CLIMATE CHANGE

THE KNOWNS, THE KNOWN UNKNOWNS, AND THE UNKNOWN UNKNOWNS

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U.S. DEPARTMENT OF ENERGY

Brookhaven Area Office
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http://www.ecd.bnl.gov/steve

THE UNKNOWN

As we know,
There are known knowns.
There are things we know we know.

We also know
There are known unknowns.

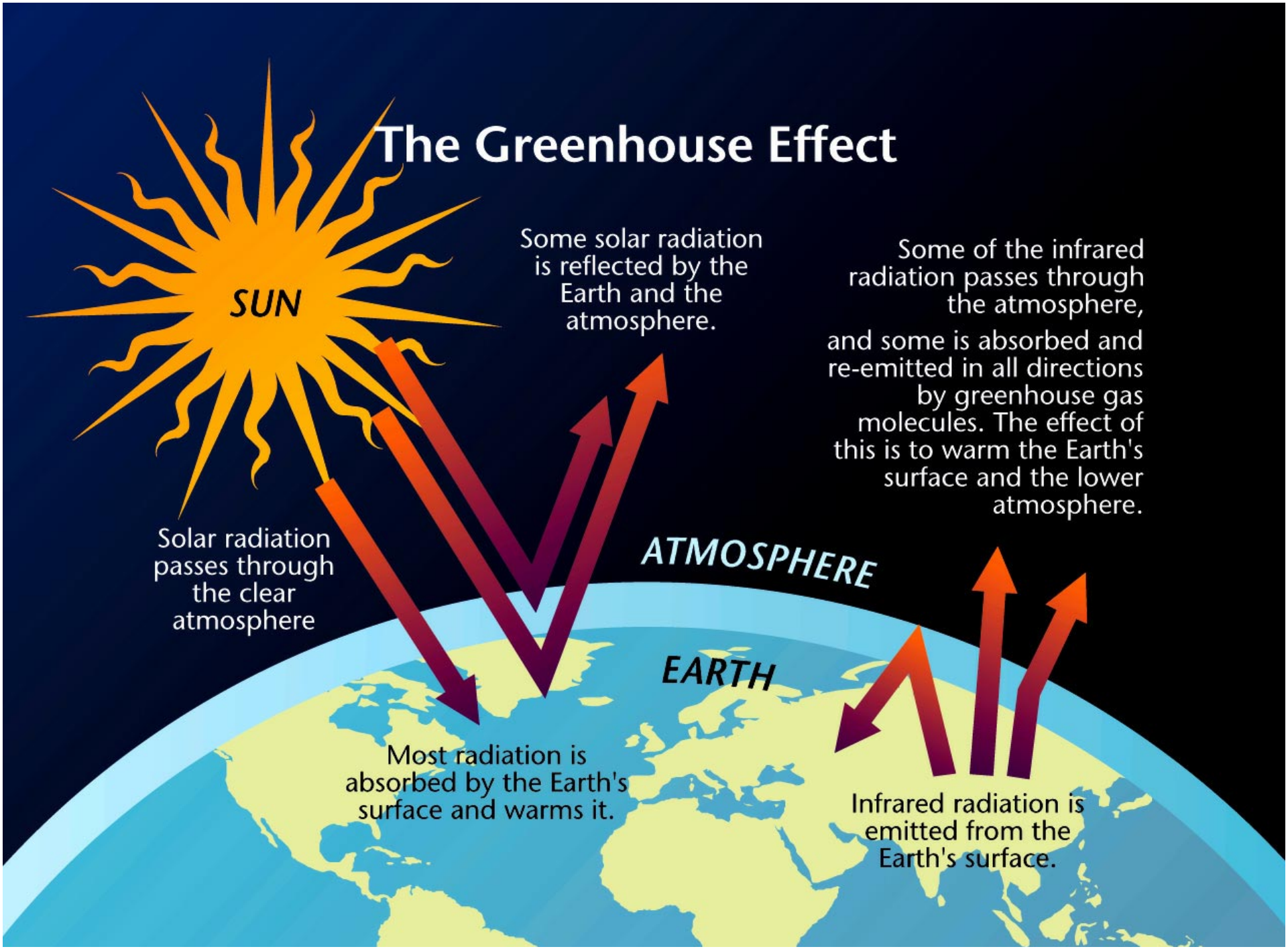
That is to say
We know there are some things
We do not know.

But there are also unknown unknowns,
The ones we don’t know
We don’t know.

Donald Rumsfeld, 2002

OUTLINE

- Earth's energy balance
  - Perturbations
  - Key questions
  - Influence of aerosols
- Climate research at BNL
  - Atmospheric Science Program ASP
  - Atmospheric Radiation Measurement ARM
  - Blue Gene BLUE GENE
- Looking to the future
- Concluding remarks
- Epilogue


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.

ATMOSPHERIC RADIATION

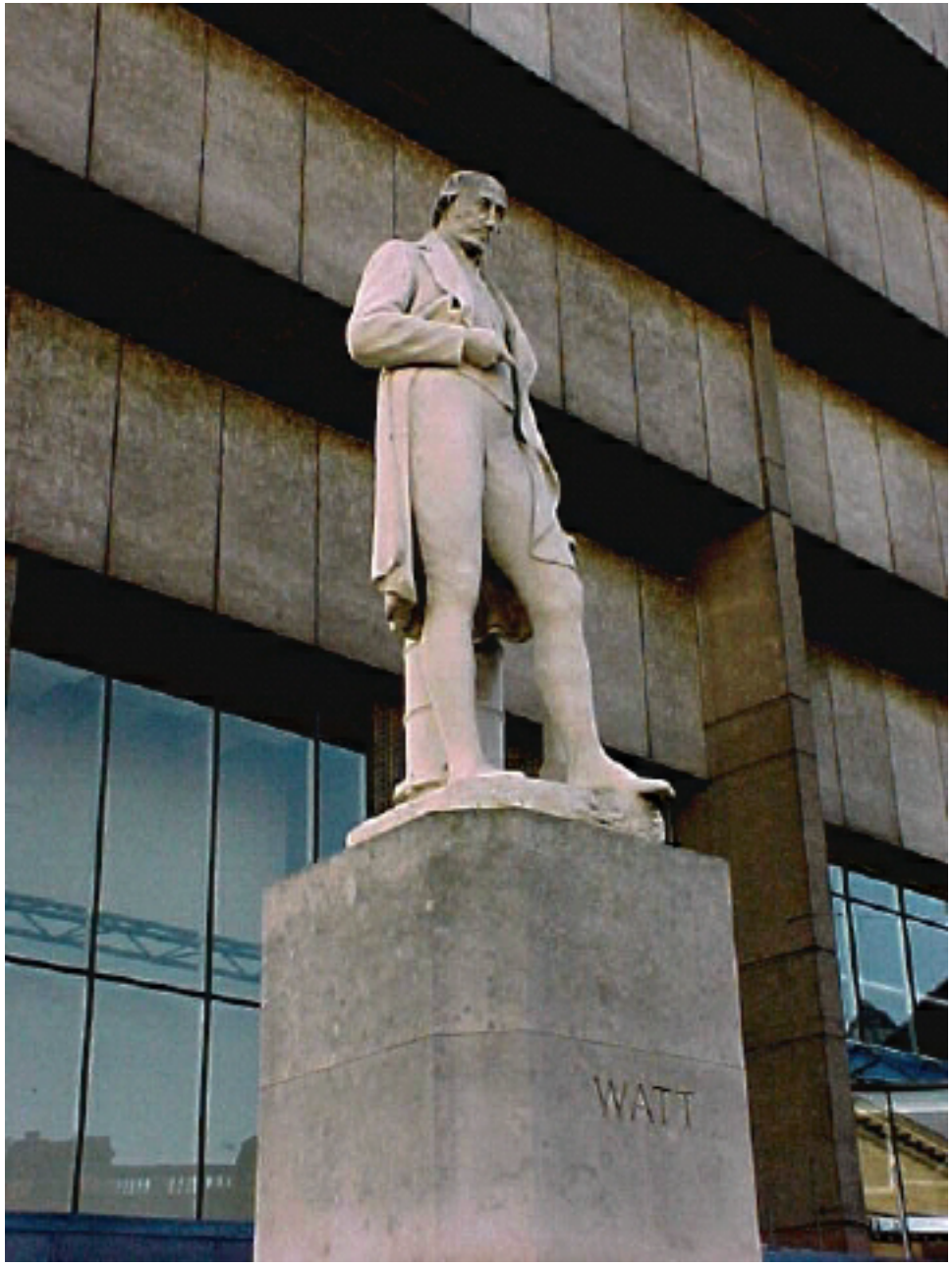
Energy per area per time

Power per area

Unit:

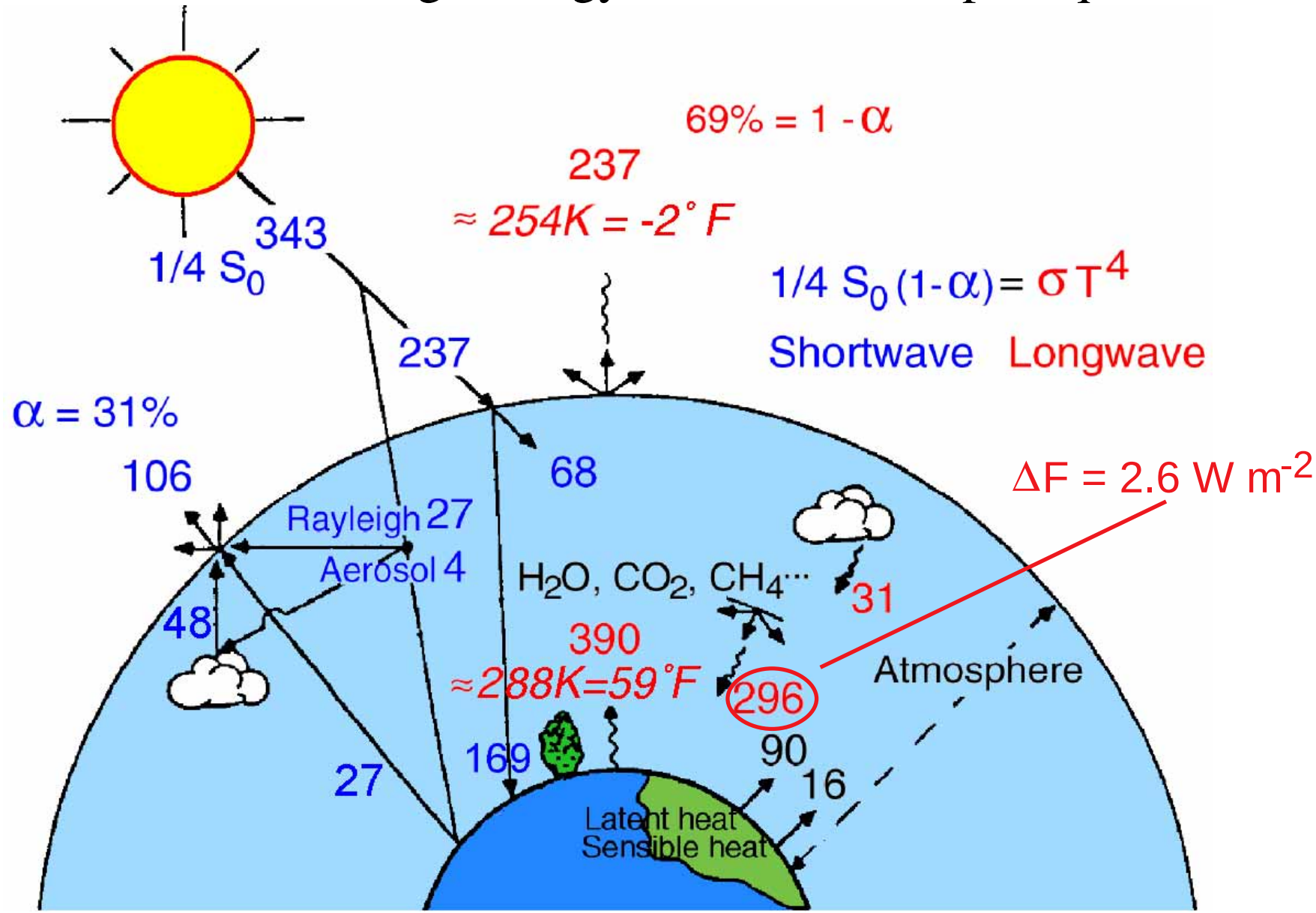
Watt per square meter

W m^{-2}



GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Schwartz, 1996, modified from Ramanathan, 1987

STEFAN - BOLTZMANN RADIATION LAW

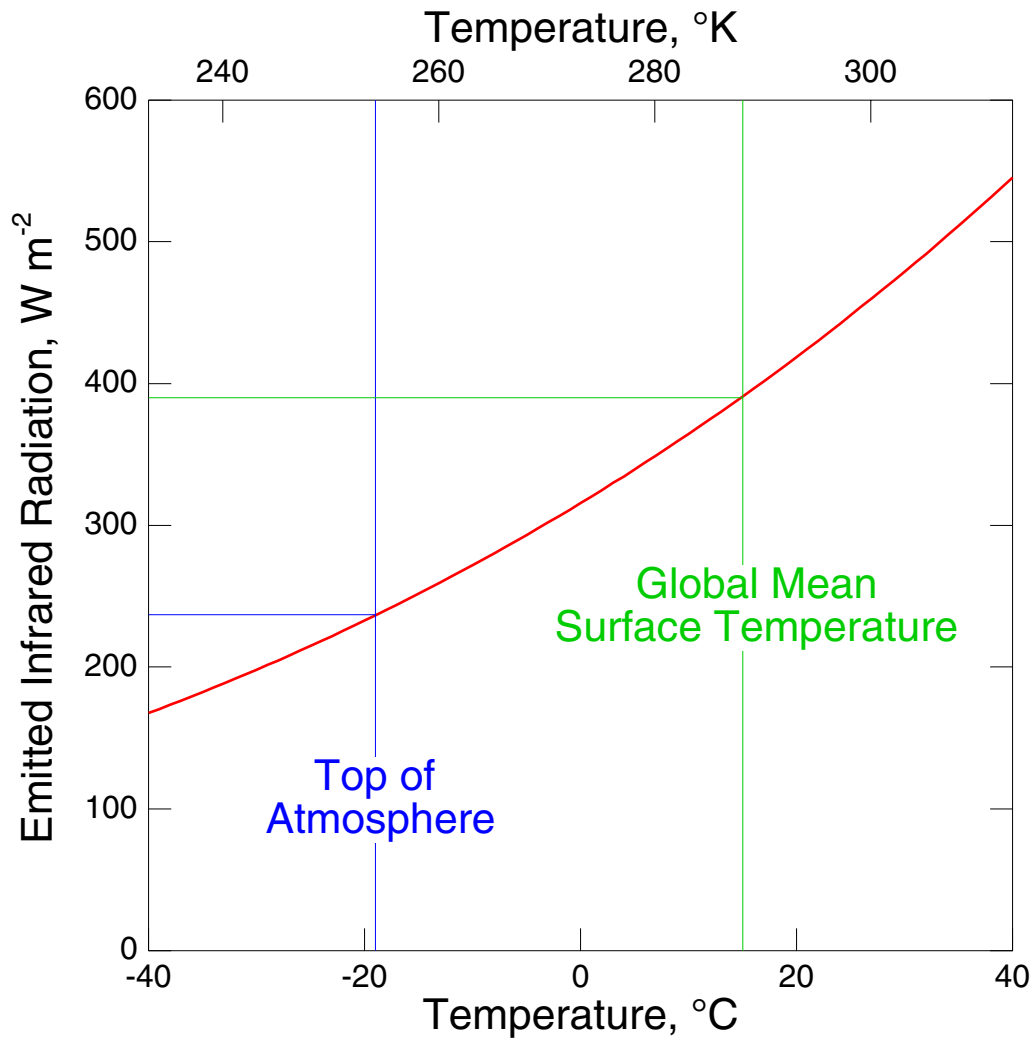
Emitted thermal radiative flux from a black body

$$F = \sigma T^4$$

F = Emitted flux, W m^{-2}

T = Absolute temperature, K

σ = Stefan-Boltzmann constant, W m^{-2} K^{-4}



Stefan-Boltzmann law "converts" temperature to radiative flux.

RADIATIVE FORCING

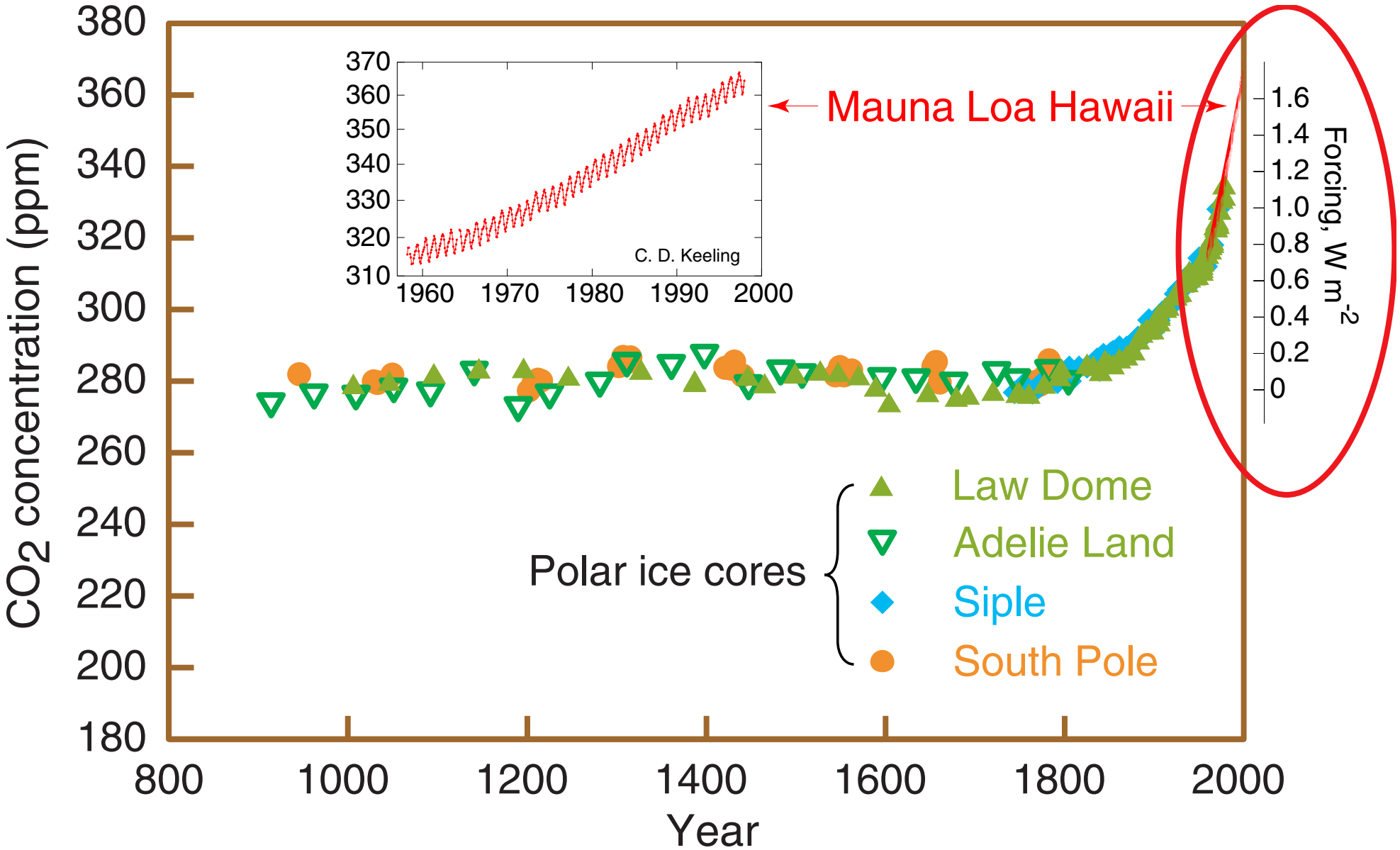
A ***change*** in a radiative flux term in Earth's radiation budget, ΔF, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and fungible.

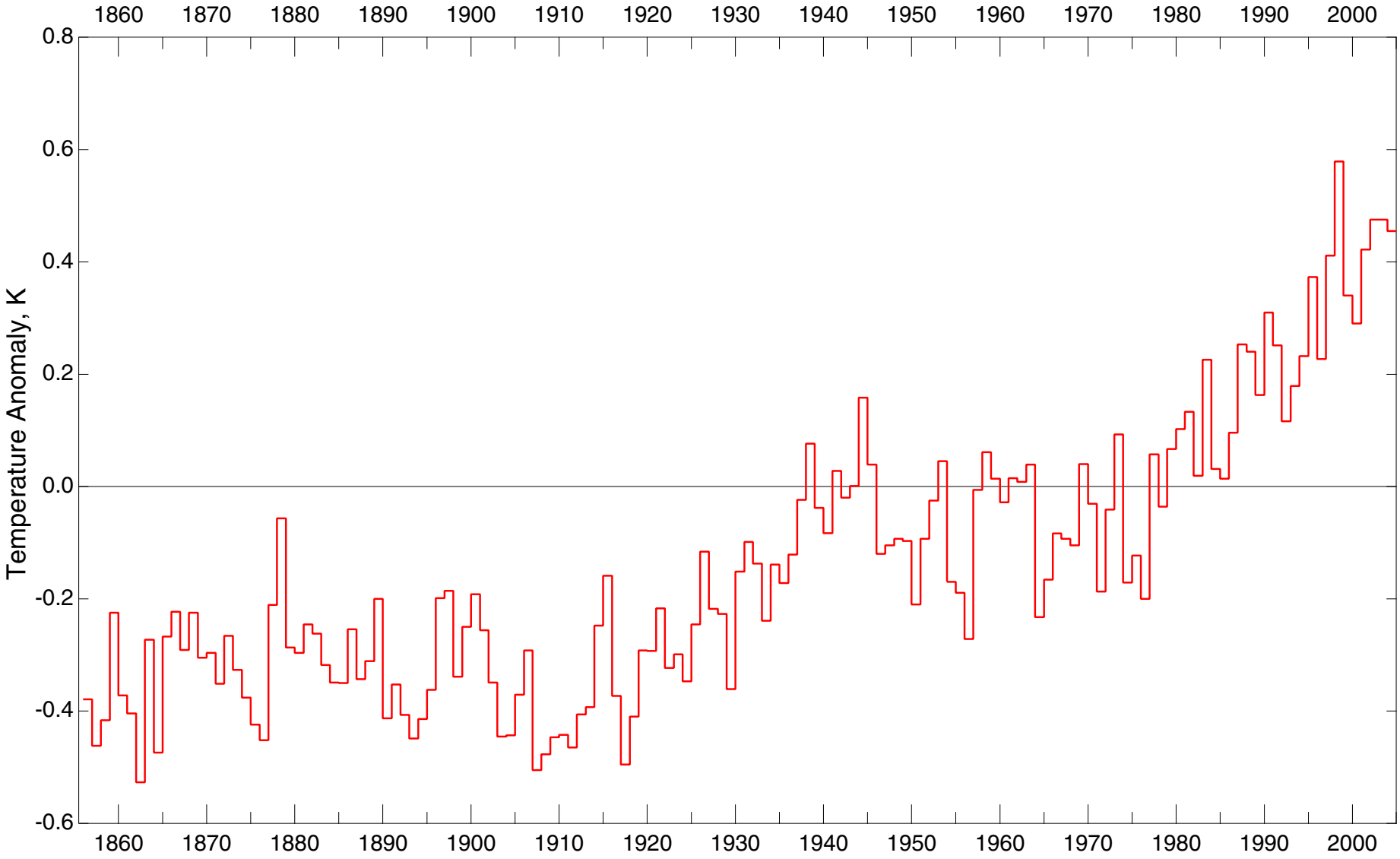
- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

ATMOSPHERIC CARBON DIOXIDE IS INCREASING



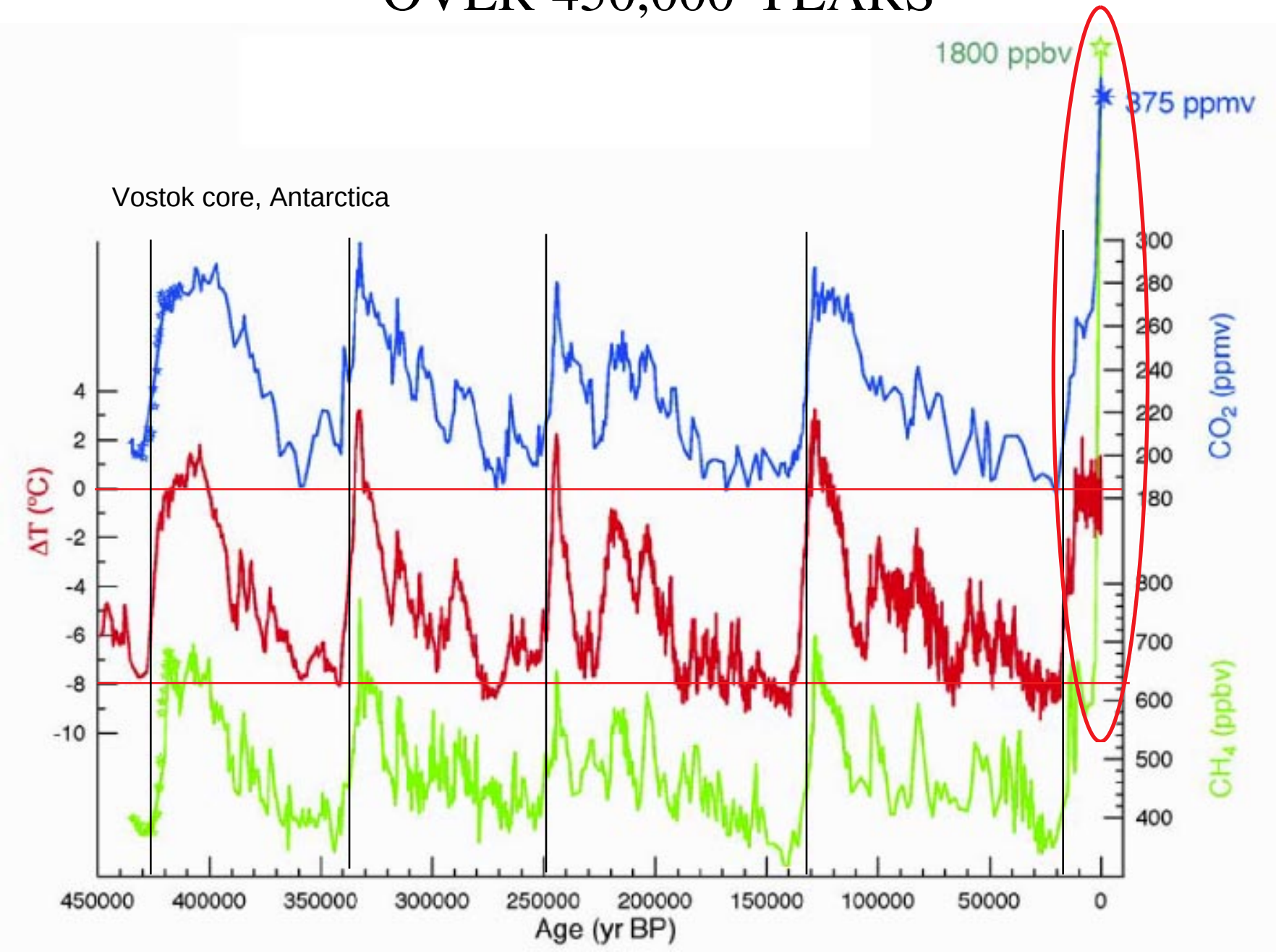
Global carbon dioxide concentration and infrared radiative forcing over the last thousand years

CHANGE IN GLOBAL MEAN SURFACE TEMPERATURE 1855-2004



Climate Research Unit, University of East Anglia, UK

GREENHOUSE GASES AND TEMPERATURE OVER 450,000 YEARS



Modified from Petit et al., Nature, 1999

KEY QUESTIONS

Is the observed temperature increase due to the increase in CO_2?

Can the observed temperature increase be ***quantitatively attributed*** to the increase in CO_2?

How much more will Earth's temperature increase?

- Geophysics
- Future emissions

Understanding the properties of Earth's climate system is essential to informed decision making on future emissions and energy policy.

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.

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

where ΔF, the change in radiative flux, is the forcing.

CLIMATE SENSITIVITY

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

$$\boxed{S = \Delta T/\Delta F.}$$

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

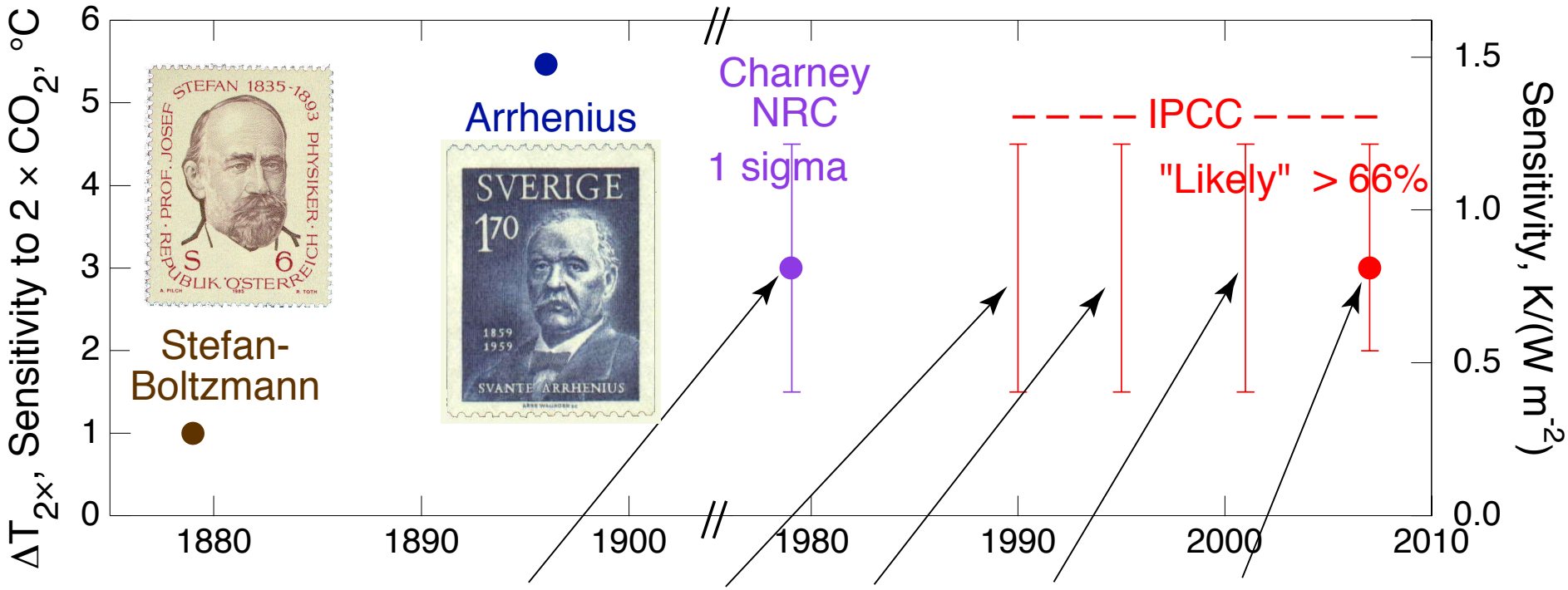
Climate sensitivity is often expressed as the temperature for doubled CO_2 concentration $\Delta T_{2\times}$.

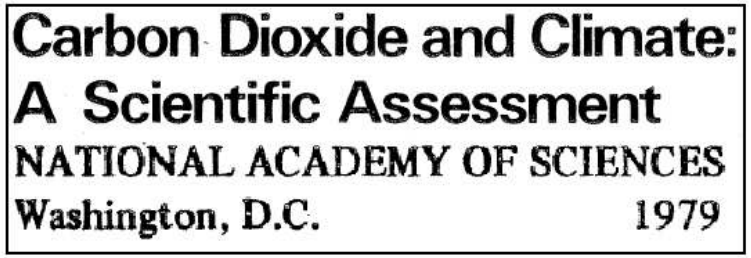
$$\Delta T_{2\times} = S\Delta F_{2\times}$$

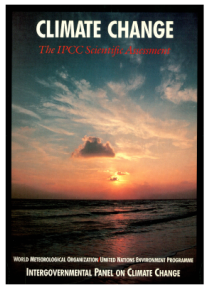
$$\Delta F_{2\times} \approx 3.7 \text{ W m}^{-2}$$

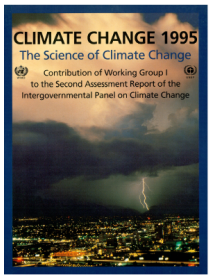
CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

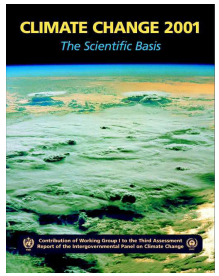
Estimates of central value and uncertainty range from major national and international assessments

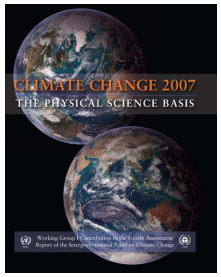






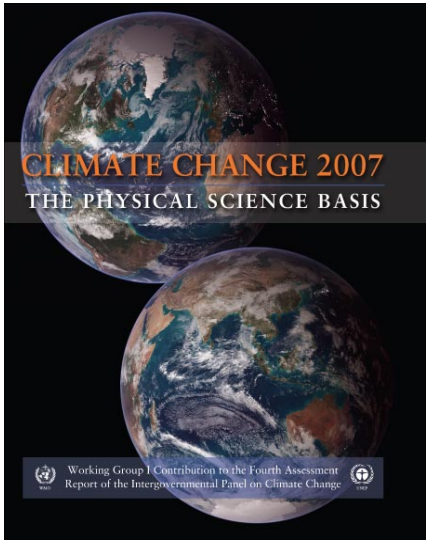






Despite extensive research, climate sensitivity remains ***highly uncertain***.

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 skeptics.

It can be downloaded.

IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

Uncertainty in climate sensitivity translates directly into . . .

- Uncertainty in the amount of ***incremental atmospheric*** $\mathbf{CO_2}$ 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 more than a factor of 2.

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

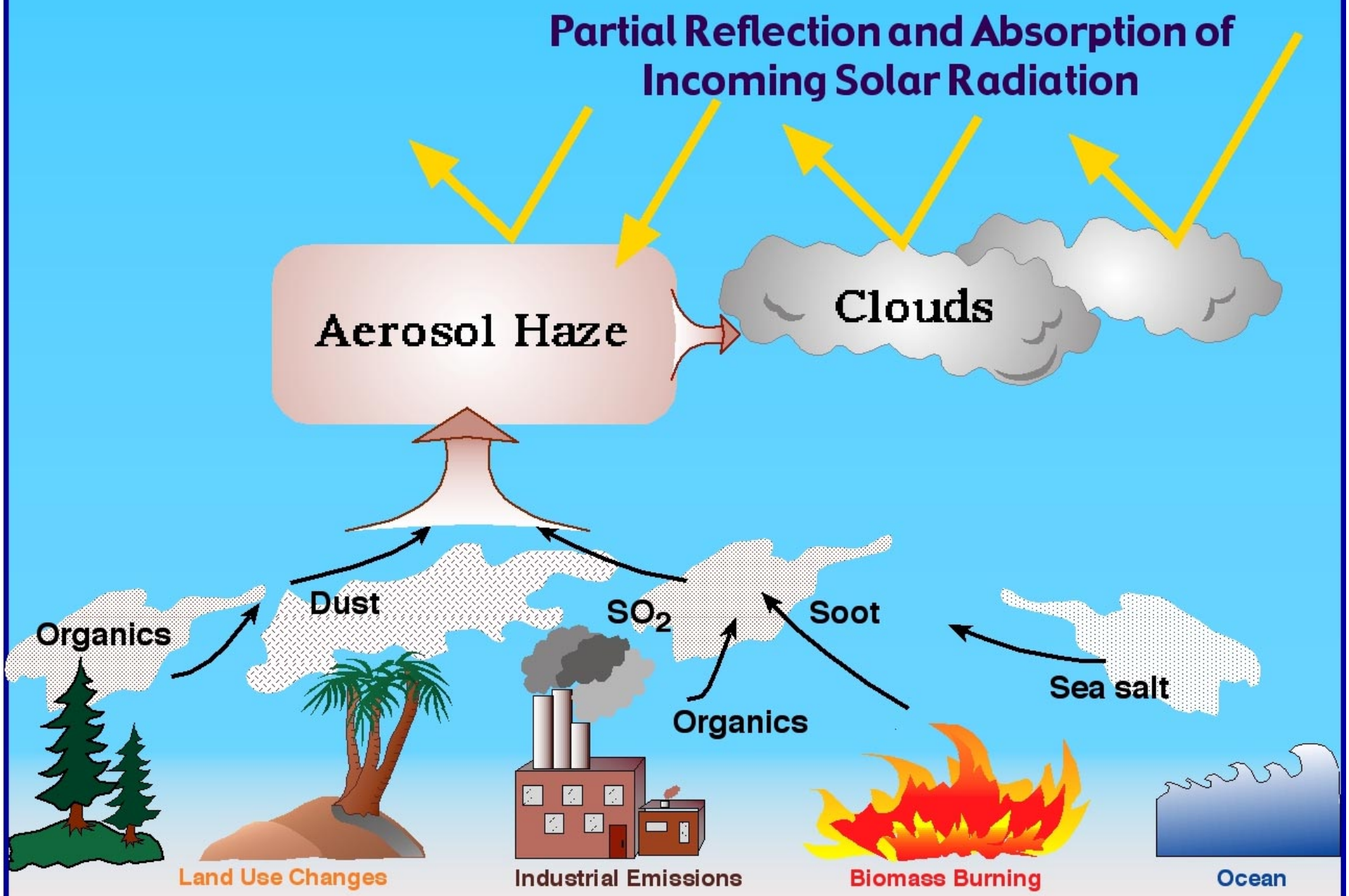
- The half life of incremental atmospheric CO_2 is about 100 years.
- The expected life of a new coal-fired power plant is 50 to 75 years.

Actions taken today will have long-lasting effects.

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

AEROSOLS
THE “MONKEY WRENCH” OF FORCING

Radiative Forcing by Tropospheric Aerosol

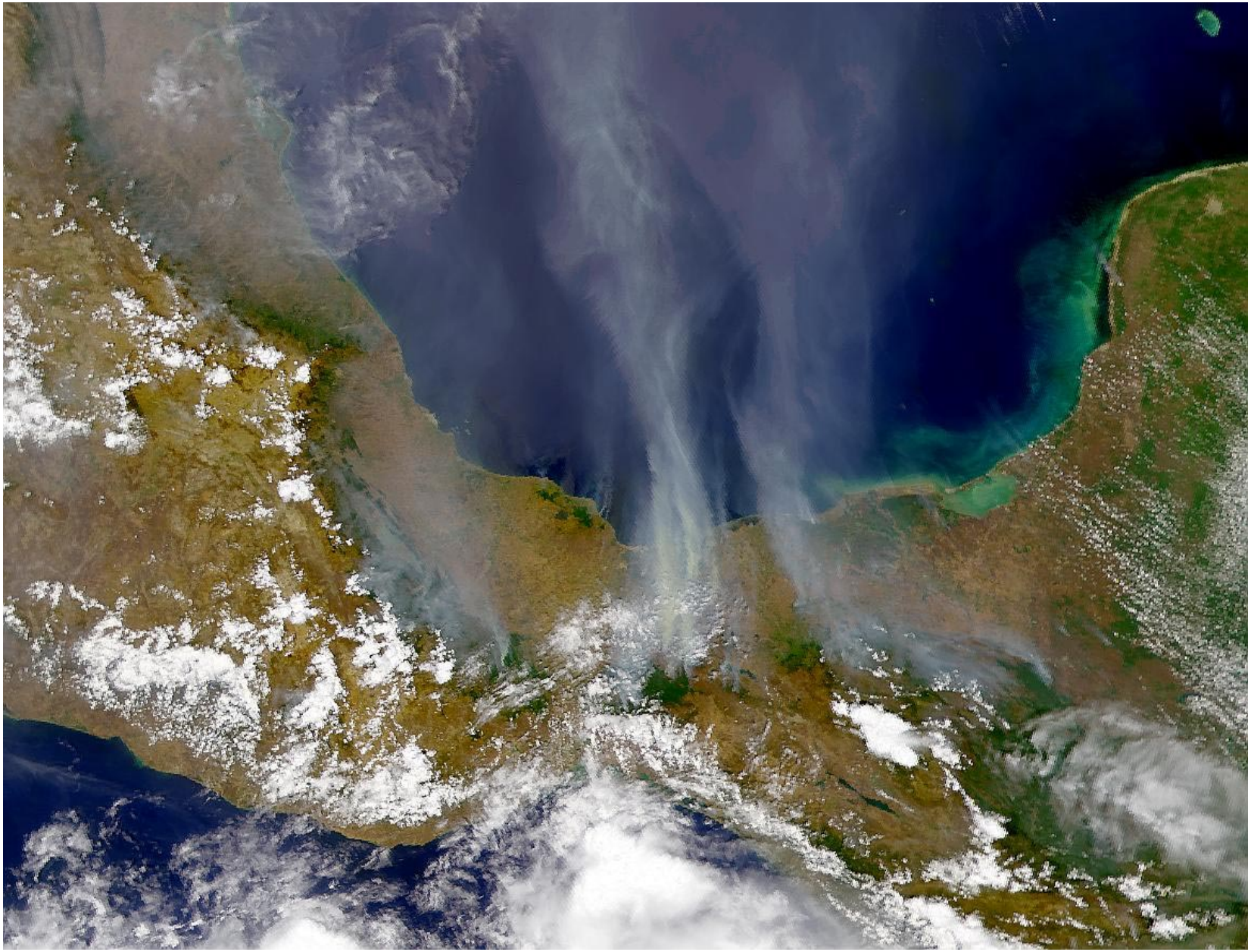


AEROSOL IN MEXICO CITY BASIN

AEROSOL IN MEXICO CITY BASIN

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

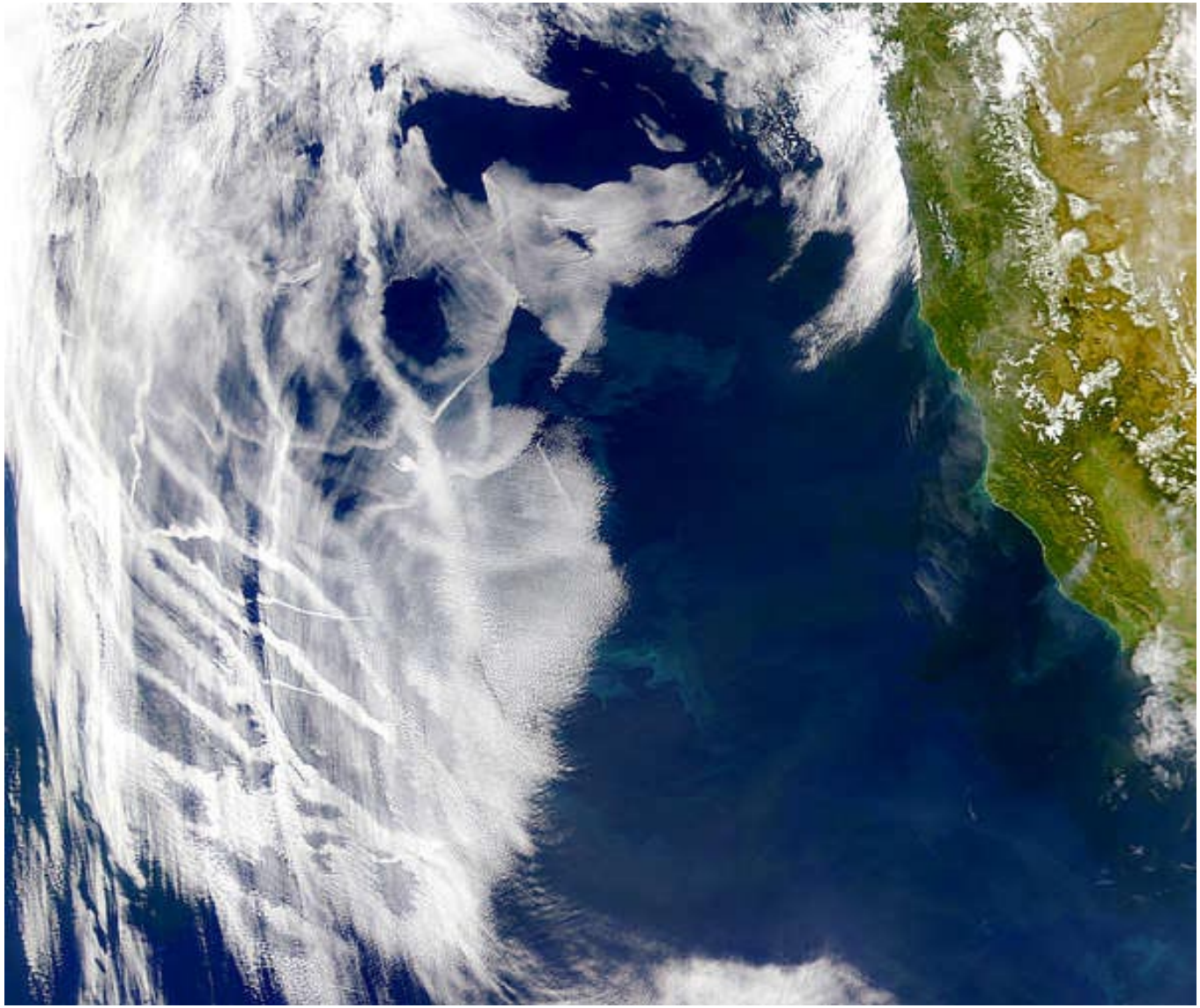
AEROSOLS AS SEEN FROM SPACE



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

CLOUD BRIGHTENING BY SHIP TRACKS

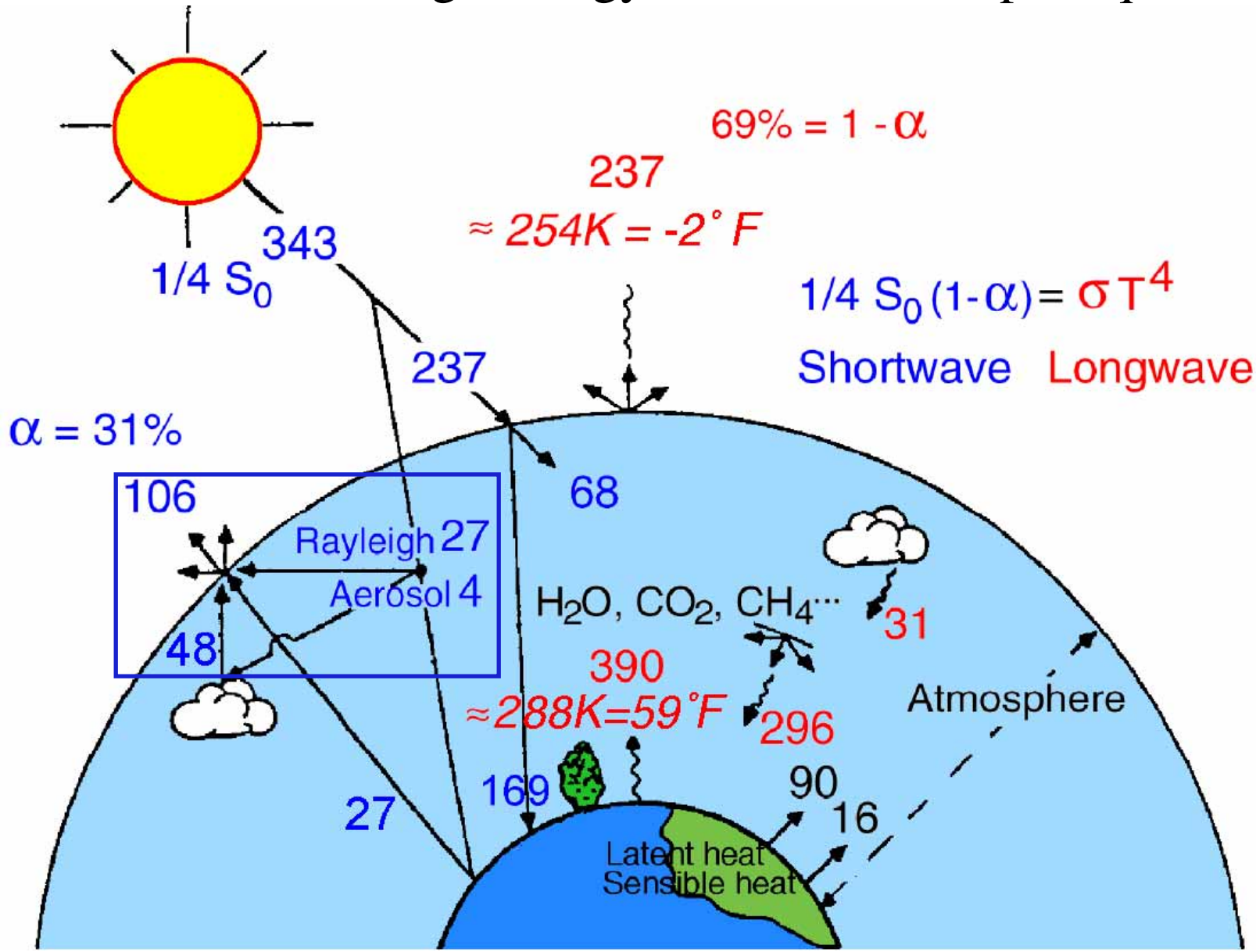
Satellite photo off California coast



Aerosols from ship emissions enhance reflectivity of marine stratus.

GLOBAL ENERGY BALANCE

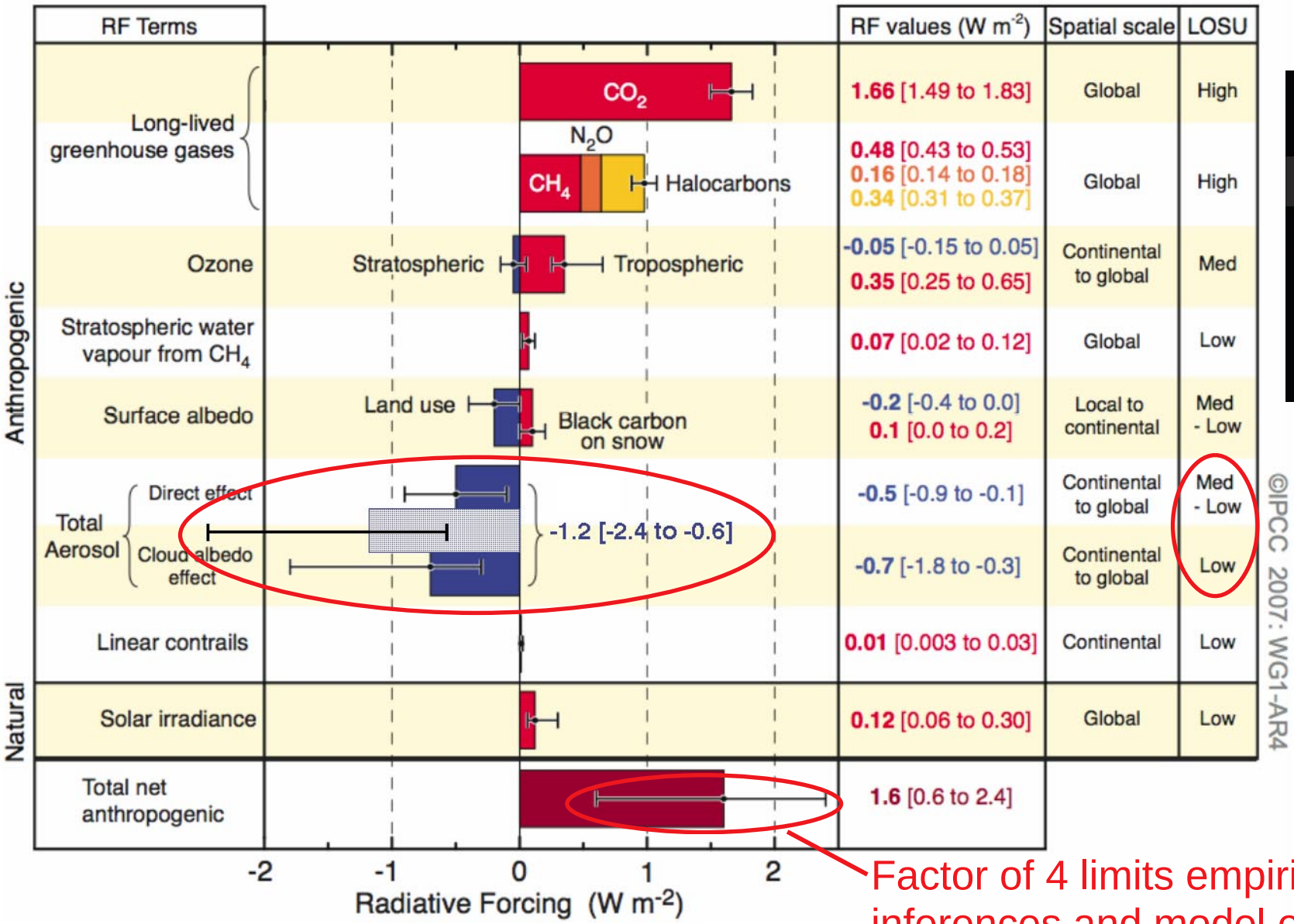
Global and annual average energy fluxes in watts per square meter

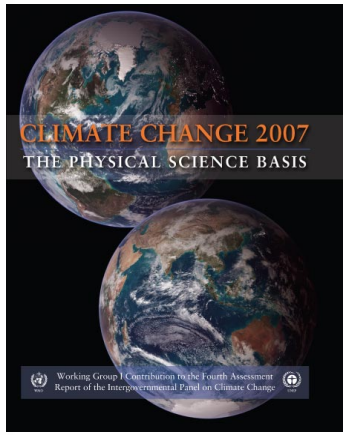


Schwartz, 1996, modified from Ramanathan, 1987

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

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





Factor of 4 limits empirical inferences and model evaluation.

LOSU denotes level of scientific understanding.

Uncertainty range: 5 - 95%.

CLIMATE RESEARCH AT BNL

Atmospheric Science Program

Radiative forcing by atmospheric aerosols
Field programs, instrument development, modeling

Atmospheric Radiation Measurement Program

Atmospheric radiation and controlling variables, esp. clouds
Measurement, modeling, data management

New York Center for Computational Sciences

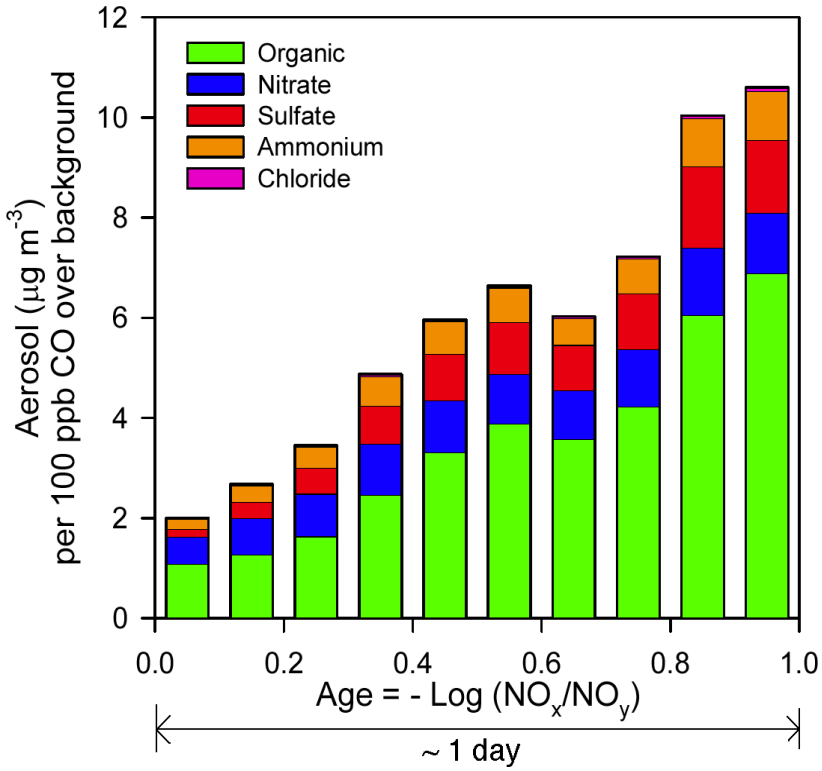
Cooperative effort between BNL and Stony Brook University with support from New York state

ASD INVESTIGATORS AT FIELD PROJECT IN MEXICO, 2006

AIRCRAFT MEASUREMENTS

SECONDARY AEROSOL PRODUCTION

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



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***.

ARM MOBILE FACILITY

DEPLOYMENT IN NIAMEY, NIGER

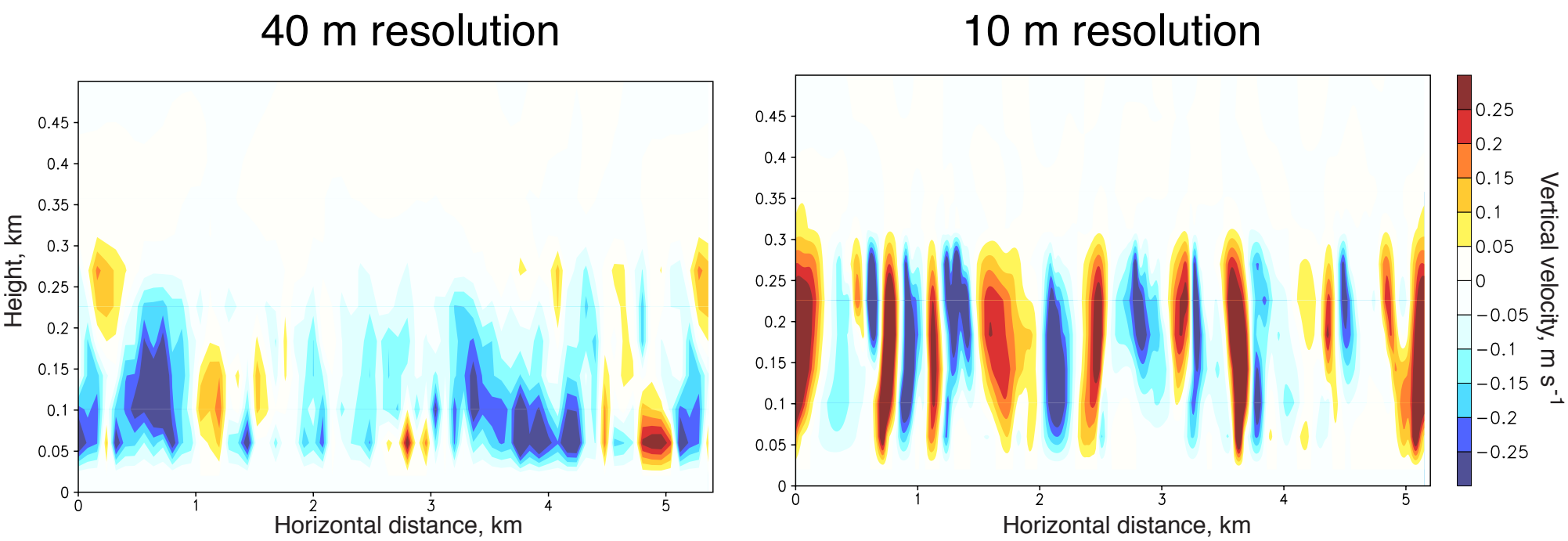
ADVANCING CLIMATE SCIENCE THROUGH GROUNDBREAKING COMPUTATIONS

Massively parallel "Blue Gene" computer increases understanding of climate processes

New York Center for Computational Sciences – Cooperative effort between BNL and Stony Brook University with support from New York state.

CLOUD STUDIES WITH BLUE GENE COMPUTER

Liquid water path in 5 km × 5 km cloud at two model resolutions

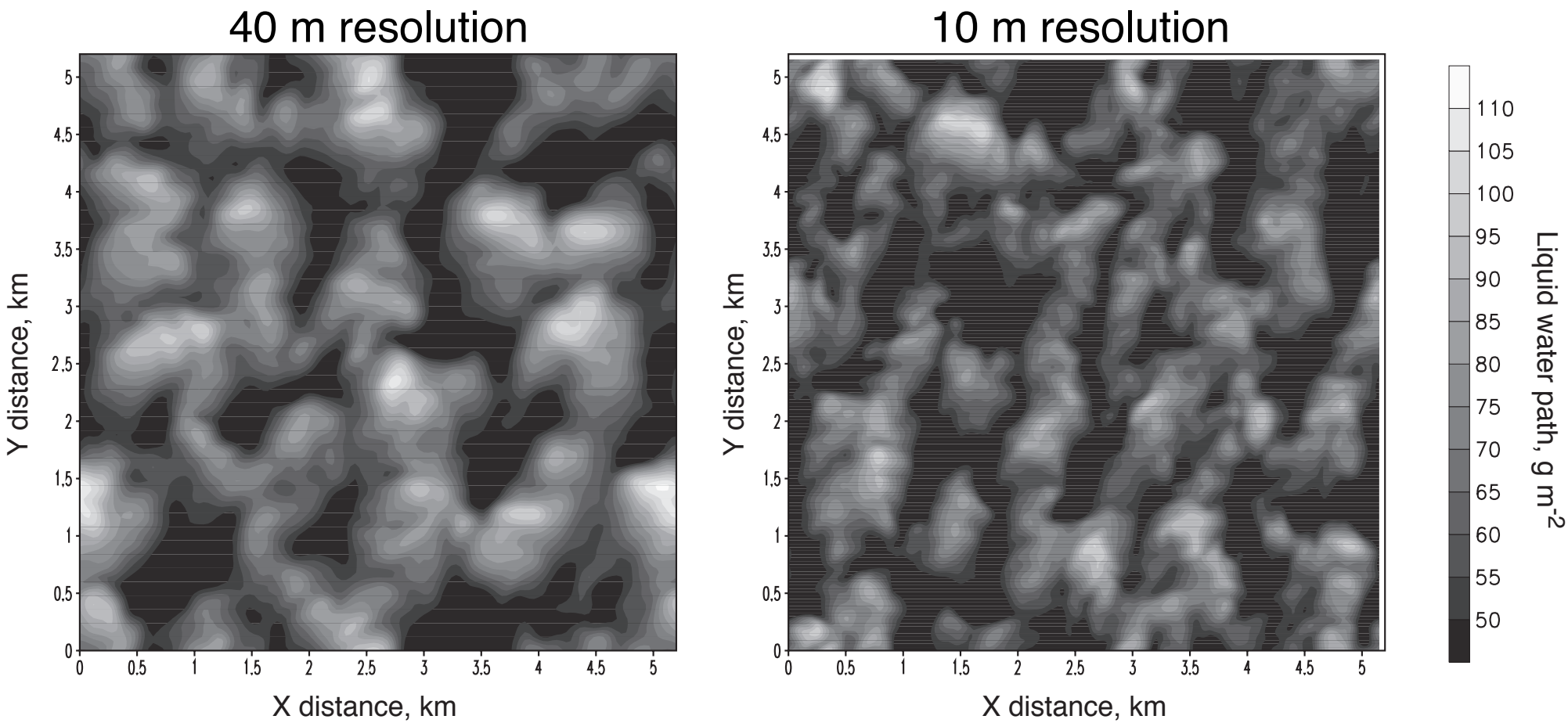


Increased computational power permits increased model resolution and improved representation of physical processes.

Higher resolution reveals stronger updrafts and downdrafts controlling cloud liquid water content and reflectivity.

CLOUD STUDIES WITH BLUE GENE COMPUTER

Liquid water path in 5 km × 5 km cloud at two model resolutions

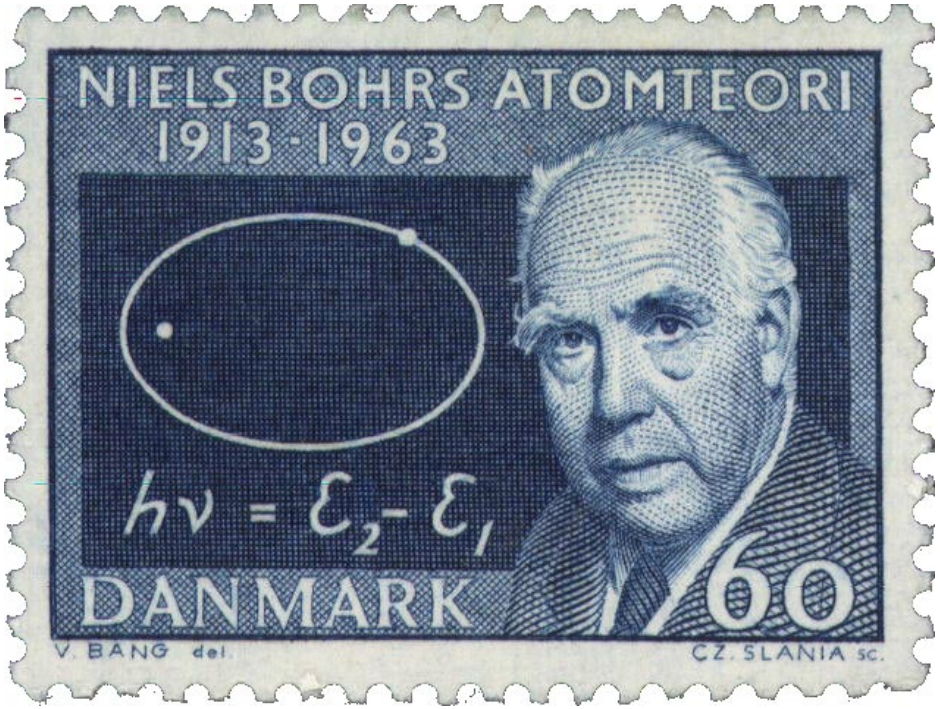


Increased computational power permits increased model resolution and improved representation of physical processes.

Average liquid water content is similar (7% decrease), but standard deviation is increased 50%.

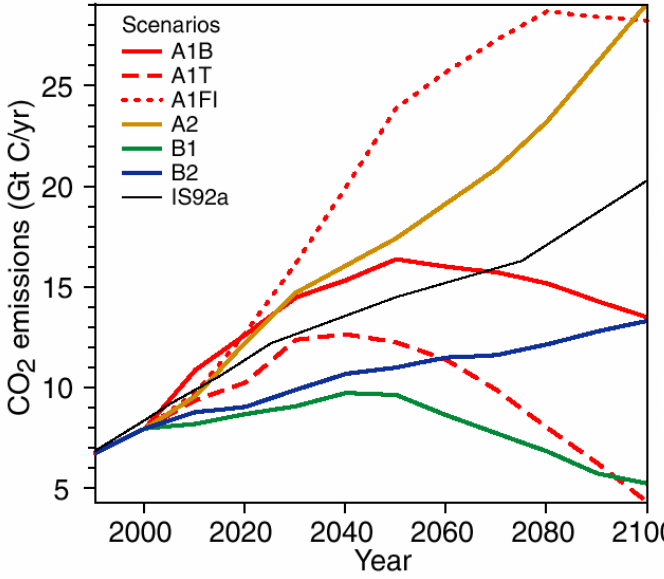
Looking to the Future . . .

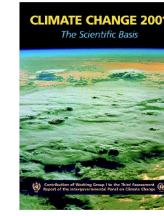
Prediction is difficult, especially about the future.



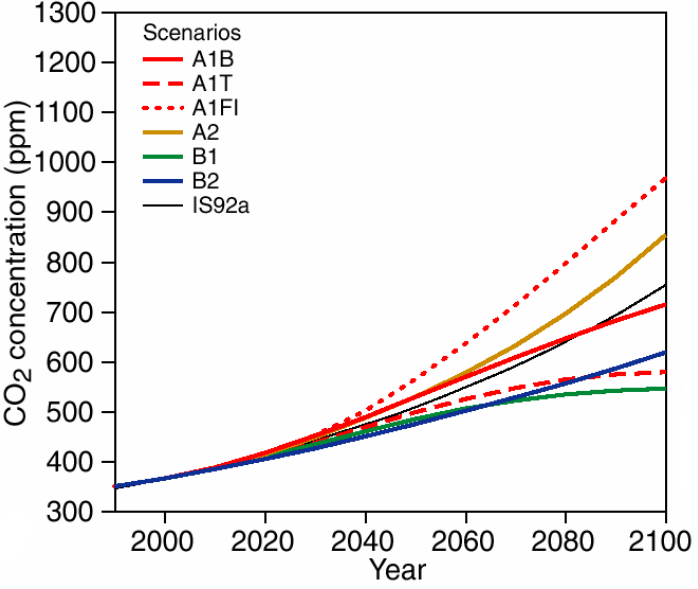
– Niels Bohr

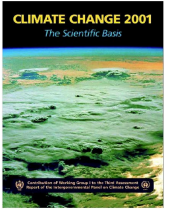
PROJECTIONS OF FUTURE CO2 EMISSIONS



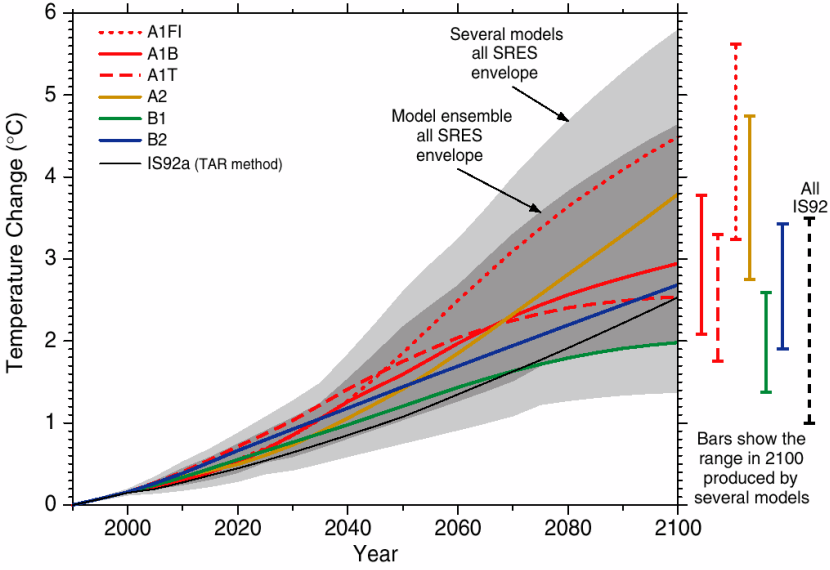


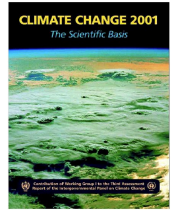
PROJECTIONS OF FUTURE CO2 CONCENTRATIONS



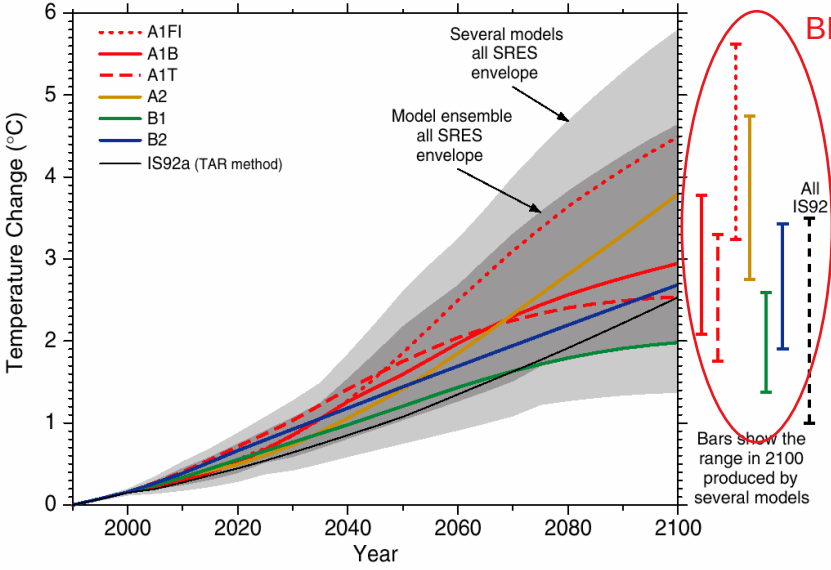


PROJECTIONS OF FUTURE TEMPERATURE CHANGE

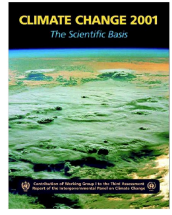




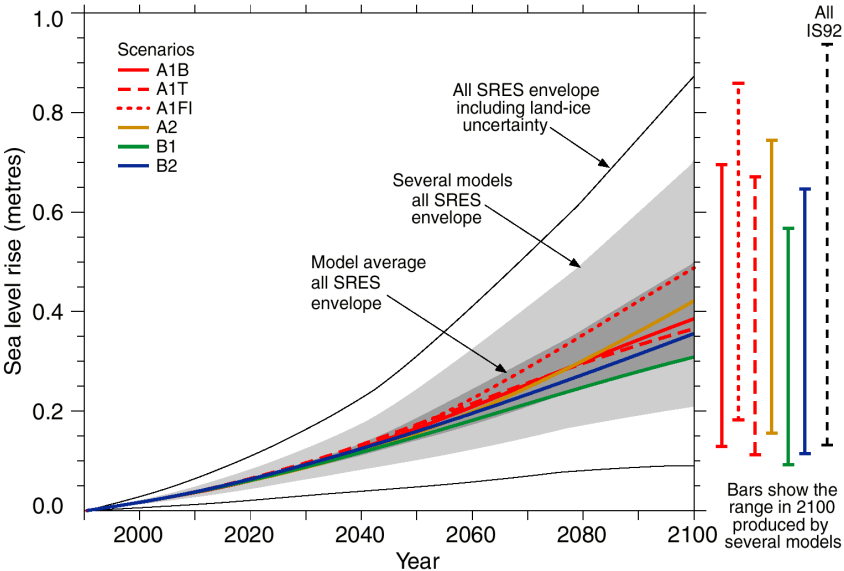
PROJECTIONS OF FUTURE TEMPERATURE CHANGE

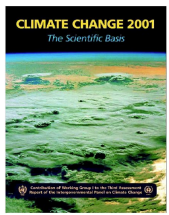


BNL Research

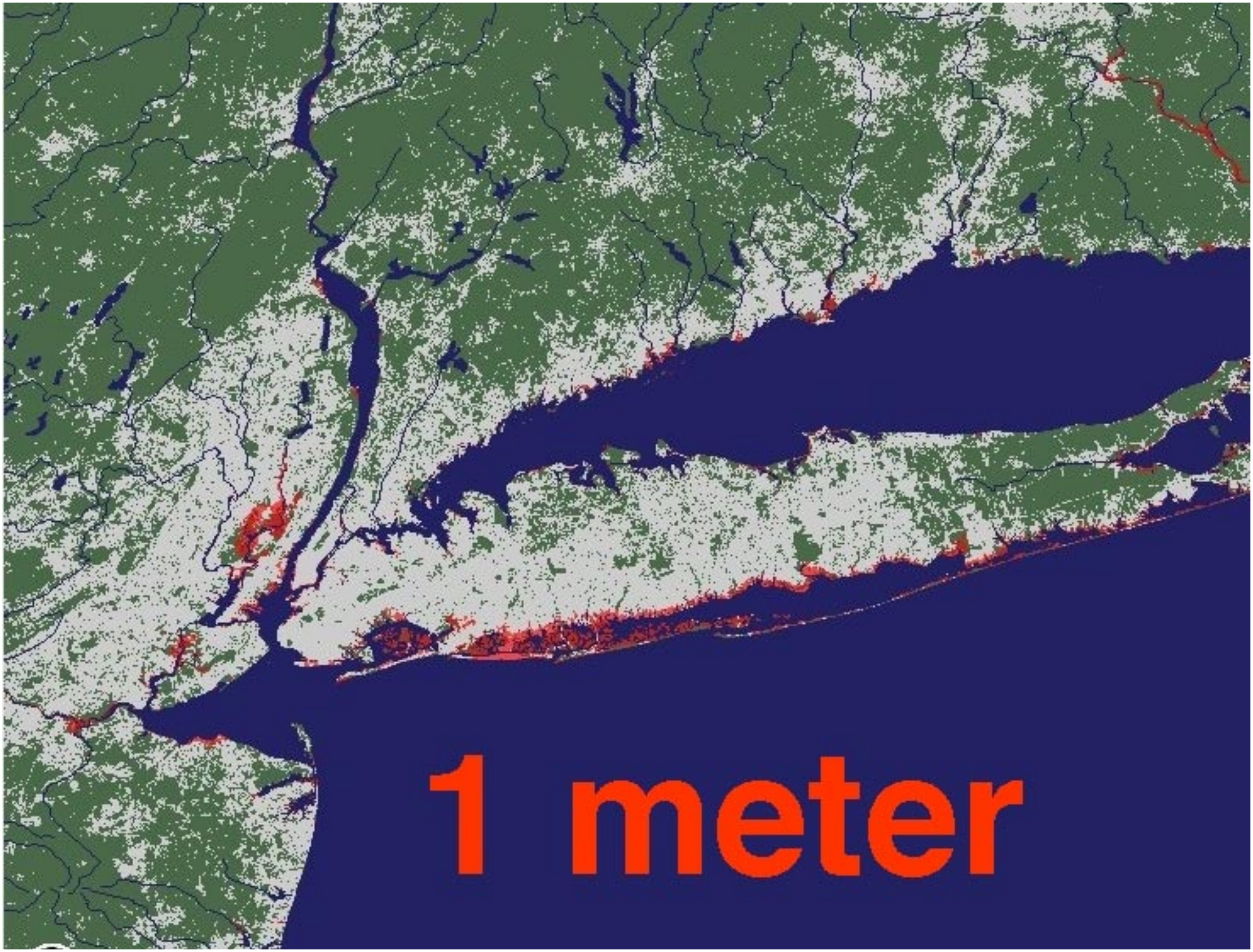


PROJECTIONS OF FUTURE SEA LEVEL RISE





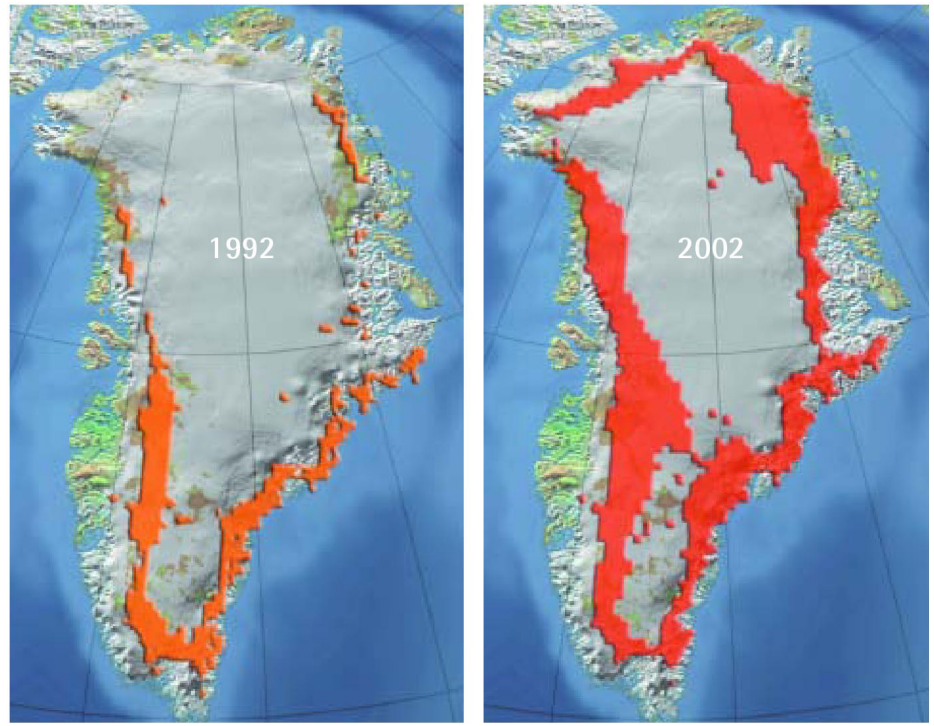
present


1 meter

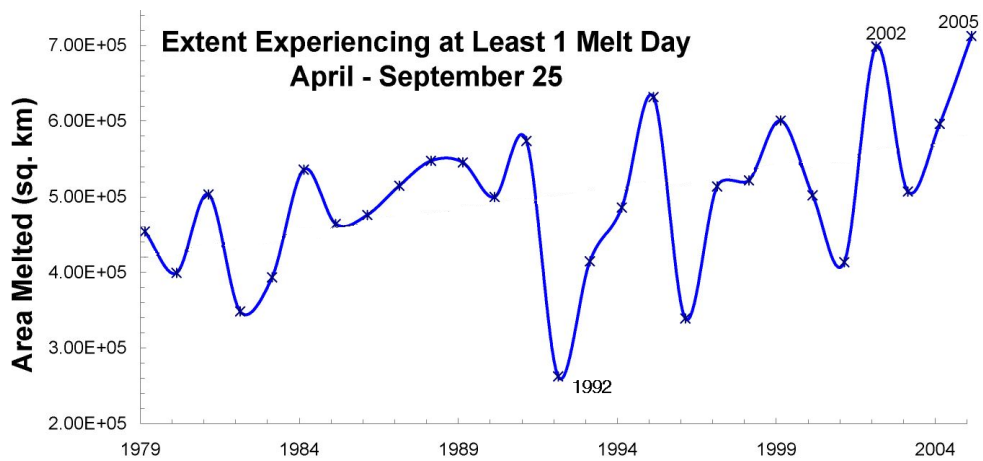
MELTING OF GREENLAND ICE CAP

Satellite determination of extent of glacial melt 1992 vs 2002

NASA

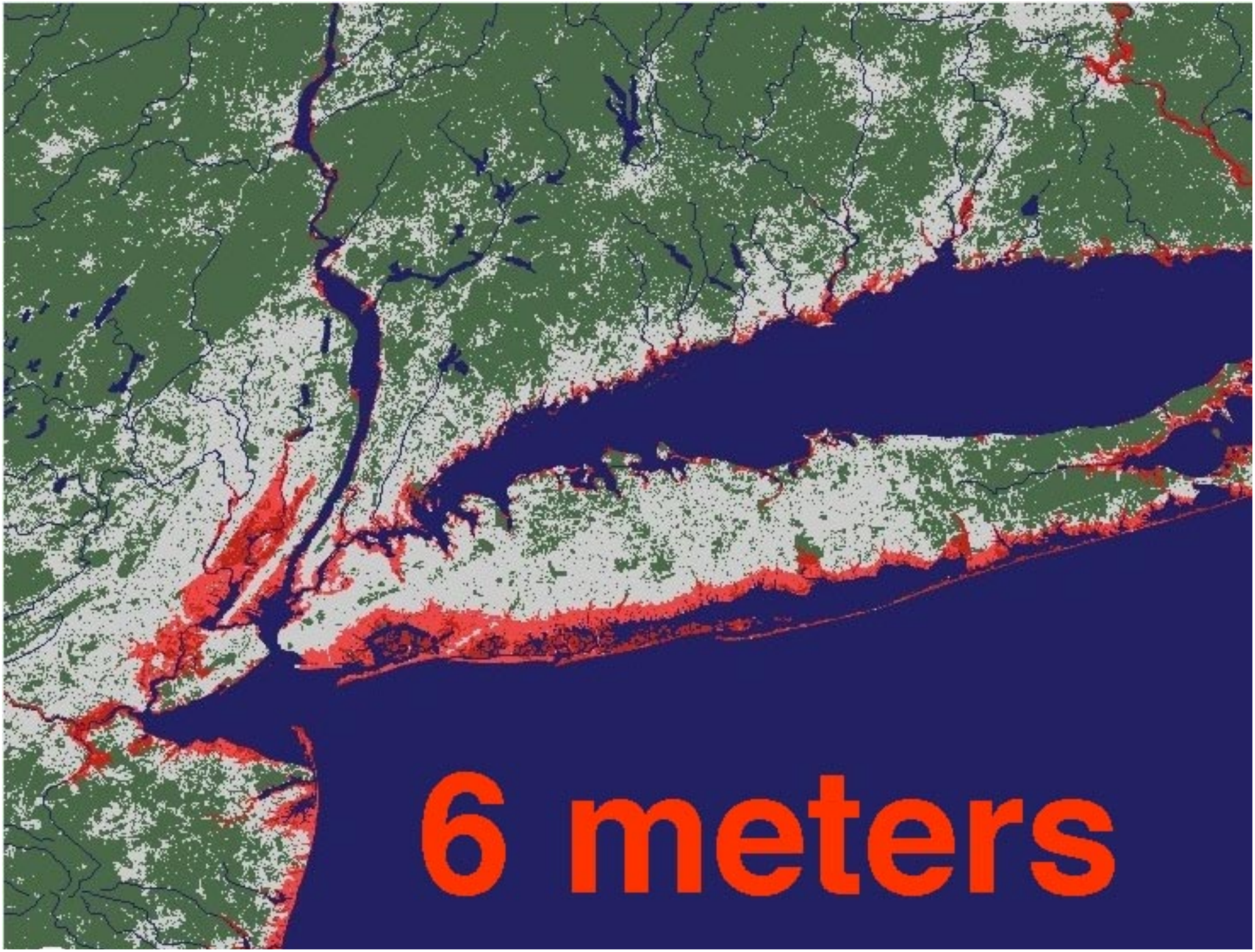


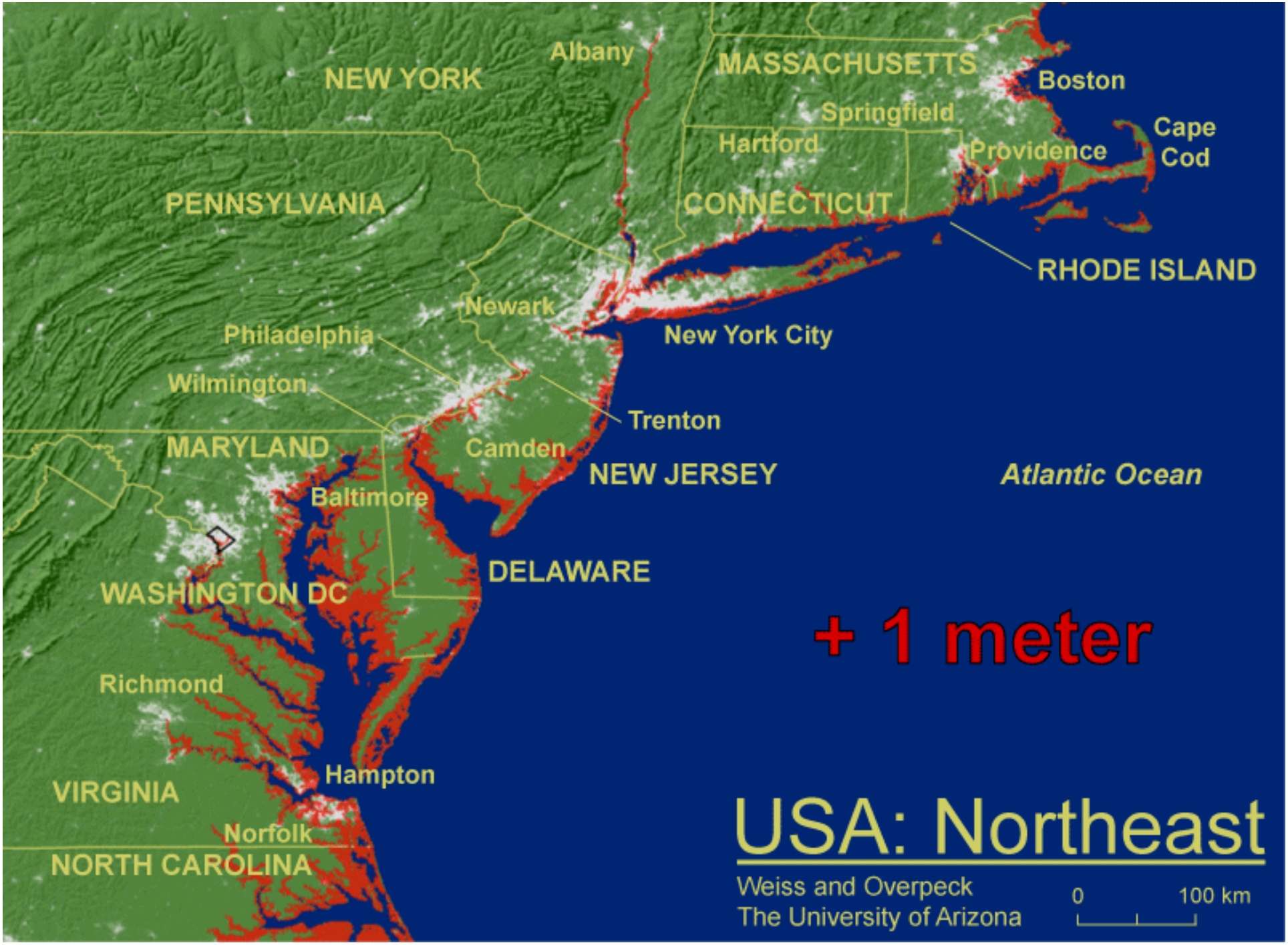
Arctic Climate Impact Assessment, Cambridge, 2004



Steffen & Huff , Univ. Colo., 2005

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


6 meters


NEW YORK
Albany
MASSACHUSETTS
Boston
Springfield
Hartford
Providence
Cape Cod
PENNSYLVANIA
CONNECTICUT
RHODE ISLAND
Newark
New York City
Philadelphia
Wilmington
Trenton
MARYLAND
Camden
NEW JERSEY
Atlantic Ocean
Baltimore
DELAWARE
WASHINGTON DC
+ 1 meter
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."

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***.

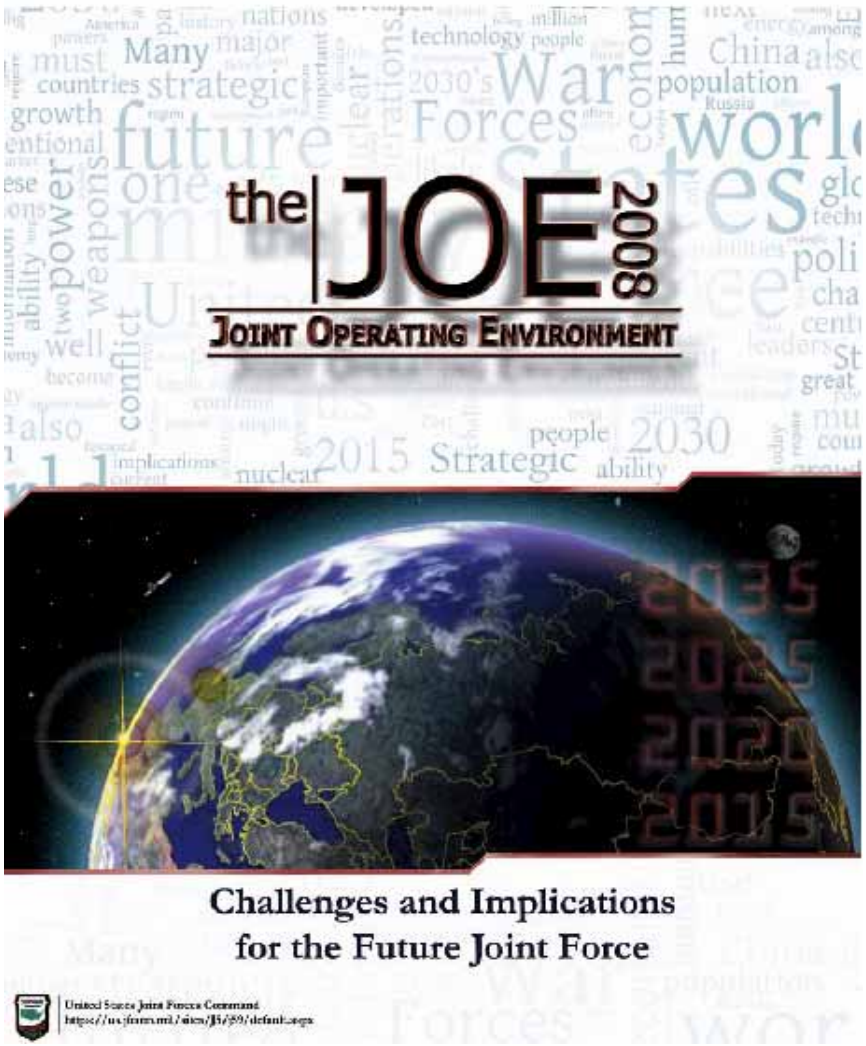
Present scientific understanding is sufficient to permit "no regrets" decision making.

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

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

JOINT OPERATING ENVIRONMENT 2008

DEPARTMENT OF DEFENSE

Climate Change and Natural Disasters

The impact of global warming and its potential to cause natural disasters and other harmful phenomena such as rising sea levels has become a prominent — and controversial — national and international concern. Some argue that there will be more and greater storms and natural disasters, others that there will be fewer. In many respects, scientific conclusions about the causes and potential effects of global warming are contradictory.