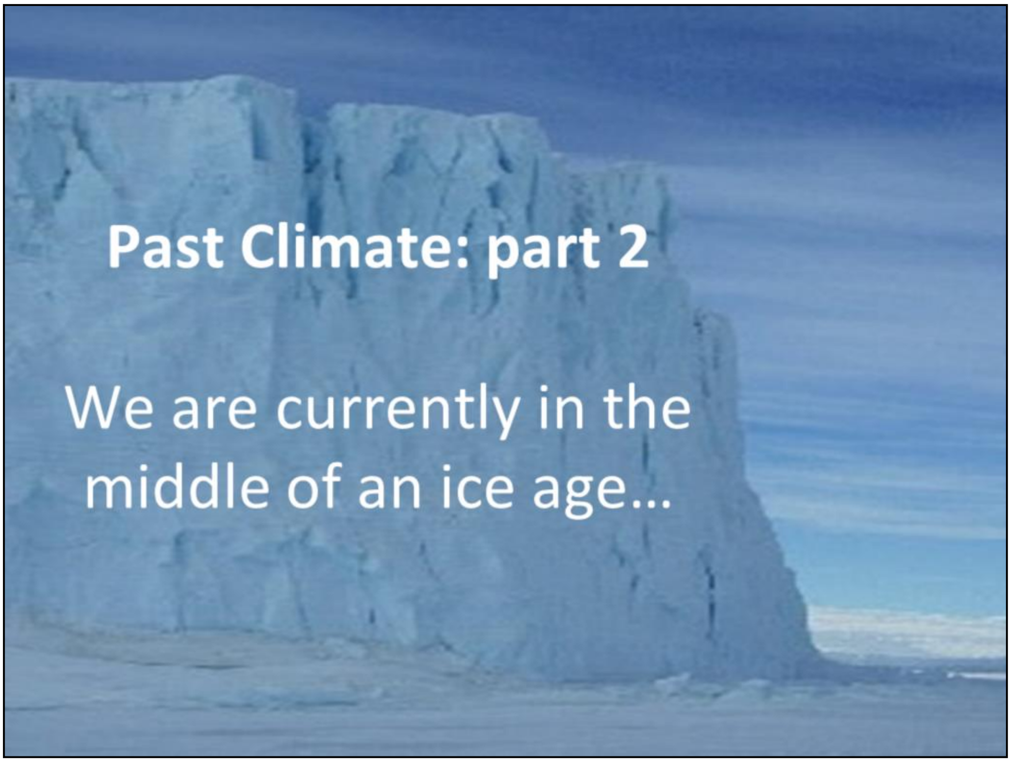
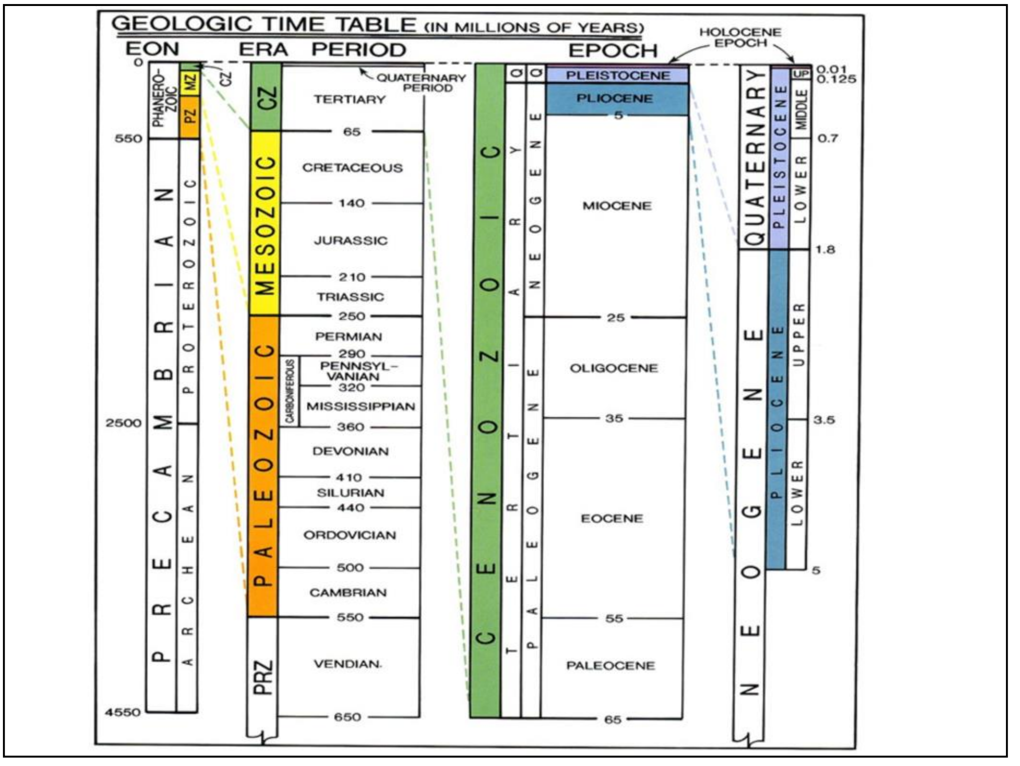
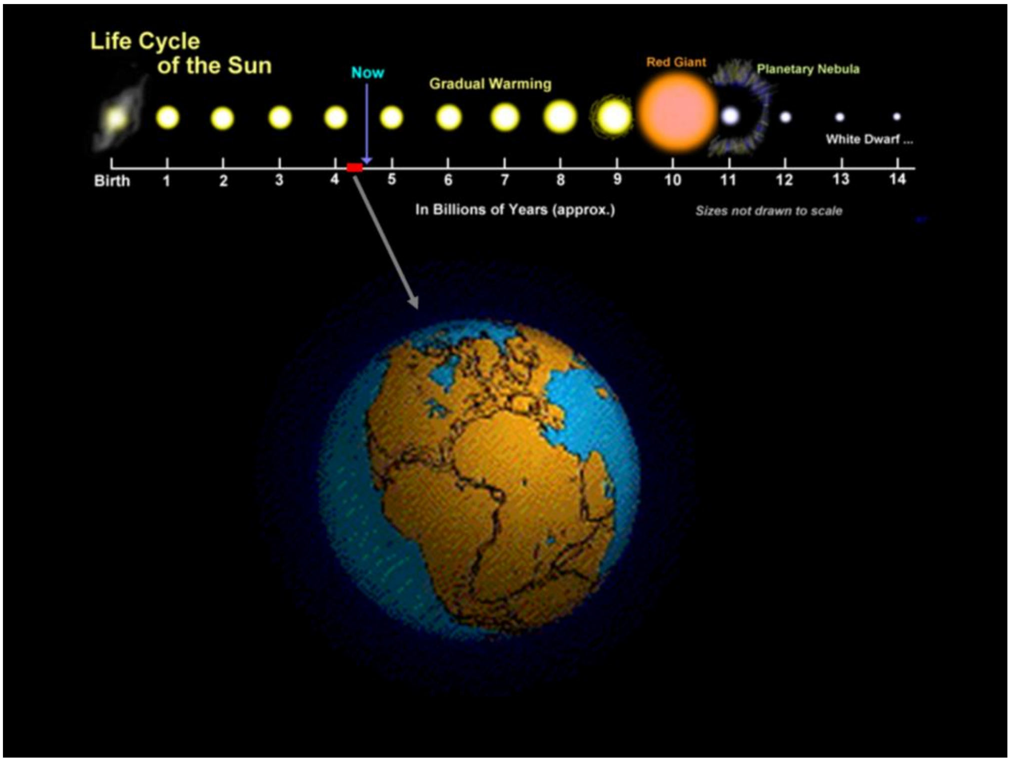


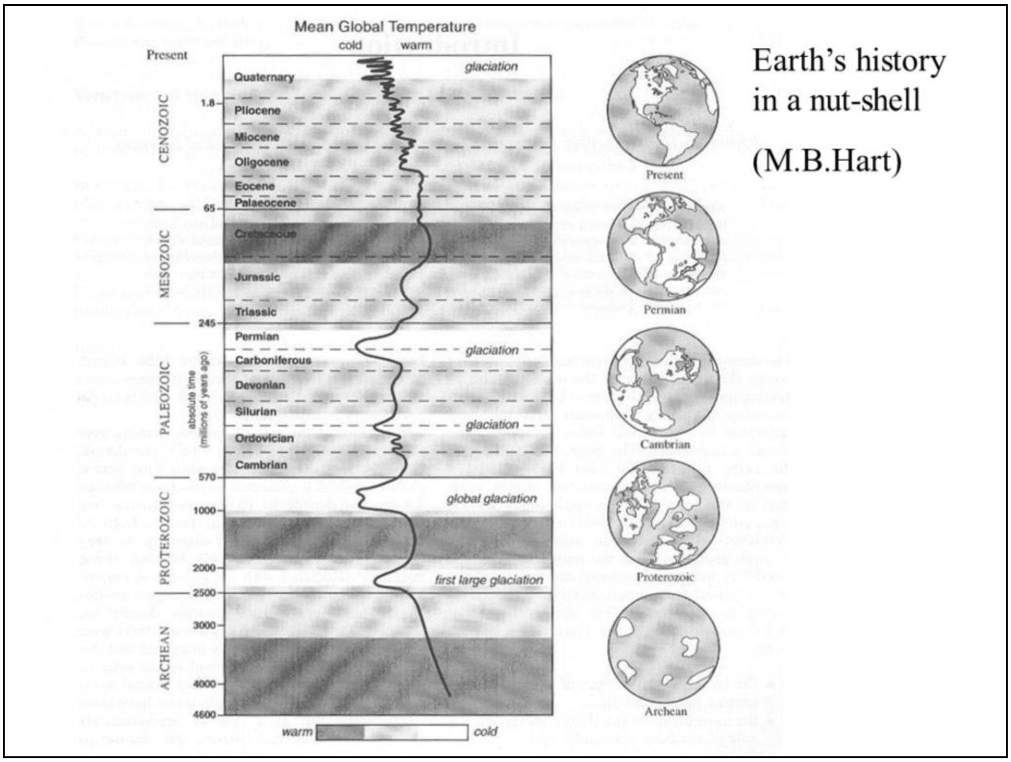
There were times in the past when little permanent ice existed on Earth for millions of years (e.g. the Cretacious period). At present, large ice sheets do exist at both poles which advance and retreat over periods of tens of thousands of years; the present series of glacial/interglacial cycles copvering the past few million years are termed ice-ages by scientists interested in geological time-scales. We're in a "brief" mild interlude (inter-glacial) in between glacial periods.



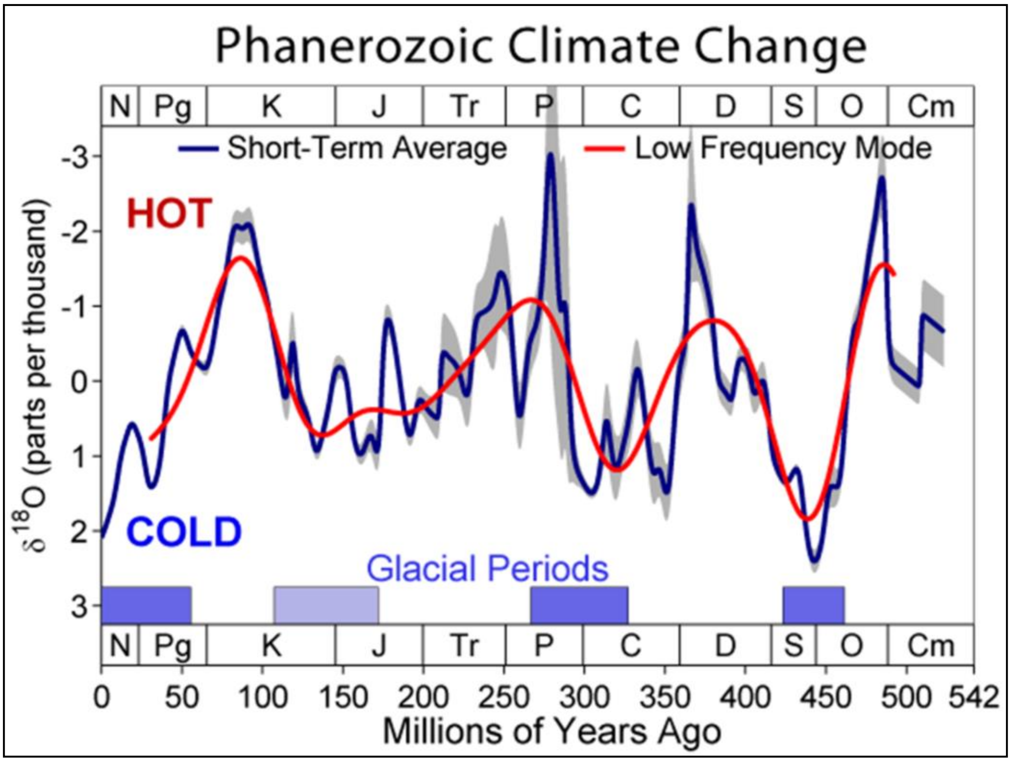
Different portions of the Earth’s 4.6 billion year history are split up into sections as above. The **geological time scale** is used by geologists and other scientists to describe the timing and relationships between events that have occurred during the history of the Earth. The last 1.8 million years are when the glacial/interglacial cycles of the current “ice age”, the Pleistocene, occurred.



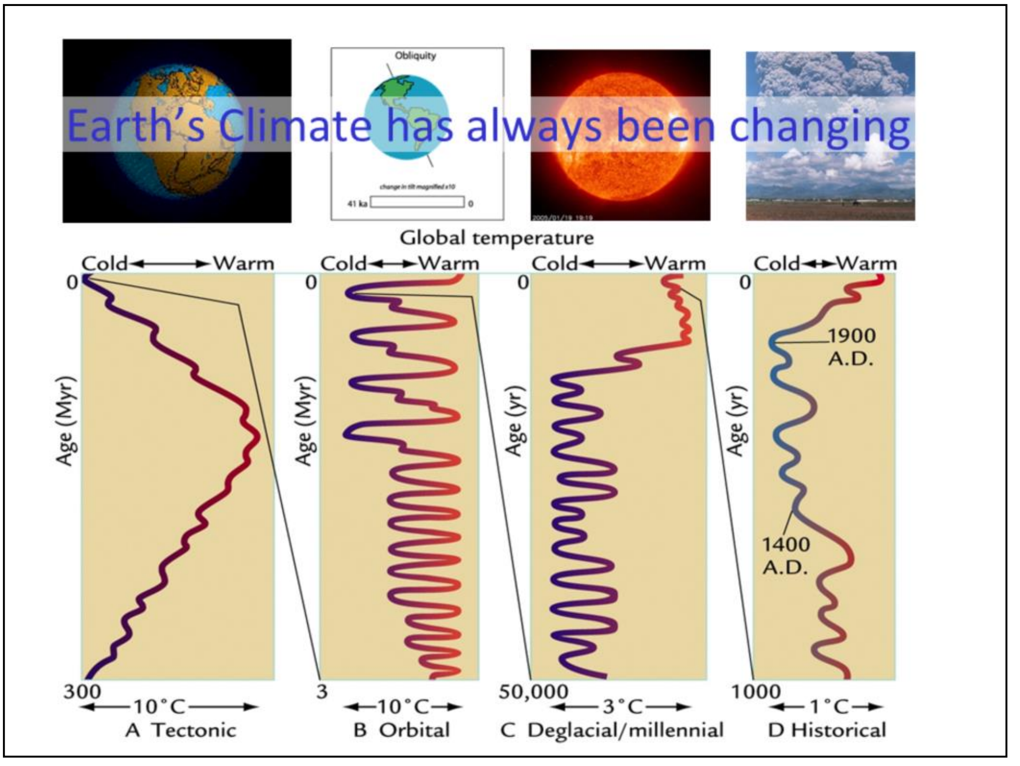
Over the 4.6 billions years of the Earth’s history the energy output of the sun as increased, and the Earth’s atmosphere has altered in symbiosis with the evolution of life. The distribution of land and ocean have also changed markedly. All of these factors have caused massive changes in climate, but on unimaginably long periods of time in the context of the presence of anatomically modern human societies (around 200,000 years which is 0.004% of 4.6 billion years). So it is important to appreciate that the causes of climate change on geological time-scales may have little relevance for climate change over time-scales relevant for human societies.



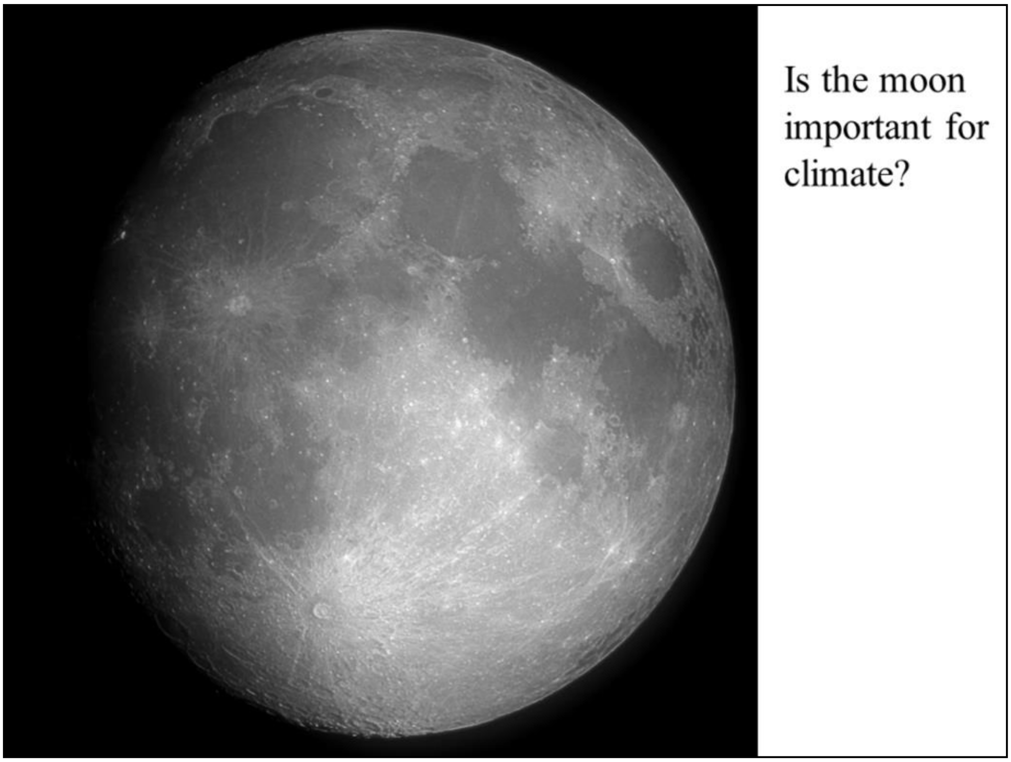
An increase in the output of the sun over billions of years warmed the Earth although changes in the atmosphere, in part due to volcanic emissions and in part due to the development of life, caused changes in the greenhouse effect. Plate tectonics and the associated positioning of continental land masses, mountains and ocean basins shaped much of the climate fluctuations over millions of years; the second ice age may have resulted in a completely glaciated Earth ("snowball Earth") after which followed the Cambrian "explosion" of life (lots of fossils). Over millions of years changes in the positions of continents alter the climate through changes in ocean circulation and the ability to generate land-based ice sheets. The lack of polar land masses in the Cretacious contributed to high global temperatures. The Earth cooled as Antarctica moved over the South pole. The formation of the land bridge between south and north America also helped to make conditions more suitable for the formation of giant ice sheets. As India crashed into Asia, producing the Himalayas, this may also have cooled the planet through the generation of high altitude icy regions and the increased weathering of rock that allowed increased trapping of carbon dioxide in the oceans.



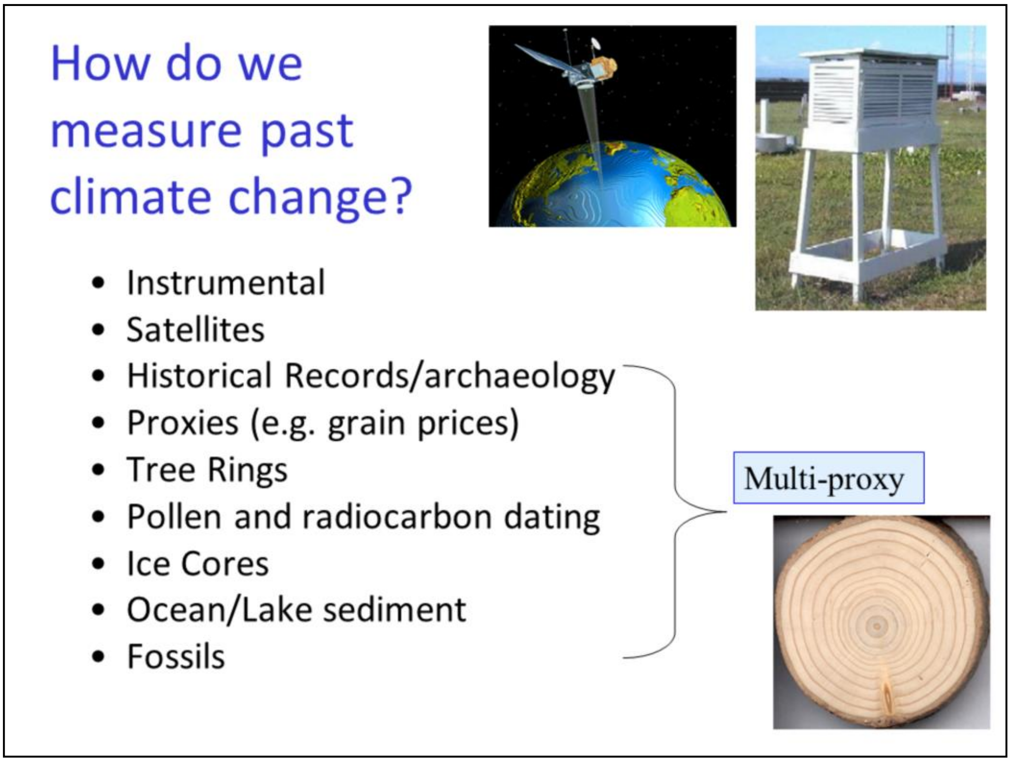
Oxygen isotope measurements in sediments indicate warm and cold periods over millions of years relating to continental drift and changes in atmospheric composition. Superimposed upon these slow cycles are more regular fluctuations relating to the Earth's orbit around the sun. The current "ice age" includes colder "glacial" times and temperate "inter-glacial" times caused by these orbital changes. The current inter-glacial began about 10,000 years ago and is likely to last for many tens of thousands of thousand years.



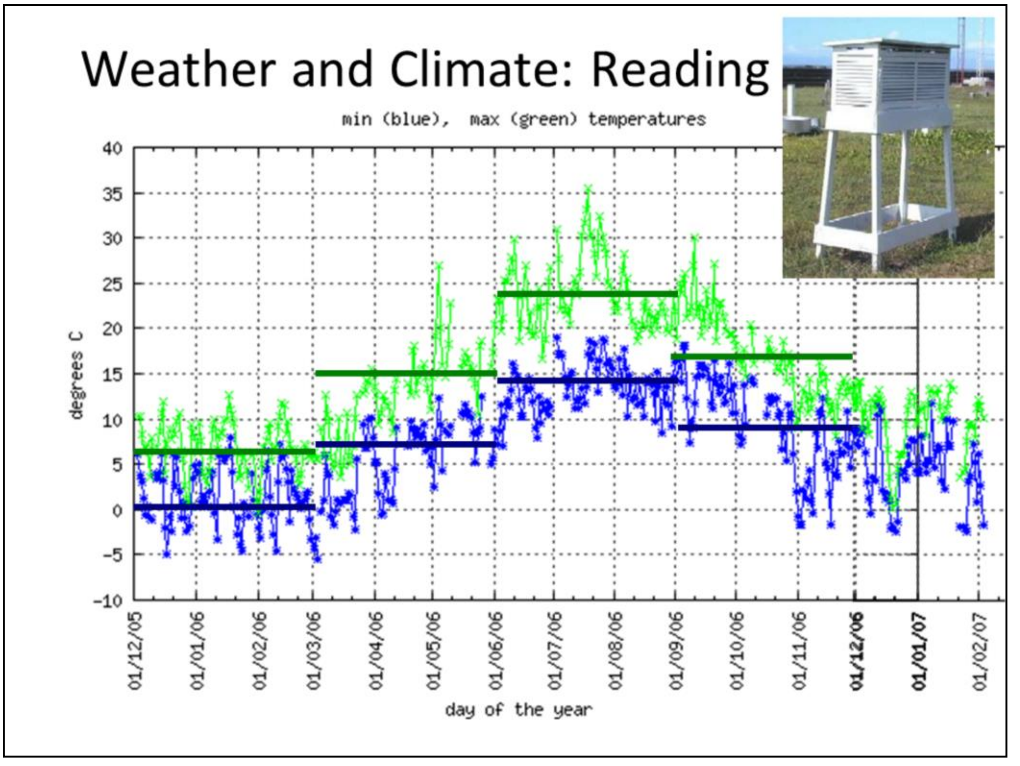
Climate changes on all time-scales, including "shorter" time-scales relative to the geological past covering billions of years. Over millions of years, continents drift and the position of the oceans and mountains alter the atmospheric and oceanic flows, changing how efficiently Earth can lose the absorbed energy from sunlight to space. Over tens and hundreds of thousands of years, changes in the Earth's orbit around the sun alter the amount of solar radiation reaching different parts of the planet. These cycles are predictable (they depend upon the gravitational pulls of the sun, planets and the moon) and can explain the timings of glacial-interglacial cycles in which global temperatures swing by up to 10^{o}C. Crucial to these swings are *feedbacks* which either amplify or dampen the radiative *forcing* from these *Milankovic* cycles. For example, cooler temperatures lead to more ice and greater reflection of solar radiation which amplifies the cooling. Over shorter time-scales, changes in the sun, volcanic eruptions, chaotic fluctuations in the oceans and human activity all explain climate change over tens to hundreds of years.



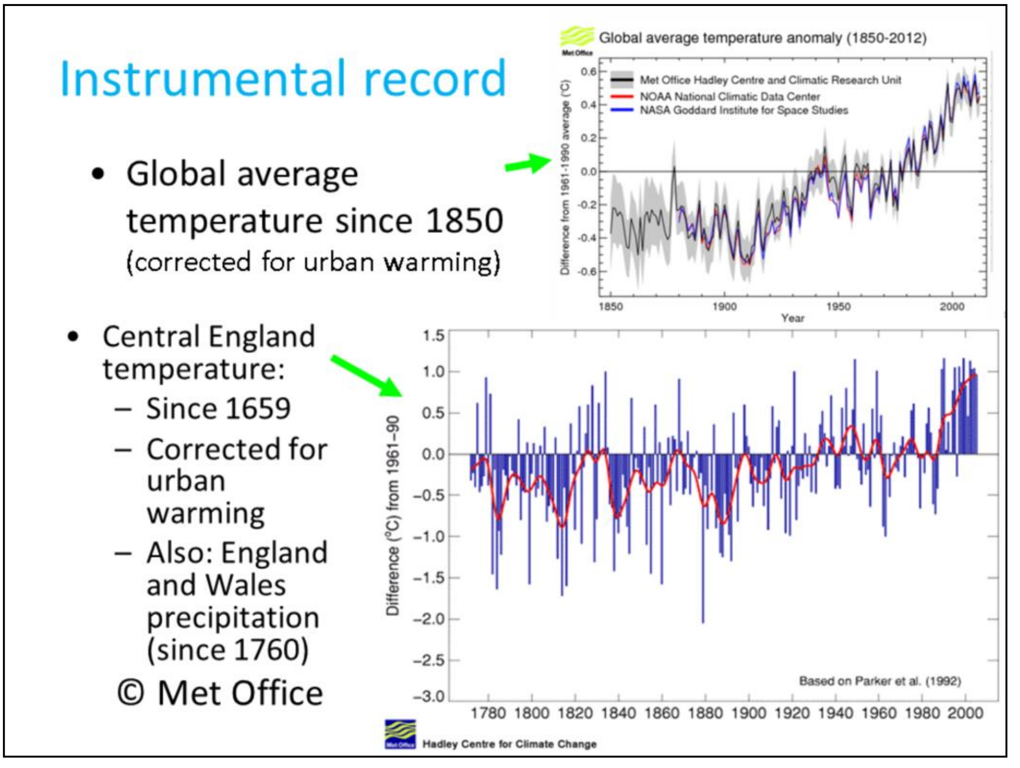
Is the moon important for climate? Our relatively large moon helps to reduce the changes in the tilt of the Earth's axis around the sun disallowing wild fluctuations seen on some other planets (e.g. Mars).



To determine whether 20th century warming is unusual, it is essential to place it in the context of longer-term climate variability. Owing to the sparseness of instrumental climate records prior to the 20th century (especially prior to the mid-19th century), estimates of global climate variability during past centuries must often rely upon indirect "proxy" indicators − natural records or human documentary archives that record past climate variations, but must be calibrated against instrumental data for a meaningful climate interpretation (IPCC 2001). A proxy refers to an indirect measure of climate change. For example if wheat prices are sensitive to European summer temperature and provide a long, "homogenous" record (non-climatic signals relating to other factors are removed) then they can be used as a climate proxy. Combining a variety of proxy records and calibrating with the instrumental record can provide evidence of past climate change at regional and global scales.



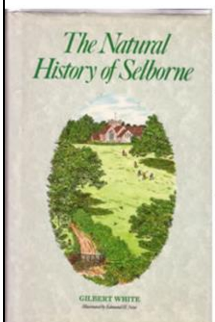
Thousands of meteorological stations routinely take standardised measurements, for example of maximum and minimum air temperature. Only the highest quality stations are included that generally contain long records that are corrected for changes in observing practice. There are also measurements of rainfall, evaporation, radiation (thermal and solar), wind speed and direction, and much more. The information is used for research purposes and for weather and climate monitoring purposes.



Central England Temperature (CET) is representative of a roughly triangular area of the United Kingdom enclosed by Bristol, Lancashire and London. The monthly series begins in 1659, and to date is the longest available instrumental record of temperature in the world. Since 1974 some stations have been adjusted to allow for urban warming. **Global near-surface temperatures**, consisting of annual differences from the 1961-90 average. This information is based on regular measurements of air temperature at land stations and on sea-surface temperatures measured from ships and buoys. Global near-surface temperatures may also be given as the differences from the average values at the beginning of the 20th century. The Global and Hemispheric plots may be viewed within the climate indicators.

Historical Records/Archaeology

- For example:-
  - the Norse Greenland sagas and archaeological evidence
  - Agricultural records
  - “A natural history of Selbourne”
  - Wheat prices, etc



Historical documentary data are valuable sources of information about past climate. However, their use requires great care, as such documents may be biased towards describing only the more extreme events, and are, in certain cases, prone to the use of inconsistent language between different writers and different epochs, and to errors in dating. As for all proxy information, historical documents require careful calibration and verification against modern instrumental data (IPCC 2001).

Archaeology provides evidence of crops/livestock eaten and the state of health and state of the ground (e.g. Greenland colonies)

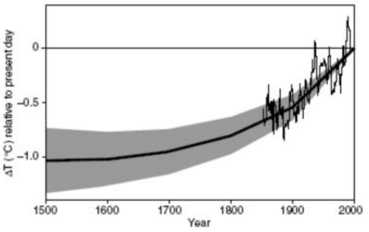
Tree Rings

- Can measure climate over 100s years
- Precisely dated (carbon dating)
- Need information of what climate variables the trees are most sensitive to
  - Length of growing season, rainfall, mean warm-season temperature, …
- Limitations: land-based, removal of biological factors (tree life cycle), CO_2 “fertilisation”, useful in combination with other proxies

Tree-ring records of past climate are precisely dated, annually resolved, and can be well calibrated and verified. They typically extend from the present to several centuries or more into the past, and so are useful for documenting climate change in terrestrial regions of the globe. Many recent studies have sought to reconstruct warm-season and annual temperatures several centuries or more ago from either the width or the density of annual growth rings. Recently, there has been a concerted effort to develop spatial reconstructions of past temperature variations and estimates of hemispheric and global temperature change.

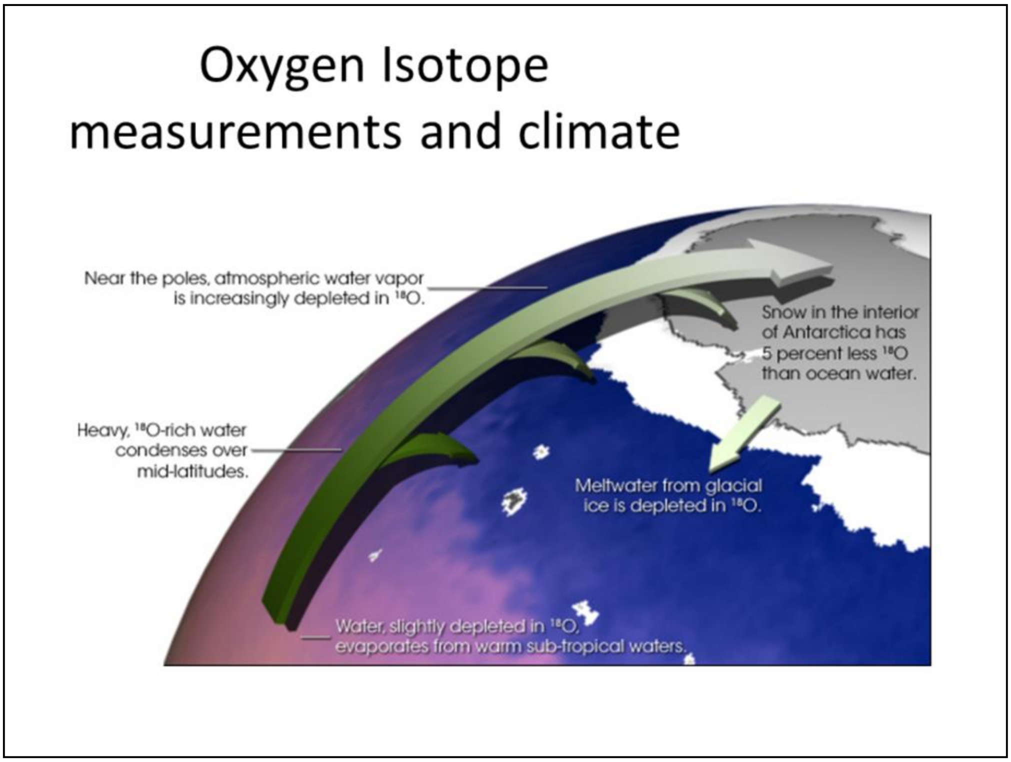
Other proxies

- Ice cores
  - Gas concentrations from air trapped in the ice
  - Oxygen isotope ratio sensitive to temperature and precipitation
- Corals
  - Sensitive to changes in shallow tropical ocean temperature;
- Lake sediments
  - Thousands to millions of years
- Mountain glacier moraines
- Borehole temperature
  - data back as far as 1500s →



Lake sediments: Three primary climate variables may influence lake varies: (a) summer temperature, serving as an index of the energy available to melt the seasonal snowpack, or snow and ice on glaciers; (b) winter snowfall, which governs the volume of discharge capable of mobilising sediments when melting; and (c) rainfall (IPCC 2001).

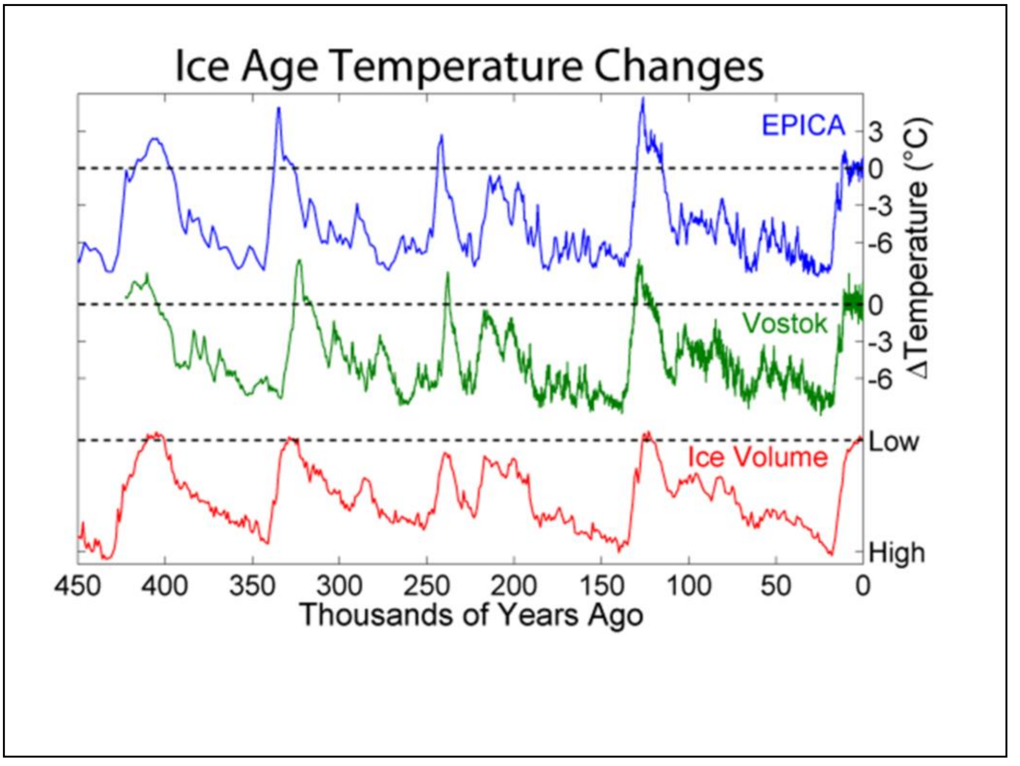
Borehole measurements attempt to relate profiles of temperature with depth to the history of temperature change at the ground surface (using understanding of energy flows through soil).



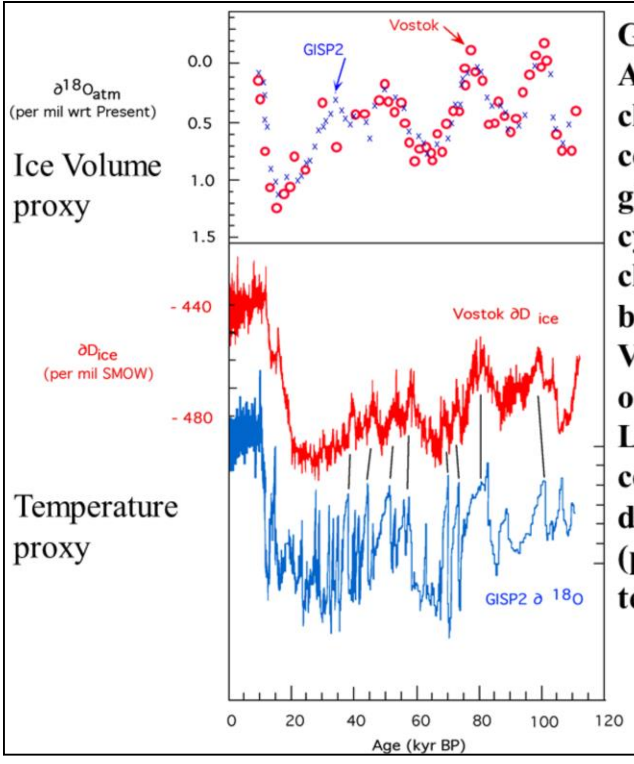
Oxygen-18 (^{18}O) and Oxygen-16 (^{16}O) are "isotopes" of Oxygen. They are the same chemically but are different weights due to the number of neutrons in the nucleus (^{16}O is lighter than ^{18}O). 99.765% of Oxygen is ^{16}O while only 0.2% is ^{18}O but the ratio of these isotopes is a valuable climate indicator. This is because (i) the ratio of ^{18}O/^{16}O depends on evaporation and condensation processes and (ii) these processes are strongly linked to temperature. Because ^{18}O is heavier than ^{16}O, ^{18}O is less likely to evaporate from the ocean leaving the ocean rich in ^{18}O (large ^{18}O/^{16}O ratio) and the atmosphere depleted in ^{18}O (lower ^{18}O/^{16}O ratio). The heavier ^{18}O condenses as rain drops more easily so as air moves polewards and water continues to lose ^{18}O and becomes more depleted in ^{18}O (lower ^{18}O/^{16}O ratio). The snow that falls over the poles has the lowest ^{18}O/^{16}O ratio.

<u>During colder glacial periods:</u>

1) More ^{16}O is locked away in ice sheets so there is higher ^{18}O in oceans & air bubbles in ice cores: a proxy for ice volume
2) There is a larger equator to pole temperature difference leading to a greater depletion of ^{18}O in snow compacted in ice cores: a proxy for polar temperature

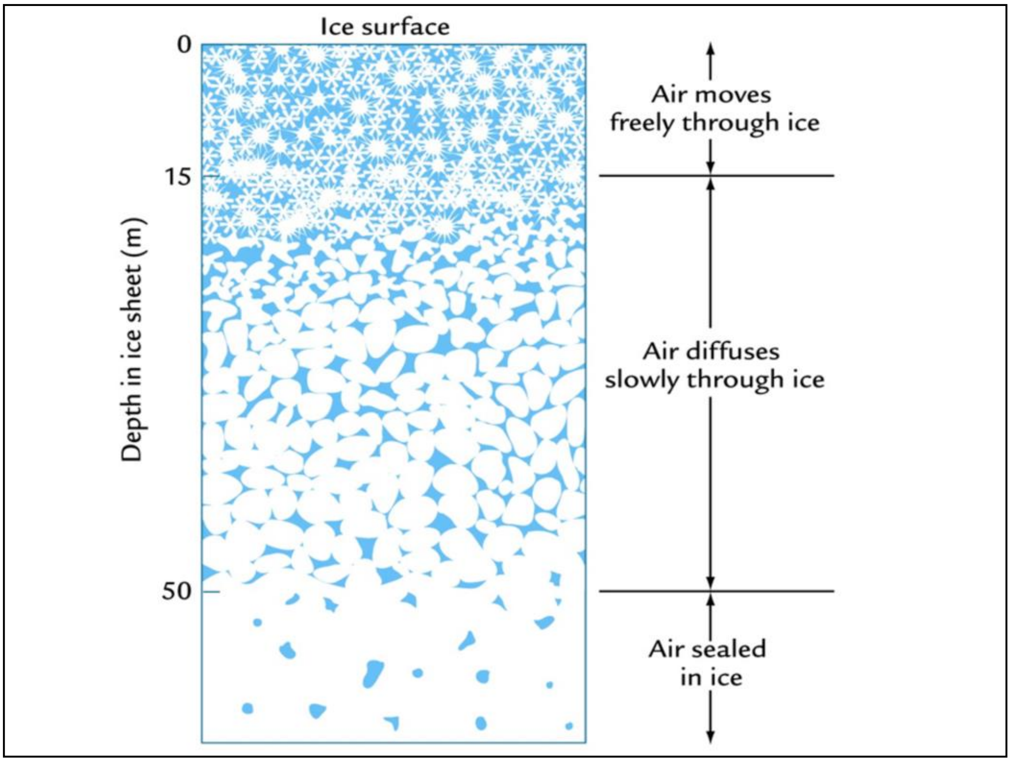


During glacials, polar temperature was up to 10^{o}C cooler than today; the global average temperature was about 5^{o}C cooler than today. But if the ice ages are caused by northern hemisphere sunshine, why are the glacial-glacial cycles evident in Antarctica (above)?



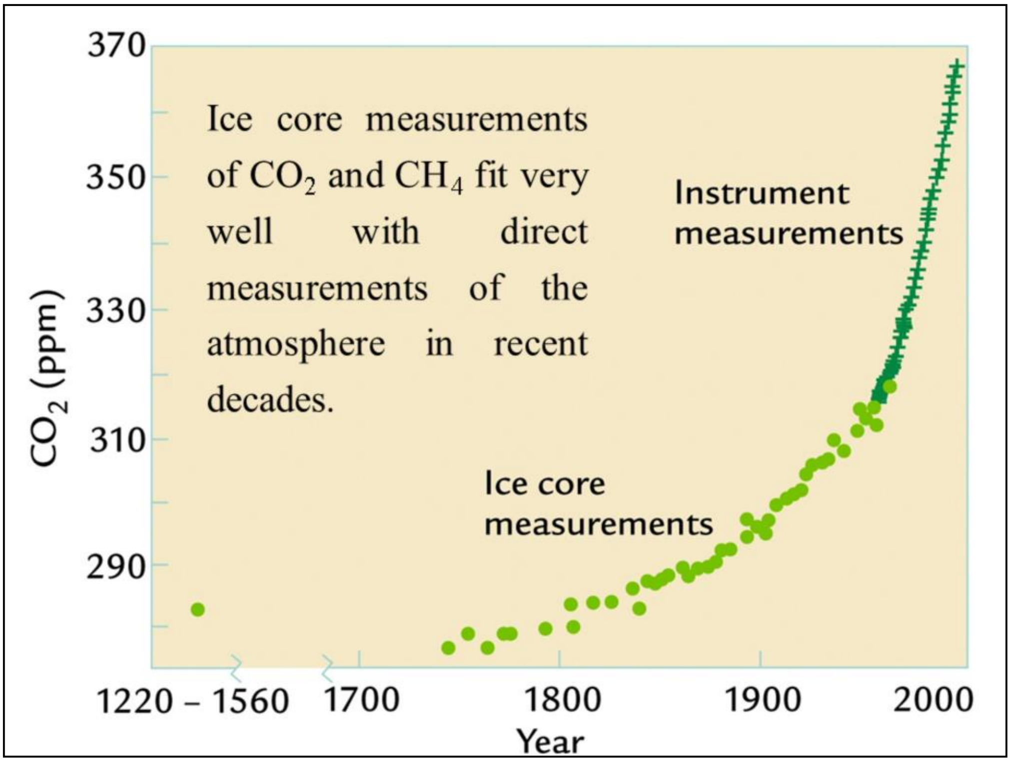
Greenland (GISP2) and Antarctic (Vostok) climate records covering the last glacial-interglacial cycle. Upper part shows close correlation between GISP2 and Vostok in the delta ^{18}O of air in these ice cores. Lower part shows close correlation between the delta D and delta^{18}O (proxies for temperature) of the ice.

The ice volume in both Greenland and Antarctica appears to correspond with solar radiation at 65N due to orbital variations. There must be a mechanism that links the poles (CO_2, ocean currents, ice reflection, etc).

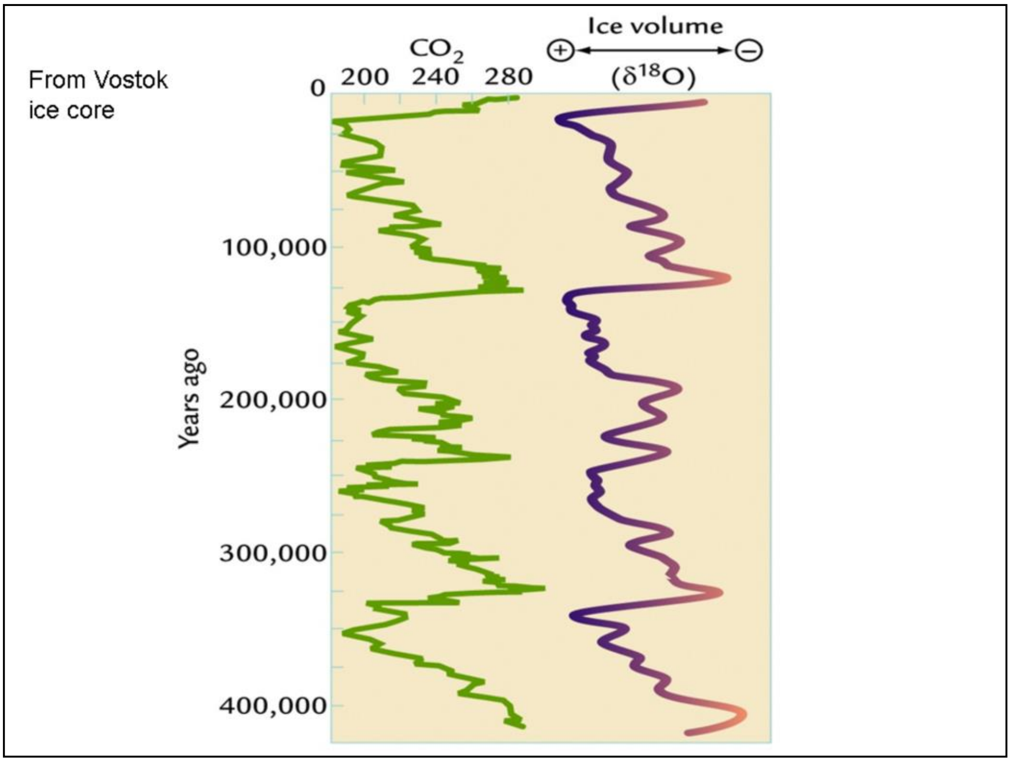


Gases trapped in the ice provide information on the atmospheric composition

The sintering process seals air bubbles in ice. Air moves freely through snow and ice in upper 15 m of an ice sheet, but flow is increasingly restricted below this level. Bubbles of old air are eventually sealed completely in ice 50-100 metres below the surface.

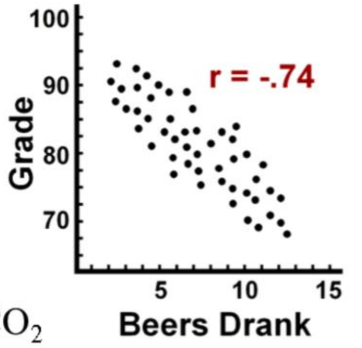


The measurements suggest a rapid increase in greenhouse gases such as carbon dioxide and methane, with time. Since the pre-industrial era, the increases year upon year have generally increased (an increased rate of increase). Carbon dioxide levels today are around a third higher than pre-industrial levels (280 ppm → 400 ppm; ppm=parts per million, so 400 ppm means 400 molecules per million molecules of dry air).



CO_2 concentration measured in ice cores correlates with ice volume inferred from the oxygen isotope ratio measurements made from the same cores (high CO_2 corresponds with low ice volume). However, correlation is not causation. Amplifying “feedbacks” are required to explain the magnitude of climate change response to the orbital cycles. Over glacial cycles, greenhouse gas concentrations respond to the warming and cooling and amplify the temperature response in the same way as ice coverage changes. Today, increases in greenhouse gases, rather than acting as an amplifying agent, have driven much of the current global warming since the 1950s (IPCC 2013). Further in the past, changes in greenhouse gases may also have driven climate changes, for example through volcanic emissions and through emission from the ocean following tectonic influences on the chemical nature of river water.

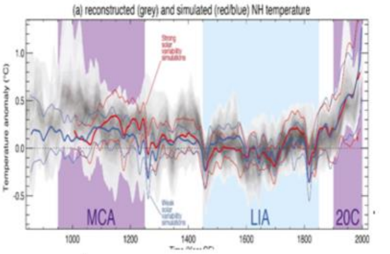
Correlation is not causation



- CO_2 lags the estimated changes in ice volume (~800 yrs?)
- A colder ocean dissolves more CO_2
- The timings of glaciation are determined by the Croll/Milankovitch cycles but the CO_2 variations are large enough to amplify the changes in global temperature
- Also important are changes in ice reflection, water vapour, dust… more in “Forcings and feedbacks”

At least three careful ice core studies have shown that CO_2 starts to rise about 800 years (600-1000 years) after Antarctic temperature during glacial terminations. This of course does not disprove the influence of CO_2 on current climate change. During glacial-interglacial cycles, changes in temperature initiated by variations in Earth’s orbit around the sun, initiate the advance or retreat of huge ice sheets that further alter the amount of sunlight absorbed by the surface. Since CO_2 is more soluble in cold water, as the climate begins to warm, the ocean emits CO_2 which amplifies the warming. Without the changes in greenhouse gases through glacial cycles, the changes in global temperature would be significantly smaller. For the present day, rather than CO_2 being a “slave” to the temperature changes, it is driving the warming itself (along with other greenhouse gases). Other factors such as water vapour amplify this warming. The changes in the radiation budget due to present day increases in CO_2 are consistent with those required to explain the amplification of glacial-interglacial changes in temperature.

Multi-proxy reconstructions of the last millennium



- A careful combination of proxies and the instrumental record
- Large uncertainty but suggests a cooling trend from 1000AD to 1900AD (with fluctuations) and a rapid rise in temperature thereafter
- Highly controversial at one stage but the magnitude and rapidity of the late 20th century warming are now shown to be highly unusual in the climate record of the last 1300 years

Instrumental data describing large-scale surface temperature change are only available for roughly the past 150 years. Estimates of surface temperature changes further back in time must therefore make use of the few long available instrumental records or historical documents and natural archives or 'climate proxy' indicators, such as tree rings, corals, ice cores and lake sediments, and historical documents to reconstruct patterns of past surface temperature change. Due to the paucity of data in the Southern Hemisphere, recent studies have emphasized the reconstruction of Northern Hemisphere (NH) mean, rather than global mean temperatures.

Multi-proxy reconstruction of the last millennium: the “hockey stick” plot (IPCC 2001)

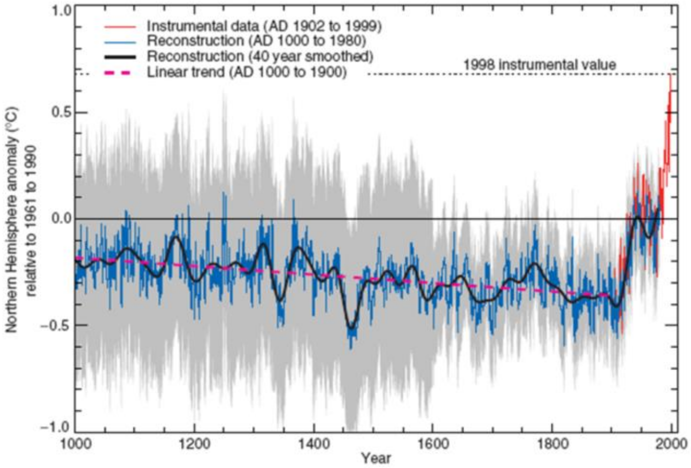
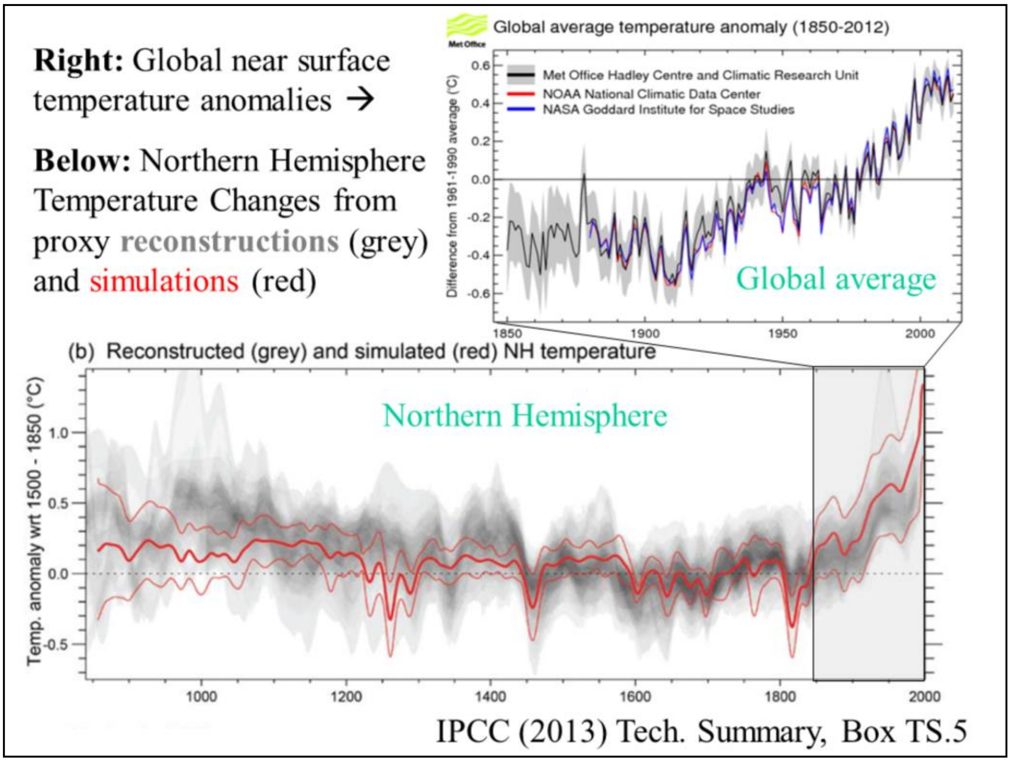


Figure 2.20: Millennial Northern Hemisphere (NH) temperature reconstruction (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann *et al.* (1999). Smoother version of NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown.

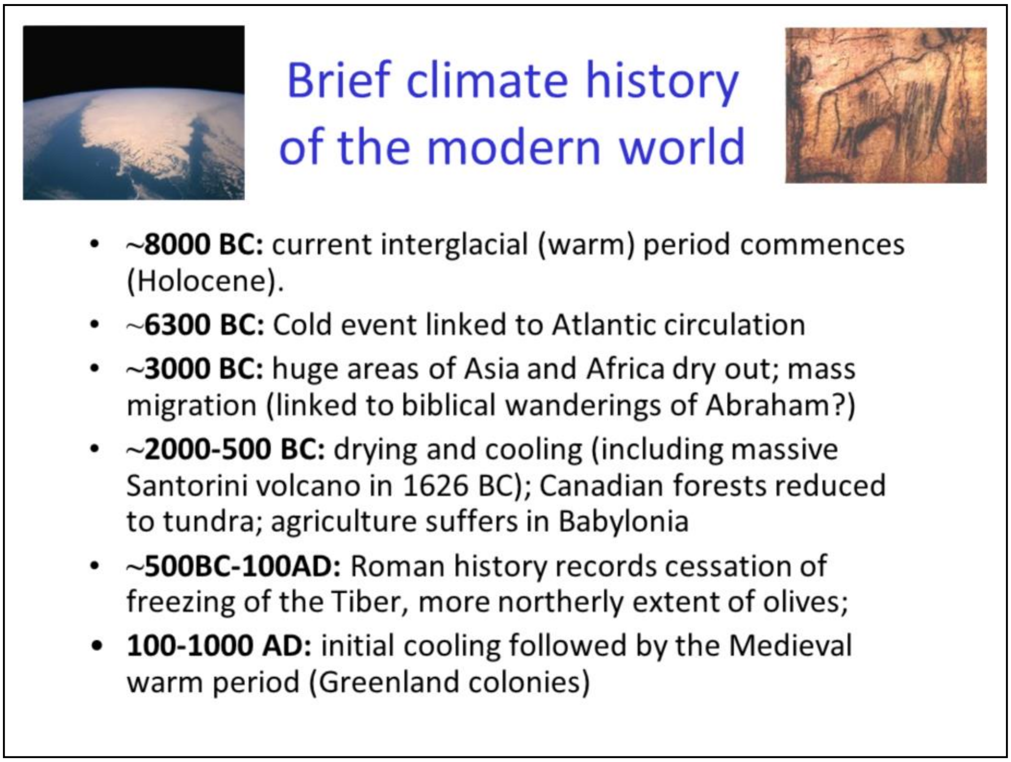
This infamous “hockey-stick” plot by Mann et al. and others indicated a long-term cooling trend from the so-called "Medieval Warm Period" (broadly speaking, the 10th-mid 14th centuries) through the "Little Ice Age" (broadly speaking, the mid 15th-19th centuries), followed by a rapid warming during the 20th century that culminates in anomalous late 20th century warmth. The late 20th century warmth is highly unusual compared to at least the past 1000 years. The reconstruction has uncertainties but these have been estimated (see grey shading).

There are dozens of other reconstructions and modelling studies which indicate a similar picture of climate change over the last 1300 years.

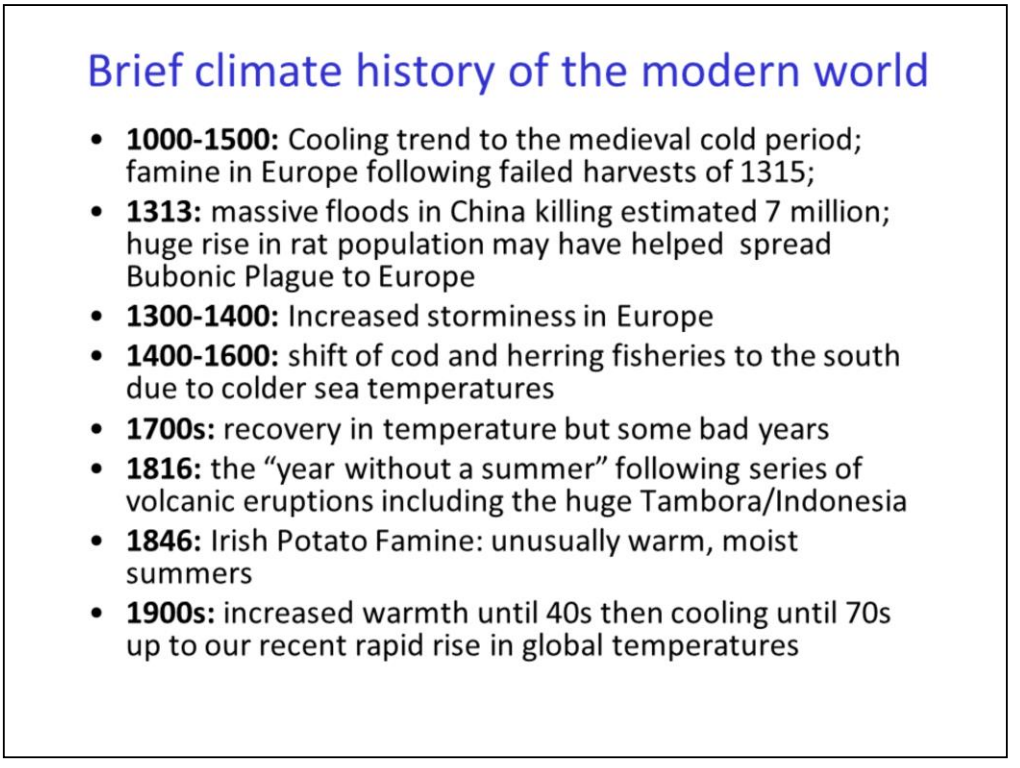
Simulations using sophisticated computer models of the Earth’s environment all show that it is not possible to explain the anomalous late 20th century warmth without including the contribution from *man-made emissions*, in particular, modern greenhouse gas concentration increases.



The current warming is highly unusual in the context of the last 1800 year record based on data from climate proxies such as tree rings, ice cores and historical records. The IPCC report (2007) states that "**Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years" and the IPCC(2013) states that "1983-2012 was likely the warmest 30-year period of the last 1400 years".**



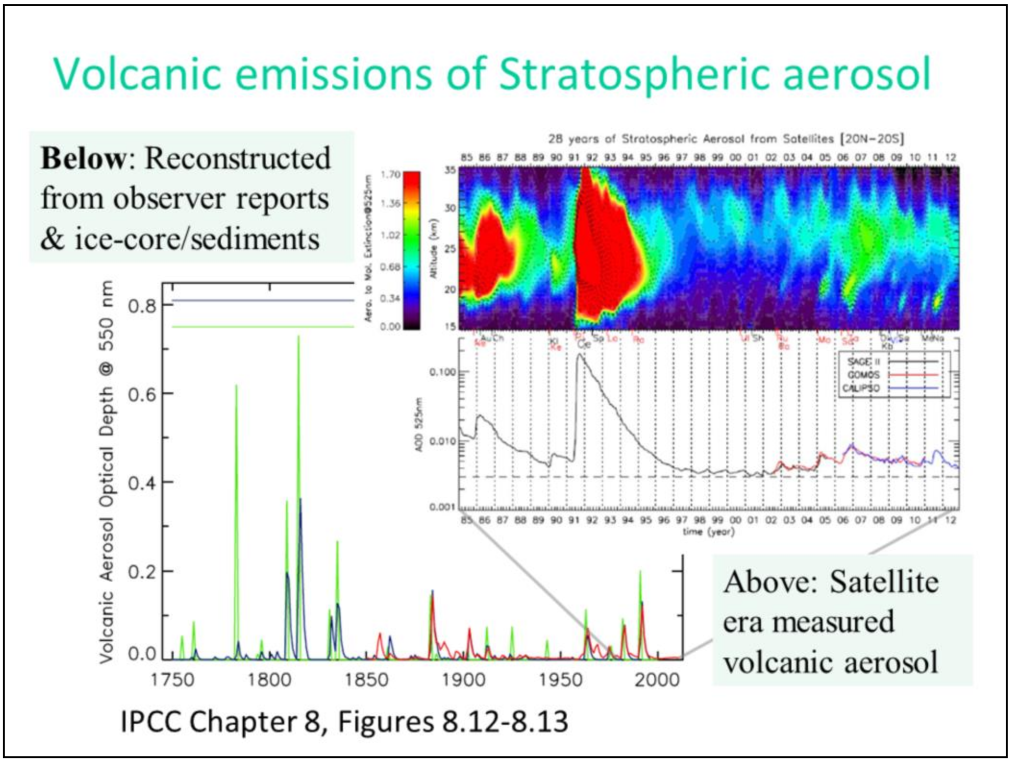
The terms “Little Ice Age” and “Medieval Warm Period” have been used to describe two past climate epochs in Europe and neighbouring regions during roughly the 17th to 19th and 11th to 14th centuries, respectively. The timing, however, of these cold and warm periods varies geographically over the globe. The “Little Ice Age” appears to have primarily influenced the North Atlantic region through altered patterns of atmospheric circulation. Unusually cold, dry winters in central Europe (e.g., 1 to 2°C below normal during the late 17th century) were very likely to have been associated with more frequent flows of continental air from the north-east, consistent with negative or enhanced easterly wind phase of the North Atlantic Oscillation. Such strong influences on European temperature demonstrate the difficulty in extrapolating the sparse early information about European climate change to the hemispheric, let alone global, scale. Similarly, although periods during the Medieval Climate Anomaly (year 950 to 1250) were in some regions as warm as in the late 20th century, these regional warm periods did not occur as coherently across regions as the warming in the late 20th century (IPCC 2013).



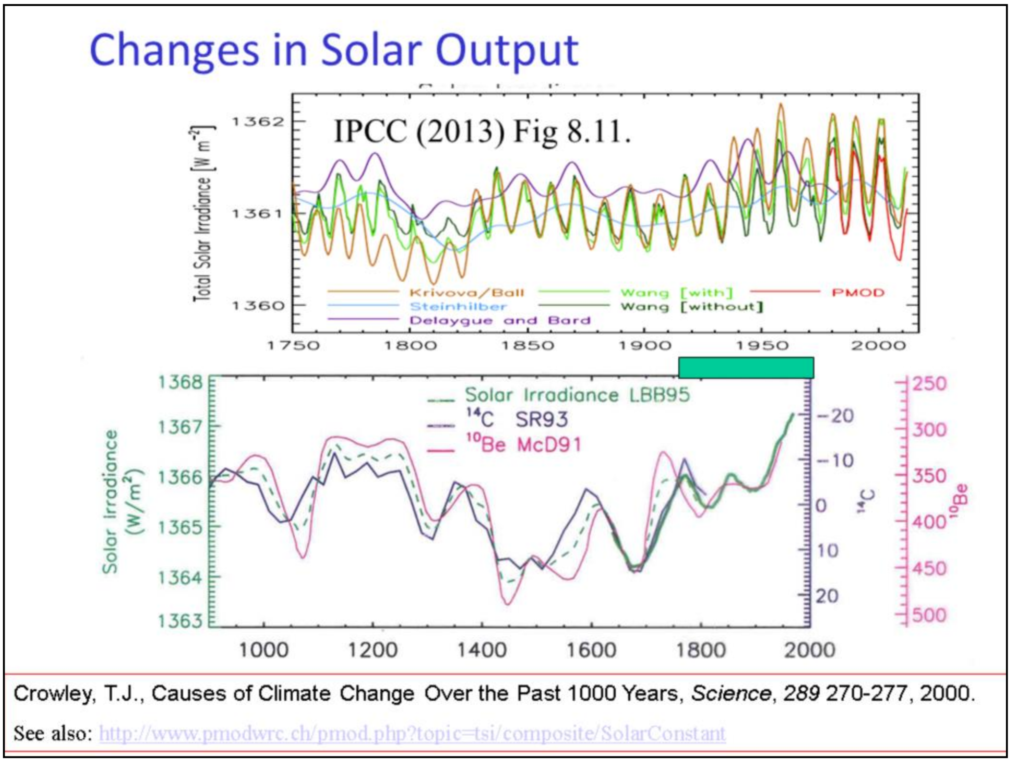
Was there a “Medieval Warm Period” and “Little Ice Age?

The Little Ice Age has now come to be used to characterize the interval from around A.D. 1300 to 1450 until A.D. 1850 to 1900 during which regional evidence in Europe and elsewhere suggest generally cold conditions. The attribution of the term at regional scales is complicated by significant regional variations in temperature changes due to the influence of modes of climate variability such as the North Atlantic Oscillation and the El Nino/Southern Oscillation. Indeed, the utility of the term in describing past climate changes at regional scales has been questioned. There is evidence to suggest that changes in the Atlantic ocean circulation, using observations of ocean sediment in the Caribbean, may have caused the reduction of north Atlantic and European temperatures as well as influencing rain patterns in the tropics. The Little Ice Age coincides with minima in sun-spot activity; the link between this and the ocean circulation is possible but requires more research. Recent research suggests that at least some of the drop in European temperature can merely be explained by “random” internal fluctuations in the ocean circulation.

Medieval Warm Period ("MWP") Period of relative warmth in some regions of the Northern Hemisphere in comparison with the subsequent several centuries (~900–1300 AD). As with the Little Ice Age, the attribution of the term at regional scales is complicated by significant regional variations in temperature changes, and the utility of the term in describing regional climate changes in past centuries has been questioned in the literature.



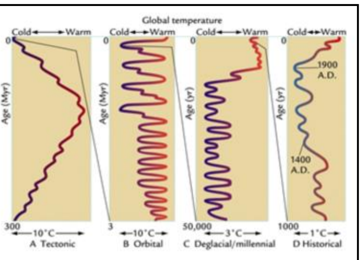
Explosive volcanic eruptions cool the planet by emitting large quantities of sulphur dioxide which converts to sulphate aerosol particles (considered pollution near to the surface) that reflect sunlight back to space. Depending upon the size of the eruptions, they can cool the planet by a few tenths of a ^{o}C over the following 2-3 years (larger eruptions have a larger and longer lasting effect). Although satellite data can now monitor the amount of volcanic aerosol, historical and proxy reconstructions are required to compile past volcanic activity over the last few centuries. Clusters of large volcanic eruptions occurred in the 1700-1800s (and 1200-1300s) which had a cooling influence on climate. Over millions of years, volcanic eruptions can have a heating effect on climate through their accumulated emissions of greenhouse gases. This is one theory for how Earth escaped “snowball” state in the past (reduced weathering of rocks in a snow-bound Earth allowed greenhouse gases to build up).



Lower graph: evidence from Carbon and Berillium isotope analysis indicates that there was slightly less solar radiation received during the little ice age period. Only a fraction of this is absorbed on one face of the Earth, so the changes in solar radiation in space of ~2 Wm^{-2} are more like 0.3 Wm^{-2}, rather small to explain a global climate change but possibly large enough to influence the global circulation.

Upper diagram: Forcing of the climate system due to solar radiation change is estimated to be 0.3 ±0.2 Wm^{-2} for the period 1750 to the present, and most of the change is estimated to have occurred during the first half of the 20th century. The solar output has weakened somewhat over the last decade.

Summary



- Climate Changes on all time scales
- Changes in continents/oceans & the evolving atmosphere alter climate change over millions of years
- Cyclical changes in the Earth's orbit around the sun are thought to explain current cycles of glaciation over tens to hundreds of thousands of years
  - Amplifying feedbacks are required to explain the magnitude of the changes in climate
- A variety of proxy measurements builds up a picture of past climatic change; all have their strengths and weaknesses