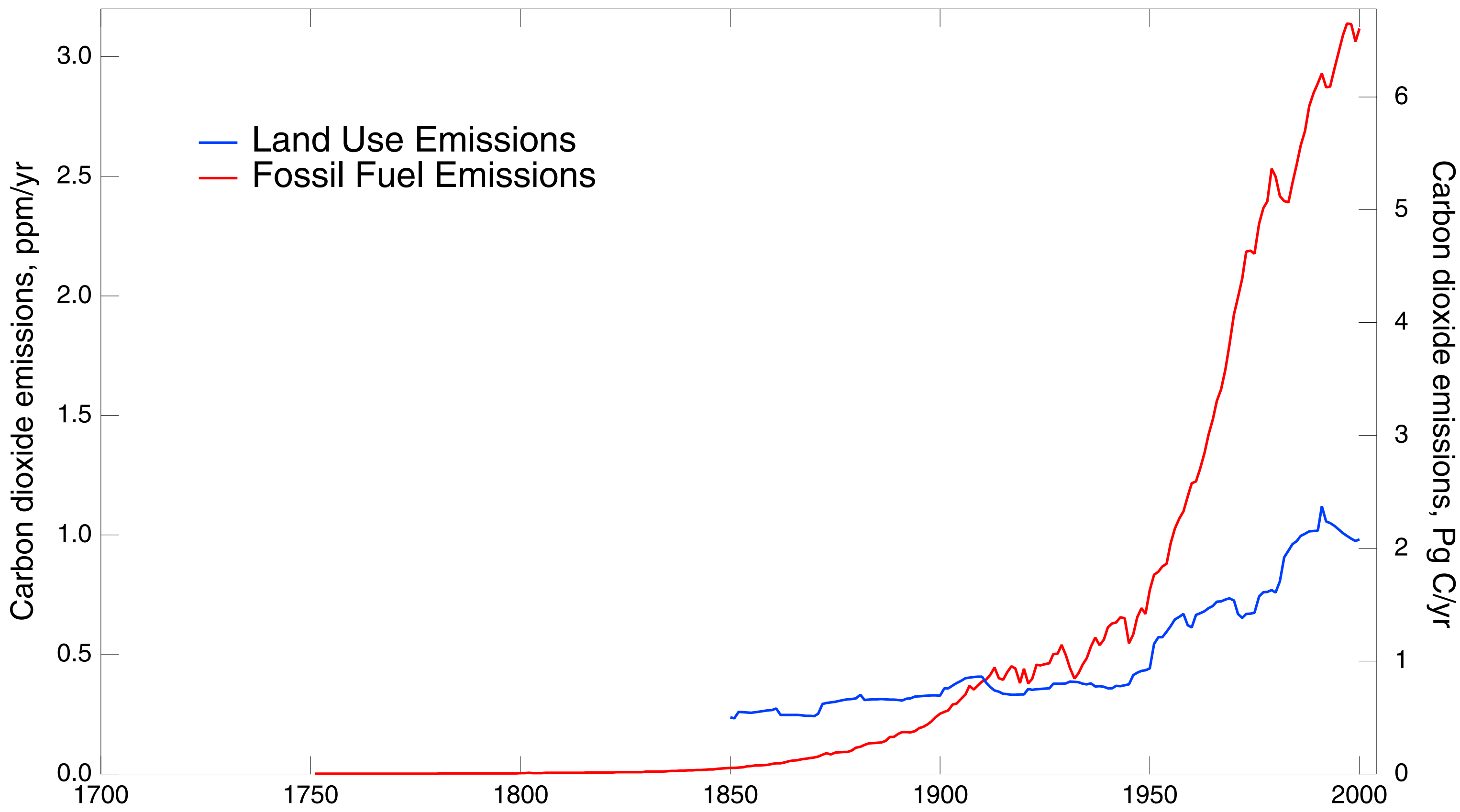
On a global basis radiative forcings are additive and fungible.

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

INCREASES IN CO_2 OVER THE INDUSTRIAL PERIOD

ATMOSPHERIC CO_2 EMISSIONS

Time series 1700 - 2003



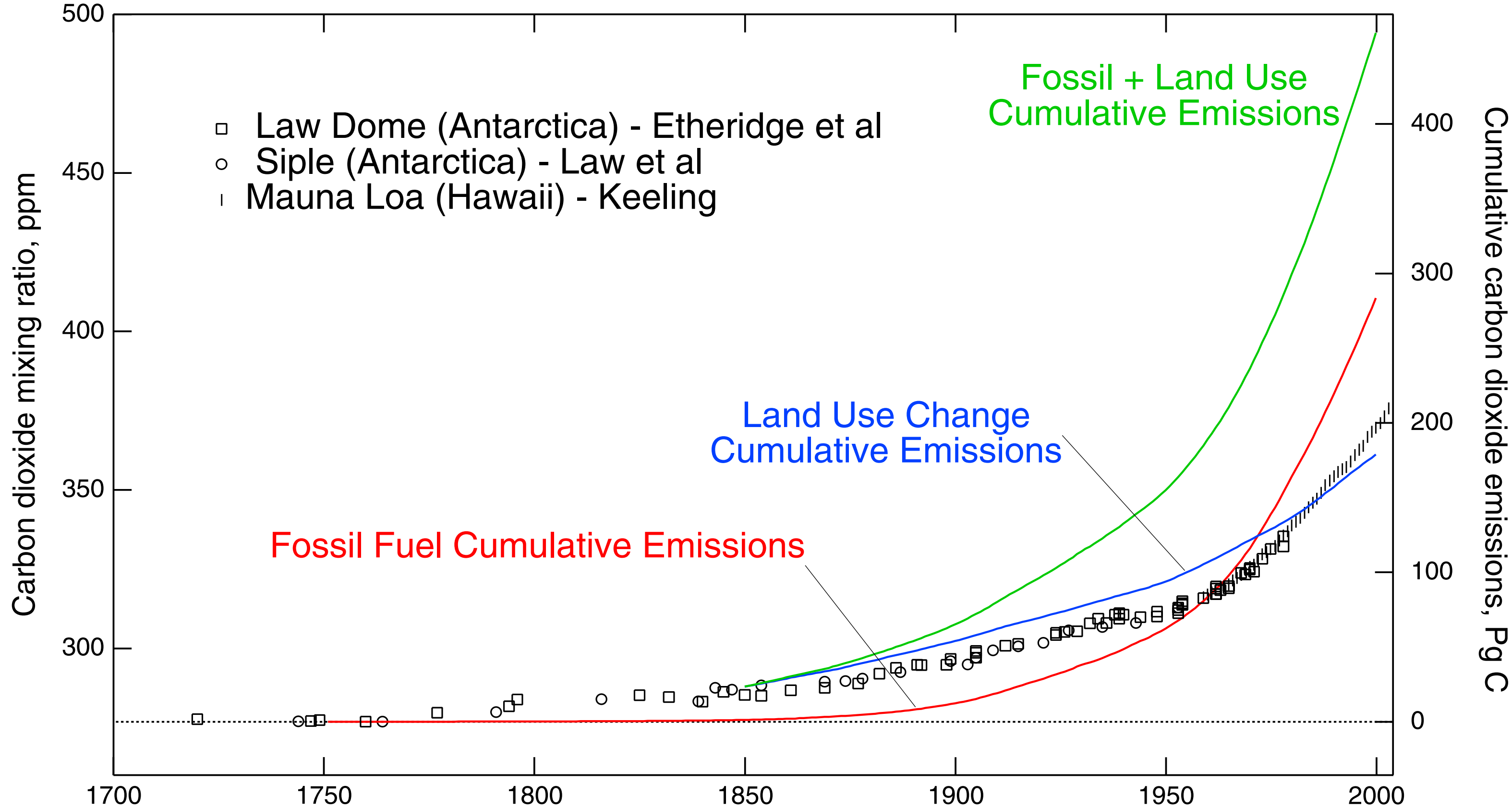
Fossil Fuel - Marland
Land Use - Houghton

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 INCREASE IN ATMOSPHERIC CO_2

Comparison of ***cumulative*** CO_2 emissions from fossil fuel combustion and land use changes with measured increases in atmospheric CO_2.

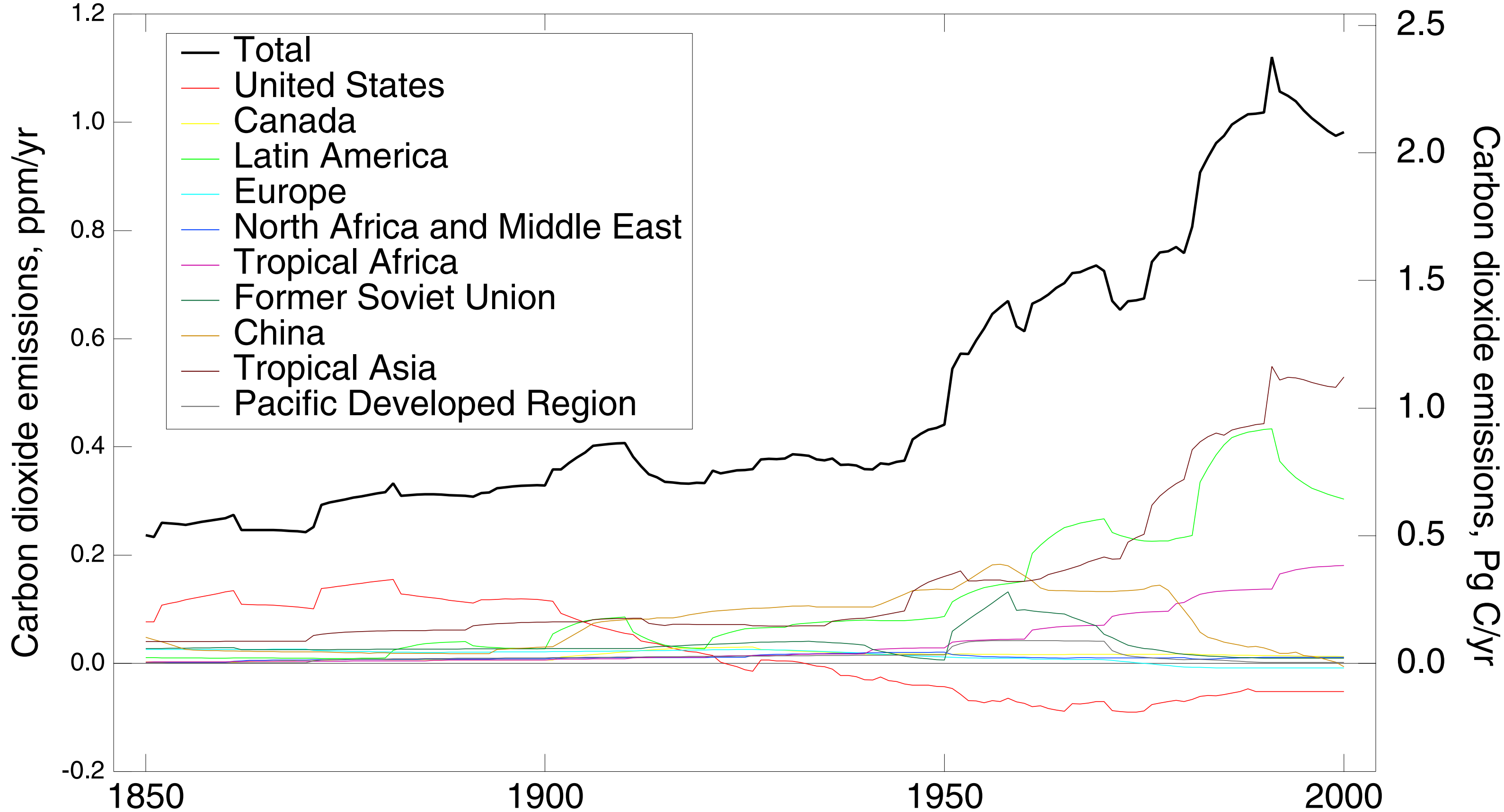


Prior to 1970 the increase in atmospheric CO_2 was dominated by emissions from land use changes, not fossil fuel combustion.

DEFORESTATION AS A SOURCE OF ATMOSPHERIC CO_2

ATMOSPHERIC CO_2 EMISSIONS

Land-use changes 1850 - 2000



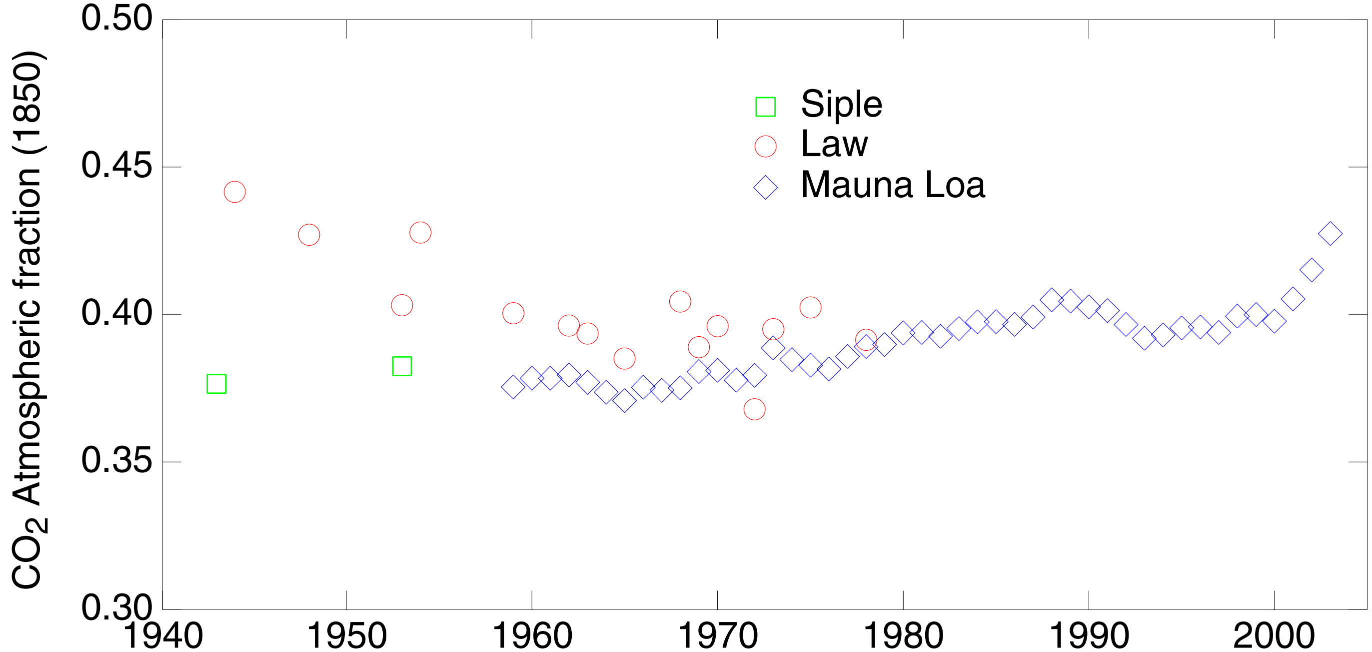
Houghton, *Tellus*, 1999; Houghton and Hackler, 2002

Carbon flux estimated as land area times carbon emissions associated with deforestation (or uptake associated with afforestation).

United States dominates emissions before 1900 and uptake after 1940.

FRACTION OF EMITTED CO_2 REMAINING IN THE ATMOSPHERE

Excess atmospheric CO_2 (relative to 1850) as fraction of cumulative emissions from 1850.



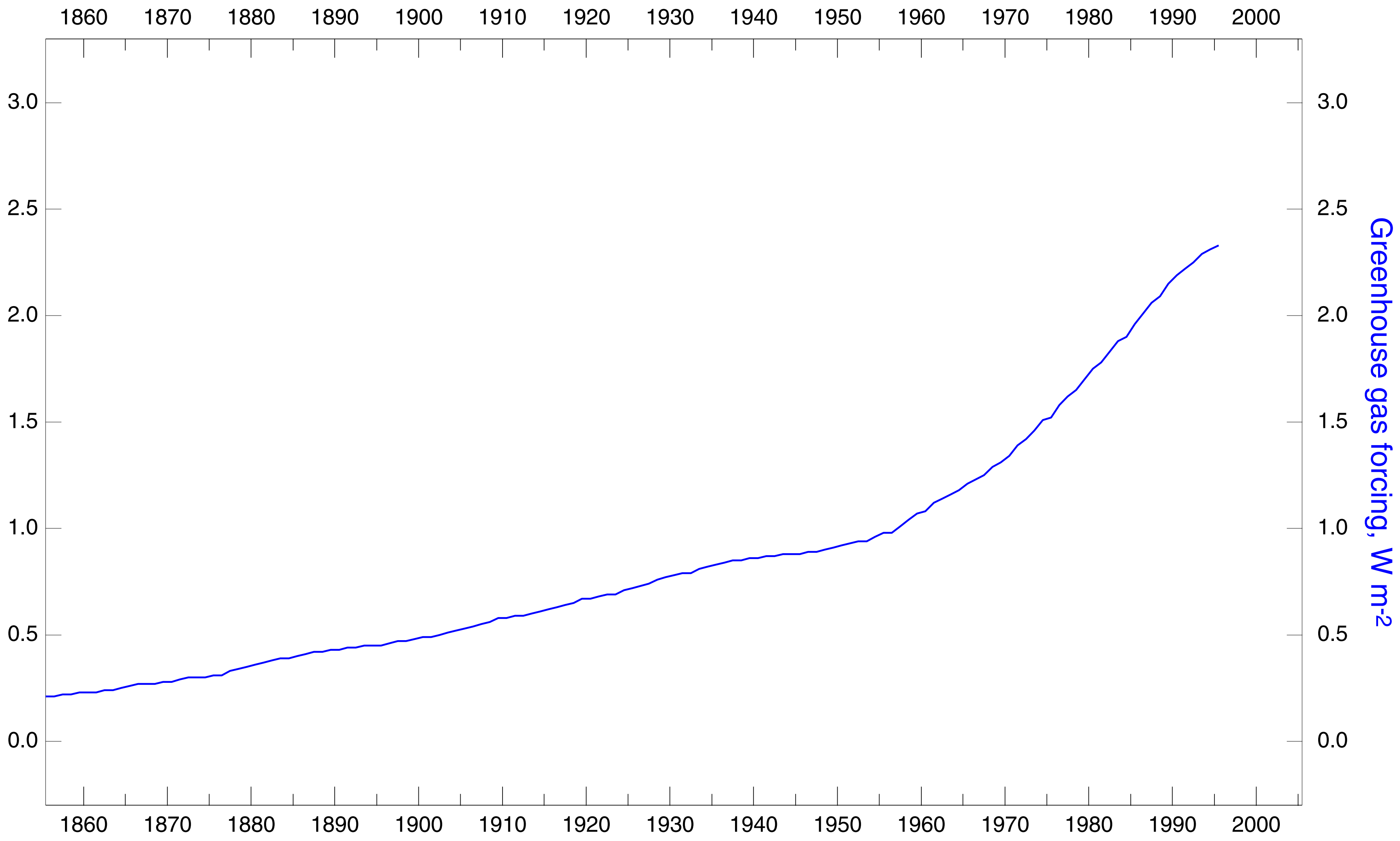
Is the atmospheric CO_2 fraction increasing?

What are the implications for future CO_2?

CLIMATE FORCING AND RESPONSE

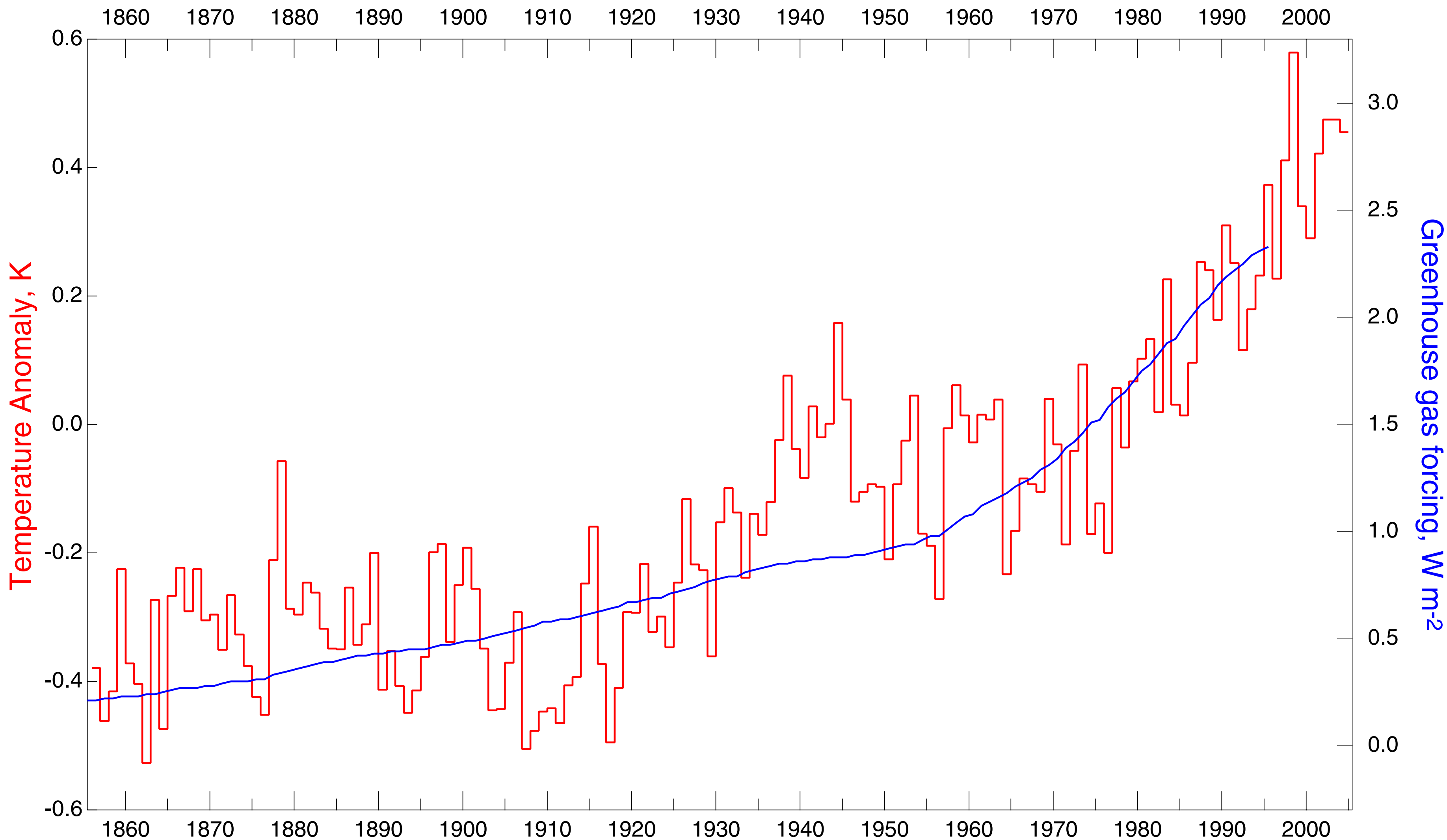
GREENHOUSE GAS FORCING 1855-2004

Well mixed greenhouse gases: carbon dioxide, methane, nitrous oxide, CFC's



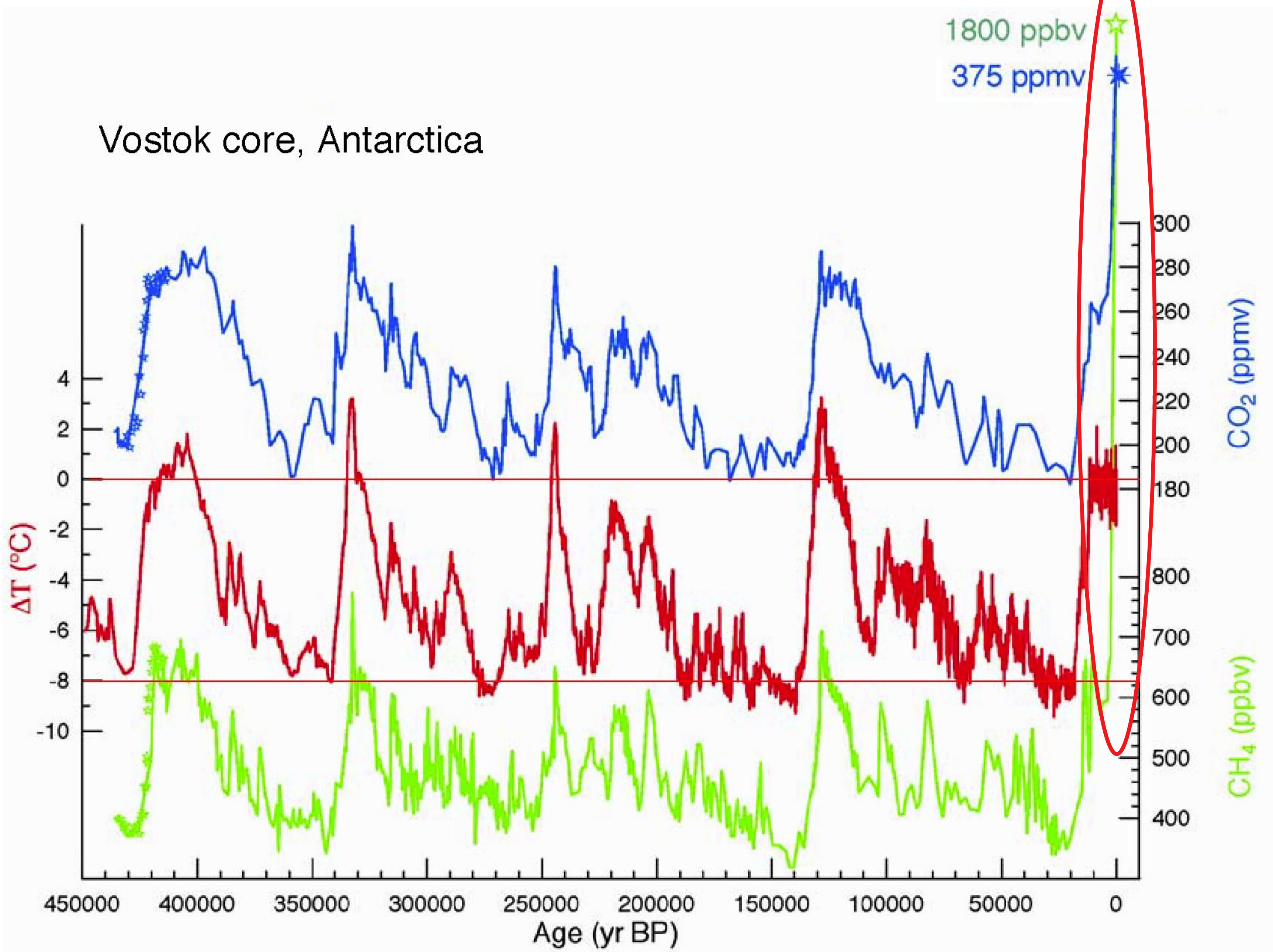
IPCC, 2001

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 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.

$$\Delta T = \lambda \, \Delta F$$

CLIMATE SENSITIVITY

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

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

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

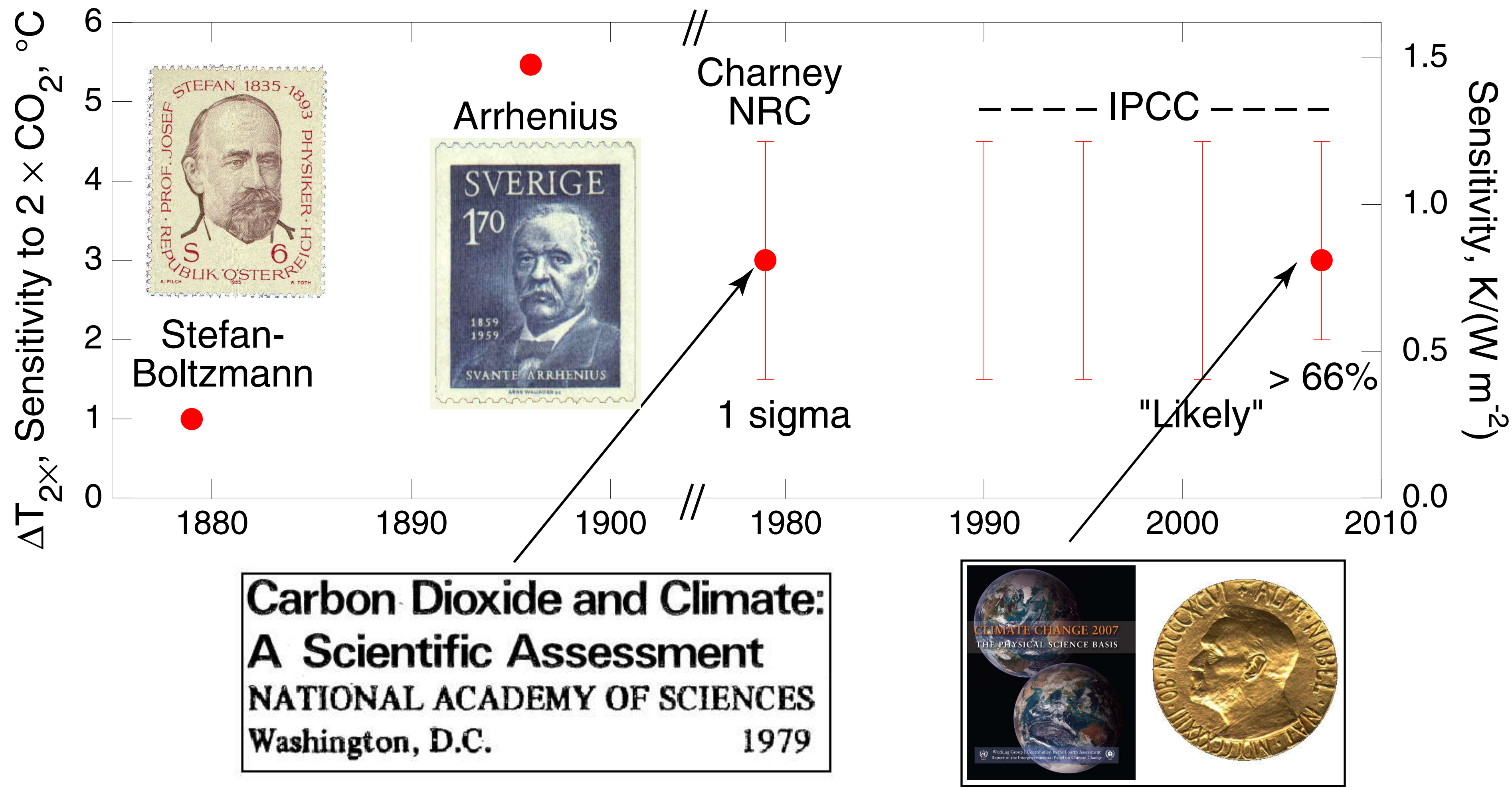
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

$$\Delta T_{2\times} = \lambda \, \Delta F_{2\times}$$

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

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***.

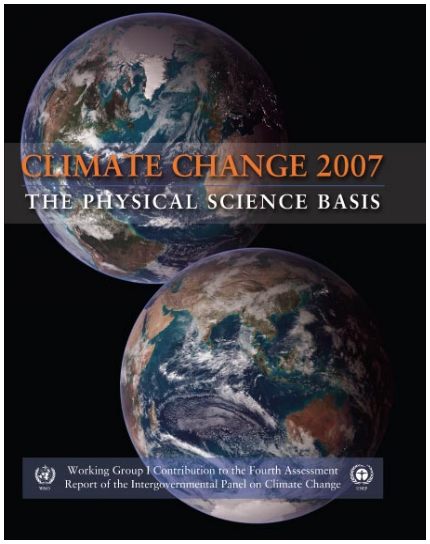
THE 'BIBLE' OF CLIMATE CHANGE

It's big and thick.

Every household should have one.

No one reads it from cover to cover.

You can open it up on any page and find something interesting.



It was written by a committee.

It is full of internal contradictions.

It deals with cataclysmic events such as floods and droughts.

It has its true believers and its rabid skeptics.

http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

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.

KEY APPROACHES TO DETERMINING CLIMATE SENSITIVITY

- Paleoclimate studies.
- Empirical, from climate change over the instrumental record.
- Climate modeling.

Climate models evaluated by comparison with observations are essential to informed decision making.

IMPORTANCE OF KNOWLEDGE OF CLIMATE TO INFORMED DECISION MAKING

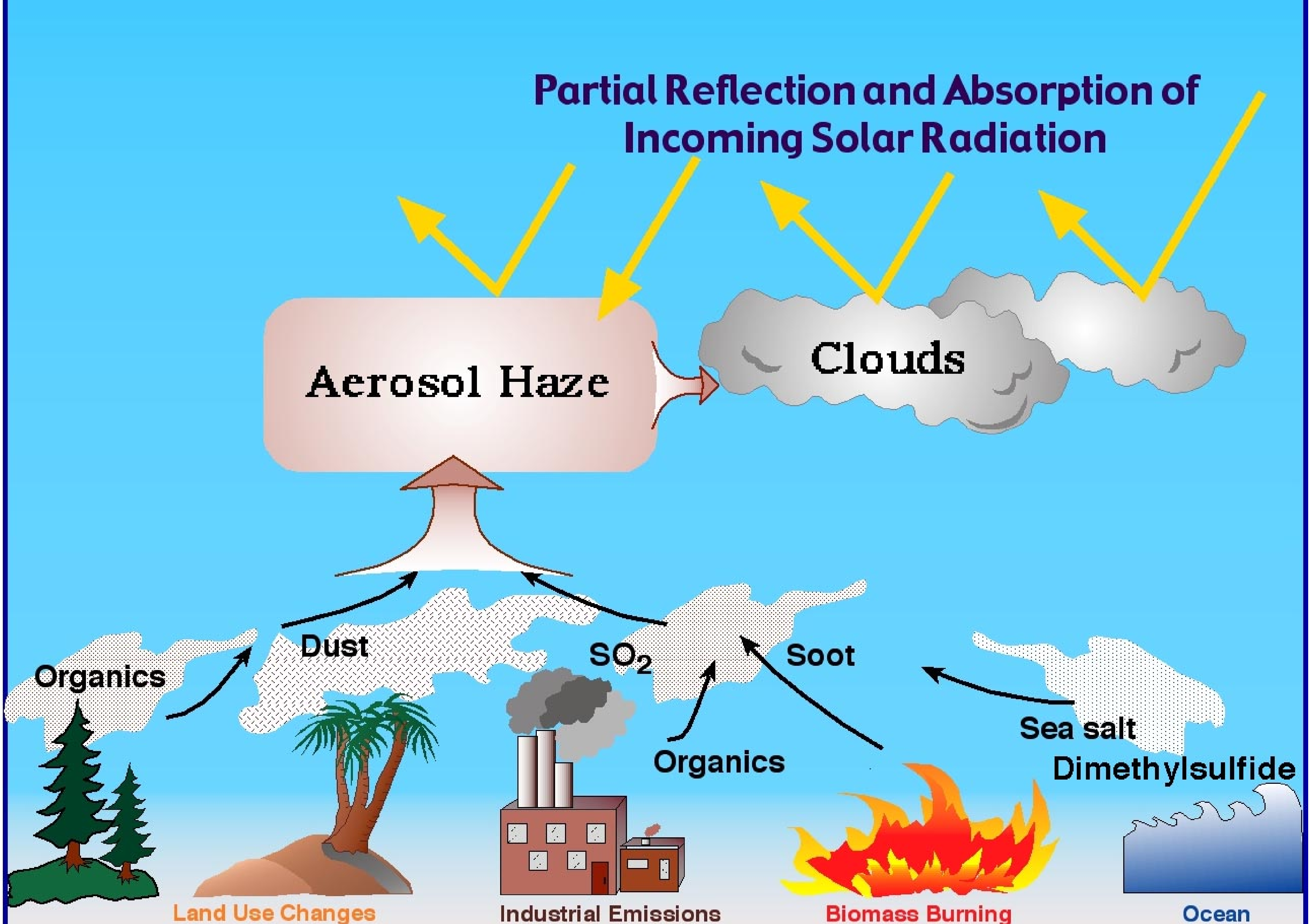
- The lifetime of incremental atmospheric CO_2 is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

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

INFLUENCE OF AEROSOLS

Radiative Forcing by Tropospheric Aerosol

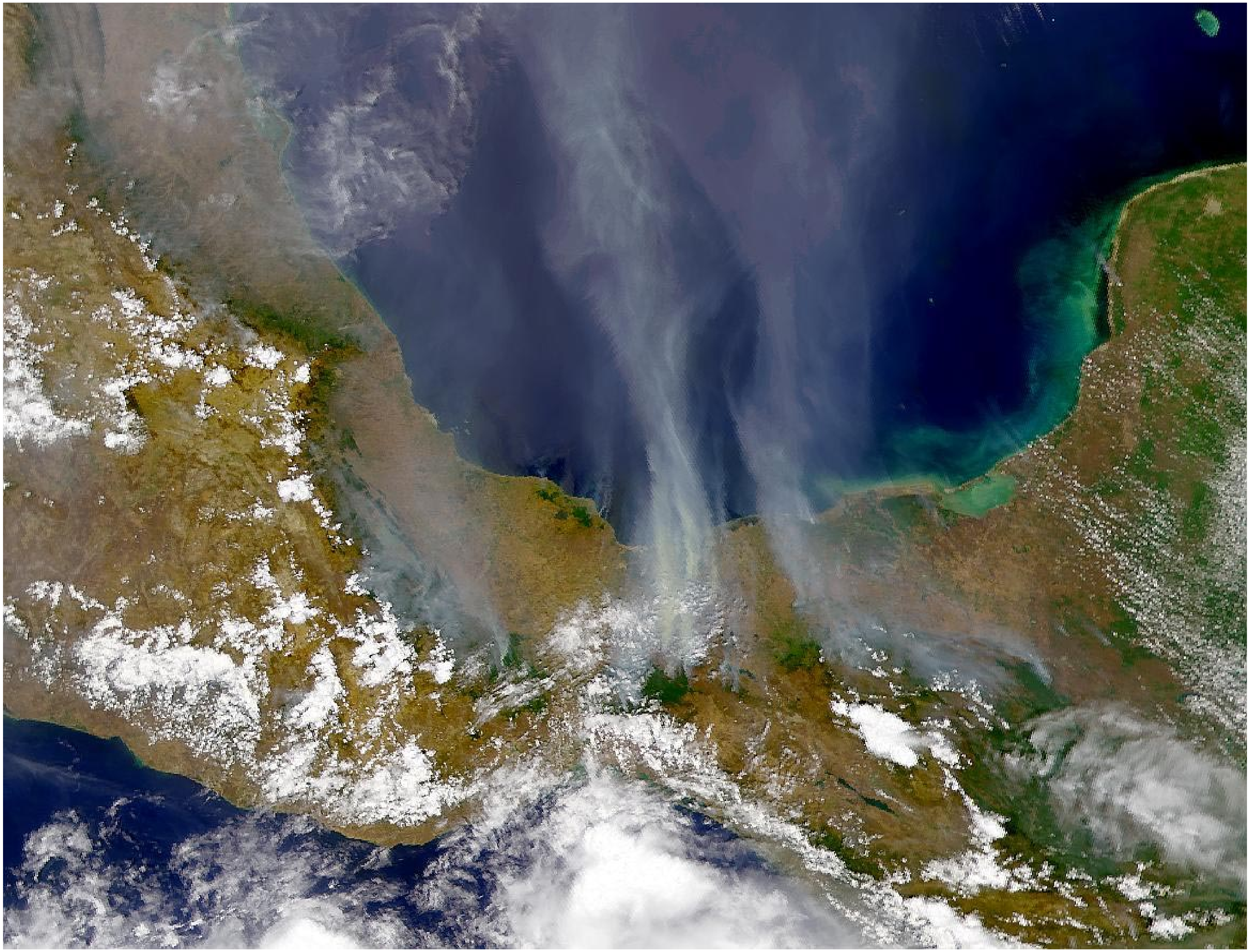


AEROSOL IN MEXICO CITY BASIN

AEROSOL IN MEXICO CITY BASIN

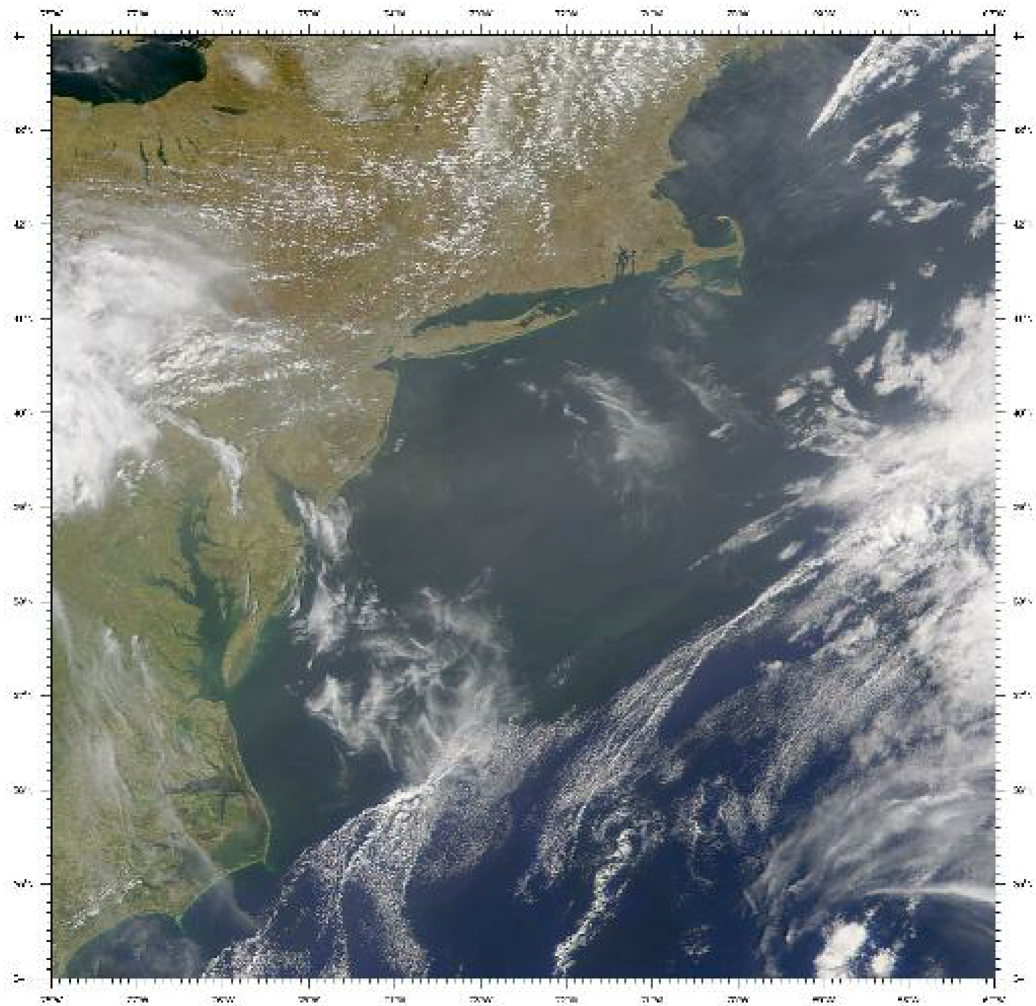
Mexico City is a wonderful place to study aerosol properties and evolution.

AEROSOLS AS SEEN FROM SPACE



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

AEROSOL: A suspension of particles in air

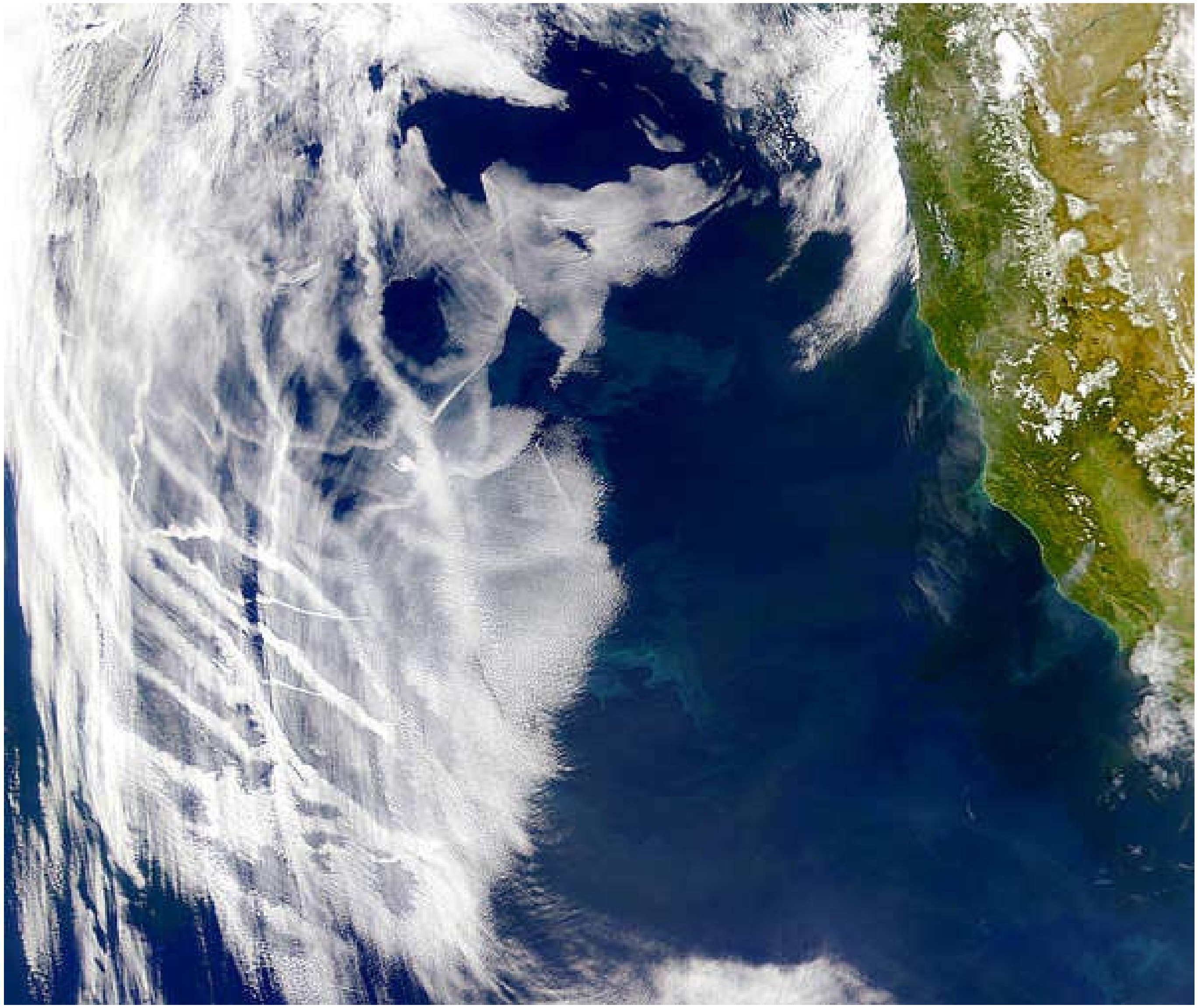


2001-04-22-17:28
SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).

CLOUD BRIGHTENING BY SHIP TRACKS

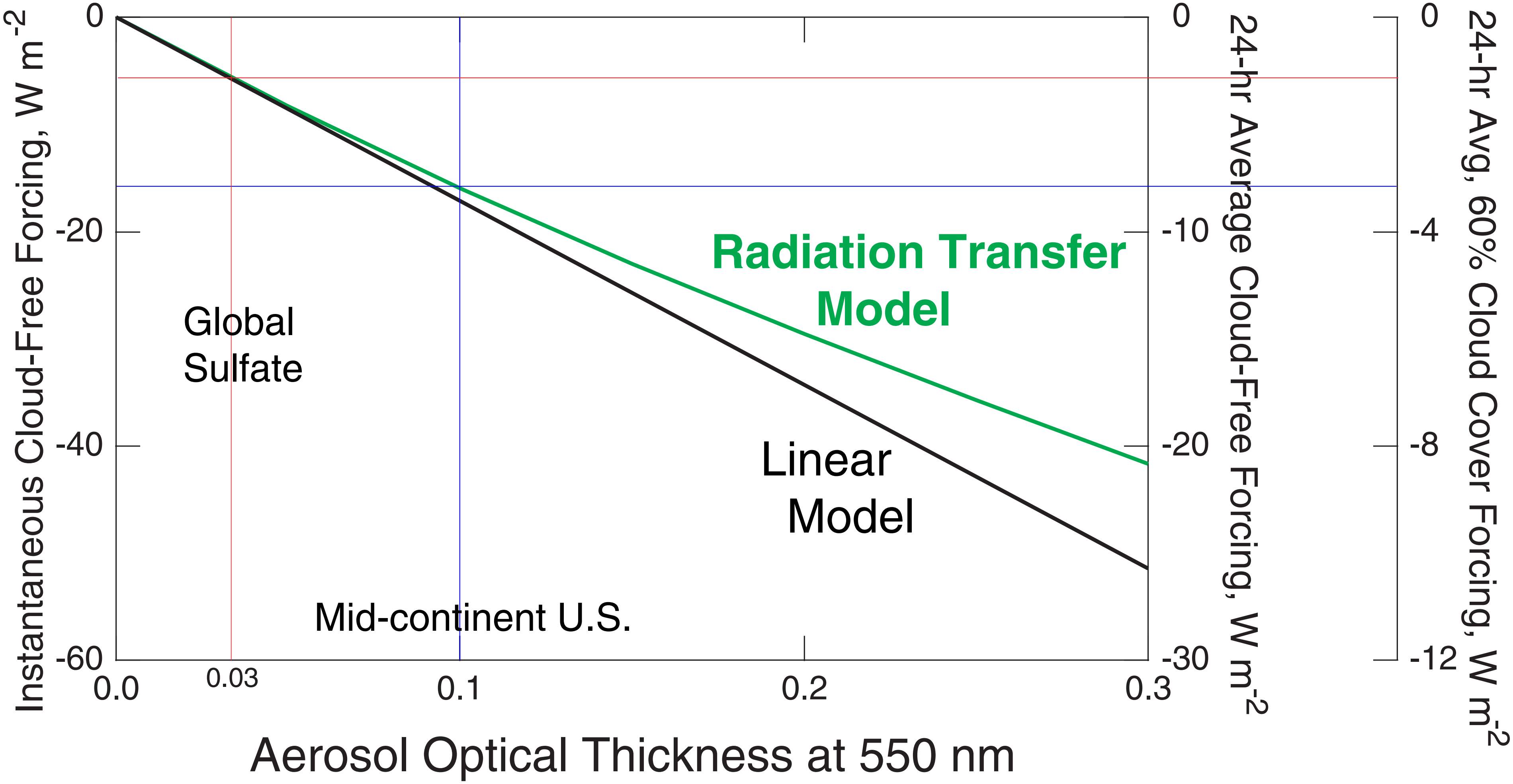
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

ESTIMATES OF AEROSOL DIRECT FORCING

By linear model and by radiation transfer modeling

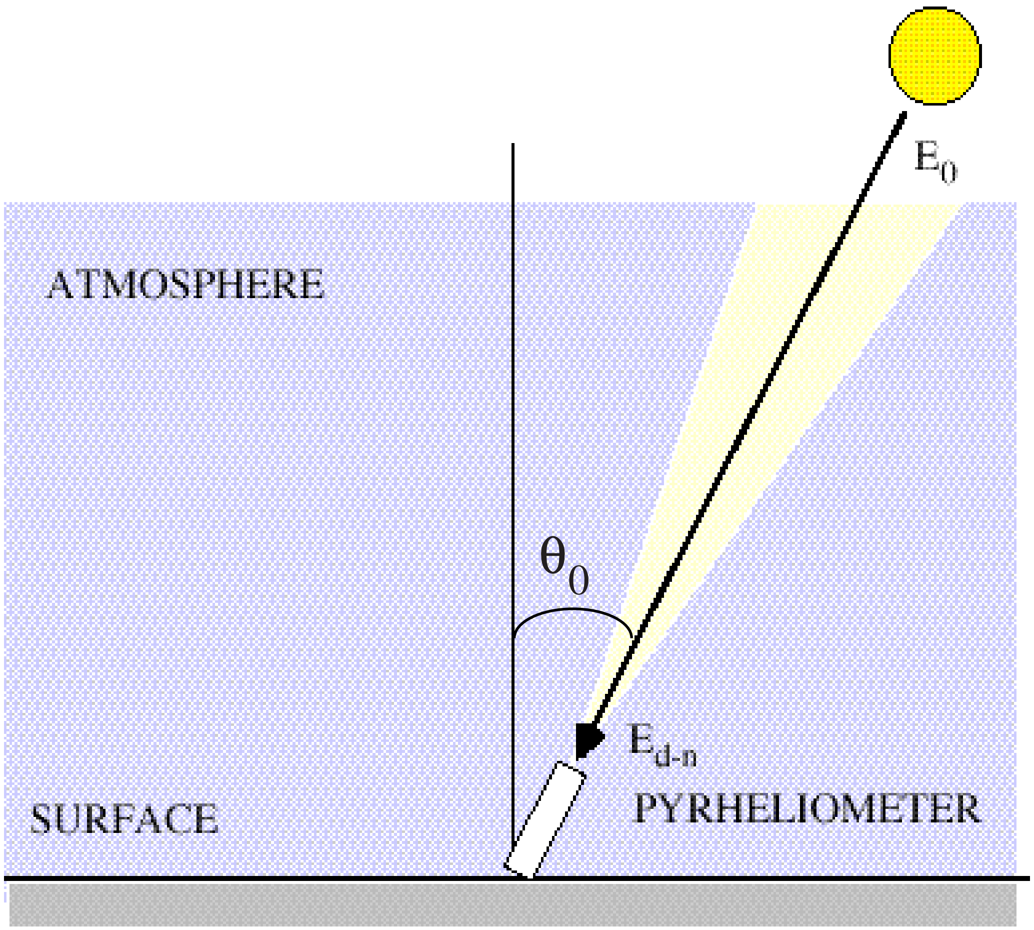


Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling.***

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

AEROSOL OPTICAL DEPTH

Determination by sun photometry



Beer's law in the atmosphere:

$$E_{\text{d-n}} = E_0 e^{-\tau/\cos(\theta_0)}$$

$$\tau = -\cos(\theta_0)\ln\left(\frac{E_{\text{d-n}}}{E_0}\right)$$

$$\tau = \tau_{\text{gas}} + \tau_{\text{aerosol}}$$

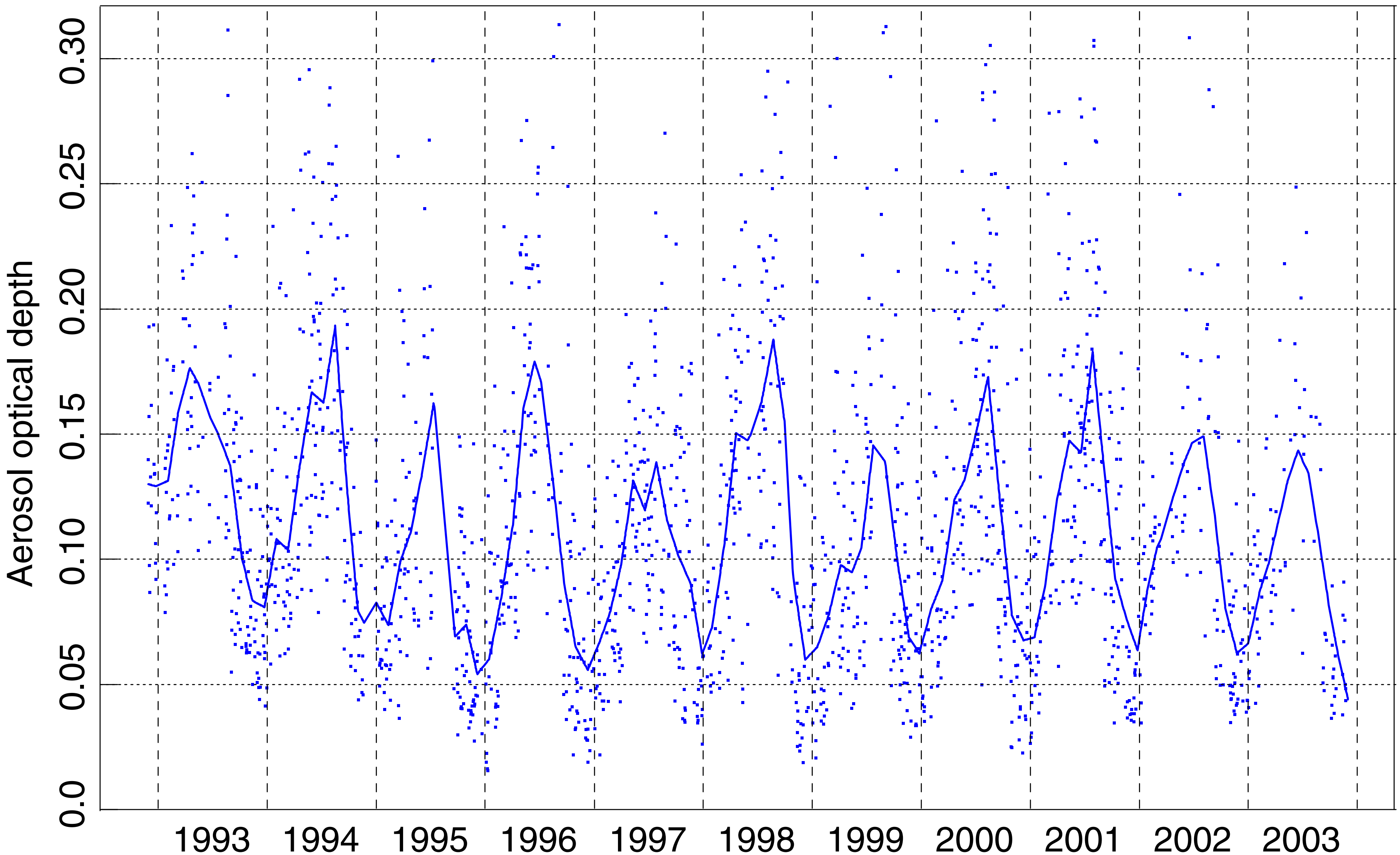
$$\tau_{\text{aerosol}} = \tau - \tau_{\text{gas}}$$

τ_{gas} calculated from known properties of air

AEROSOL OPTICAL DEPTH

Determined by sunphotometry

North central Oklahoma - Daily average at 500 nm



J. Michalsky et al., JGR, 2001

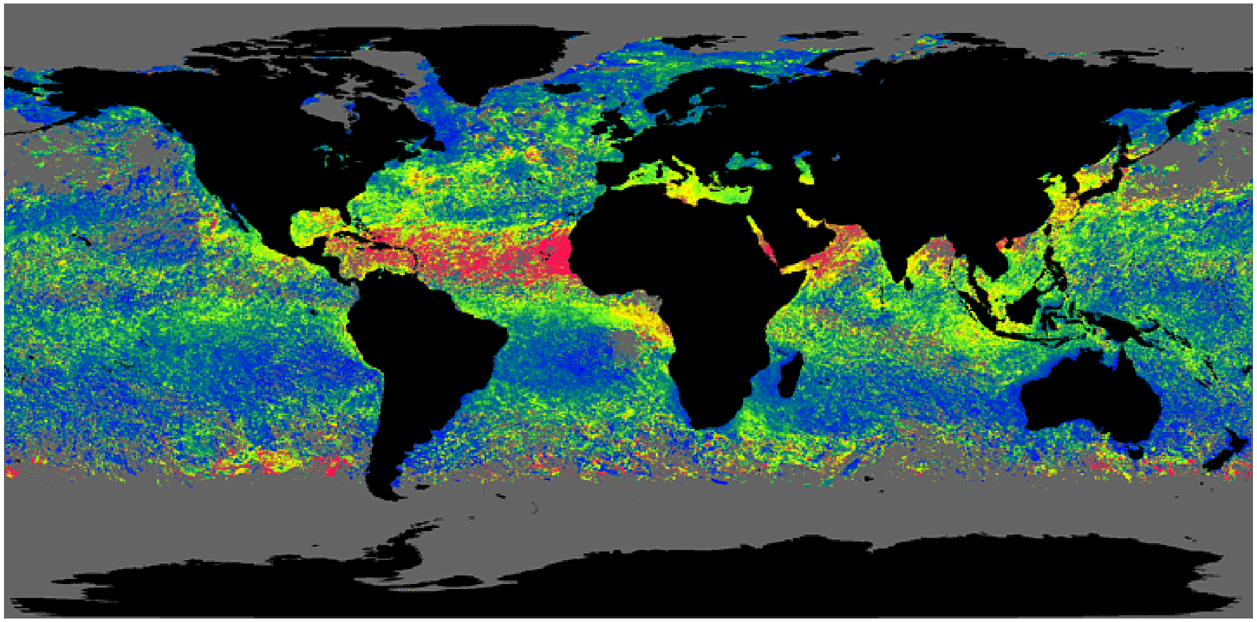
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

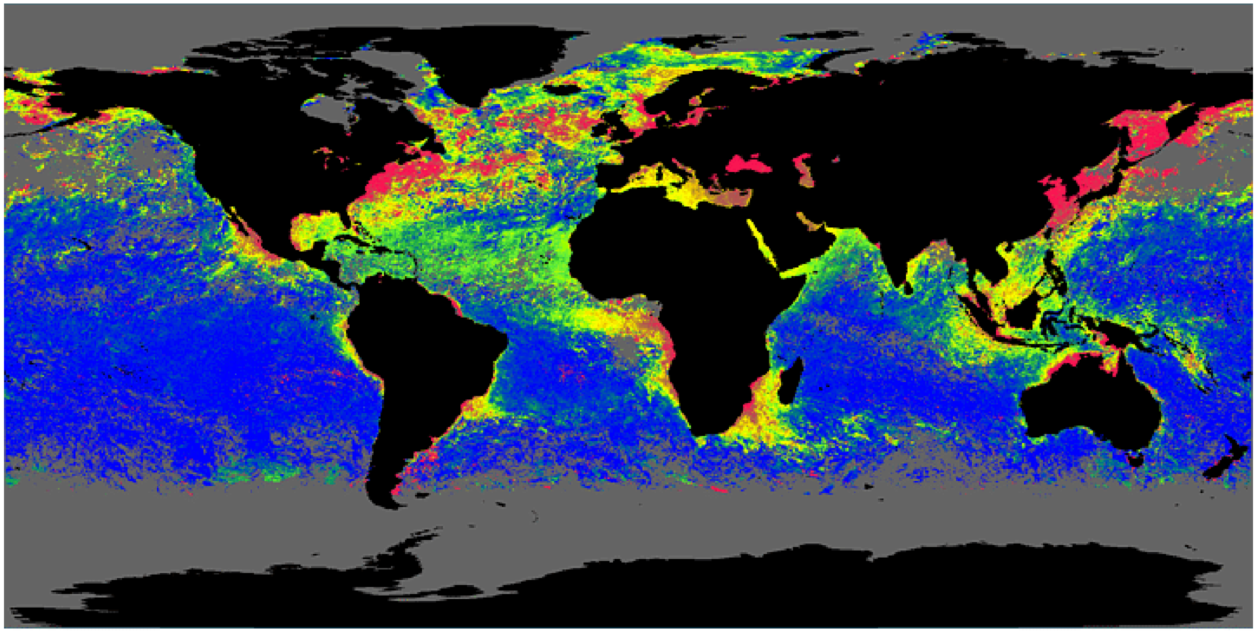
0 0.5



Ångström Exponent α

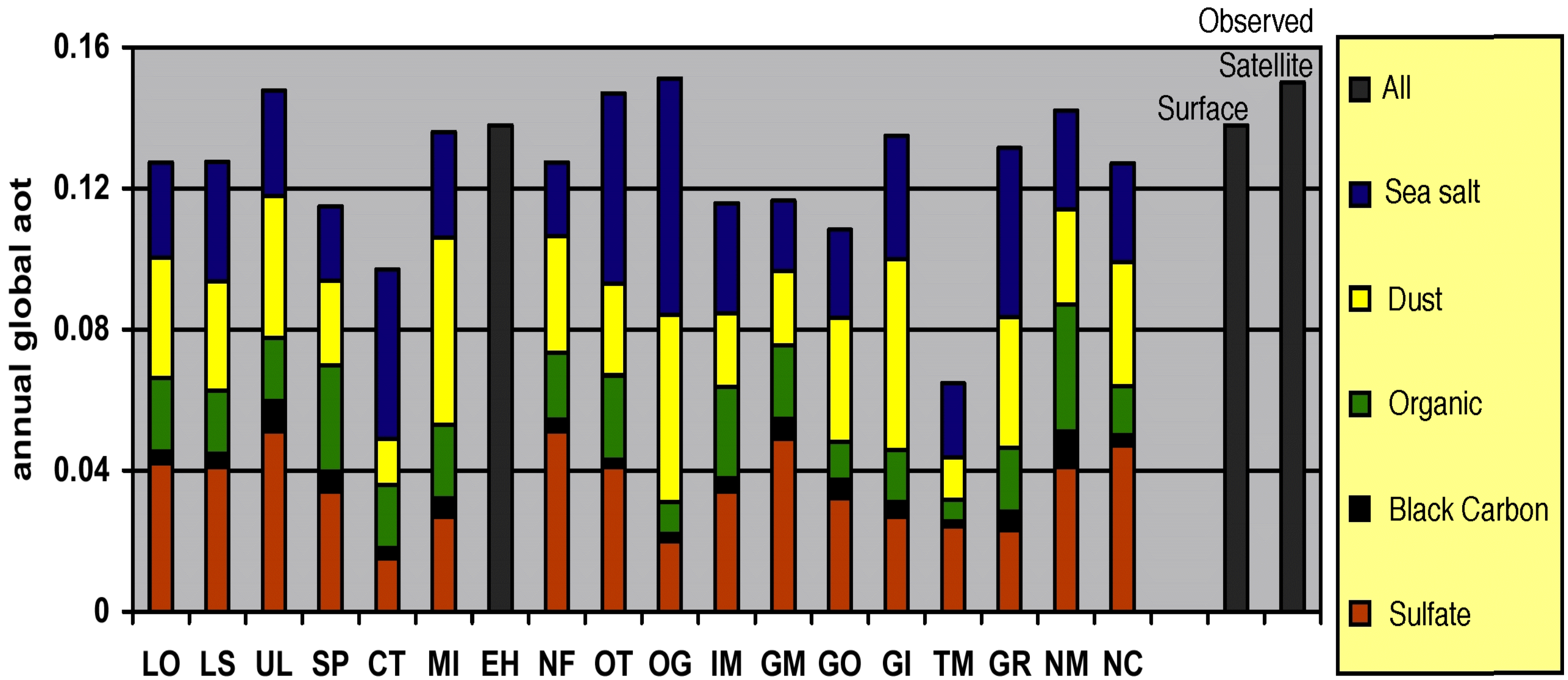
$$\alpha = -d \ln \tau / d \ln \lambda$$

-0.2 1.2



AEROSOL OPTICAL DEPTH IN 18 MODELS (AEROCOM)

Comparison also with surface and satellite observations



Kinne et al., ACP, 2006

Surface measurements: AERONET network.

Satellite measurements: composite from multiple instruments/platforms.

Are the models getting the “right” answer for the wrong reason?

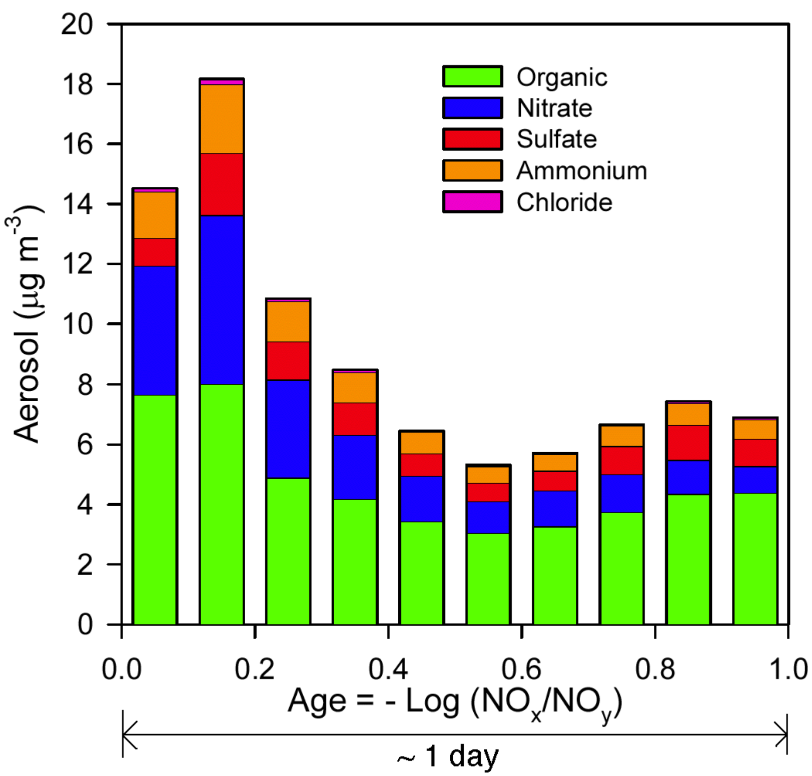
Are the models getting the “right” answer because the answer is known?

Are the satellites getting the “right” answer because the answer is known?

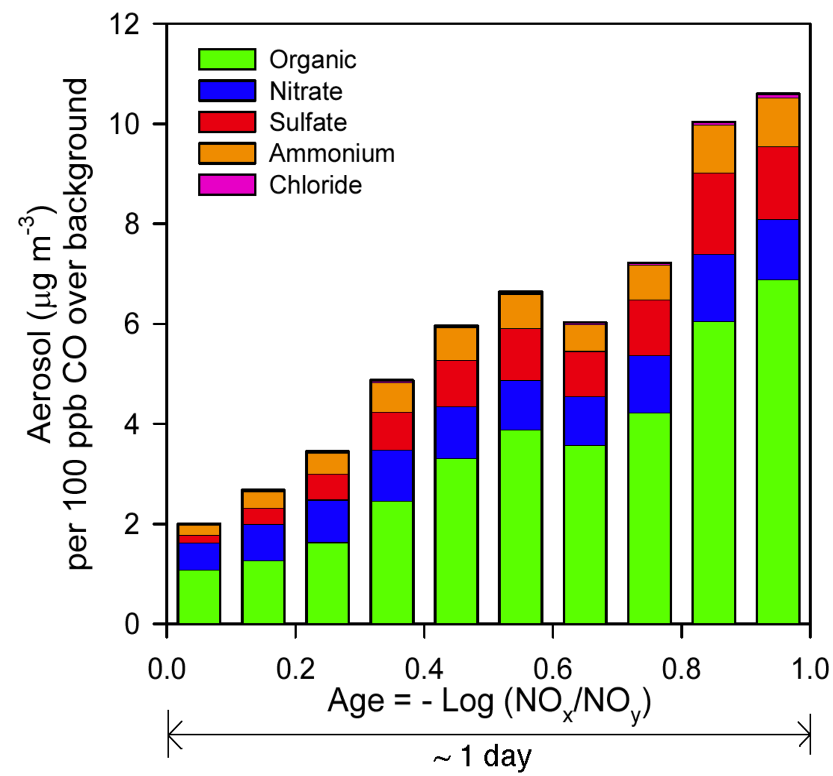
SECONDARY AEROSOL PRODUCTION

Parcel age measured using $-\log(NO_x/NO_y)$ as clock

Concentration



Normalized concentration



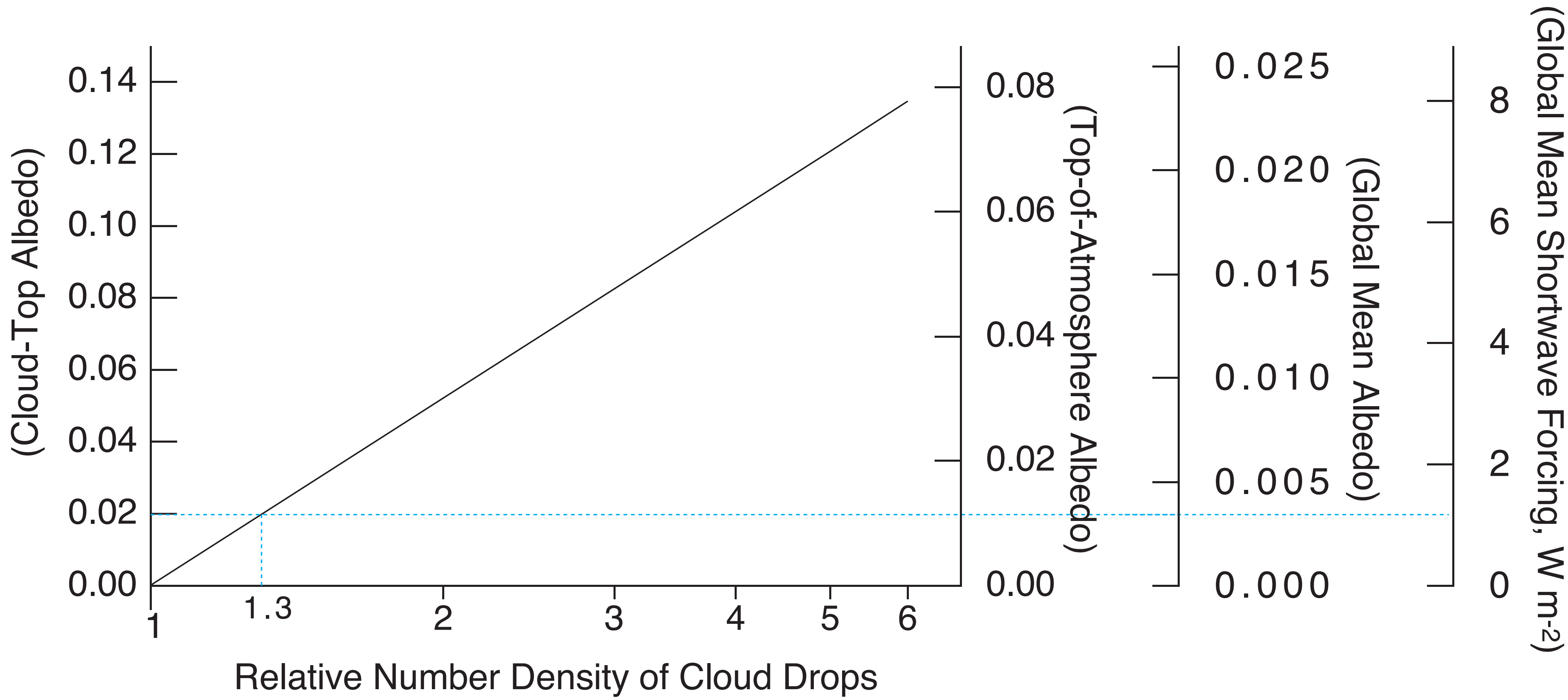
L. Kleinman et al., ACPD, 2007

Dilution is accounted for by normalizing aerosol concentration to CO above background.

~5 × ***increase*** in total aerosol; **~7 ×** ***increase*** in organic aerosol.

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

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION



Schwartz and Slingo (1996)

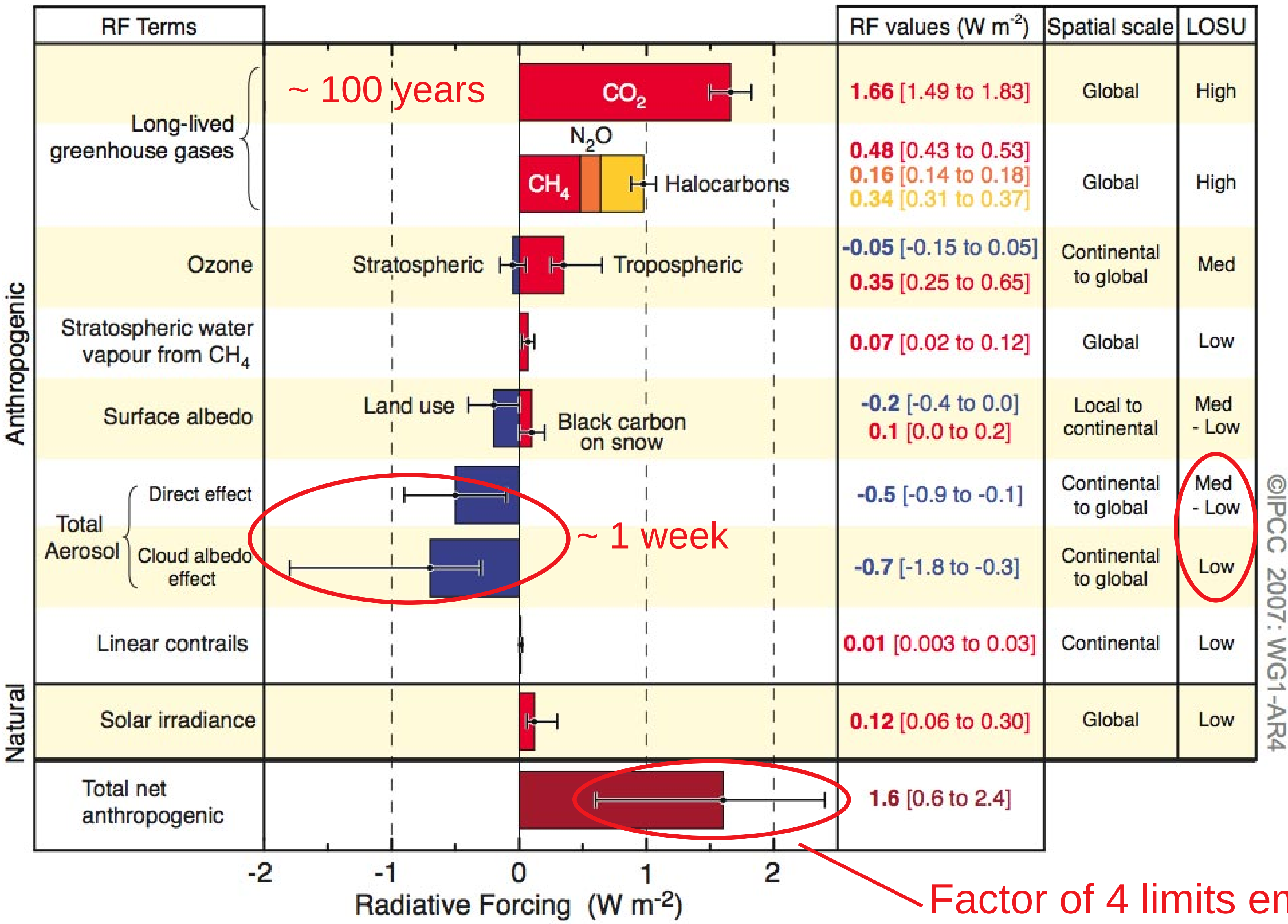
Indirect forcing is highly sensitive to perturbations in cloud drop concentration.

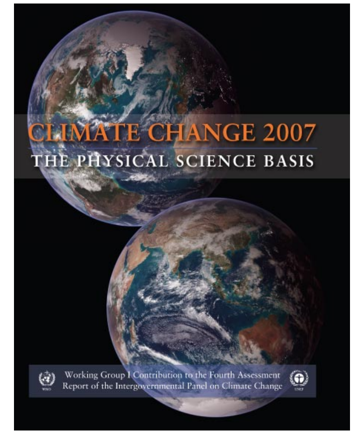
A 30% increase in cloud drop concentration results in a forcing of ~1 W m^{-2}.

UNCERTAINTY IN CLIMATE FORCING

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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



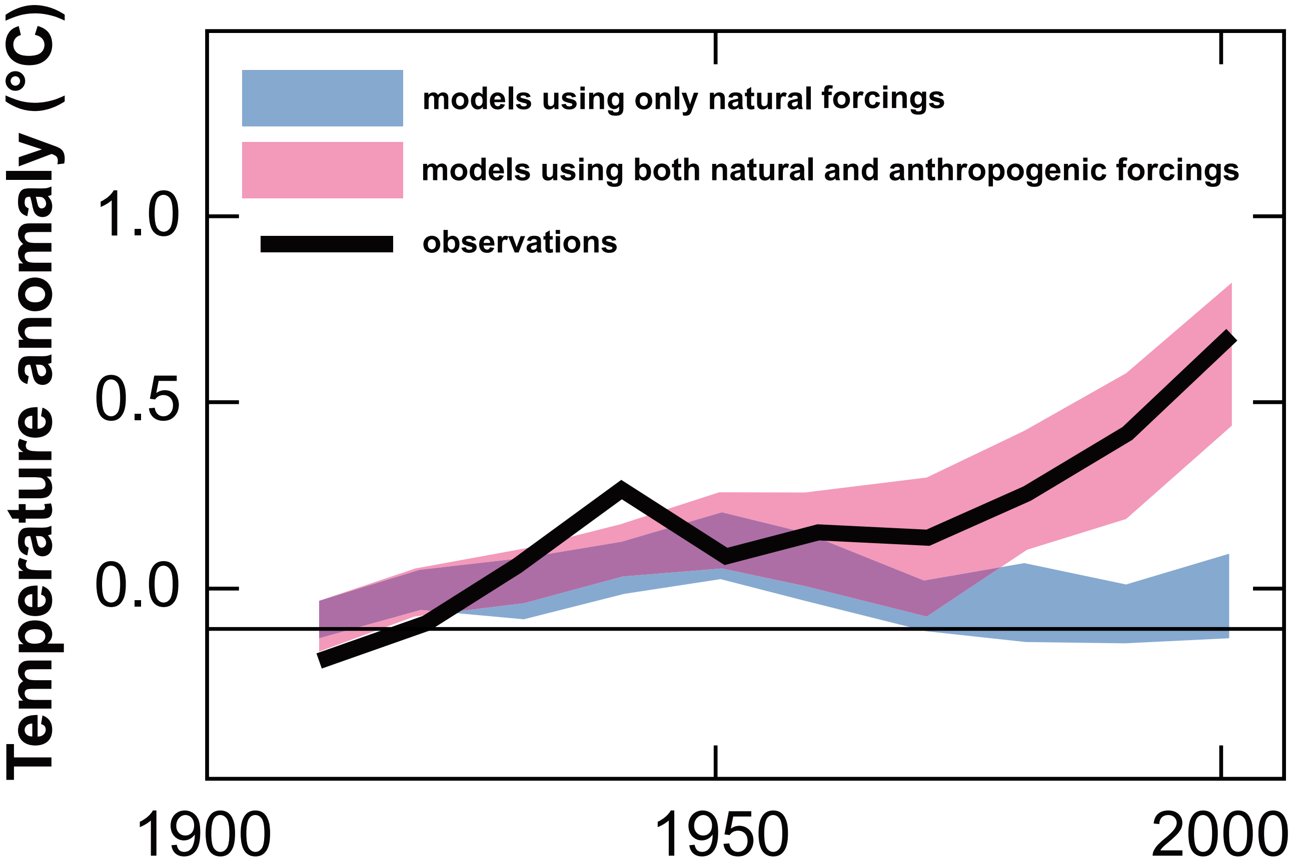


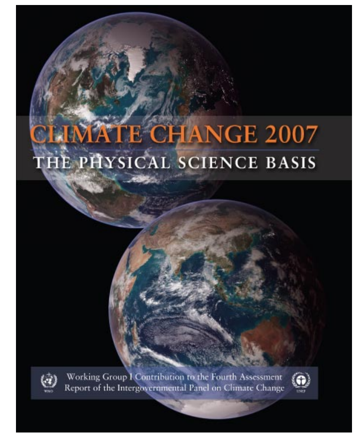
Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



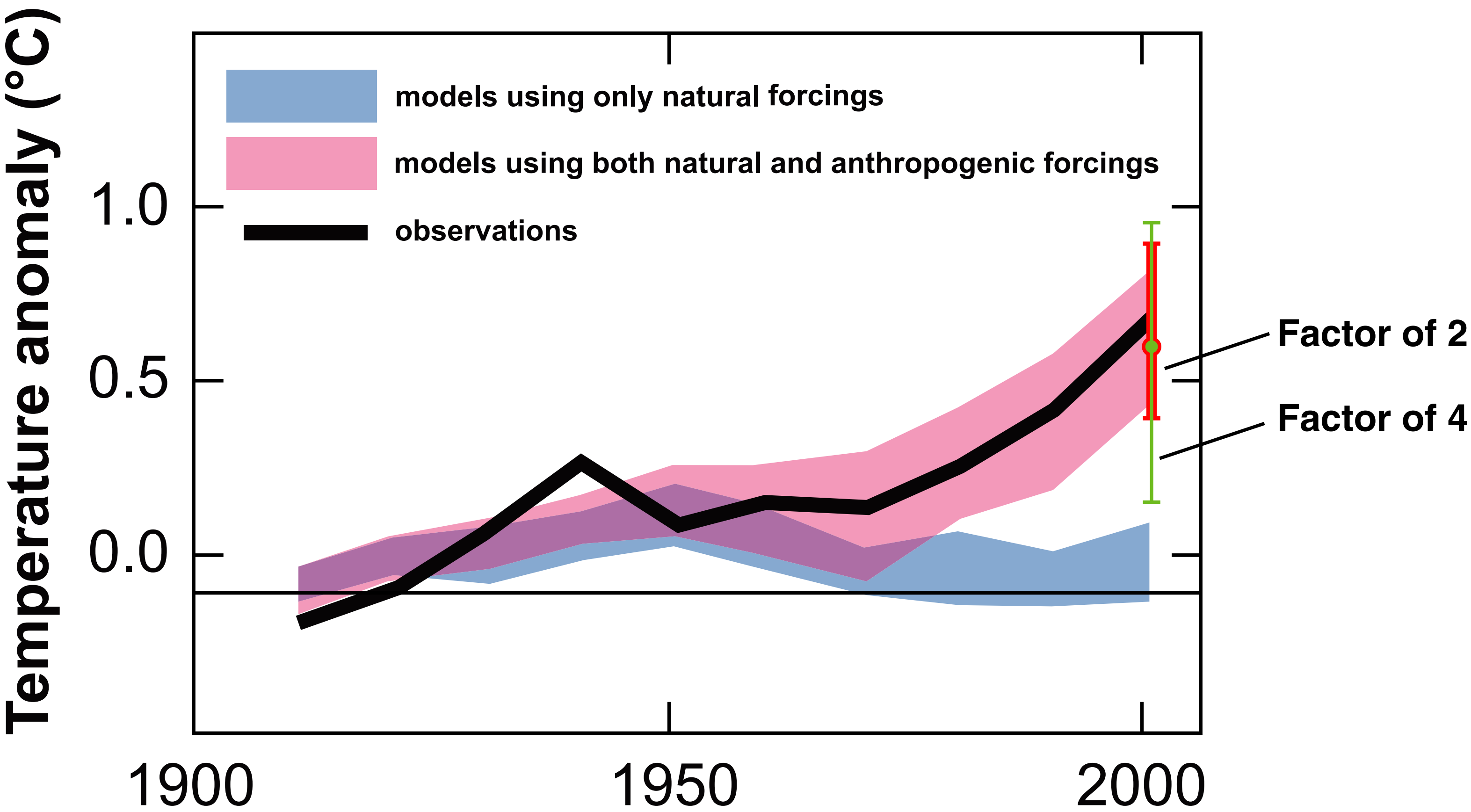


“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

“ 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

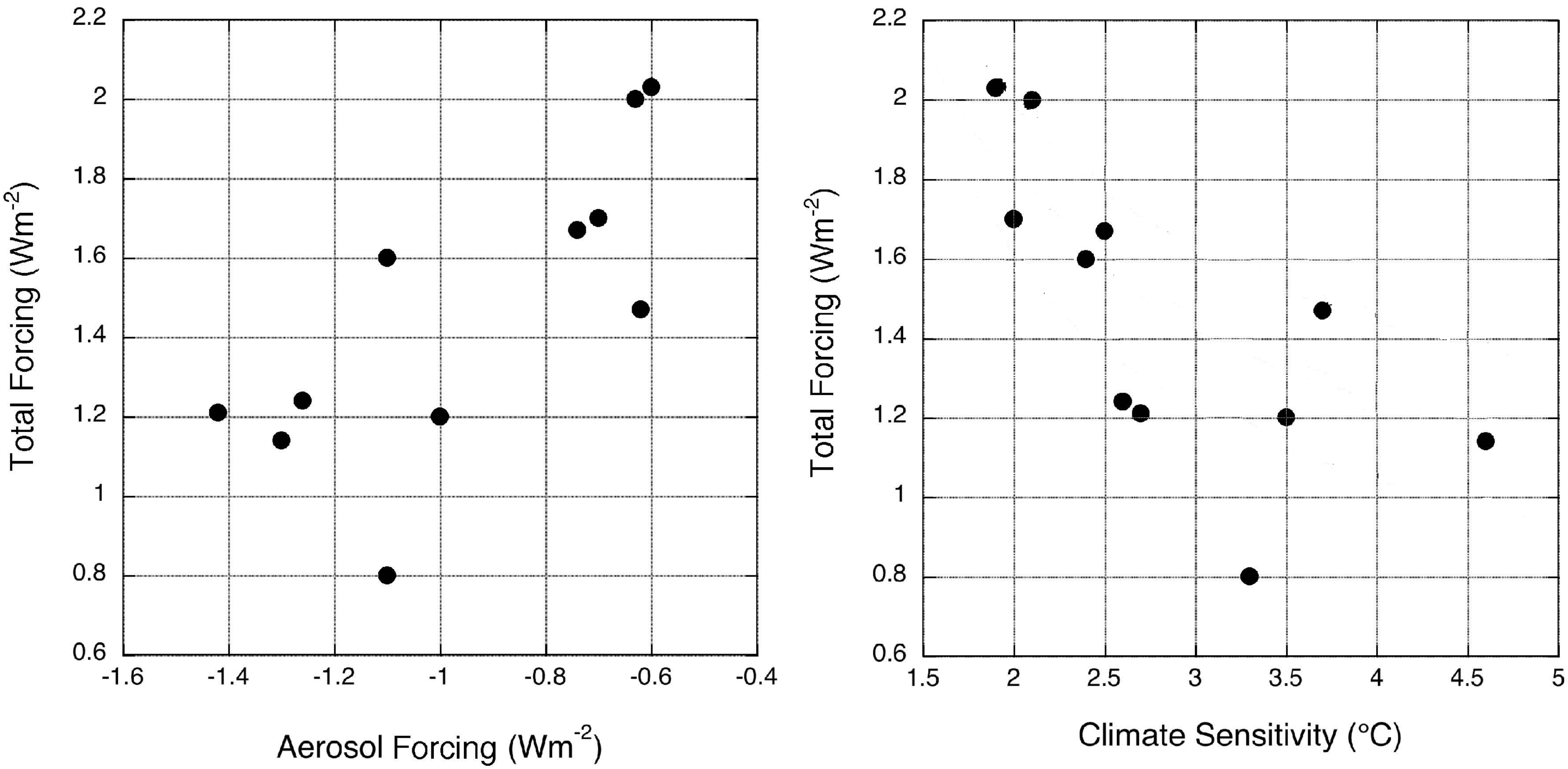
Uncertainty in modeled temperature increase – less than a factor of 2, red – is ***well less than uncertainty in forcing*** – a factor of 4, green.

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



J. Kiehl (NCAR), GRL, in press, 2007

Total forcing increases with decreasing (negative) aerosol forcing.

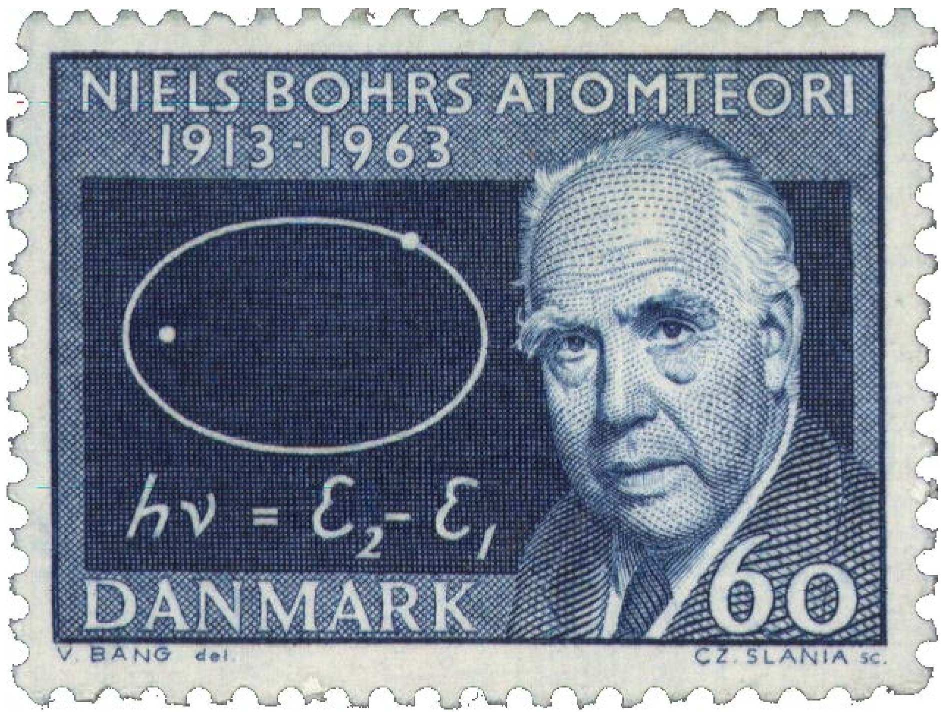
Climate models with higher sensitivity have lower total forcing.

These models cannot all be correct.

This situation limits confidence that can be placed in the models.

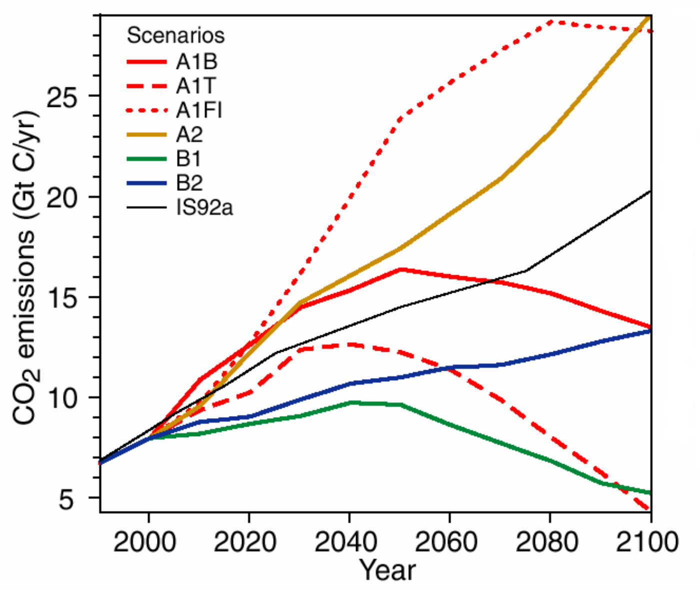
Looking to the Future . . .

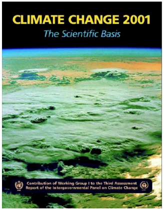
Prediction is difficult, especially about the future.



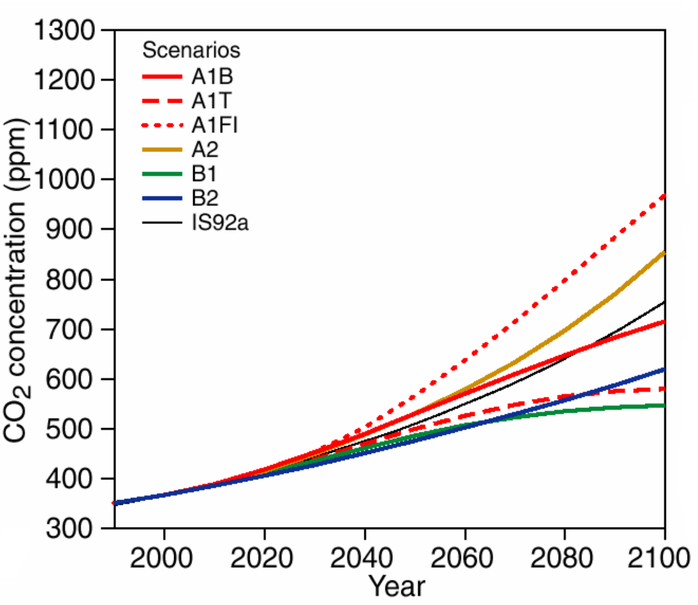
– Niels Bohr

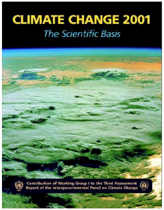
PROJECTIONS OF FUTURE CO2 EMISSIONS



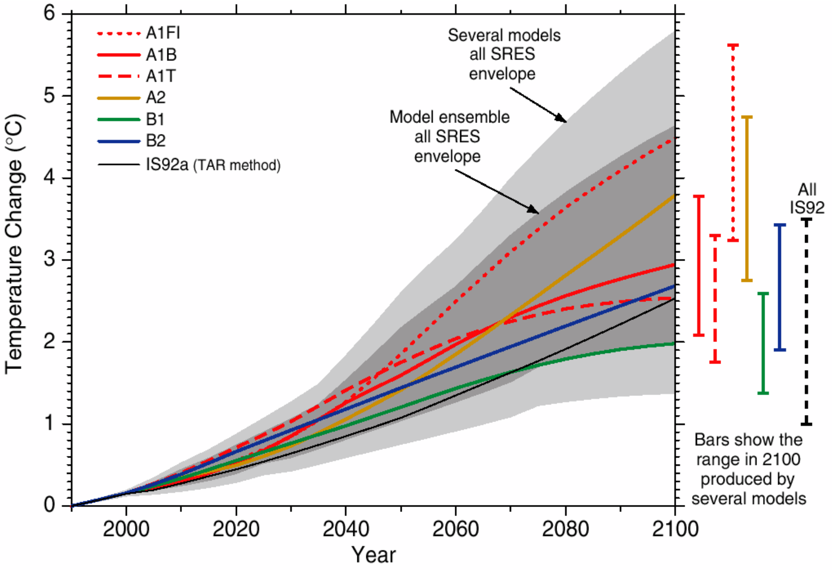


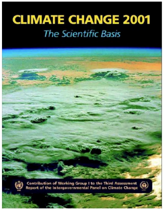
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS





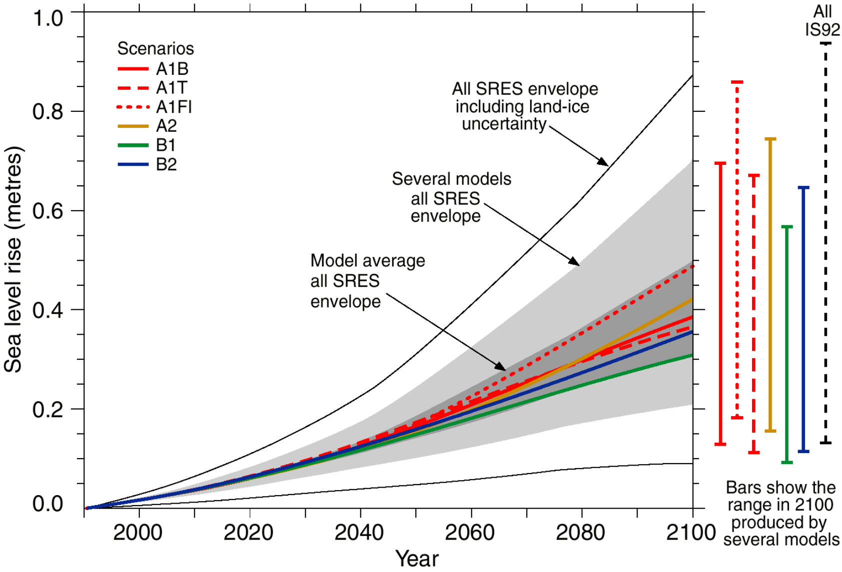
PROJECTIONS OF FUTURE TEMPERATURE CHANGE

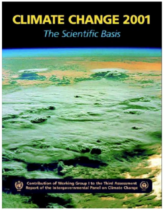




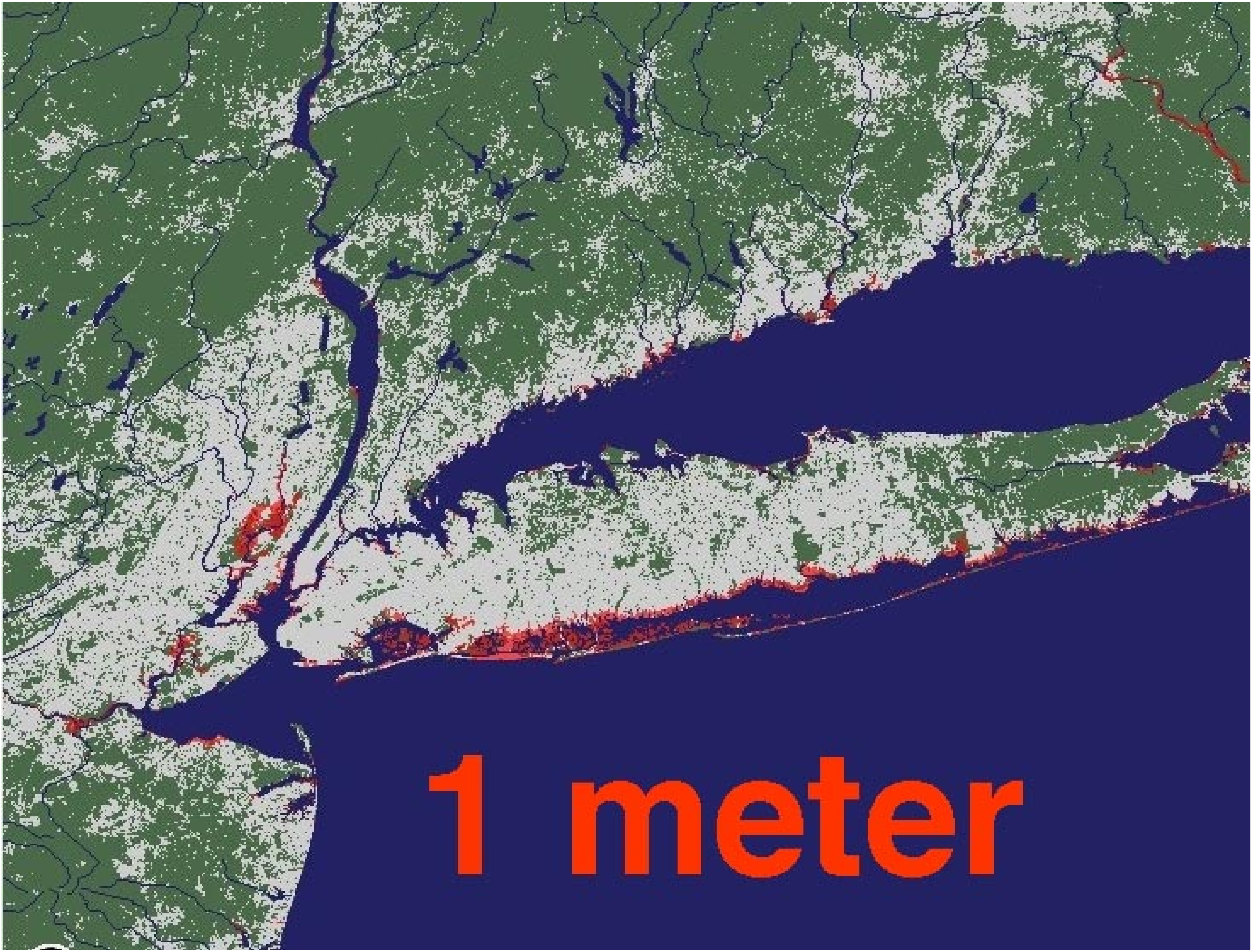
PROJECTIONS OF FUTURE SEA LEVEL RISE

Thermosteric (density change) only





Weiss and Overpeck, University of Arizona

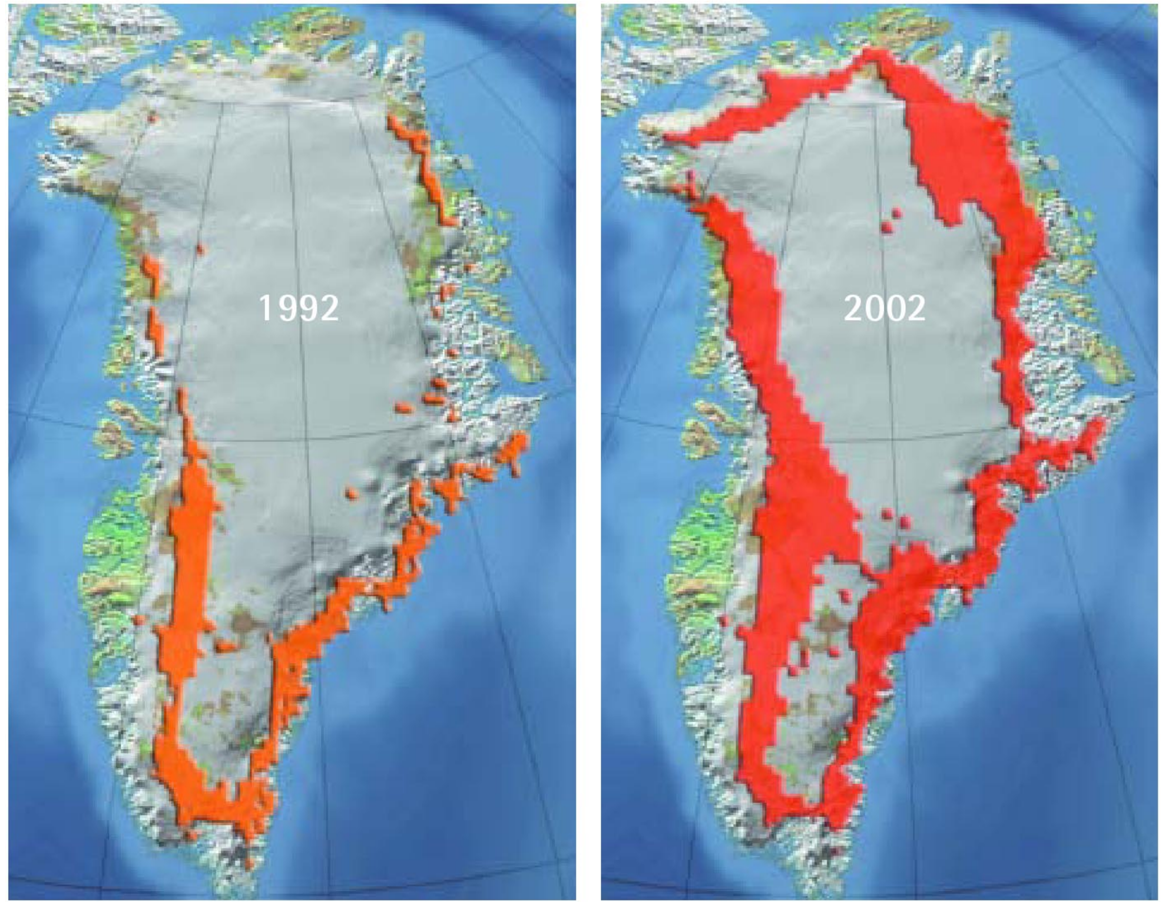


Weiss and Overpeck, University of Arizona

MELTING OF GREENLAND ICE CAP

Satellite determination of extent of glacial ice 1992 vs 2002

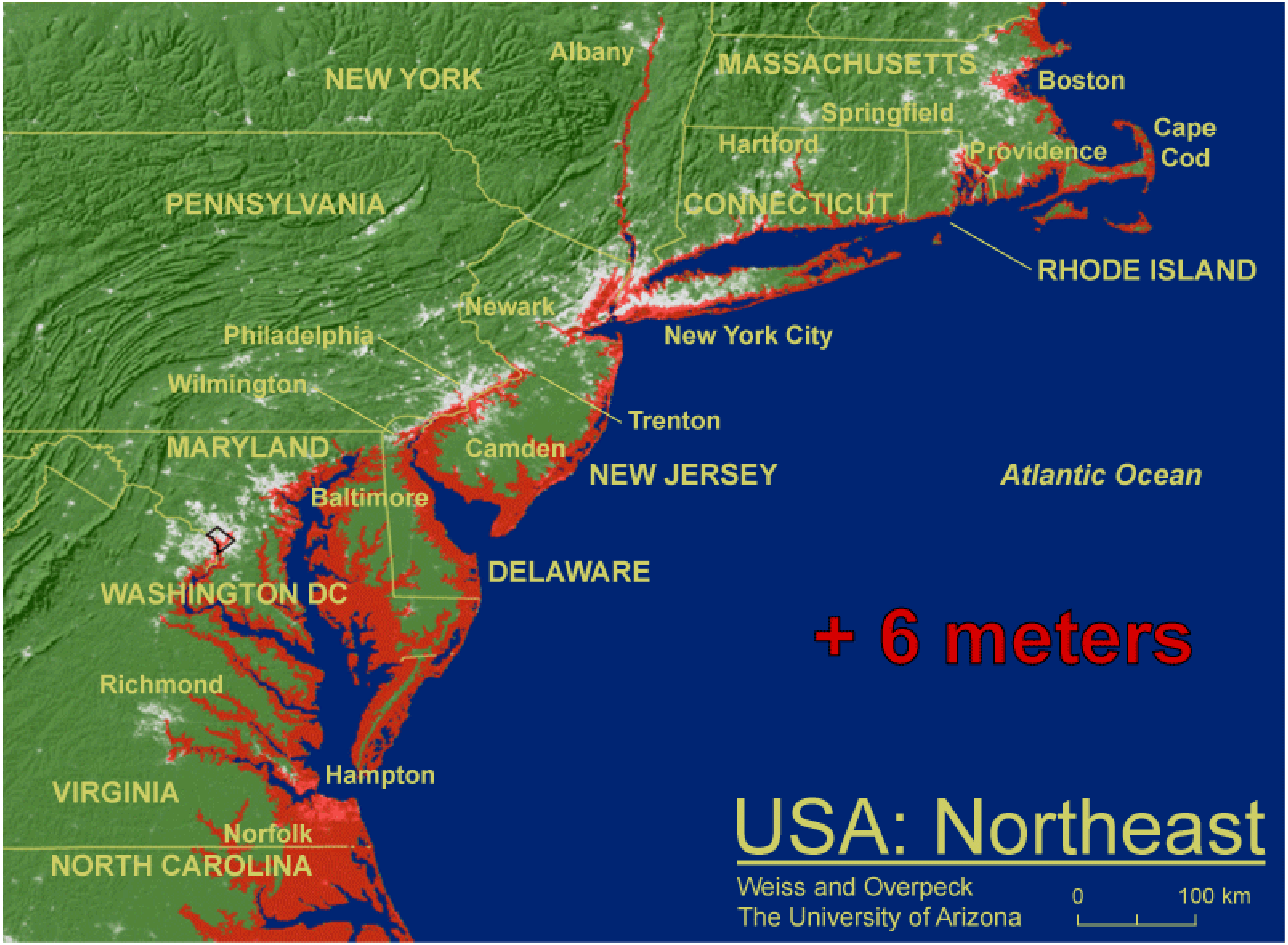
NASA



Arctic Climate Impact Assessment, Cambridge, 2004

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

Weiss and Overpeck, University of Arizona


NEW YORK
Albany
MASSACHUSETTS
Boston
Springfield
Cape
Cod
Hartford
Providence
PENNSYLVANIA
CONNECTICUT
RHODE ISLAND
Newark
Philadelphia
New York City
Wilmington
Trenton
MARYLAND
Camden
NEW JERSEY
Atlantic Ocean
Baltimore
DELAWARE
WASHINGTON DC
+ 6 meters
Richmond
Hampton
VIRGINIA
Norfolk
NORTH CAROLINA
USA: Northeast
Weiss and Overpeck
The University of Arizona
0
100 km

"Gentlemen, it's time we gave some serious thought to the effects of global warming."

The New York Times

Saturday, November 17, 2007

U.N. Report Describes Risks of Inaction on Climate Change

By ELISABETH ROSENTHAL

VALENCIA, Spain, Nov. 17 — United Nations Secretary General Ban Ki-moon called climate change "the defining challenge of our age" today and called on the United States and China, the greatest emitters of greenhouse gases, to be play "a more constructive role" in coming negotiations for a new global climate treaty.

The panel, co-winner of this year's Nobel Peace Prize, said the world would have to reverse the growth of greenhouse gas emissions by 2015 to avert major problems. "If there's no action before 2012, that's too late, there is not time," said Rajendra Pachauri, a scientist and economist who heads the Intergovernmental Panel on Climate Change. "What we do in the next two, three years will determine our future. This is the defining moment."

IPCC SYNTHESIS REPORT - KEY FINDINGS

November, 2007

Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity, and attitudes to risk.

Impacts of climate change are *very likely* to impose net annual costs which will increase over time as global temperatures increase.

Aggregate estimates of costs mask significant differences in impacts across sectors, regions and populations and *very likely* underestimate damage costs because they cannot include many non-quantifiable impacts.

Costs and benefits of mitigation are broadly comparable in magnitude.

An emissions pathway or stabilisation level where benefits exceed costs cannot be unambiguously determined.

Climate sensitivity is a key uncertainty for mitigation scenarios for specific temperature levels.

Choices about the scale and timing of GHG mitigation involve balancing the economic costs of more rapid emission reductions now against the corresponding medium-term and long-term climate risks of delay.

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***.

Uncertainty in forcing by aerosols greatly limits present understanding of climate change.

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

Research is urgently needed to refine "what if" projections.

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