Palaeoclimate - Understanding the past to predict the future

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Points to discuss

• Part I (Tuesday: 12.3.1 – 12.3.3)
  – Learn how we can reconstruct past climates
    • Palaeoclimate archives and – proxies
  – Climate change as a constant feature of Earth’s deep time history (the tectonic time-scale)
  – Cretaceous Greenhouse climate

• Part II (Wednesday) (12.3.4.-12.3.6)
  – “Icehouse” climates
  – The rhythm of past climatic changes (Milankovitch)
  – Post glacial climate variability and future climate change
Resources

• Powerpoint presentations
• Additional reading:
  – W. F. Ruddiman Earth’s Climate
    • Chapters 3, 4-7…
• NOAA Paleoclimate Data
  – https://www.ncdc.noaa.gov/data-access/paleoclimatology-data
• Quote of the 1st lines ch.12.3: “Study of paleoclimate is an extremely exciting area of research, a fascinating detective story in which scientists study evidence of past climates recorded in ocean and lake sediments, glaciers and ice sheets, and continental deposits.”
Climate Change

• What is climate?
  – Climate is the long term expression of weather.

• Climate changed since the beginning of the earth.

• Analysis of potential causes of past climate change offers predictions for the future.
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Figure 12.1
Archives and Proxies

• GOAL: Reading the history of past climate from the natural archive

• Measured weather records (time series)
  – BUT instrumental record goes back only into 17th century (major parts on earth much less)

• Historical Archives

• Geological (sedimentary archives)

• Climate proxies:
  – The term proxy (meaning “substitute” / “approximation”) is used in palaeoclimatology because the extraction of climate signals from the indicators in the archive is NOT A DIRECT observation of the palaeoclimate.
DUIZEND JAAR WEER, WIND EN WATER IN DE LAGE LANDEN

Onder redactie van A.F.V. van Engelen

J. Buisman
Observations Cruquius Delft in Rijnsburg February/March 1727
(source: Archief Hoogheemraadschap van Rijnland)
Types of proxies

- **Sedimentary proxies**
  - Type of sedimentary rock indicating for a certain climate (dunes, coals, grain size->varves)

- **Biotic proxies**
  - Organisms (animals / plants) preserved in the geological archive (terrestrial: plants, marine: corals)

- **Geochemical proxies**
  - Oxygen isotope composition of carbonate shells (palaeothermometer water)
• The Santa Maria Basin in NW Argentina between opposite El Niño influences.
• These influences have changed for the Santa Maria Basin during the Holocene. Varved lake sediments from the Santa Maria Basin offer an archive of variations in the rainfall 30000 years ago.
Particles settling

Deposition on seafloor

Intense mixing

Less intense mixing

Permanent sedimentary record
Distribution of natural climate archives
Distribution of natural climate archives
Pollen distribution diagram from lake sediments

Minnesota lake sediment core

Depth in core (m)

Depth in core (m)

Depth in core (m)

Spruce pollen (%)

Oak pollen (%)

Prairie pollen (%)

$^{14}$C ages (years)

- 1660
- 5450
- 7,120
- 10,230
- 13,270

Spruce

Oak

Sunflower

Sage
Distribution of natural climate archives
Annual ...
**dendrochronology** -- the study of the annual variability of tree ring widths

- climate information: temperature, runoff, precipitation, soil moisture
- present-8000 years of climate change

- see *Our Changing Planet*, Table 11-1
ENSO

palaeo-records
Annual growth “rings” in a *Pavona clavus* coral -seasonal differences
Coral $\delta^{18}O$ at Punta Pitt, Galápagos Provides a Record of Sea Surface Temperatures in an El Niño Sensitive Area

Data from Shen et al. (1992)
A 350-year δ¹⁸O Record from a Specimen of *Pavona clavus* Provides a History of Paleotemperature in the Eastern Pacific (Urvina Bay, Galápagos)

Data from Dunbar *et al.* (1994). Graph presented as a 5-year moving average to filter out high frequency variability.
Earth has been habitable for about 3.55 Billion Years

- Sediments amount to an ancient and long record of **liquid** water
- Life present at 3.55 billion years or earlier
- Earth was never frozen (or boiled)
- Two main climate states:
  - **icehouse** – ice sheets present
  - **greenhouse (hothouse)** - no ice sheets present
Why Has Earth Been Habitable?

Venus compared to Earth:

- Twice the solar flux
- Same carbon, but all in atmosphere as CO₂
- Higher albedo

- Venus stinking hot, Earth “just right”
- Factors? Distance from Sun? radiation balance?
Tectonic-Scale Climate Change /Faint Young Sun Paradox

• Due to lower solar luminosity, there must have been more greenhouse gas in Earth’s early atmosphere

  – competition between volcanism (source) and weathering (sink) of CO$_2$
  – 3.0 billion years ago (50-100x PAL) surface temperatures near 60$^\circ$C?
Climate over Earth’s history (12.3.1)

**Phanerozoic (543 Ma - Present)**
- Cenozoic
  - Quaternary (1.8 Ma - Present)
  - Holocene (10,000 years - Present)
  - Pleistocene (1.8 Ma - 100,000 years)
- Mesozoic
  - Cretaceous (144 - 65 Ma)
  - Jurassic (206 - 144 Ma)
  - Triassic (248 - 206 Ma)
- Paleozoic
  - Permian (290 - 248 Ma)
  - Carboniferous (354 - 290 Ma)
  - Devonian (417 - 354 Ma)
  - Silurian (443 - 417 Ma)
  - Ordovician (490 - 443 Ma)
  - Cambrian (543 - 490 Ma)

**Precambrian (4500 Ma - 543 Ma)**
- Proterozoic
  - Archaen (3800 - 2500 Ma)
  - Hadean (4500 - 3800 Ma)
Climate change on a million-year time scale

A. Alternating greenhouse and icehouse states

B. The Cretaceous greenhouse

C. post-Cretaceous cooling

Major ice ages occurred in the Pleistocene, Permian and Carboniferous, Ordovician, late and early Proterozoic
Major carbon reservoirs (gigatons; 1 gigaton = $10^{15}$ grams)
“Faint Young Sun” Paradox

• Sun’s output must have increased by ~50%
• Somehow the increase in solar output has just been compensated
• Implies a natural thermostat exists
• Greenhouse gases must be involved

Even with a modern atmosphere, Earth frozen for much of its history
Plausible explanation of the faint young Sun paradox: (A) the weakness of the early Sun was compensated by a stronger greenhouse effect due to higher CO₂ in atmosphere (or CH₄). (B) when Sun strengthend increased chemical weathering transfers atm. C into rocks.
Negative feedback loop: Chemical weathering acts as a negative climate feedback by reducing the intensity of imposed climate warming (A) and climate cooling.
(a) Comparison of CO2 concentrations from a geochemical model (continuous line) with a compilation (Berner, 1997) of proxy CO2 observations (horizontal bars). RCO2 is the ratio of past atmospheric CO2 concentrations to present day levels.
(b) CO2 radiative forcing effects. (c) Combined CO2 and solar radiance forcing effects. (d) Glaciological evidence for continental-scale glaciation deduced from a compilation of many sources.
Paleogeographic reconstructions for (top) the Jurassic (170 My ago), (middle) the Cretaceous (100 My ago), and (bottom) the Eocene (50 My ago). Panthalassa was the huge ocean that in the paleo world dominated one hemisphere. Pangea was the supercontinent in the other hemisphere. The Tethys Sea was the body of water enclosed on three sides by the generally “C-shaped” Pangea.
Long term trend in temperatures over the past 70 Mio. Years (12.3.2.)

- **Later phase:** Ice sheet growth and > 7°C additional cooling of deep water
- **Early phase:** > 6°C cooling of deep water

- Some Antarctic ice present
- No known ice

![Graph showing long term trend in temperatures](image)
Isotopes of Oxygen

More negative values mean enrichment in the lighter $^{16}$O

$^{18}$O is 99% of the total amount of O
Why should we care about $pCO_2$ in the Miocene?

Zachos et al., 2001
Influences of oceanic gateways on long term climate change

Opening of an ocean gap between S-America and Antarctica around 25 Mio years allow strong Antarctic circumpolar current to flow uninterrupted around the Antarctic continent. The passage between Australia and Antarctica had opened around 10 Mio years earlier.
Cut-off of warm, salty water inflow

Cut-off of cool, low-salinity water outflow

More ocean heat released to atmosphere

Stronger northward flow of warm, salty water
High latitudes vegetation

Early Tertiary

Present day
Cenozoic orogeny and cooling

Increased weathering of the continents due to uplift of the Himalaya Mountains and Tibetan Plateau
Tectonic Uplift Hypothesis after Raymo & Ruddiman (1985)

- Tectonic uplift of the Himalayas
- Enhanced silicate weathering
- Reduction of atmospheric CO$_2$
- Inverse greenhouse effect triggers cooling and extension of East Antarctic Ice Sheet
Collision of India and Asia produced the Tibetan plateau.
The rate of influx of sediments from the Himalayas and Tibet to the deep Indian ocean has increased 10-fold since 40 Mio years ago.
Global cooling produces more ice (A), and the ice increases rock fragmentation (B) and near ice sheets (C).
- fossil evidence for reptiles, tropical plants in the Arctic
- atmospheric CO₂ some 3-5x PAL
- abundant volcanism
The world in the Cretaceous period (100 Mio years ago)

Pangean supercontinent broke apart in smaller continents which were flooded by shallow seas.
Palaeoclimate scientist gathered geological data (fauna, flora, and geochemical) to compile an estimate of temperature. Temperature was warmer than present day at all latitudes, in particular in the high latitudes.
Climate models are matched against the palaeotemperature data inferred from geological data. One model with changes in geography and another model with changes in geography plus palaeoatmospheric CO$_2$ reproduce some aspect of the palaeoclimate data but none of them can reproduce the warmth at high latitudes.
Climate models (GCM) run sensitivity test of the effects of elevated CO2 on global temperature show greater warmth for higher CO2 levels, but the rise is not a linear relationship.

Greenhouse world (>800): Large changes in CO2 have little effect on temperature (CO2 saturation effect)

Icehouse world (<400): Small changes in CO2 have a great effect on temperature because of the positive feedback of lower temperature on snow and sea ice extension and related changes in albedo.
Unresolved problems of the Cretaceous greenhouse climate

• Possible causes:
  – High pCO2 (3-5x present day CO2 level)
  – Enhanced oceanic heat transport poleward
  – Oceanic deep water was warmer and saltier causing convection in the low latitudes (tropics)

• Presence of reptiles and tropical plants indicates warm frost free winters

• Climate models simulate freezing conditions in the continental interior
Glaciers were during ice ages not restricted to high latitudes/altitudes
Quaternary ice age

• Quaternary is characterized by ice ages which show a prominent cycle between cold “glacial stages” and warm “interglacial stages”.
• The Quaternary starts with the establishment of the N-Atlantic ice shield at ~2.1 Mio years ago.
• The glacial-interglacial changes appear to occur periodically.
• What causes this periodicity?
Several lines of evidence for ice ages

- Landscape formed by glaciers
  - U form valleys
- Occurrence of ice transported rocks (Erratics)
- Surface structures on bedrocks parallel striations
- Vegetation changes
Natural vegetation in Europe:

A Modern vegetation
- Ice
- Boreal forest
- Mediterranean scrub
- Tundra and mountain
- Deciduous and conifer forest

B Glacial vegetation

Pollen diagram indicating vegetation changes during Glacial – Interglacial climate cycle
CLIMAP reconstruction of glacial maximum ocean temperatures

Map showing the changes in sea surface temperature between LGM and today
Greenland ice sheet as palaeoclimate archives
19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.
GISP2 Ice Core Cross Section

Full Core Cross Section Area = 137 cm² Diameter = 13.2 cm

Heavy dashed lines indicate saw cuts made on each piece of core.
Light dashed lines indicate saw cuts made only at depths selected for sample.
Labels indicate the area of the core used for each of the primary GISP2 analyses.
Left: $\delta^{18}$O over the last 2.5 million years recorded in the calcite shells of bottom dwelling foraminifera. Shown is the average of tens of $\delta^{18}$O records sampled from various marine sediment cores (Huybers, 2006). Values are reported as the anomaly from the average $\delta^{18}$O over the past million years. More negative values (rightward) indicate warmer temperatures and less ice volume.

Right: $\delta^{18}$O of ice over the last 50 k y years measured in the GISP2 ice-core (Grootes and Stuiver, 1997). In contrast to the $\delta^{18}$O of marine shells, less negative values in the $\delta^{18}$O of ice indicate warmer atmospheric temperatures, in this case in the vicinity of Greenland.
Ice-core records of atmospheric carbon dioxide (left) and methane (middle) concentrations obtained from bubbles trapped in Antarctic ice. Values to 400 k y ago are from Vostok), whereas earlier values are from EPICA Dome C. (right) $\delta D$ concentrations from EPICA Dome C measured in the ice, as opposed to the bubbles, are indicative of local air temperature variations, similar to $\delta^{18}O$ of ice measurements.
Milankovitch theory (1941)

- Glaciations are a function of variations in the Earth’s orbital parameters and the resulting changes in the distribution of the solar radiation.
- The availability of continuous palaeoclimatic records from the ocean floor makes testing of this hypothesis possible.
(a) The eccentricity of the Earth’s orbit varies on a 100k y & 400k y timescale from (almost) zero, a circle, to 0.07, a very slight ellipse. The ellipse shown on the right has an eccentricity of 0.5, vastly greater than that of Earth’s path around the Sun.

(b) The change in the tilt of the Earth’s spin axis—the obliquity—varies between 22.1° and 24.5° on a timescale of 41k ys. The tilt of the Earth is currently 23.5°.

(c) The direction of the Earth’s spin vector precesses with a period of 23k y.
Variations in eccentricity, precession, and obliquity over 300k y, starting 200k y in the past, through the present day and 100k y in to the future. From Berger and Loutre, (1992).
Abrupt Climate Change
The transition from the Last Glacial Maximum to the relatively ice-free conditions of the Holocene took roughly ten thousand years. In certain regions this transition was punctuated by rapid climate variations having timescales of decades to millennia. Shown is the GISP2 ice-core (Grootes and Stuiver, 1997) with shading indicating the return to glacial-like conditions known as the Younger Dryas. The Younger Dryas is a prominent feature of many North Atlantic and European climate records and its presence can be detected in climate records across much of the Northern Hemisphere.
Evidence of a cold episode that interrupted the general deglaciation warming:

(A) Southward return of cold polar water in the N-Atlantic

(B) Reversal toward Arctic vegetation in Europe (Dryas)

(c) cooler continental temperatures indicated by fossil insects
Retreat of the N-American ice sheet during deglaciation
Routes of meltwater flow:

Formation of proglacial lakes in morphological depressions

During the deglaciation the main water flow changed from southward to the Gulf of Mexico to the north into the Arctic Ocean late in the deglaciation.
Estimates of Northern Hemisphere surface air temperature during the last 1100 years. Temperatures obtained from instruments (Jones and Moberg, 2003) are shown in black. Colored curves indicate different proxy reconstructions of temperature. Proxies, such as tree rings, ice cores, and corals, are necessary for estimating temperature before widespread instrumental coverage, before about 1850.

The spread between the reconstructions indicates a lower-bound on the uncertainty in these estimates. All records have been smoothed using a 20-year running average and adjusted to have zero-mean between 1900 and 1960.