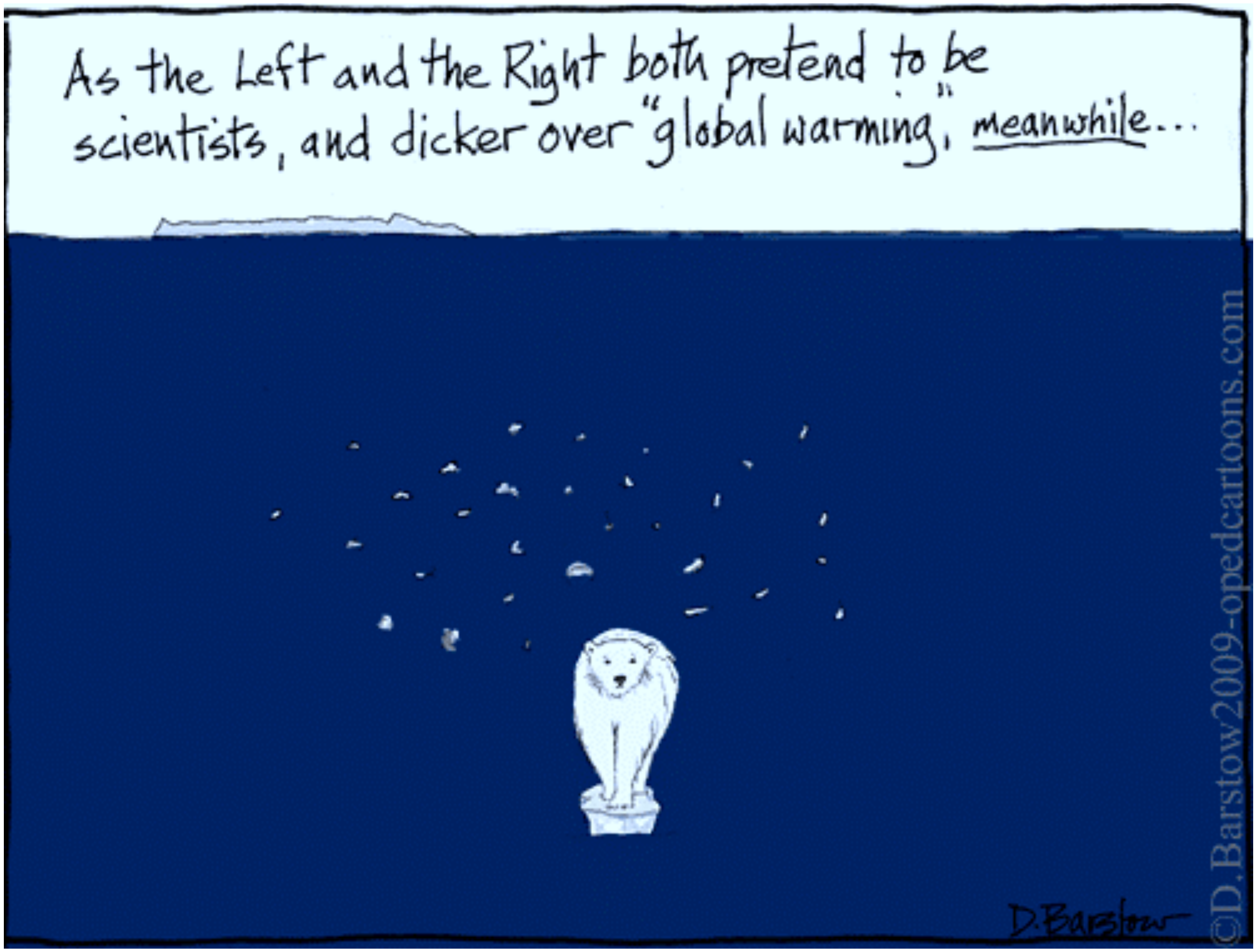
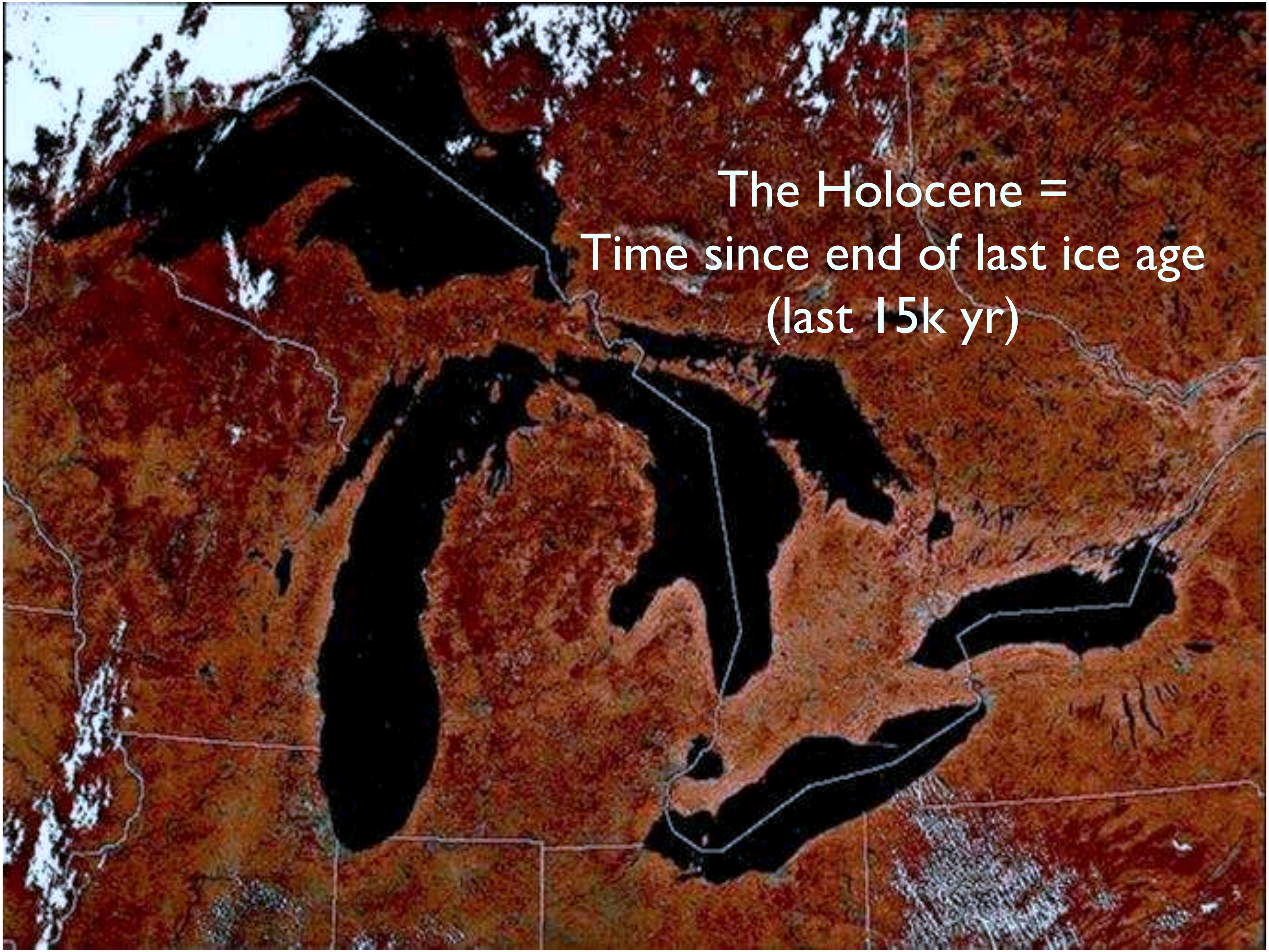
Welcome to ATMS 111 Global Warming

http://www.atmos.washington.edu/2010Q1/111




The Holocene =
Time since end of last ice age
(last 15k yr)

The Holocene Epoch

About 15,000 years ago, the earth began to warm* and the huge ice sheets began to melt. This had a number of impacts:

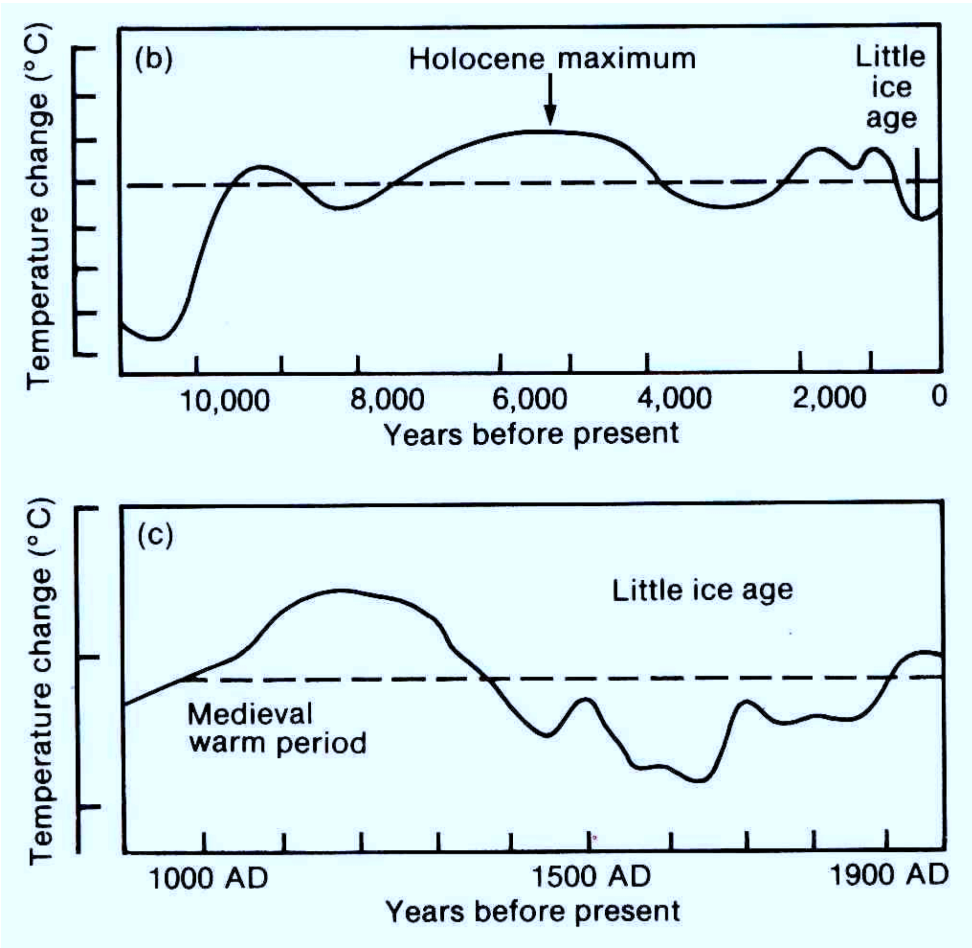
(1) lake formation in regions left behind by glaciers

(2) sea level rise

(3) Vegetation expanded

*warming leads CO2 rise

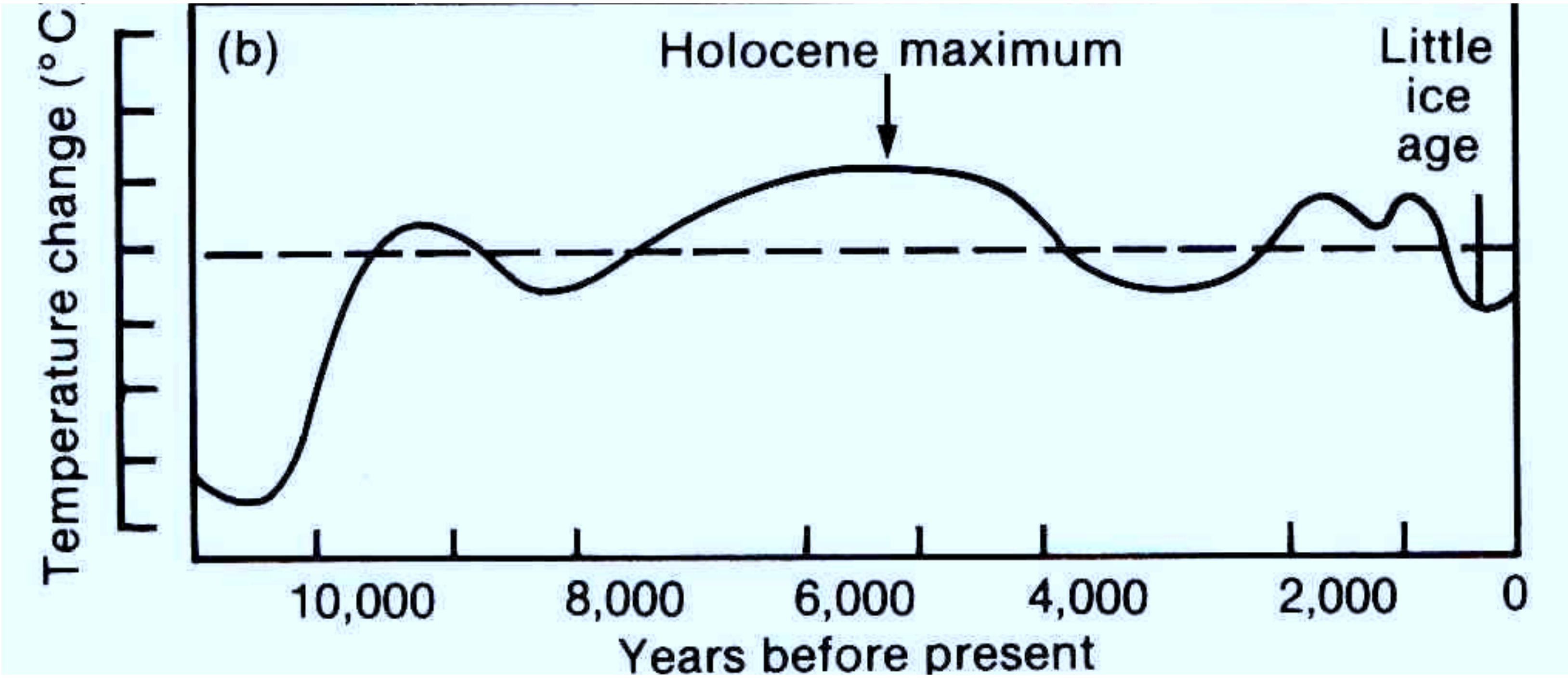
IPCC 1990



looking back at the history of global temperature

Note that there are no numbers on the temperature scales

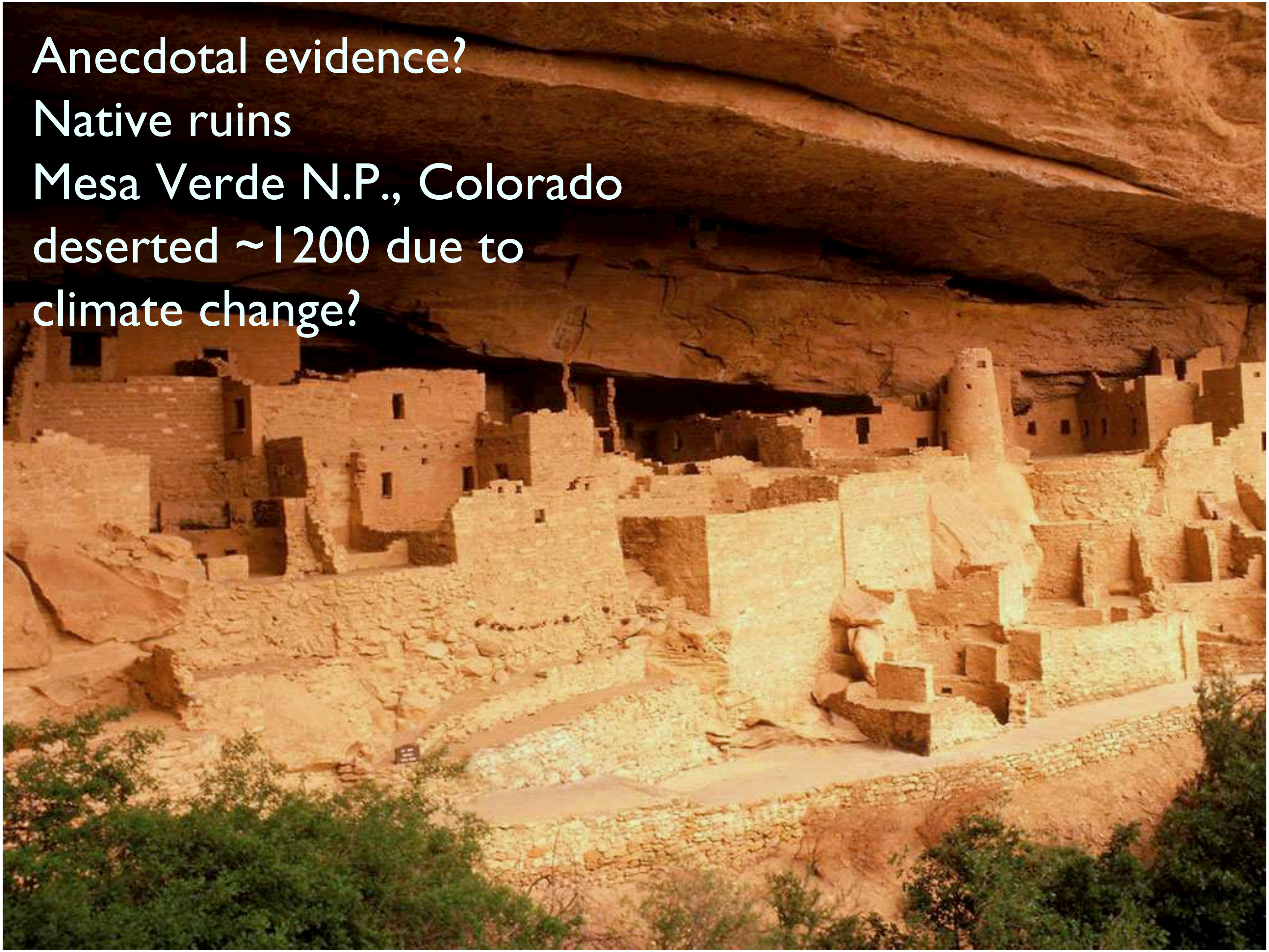
We have learned much about paleoclimate in the intervening years



Temperature change (°C
(b)
Holocene maximum
Little
ice
age
10,000
8,000
6,000
4,000
2,000
0
Years before present

IPCC 1990

Holocene


Anecdotal evidence?
Native ruins
Mesa Verde N.P., Colorado
deserted ~1200 due to
climate change?

Anecdotal evidence?
Several thousand people settled on Greenland from 1100-1450.

(56,000 people live on Greenland today)

“Hunters in the Snow” painted by Peter Bruegel in Feb 1565

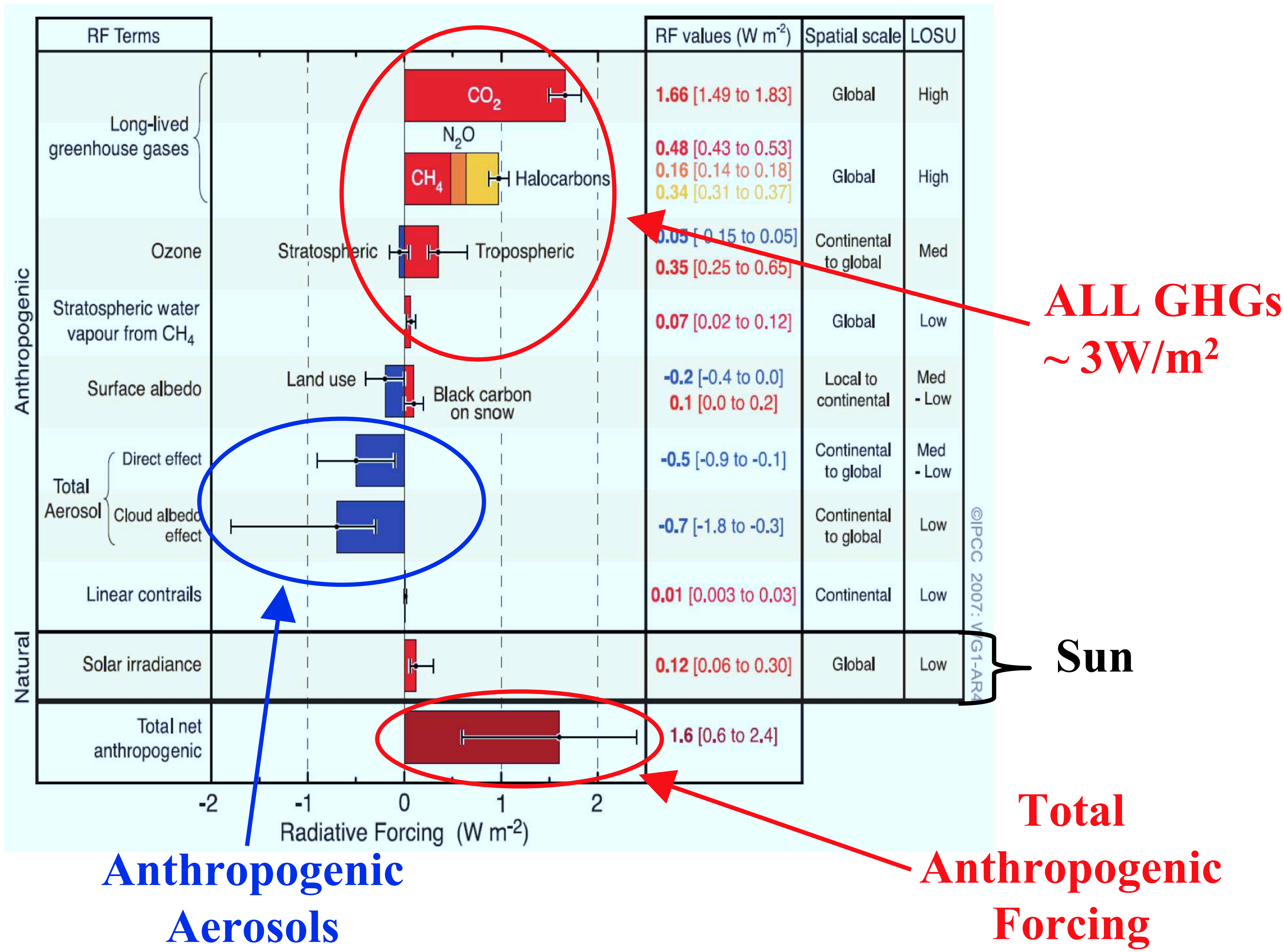
Medieval warmth and English wine

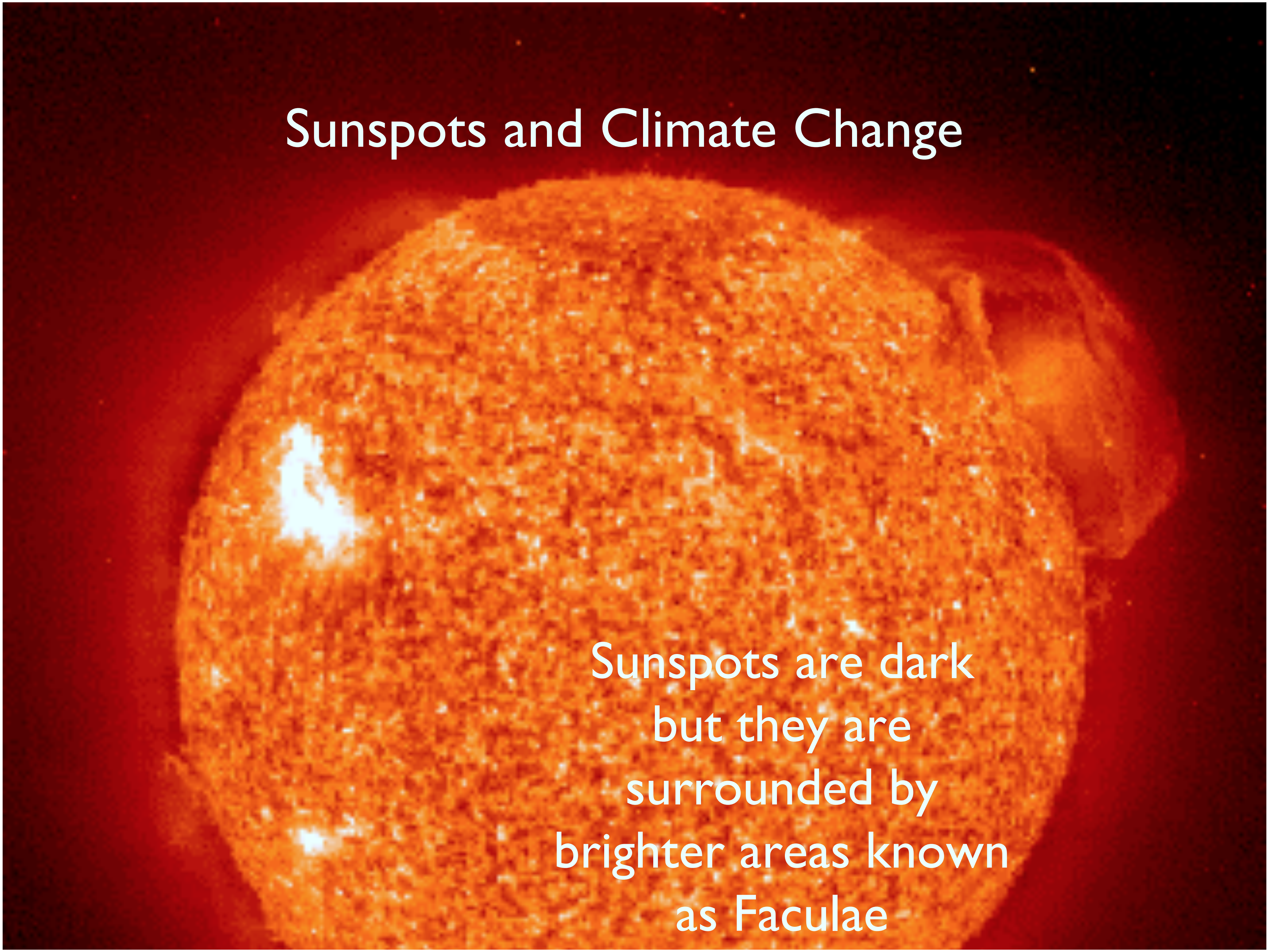
www.realclimate.org Blog by Gavin Schmidt

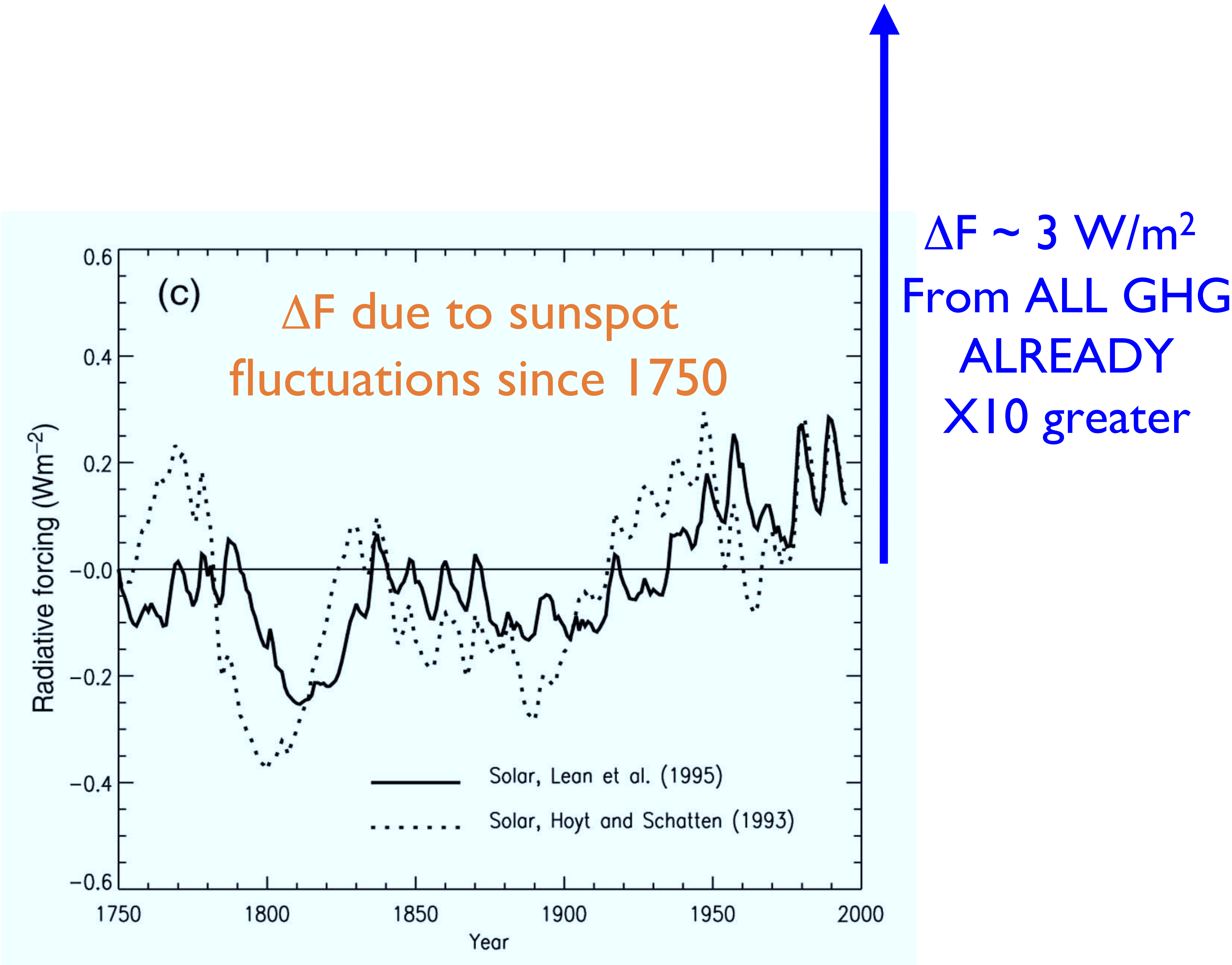
"Contemporary popular sentiment towards English (and Welsh) wine can be well judged by a comment in Punch (a satirical magazine) that the wine would require 4 people to drink it: one victim, two to hold him down, and one other to pour the wine down his throat."

Nonetheless there are over 200 vineyards in Enland today.

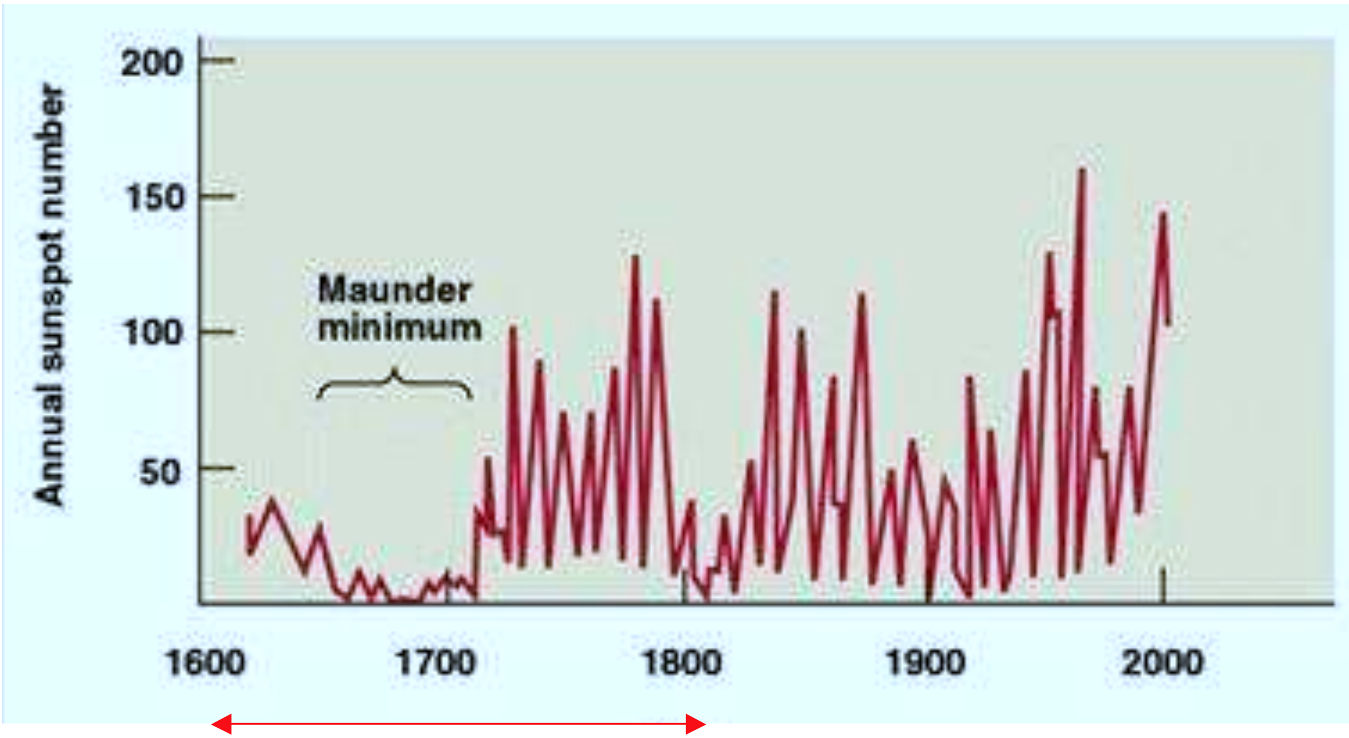
Forcing In 2005 relative to **preindustrial**




Sunspots and Climate Change
Sunspots are dark
but they are
surrounded by
brighter areas known
as Faculae


ΔF due to sunspot fluctuations since 1750
ΔF ~ 3 W/m²
From ALL GHG
ALREADY
X10 greater
(c)
Radiative forcing (Wm⁻²)
0.6
0.4
0.2
−0.0
−0.2
−0.4
−0.6
1750
1800
1850
1900
1950
2000
Year
Solar, Lean et al. (1995)
Solar, Hoyt and Schatten (1993)

Prior to satellite era, we rely on sunspot number to infer the Solar (roughly) constant, S



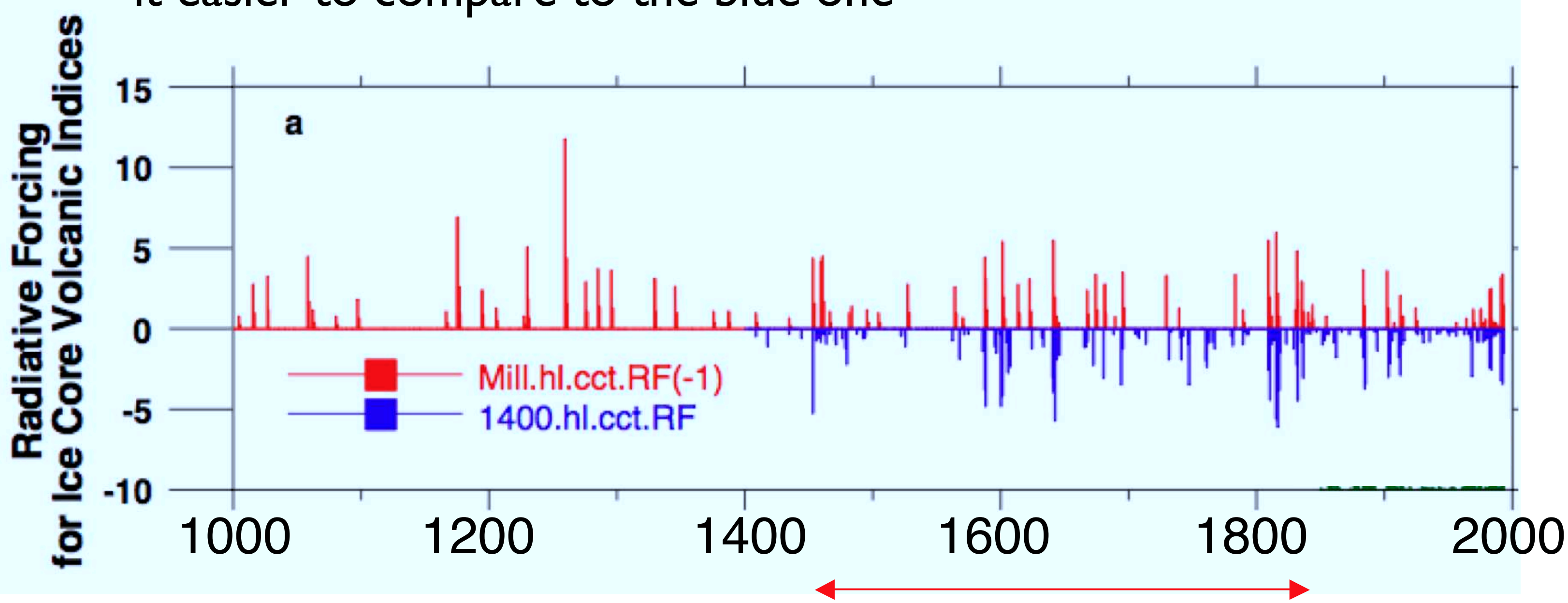
Little Ice Age?

But their number is related to S in an uncertain way => controversy

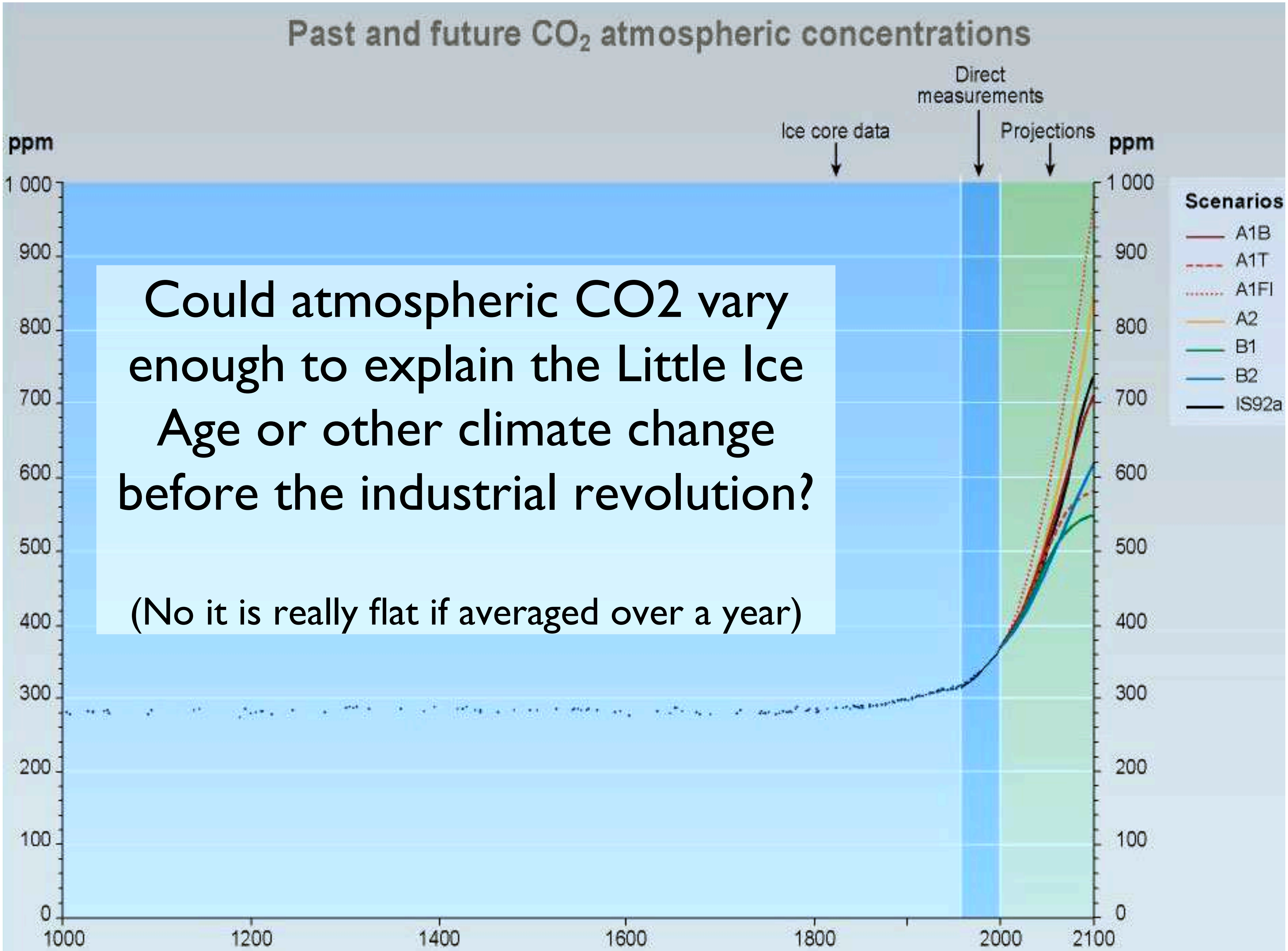
Could enhanced volcanic activity be the primary cause of the Little Ice Age??

We know that global-mean temperature drops after volcanic eruptions and takes ~5 years to recover.

Ice core records provide evidence of volcanic eruptions extending back over 1000 years. Here the red estimate is flipped up to make it easier to compare to the blue one



Little Ice Age?



Could atmospheric CO2 vary enough to explain the Little Ice Age or other climate change before the industrial revolution?

(No it is really flat if averaged over a year)

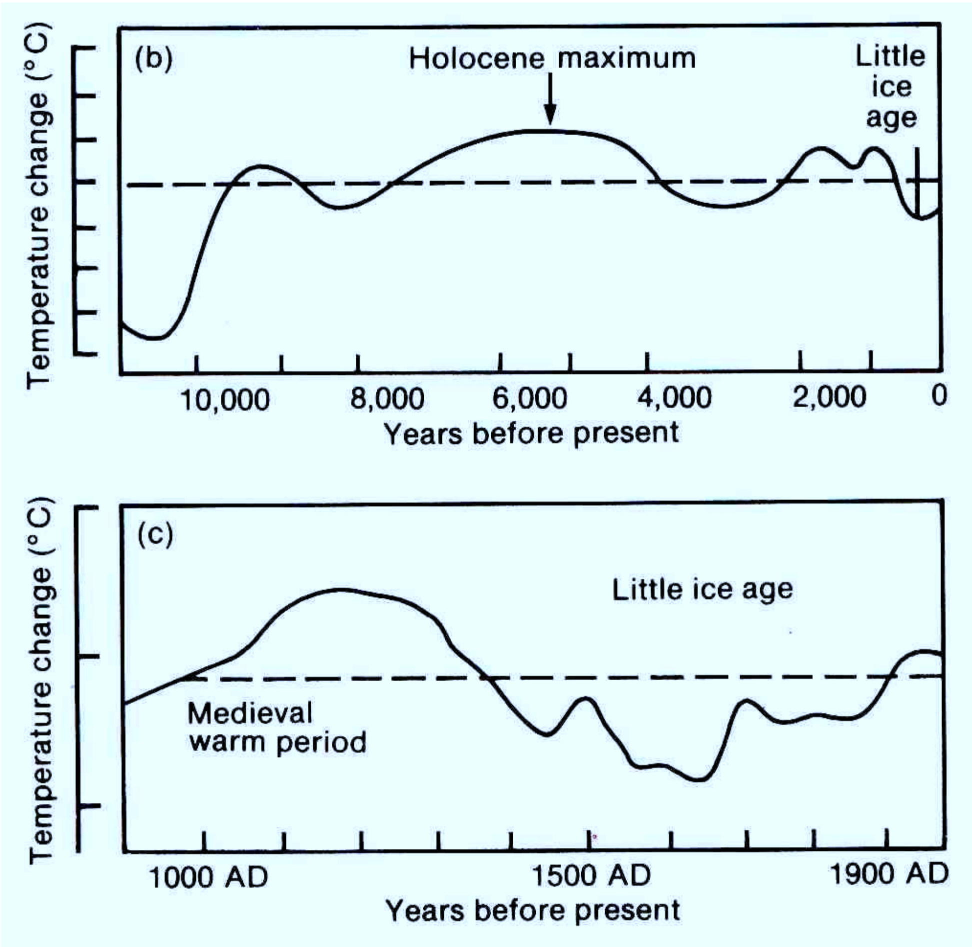
Causes of climate variability on a scales of 1000 years

Variations in sunspots, volcanoes, and CO_2 are a partial explanation of the Little Ice Age and Medieval Warm Period.

Therefore it is quite likely just natural variability.

If there were big natural climate swings, then is the last ~150 yr climate change natural too?

IPCC 1990



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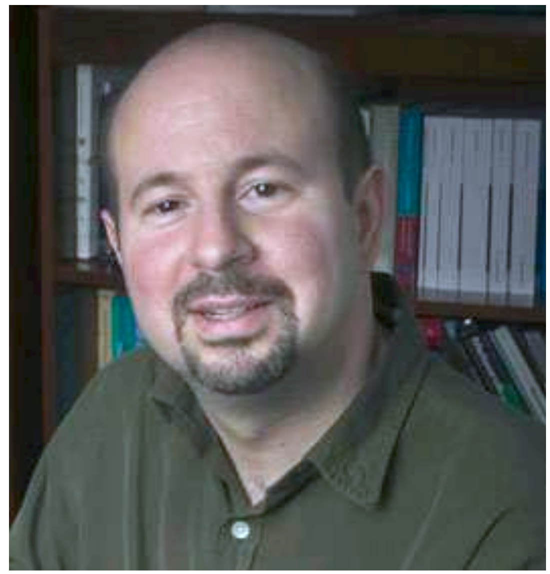
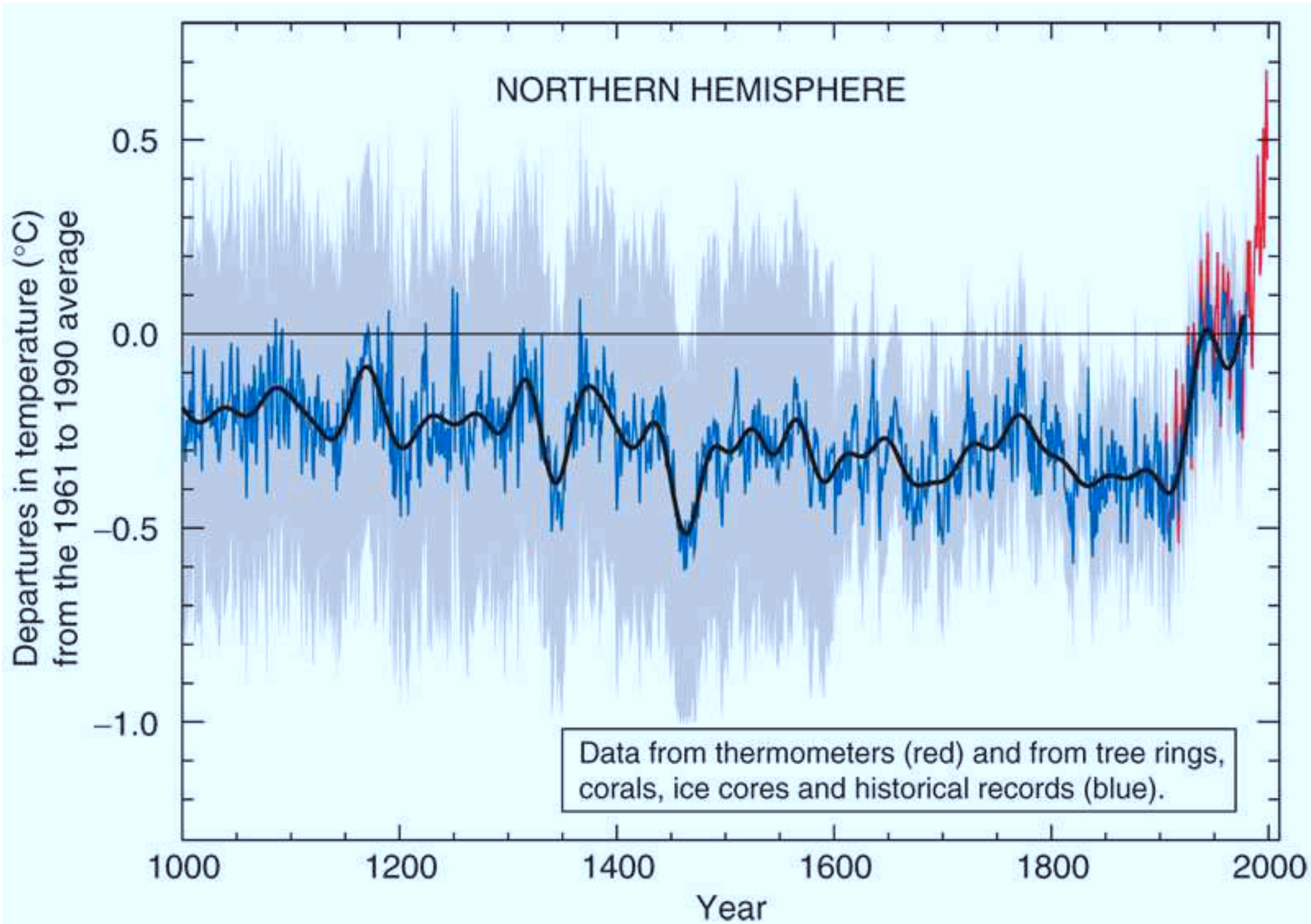
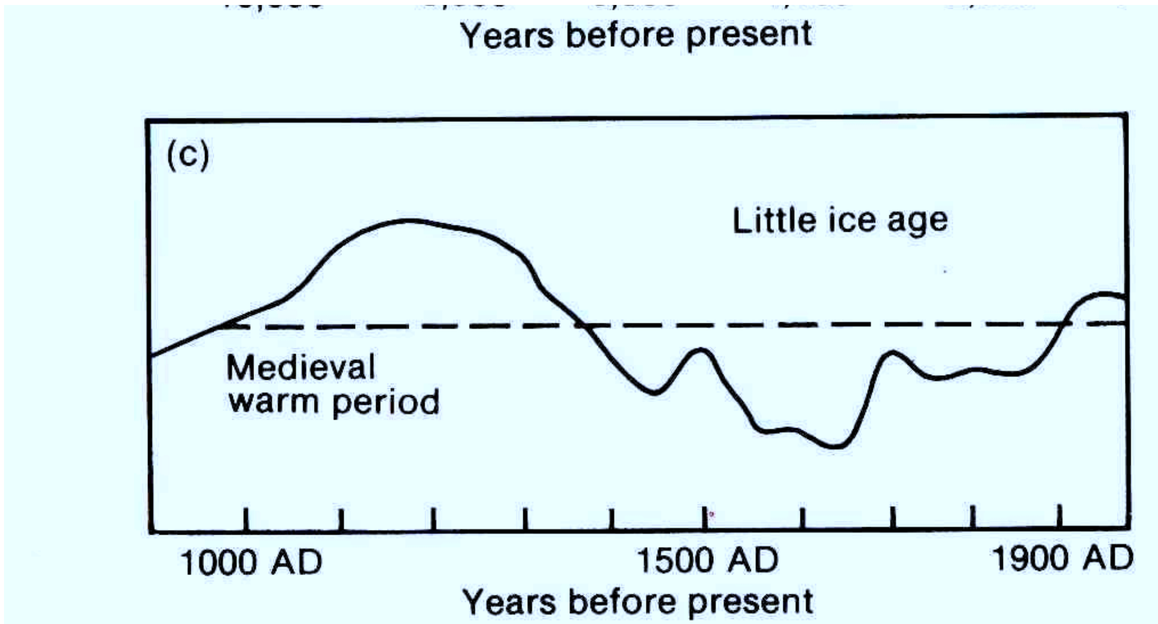


Michael E. Mann
Pennsylvania State University

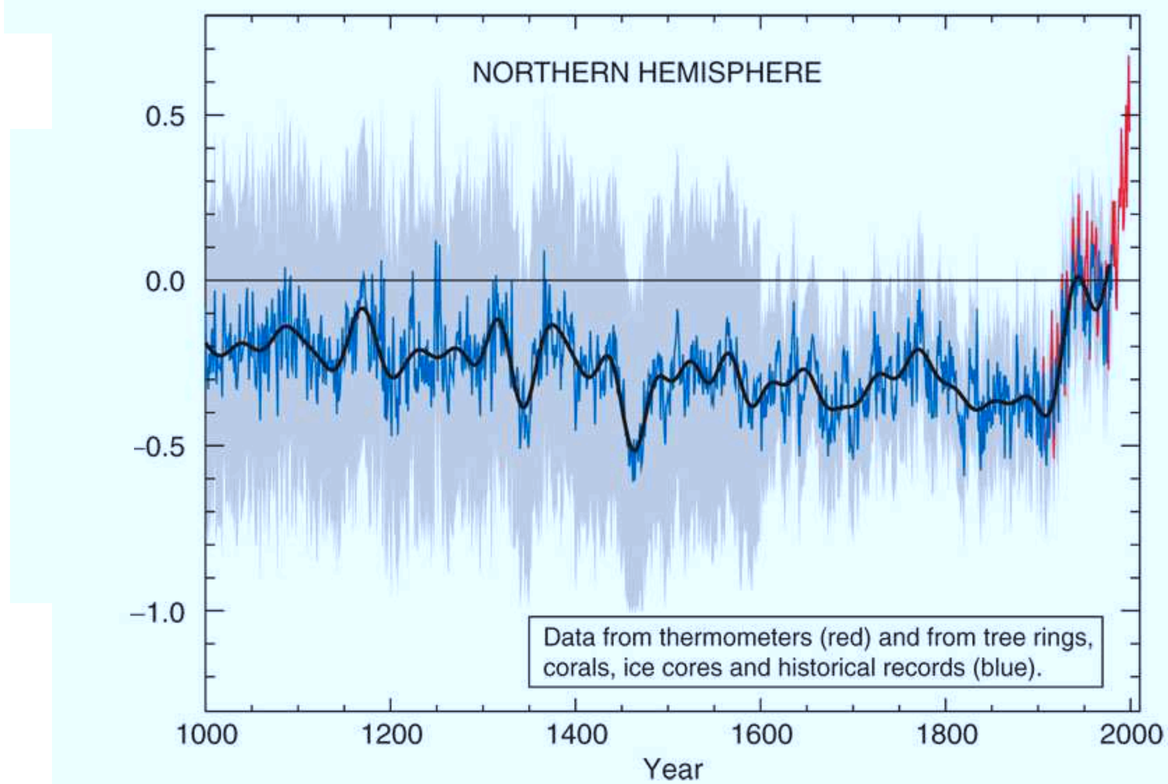
The infamous “hockey stick curve

IPCC 2001


NORTHERN HEMISPHERE
0.5
0.0
−0.5
−1.0
Departures in temperature (°C) from the 1961 to 1990 average
1000
1200
1400
1600
1800
2000
Year
Data from thermometers (red) and from tree rings, corals, ice cores and historical records (blue).



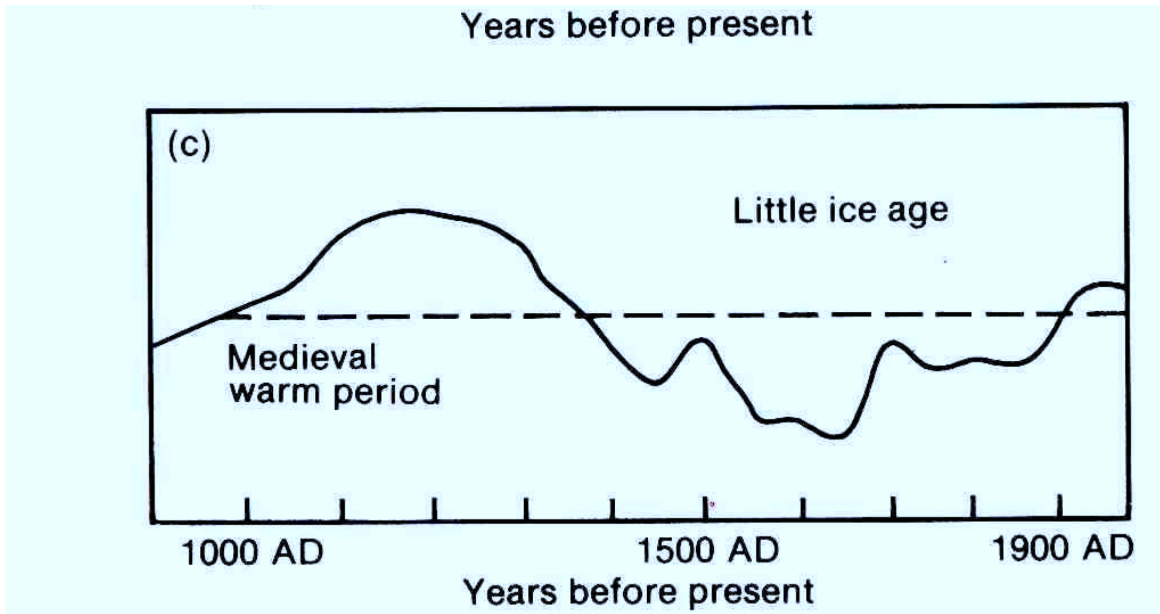
IPCC 1990

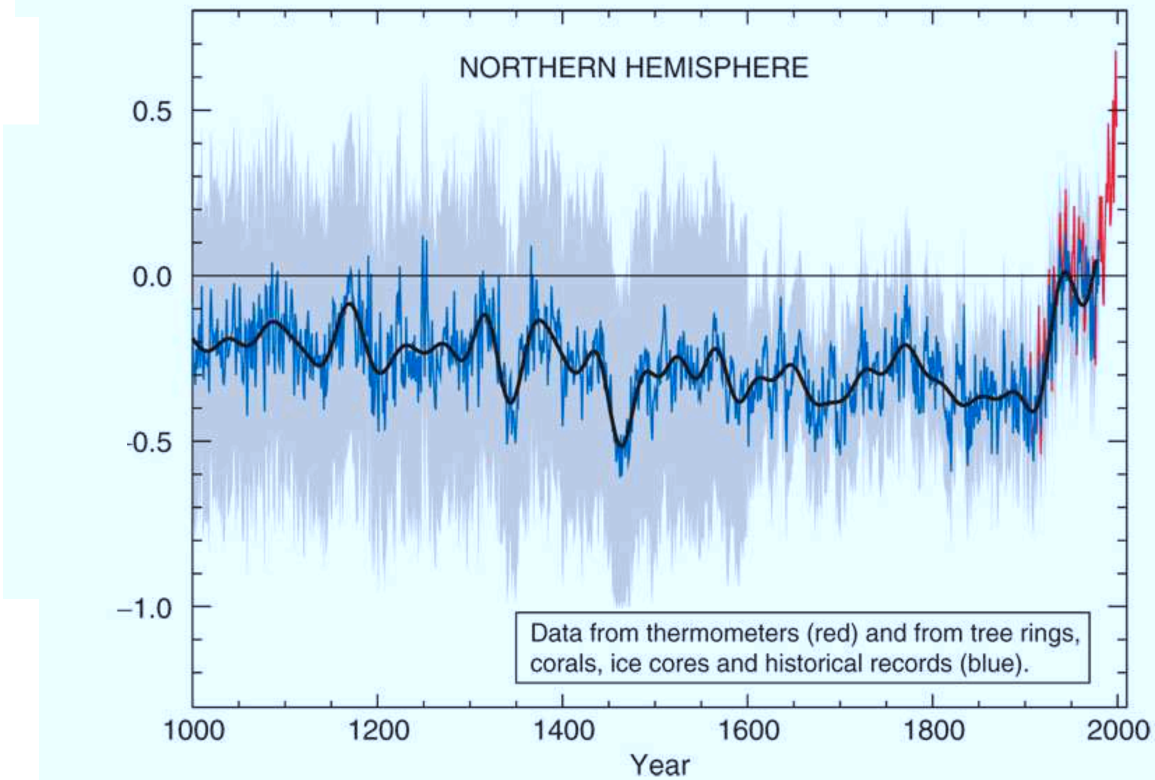


IPCC 2001

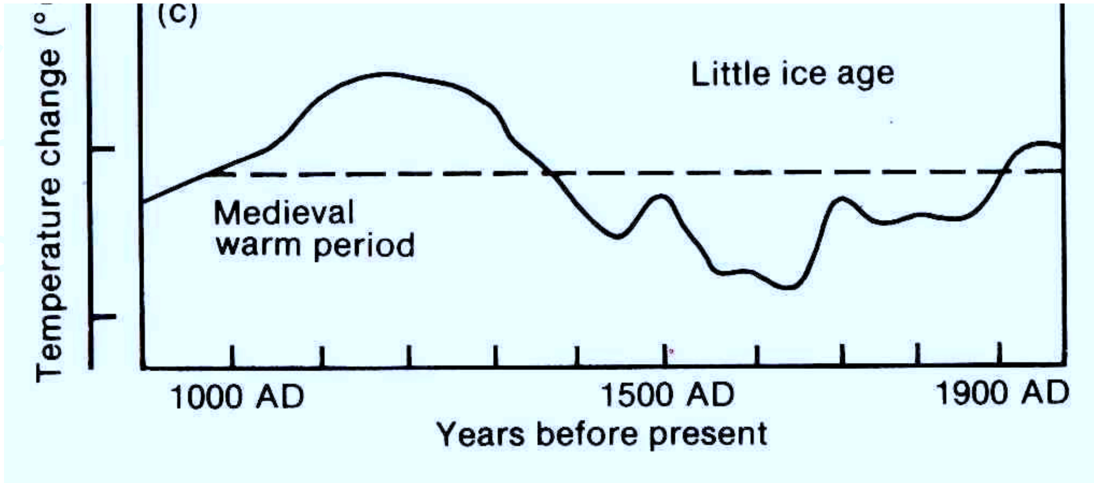
Revisionism!!

Skeptics were incensed!

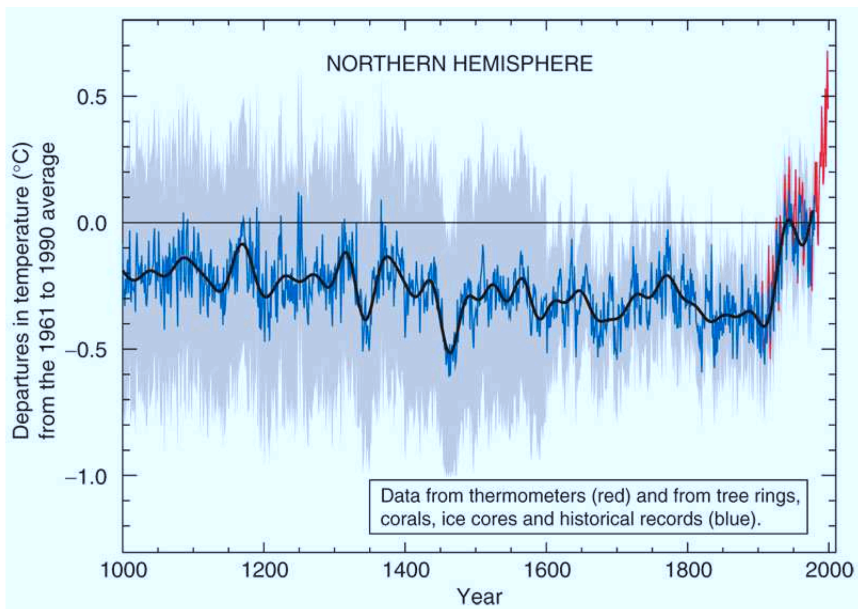




Anasazi r
Mesa Ver
Colorado



Climate alarmists have been attempting to erase the inconvenient Medieval Warm Period from the Earth's climate history for at least a decade......



When the "Hockey Stick" first appeared in 1998, it did just that.

Anasazi ruins
Mesa Verde N.P.,
Colorado

Rep. Joe Barton, R. TX

Demanded that Mann and colleagues should send details from the whole of their careers, covering sources of funding, whereabouts of raw data, and full computer codes.

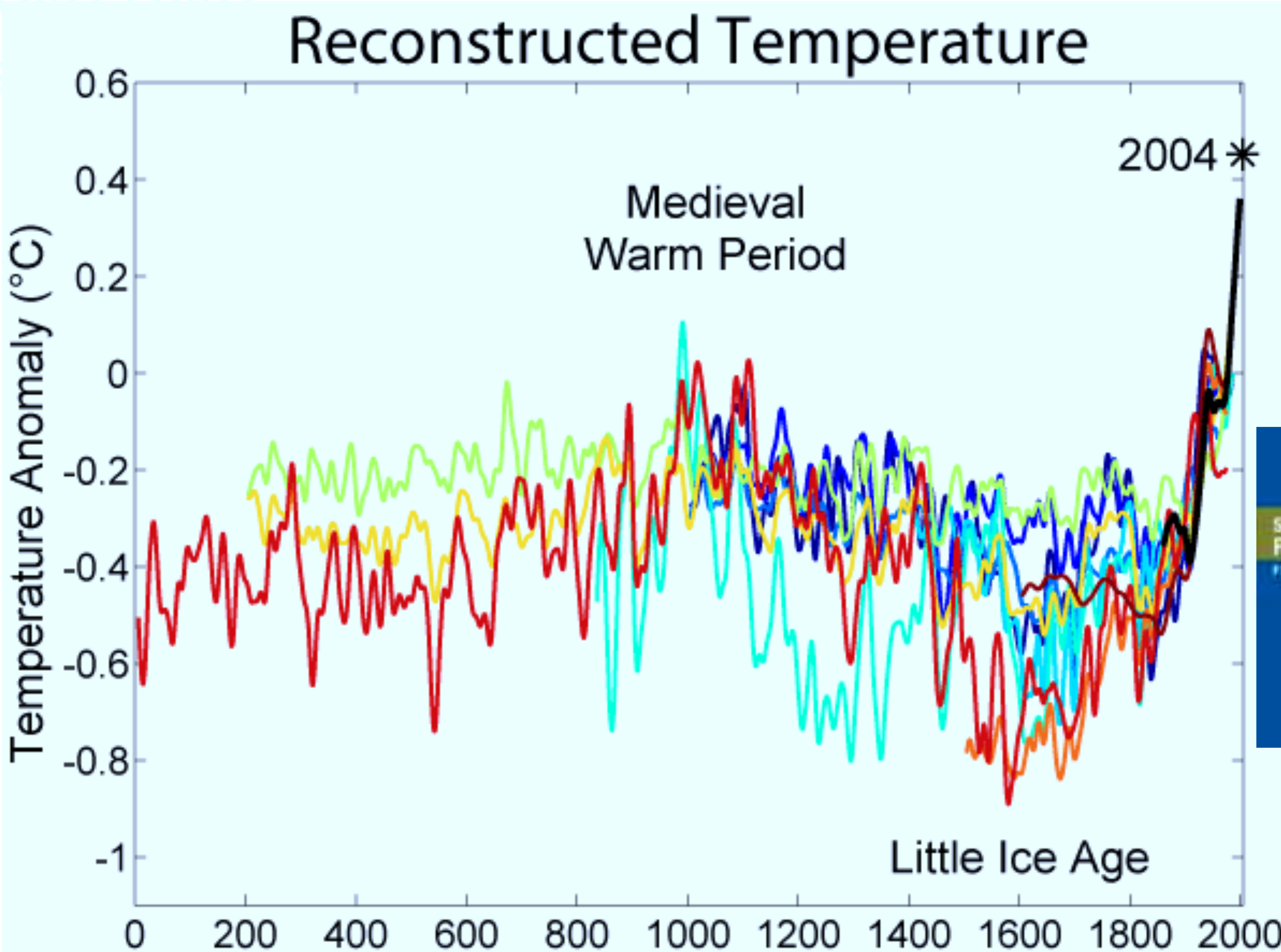
His letters also talk of "methodological flaws", "data errors", and of questions about the authors' willingness to share their data.

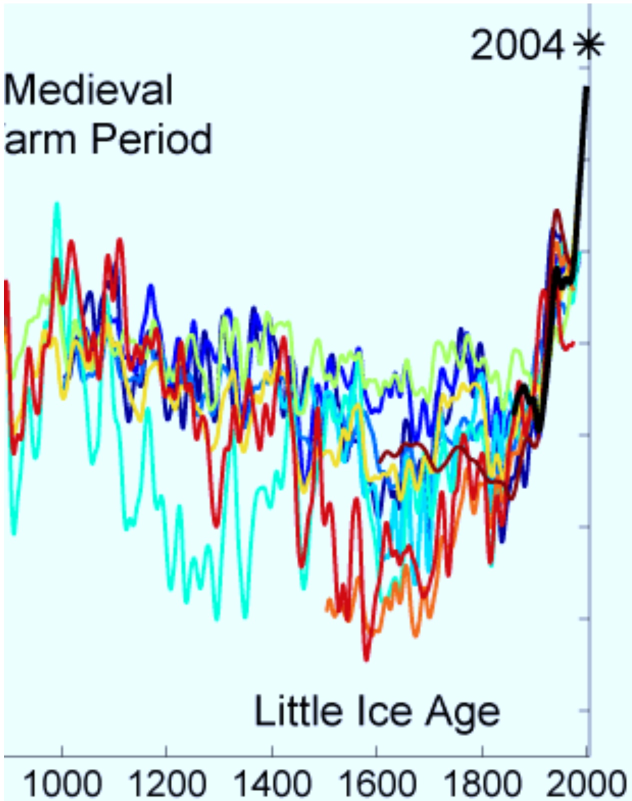
Appointed his own committee of experts which confirmed his accusations about flaws in the science (the Wegman Report)

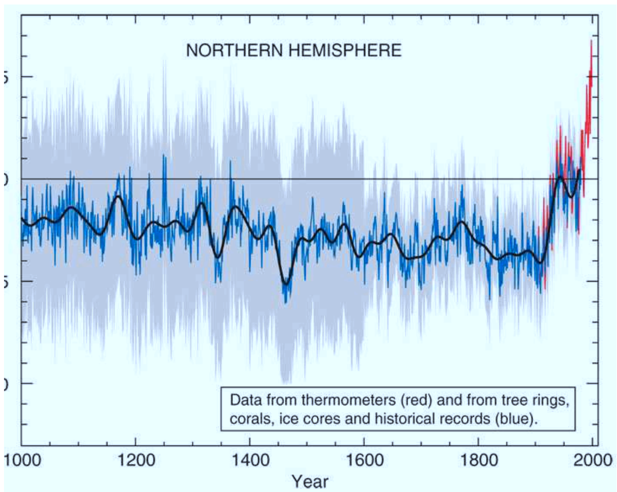
Anasazi ruins
Mesa Verde N.P.,
Colorado

Rep. Sherwood Boehlert R. NY
Got the National Academy of Sciences involved

Anasazi ruins
Mes
Col

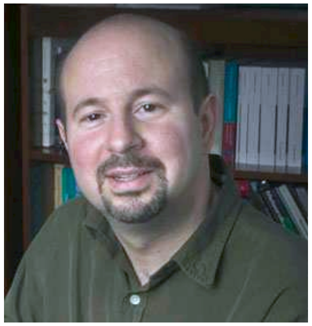






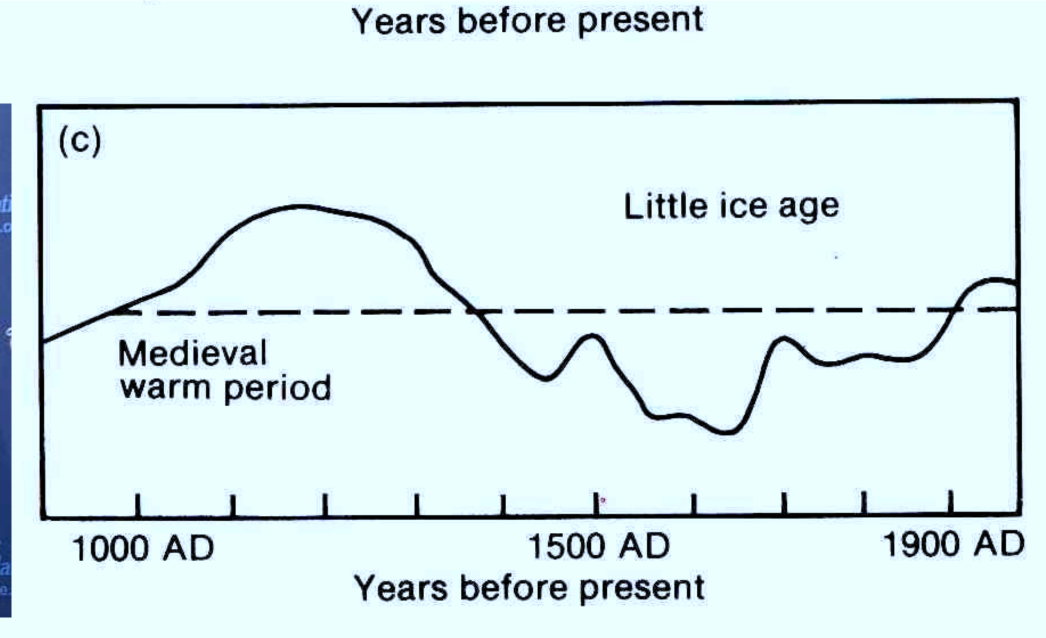
Conclusion: Mann et al results are confirmed but the level of uncertainty is large.

“plausible evidence”



Some shortcoming, but minor

Anasazi ruins



Sen. James Inhofe (R. OK)

Speech delivered on Senate floor
September 2006

The National Academy of Sciences report reaffirmed the existence of the Medieval Warm Period from about 900 AD to 1300 AD and the Little Ice Age from about 1500 to 1850. Both of these periods occurred long before the invention of the SUV or human industrial activity could have possibly impacted the Earth’s climate. In fact, scientists believe the Earth was warmer than today during the Medieval Warm Period, when the Vikings grew crops in Greenland.

Take home messages (working backwards in time)

The warming since the industrial revolution stands out above the temperature variability within the *Holocene Epoch*

Variations in the sun's emission and the frequency of occurrence of volcanic eruptions are believed to be the major drivers of temperature variability within the Holocene Epoch, but natural variability is probably needed to explain the little ice age.

Dramatic warming and sea level rise from the *last glacial maximum LGM*, 20,000 years ago to the beginning of the Holocene ~10,000 years ago

Orbital variations allow continental ice sheets to grow over high latitudes of the NH when summer insolation is weak; CO2 variations provide a strong positive feedback

Large contrasts in global temperatures between *glacials* and *interglacials*;

Strong *polar amplification* of the temperature fluctuations due to ice-albedo feedback

The previous interglacial 130,000 years ago (the Eemian) may have been warmer than the present one with melting of much of the Greenland ice cap.

Global warming over the 21st century is projected to be roughly comparable to the difference between glacials and interglacials

Homo-sapiens survived the LGM; Neanderthals nearly survived two ice ages

What is the difference between a theory and a model?

•Theory: complex construct of ideas and mathematics that summarizes what we know about some scientific area (often codified in scientific "Laws"); has predictive capability

•Model: a set of statements, usually mathematical, that attempts to explain the how or why of some phenomena

Theory

The principle criterion of a scientific theory is its falsifiability, refutability, or testability. Therefore,

1. We should be able to confirm or verify the theory, usually by making a prediction and testing it.

2. Every "good" scientific theory forbids certain things to happen. The more a theory forbids, the better it is.

3. Every genuine test of a theory is an attempt to falsify it, or to refute it.

Models test theories

True or False?

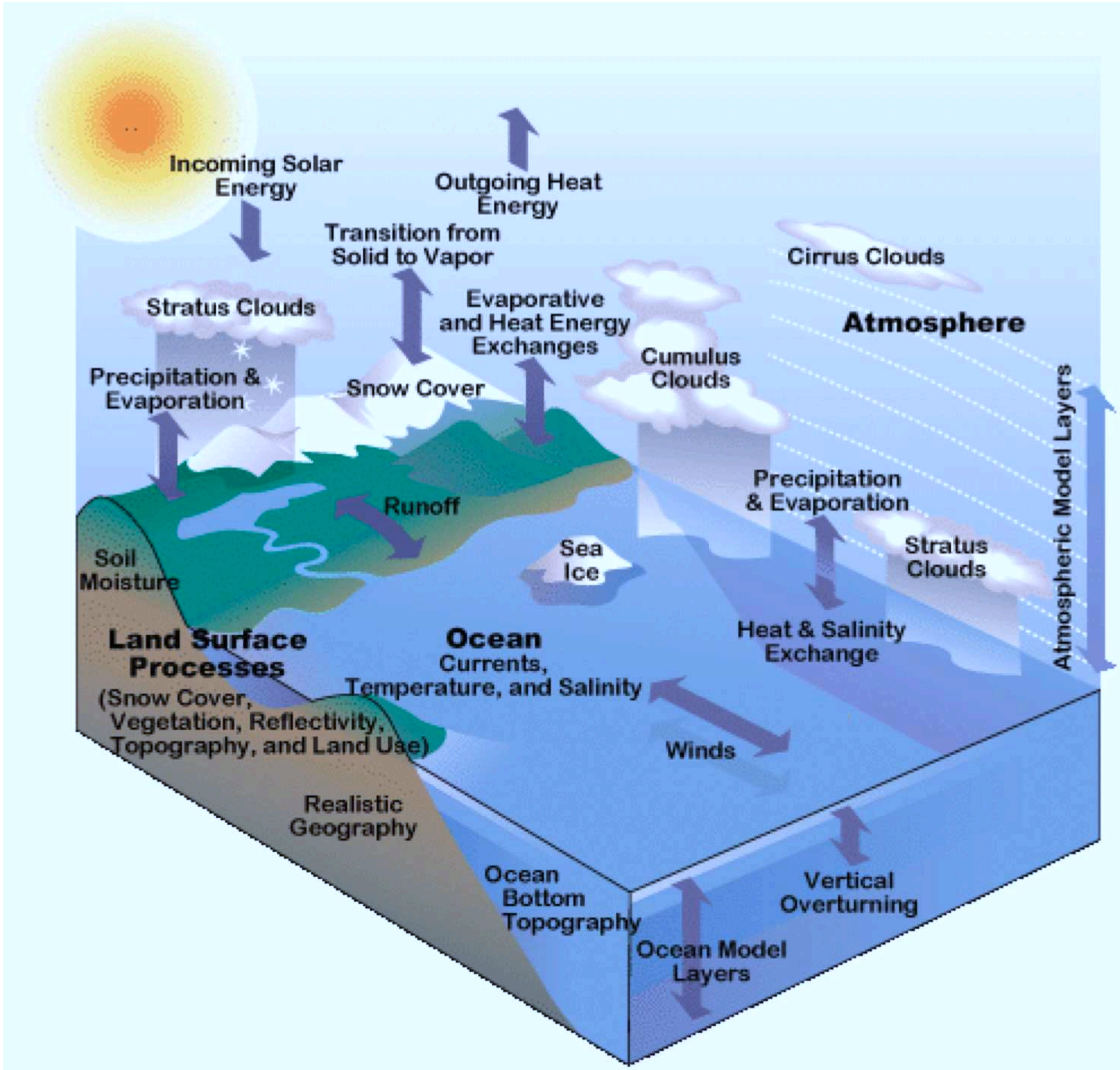
- True or False about theories?
  - The more a theory prohibits certain things to happen the better
  - If no conceivable event can refute a theory, it is a good one
  - Theories are provisional
  - A theory is a weak proposition

Why Model Climate?

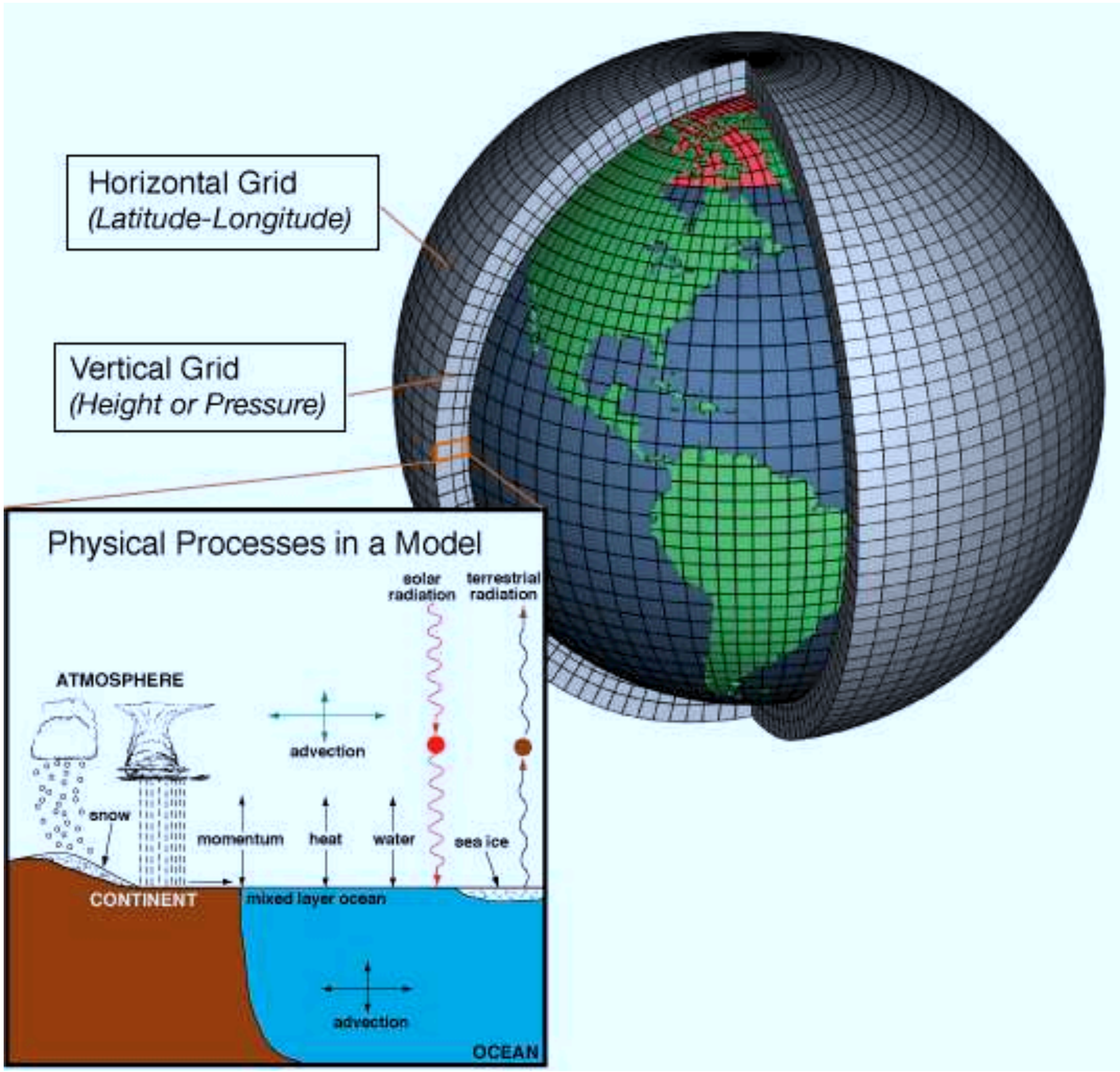
- Scientific Curiosity

- Test theories about
  What controls the climate
  How climate evolves
  The natural variability

- Social Responsibility
  What are we doing to Earth's climate?
  What are the implications for our future?

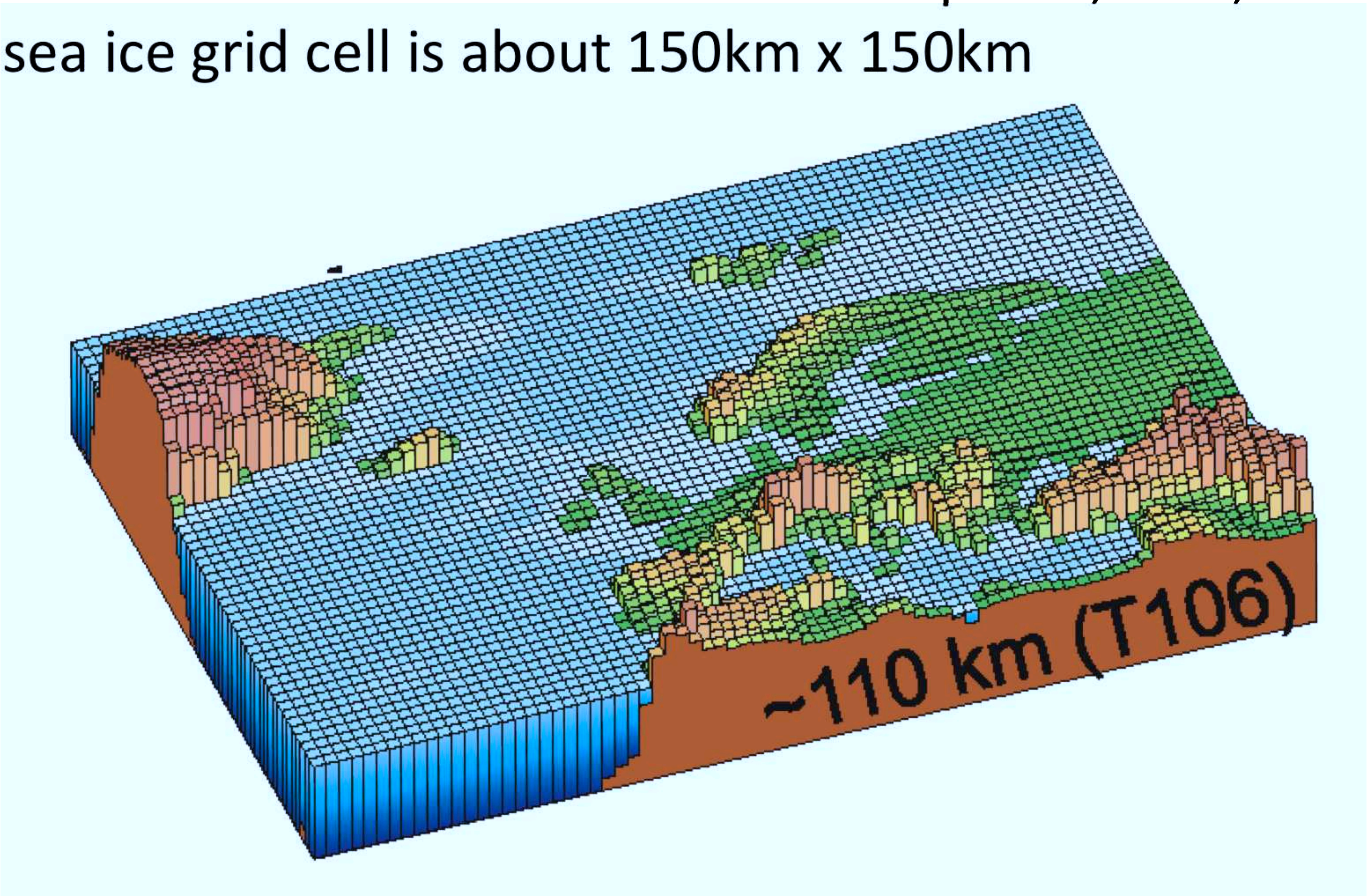

Incoming Solar Energy
Outgoing Heat Energy
Transition from Solid to Vapor
Cirrus Clouds
Stratus Clouds
Evaporative and Heat Energy Exchanges
Atmosphere
Cumulus Clouds
Precipitation & Evaporation
Snow Cover
Atmospheric Model Layers
Precipitation & Evaporation
Runoff
Stratus Clouds
Sea Ice
Soil Moisture
Heat & Salinity Exchange
Land Surface Processes
(Snow Cover, Vegetation, Reflectivity, Topography, and Land Use)
Ocean
Currents, Temperature, and Salinity
Winds
Realistic Geography
Ocean Bottom Topography
Vertical Overturning
Ocean Model Layers

Climate Models Chop up the Earth into Grid Cells



A close up of Europe

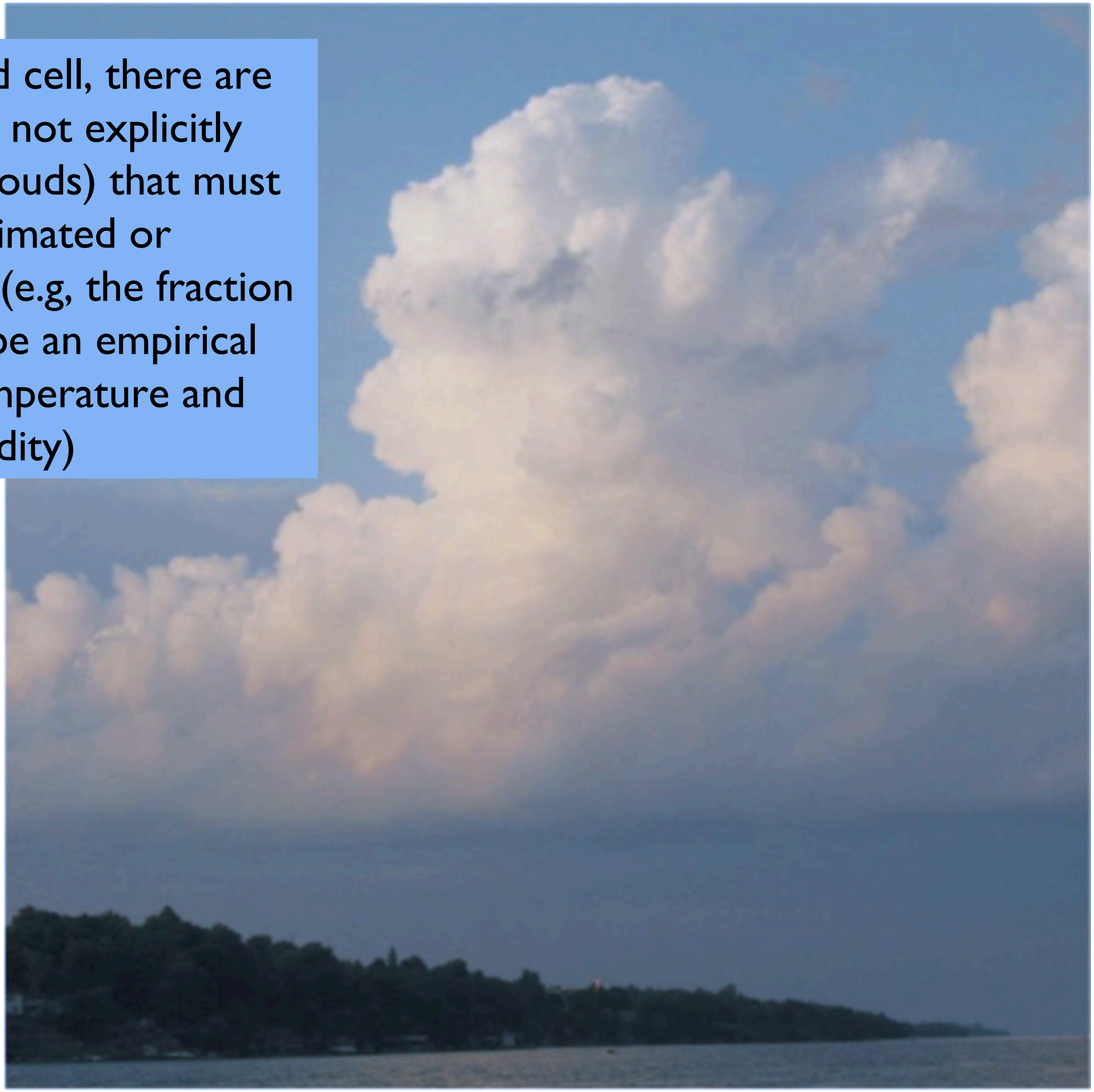
- The current horizontal size of an atmosphere, land, ocean or sea ice grid cell is about 150km x 150km



The vertical extent of a box is typically:

Atmosphere/Ocean: 80-500m Sea Ice: 50cm Land: 10cm

Within each grid cell, there are things that are not explicitly modeled (e.g., clouds) that must be approximated or "parameterized" (e.g, the fraction of clouds may be an empirical function of temperature and humidity)



Community Climate System Model (CCSM)

One of three US climate models, the others are NOAA GFDL and NASA GISS

Who is involved?

- National Center for Atmospheric Research

    also the project's home base

- Other National Labs
- Universities

~300 people attend the annual meeting

All are part of the "community"

Challenge of Community Effort

Given that:

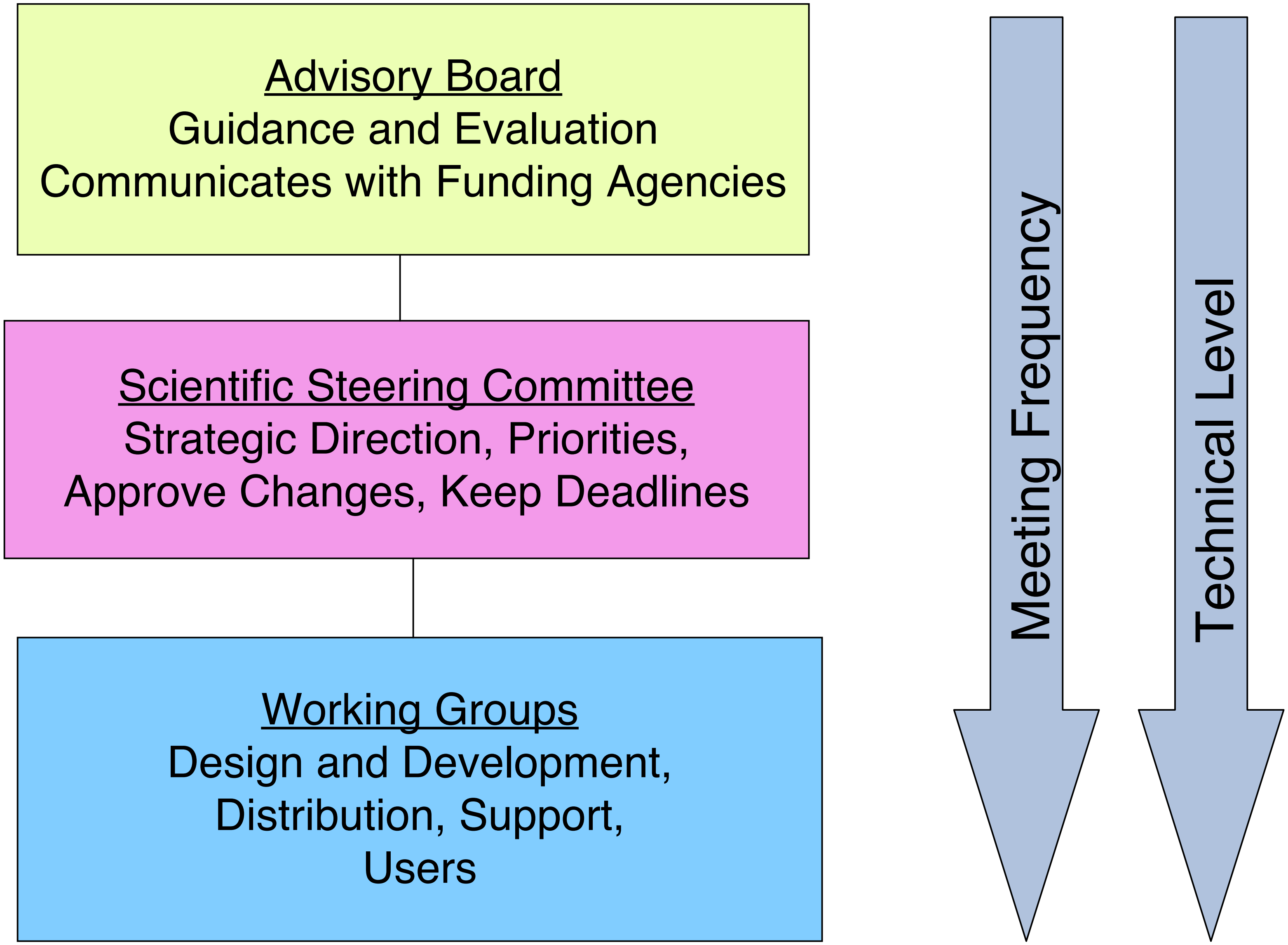
Ideas Originate from Creative Individuals
Scientists are Strongly Individualistic
People Have Unique Approaches to Problem Solving
People Seek Rewards for their Creativity

How Do We Create a Community Effort that

Motivates Scientists to Work on a Common Goal
Allows All to Feel Involved and Appreciated
Allows All to Feel a Sense of Ownership
Allows All to Feel Rewarded

slide from Jeff Kiehl, former CCSM director

Organization



Advisory Board meeting at National Science Foundation Headquarters in ~2004

Me

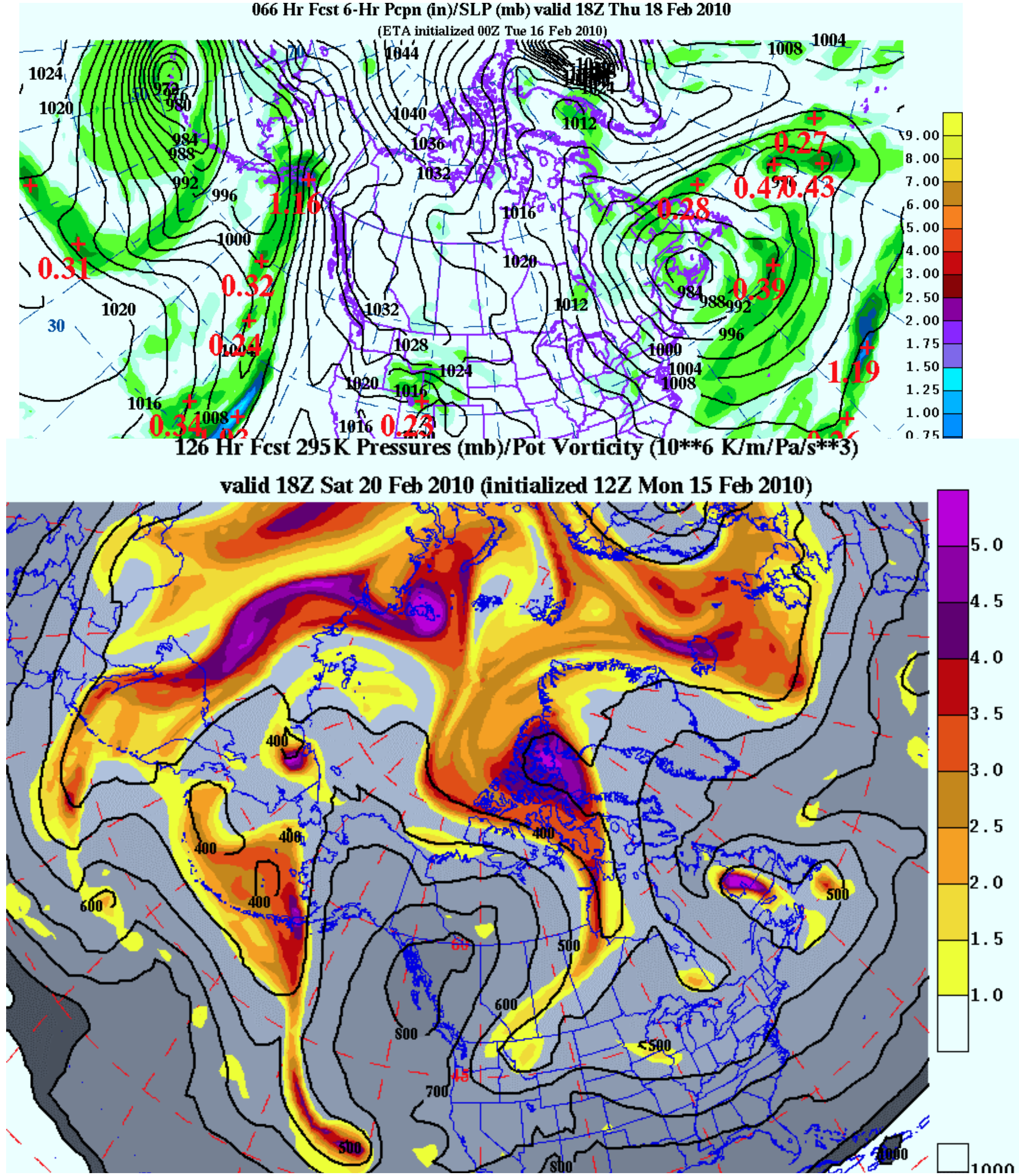
NSF director

How far in advance can we predict the weather?

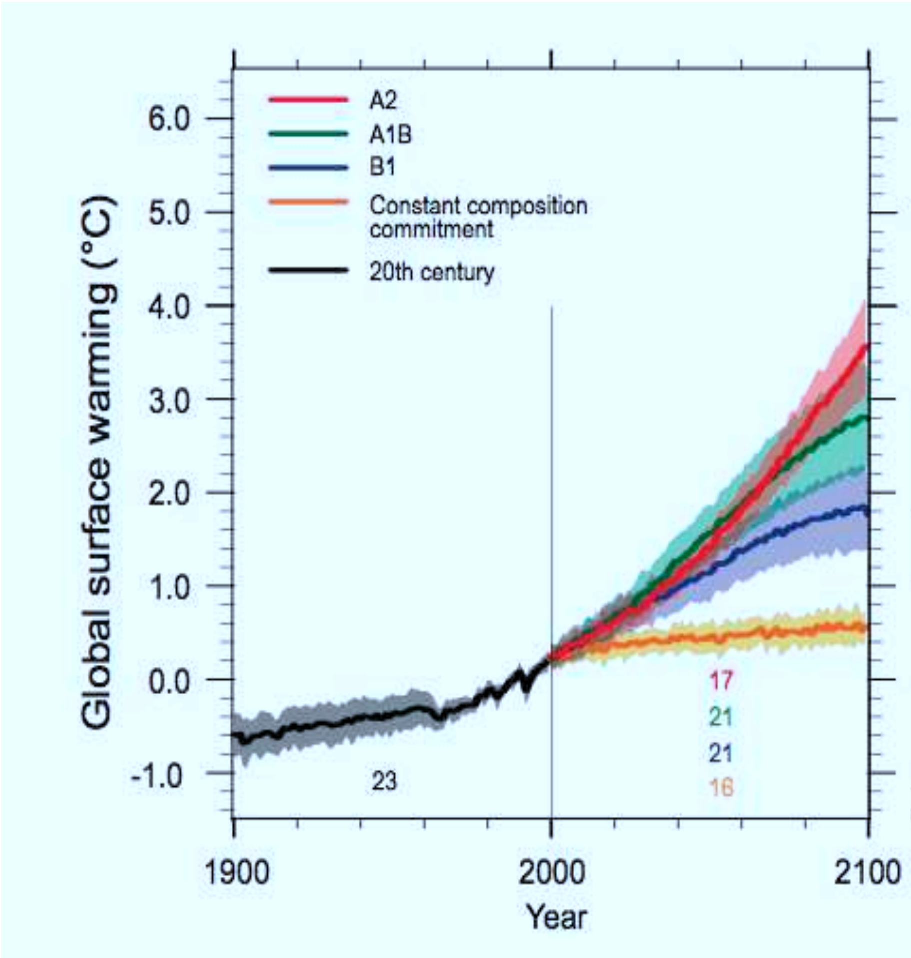
What do we need to know to project climate?

	Weather Model	Climate Model
Goal	Predict Weather	Predict Climate
Time Range	days	years
Spatial Resolution	5-10 km	20-100km
Relevance of initial conditions	high (thus taken from weather balloons)	low (only the ocean and sea ice matter much)
Relevance of GHG concentration	low	high
Relevance of ocean dynamics	low	high
Relevance of energy balance	low	high

Weather models have cool looking visualizations of their output

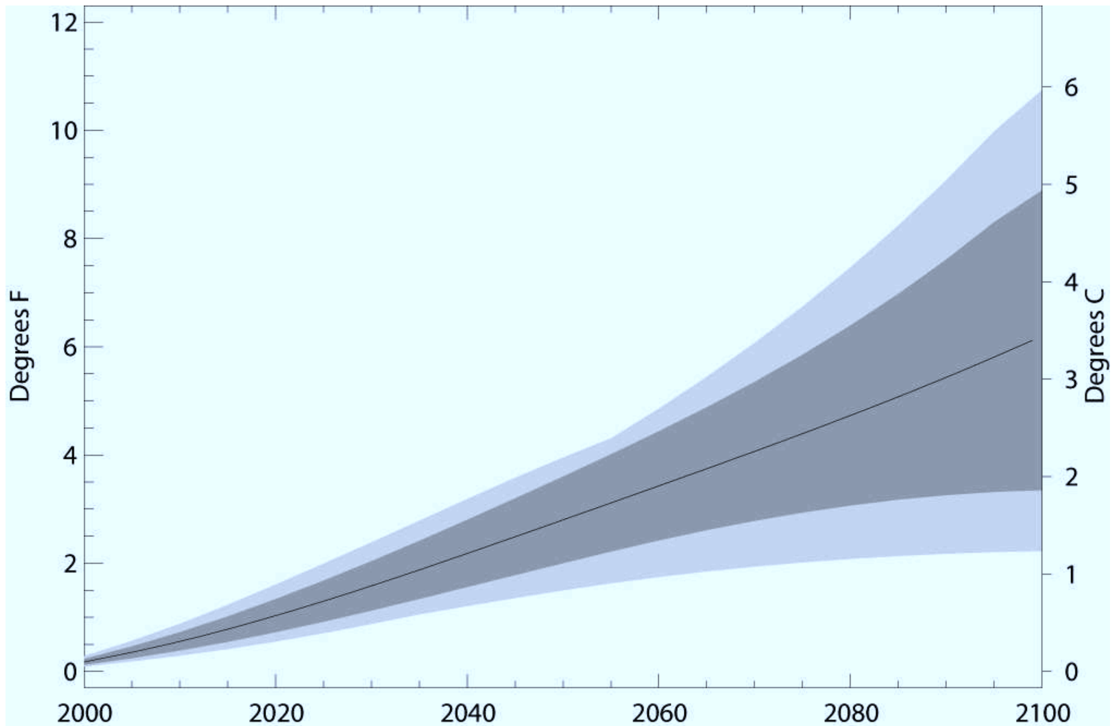


While we often look as something as simple as global mean temperature from climate models (no one would EVER look at global mean temperature in a weather model)



2007 IPCC Figure

Average Northwest warming, 2000-2100



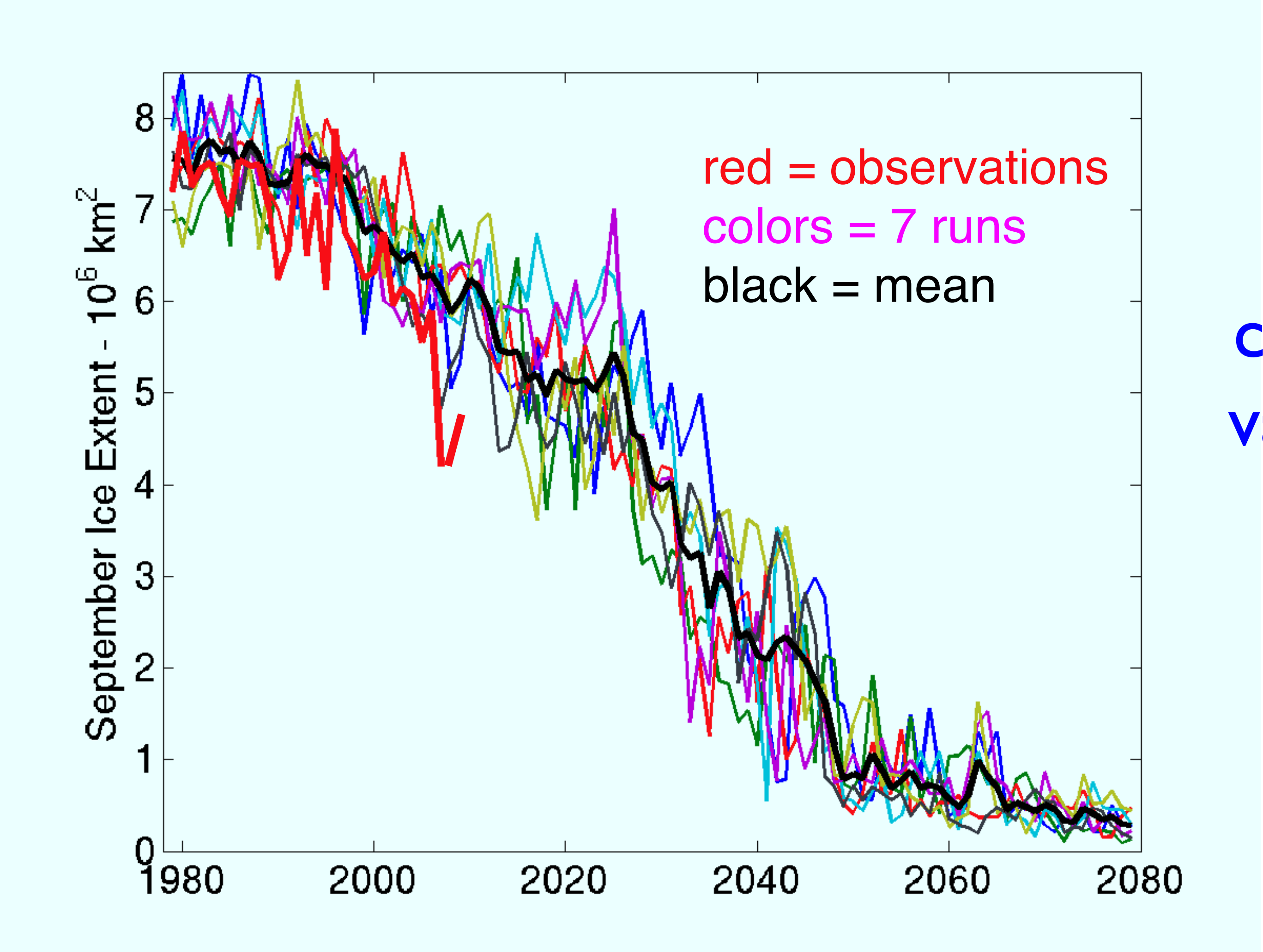
Degrees C

Grey shading includes predictions from 10 models for two scenarios. Why is the range larger locally than globally?

Source: Mote, Salathé and Peacock 2005

CCSM3 Arctic September Sea Ice Projections
7 runs from one climate model

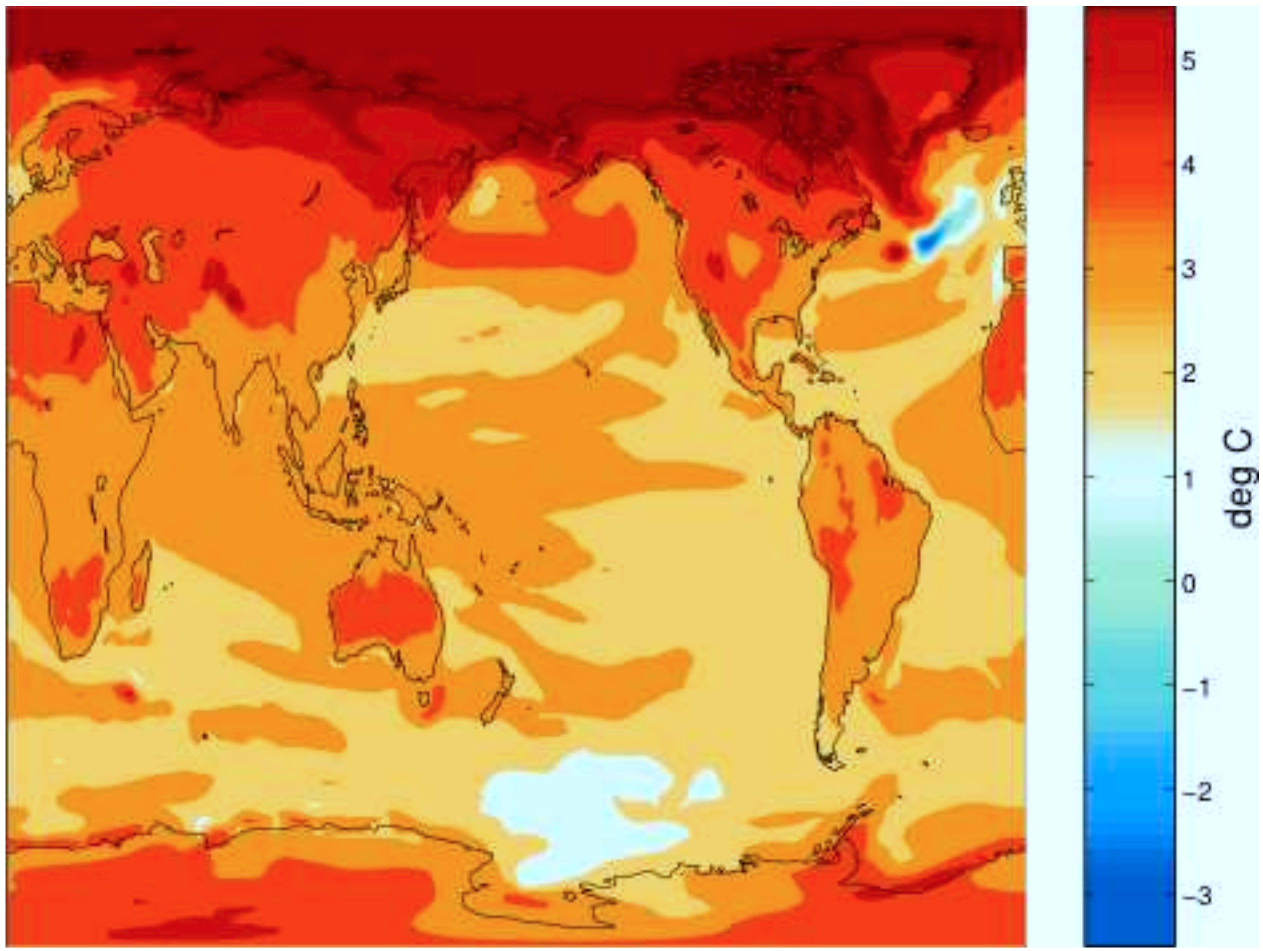
(no one would EVER look at sea ice in a weather model)



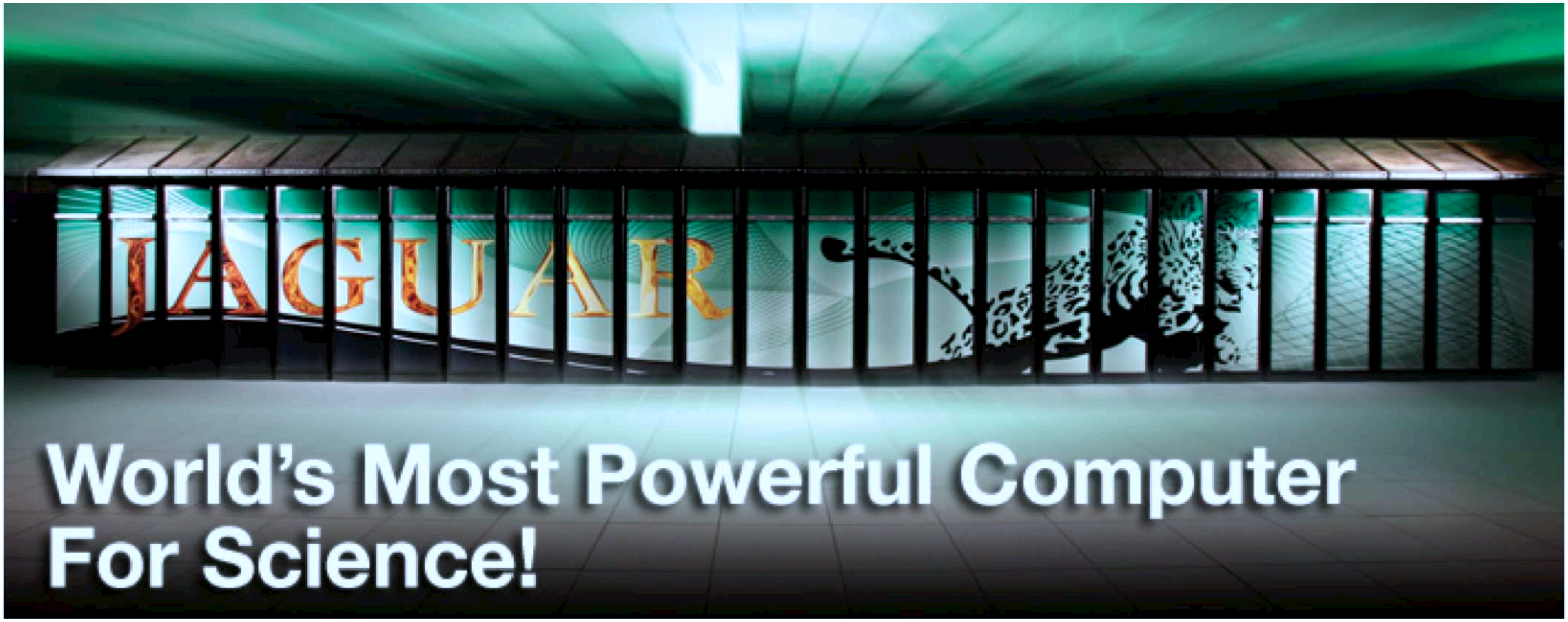
The initial conditions are varied here on purpose.

Why?

Surface Temperature Change at end of 21st century relative to end of last century (climate modelers can make nice graphics, if we want to)



Climate modelers use cooler computers



With a peak speed of 2.33 petaflops (over two thousand trillion calculations per second), "Jaguar," a Cray XT5 supercomputer. Owned by the Department of Energy. Not just for climate science. But not used for weather.

My project running on Kraken will use 4,000 processors continuously for a year, which will give us ~500 yr of model output at very good resolution. So far we have produced ~100,000 Gbytes of output.

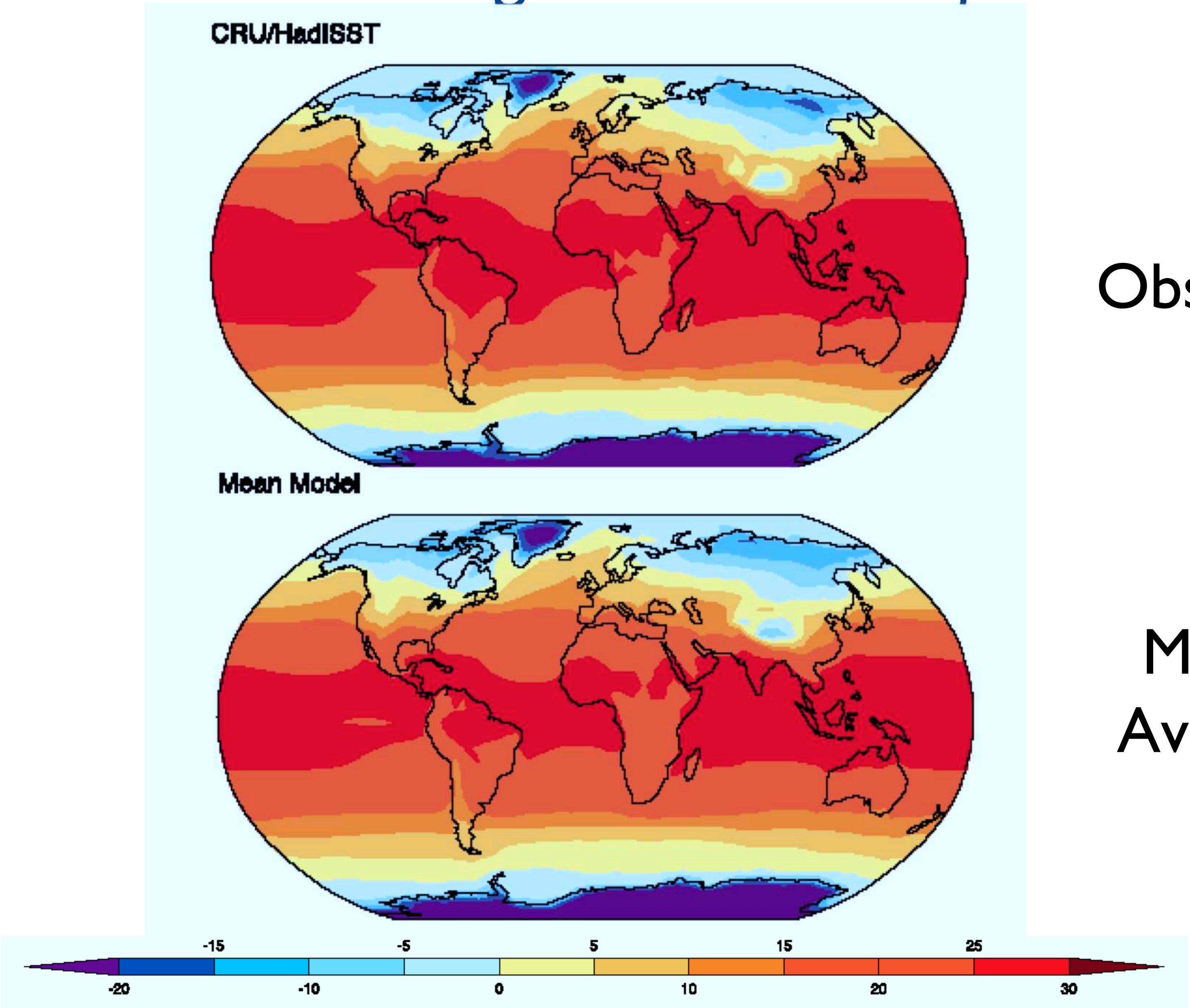
1.03 petaflops, with nearly 100,000 processors. Cost $65 million. Owned by the National Science Foundation. Also not just for climate science.

Climate models have been in use for ~40 yrs

Weather models were invented 20 yrs earlier

How do we know if climate models are right?

Annual Average Surface Temperature



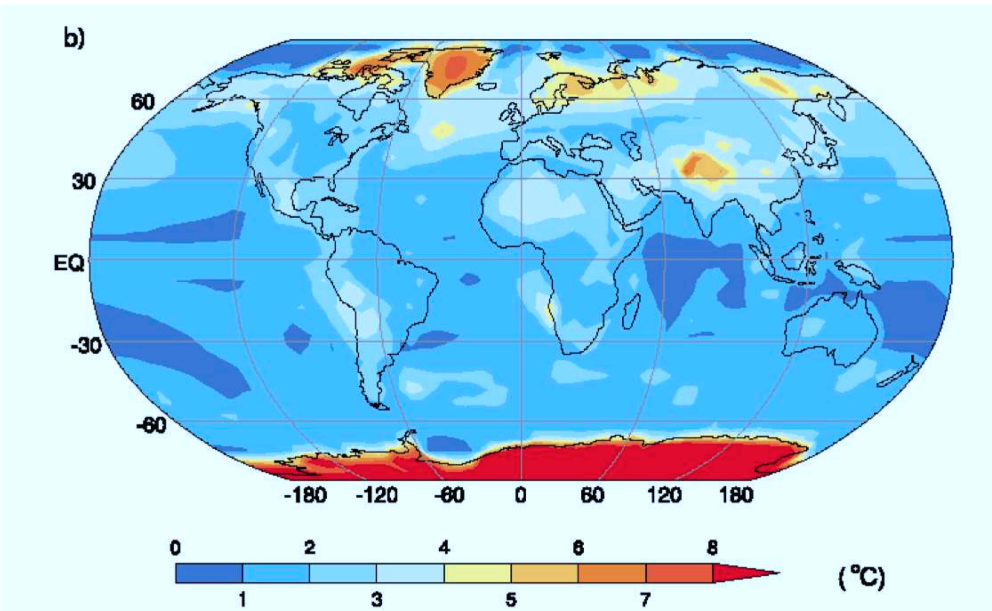
Observed

Model Average

°C

IPCC 2007

Annual Average Surface Temperature

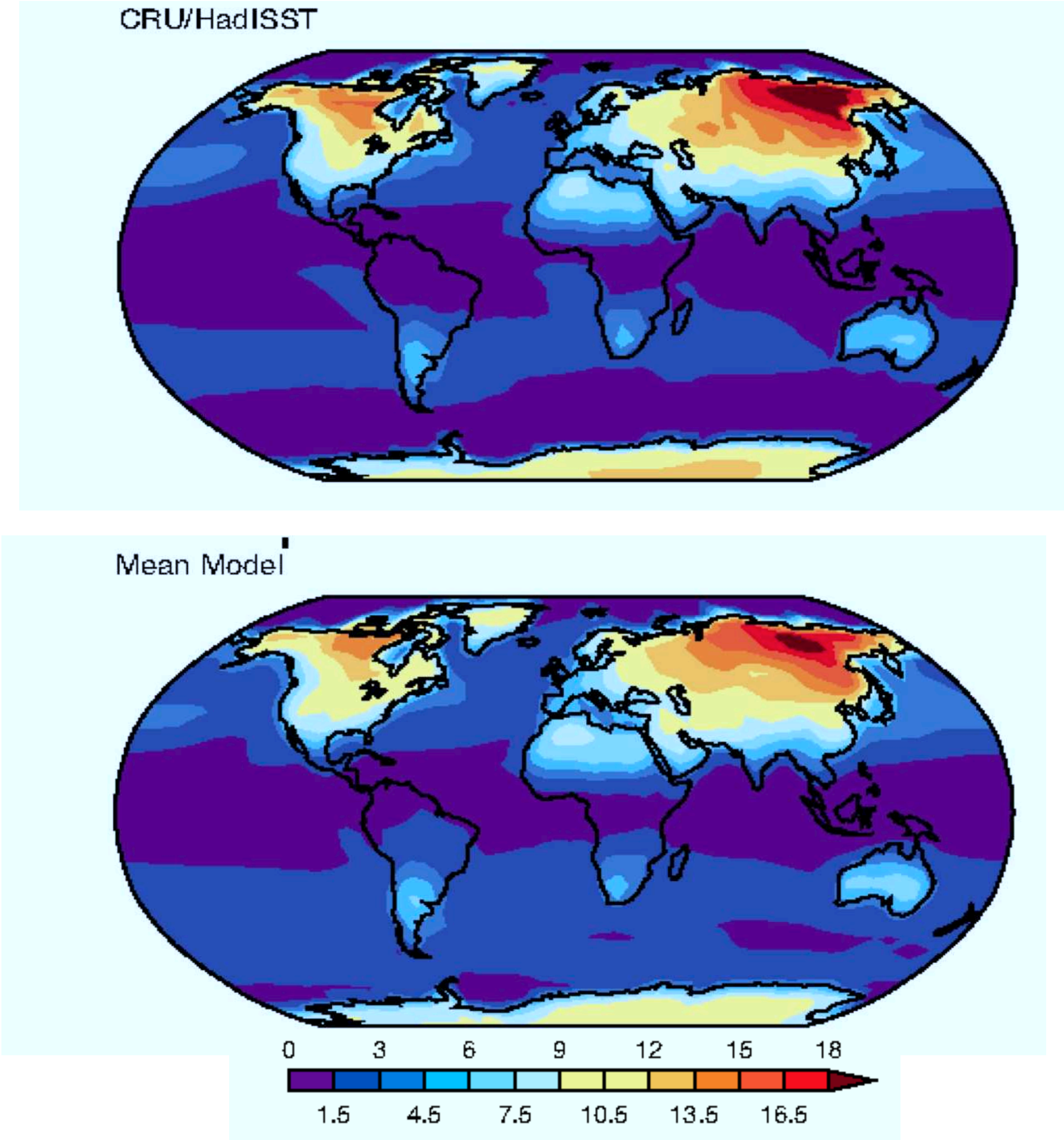


Error in a typical model

IPCC 2007

"Annual Cycle*" in Temperature

* Multiply by ~3 to get approximately the difference in July and January temperature

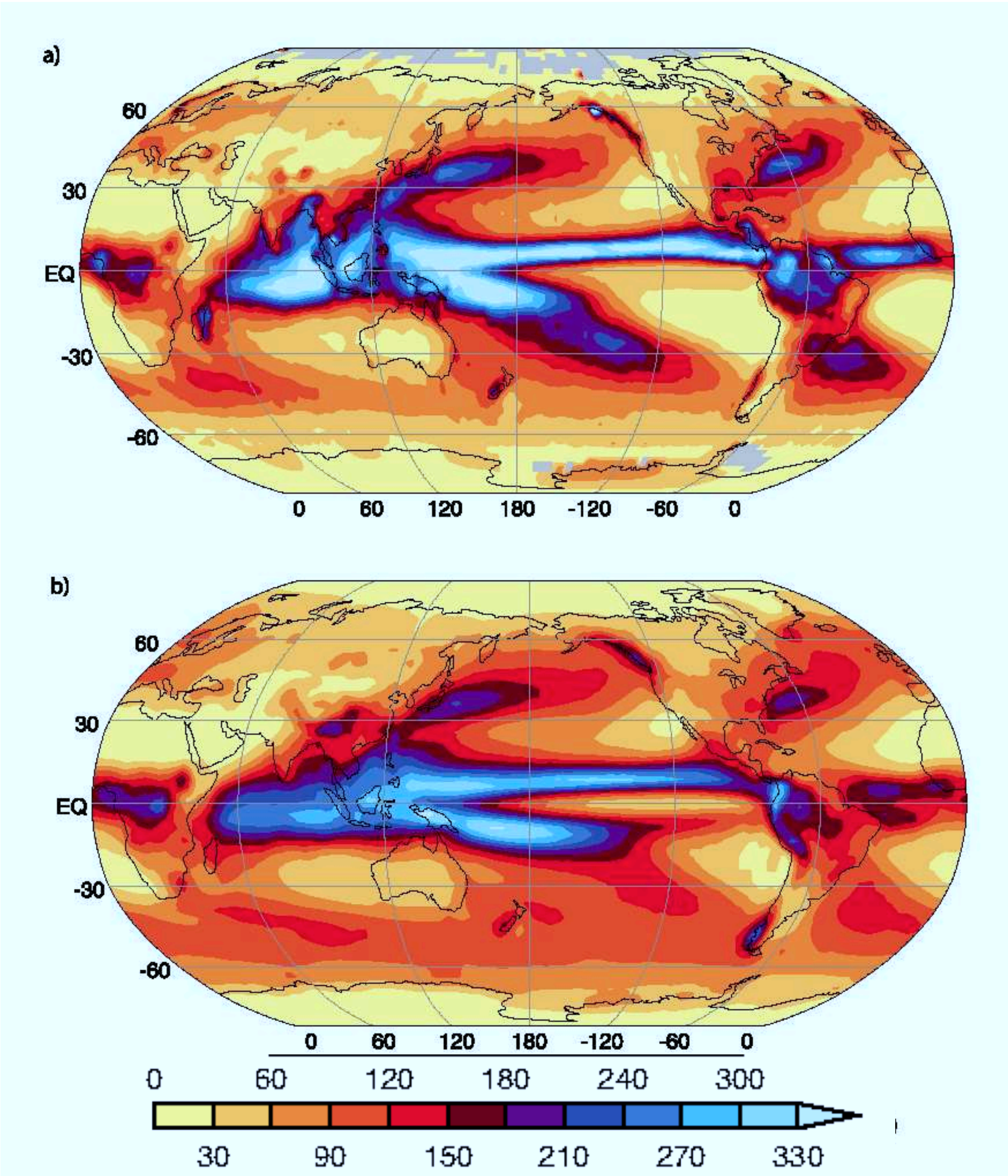


Observed

Model Average

IPCC 2007

Annual Average Precipitation



Observed (cm/year)

Average of the models

IPCC 2007

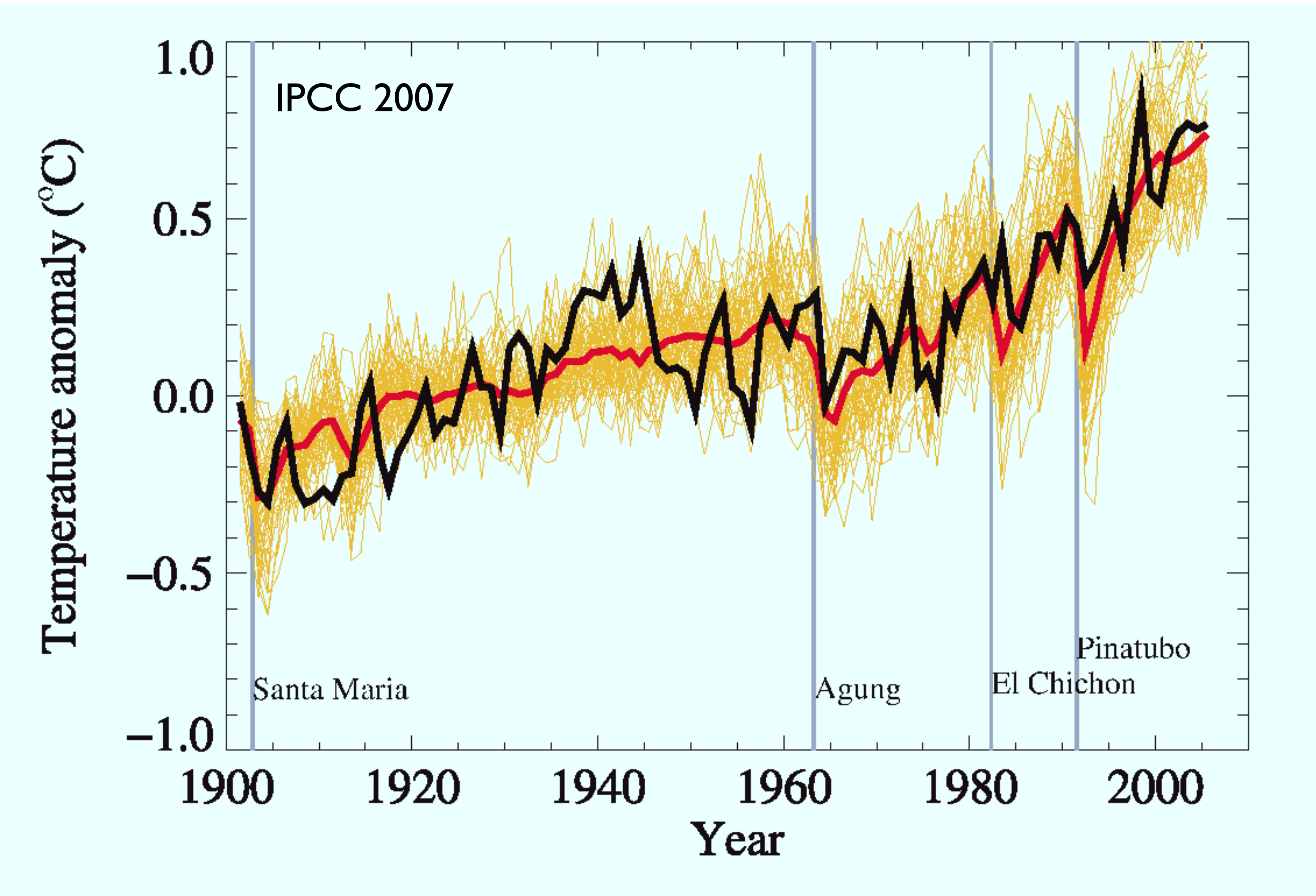
Natural Variability

- The models simulate with reasonable accuracy the weather, but not in sync with any real weather
- The models simulate accurately the natural patterns of variability in the atmosphere
  - North Atlantic Oscillation, the eastern Atlantic pattern, the Pacific North American pattern, the Western Pacific pattern, etc
- The models do very poorly the El Nino/Southern Oscillation (ENSO) phenomenon
- The models do poorly in places where topography changes markedly on scales that are smaller than the atmospheric grid (e.g., Puget Sound)
  - In these cases, useful information can be obtained by 'downscaling' (later)

More test of the Models

- They have been used to simulate climates of the past and evaluated against the paleo (proxy) data
  - The Early Holocene: 6000 and 8500 years before present (yr BP), when the Sahara was green
  - The Last Glacial Maximum: 23,000 yr Before Present, the maximum extent of the most recent glacial period
    - Climate models do a decent job
  - The Eocene: 65 million yr BP, when the earth was ice free and much warmer than today (by ~10-15ºC) and CO_2 levels were 2-4 times more than today.
    - Climate models used systematically underestimate the warming of the Eocene (could be a sign they are not sensitive enough)
- They have been used to simulate the climate of the 20^{th} Century

Simulating the Global Average Temperature over the 20th Century



Each yellow line is one simulation.

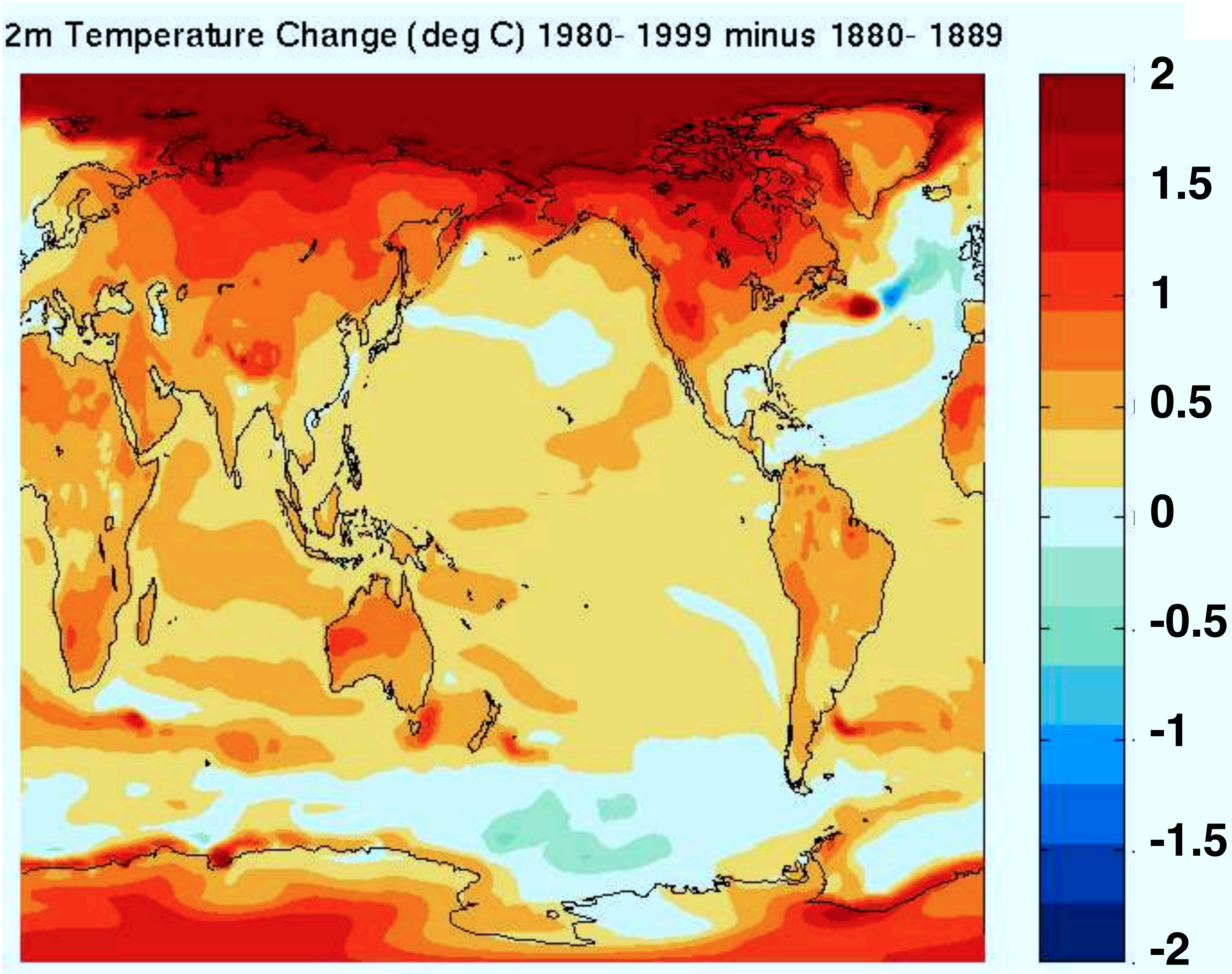
Red line = average of all 58 simulations

Black line = observed

Simulations include natural (solar and volcanic) and human (carbon dioxide, etc) forcing

14 models were used in this figure with a total of 58 simulations

CCSM Model "hindcast" - validate models with past



What do climate models predict for the future?

(but first what is the right forcing?)

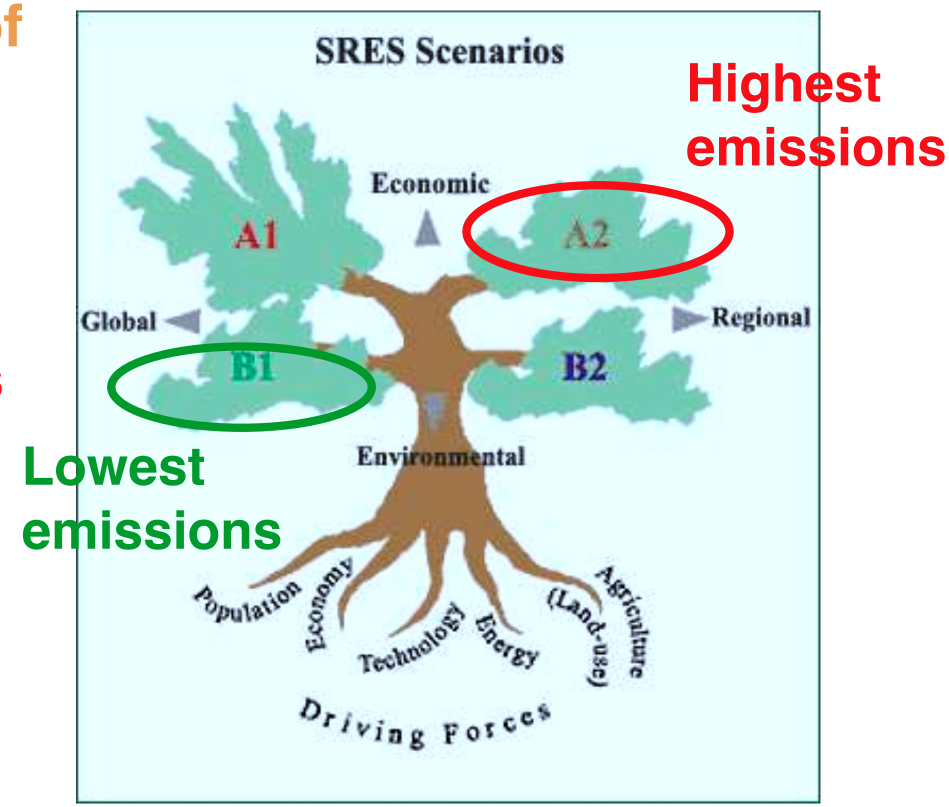
IPCC Scenarios summarized

A1: Rapid economic growth followed by rapid introductions of new and more efficient technologies

A2: A very heterogenous world with an emphasis on local values and traditions

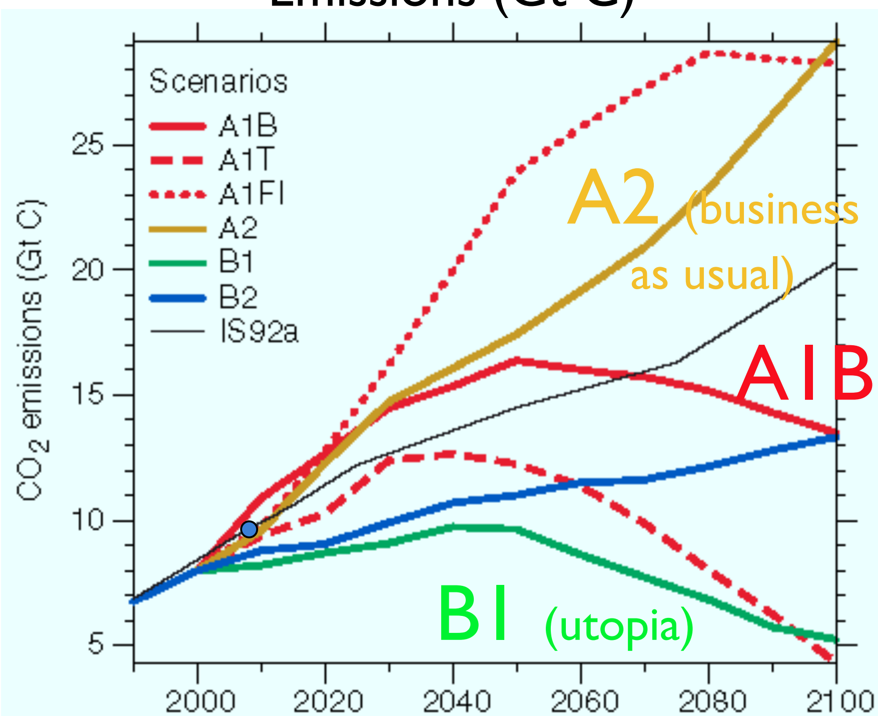
B1: Introduction of clean technologies

B2: Emphasis on local solutions to economic and environmental sustainability

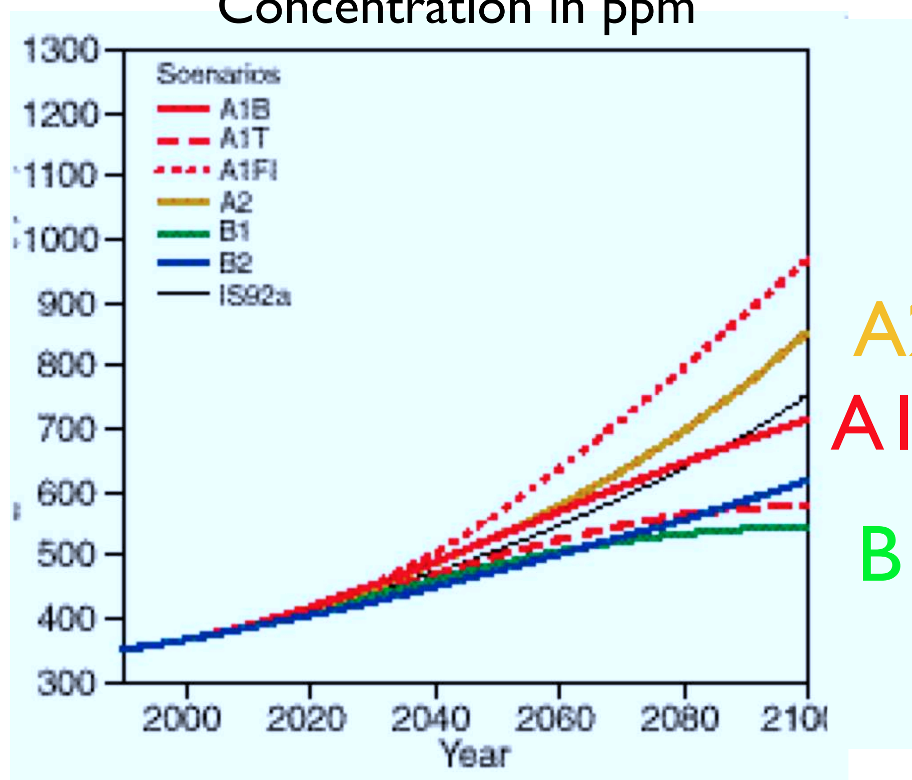


How much Carbon Dioxide will be released into the atmosphere?

Emissions (Gt C)



Concentration in ppm

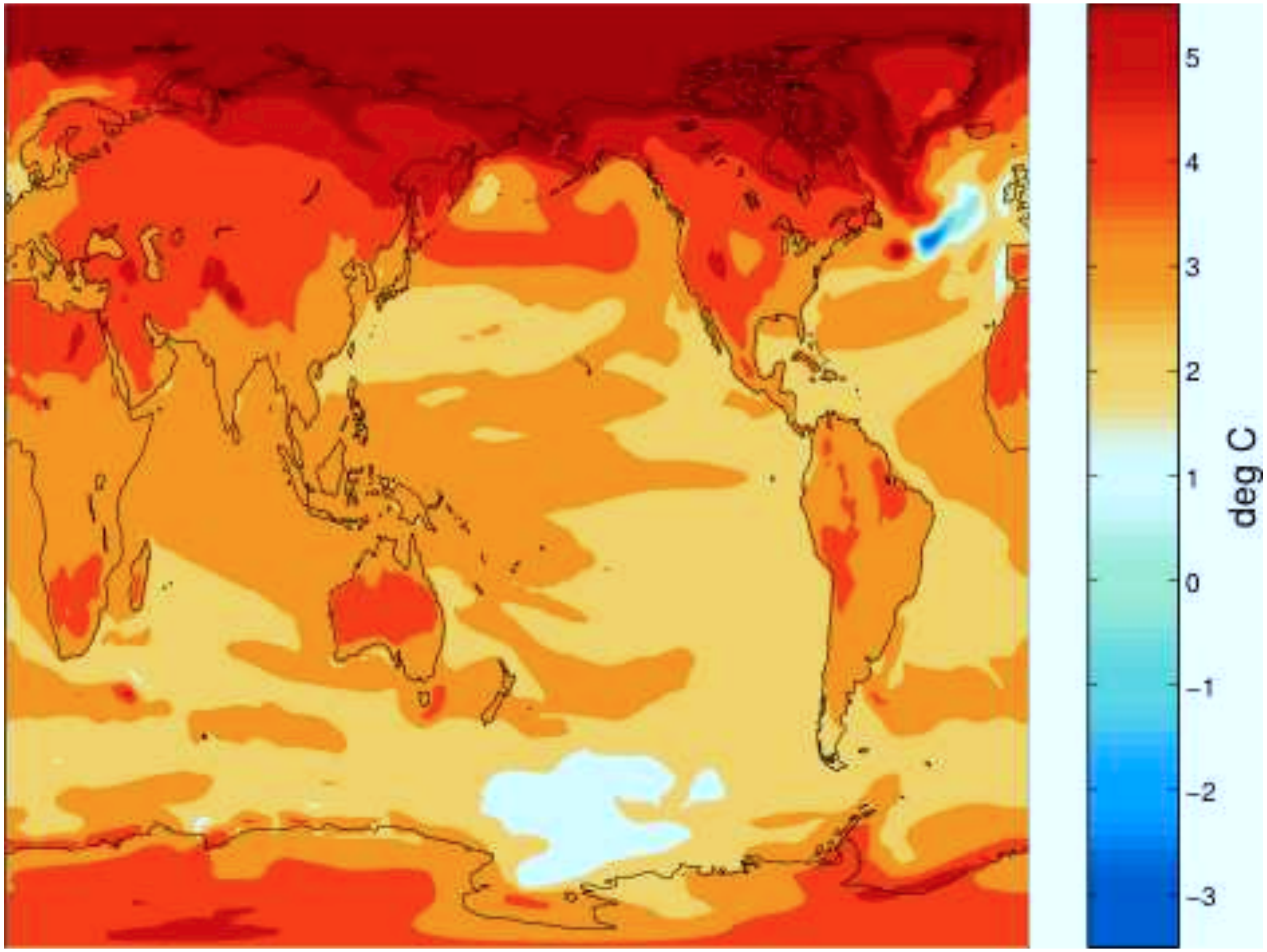


The 4 on the previous slide weren't enough…

Many of us show A1B (wishful thinking)

CCSM Models used for future prediction

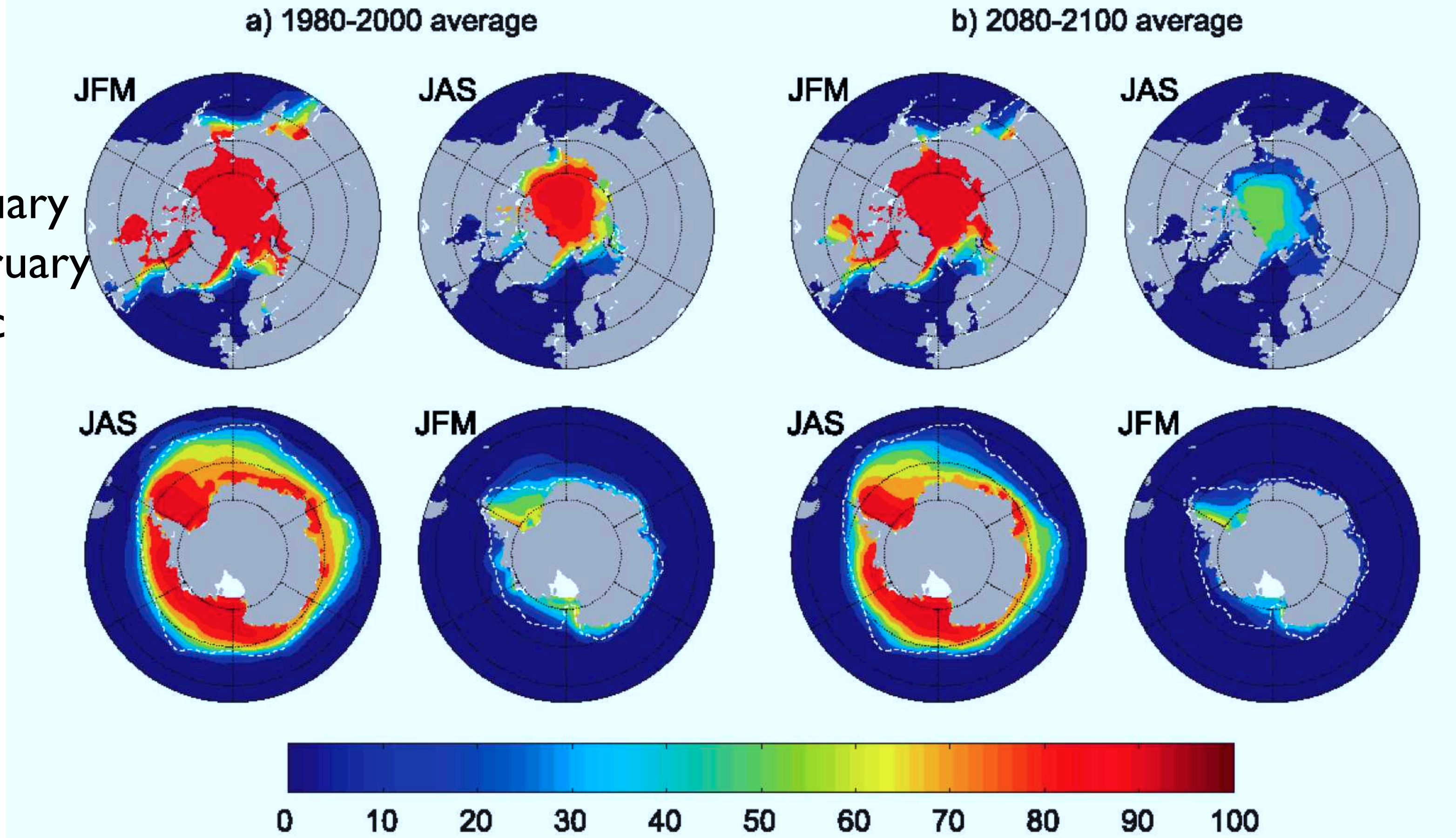
2080-2100 minus 1980-2000 temperature change (in deg C) A1B Scenario



Projected Sea Ice Extent

"2080-2100" minus "1980-2000"

J=January
F=February
etc



Sea ice concentration (%)

Largest decreases in northern hemisphere

Scenario A1B

IPCC AR4, Fig 10.14

If we eliminated human CO_2 emissions today:

How long will it take for the Earth system to reach a new equilibrium?

It will take many centuries to thousands of years

What are the factors?

Deep ocean heat uptake

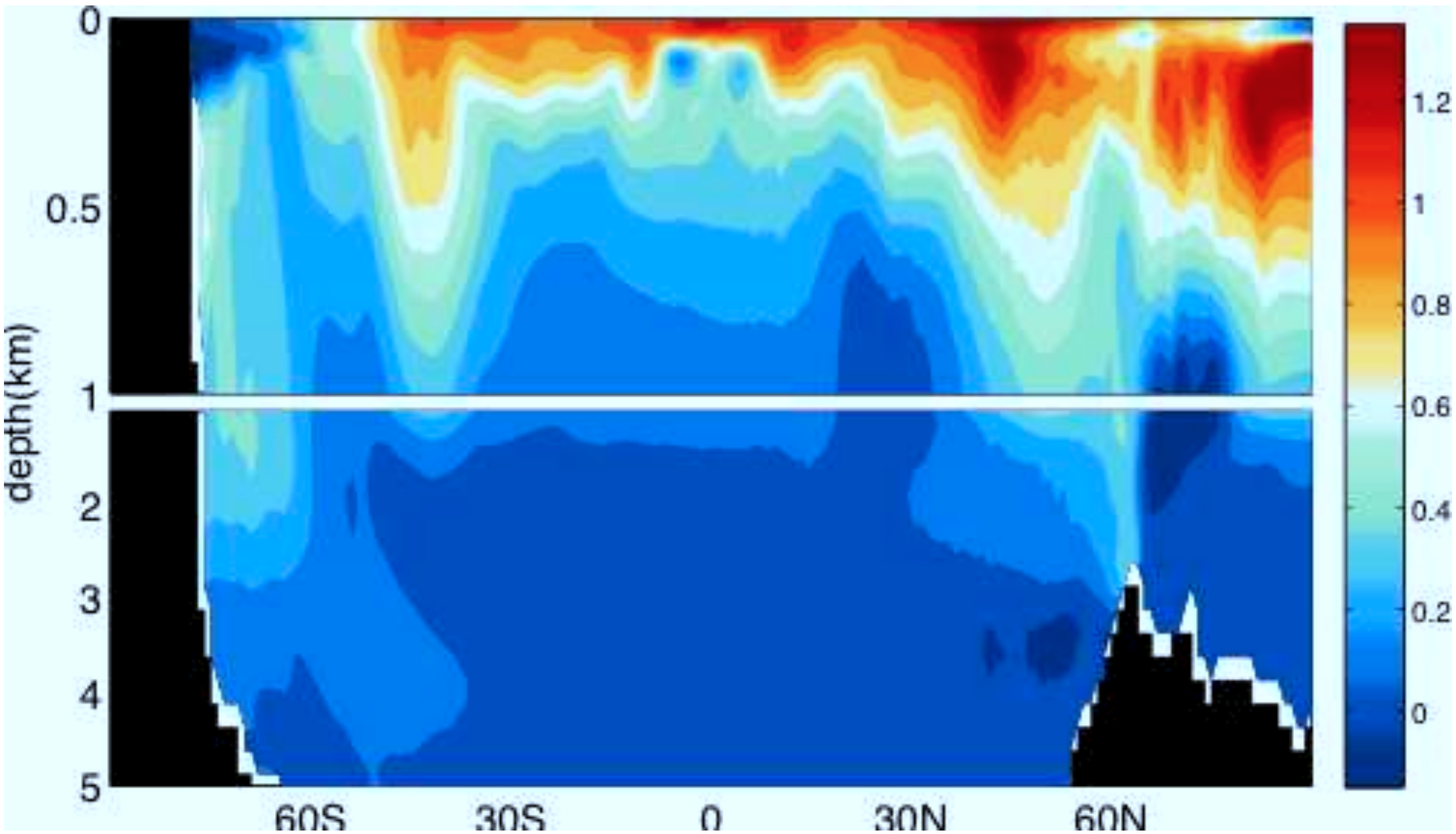
Carbon cycling between upper and deep ocean

Past climate models didn't predict carbon cycle well – Instead we "prescribed" CO_2 concentrations

So we could only consider

Deep ocean heat uptake

Ocean heat uptake - warming in the ocean mid 21st century (deg C) (not perfectly mixed)



Antarctic
Deep
Heats up!

Arctic
Near Surface
Heats up

About ocean heat uptake

• Surface ocean provides thermal inertia on time scale of several years

• Deep ocean provides thermal inertia on time scale of many centuries (our estimate is even shorter than reality due to perfect mixing assumption)

• Oceans have a very strong stabilizing effect on climate

Motivation for simpler warming “scenario”

Ocean heat uptake is complex and leads to major differences among models

At equilibrium the deep heat content is constant so no further heat “uptake”

Uncertainty about future emissions scenario is source of future uncertainty in the climate

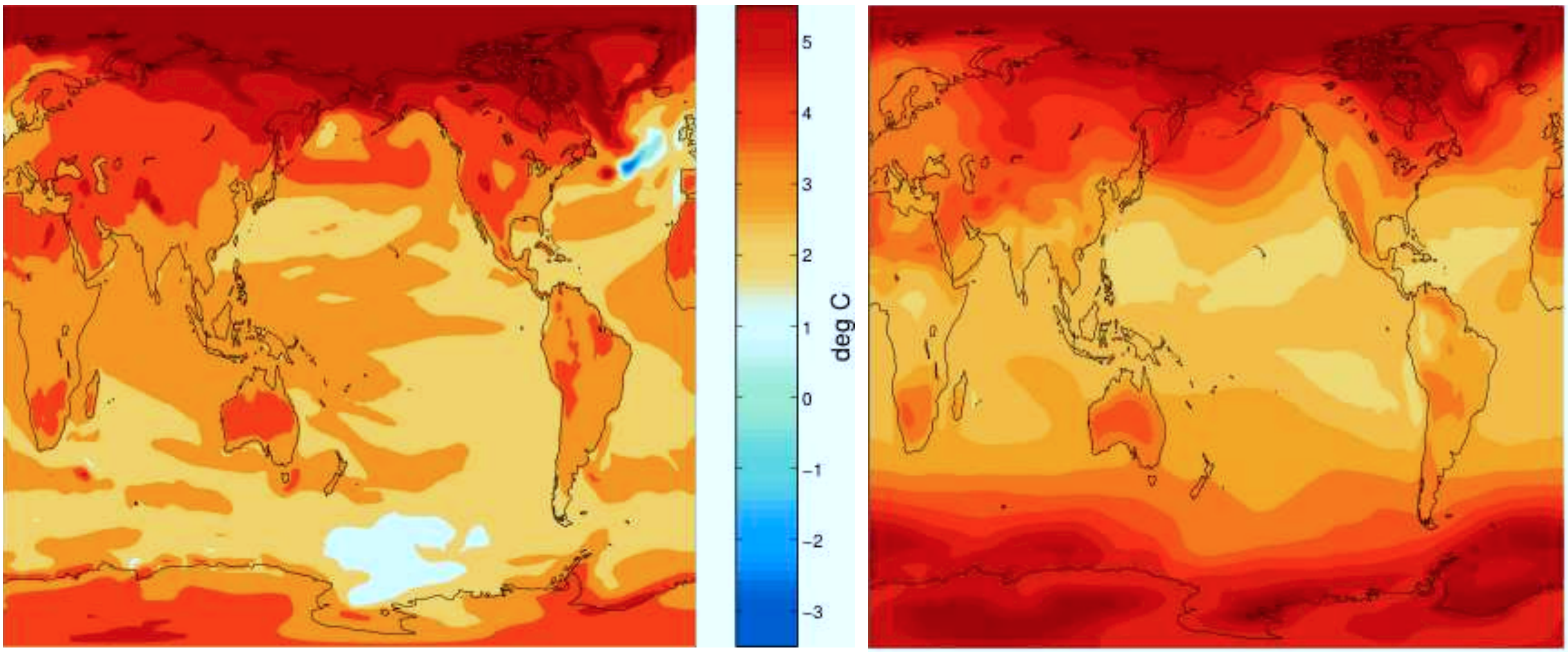
Solution:

1. Run models without deep ocean - replace ocean component with shallow mixed layer only
2. Instantly double CO_2
3. Wait about 10 yrs to get equilibrium response

Transient versus Equilibrium warming

Warming at 2100
relative to end of last century

Warming from 2XCO2



- Transient warming is smaller, yet forcing is much larger
- Transient warming is asymmetric across hemispheres
- Transient warming is modest in the northern North Atlantic

Equilibrium warming from 2XCO2

We use it as a simplification (see two slides back)

Used to compare models without worrying about there deep ocean heat uptake. But still

ΔT_{EQ} ranges from 1.5-4.5 C

- **The range is awfully large (factor of three!)**
- **Hasn't narrowed in 30 years - makes scientists look bad, but models have a lot more features now**
- **Are predictions even useful for policy-making purposes?**

Global Warming Theory – we can make a model to solve with pencil and paper

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

Note:

Δ: common symbol to refer to change in some quantity

ΔF: radiative forcing (change in energy balance)

ΔT: response (change in surface temperature)

λ: climate sensitivity (everything else)

λ: does not represent the wavelength of light here!

Except we usually run a Climate Model to estimate λ

Recall ΔF = 3.7 W/m2 for doubling of CO_2

Run model until the ocean comes into equilibrium with the atmosphere and find ΔT is about 2-4.5 deg C.

So λ is ?

$$\lambda = \Delta T / \Delta F = 2/3.7 \text{ to } 4.5/3.7$$
$$= 0.54 \text{ to } 1.2 \ \text{K} / (\text{W/m}^2)$$

But now apply the model to solar variations

Where Tuesday we learned

$\Delta F = 0.2\ W/m^2$

$\Delta T_{EQ} = \lambda\ \Delta F$

Where I let $\lambda = 0.5\ K/(W/m^2)$ and

$\Delta T_{EQ} = 0.5x0.2 = 0.1\ C$