Explaining the Present (conclusion) And Projecting the Future

OLLI Winter 2014

Climate Change L809

Climate MOOCs

(adapted from RealClimate)

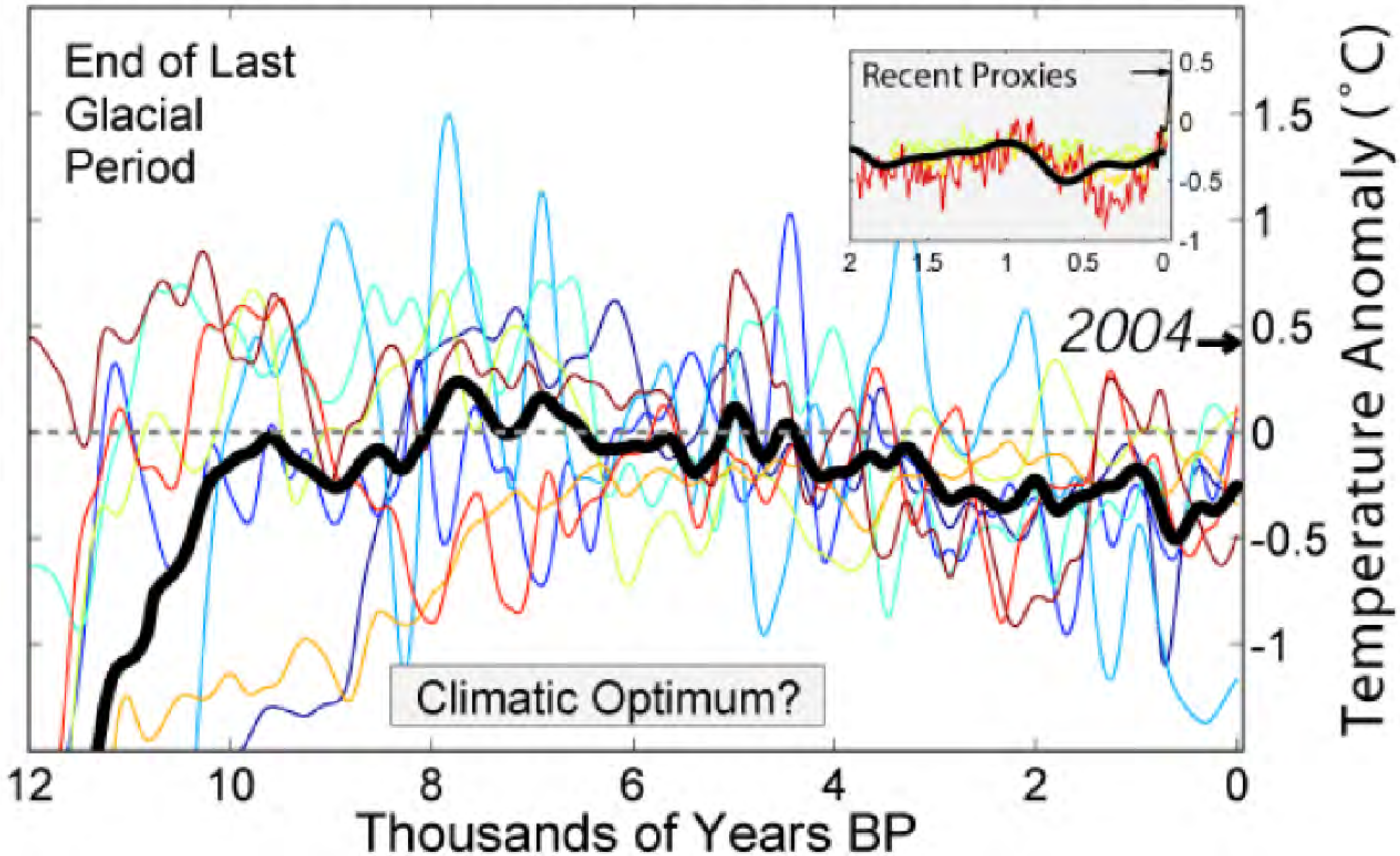
- David Archer Global Warming: The Science of Climate Change March 31.
- Turn Down the Heat: Why a 4ºC Warmer World Must be Avoided 4-week World Bank course started Jan 24. (Coursera)
- Richard Alley 8-week course Energy, the Environment, and Our Future started Jan 6. (More background here). (Coursera)
- Exeter University – Climate Change: Challenges and Solutions on Future Learn. 8 week course currently running (at week 3)
- Tim Lenton, University of Exeter Climate change: challenges and solutions
- Climate Change in Four Dimensions from Charles Kennel, et al. (Coursera)

MEASURING TEMPERATURE

Measurement Issues

- CO_2: organization and engineering
  - Mauna Loa and a 2.2-mile ice core
- Temperature
  - Establishing data points
    - Instrument records: measurement protocols
    - Proxies before late 19th century
    - The Arctic hole
  - No Mauna Loa leads to statistical issues
- CO_2-temperature relationship
  - Pre-instrumental: dating
  - Modern: separating CO_2 from other factors

Holocene Temperature Variations



1. 1961-1990 equals 0.
2. Due to smoothing, graph cannot resolve changes for periods shorter than 300 years; therefore would not capture earlier short-term temperature spikes.

What Does the "Average" Mean: A Guide to the Reconstruction

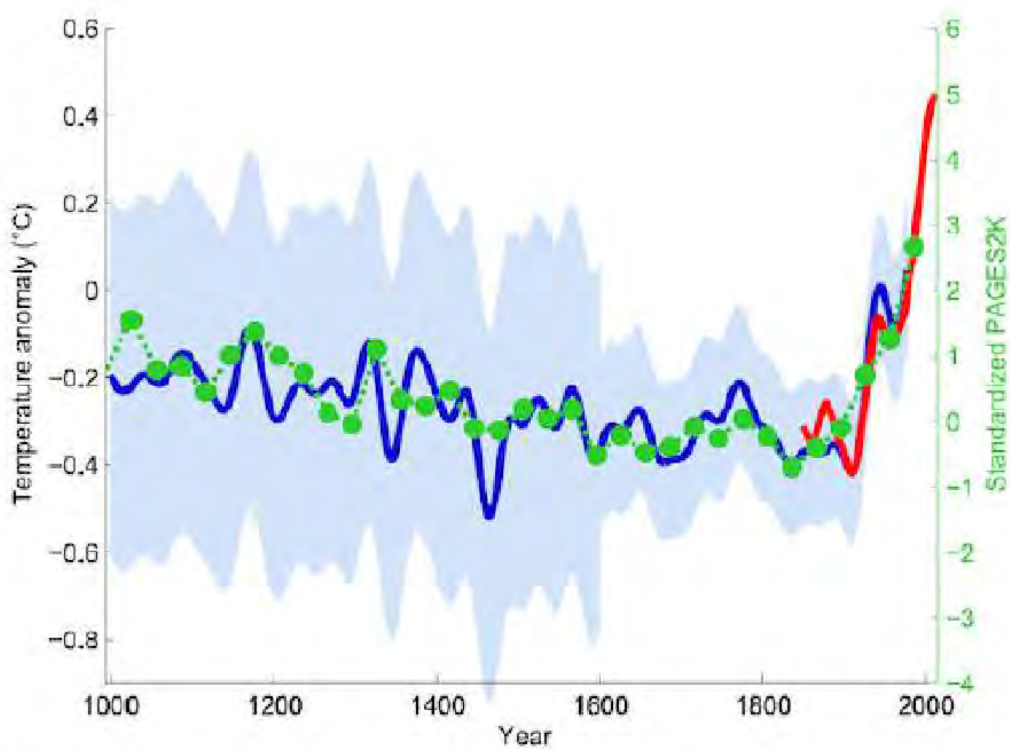
Line Color	Proxy Type	Location
Dark blue	Sediment core	Eastern Tropical Atlantic
Blue	Ice core	Central Antarctica
Light blue	Ice core	Greenland
Green	Ice core	Kilimanjaro
Yellow	Sediment core	North Atlantic
Orange	Pollen	Europe
Red	Ice core	Central Antarctica
Dark red	Sedimentary core	Western Tropical Pacific

The Reconstruction in Context

"The general pattern of high-latitude cooling in both hemispheres opposed by warming at low latitudes is consistent with local mean annual insolation forcing associated with decreasing orbital obliquity since 9000 years ago (**Fig. 2C**). The especially pronounced cooling of the Northern Hemisphere extratropics, however, suggests an important role for summer insolation in this region, perhaps through snow-ice albedo and vegetation feedbacks."

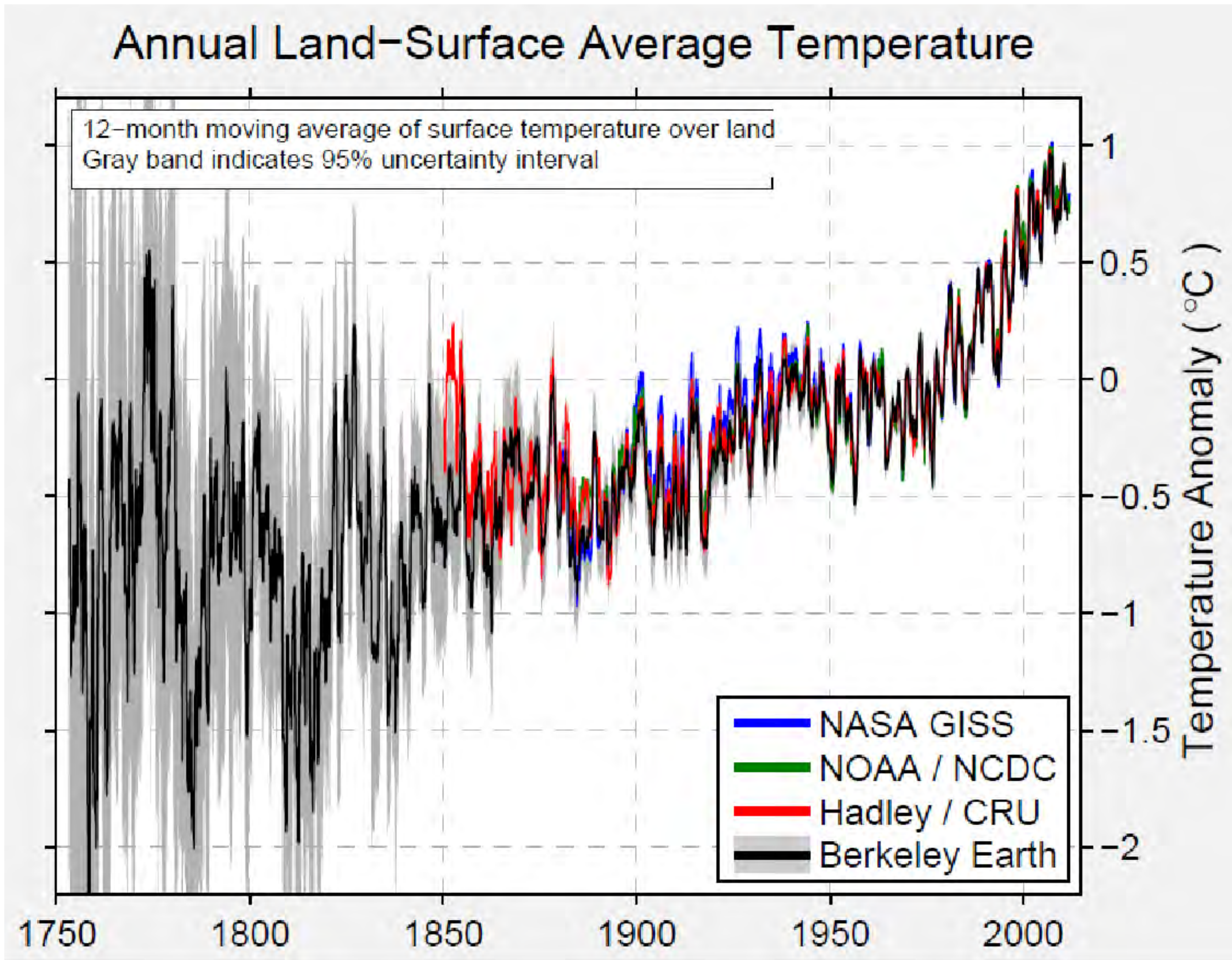
"Our global temperature reconstruction for the past 1500 years is indistinguishable within uncertainty from the Mann *et al*. (*2*) reconstruction; both reconstructions document a cooling trend from a warm interval (~1500 to 1000 yr B.P.) to a cold interval (~500 to 100 yr B.P.), which is approximately equivalent to the Little Ice Age."

An Updated Hockey Stick

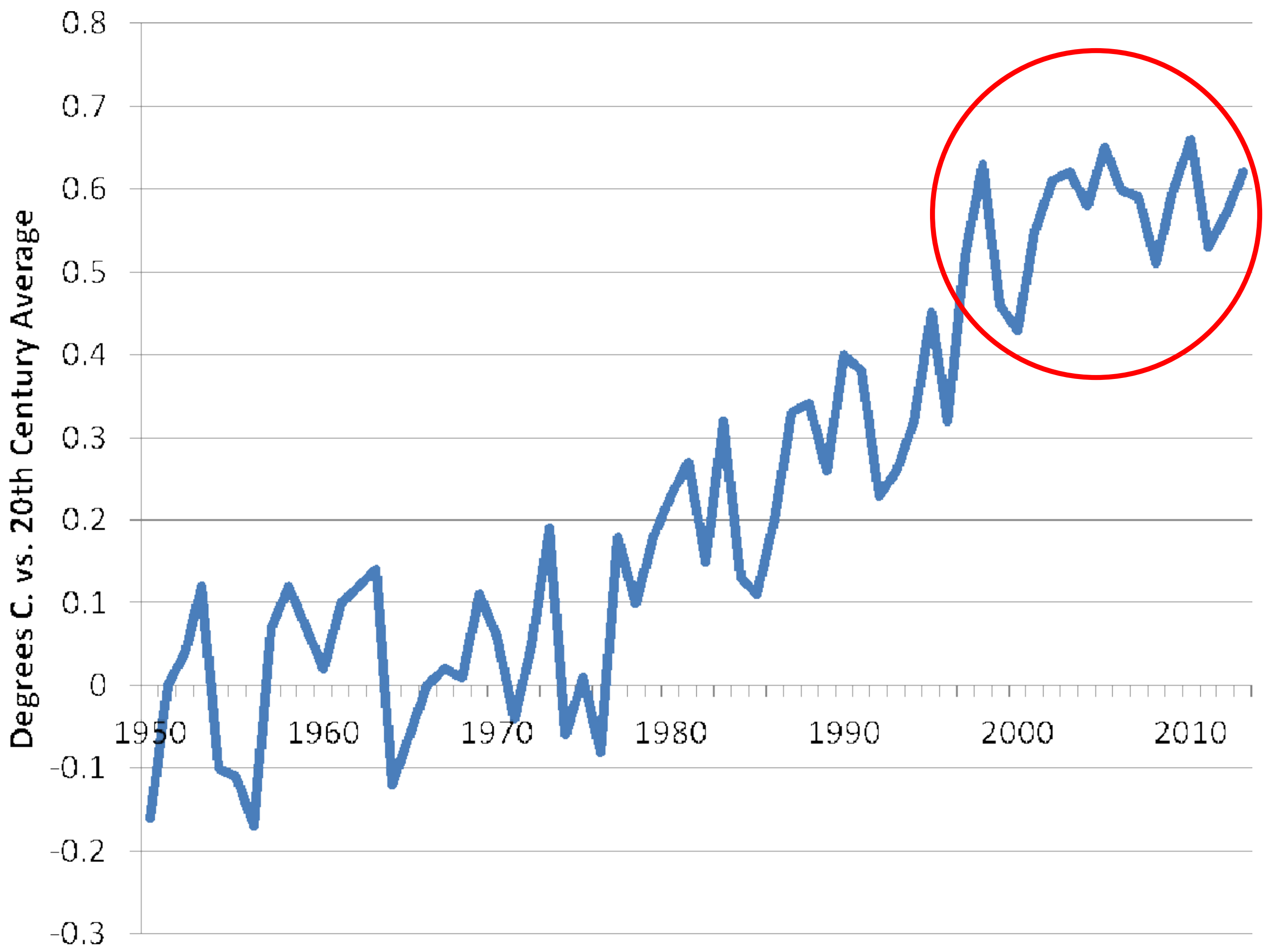


Green dots show the 30-year average of the new PAGES 2k reconstruction. The red curve shows the global mean temperature, according HadCRUT4 data from 1850 onwards. In blue is the original hockey stick of Mann, Bradley and Hughes (1999) with its uncertainty range (light blue). Graph by Klaus Bitterman.

Berkeley Earth Project Reanalysis



The Halt/Pause/Slowdown

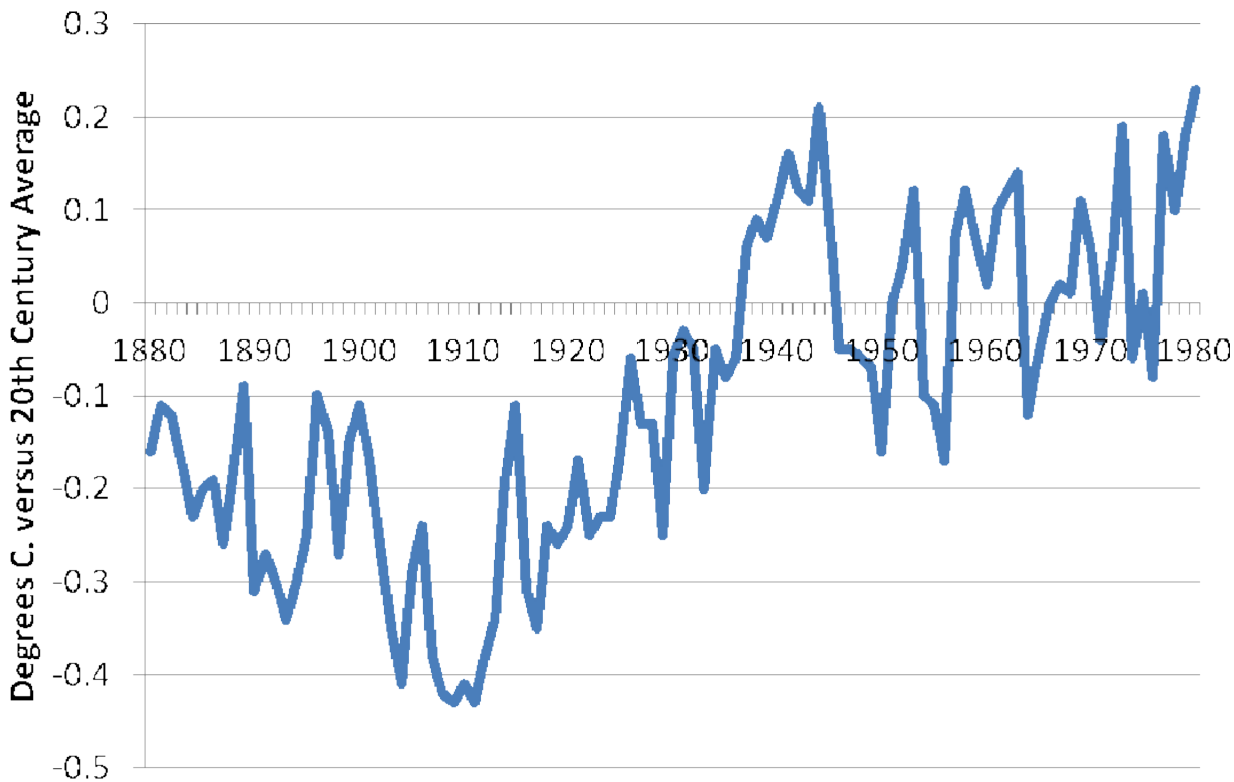


The State of Play Mid-2013: Status of Current Temperature

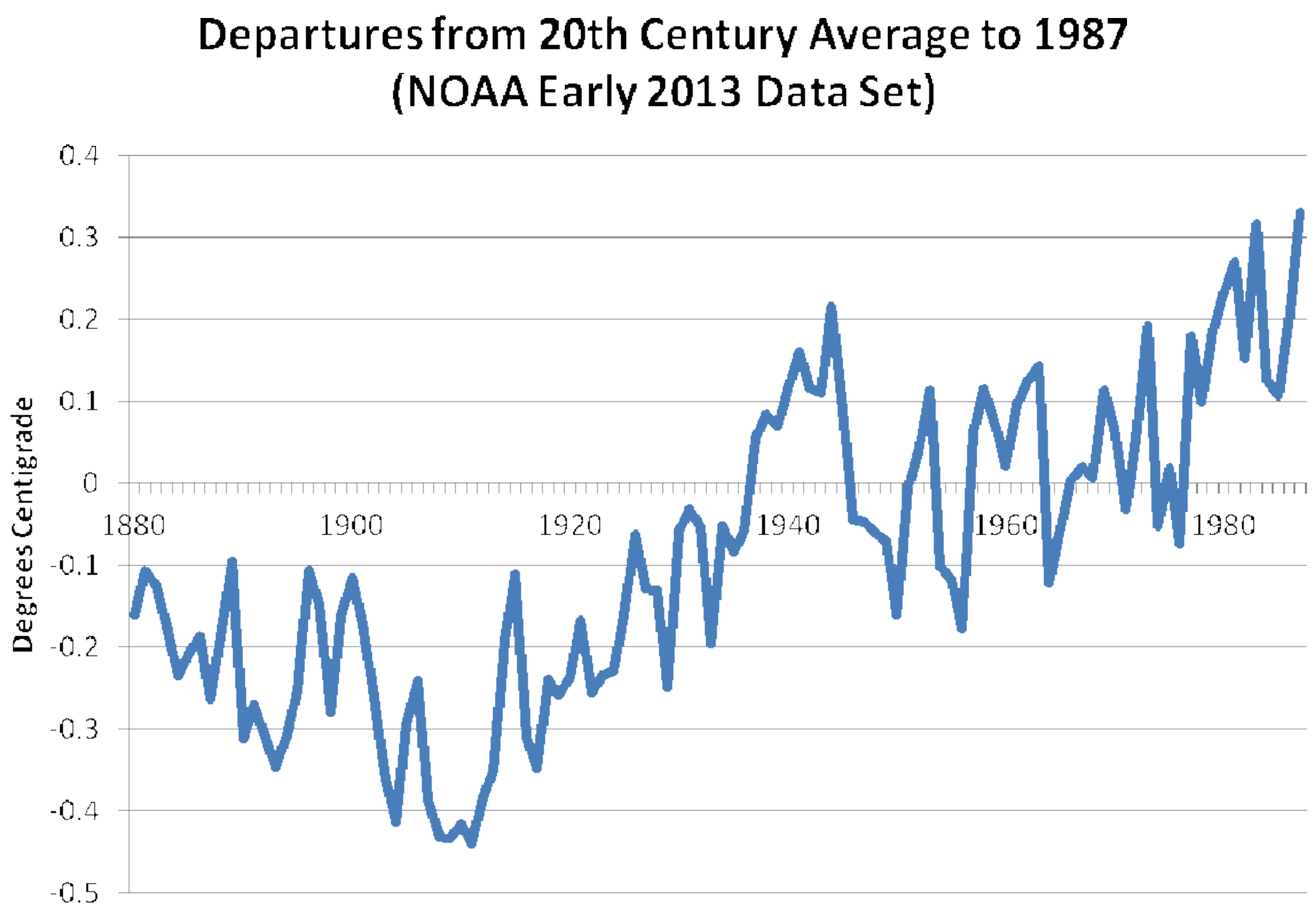
- May be highest of the Holocene but low temporal resolution
- Probably highest of Christian era but not outside uncertainty band
- Current pause or near-pause

MEASUREMENTS AND POLICY

The View from 1980:
What Warming?



1980-1992 Climate Moves to Policy Agenda: Observations



1988-1992 Climate Moves to Policy Agenda: Institutional

- Domestic: James Hansen 1988 testimony
  - "Global warming is now large enough that we can ascribe, with a high degree of confidence, a cause-and-effect relationship to the greenhouse effect."
- International
  - 1991: First assessment report from IPCC
  - 1992: UNFCCC

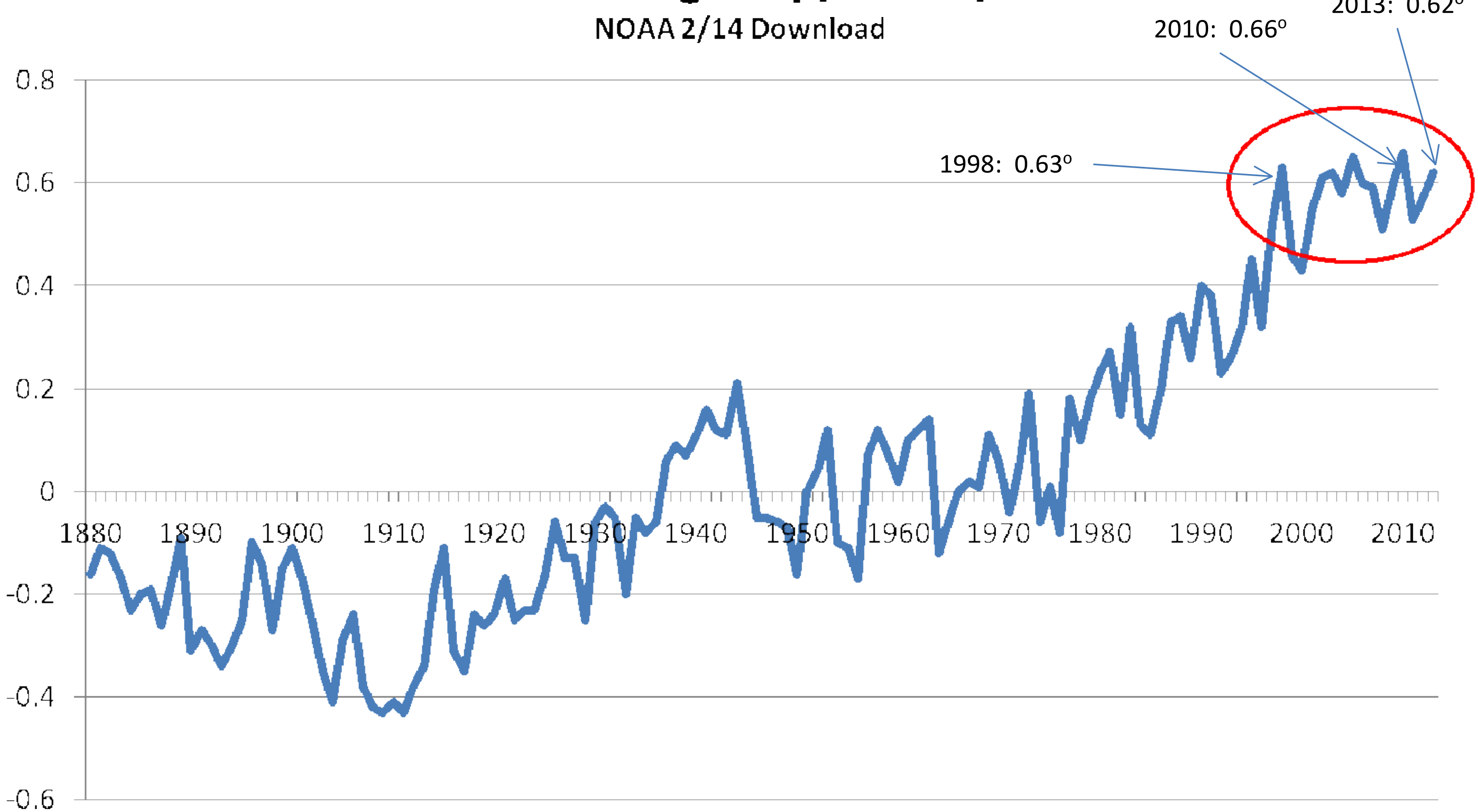
A Guide to the Alphabet

- IPCC: Intergovernmental Panel on Climate Change
  - Does not promote/implement policy or conduct research
  - Issues assessment reports based on existing literature

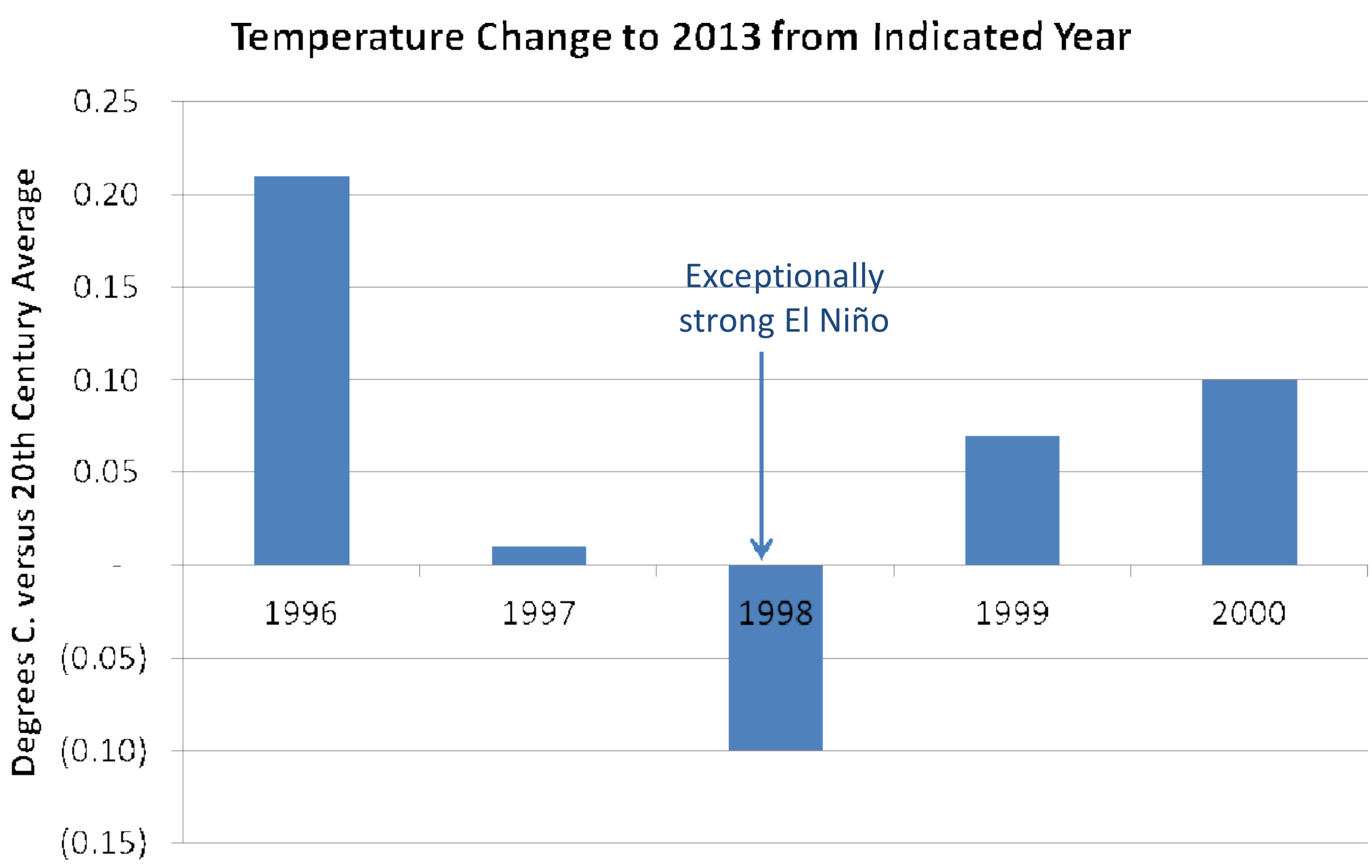
- UNFCCC: United Nations Framework Convention on Climate Change: Framework for protocols with national commitments

- U.S.
  - Ratified UNFCCC
  - Did not ratify Kyoto Protocol
  - Participating in post-Kyoto negotiations under UNFCCC

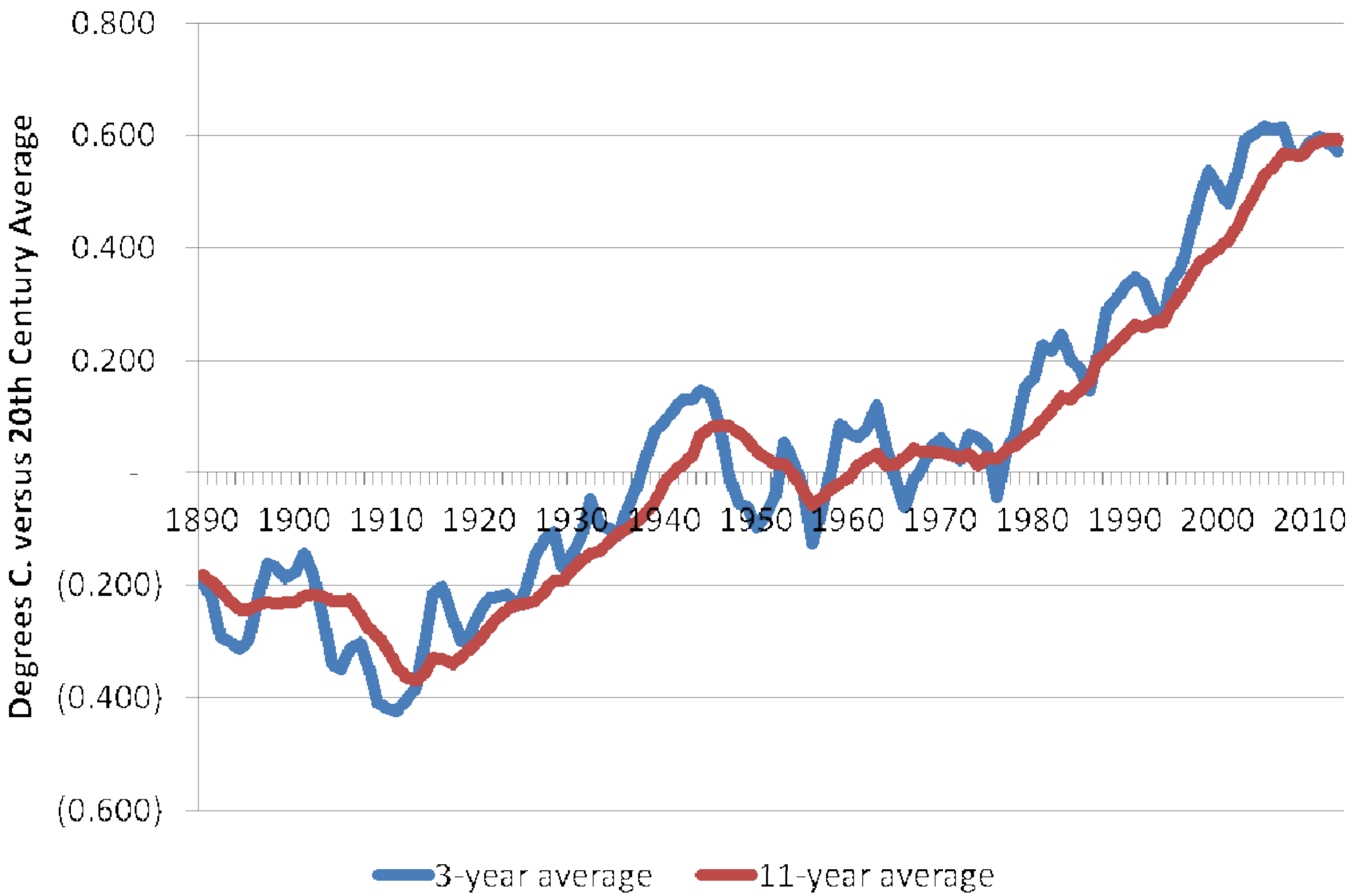
The Global Warming Stop/Pause/Slowdown



Picking Cherries

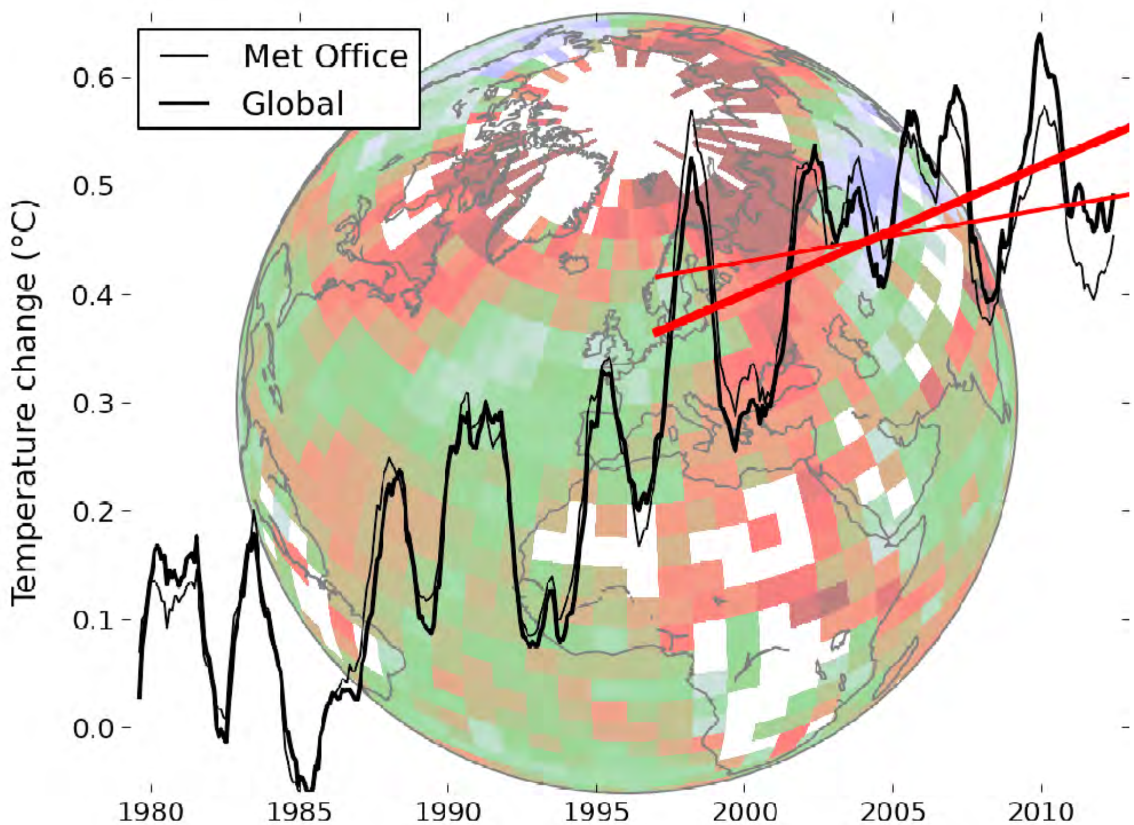


Smoothing the Curve: At Least a Slowdown



The Slowdown: Reality or Measurement?

- Dealing with the Arctic weather station gap
  - Hadley: assumes Arctic changes at global rate
  - NASA: fills gaps by interpolation
  - NOAA: like Hadley?
- Cowtan and Way methodology (November 2013)
  - Begin with satellite data
  - Develop algorithm for relating data to surface temperature
  - Test algorithm for known surface temperatures
- Result: a slowdown but a more modest one



Met Office
Global
Temperature change (°C)
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1980
1985
1990
1995
2000
2005
2010

Rank of Highest Recorded Temperatures

Rank	NASA	NOAA	HADLEY	COWTAN and WAY
1	2010	2010	2010	2010
2	2005	2005	2005	2005
3	2007	1998	1998	2007
4	2002	2013	2003	2009
5	1998	2003	2006	2013

Explaining the Slowdown: The Suspects

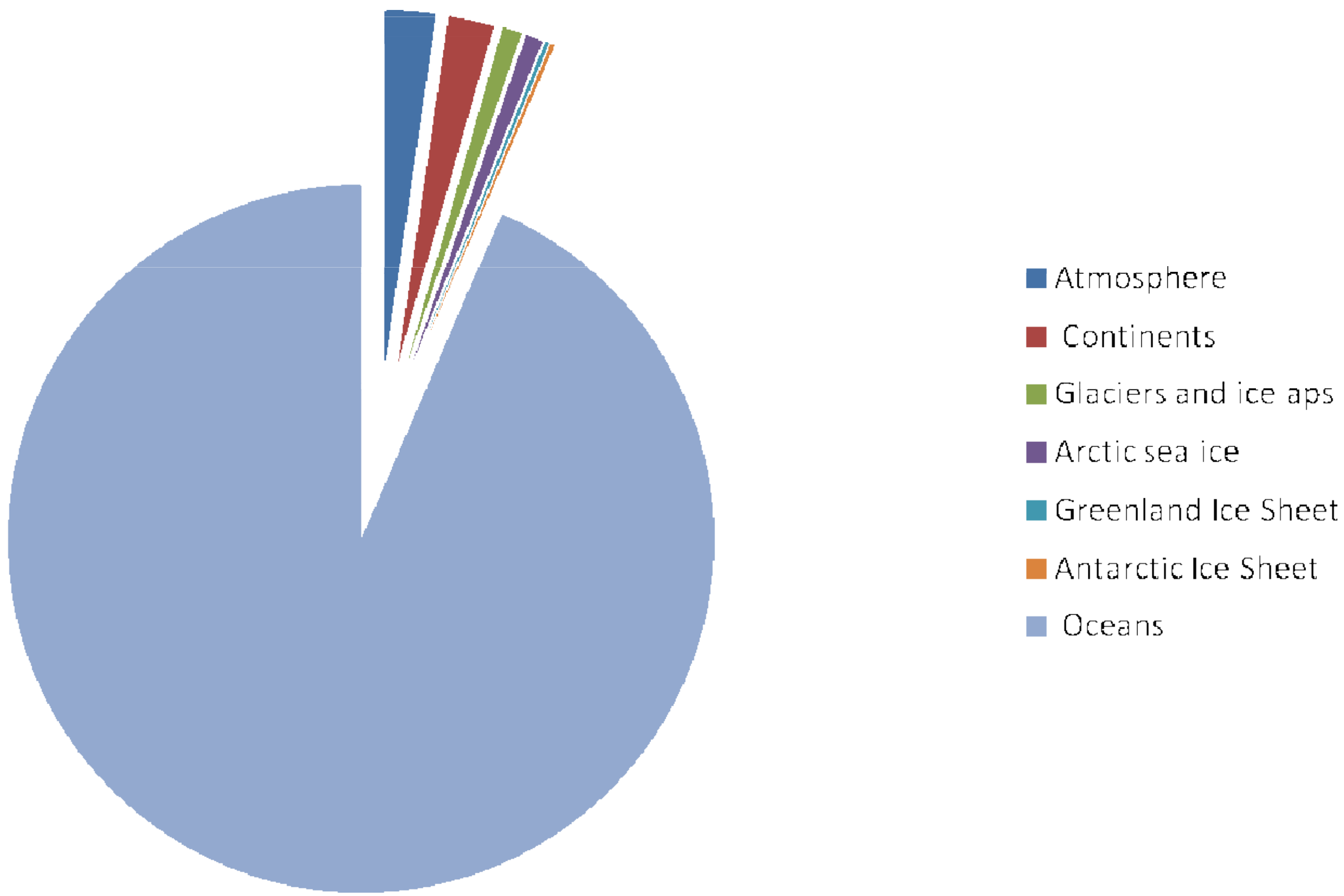
- Reduced radiative forcing: the elements
  - CO_2 concentration: continued growth
  - Top-of-atmosphere solar radiation: below-average but small impact
  - Albedo: effect of tropical volcanoes and Asian factories?

- Distribution of thermal energy

Distribution of Earth's Thermal Energy

- Horizontal: distribution over surface
  - The no-Mauna Loa problem
  - Polar vortex
- Vertical: surface and upper atmosphere
  - Measurement issue but little effect
- Vertical: surface and deep ocean

Where the Added Thermal Energy Goes

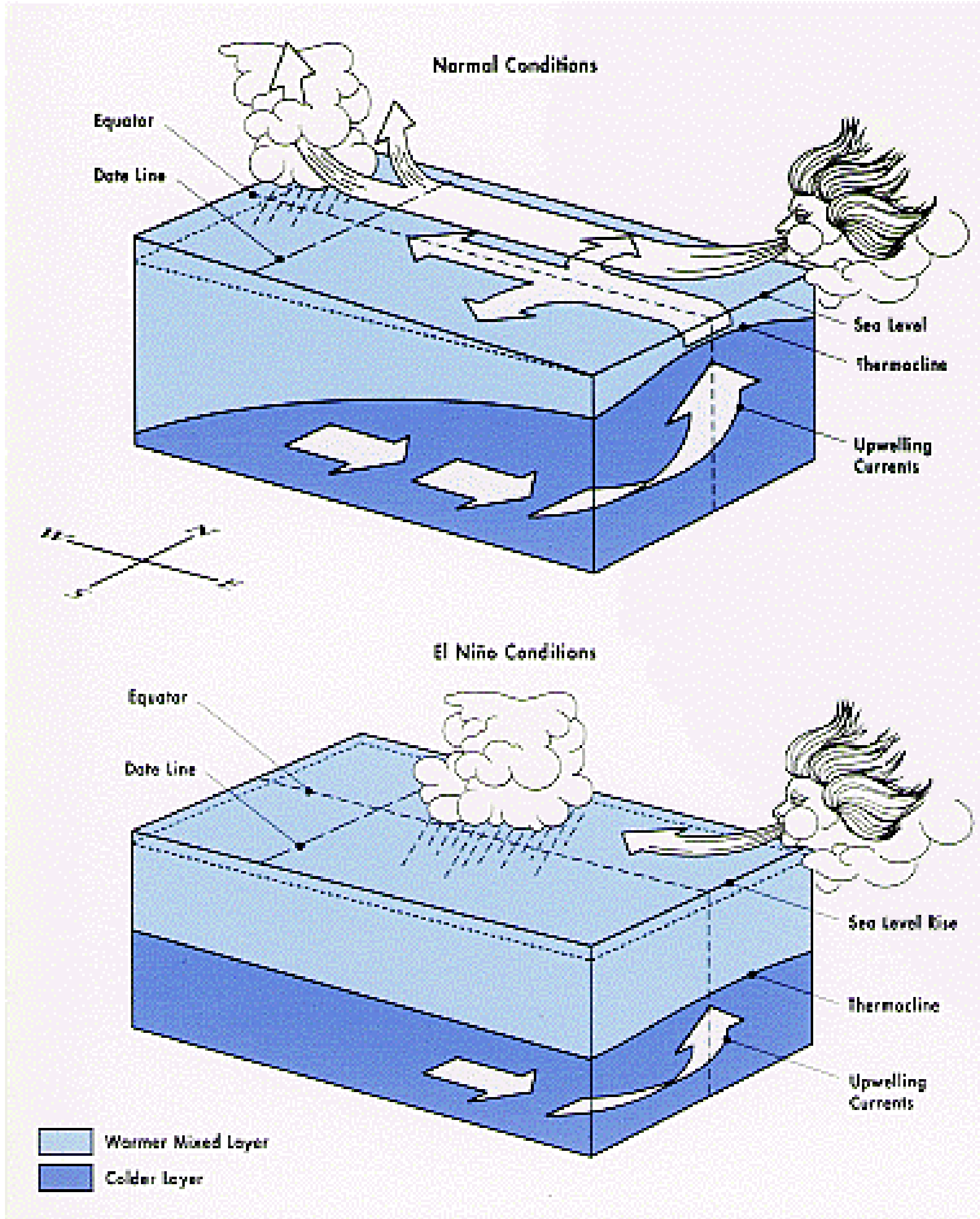


The Ocean's Role

- Small relative change in thermal energy to deep ocean → larger relative change for atmosphere

- Mechanism for change: El Niño-Southern Oscillation (ENSO)

- Underlying ENSO: longer-term Interdecadal Pacific Oscillation (IPO)/Pacific Decadal Oscillation (PDO)


Normal Conditions
Equator
Date Line
Sea Level
Thermocline
Upwelling Currents
El Niño Conditions
Equator
Date Line
Sea Level Rise
Thermocline
Upwelling Currents
Warmer Mixed Layer
Colder Layer

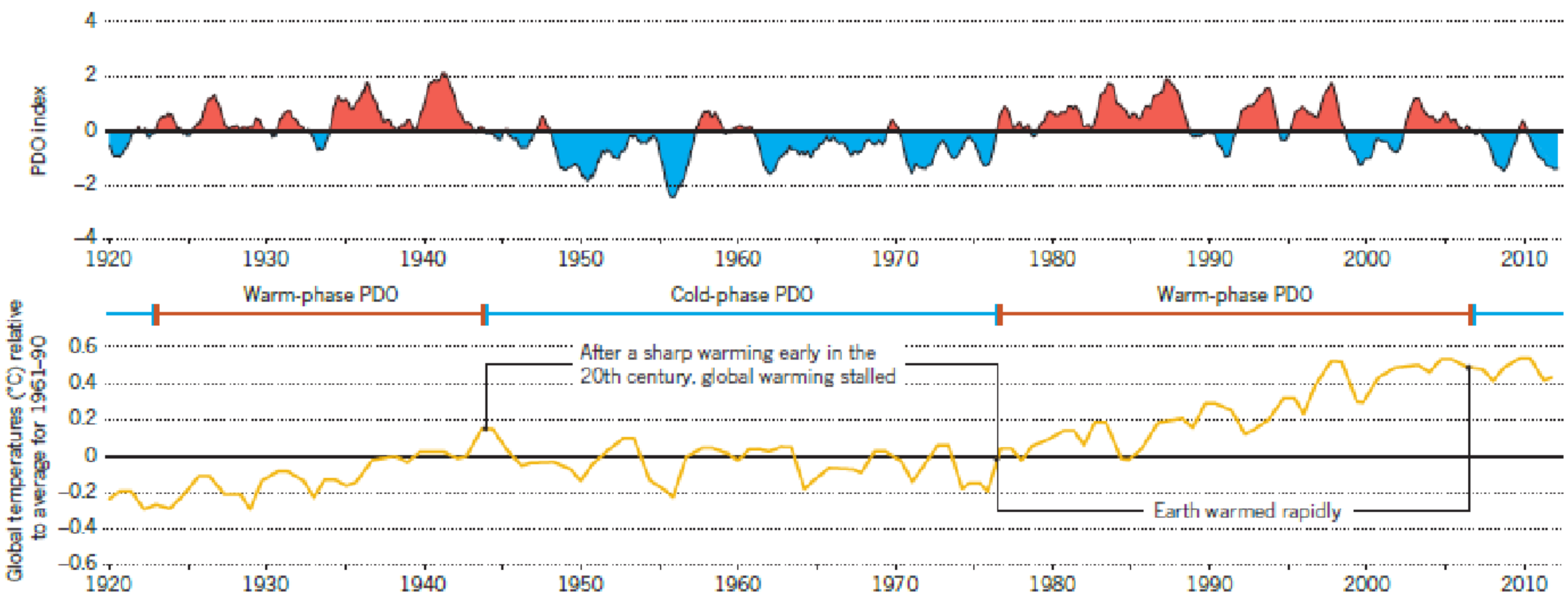
ENSO and IPO

- ENSO
  - Three to seven year cycle of varying strength
  - El Niño: reduced upwelling of cold deep water increases surface temperature and lowers deep ocean temperature
  - La Niña: reverse of El Niño
- IPO
  - Can last two or three decades
  - Positive phase:
    - Increased tendency for El Niño
    - Weaker winds reduce circulation of heat to deep ocean
  - Negative phase: reverse of positive phase

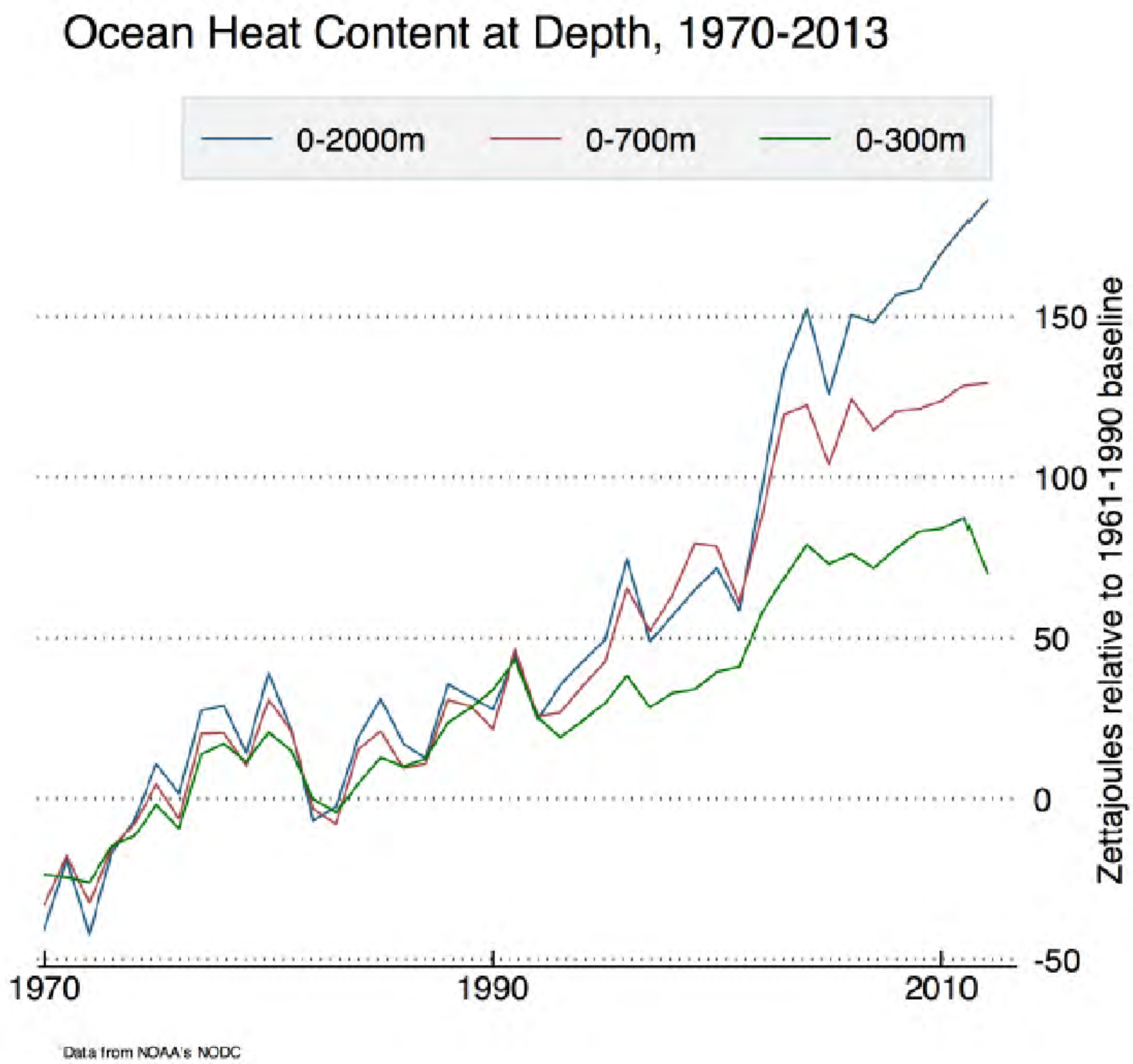
The Pacific Decadal Oscillation

THE PACIFIC'S GLOBAL REACH

As researchers have investigated why global temperatures have not risen much since 1998, many have focused on an ocean cycle known as the Pacific Decadal Oscillation (PDO). During periods when the PDO index is positive and the eastern Pacific is warm, global temperatures have risen quickly. During spells when the PDO index is negative, the warming has stagnated.



Zettajoules: 10^{21} Joules



Change in Ocean Heat Content

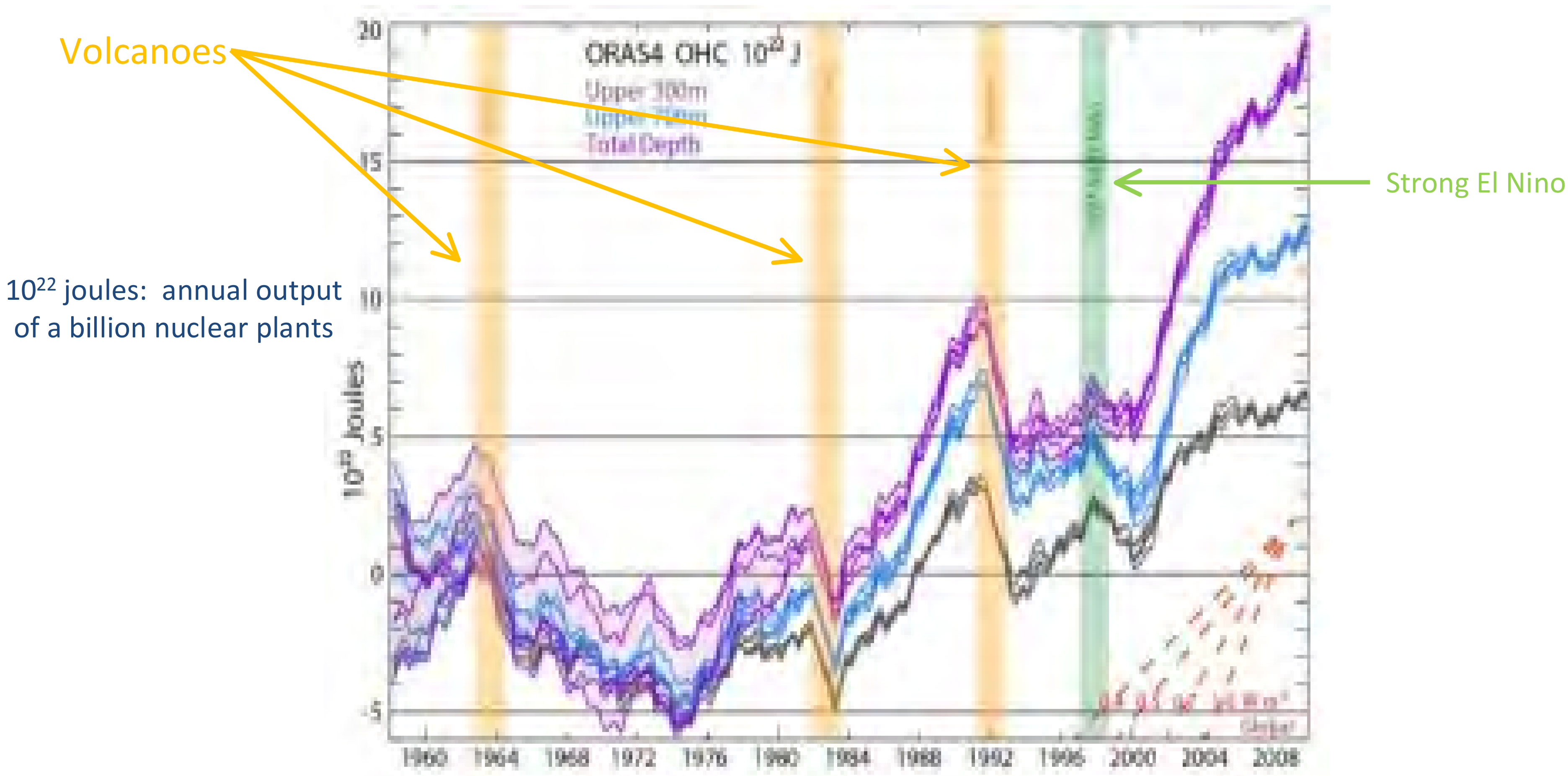


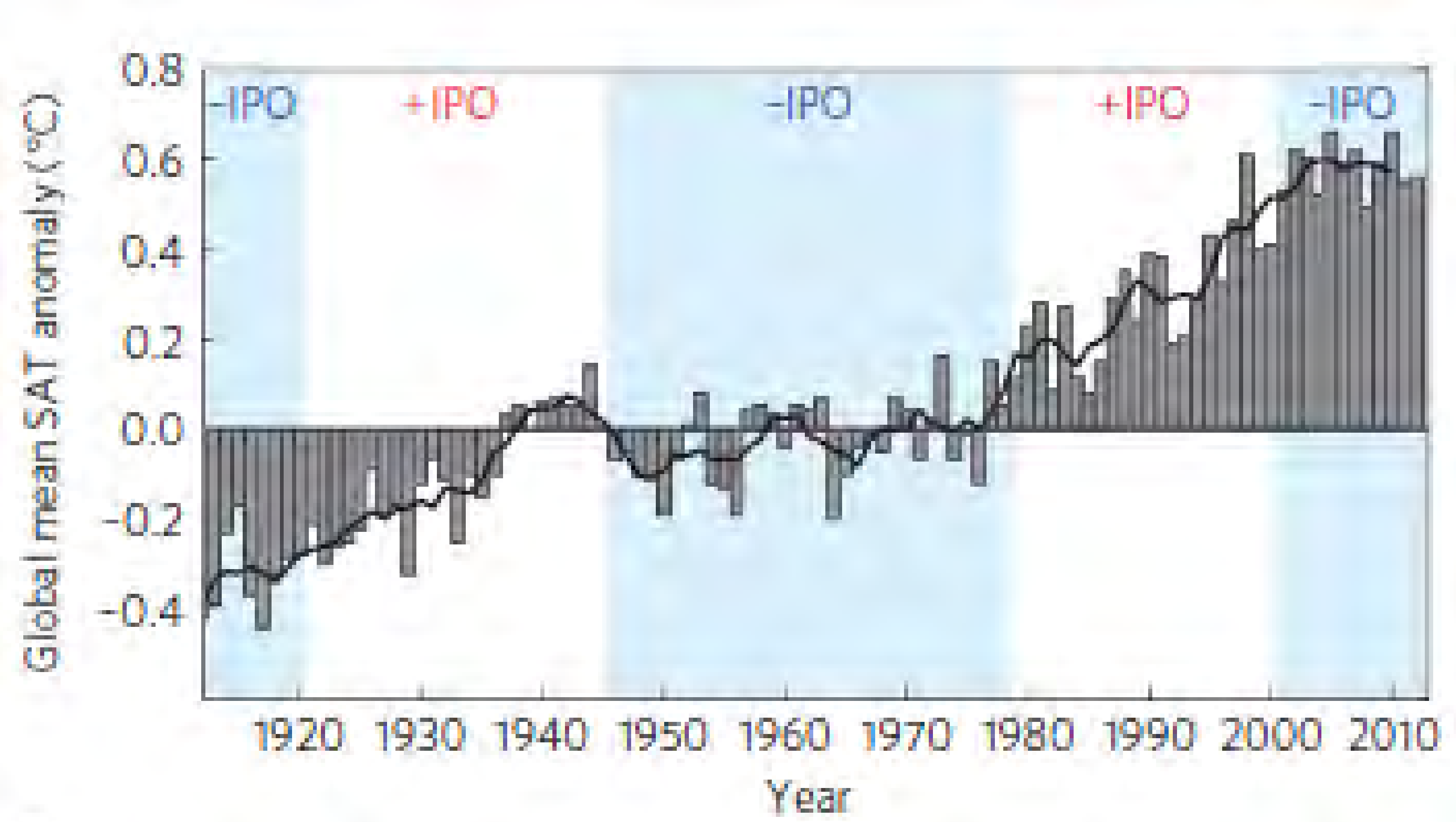
Figure 1: Ocean Heat Content from 0 to 300 meters (grey), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members.

Late-Breaking News

- Background
  - Geophysical Research Letters (5/13): ocean below 700 meters has absorbed more heat since 1999
  - Nature (8/13): links hiatus to cooling of eastern Pacific surface waters

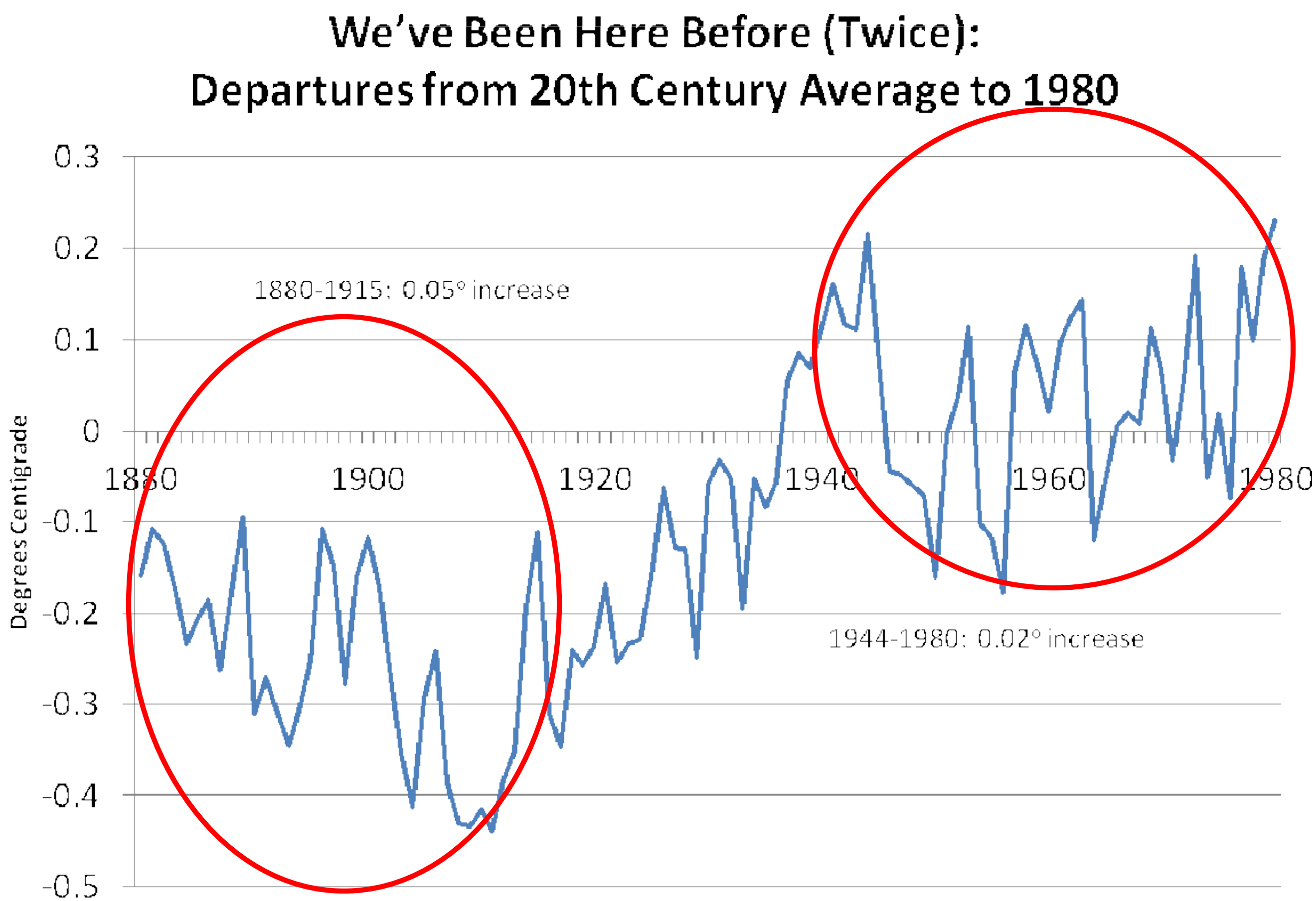
- Nature Climate Change (2/14)
  - Increased overturning driven by unusually strong La Niña surface winds
  - Estimated cooling impact: $0.1^{o} – 0.2^{o}$ C.

From February 2014 Paper



Current Explanation (Your instructor's evaluation)

- Approaching consensus: Increased ocean overturning plays a significant role
- Probable: Reduced solar radiation plays a role but a minor one
- ??: Increased albedo from volcanoes and Asian factories
- Needs confirmation: NOAA-NASA-Hadley may overstate extent of slowdown



We've Been Here Before (Twice):
Departures from 20th Century Average to 1980
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Degrees Centigrade
1880
1900
1920
1940
1960
1980
1880-1915: 0.05° increase
1944-1980: 0.02° increase

1940s-1970s Cooling

- Talk of new "ice age" mostly in popular press

•Contemporaneous understanding: Two offsetting anthropogenic forces

– Greenhouse effect of CO_2 emissions

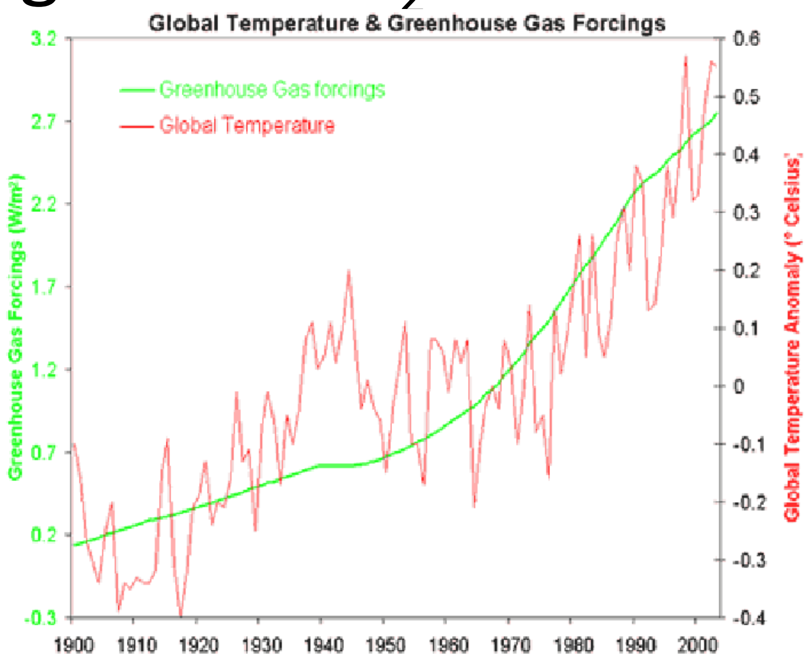
– Increased albedo from sulfate aerosols

•But also coincides with IPO negative phase

Early 20th Century

- Also coincides with negative IPO phase

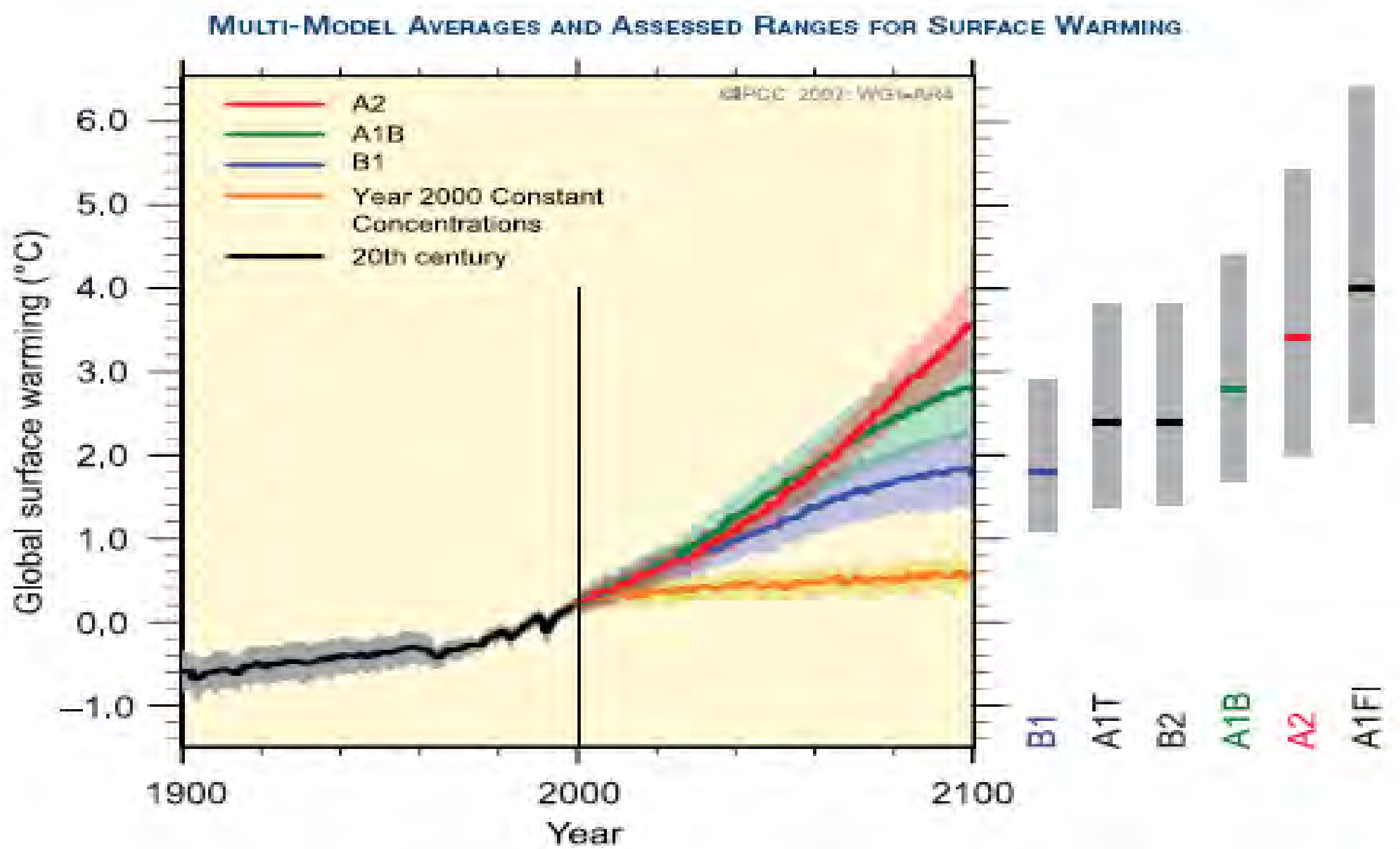
- Offsetting lower CO_2 concentration



Politically, the most important characteristic of previous two pauses is that they ended

PROJECTING THE FUTURE

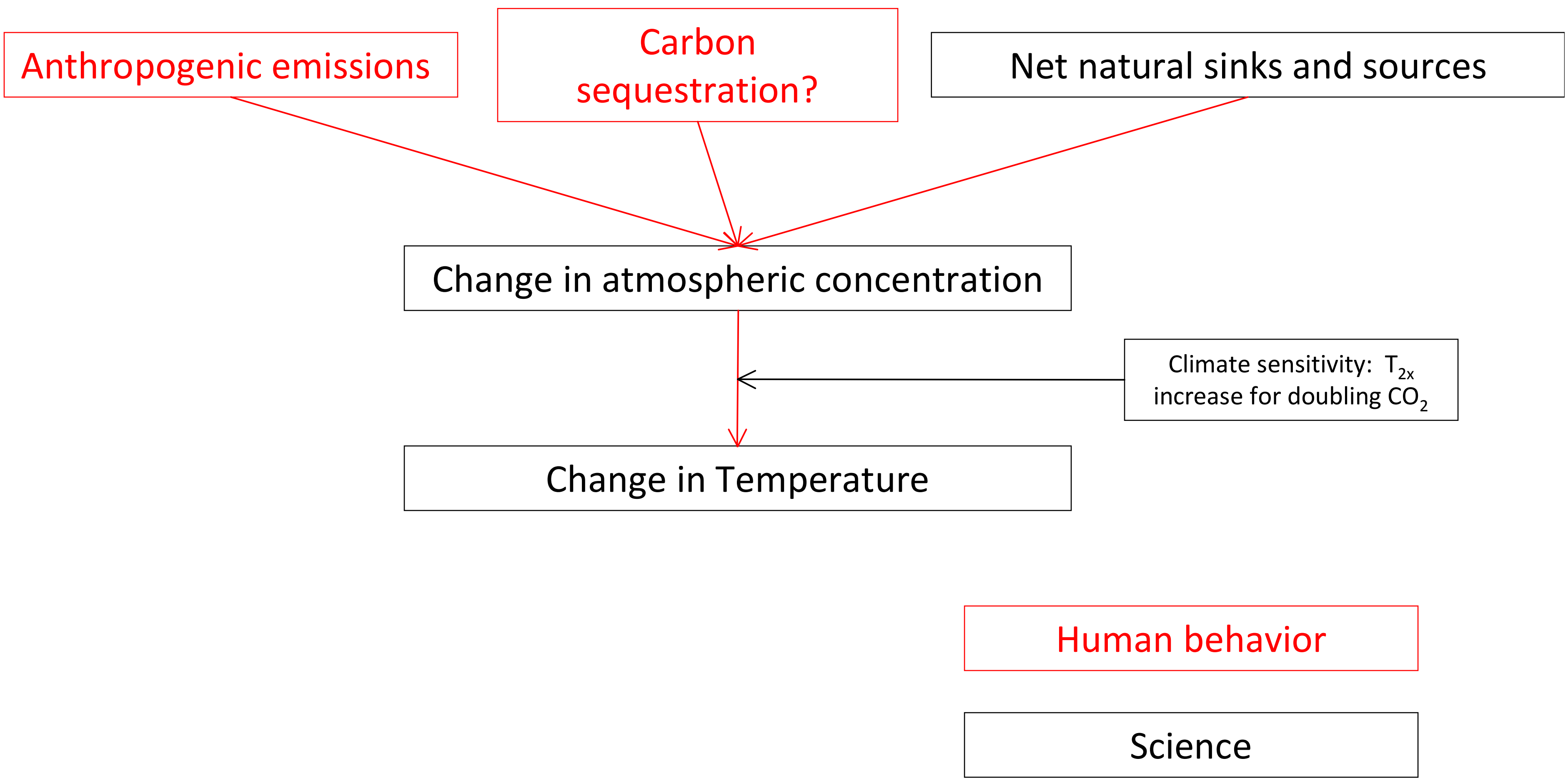
IPCC 2007 Projections



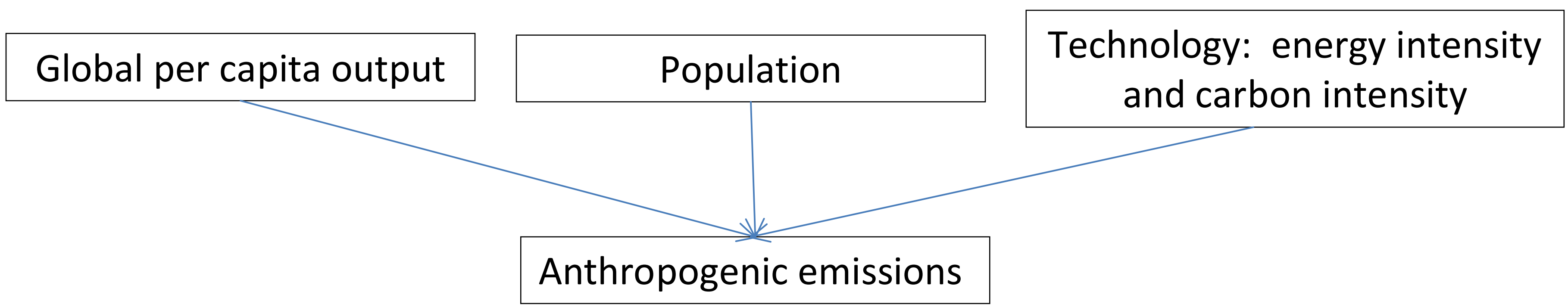
How Warm Will It Get?

- Behavioral issue: Future CO_2 emissions
- Scientific issue: Natural absorption of CO_2 by ocean and biosphere
- Behavioral issue: Human sequestration of CO_2?
- Scientific issue: Quantitative CO_2-temperature relationship (climate sensitivity)

The Causal Chain
(without radiation management)



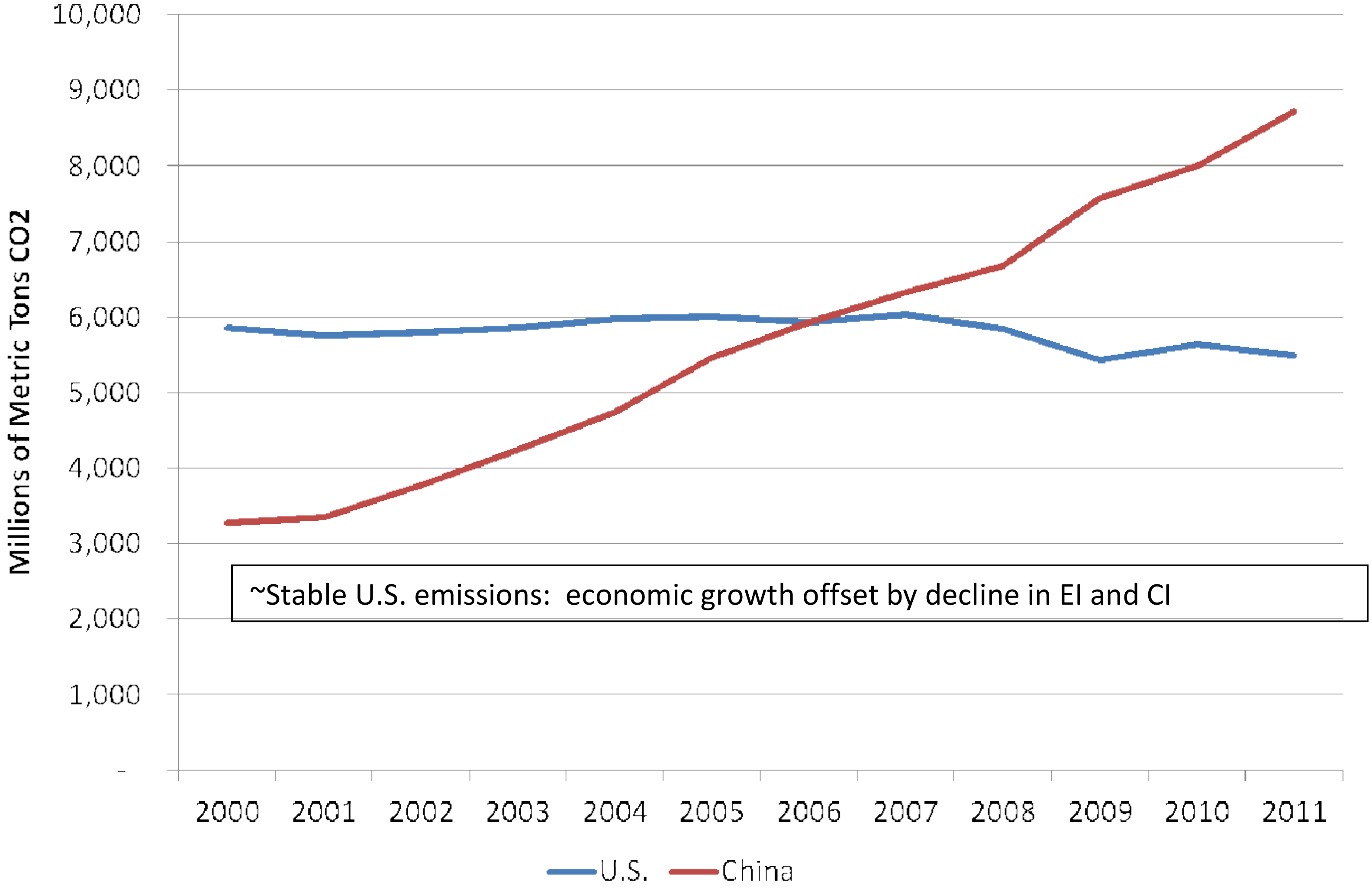
Determining Emissions



Kaya Identity

Emissions = Per capital production x population x energy intensity x carbon intensity

Example: U.S. and China CO_2 Emissions



What is the appropriate metric?

	China	U.S.
Energy-related missions (2011 million MT)	8,715	5,491
Estimated population (2013 millions)	1350	316
MT/person	6.46	17.38
GDP (2012 $trillion PPP)	12.26	16.24
MT/$1000	0.71	0.34

Example: Generating Electricity

	30% Efficient Coal Plant	50% Efficient Combined Cycle Natural Gas Plant
Energy intensity: energy consumed per MWh (GJ)	10.8	7.2
Carbon intensity: CO_2 emissions per GJ (kg)	93	53
CO_2 emissions per MWh (kg)	1004	382

Effect of Low Natural Gas Prices

- Displaces output from existing coal plants: To date, more important than coal plant closures
- Low electricity prices
  - Reduces profitability of wind and solar
  - Shrinks boundaries of markets where they are profitable with any given subsidy

Projections' Technological Vulnerability

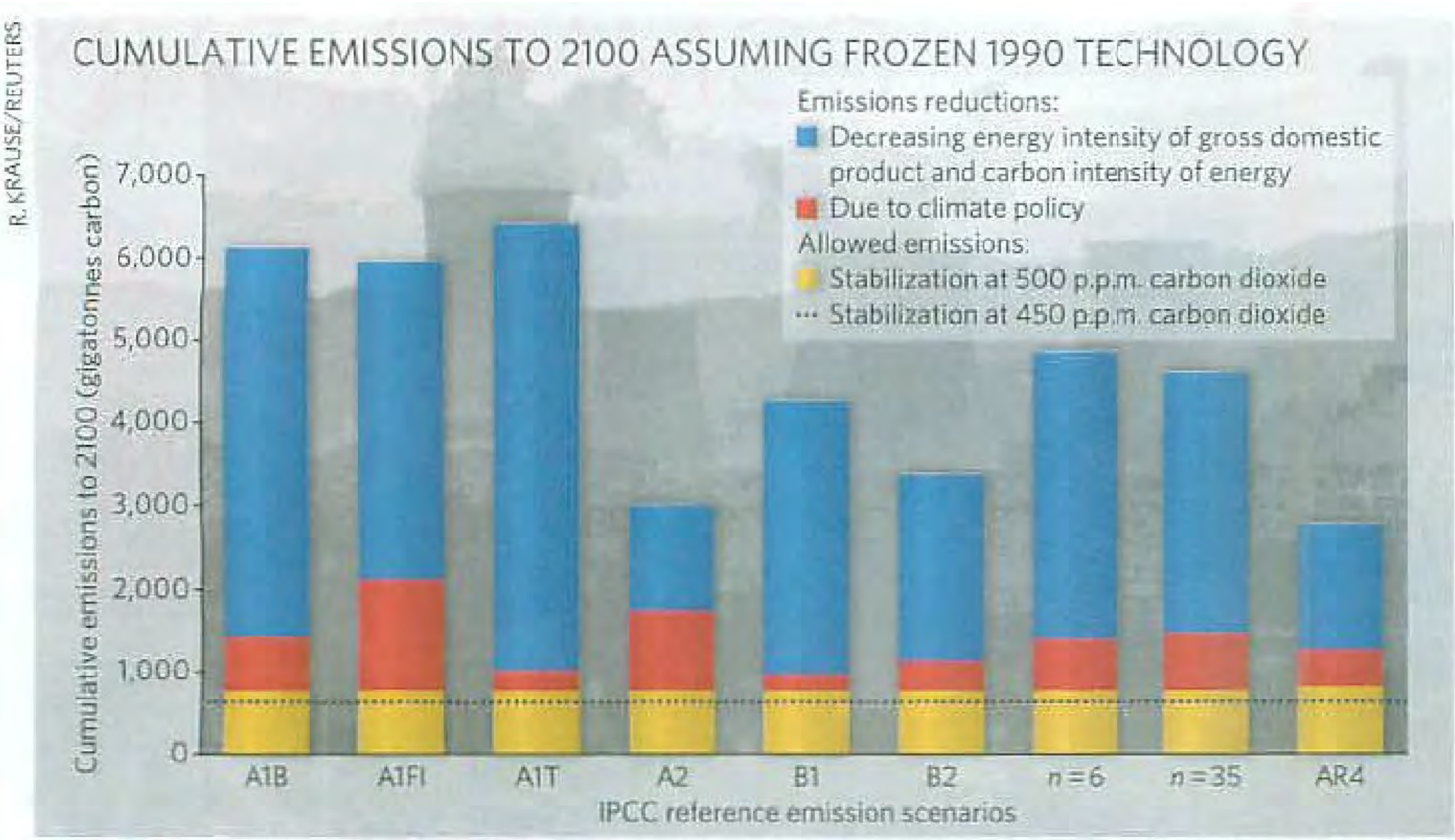
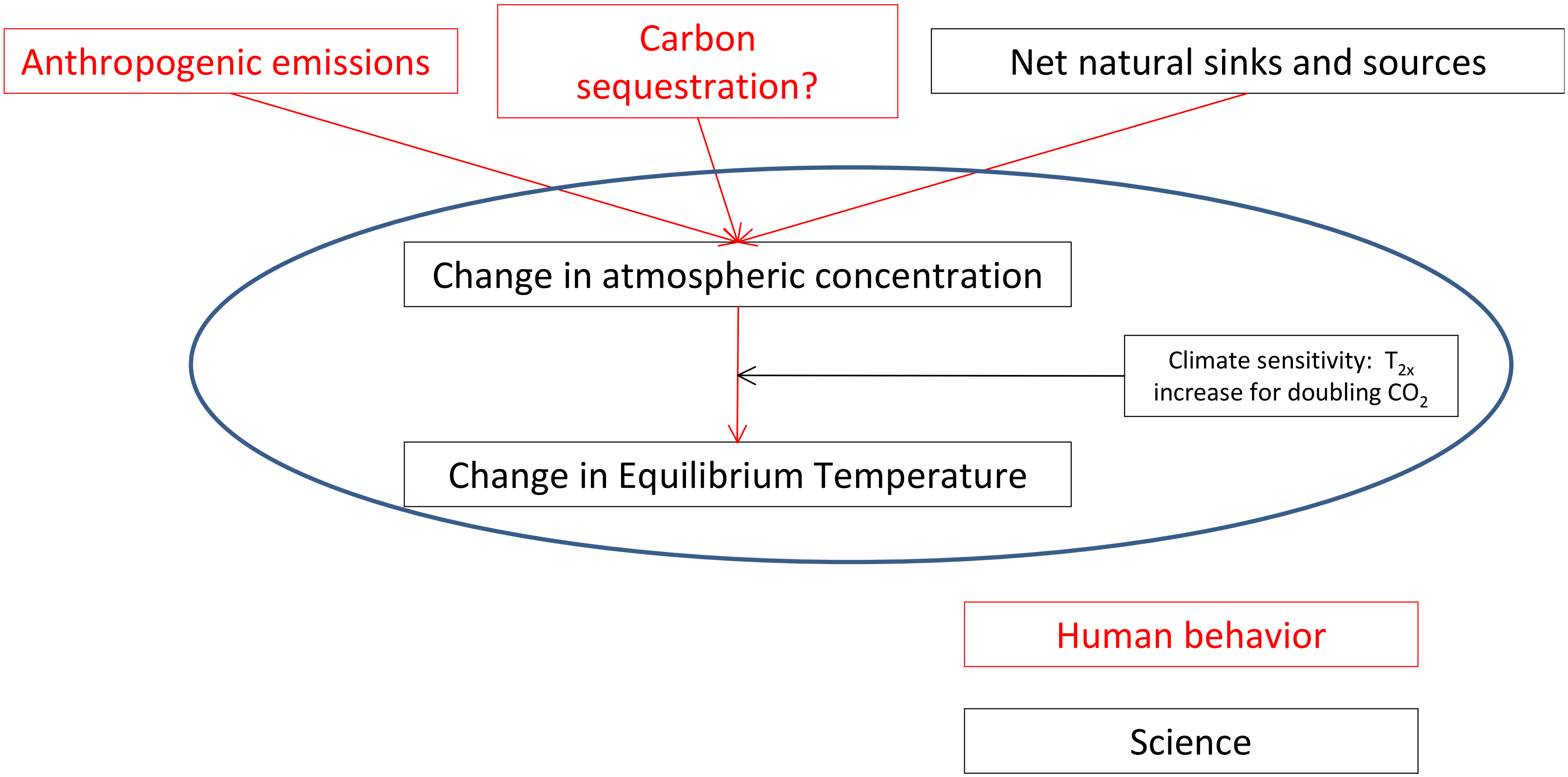


Figure 1 | **Cumulative emissions.** A range of 'built-in' emissions reductions (blue) in the scenarios used

CLIMATE SENSITIVITY

The Role of Climate Sensitivity



They Weren't Entirely Wrong

- Don't worry: oceans will absorb the CO_2
  - They don't absorb all of it (Revelle and Keeling)
  - But much higher concentration without them
- Don't worry: the atmosphere already is saturated with greenhouse gases
  - More greenhouse gases mean more radiative forcing even at Venusian level
  - But an additional ton has a smaller impact at a higher concentration

Climate Sensitivity

- ΔT_{2x}: Increase in equilibrium temperature from doubling CO_2 concentration
  - Most estimates: 1.5^o to 4.5^o C
  - Not an estimate of temperature at time CO_2 doubles: transient temperature
- Calculating impact of increasing concentration: $\Delta T = \Delta T_{2X} * (\ln(\text{New } CO_2/\text{Old } CO_2)/\ln(2)$, where temperatures are in degrees Kelvin
- For doubled CO_2: $\Delta T = \Delta T_{2X} * \ln 2/\ln 2 = \Delta T_{2X}$

Logarithms

- Power to which a base number must be raised in order to equal a certain number
  - $Log_{10}(100) = 2$ because $10^2 = 100$
  - Natural logs (Ln) use base e (2.718 . . .)

- Pre-computer practical use: slide rules

- Today: describes relationship between rates of change of two variables

Increase from 280 ppm to 400 ppm With 3^o Sensitivity

- Linear relationship: $400/280 \times 3^o = 4.29^o$
- Logarithmic relationship: $\Delta T_{2x} = 3^o$
  - Ln(400/280) = 0.36
  - Ln(2) = 0.69
  - $3^o * 0.36/0.69 = 1.54^o$ temperature increase

Review of Measurement and Time

- Sensitivities of temperature
  - To forcing: Stefan-Boltzmann equation
  - To GHG: climate sensitivity
- Lag in full temperature impact
  - With positive forcing, equilibrium temperature > transient temperature:
  - With no changes in GHG or albedo, warming "in the pipeline"

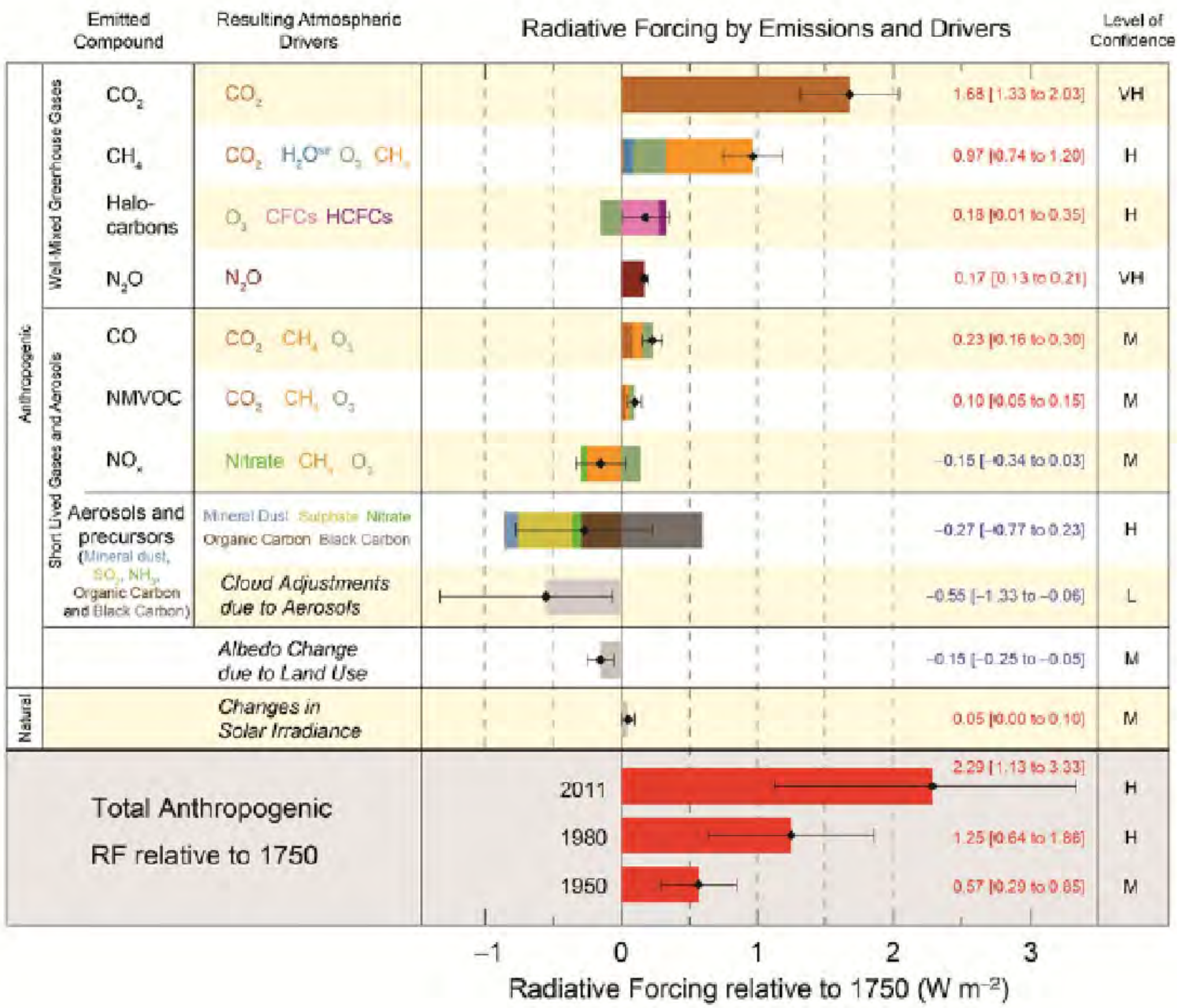
Difficulty of Determining Climate Sensitivity

- Empirical
  - Temperature and CO_2 at two points in time
  - Solve for climate sensitivity
- Problems
  - Soldiers in a ditch
  - Equilibrium temperature

Soldiers in a Ditch

- Task: Determine height of soldiers on other side of field
- Known distance and surveying instruments
- But they’re standing in a ditch
- How deep is the ditch? <u>We don’t know</u>

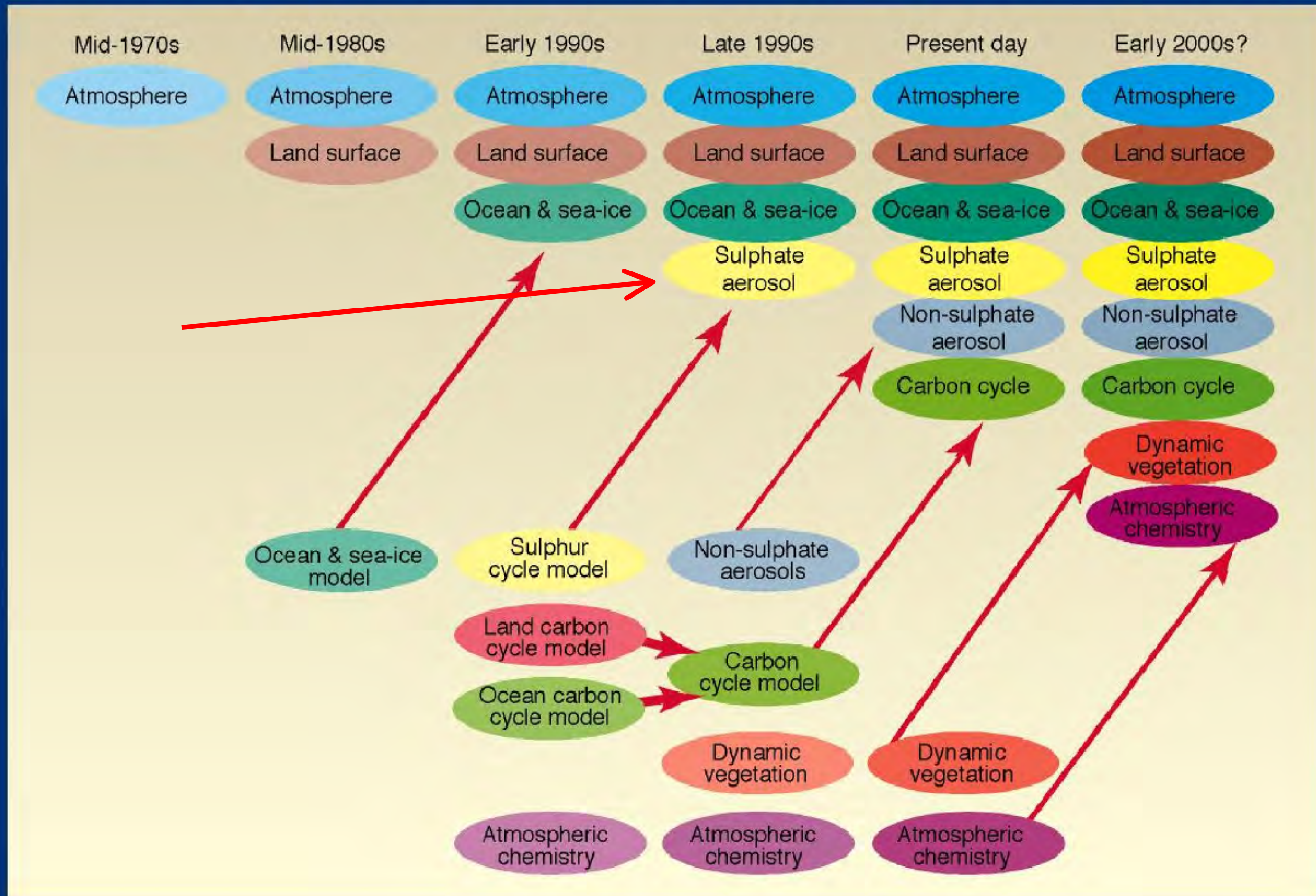
Figure SPM.5 [FIGURE SUBJECT TO FINAL COPYEDIT]



Computer Models

- More powerful computers plus increased scientific understanding
  - Smaller grid cells –still too large for some features
- Result
  - More confidence but little reduction in uncertainty range
  - Role for simpler models to permit multiple runs: intermediate complexity models

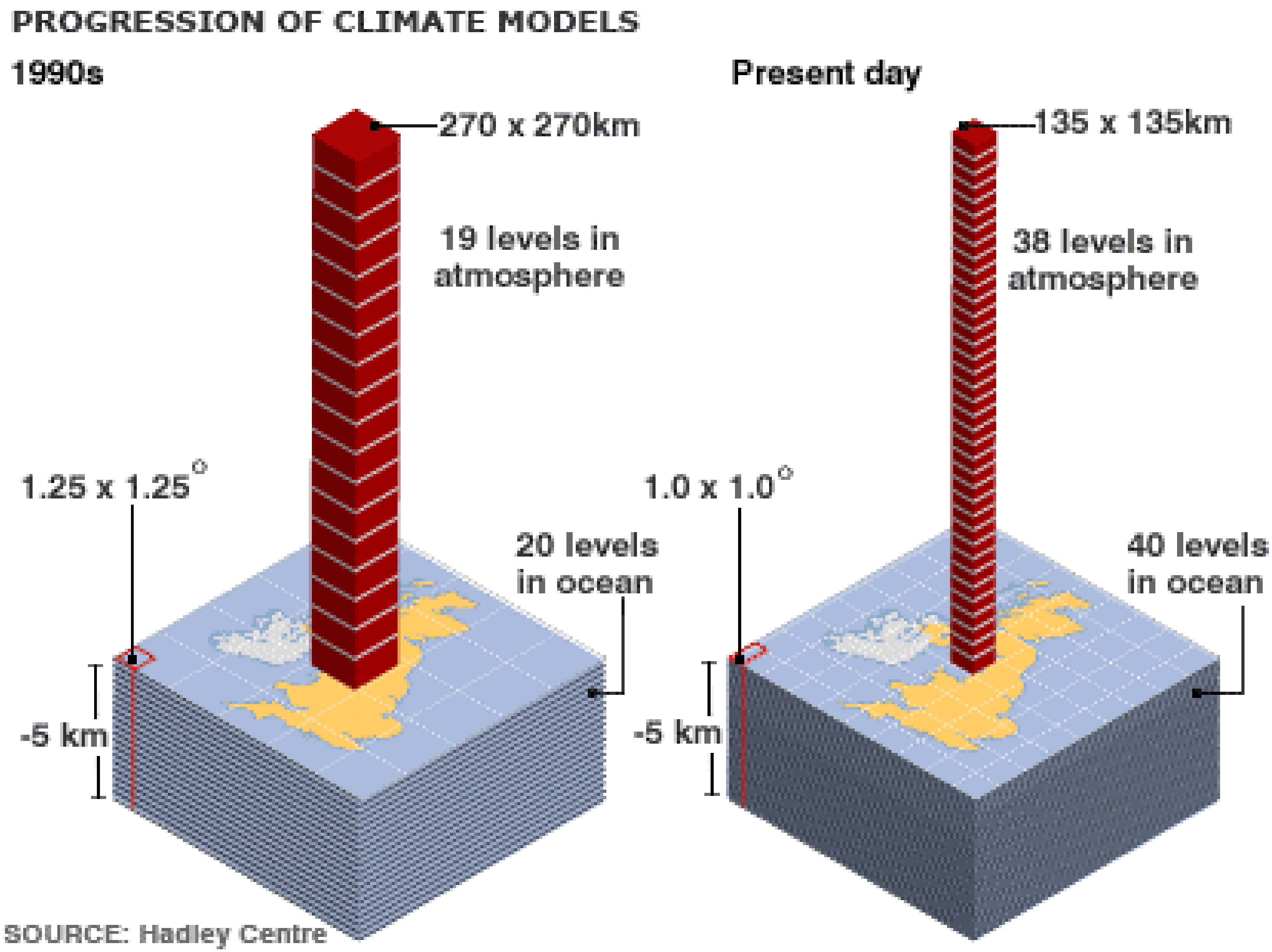
The development of climate models, past, present and future



WG1 - TS BOX 3
FIGURE 1

IPCC
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP



PROGRESSION OF CLIMATE MODELS
1990s
Present day
270 x 270km
19 levels in atmosphere
1.25 x 1.25°
20 levels in ocean
-5 km
135 x 135km
38 levels in atmosphere
1.0 x 1.0°
40 levels in ocean
-5 km
SOURCE: Hadley Centre

Computer Models and Effect of Aerosols and Clouds

- Incomplete scientific understanding of processes

- Scale of processes is smaller than computer model grid

Forcing, Heat and Temperature

- Forcing: Rate of change in Earth system heat content
- Amount and rate of temperature change depend on system's thermal inertia
- Most heat content (and therefore most thermal inertia) is in ocean

Transient and Equilibrium Temperature

- Thermal inertia → Temperature change lags behind change in forcing
- Transient temperature – temperature on (e.g.) January 1, 2100 or day CO_2 doubles
- Equilibrium temperature: No net forcing – outgoing thermal and reflected solar equal incoming solar

Without Thermal Inertia

- Earth system as a cheap pan

- Instantaneous response to change in radiative balance: temperature always at equilibrium and no radiative forcing

- "Transient temperature" is meaningless

Implications of Forcings as of 2005: Time and Inertia

- Temperature increase to date: 0.7^0 C
  - Full response to ~one w/m^2 of net forcing

- Assuming ~1.85 w/m^2 <u>cumulative</u> net forcing since 1880, 0.85 w/m^2 forcing still "in the pipeline"

- Implies ~0.6^0 further increase <u>with no further change in GHG, aerosols, etc.</u>

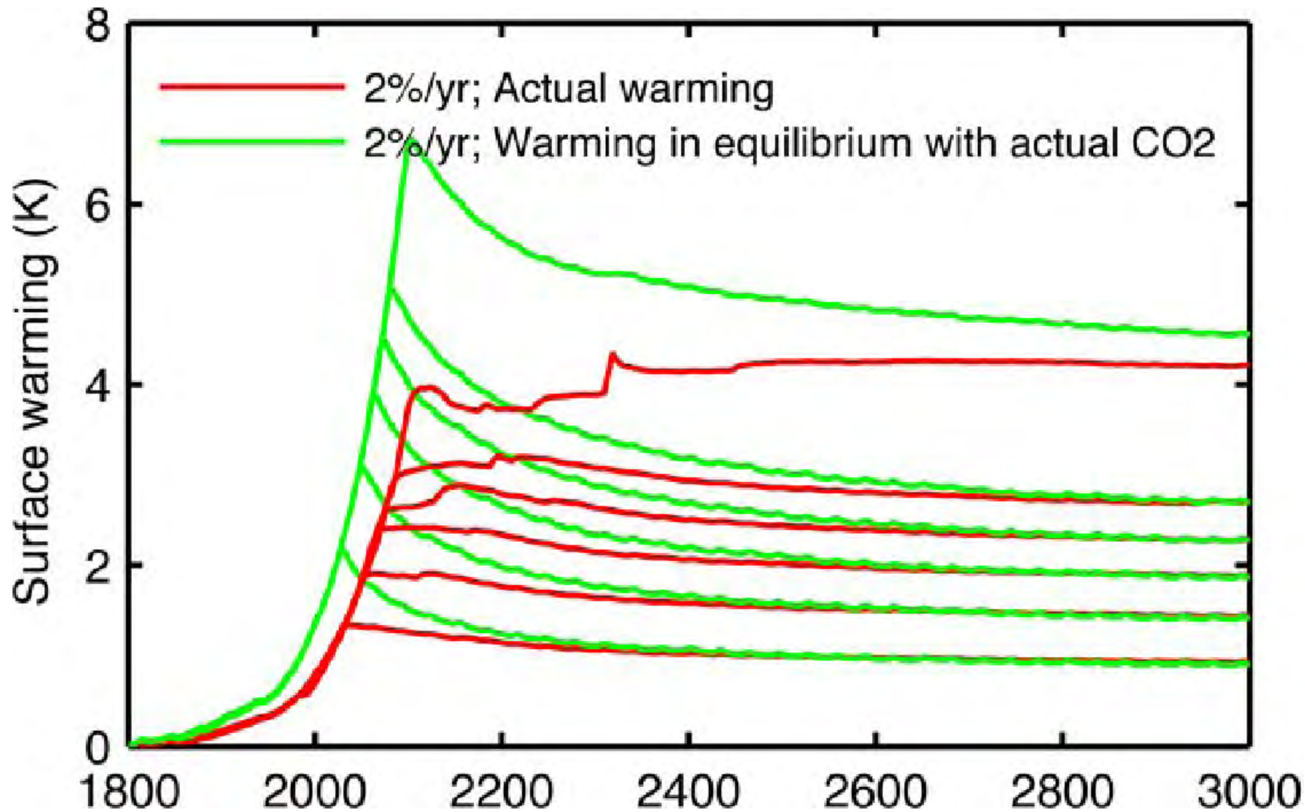
Cumulative forcing vs. current forcing

- GHG concentration and albedo <u>immediately</u> changed to 2005 level in 1880
- Resulting forcing of 1.85 watts/m^2 is cumulative forcing since 1880.
- Partly "used up" since 1880 by temperature increase
- <u>If</u> GHG concentration unchanged, further 0.7^o temperature increase eliminates radiative forcing

The Long Term

- Short-term CO_2 concentration: 50% absorbed, mostly in ocean
  - Good news: Cuts atmospheric increase in half
  - Bad news: ocean acidification

- Long term: Next 1000 years dominated by ocean turnover
  - Absorbs CO_2 -- reduces cumulative radiative forcing
  - Ocean warms – less heat transfer from atmosphere



Curves represent peak CO_2 of 450 to 1200 ppm

What's Happening?

- At millennial time scale, CO_2 largely equilibrates between ocean (~80%) and atmosphere (~20%)
  - Result: Radiative forcing reduced from peak
- But oceans gradually warm
  - Result: reduced transfer of heat to ocean
- Net result: near-constant temperature over millennium

What does 1000 years mean?

- 1000 years ago
  - William the Conqueror not yet born
  - Not quite half way from Charlemagne to Thomas Aquinas
- One percent annual growth in PCNP – increases 29000 times.

Policy Implications

- We have to deal with additional warming
- To avoid it, eliminate current radiative forcing <u>without temperature increase</u>
  - Immediately reduce GHG emissions below current level of their absorption by ocean and biosphere, <u>or</u>
  - Increase albedo

What do you want to (or think you're able to) achieve?

- Reduce ocean acidification: Only measures directed at GHG
- Reduce global <u>average</u> temperature: Large-scale radiation management may be an alternative
- Protect particular human/non-human populations or systems: Adaptation