Global Warming: State of the Science

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Insight Cruises/Scientific American

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Climate Change - Ancient History

- 19th Century: Fourier, Tyndall, Langley
  - Greenhouse gases warm Earth
- 1896: Arrhenius
  - 5-6˚C rise for CO_2 doubling
- 1970s: Which way will it go?
  - Global cooling?
  - Nuclear Winter?
- 1980s: Summer of 1988
  - Hansen testifies
  - *End of Nature* (McKibben), *Global Warming: Are We Entering the Greenhouse Century?* (Schneider)

Climate Change: IPCC* Era

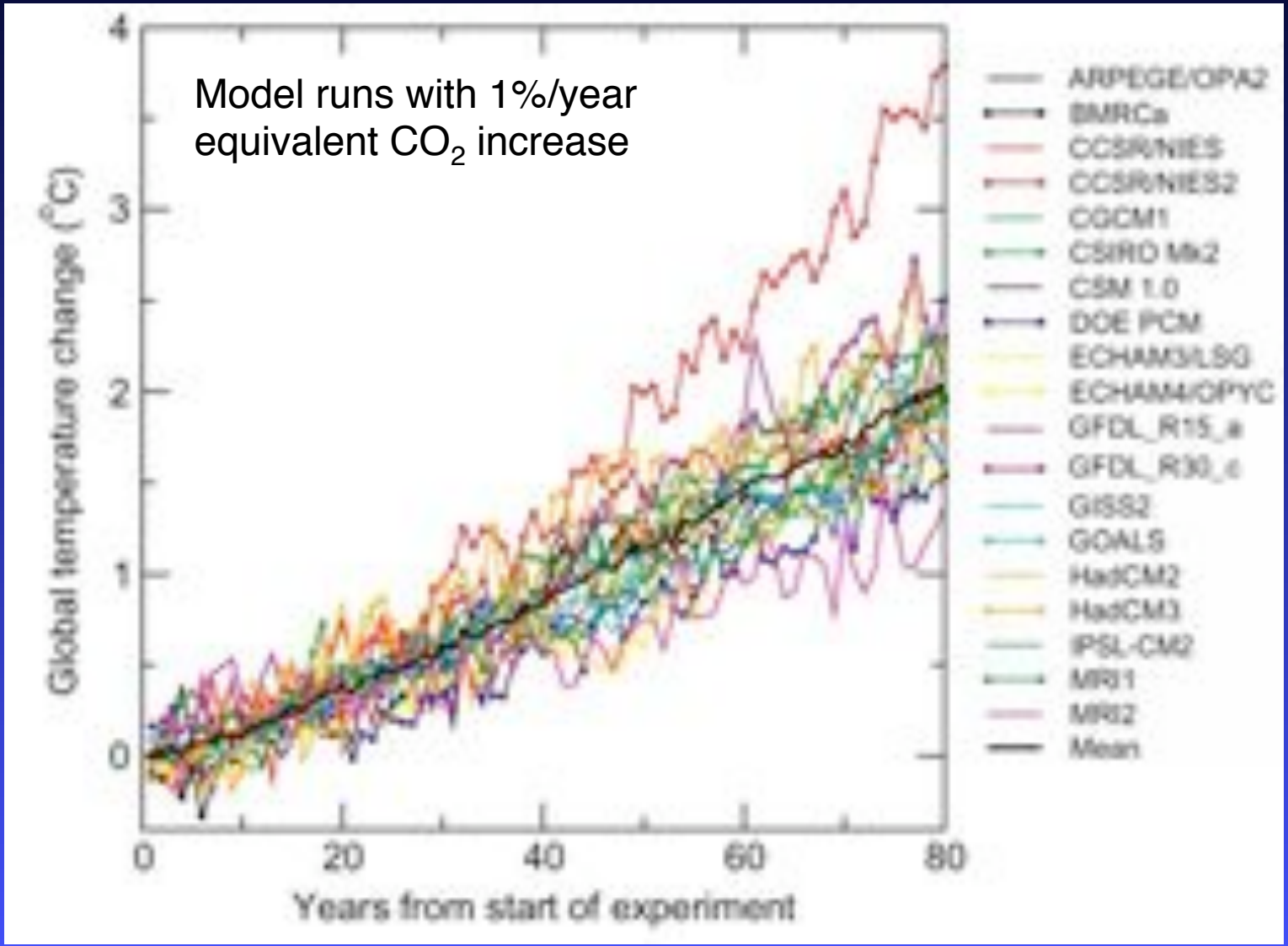
- 1991 IPCC First Assessment Report (FAR): observed climate "broadly consistent" with anthropogenic greenhouse effect
- 1996 IPCC SAR: "discernible human influence on global climate"
- 2001 IPCC TAR: "most of the warming observed over the last 50 years is attributable to human activities"
- 2007 IPCC AR4: "Warming of the climate system is unequivocal…Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations…"

*Intergovernmental Panel on Climate Change

What is this IPCC?

- Intergovernmental Panel on Climate Change
- Established 1988 by
  - World Meteorological Organization
  - United Nations Environment Program
- Major assessment reports every ~six years
  - Summarize climate research
- Three Working Groups
  - Science, Impacts, Mitigation
- Hundreds of scientists & policymakers
  - AR4 WG1 (Science): ~600 authors, 620 expert reviewers, representatives from 113 governments
- AR5 due 2014

IPCC: Synthesizing Research



IPCC 2001 WG1 Fig. 9.3

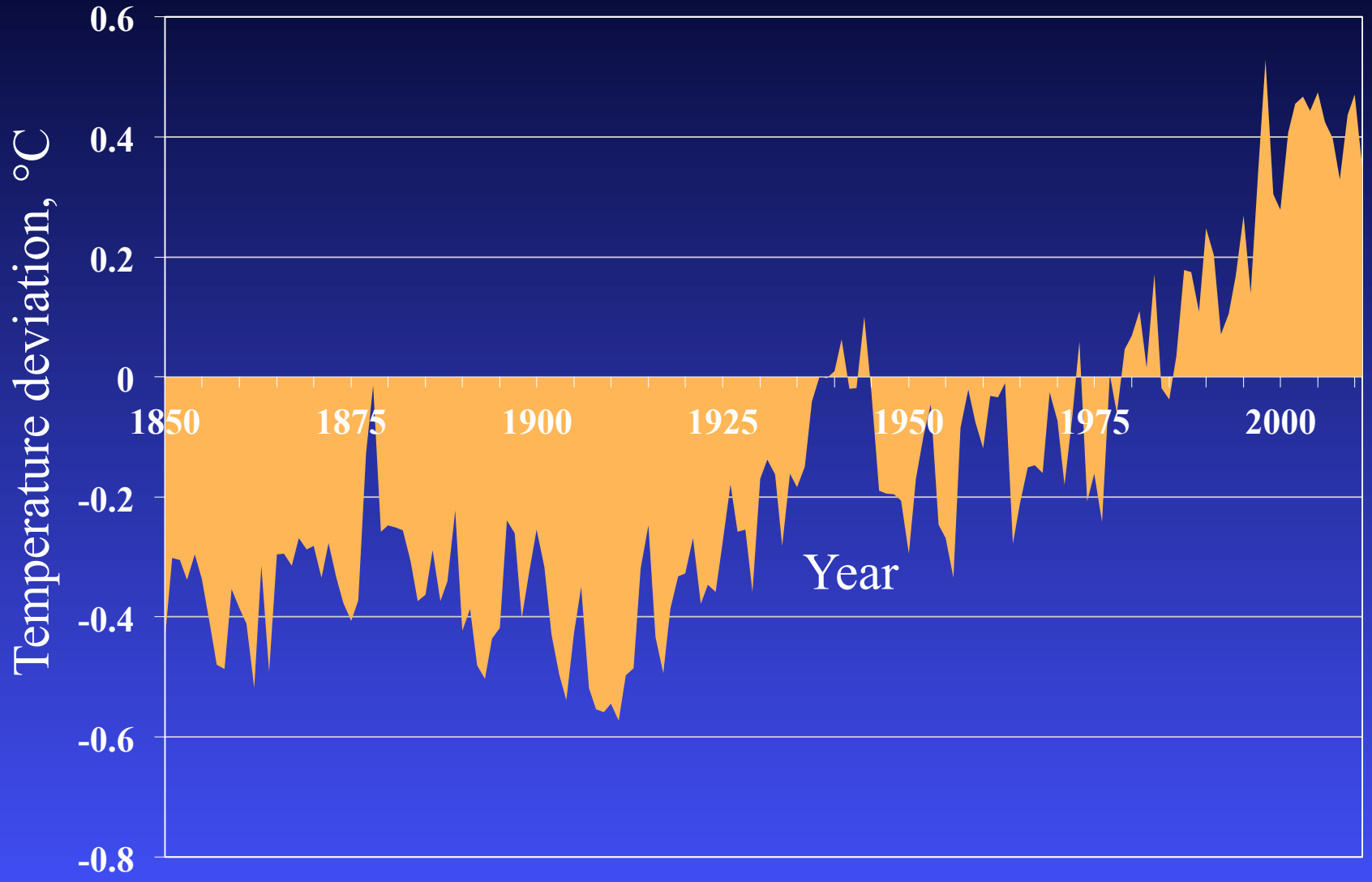
Highlights of IPCC AR4

- Generally confirms IPCC TAR findings
  - But with greater certainty
    - 90-95% probability that we're the cause of warming
    - Probable global average temperature rise by 2100: 1.7 - 4˚C (3-7˚F) [A1B; all scenarios 1.1 - 6.4˚C]
  - Other changes
    - More heat waves (90-95% likelihood)
    - More intense tropical storms (60-90% likelihood)
    - Estimates of sea-level rise lowered (21-48 cm; A1B scenario)

Since IPCC AR4

- Acceleration of Gree
  - Higher estimates of proje
- Record low Arctic se
  - Ice-free North Pole in se
- Feedbacks in the carb
  - Reduced ability of land a
- New criteria for "dan
  interference in the cli
  - 2˚C maximum global ten
  - "350" movement
- "Even higher confide
  dominate observed w
  - Huber & Knutti, *Nature*

Climate Change: Is it Happening?



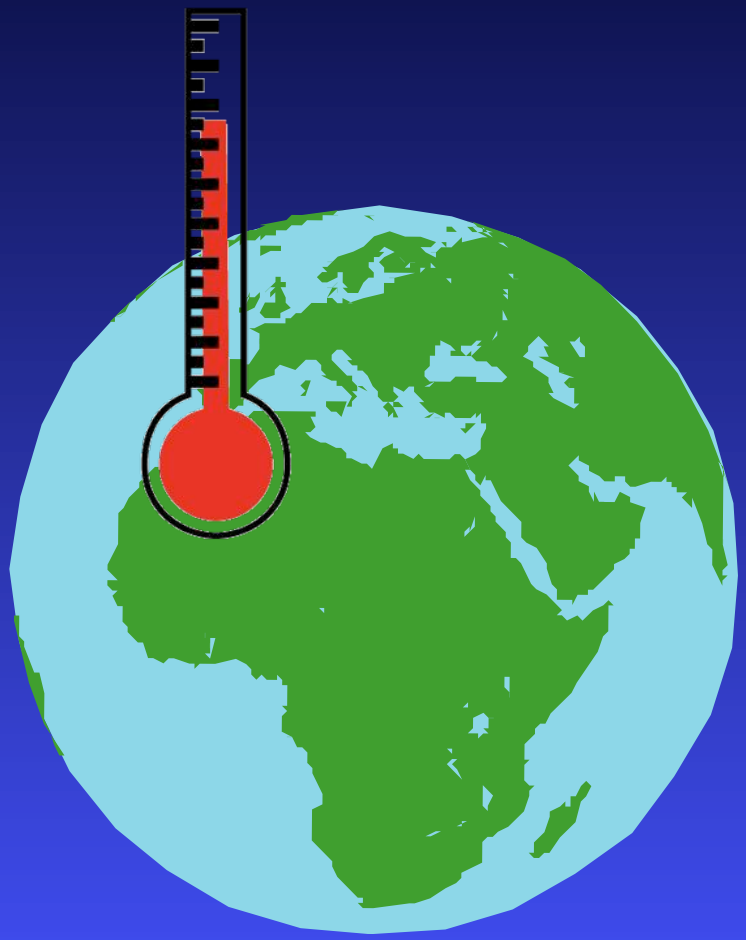
Source: University of East Anglia, Climatic Research Unit, updated 1/2012
http://www.cru.uea.ac.uk/cru/data/temperature/hadcrut3vgl.txt

20 Hottest Years on Record

University of East Anglia Climatic Research Unit, HadCRUT3vGL, 1/2012

- Top 10
  - **1998**
  - **2005**
  - **2010**
  - **2003**
  - **2002**
  - **2004**
  - **2009**
  - **2006**
  - **2001**
  - **2007**
- Next 10
  - **1997**
  - **2011**
  - **2008**
  - **1999**
  - **2000**
  - **1995**
  - **1990**
  - **1991**
  - **1987**
  - **1988**

Taking Earth's Temperature?



Temperature Corrections

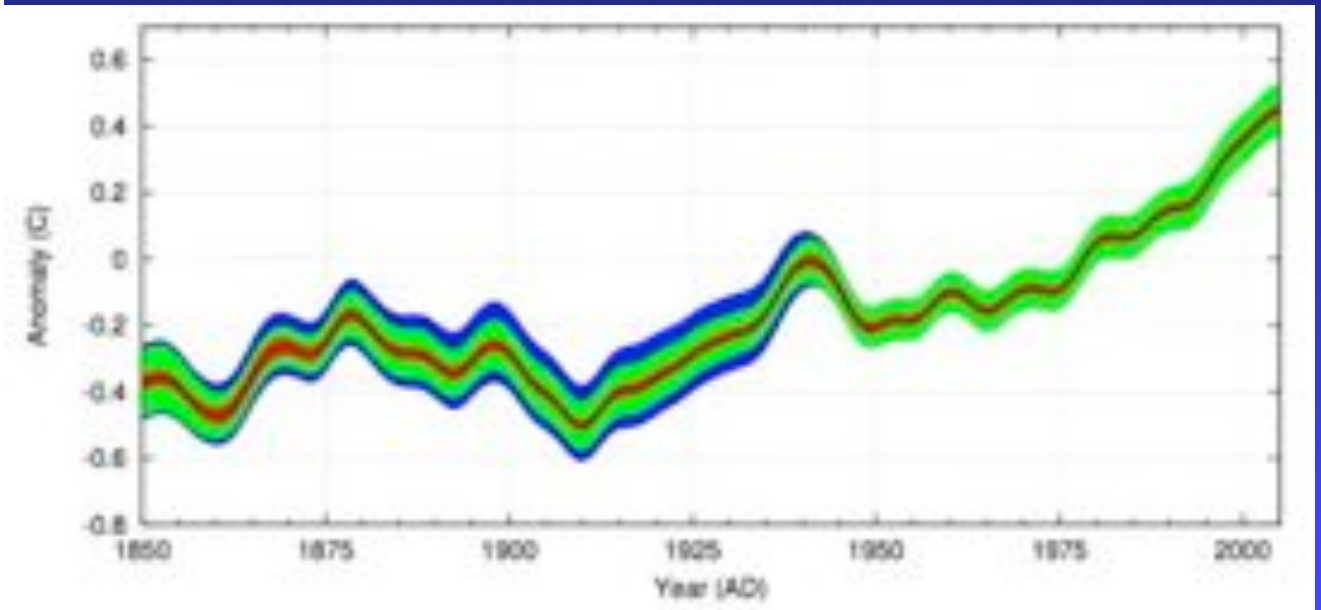
- Instrumentation changes
- Sampling techniques
  - Example: Sea-surface temperatures
- Urban heat island effect

Boston, 1800s
http://www.donandres.com/smallbox.htm

Boston, today
http://www.cpcs.umb.edu/rsci/venue.html

How Well Do We Know Earth's Temperature?

- Quick answer:
  - Today: Within about 0.05˚C
  - 1850: Within about 0.2˚C
- Detailed answer:

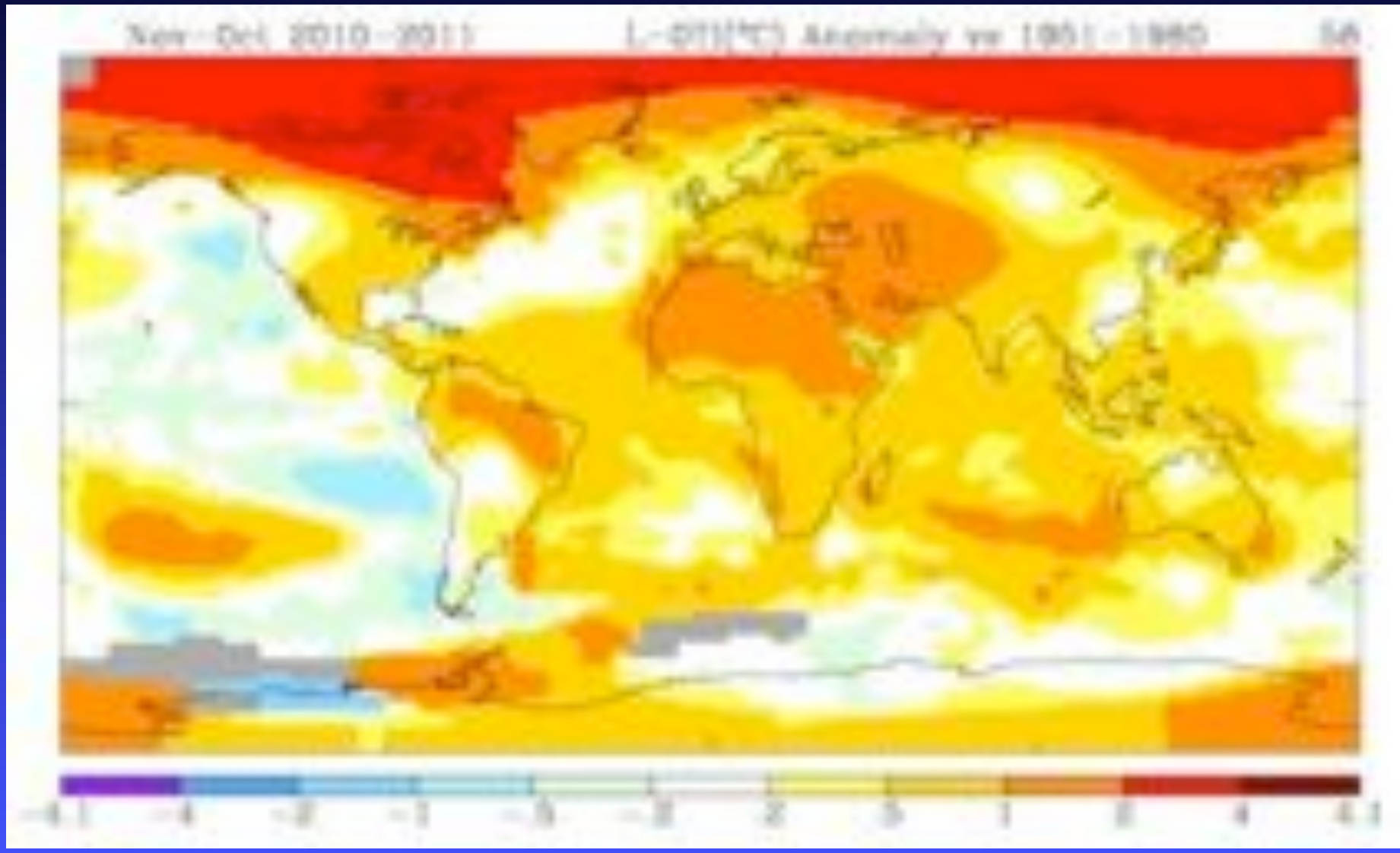


Red: Instrument uncertainties
Green: Limited coverage
Blue: Sampling bias

From Fig. 10 in Brohan, P., J.J. Kennedy, I. Haris, S.F.B. Tett and P.D. Jones, 2006:
Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. *J. Geophysical Research* **111**, D12106

Patterns of Temperature Change

Nov 2010 – Oct 2011 versus 1951-1980 average

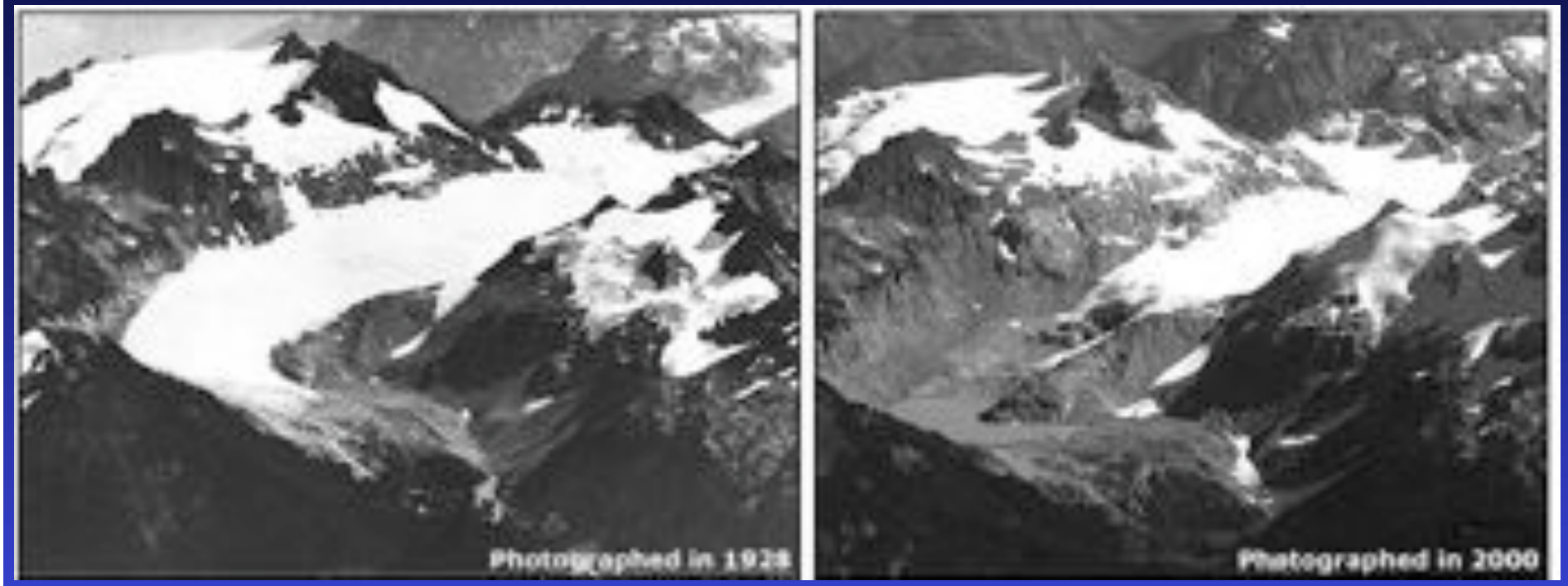


Other Indicators of Recent Change

- Ice and snow
  - 40% decrease in arctic ice thickness in recent decades
  - 40% decrease in arctic ice extent since 1950
  - 10% decrease in global snow cover area since 1960s
  - Widespread retreat of non-polar glaciers
- El Niño events
  - More frequent, persistent, and intense past 30 years
- Biological indicators
  - Growing season increasing 1-4 days/decade
  - Plant and animal ranges shifting poleward 6 km/decade
  - Coral reefs bleaching

Glacier Retreat

Cascade Mountains, Washington



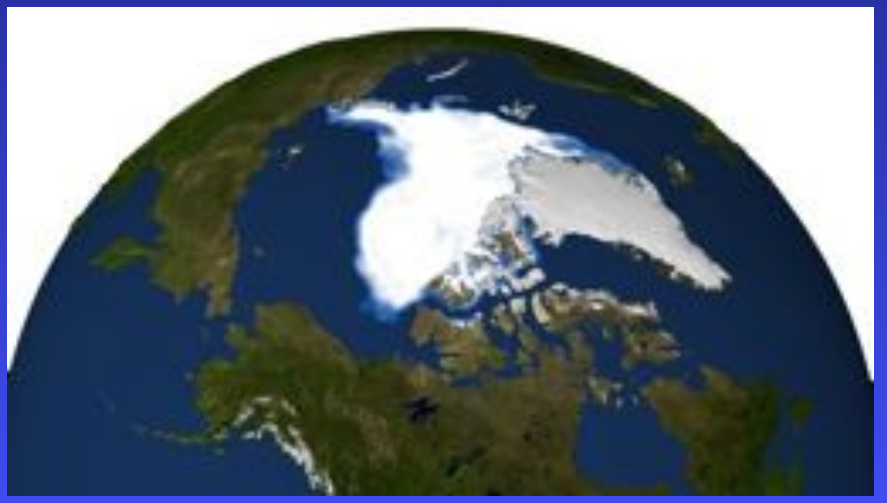
1928 2000

U.S. Geological Survey South Cascade Glacier 1928 - 2000; http://nsidc.org/sotc/glacier_balance.html

The Shrinking Arctic

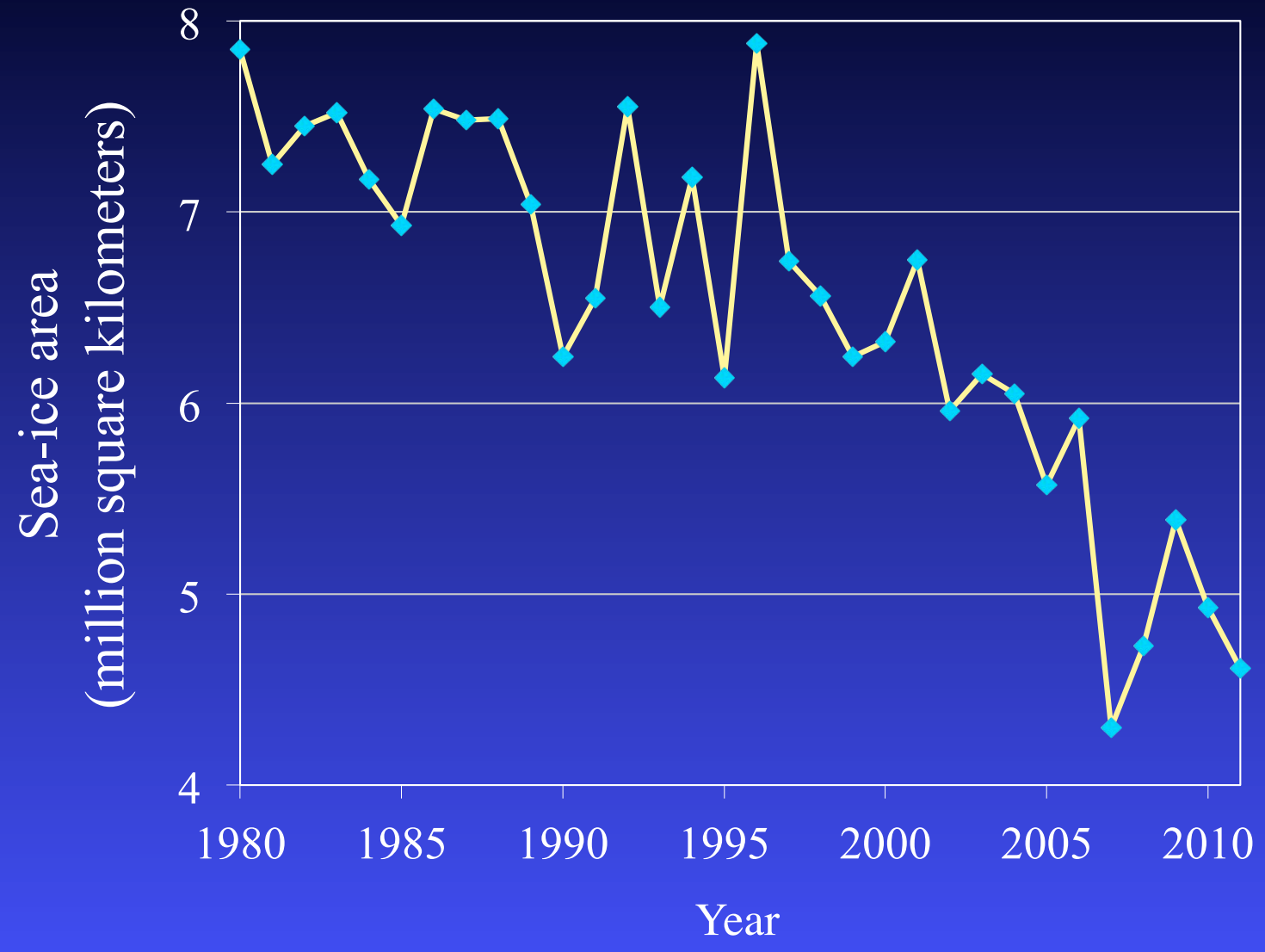
Sea ice minimum, 1980

Sea ice minimum, 2007



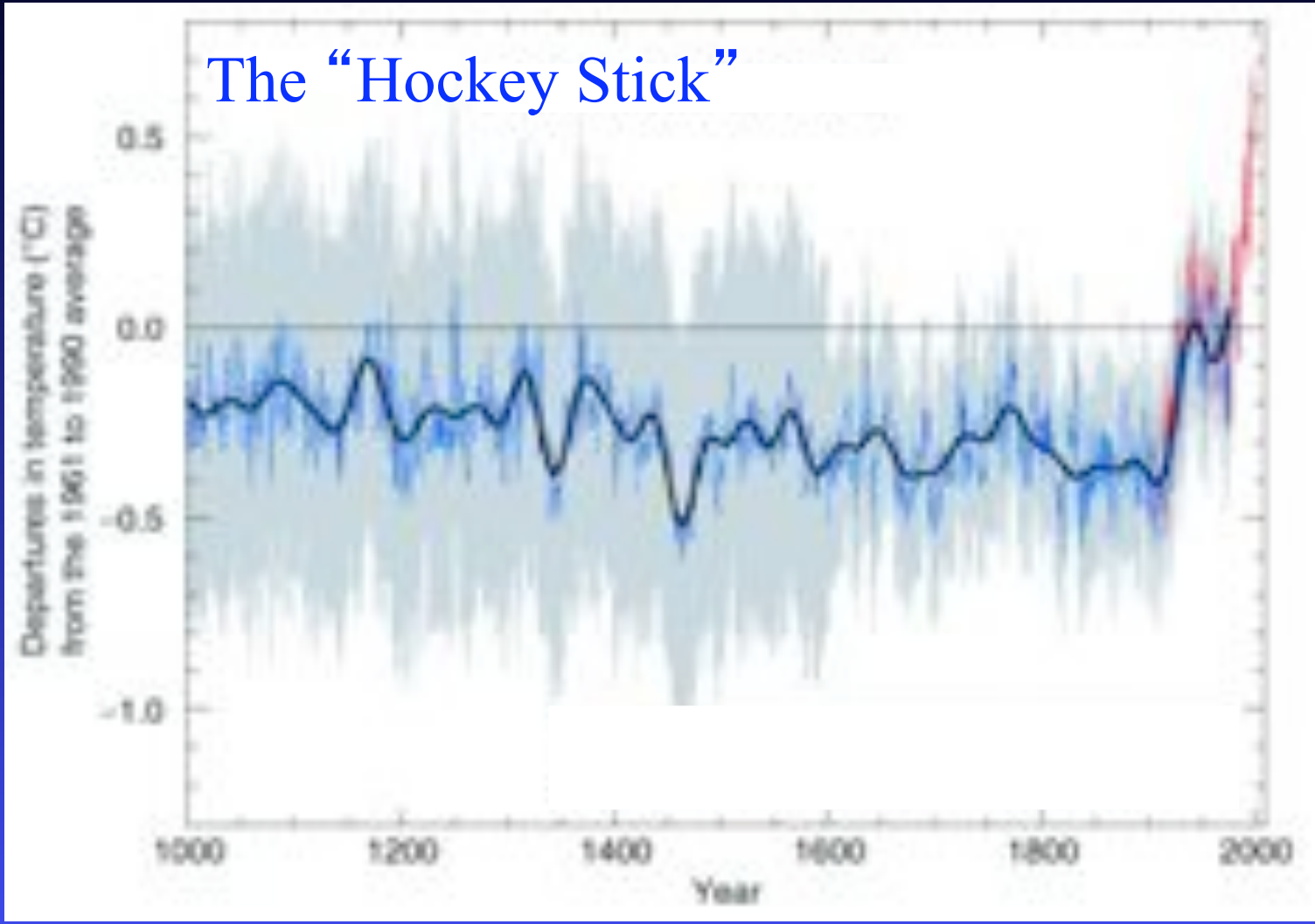
Source: Rob Gersten, NASA GSFC

The Shrinking Arctic



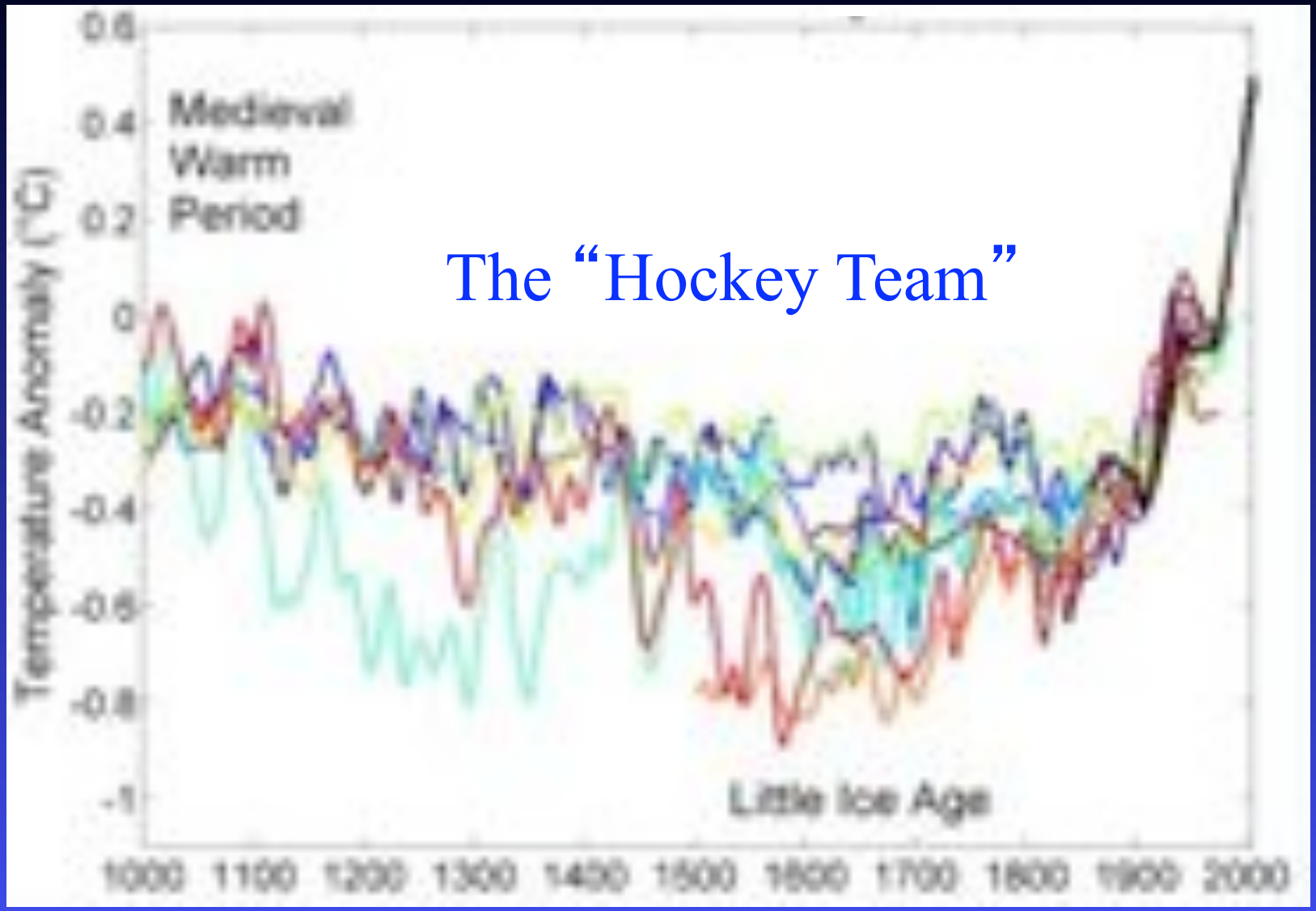
Data source: National Snow and Ice Data Center; 2012

Going Further Back . . .



Source: Mann et al., "Northern Hemisphere Millennial Temperature Reconstruction," *Geophys. Res. Let.*, 26, 759, 1999 as reproduced in IPCC 2001 WG1

Going Further Back . . .



Source: Robert A. Rhode, Global Warming Art
http://www.globalwarmingart.com/wiki/Image:1000_Year_Temperature_Comparison.png

Millennial Temperature Reconstructions

- Use multiple proxies to reconstruct 1000-year temperature record
  - Up to 112 indicators (tree rings, ice cores, ice melt, solar activity, sediment cores, coral reefs, etc)

  - Recent warming unprecedented in past millennium
  - Solar variability and volcanism are dominant influences on climate before 20th century
  - Anthropogenic greenhouse gases are dominant 20th century influence
  - Provides independent confirmation of human influence on climate

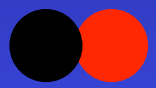
Tree ring photo from http://web.utk.edu/~grissino/images/small%20red%20pine.jpg
Graph from http://en.wikipedia.org/wiki/Image:Solar_Activity_Proxies.png
Coring photo from http://serc.carleton.edu/microbelife/topics/proxies/paleoclimate.html

Measuring Ancient Climates: Isotopes

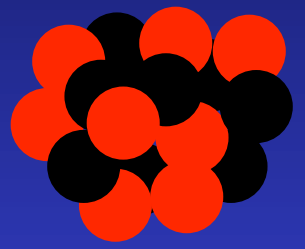
- Isotopes are versions of the same element that differ in the number of neutrons in their nuclei
  - Therefore they have different masses

Proton: Neutron:

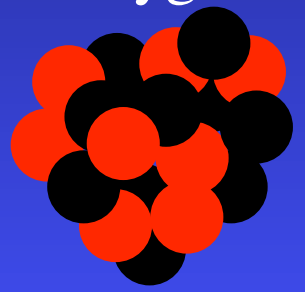
Hydrogen (H-1)



Deuterium (H-2)



Oxygen-16



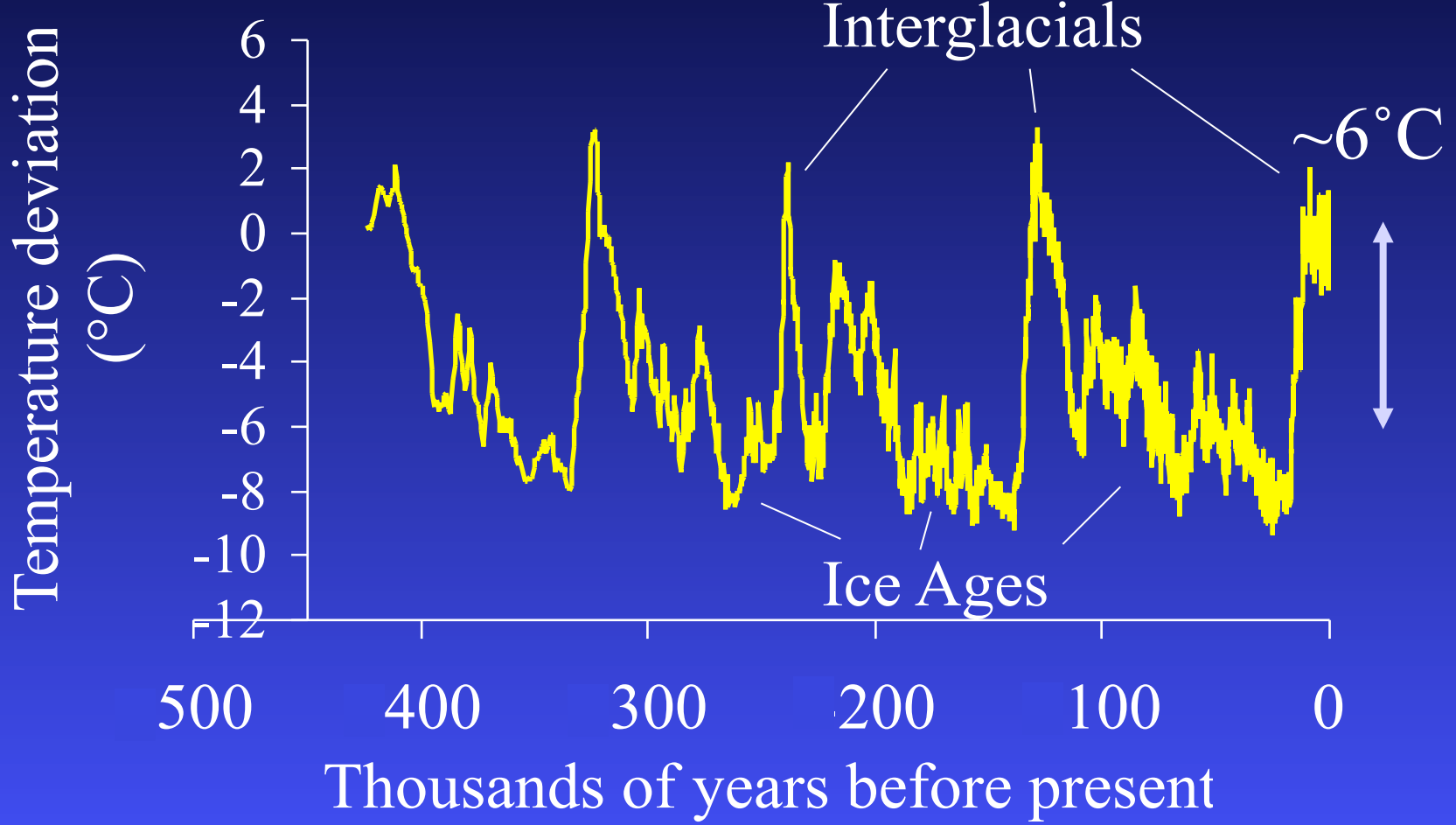
Oxygen-18

Measuring Ancient Climates: Isotopes

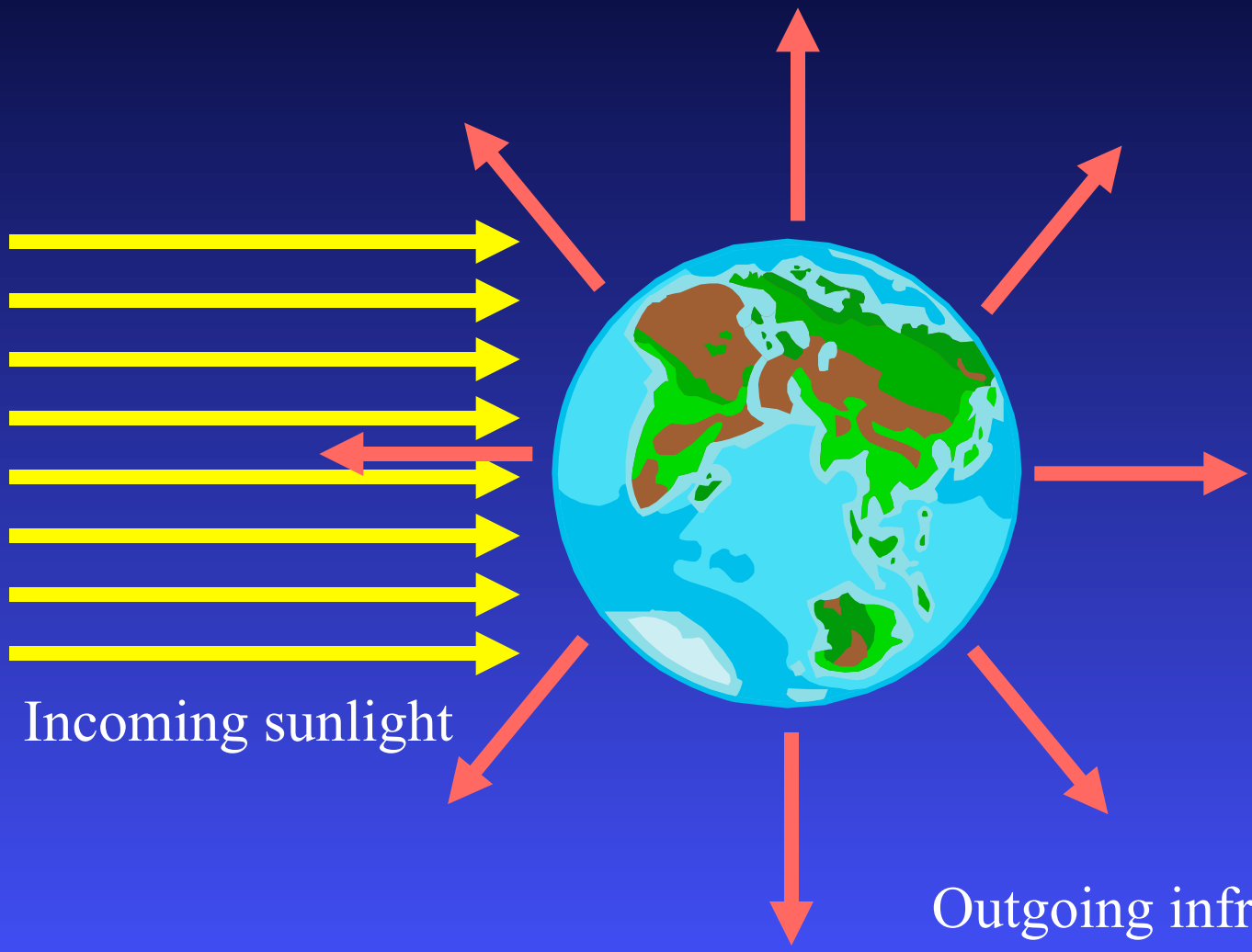
- Most oxygen is the lighter isotope O-16; 0.2% is heavier O-18
- Water containing the lighter isotope evaporates more readily, leaving atmospheric water vapor depleted in O-18
- O-18 also condenses and precipitates out more readily, leaving Arctic/Antarctic precipitation further depleted in O-18
- Depletion depends on temperature; the cooler the climate, the sooner O-18 precipitates out, and the more depleted is the arctic precipitation
- Annual layers in ice cores therefore provide a datable record of the temperature at the time precipitation fell
- A similar technique uses hydrogen isotopes

Photo by Reto Stokli,
NASA Goddard Space Flight Center

Going Back Further Still…



Climate Science: Quick Summary



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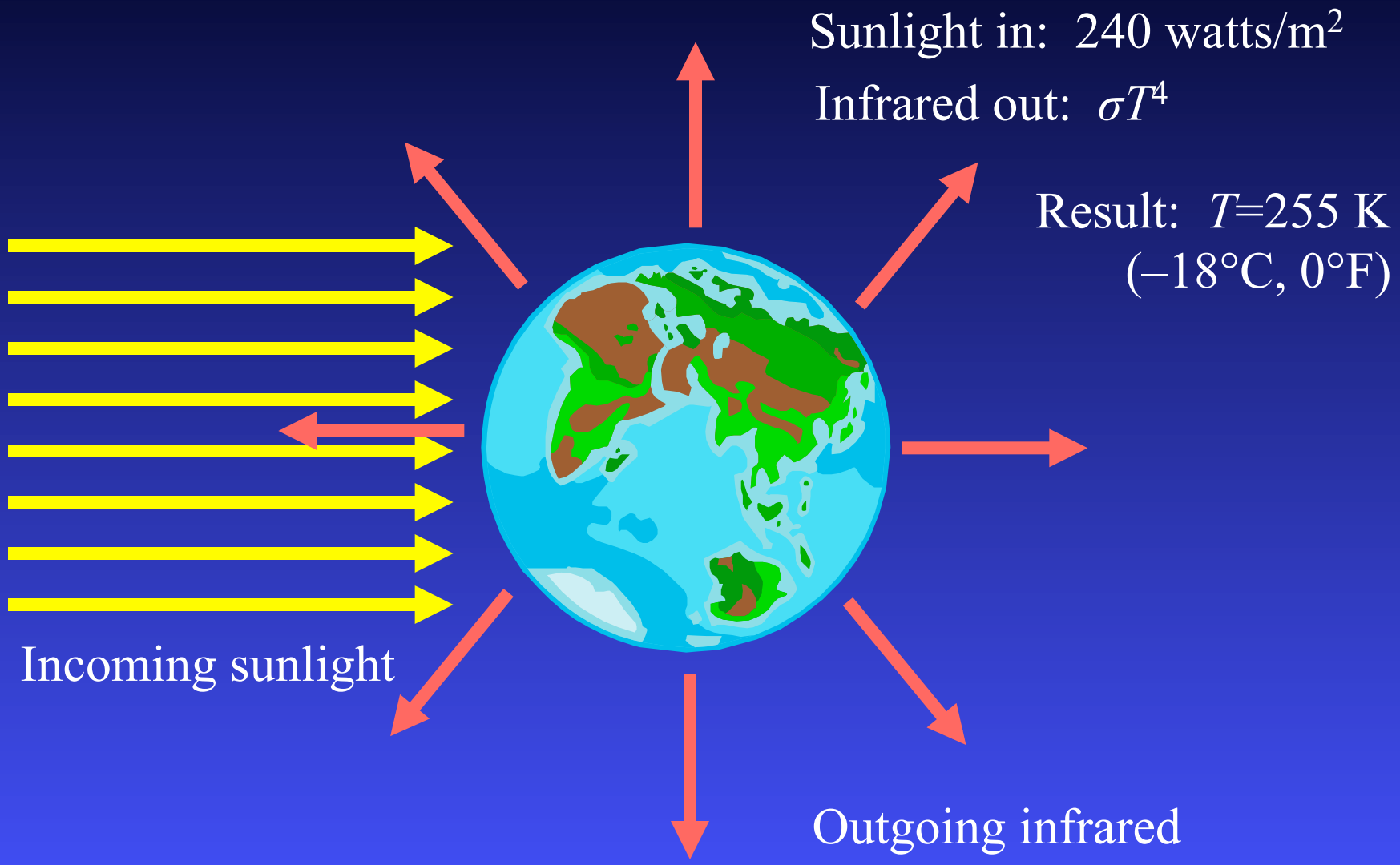
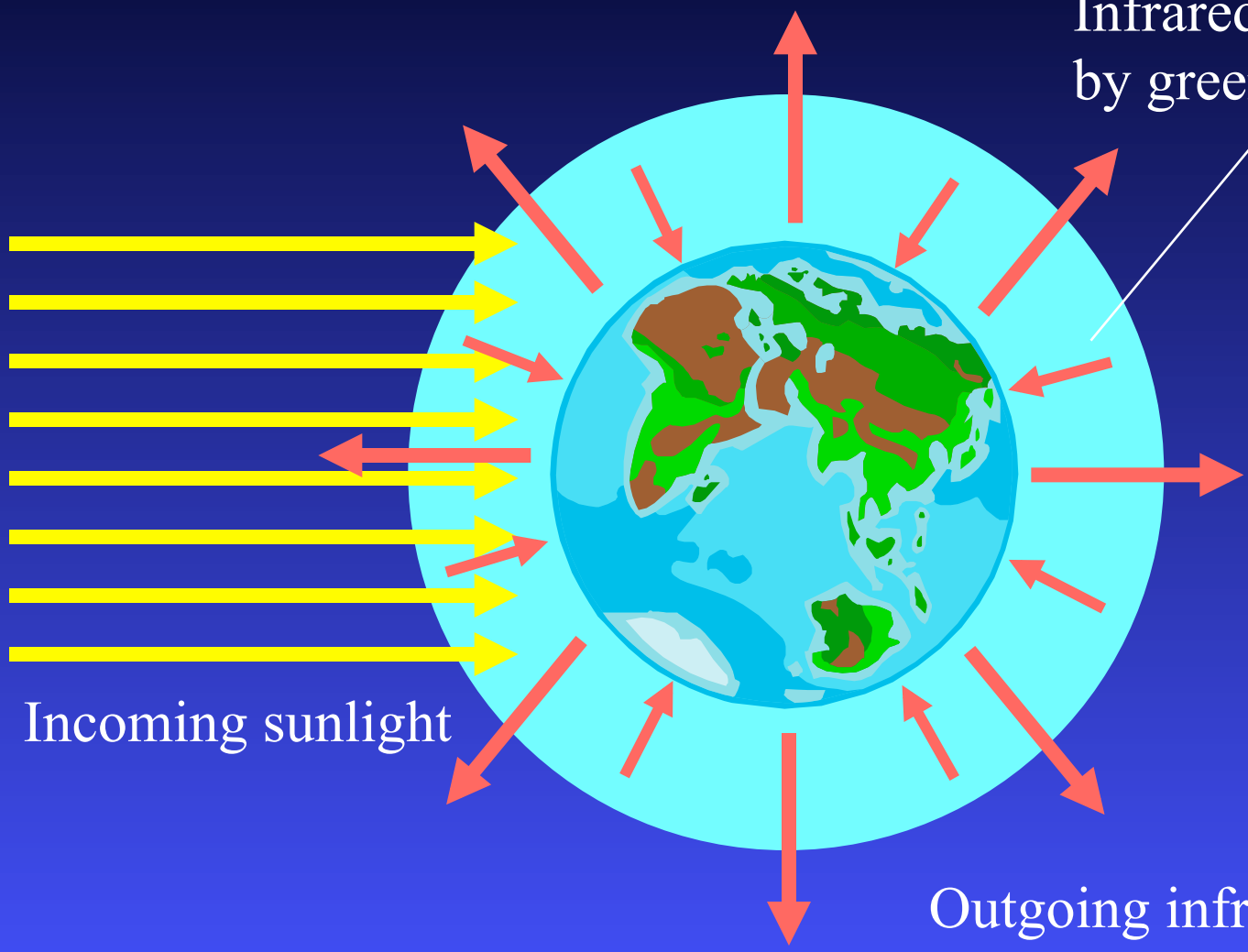


The Greenhouse Effect

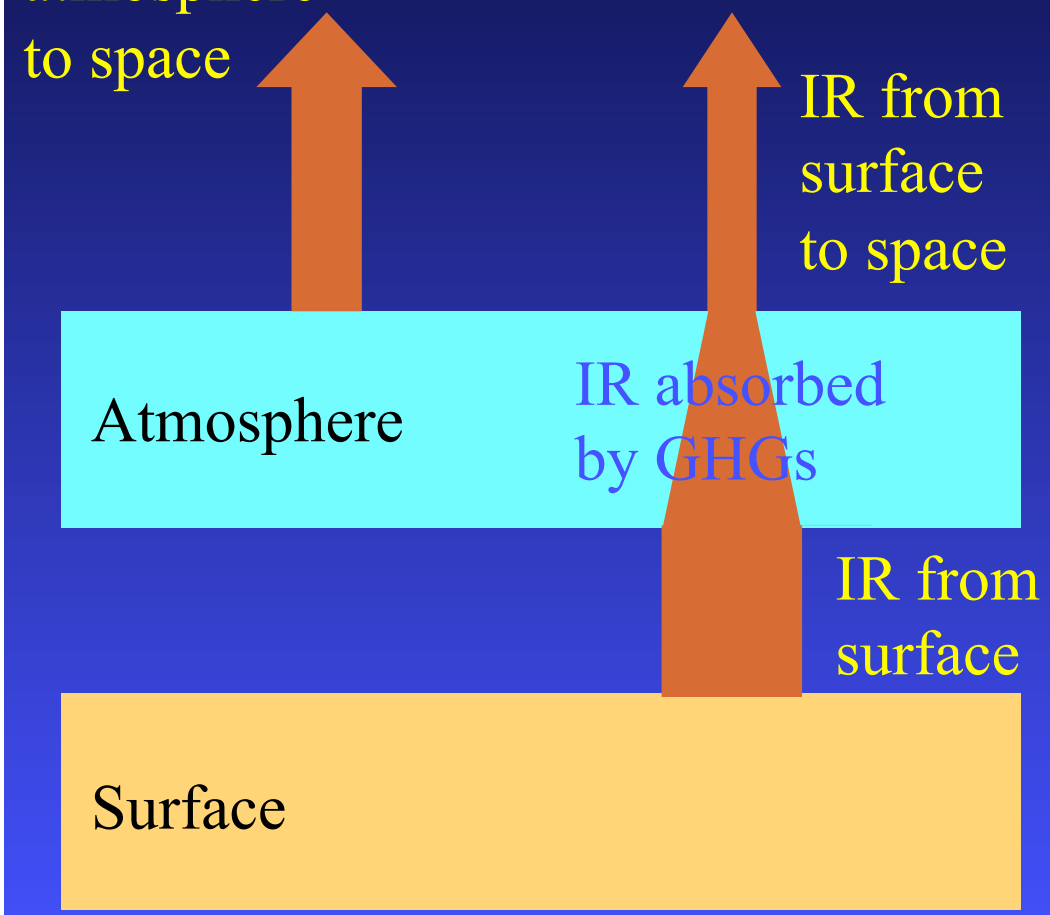


A Tale of Three Planets

Planet	Calc. Temp	Actual Temp
Venus	50	500
Earth	–18	15
Mars	–60	–50

Temperatures in ˚C

Greenhouse: A More Sophisticated Look



Verbal math:

IR to space =

IR from atmosphere

+ IR from surface

– IR absorbed by GHGs

Rearrange:

IR to space =

IR from surface

+ (IR from atmosphere

– IR absorbed)

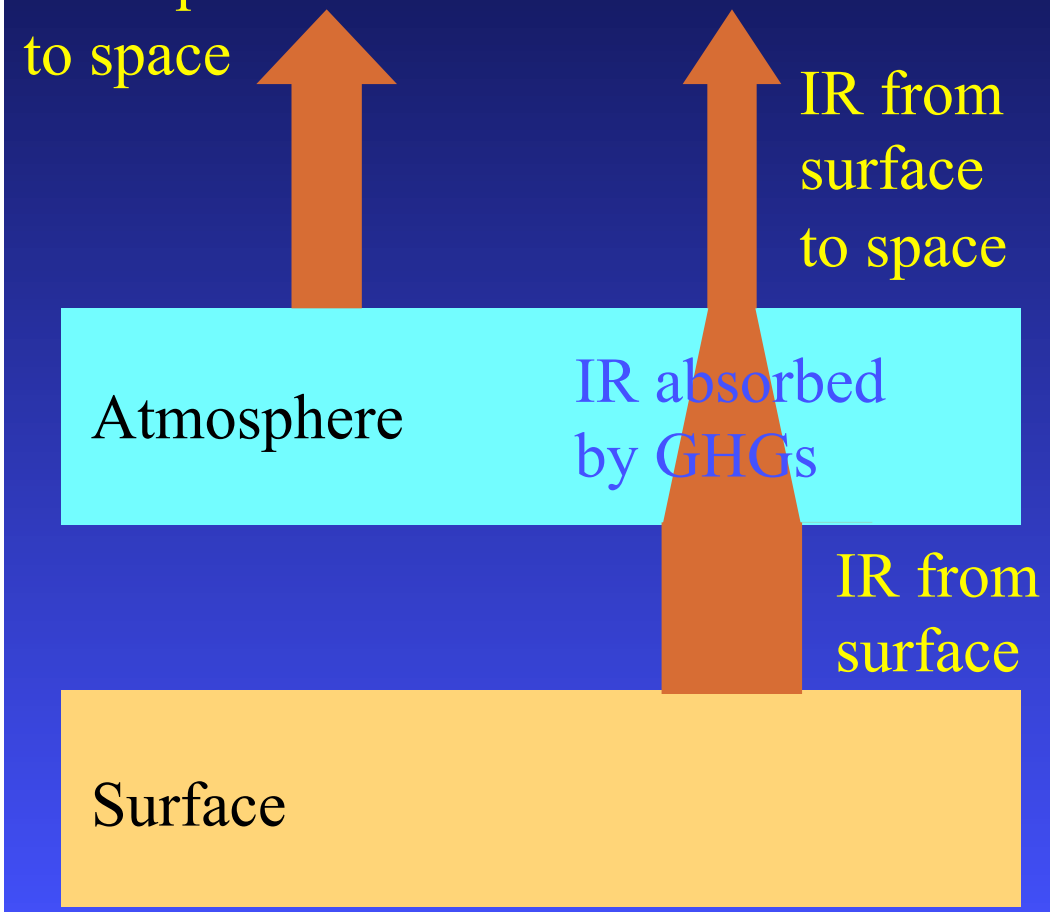
Greenhouse: A More Sophisticated Look

Verbal math:

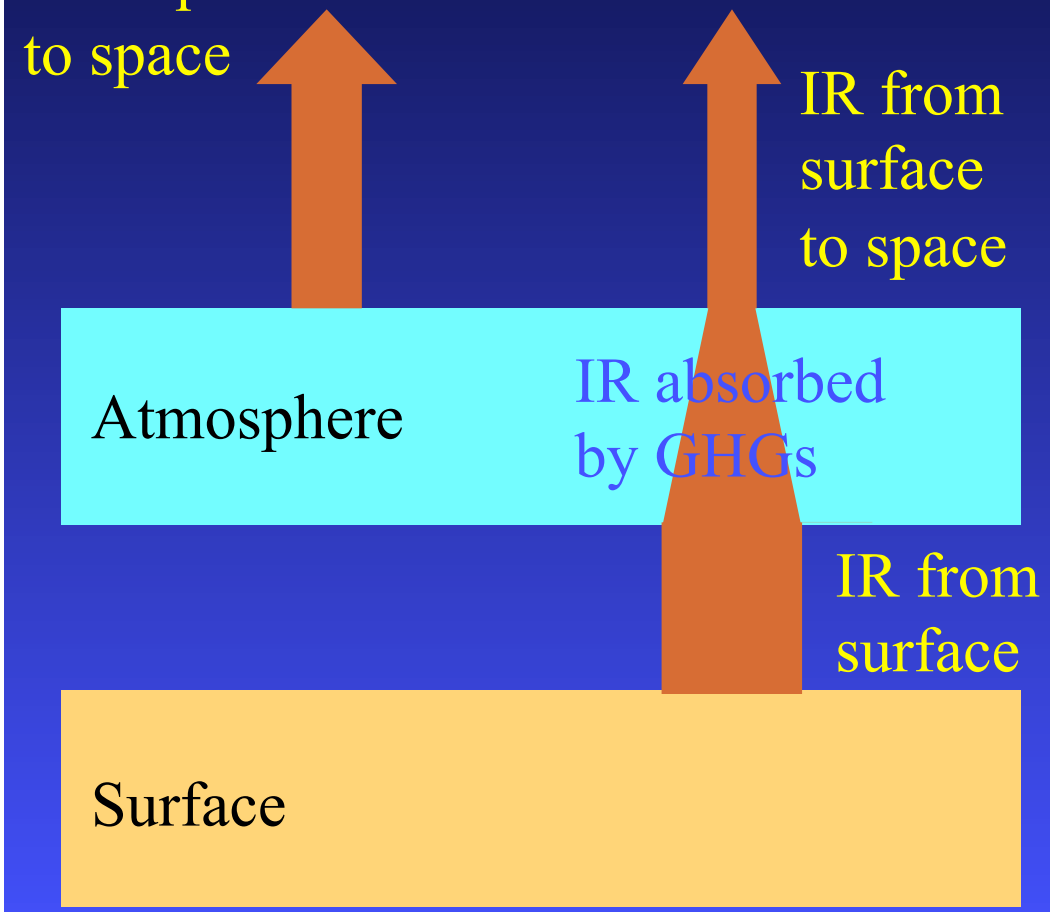
IR to space =

IR from surface

+ (IR from atmosphere – IR absorbed)



Greenhouse: A More Sophisticated Look



IR to space =

IR from surface

+ (IR from atmosphere – IR absorbed)

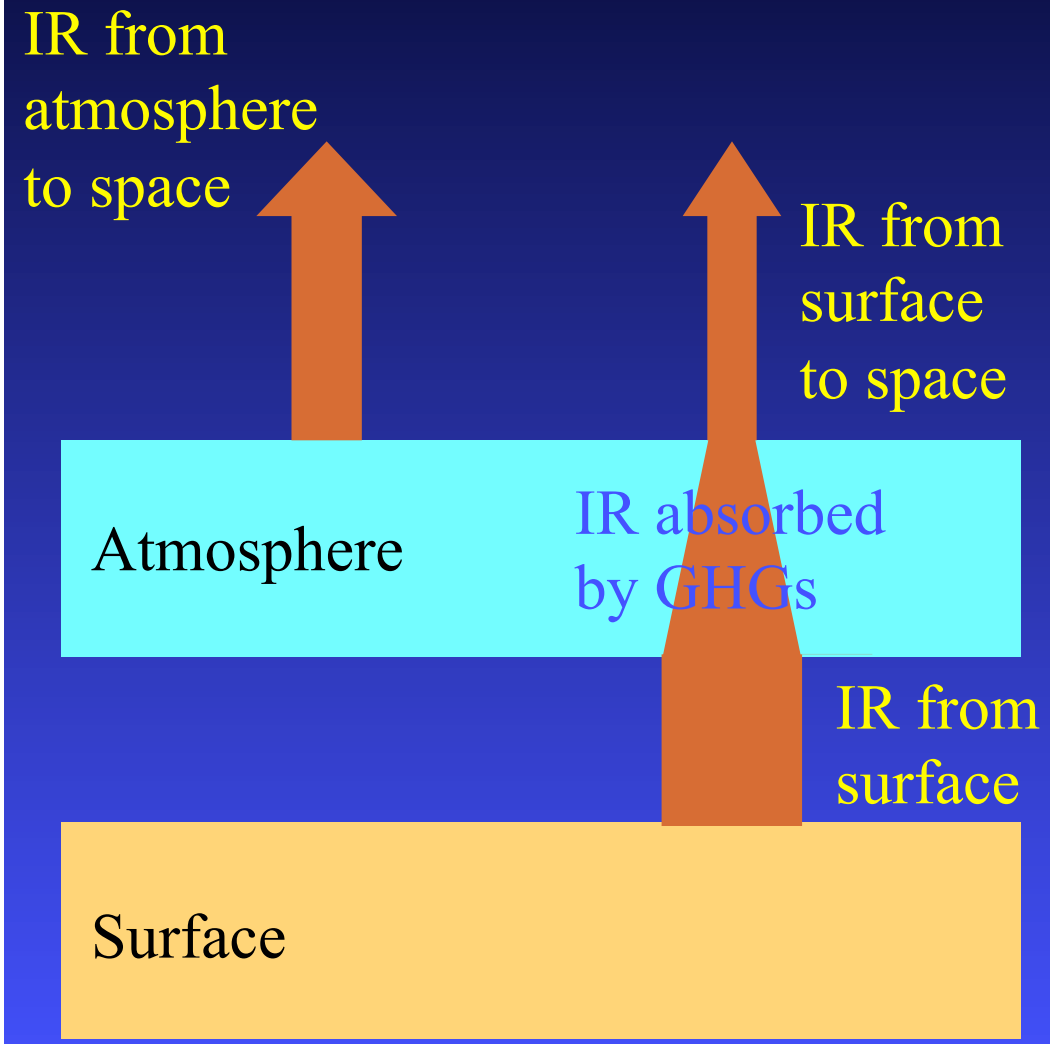
Physics fact:

IR from atmosphere depends on atmospheric temperature

IR absorbed depends on surface temperature

They're equal if temperatures are equal

Greenhouse: A More Sophisticated Look



IR to space =

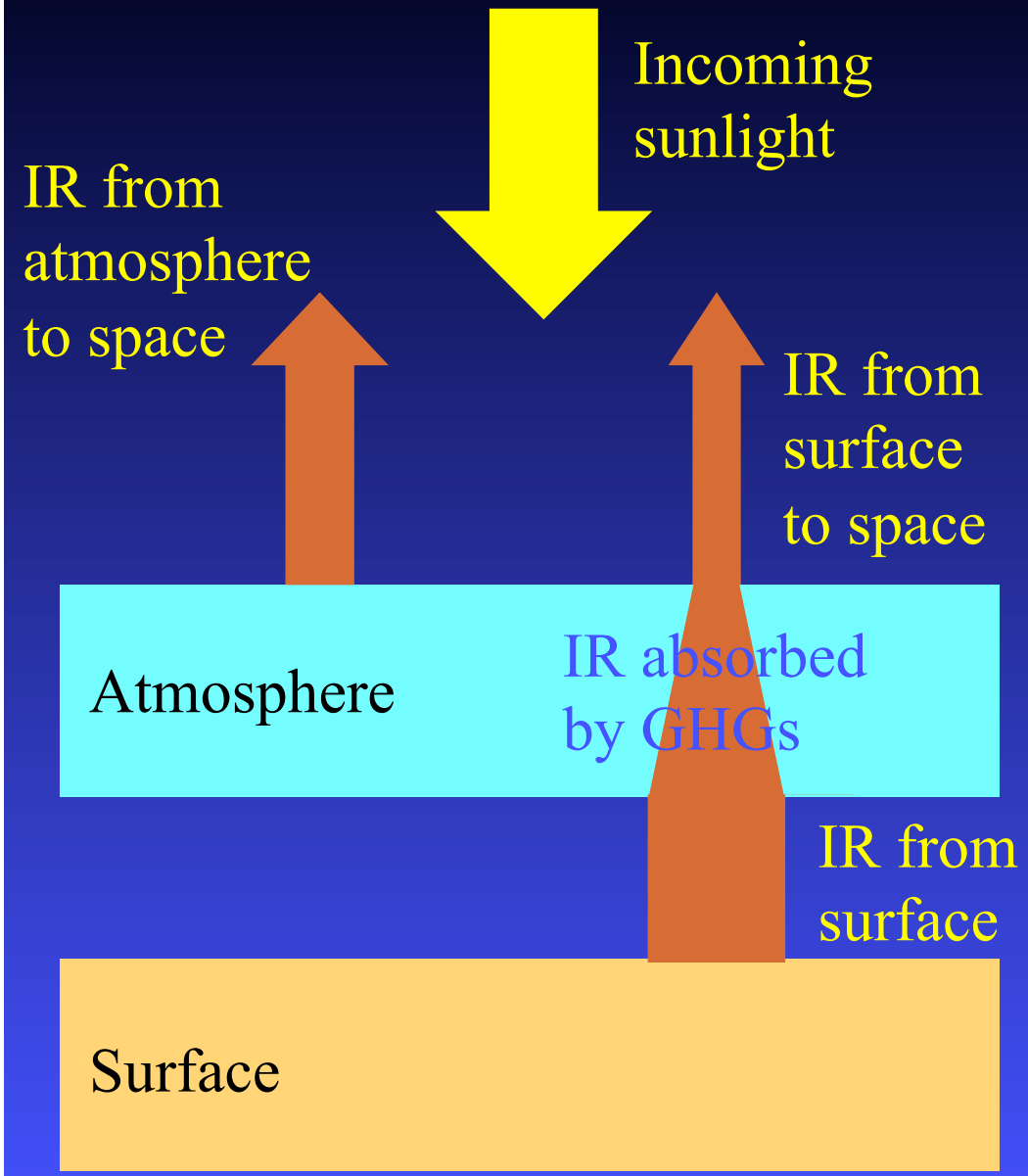
IR from surface

+ (IR from atmosphere – IR absorbed)

Yellow term is zero if temperatures are equal

Yellow term is negative if atmosphere is cooler than surface

Greenhouse: A More Sophisticated Look



IR to space =

IR from surface

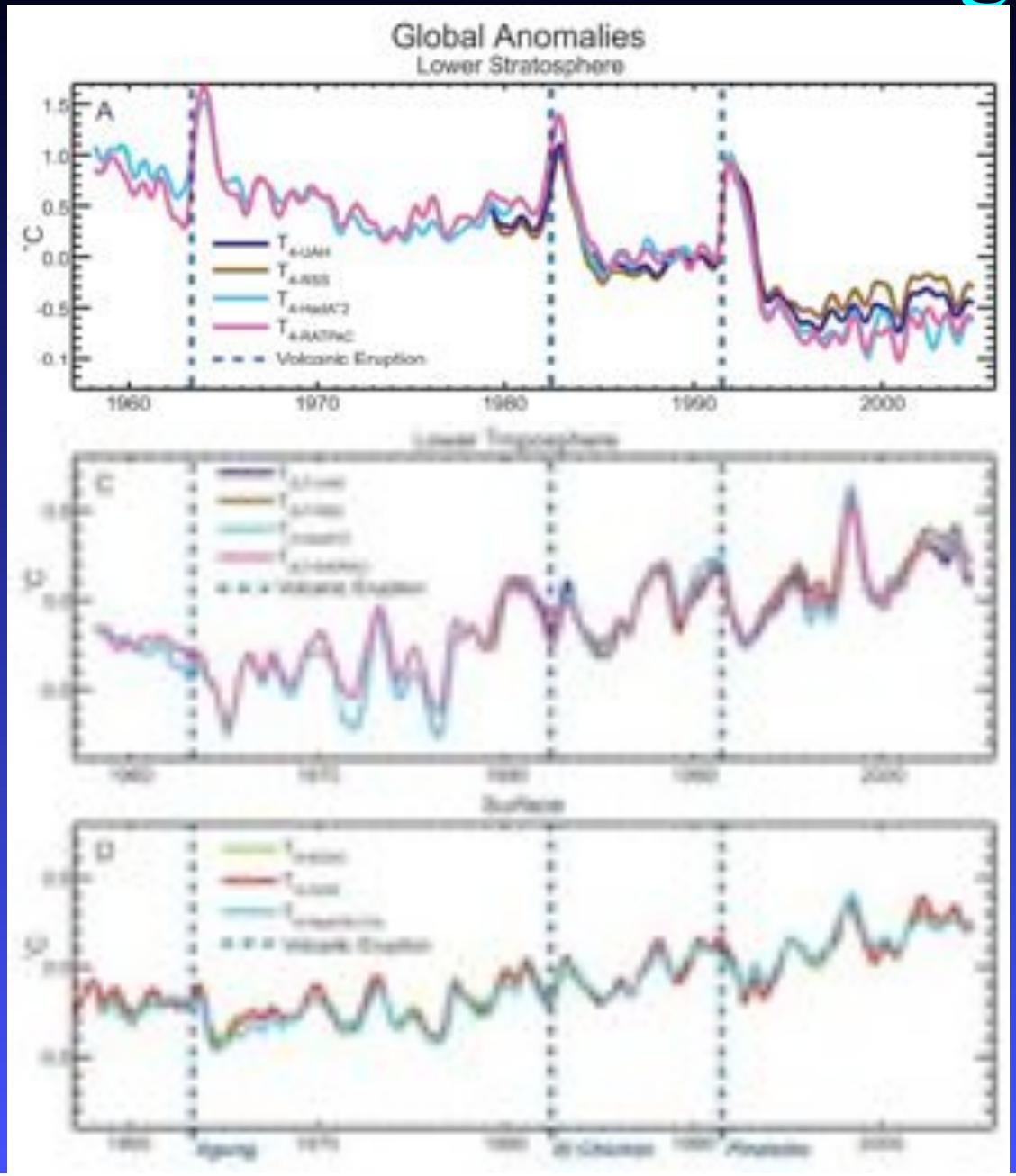
+ (IR from atmosphere – IR absorbed)

Yellow term is negative if atmosphere is cooler than surface

Energy balance:
IR to space =
solar energy input

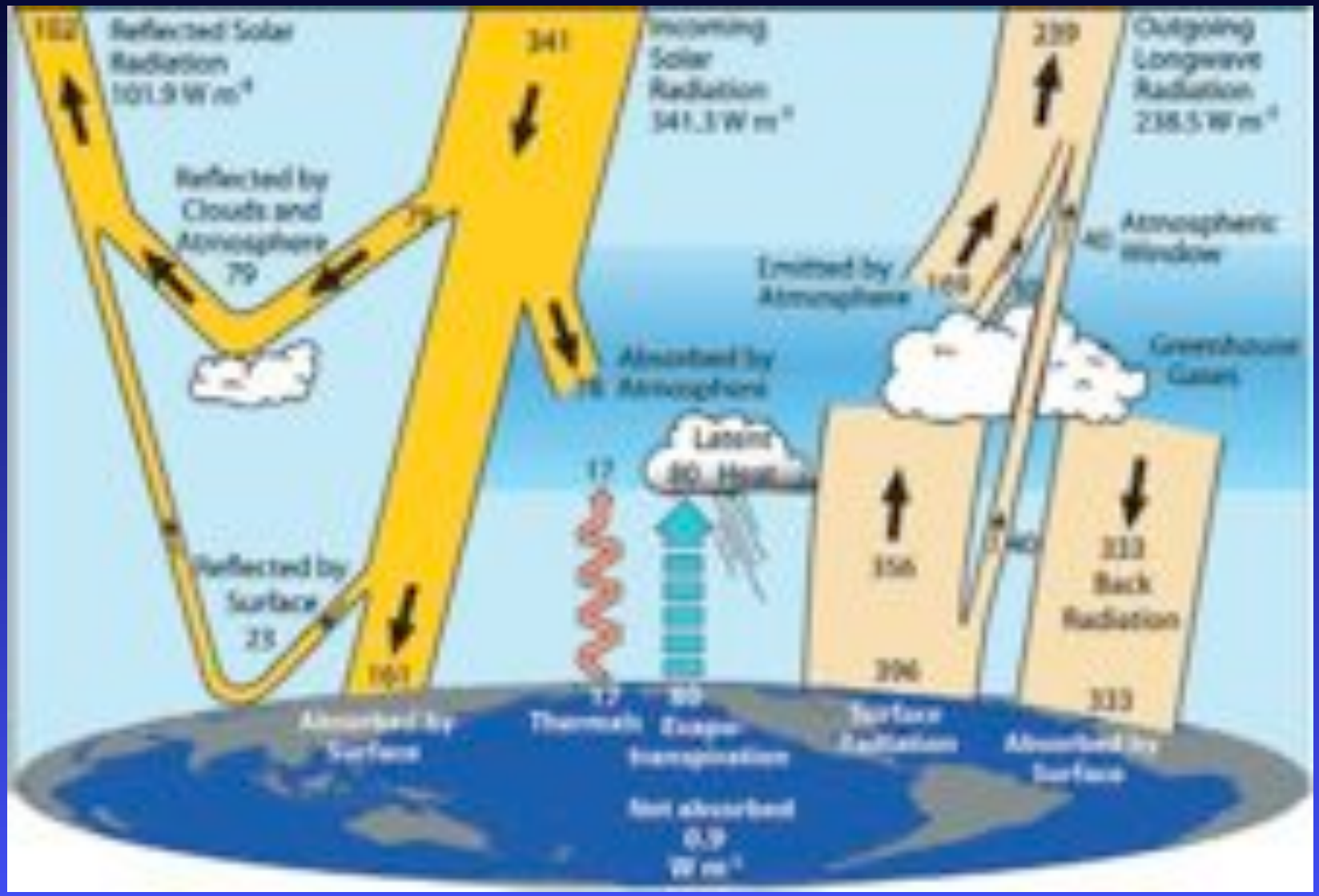
Conclusion: cooler atmosphere requires surface to be warmer than it would be without greenhouse gases

…and a Greenhouse "Fingerprint"



Adapted from
IPCC AR4 Fig 3.17

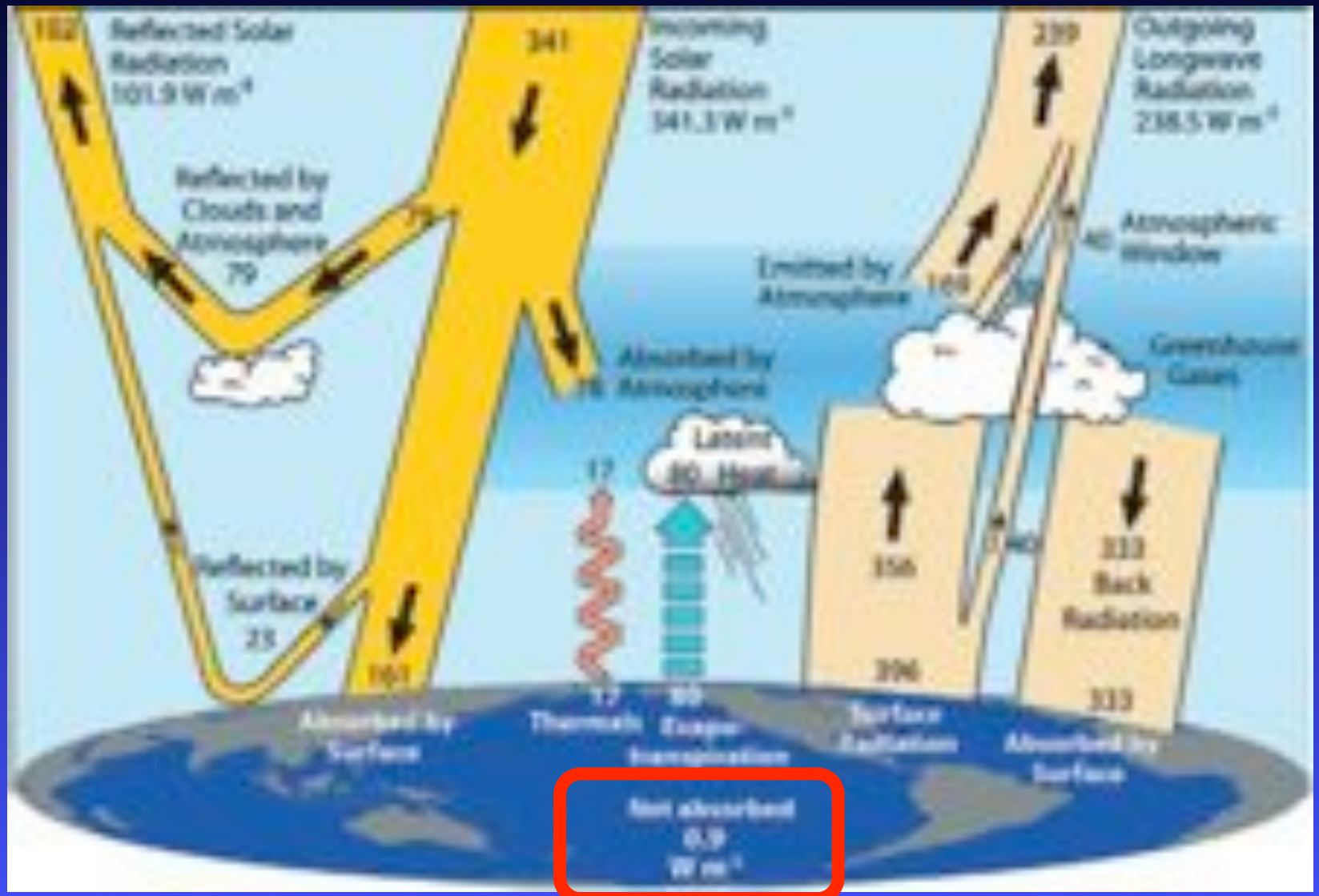
Earth's Energy Balance: Details



Source: Trenberth, Fasullo, & Kiehl, 2009, *Bull. Am. Met. Soc.*, 90, 311, March 2009; DOI:10.1175/2008BAMS2634.1

Earth's Energy (im)Balance

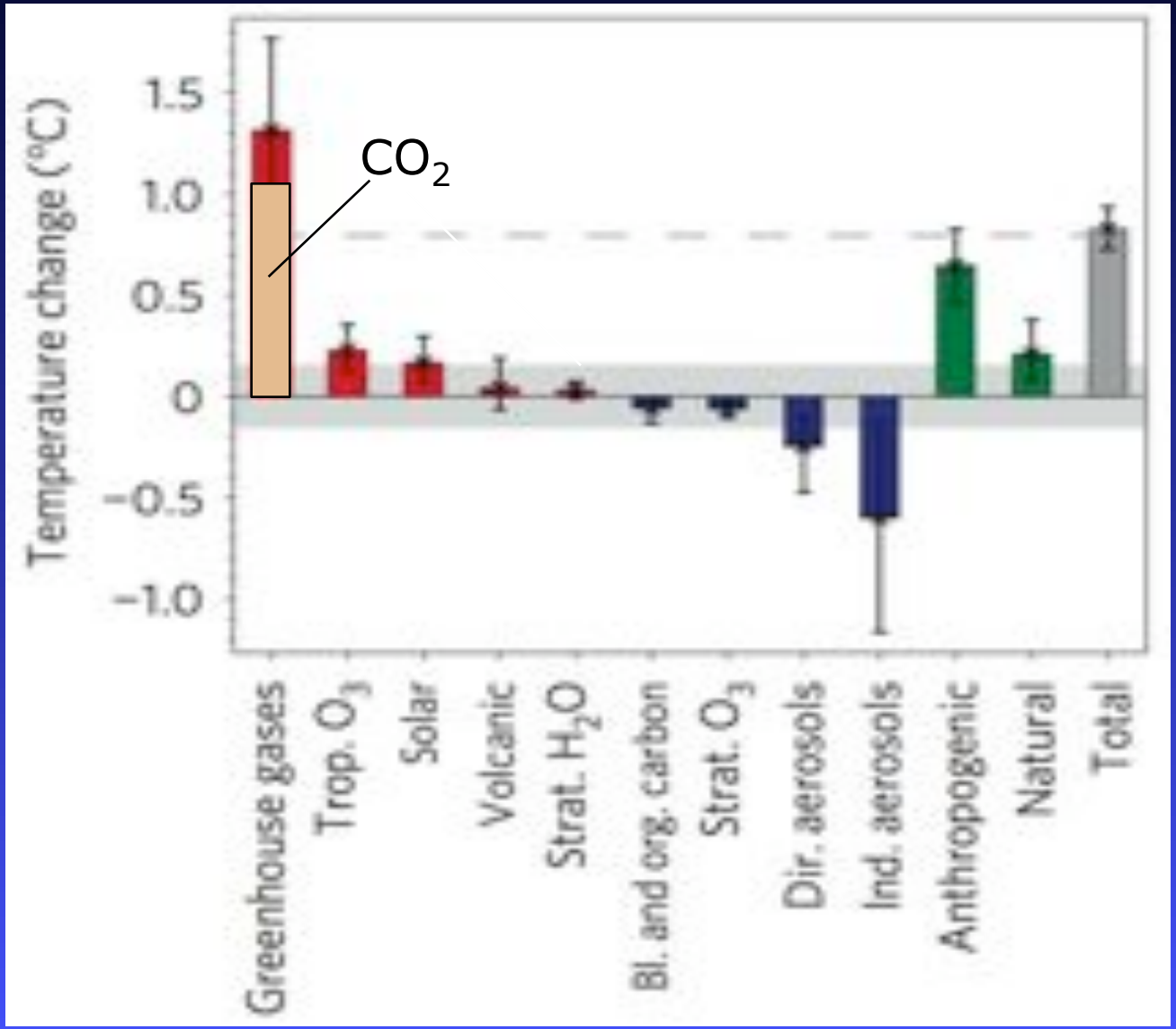
Incoming: 341.3 Outgoing: 101.9 + 238.5 = 340.4 Imbalance: 0.9 W/m^2



Source: Trenberth, Fasullo, & Kiehl, 2009, *Bull. Am. Met. Soc.*, 90, 311, March 2009; DOI:10.1175/2008BAMS2634.1

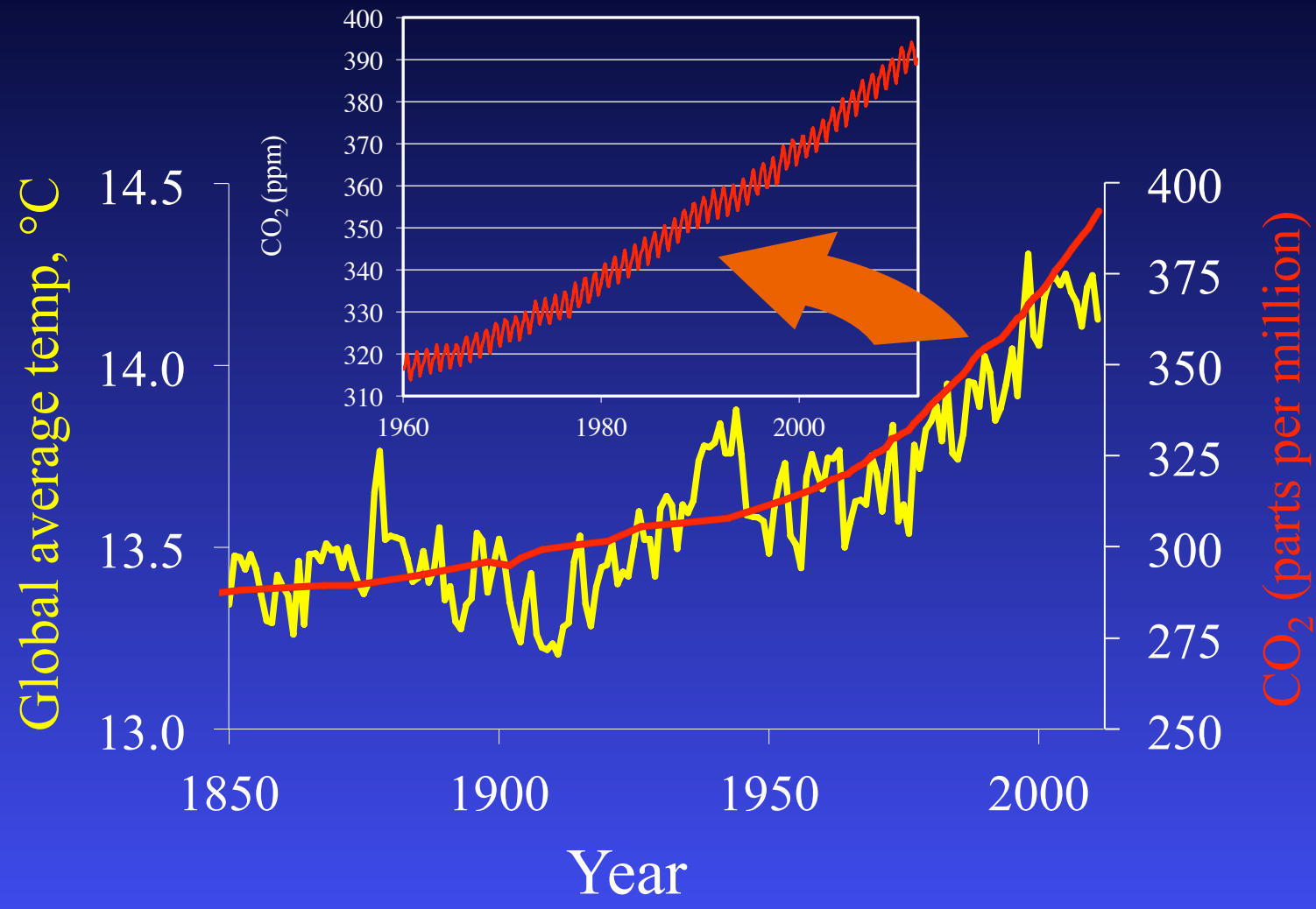
A Human Influence?

Causes of temperature change, 1850s to 2000s



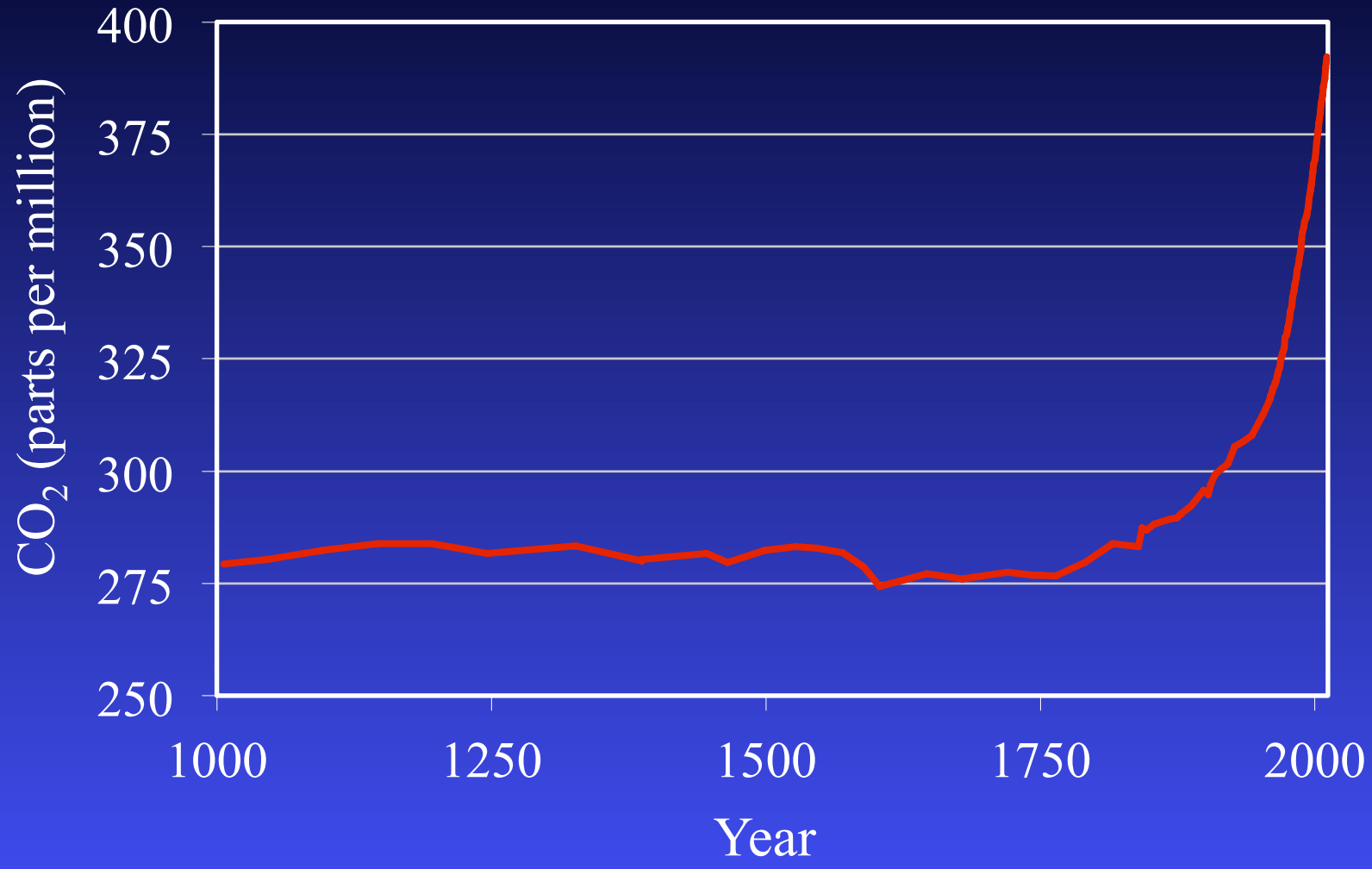
Source: Huber & Knutti, *Nature Geoscience* 4 December 2011; DOI 10.1038/NGEO1327

Focus on CO_2



Sources: Temperature: University of East Anglia Climate Research Unit, updated 1/12; CO_2: Through 1953 - Siple Station, Antarctica; Friedli et al. 1986 *Nature* 324, 237; 1959 – NOAA at ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/

CO_2 Over the Millennium

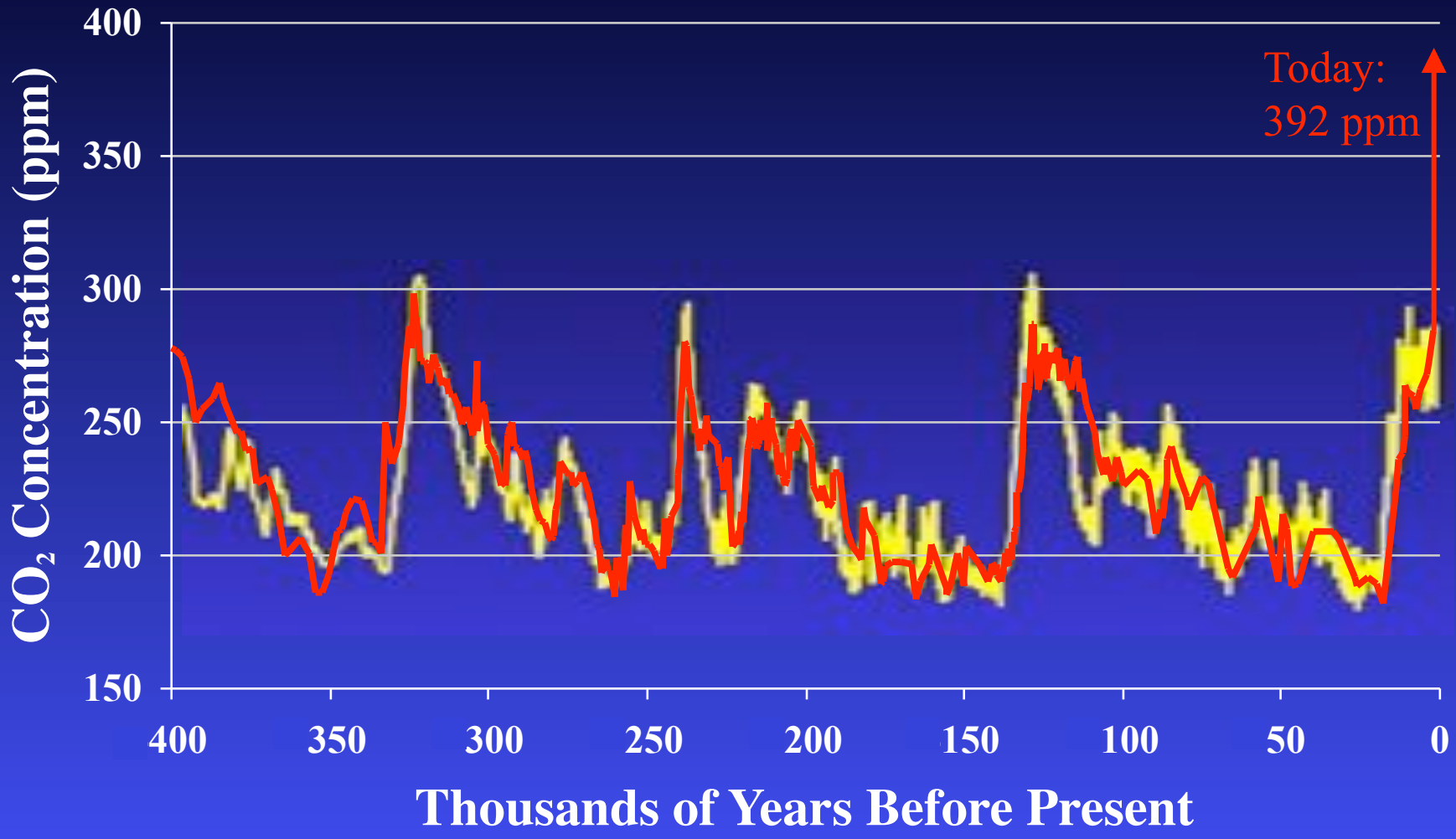


How do we know we've caused the recent CO_2 increase?

- Fossil fuels are commercial commodities
  - We track their consumption; it's consistent with increases in atmospheric CO_2
- The atmosphere is becoming depleted in radioactive carbon-14 ($t_{1/2}$=5700 years) and in stable carbon-13
  - C-14 depletion means new carbon has been out of contact with the atmosphere for a long time
  - Plants take up C-12 preferentially over C-13, so C-13 depletion suggests new carbon originated in plant biomass
  - Fossil fuels have been buried for hundreds of millions of years, and they come from plants
- Oxygen content of the atmosphere is decreasing, consistent with fossil fuel combustion
  - O_2 combining with carbon to make CO_2

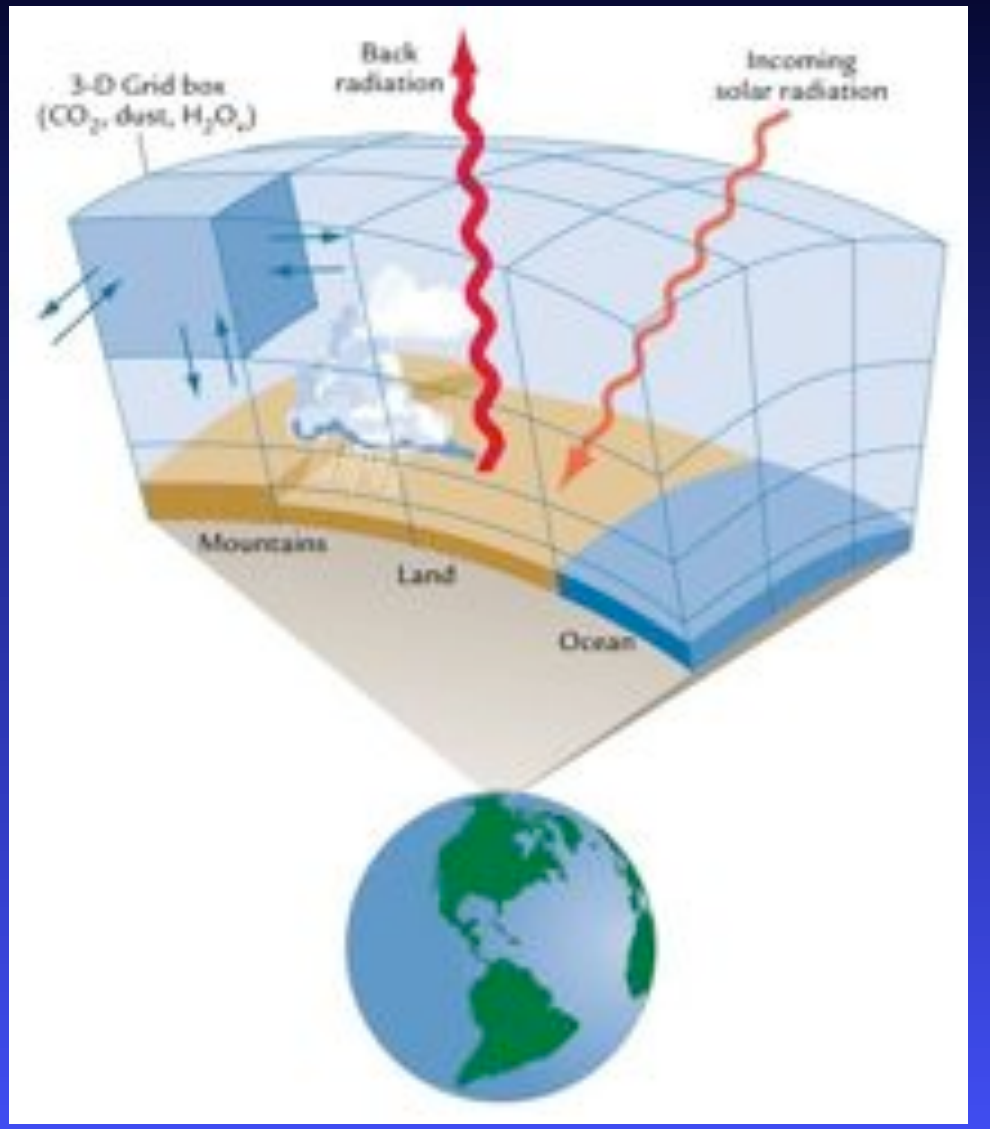
400,000 Years of CO_2

and Temperature



Climate Models: Projecting Future Climate

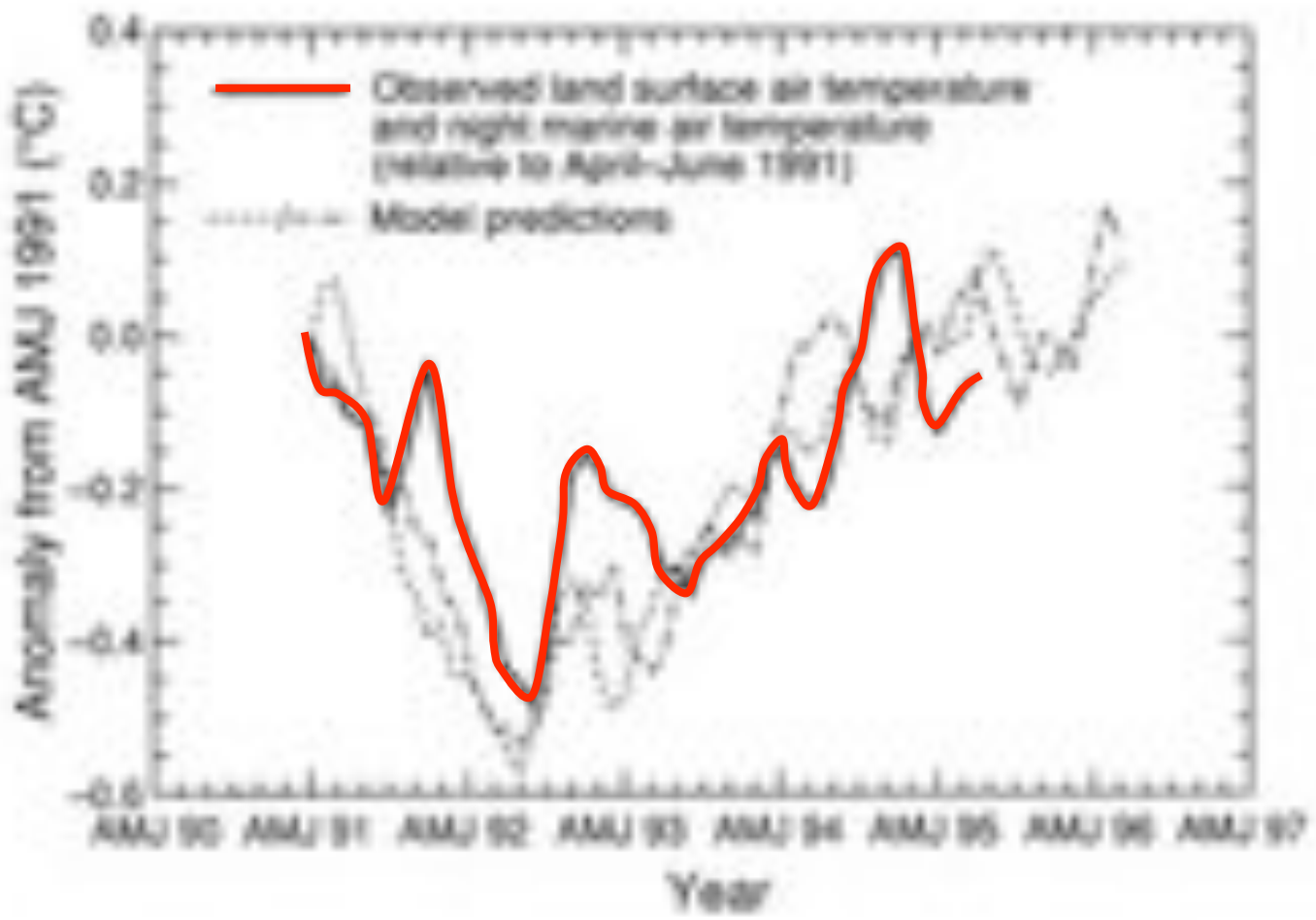
- A contemporary climate model: HadGEM2-ES
  - >1 million atmosphere cells
  - 40 ocean levels
  - 9 types of vegetation
  - Carbon & sulfur cycles
  - Atmospheric chemistry
  - 1 hour computer time = 1 month's climate



Source: Ruddiman, *Earth's Climate: Past and Future*

Why Believe Climate Models?

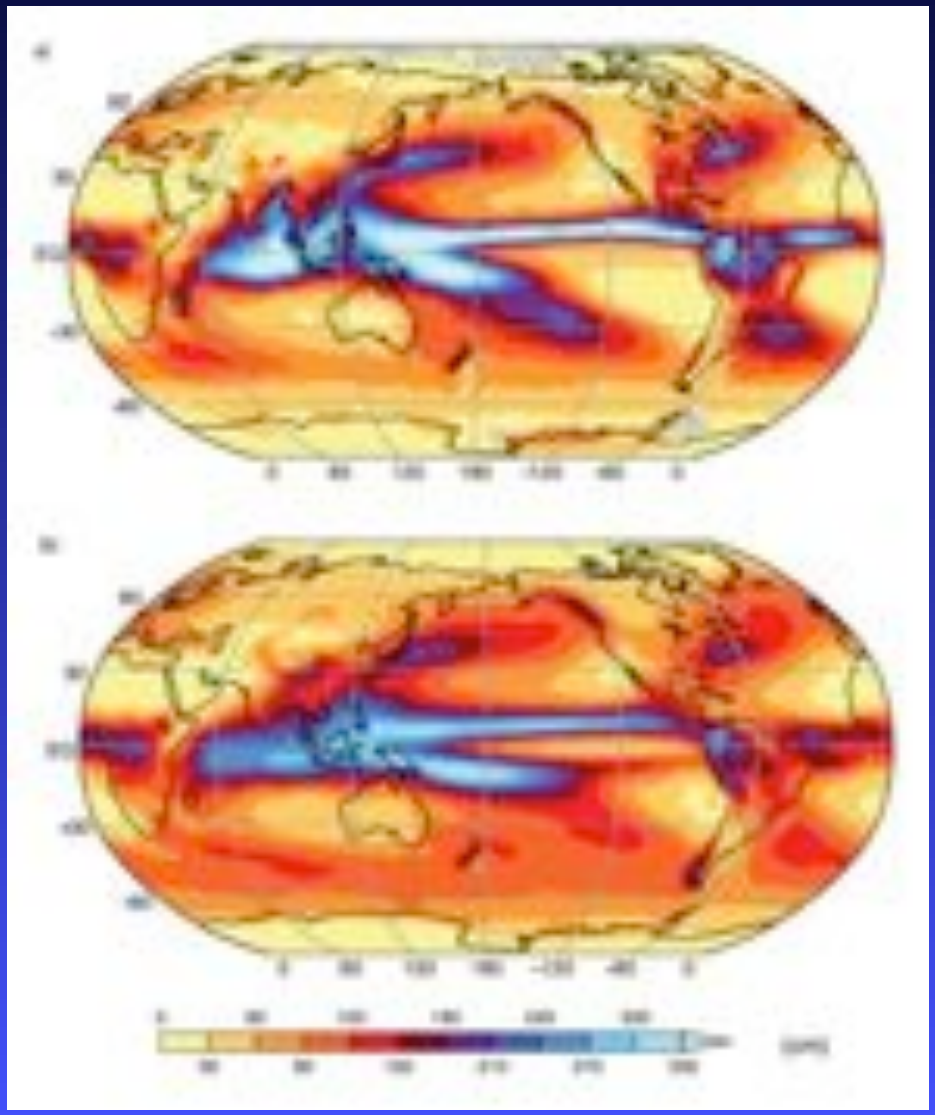
The Pinatubo "Experiment"



Source: IPCC 1996 WG1 p. 33

Why Believe Climate Models?

They reproduce observed patterns, and not just temperature:



Annual mean precipitation

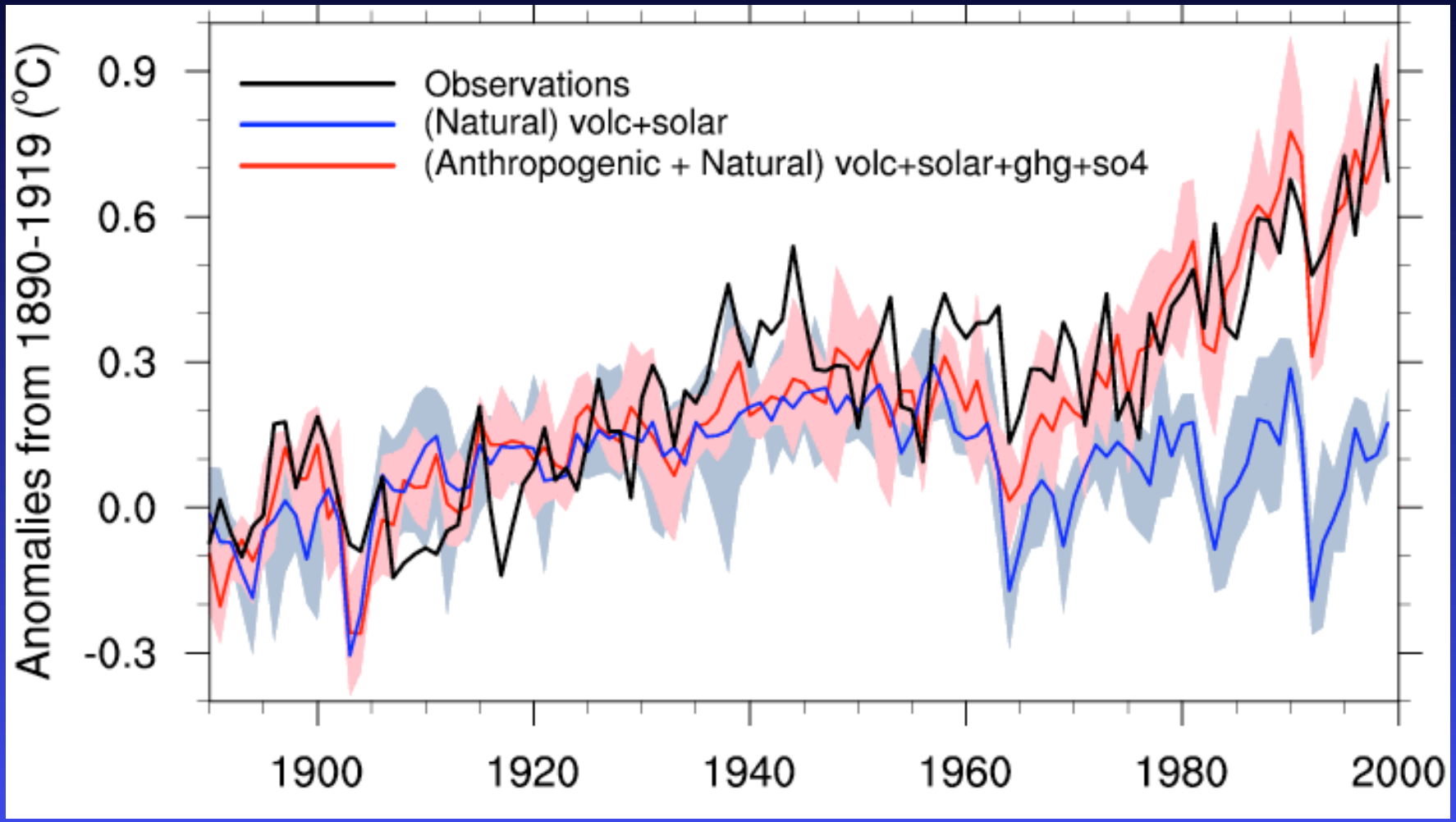
Observed

Simulation,
multi-model mean

Source: IPCC AR4 WG1 Fig 8.5

Why Believe Climate Models?

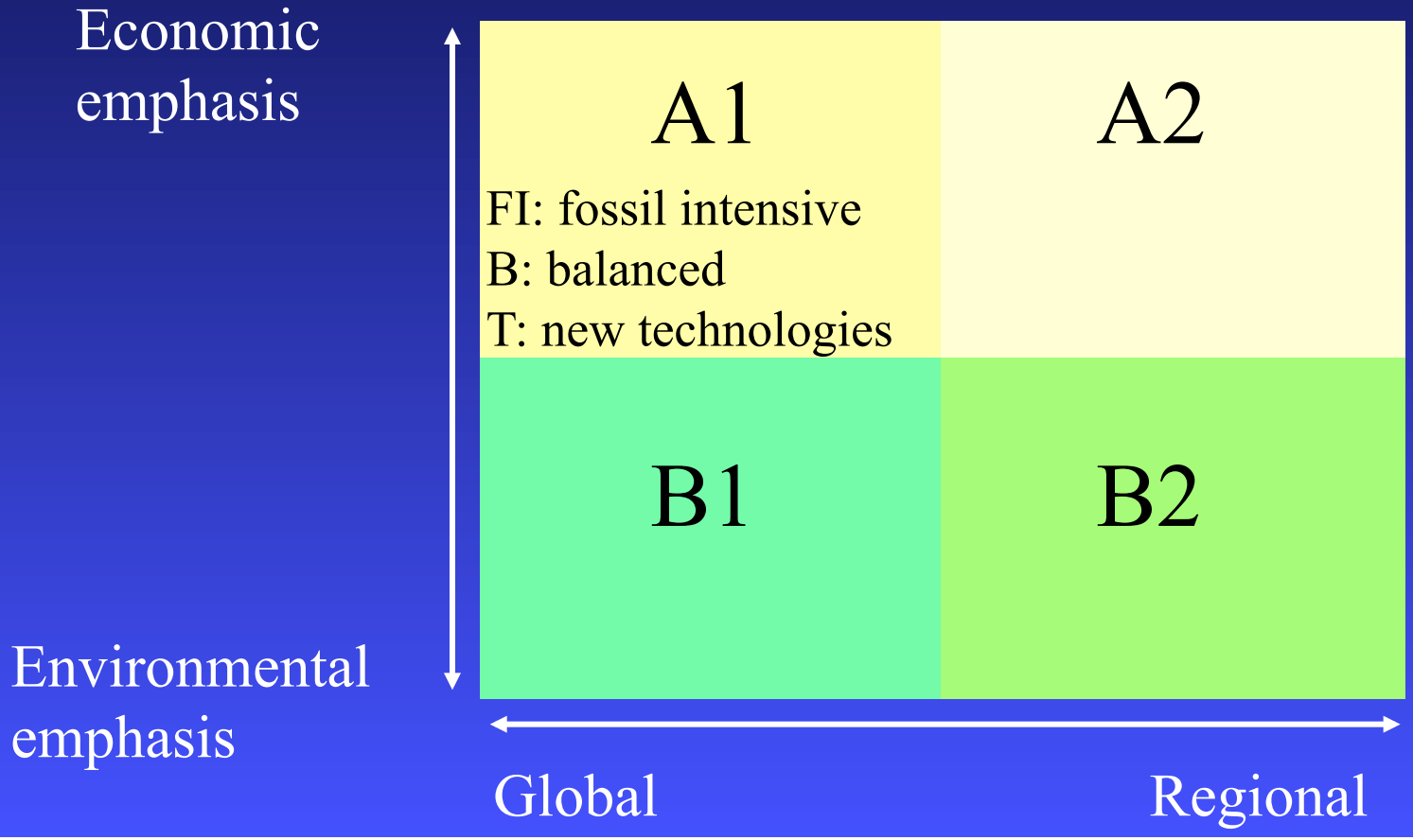
They explain recent climate change:



Source: Caspar Ammann, National Center for Atmospheric Research

IPCC Climate Projections

- Depend on human behavior
- IPCC Emissions Scenarios (SRES)



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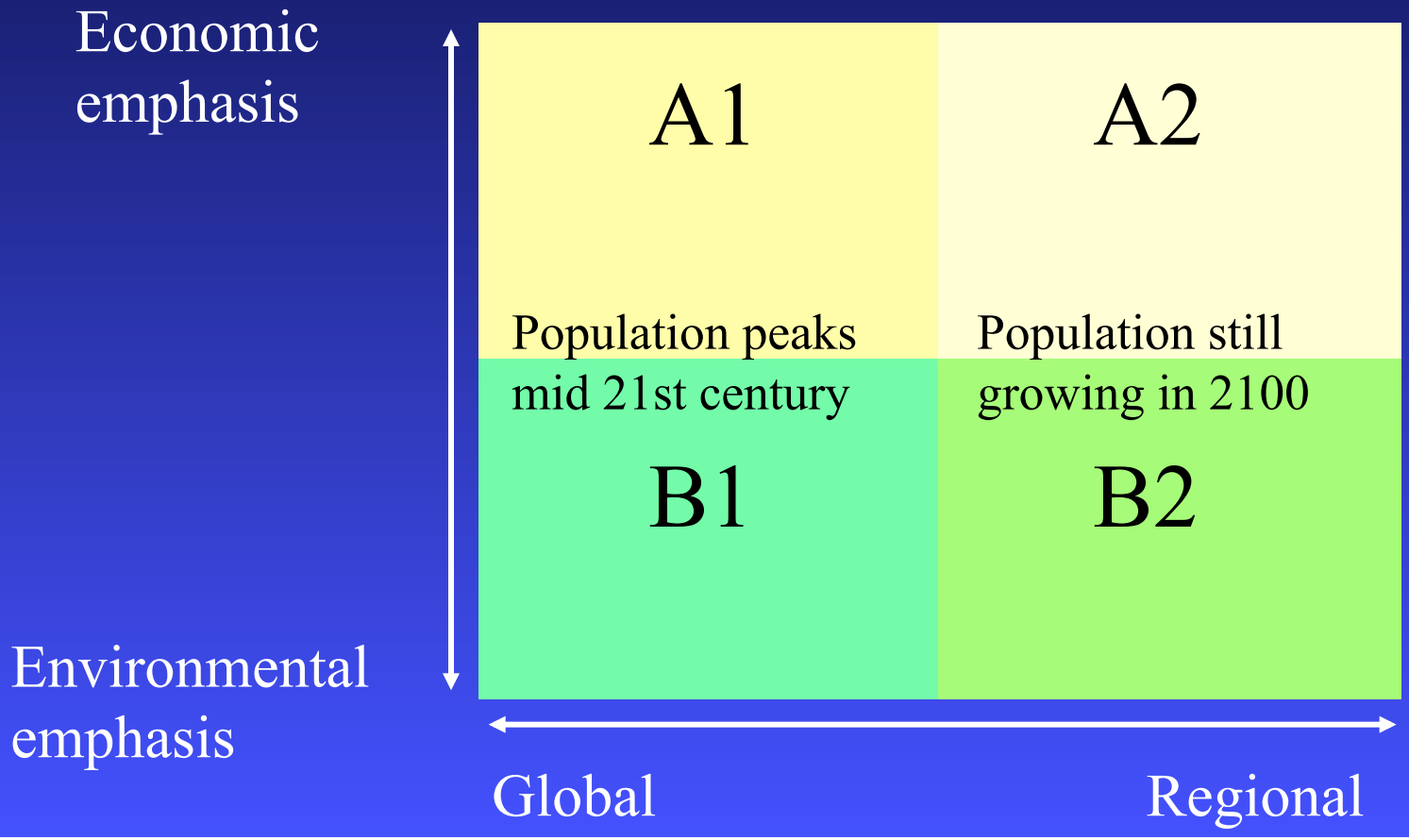
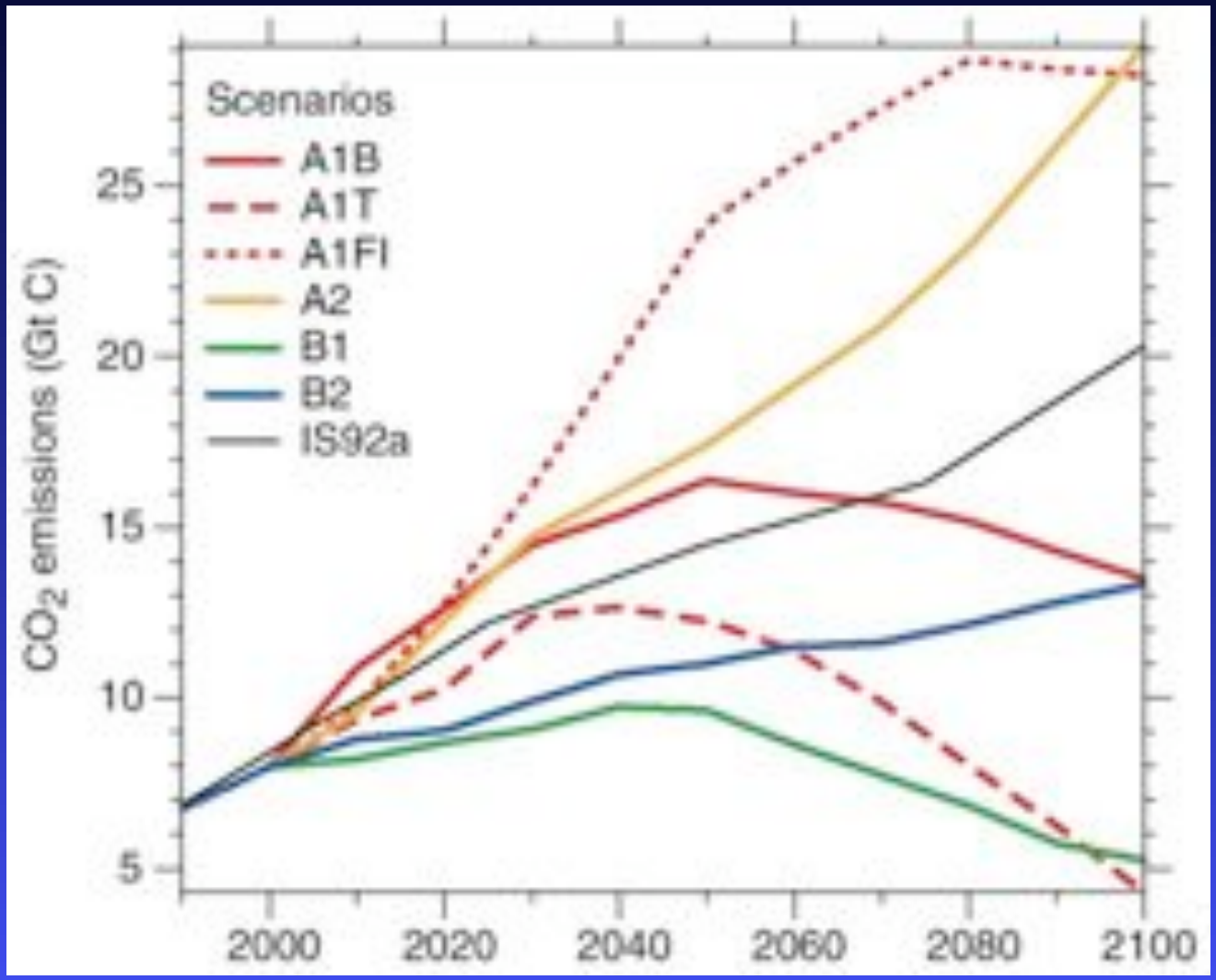
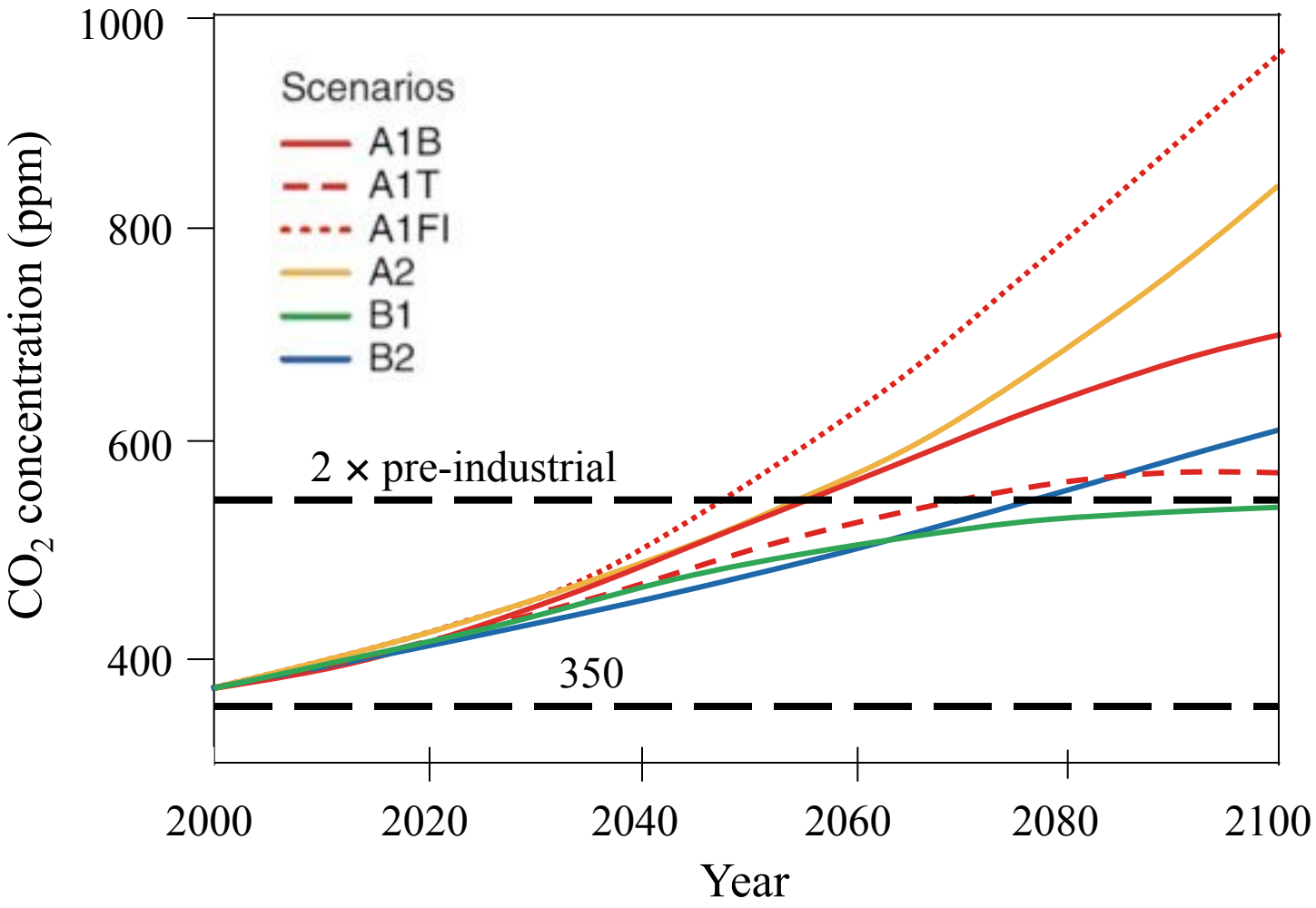


CO_2 Emissions in the IPCC Scenarios



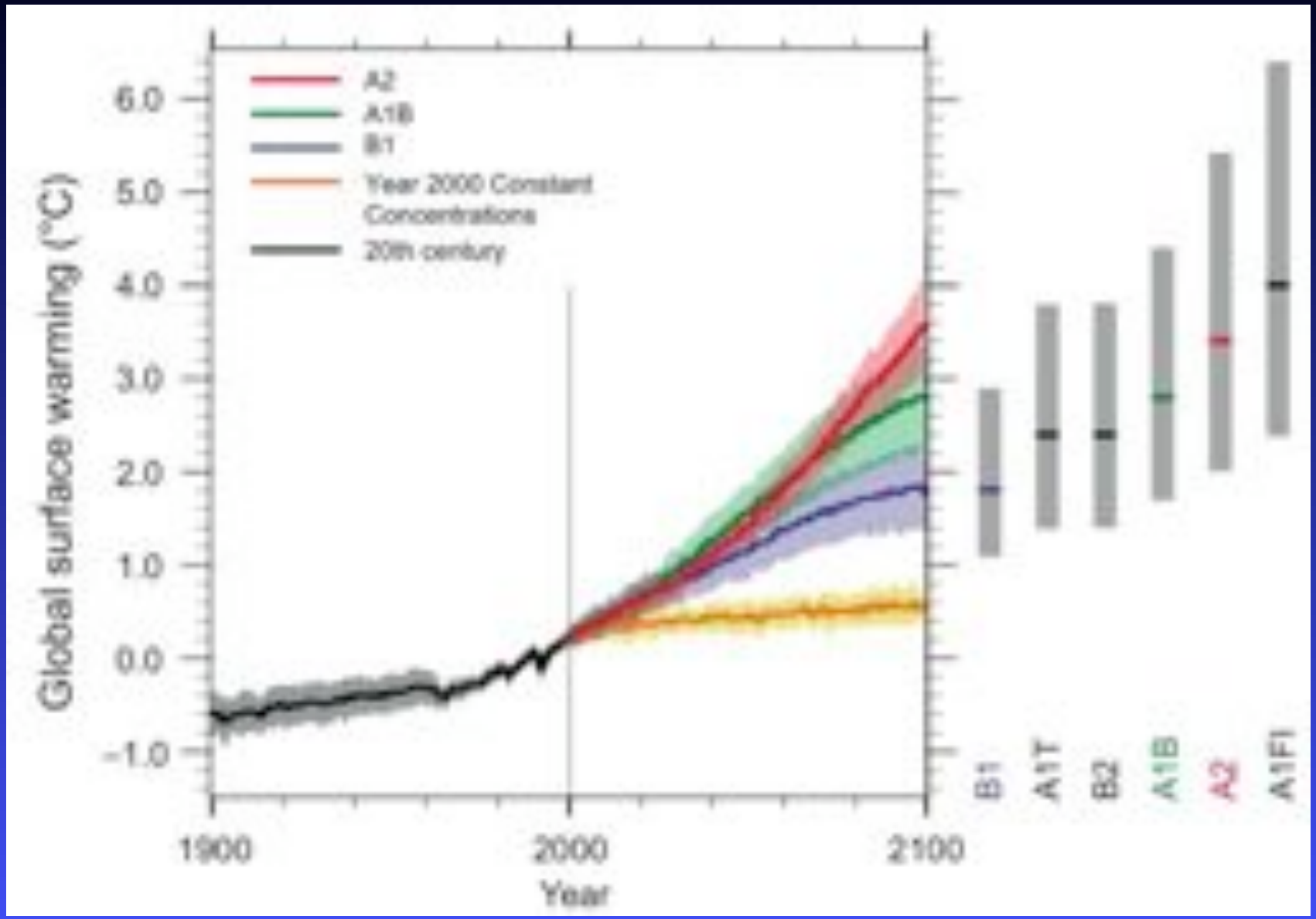
Source: IPCC 2001 WG1 TS Fig 17

CO_2 Concentration Scenarios



Source: IPCC 2001 WG1 TS Fig 17

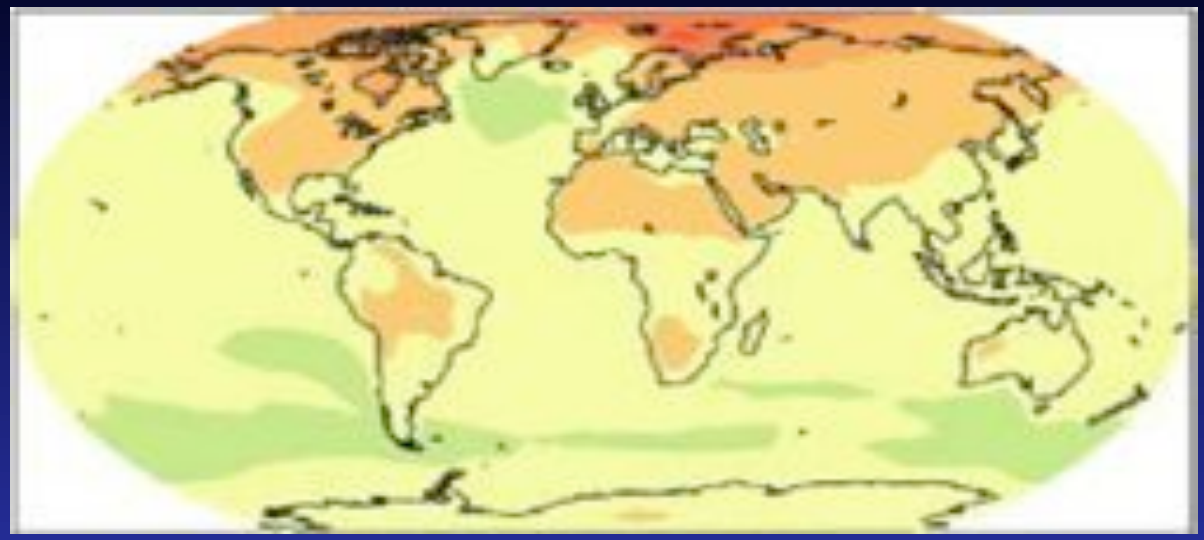
Temperature Scenarios



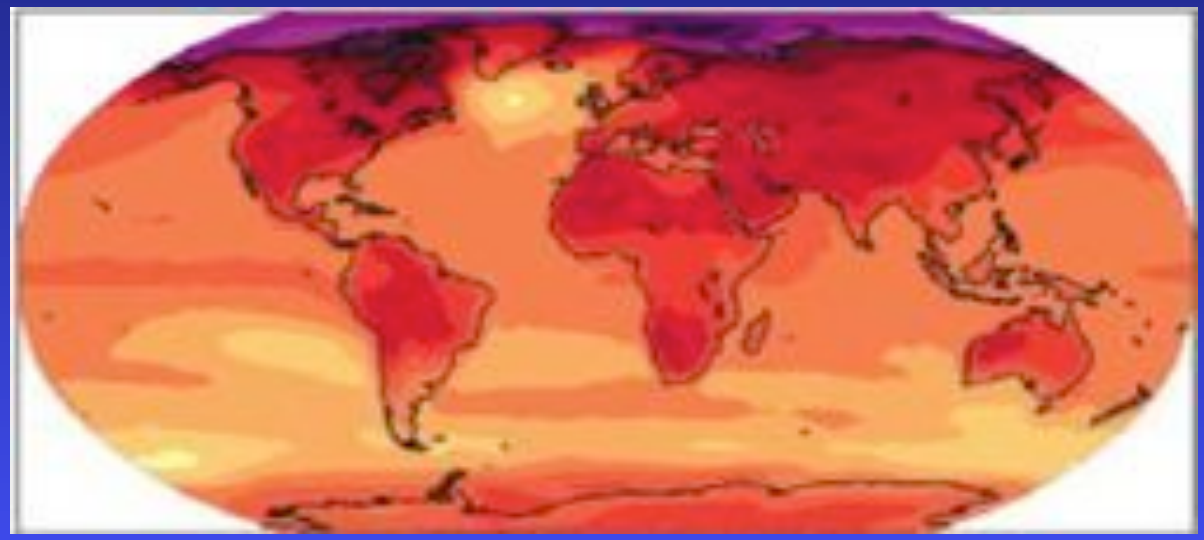
Source: IPCC AR4 WG1 Fig. SPM-5

Projected Temperature Increases

A1B scenario
2020-2029



A1B scenario
2090-2099

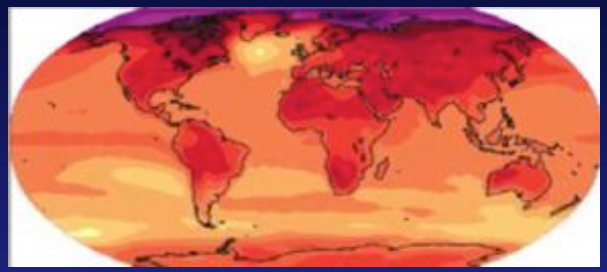


Temperature increase, ˚C

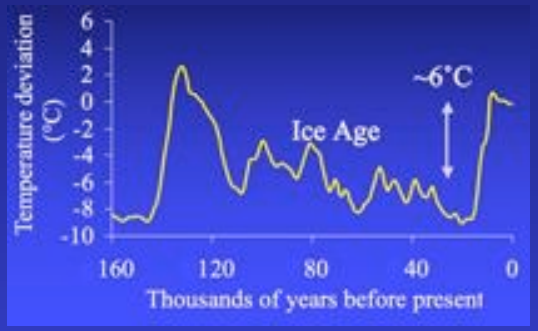
Source: IPCC 2007 WG1 Fig SPM-6

Why Do a Few Degrees Matter?

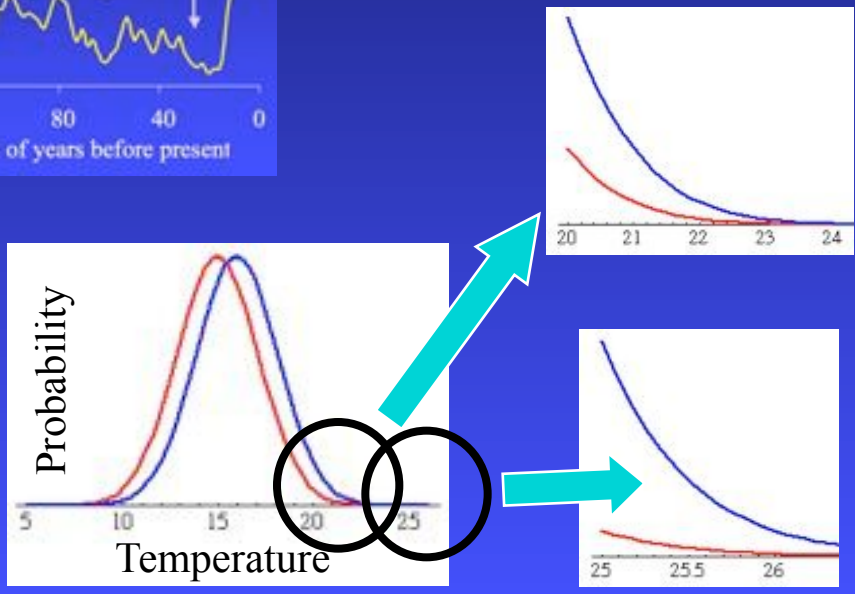
- That's a global average; many areas will warm a lot more (previous slide)



- A few degrees is climatological significant; ~6˚ separates us from the last ice age

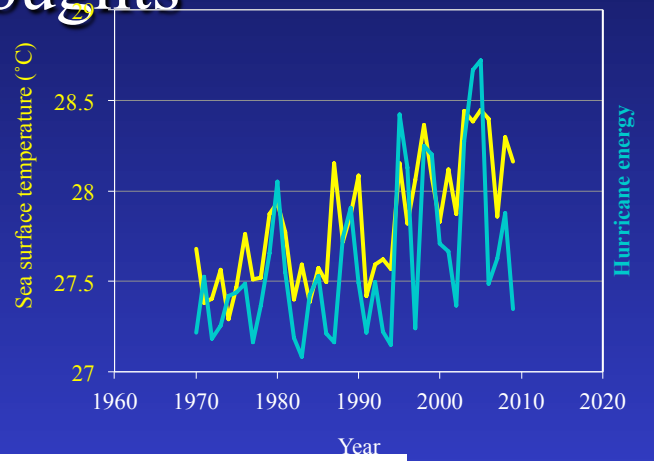


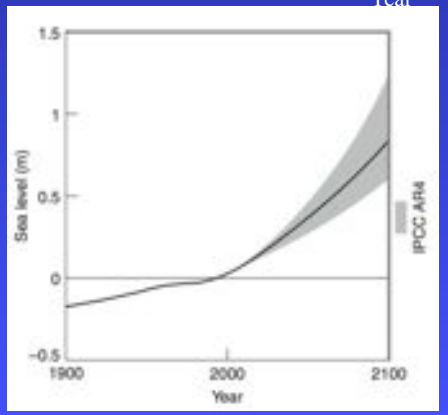
- A small rise in the mean temperature greatly increases the probability of extreme events



Other Impacts

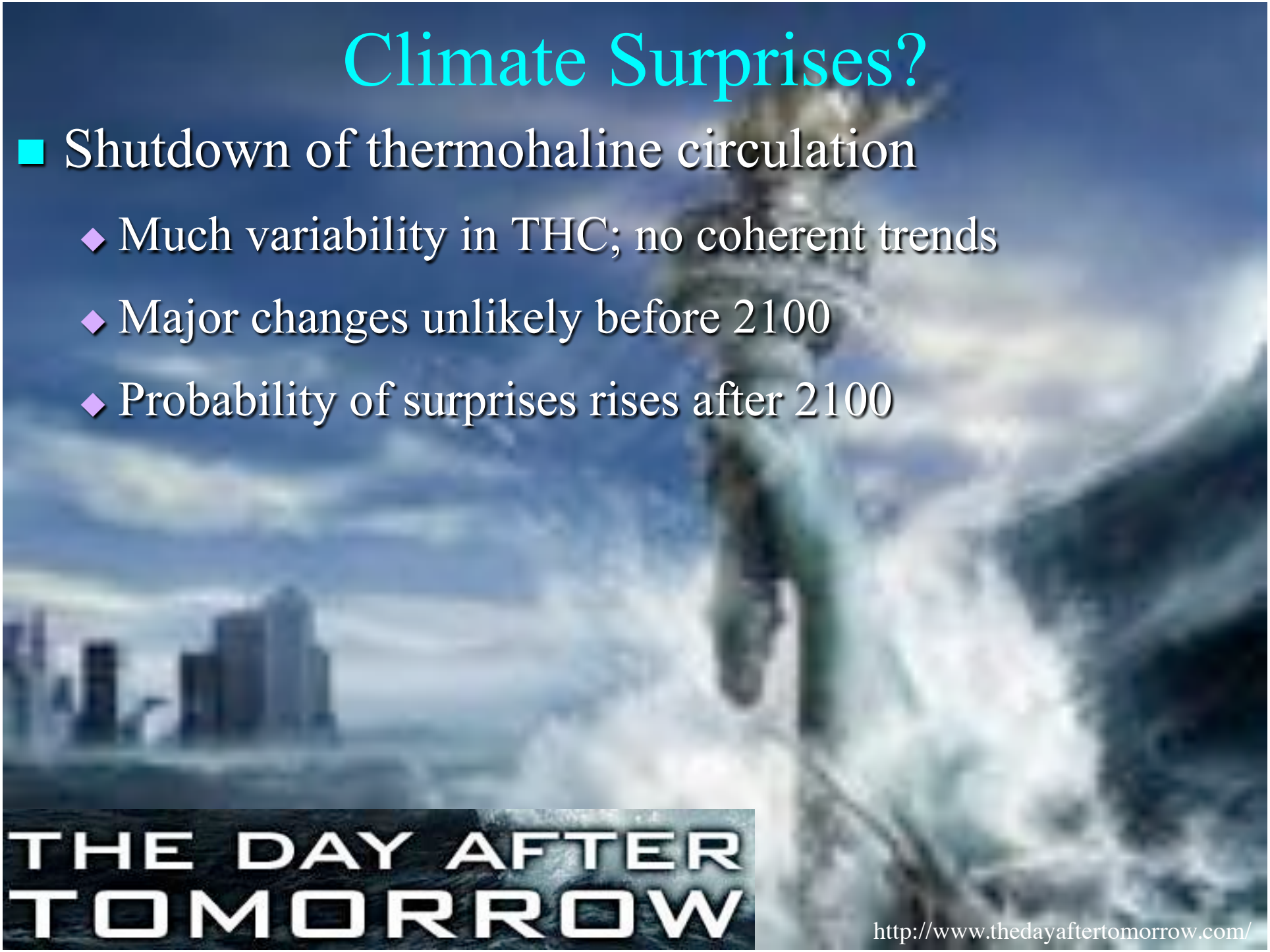
- Precipitation changes
  - More overall precipitation
  - More intense precipitation events - more floods
  - Drier continental interiors - more droughts
- Increased tropical storm intensity
  - Storm frequency uncertain
- Sea-level rise
  - Melting land ice
  - Thermal expansion
  - ~1 meter by 2100
- Ocean acidification
  - $CO_2 + H_2O \rightarrow H_2CO_3$



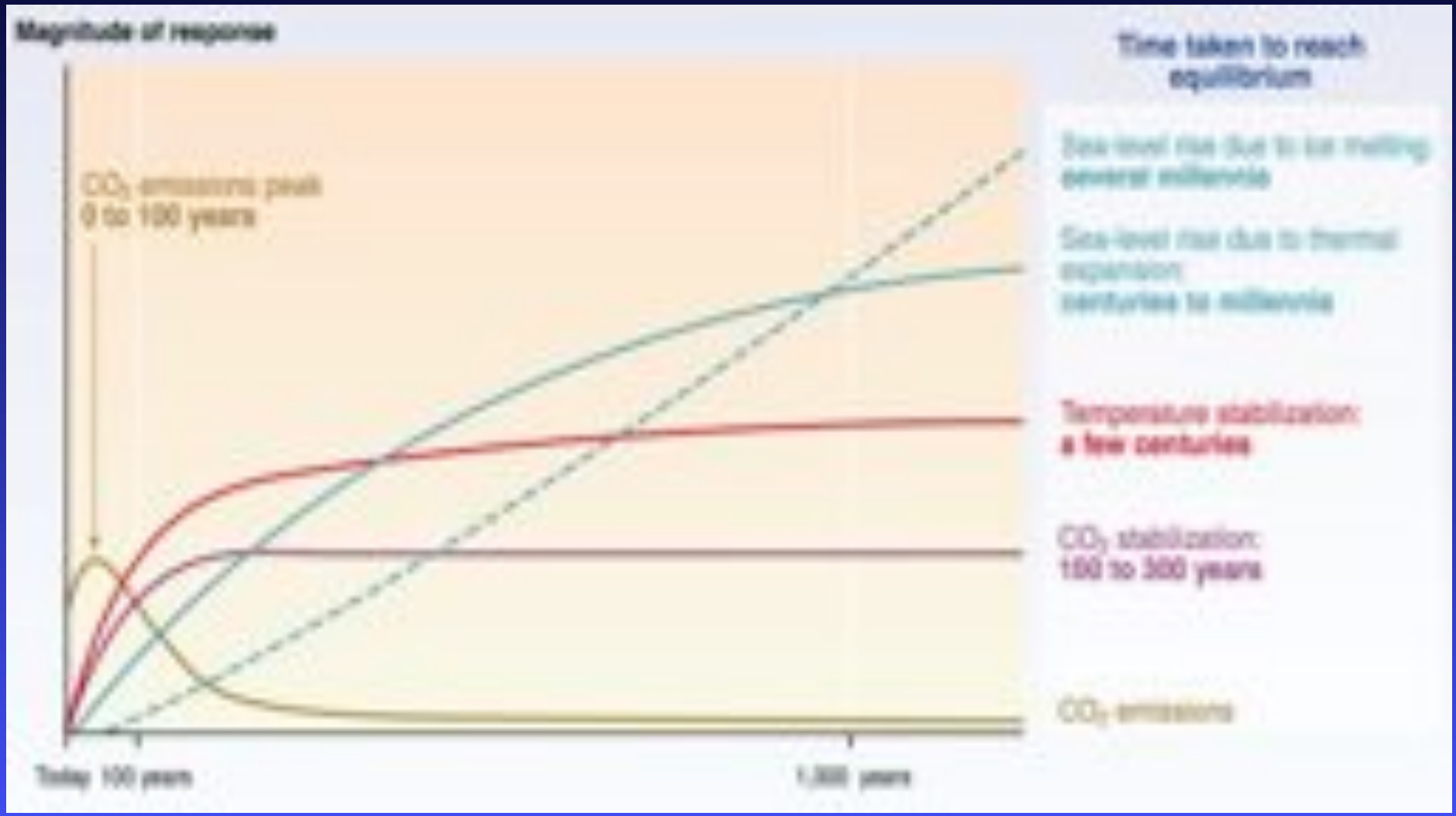


Climate Surprises?

- Shutdown of thermohaline circulation
  - Much variability in THC; no coherent trends
  - Major changes unlikely before 2100
  - Probability of surprises rises after 2100



It Doesn't Stop at 2100



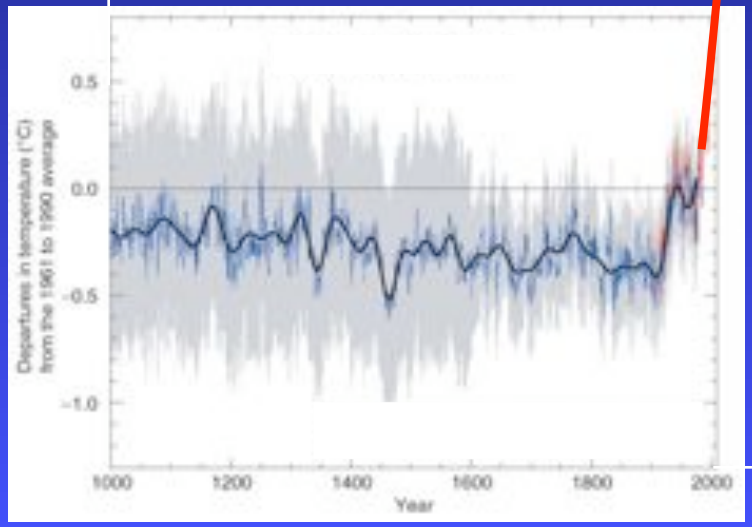
Source: IPCC 2001 *Synthesis Report* Fig SPM-5

21st Century Warming:
A Millennial Perspective

3˚C
~600 ppm CO_2

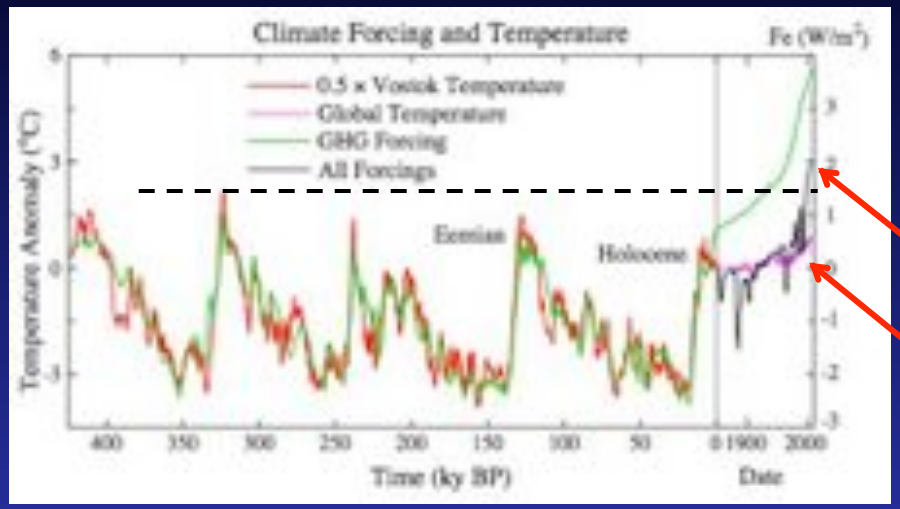
21st century temperature rise
IPCC mid-range projection

Copenhagen, Cancun goal:
Limit temperature rise to
2˚C above preindustrial



2100

350: The Science Behind the Number

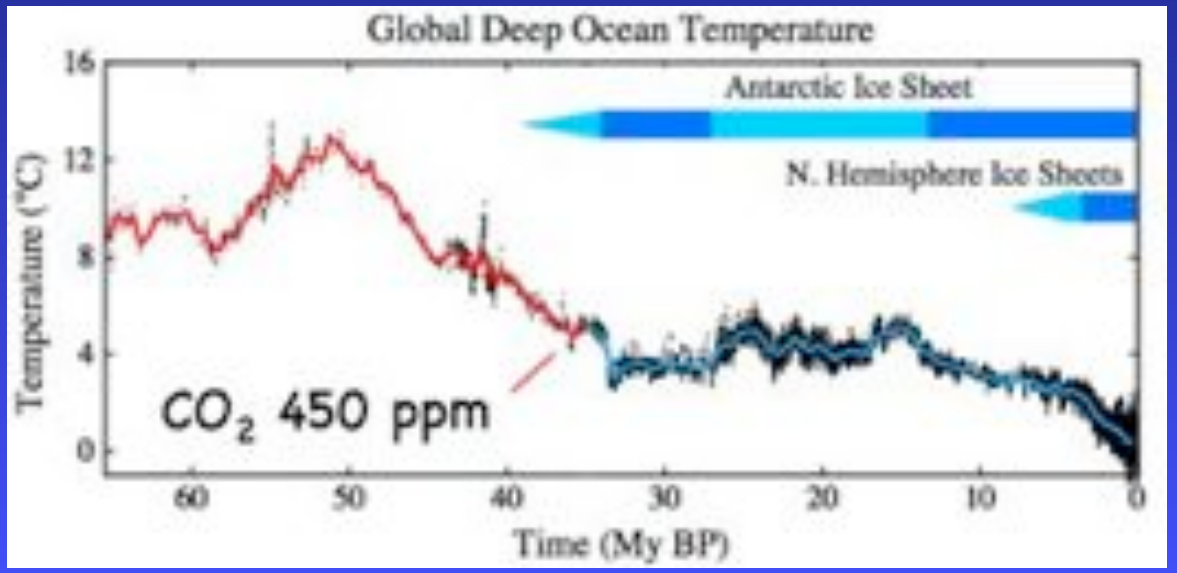


The Argument for 350

Hansen et al., "Target Atmospheric CO_2: Where Should Humanity Aim?"
The Open Atmospheric Science Journal, 2008, 2, 217-231

Forcing

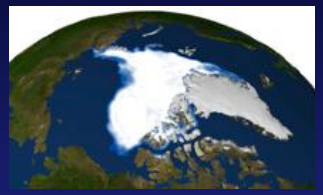
Global temperature change



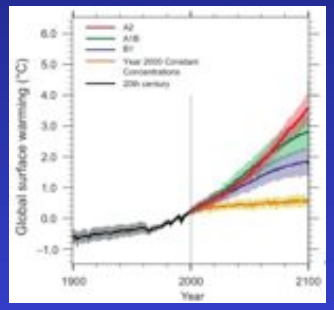
Climate Change: Sound and Sight Bites

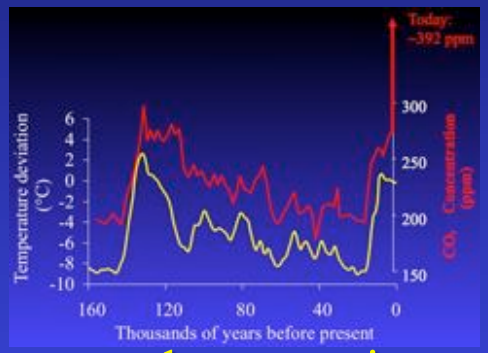
- Global temperature rising

- Arctic ice disappearing



- Why? Anthropogenic greenhouse gas emissions
- CO_2 levels 40% higher than in past 20 million years
- The future
  - Substantial warming
  - Significant impacts





- Soundbites
  - IPCC 2007: "warming is unequivocal…due to anthropogenic greenhouse gas[es]"
  - *Nature Geoscience* 2011: "Even higher confidence that human-induced causes dominate observed warming"