The long term record of climate change

Or: 60 million years of climate change in 80 minutes
A bit of background on carbonates

CaCO₃ (solid)
Organisms need both carbon dioxide and carbonate.
The two pumps put $\Sigma CO_2$ into the deep ocean
... and onto the long term record of climate change

How what controls climate really depends on the time scale.
Controls on climate

Tectonics
Ocean circulation
Orbital parameters
Oxygen isotopes have different controls on different time scales

(after Siegenthaler, 1979)
The isotopic change has 2 forcings

More ice
colder
Isotopes record broad climate change

Figure 19-9 Oxygen isotopic trends for foraminifera through the Tertiary low latitudes (left) and high latitudes (right). Left: Isotopic paleotemperature data for planktonic foraminifera (open symbols) and benthonic foraminifera (closed symbols) primarily from the North Pacific (after Savin, 1977). Right: Isotopic paleotemperature analyses of planktonic and benthonic foraminifera from the subantarctic Pacific by Shackleton and Kennett [1975]. The Modern and Tertiary benthonic temperature scales were calculated assuming water $\delta^{18}O$ values of $-0.08$ and $-1.00$ per mil, respectively. (After Savin, 1977)

But why did it occur?..... Tectonics..
The Cretaceous world

Figure 19-4  Occurrence of black, carbonaceous-rich sediments of 100 m.y. age (Aptian-Albian Stages) in drilled sites shown by black circles. Sites lacking such sediments are shown as open circles. Occurrences of black, organic-rich sediments are shown on shaded continents. (From A. G. Fischer and M. A. Arthur, Secular Variations in the Pelagic Realm, Society of Economic Paleontologists and Mineralogists, Spec. Publ. No. 25, p. 32, 1977)
Circulation in the Cretaceous was restricted at high latitudes.
Ocean circulation in the early Tertiary

Figure 19–10  Inferred circulation patterns of surface waters at 45 Ma (middle Eocene). (From B. U. Haq, *Oceanologica Acta*, vol. 4, in press, 1981)
Eocene continental placement

Figure 19–12  Reconstruction of the Southern Ocean and suggested bottom-water circulation during the early Eocene 53 m.y. ago. A spreading ridge has formed between Australia and Antarctica heralding the beginning of northward drift of Australia. India has now moved northward off the map projection. Spreading ridges and connecting fracture zones are shown as jagged lines. Dashed line in South Atlantic represents fracture zone. Reconstructions are compiled from those produced for different sectors by Weissel and others [1977] and Sclater and others [1977a, b]. (From J. P. Kennett, Marine Micropaleontology, vol. 3, pp. 301–345, 1978)
Oligocene continental placement
In the Tertiary, the Southern Ocean began to open...

The Cretaceous world comes apart.

At the same time the Southern Ocean opens, the Atlantic began to open.

Figure 19-11  Successive positions of Australia relative to Antarctica as Australia moved northward during the Cenozoic. The position of Australia at 38 m.y. ago (Eocene–Oligocene boundary) is shown (stippled) to include the South Tasman rise, which is of continental crust and which prevented the development of deep circum-Antarctic circulation well after spreading commenced. (Modified after Weissel and Hayes, 1972; from J. P. Kennett, 1977)
Ocean circulation at 25 Ma

Figure 19–16  Inferred circulation patterns of surface waters at 25 Ma (late Oligocene). (From B. U. Haq, Oceanologica Acta, vol. 4, in press, 1981)
This isotopic change has tectonic forcing.
Figure 19-17 Reconstruction of the Southern Ocean and suggested bottom-water at the time of the Paleogene–Neogene boundary 21 m.y. ago. Australia and the South Tasman rise are now well separated from Antarctica, and the Drake Passage is open. The movement of previously obstructing landmasses has, by this time, allowed the formation of the circum-Antarctic water-mass system, and bottom-water transportation south of the South Tasman rise and through the Drake Passage is feasible. Spreading ridges and connecting fracture zones are shown as jagged lines. Reconstructions are completed from those produced for different sectors by Weisel and others [1977] and Sclater and others [1977a, b]. (From J. P. Kennett, *Marine Micropaleontology*, vol. 3, pp. 301–345, 1978)
Change in continental placement through the tertiary controls circulation and climate

Figure 18-1 Postulated changes in the surface circulation of the Pacific Ocean as the continental configurations changed with time. (From Tj. H. van Andel, 1979)
The final piece

• The isthmus of Panama closes at 3.3 Ma
• The basins are set (as today)
• Northern hemisphere glaciation begins at ~2.4 Ma
• Pulsing at ~40 ka periodicity.
The broad brush misses lots of detail...
Tectonic control $\rightarrow$ orbital control

Orbital parameters were always an influence– but as the basin shape is set up they become more influential.

Also, we have a better record and can see the record of glacial pulsing in more detail.

What are the orbital parameters?
Glacial cycles of the last 2 million years
Orbital changes cause changes in insolation

- Insolation at different times of the year has different effects on global climate
- The earth's orbit varies in shape on long time scales.
  - These changes vary total insolation
  - And they vary seasonal insolation.
  - Local insolation varies
Sum total of the orbital control

Gives us an added wave pattern that “resembles” the $^{18}O$ record

The elliptical-ness of the orbit

Is the tilt of the poles and its variation

~22,000 years later:

Earth’s axis has precessed $22/26$ of a cycle, and the eccentricity of the orbit has precessed “backwards” $4/26$ of a cycle, bringing us back to a configuration which is equivalent in terms of radiation

The obliquity is $23.44^\circ$. Affects the 1,000 years, and is relatively regular. Aum oscillator (angular momentum objects).
These patterns sum to give us total insolation.
Sum total of the orbital control

Obliquity, precession and eccentricity:

Produce a wave pattern sum that “resembles” the $^{18}$O record
Climate record for the last 120ka

$\delta^{18}O$ in the sediment record

Emerson and Hedges 2008
The congress effect on climate

- tectonics
- https://www.youtube.com/watch?v=symYfq51aho
- Orbital
- https://www.youtube.com/watch?v=ud7fHTswj5k
- snowball
- https://www.youtube.com/watch?v=3E0a_60PMR8
Climate record for the last 120ka

$\delta^{18}$O in the sediment record

Emerson and Hedges 2008
Northern Hemisphere ice sheets and summer high-latitude solar radiation co-vary over the past 500,000 years

- $\delta^{18}O$ (higher numbers mean smaller ice sheets)
- Solar radiation at 65°N in June (higher numbers mean more solar radiation)

![Graph showing variations in $\delta^{18}O$ and solar radiation over time.]

- When Cape Cod formed (Wisconsin glacial advance)

Age (thousands of years ago)

Time runs this way
Glacial cycles of the last 2 million years

Past 2 million years shift from a 40k to 100k cyclicity
Climate and circulation feedback

Past 300k – 3 cycles

V19-30 (Shackleton and Pisias, 1984)
Record of CO$_2$ in the atmosphere

The record of CO$_2$ levels in the atmosphere has the same pattern as ice volume.
“Rapid” climate change

- Ocean circulation between glacial and interglacial modes
- The triggers that can shift the circulation between modes can be rapid.
- Modes can switch like a “switch”
The conveyor belt circulation

And thermohaline circulation moves CO$_2$ through the system…
Last glacial shutdown of NADW

The polar front moved south. The location and character of NADW water formation changed
Figure I-80: A meridional schematic section of the largest-scale overturning (thermohaline) cell in the North Atlantic, including a possible mixing mechanism, according to M. McCartney and R. Curry (personal communication, 1996). See text (especially Table I-1) for water mass nomenclature.
The NADW that formed was less in volume and shallower.
The $\delta^{13}C$ reflects traces the concentration of $\Sigma CO_2$ in the deep ocean.
NADW became NAIW

Our tracer is $^{13}$C

Curry and Oppo, 2005
The deep ocean had more CO$_2$

It looked more like the Pacific today than the Atlantic today
The biological pump interacts with the excess CO$_2$ we are putting into the atmosphere.

- The marine system is taking up CO$_2$ in surface waters fixing it to organic carbon and carbonate and
- Putting it into the deep ocean.
- Because most of the deep ocean is “capped” by the thermocline, the respired ΣCO$_2$ remains there…..
- If carbonate dissolves then the capacity of the water is increased (balanced by the alkalinity)
Controls on the fractionation of $^{13}$C

Water downwells:
- DIC enriched
- Low nutrients
- High $O_2$

DIC (in Water) more depleted with increasing age

Porewaters very sensitive to remineralization can be very depleted in $^{13}$C
Controls on the distribution of $\Sigma$CO$_2$

Water downwells:
- Low nutrients
- High O$_2$
- Low CO$_2$ content

DIC content of water increases with increasing age.

Carbonate sediments are a source and sink of carbon, both Corg and $\Sigma$CO$_2$. 
Record of CO$_2$ in the atmosphere through time

Temperature records change in sync with carbon dioxide records
We now have all the pieces: Ocean controlled carbon cycling

• There is a balance between atmosphere and ocean …

• If ocean circulation is changed there is a moderately long-term effect on carbon cycling.
The CO$_2$ Climate connection

How much CO$_2$ in the ocean controls the levels in the atmosphere

How fast the ocean circulates controls can change the amount of CO$_2$ in the atmosphere (to change climate)

The carbon cycle IS the climate cycle.
The carbon cycle summary
Two pumps put $\Sigma CO_2$ into the deep ocean
Changes in circulation affect the CCD

In the glaciation the CCD rose about 1000m

More dissolved $\Sigma$CO$_2$ stayed in the ocean and it came out of the atmosphere.
To reiterate.....

The depth of the CCD shallowed in the LGM
Long term change in circulation has long term effects on CO₂ cycling

The CCD permanently dropped when deep circulation as we know it began after the Cretaceous (when the Atlantic opened).

This “permanently” changed the oceans CO₂ capacity
The “Wilson cycle”

Are the very long term processes that affect CO₂ and climate.
carbon cycling time frames

Longer:

The tectonic time Frame
the Wilson Cycle

The sedimentary time frame \( \sim \) millions-thousands yrs

Shorter:

Thermohaline circulation

The bio pump (organic and carbonate)

Respiration and dissolution
Timescales

Climate change

~ 10,000 yr

Ecosystems

Time-scales affecting nutrient supply and carbon transport

(-500 yr) (30 yr) (-10 yr) (1 yr) (-1 wk)

Photic zone

Annual cycle

Storms

Thermohaline circulation

Thermocline outcroppings, vertical mixing at lateral boundaries, & isopycnal diffusion
The importance of limestone

• Most of the carbon stored near the surface of the earth is found as CaCO$_3$ skeletal remains.

• Organic carbon is significant, but limestone is the largest reservoir
Oil reserves
Carbonate sediments
Carbonate sediment-carbon cycle

Weathering of carbonate consumes CO₂

Organic carbon sequestration occurs on the same time frame as carbonates

These both contribute to the mid & long term cycling

1000-100,000 yrs
Very long term changes in Atmosphere CO₂ content

Figure 5.4  Model calculation of atmospheric carbon dioxide during Phanerozoic time. Abbreviations indicate geologic times shown in Figure 1.3. (After Berner, 1991.)
Not just CO$_2$ changed

As CO$_2$ decreases O$_2$ increases.

They are linked through photosynthesis, respiration, and weathering.

**Figure 5.4** Model calculation of atmospheric carbon dioxide during Phanerozoic time. Abbreviations indicate geologic times shown in Figure 1.3. (After Berner, 1991.)
Atmospheric oxygen

**Figure 5.6** Model calculation of atmospheric oxygen during Phanerozoic time. Abbreviations indicate geologic times shown in Figure 1.3. (After Berner and Canfield, 1989.)
Carbon in the ocean and sediments

The deep ocean reservoir is 50x atmospheric sediment reservoir is 4 orders of magnitude larger. It is both organic and carbonate carbon.
The scientist view on climate

• John Oliver’s take on the debate
  https://www.youtube.com/watch?v=cjuGCJJUGsg

…and for good measure:
Jon Stewart on ice displacement
  https://www.youtube.com/watch?v=lPgZfhnCAdI&t=337s