Glacial-Interglacial Cycling:

Ice, orbital theory, and climate

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Outline

-The past

- discovery of glacial periods

- introduction of orbital theory

-The present

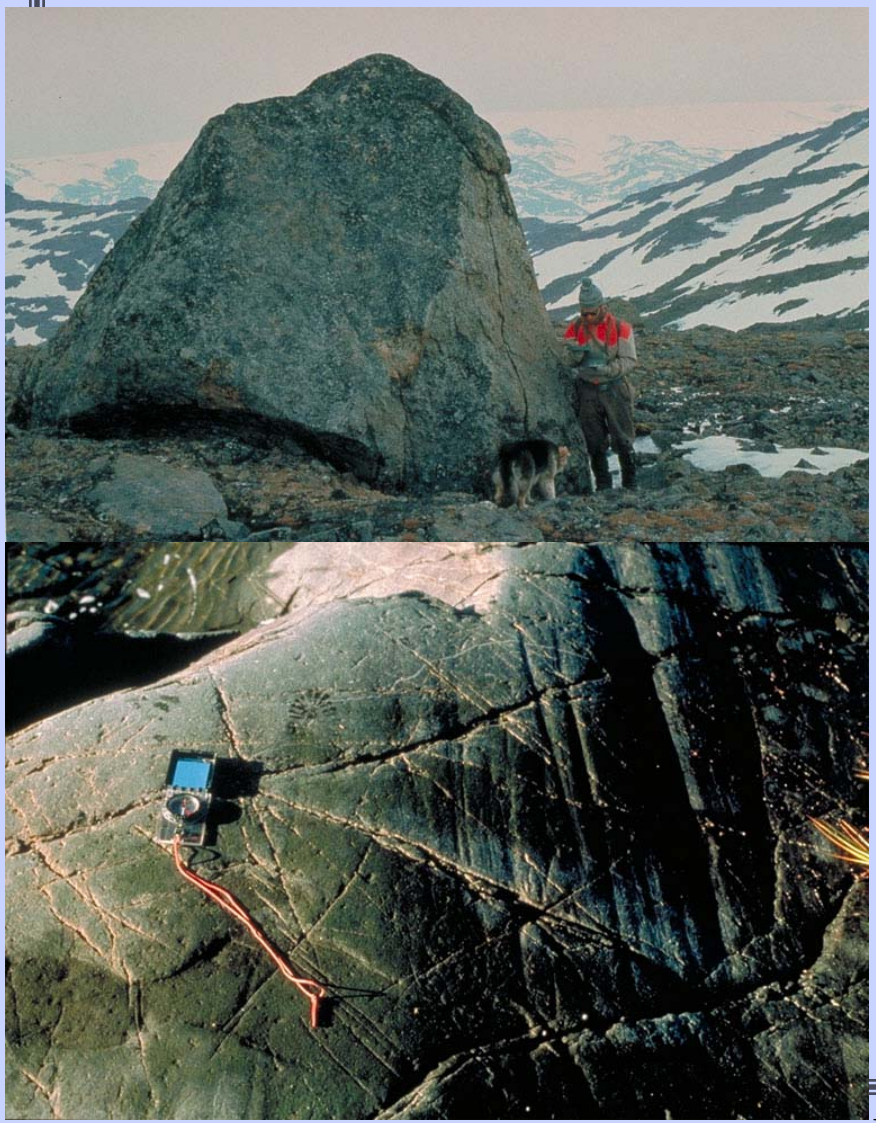
- ice and sediment records

- spectral analysis

-The future

-Implications for climate change

The Existence of Ice Ages



Scientists studying the Alps discovered striated rocks and erratics

Initially thought to result from the biblical Great Flood

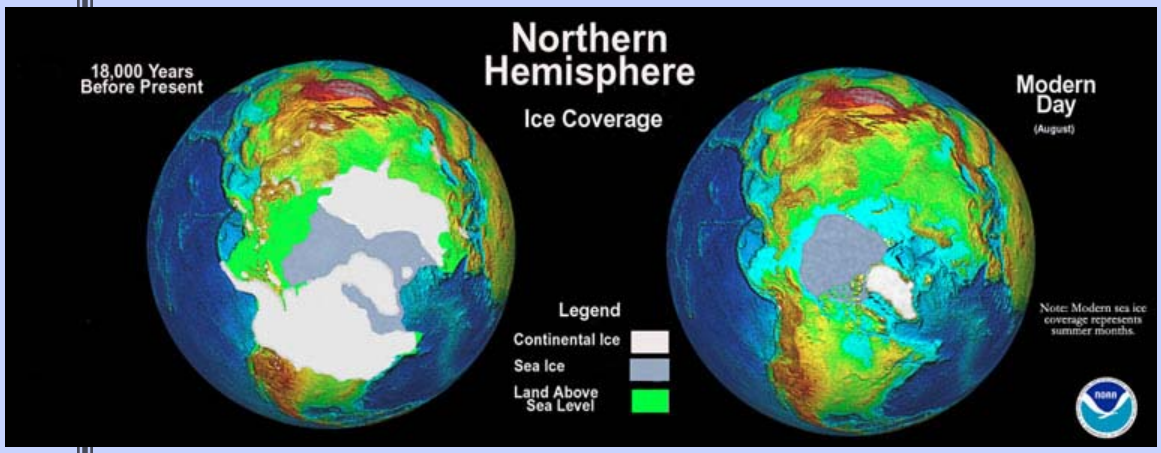
Really indicated extensive glaciation into Europe and N. America

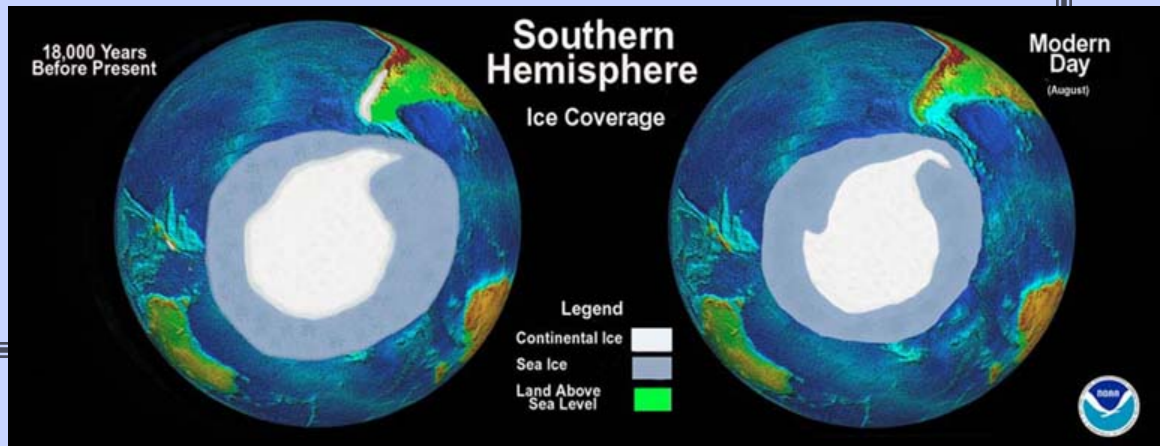
In 1837, Louis Agassiz delivered an address titled “Upon Glaciers, Moraines, and Erratic Blocks”

NOAA; John T. Andrews

By the end of the 19th century, scientists had identified 4 ice ages each separated by warmer interglacial periods

Ice covered approx. 17 million square miles, mostly in the N. Hemisphere





Mark McCaffrey
NGDC/NOAA

What caused the ice ages?

Several theories proposed to explain ice ages, including:

- decrease in solar output (sunspots, space dust)
- changes in CO_2
- volcanic eruptions
- crustal movement

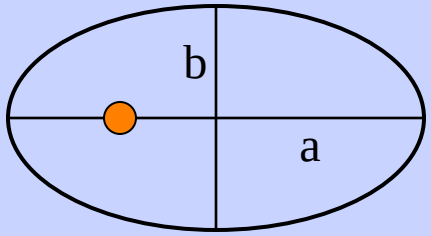
Orbital theory proposed in 1842 by Adhémar; refined by Croll and calculated by Milankovitch in 1924

Orbital Theory

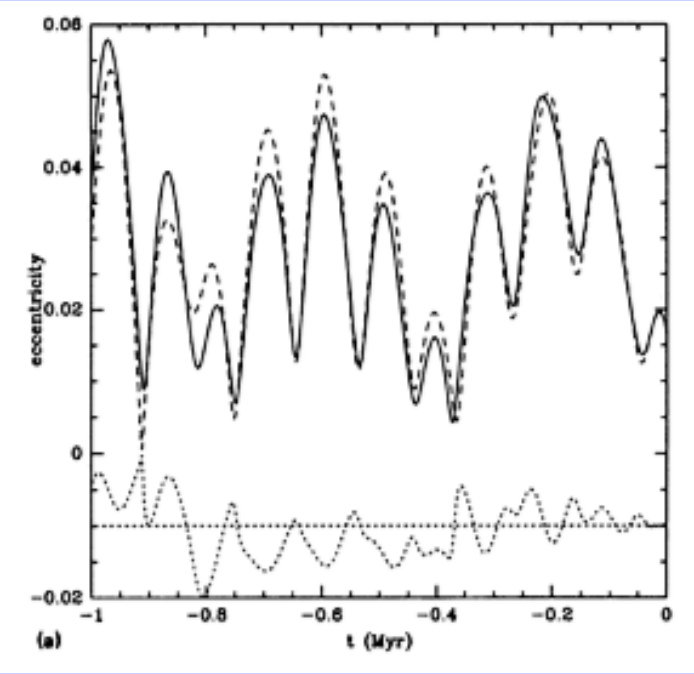
The basis of orbital theory is that ice ages result from changes in the solar irradiance (insolation) derived from variations in the Earth's orbital parameters: eccentricity, precession, and obliquity

Milankovitch compiled data regarding the periodicity of these variations, then calculated the changes in insolation at various latitudes

Eccentricity



$e=(a^2+b^2)^{1/2}/a$



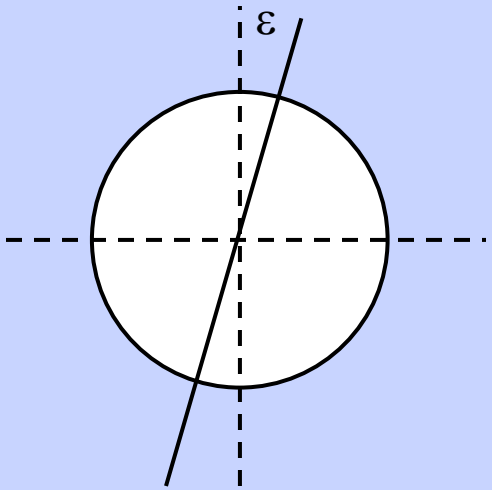
Eccentricity is the shape of Earth's orbit around the sun

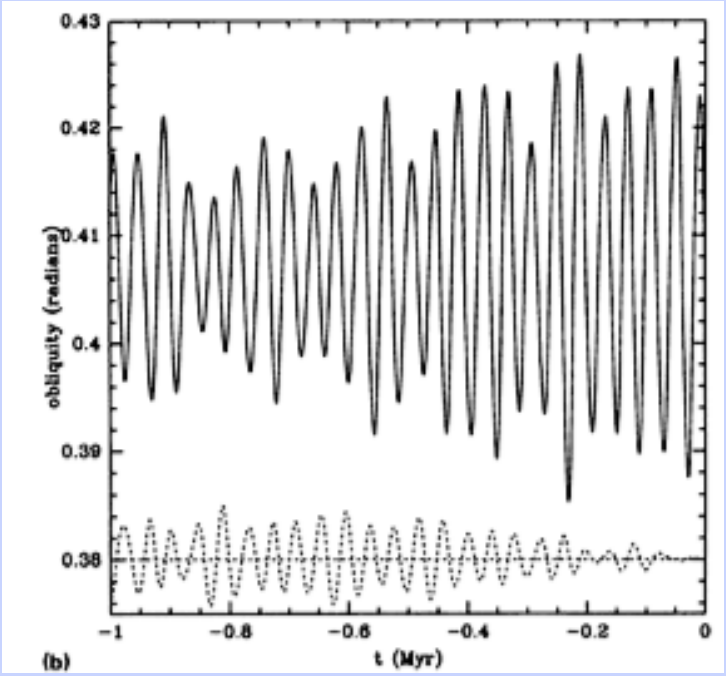
Varies from 0 to 0.06

Cyclicity of ~100,000 years and a longer, higher amplitude cyclicity of ~400,000 years

Quinn et al., 1991

Obliquity





Obliquity (ε) is the tilt of the earth's axis relative to the plane of the solar system

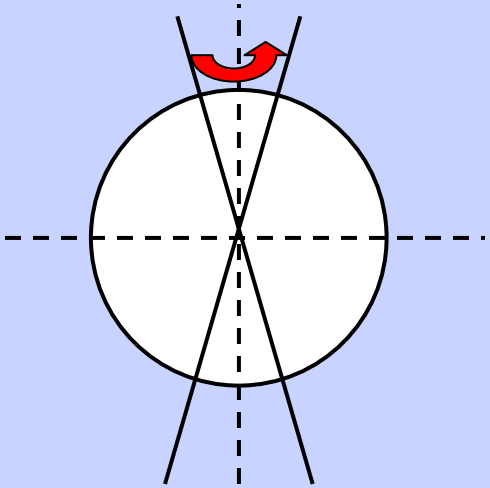
Varies between 21.8˚ and 24.4˚

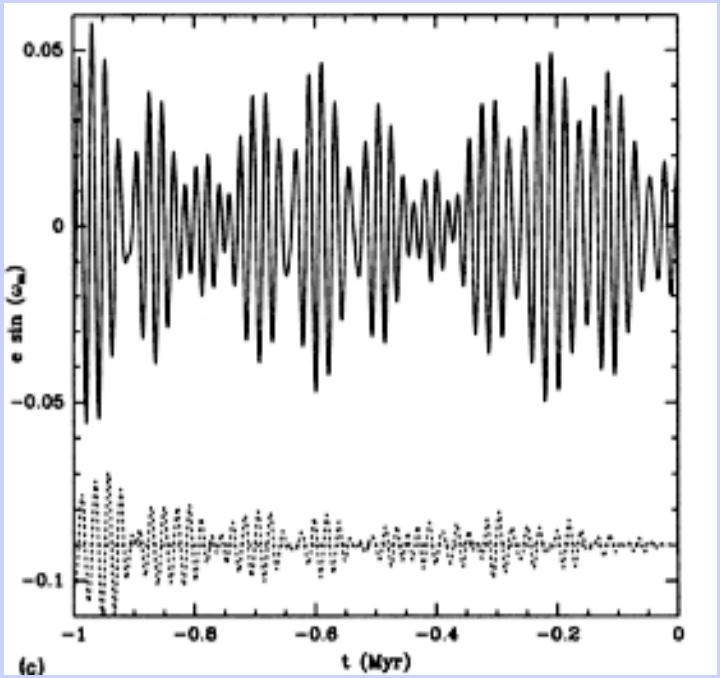
Affects the insolation intensity of the tropics vs the poles

Period is ~41,000 years

Quinn, 1991

Precession





Precession is the ‘wobble’ of the Earth’s axis of rotation due to the sun’s torque on the non-spherical Earth

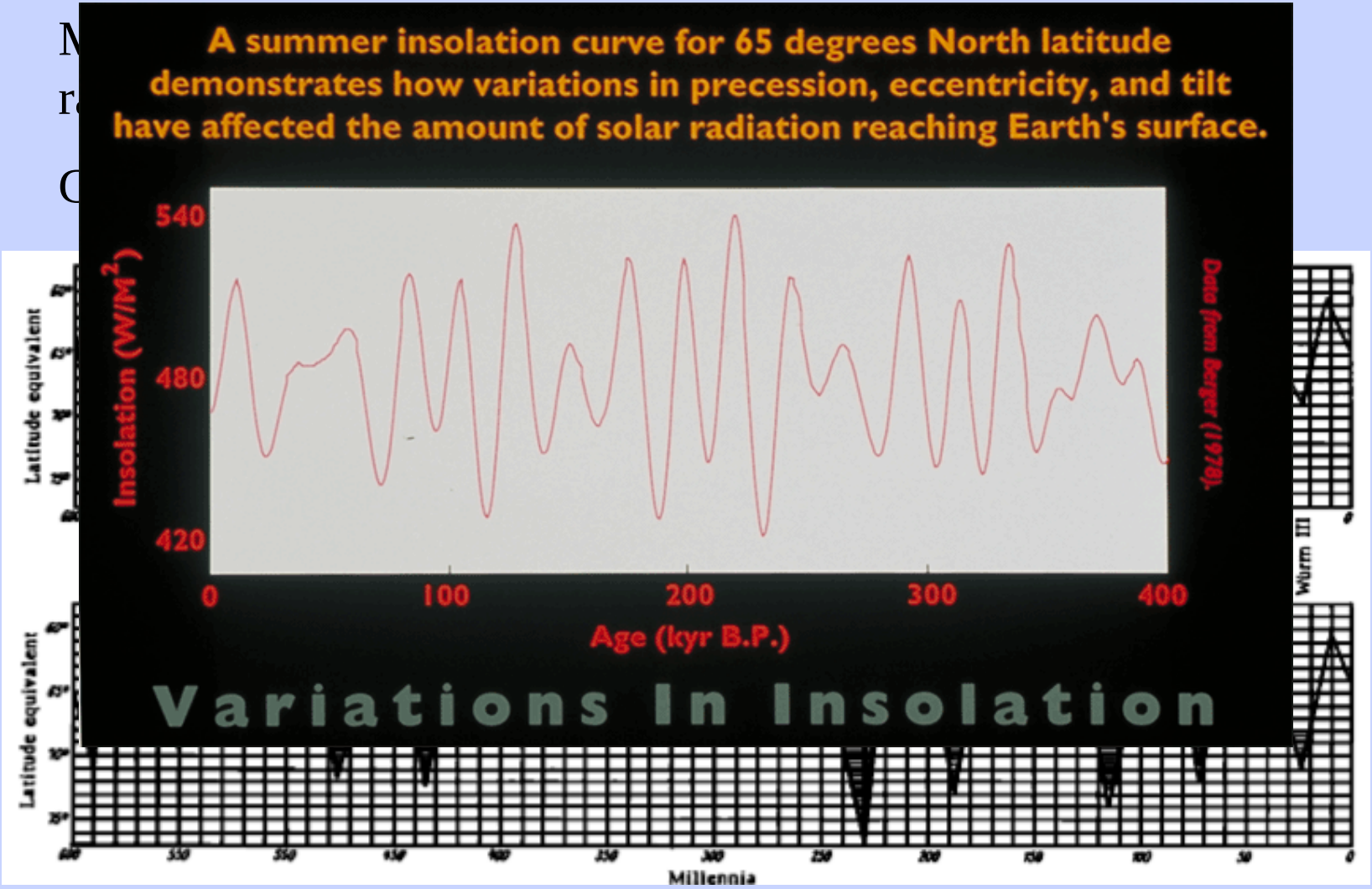
Period of ~23,000 years

Measured as the Earth to sun distance in June

Eccentricity amplitude modulates

Quinn, 1991

Calculation of Insolation



Berger 1988, adapted from Milankovitch at 65˚N, summer

Testing Milankovitch, part I

Debate about Milankovitch's curves in early years

- trouble identifying and dating glacials on land
- ignored heat transport by ocean and atmosphere
- changes were relatively small
- accuracy of calculations for the high latitudes

Needed to connect theory with geologic evidence

It took new types of samples, new climate proxies, and new ways of evaluating data to resolve these issues

Testing Milankovitch, part II

In the post WWII years, several techniques advanced geological studies of glacial-interglacial periods

Improved dating using radiocarbon, chronology, magnetic reversals

Oceanic and ice core samples gave long records at non-continental locations

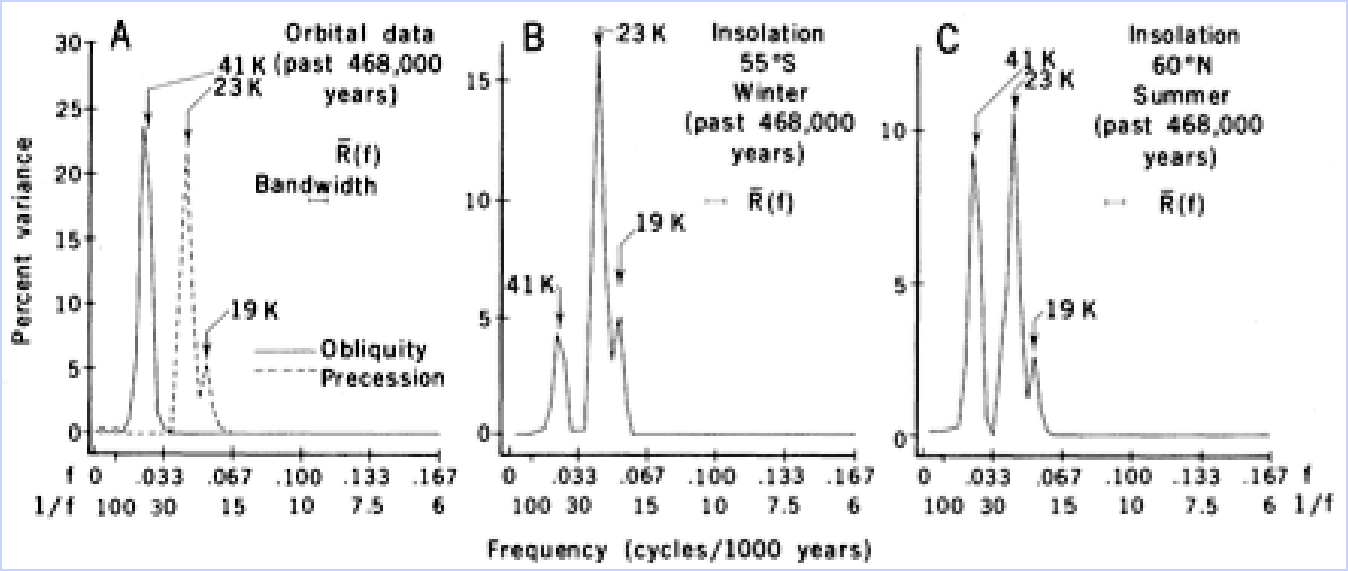
New measurements of climate proxies

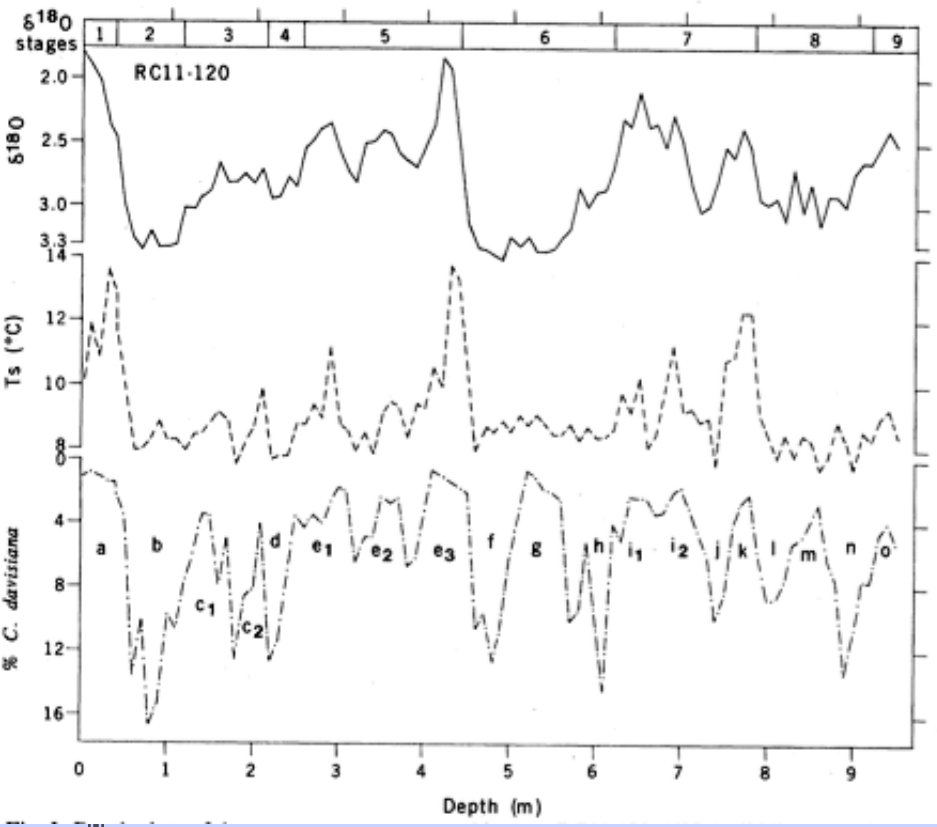
- organism abundances and type
- CO_2 and CH_4 trapped in ice cores
- isotopic measurements (δD, $\delta^{18}O$ of forams)
- biomarkers as T estimates (UK_{37})

“Pacemaker of the Ice Ages”

Hays, Imbrie and Shackleton, 1976 succeeded in tying changes in $\delta^{18}O$ (glacial indicator) to astronomical theory

Used spectral analysis to determine predominant frequency patterns in data





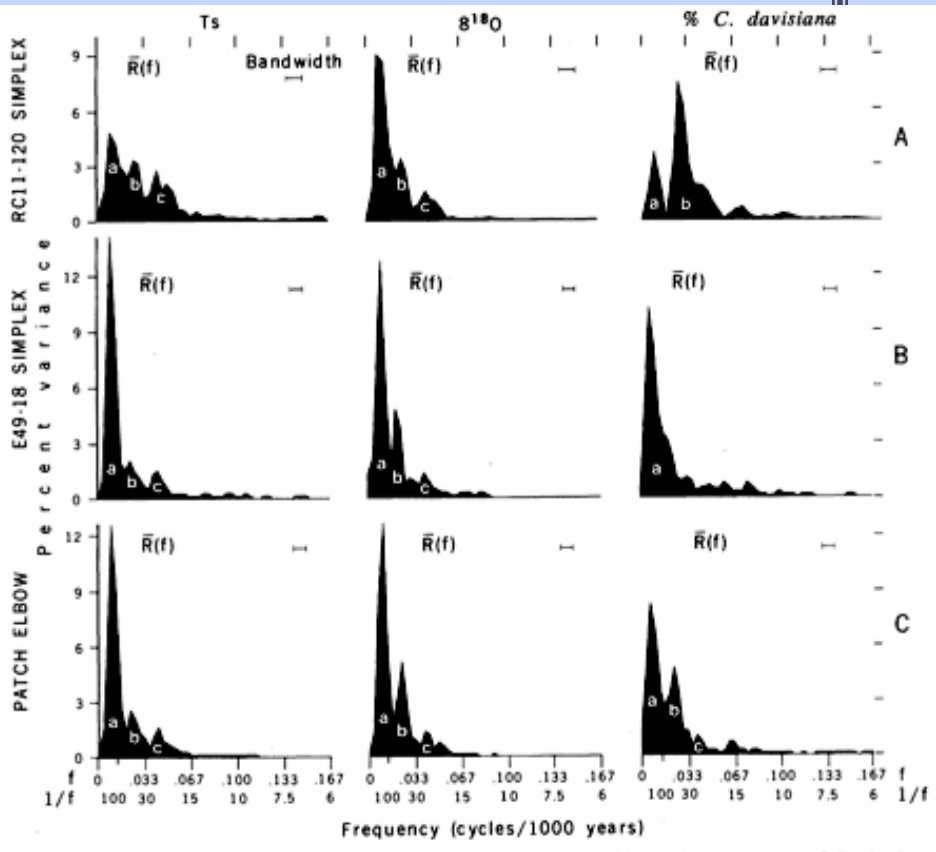
Lighter $\delta^{18}O$=interglacial=odd

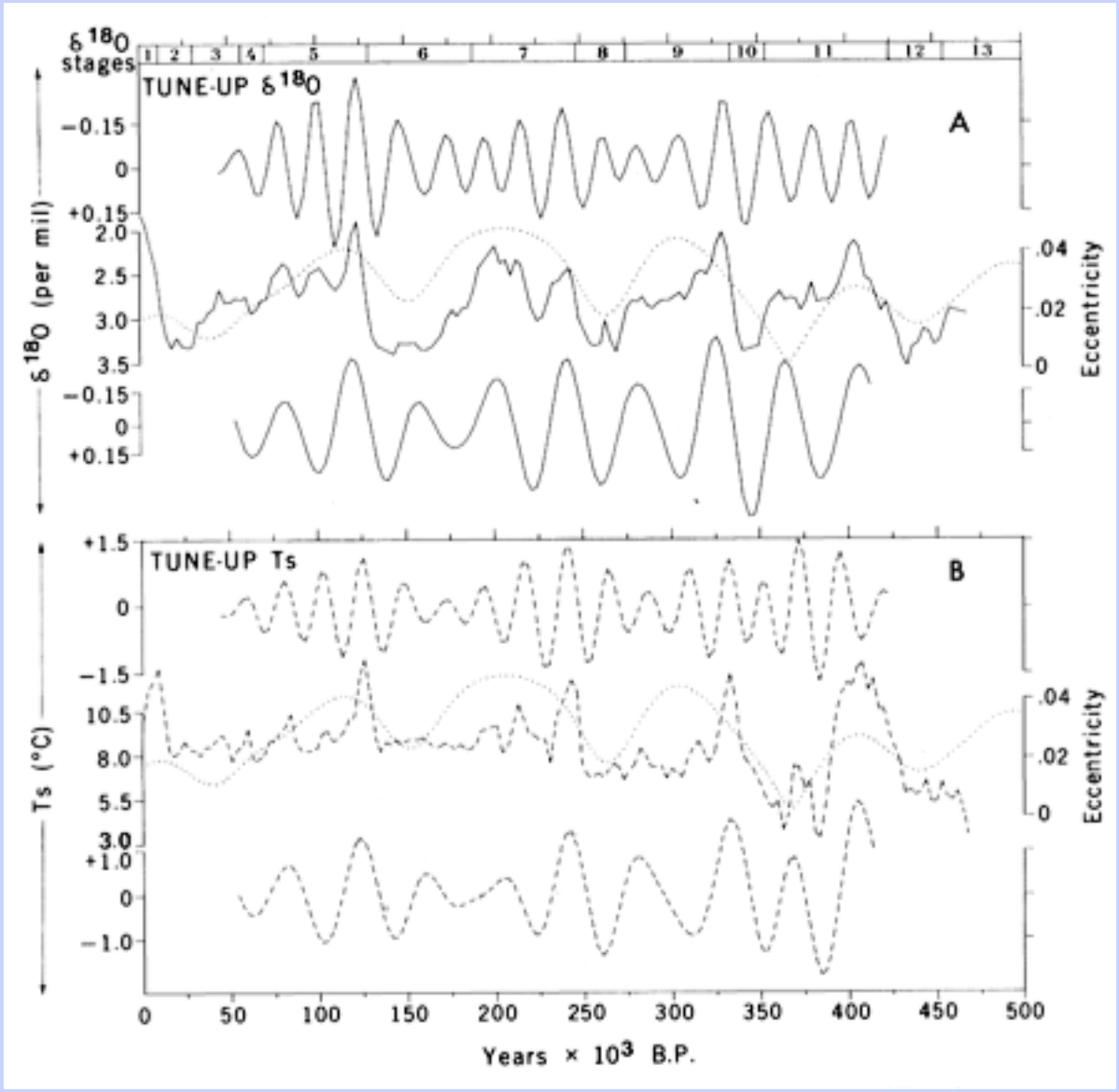
Heavier $\delta^{18}O$=glacial=even

a~100,000 years

b~40,000 years

c~24,000 and 19,500 years




δ18O stages
1 2 3 4 5 6 7 8 9 10 11 12 13
TUNE-UP δ18O
A
−0.15
0
+0.15
2.0
2.5
3.0
3.5
δ18O (per mil)
.04
.02
0
Eccentricity
TUNE-UP Ts
B
+1.5
0
−1.5
10.5
8.0
5.5
3.0
Ts (°C)
+1.0
−1.0
0 50 100 150 200 250 300 350 400 450 500
Years × 10³ B.P.

But is Milankovitch the answer?

Orbital forcing is clearly linked to glacial-interglacial cycles

But can the small changes in energy really initiate ice ages?

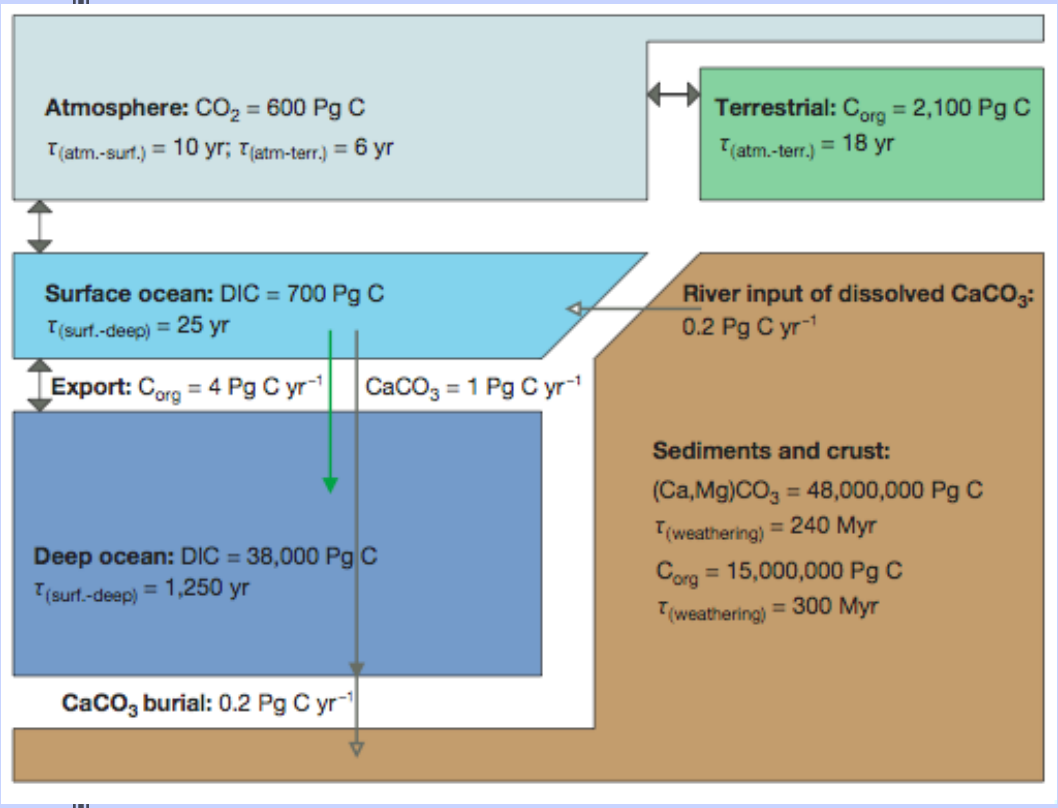
How does climate change so quickly?

How do the land-atmosphere-ocean feedbacks help/hinder climate change?

How to explain CO_2 variations coincident with glacial-interglacial periods?

The answer? No-one knows for sure.

The role of atmospheric CO_2



Sigman and Boyle, 2000

Milankovitch forcing is not enough to explain large climate change or rapid transitions

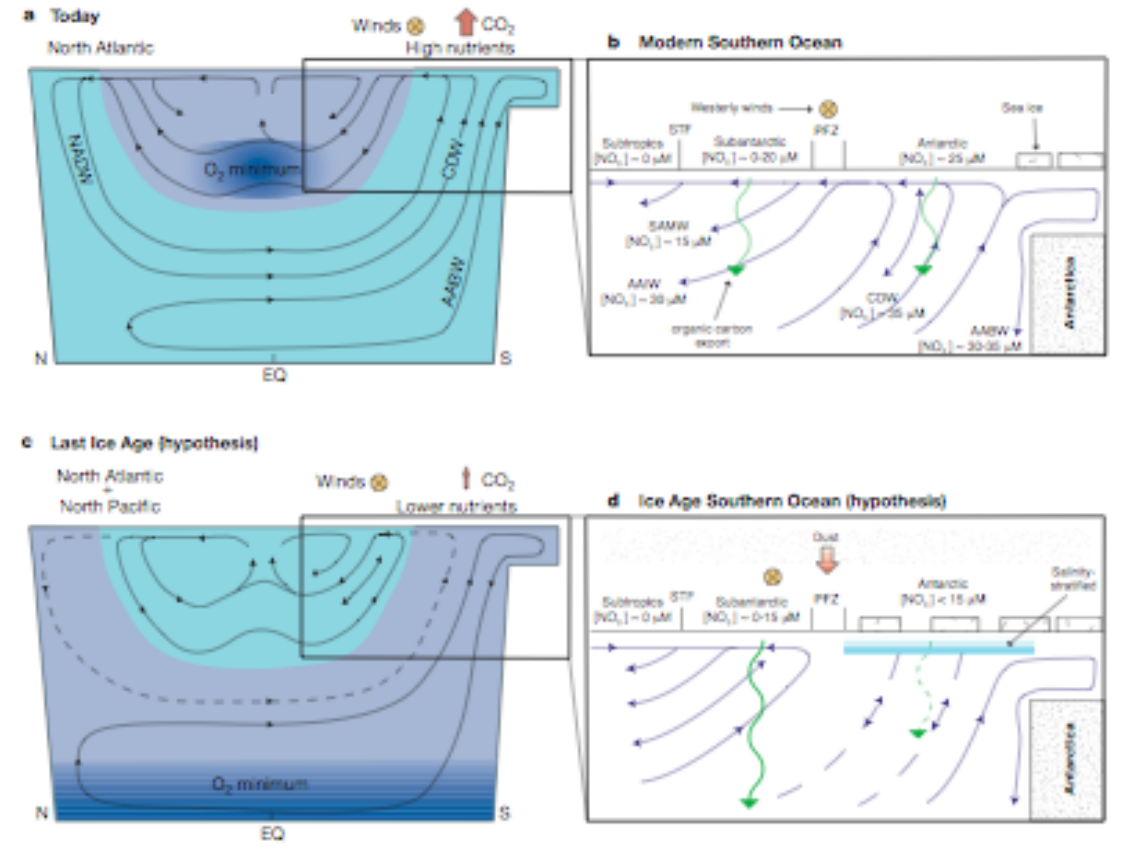
CO_2 is a greenhouse gas

Regularity suggests a dominant mechanism

Must also alter deep ocean carbon pool

Need to remove 80-100 p.p.m.v each glacial

Changes in high latitude nutrient utilization



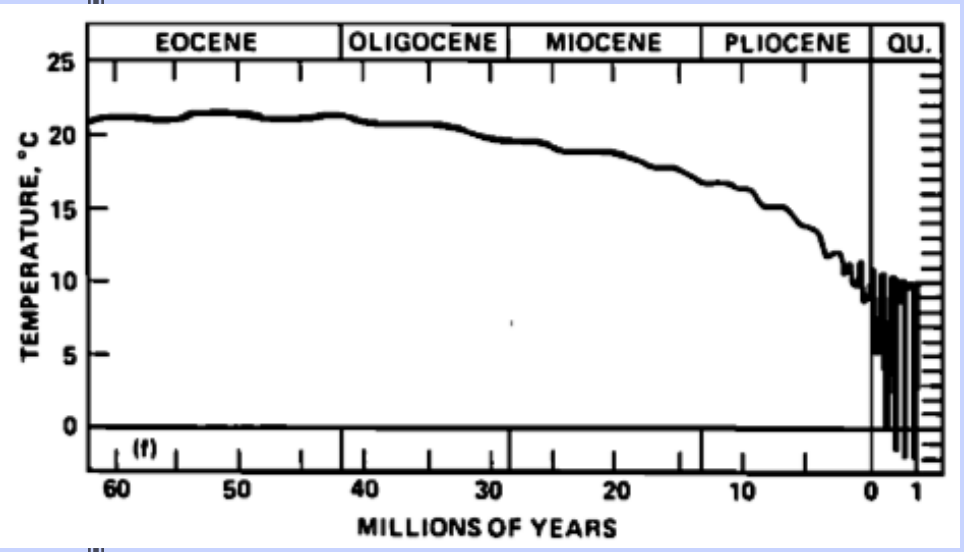
Lower nutrients but higher utilization, reduced CO_2 out

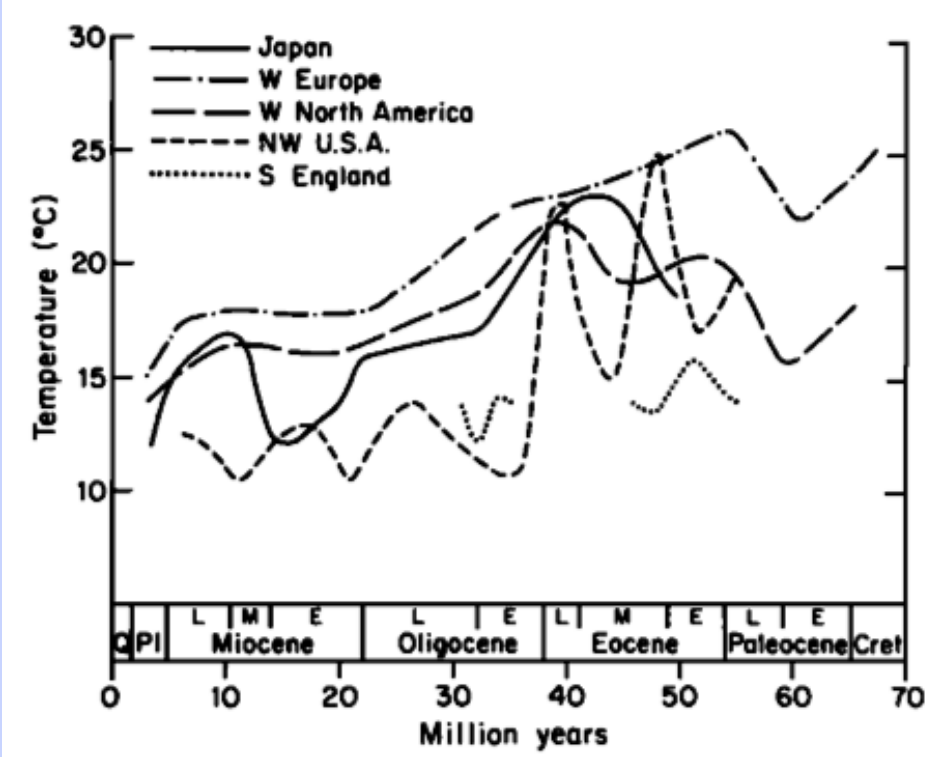
Unproven due to limitations in proxy measurements and lack of data

More unanswered questions

How did the glacial-interglacial cycles start?

opening of the Drake Passage (Eocene) allowed circumpolar circulation and S. Hem. glaciation

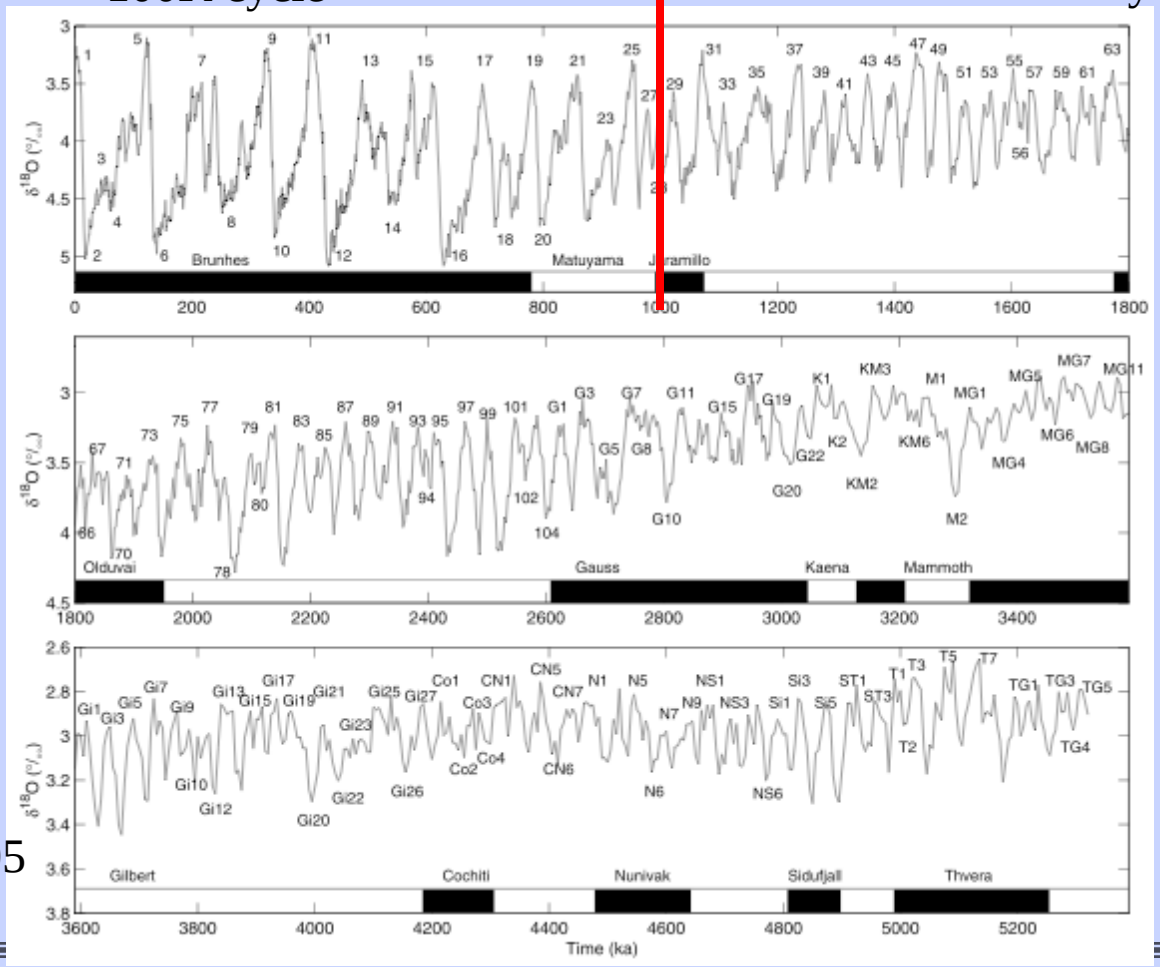




Berger, 1988

What caused the switch from predominant 41,000 year cycles before 1Mya to 100,000 year dominant cyclicity?

100K cycle ← → 41K cycle



Lisiecki & Raymo, 2005

Glacial-interglacials and climate change

Significant climate shifts may be used to predict Earth systems response to human-influenced change

How was CO_2 removed from the atm during glacials, and can we replicate it to get rid of excess CO_2 today?

What sort of feedbacks occur as CO_2 rises?

Can we recognize signs of climate change?

Additional Reading

Berger, 1988 Reviews of Geophysics 26(4), 624-657

Lisiecki & Raymo, 2005 Paleoceanography 20, PA1003, doi:10.1029/2004PA001071

Hays et al., 1976 Science 194(4270), 1121-1132

Imbrie & Imbrie 1979 Ice Ages: Solving the Mystery

Petit et al., 1999 Nature 399, 420-436

Broecker, 1982 Progress in Oceanography, 2, 151-197

Quinn et al., 1991 The Astronomical Journal 101(6), 2287-2305