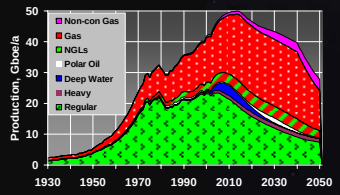
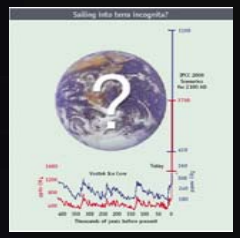


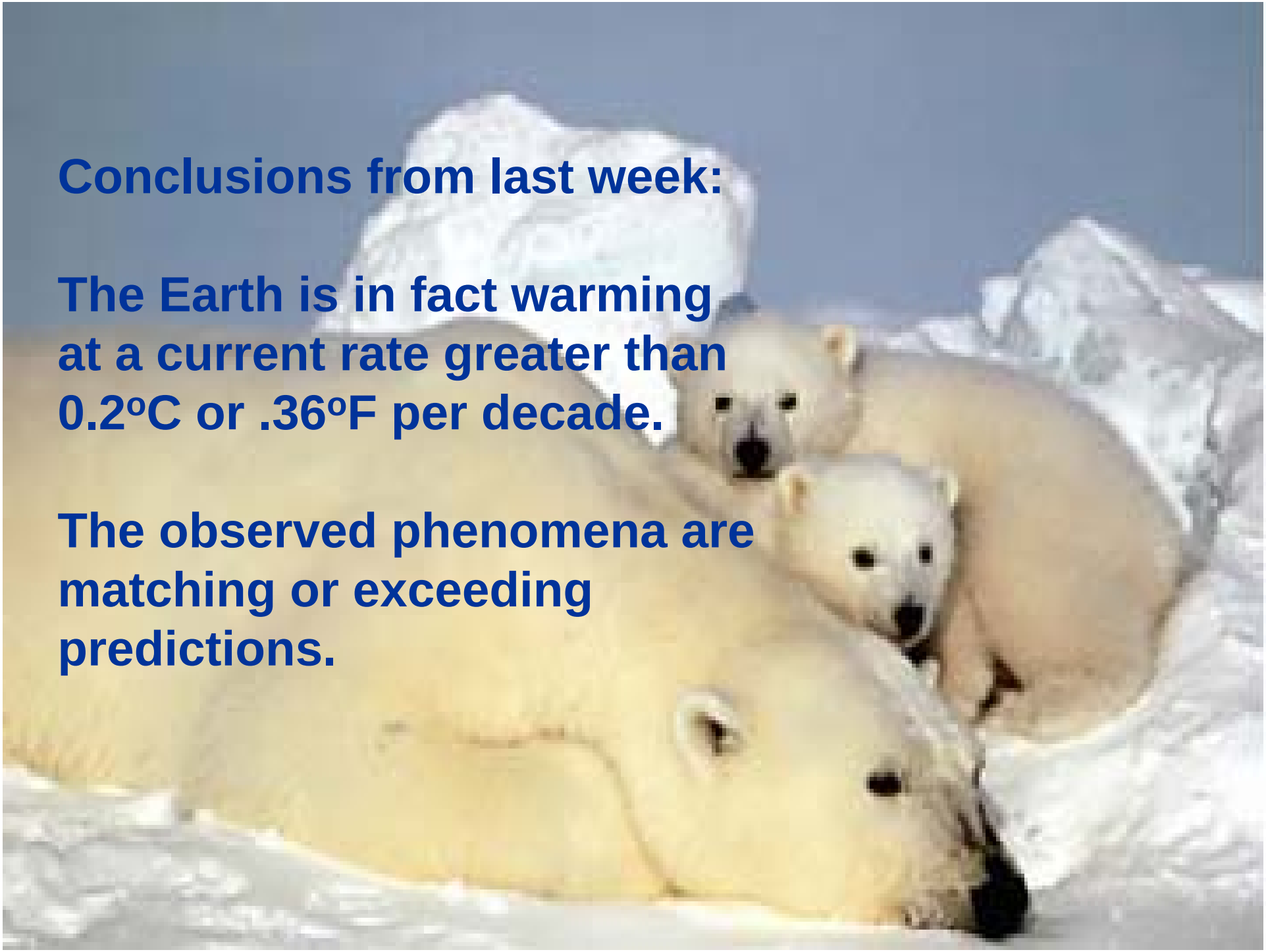
Anthropogenic Global Warming

February, 2008



Four questions

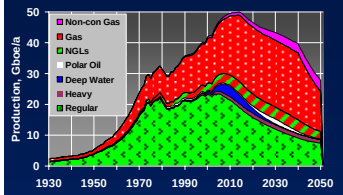
- Is the Earth warming?
- If so, then what is or are the causes?
- What are the consequences?
- What can we do about it?



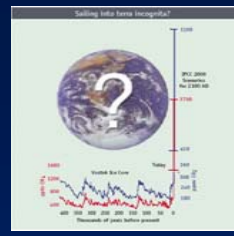
Conclusions from last week:

The Earth is in fact warming at a current rate greater than 0.2ºC or .36ºF per decade.

The observed phenomena are matching or exceeding predictions.

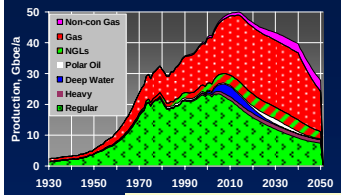


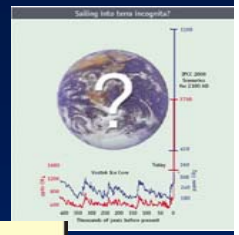
This week

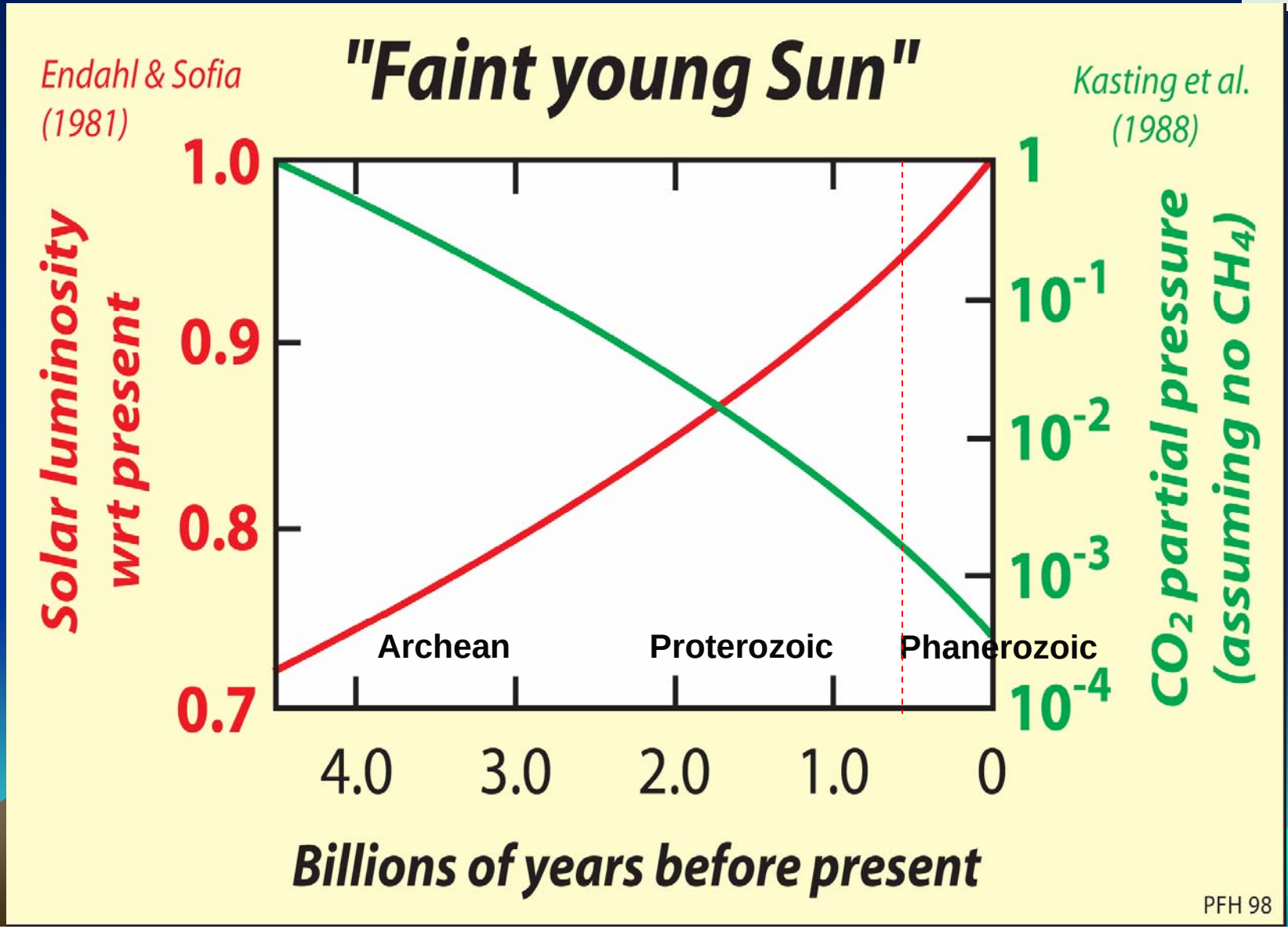


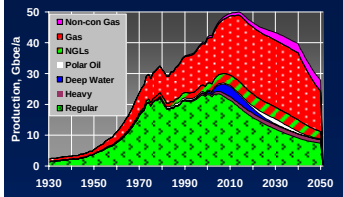
- What was the climate like on Earth in the past?
- What caused the Earth's climate to change in the past?
- What is causing it to change today?
- What can we expect in the future?

Solar luminosity and atmospheric carbon

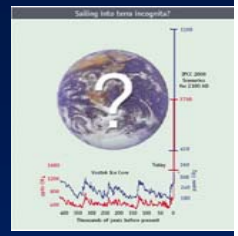


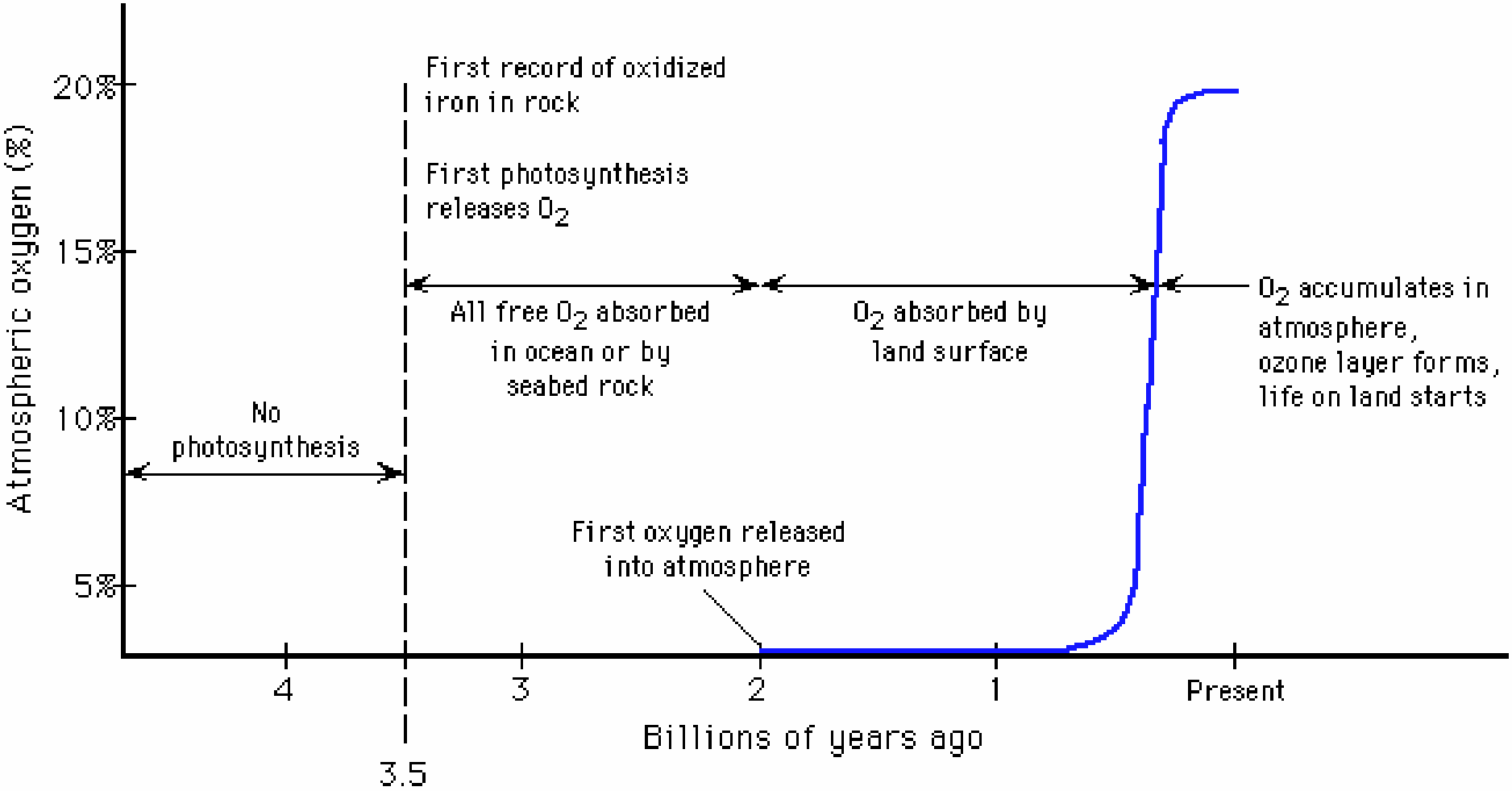


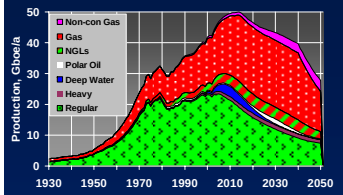




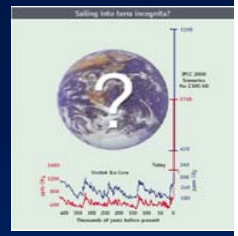
Photosynthesis

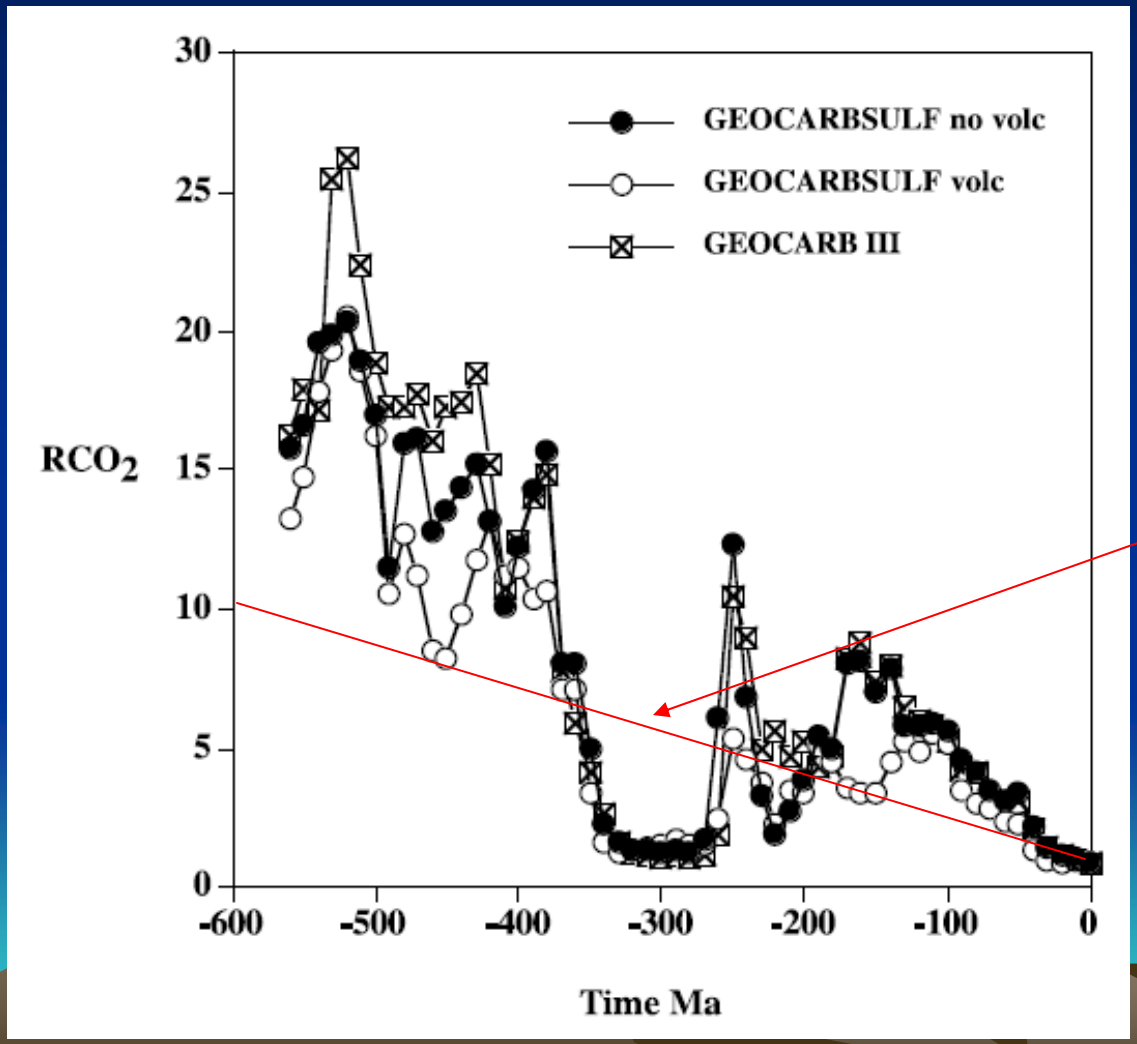




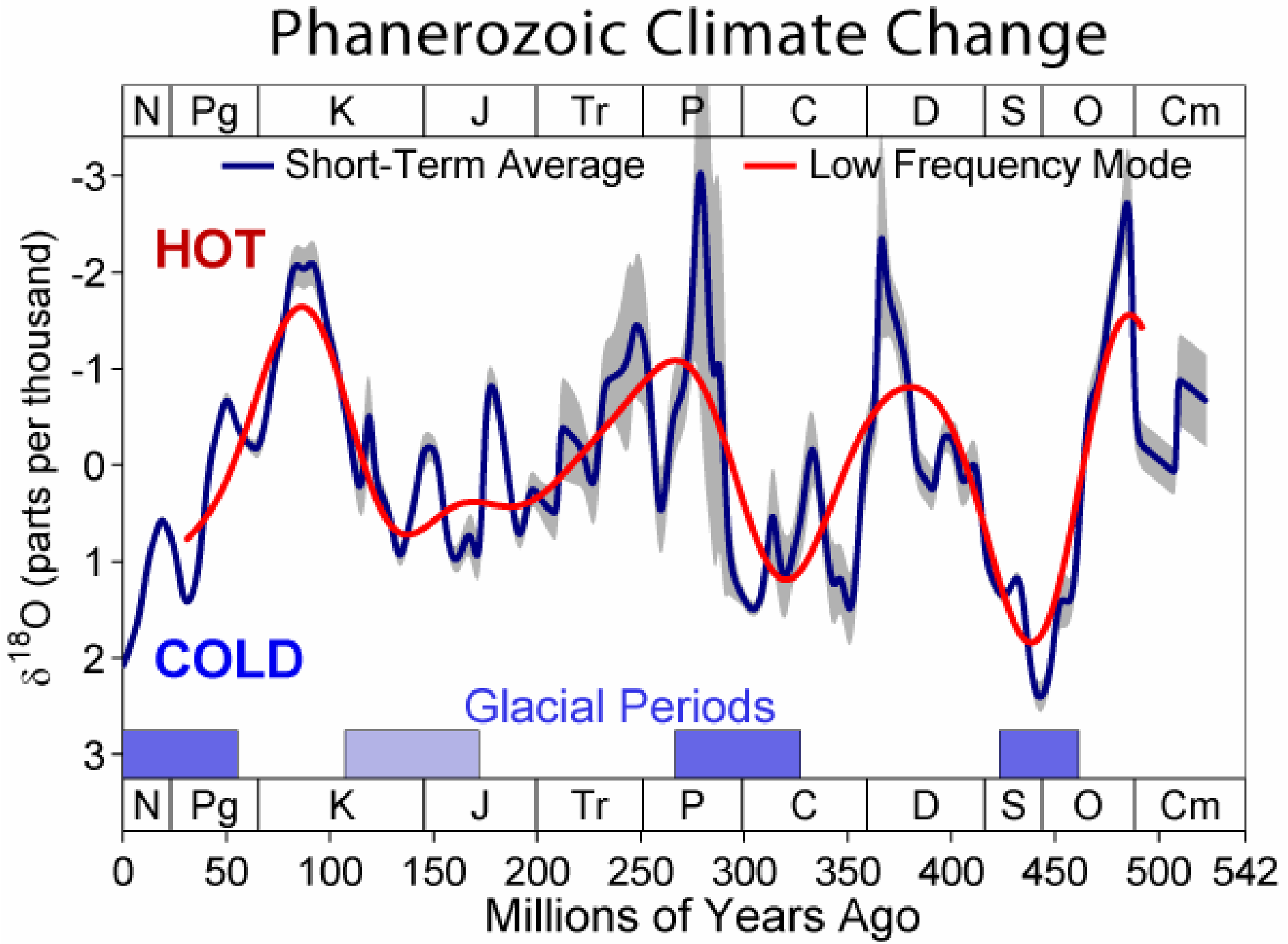


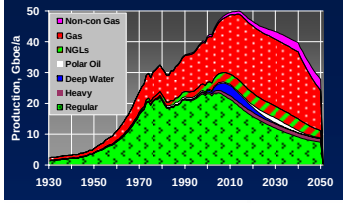
CO2 in the Phanerozoic

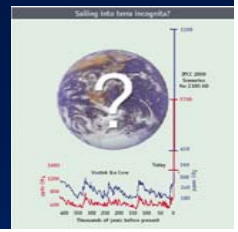


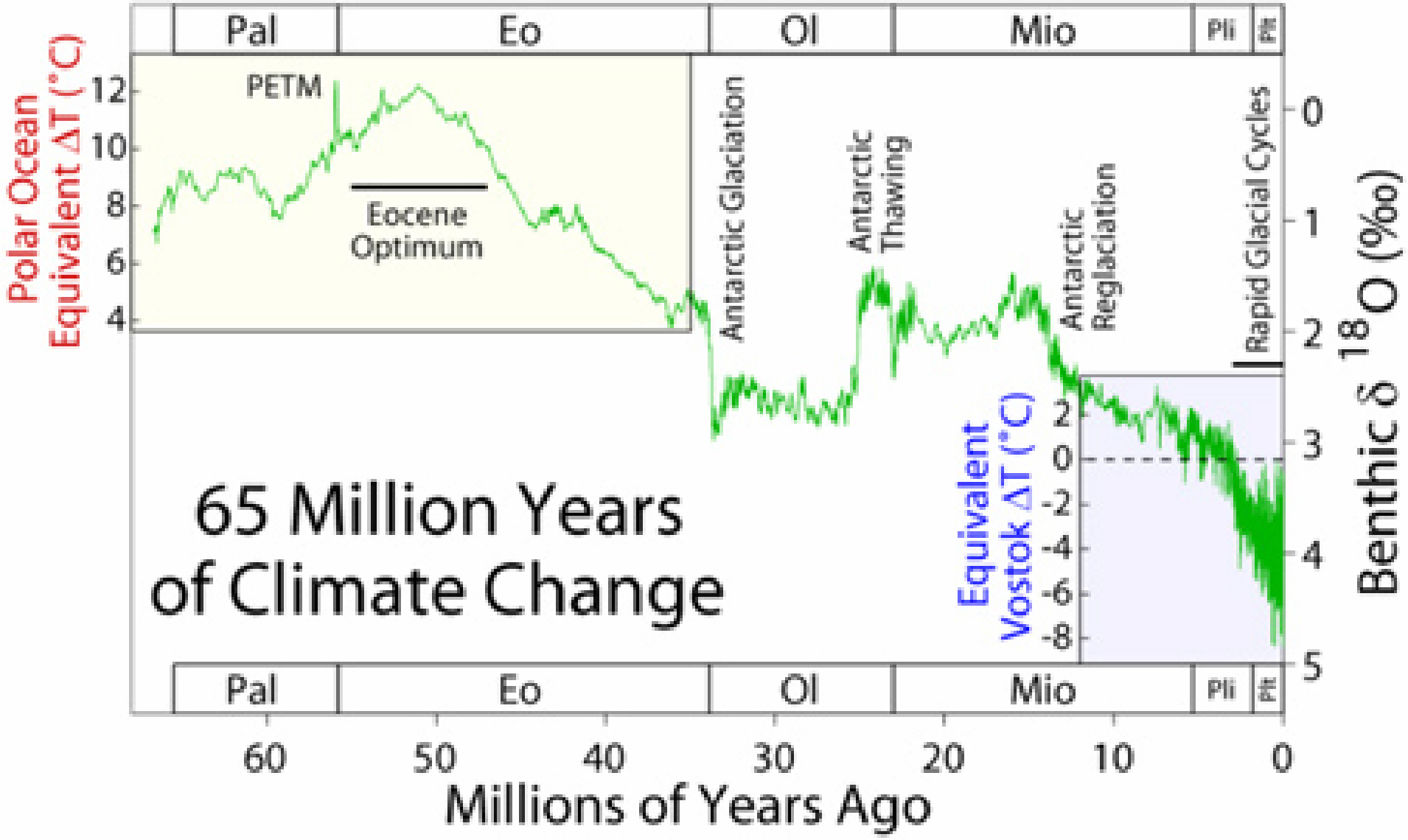


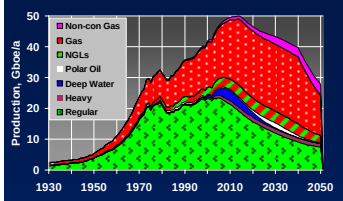
Carbon dioxide level required to achieve today's climate . (Berner The Phanerozoic Carbon Cycle)


Phanerozoic Climate Change
N
Pg
K
J
Tr
P
C
D
S
O
Cm
Short-Term Average
Low Frequency Mode
HOT
COLD
Glacial Periods
δ18O (parts per thousand)
-3
-2
-1
0
1
2
3
0
50
100
150
200
250
300
350
400
450
500
542
Millions of Years Ago

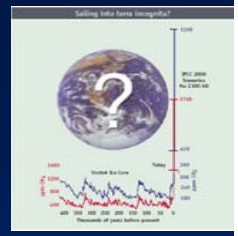

Production, Gboe/a
50
40
30
20
10
0
1930
1950
1970
1990
2010
2030
2050
Non-con Gas
Gas
NGLs
Polar Oil
Deep Water
Heavy
Regular



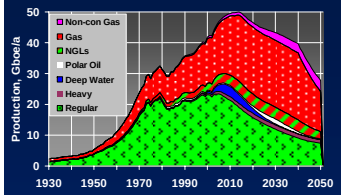

Pal
Eo
Ol
Mio
Plio
Ple
Polar Ocean
Equivalent ΔT (°C)
12
10
8
6
4
PETM
Eocene
Optimum
Antarctic Glaciation
Antarctic
Thawing
Antarctic
Reglaciation
Rapid Glacial Cycles
Equivalent
Vostok ΔT (°C)
2
0
-2
-4
-6
-8
Benthic δ 18O (‰)
0
1
2
3
4
5
65 Million Years
of Climate Change
60
50
40
30
20
10
0
Millions of Years Ago



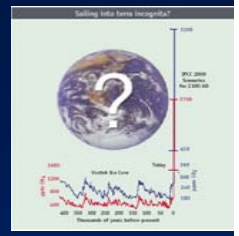
What caused the climate to vary in the past?



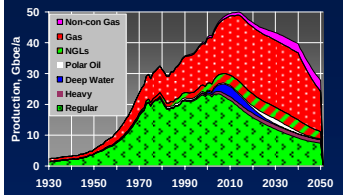
- Solar luminosity
- Atmospheric carbon greenhouse effect
- Earth orbital variation
- Plate tectonics
  - Position of continents and oceans
  - High mountains (long term weathering and winds)
  - Ocean circulation
- Volcanism contributes CO2 (carbon cycle)
- Plant and bacterial life via photosynthesis Carbon cycle
- Mountain weathering carbon cycle
- Surface Albedo
- Water vapor

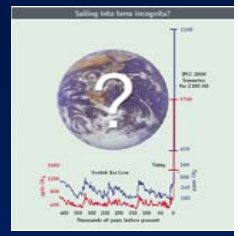


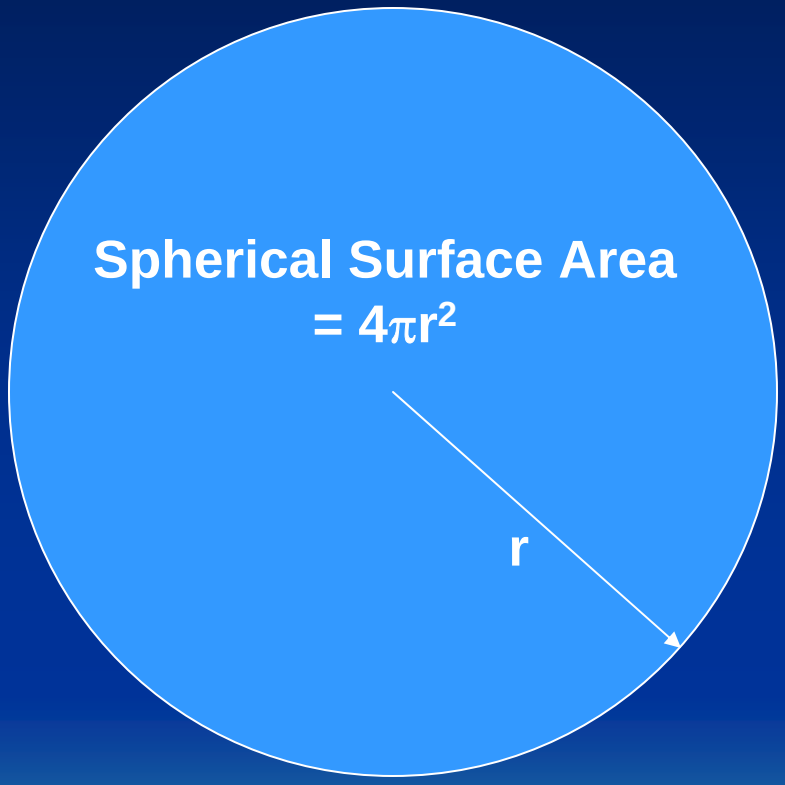
Earth's energy balance

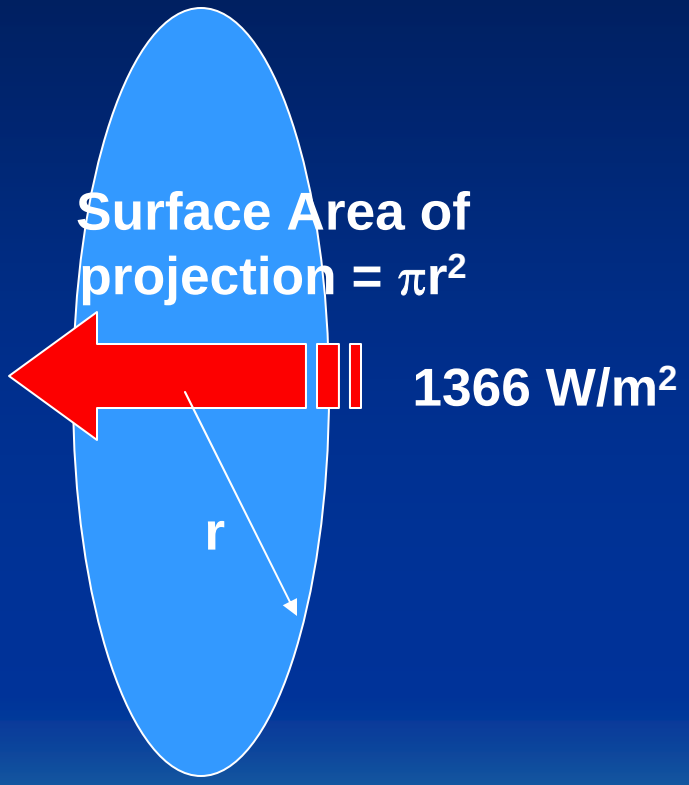


- Joseph Fourier published the first attempt to calculate the Earth's energy balance in 1824. He calculated that the Earth should be about 40°C colder than it was and speculated that the atmosphere had a greenhouse effect. Actually, we now know the Earth is 32°C warmer that it would be without an atmosphere.



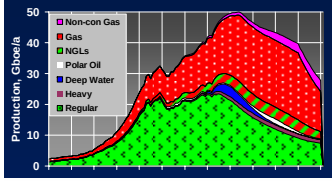


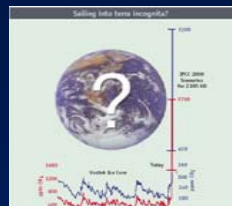


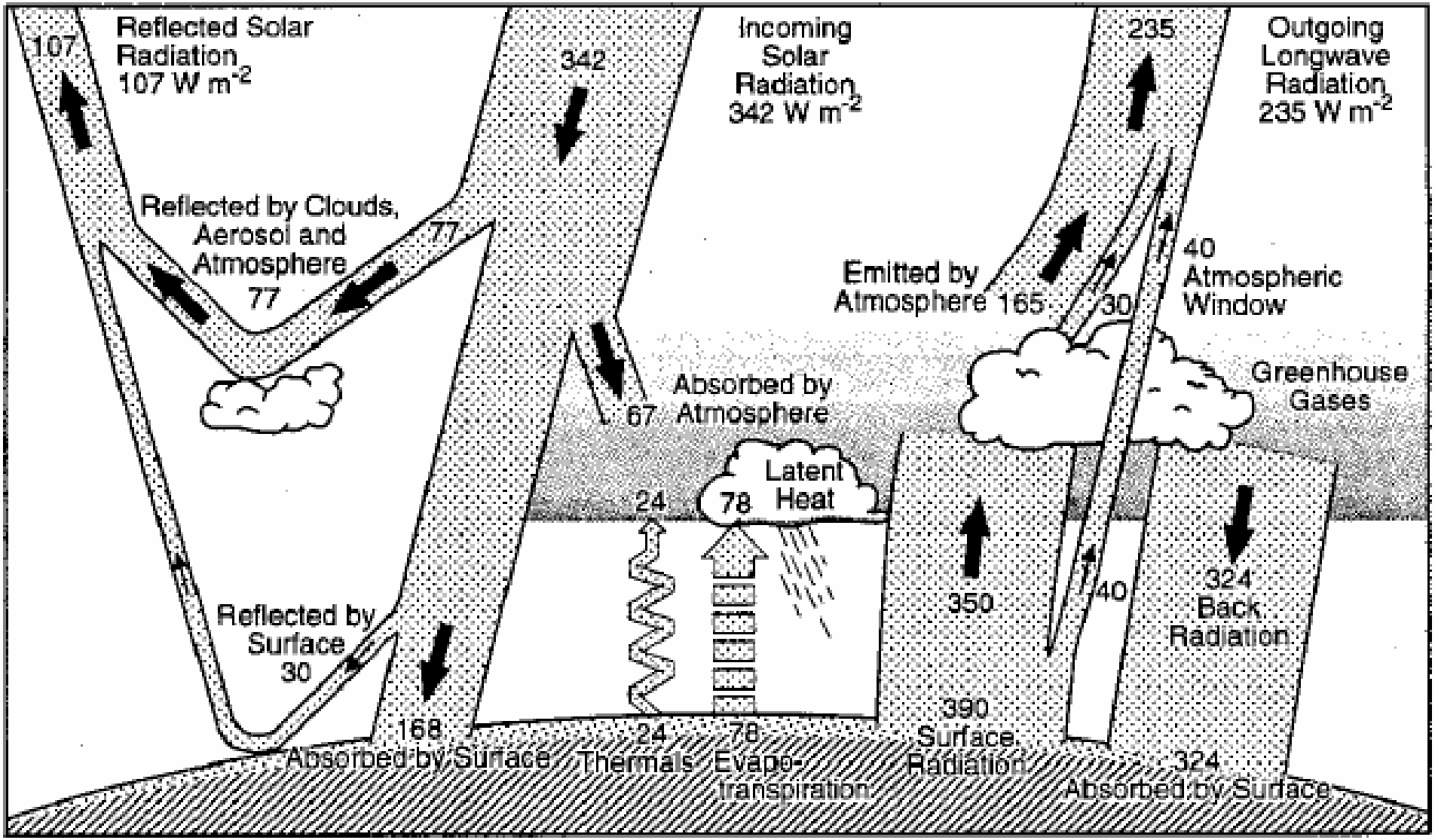


Average incident radiation = 1366/4 = 342 W/m²

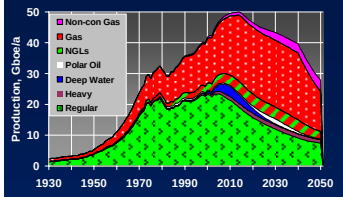
Earth's annual global mean energy budget



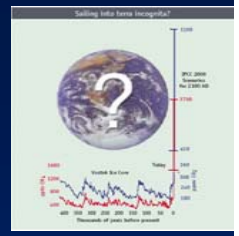




Kiehl and Trenberth, 1997



Greenhouse effect



Solar Radiation absorbed by Earth 235 W/m²

Thermal radiation into space: 195

Directly radiated from surface: 40

Greenhouse gas absorption: 350

67

Heat and energy in the atmosphere

452

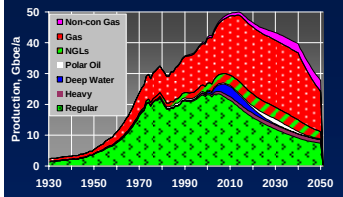
168

324

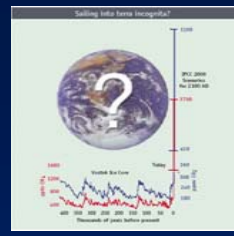
The Greenhouse Effect

Earth's land and ocean surface warmed to an average of 14°C

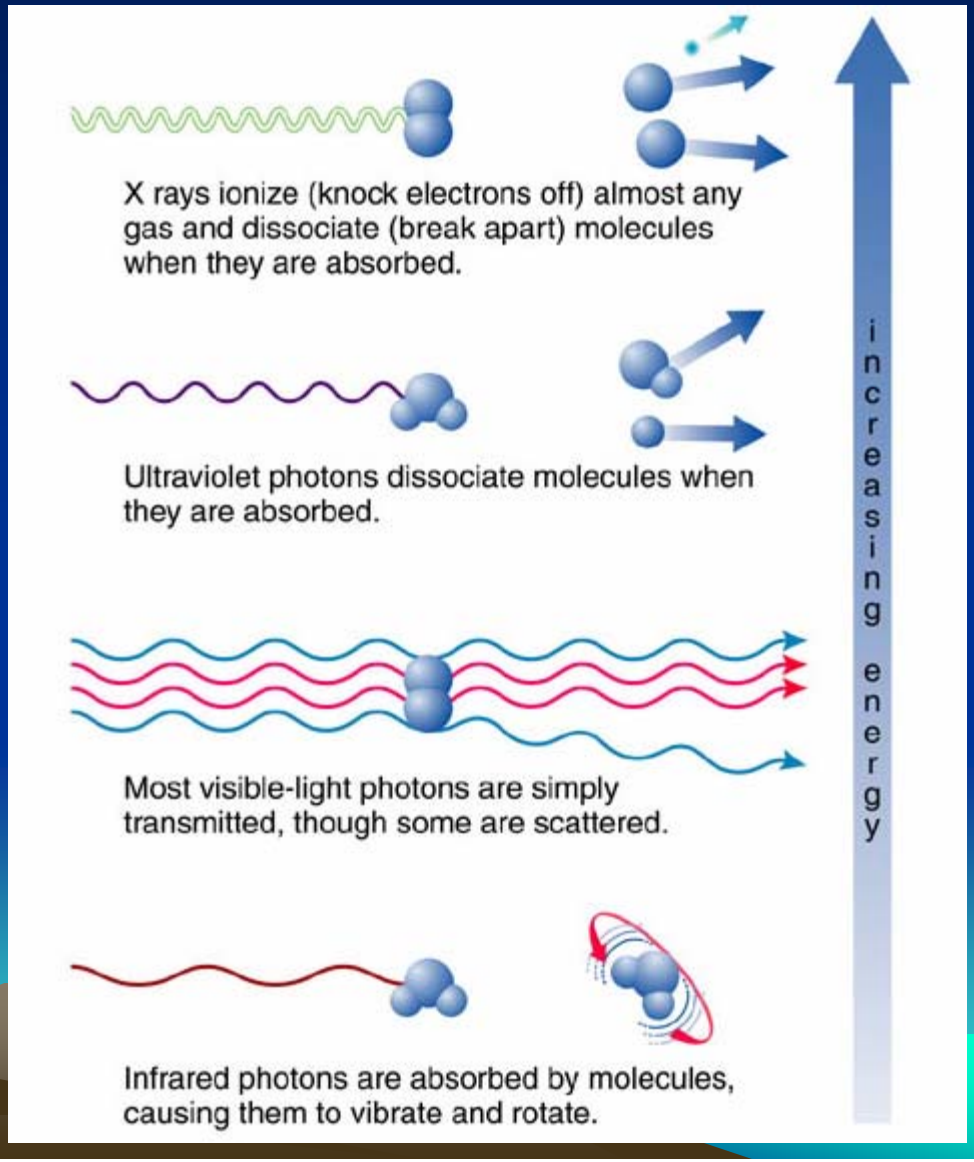
Without the greenhouse effect the Earth would be -18°C

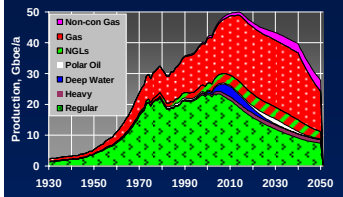


Solar radiation

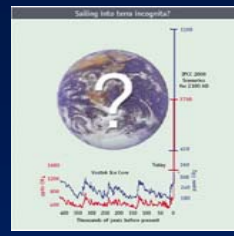


John Tyndall explained atmospheric heat in terms of the capacities of various gases to absorb or transmit radiant heat. He constructed the first ratio spectrophotometer which he used to measure the absorptive powers of the gases nitrogen, oxygen, water vapour, carbon dioxide, ozone, hydrocarbons, etc. Tyndall correctly identified water vapour as the primary greenhouse gas.



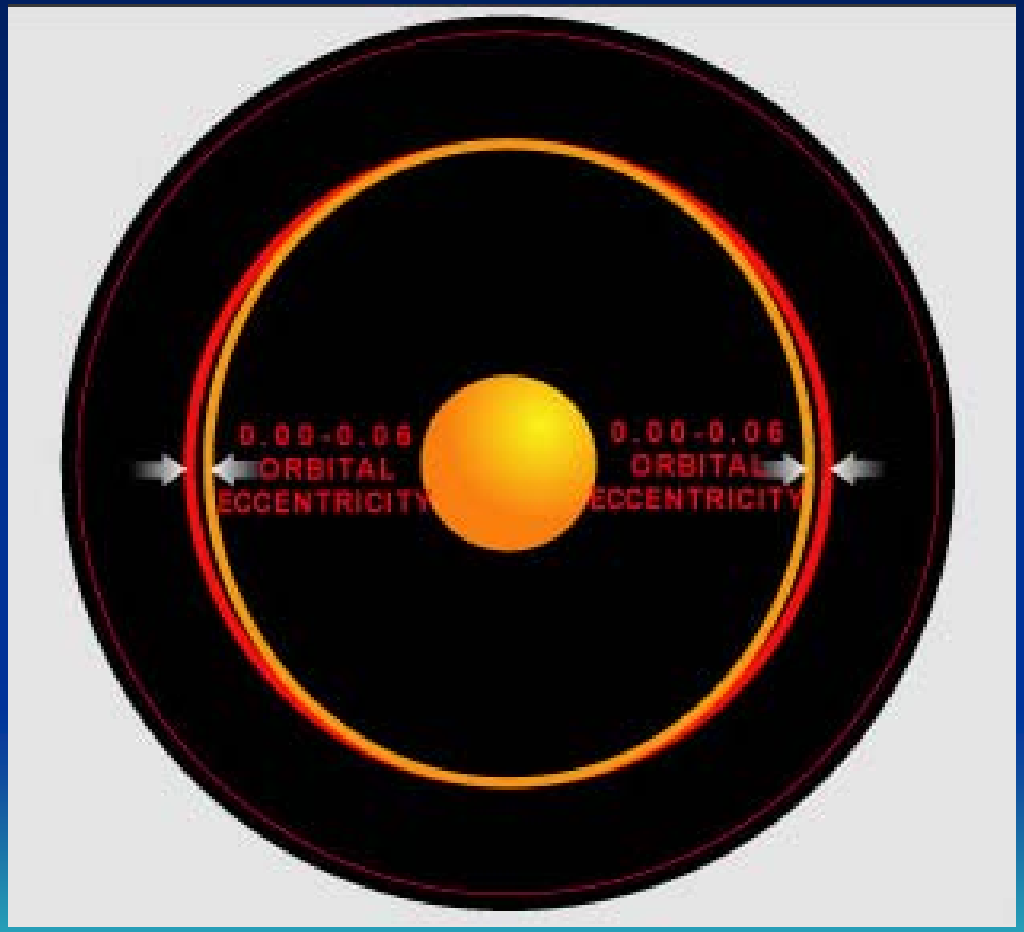


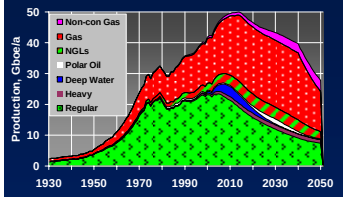
Earth's orbital variation



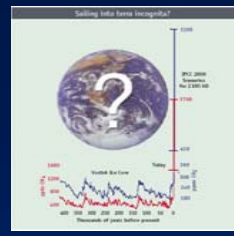
James Croll proposed that the Earth's orbital variations were the cause of the ice ages. This in fact is correct, but Croll assumed that maximum glaciations would occur at maximum eccentricity because this would lead to coldest winters over the northern hemisphere. Croll included surface albedo as a feedback function.

Eccentricity on a 100,000 year cycle



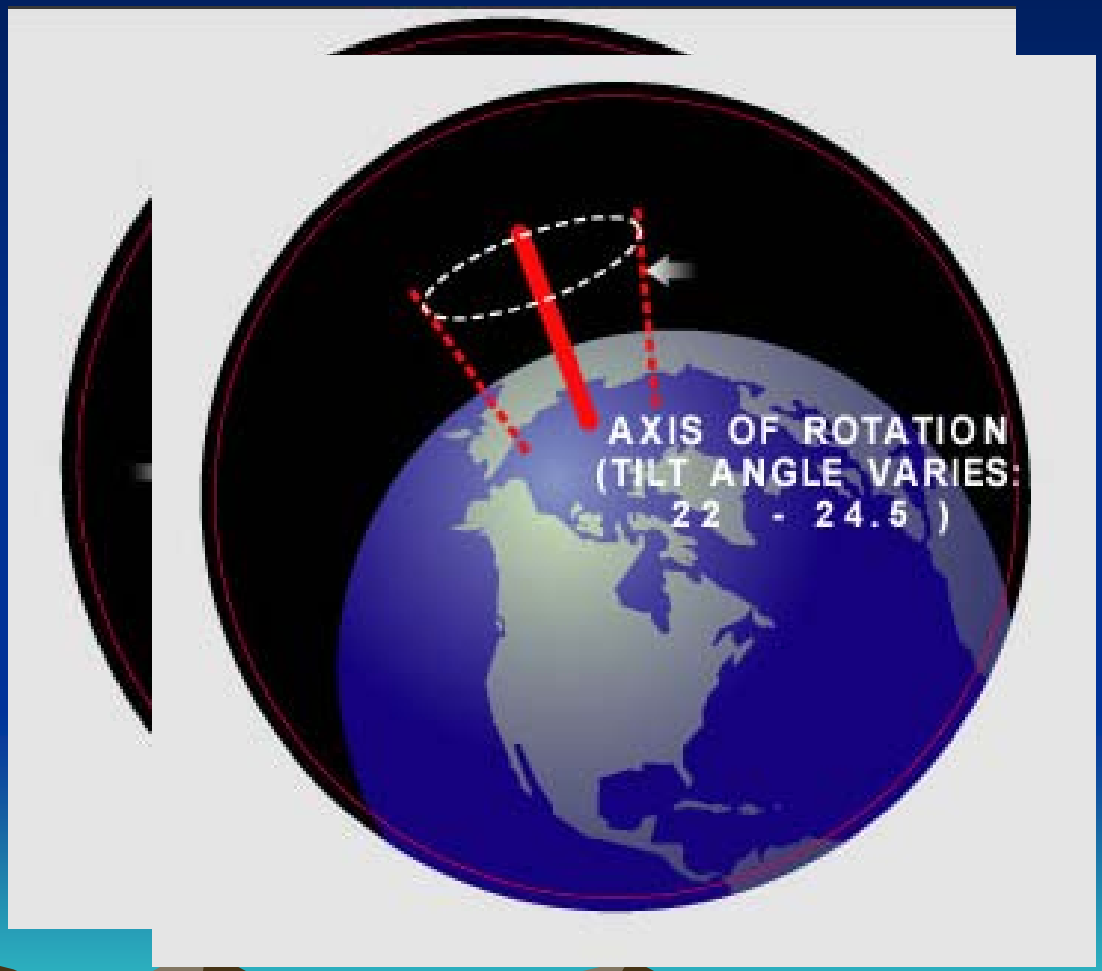


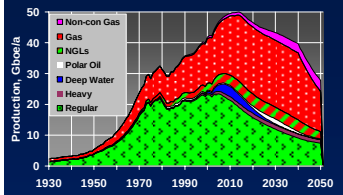
Earth's orbital variation



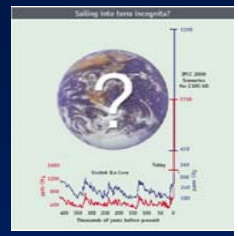
Axis of rotation varies on a 40,000 year cycle

Sample albedos	
Surface	**Typical Albedo**
Fresh asphalt	0.04[1]
Conifer forest (Summer)	0.08[2]
Worn asphalt	0.12[1]
Bare soil	0.17[3]
Green grass	0.25[3]
Desert sand	0.40[4]
New concrete	0.55[3]
Fresh snow	0.80–0.90[3]



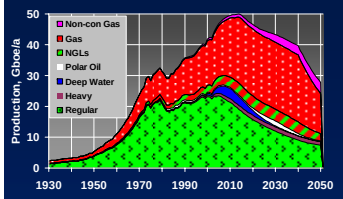


Earth's orbital variation

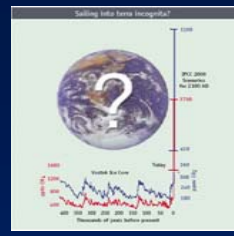


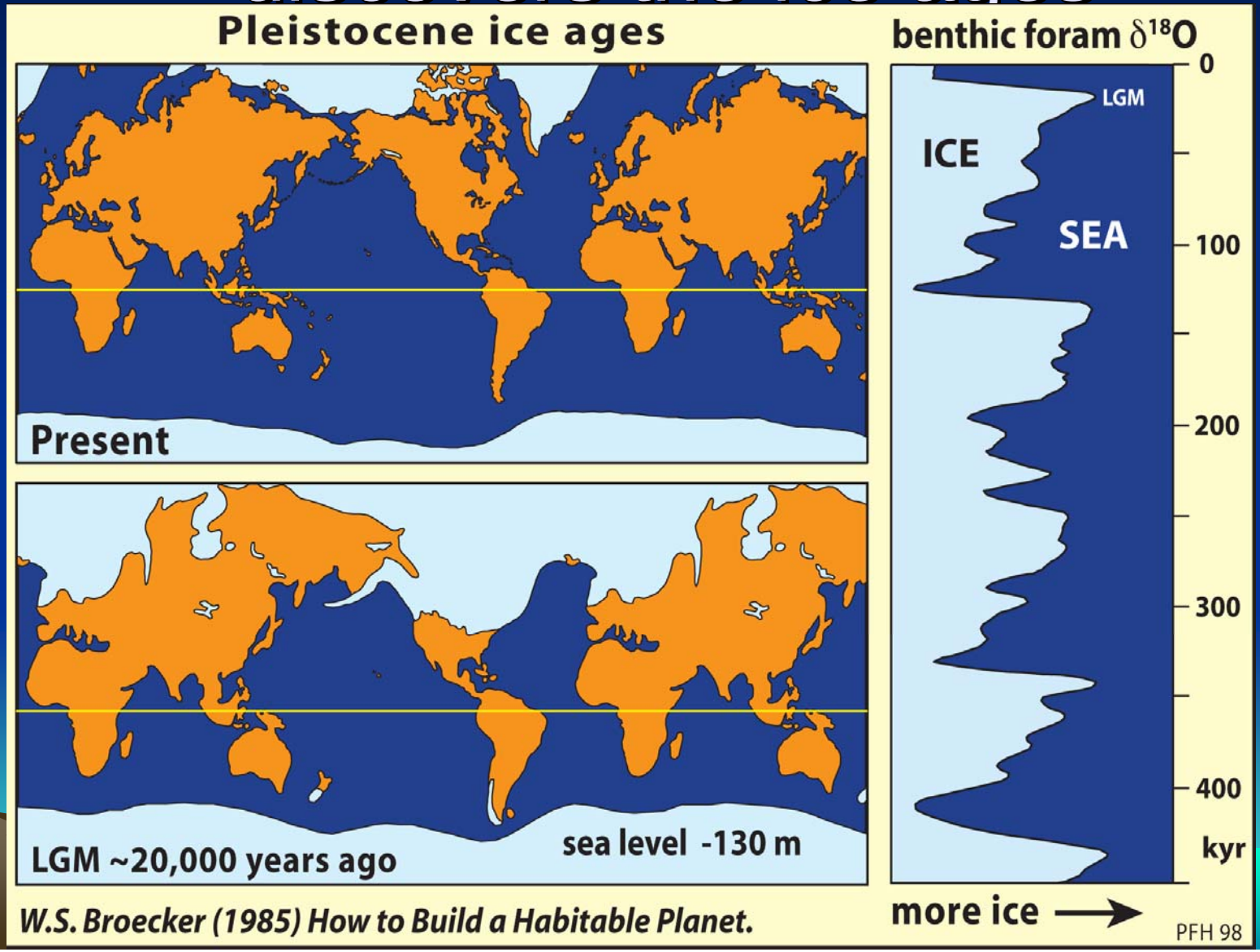
Axis wobble varies on a 23,000 year cycle

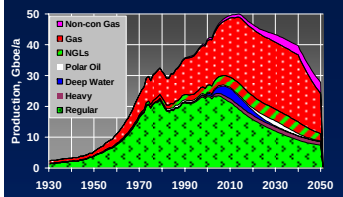
Sample albedos	
Surface	**Typical Albedo**
Fresh asphalt	0.04[1]
Conifer forest (Summer)	0.08[2]
Worn asphalt	0.12[1]
Bare soil	0.17[3]
Green grass	0.25[3]
Desert sand	0.40[4]
New concrete	0.55[3]
Fresh snow	0.80–0.90[3]



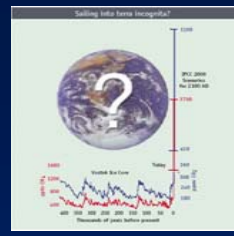
Louis Agassiz discovers the ice ages



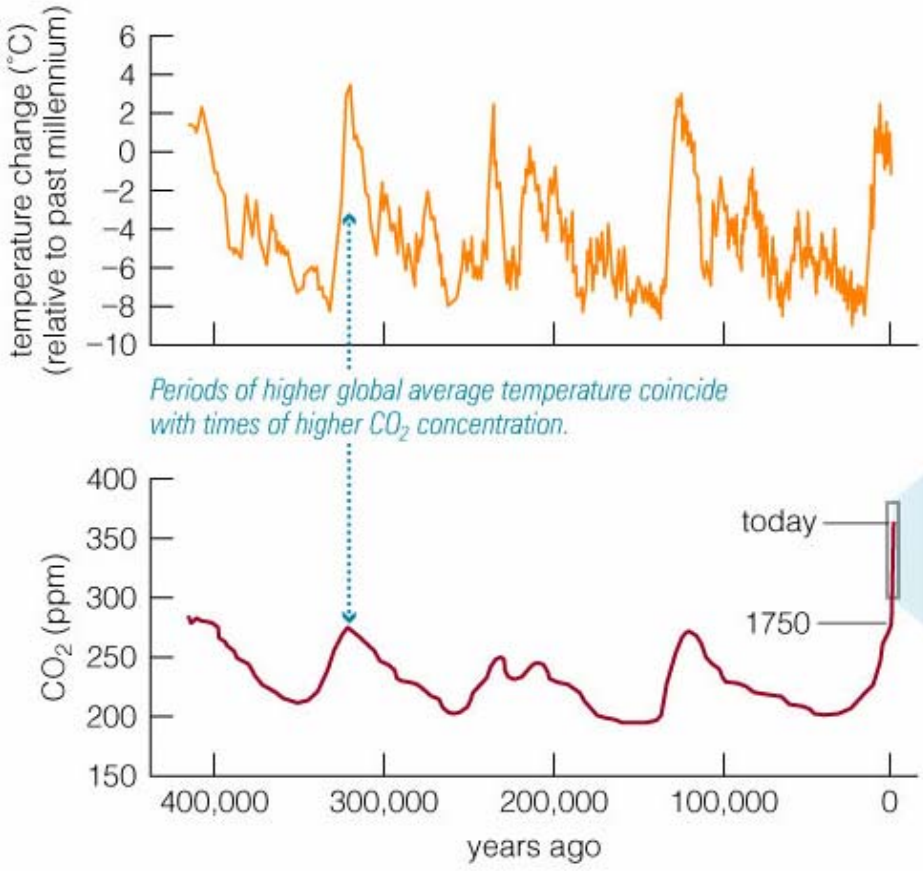


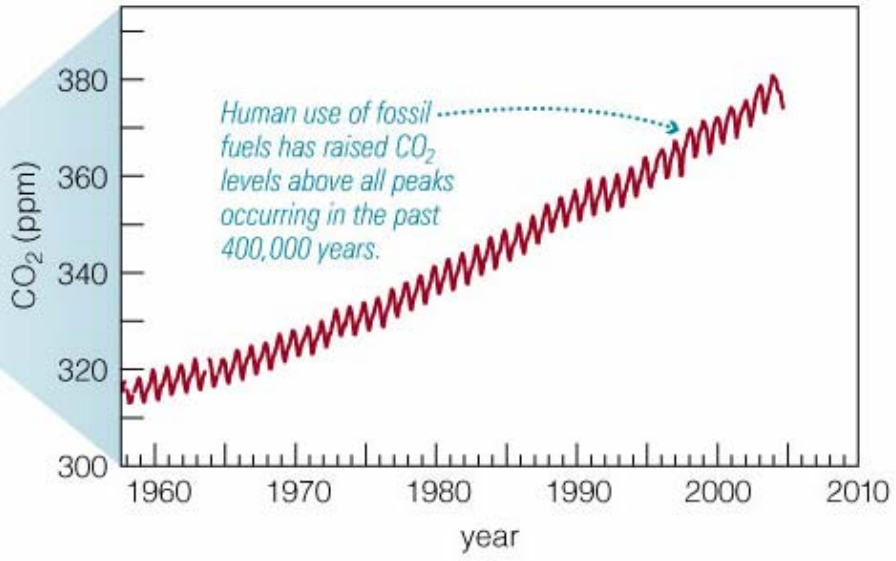


Late Pleistocene Atmospheric Carbon



190 ppmV corresponds to 400 Gt carbon
280 ppmV corresponds to 580 Gt carbon
385 ppmV corresponds to 810 Gt carbon





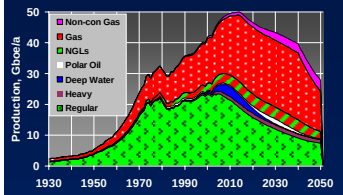
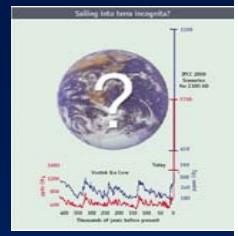
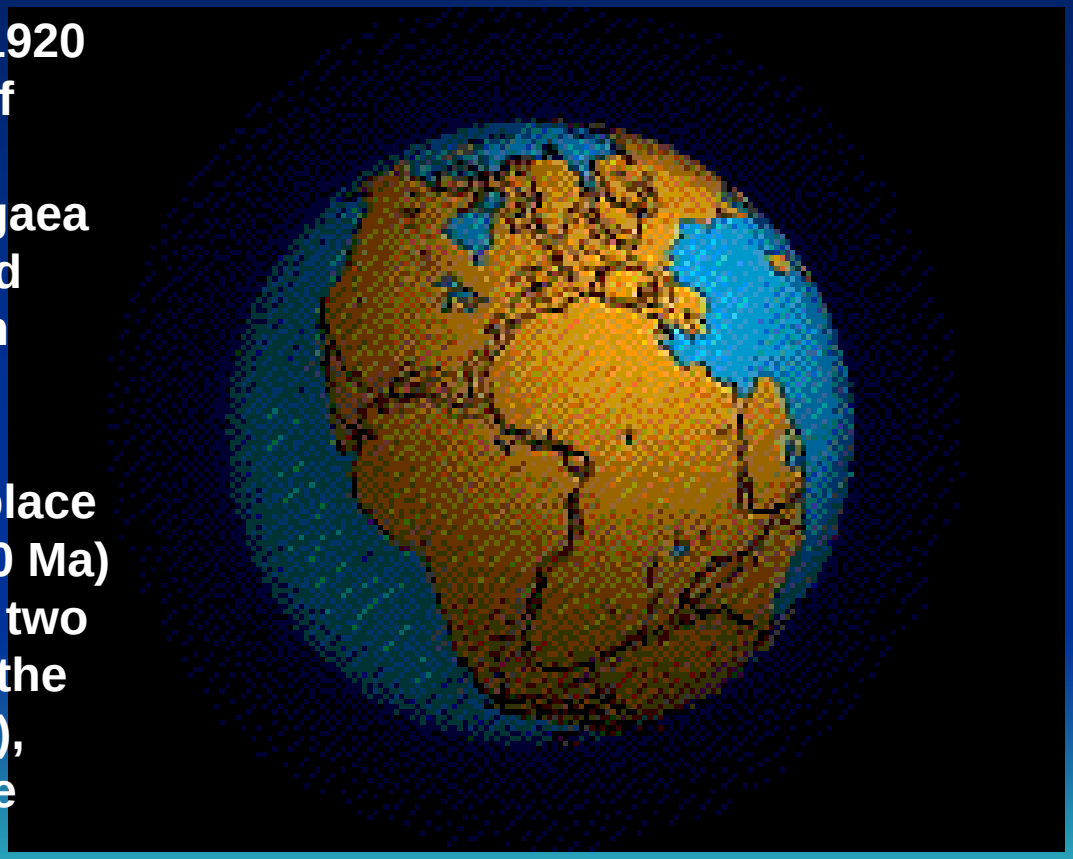


Plate tectonics

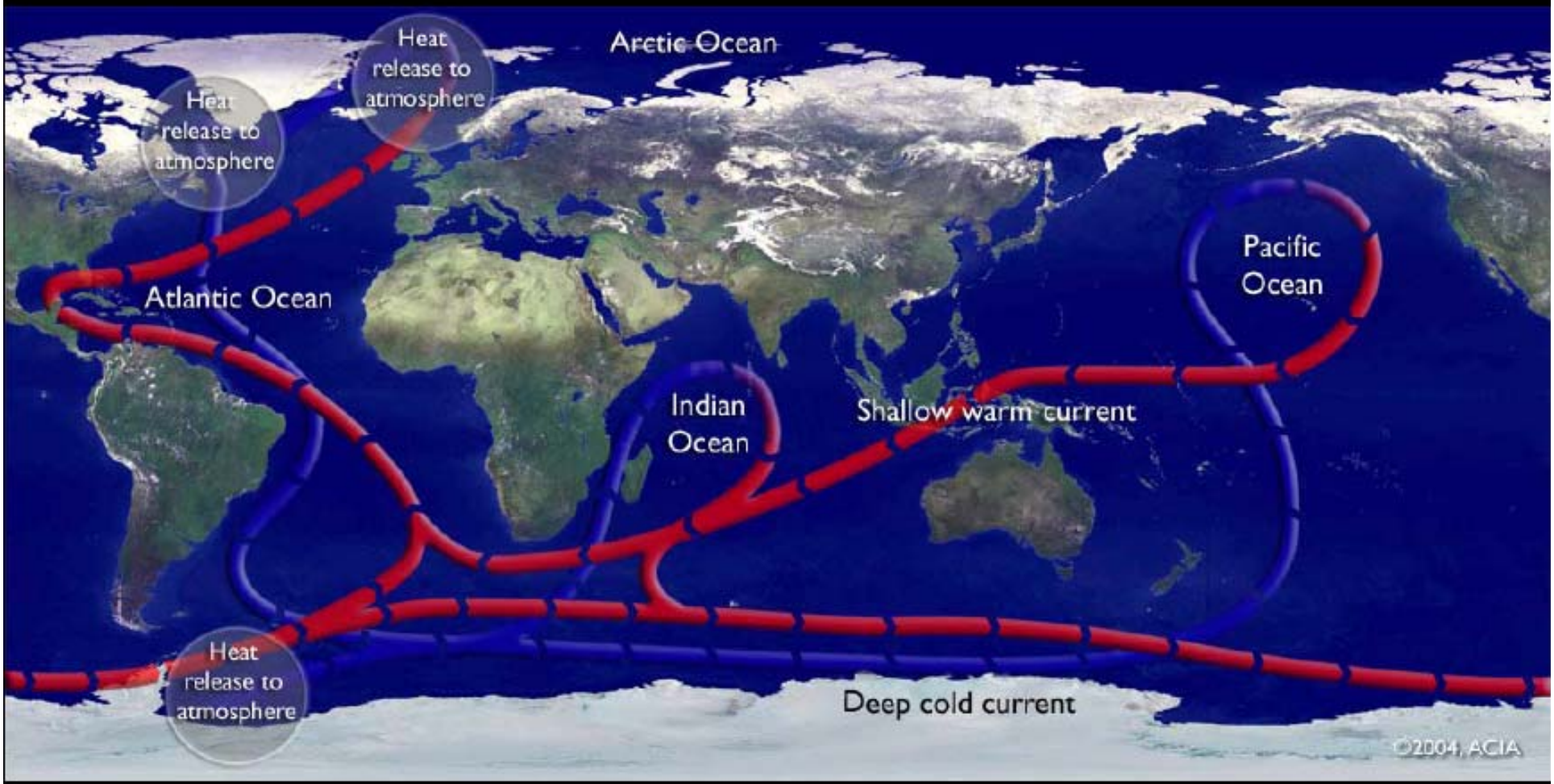


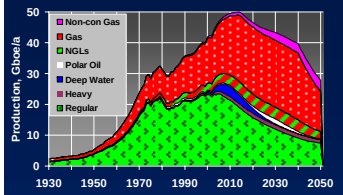
Alfred Wegener originated the continental drift theory. In the 1920 edition of his book The Origin of Continents and Oceans, he postulated supercontinent Pangaea existed during the Paleozoic and Mesozoic eras about 250 million years ago.



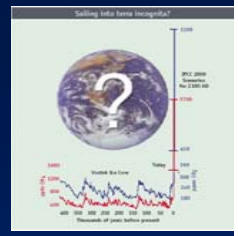
The break-up of Pangaea took place about 180 million years ago (180 Ma) in the Jurassic Period, first into two supercontinents (Gondwana to the south and Laurasia to the north), thereafter into the continents we have today.

Ocean circulation feedbacks?





Carbon



Long-Term Carbon Cycle

volcanoes release CO_2

weathering consumes CO_2; weathering products carried to ocean

CO_2 rising in magma

sediments are subducted

ocean crust

open-ocean carbonate sedimentation

CO_2 released at mid-ocean ridges

shallow-water carbonate sedimentation

sediments

weathering consumes CO_2; weathering products carried to ocean

metamorphism of older sedimentary rocks liberates CO_2

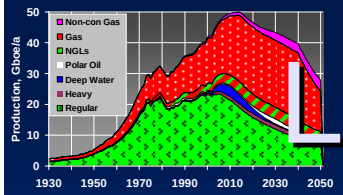
continental crust

mantle lithosphere

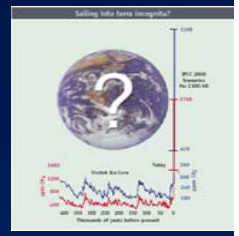
partial melting of subducted materials liberates CO_2

mantle asthenosphere

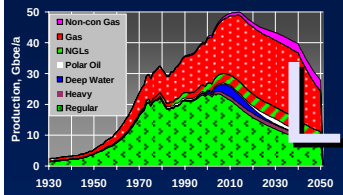
CO_2 is slowly carried to mid-ocean ridge by flow within asthenosphere



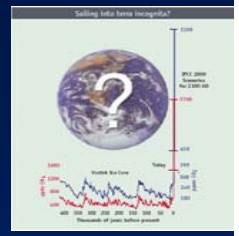
Long Term Carbon Cycles



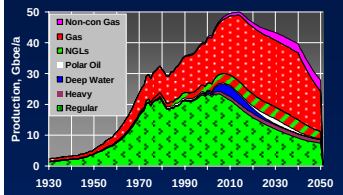
- Organic carbon cycle
- Net photosynthesis
  - $CO_2 + H_2O \rightarrow CH_2O + O_2$
- Georespiration
  - $CH_2O + O_2 \rightarrow CO_2 + H_2O$



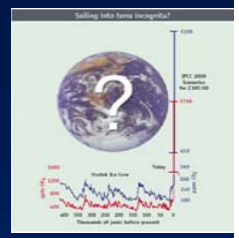
Long Term Carbon Cycles



- Inorganic carbon cycle
- Weathering and marine carbonate sedimentation
  - $CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$
- Decarbonation via volcanism, metamorphism and diagenesis
  - $CaCO_3 + SiO_2 \rightarrow CO_2 + CaSiO_3$



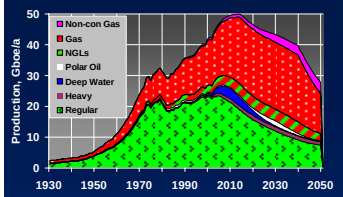
Rate of oil consumption

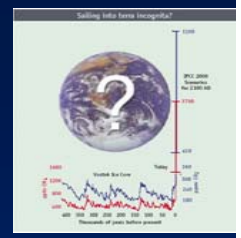


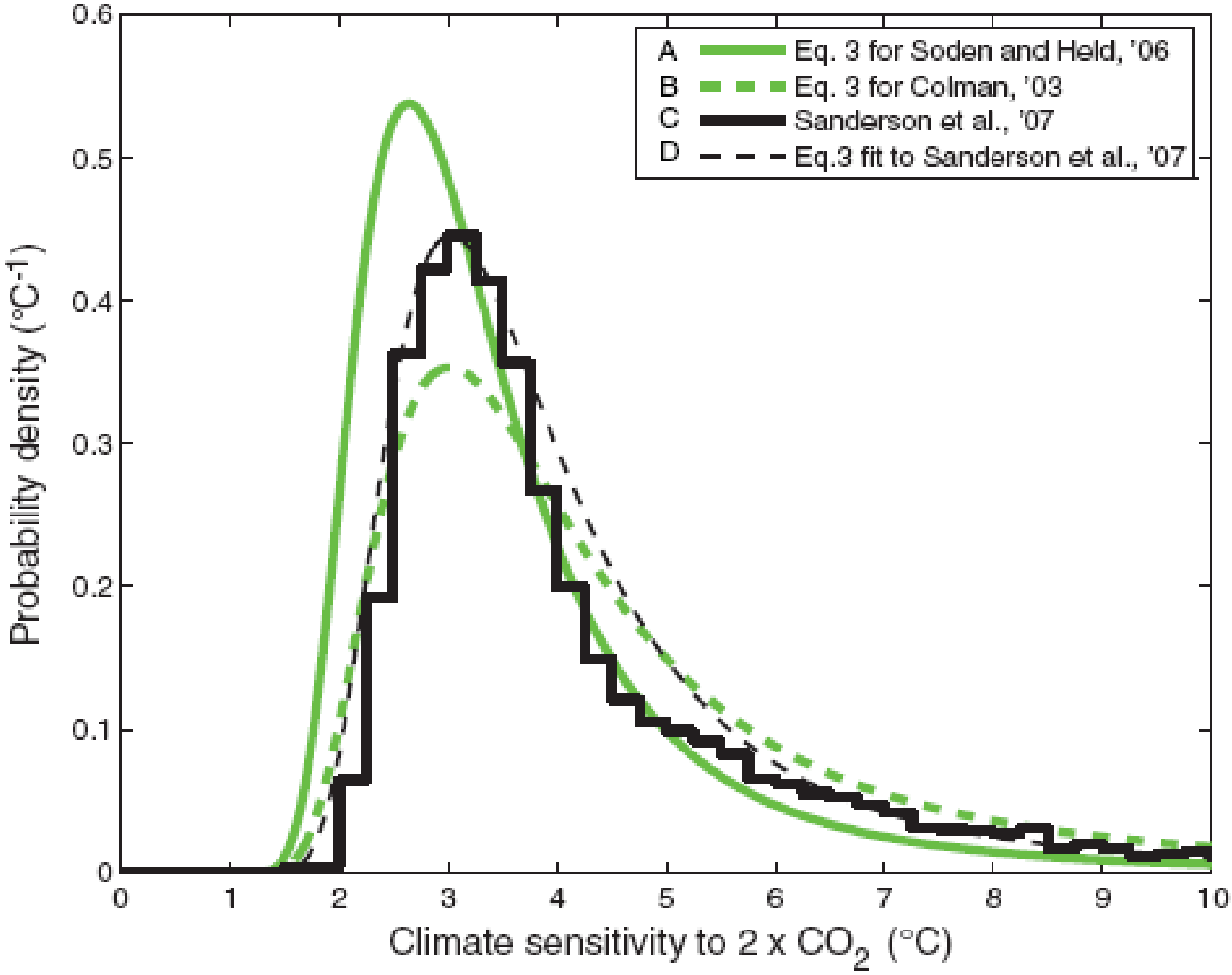
- Ultimate recoverable reserves (URR) oil equals 2.1 trillion barrels of which there may be 800 billion barrels left.
- Assume all oil was formed after the Cambrian explosion 542 million years ago.
- Average rate 2100000/542 = 3900 barrels/yr sequestered
- We use 31.025 billion barrels/yr
- 31025/3900 = 8 million years worth of URR oil sequestration is burned every single year

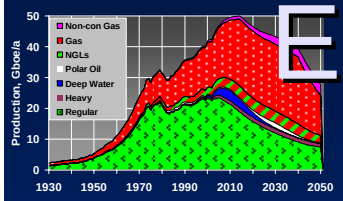
- Humans have extracted these substances from the ground so quickly, from a geological perspective, that oxidation of carbon occurs at a rate about 100 times faster than what would occur naturally. (Berner, 2007)

Equilibrium climate sensitivity

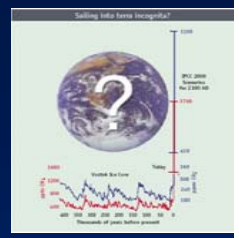






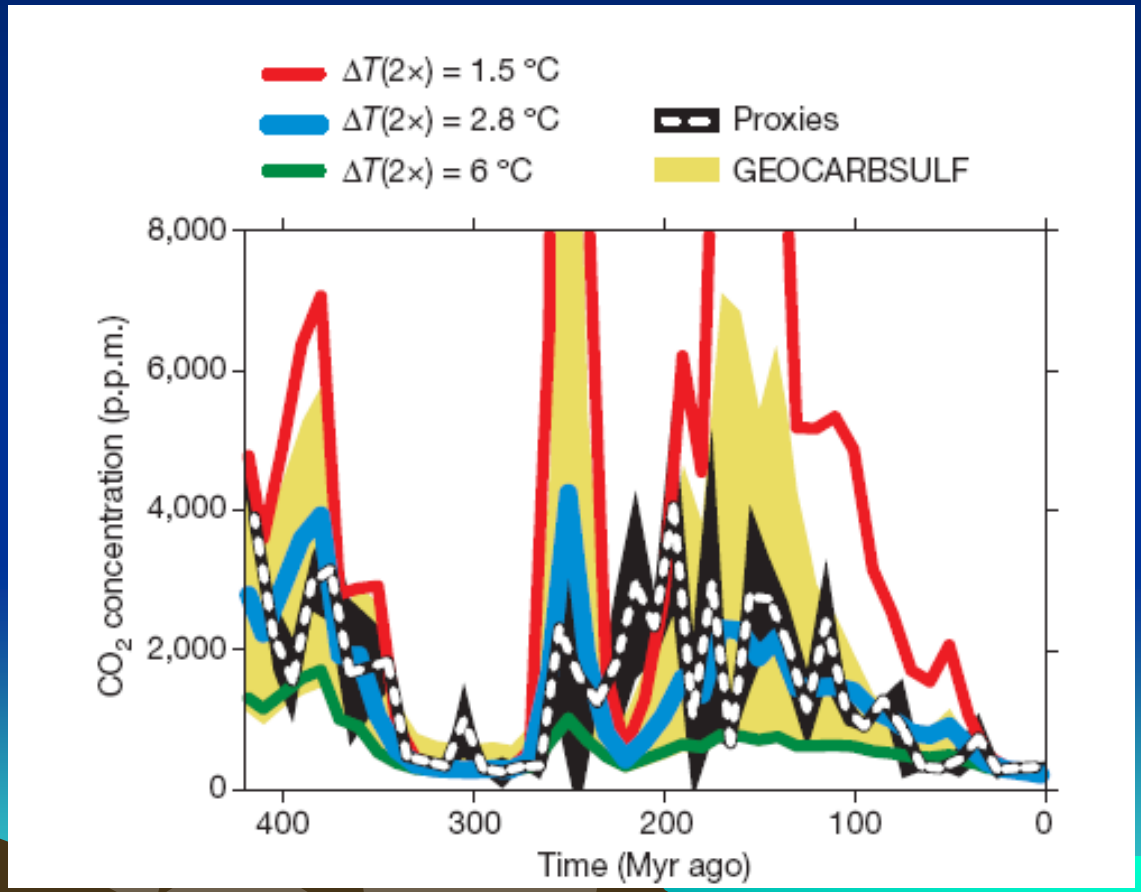


Equilibrium climate sensitivity during the Phanerozoic

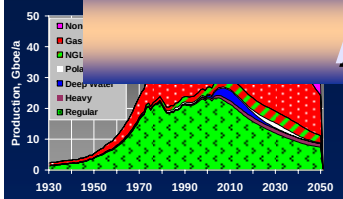


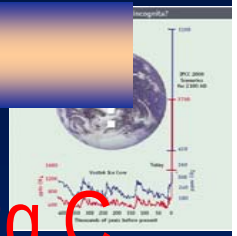
We conclude that a climate sensitivity greater than 1.5°C has probably been a robust feature of the Earth's climate system over the past 420 million years, regardless of temporal scaling.

-Royer (2007)



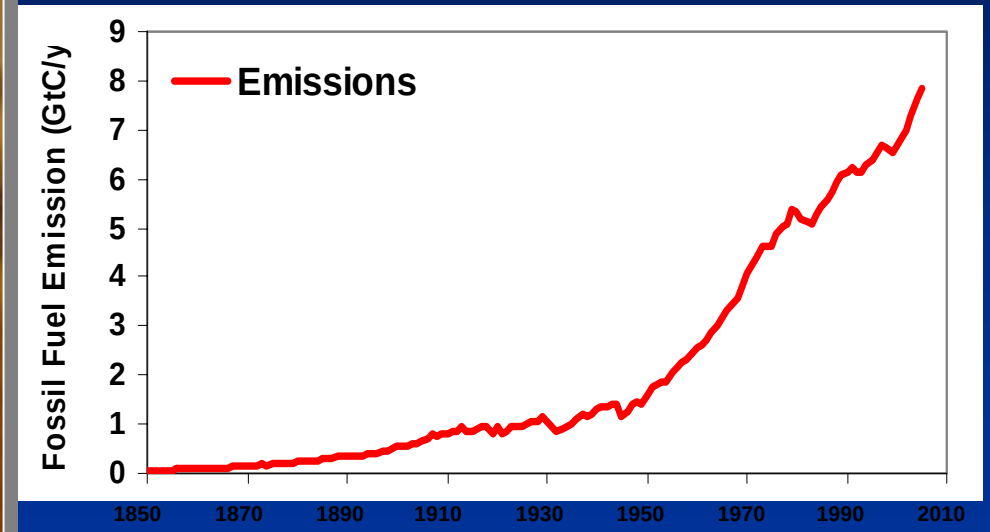
Anthropogenic C Emissions: Fossil Fuel





2006 Fossil Fuel: 8.4 Pg C

[2006-Total Anthrop. Emissions:8.4+1.5 = 9.9 Pg]

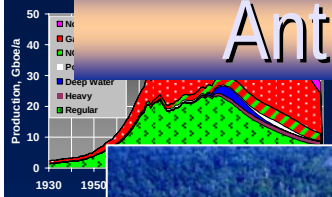


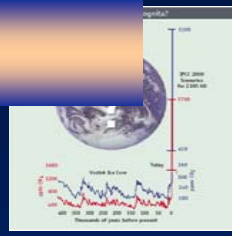
1990 - 1999: 1.3% y^{-1}

2000 - 2006: 3.3% y^{-1}

Raupach et al. 2007, PNAS; Canadell et al 2007, PNAS

Anthropogenic C Emissions: Land Use Change





Borneo, Courtesy: Viktor Boehm

Tropical deforestation

13 Million hectares each year

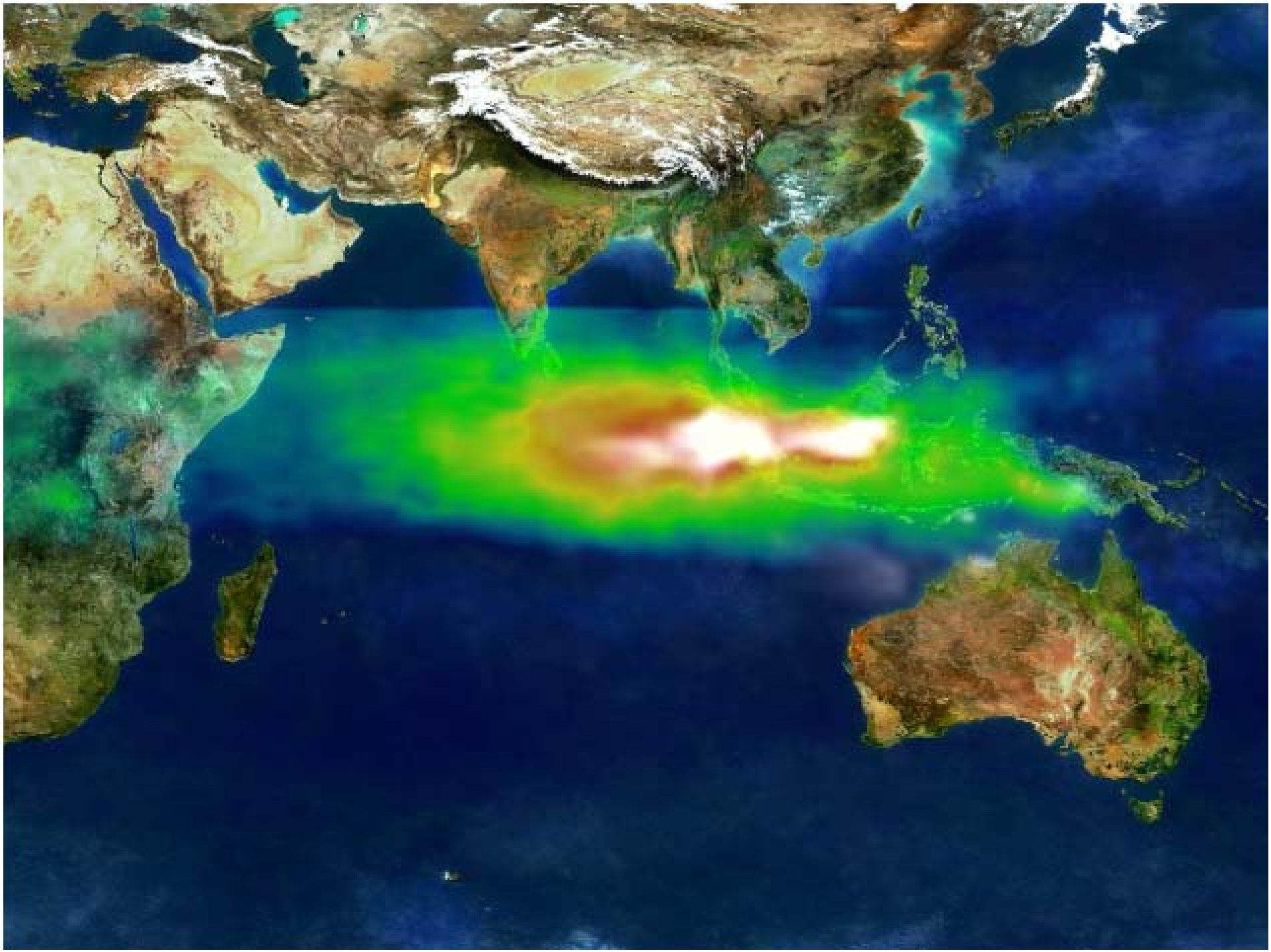
2000-2005

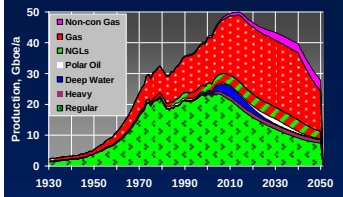
Tropical Americas	0.6 Pg C y^{-1}
Tropical Asia	0.6 Pg C y^{-1}
Tropical Africa	0.3 Pg C y^{-1}
	1.5 Pg C y^{-1}

FAO-Global Resources Assessment 2005; Canadell et al. 2007, PNAS

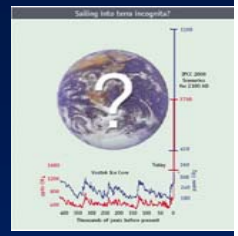
Strip mining tar in Alberta

Mountaintop removal for coal in West Virginia

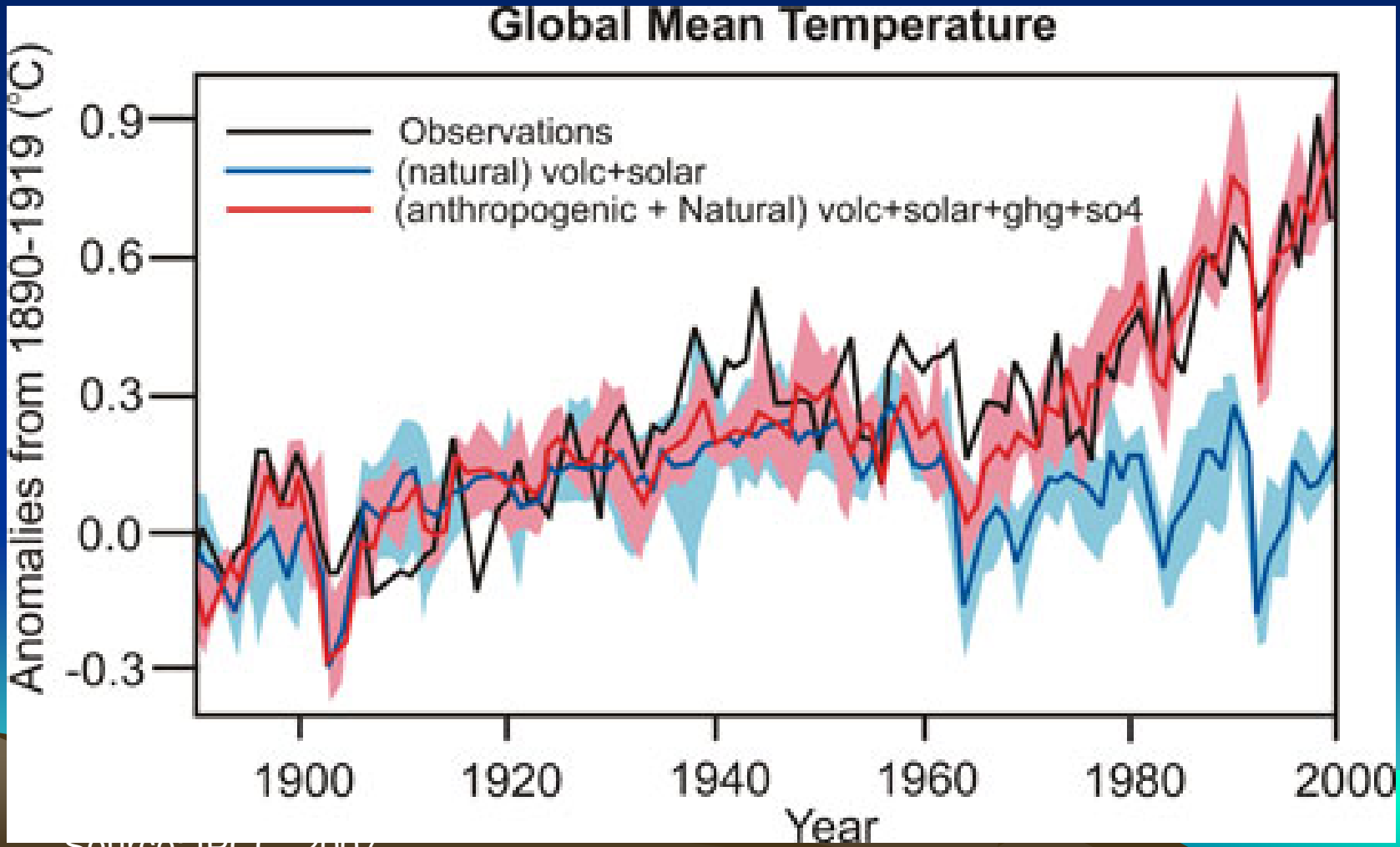




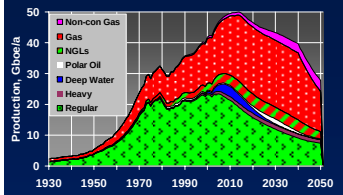
A Warming Earth



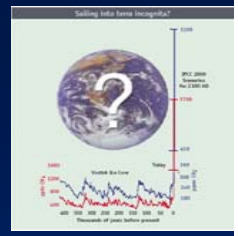
We know the Earth is warming by direct measurements



Source: IPCC, 2007



Cosmic Rays?

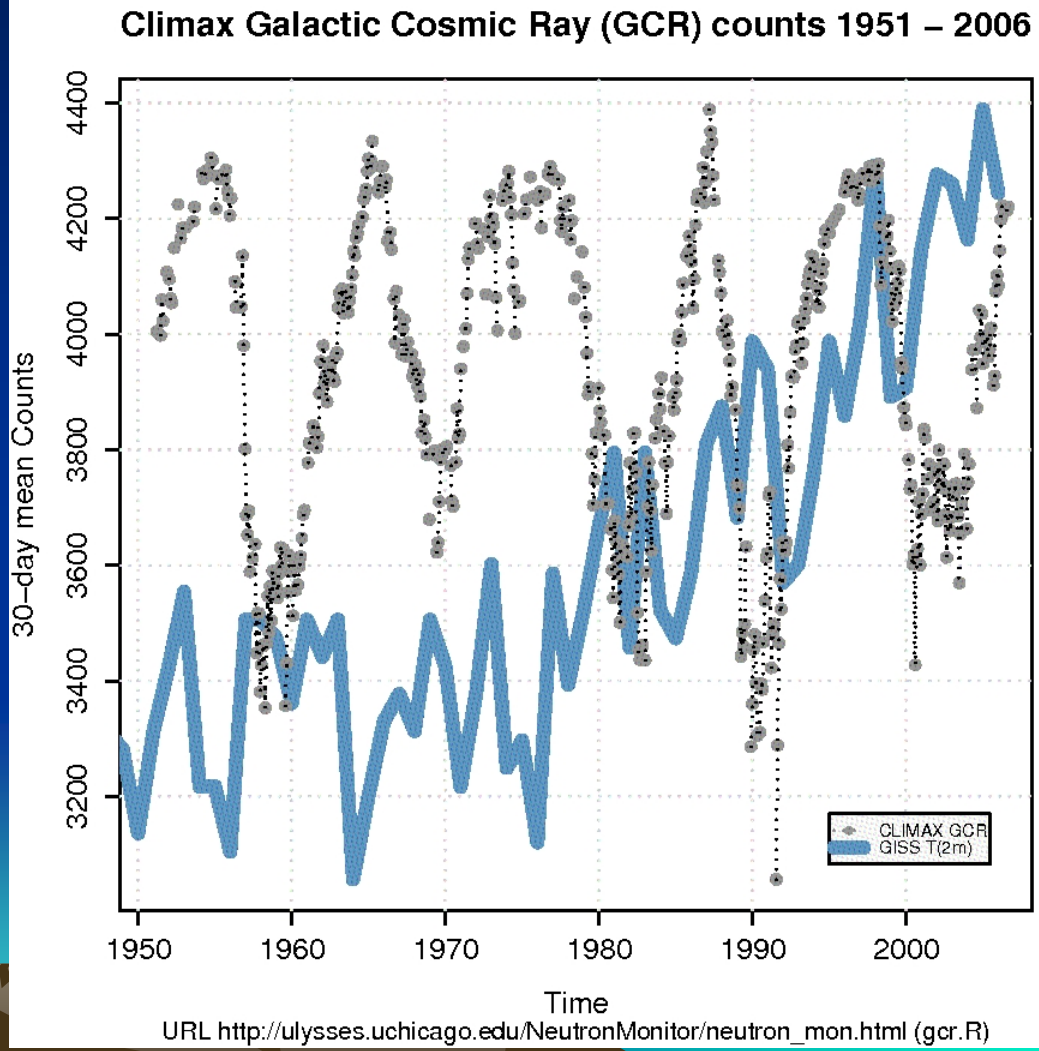


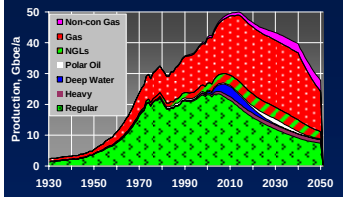
Since 1950 there is no trend at all in GCR which might explain the recent warming.

We estimate that less than 15% of the 11-year cycle warming variations are due to cosmic rays and less than 2% of the warming over the last 35 years is due to this cause. (Sloan, 2007)

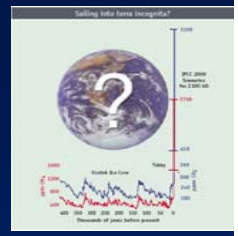
…over the past 20 years, all the trends in the Sun that could have had an influence on the Earth's climate have been in the opposite direction to that required to explain the observed rise in global mean temperatures. (Lockwood, 2007)

Changes in the cosmic ray flux cannot be responsible for more than 15% of the recent warming. (Kirvova, 2003)

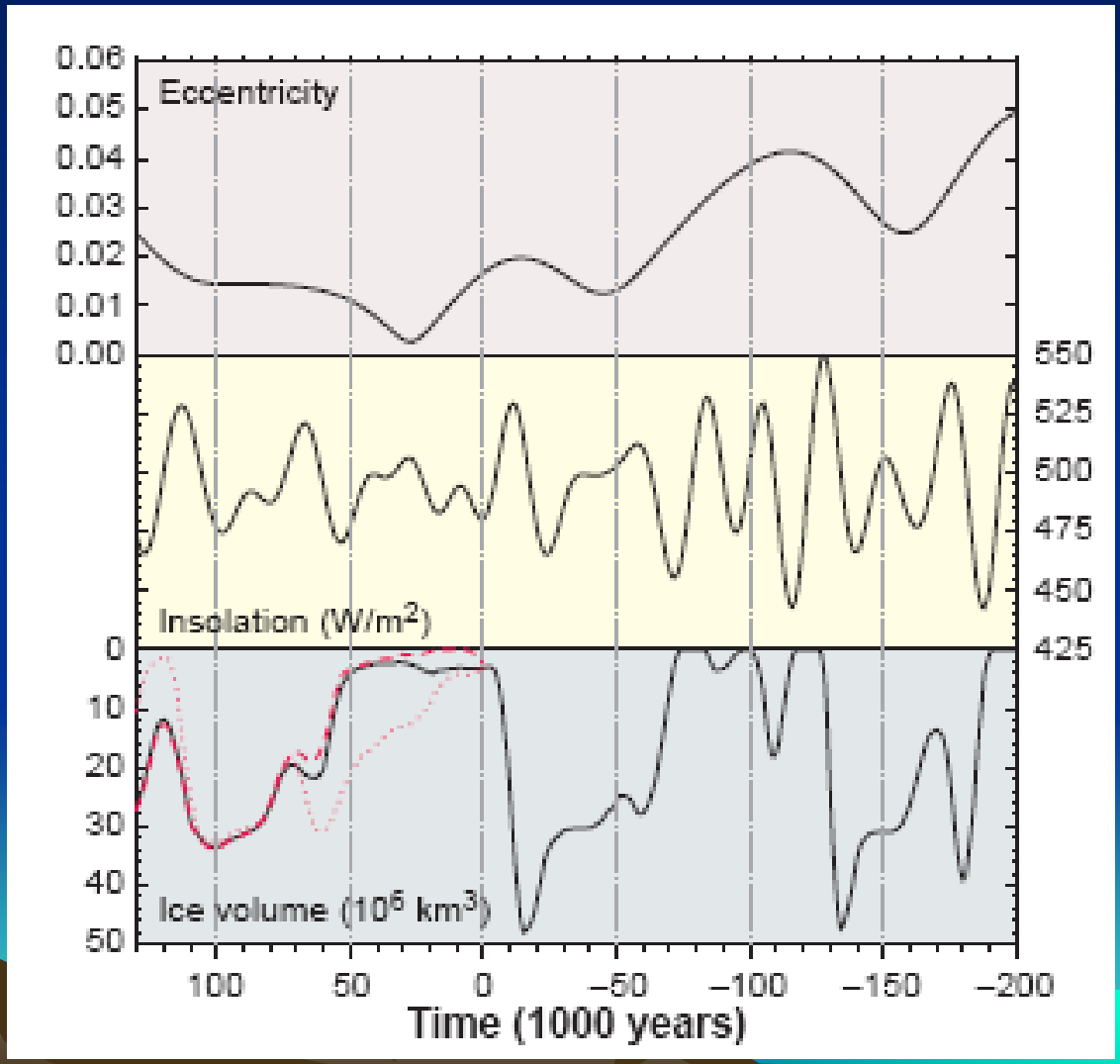


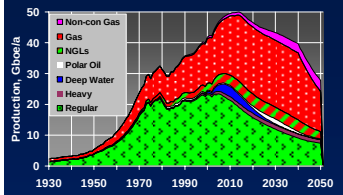


An exceptionally long interglacial ahead

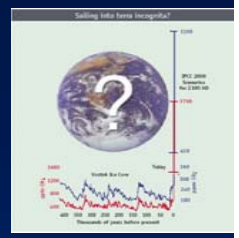


…an "irreversible greenhouse effect" could become the most likely future climate. If the Greenland and west Antarctic Ice Sheets disappear completely, then today's "Anthropocene" may only be a transition between the Quaternary and the next geological period. (A. Berger and M. F. Loutre, 2008)

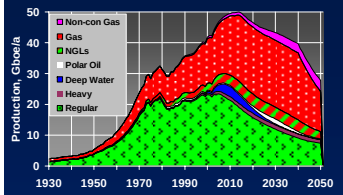




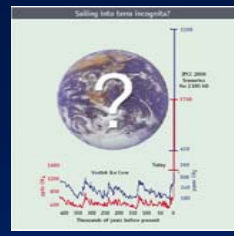
Conclusion



- Lots of different factors influence the Earth's climate, sometimes as a forcing function and sometimes as amplifying or attenuating feedbacks.
- Solar radiation and the greenhouse effect driven by the short and long term carbon cycles are the main determinants of climate.



Conclusion



- Human emissions of greenhouse gases occurs 100 times faster than what would occur normally.
- Human consumption of fossil fuels and deforestation are causing the current warming trend.