Class 2
Measuring CO_2 and Temperature

OLLI

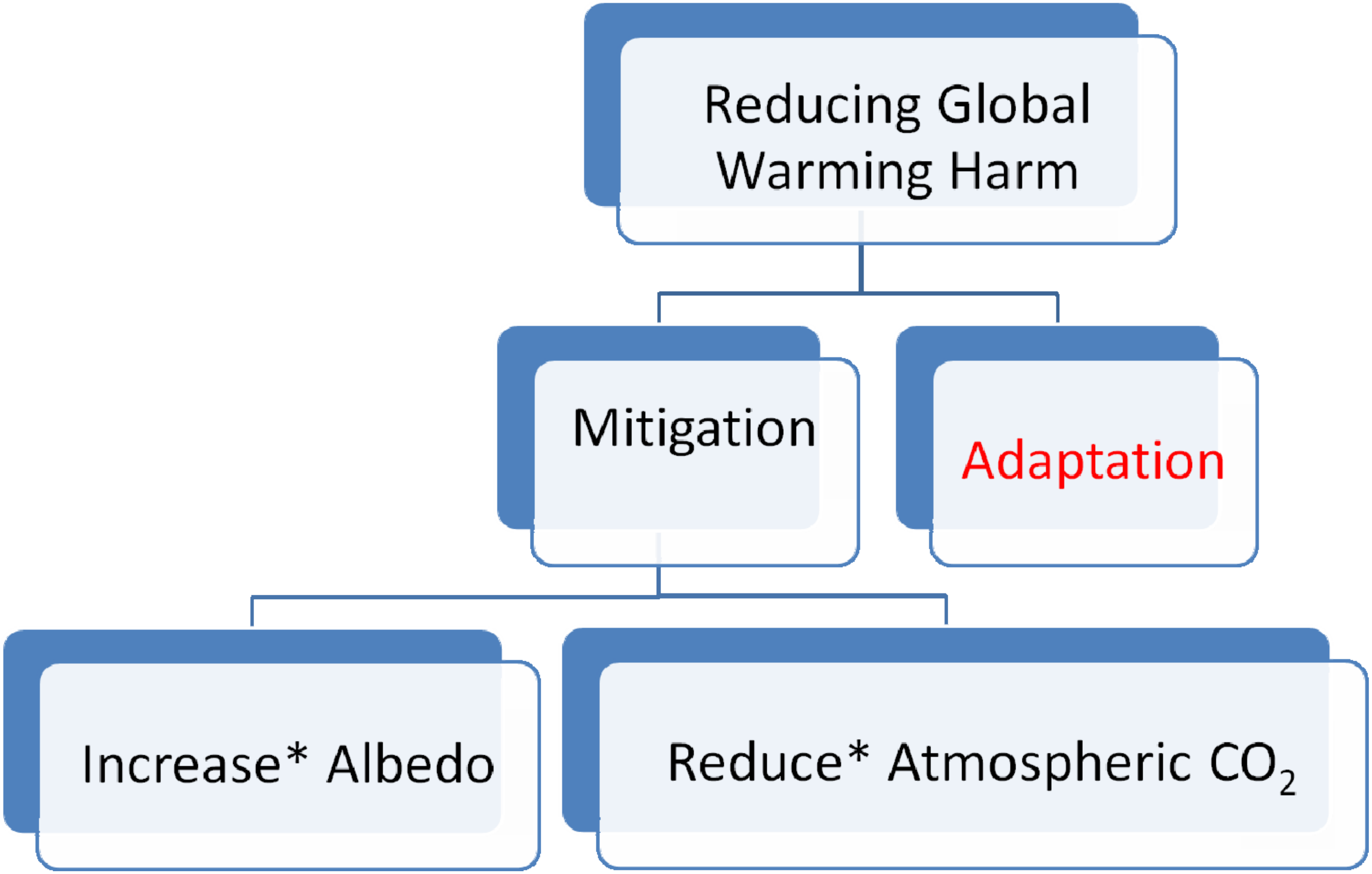
L809 Climate Change

January-February 2014

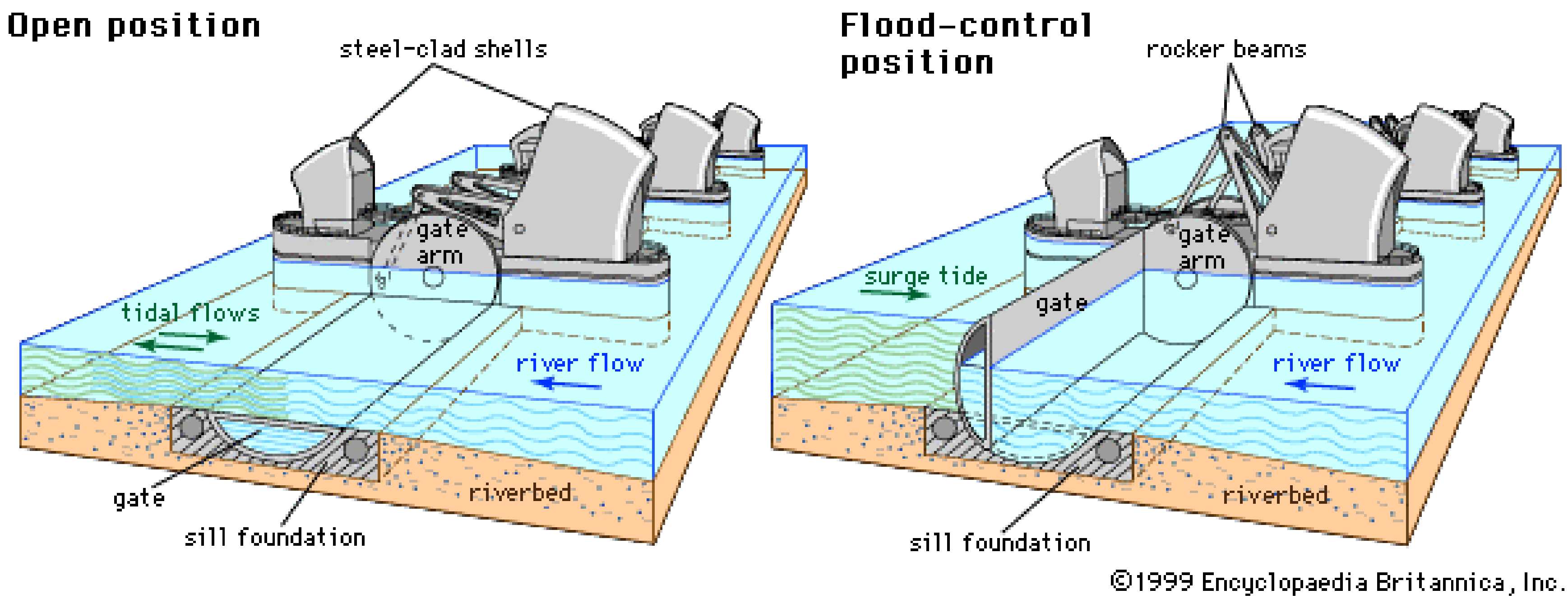
Carry-Over Issues

- Responding to climate change
- Oceans' absorption of CO_2
- Potential future temperature increase

RESPONDING TO CLIMATE CHANGE: AN OVERVIEW OF THE FRAMEWORK


Reducing Global Warming Harm
Mitigation
Adaptation
Increase* Albedo
Reduce* Atmospheric CO_2

Adaptation: The Thames Barrier


Open position
steel-clad shells
gate
arm
tidal flows
river flow
gate
sill foundation
riverbed
Flood-control position
rocker beams
gate
arm
surge tide
gate
river flow
sill foundation
riverbed
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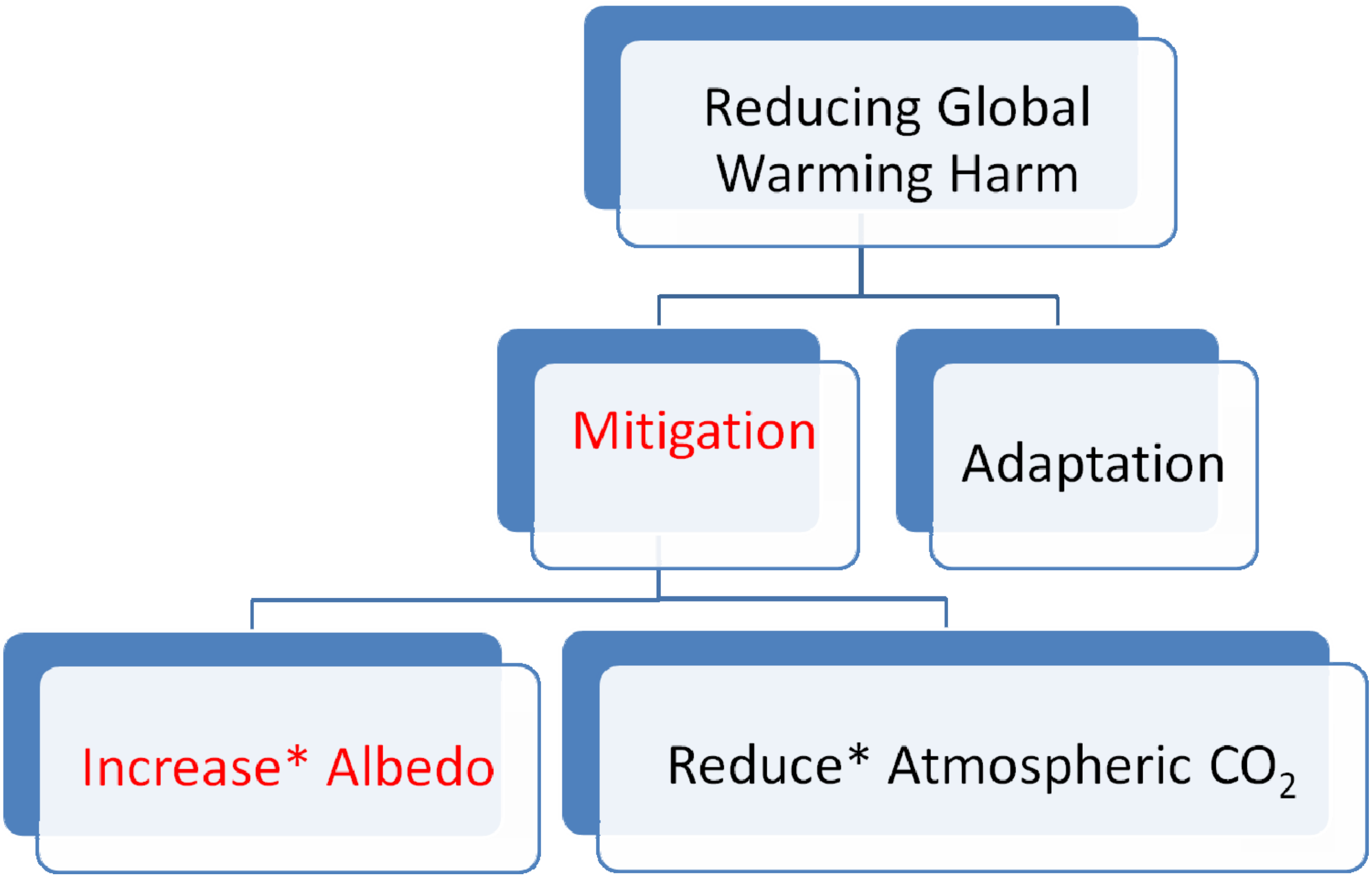
Characteristics of Adaptation And Their Implications

- Limited geographical and functional impact
  - Match between who pays and who benefits
  - Whom/what will we protect?

- Time: Most implementable in a few years

- Money: Comparison with mitigation



* “Increase/reduce:” from current level or projected business-as-usual (BAU) level

Radiation Management

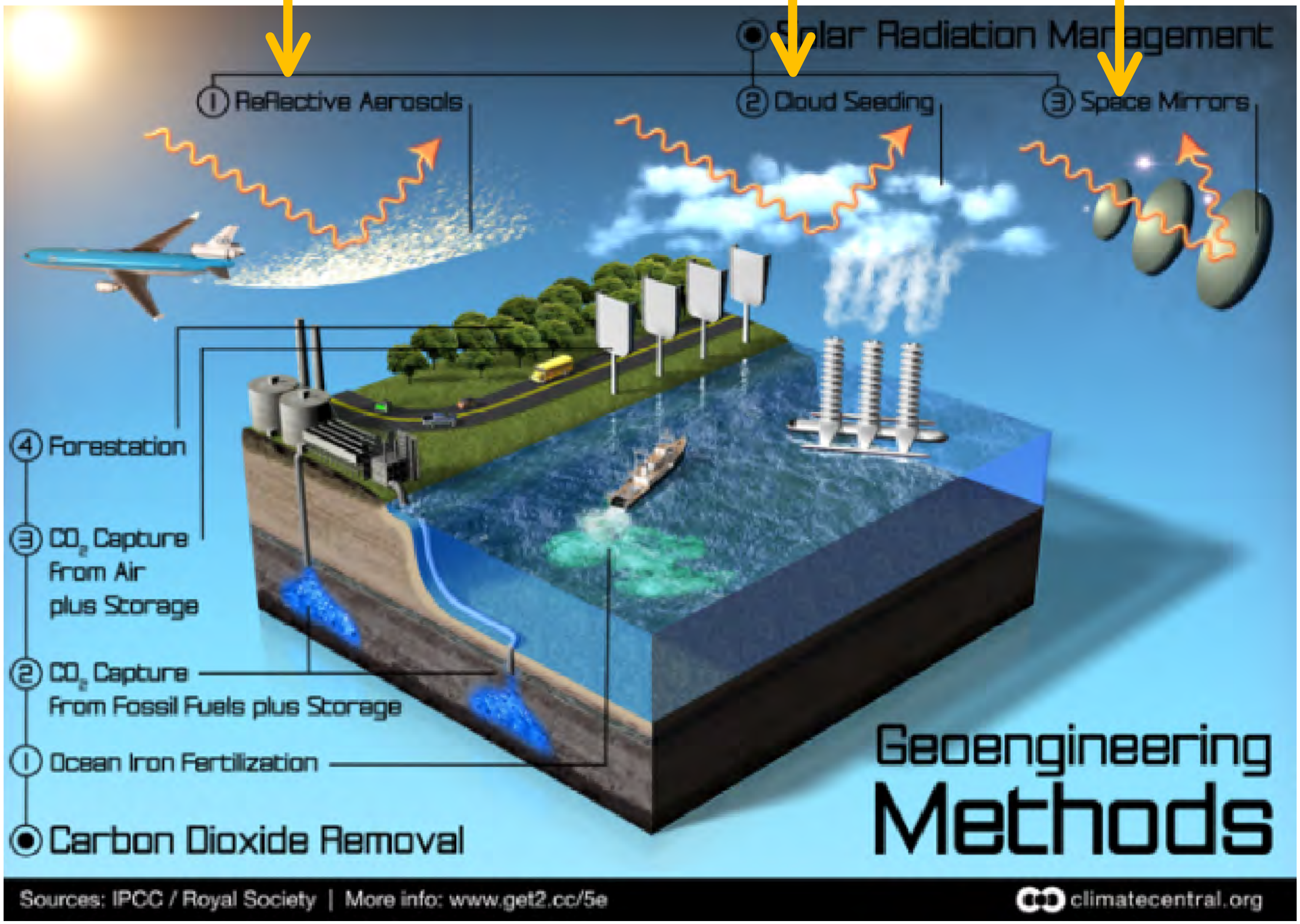
- Goal: Increased albedo –> less thermal radiation → lower equilibrium temperature
- Scale: white roofs to global reflectivity (sub-set of geoengineering)
- Terraforming*: geoengineering on steroids

* See Kim Stanley Robinson's Mars trilogy.

Low Cost – Big Impact

Low Cost – modest Impact

Enormous Cost – Big Impact (if it works)



Radiation Managrment

Doing it with aerosols

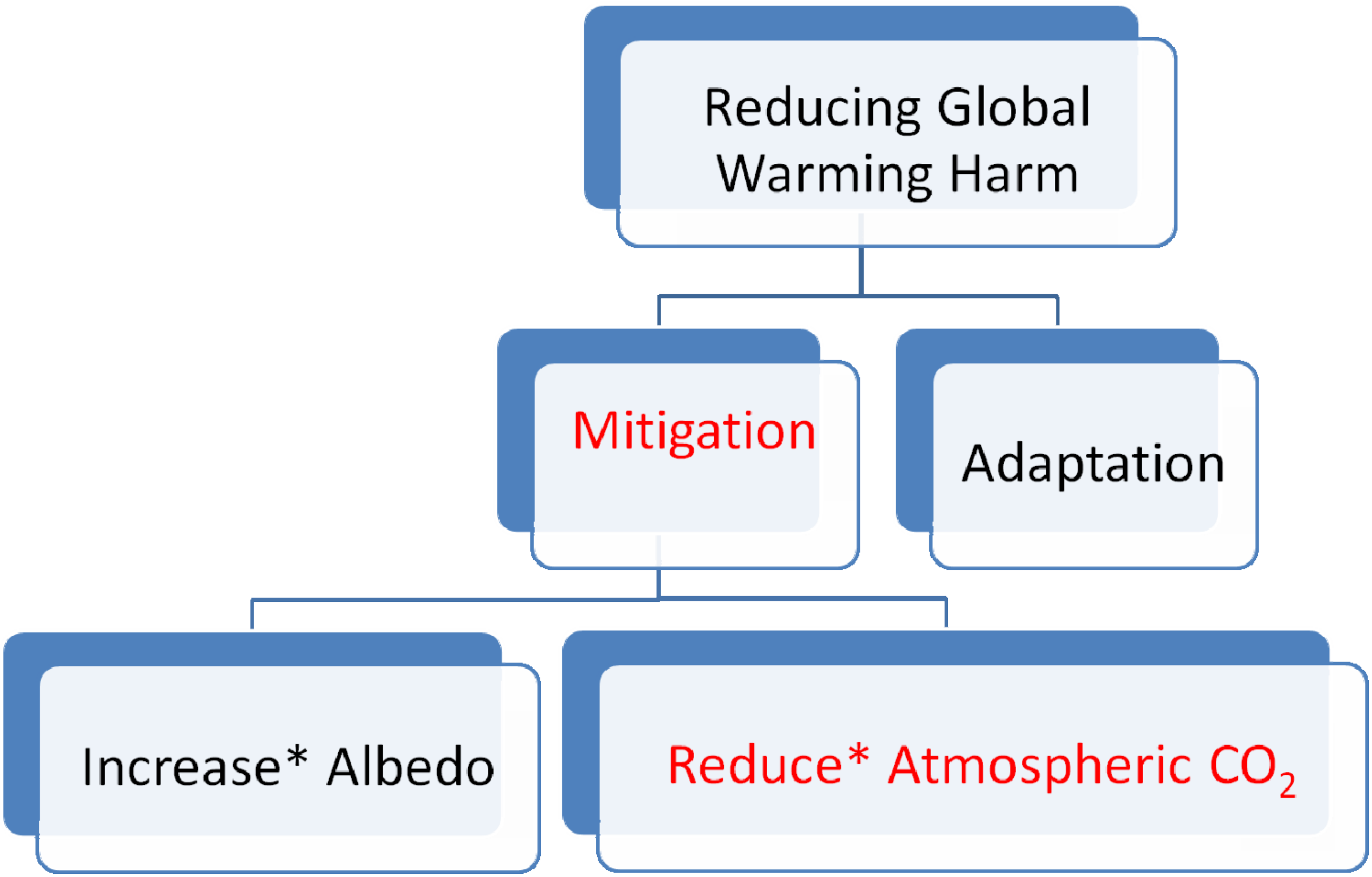
- Fast-acting
  - Reduces surface temperature within months
  - Quickly stopped: short atmospheric residence time
- Effect well-established for one-two years: volcanoes
- Relatively low cost and low-tech: Lear jets

But . . .

- Effect of sustained use is unknown – begin small-scale experiments?
- Achieves lower average temperature, but
  - Different temperature and rainfall distribution
  - Different radiation spectrum
  - Doesn’t reduce ocean acidification
- Growing temperature overhang
- May undermine efforts to reduce emissions

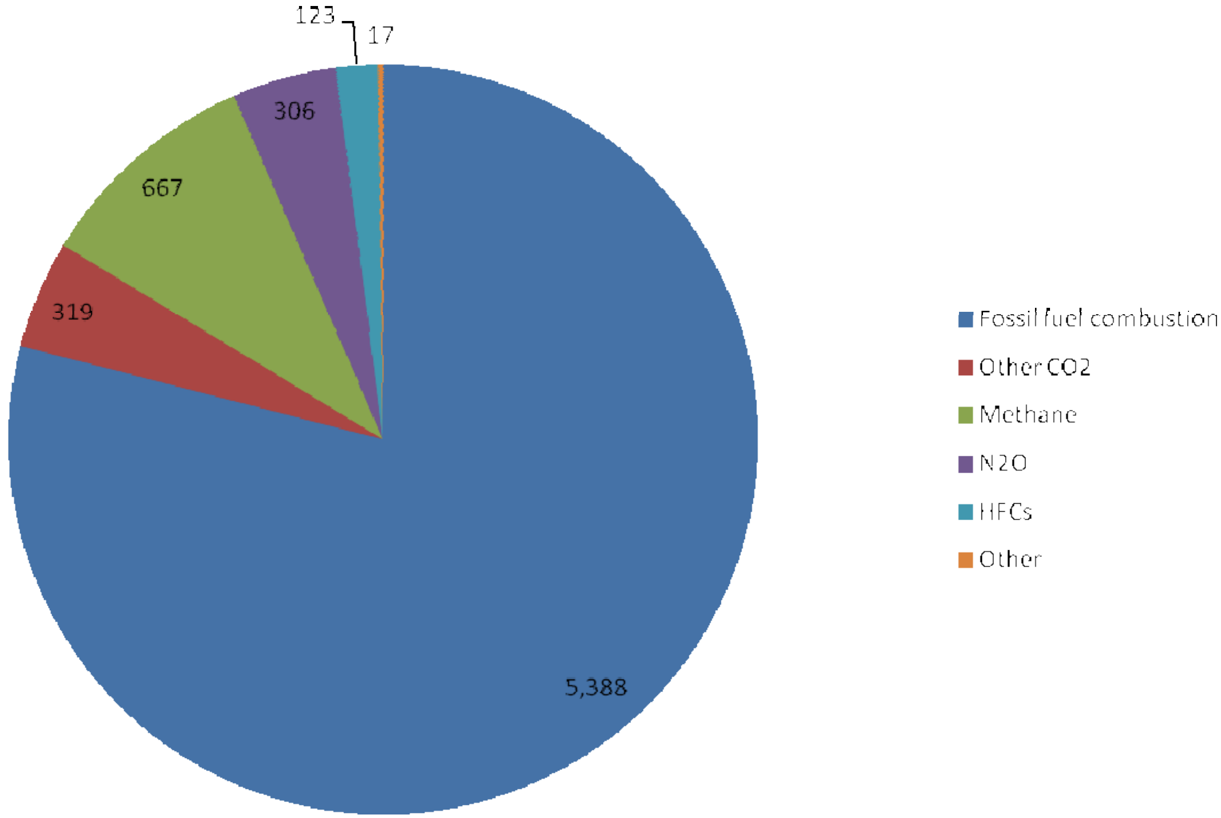
General Pro-Geoengineering View

- Continue efforts to reduce emissions
- But need a SCRAM button
- SCRAM (apocryphal?) etymology: “safety control rod axe man”

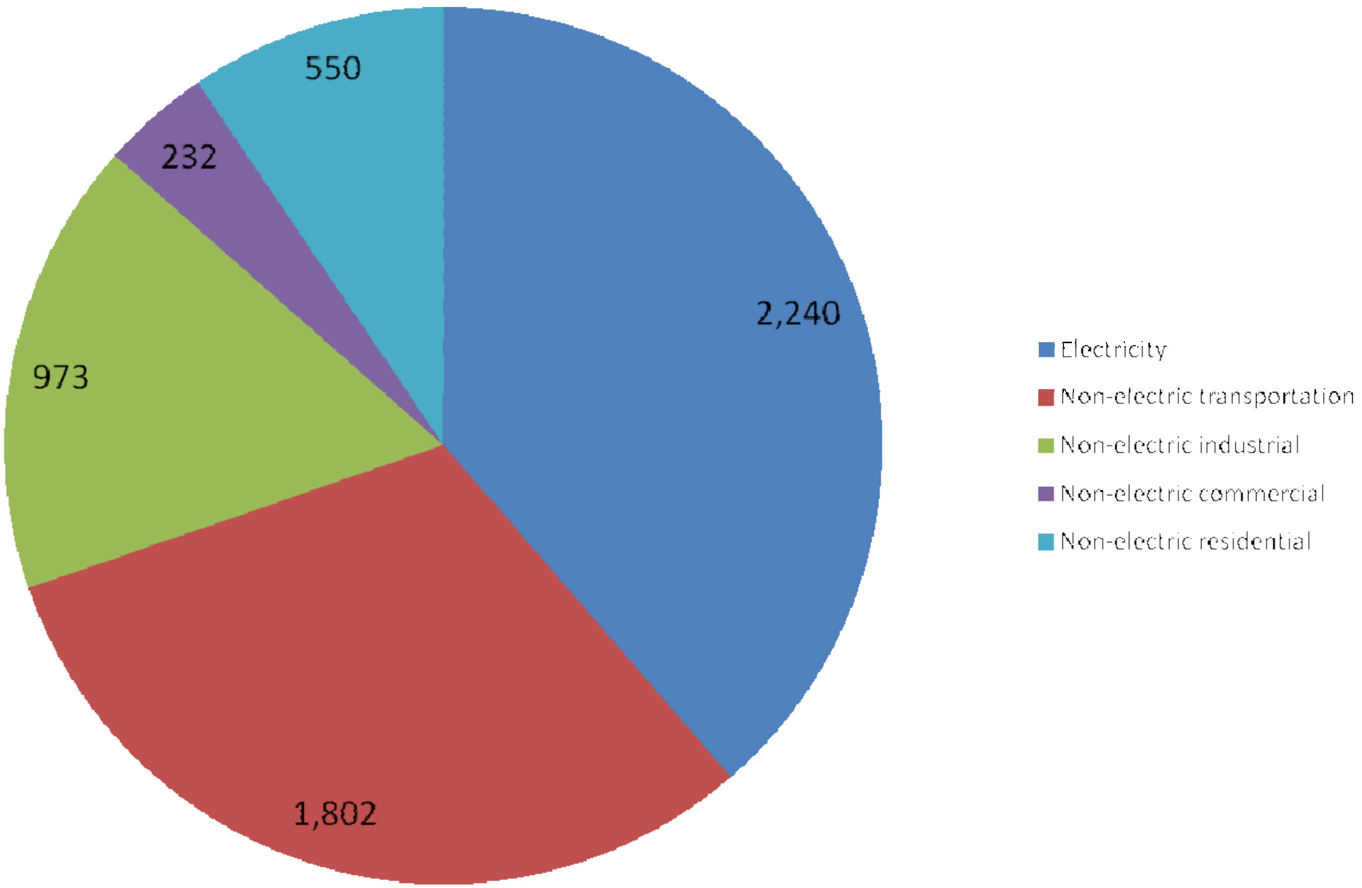


* “Increase/reduce:” from current level or projected business-as-usual (BAU) level

US GHG Emissions 2010: Gigatons



Energy-Related 2011 CO_2 Emissions



Reducing Emissions

- A quick way: the Soviet collapse
- The politically acceptable way: reduce emissions without reducing energy services
- Time: the paths
  - Reduce net anthropogenic emissions to ~0
  - From transient to equilibrium temperature
- Cost: Compare social cost of carbon (SCOC)

Alternatives

- Reduce energy intensity: supply service with less energy – LED bulbs
- Reduce carbon intensity: produce energy with fewer emissions: Coal emissions > natural gas > nuclear and renewables
- National emissions: GDP x EI x CI
- Capture and store the emissions: in effect reduces carbon intensity

CARBON DIOXIDE

Resolved:
Doubling CO_2 Would Raise Global Temperature

- Follows from mid-19th century science (Tyndall)

- Relevant boundary condition? (Angstrom)

- Ceteris paribus: Offsetting changes?
  - Reduced top-of-atmosphere solar radiation
  - Increased albedo

- The factual premise: Occurrence of doubling

CO_2 and GHG Metrics

- Atmospheric concentration: parts per million (ppm) or billion (ppb)

- Emissions
  - Most common: metric tons of CO_2
  - Alternatives
    - Metric tons of carbon = CO_2/3.67
    - CO_2 equivalent: 100-year global warming potential
      - CO_2 = 1.0
      - CH_4 = 26

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

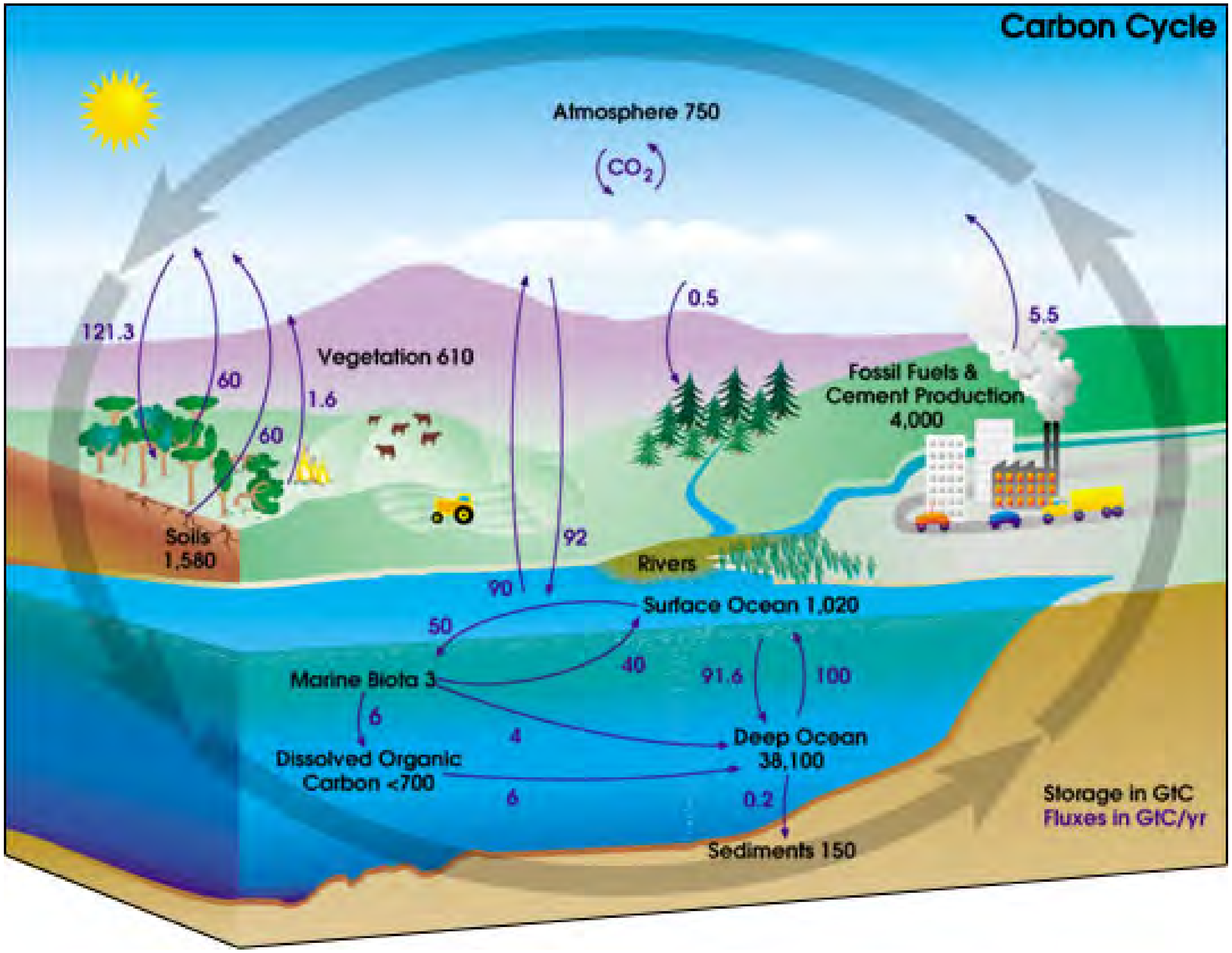
- GWP of one carbon atom:
  - In CO_2: 1
  - In CH_4: 26 x 16/44 = 9.5

Where's the Carbon?

Sink	Amount in Billions of Metric Tons
Atmosphere	578 (as of 1700) - 766 (as of 1999)
Soil Organic Matter	1500 to 1600
Ocean	38,000 to 40,000
Marine Sediments and Sedimentary Rocks	66,000,000 to 100,000,000
Terrestrial Plants	540 to 610
Fossil Fuel Deposits	4000

Note: Quantities are in tons of carbon

Carbon Flows



Measuring CO_2 Concentration

- Changed by difference between flows into/out of atmosphere

- Early 1950s: no consensus on size (or even sign) of the difference

- The problems
  – Lack of continuous measurements
  – Existing measurements affected by local sources and sinks

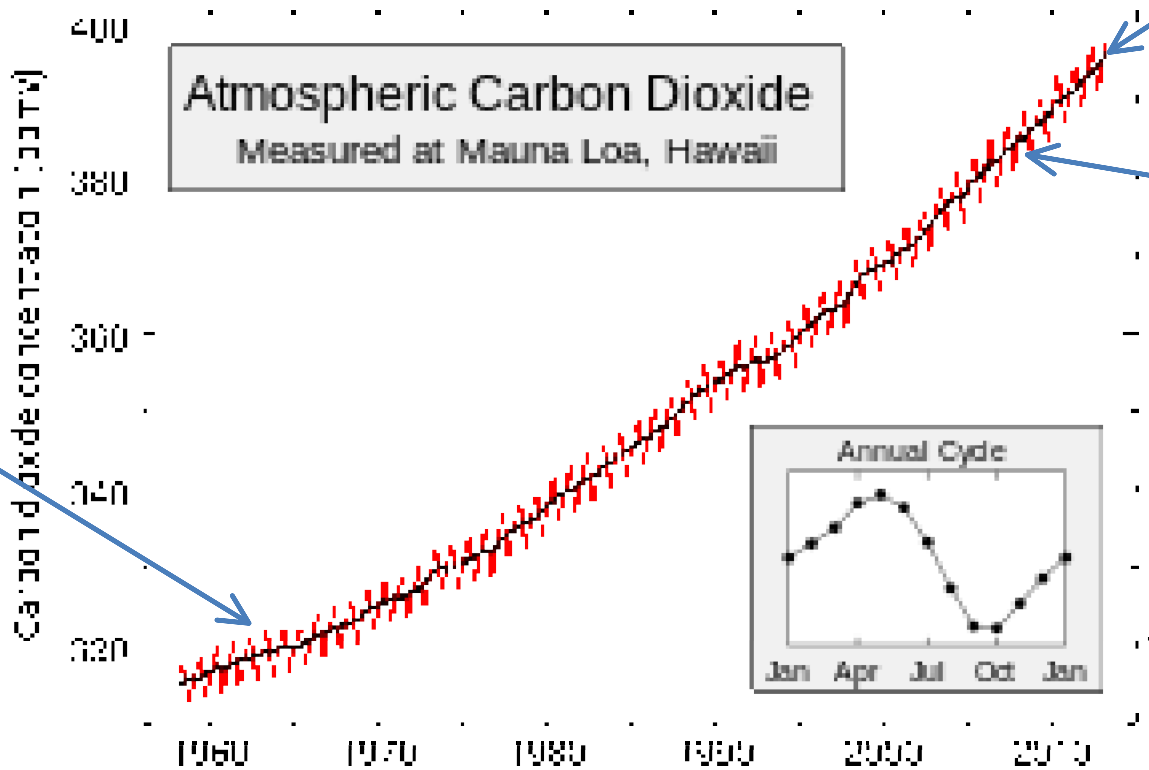
The Solution

- Monitor at isolated location: Mauna Loa
  - Mauna Loa Observatory at 3,397 meters
  - No nearby industry or motorized vehicle traffic
  - In barren lava field

- Monitor frequently and continuously: Begun by David Keeling in 1956 and continues to date

The Keeling Curve

2013: 396 ppm CO_2 and 478 ppm CO_{2eq}



2005: Keeling dies

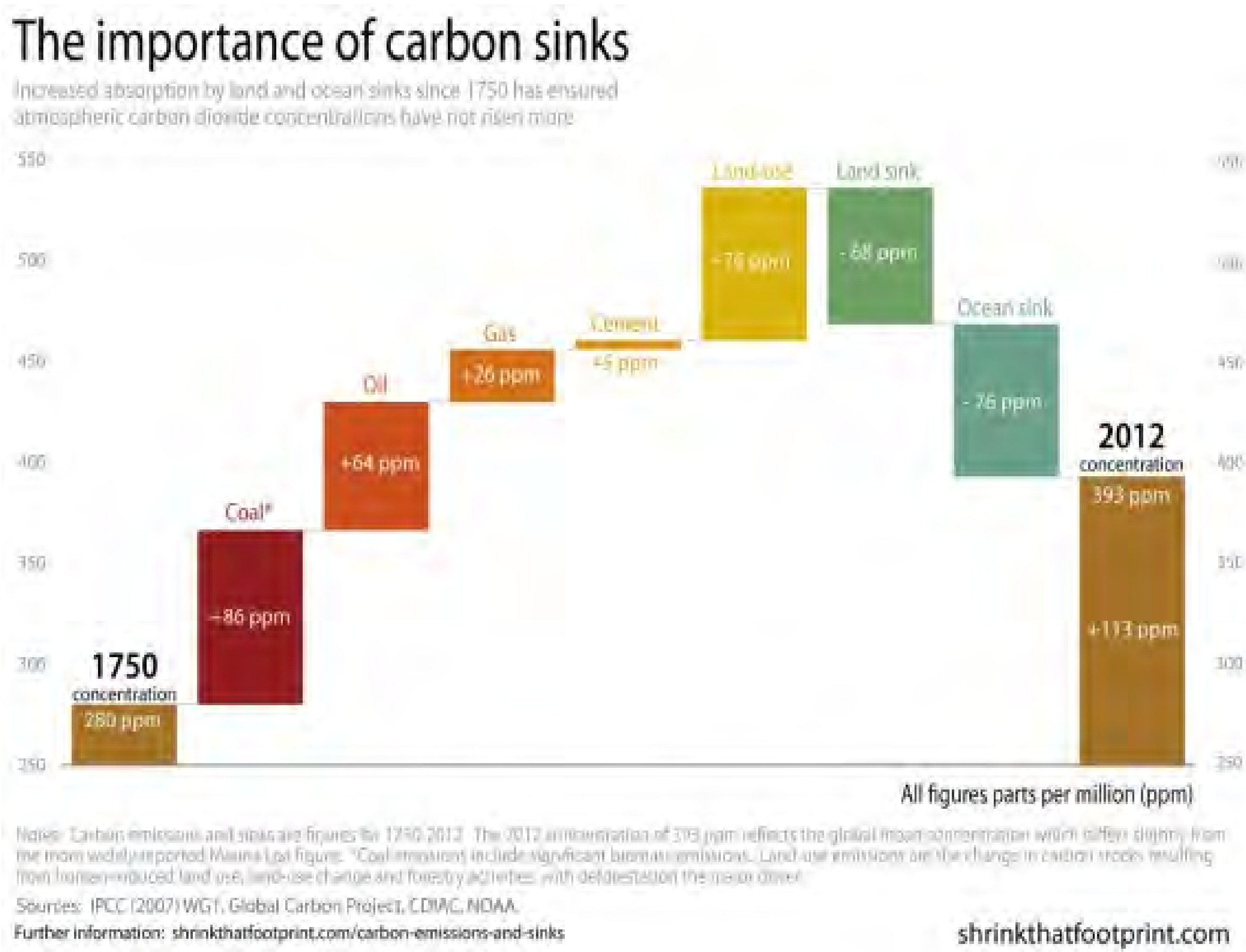
NSF stops supporting "routine" research – Revelle to the rescue

The Keeling Carbon Cycles

- Biological:
  - Dominates intra-annual cycle
  - Little interannual impact

- Fossil fuels dominate interannual changes

- Carbon sinks moderate fossil fuel impact

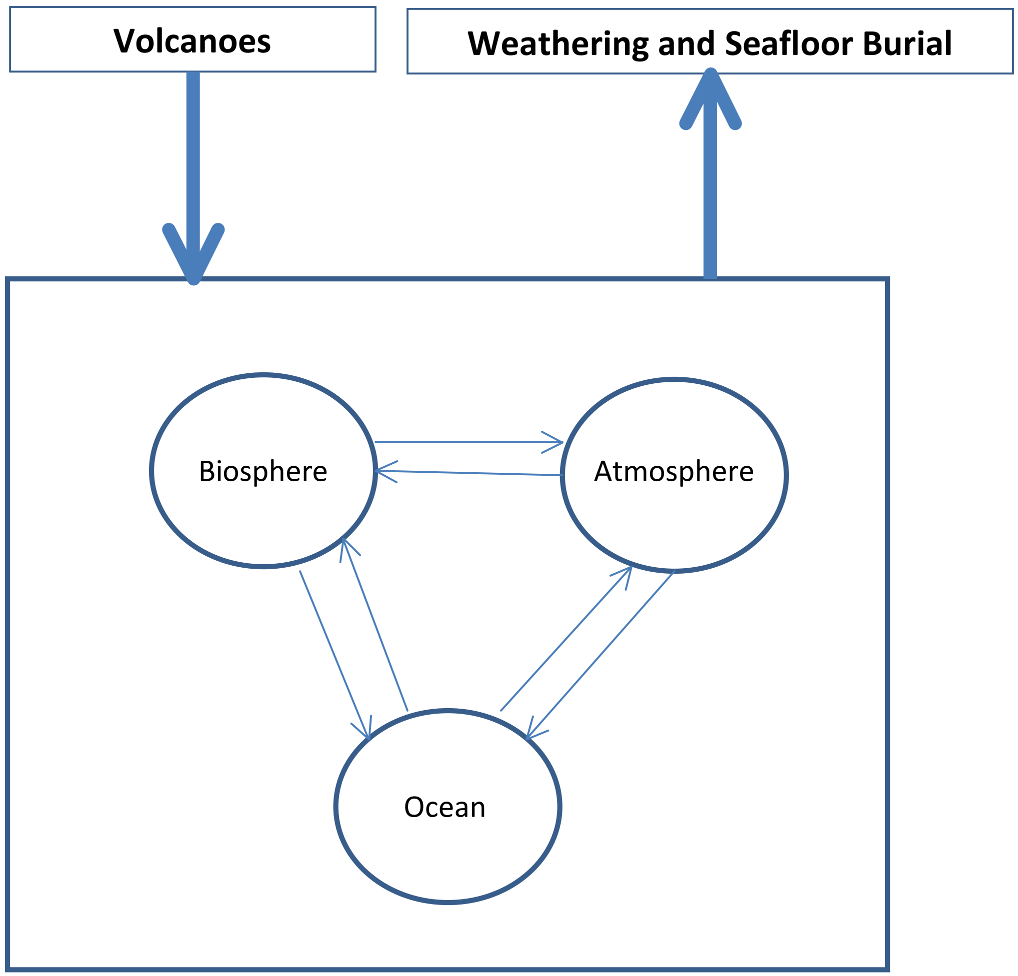

The importance of carbon sinks
Increased absorption by land and ocean sinks since 1750 has ensured atmospheric carbon dioxide concentrations have not risen more
1750
concentration
280 ppm
Coal*
+86 ppm
Oil
+64 ppm
Gas
+26 ppm
Cement
+5 ppm
Land sink
- 68 ppm
Ocean sink
- 76 ppm
2012
concentration
393 ppm
+113 ppm
550
500
450
400
350
300
250
All figures parts per million (ppm)
Sources: IPCC (2007) WG1, Global Carbon Project, CDIAC, NOAA
Further information: shrinkthatfootprint.com/carbon-emissions-and-sinks
shrinkthatfootprint.com

Longer Term

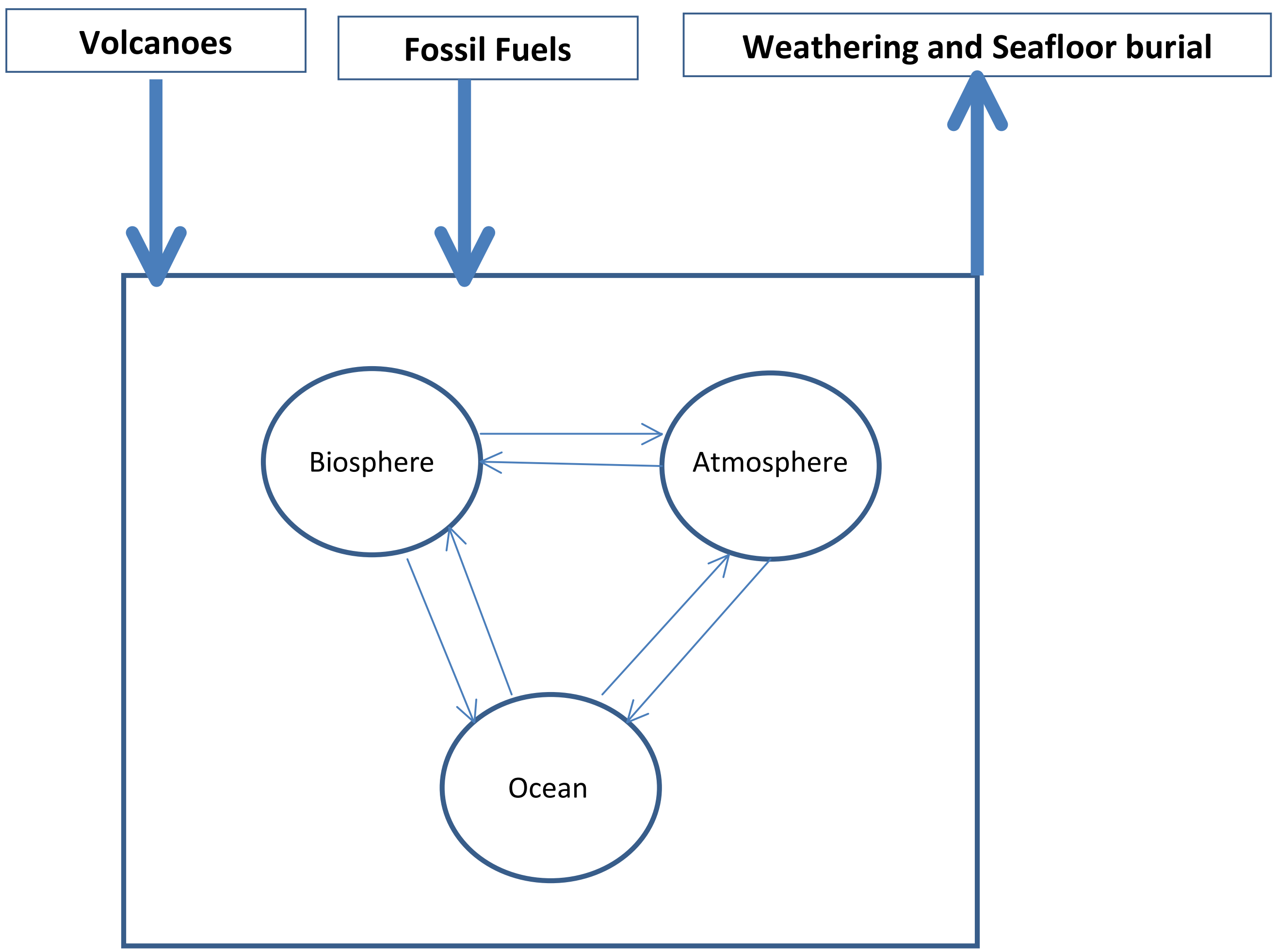
- Geological cycle: millions of years
  - Volcanoes add CO_2 to surface-atmosphere-ocean system
  - Rock weathering and burial of biogenic sediment remove CO_2 from system

- Glacial cycle: tens of thousands of years

Pre-Industrial Geological Cycle



Post-Industrial Revolution



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

The Glacial Cycle: Cooling the Earth

- From 50 MYA geologic burial exceeds volcanic emissions → declining CO_2

- Temperature falls
  - By 10 MY A: permanent Antarctic ice sheet
  - From 2.75 MYA: alternating northern glaciation (most of the time) and interglacials (like now)

Mechanisms

- Orbital cycles periodically cause cool northern summers
- More snow remains at beginning of following winter → year-by-year growth of snow cover
- Increased albedo → cooling but not enough for glacial cycle
- CO_2 transferred from atmosphere to deep ocean
  - Begins after initial temperature decline: a feedback
  - Causes large further decline in global temperatures
- Land mass alignment allows spread of glaciers

The Glacial Cycle: Earth's Orbit

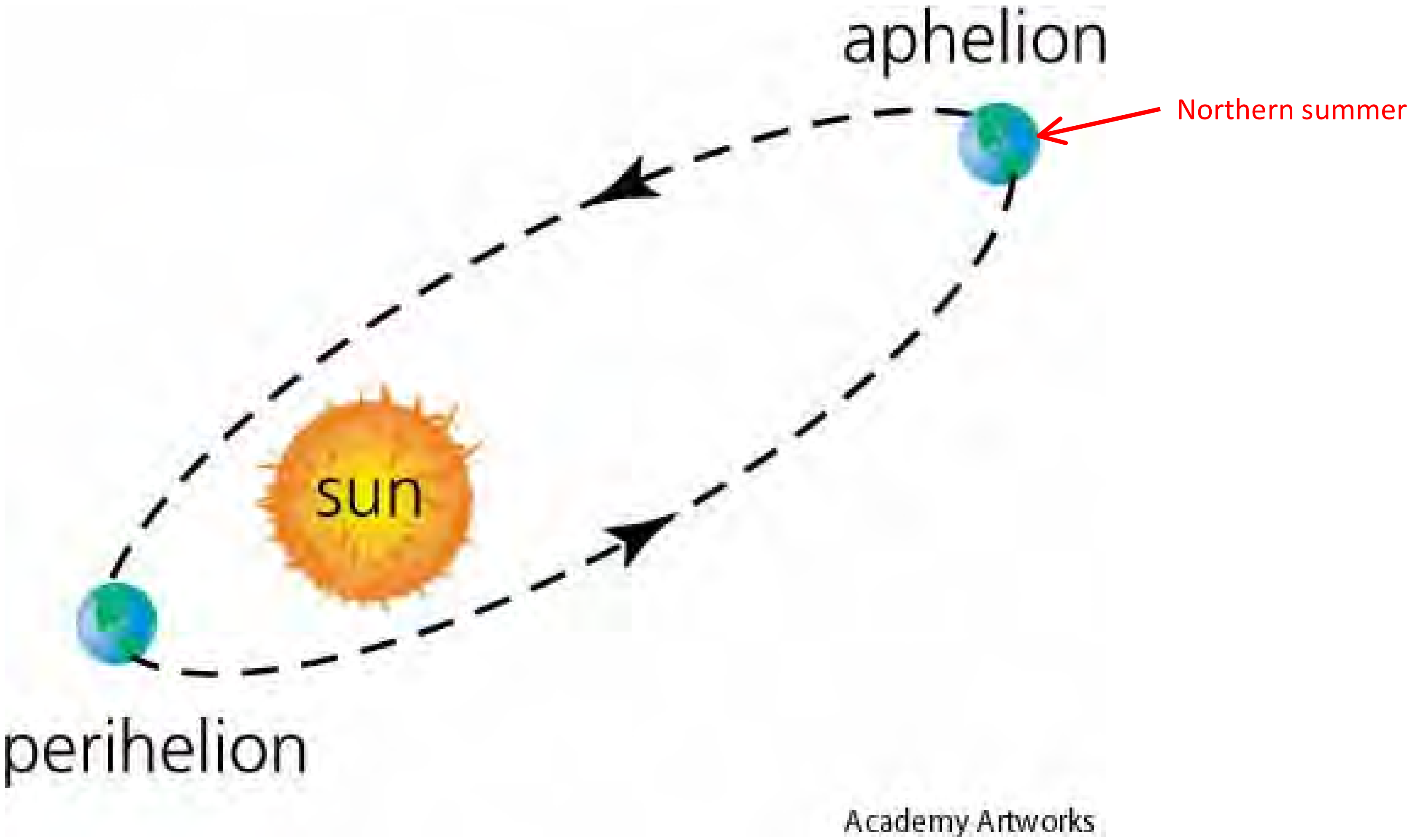
- Eccentricity: Cycle from more circular to less circular orbit – 100 thousand years
- Precession: Cyclical change in relationship between season and distance from sun – 22 thousand years
- Obliquity: Cyclical rocking of Earth's angle to rotation plane – 41 thousand years

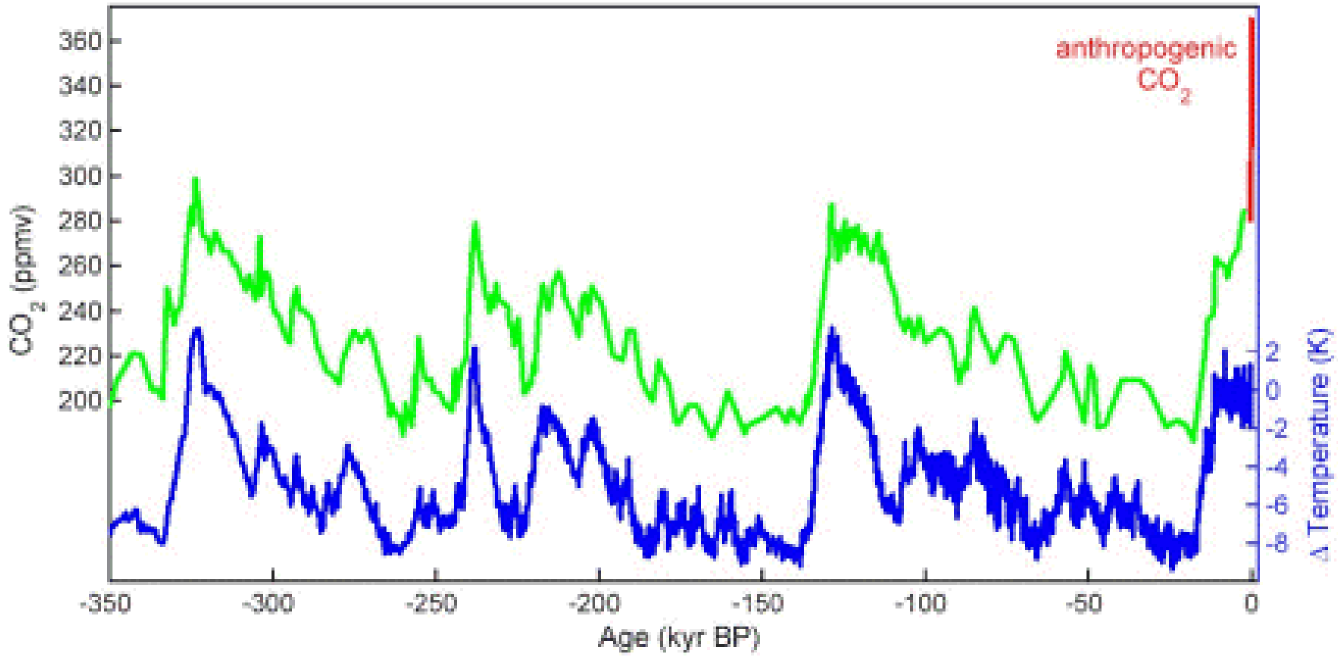
The Glacial Cycle: Cooler Northern <u>Summers</u>

- More elliptical orbit (eccentricity) <u>and</u> northern summer at aphelion (precession), <u>or</u>

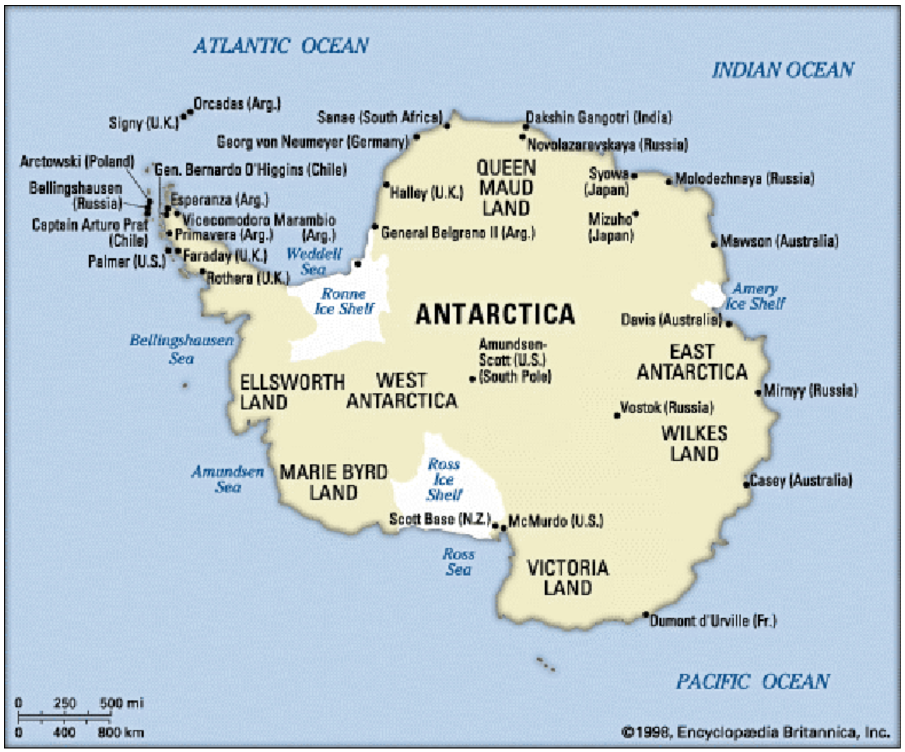
- Smaller tilt (obliquity), <u>or</u>

- Both


aphelion
Northern summer
sun
perihelion
Academy Artworks


anthropogenic
CO_2
CO_2 (ppmv)
360
340
320
300
280
260
240
220
200
2
0
-2
-4
-6
-8
Δ Temperature (K)
-350
-300
-250
-200
-150
-100
-50
0
Age (kyr BP)

Glaciers Spread



Glacier starting point

Videos

- Animated video of 800,000 years of CO_2:
- http://www.youtube.com/user/CarbonTracker#p/a/u/2/H2mZyCblxS4

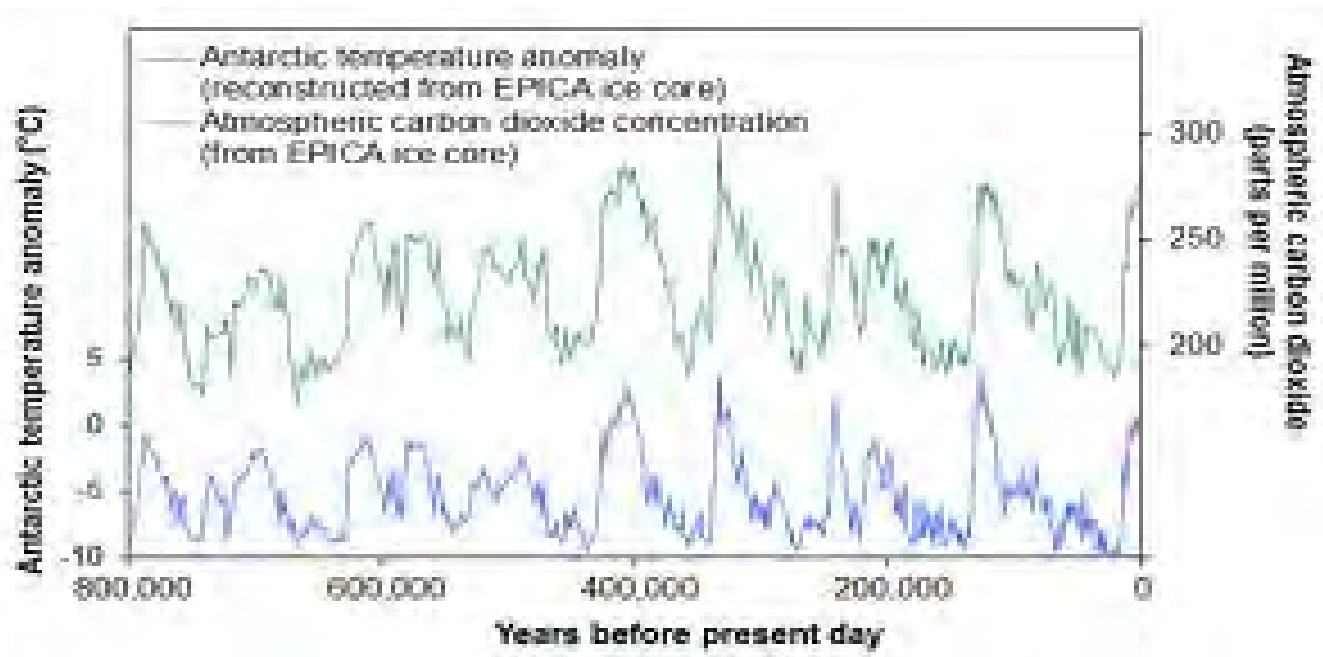
- Video on temperature-carbon relationship in glaciation/deglaciation: http://www.youtube.com/watch?v=hWJeqgG3Tl8#t=16

Questions

- Why the change from 41,000 years (obliquity) to weaker 100,000 years (precession) cyce?

- Details of CO_2 feedback mechanism: possible elements
  - Colder water absorbs more CO_2
  - Cooler → drier → dustier → increased micronutrients to Southern Ocean

41,000 Year – 100,000 Year Shift

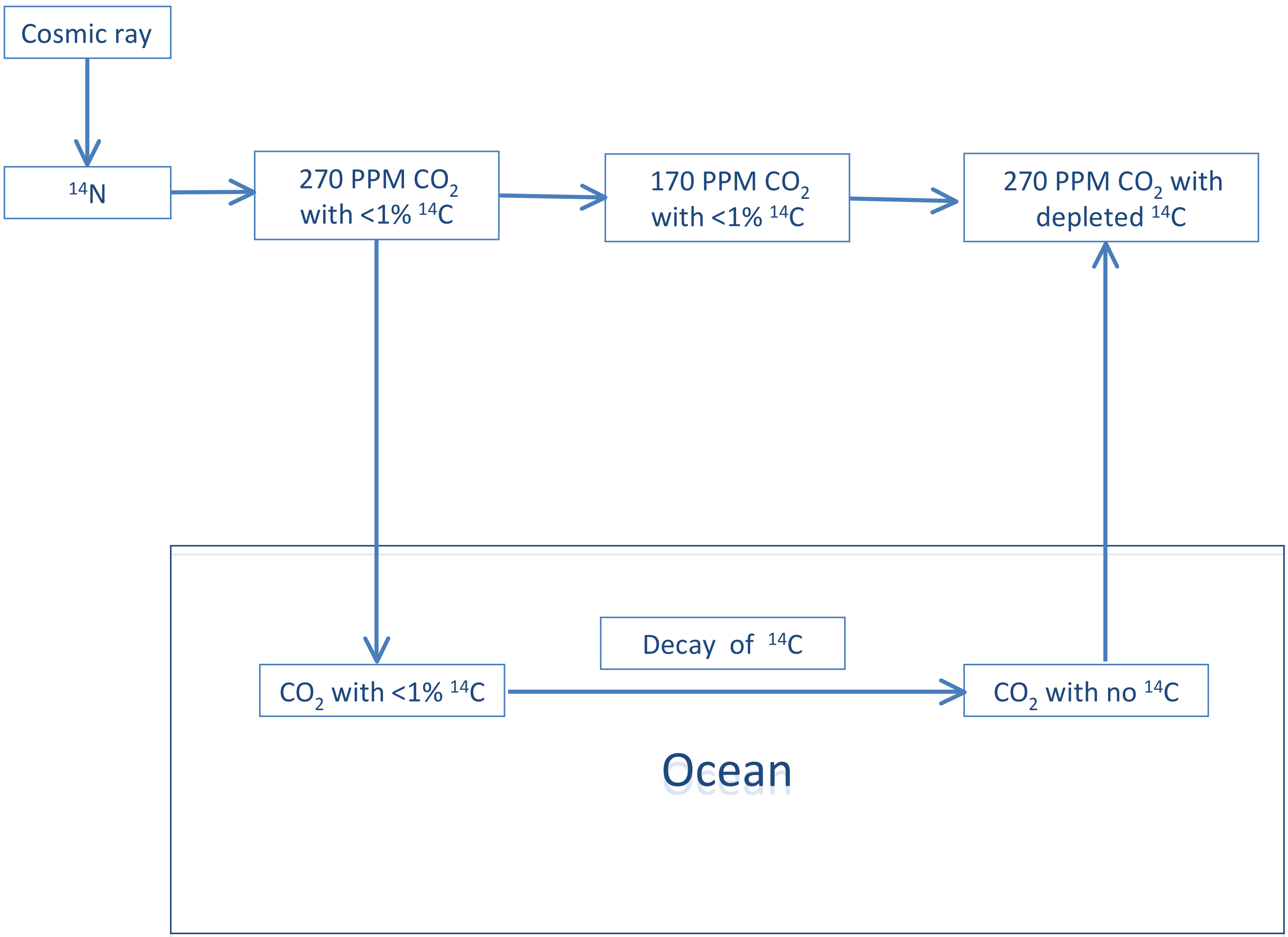


So Why Believe?

- Sustained correlation with orbital cycles and plausible link to initial cooling
- Need for additional forcing and lagged temperature-CO_2
- Changing isotopic composition of CO_2

^{14}Carbon and Its Implications

- ^{12}Carbon: Six protons and six neutrons
  – 99% of carbon
- ^{14}Nitrogen: seven protons and seven neutrons
  – Cosmic rays (and nuclear tests) transform into ^{14}Carbon: six protons and 8 neutrons
- Atom decays back to ^{12}C – half-life of 5730 years
  – In atmosphere, constant new supply of ^{14}C maintains concentration
  – Isolated from atmosphere, concentration declines


Cosmic ray
^{14}N
270 PPM CO_2 with <1% ^{14}C
170 PPM CO_2 with <1% ^{14}C
270 PPM CO_2 with depleted ^{14}C
Decay of ^{14}C
CO_2 with <1% ^{14}C
CO_2 with no ^{14}C
Ocean

MEASURING TEMPERATURE

Temperature and CO_2

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

Measuring Temperature: Problems

- Spatial
  - Large gaps: Arctic and central Africa
  - No spot represents global temperature: No Mauna Loa
- Temporal
  - Wide-spread instrument record only from ~1850
  - Temperature (unlike chemical composition) not retained in ice cores

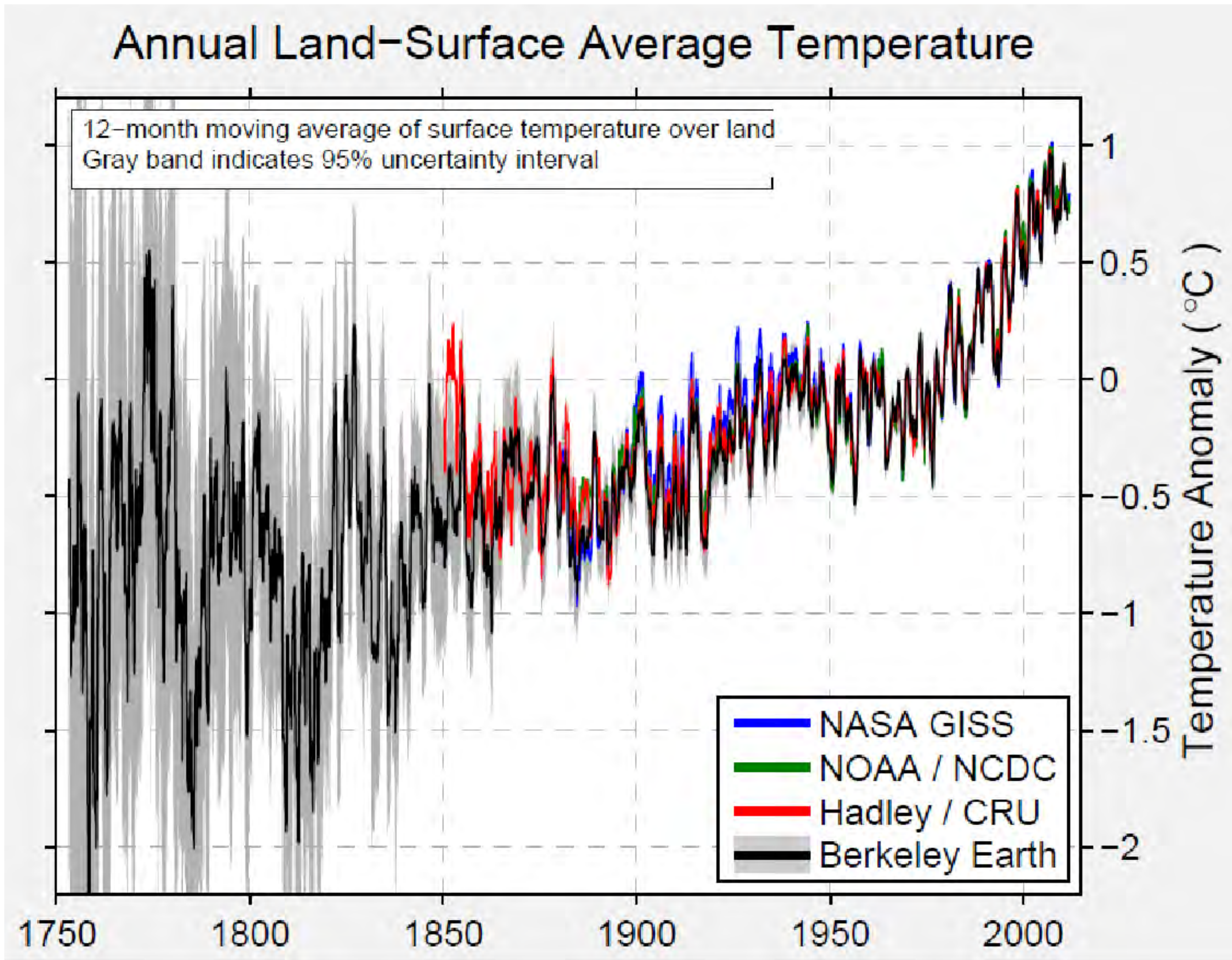
Tasks

- Develop algorithms for combining instrument readings into global average
- Use proxies to estimate temperatures for pre-instrument period
- Deal with (or not) the Arctic gap

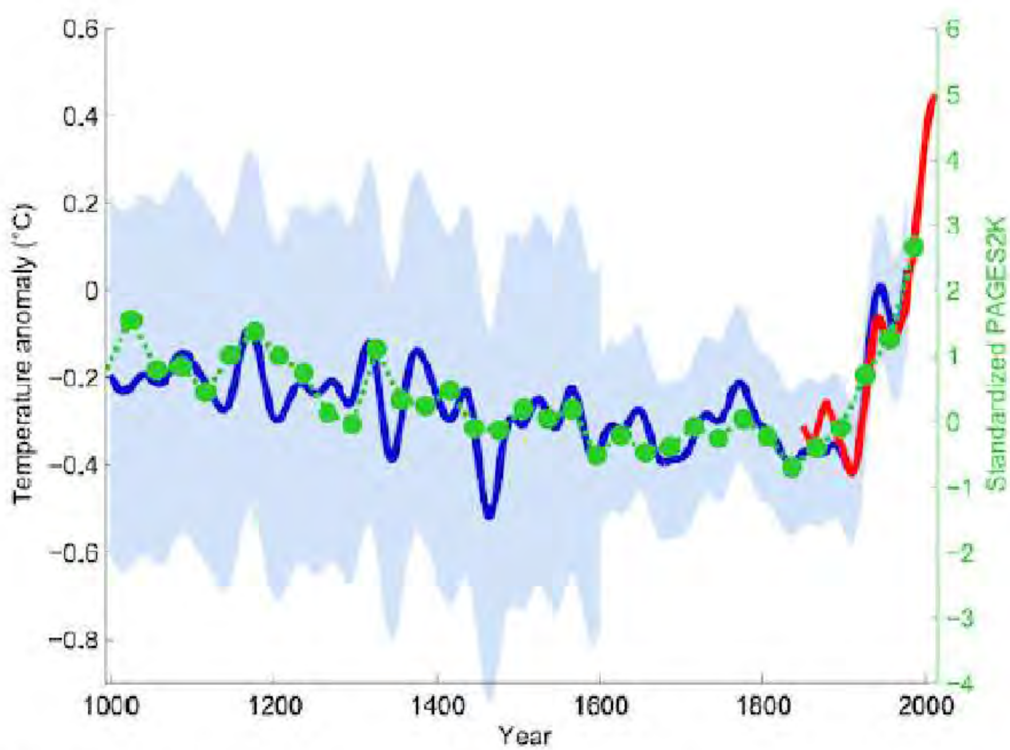
Milestones: 1980 to mid-2013

- ~1980: NASA, NOAA and Hadley Center develop estimates of global temperature from 1880
- 1998-99: Mann and co-authors estimate temperatures from 1000 AD primarily from tree rings
- 2011-2012: Berkeley Earth Project publishes reanalysis of temperature data from 1750
- 2013 Marcott and co-authors reconstruct temperatures for Holocene (past 11,300 years)

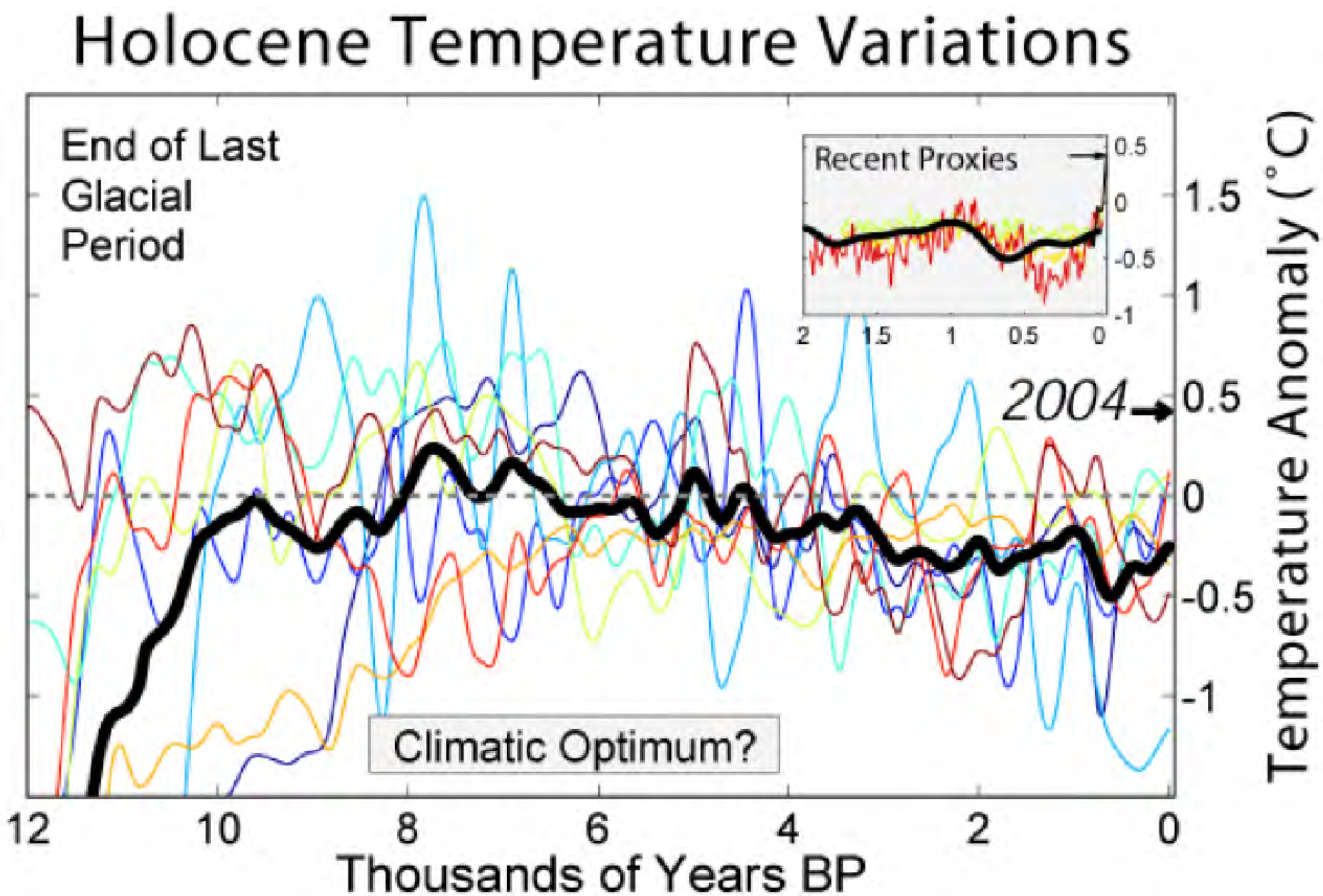
Berkeley Earth Project Reanalysis



An Updated Hockey Stick

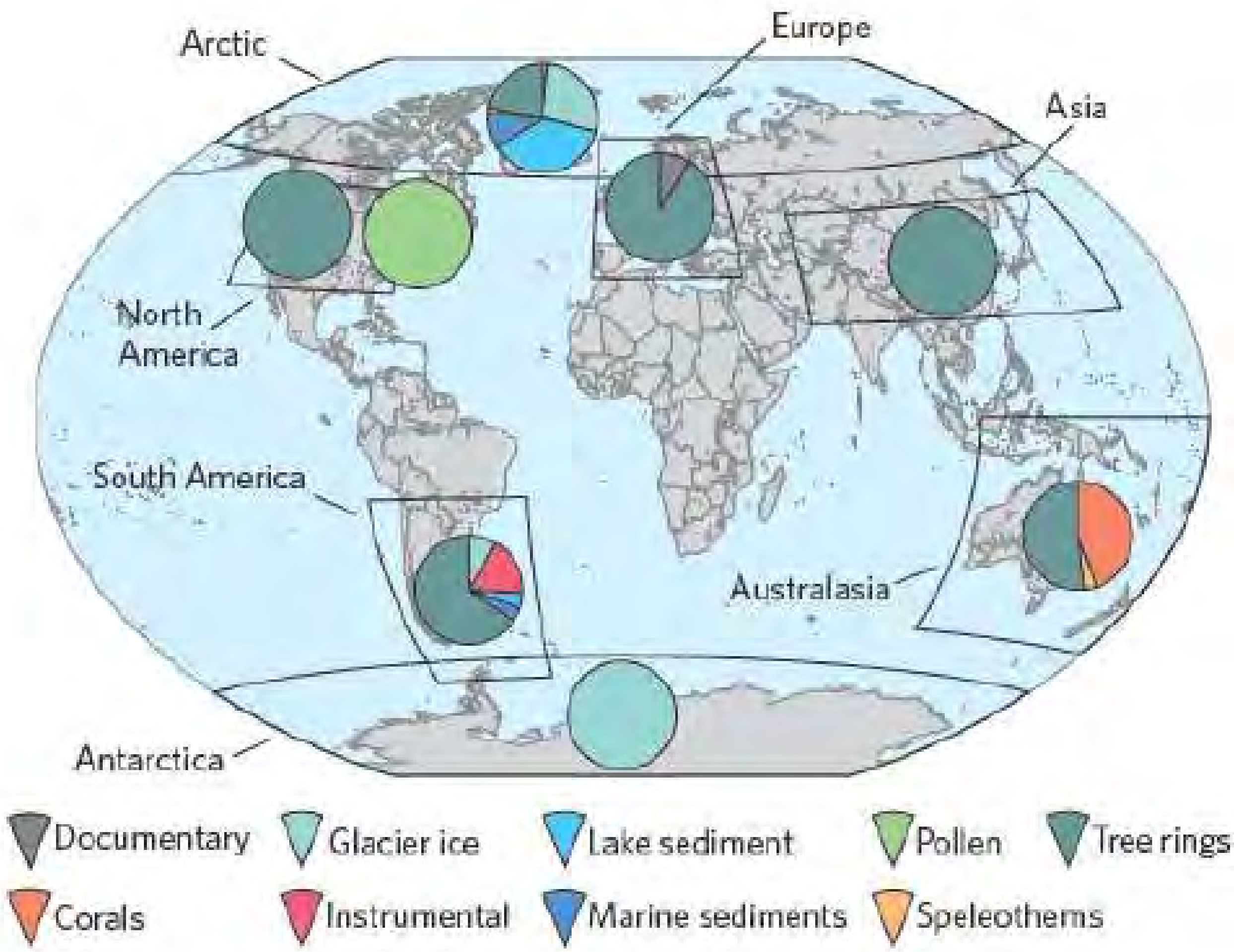


Green dots show the 30-year average of the new PAGES 2k reconstruction. The red curve shows the global mean temperature, according HadCRUT4 data from 1850 onwards. In blue is the original hockey stick of Mann, Bradley and Hughes (1999) with its uncertainty range (light blue). Graph by Klaus Bittermann.



1961-1990 e quals 0. Due to smoothing, graph cannot resolve changes for periods shorter than 300 years.

Data Sources



MEASUREMENTS AND POLICY

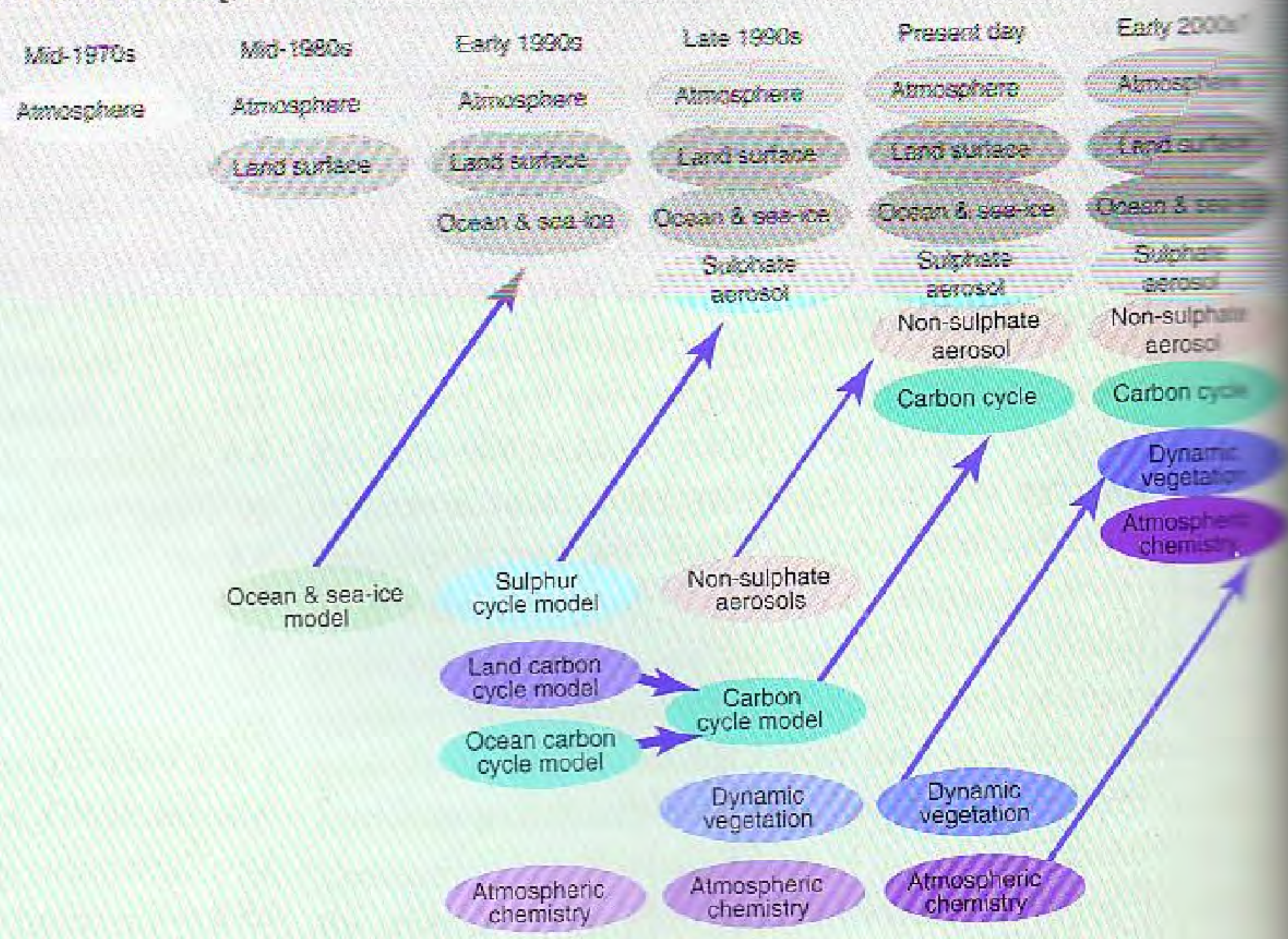
1960s-1980s: Three Linked Elements

- Increased scientific understanding

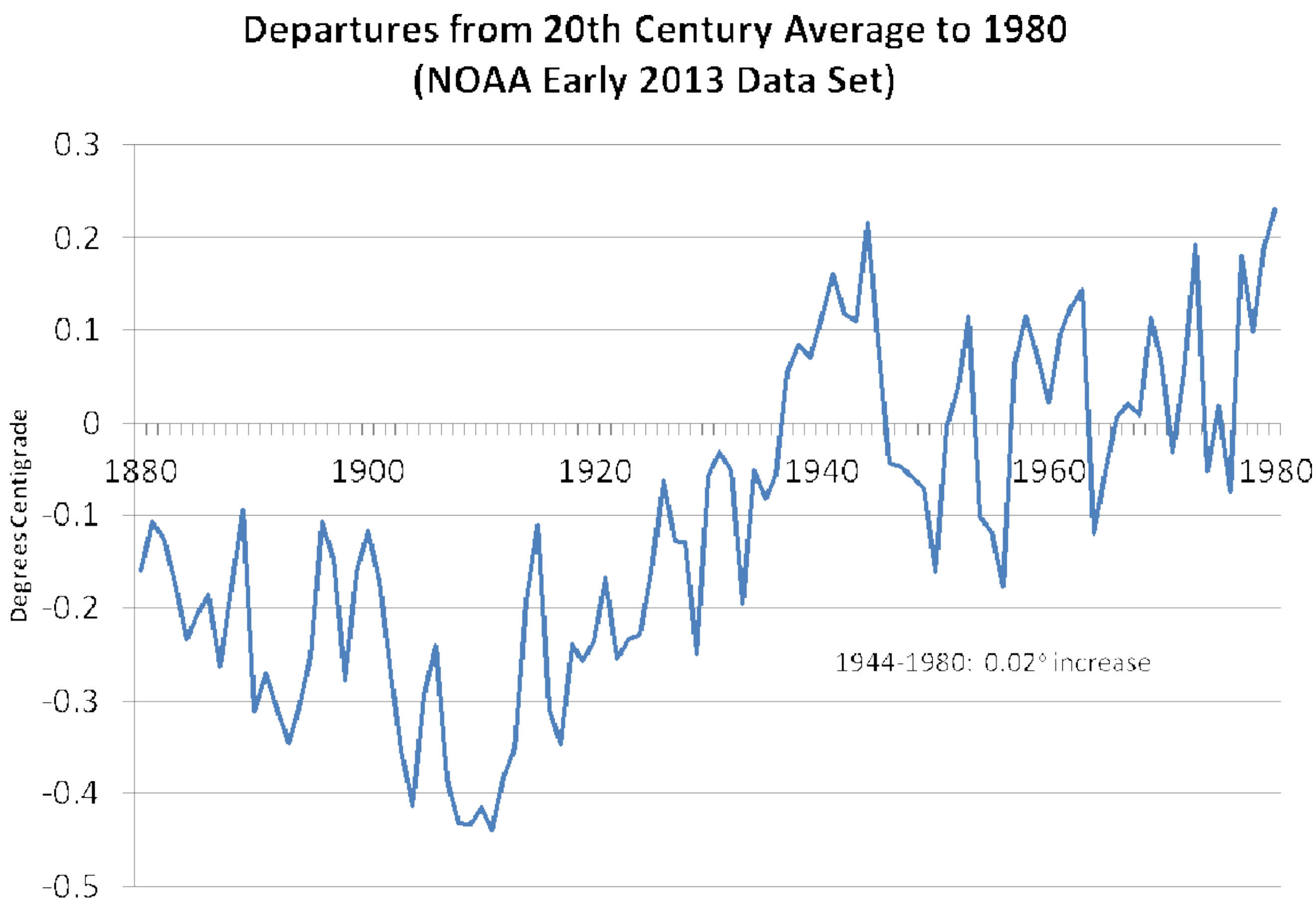
- Understanding + computer power: Improved (but still inadequate) computer models

- Temperature observations

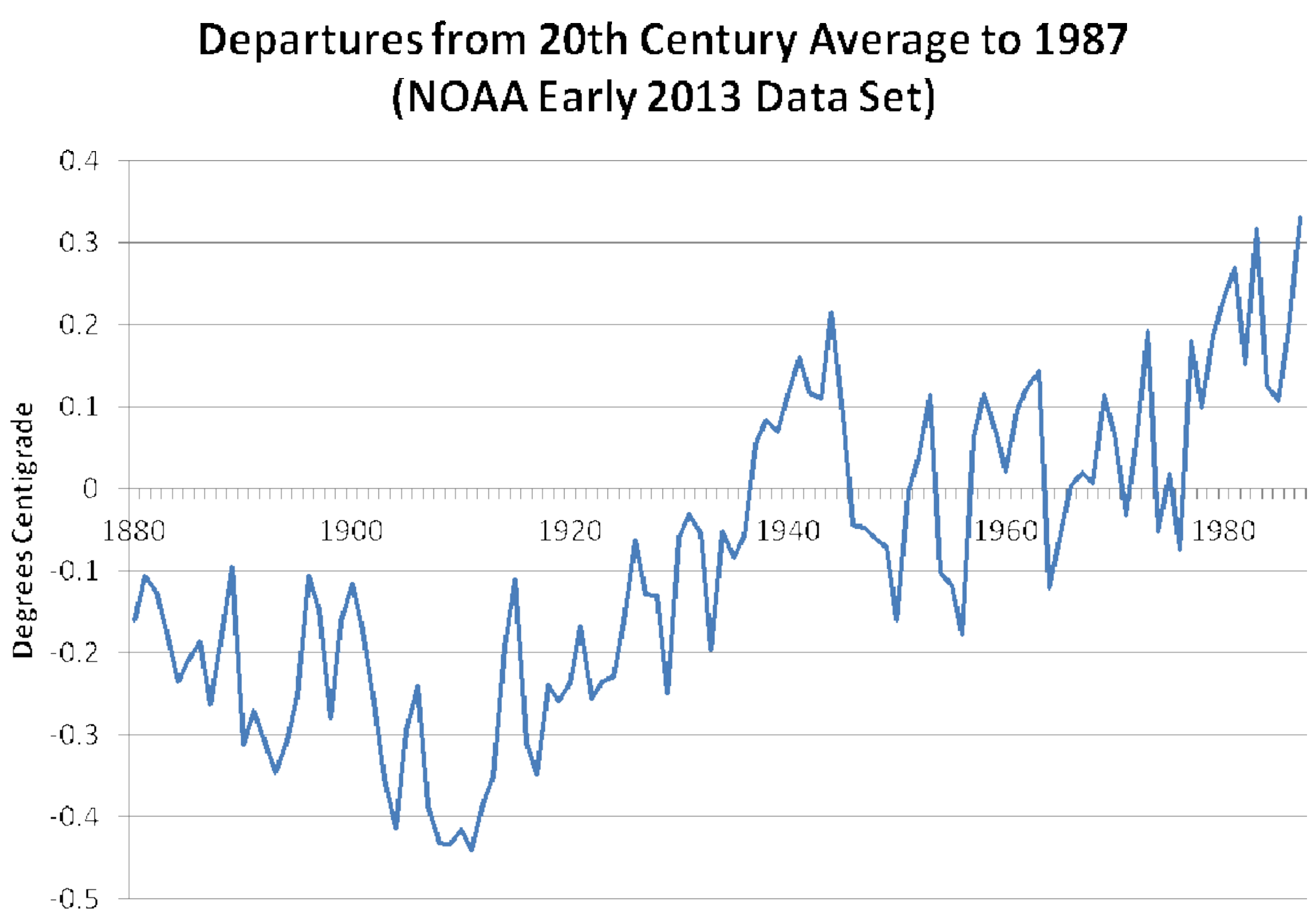
The Development of Climate models, Past, Present and Futur



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


Departures from 20th Century Average to 1980
(NOAA Early 2013 Data Set)
Degrees Centigrade
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
1880
1900
1920
1940
1960
1980
1944-1980: 0.02° increase

1988-1992 Climate Moves to Policy Agenda: Observations



1988-1992 Climate Moves to Policy Agenda: Institutional

- Domestic: James Hansen 1988
  - "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

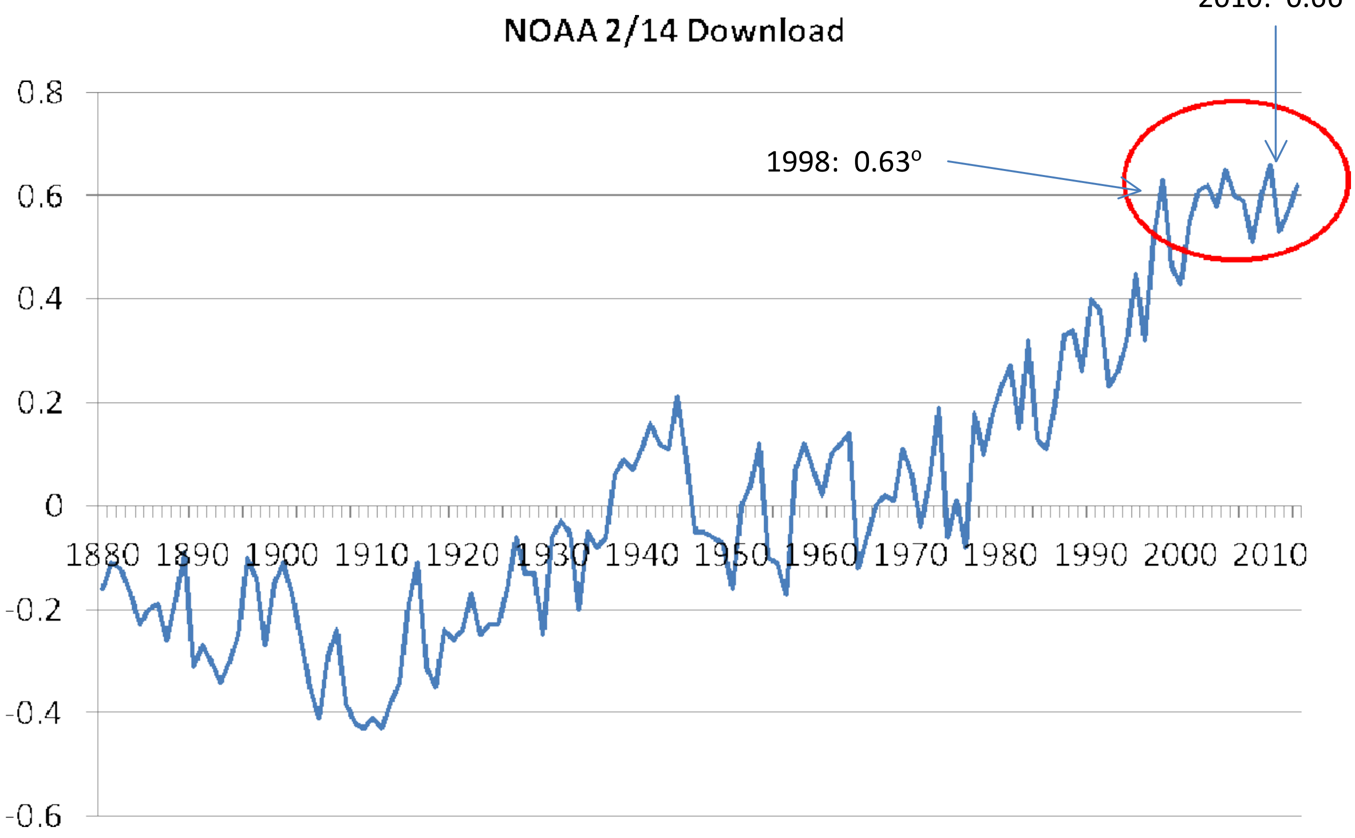
A Guide to the Alphabet

- 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
  - Ratified by U.S.
  - Framework for protocols with national commitments
  - Kyoto Protocol (not ratified by U.S.)
  - U.S. participating in negotiation of post-Kyoto protocol

THE CURRENT ISSUE:
GLOBAL WARMING HAS/HAS NOT STOPPED/PAUSED/SLOWED

Who Did It?


NOAA 2/14 Download
2010: 0.66º
1998: 0.63º
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010

The Suspects

- Reduced radiative forcing
  - No pause in growth of CO_2 concentration
  - Plausible contributors but not large enough
    - Reduced solar radiation: below-average solar cycle
    - Increased albedo: tropical volcanoes and Asian factories

- Distribution of thermal energy within Earth system

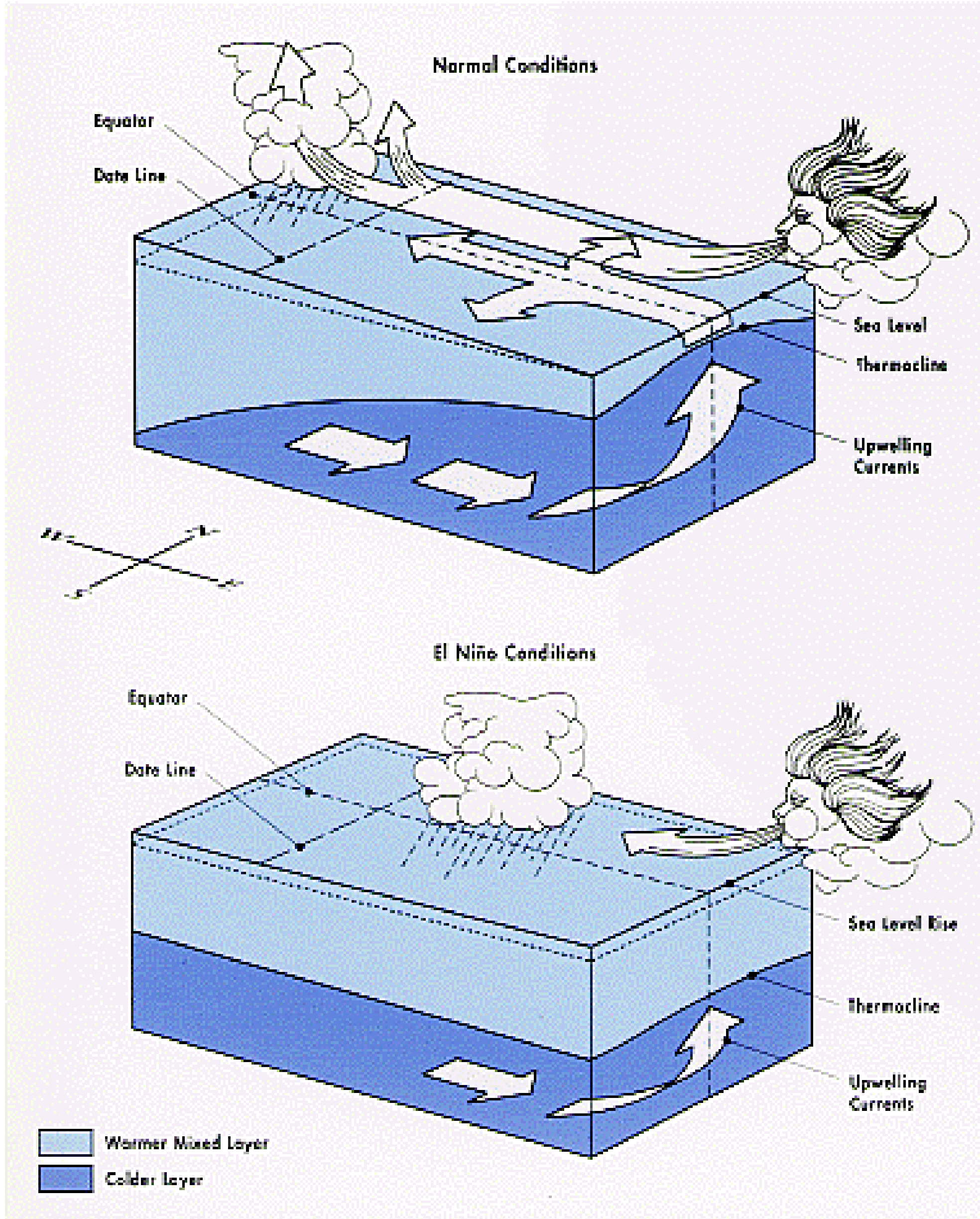
Distribution of Earth's Thermal Energy

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

Role of the Oceans

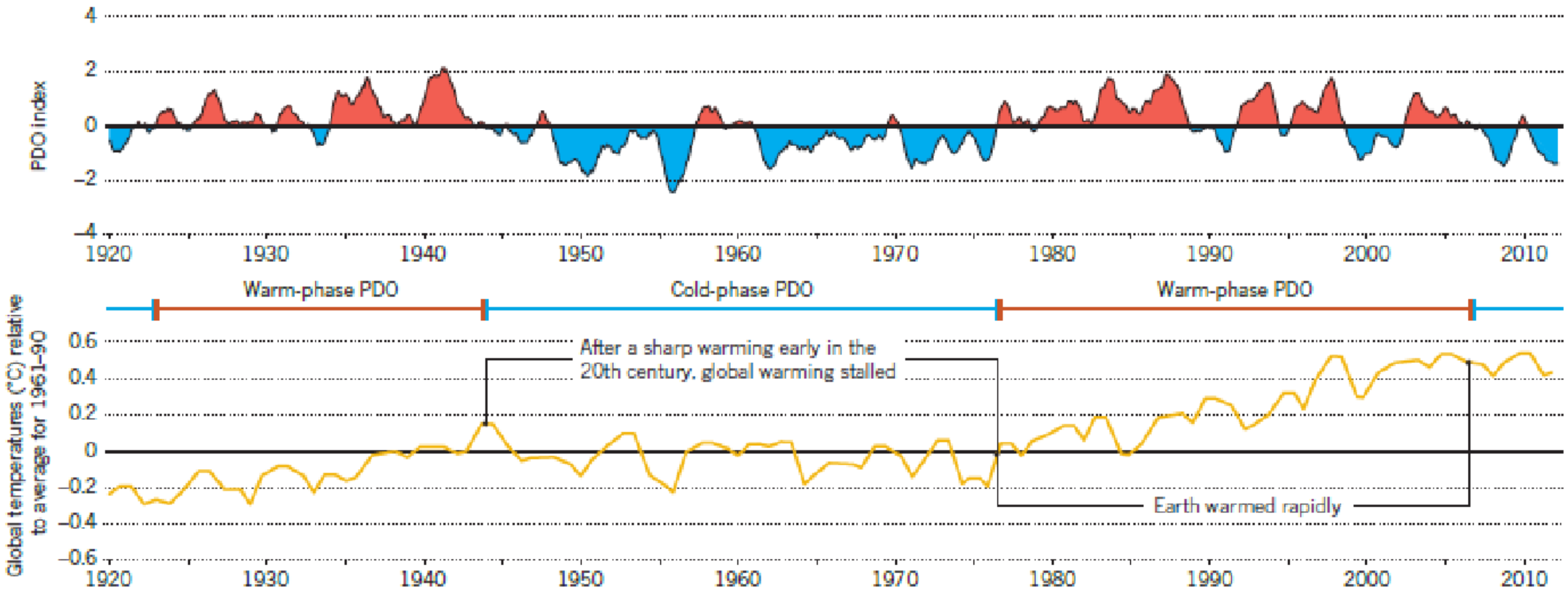
- >90% of warming goes to heating the oceans

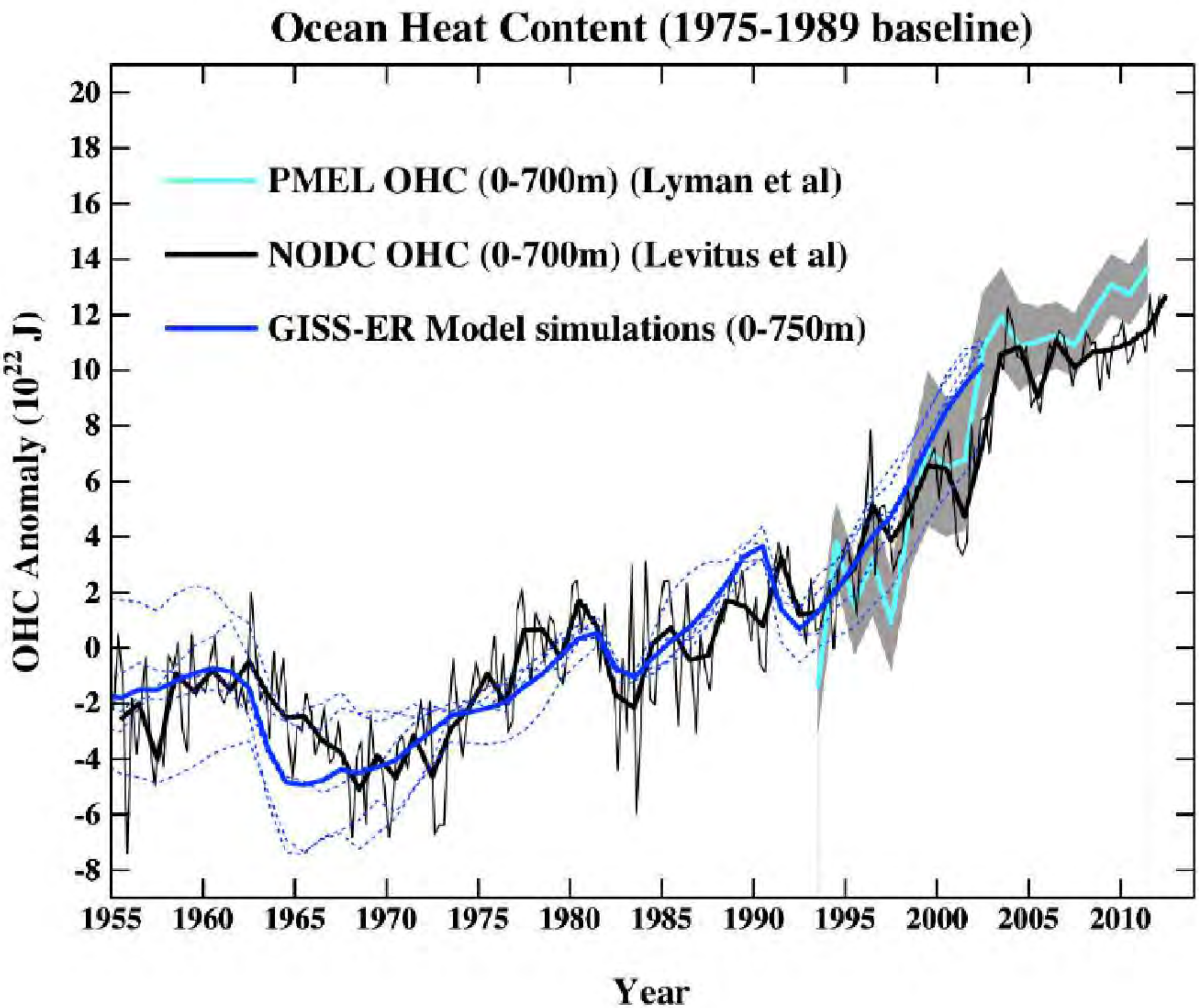
- El Niño-La Niña change rate of warming by affecting distribution of between ocean and atmosphere


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

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.





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)
Year
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

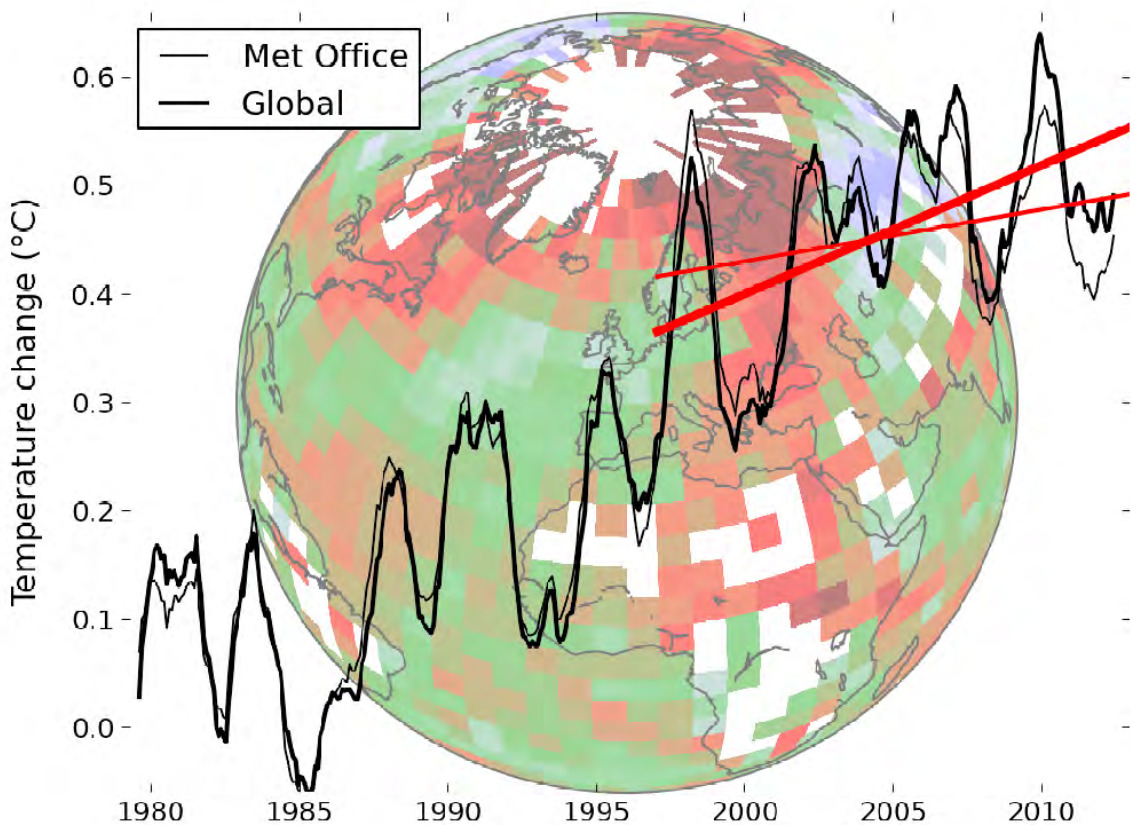
But is there a problem?

- The Arctic weather station gap
  - Hadley: assumes Arctic temperature changes at global rate
  - NASA: fills gaps by interpolation
  - NOAA: like Hadley?

- Cowtan and Way
  - Begin with satellite data
  - Develop algorithm for relating satellite data to surface temperature
  - Test algorithm for known surface temperatures

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


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