IMPROVING PREDICTIONS OF CLIMATE CHANGE

OBSERVATIONAL AND MODELING REQUIREMENTS

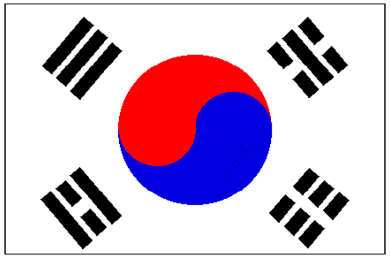
Stephen E. Schwartz

BROOKHAVEN NATIONAL LABORATORY

International Workshop on Integrated Responses to Climate Change

Seoul, Korea   October 16, 2008

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

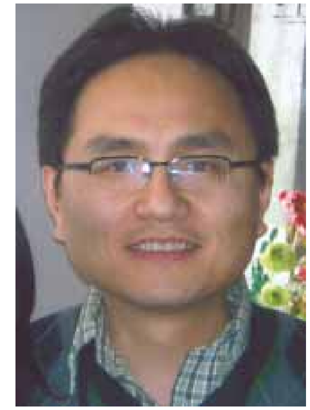


KOREAN ATMOSPHERIC SCIENTISTS AT BROOKHAVEN

BROOKHAVEN NATIONAL LABORATORY

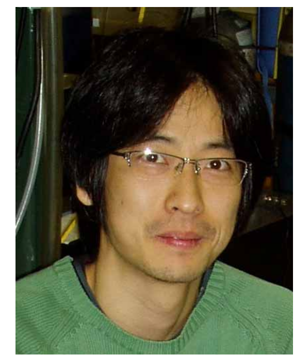
O-Ung Kwon
1996-1998
Korea Meteorological Administration

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 budget

Perturbations

Carbon dioxide

Temperature change

Climate sensitivity

Climate forcing by anthropogenic aerosols

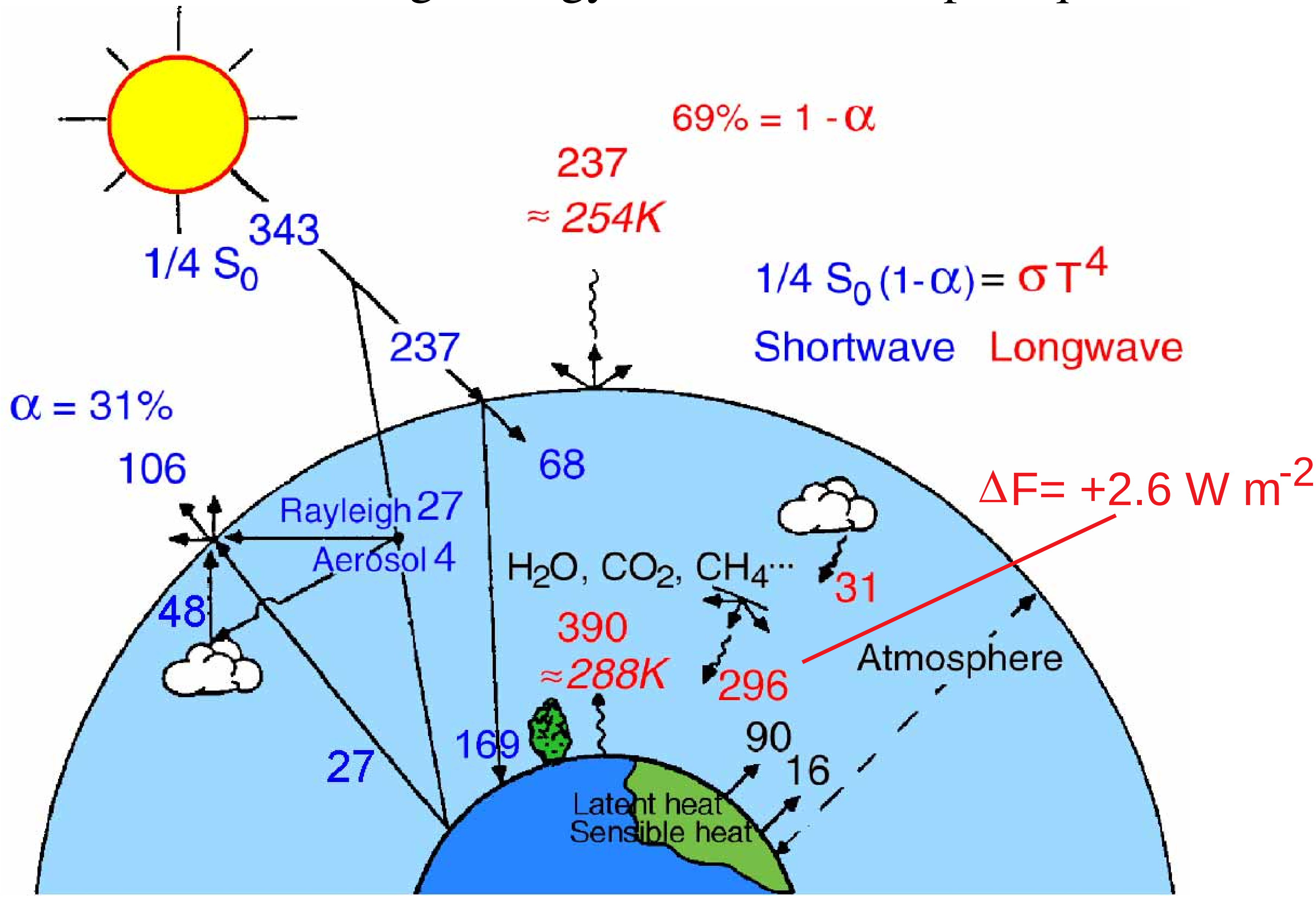
Understanding Earth's climate sensitivity

Future directions

Concluding observations

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



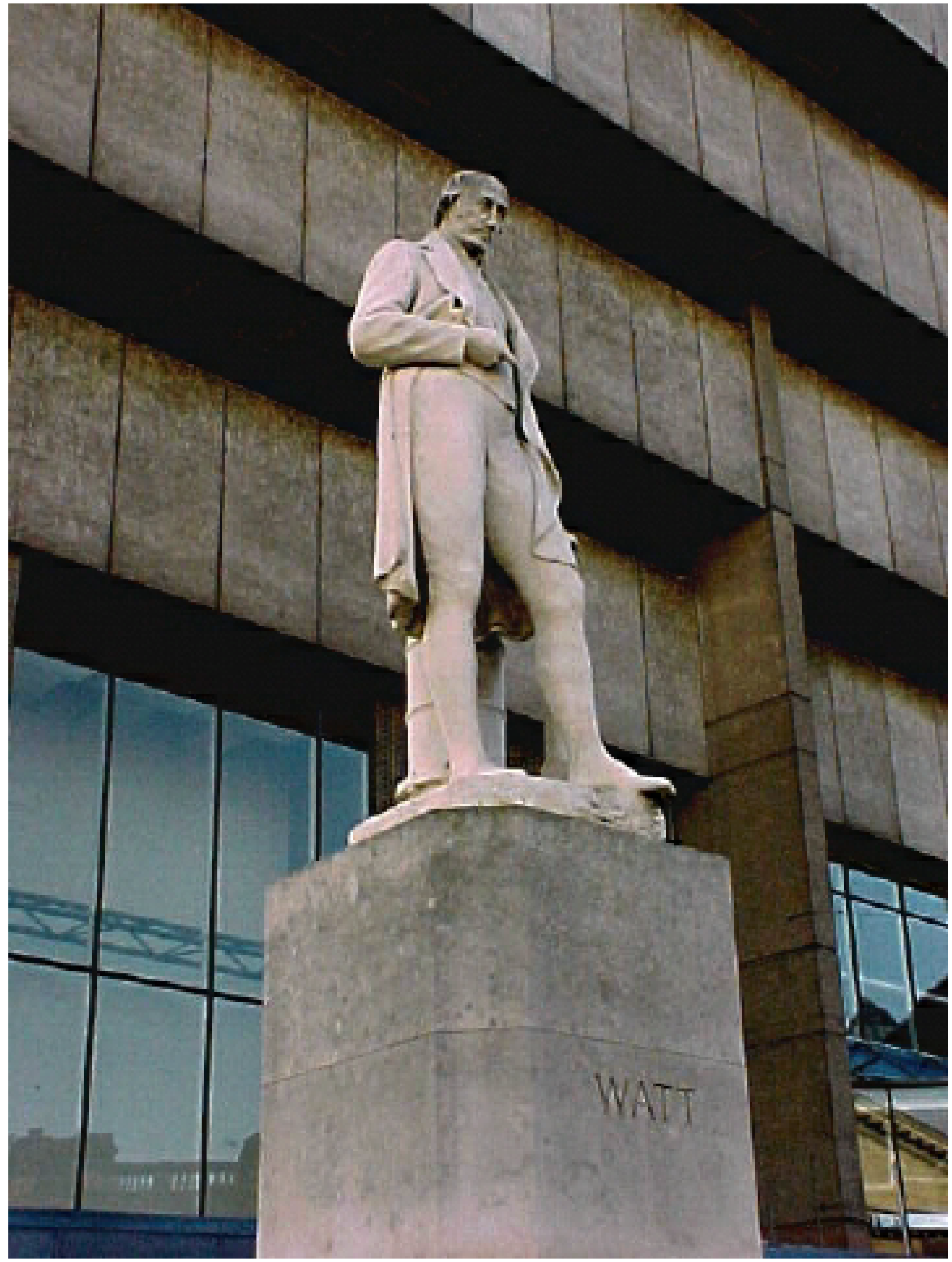
Schwartz, 1996, modified from Ramanathan, 1987

ATMOSPHERIC RADIATION

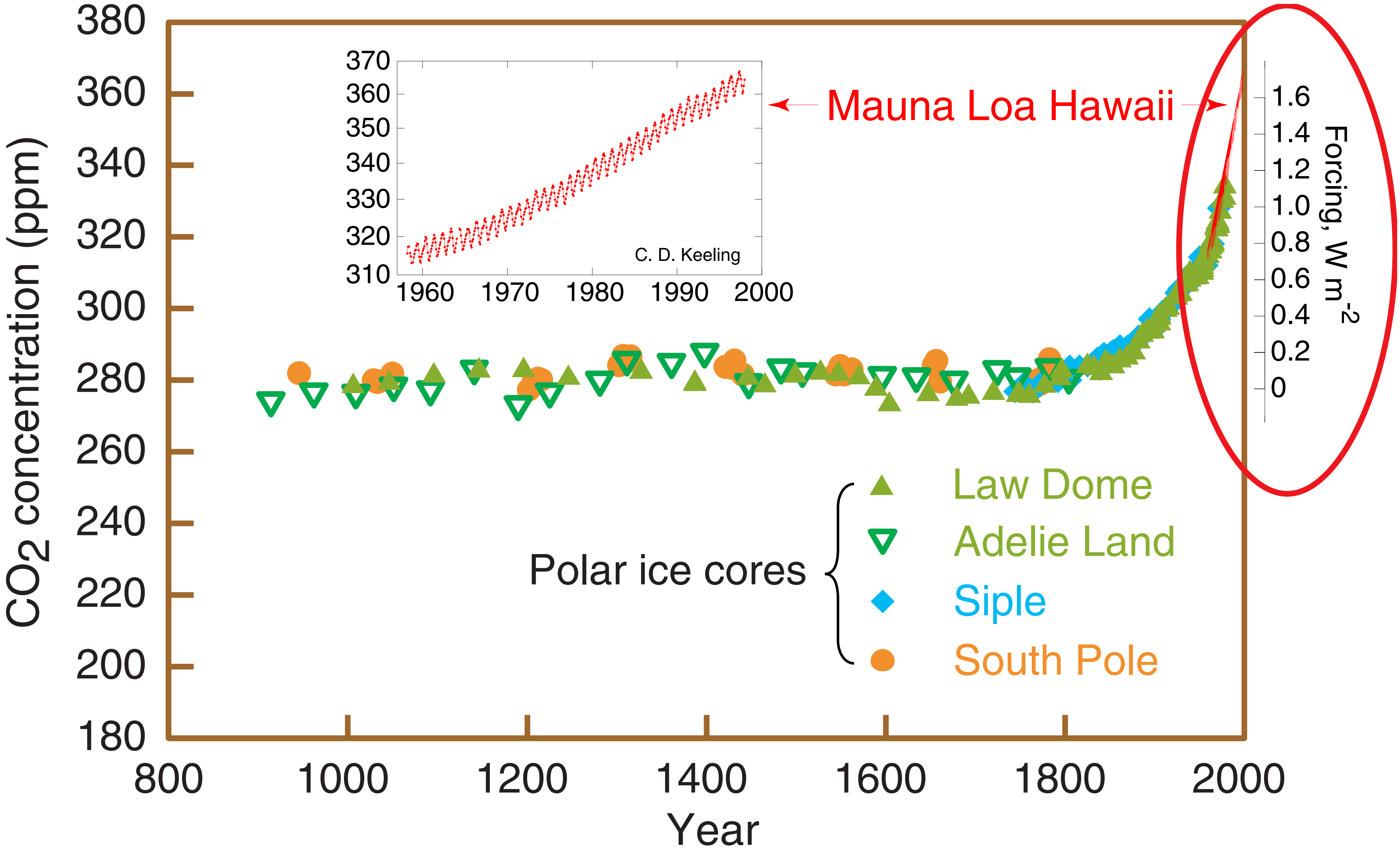
Energy per area per time

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}.

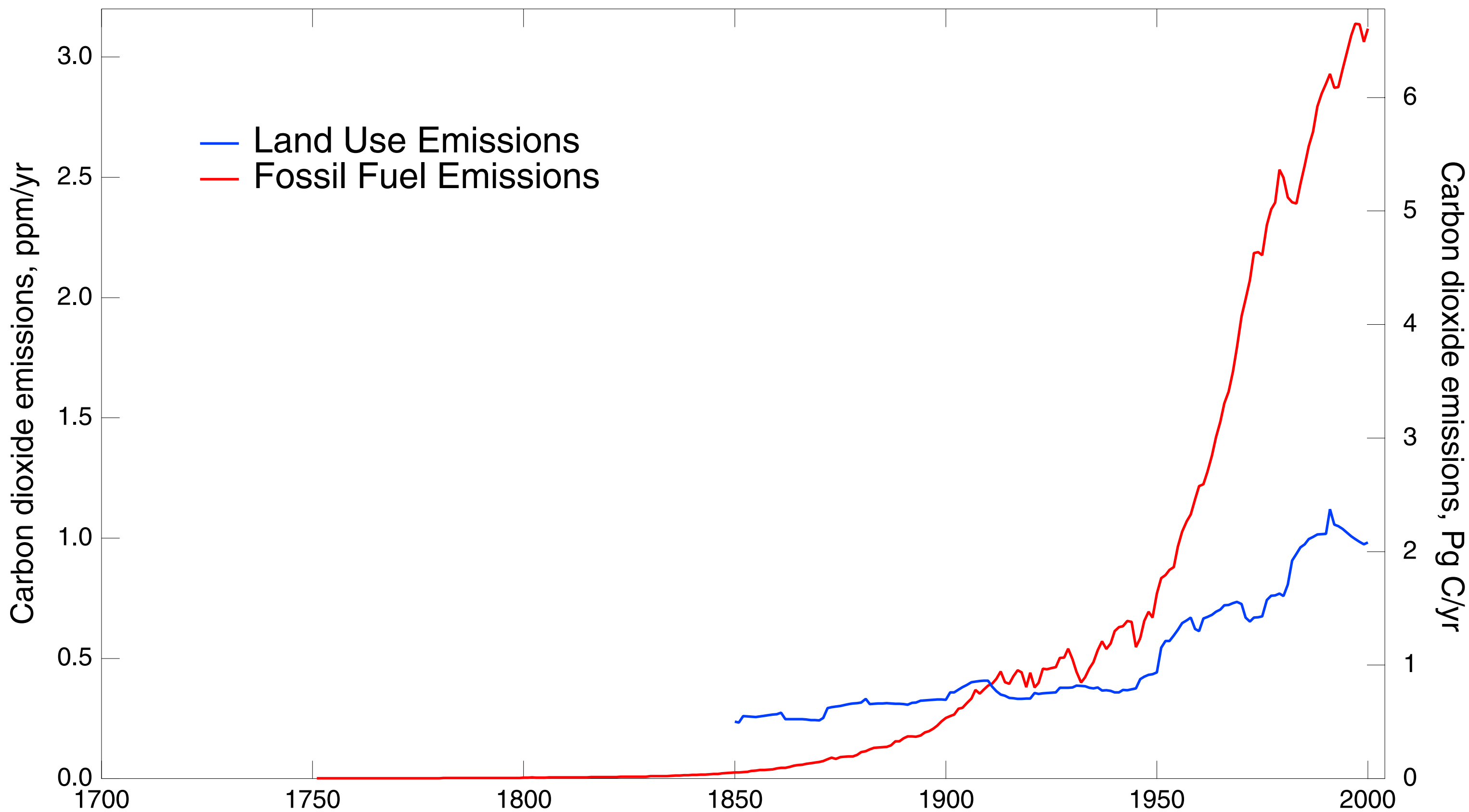
Working hypothesis:

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.

ATMOSPHERIC CO_2 EMISSIONS

Time series 1700 - 2003



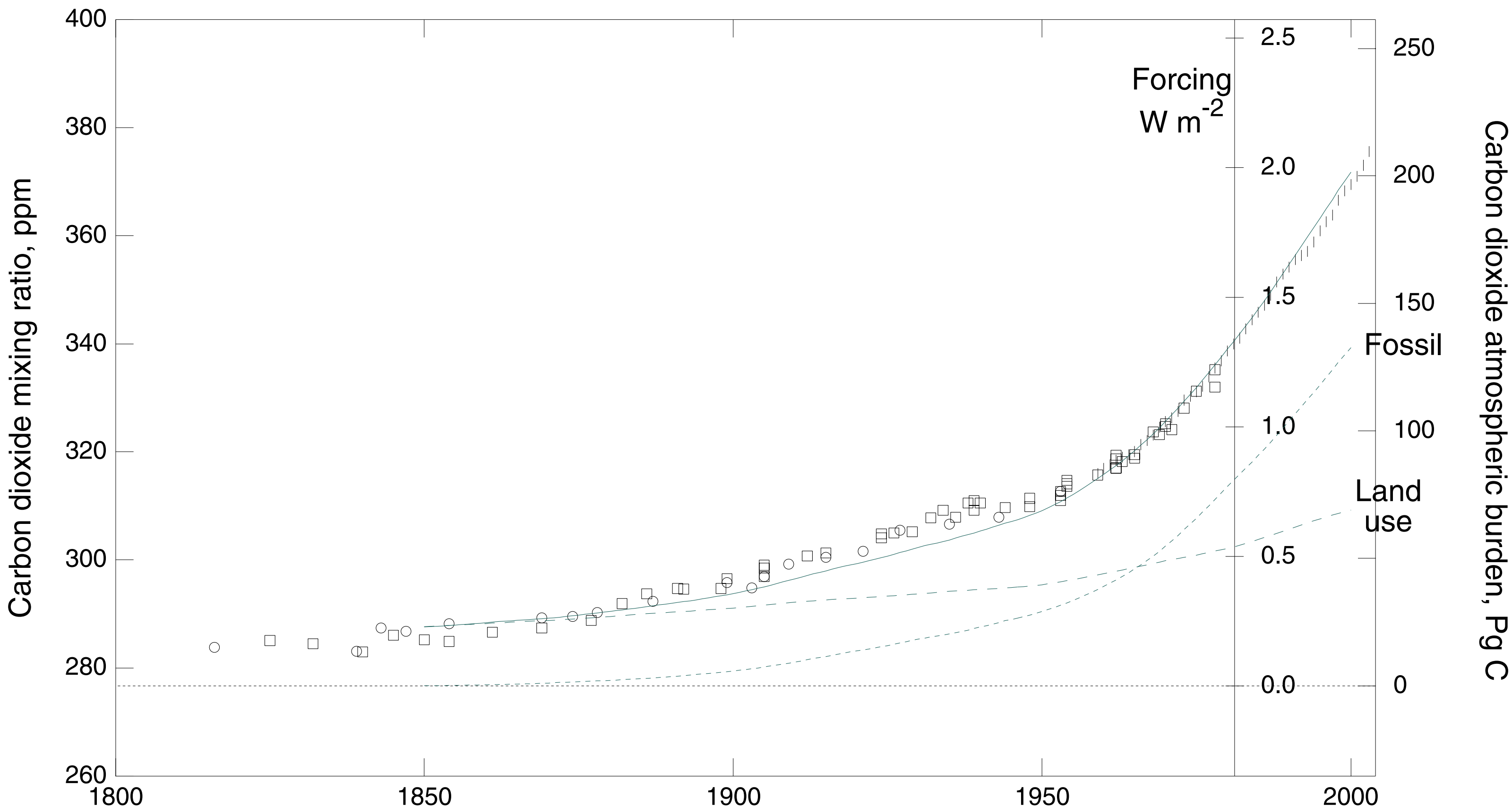
Fossil Fuel - Marland
Land Use - Houghton

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

Subsequently fossil fuel CO_2 has been dominant and rapidly increasing!

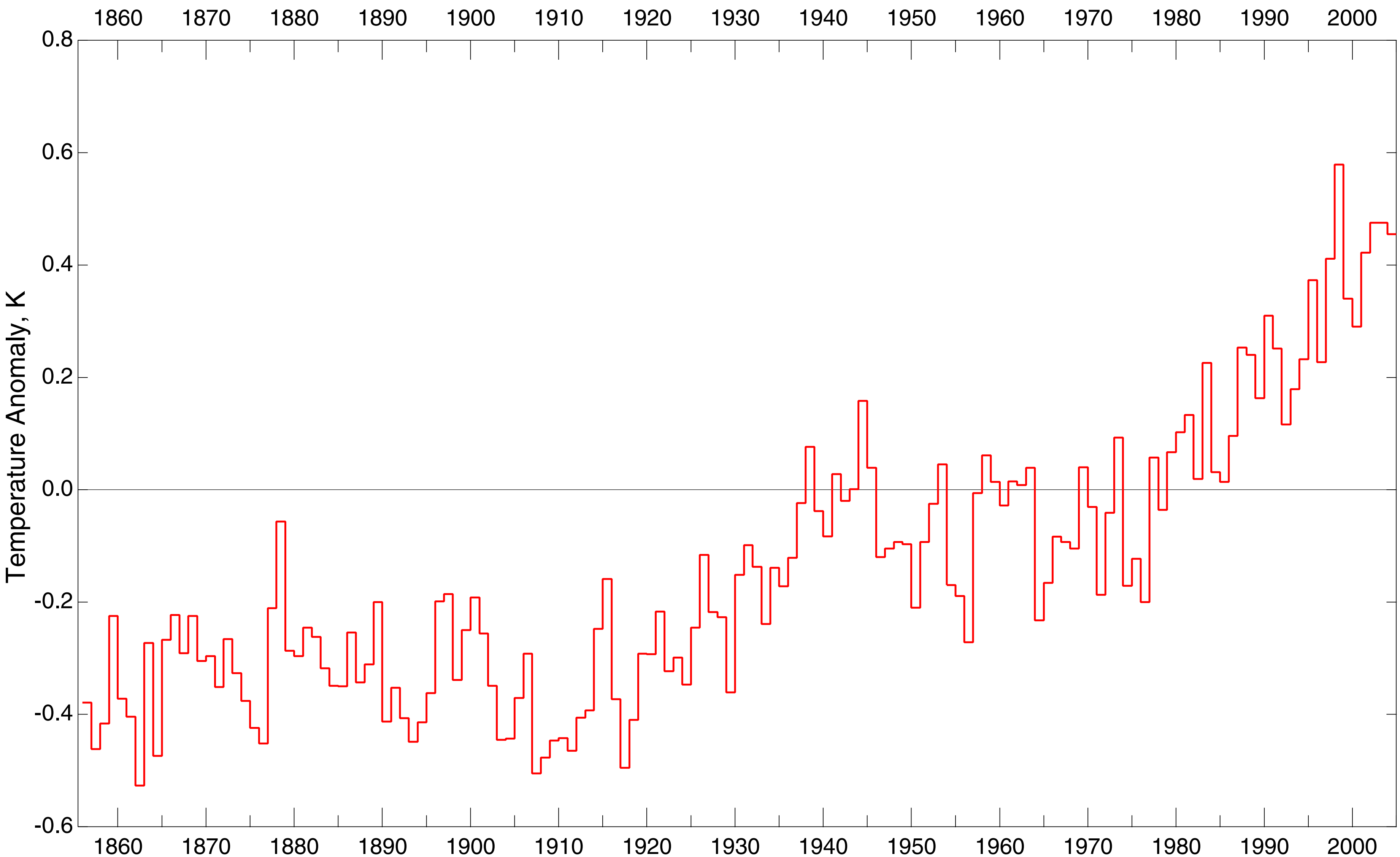
ATTRIBUTION OF ATMOSPHERIC CO_2

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.

CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004



Climate Research Unit, University of East Anglia, UK

CLIMATE RESPONSE

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

Working hypothesis:

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

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

CLIMATE SENSITIVITY

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

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

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

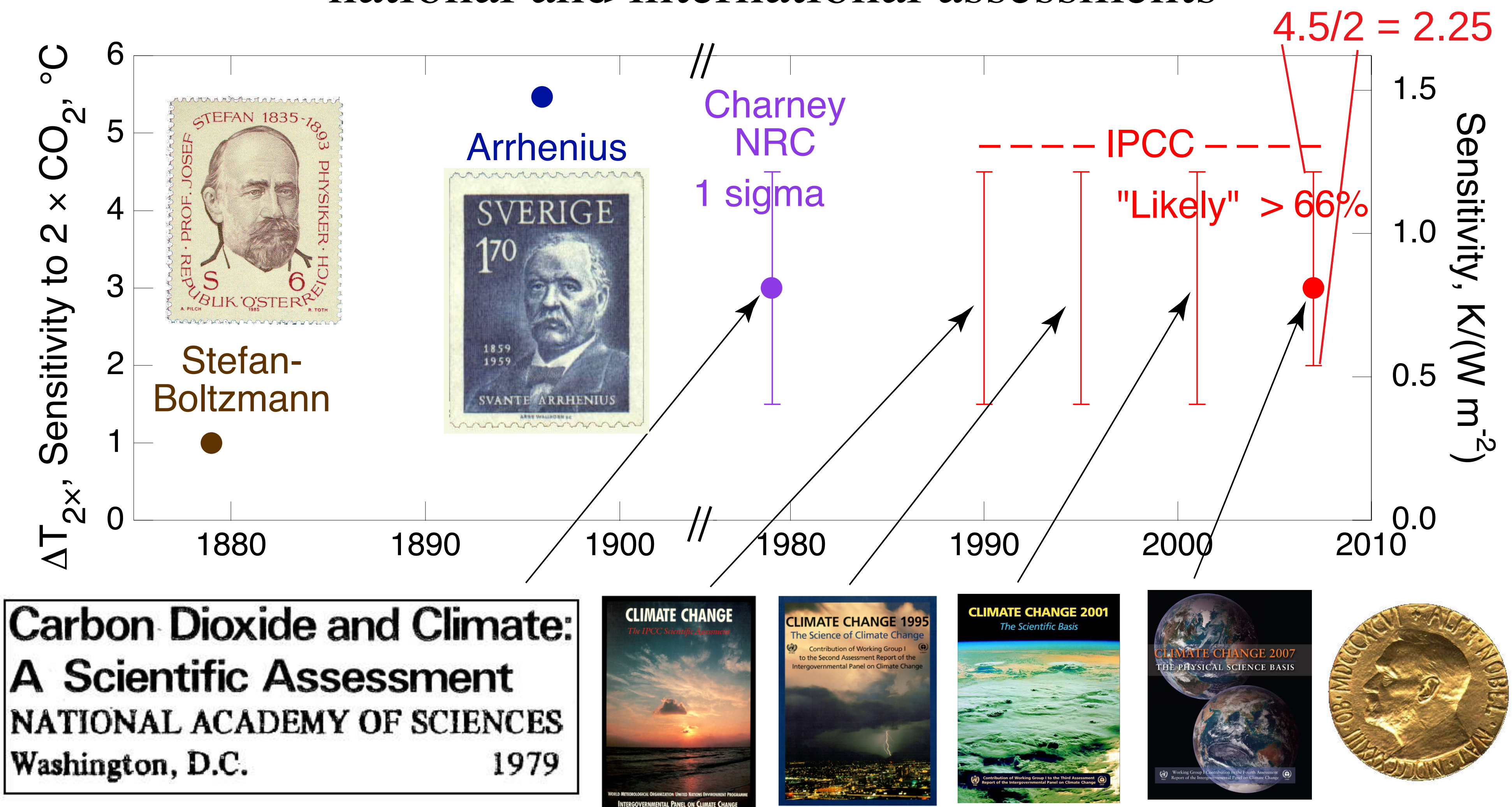
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

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

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

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

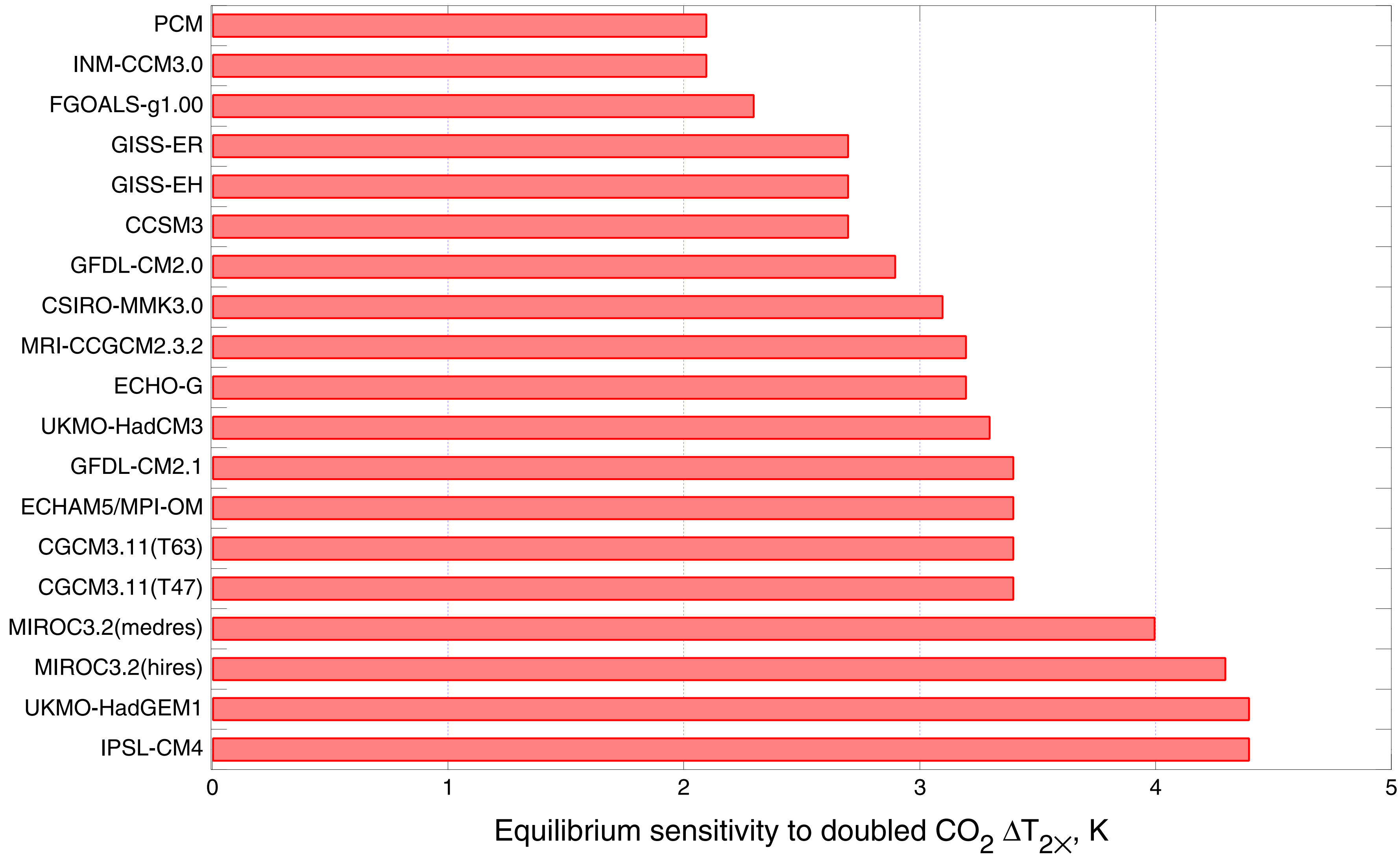
Estimates of central value and uncertainty range from major national and international assessments



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.

CLOUDS

THE ACHILLES HEEL OF CLIMATE MODELS

CLOUD FEEDBACK STRENGTH AND CLIMATE SENSITIVITY IN 9 GCMS

$$S = S_{SB}\frac{1}{1-\Phi}$$

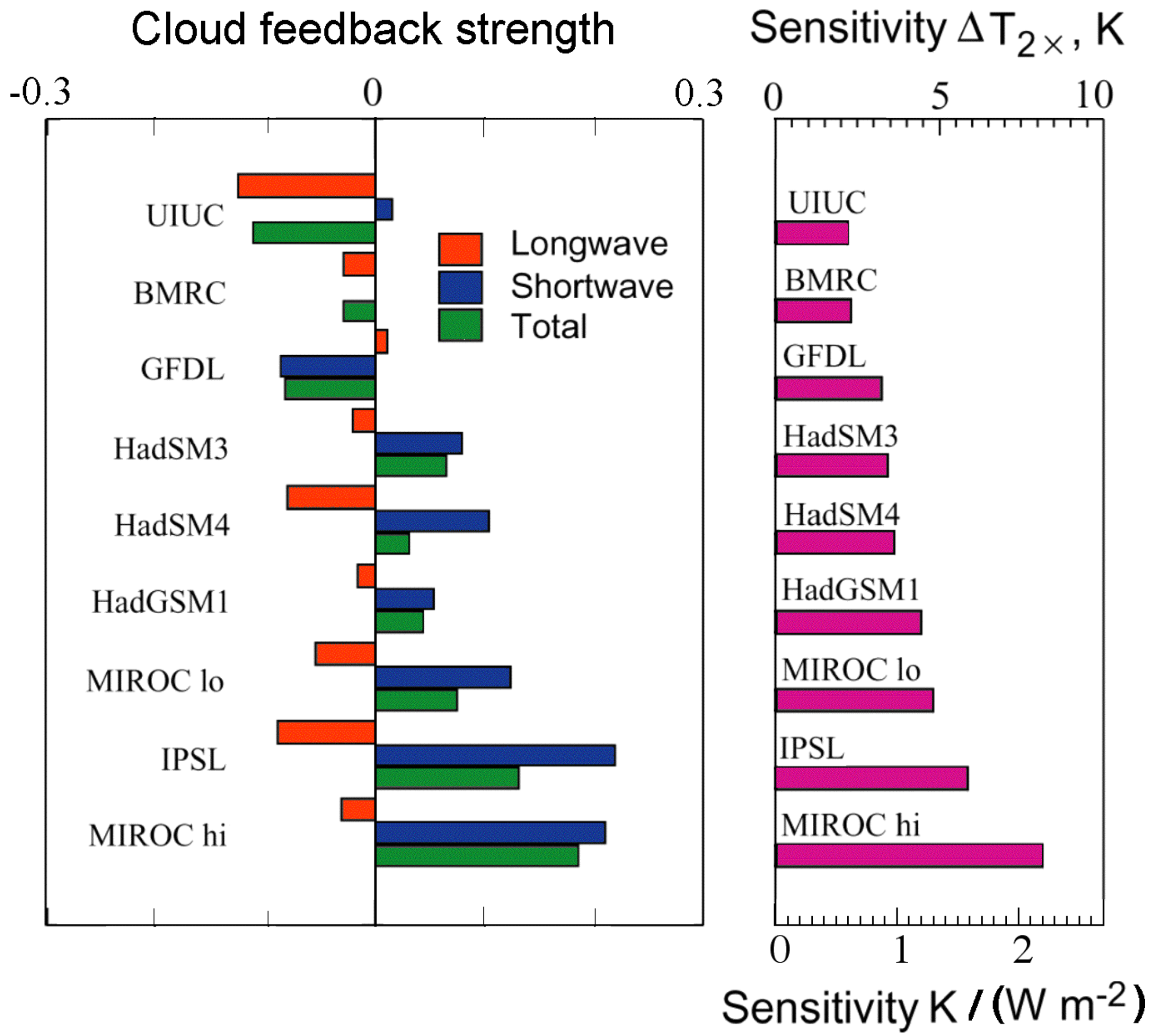
S = Climate sensitivity

S_{SB} = Stefan-Boltzmann sensitivity

Φ = feedback strength

$$\Phi = \sum \Phi_i$$

sum over all feedbacks

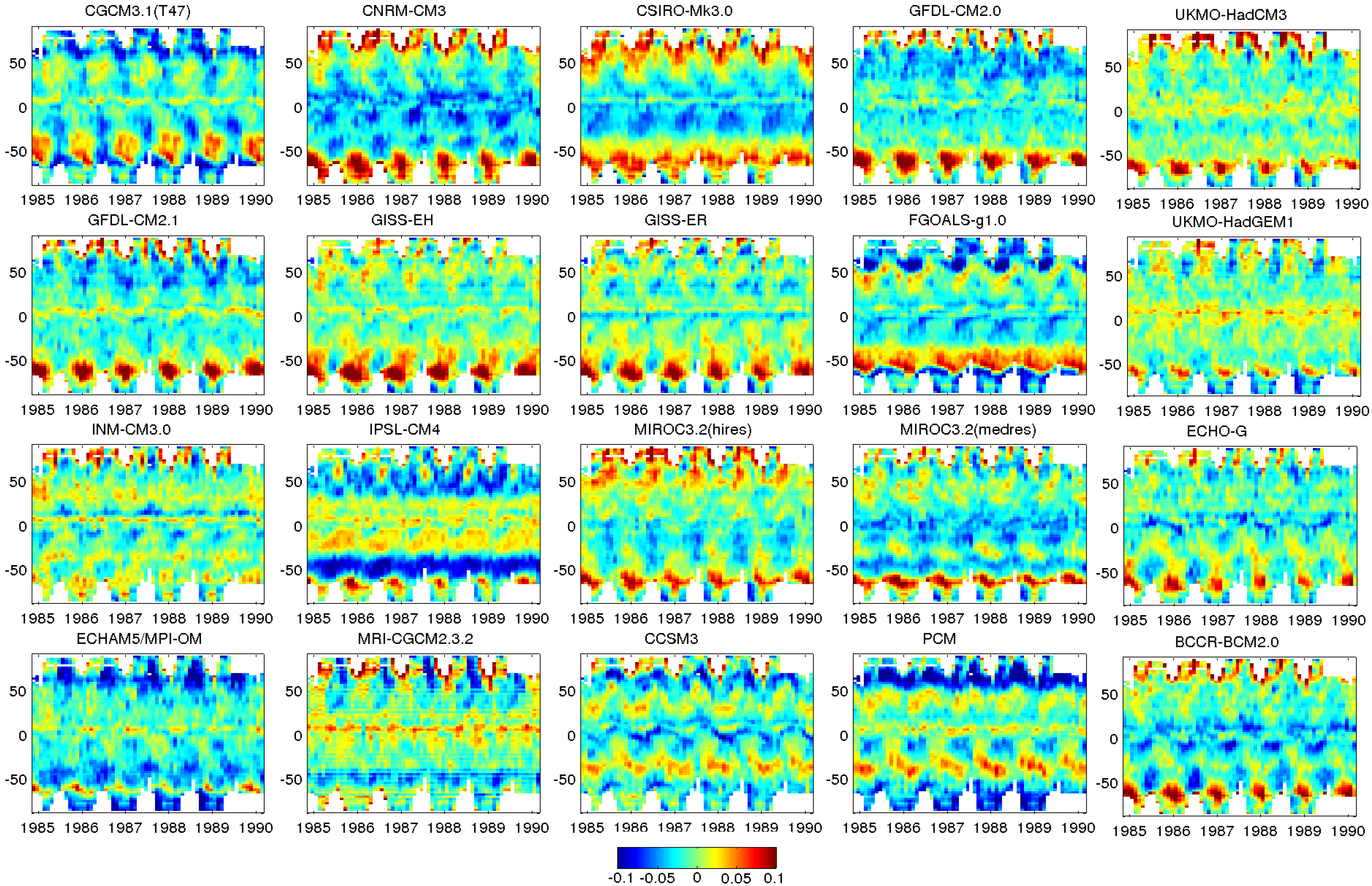


Adapted from Webb et al., Clim. Dyn., 2006

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

ZONAL MONTHLY MEAN ALBEDO

20 GCMs – Difference vs. ERBE Satellite

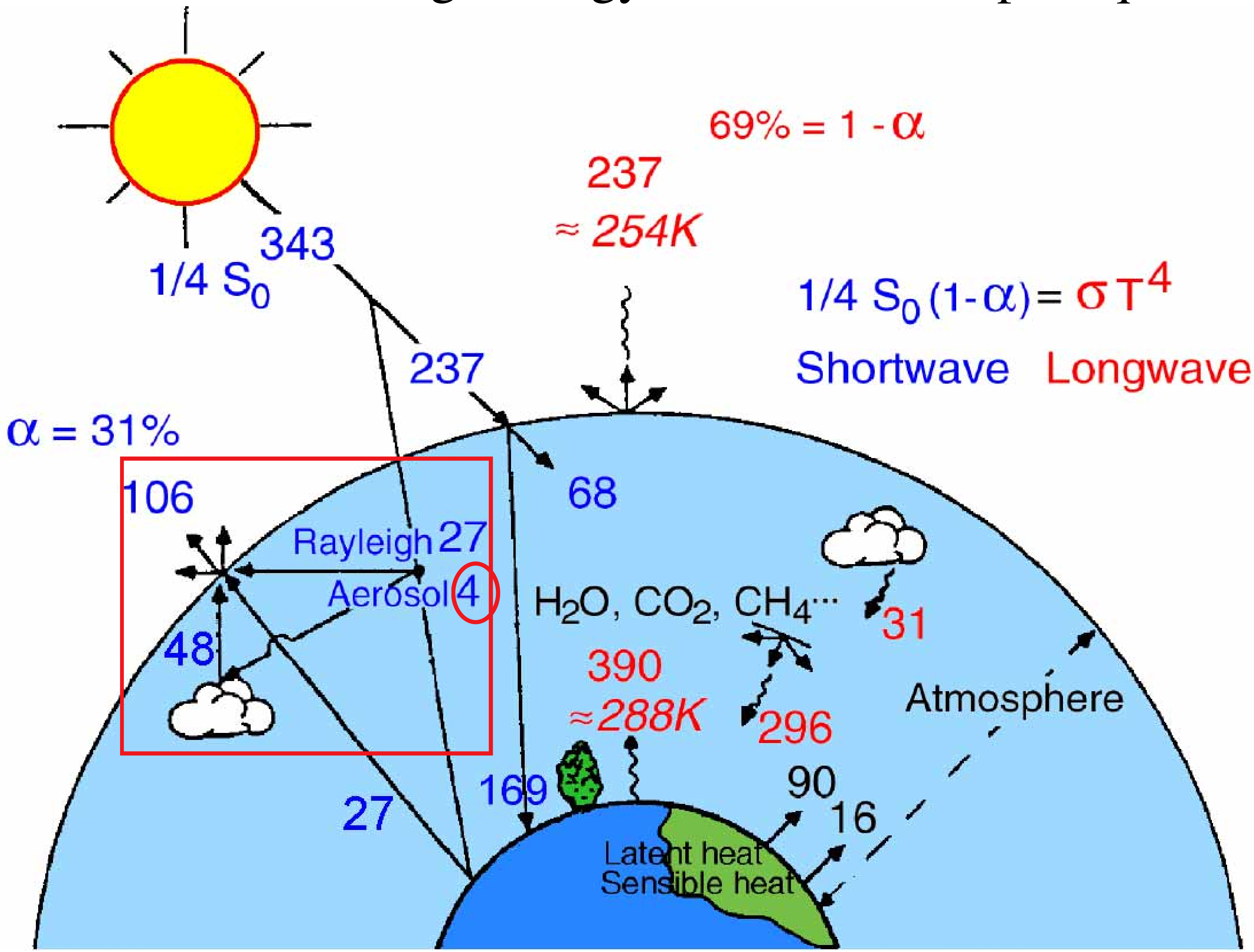


Modified from Bender et al., Tellus, 2006

CLIMATE FORCING BY ANTHROPOGENIC AEROSOLS

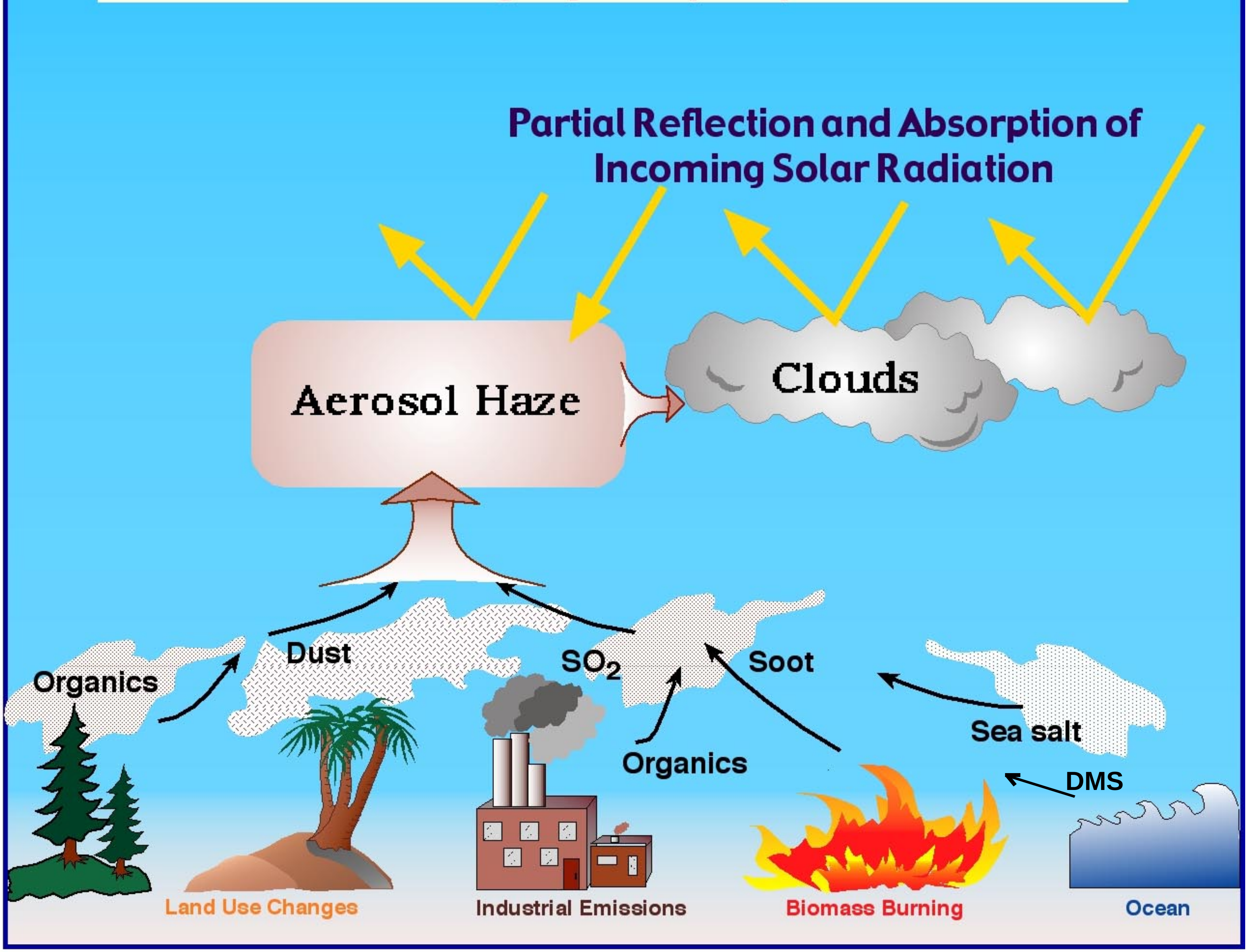
GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter

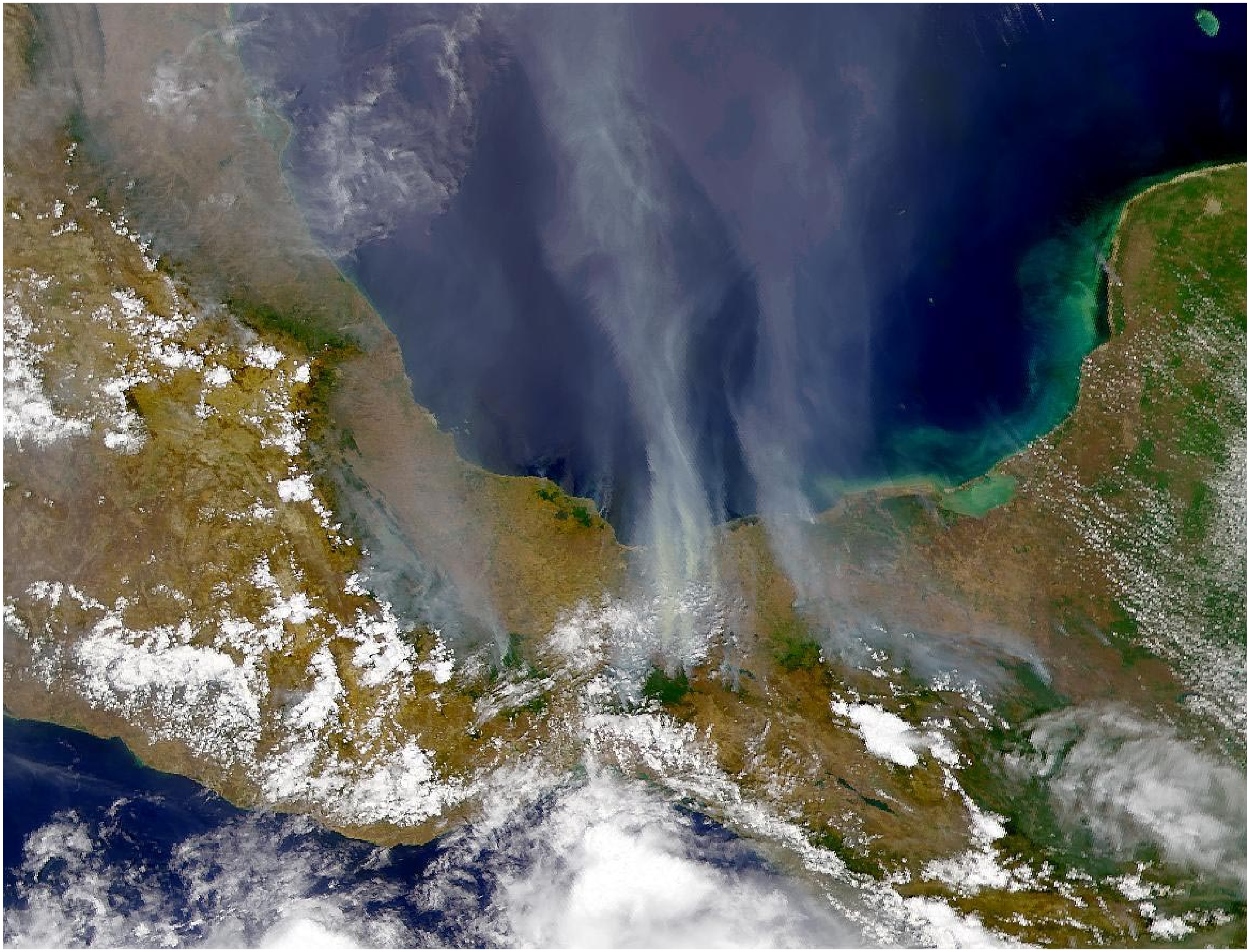


Schwartz, 1996, modified from Ramanathan, 1987

Radiative Forcing by Tropospheric Aerosol



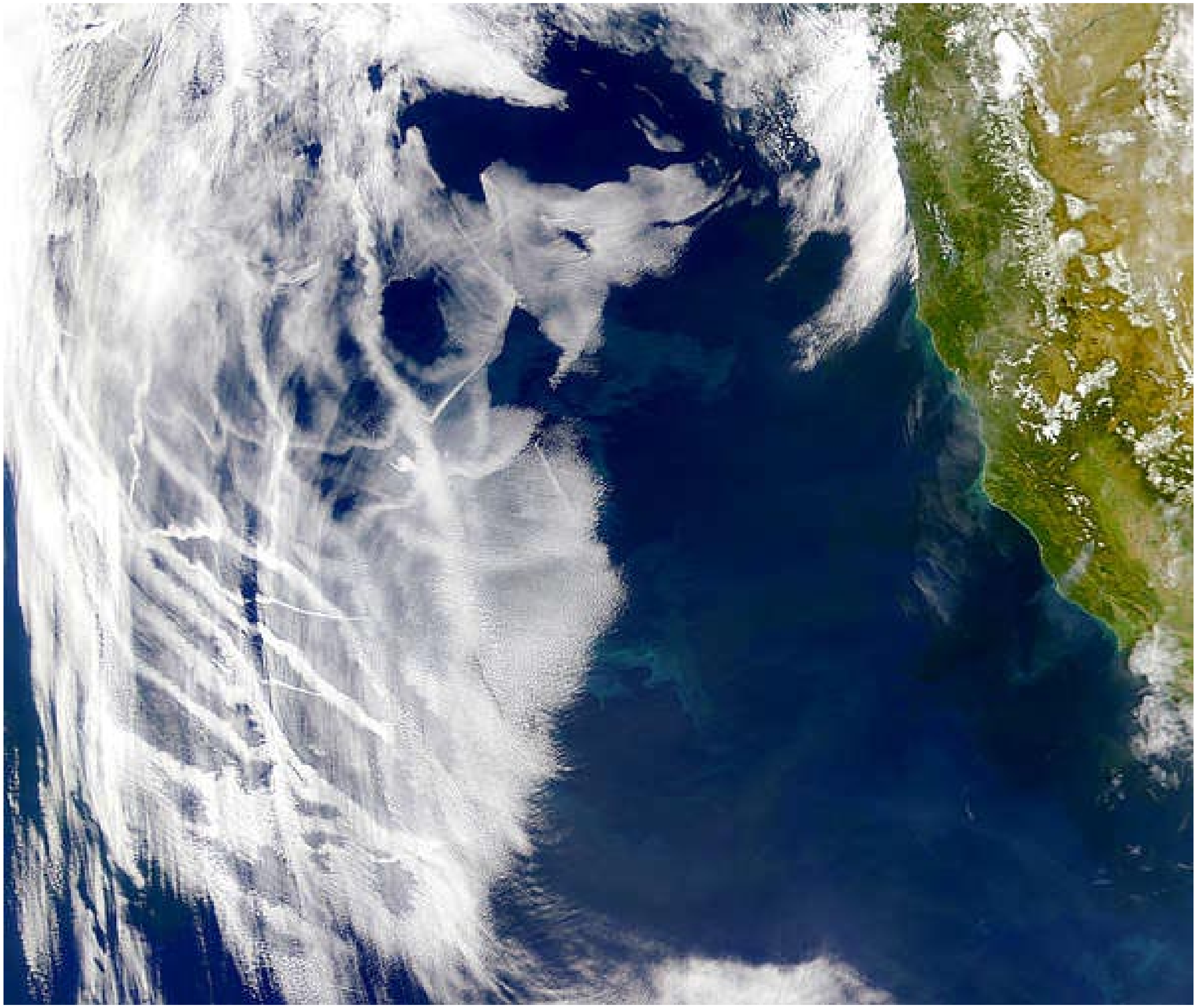
AEROSOLS AS SEEN FROM SPACE



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

CLOUD BRIGHTENING BY SHIP TRACKS

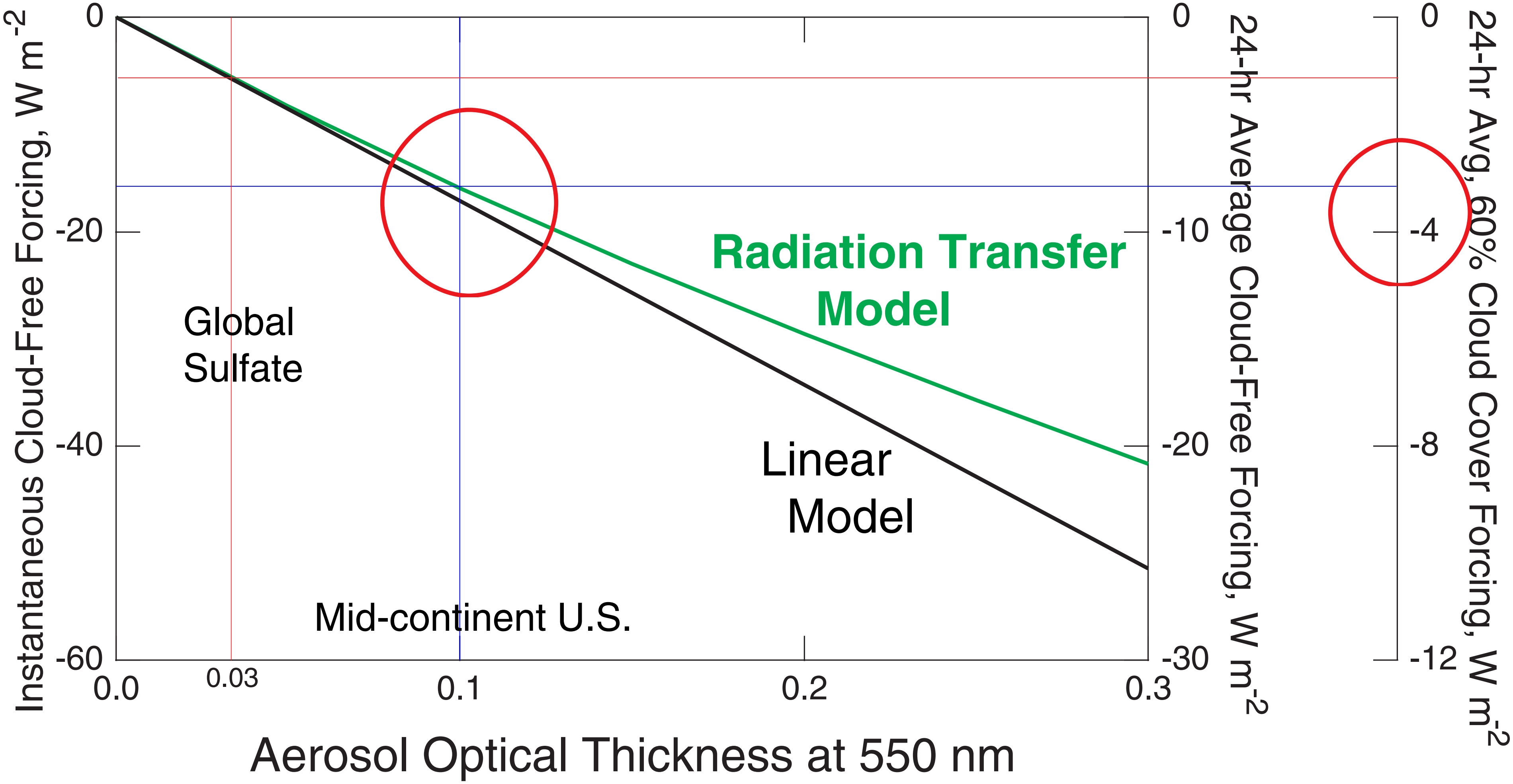
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

ESTIMATES OF AEROSOL DIRECT FORCING

By linear model and by radiation transfer modeling



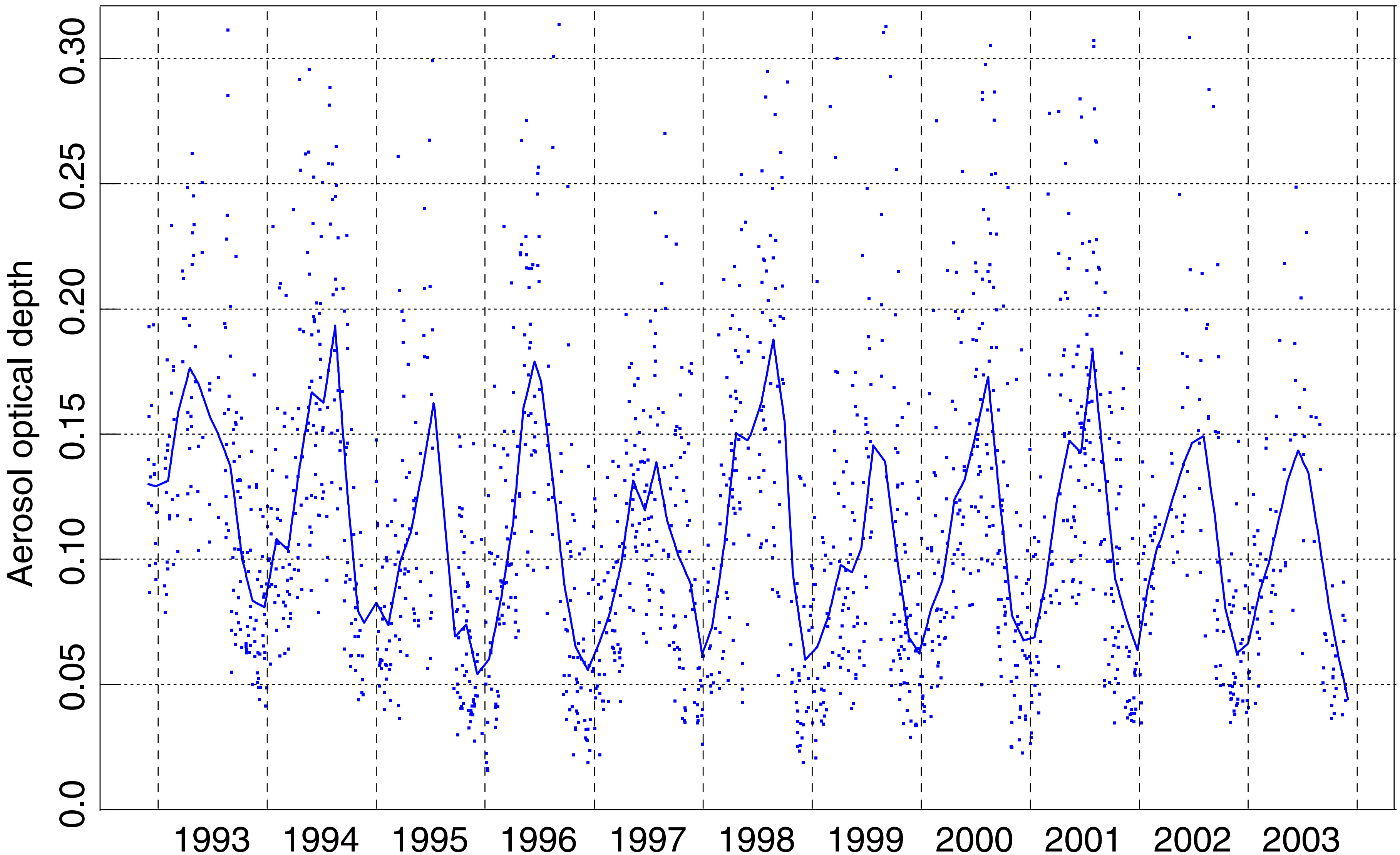
Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling.***

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

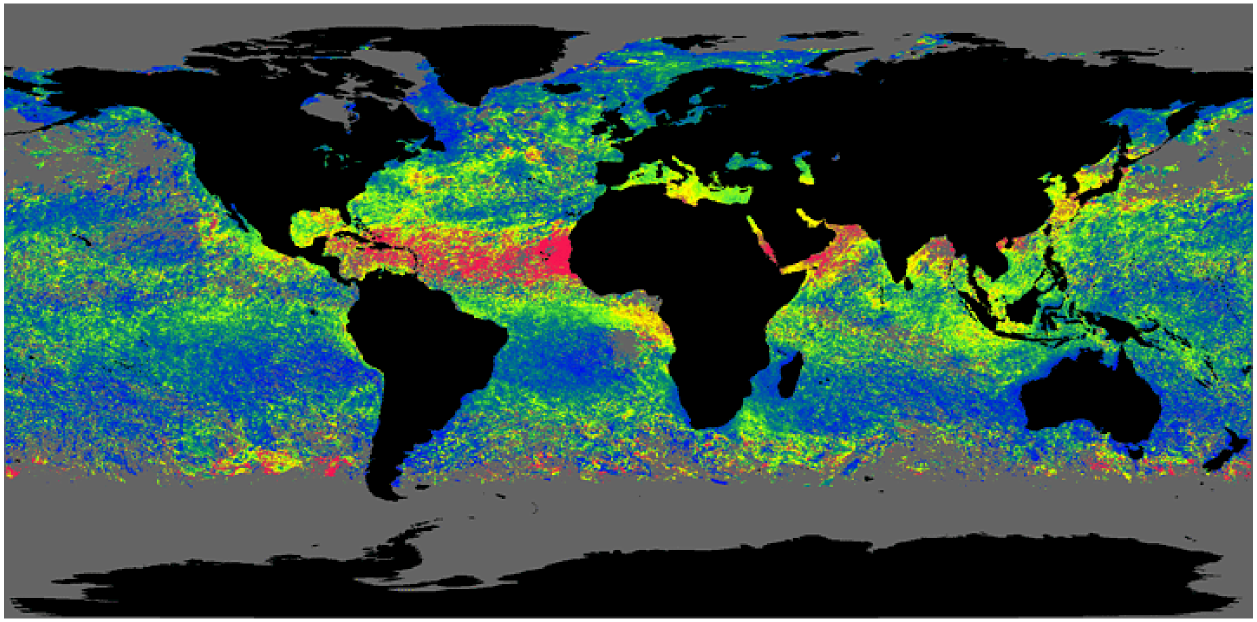
MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

Optical Thickness τ

$\lambda = 865$ nm

0 — 0.5

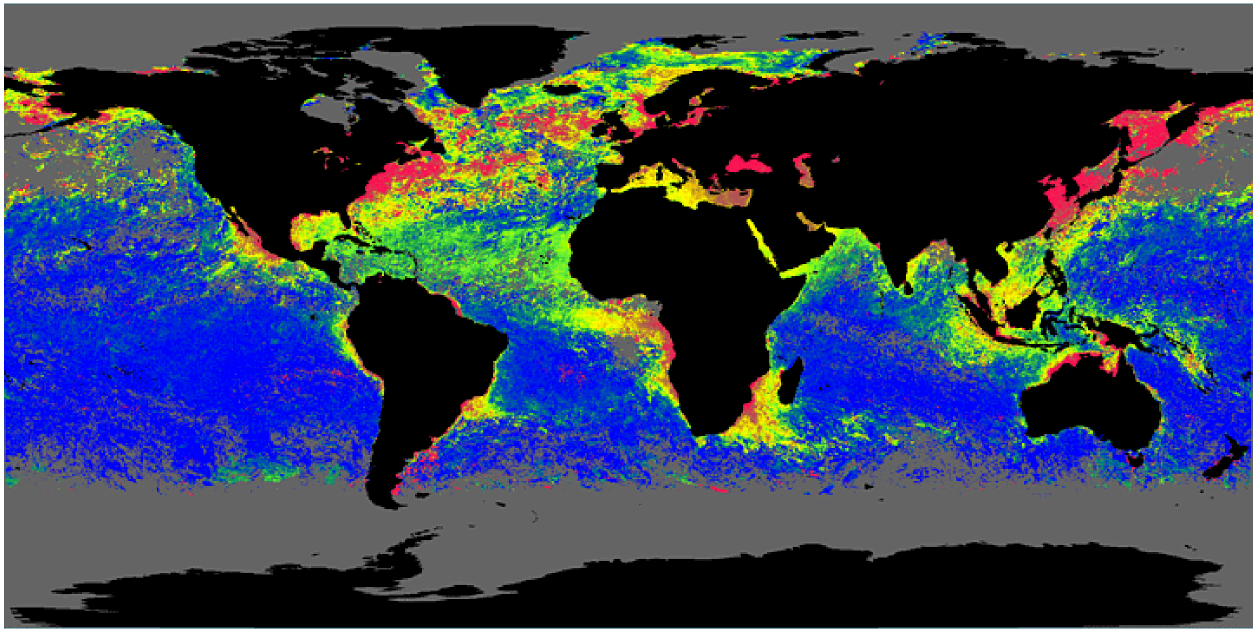


Ångström Exponent α

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

-0.2 — 1.2

Large Particles — Small Particles

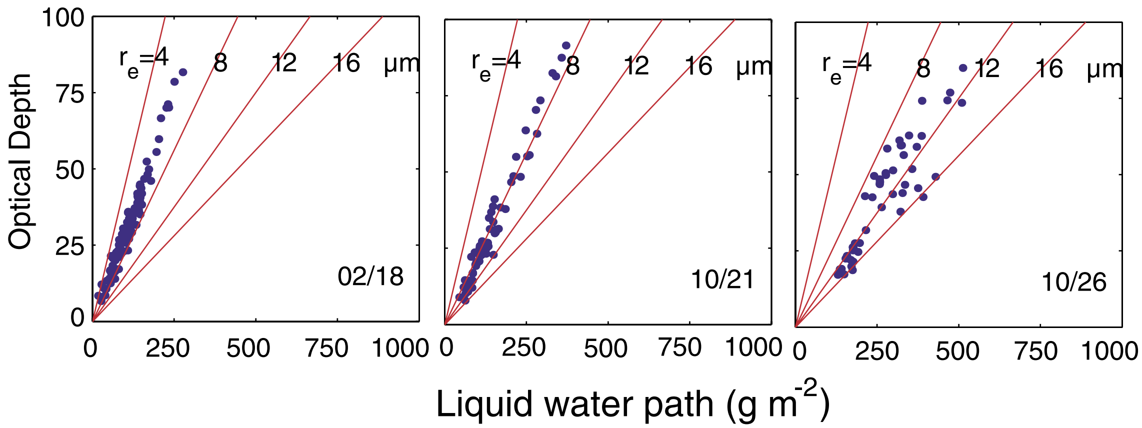


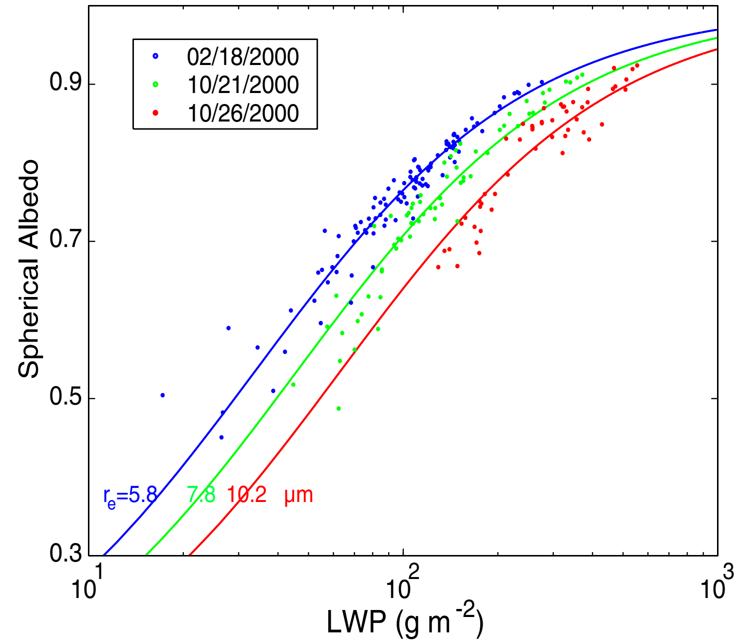
Small particles are from gas-to-particle conversion.

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.

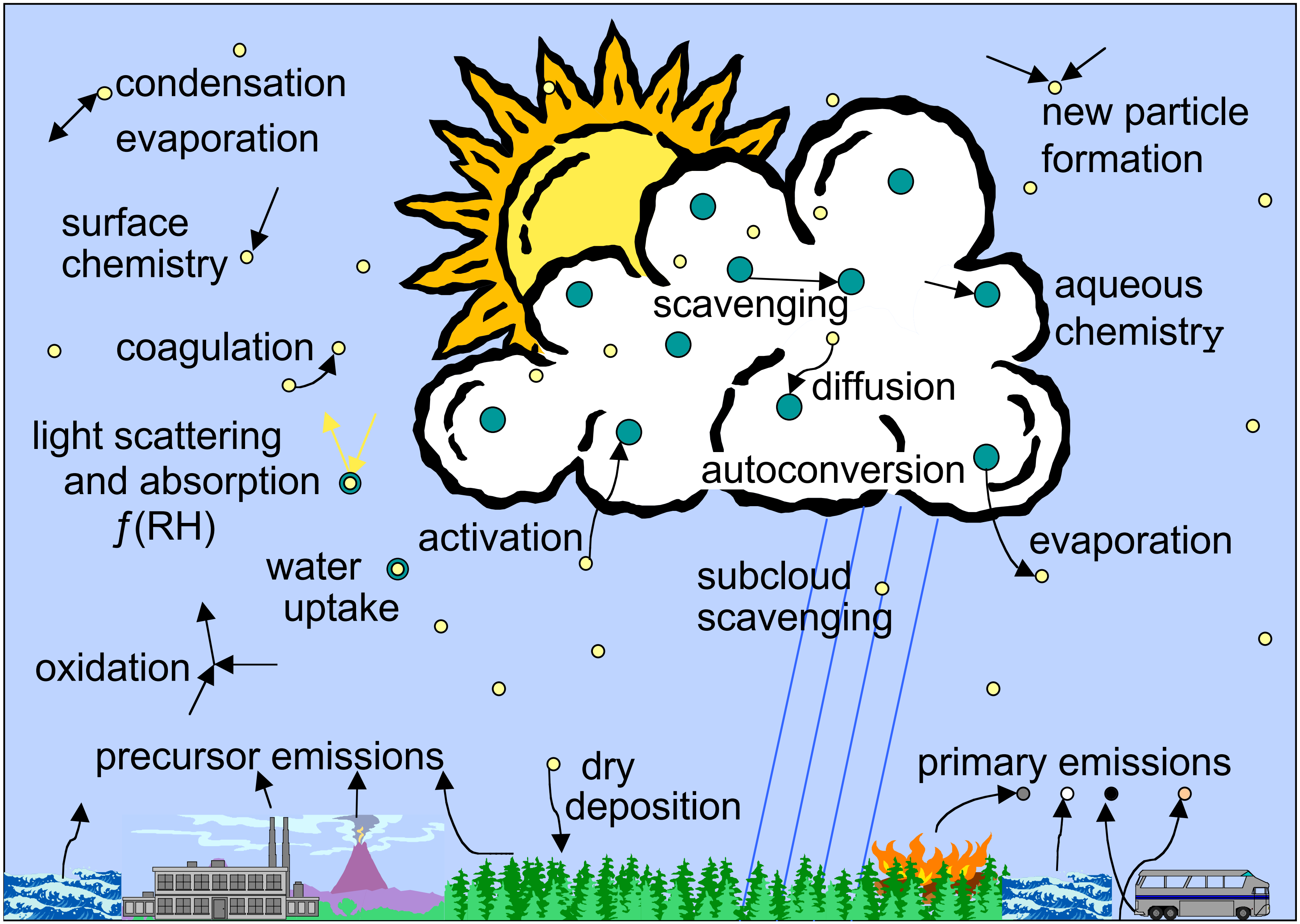
Radiative forcing for solar zenith angle 60° and liquid water path 100 g m^{-2}

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 CLIMATE MODELS

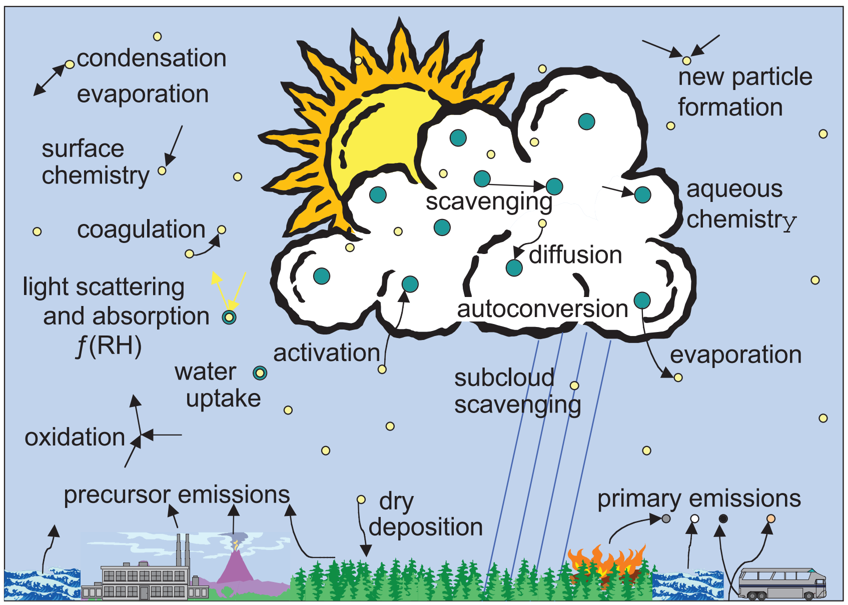
AEROSOL PROCESSES THAT MUST BE UNDERSTOOD AND REPRESENTED IN MODELS



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.

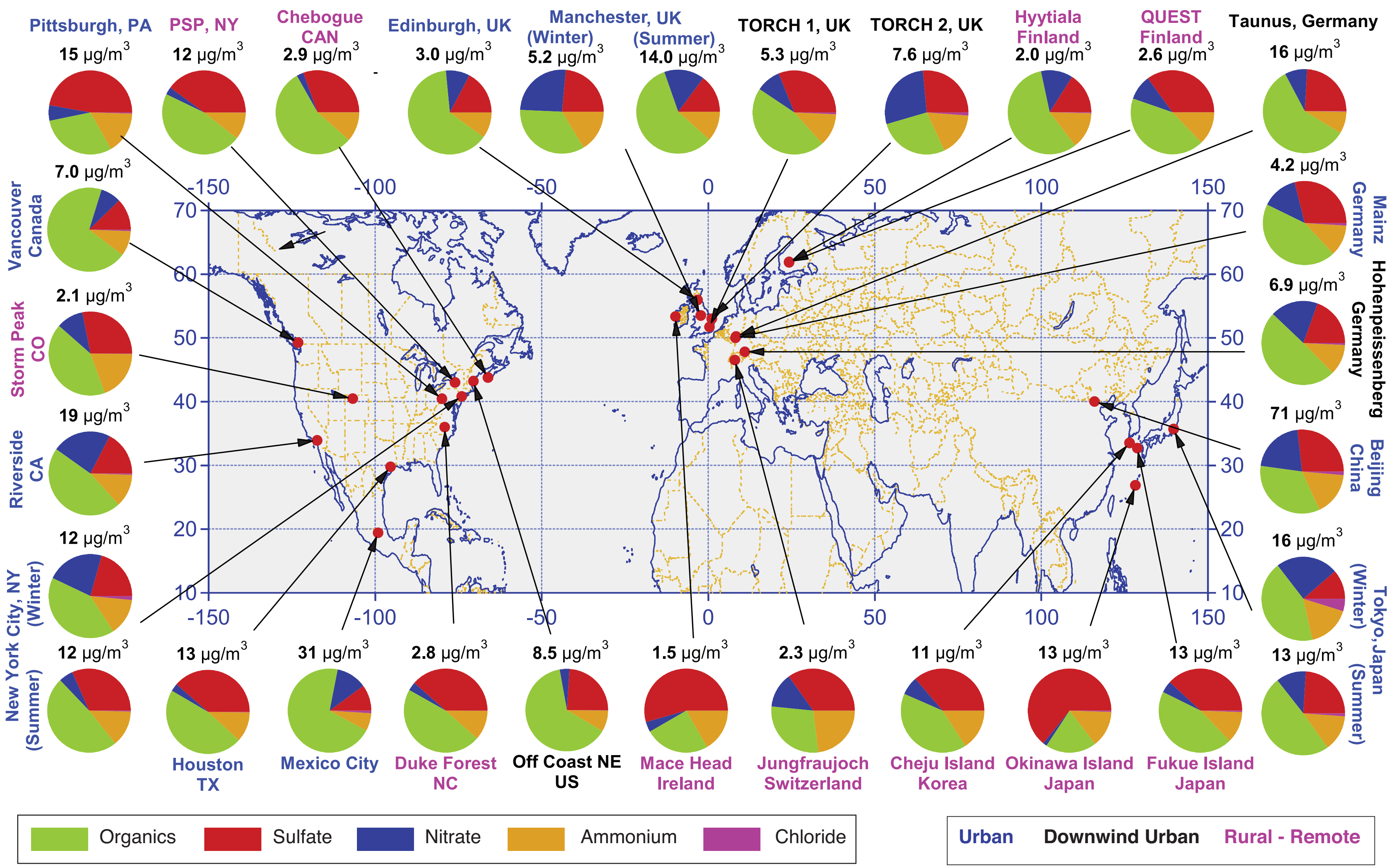
AEROSOL FORCING

WHAT'S NEW?

Organics

DOMINANCE OF ORGANIC AEROSOL

Measurements by aerosol mass spectrometer

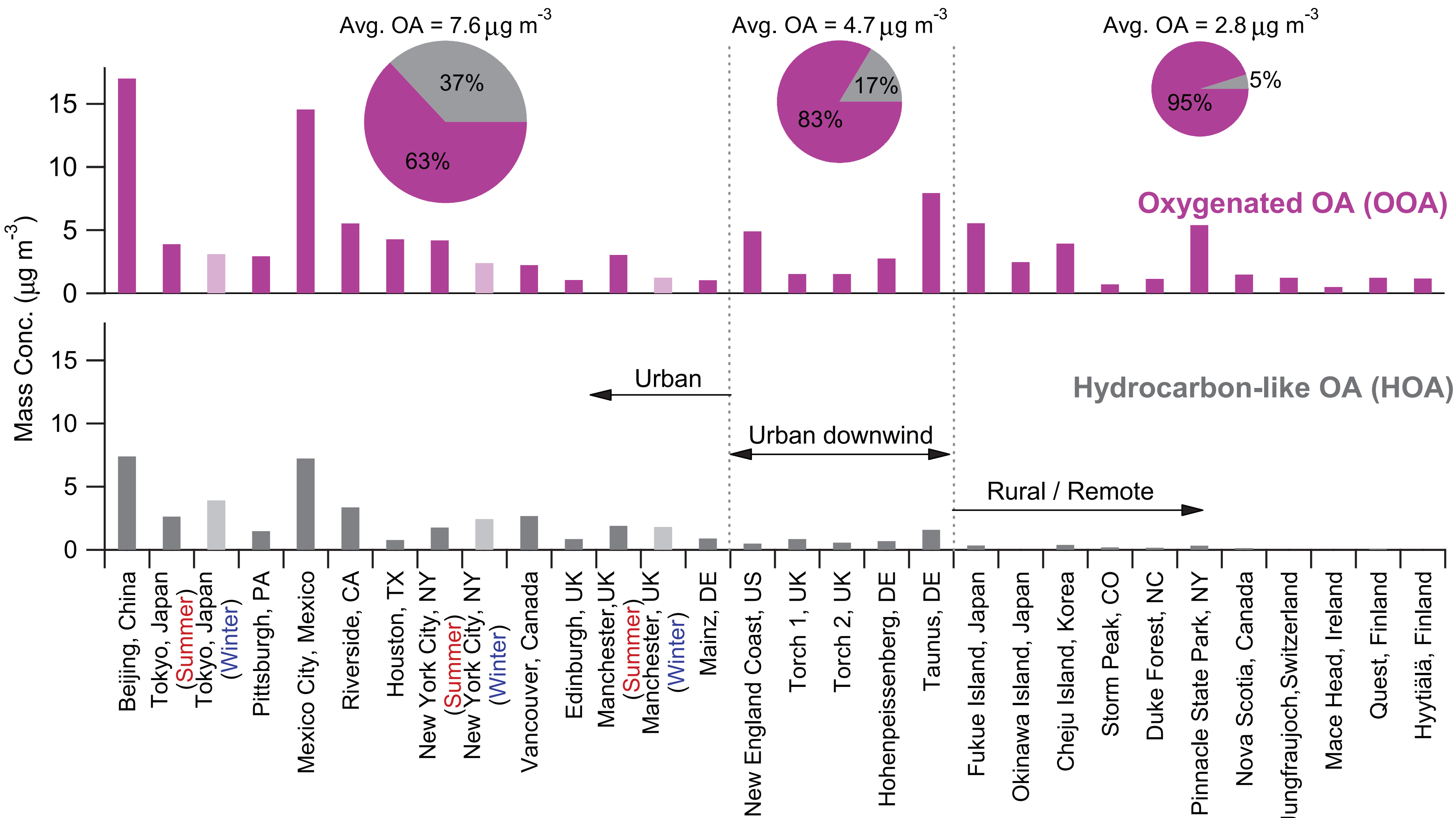


Zhang et al., GRL, 2007

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.

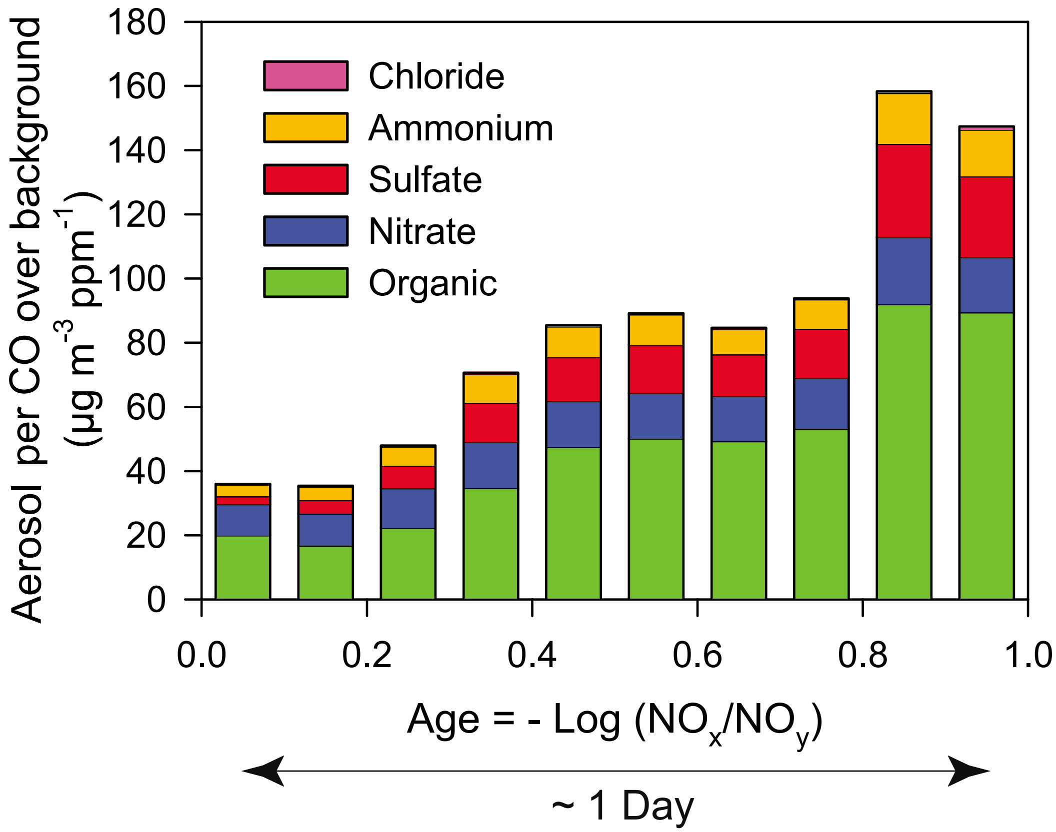
AEROSOL IN MEXICO CITY BASIN

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

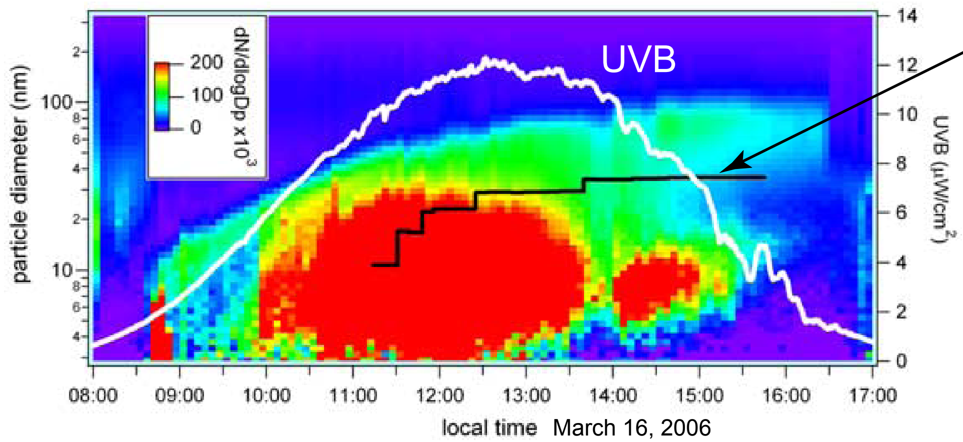
Parcel photochemical age measured using $-\text{Log}(NO_x/NO_y)$ as clock.

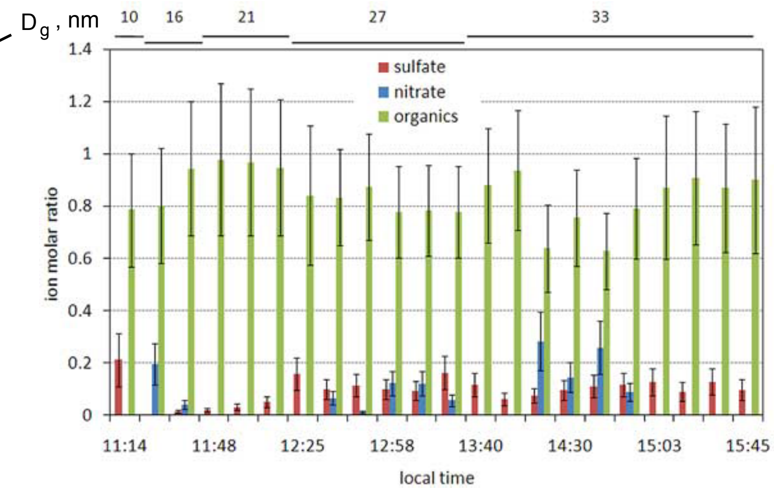
Aerosol normalized to CO above background to account for dilution.

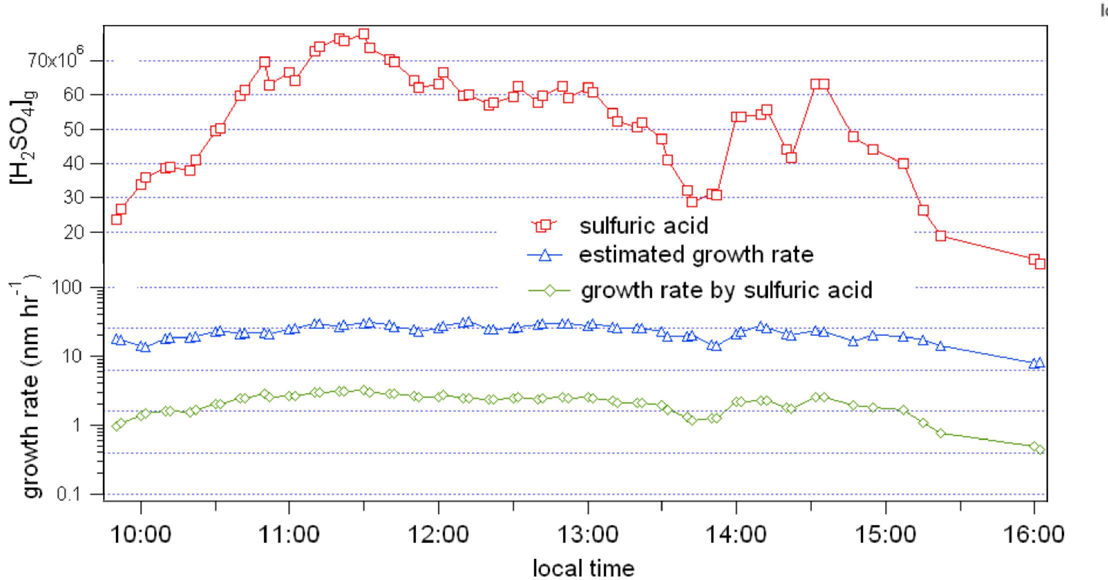
Fivefold increase in organic aerosol.

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

Following the growth of particles formed from nucleation at Tecamac, Mexico







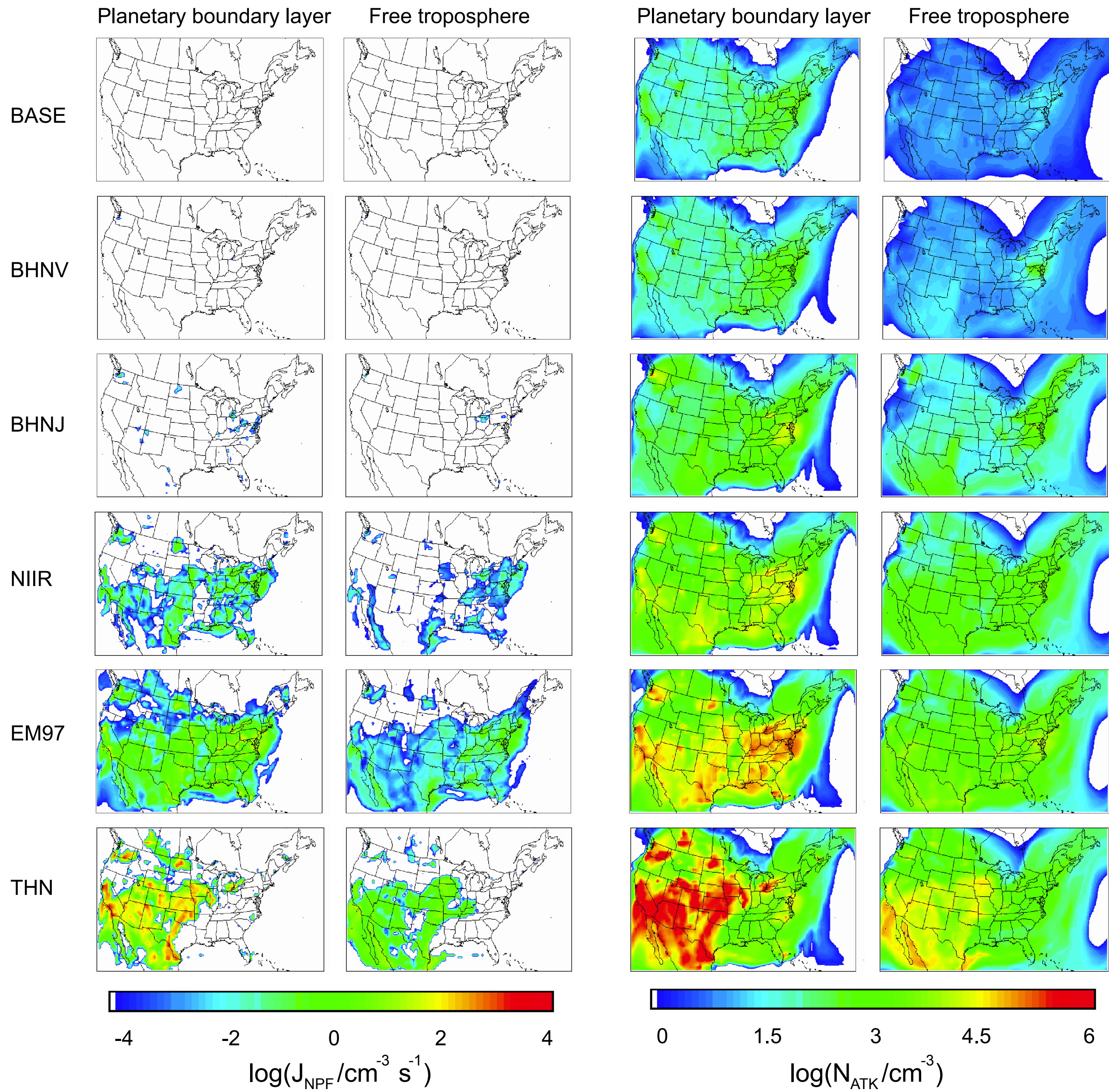
Sulfate accounts for only ~10% of particulate mass.

Growth rate exceeds that from sulfuric acid by order of magnitude.

Smith, McMurry et al., GRL, 2008

NEW PARTICLE FORMATION RATE AND AITKEN PARTICLE NUMBER CONCENTRATION

Dependence on formation mechanism



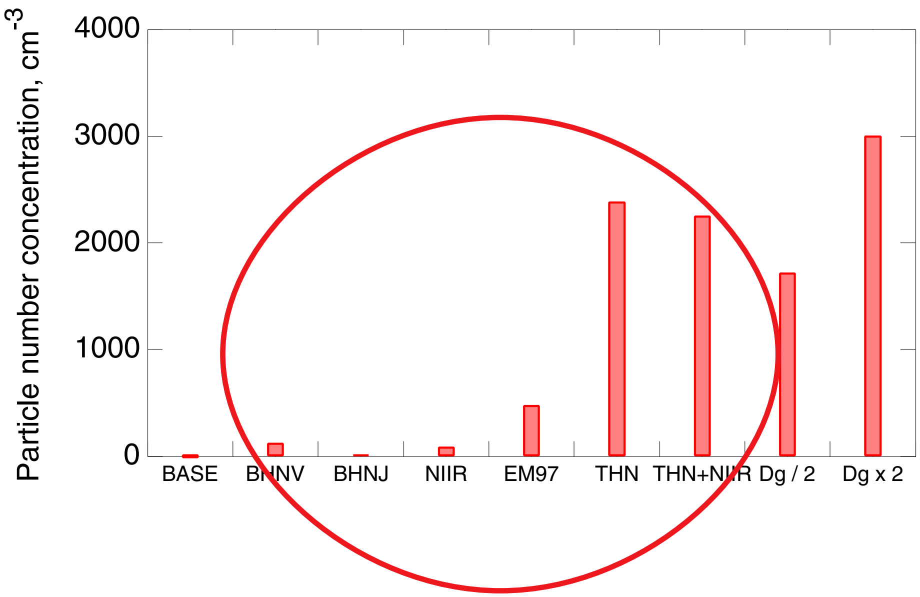
L. S. Chang et al, JGR, 2008, in review

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

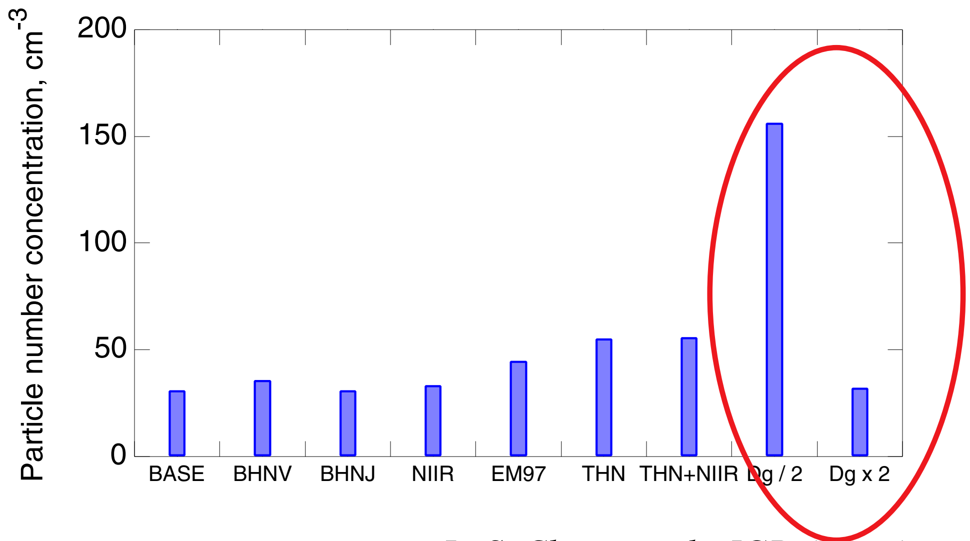
AEROSOL PARTICLE NUMBER CONCENTRATION

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

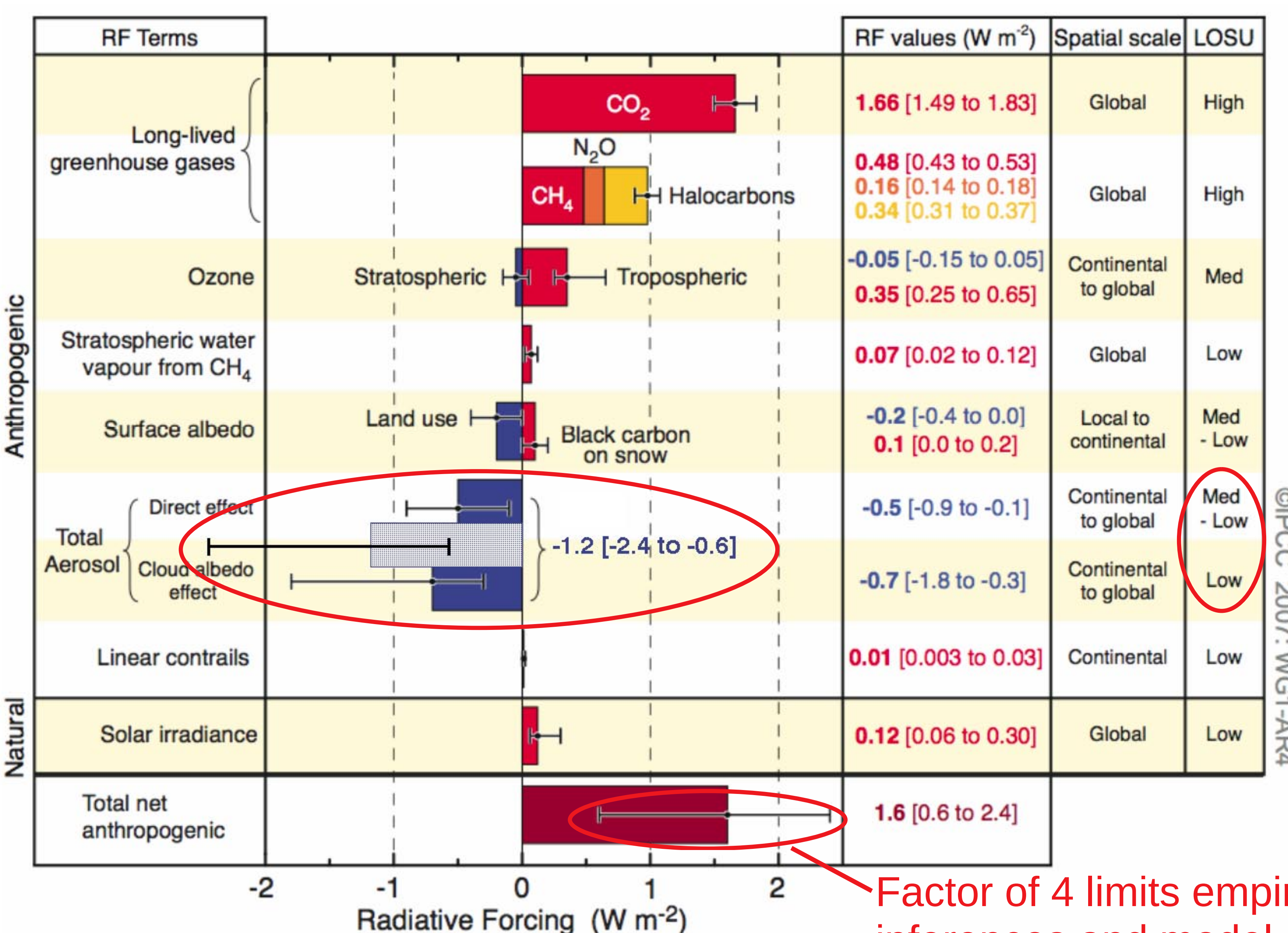
Strong dependence on new particle formation mechanism

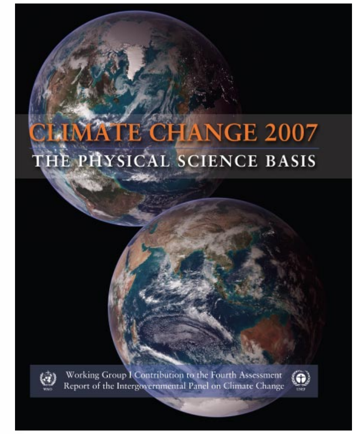
Strong dependence on size of primary emissions

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

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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





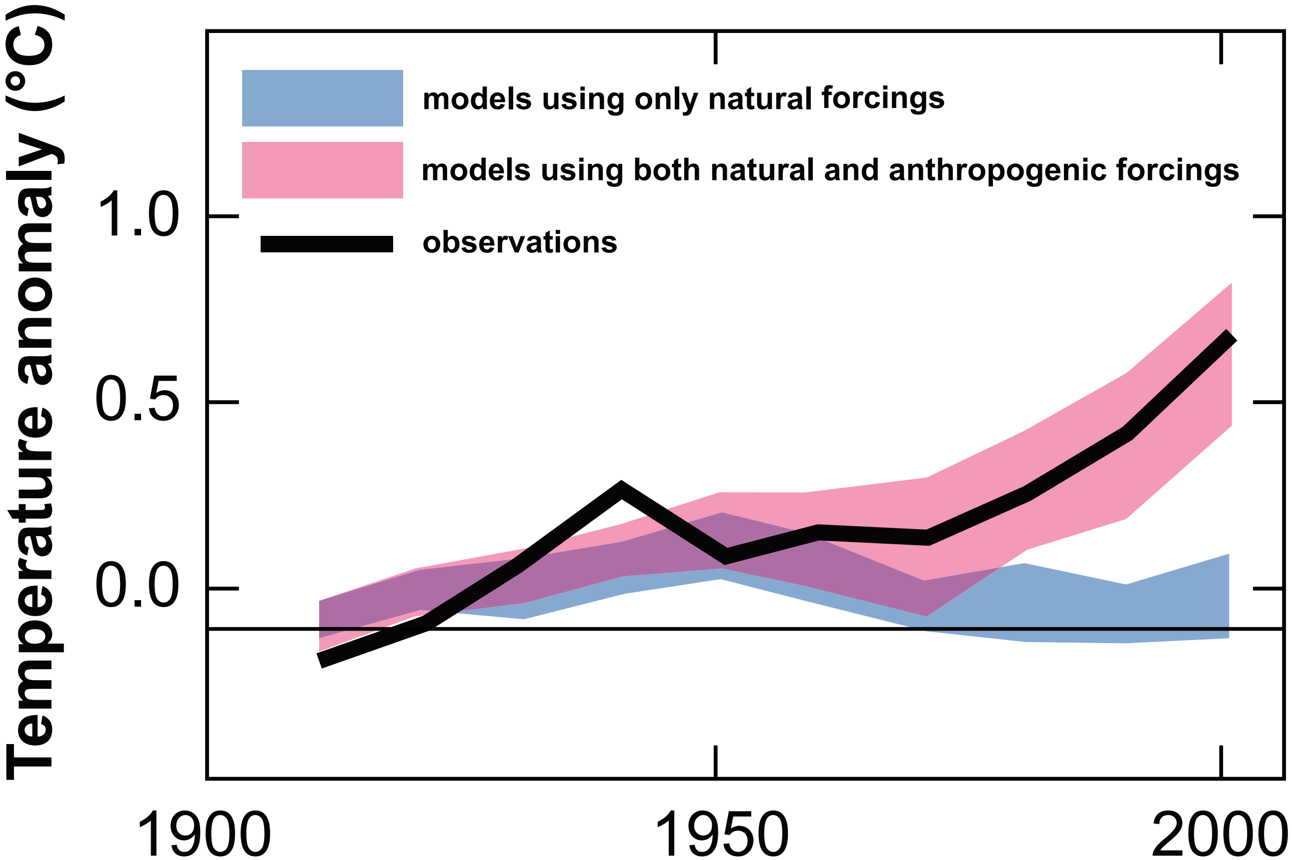
Factor of 4 limits empirical inferences and model evaluation.

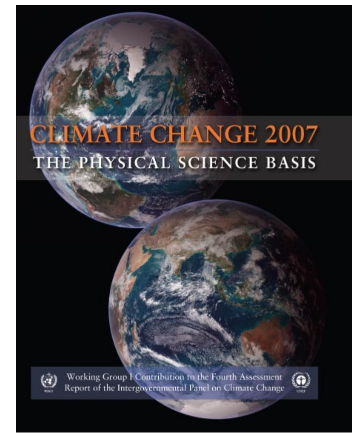
LOSU denotes level of scientific understanding.

Uncertainty range: 5 - 95%.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



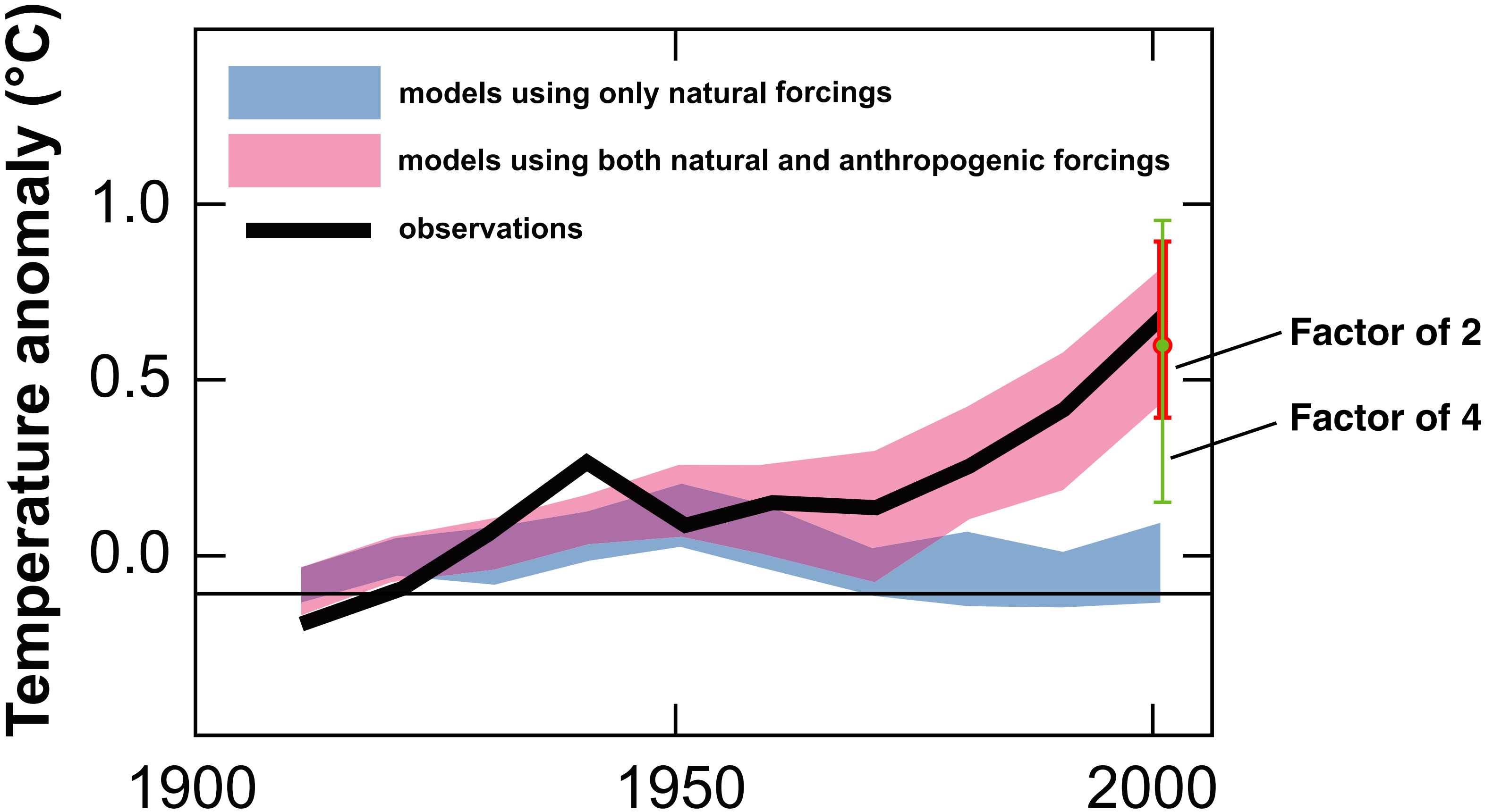


“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

“ 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



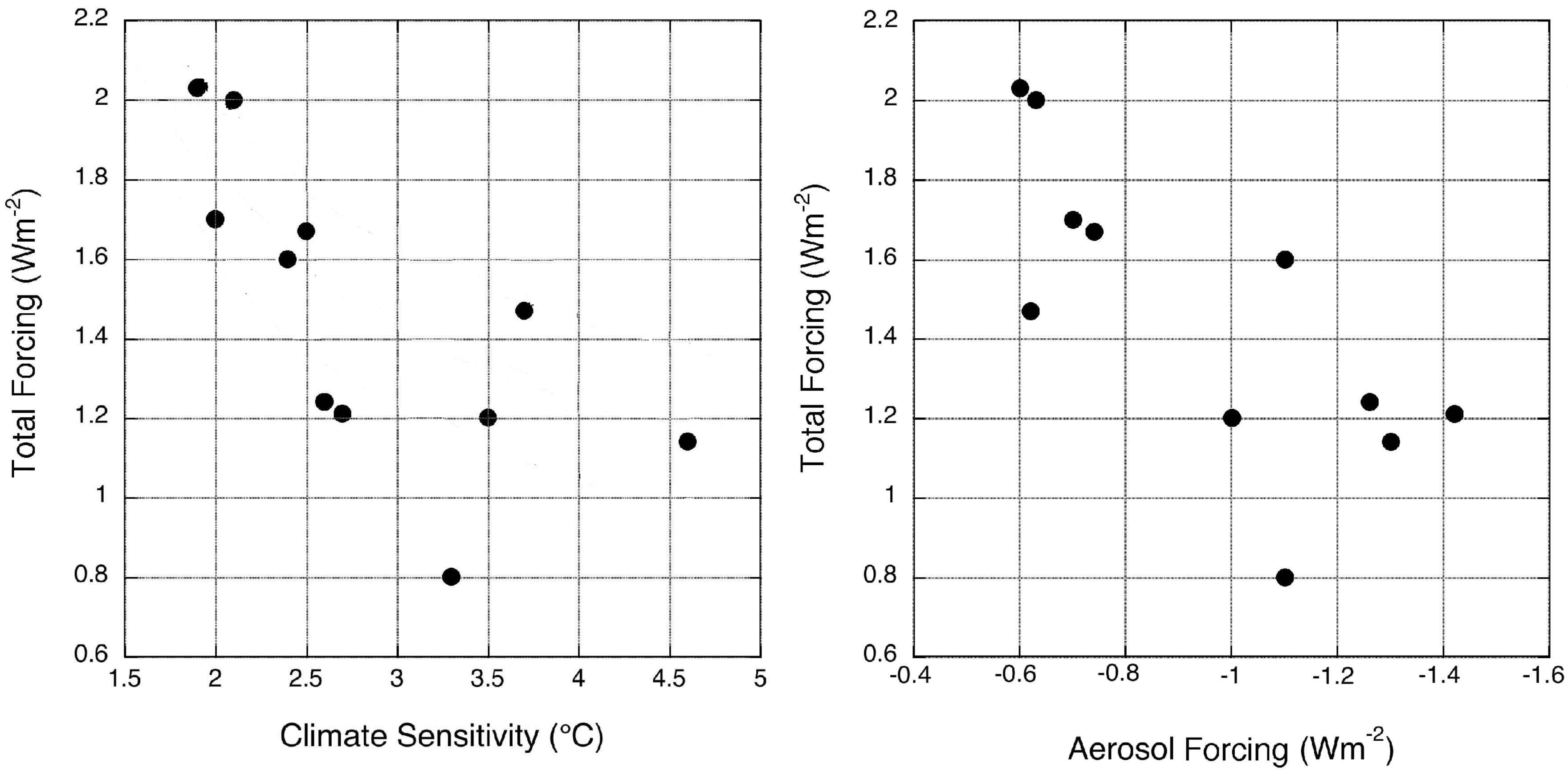
Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007

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.

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.

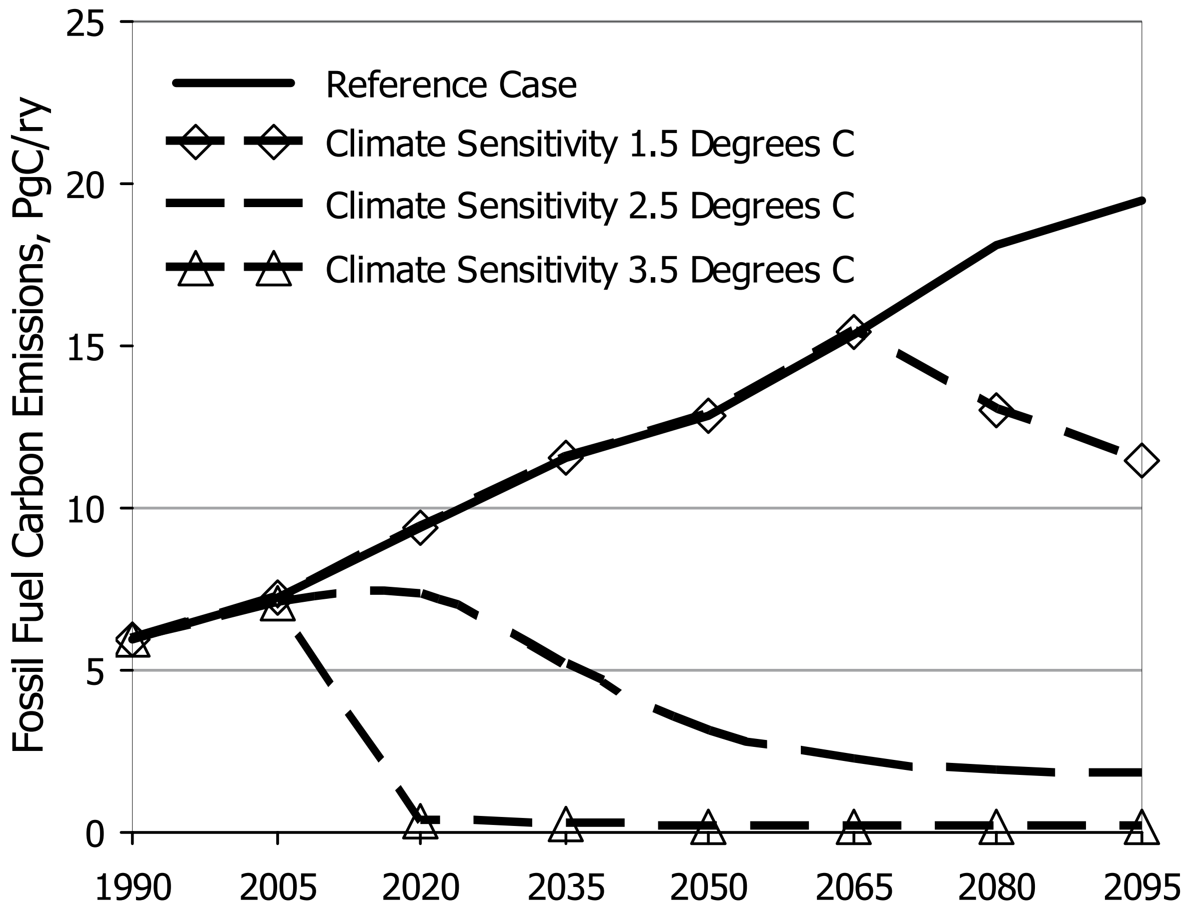
Actions taken today will have long-lasting effects.

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

CARBON EMISSIONS PATHWAYS TO STABILIZE GLOBAL MEAN TEMPERATURE

Emissions for ΔT not to exceed 2 K above preindustrial

Dependence on climate sensitivity



Edmonds and Smith, 2006

Climate sensitivity expressed as equilibrium increase in GMST for doubled atmospheric CO_2 mixing ratio $\Delta T_{2\times}$.

IMPROVING CLIMATE MODELS RAPIDLY

A new approach to climate modeling

U.S. Department of Energy Atmospheric Radiation Measurement site, Maunus, Paupa New Guinea

Run climate models in ***real-time forecast mode***, initialized by observations.
Compare forecasts with global meteorological observations.
Compare with detailed observations at multiple highly instrumented sites.
Identify needed improvements in parameterizations, ***revise, test***.

CONCLUDING OBSERVATIONS

- Earth's climate sensitivity is ***uncertain to at least a factor of 2***.
- This uncertainty has ***decreased little in 30 years***.
- This uncertainty greatly ***limits effective and efficient energy planning***.
- The range in climate model sensitivity arises largely from ***differing cloud feedbacks***.
- ***Uncertainty in climate forcing by aerosols*** greatly limits the ability to constrain climate sensitivity and to evaluate climate models.
- Substantially decreasing uncertainty in Earth's climate sensitivity will require ***bold new approaches***.