Measuring CO_2 and Temperature

Climate Change

OLLI Summer 2013

Review: Essential Points I

- Temperature: average kinetic energy of system's atoms
- Planets gain/lose energy through radiation
- Thermal radiation
  - Produced by above absolute zero temperature
  - Energy of photons determined by temperature

Review: Essential Points II

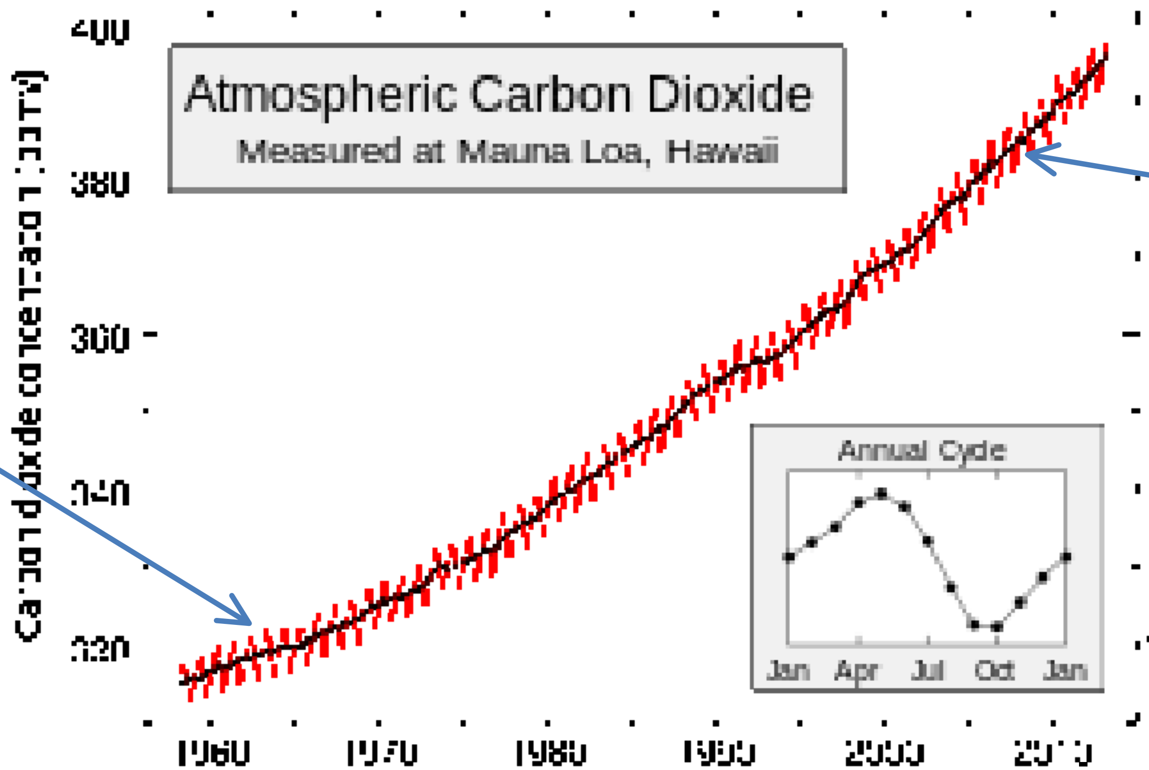
- Many gases occupy only certain energy levels
- Absorb photons with energy matching difference in energy levels
- Greenhouse gases: difference matches photons of Earth's thermal radiation

MEASURING CO_2

Problem and Solution

- Early 1950s: no consensus on how much (or whether) CO_2 concentration was growing
- The problem
  - In long run, geographical source doesn't matter
  - But does matter for months
- Two-part solution:
  - An isolated location: Manu Loa
  - Continuous careful measurements: David Keeling

The Keeling Curve



2005:
Keeling dies

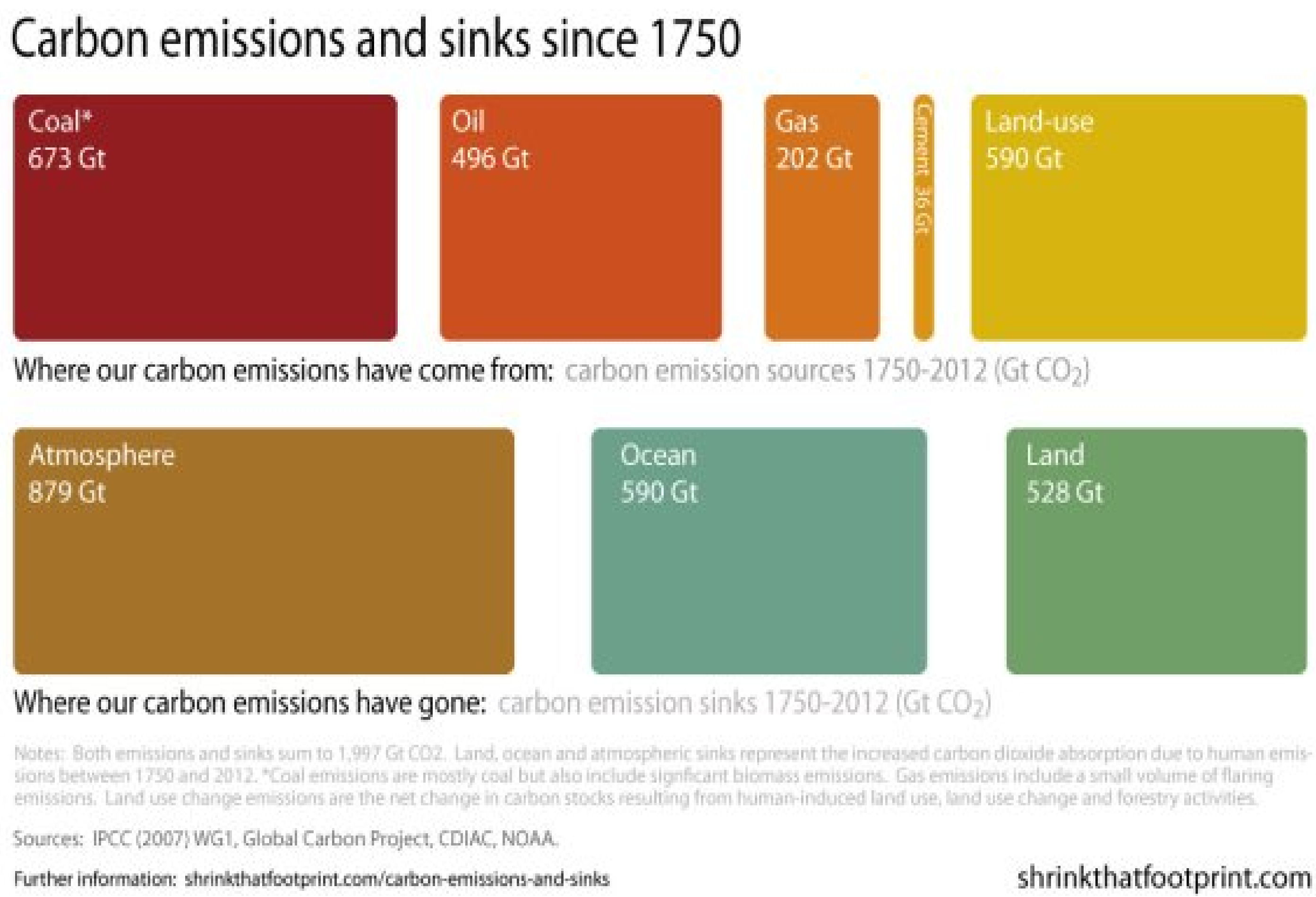
NSF stops supporting “routine” research – Revelle to the rescue

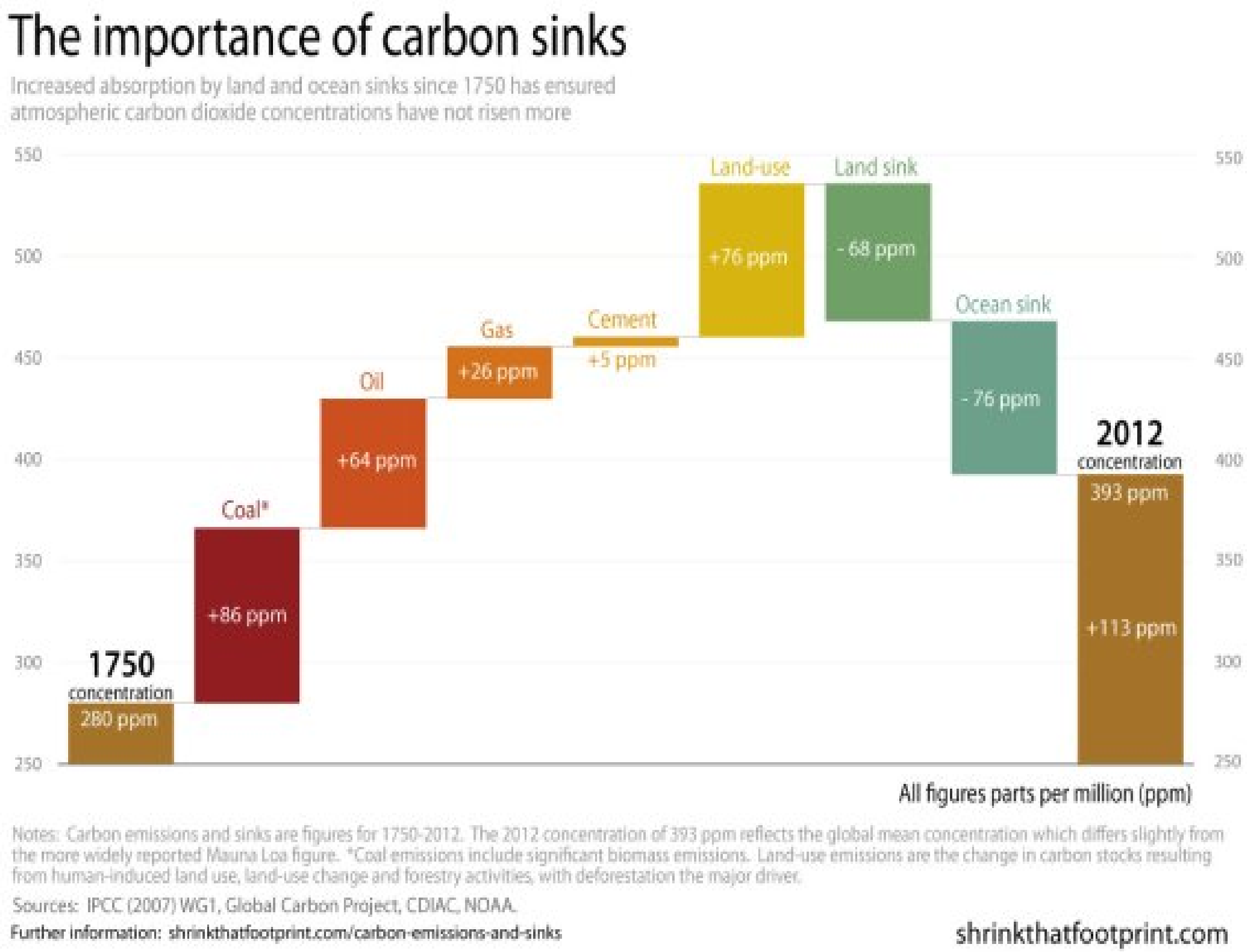
Three Carbon Cycles

- Geological: volcanoes vs. burial
  - Without us, determines total content of atmosphere-biosphere-ocean system
  - Time span: tens of millions of years
- The "Keeling cycles"
  - Biological:
    - Dominates intra-annual cycle
    - Little interannual impact
  - Fossil fuels: volcanoes on steroids

CO_2 Emissions: Man vs. Volcanoes

	tons per year (Gt/y)
Global volcanic emissions (highest preferred estimate)	0.26
Anthropogenic CO_2 in 2010 (projected)	35.0
Light-duty vehicles (cars/trucks)	3.0
Approximately 24 1000-megawatt coal-fired power stations *	0.22
Argentina	0.20
Pakistan	0.18
Saudi Arabia	0.44


Carbon emissions and sinks since 1750
Coal*
673 Gt
Oil
496 Gt
Gas
202 Gt
Cement 36 Gt
Land-use
590 Gt
Where our carbon emissions have come from: carbon emission sources 1750-2012 (Gt CO2)
Atmosphere
879 Gt
Ocean
590 Gt
Land
528 Gt
Where our carbon emissions have gone: carbon emission sinks 1750-2012 (Gt CO2)
Notes: Both emissions and sinks sum to 1,997 Gt CO2. Land, ocean and atmospheric sinks represent the increased carbon dioxide absorption due to human emissions between 1750 and 2012. *Coal emissions are mostly coal but also include signficant biomass emissions. Gas emissions include a small volume of flaring emissions. Land use change emissions are the net change in carbon stocks resulting from human-induced land use, land use change and forestry activities.
Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA.
Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks
shrinkthatfootprint.com


The importance of carbon sinks
Increased absorption by land and ocean sinks since 1750 has ensured atmospheric carbon dioxide concentrations have not risen more
1750
concentration
280 ppm
Coal*
+86 ppm
Oil
+64 ppm
Gas
+26 ppm
Cement
+5 ppm
Land-use
+76 ppm
Land sink
- 68 ppm
Ocean sink
- 76 ppm
2012
concentration
393 ppm
+113 ppm
550
500
450
400
350
300
250
All figures parts per million (ppm)
Notes: Carbon emissions and sinks are figures for 1750-2012. The 2012 concentration of 393 ppm reflects the global mean concentration which differs slightly from the more widely reported Mauna Loa figure. *Coal emissions include significant biomass emissions. Land-use emissions are the change in carbon stocks resulting from human-induced land use, land-use change and forestry activities, with deforestation the major driver.
Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA.
Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks
shrinkthatfootprint.com

Measures

- Most common today: metric tons or gigatons (Gt) of CO_2
- Alternative: tons of carbon
  - Molecular weight of carbon: 12
  - Molecular weight of CO_2: 12 + 2 x 16 = 44
    - CO_2 emissions = 3.67 x carbon emissions
    - Tax/ton on CO_2 = tax/ton on carbon/3.67

More Inclusive Measure: CO_{2eq}

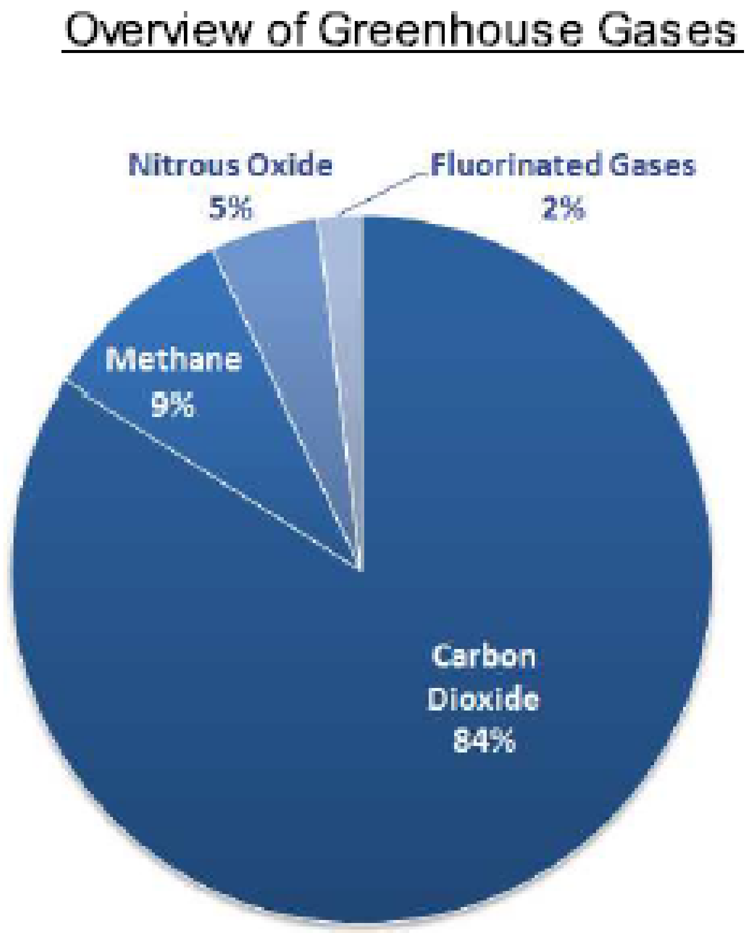
- Definition
  - Global warming potential (GWP) per unit weight over 100 years
  - CO_{2eq} for CO_2 = 1

- 2010 atmospheric concentration (parts per million)
  - CO_2: 389
  - CO_{2eq} of the "Kyoto Six": 444

Why it's better to flare natural gas (CH_4)

- More powerful than CO_2 but shorter residence time: CO_{2eq} = 26
- But also lighter: 12 + 4 x 1 = 16
- GWP of one carbon atom:
  - In CO_2: 1
  - In CH_4: 26 x 16/44 = 9.5

U.S. GHG Emissions 1990-2011



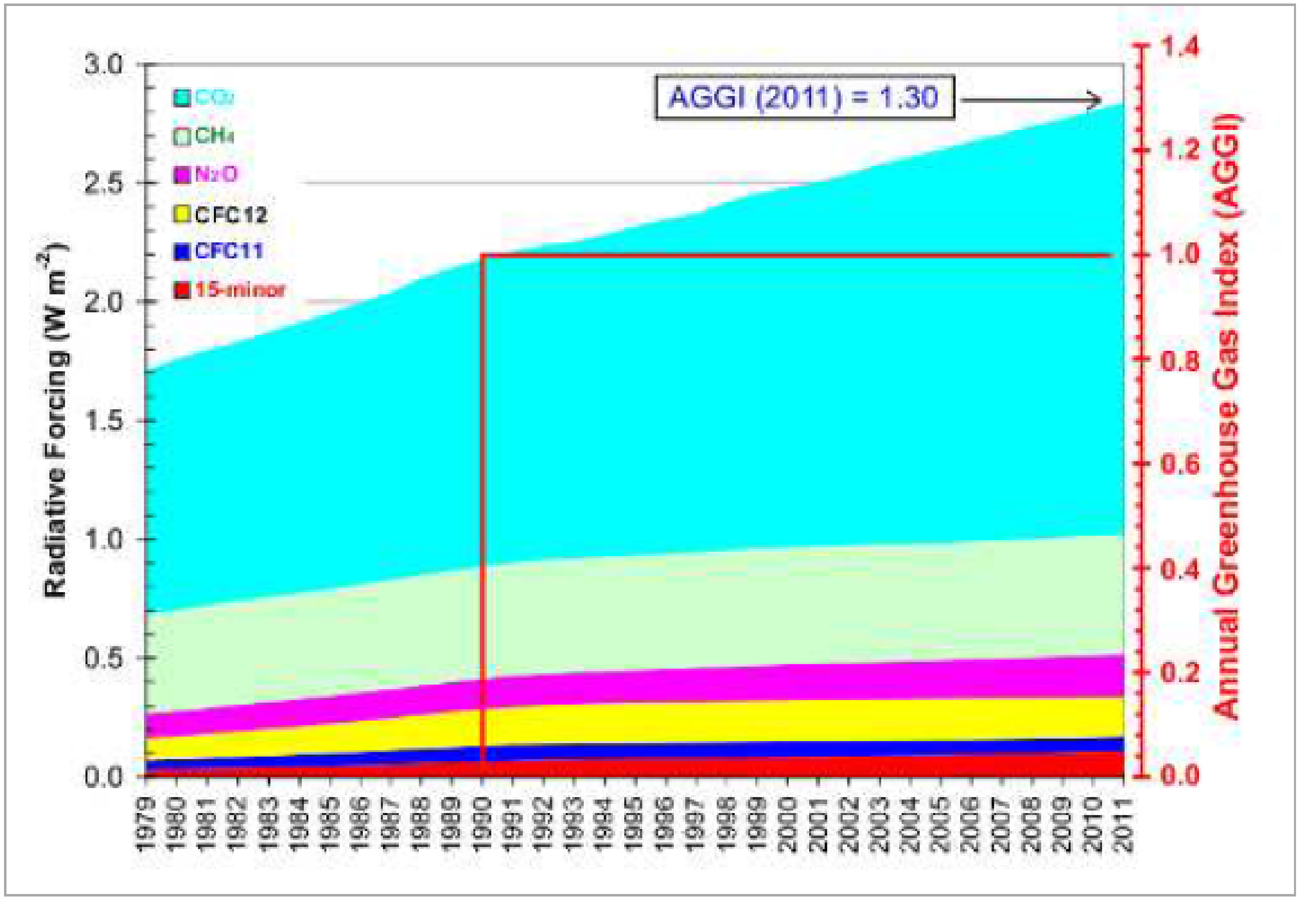


Figure 4. *Radiative forcing, relative to 1750, of all the long-lived greenhouse gases. The NOAA Annual Greenhouse Gas Index (AGGI), which is indexed to 1 for the year 1990, is shown on the right axis.*

Click on image to view full size figure.

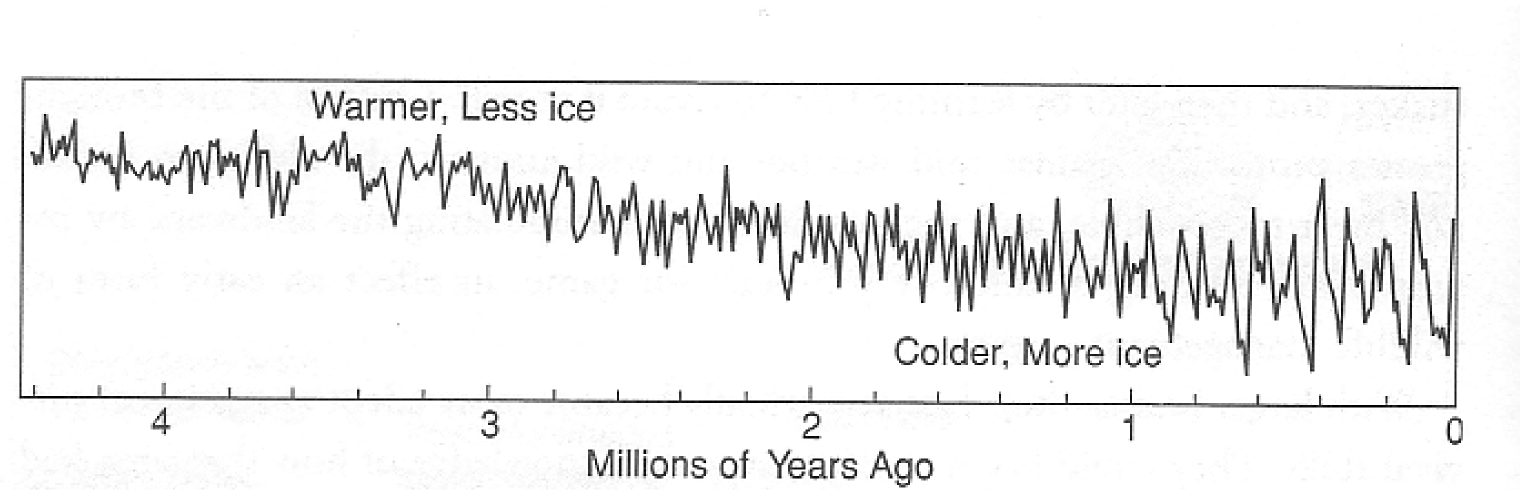
The Fourth Carbon Cycle

- http://www.youtube.com/user/CarbonTracker#p/a/u/2/H2mZyCblxS4

The Glacial Cycle: Cooling the Earth

- Declining atmospheric CO_2 from 50 MYA
  - Geologic burial > volcanic emissions
  - Arrhenius but change probably on burial side
- Temperature falls
  - By 10 MYA: permanent Antarctic ice sheet
  - From 2.75 MYA: alternating northern glaciation (most of the time) and interglacial periods (like now)

Temperature from 5 MYA



The Glacial Cycle: Earth's Orbit

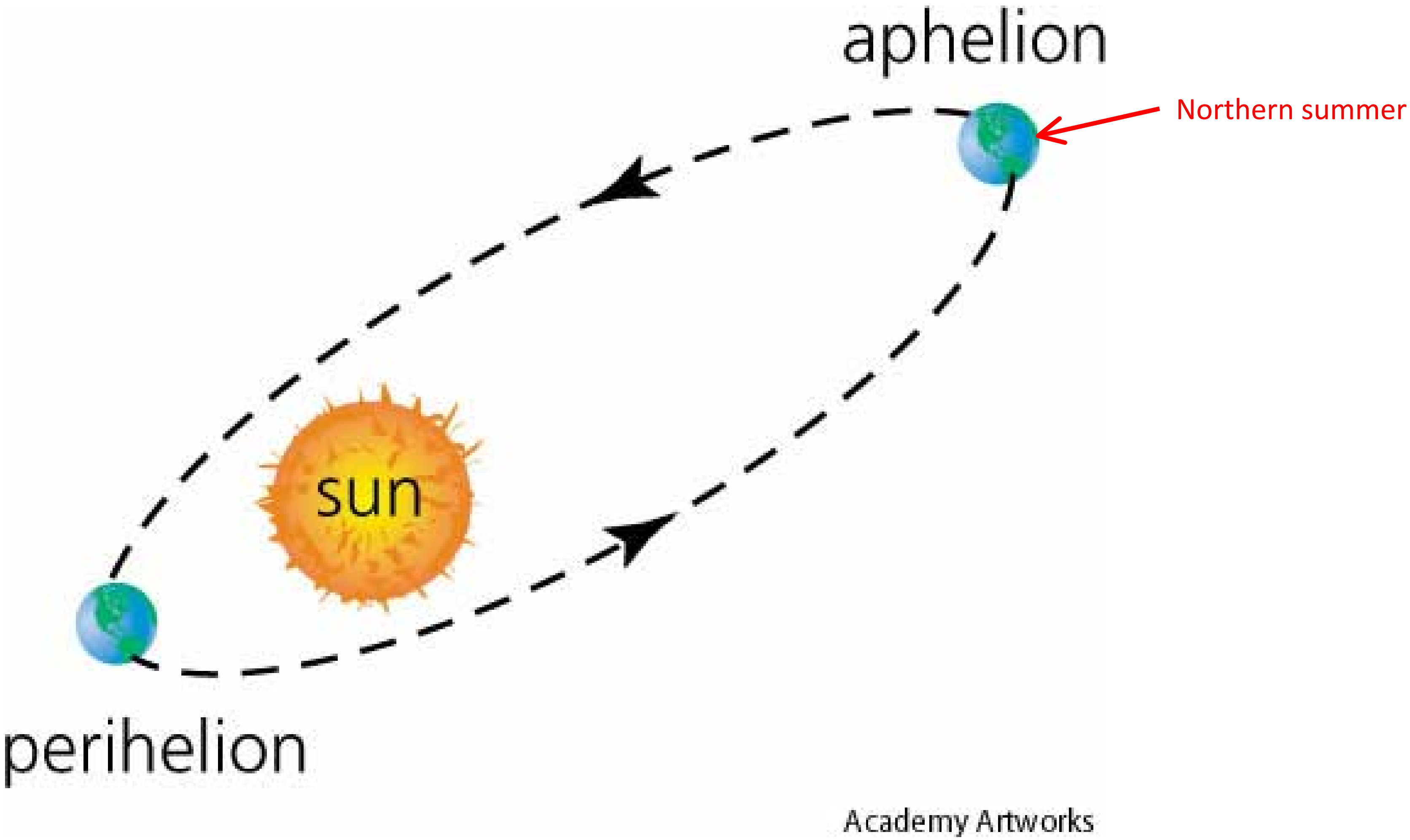
- Eccentricity: Cycle from more circular to less circular orbit – 100 thousand years
- Precession: Cyclical wobble changes relationship between season and distance from sun – 22 thousand years
- Obliquity: Cyclical rocking of Earth's angle to rotation plane – 41 thousand years

The Glacial Cycle: Cooler Northern Summers

- More elliptical orbit (eccentricity) and northern summer at aphelion (precession), or

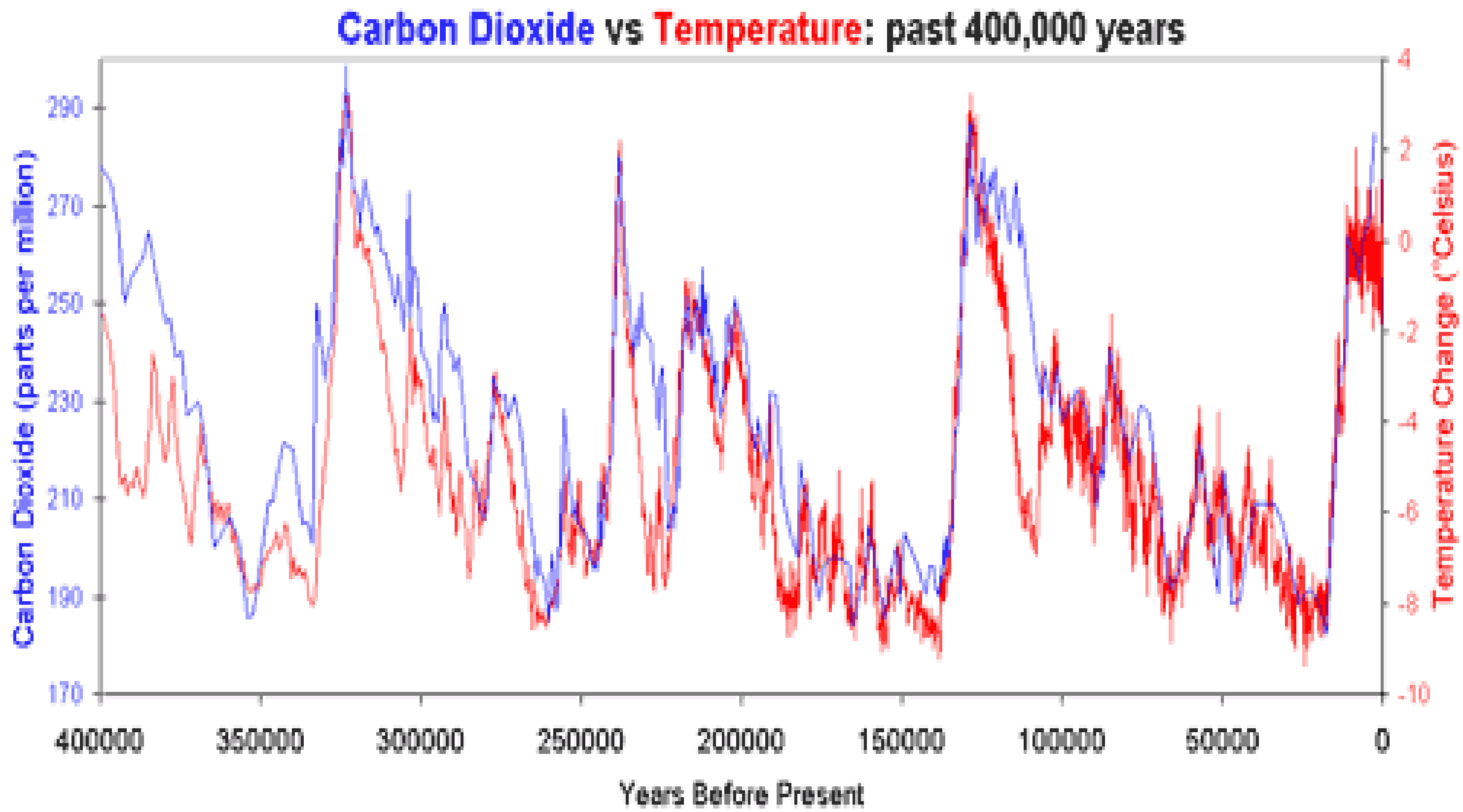
- Smaller tilt (obliquity), or

- Both

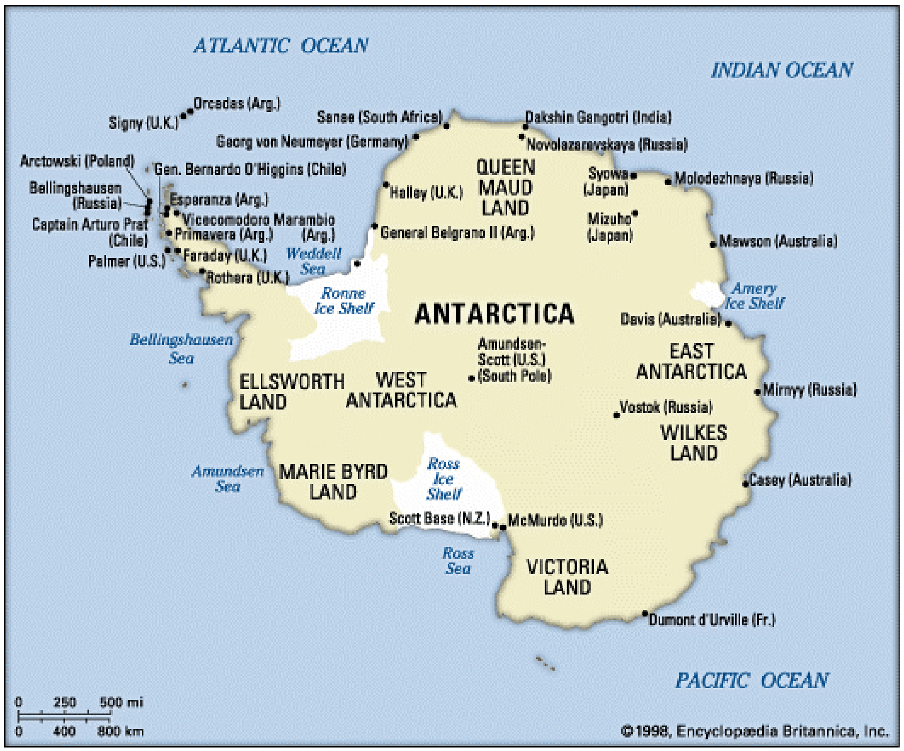

aphelion
Northern summer
sun
perihelion
Academy Artworks

The Glacial Cycle: Feedbacks

- Feedback 1
  - Cool summer → more snow remains → increased albedo → More cooling
  - Not enough
- Feedback 2: Transfer of CO_2 to deep ocean
  - Begins <u>after</u> temperature decline begins
  - Implication: a feedback


Carbon Dioxide vs Temperature: past 400,000 years
Carbon Dioxide (parts per million)
290
270
250
230
210
190
170
Temperature Change (°Celsius)
4
2
0
-2
-4
-6
-8
-10
400000
350000
300000
250000
200000
150000
100000
50000
0
Years Before Present

Glaciers Spread



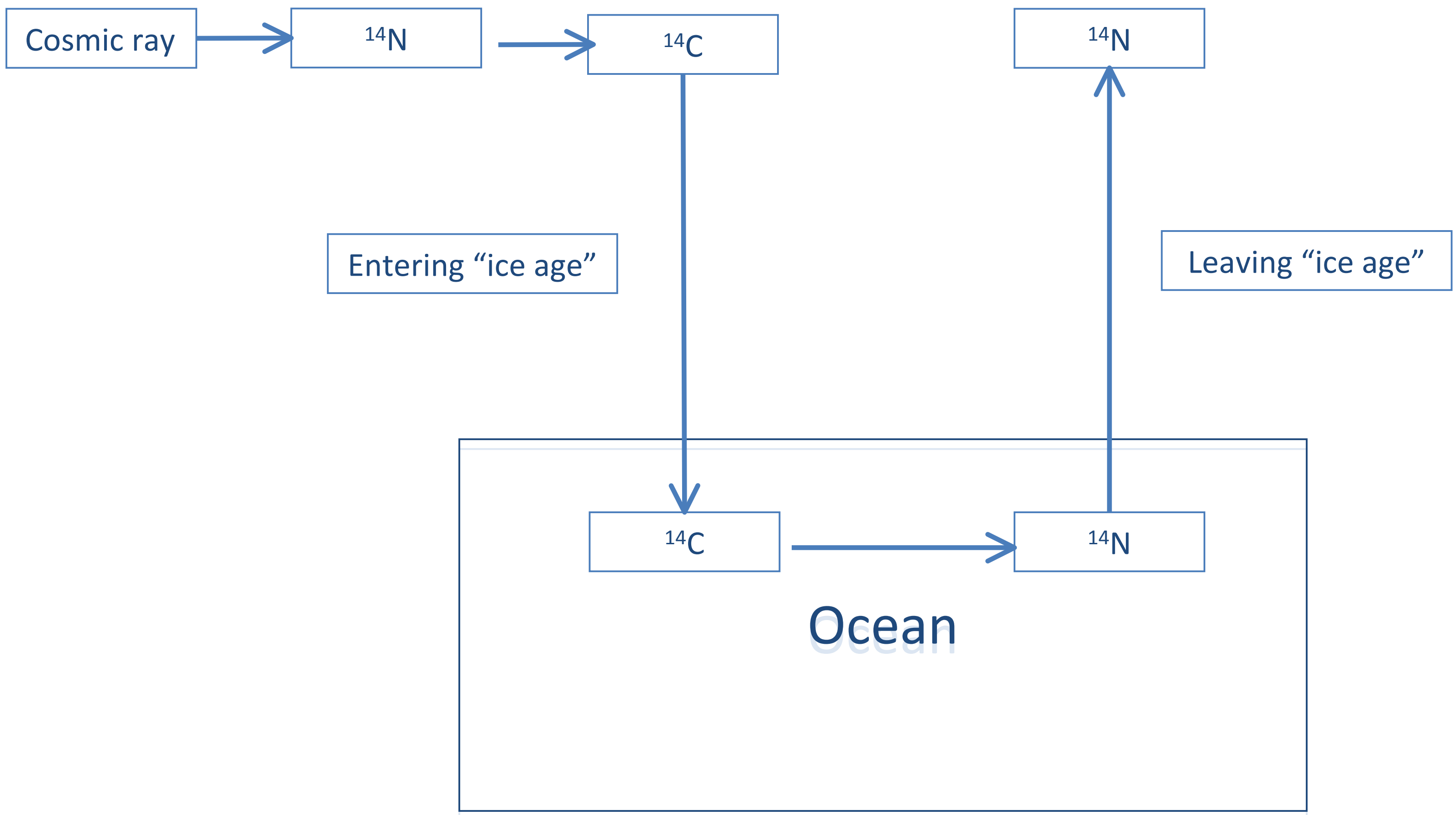
Glacier starting point

Concluding Points

- Video on temperature-carbon relationship in glaciation/deglaciation: http://www.youtube.com/watch?v=8nrvrkVBt24
- Questions
  – Why the change from 41,000 years (obliquity) to weaker 100,000 years (precession)?
  – Details of CO_2 feedback mechanism
  – So why believe?
    - Implications of science
    - Carbon isotopes

^{14}Carbon and Its Implications

- ^{12}Carbon: Six protons and six neutrons
  - 99% of carbon
- ^{14}Nitrogen: seven protons and seven neutrons
  - Cosmic rays constantly transform into ^{14}Carbon: six protons and 8 neutrons
  - Decays back to ^{12}C – half-life of 5730 years
- Depleted ^{14}C: isolated from cosmic rays


Cosmic ray
14N
14C
14N
Entering "ice age"
Leaving "ice age"
14C
14N
Ocean

MEASURING TEMPERATURE

Temperature and CO_2

- Atmospheric concentration of CO_2 is rising
- Science: Should produce rising temperature
- Is it?

Measuring Temperature Compared with CO_2 Problems I: Since Mid-Late 19th Century

- Longer instrument record, but--

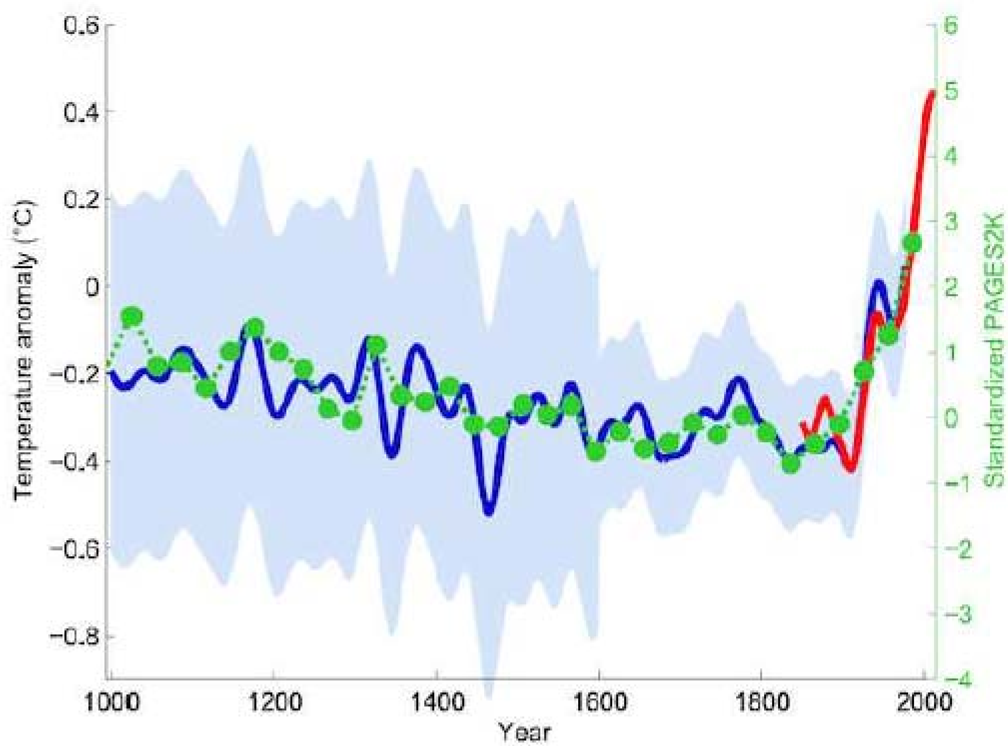
- Reliability of individual readings – examples
  - Development of heat islands
  - U.S. vs. British maritime measurements

- Temperature unevenly distributed: No Manu Loa

Measuring Temperature Compared with CO_2 Problems II: Before Mid-19th Century

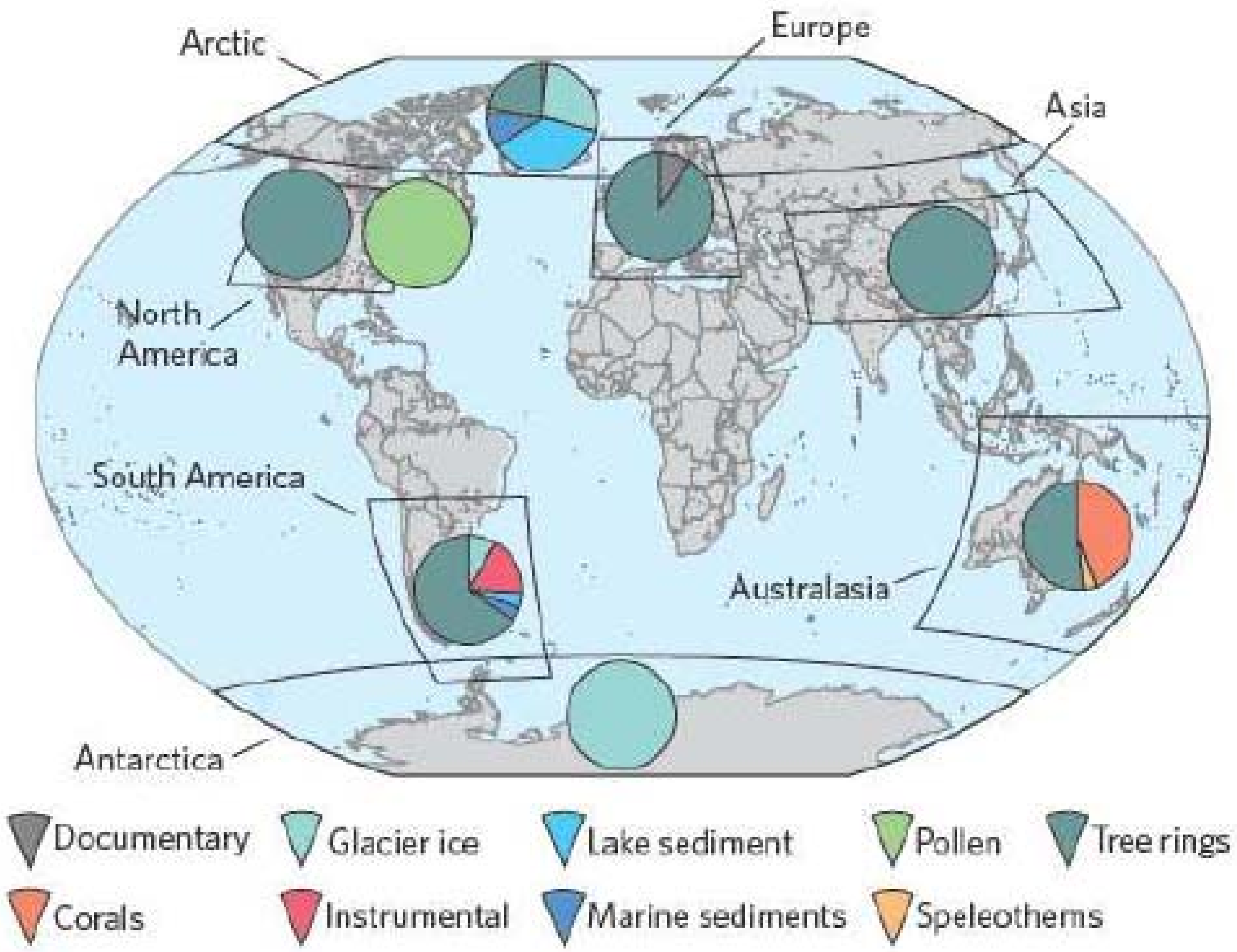
- No pre-instrument direct measurement
- Temperature not retained: no ice cores
- Reliance on proxies
- Manu Loa problem again
  - Global Medieval Warm Period?
  - Global Little Ice Age?

An Updated Hockey Stick

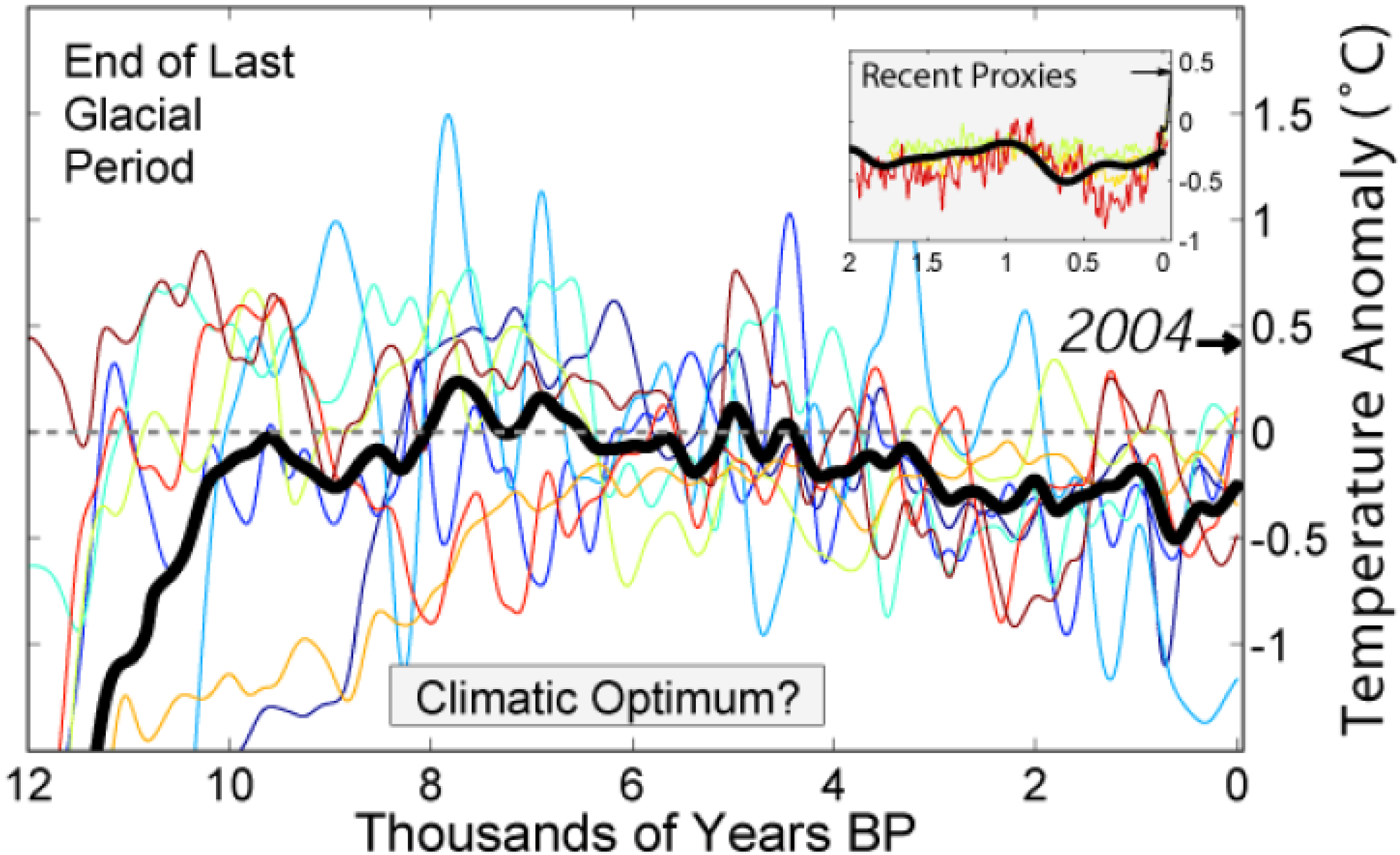


Green dots show the 30-year average of the new PAGES 2k reconstruction. The red curve shows the global mean temperature, according HadCRUT4 data from 1850 onwards. In blue is the original hockey stick of Mann, Bradley and Hughes (1999) with its uncertainty range (light blue). Graph by Klaus Bitterman.

Data Sources

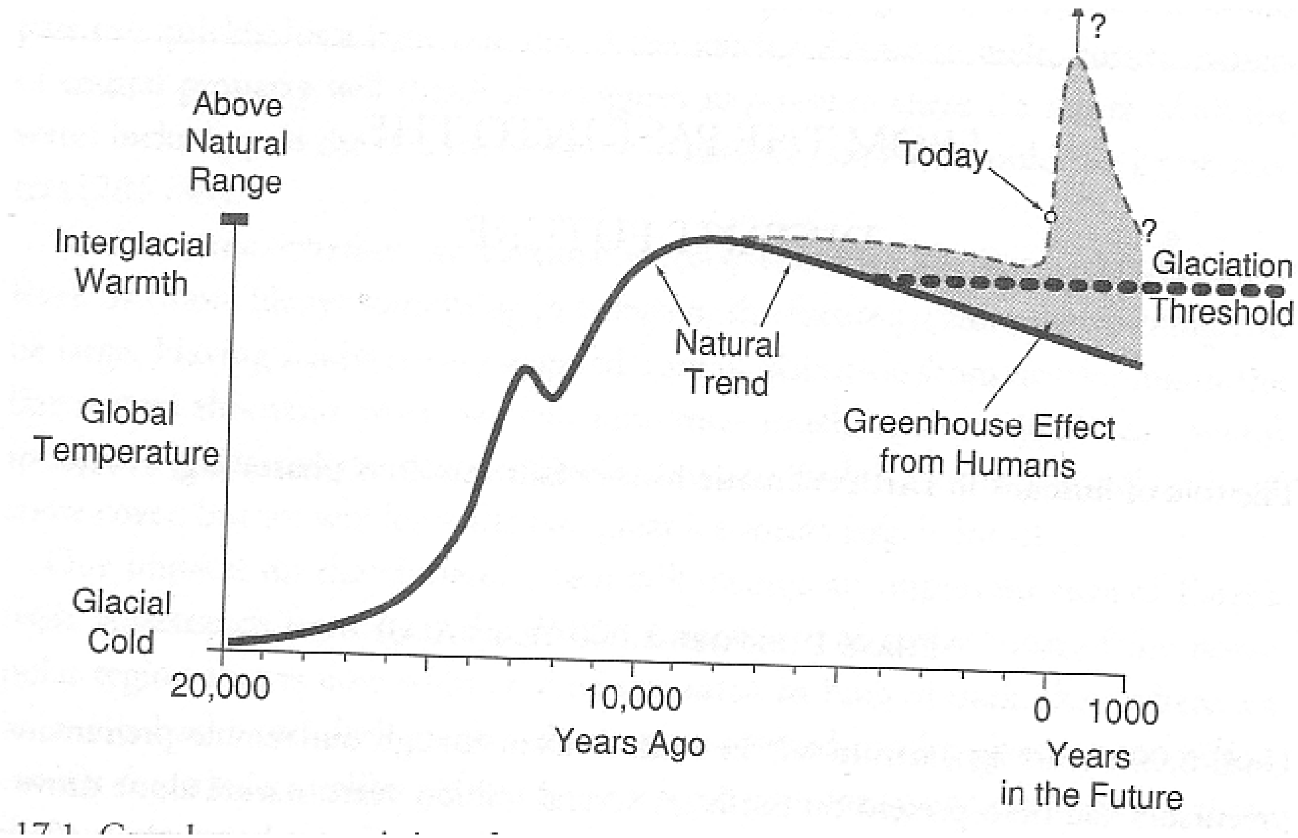


Holocene Temperature Variations



Note: Due to smoothing, graph cannot resolve changes for periods shorter than 300 years.

The Future With and Without Anthropogenic Warming

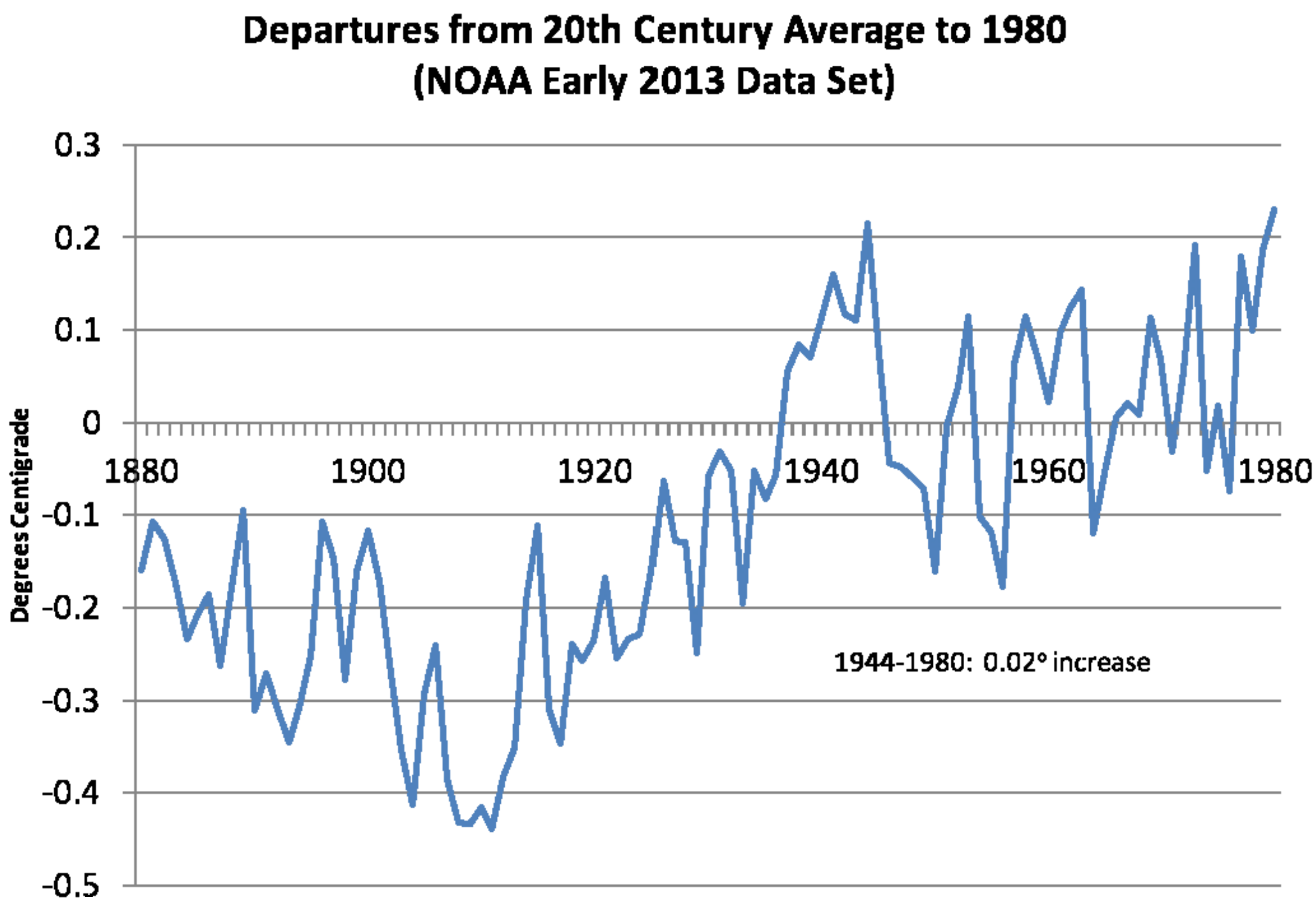


1960s-1980s: Three Linked Elements

- Increased scientific understanding
- Understanding + computer power: Improved (but still inadequate) computer models
  - One product: Explanation for lack of temperature increase 1930-1970
- Temperature observations

1988-1992: Moves to Policy Agenda

- Domestic 1988: James Hansen testimony
  - "[G]lobal 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 UNFCC
  - 1992: United Nations Framework Convention on Climate Change (UNFCCC)
    - U.S. ratification: October 15, 2002


Departures from 20th Century Average to 1980
(NOAA Early 2013 Data Set)
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
1944-1980: 0.02° increase

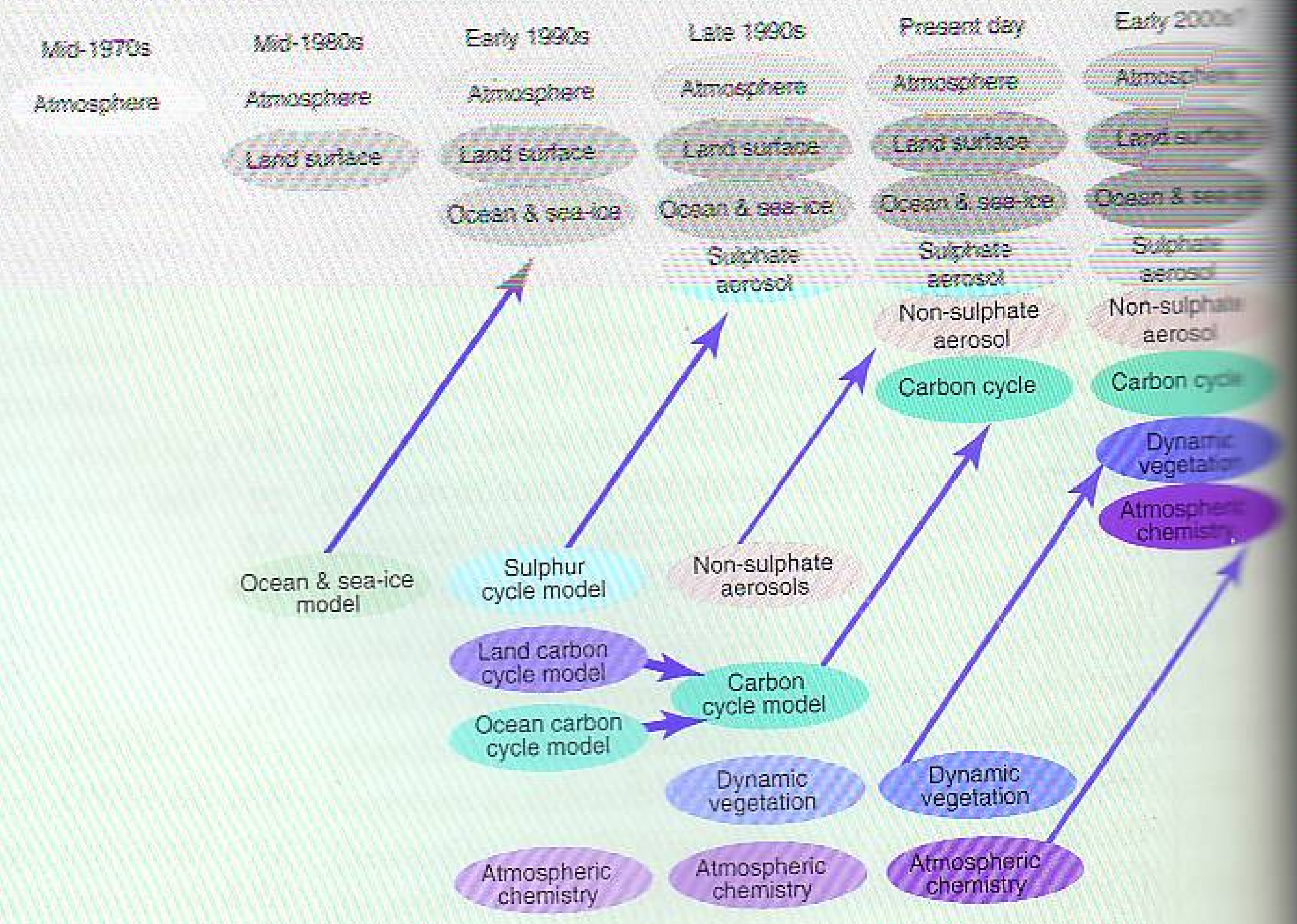
What's Happening?

- Science is wrong
- Science is correct but by 1940 atmosphere was saturated with CO_2
- CO_2 radiative forcing is offset by changes in albedo and/or solar insolation

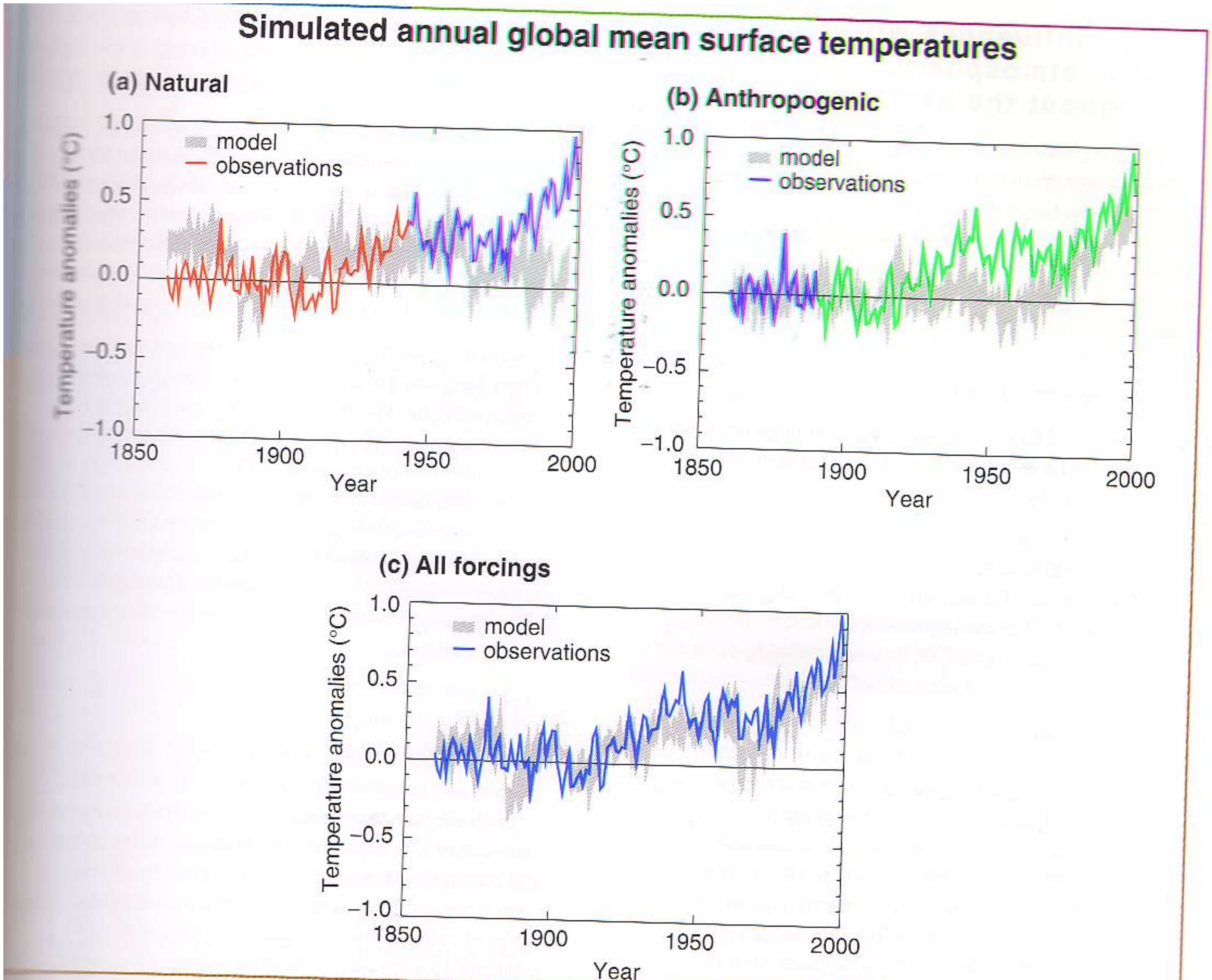
Offsets?

- Need "experiment": Compare observed temperature with effect of combinations of CO_2, insolation, and volcanoes/ pollution
- Problem:
  - Can't conduct physical experiment
  - No adequate computer models in 1980

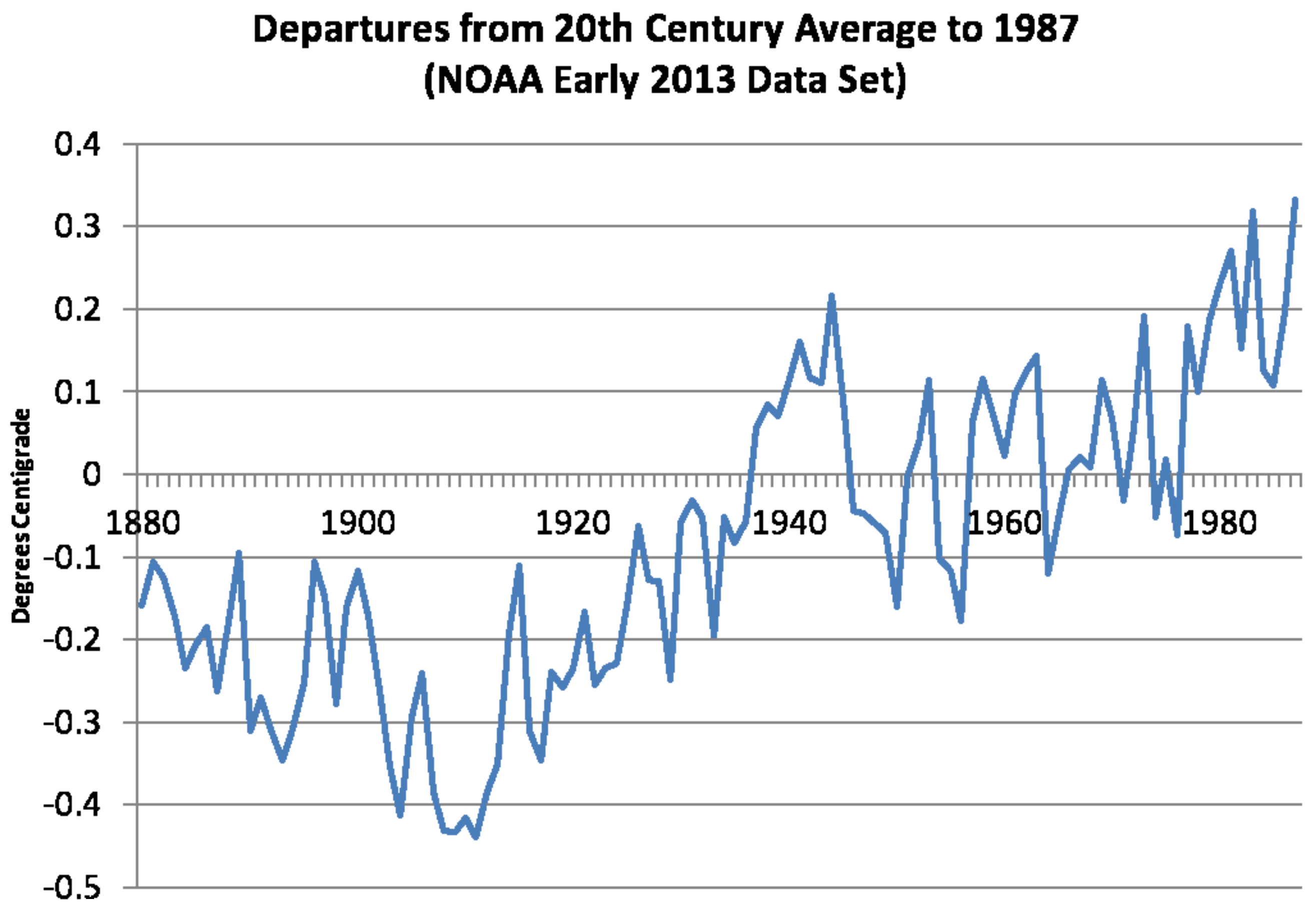
The Development of Climate models, Past, Present and Futu



Box 3, Figure 1: The development of climate models over the last 25 years showing how the different components are first developed separately and later coupled into comprehensive



gure 4: Simulating the Earth's temperature variations, and comparing the results to measured changes, can provide insight into the derlying causes of the major changes.

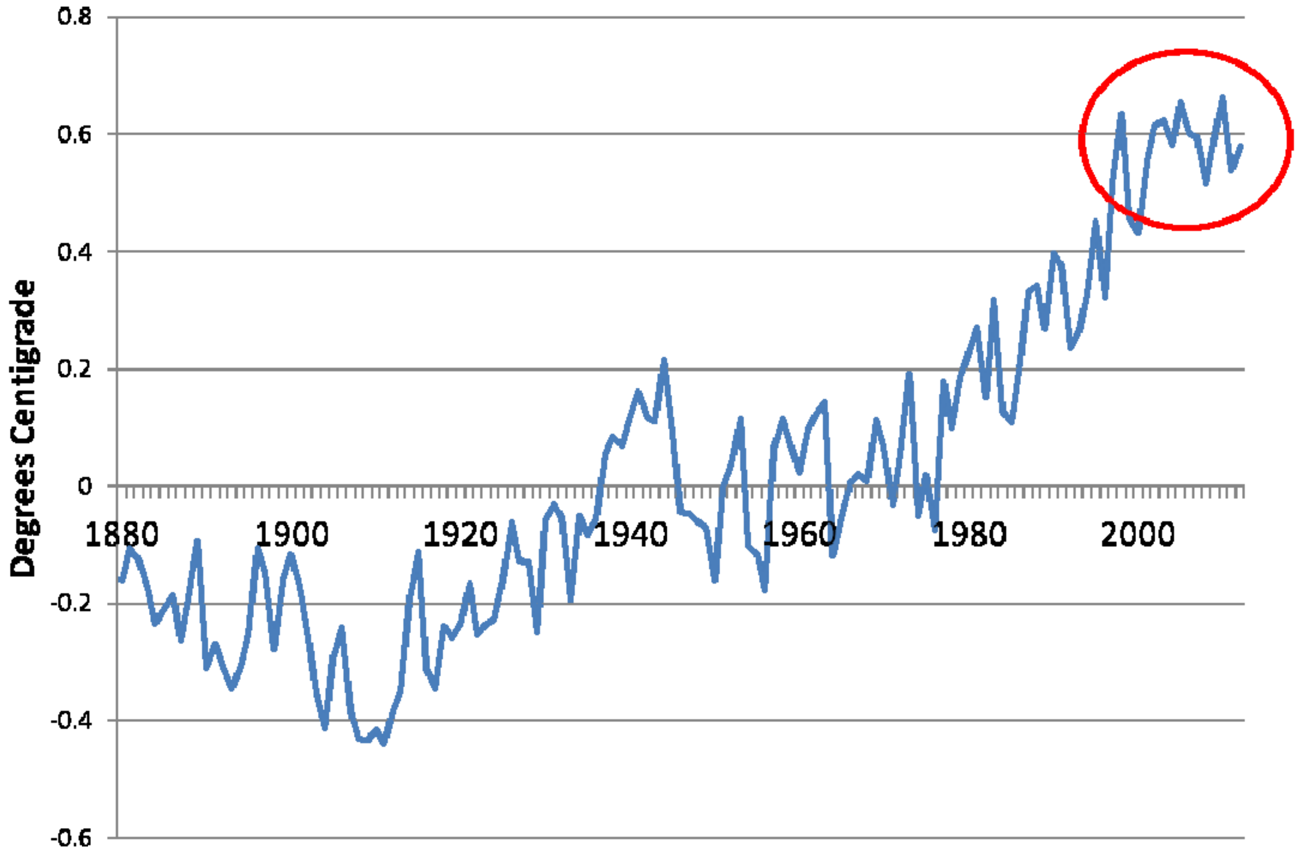

Departures from 20th Century Average to 1987
(NOAA Early 2013 Data Set)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Degrees Centigrade
1880
1900
1920
1940
1960
1980

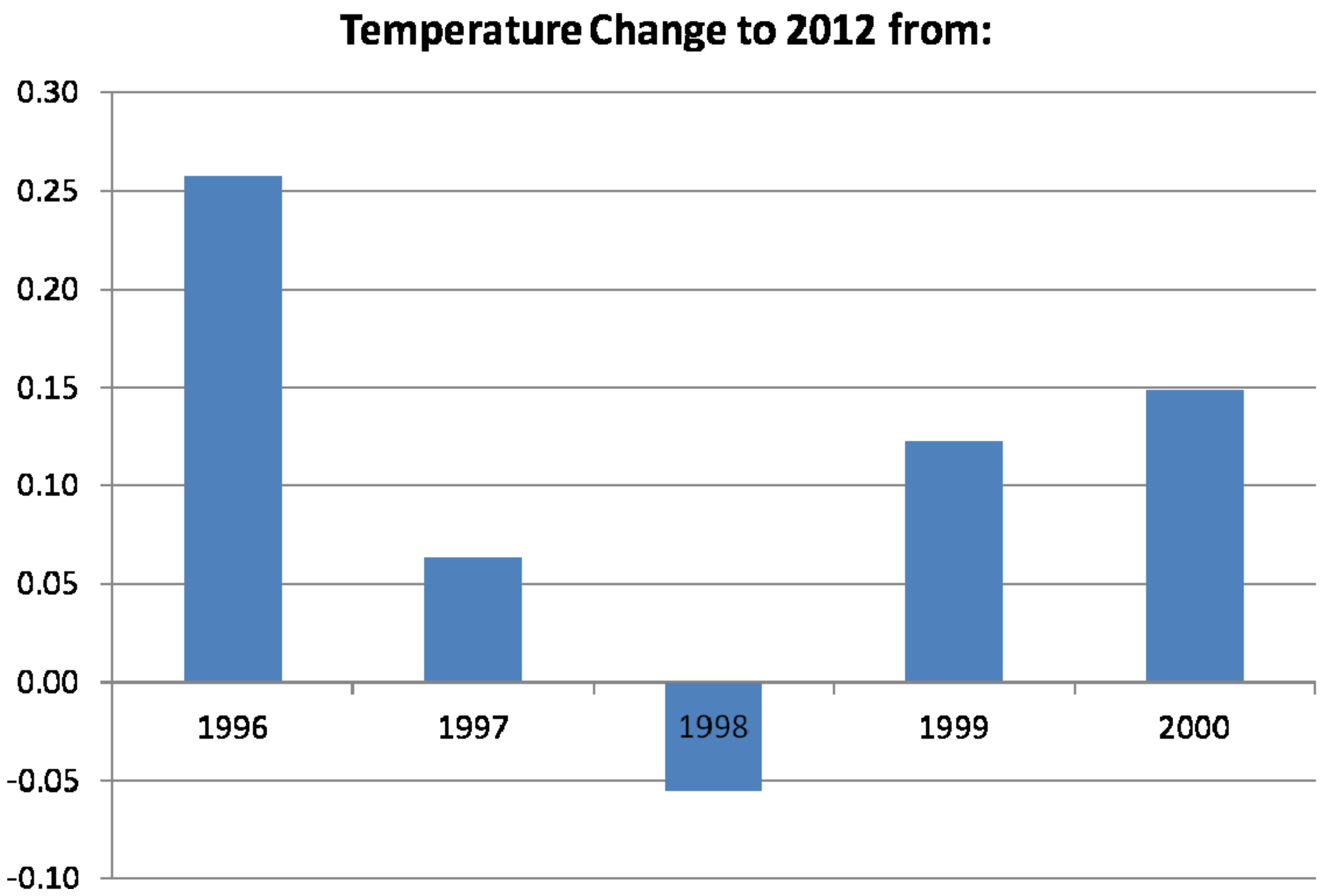
1988-1992:
Climate Change Moves to Policy Agenda

- Domestic 1988: James Hansen testimony
  - "[G]lobal warming is now large enough that we can ascribe, with a high degree of confidence, a cause-and-effect relationship to the greenhouse effect."

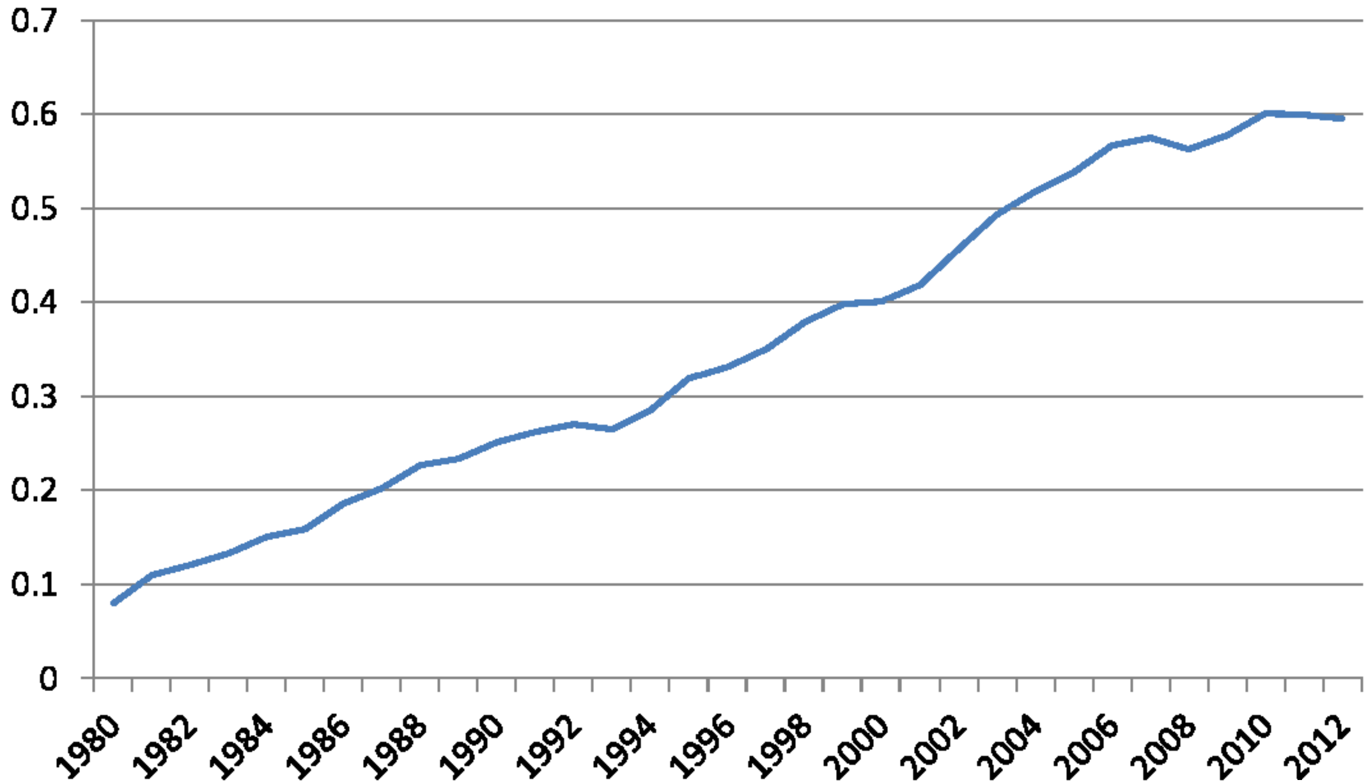
- International
  - 1991: First assessment report from UNFCC
  - 1992: United Nations Framework Convention on Climate Change (UNFCCC)
    - U.S. ratification: October 15, 2002

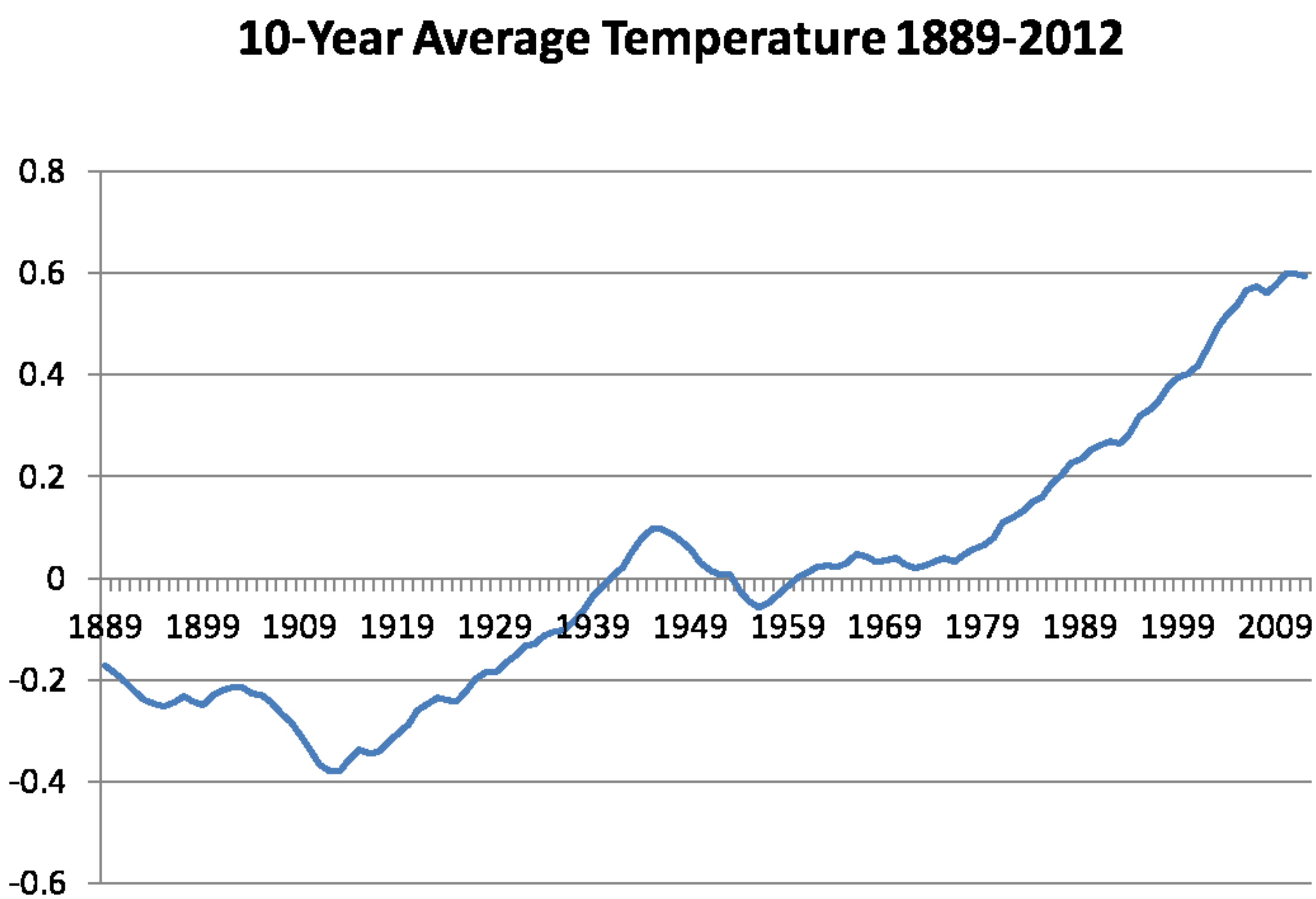
Departures from 20th Century Average to 2012
(NOAA Early 2013 Data Set)




Temperature Change to 2012 from:
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
1996
1997
1998
1999
2000

10-Year Average Temperature Increase 1980-2012




10-Year Average Temperature 1889-2012
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1889 1899 1909 1919 1929 1939 1949 1959 1969 1979 1989 1999 2009

We’ve Been Here Before – But Why This Time? Three Possibilities Plus a Fourth

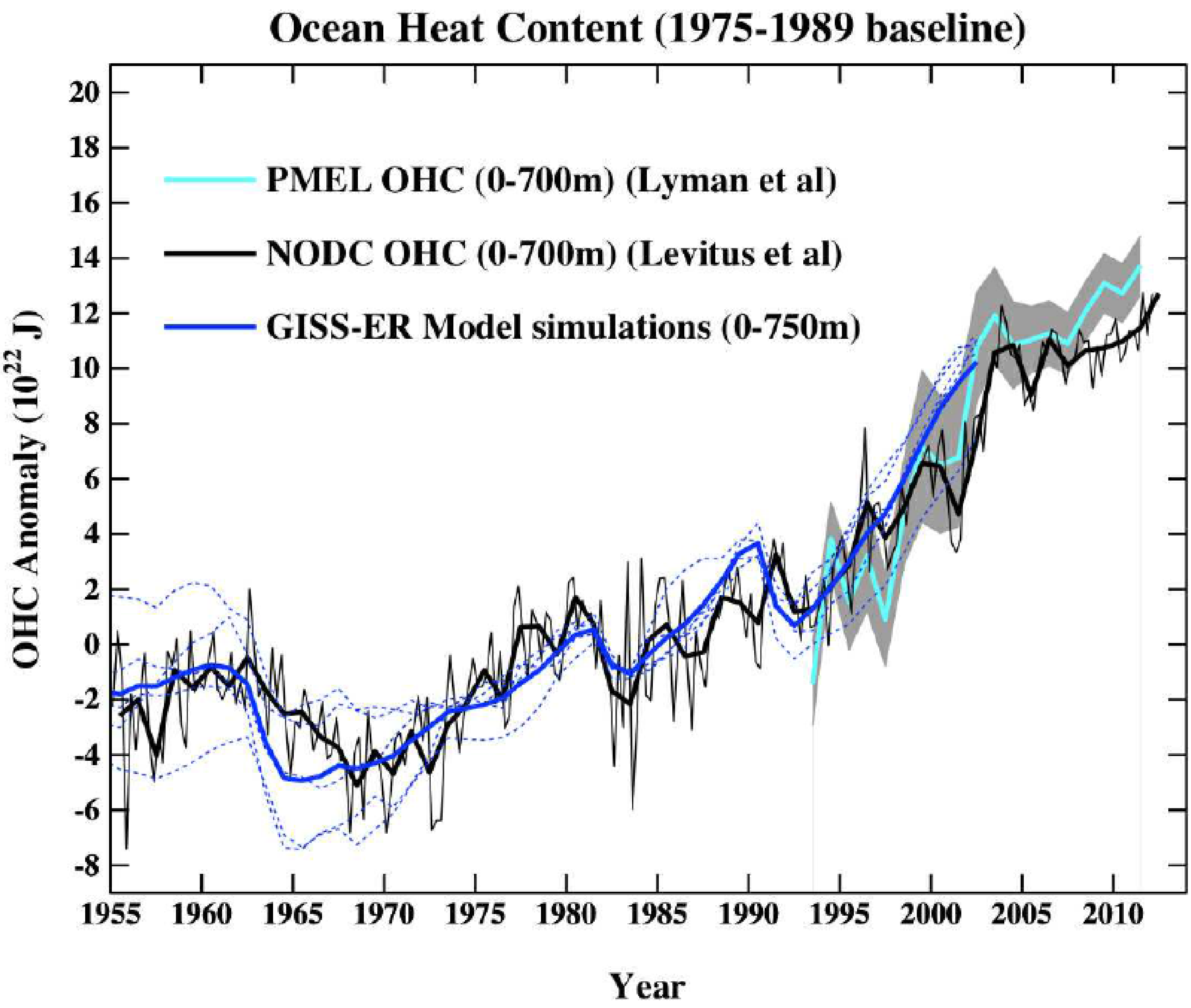
- Science is wrong
- Atmosphere is saturated with greenhouse gases
- GHG radiative forcing is being offset by increased albedo or reduced insolation
- Change distribution of thermal energy within Earth system

Distribution of Earth's Thermal Energy

- Vertical: surface and upper atmosphere
  – Measurement issue but little effect

- Horizontal: distribution over surface
  – The no-Manu Loa problem

- Vertical: surface and deep ocean


Ocean Heat Content (1975-1989 baseline)
PMEL OHC (0-700m) (Lyman et al)
NODC OHC (0-700m) (Levitus et al)
GISS-ER Model simulations (0-750m)
OHC Anomaly (10^{22} J)
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6
-8
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

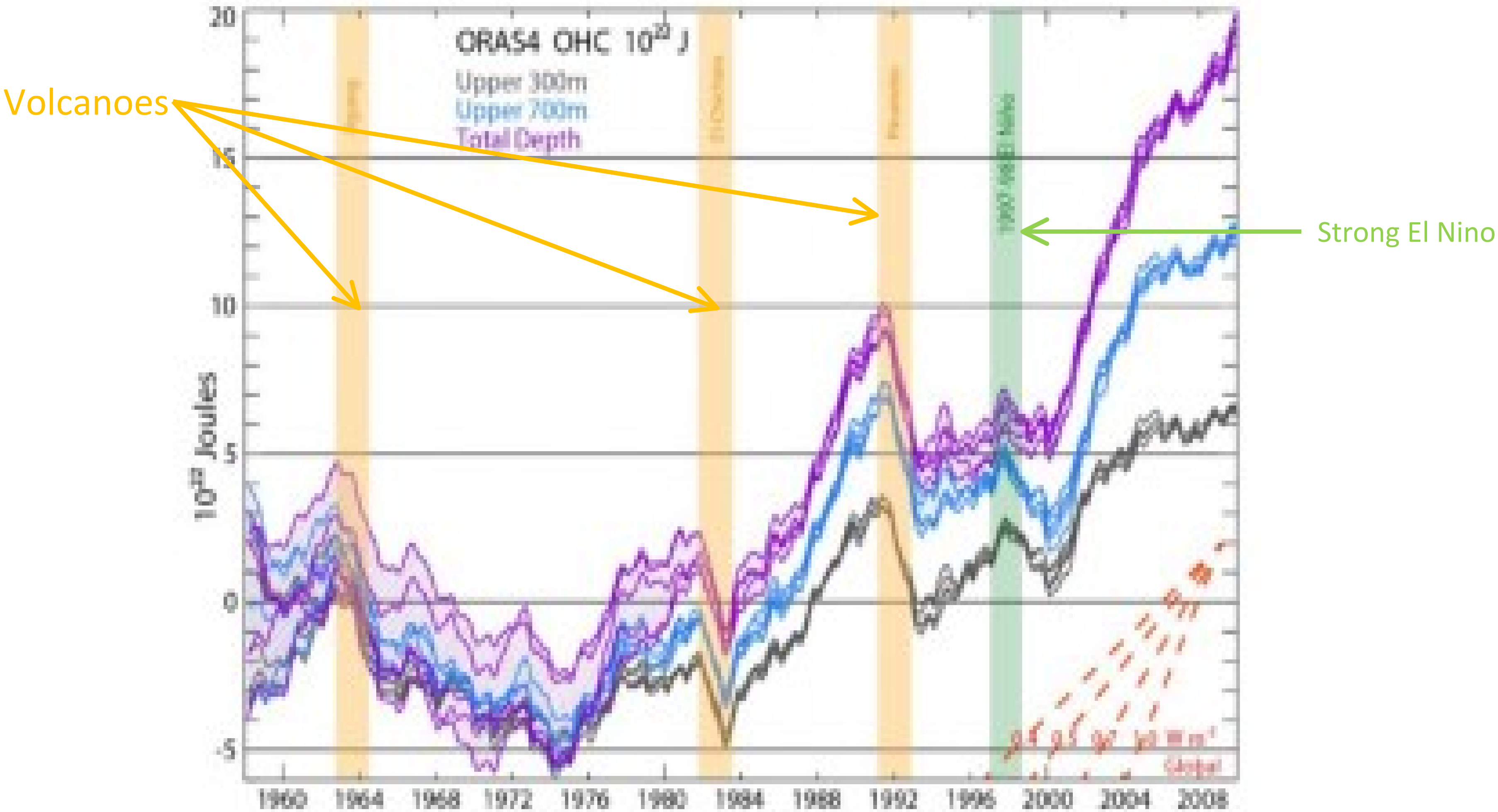
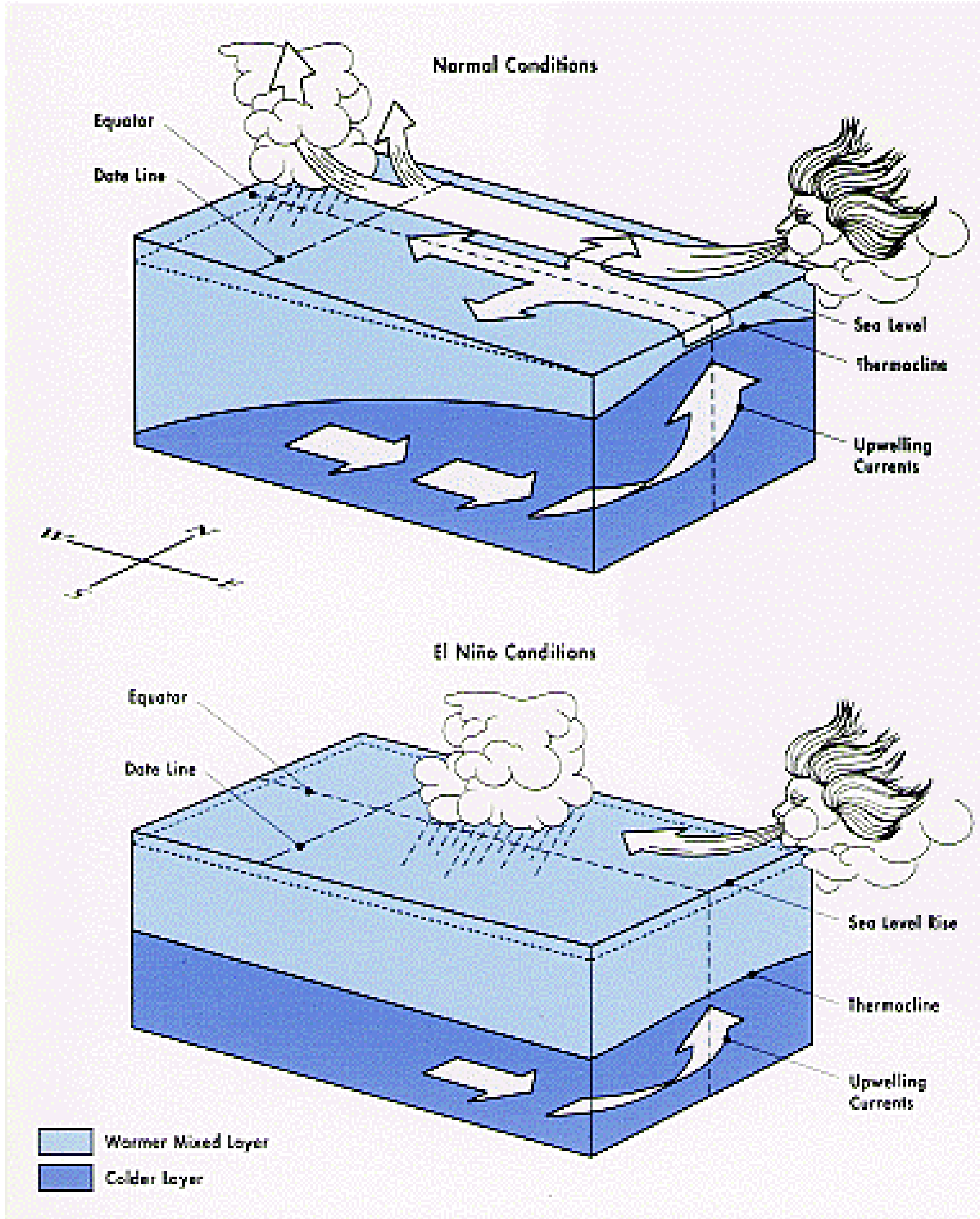


Figure 1: Ocean Heat Content from 0 to 300 meters (grey), 700 m (blue), and total depth (violet) from ORAS4, as represented by its 5 ensemble members.

Role of the Oceans

- Absorbs about a quarter of CO_2 emissions
- 90% of warming goes to heating the oceans
- El Niño-La Niña change rate of warming by redistributing heat between ocean and atmosphere


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

“Missing” Heat and Its Implications

- Since 2004 <u>measured</u> warming less than implied by <u>measured</u> radiative forcing
- New studies: increased warming in deep ocean
- Issues
  - Accounts for much but not all “missing heat”
  - Which future
    - Additional heat comes back into the atmosphere
    - Reversion to former apportionment of incremental thermal energy
    - Continued larger apportionment to deep ocean