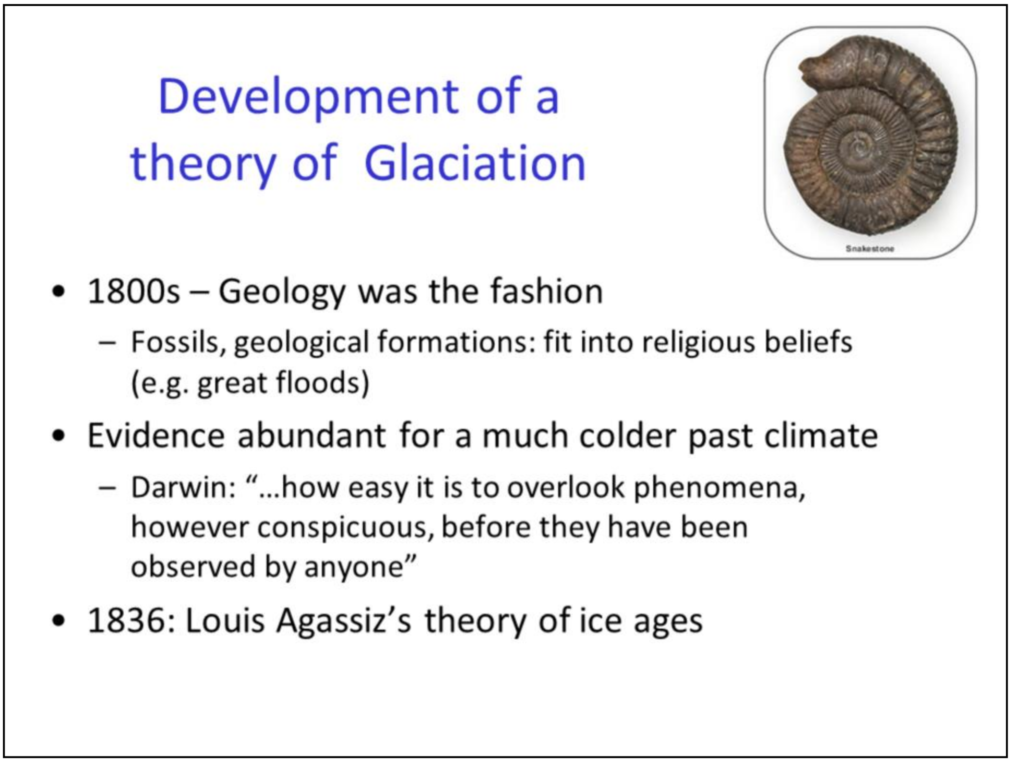
CLIMATE CHANGE:
Past, Present and Future

University of Reading

- Session 3: Past Climate 1 - Glacial Cycles
  - Recap: Greenhouse Effect
  - Past Climate Change:
    - Theory of glacial cycles
    - Milankovitch/Croll orbital variations
  - Tea/Coffee break (8pm)
  - Recap and Current climate news



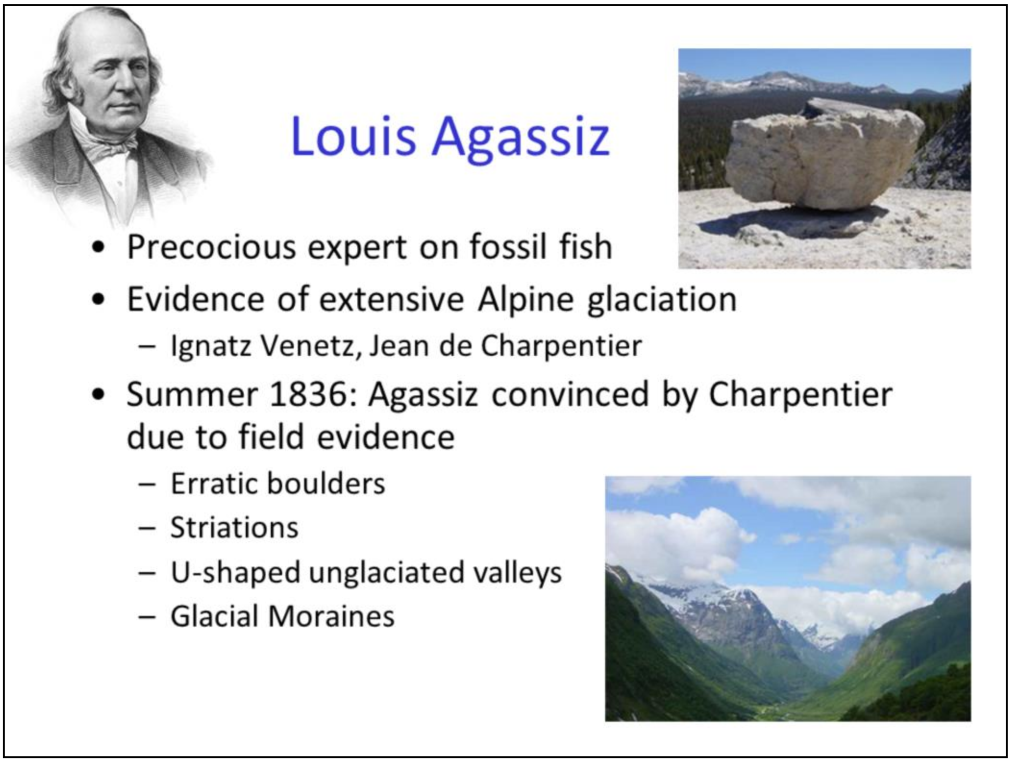
"Cilvilization exists by geological consent, subject to change without notice", Will Durant.

In 1807 the Geological Society of London had concerns that too many people would join: it was the "sexy" science of its time.

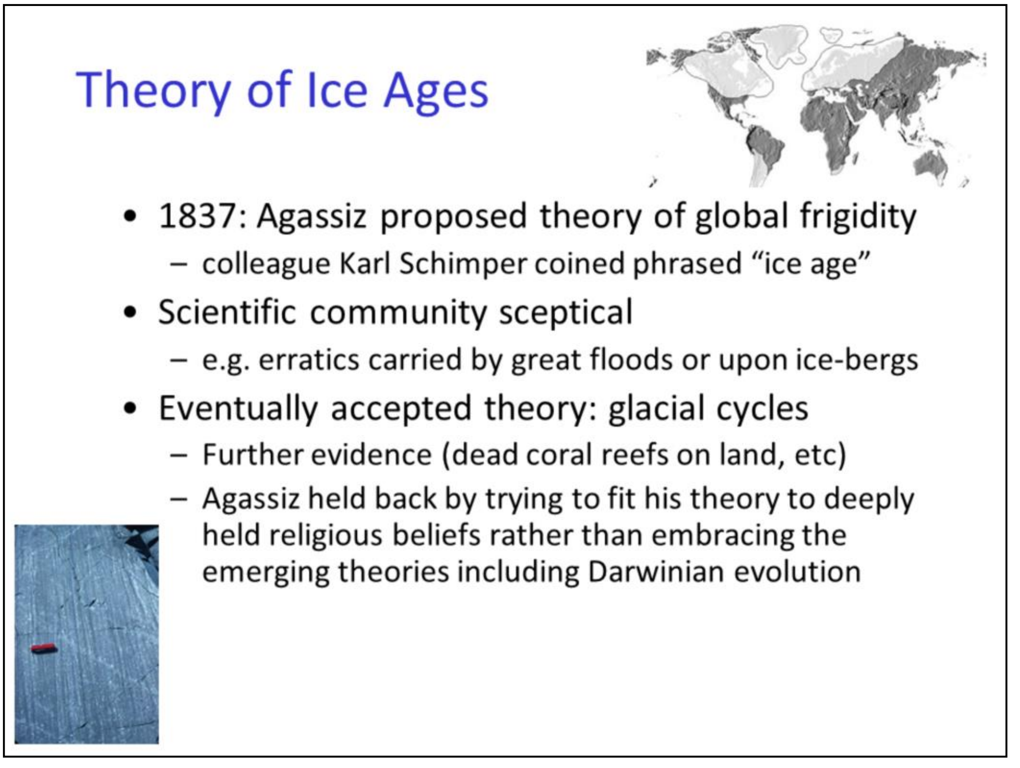
Scientists tried to piece together the evidence from rocks and fossils to understand the Earth but this was mainly contrived to fit in with religious teachings.

Louis Agassiz, a Swiss expert on fossil fish, began discussing his ideas about an ice age at scientific gatherings in 1837.

Further Reading: Frozen Earth by Doug MacDougall (Univ California Press) 2004



In the summer of 1836, Agassiz stayed with a well known geologist (Chapentier) who had been convinced by a collegue (Venetz) of extensive Alpine glaciation. Agassiz was convinced of this theory after seeing the field evidence (erratic boulders, striations, u-shaped valleys, glacial morains)



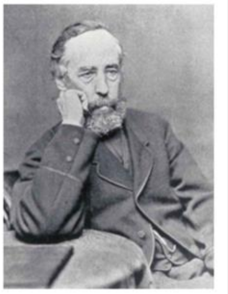
Based on geological evidence in the Alpes, Agassiz proposed the radical theory that ice had covered most of Europe during the ice age (a term coined by a German botanist named Karl Schimper in a humorous poem distributed at a scientific gathering in Switzerland, 1837). It was also suggested that ice may have covered all of the land surface at some period in time.

Causes of Glacial Cycles

- 1860s – Agassiz's "ice age" theory debated intensely in British geological community
- Causes? Possible theories…
  - Change in pole of Earth's rotation?
  - Cold and warm regions in space??
  - Changes in strength of sun?
  - Changes in sea/land distribution?
- Some of these theories had grains of truth
  - e.g. presaged theory of continental drift, working on much slower time-scales than glacial cycles

The theory initially had many fierce critics and the debate about the reality of ice ages continued to be argued throughout the 19th century. Agasiz did not propose a causal theory for glaciation; this came later with pioneering work by scientists including two from contrasting backgrounds, Croll and Milankovitch.

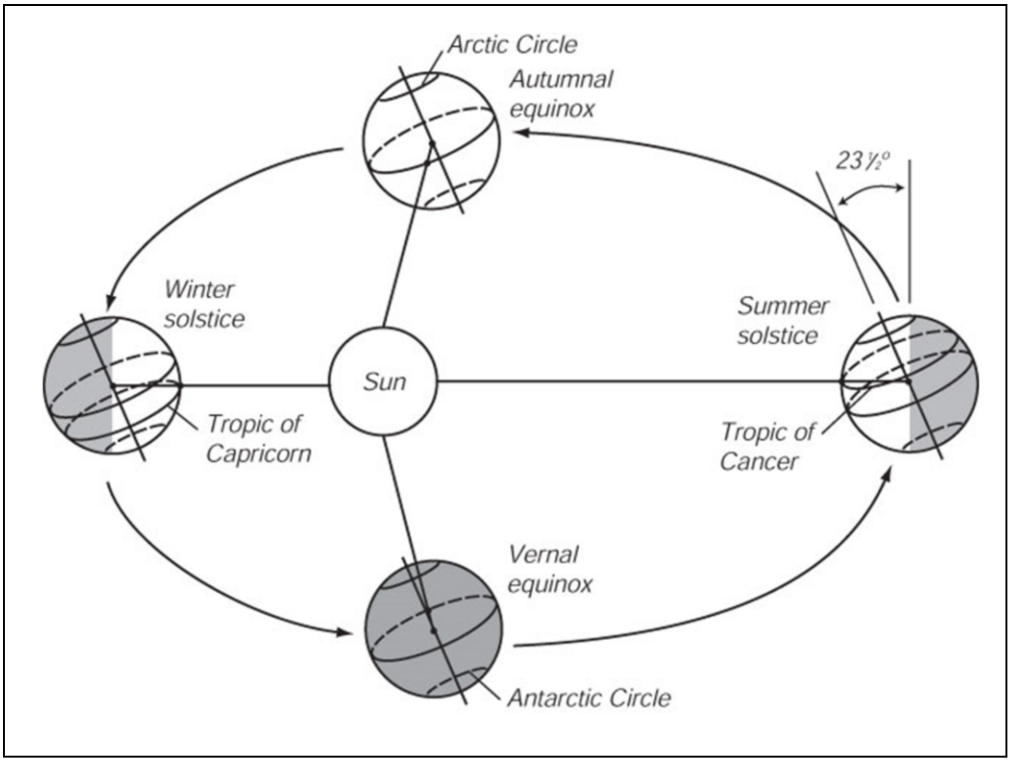
Causes of Glacial Cycles



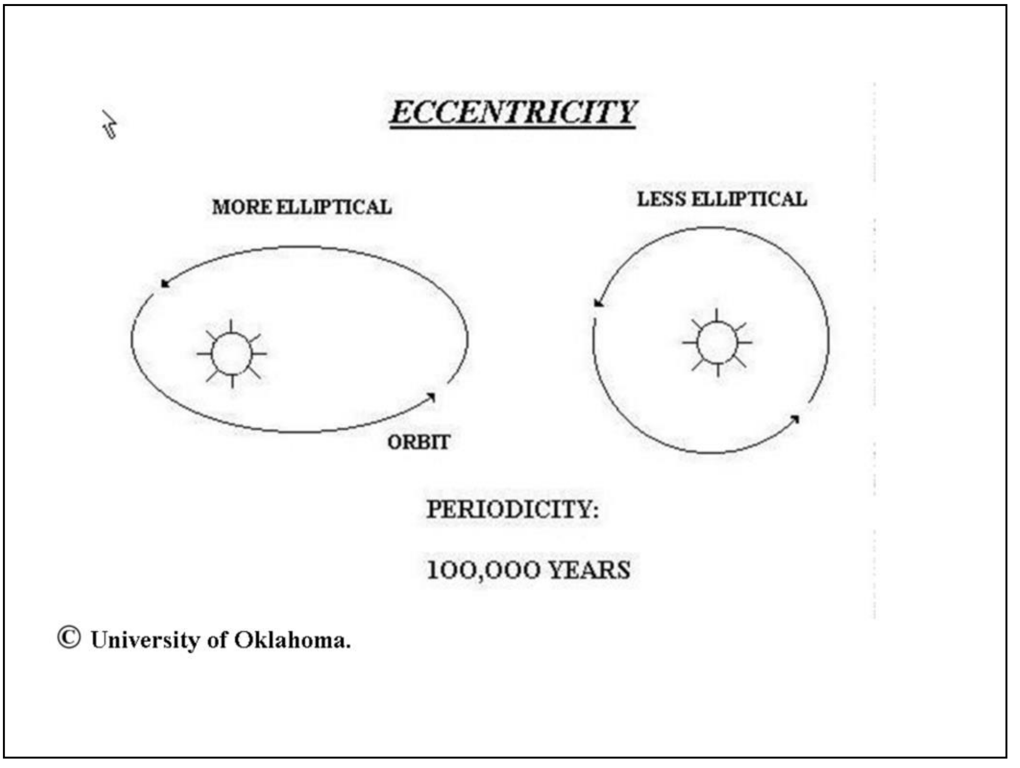
- James Croll (right)
  - Scot, poor family, self-taught
- Appreciated that Earth's orbit changes with time due to position of sun/moon/planets
  - Orbit is an ellipse (not circular) that varies
  - Tilt of Earth's pole of rotation (due to catastrophic planetary collision? Held steady by our big moon)
  - Wobble of tilt (gravitational effects)
  - Combination causes a "precession of the equinoxes"
- Links with orbital changes and glaciation?

The Earth's orbit around the sun is not constant, due to the changing gravitational balance of the sun, moon and planets in our solar system. NASA accurately predict the positions of the planets when calculating space trajectories. James Croll was one of the first that demonstrated the potential of changes in the Earth's orbit on climatic change.

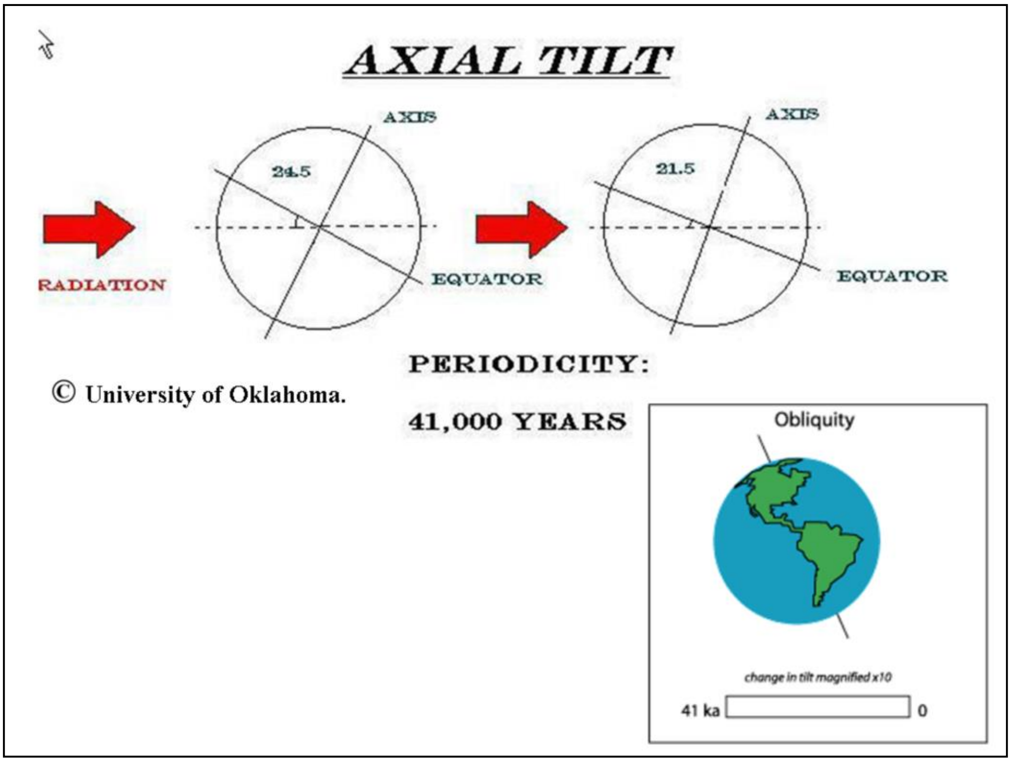
The moon, which is large compared to many other moons, is also an important player. One popular theory is that a near catastrophic planetary collision produced the moon and nearly obliterated the Earth which promptly melted and tilted its axis producing the seasons we get today. Changes in the Earth's tilt over time can have large effects on climate. The presence of the large moon helps to stabilise this effect somewhat; Mars (despite having two small moons) has much wilder swings in the axis which would produce larger swings in climate than we experience on Earth.



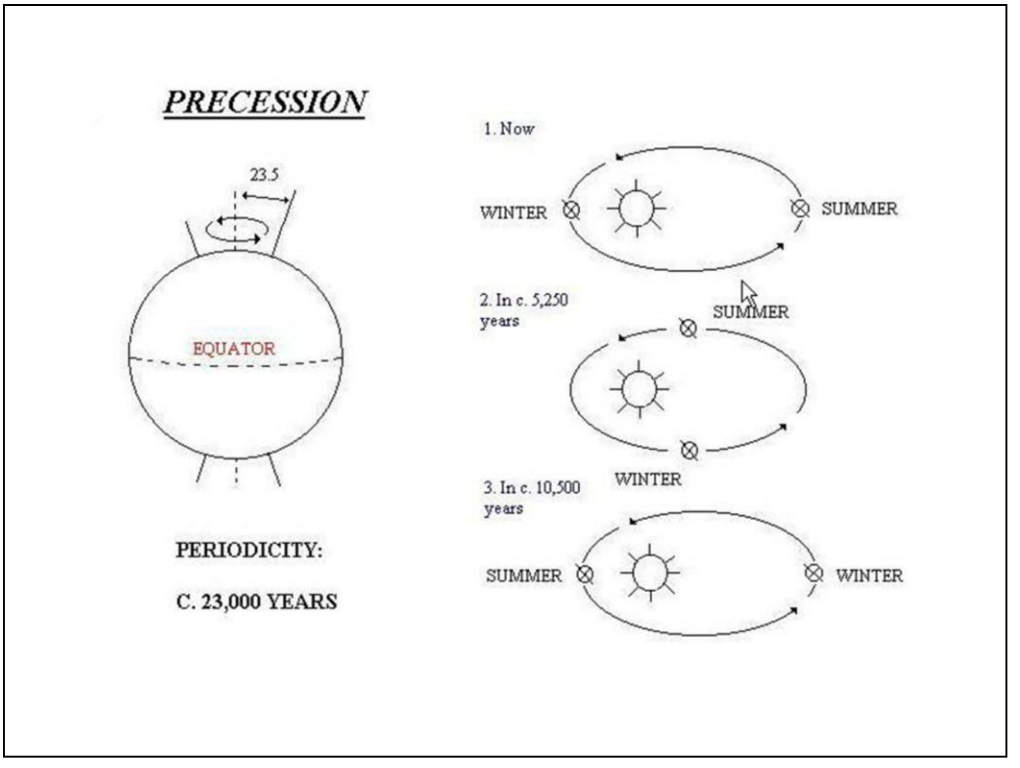
The Earth's orbit around the sun is not circular; it is an ellipse. Also, the Earth's axis of rotation is tilted at 23.5 degrees from the plane of the orbit. In northern hemisphere summer, the northern hemisphere is tilted towards the sun so it receives more heat radiation than in winter. However, this effect is offset ever so slightly because at this point in the elliptical orbit the Earth is at its furthest point from the sun. Croll and (later) Milankovich exploited this understanding to explain glacial cycles.



The degree of eccentricity (how elliptical Earth's orbit is around the sun) varies with periods of approximately 100,000 and 400,000 years.

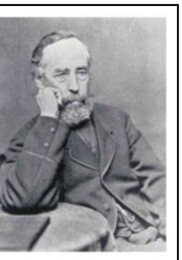


The tilt of the Earth's axis changes over tens of thousands of years varying from around 21.5 to 24.5 degrees (this determines where the tropic of Cancer and Capricorn are, the most pole-ward points at which an overhead mid-day sun can occur (during the northern or southern hemisphere summer solstices). This will affect the severity of seasons.



Additionally, a wobble in the orbit causes the equinoxes to change so that at some points in the cycle the northern summer is at the point in the orbit closest to the sun. Today, the southern hemisphere summer coincides with the closest position of the Earth to the sun. Again this will further influence the severity of seasonal changes.

Theories of glacial cycles



- Croll calculated expected changes in absorbed solar energy due to orbital changes
  - Changes too small to explain glaciation
  - Argued that ice could amplify these changes
  - Less solar energy → cooling → more snow/ice → more solar energy reflected by ice → more cooling…
  - Used eccentricity and wobble to predict that when the northern winter furthest to the sun → colder winters and increased likelihood of glaciation
  - Also recognised that increased moisture transport from tropics to poles may enhance ice formation
    - 1875: "Climate and Time in their Geological Relations"
- Theory sound but predictions were not right

James Croll correctly identified that changes in the eccentricity and wobble of the tilt of the Earth's orbit around the sun combined with ice and circulation amplification could explain glacial cycles. The theory was recognised as a way of timing the past glacial cycles evidenced by field observations. There were problems with Croll's predictions…

Milankovitch & Glacial Cycles

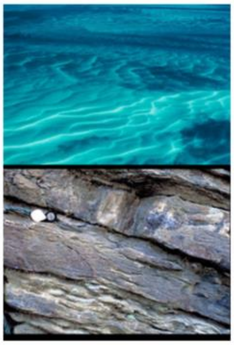
- The timings of Croll's glaciations began to be refuted by geological evidence
- 1913- Serbian mathematician, Milutin Milankovitch, refined Croll's theories to create a modern theory of glacial cycles
- Calculated surface temperature across Earth from estimated solar energy based on orbital cycles (despite 2 world wars)
  - Calculated for 130 000 yrs, also for Moon, Venus and Mars (which got most interest!)

Croll's calculated distribution of surface temperatures were not so good. Milankovitch realised that the equator to pole heat flow also contributed to temperature distribution but the global average seemed good.

Milankovitch & Glacial Cycles

- Teamed up with Koppen and his son-in-law Wegener (continental drift theory)
  - Noticed Alpine glaciation appeared to coincide with northern hemisphere temperature
  - Spring-boarded Milankovitch's theories into prominence
- Found tilt more important than previously thought:
  - Affects severity of seasons (41 000 yr cycle)
  - Proposed that low summer temperature in north allowed snow to remain all year while milder winter temperature encouraged more evaporation and snow-fall (differed to Croll's hypothesis)
  - Found 55-65 degrees north crucial (our latitude up to Iceland)

Wladimir Koppen realised the relevance of Milankovitch's work to climate change; his daughter was married to Alfred Wegener, father of the continental drift theory, also important to climate change on even longer time-scales. They noticed that glaciation in the Alps appeared to coincide with northern hemisphere temperature from Milankovitch. These big names helped to spring-board Milankovitch's theories into prominence.



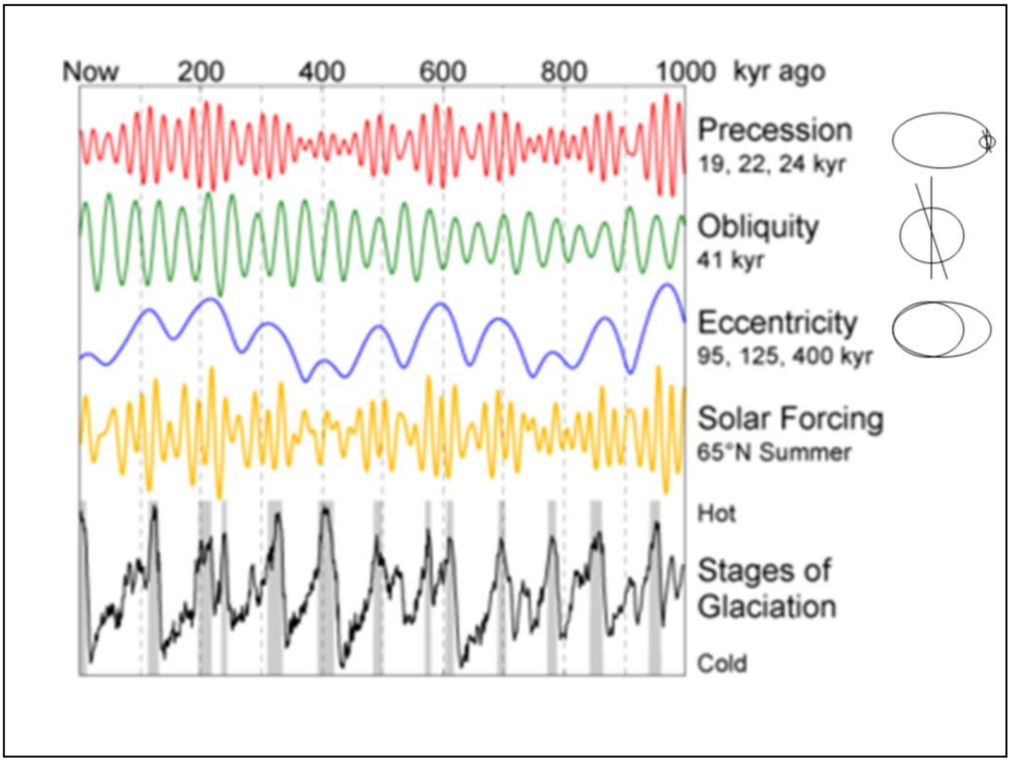
Modern theory of orbital cycles

- By Milankovitch's death in 1958, theory again in poor shape
  - 1800s geological evidence found to be spurious (Carbon dating) and not caused by glaciation
  - Climate change much larger than orbital forcing
- Further evidence from ocean sediments, oxygen isotope data and spectral analysis confirm importance of 100, 43 and 20 kyr cycles
- Precise mechanism for climate change still uncertain but Croll/Milankovitch theory accepted

Alfred Wegener died on a scientific expedition to the Greenland Ice Cap in 1931…

A recent paper by Roe (2006) in Geophysical Research Letters shows a better correlation with RATE of ice melt rather than ice volume.

Oxygen isotope analysis is used extensively as a climate proxy today (it relies on preferential fractionation of the heavier isotopes and the fact that water vapour is strongly related to temperature).

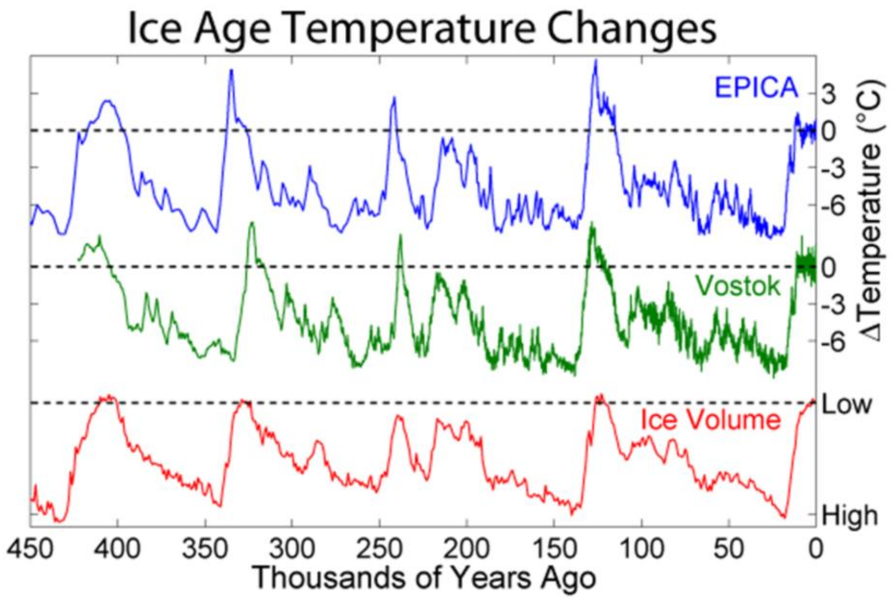


Currently, the Earth's orbit is less eccentric/elliptical than average.

The Earth's tilt is 23.44 degrees, about average.

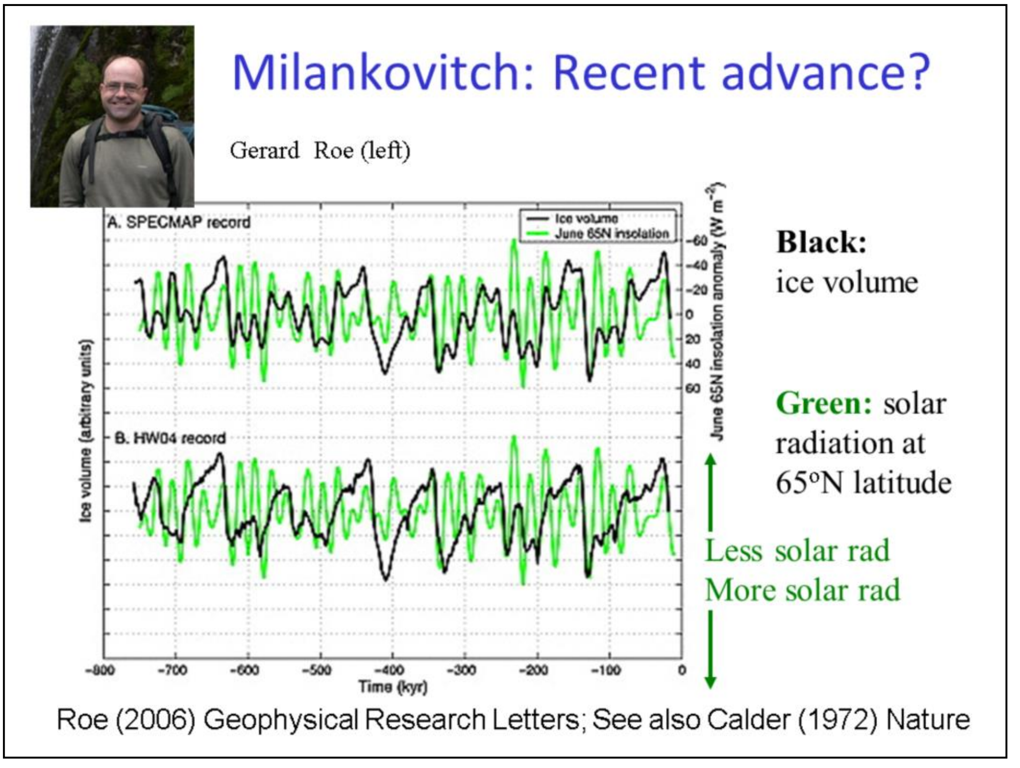
The northern hemisphere summer currently coincides with the furthest point in the Earth's orbit from the sun.

So, northern summer is slightly cooler than average due to precession, but the orbit is not very eccentric so this effect is small.

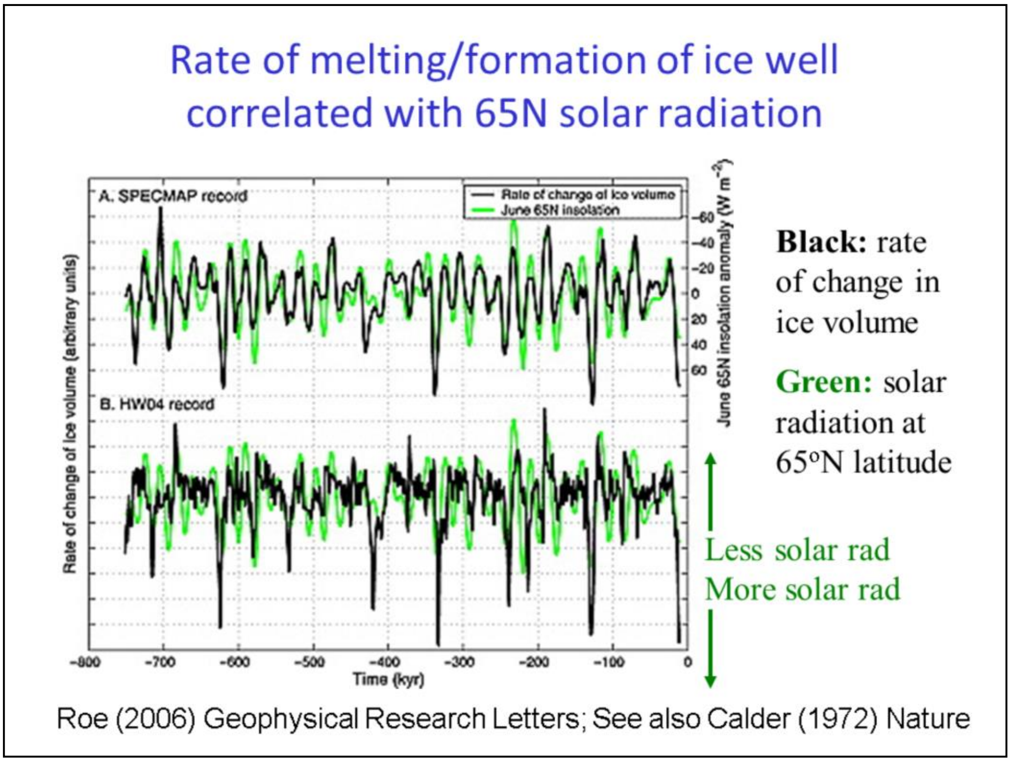


The ice volume in Greenland corresponds with solar radiation at 65N due to orbital variations. But why should the Antarctic ice volume be linked? There must be a mechanism that links the poles (CO_2, ocean currents, ice reflection, etc). More next week…

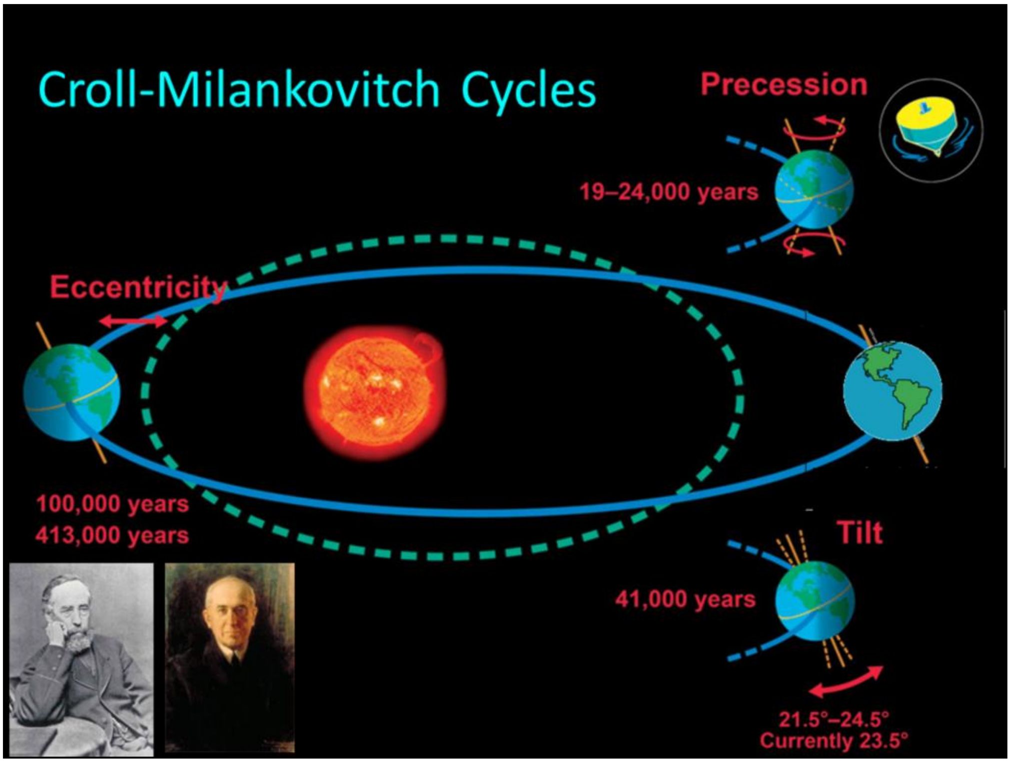
During glacials, polar temperatures were up to 10^{o}C cooler than today; the global average temperature was about 5^{o}C cooler than today.



There is some correspondence between ice volume (black) and solar radiation at 65oN latitude when the ice volume is shifted by a few thousand years (Roe 2006), for example because it takes a long time to melt the ice. However, this may give us a clue as to a better way to compare the datasets and calculations…



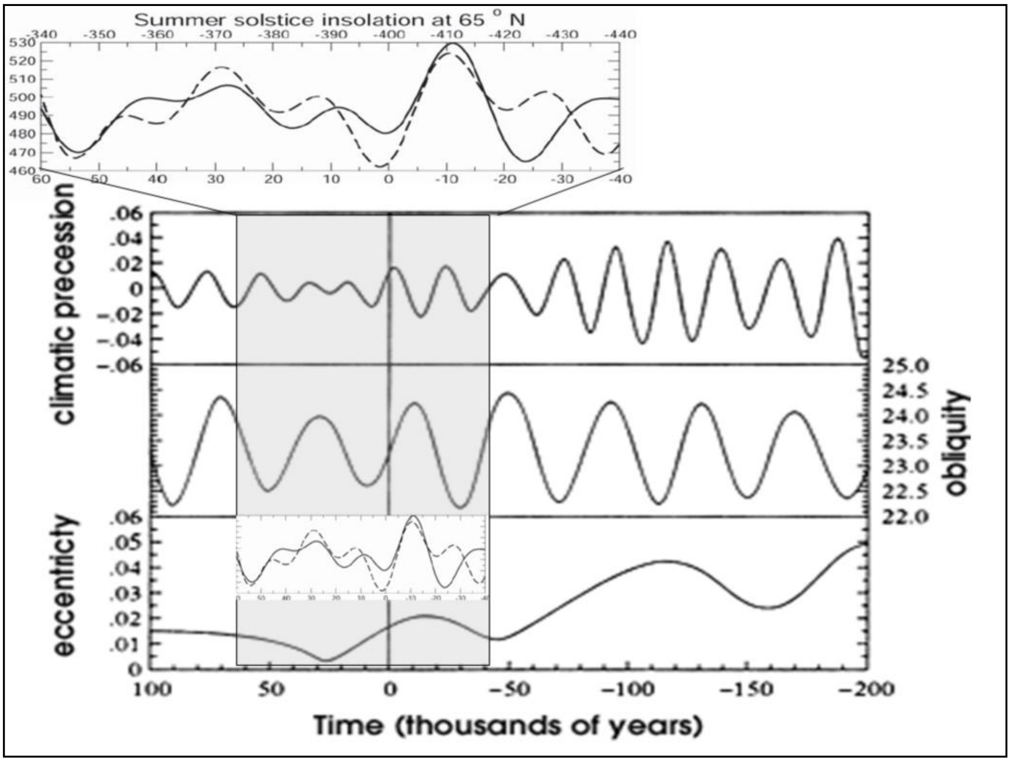
Roe (2006) argues that the solar radiation determines the rate of ice melt or formation. When the rate of ice melt and formation is calculated from the two proxy datasets of Antarctic ice volume, there is a clear correspondence with the 65°N solar radiation and there is no need to shift the ice data in time to gain better agreement. This is new research and so it remains to be seen if it can stand up to scrutiny but it certainly seems conclusive at first glance.


Croll-Milankovitch Cycles
Precession
19–24,000 years
Eccentricity
100,000 years
413,000 years
Tilt
41,000 years
21.5°–24.5°
Currently 23.5°

Group work

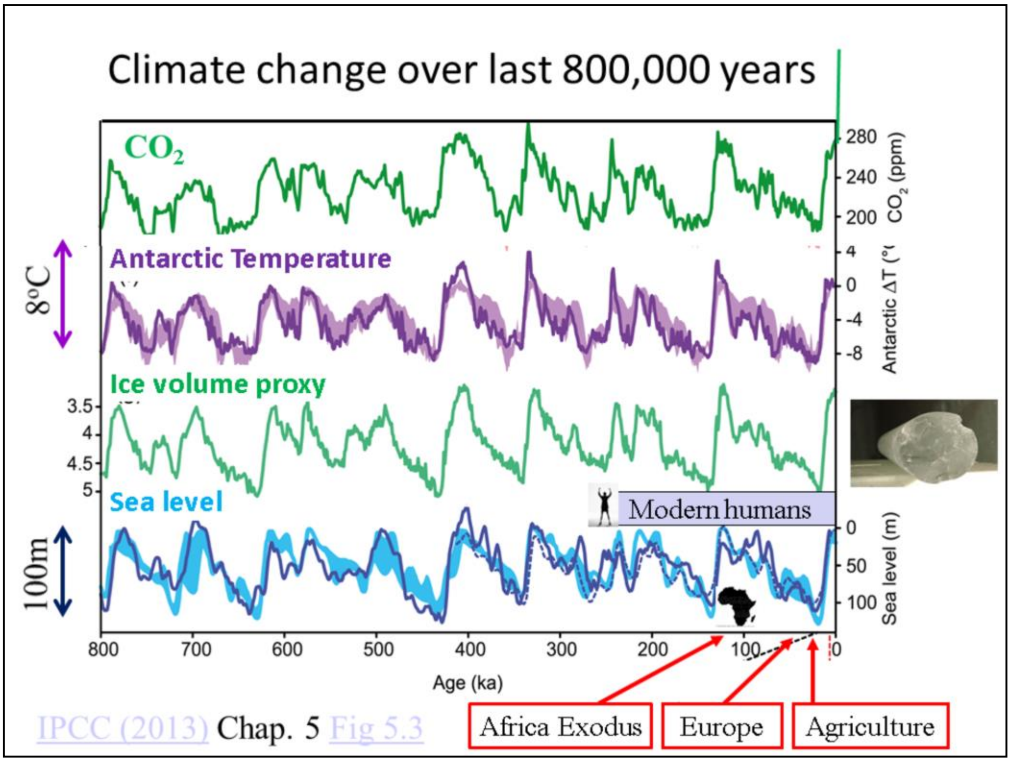
- 11,000 years ago Earth's
  - Orbit was more eccentric than today
  - Axis of rotation was tilted at 24.5 degrees
  - Northern Summer coincided with Earth's closest approach to the sun
- How would this affect solar radiation at 65°N in summer compared to today?
- Would this situation favour a glacial or interglacial climate? Why?

See also Orbital Cycles handouts.

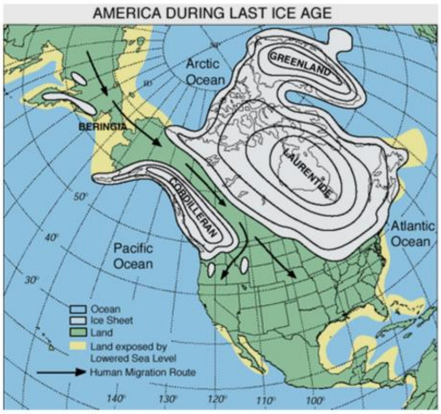


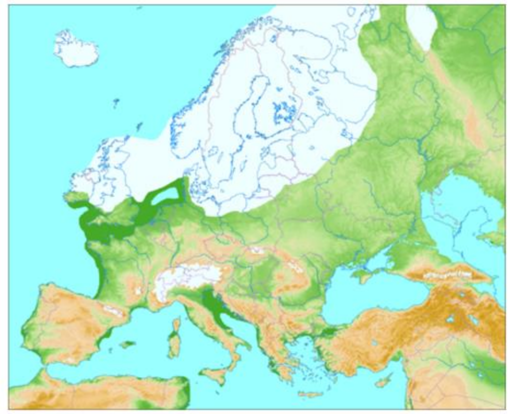
The amount of solar radiation (insolation) in the Northern Hemisphere at 65°N seems to be related to occurrence of an ice age. Some studies suggest that 65°N summer insolation should increase gradually over the next 25,000 years, and that no declines in 65°N summer insolation sufficient to cause an ice age are expected until at least 50,000 years time.

There is some work ongoing that attempts to find comparable periods of orbital variation to the present one and infer future evolution of climate from this. Of course, the large CO_2 concentrations over the next 1000 years are likely to have an additional impact on this evolution.



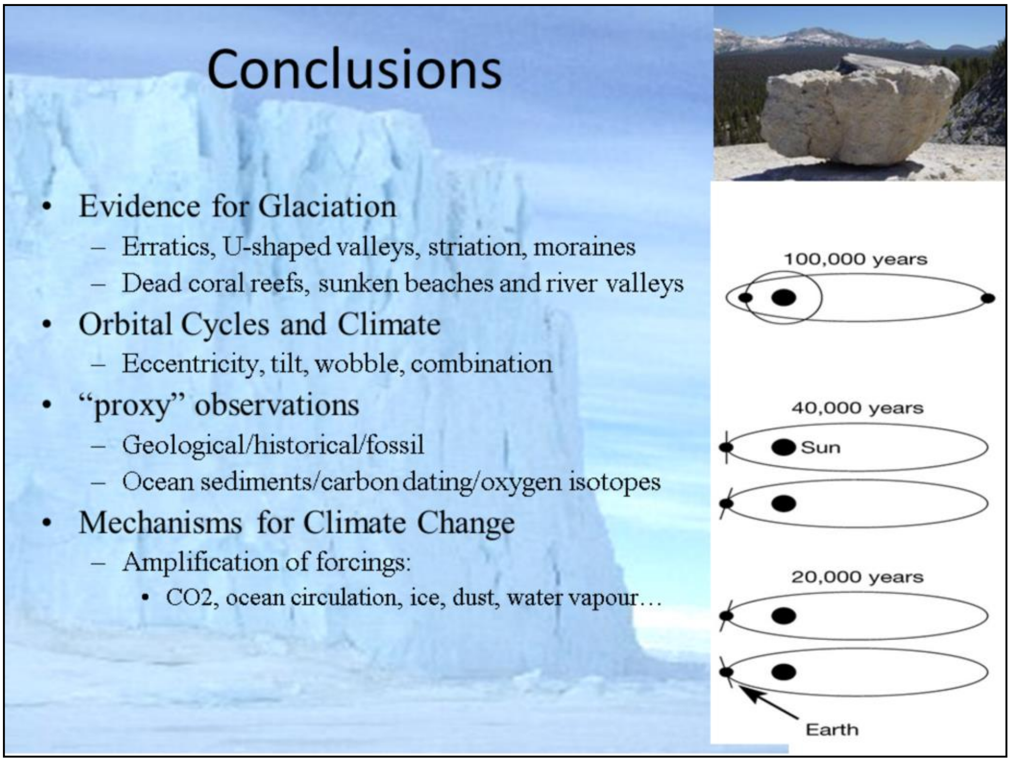
Ice cores from Antarctica provide abundant evidence of climate change over the past 800,000 years. Trapped air bubbles record past atmospheric composition, including carbon dioxide and methane, and isotopic analysis of oxygen and hydrogen in the air bubbles or of the ice itself can tell us indirectly about changes in Antarctic temperature (or temperature difference between tropics and poles) and ice volume (additional evidence from ocean sediments is also particularly valuable). A series of milder interglacials punctuate the longer glacial periods of low temperature and high ice volume, the timings of which relate to changes in the Croll-Milankovic orbital cycles. Natural changes in carbon dioxide (and methane) in response to the substantial climate changes act to amplify the temperature responses over glacial cycles (more next week).





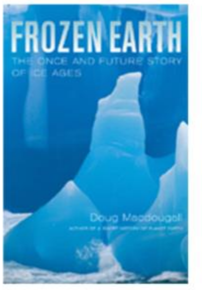
During glacial times global temperatures were 4-7°C cooler; cooling was greater over Antarctica but more modest for tropical ocean

Temperature changes over glacial cycles were largest over polar regions and much smaller over tropical oceans. Giant ice sheets occupied North America and Eurasia, pressing down the land in these regions; Canada and Scandanavia are rising in altitude due to the recovery from the weight of the ice sheets (isostatic rebound). Since large amounts of water was locked away in ice sheets during the last glacial maximum 20,000 years ago, sea levels were much lower and the UK was connected to the continent.



It is widely believed that ice sheets advance when summers become too cool to melt all of the accumulated snowfall from the previous winter. Some workers believe that the strength of the orbital forcing is too small to trigger glaciations, but feedback mechanisms like CO2 may explain this mismatch .

Further Reading



- Frozen Earth – Doug MacDougall
- IPCC AR4 (2007):
  - Box 6.1, p.445
    www.ipcc.ch/publications_and_data/ar4/wg1/en/ch6s6-4.html
  - FAQ 6.1, p.449-450
    http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-6-1.html

- Update: IPCC AR5 (2013) Chapter 5
  http://www.ipcc.ch/report/ar5/wg1/