Global Climate Change

Evidence for anthropogenic climate change

1 February 2010

No Atmosphere

$R_S = 2.3$ c s

$T_S = 5778$ K

$\omega_0 = 0.3$

$$P_S = 4\pi R_S^2\, \sigma T_S^4$$

$$P_{\text{abs}} = P_S \frac{\pi R_E^2}{4\pi r^2}(1-\omega_0)$$

$$P_{\text{rad}} = 4\pi R_E^2\, \sigma T_E^4$$

$$T_E = T_S\sqrt{\frac{R_S}{2r}}(1-\omega_0)^{1/4} = 255\ \text{K} = -18^\circ\text{C}$$

“Greenhouse” effect

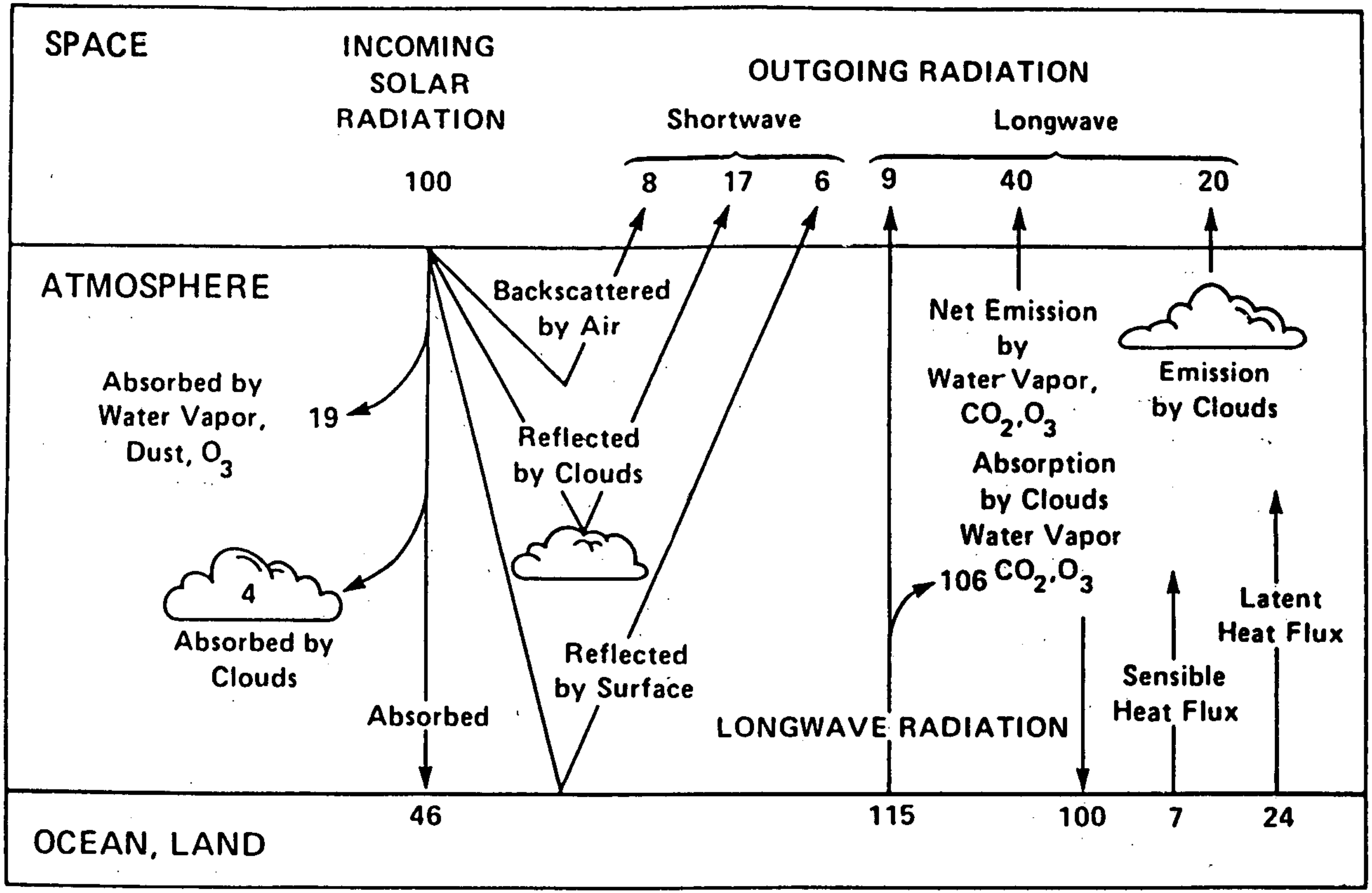
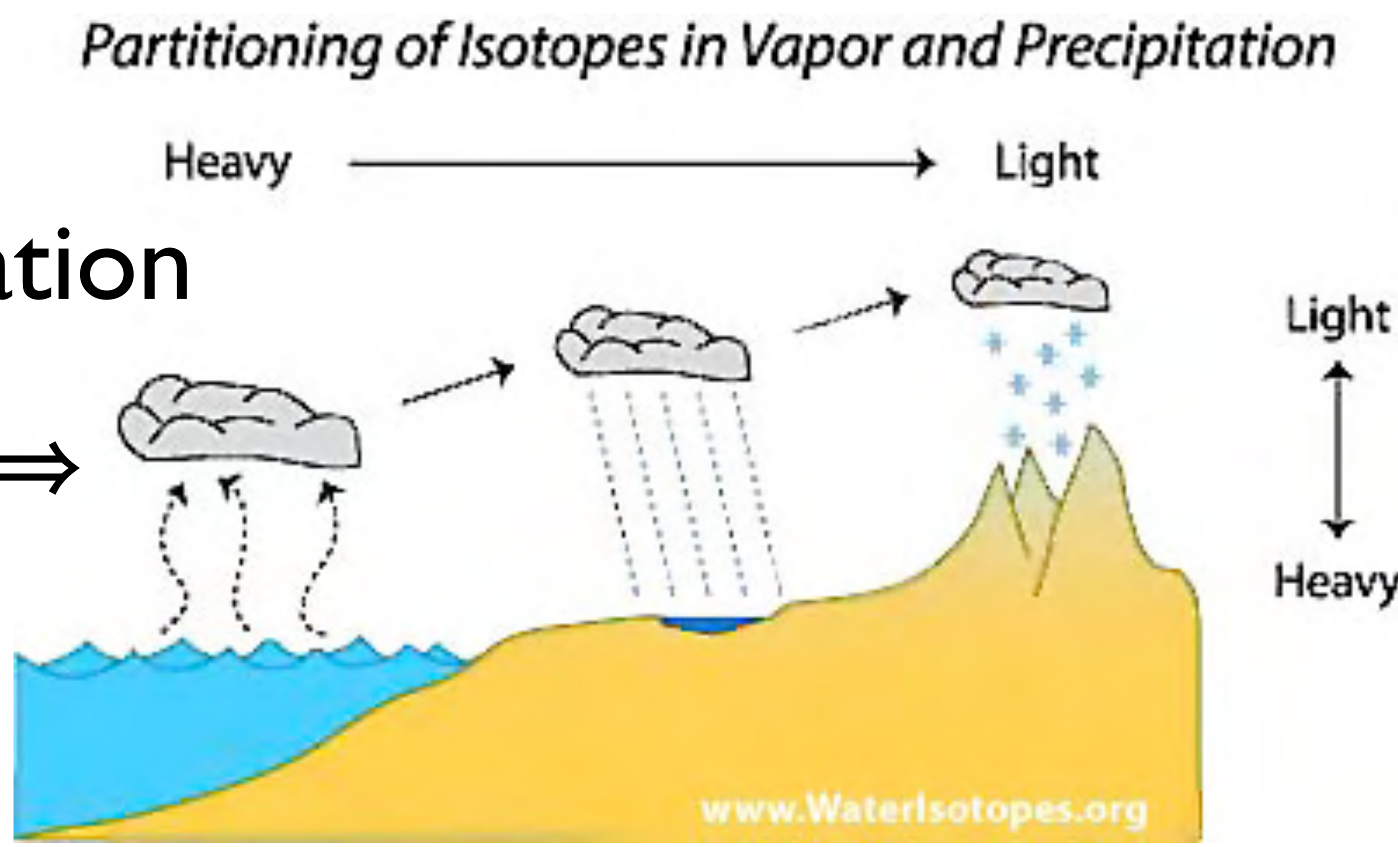


FIG. 6. Schematic representation of the atmospheric heat balance. The units are percent of incoming solar radiation. The solar fluxes shown on the left-hand side, and the longwave (thermal IR) fluxes are on the right-hand side (from MacCracken and Luther 1985).

Methods

- Trapped gas bubbles in ice cores
  - absolute gas concentration
  - isotopic ratios (D:H) ⇒ temperature
- Tree rings
- Glacier length



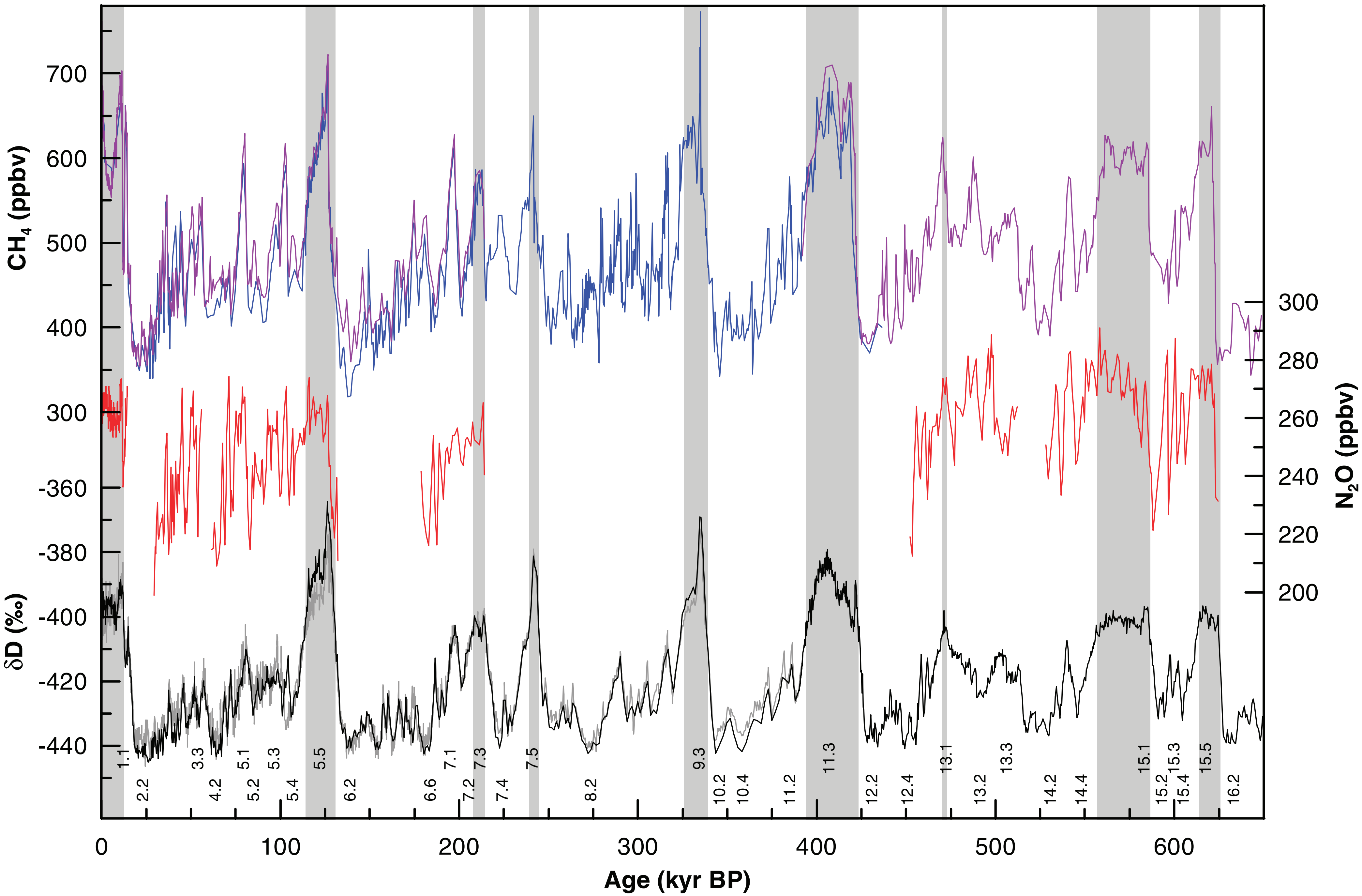


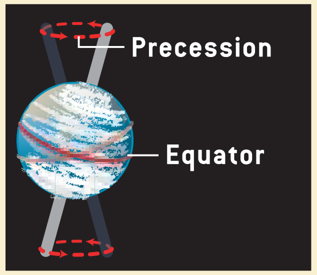
Fig. 4. CH_4 record over the past 650 ky, composed of Dome C CH_4 (purple line) [(*8*, *9*) and new data] and Vostok CH_4 (blue line) (*2*, *15*). Also shown are the N_2O data measured along the Dome C ice cores (red line) [(*8*, *20*, *36*) and new data] and δD records from Dome C (black line) (*24*) as well as those from Vostok +42‰ (gray line) (*2*). N_2O artifacts are not shown in this figure. Gray shaded areas highlight interglacial periods with a δD value >–403‰ as defined in (*3*). Numbers of MISs are given at the bottom of the figure (*25*). Data are shown on the EDC2 time scale (*3*).

- Long glacials, short interglacials
- CH4 = wetland production
- CO2 = – plant growth
- isotope ratio = temperature proxy

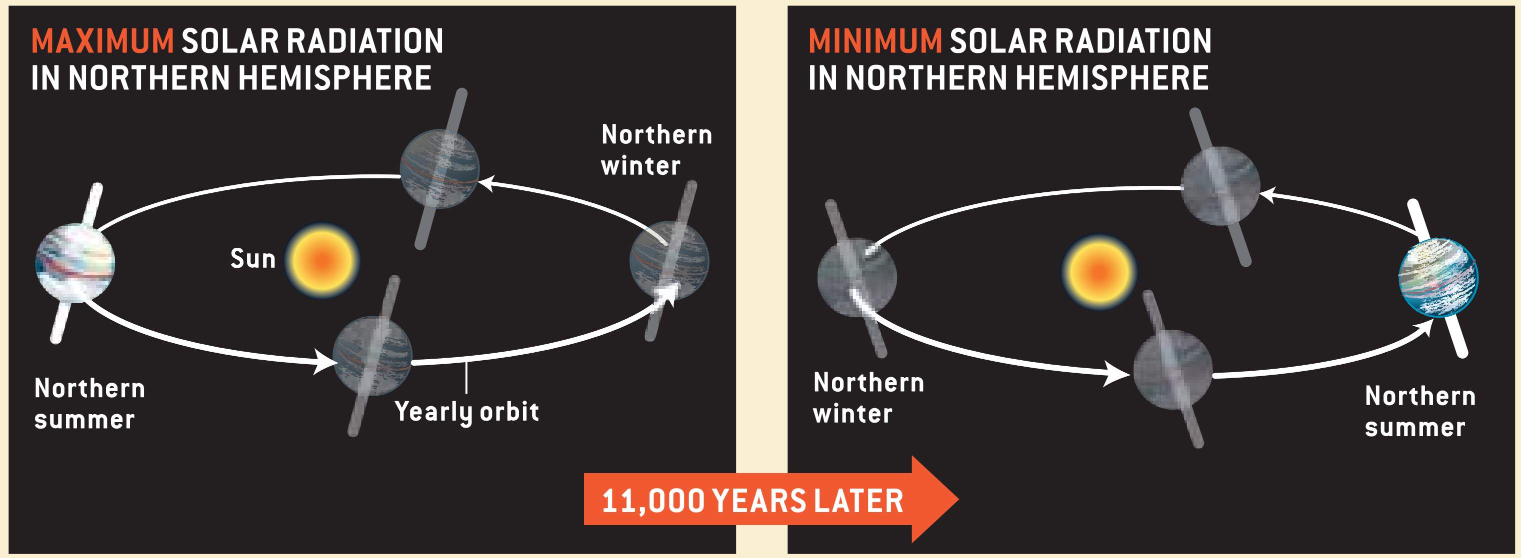
Renato Spahni *et al.*, *Science* **310** 25 November 2005, p. 1317

Orbital Controls over Greenhouse Gases

Natural variations in the earth's orbit, such as those related to precession (*diagrams*), redistribute the sunlight that reaches the globe over long timescales. For the past million years, these subtle changes have driven major dips and swells in atmospheric concentrations of methane and carbon dioxide (*graphs*). Although scientists do not fully understand why, global concentrations of these greenhouse gases respond mainly to changes that occur during summer in the Northern Hemisphere, the time of year when the North Pole is pointed most directly at the sun.

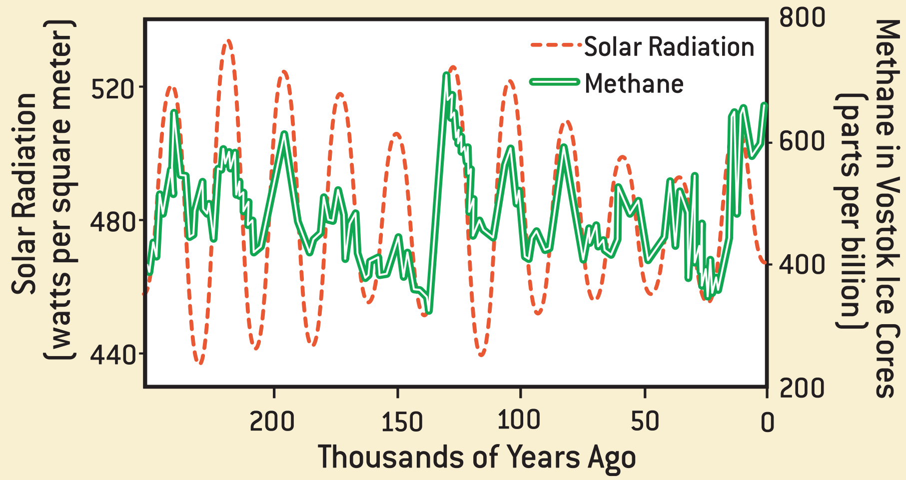


Wobble in the earth's axis of rotation, known as precession, is one of the three orbital cycles that account for sunlight variations in the Northern Hemisphere. Like a toy top about to fall, the earth's axis traces imaginary circles in space, making one revolution every 22,000 years.

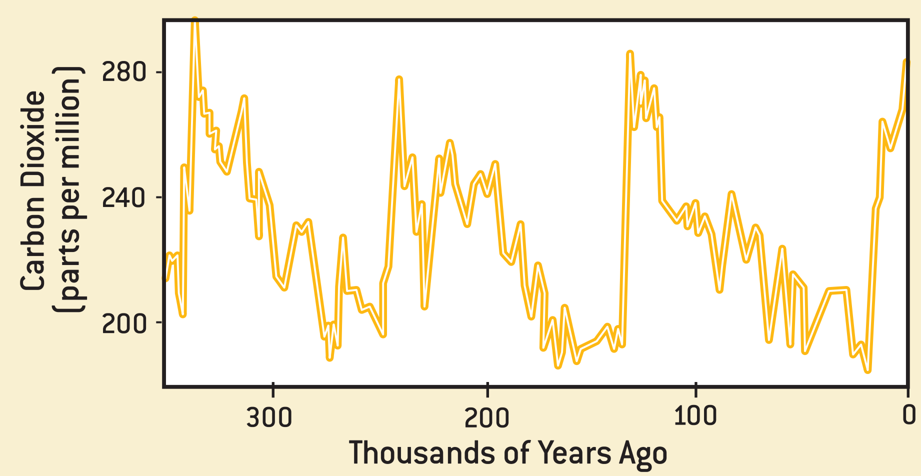


Summer warmth in the Northern Hemisphere peaks once every 22,000 years, when the yearly northern summer coincides with the earth's closest passage to the sun and the Northern Hemisphere receives the most intense sunlight.

Summer heat bottoms out 11,000 years later, after the earth's axis has shifted (precessed) to the opposite position. The Northern Hemisphere then receives the least summer sunlight, because the earth is farthest from the sun.



Methane concentrations rose and fell over the past 250,000 years in near harmony with the precession-induced ups and downs of solar radiation in the Northern Hemisphere. The highest temperatures stimulated extreme methane production in wetlands, which are the atmosphere's primary natural source of this greenhouse gas.



CO_2 concentrations, which fluctuated in cycles over the past 350,000 years, varied in response to precession as well as to shifts in the tilt of the earth's rotational axis and in the shape of its orbit. These other cycles occur every 41,000 and 100,000 years, respectively.

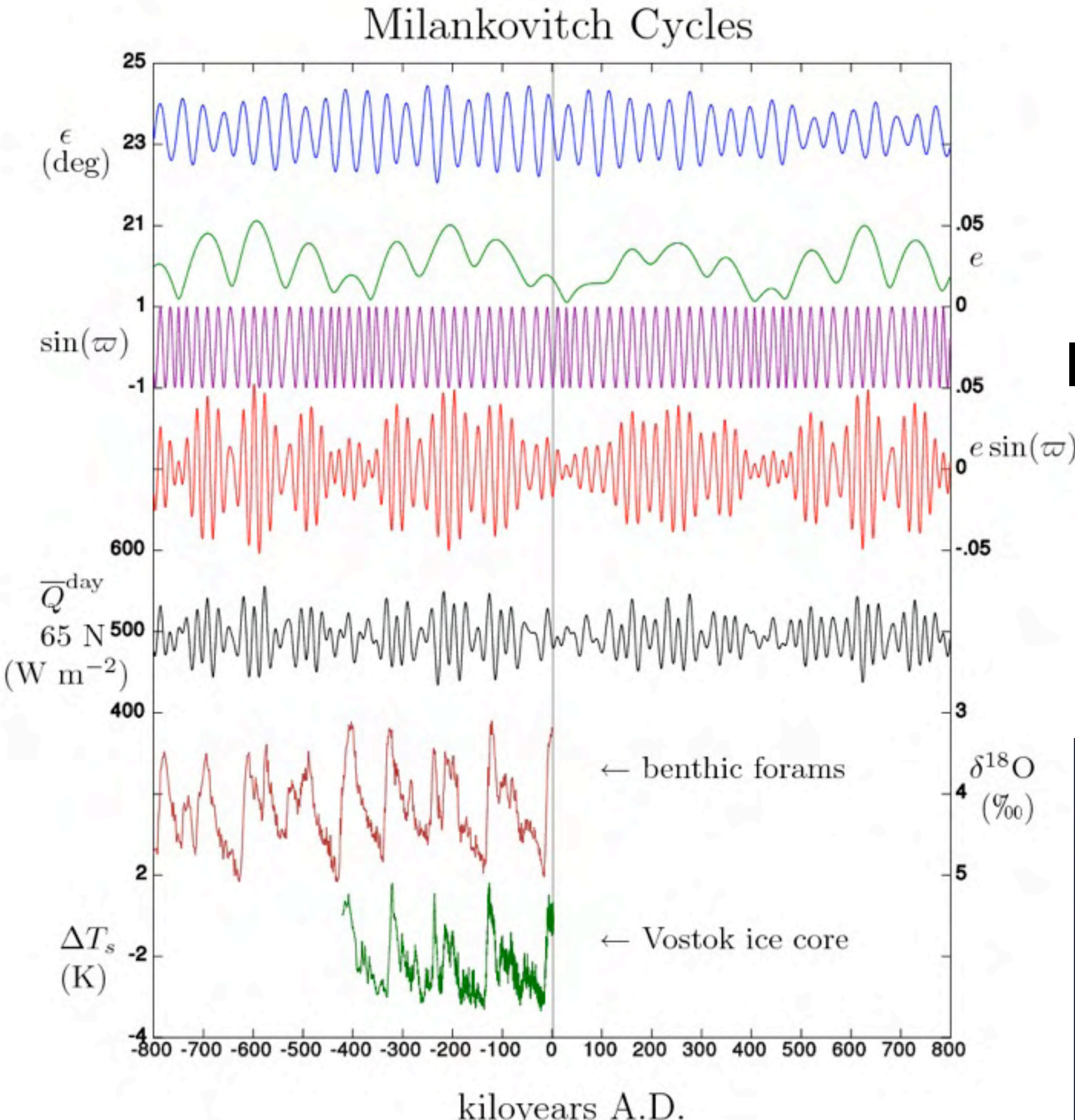
William F. Ruddiman, *Scientific American*, March 2005, p. 46

Astronomical Clues

- Eccentricity of earth orbit varies between near 0 and 0.06 at periods of ~100 ky and 400 ky
- Tilt in earth's axis varies between 22° and 25° with a period of ~41 ky
- Axis precession caused by torque on equatorial bulge: 26 ky
- Precession of the equinoxes: 22 ky

} **Portions of winter hemisphere get 10% more insolation than 11 ky later**

T. J. Crowley, G. R. North, *Paleoclimatology* (Oxford U. Press, New York, 1991), Chapter 7.

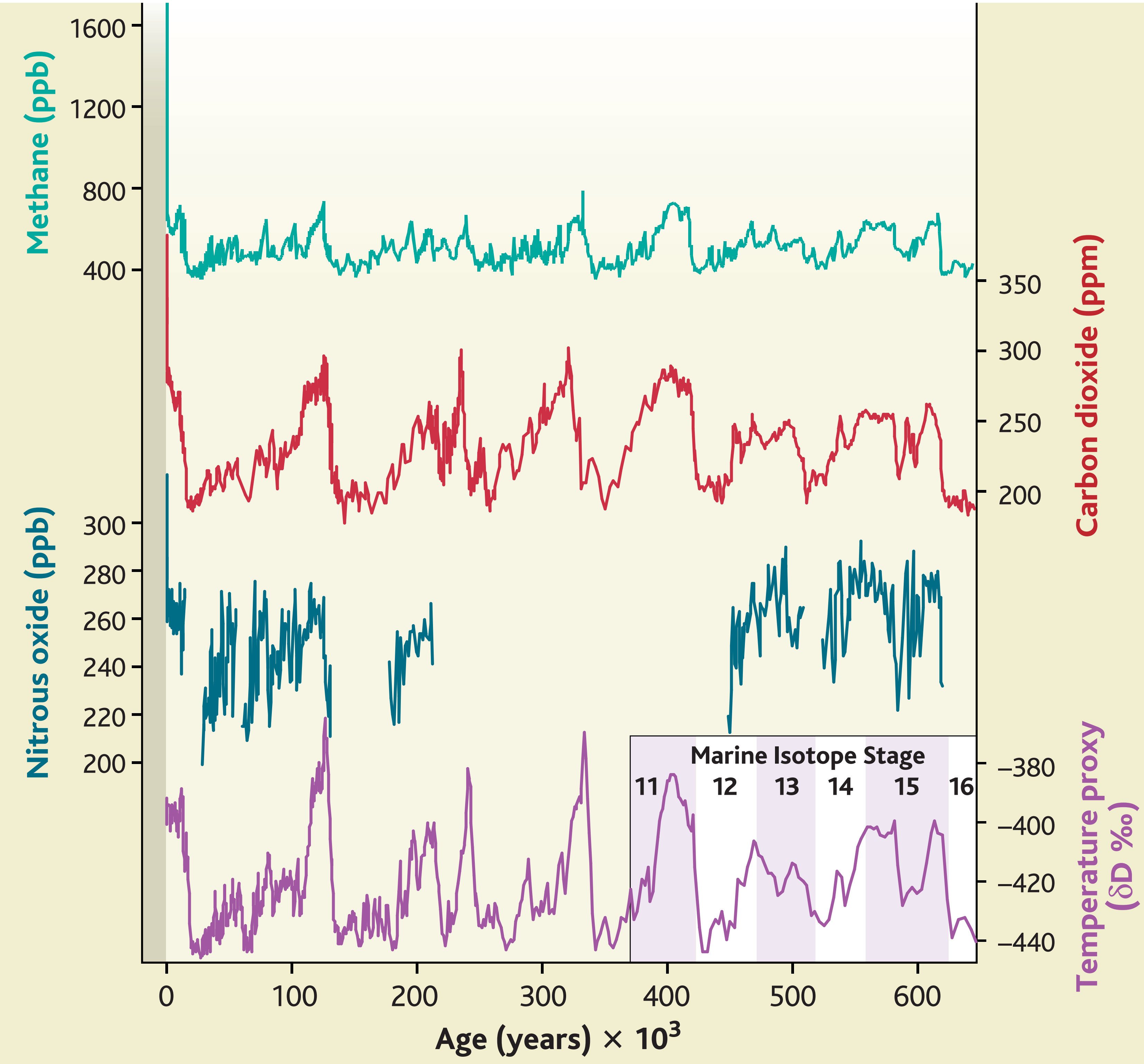


axis tilt (41 ky)

orbit eccentricity

precession (26 ky)

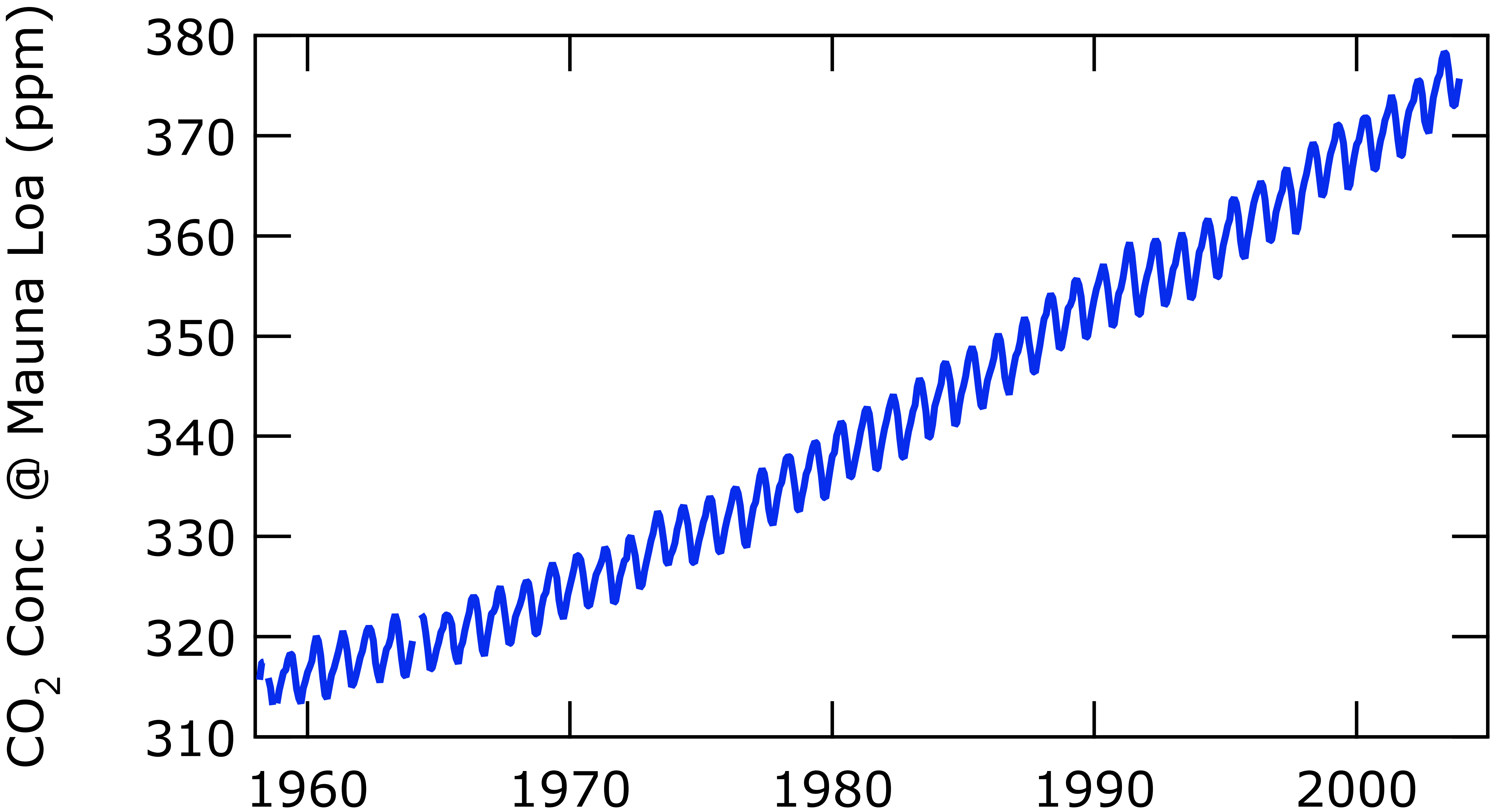
Wikipedia



The long view. The greenhouse gas (CO_2, CH_4, and NO_2) and deuterium (δD) records for the past 650,000 years from EPICA Dome C and other ice cores, with marine isotope stage correlations (labeled at lower right) for stages 11 to 16 (*2*, *3*). δD, a proxy for air temperature, is the deuterium/hydrogen ratio of the ice, expressed as a per mil deviation from the value of an isotope standard (*4*). More positive values indicate warmer conditions. Data for the past 200 years from other ice core records (*20–22*) and direct atmospheric measurements at the South Pole (*23*, *24*) are also included.

Edward J. Brook, *Science* **310**, 25 Nov 2005, p. 1285

Mauna Loa CO_2



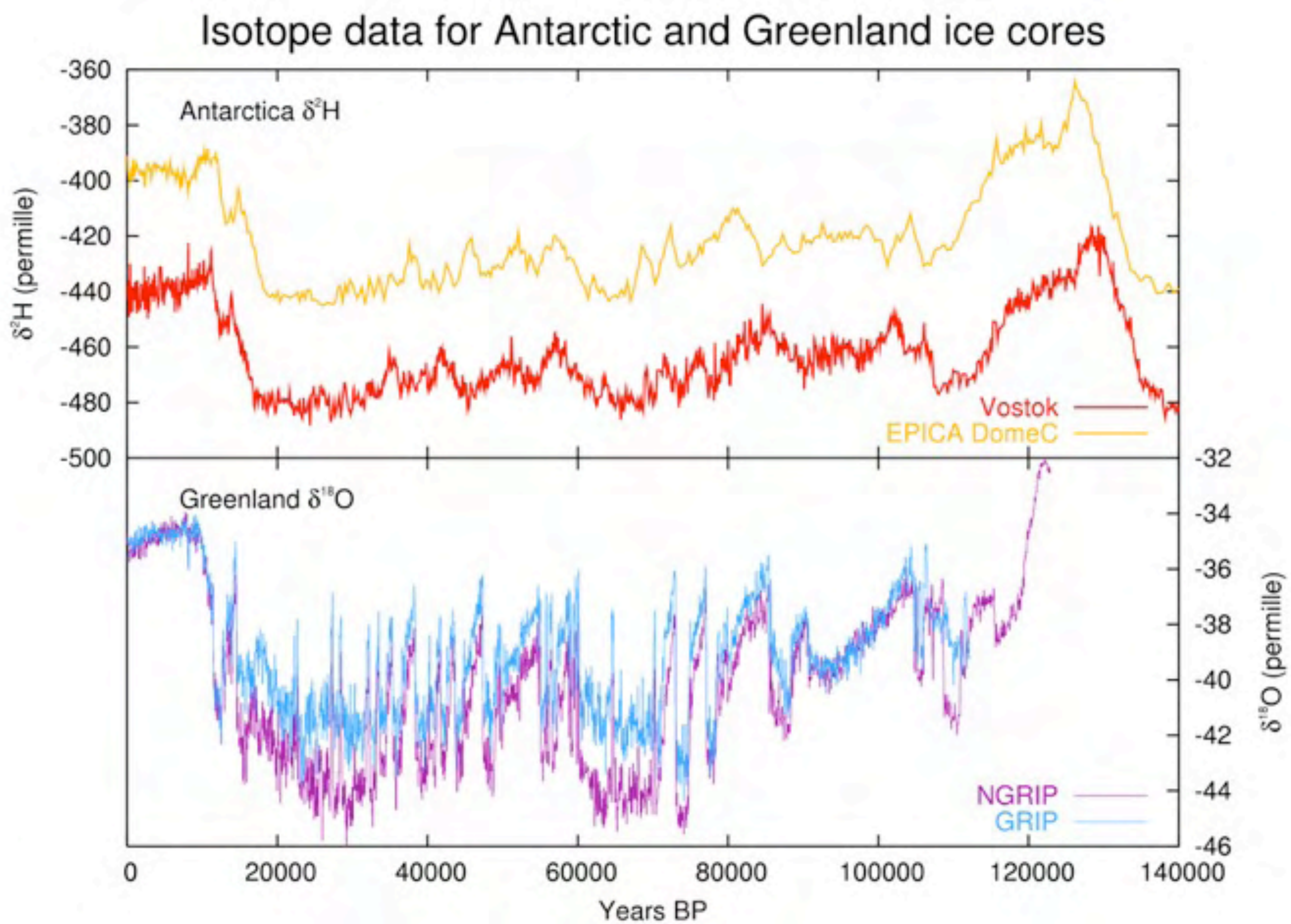
http://cdiac.ornl.gov/ftp/ndp001/maunaloa.co2

Charles Keeling

- Dansgaard-Oeschger events: in Northern Hemisphere, rapid rise (a few decades), followed by gradual cooling over a longer period

- 23 D/O events in 110 - 23 ky BP

- Related to Heinrich events, which are disruptions in the North Atlantic thermohaline circulation



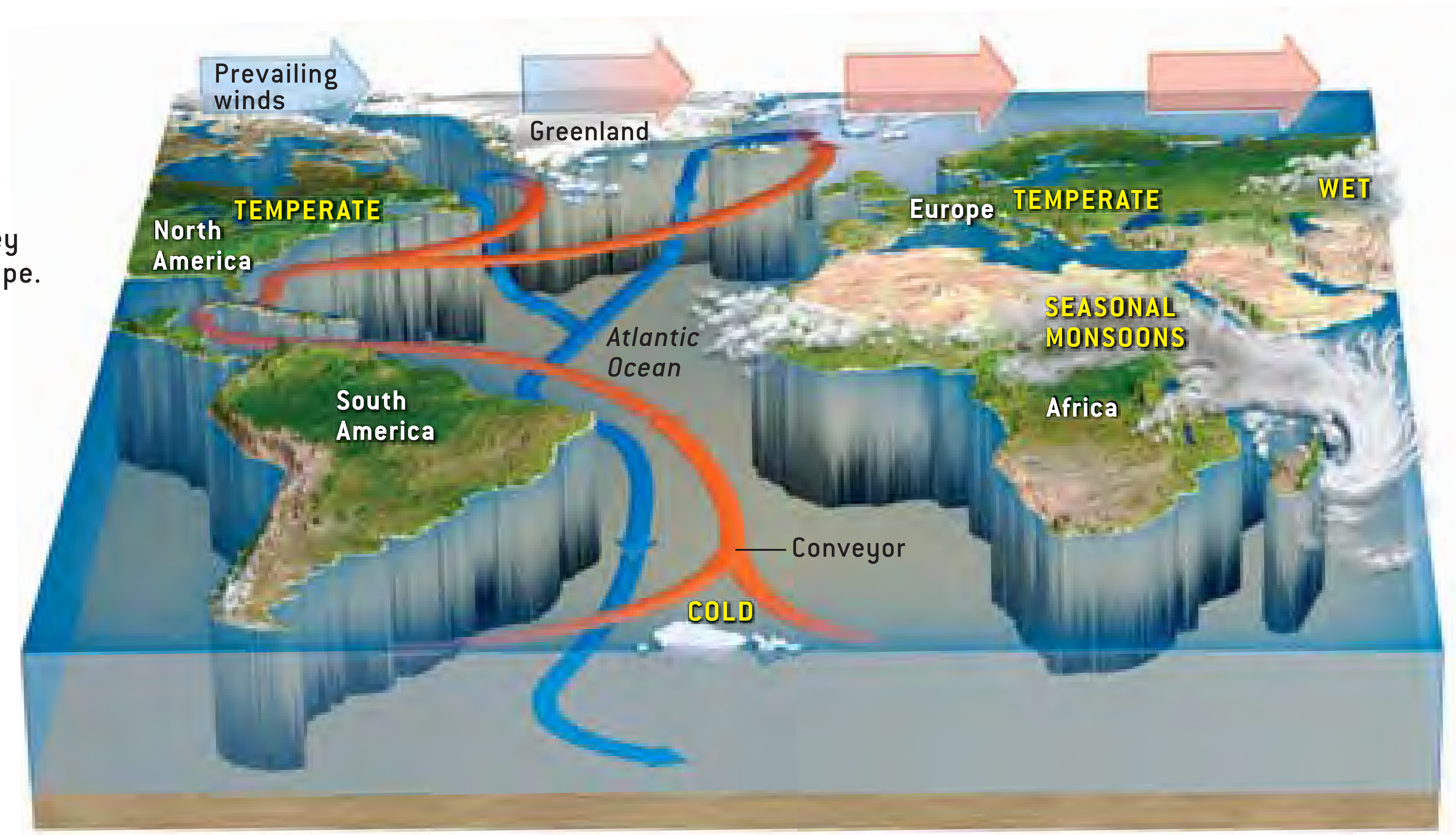
http://en.wikipedia.org/wiki/Dansgaard-Oeschger_events
accessed 20 February 2006

MELTING TOWARD A COLD SNAP?

As global warming continues to heat up the planet, many scientists fear that large pulses of freshwater melting off the Greenland ice sheet and other frozen northern landmasses could obstruct the so-called North Atlantic conveyor, the system of ocean currents that brings warmth to Europe and strongly influences climate elsewhere in the world. A conveyor shutdown—or even a significant slowdown—could cool the North Atlantic region even as global temperatures continue to rise. Other challenging and abrupt climate changes would almost certainly result.

CONVEYOR ON

Salty ocean currents (*red*) flowing northward from the tropics warm prevailing winds (*large arrows*) as they blow eastward toward Europe. The heat-bearing currents, which are dense, become even denser as they lose heat to the atmosphere. Eventually the cold, salty water becomes dense enough to sink near Greenland. It then migrates southward along the seafloor (*blue*), leaving a void that draws more warm water from the south to take its place.



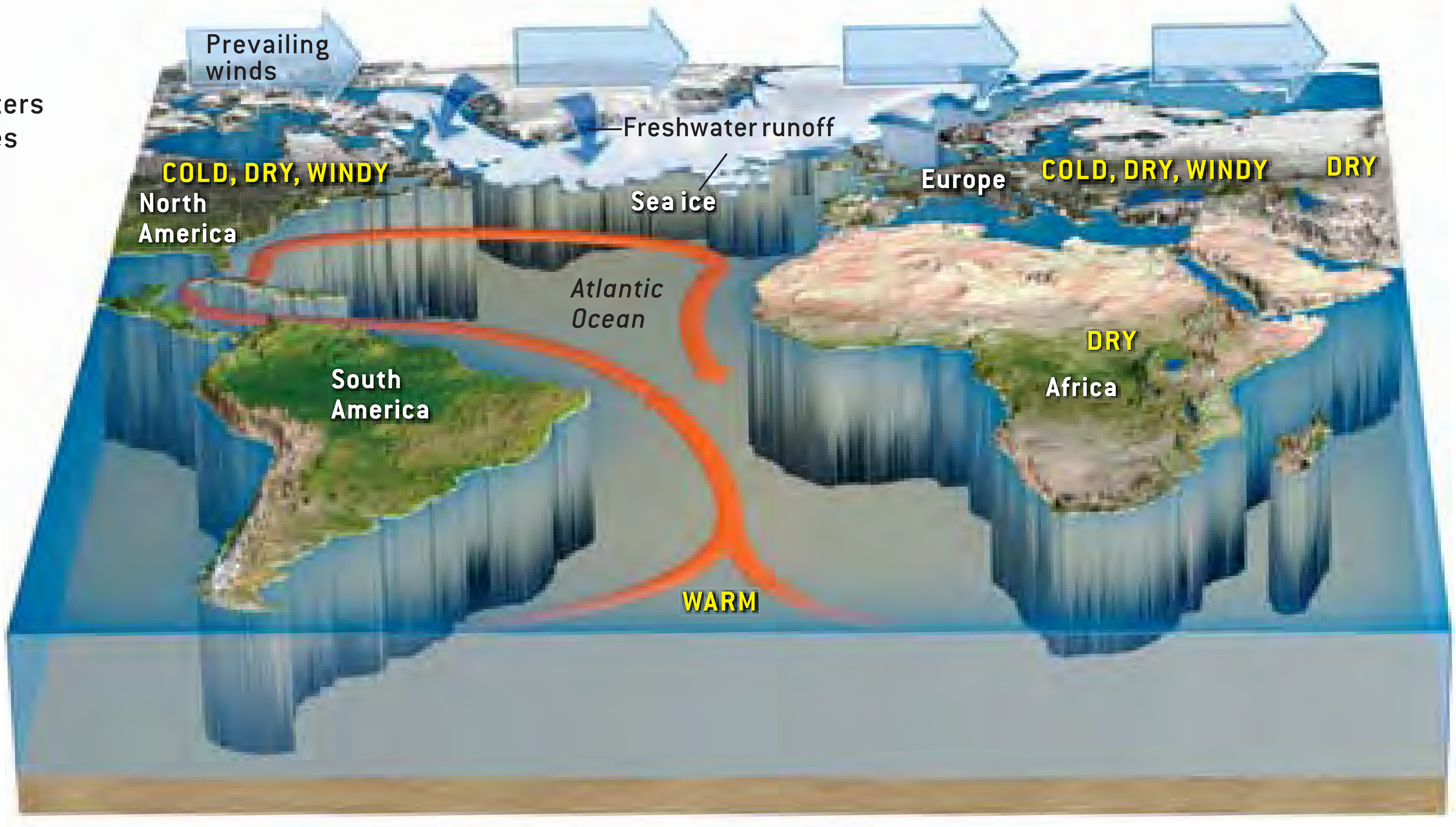
RESULTING CLIMATE

When the North Atlantic conveyor is active, temperate conditions with relatively warm winters enable rich agricultural production in much of Europe and North America. Seasonal monsoons fuel growing seasons in broad swaths of Africa and the Far East. Central Asia is wet, and Antarctica and the South Atlantic are typically cold.

Richard B. Alley, *Scientific American*, November 2004, p. 62

CONVEYOR OFF

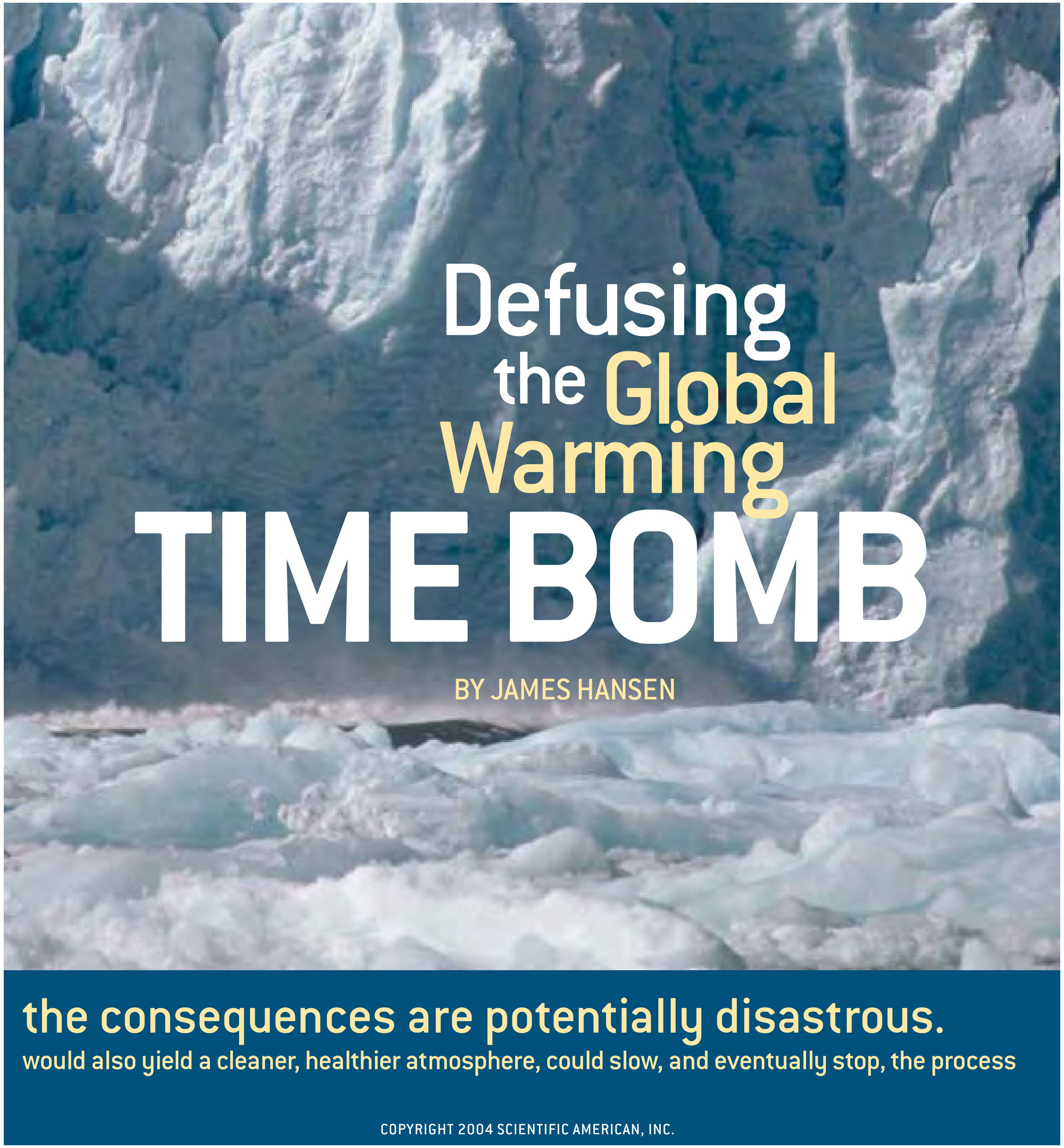
If too much freshwater enters the North Atlantic, it dilutes the salty currents from the south. Surface waters no longer become dense enough to sink, no matter how cold the water gets, and the conveyor shuts down or slows. Prevailing winds now carry frigid air eastward (*large arrows*). This cold trend could endure for decades or more—until southern waters become salty enough to overwhelm the fresher water up north, restarting the conveyor in an enormous rush.



RESULTING CLIMATE

As the conveyor grows quiet, winters become harsher in much of Europe and North America, and agriculture suffers. These regions, along with those that usually rely on seasonal monsoons, suffer from droughts sometimes enhanced by stronger winds. Central Asia gets drier, and many regions in the Southern Hemisphere become warmer than usual.

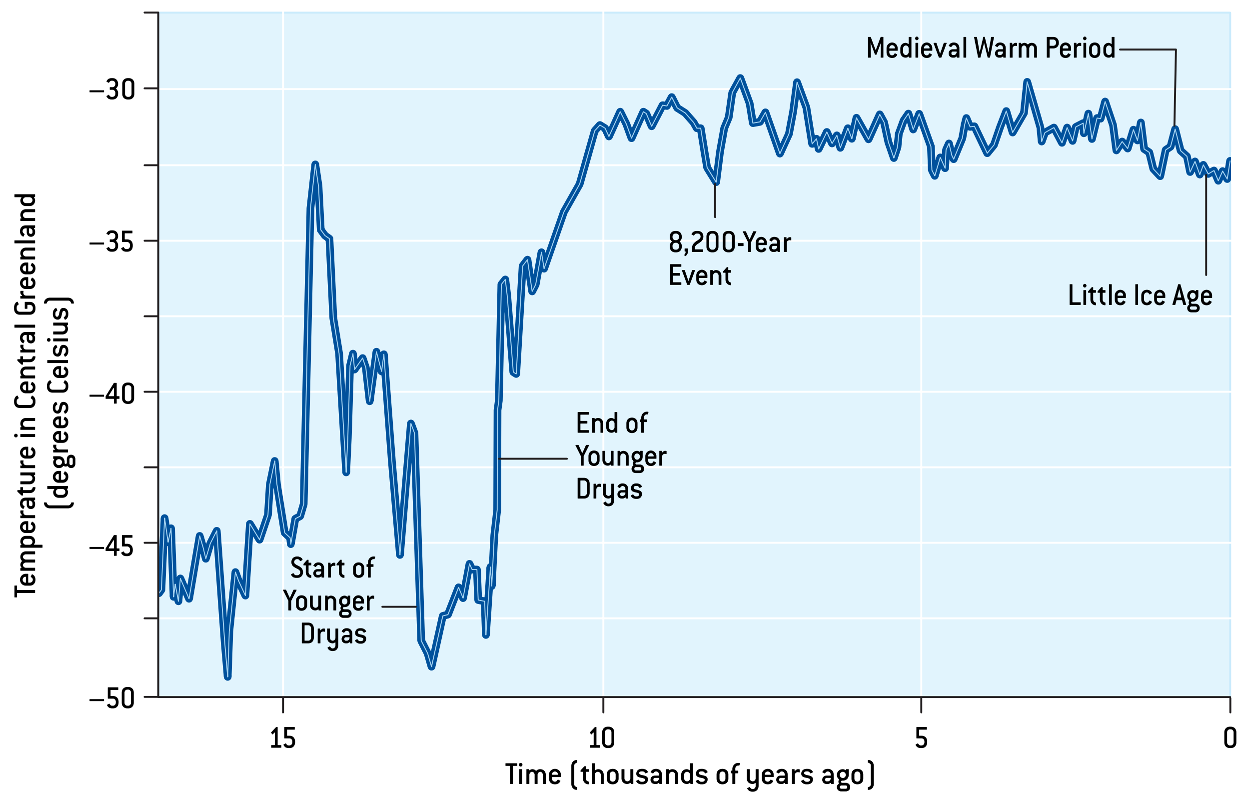
Richard B. Alley, *Scientific American*, November 2004, p. 62



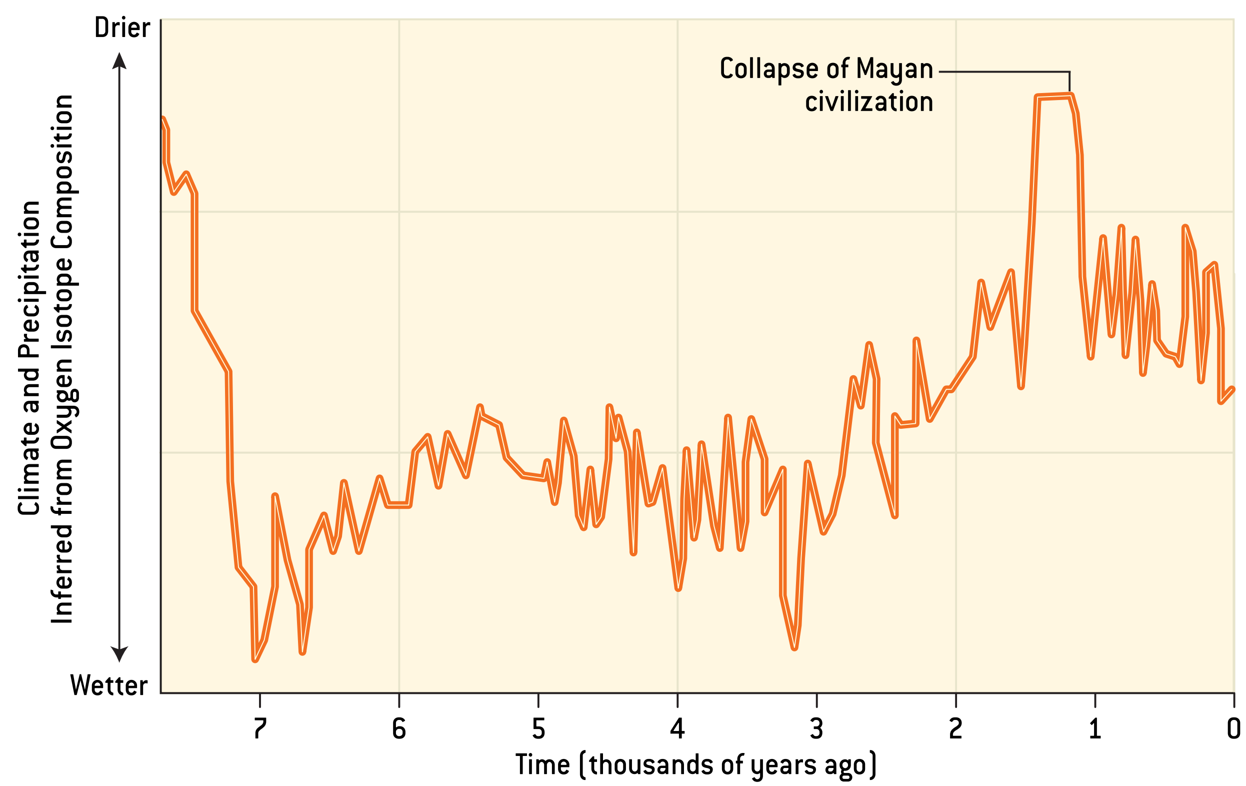
James Hansen, *Scientific American*, March 2004, p. 68

PAST AS PROLOGUE?

Abrupt climate change has marked the earth's history for eons. Ice cores from Greenland, for instance, reveal that wild temperature swings (*top left*) punctuated the gradual warming that brought the planet out of the last ice age starting about 18,000 years ago. Fossil shells in lake sediments from Mexico's Yucatán Peninsula record sudden and severe droughts (*bottom left*) because a diagnostic ratio of oxygen isotopes in the shells shoots up when more water evaporates from the lake than falls as rain. Societies have often suffered as a result of these rapid shifts (*photographs*).



Viking settlement, now in ruins, was among those in Greenland abandoned during an abrupt cold spell called the Little Ice Age.

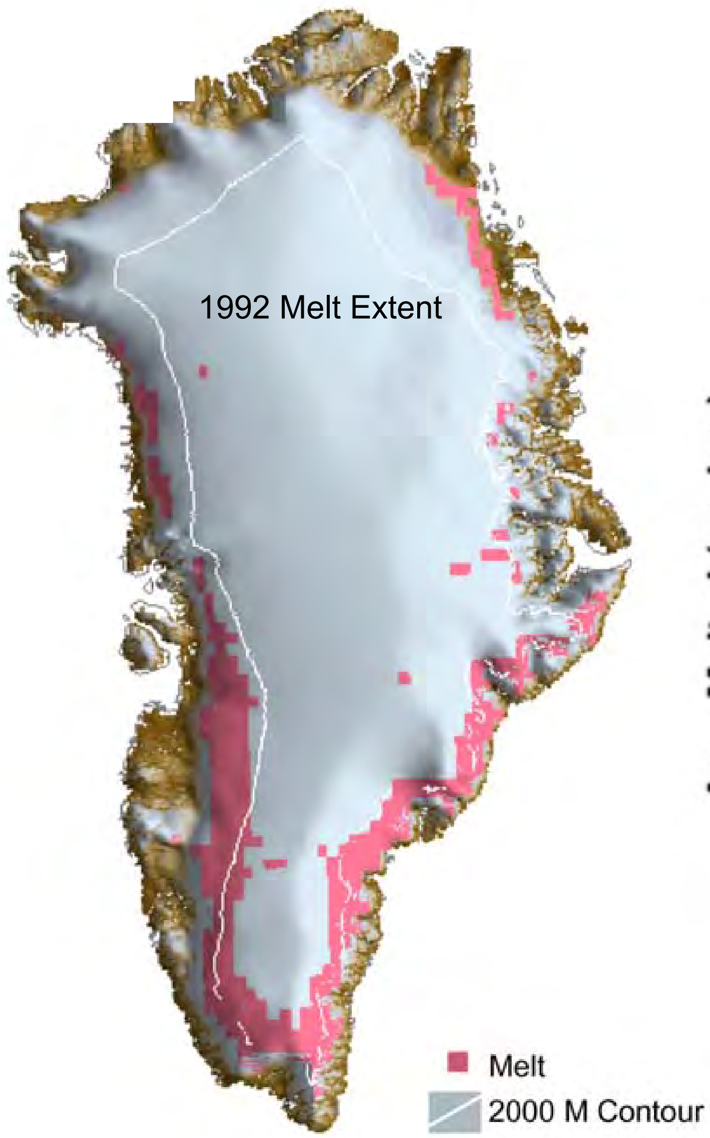


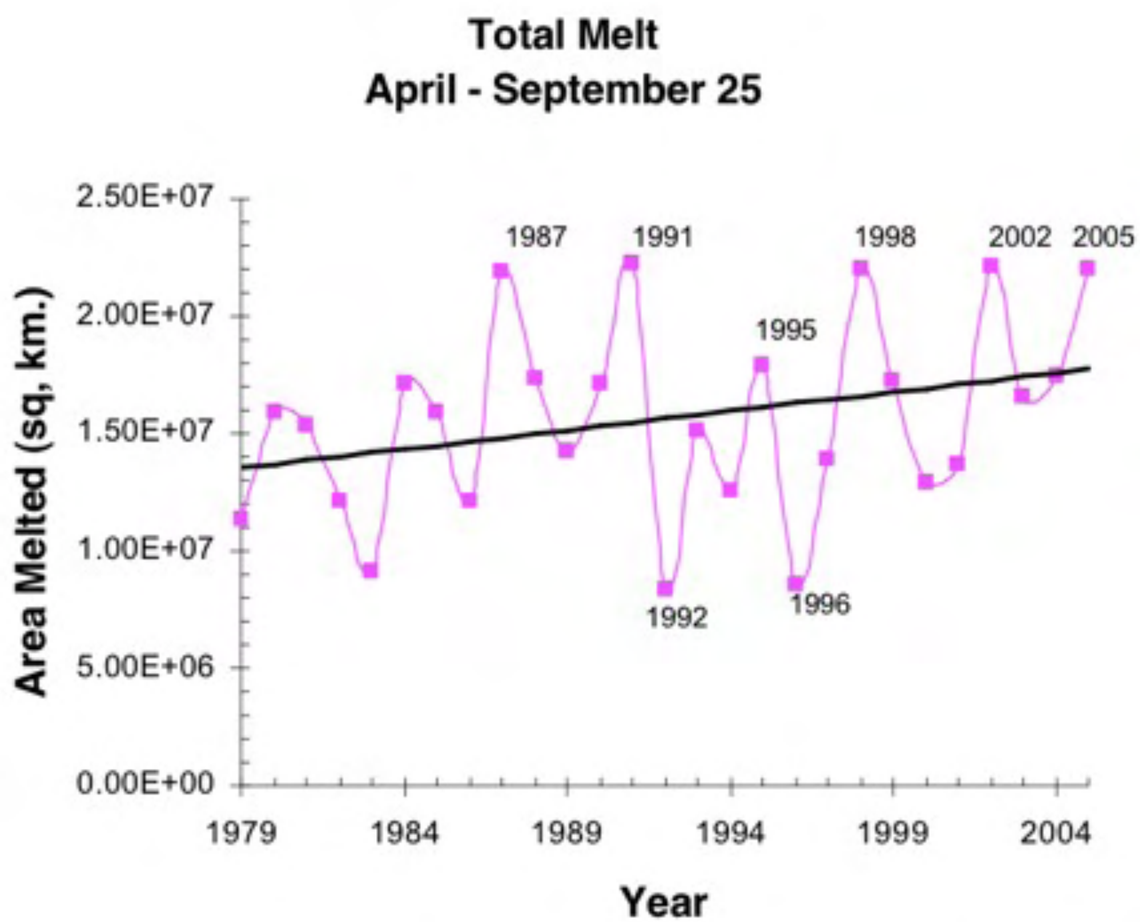
Mayan rain god (*statue in foreground*) was apparently no match for the drought now widely blamed for the collapse of Mayan civilization about 1,100 years ago.

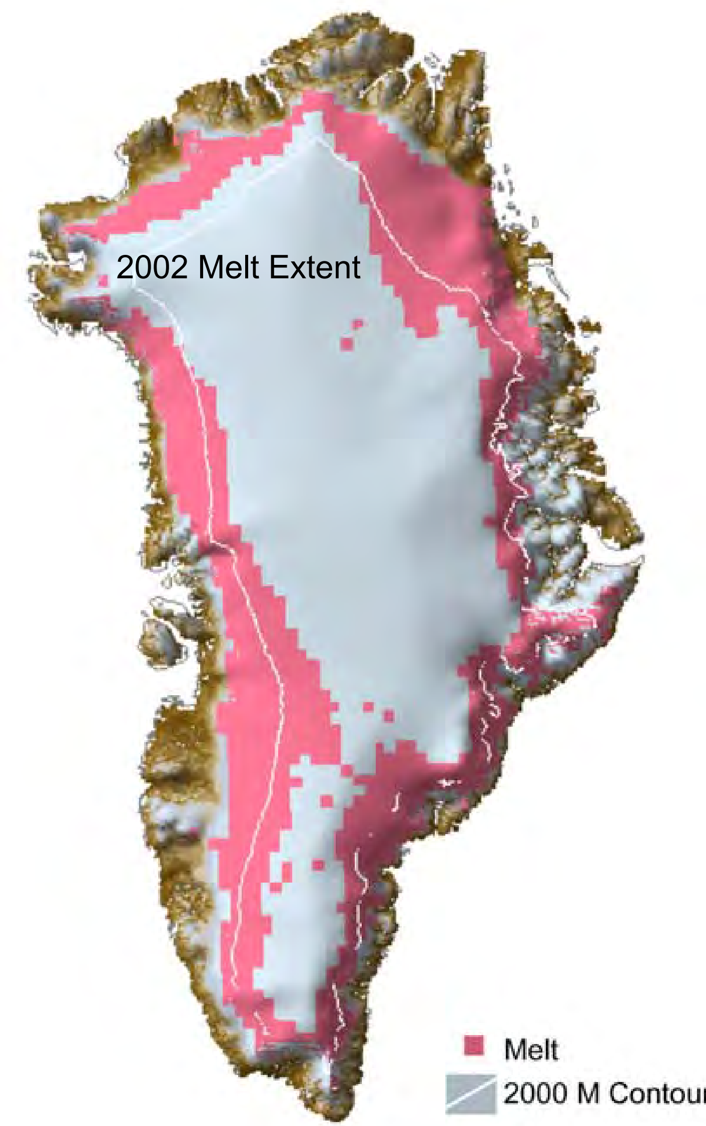
Grinnell Lake
Glacier National Park

http://www.nrmsc.usgs.gov/images/grlake3.jpg

Response of the Greenland Ice Sheet to Climatic Forcing







Greenland ice sheet melt area increased on average by 16% from 1979 to 2002.
The smallest melt extent was observed after the Mt. Pinatubo eruption in 1992

University of Colorado

Konrad Steffen and Russell Huff, University of Colorado at Boulder

CIRES

Extracting a Climate Signal from 169 Glacier Records

J. Oerlemans

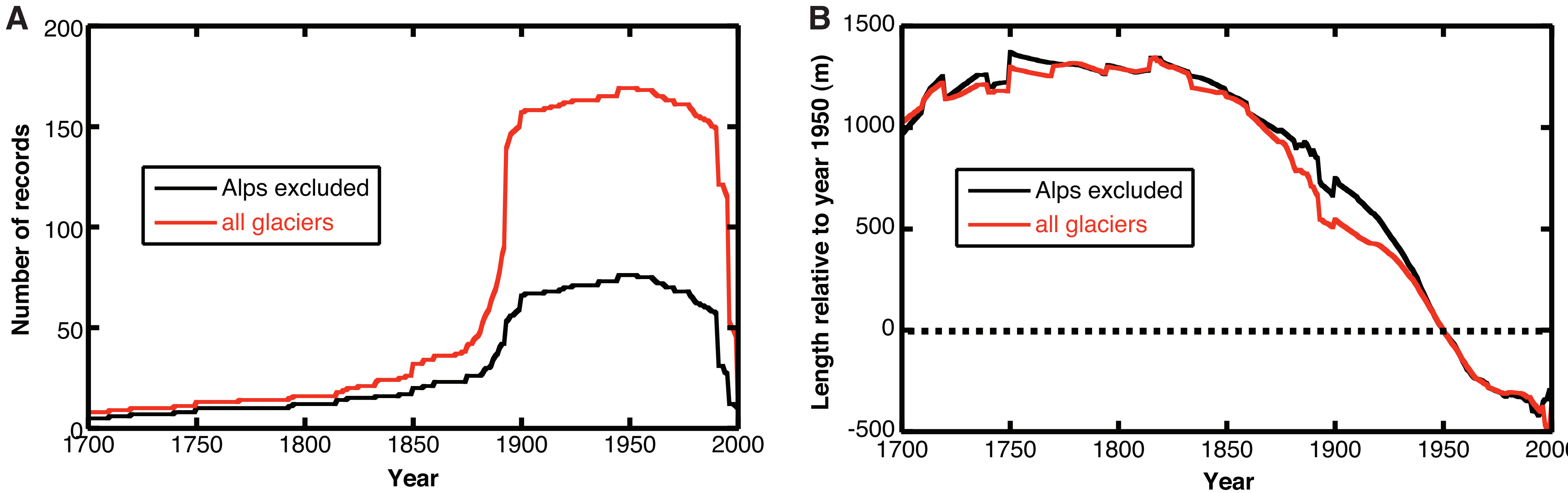
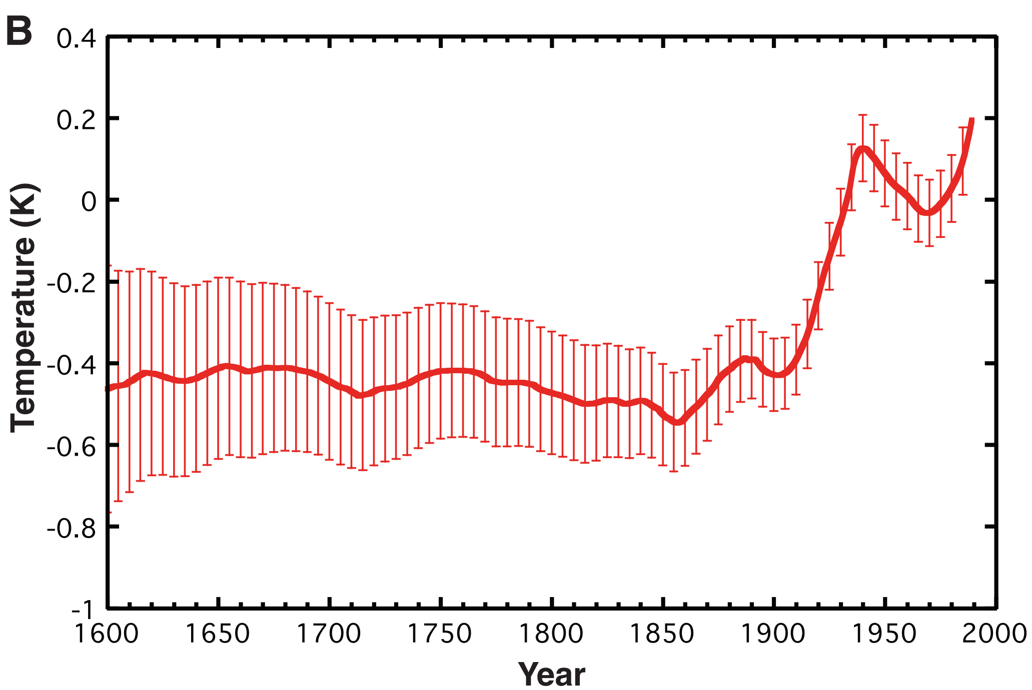


Fig. 2. (**A**) Number of records for the last 300 years. The decline after 1990 is due to a large delay in the reporting and publishing of data in a suitable form. (**B**) Stacked records of glacier length. Irregularities occur when a glacier with a large length change is added. However, this does not necessarily involve a large change in climatic conditions because glaciers exhibiting large changes are normally those that have a large climate sensitivity (and thus respond in a more pronounced way to, for instance, a temperature change). After 1900, the irregularities disappear because the number of glaciers in the sample increases strongly.



(**B**) Best estimate of the global mean temperature obtained by combining the weighted global mean temperature from 1834 with the stacked temperature record before 1834. The band indicates the estimated standard deviation.

- Glacier length has a response time of 50-100 y
- Depends on *T* much more than precipitation

J. Oerlemans, *Science* **308** 29 April 2005, p. 675

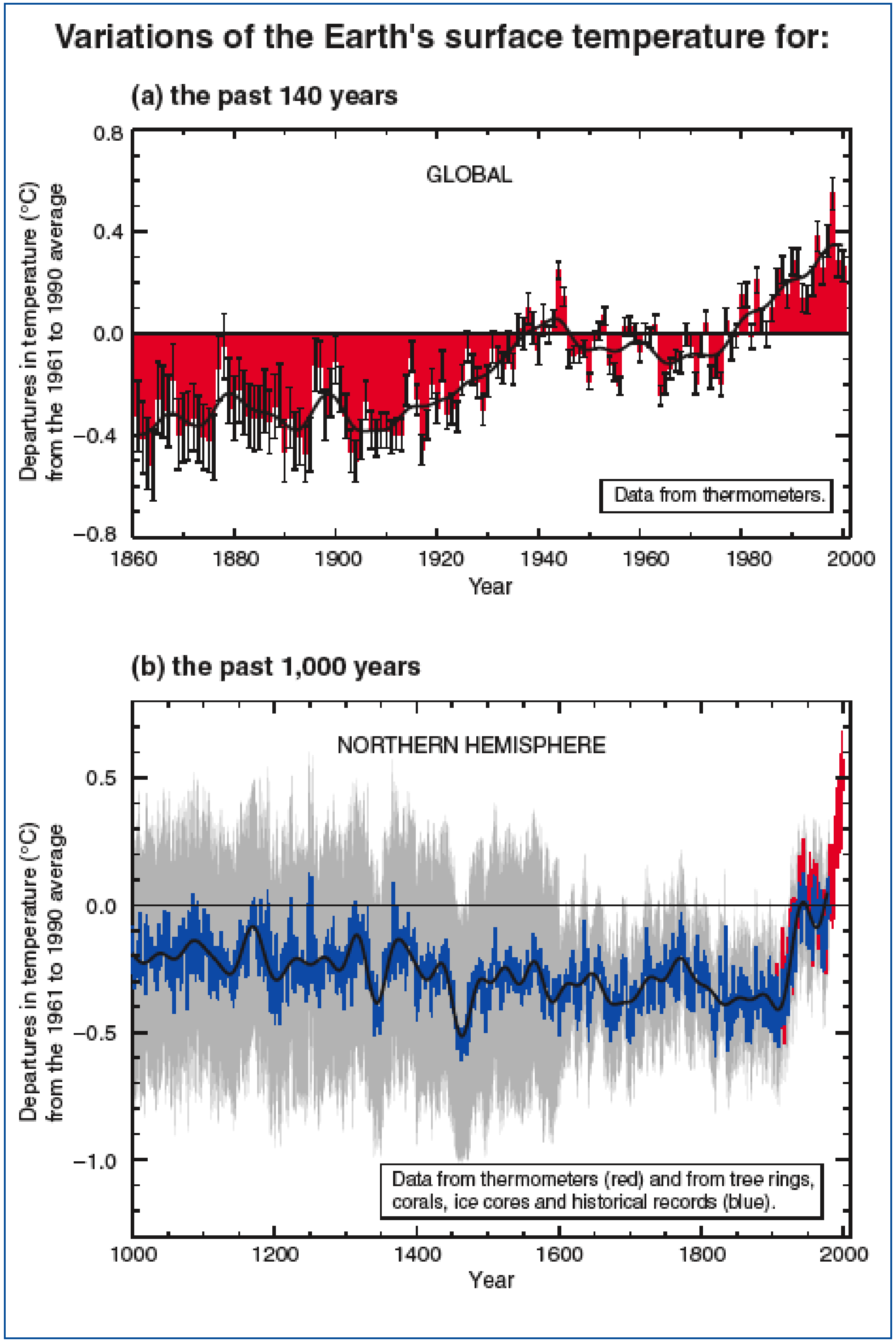


Figure 1: Variations of the Earth's surface temperature over the last 140 years and the last millennium.
(a) The Earth's surface temperature is shown year by year (red bars) and approximately decade by decade (black line, a filtered annual curve suppressing fluctuations below near decadal time-scales). There are uncertainties in the annual data (thin black whisker bars represent the 95% confidence range) due to data gaps, random instrumental errors and uncertainties, uncertainties in bias corrections in the ocean surface temperature data and also in adjustments for urbanisation over the land. Over both the last 140 years and 100 years, the best estimate is that the global average surface temperature has increased by 0.6 ± 0.2°C.

(b) Additionally, the year by year (blue curve) and 50 year average (black curve) variations of the average surface temperature of the Northern Hemisphere for the past 1000 years have been reconstructed from "proxy" data calibrated against thermometer data (see list of the main proxy data in the diagram). The 95% confidence range in the annual data is represented by the grey region. These uncertainties increase in more distant times and are always much larger than in the instrumental record due to the use of relatively sparse proxy data. Nevertheless the rate and duration of warming of the 20th century has been much greater than in any of the previous nine centuries. Similarly, it is likely [7] that the 1990s have been the warmest decade and 1998 the warmest year of the millennium.
[Based upon (a) Chapter 2, Figure 2.7c and (b) Chapter 2, Figure 2.20]

Summary for Policymakers
A Report of Working Group I of the Intergovernmental Panel on Climate Change

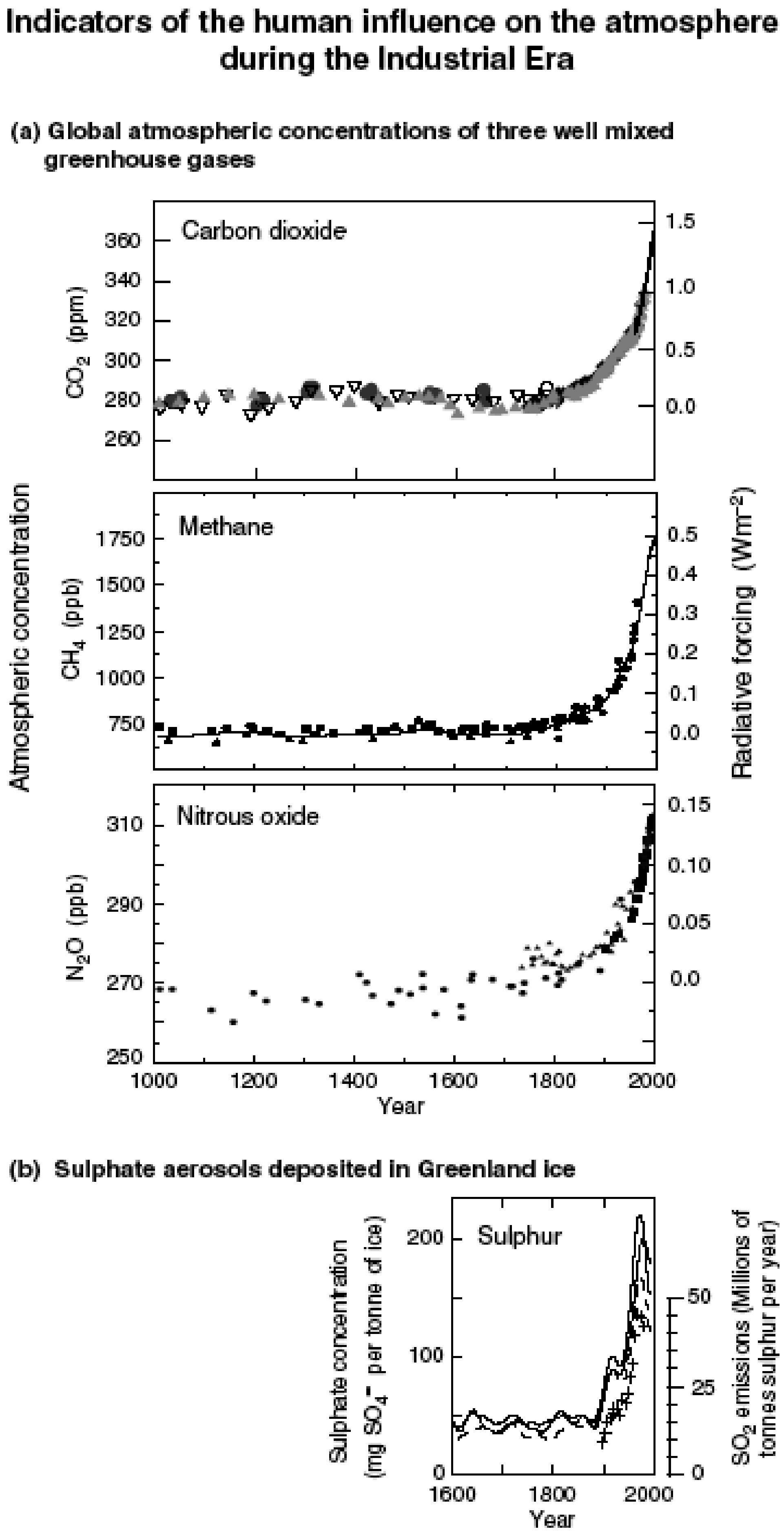
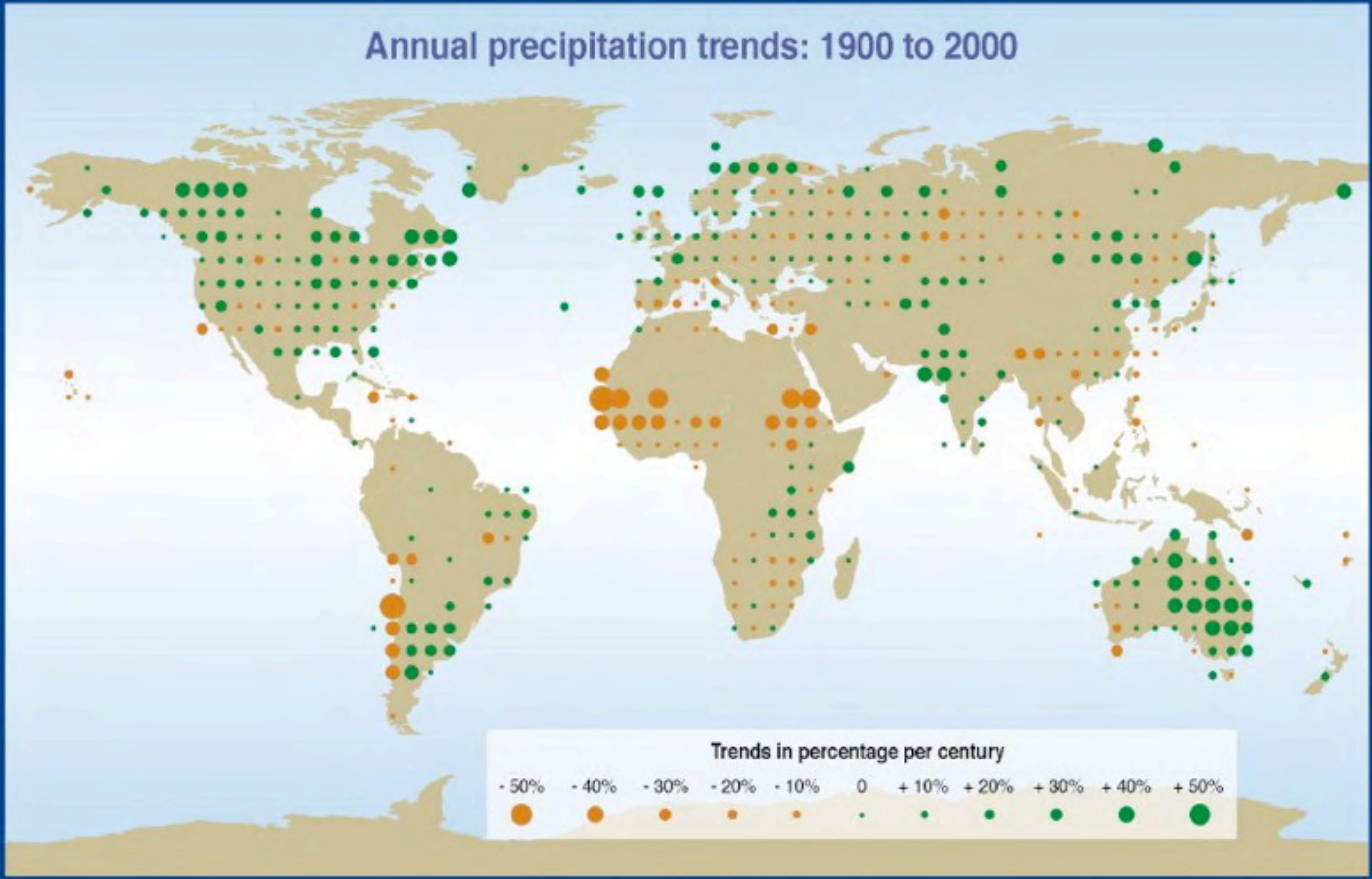


Figure 2: Long records of past changes in atmospheric composition provide the context for the influence of anthropogenic emissions. (a) shows changes in the atmospheric concentrations of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) over the past 1000 years. The ice core and firn data for several sites in Antarctica and Greenland (shown by different symbols) are supplemented with the data from direct atmospheric samples over the past few decades (shown by the line for CO2 and incorporated in the curve representing the global average of CH4). The estimated positive radiative forcing of the climate system from these gases is indicated on the righthand scale. Since these gases have atmospheric lifetimes of a decade or more, they are well mixed, and their concentrations reflect emissions from sources throughout the globe. All three records show effects of the large and increasing growth in anthropogenic emissions during the Industrial Era. (b) illustrates the influence of industrial emissions on atmospheric sulphate concentrations, which produce negative radiative forcing. Shown is the time history of the concentrations of sulphate, not in the atmosphere but in ice cores in Greenland (shown by lines; from which the episodic effects of volcanic eruptions have been removed). Such data indicate the local deposition of sulphate aerosols at the site, reflecting sulphur dioxide (SO2) emissions at mid-latitudes in the Northern Hemisphere. This record, albeit more regional than that of the globally-mixed greenhouse gases, demonstrates the large growth in anthropogenic SO2 emissions during the Industrial Era. The pluses denote the relevant regional estimated SO2 emissions (right-hand scale). [Based upon (a) Chapter 3, Figure 3.2b (CO2); Chapter 4, Figure 4.1a and b (CH4) and Chapter 4, Figure 4.2 (N2O) and (b) Chapter 5, Figure 5.4a]

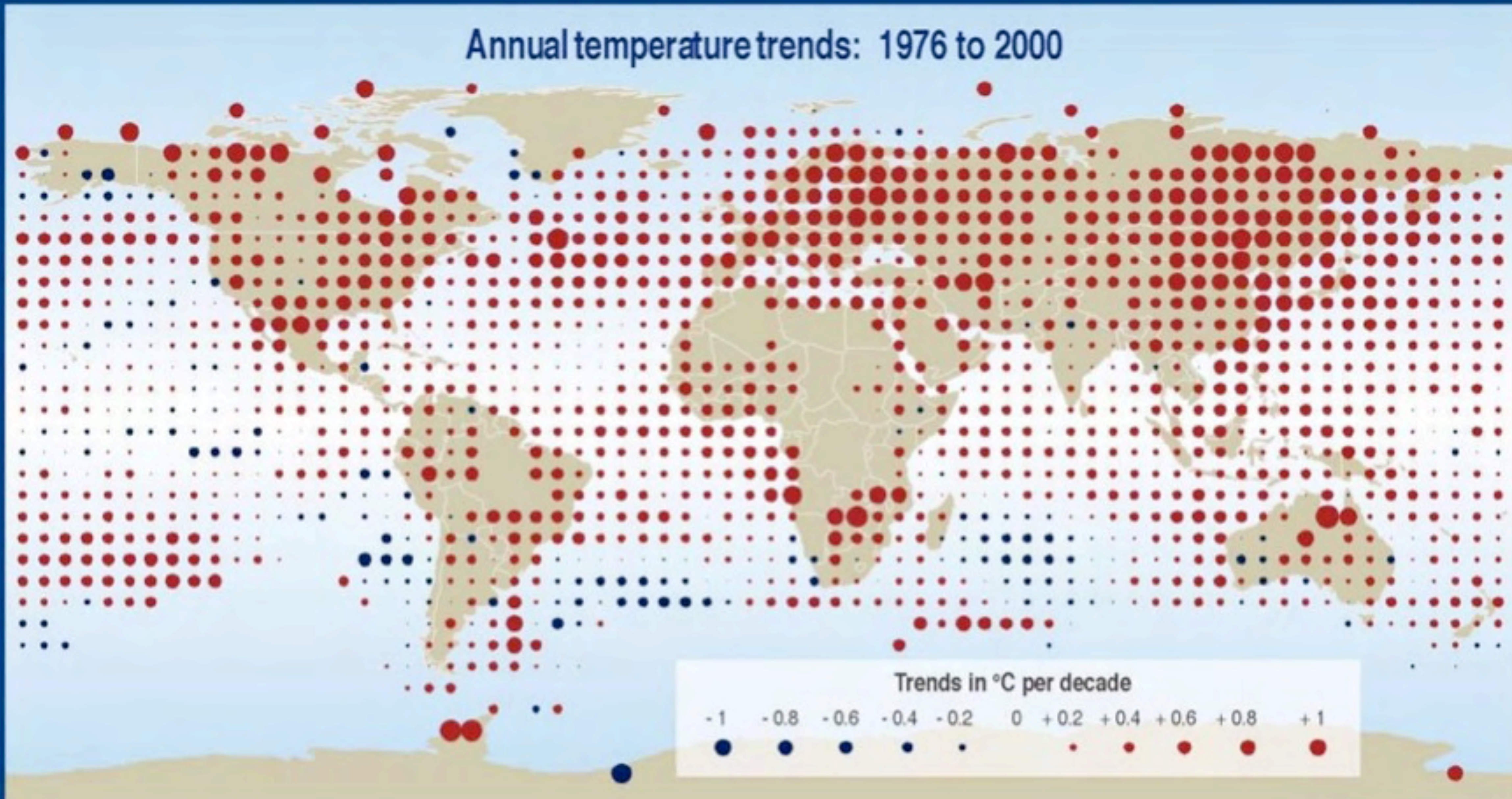


SYR - FIGURE 2-6a

WMO UNEP

IPCC

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

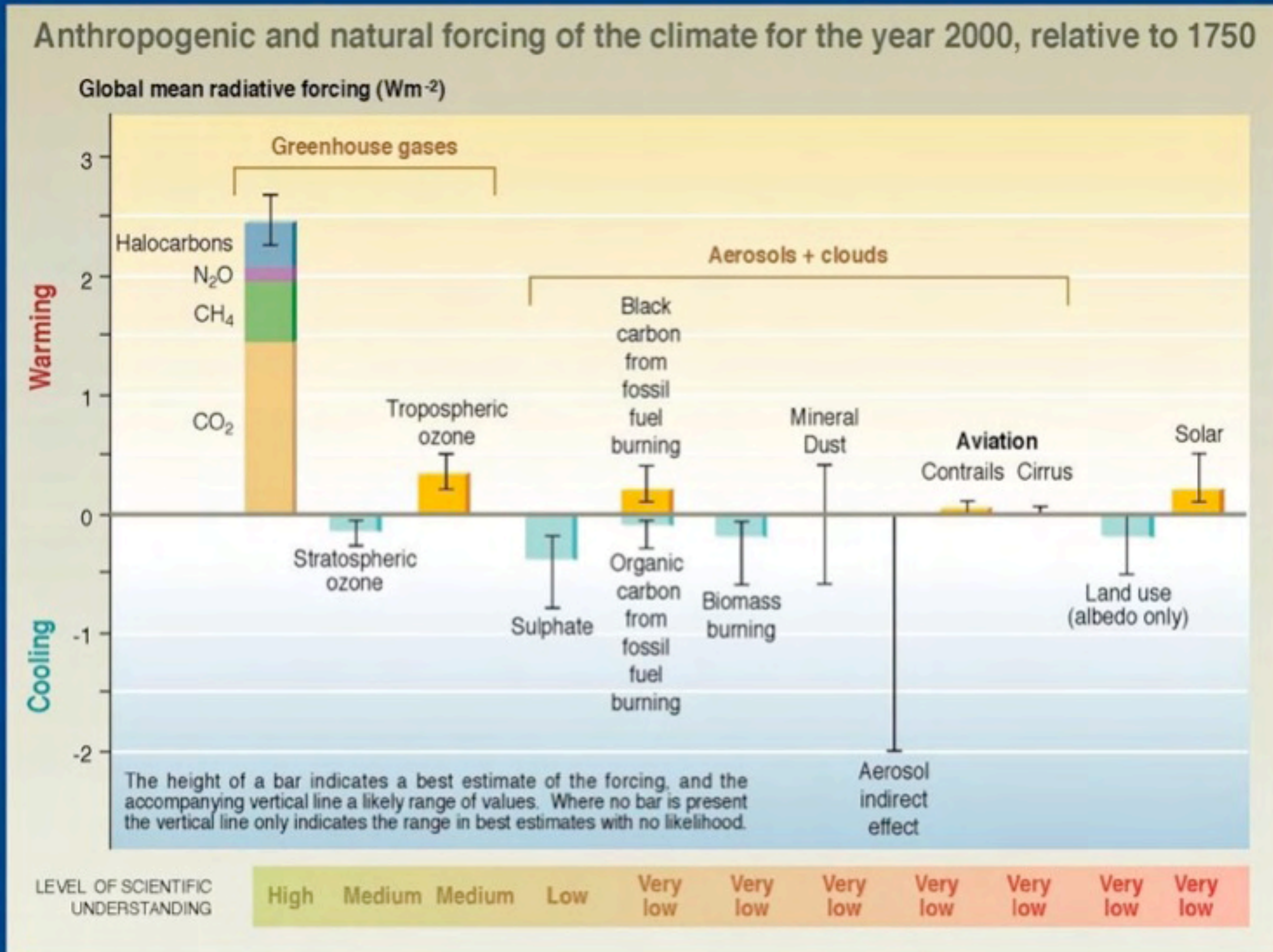


SYR - FIGURE 2-6b

IPCC

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP



SYR - FIGURE 2-2

WMO UNEP

IPCC

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

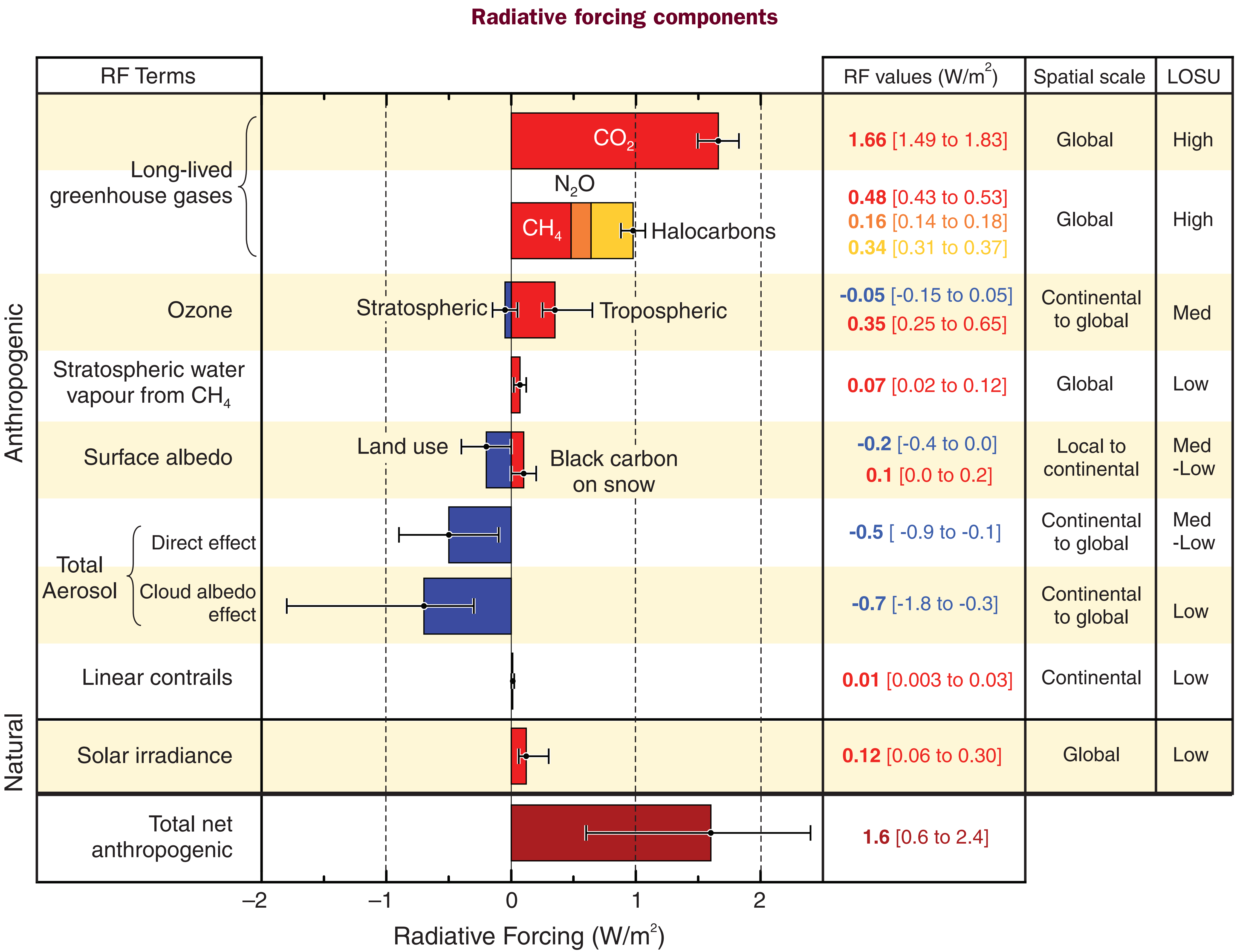


Figure 2.4. *Global average radiative forcing (RF) in 2005 (best estimates and 5 to 95% uncertainty ranges) with respect to 1750 for CO_2, CH_4, N_2O and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU). Aerosols from explosive volcanic eruptions contribute an additional episodic cooling term for a few years following an eruption. The range for linear contrails does not include other possible effects of aviation on cloudiness. {WGI Figure SPM.2}*

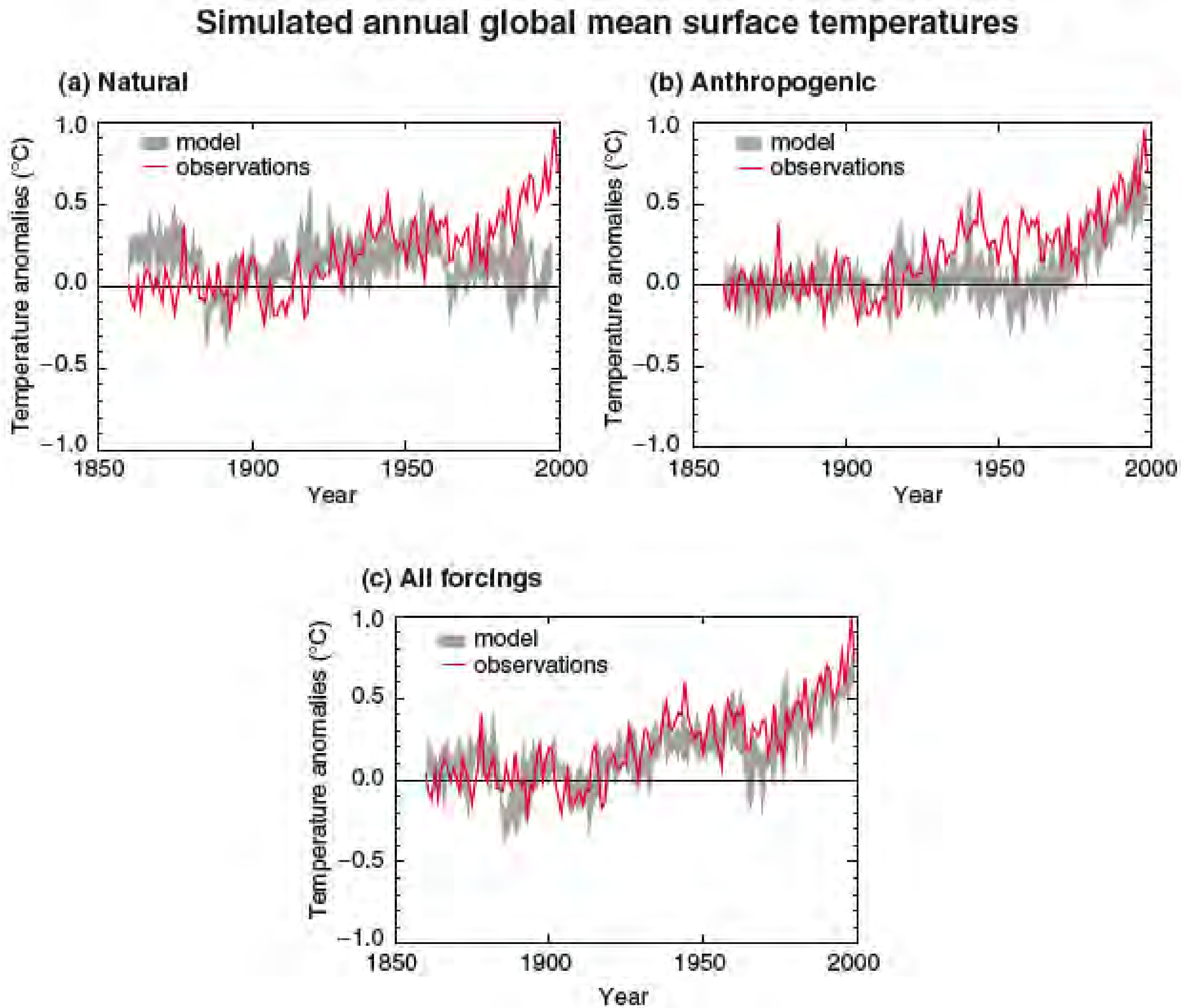
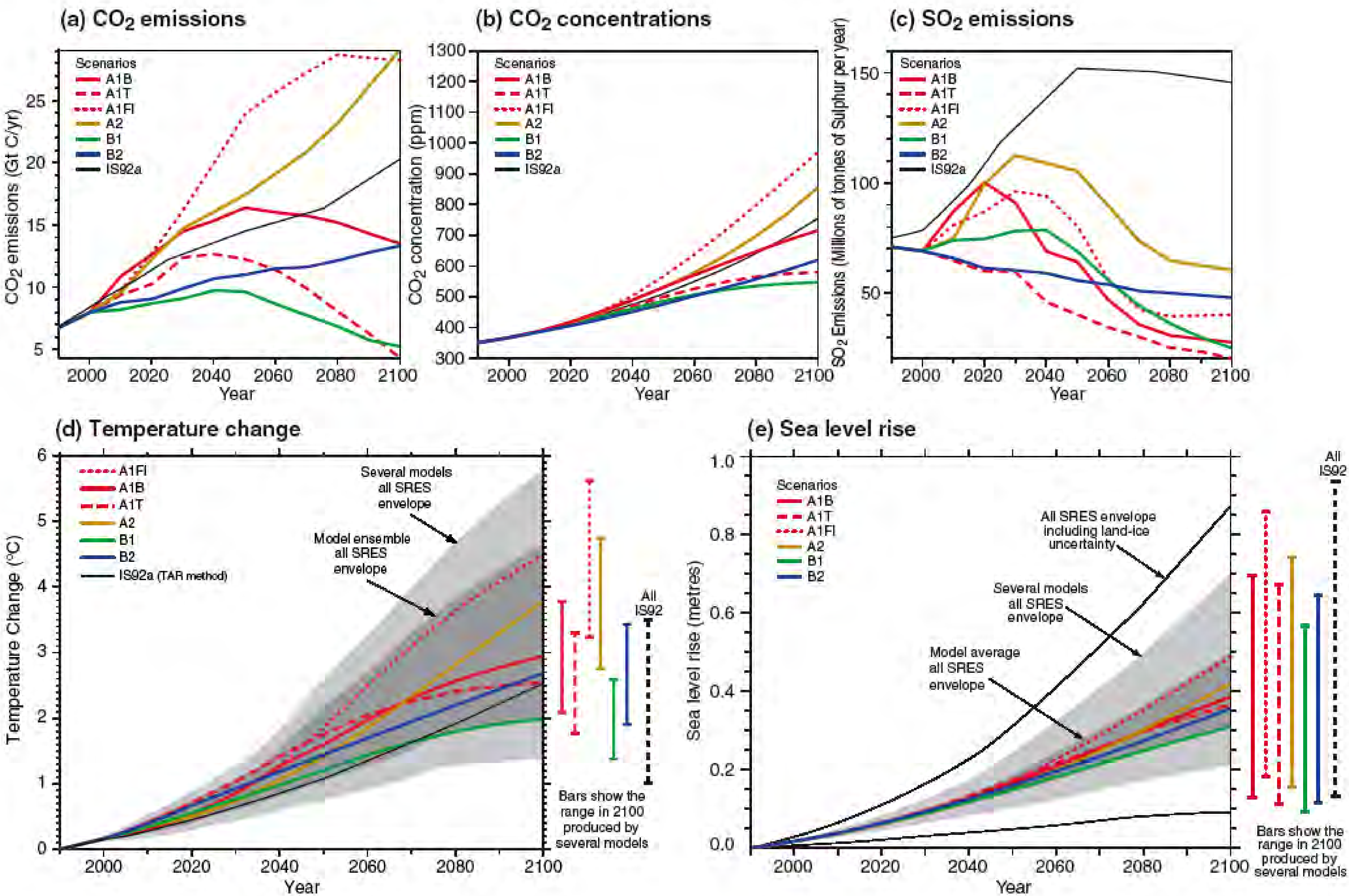


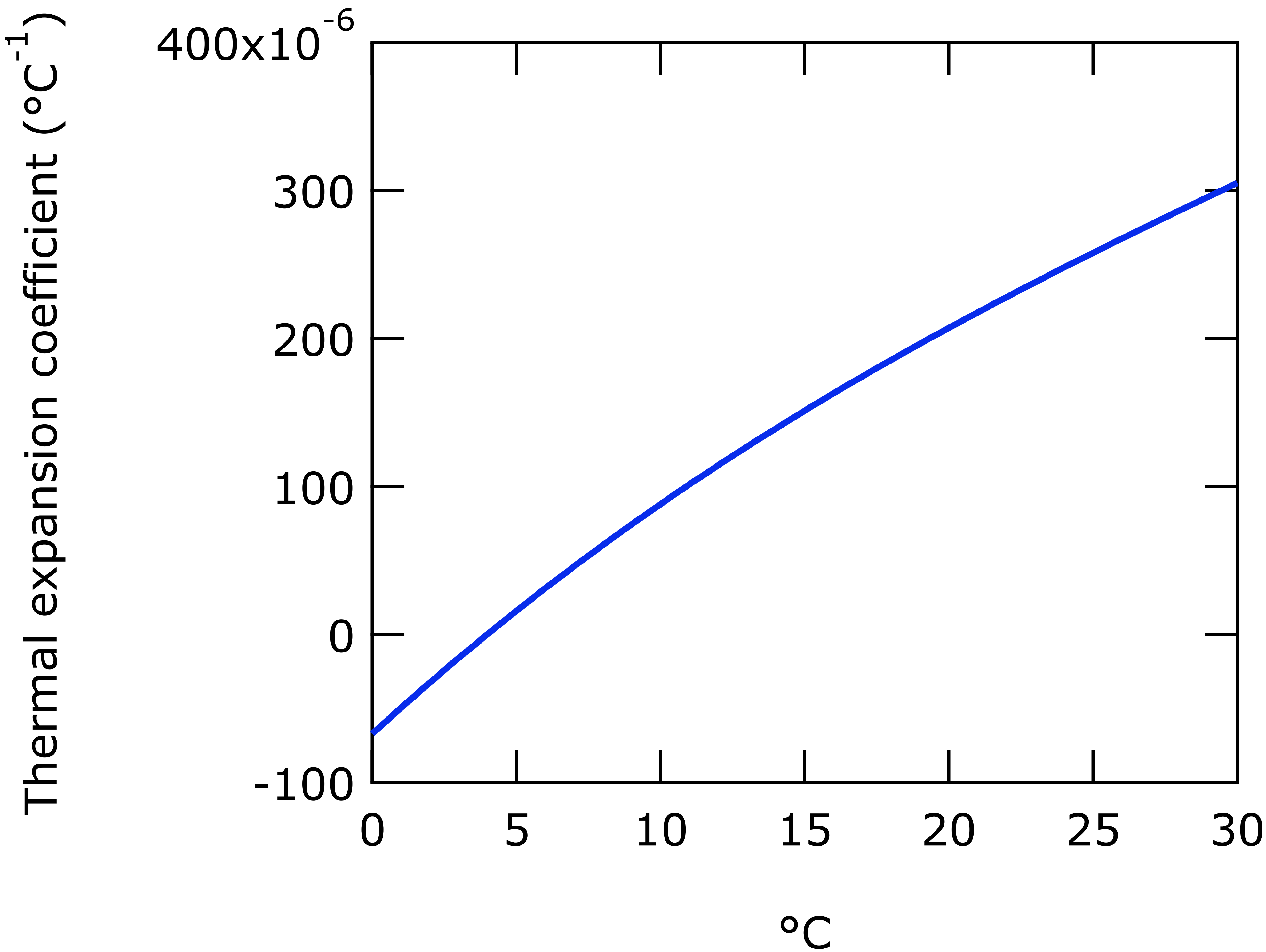
Figure 4: Simulating the Earth's temperature variations, and comparing the results to measured changes, can provide insight into the underlying causes of the major changes.

A climate model can be used to simulate the temperature changes that occur both from natural and anthropogenic causes. The simulations represented by the band in (a) were done with only natural forcings: solar variation and volcanic activity. Those encompassed by the band in (b) were done with anthropogenic forcings: greenhouse gases and an estimate of sulphate aerosols, and those encompassed by the band in (c) were done with both natural and anthropogenic forcings included. From (b), it can be seen that inclusion of anthropogenic forcings provides a plausible explanation for a substantial part of the observed temperature changes over the past century, but the best match with observations is obtained in (c) when both natural and anthropogenic factors are included. These results show that the forcings included are sufficient to explain the observed changes, but do not exclude the possibility that other forcings may also have contributed. The bands of model results presented here are for four runs from the same model. Similar results to those in (b) are obtained with other models with anthropogenic forcing. [Based upon Chapter 12, Figure 12.7]

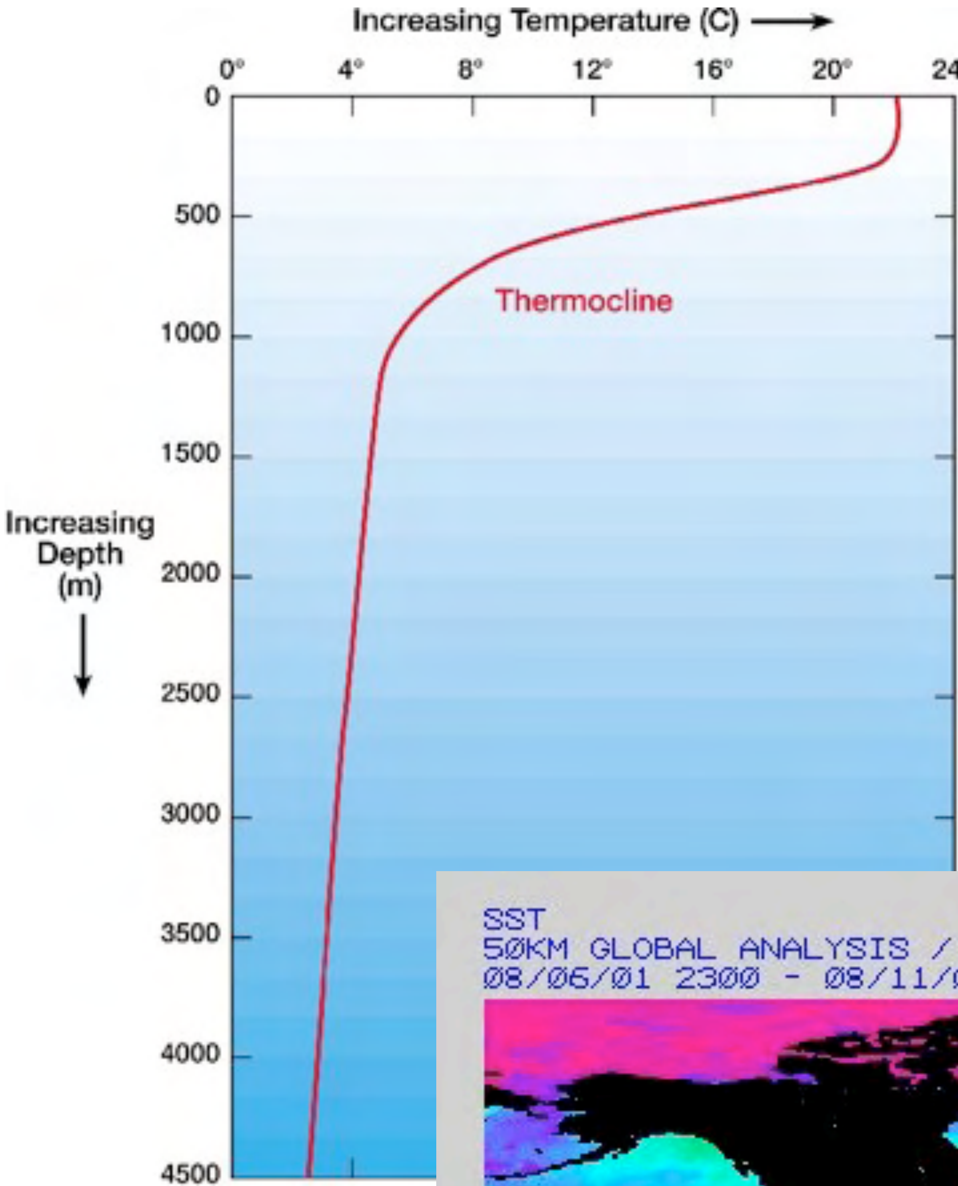
The global climate of the 21st century

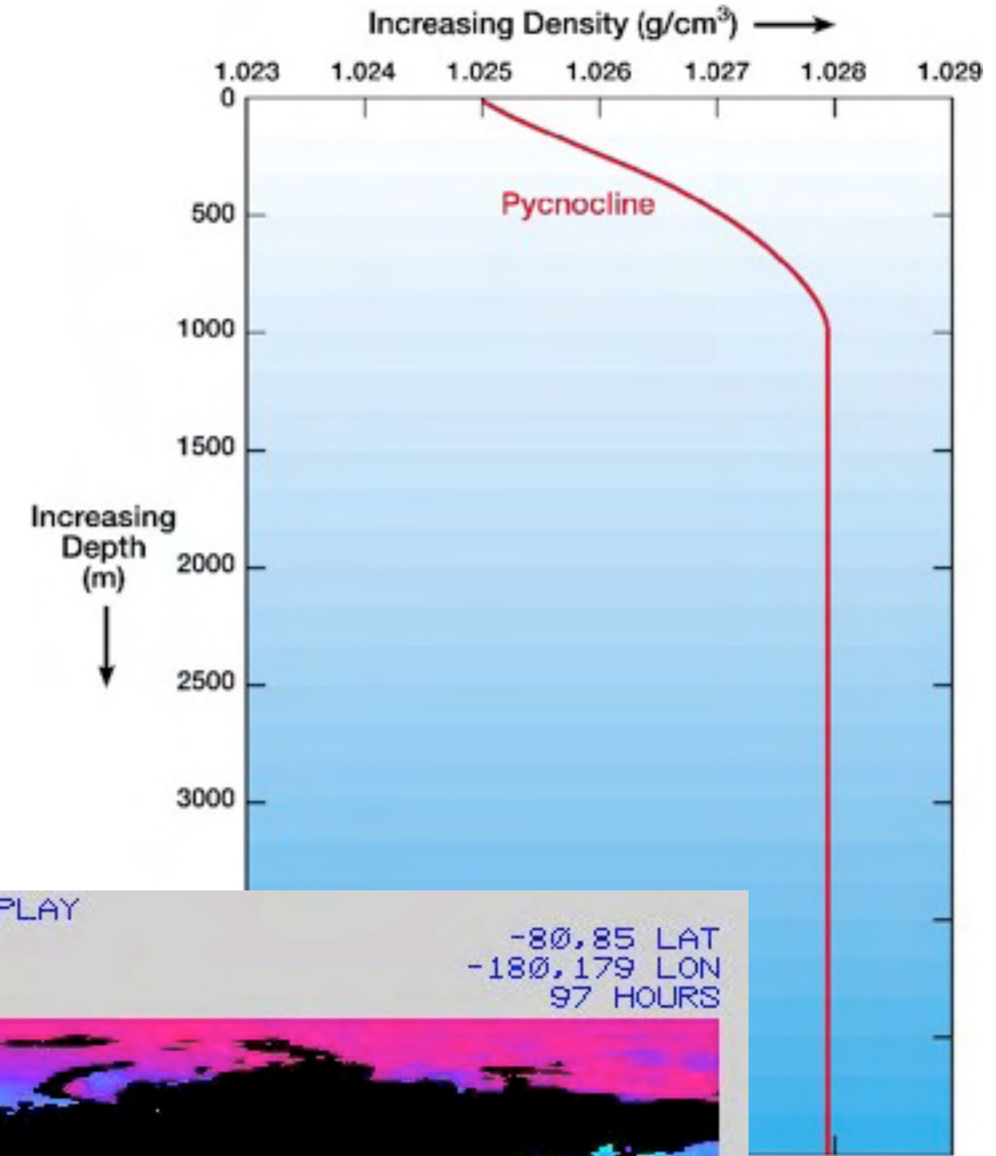


Ocean Heating



Thermal expansion coefficient (°C^{-1})
400x10^{-6}
300
200
100
0
-100
0
5
10
15
20
25
30
°C


Increasing Temperature (C)
0° 4° 8° 12° 16° 20° 24°
0 500 1000 1500 2000 2500 3000 3500 4000 4500
Increasing Depth (m)
Thermocline


Increasing Density (g/cm³)
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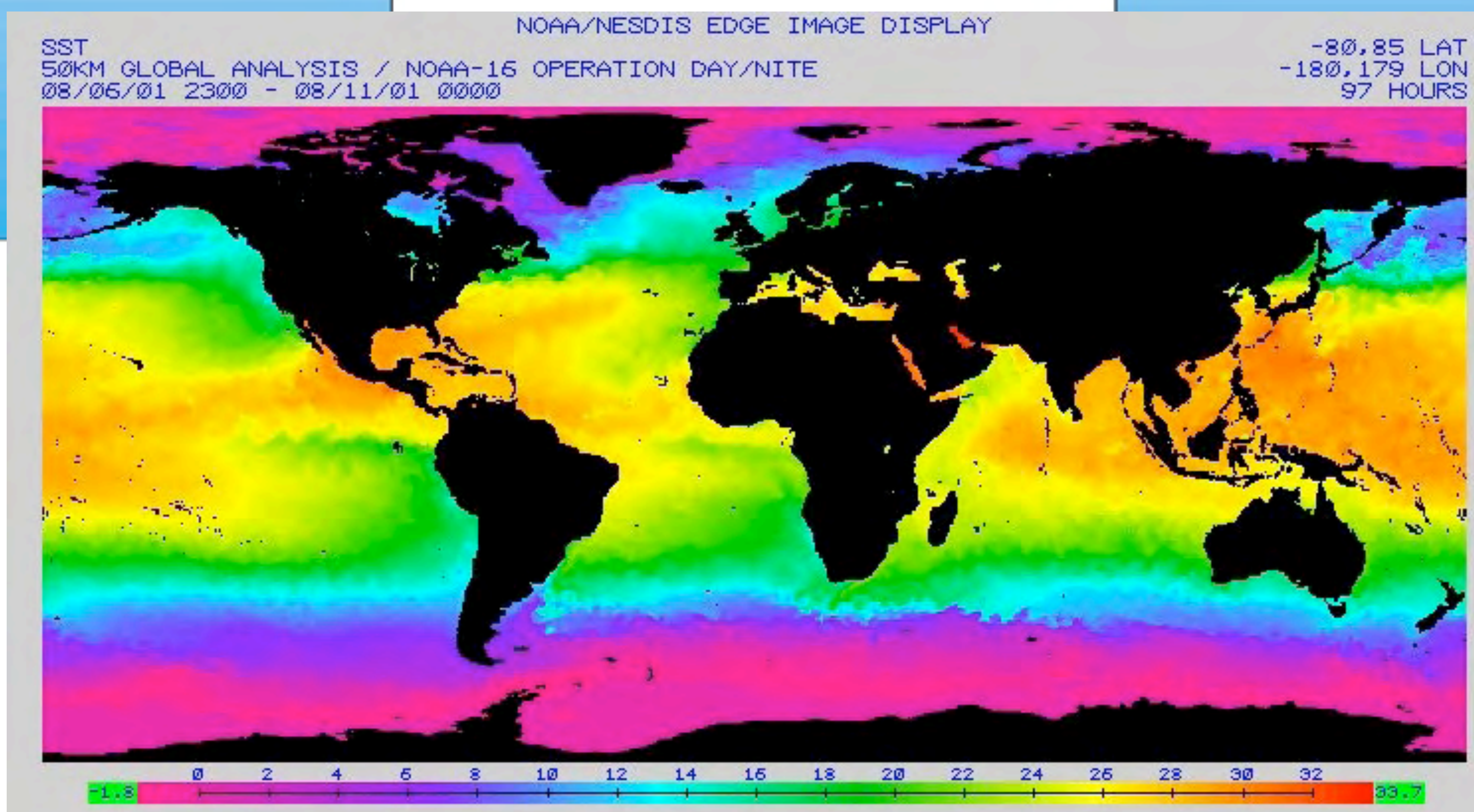
0 500 1000 1500 2000 2500 3000
Increasing Depth (m)
Pycnocline


NOAA/NESDIS EDGE IMAGE DISPLAY
SST
50KM GLOBAL ANALYSIS / NOAA-16 OPERATION DAY/NITE
08/06/01 2300 - 08/11/01 0000
-80,85 LAT
-180,179 LON
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0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32
-1.8
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