Understanding past climate change

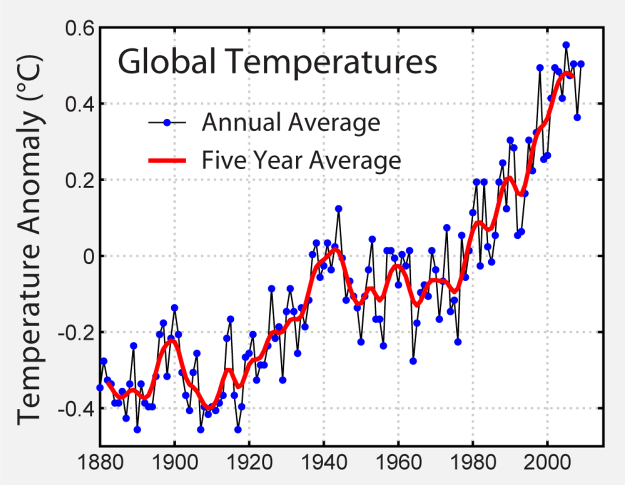
Steven J. Phipps
ARC Centre of Excellence for Climate System Science
Climate Change Research Centre
University of New South Wales

CLIM1001
Introduction to Climate Change
24 September 2014

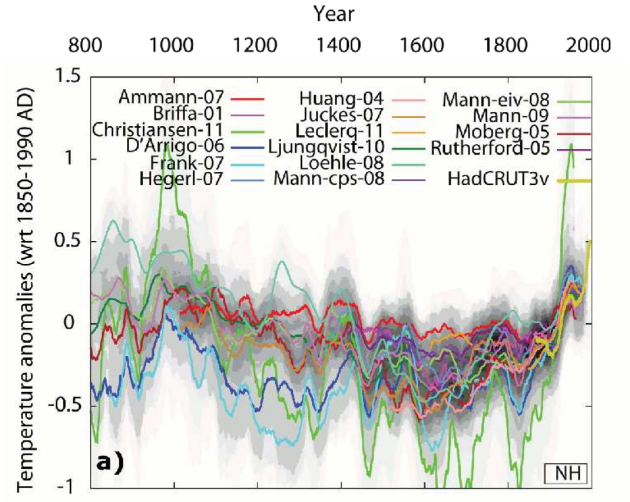
1. Why past climates are important
2. Sources of information on past climates
3. The Earth's climatic history and what it tells us
4. Conclusions

Why past climates are important

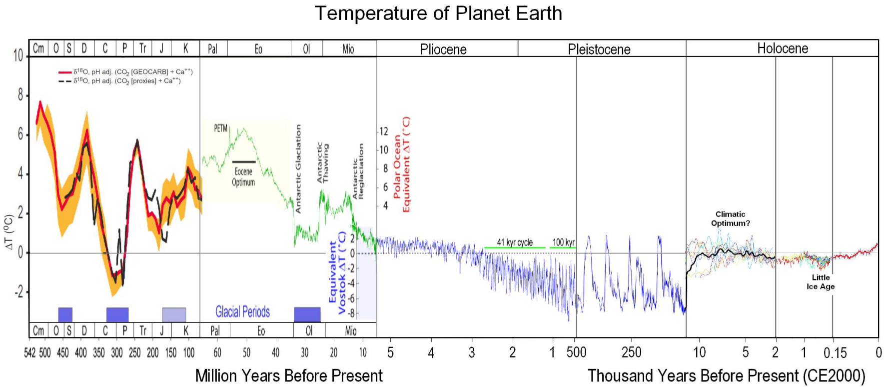
The past 100 years



The past 1000 years

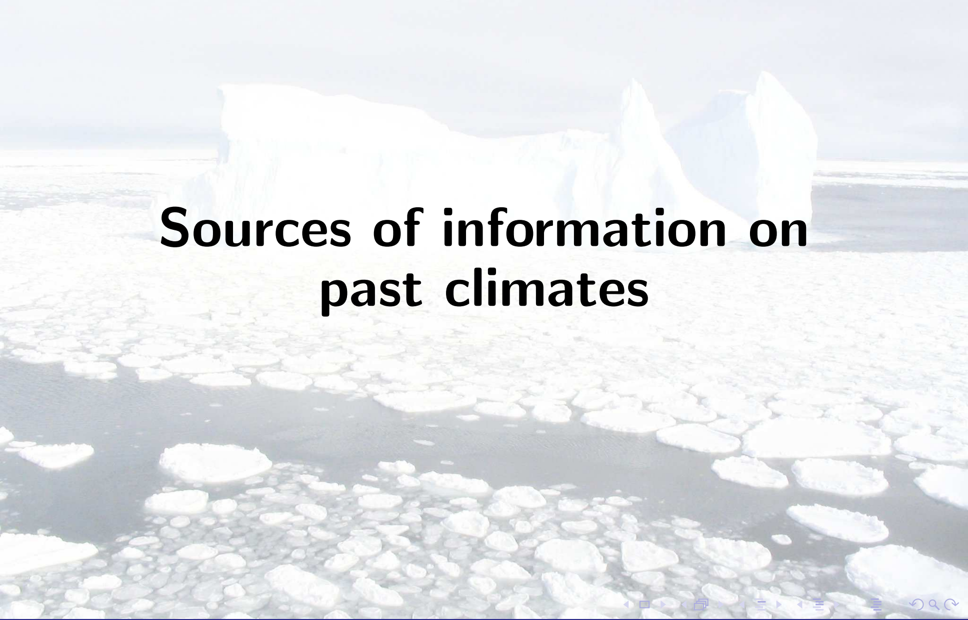


The past 542 million years



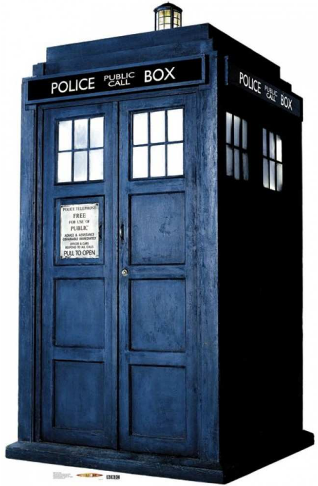
Why past climates are important

- Past climates provide a *context* which helps us to understand the world around us.
- Past climate states also provide us with possible analogues for *future* climate states.
- Past climates help us to:
  - understand the characteristics of natural climate variability and change.
  - detect and attribute human influences on the climate system.
  - explore the sensitivity of the climate system to external drivers.
  - explore the dynamics of the climate system.
  - evaluate the ability of climate models to simulate climate variability and change.



Sources of information on past climates

What we really want...



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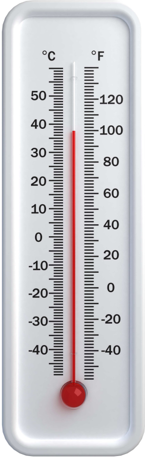
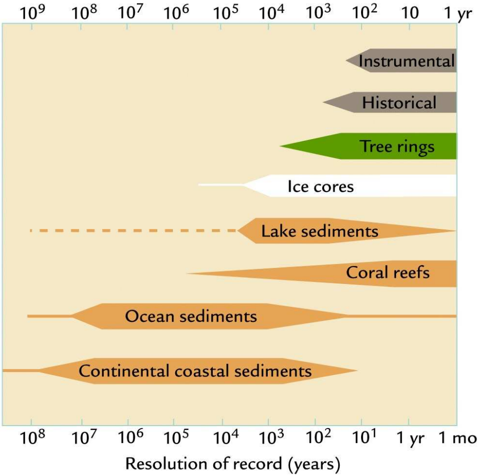
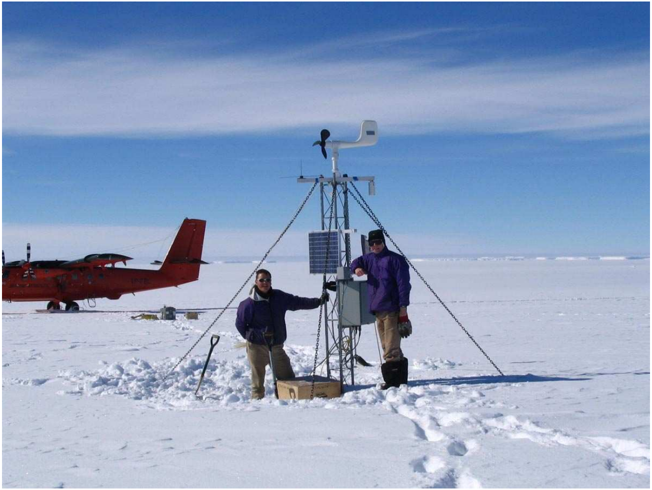


Sources of information: both direct and indirect

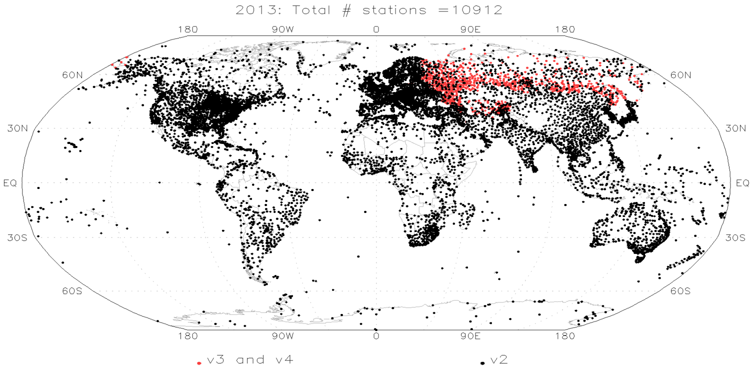


The instrumental record: manual weather stations

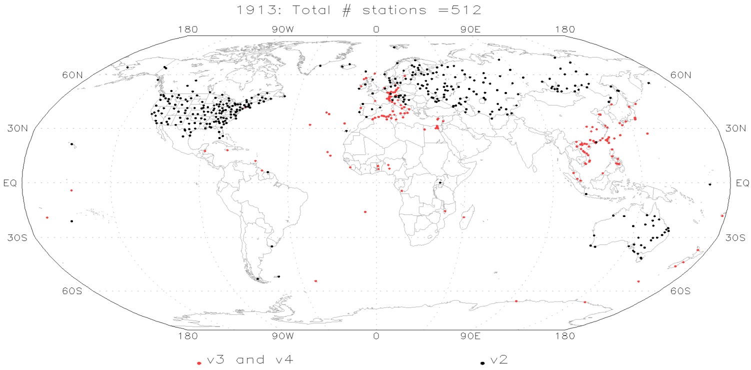
The instrumental record: automatic weather stations



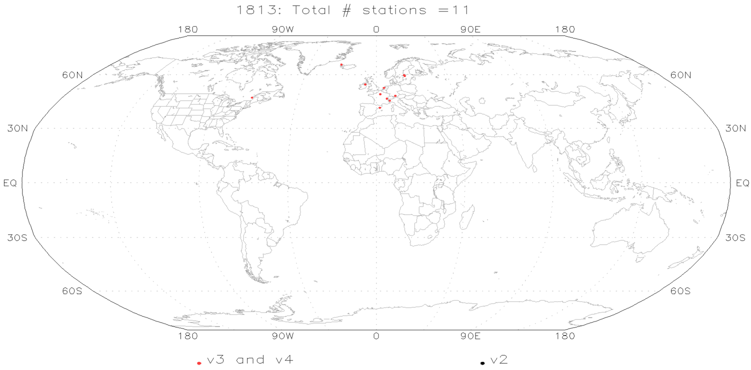
The instrumental record: surface weather stations (2013)



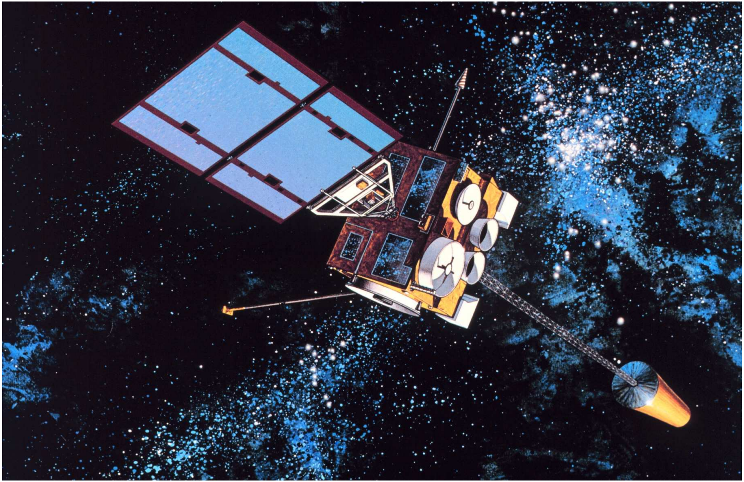
The instrumental record: surface weather stations (1913)



The instrumental record: surface weather stations (1813)



The instrumental record: satellites



The historical record: the Little Ice Age

The historical record: the Mediaeval Warm Period

The historical record: even wine can tell us a story!

brief communications

Grape ripening as a past climate indicator

Summer temperature variations are reconstructed from harvest dates since 1370.

French records of grape-harvest dates in Burgundy were used to reconstruct spring–summer temperatures from 1370 to 2003 using a process-based phenology model developed for the Pinot Noir grape. Our results reveal that temperatures as high as those reached in the 1990s have occurred several times in Burgundy since 1370. However, the summer of 2003 appears to have been extraordinary, with temperatures that were probably higher than in any other year since 1370.

Biological and documentary proxy records have been widely used to reconstruct temperature variations to assess the exceptional character of recent climate fluctuations[1–3]. Grape-harvest dates, which are tightly related to temperature, have been recorded locally for centuries in many European countries. These dates may therefore provide one of the longest uninterrupted series of regional temperature anomalies (highs and lows) without chronological uncertainties[1].

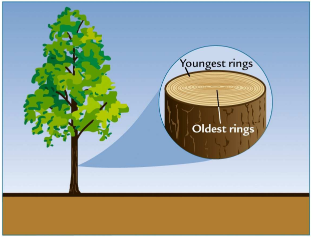
In Burgundy, these officially decreed dates have been carefully registered in parish and municipal archives since at least the early thirteenth century. We used a corrected and updated harvest-date series[4] from Burgundy, covering the years from 1370 to 2003, to reconstruct spring–summer temperature anomalies that had occurred in eastern France. To convert historical observations into temperature anomalies, we used a process-based phenology model for Pinot Noir, the main variety of grape that has been continuously grown in Burgundy since at least the fourteenth century[5] (for details, see supplementary information).

Our yearly reconstruction is significantly correlated (Table 1) with summer temperatures deduced from tree rings in central France[6] (correlation coefficient, $r = 0.53$), the Burgundy part of a spatial multi-proxy recon-

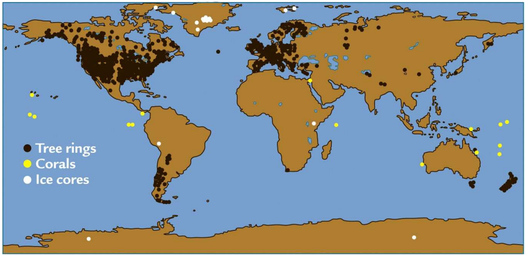
A fifteenth-century depiction of the grape harvest from *Les Très Riches Heures du Duc de Berry*, a medieval book of hours.

Tree rings

- Tree rings can provide information about changes in temperature and precipitation over the past tens to thousands of years.
- The annual layers of outer soft wood turn into harder wood.

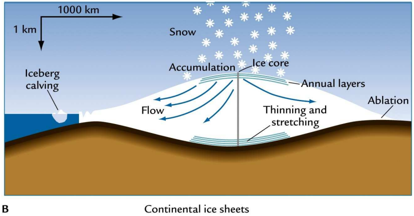


C Annual tree rings

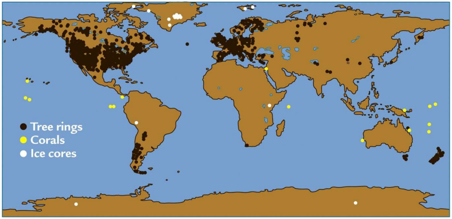


Ice cores

- Annual deposition of snow can pile up continuous sequences of ice.
- Ice core records date back at least 800,000 years in Antarctica, and at least 100,000 years in Greenland.

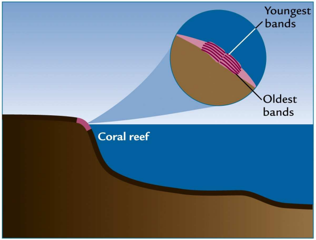


Continental ice sheets

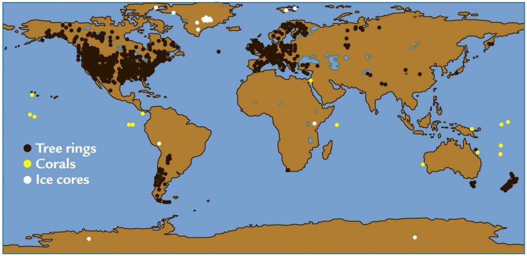


Coral reefs

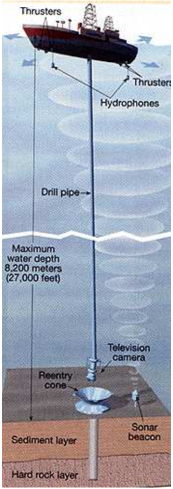
- Corals in clear sunlit waters at tropical and subtropical latitudes form annual bands of calcite ($CaCO_3$) that record information about the climate.
- Individual corals can live for hundreds of years.



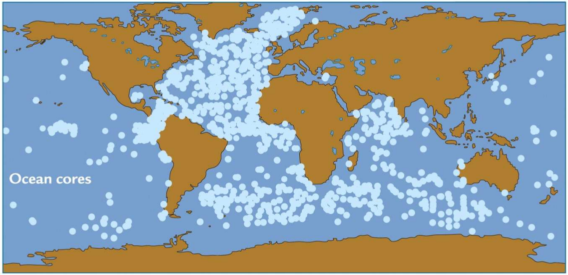
D Annual coral bands



Ocean sediments



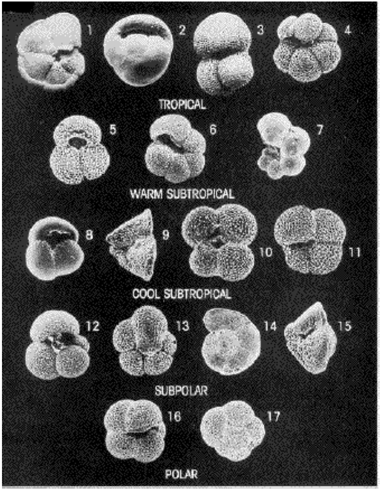
- The deep ocean is generally a quiet place with relatively slow and continuous deposition.
- It can yield climate records of higher quality than most records from land, where water, ice and wind are active agents of erosion.



A

Ocean sediments: plankton

- Plankton are very useful as natural archives because they are widely distributed: plankton live in all the world's oceans.
- Populations of plankton in different areas tend to be dominated by a small number of species with well-defined climatic preferences.

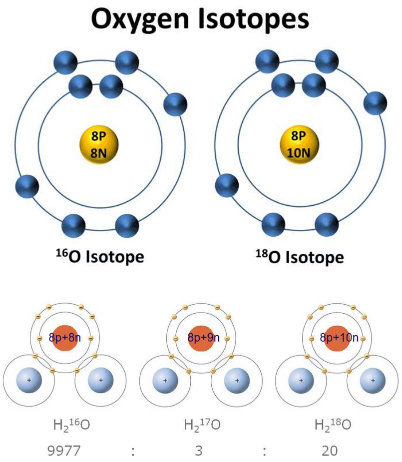


Archives versus proxies

- A *proxy* is a substitute for an actual climate measurement.
- A *proxy* measures a property of an *archive*.
- Archives can be physical or biological e.g.
  - Ice cores, lake sediments, ocean sediments (physical)
  - Tree rings, corals, plankton (biological)
- Examples of proxies are:
  - Thickness (tree rings)
  - Density (tree rings)
  - Isotopic ratios (tree rings, ice cores, sediments, corals)
- We need to understand how each proxy can be related to a climate variable.
- N.B. The word *proxy* is starting to be replaced by the word *sensor*.

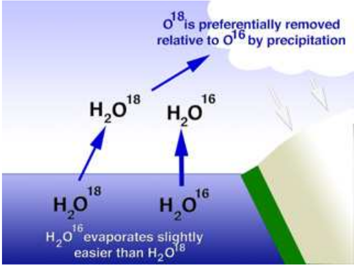
Isotopes: a quick introduction

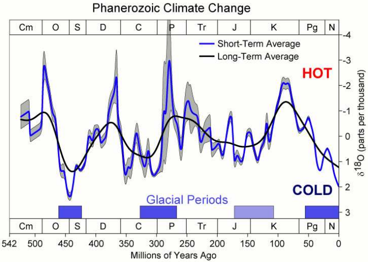
- Isotopes are variants of a particular chemical element.
- Isotopes of a given element share the same number of protons in each atom, but have different numbers of neutrons.
- Different isotopes therefore have different masses, giving them subtly different properties.
- Oxygen has three stable isotopes: ^{16}O, ^{17}O and ^{18}O.
- Most oxygen atoms are ^{16}O, but around one in 500 are ^{18}O.



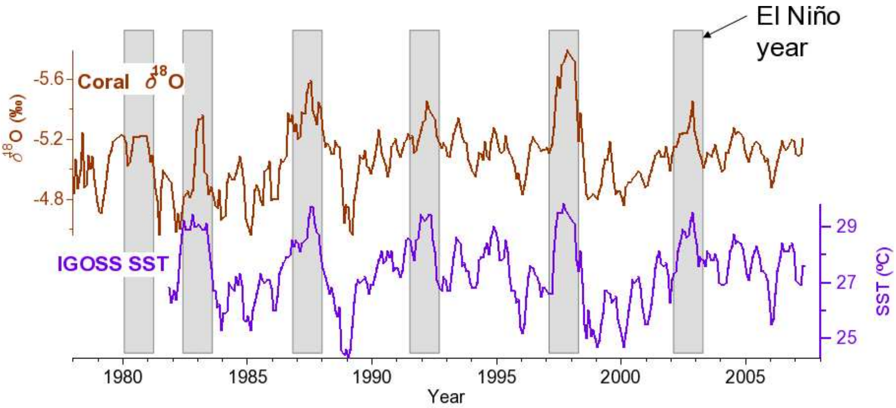
Water isotopes and temperature

- Water molecules containing ^{18}O are heavier than those that contain ^{16}O. They therefore evaporate less easily.
- During warm periods, the relative amount of ^{18}O in the ocean increases as more of the ^{16}O evaporates.
- Conversely, ^{18}O condenses more easily and is preferentially removed by precipitation.

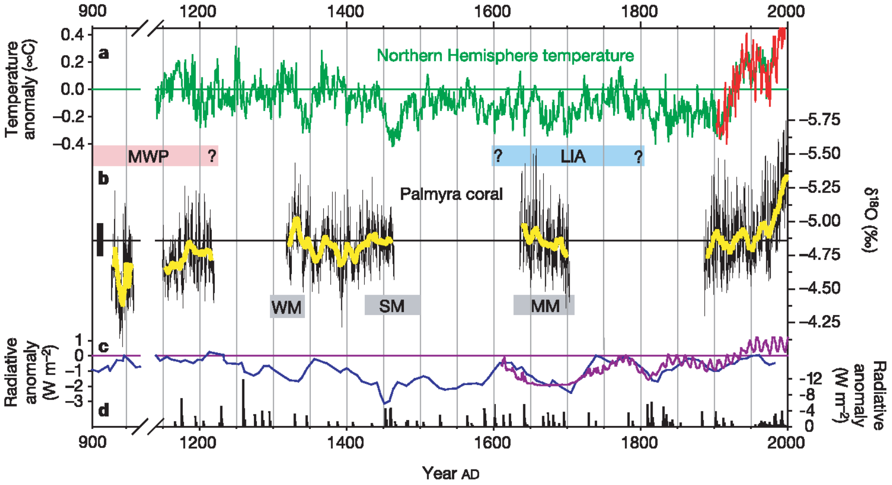




Coral $\delta^{18}O$ versus local sea surface temperature

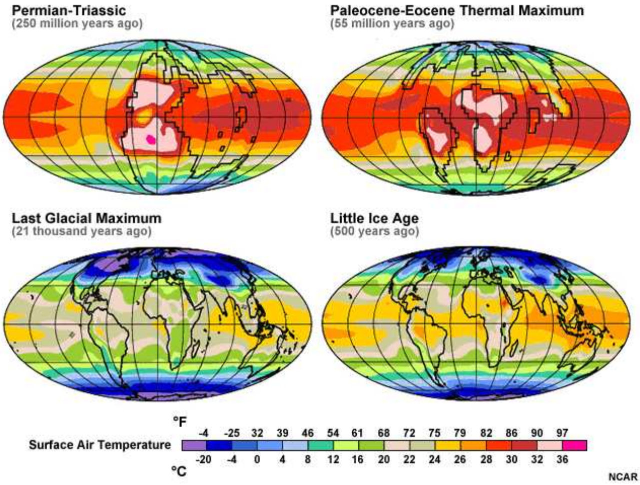


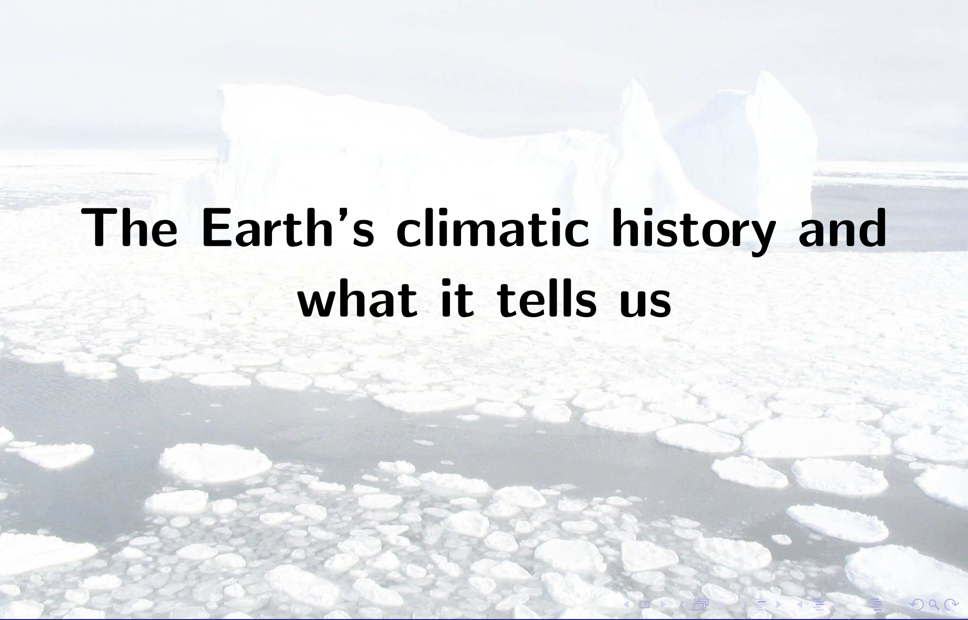
Changes in the Pacific climate over the past 1000 years



Climate modelling

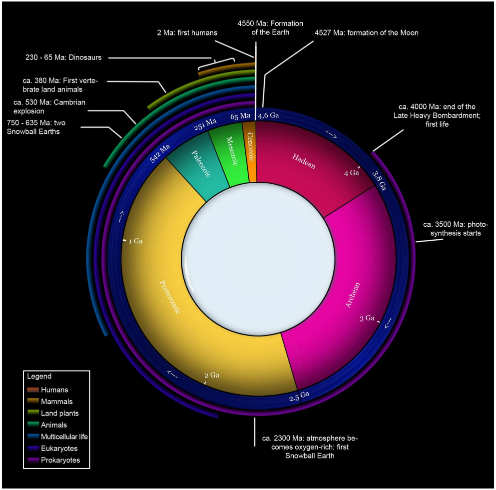
Climate modelling



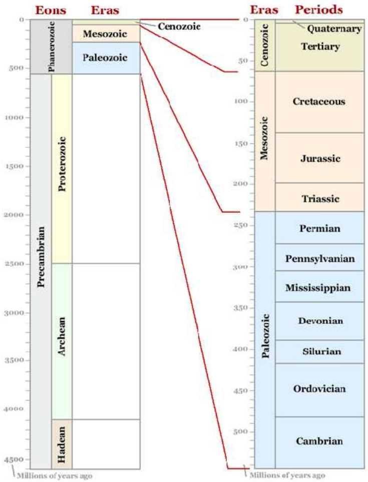


The Earth's climatic history and what it tells us

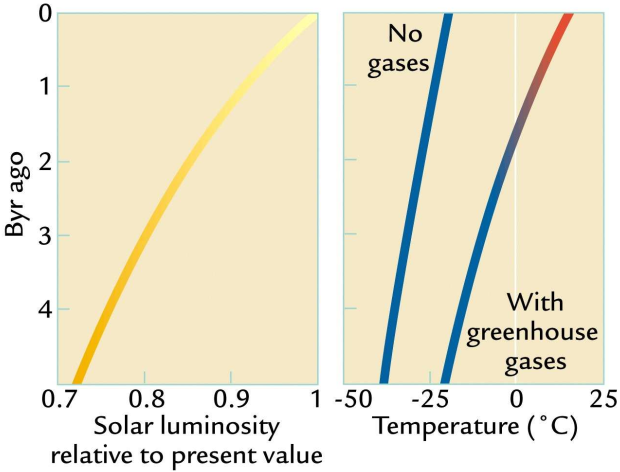
The geologic clock ...



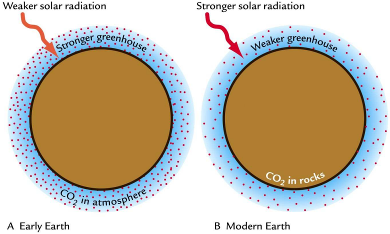
… versus the geologic timeline

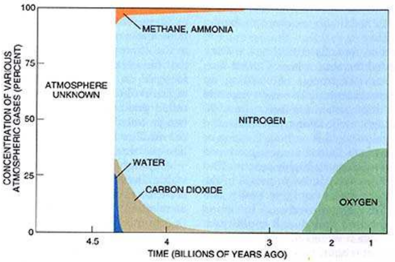


The "faint young sun" paradox



The changing composition of the Earth's atmosphere



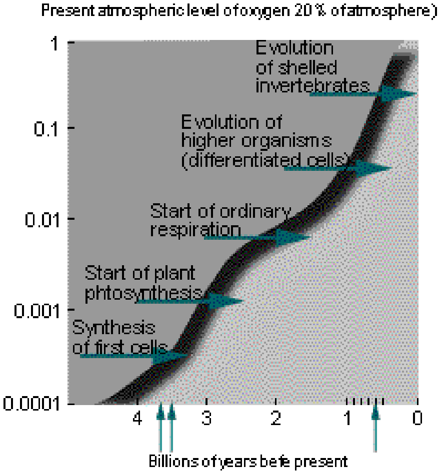


- Early Earth:
  - stronger greenhouse effect
  - weaker solar radiation
- Modern Earth:
  - weaker greenhouse effect
  - stronger solar radiation
- During the Earth's history, there have been fundamental changes in the composition of the atmosphere.

The atmosphere and life on earth

- Since life first evolved, the atmosphere and life on Earth have been influencing each other.
- Some of the earliest life forms were cyanobacteria (blue-green algae) which can still be found today.

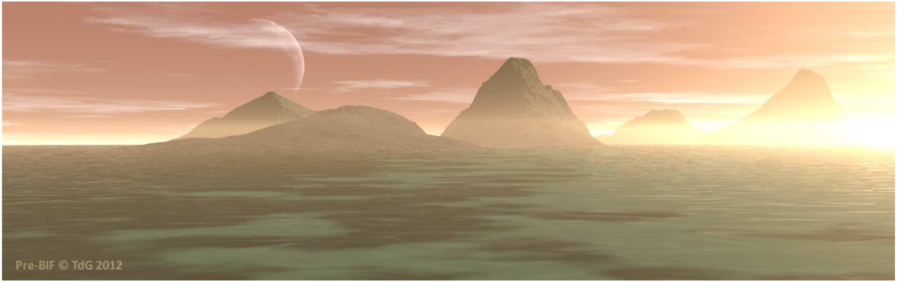
Oxygen and the atmosphere



- The concentration of oxygen in the atmosphere has gradually increased over time, as more complex life forms have evolved.

Oxygen and the atmosphere

Oxygen and the atmosphere



Oxygen and the atmosphere

The evolution of the Earth's climate

- Throughout its history, the Earth's climate has alternated between two states.
- During **greenhouse eras**, no ice sheets were present and yet the oceans did not boil.
- During **icehouse eras**, ice sheets were present and yet the oceans did not freeze solid.
- The "Goldilocks planet": never too hot nor too cold for life to survive.

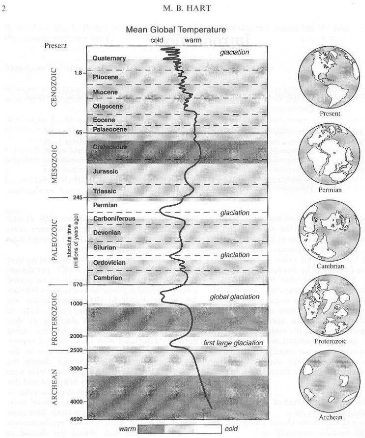
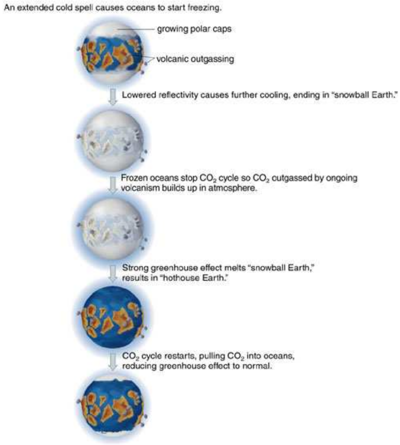


Fig. 1. Generalized temperature history of the planet (adapted from Merritts *et al.* 1998).

800 million years ago: Snowball Earth?

- There is some evidence that the tropics were glaciated around 800 million years ago, leading to the hypothesis that the Earth was nearly frozen over at this time.
- This is the Snowball Earth hypothesis, which remains controversial.

The dynamics of Snowball Earth?



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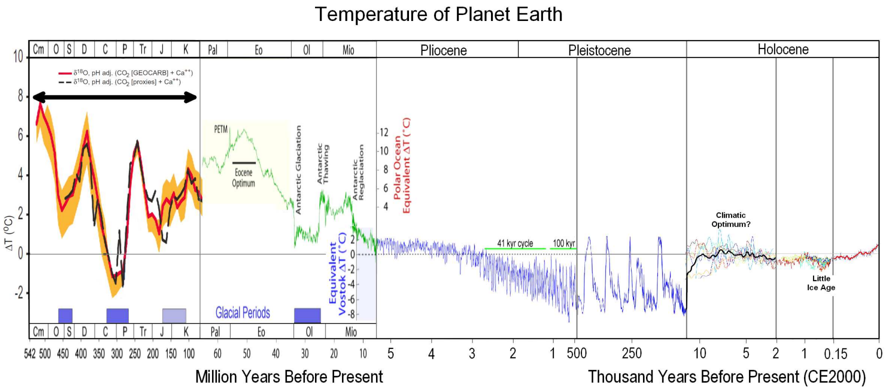
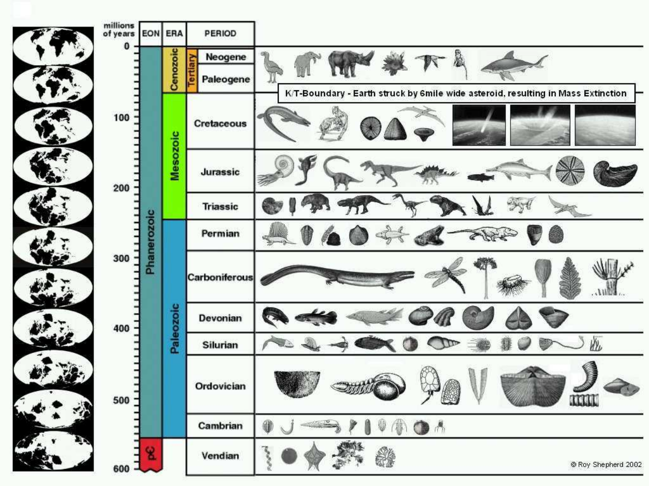
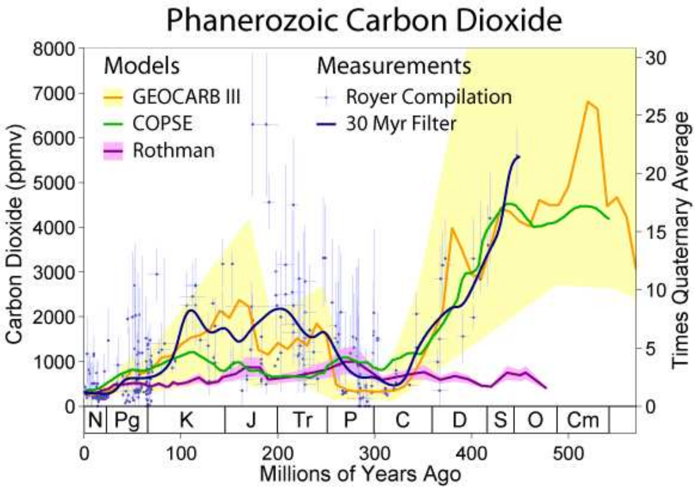
The dinosaurs and Hothouse Earth



The evolution of life on Earth

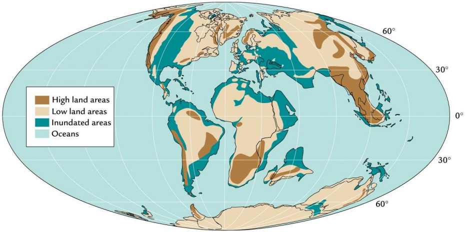


The evolution of the atmospheric CO_2 concentration



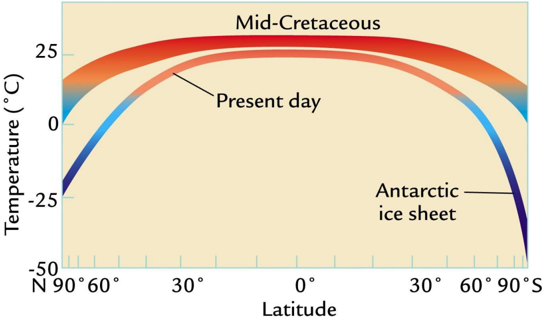
What caused the high CO_2 concentrations?

- 175 million years ago, the ancient super-continent of Pangaea begin to break apart and form six continents similar to today's.
- The extensive tectonic activity caused widespread volcanism, and hence a large amount of CO_2 was emitted.
- The total land area was smaller than today because of higher sea levels, and so CO_2 removal through weathering was dampened.



The climate of the mid-Cretaceous

- The climate of the mid-Cretaceous shows us what a high-CO_2 world can look like.
- The Earth was around 10°C warmer than today, and was completely free of ice.

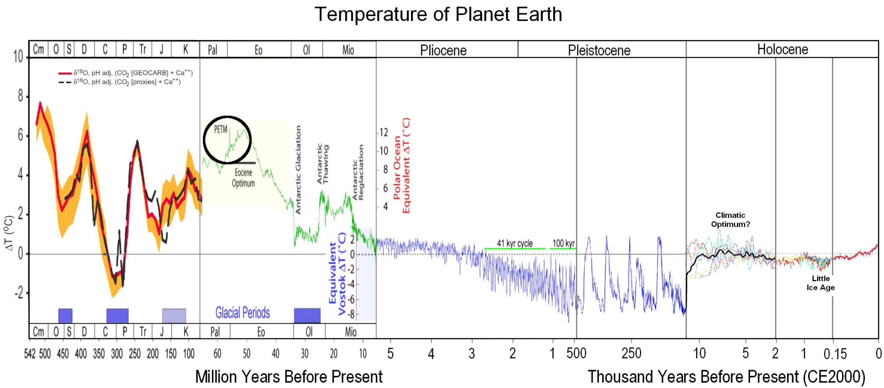


The extinction of the dinosaurs

- A 10km asteroid hit the Earth 65 million years ago.
- The resulting explosion was equivalent to four times the energy of all currently-existing nuclear weapons.
- Dust and soot blocked up to 90% of incoming solar radiation.
- Temperatures dropped 3–5°C and took 1000 years to recover.
- Up to 70% of all species were wiped out.

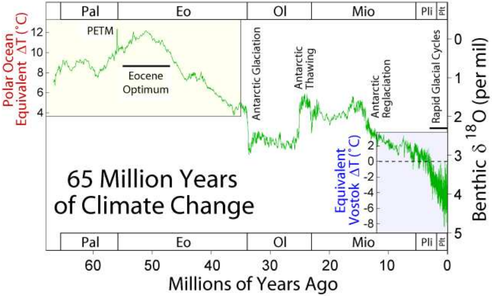
INTERMISSION

The Paleocene-Eocene Thermal Maximum (PETM)



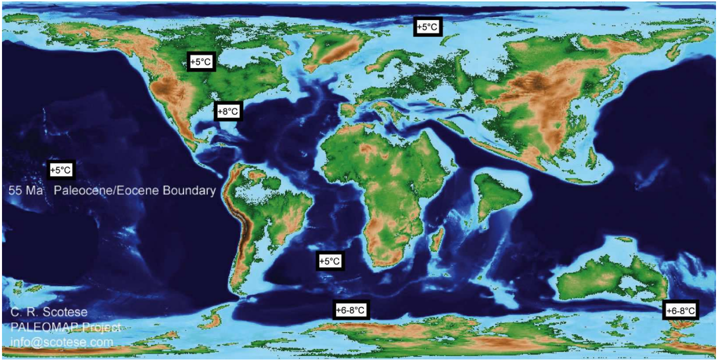
The Paleocene-Eocene Thermal Maximum (PETM)

- The most extreme change in the Earth's climate during the past 65 million years. Global temperatures rose around 6°C within approximately 20,000 years (very fast by geological standards!).
- Provides a past example of rapid climate change, which helps us to understand how the Earth might respond in future.



The PETM: the setting

- The configuration of the continents and oceans was somewhat different to today.
- Sea levels were higher and there were no significant ice sheets.



The PETM: what happened

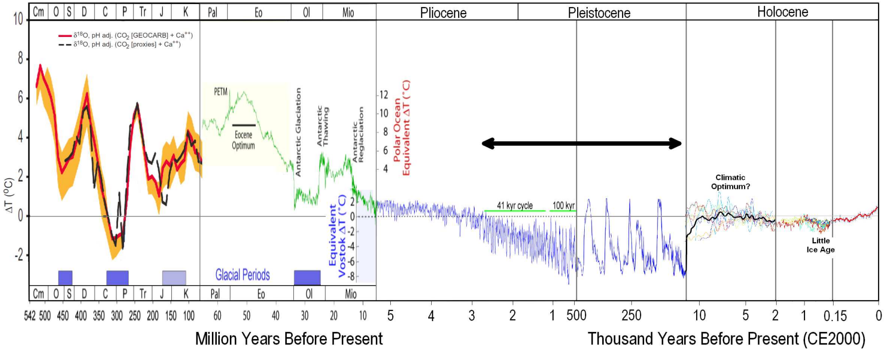
- At least 1500 gigatons of carbon was added to the atmosphere.
- The climate became much warmer and wetter.
- Sea levels rose through thermal expansion.
- Ocean circulation patterns changed radically within less than 5,000 years, with a change in the direction of the global overturning circulation.
- This change transported warm water to the deep oceans.
- There was a mass extinction of 35–50% of benthic foraminifera (bottom-dwelling organisms); this was more severe than the mass extinction 10 million years earlier when the dinosaurs became extinct.
- The climate system took around 120,000 to 170,000 years to recover.

The PETM: possible causes

- Volcanic activity
- Comet impact
- Burning of peat
- Changes in the Earth's orbit
- Methane release from clathrates ("methane ice")
- Changes in the ocean circulation
- None of these mechanisms is sufficient to explain all of the reconstructed changes in the Earth's climate
- Climate feedbacks must have played a strong role, both during the initial warming and during the subsequent recovery

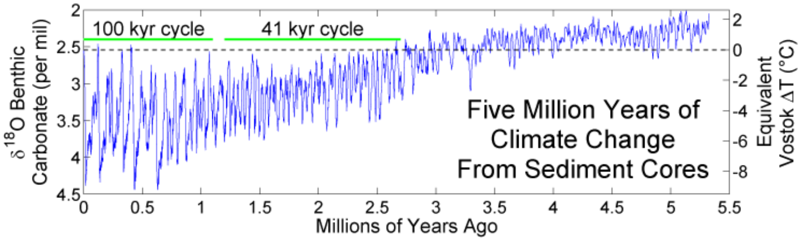
Glacial cycles

Temperature of Planet Earth

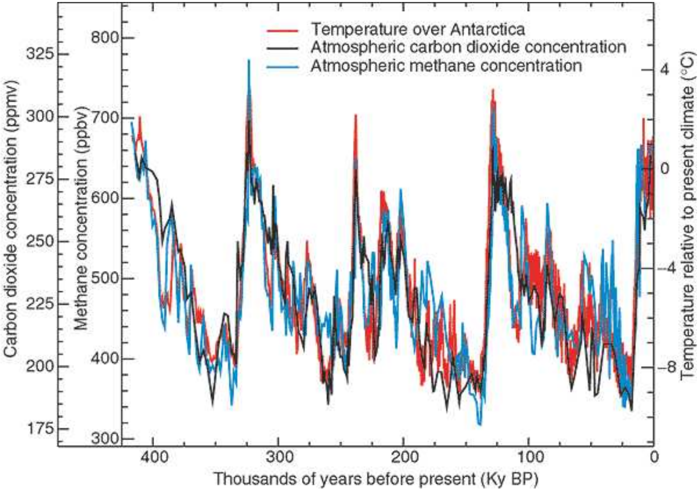


Glacial cycles

- The current ice age began around 2.5 million years ago.
- Since then, the Earth has seen regular cycles of glaciation. Ice sheets have advanced and retreated, first on a 41,000-year cycle and then on a 100,000-year cycle.
- *Glacials* are when ice sheets advance; *interglacials* are when ice sheets retreat. The Earth is currently in an interglacial.



Why is there a distinct 100,000-year cycle?

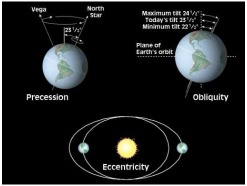


Milanković cycles

- Milutin Milanković (1879–1958).
- Serbian mathematician, astronomer, geophysicist, climatologist, civil engineer, doctor of technology, university professor and writer.
- Hypothesised that long-term changes in the Earth's climate are driven by natural variations in the Earth's orbit.
- These variations are now known as **Milanković cycles**.

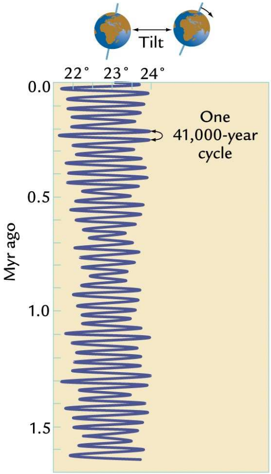
Milanković cycles

- The Earth's orbit is not perfectly circular, but rather is elliptical.
- The Earth's orbital parameters vary over time because of gravitational interactions between the Sun, the Earth, the Moon and the other planets.
- These interactions cause variations in three parameters:
  - the tilt of the Earth's axis (obliquity)
  - the eccentricity of the Earth's orbit
  - the position of the solstices and equinoxes (precession)



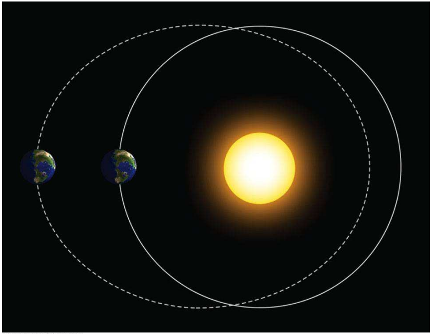
Obliquity

- The tilt of the Earth's axis varies between 22.2° and 24.5°, with a period of 41,000 years.
- The angle of tilt affects the amount of solar radiation received at each latitude.
- Increased tilt amplifies seasonal differences in the climate; decreased tilt reduces seasonal differences in the climate.



Eccentricity

- The eccentricity of the Earth's orbit varies between 0.005 and 0.061, with periods of 100,000 and 413,000 years.



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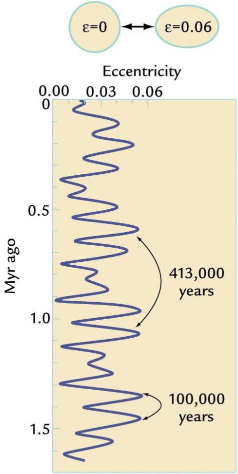
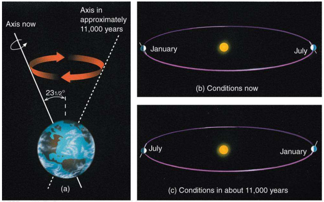


Precession

- The "wobbling" motion of the Earth's axis is called precession.
- One cycle takes 25,700 years.



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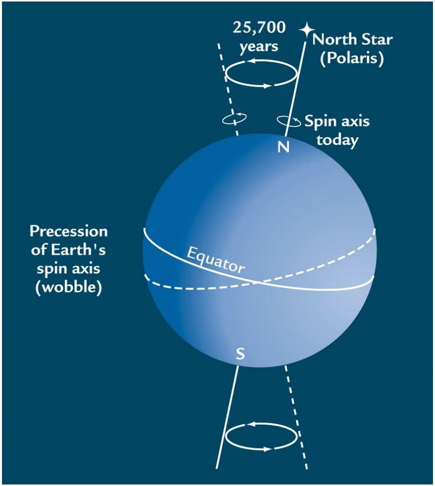
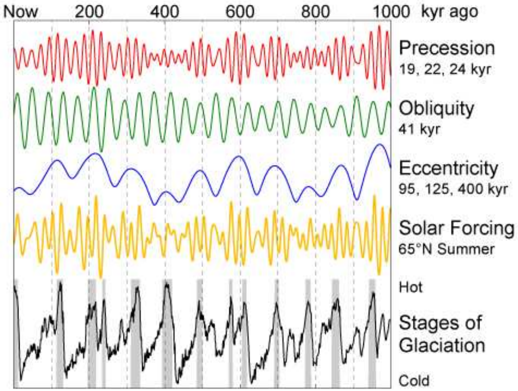
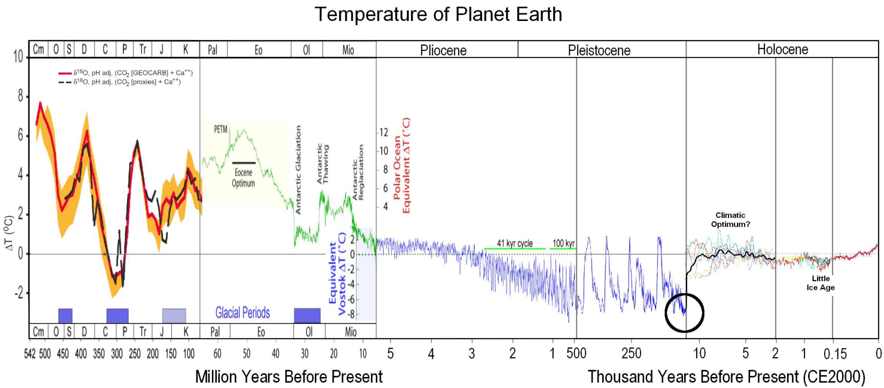


Milanković cycles and solar radiation

- Milanković cycles affect the amount of solar radiation received during summer at 65°N.

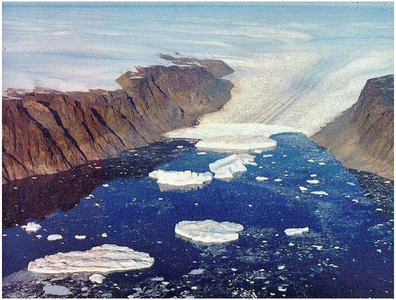


The Last Glacial Maximum (LGM)

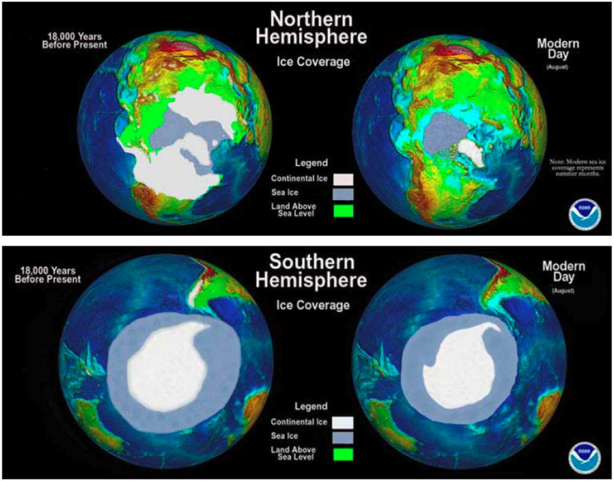


The LGM: what happened

- The peak of the last ice age, known as the Last Glacial Maximum, occurred between 18,000 and 21,000 years ago.
- The global-mean temperature was around 5°C lower than today.
- Sea levels were around 120m lower than today, because of all the additional water locked up in the ice sheets.

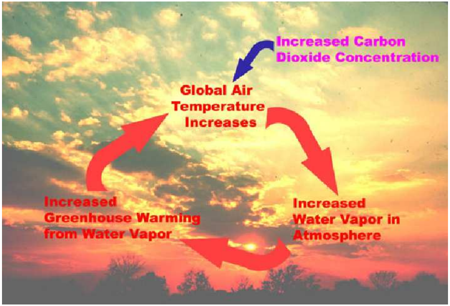


The LGM: changes in ice cover

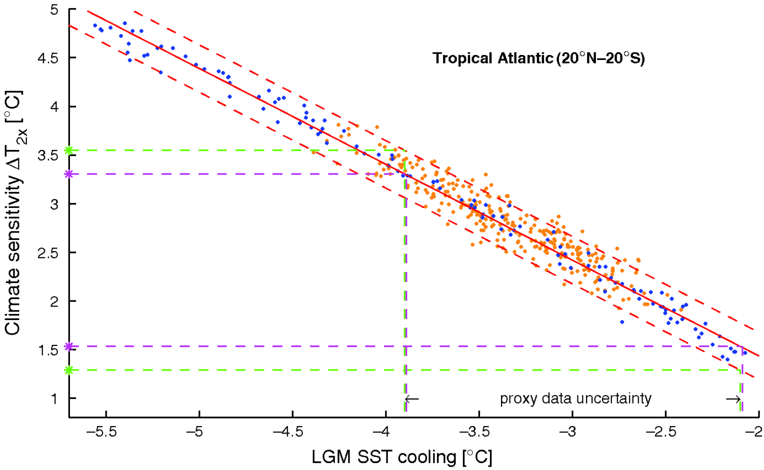


The LGM: the role of climate feedbacks

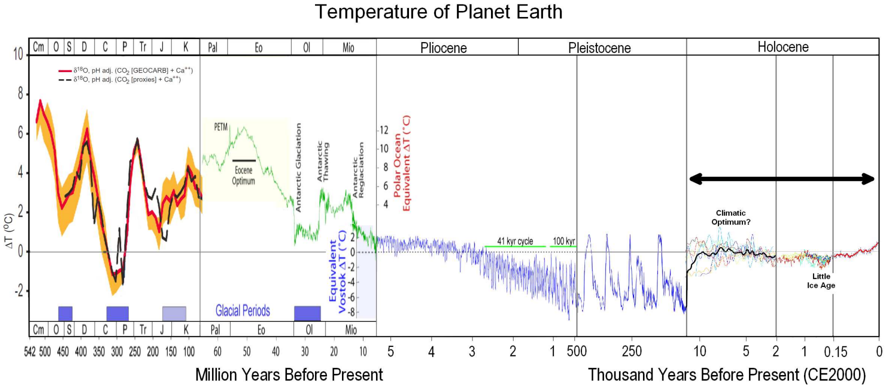
- Feedbacks involving ice albedo, water vapour and greenhouse gases amplified the original cooling due to decreased solar radiation during summer at 65°N.
- The same feedbacks also led to the subsequent deglaciation.



Using the LGM to constrain the climate sensitivity

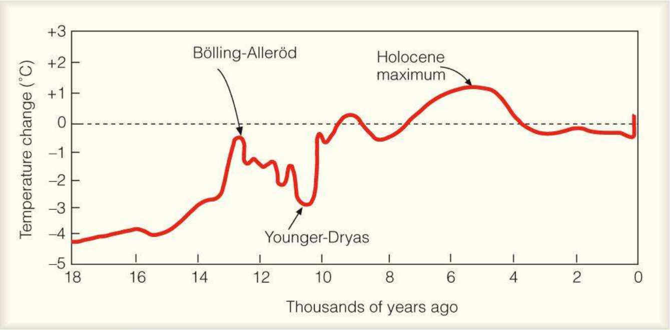


The current interglacial



The past 18,000 years

- Warming began about 15,000 years ago.
- This was interrupted by the Younger Dryas, a time when glacial conditions returned for about 1,000 years. The subsequent abrupt warming brought the Earth into the current interglacial.



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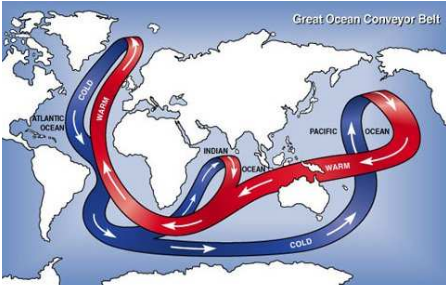
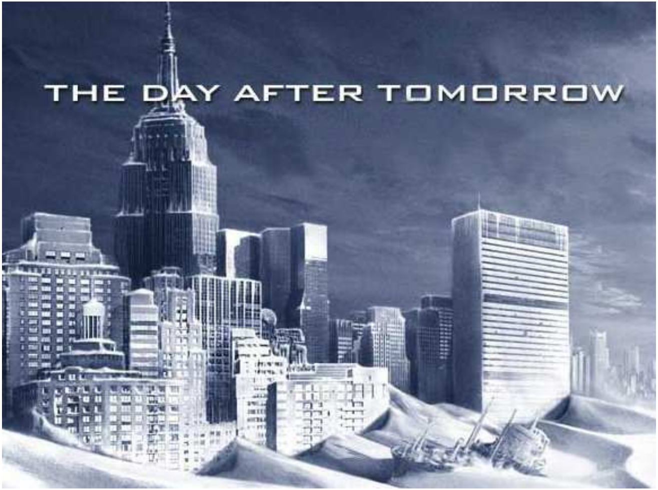
The Younger Dryas

- The leading hypothesis is that large volumes of meltwater were deposited into the North Atlantic by thawing glacial ice in North America.
- This pulse of freshwater caused the thermohaline circulation to shut down, resulting in local cooling and a return to glacial conditions.

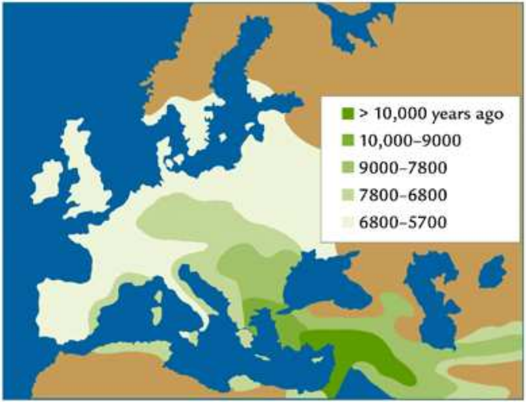


Rapid climate change?

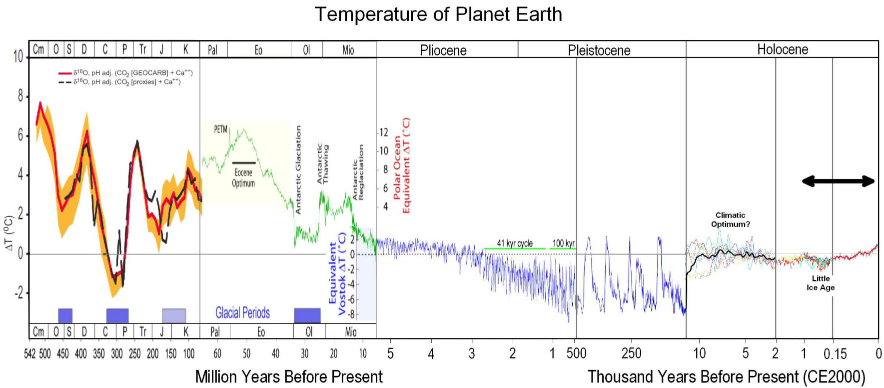


Climate and human migration

- Human civilisation migrated northwards as the ice sheets retreated.
- What does the future hold?

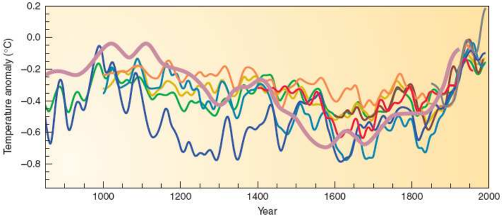


The past 1000 years



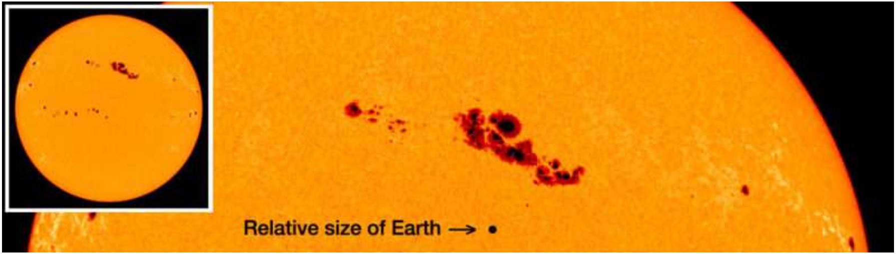
The past 1000 years

- The period ~950–1250 CE was relatively warm in the Northern Hemisphere. This **Mediaeval Warm Period** coincided with the Viking settlement of Greenland.
- The **Little Ice Age**, from ~1400–1700 CE, was a cold period globally. Temperatures fell around 0.5–1°C and glaciers advanced.
- Volcanic activity and variations in solar output appear to have been responsible.



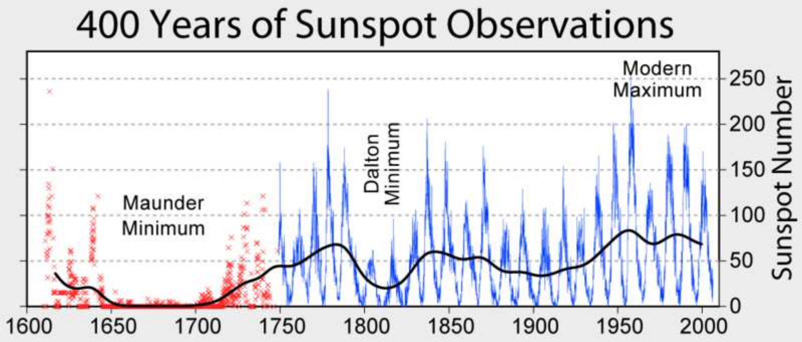
Sunspots and climate change

- A sunspot is a region on the Sun's surface marked by intense magnetic activity. This inhibits convection, forming an area of relatively low temperature.
- Sunspots occur when the sun is more active. Despite the sunspots themselves being cooler, the sun as a whole is brighter.

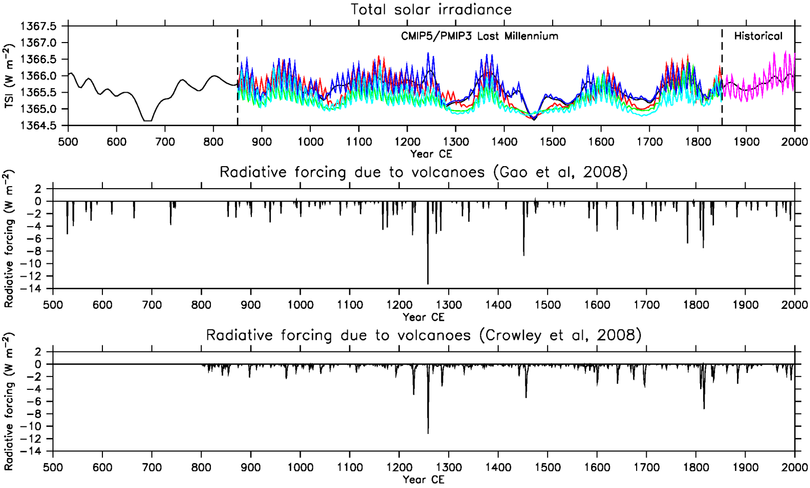


Sunspots and the Little Ice Age

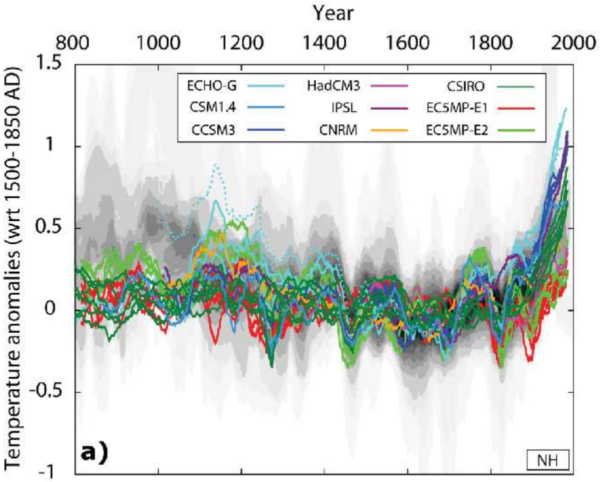
- Solar luminosity is lower during periods of low sunspot activity.
- Low solar output is likely to have been one of the drivers of the Little Ice Age.



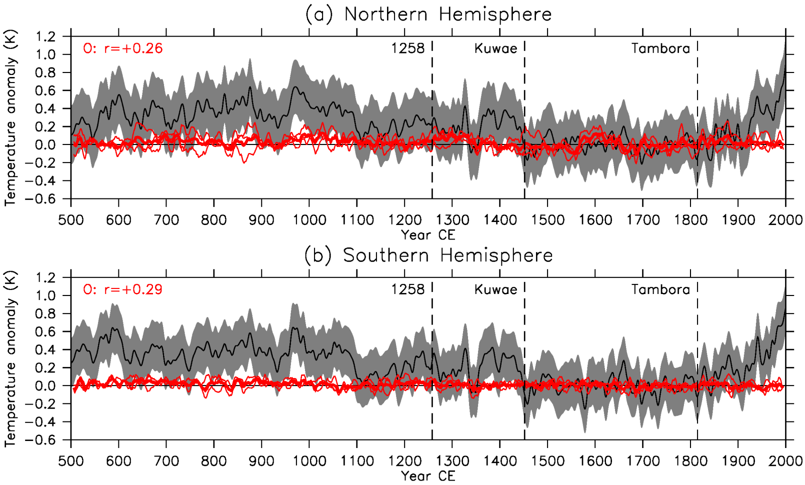
The sun and volcanoes over the past 1000 years



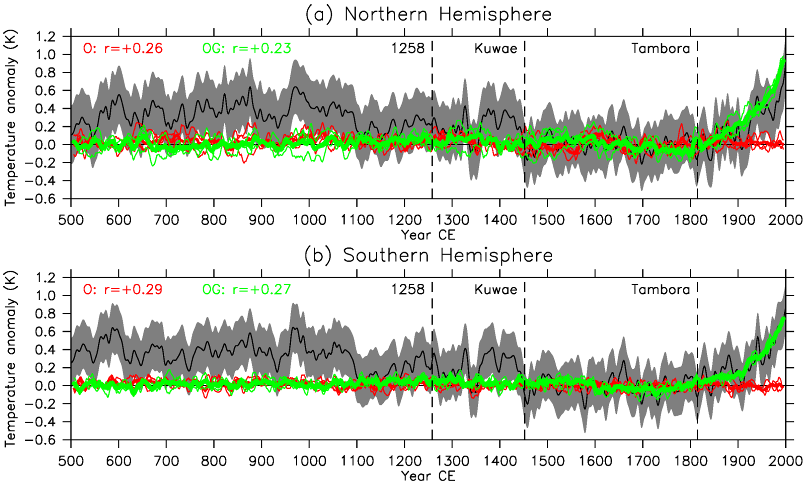
The past 1000 years: model evaluation



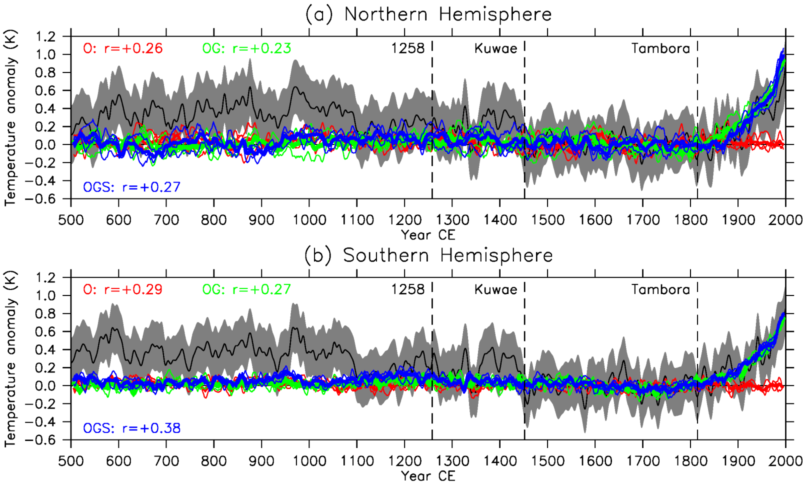
Using models to explore climate drivers



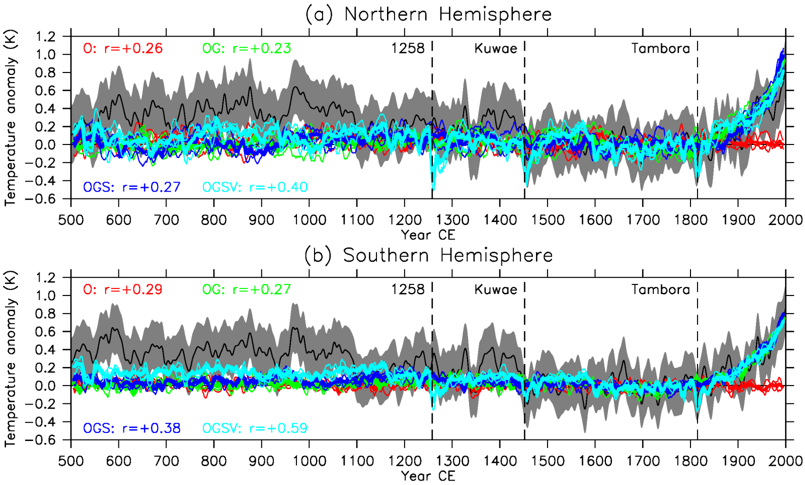
Using models to explore climate drivers

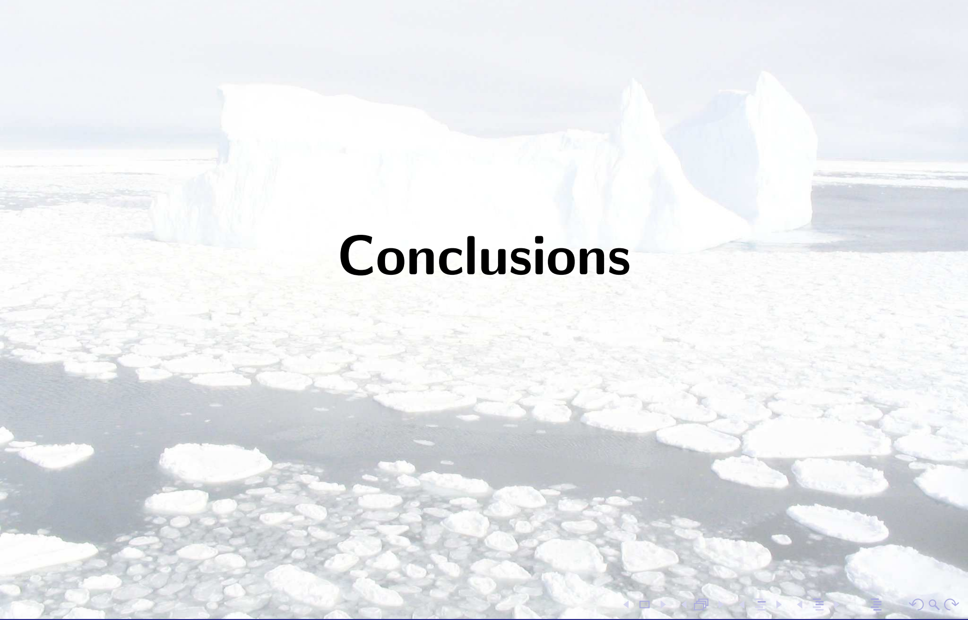


Using models to explore climate drivers



Using models to explore climate drivers





Conclusions

Conclusions: drivers of Earth's climate

- Very short term (less than 10^4 years):
  - Solar cycles
  - Volcanic activity
- Short term (10^4–10^6 years):
  - Orbital changes (Milanković cycles)
  - Greenhouse gases
- Medium term (10^6–10^8 years):
  - Continental drift (plate tectonics)
  - Uplift/weathering
- Long term (10^8–10^9 years):
  - Galactic motions
- Very long term (more than 10^9 years):
  - Solar evolution

Conclusions: past climate change

- The Earth's climate has exhibited a very diverse range of behaviour over its 4.6 billion year history.
- There are many ways of detecting these changes.
- Past climate change allows us to learn more about the behaviour of the climate system, and about the drivers of climate change.
- Past climate change also helps us to understand how the Earth's climate might change in future.