Unit 1.3: Coupled Processes and Paleoclimate

Coupled processes

- In addition to the seasonal cycle of weather variability we have already discussed, there are a number of modes of natural variability from coupled atmosphere-ocean processes that operate on multi-year to multi-decadal time scales
- There are coupled atmosphere-ocean processes in each ocean basin on a range of scales with differing regional and global implications

El Nino/La Nina

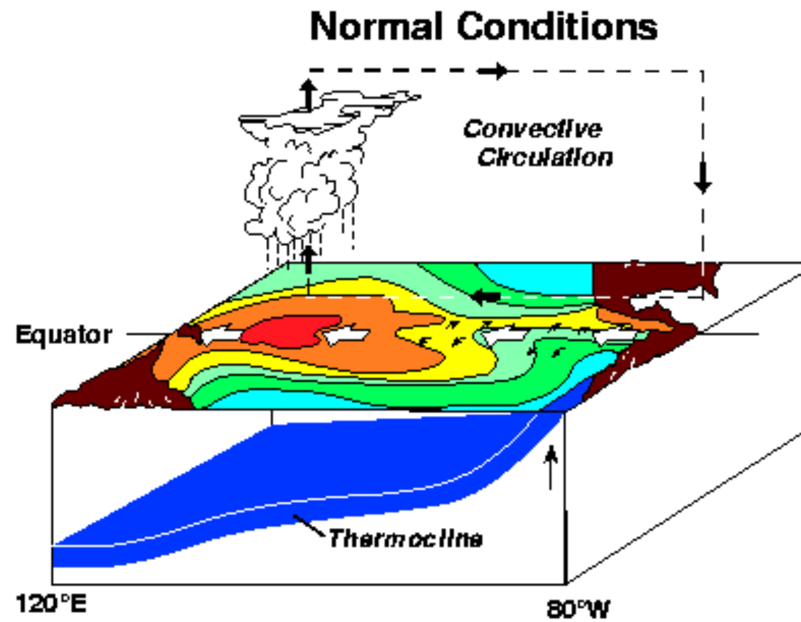
- The El Nino/La Nina phenomenon is an interannual cycle of surface winds, currents, sea surface temperatures and pressure over the tropical Pacific Ocean that has significant global impacts for temperature and precipitation around the world, especially in the tropics (but with some impacts in the mid-latitudes as well)
- Much of the interannual climate variability in the tropics is associated with the El Nino/La Nina phenomena and El Nino/La Nina phase is generally predictable on the time scale of 6-12 month lead times (although prediction through the “spring barrier” is a challenge
- The effects of El Nino and La Nina are particularly pronounced along the Pacific coast of South America and strong El Nino events often develop around Christmas time – in Spanish el nino means “the boy”, but is often used to refer to Jesus Christ

Southern Oscillation and ENSO history

- In the early 1900s, mathematician Gilbert Walker in colonial India observed that famine and drought in India were related to the sea level pressure differences between the Pacific Island of Tahiti and Darwin, Australia
- This oscillation in pressure difference is known as the Southern Oscillation and the index value is the SOI
- Around the 1960s, meteorologist Jacob Bjerknes connected the Southern Oscillation pressure differences to anomalies in the sea surface temperature pattern in the equatorial Pacific (El Nino) and was able to explain the persistence of El Nino or La Nina phases
- In the 1970s, oceanographer Klaus Wyrtki established subsurface ocean observations that shed light on how the depth of the thermocline changed with ENSO phase
- In the 1980s, oceanographer Mark Cane and meteorologist Stephen Zebiak developed the delayed-recharge oscillator model of ENSO dynamics and made the first successful prediction of an El Nino event

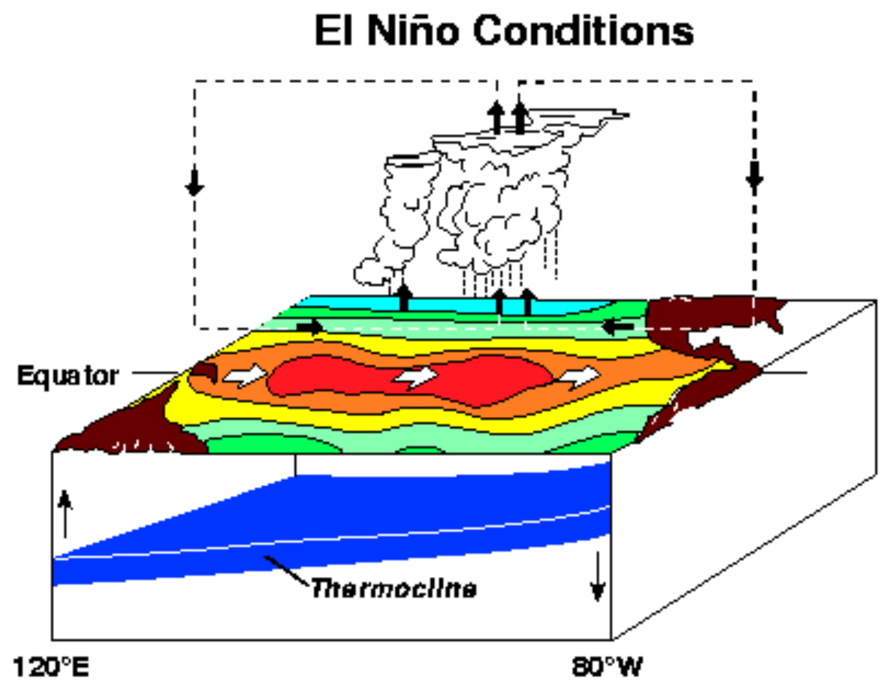
El Nino/La Nina mechanics

- Normal/Neutral conditions
  - The eastern tropical Pacific has upwelling because of Ekman transport, so the thermocline is shallow, surface waters are cool and atmospheric pressure is relatively high
  - The western tropical Pacific has warmer surface waters and a deeper thermocline and atmospheric pressure is relatively low
  - The low pressure in the western part of the basin induces convection and enhanced precipitation, while the high pressure in the eastern part of the basin suppresses precipitation
  - Surface winds blow from east to west



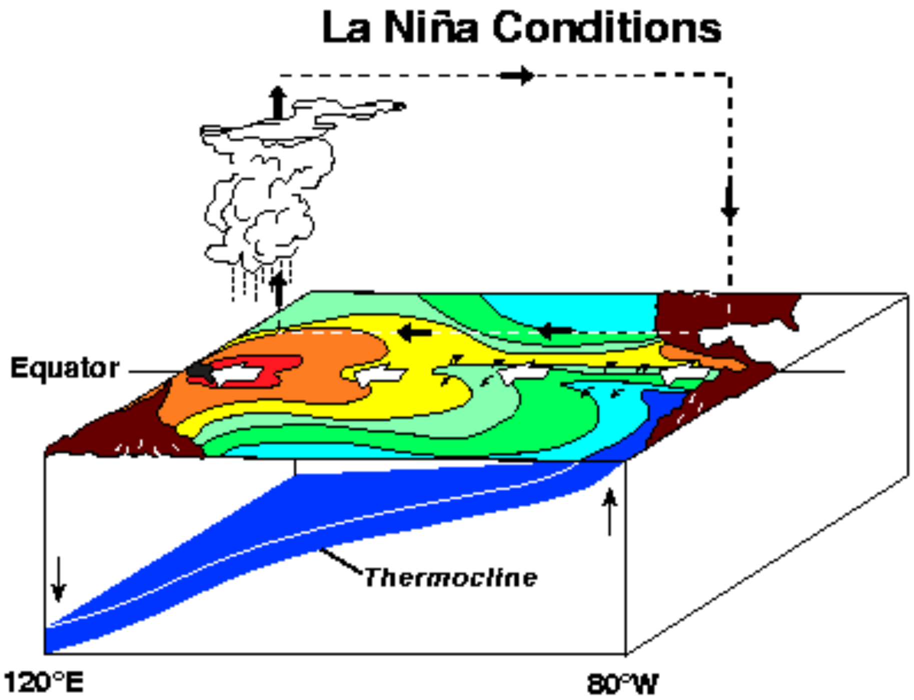
Positive/El Nino phase

- Prevailing easterly winds weaken, enabling an eastward migration of warm water to the central and eastern Pacific (there is some shoaling of the west Pacific thermocline)
- Upwelling the eastern Pacific is suppressed, the thermocline deepens and the SSTs increase
- The low pressure migrates to the east shifting the position of convective precipitation eastward
- El Ninos tend to happen roughly every 2-7 years and last for about 1-2 years



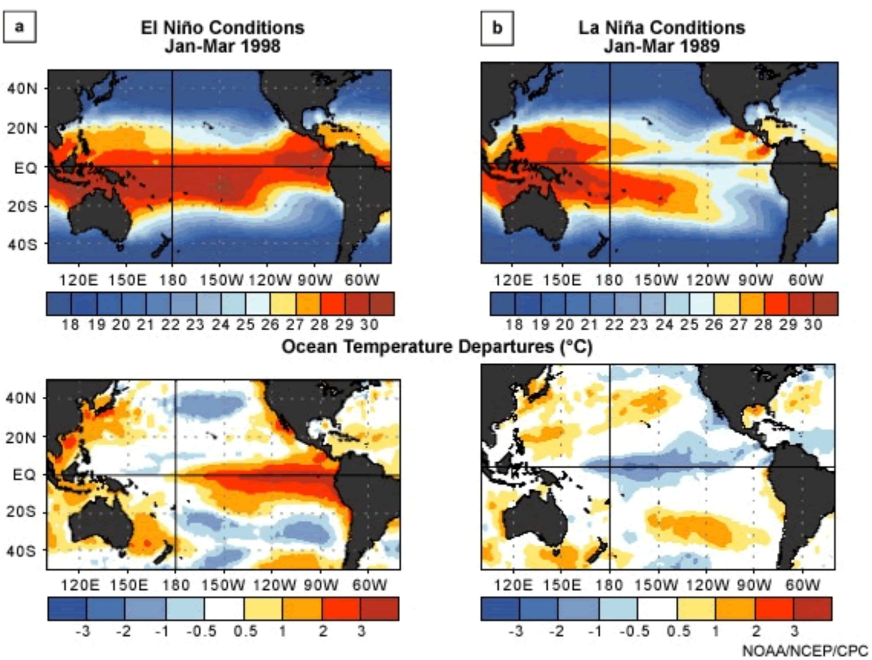
Negative/La Nina phase

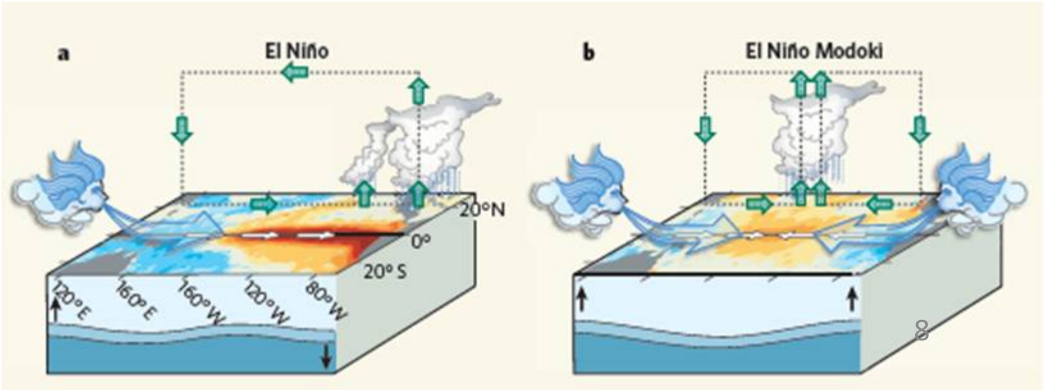
- Prevailing easterly trade winds are stronger than usual, forcing a further westward migration of warm waters in the western Pacific
- Upwelling in the eastern Pacific is enhanced, causing the SSTs to cool and the thermocline to become shallow (there is some deepening of the west Pacific thermocline)
- The cross-basin pressure gradient intensifies, convective precipitation over the western part of the Pacific basin
- La Ninas tend to last longer than El Ninos and be between El Nino events
- http://esminfo.prenhall.com/science/geoanimations/animations/26_NinoNina.html



El Nino Modoki and subtleties

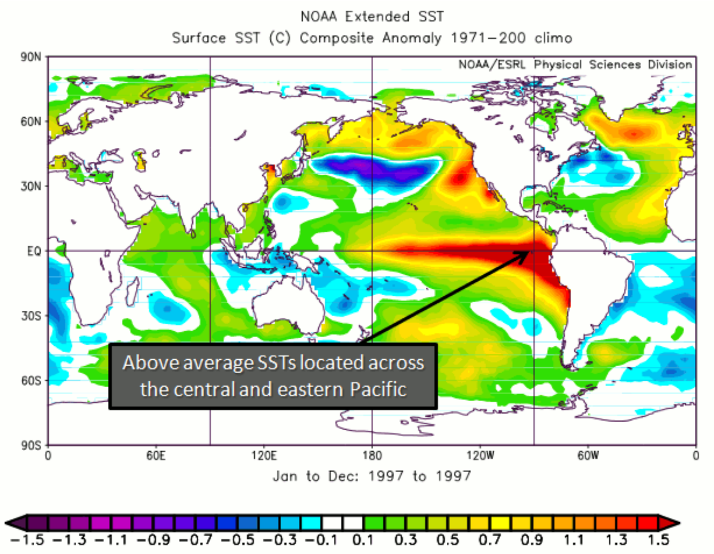
- Not all El Ninos (or La Ninas) are the same
- Some initiate from pressure or wind anomalies and others from oceanographic anomalies
- Regional effects can also be differentiated
- Recently, the term El Nino Modoki has been applied to El Nino events where the warming is greatest in the central, rather than Eastern Pacific

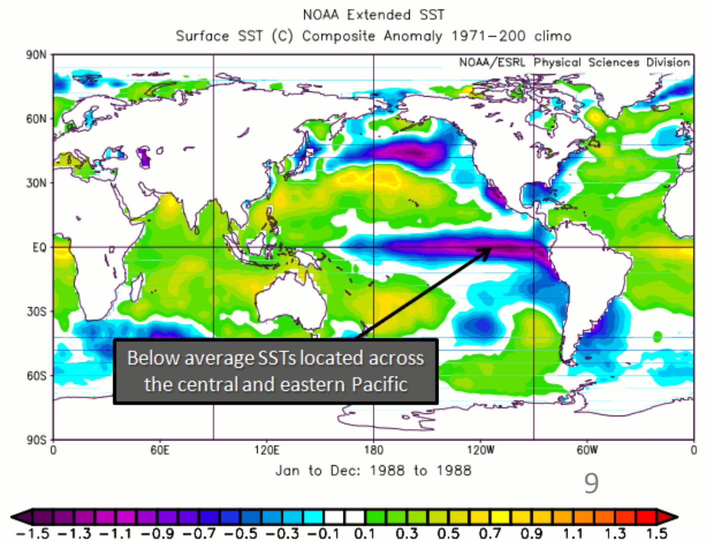




El Nino/La Nina teleconnections

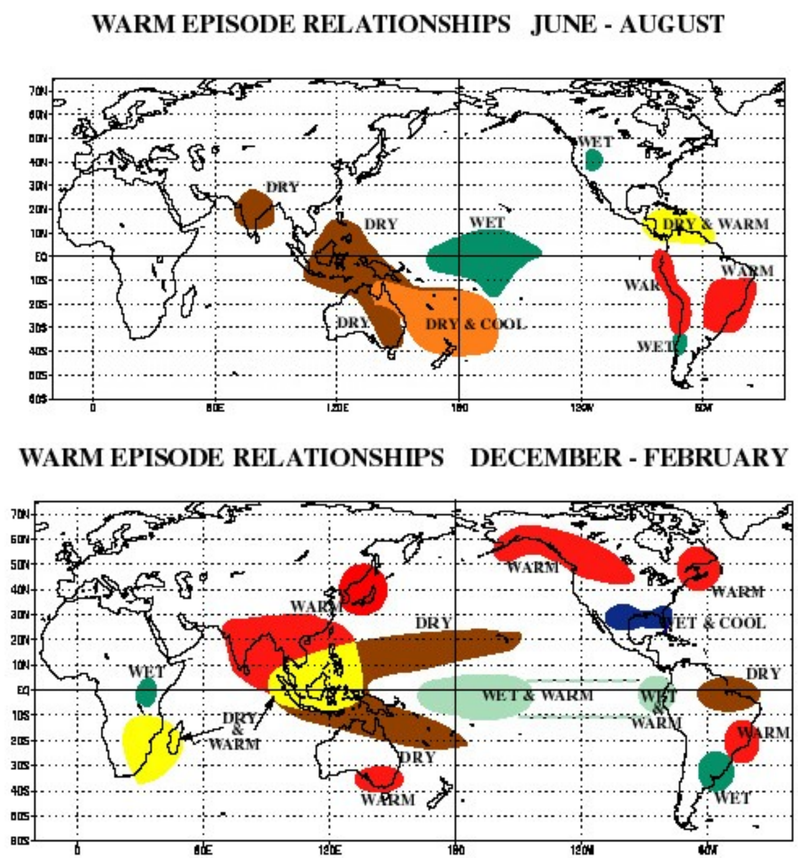
- Because the tropical Pacific is so vast and ENSO changes are so significant, changes to the tropical Pacific can have an impact on the Atlantic and Indian Ocean basins as well
- Under persistent El Nino conditions, the Caribbean Sea, Gulf of Mexico and northern tropical Atlantic often get warmer than normal (while the opposite is true during La Nina)
- Under persistent El Nino conditions, in the Indian Ocean the monsoon and equatorial countercurrents tend to weaken and a warm SST anomaly tends to form near the coast of East Africa (while the opposite is true during La Nina) and a cool SST anomaly tends to form off the coast of SE Africa





El Nino impacts

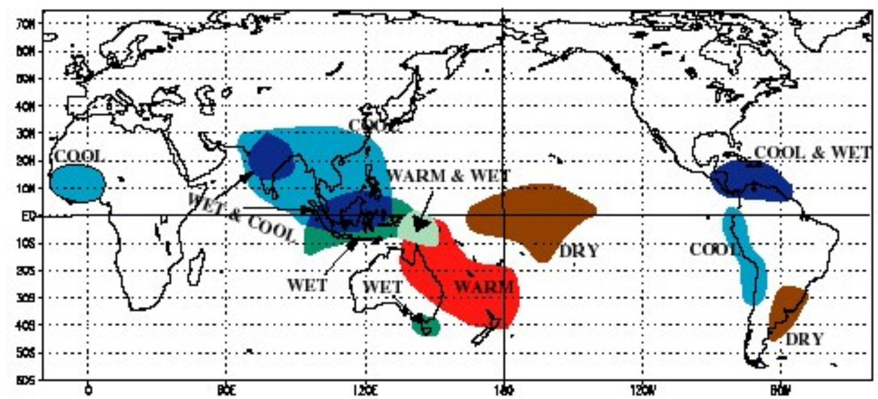
- Effects largely in the tropics but also teleconnections to middle and high latitudes
- Effects depend on season
- Wetter than normal in the central and Eastern tropical Pacific/South America, SE South America, SE and or NW US and East Africa
- Drier than normal in Indonesia and Australia, India, NE South America and Southern Africa
- In the tropics, wet areas tend to be close to warm SST anomalies and dry areas tend to be close to cool SST anomalies



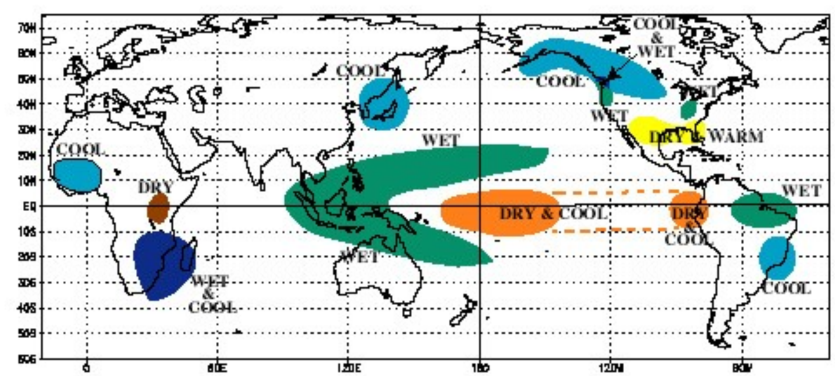
La Nina impacts

- To a large degree, La Nina impacts are the opposite of El Nino impacts (although this is not universally true)
- Wetter than normal in Indonesia, Australia, India, Southern Africa and NE South America/Caribbean
- Drier than normal in central and Eastern Pacific, East Africa, SE USA, SE South America

COLD EPISODE RELATIONSHIPS JUNE - AUGUST

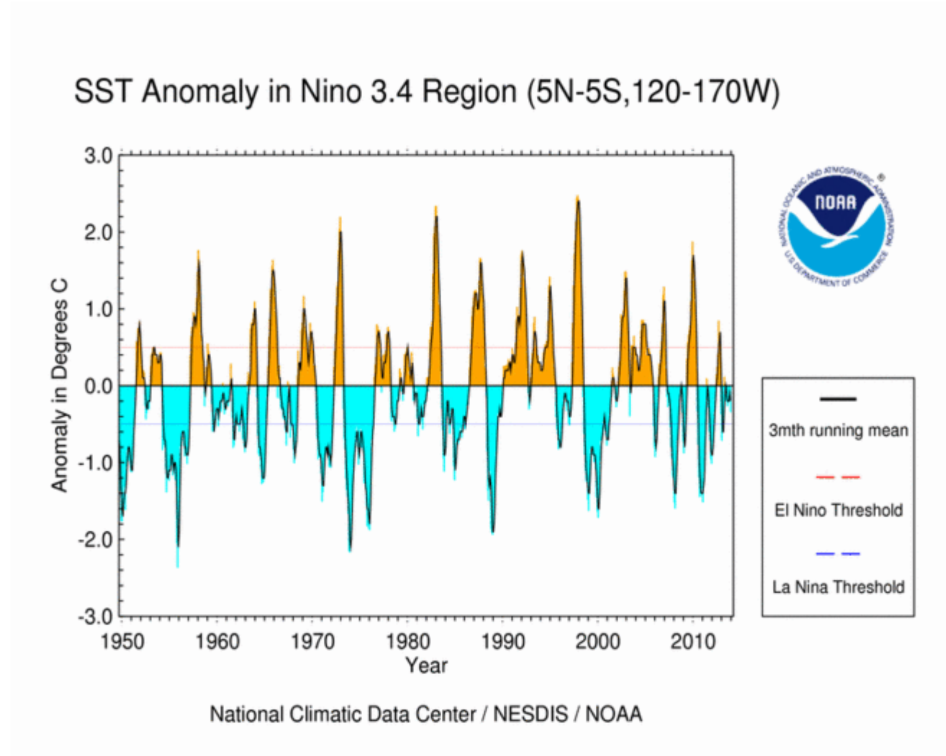


COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY

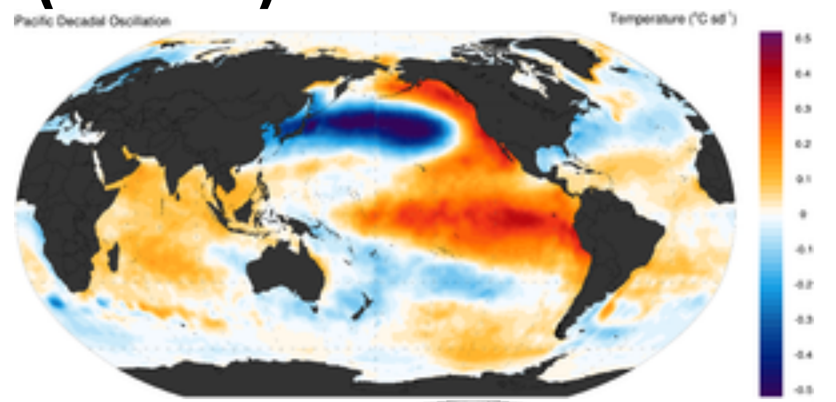


More on ENSO impacts and measurement

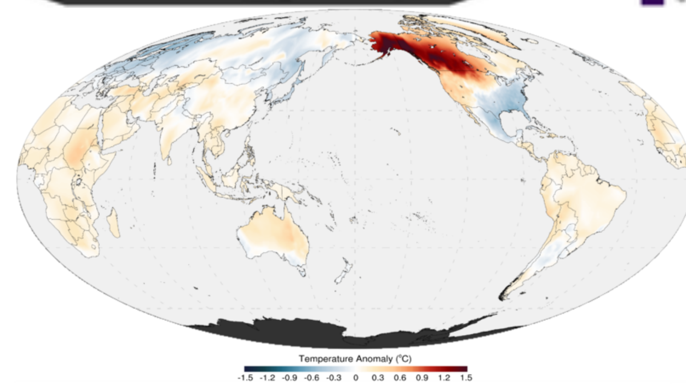
- El Nino state is generally measured by the SST anomaly in designated regions in the eastern to central tropical Pacific
- recent El Nino events: (strong) 1982/83, 1997/98, (moderate) 2002, 2009
- recent La Nina events: (strong) 1999, 2010, (moderate) 2007
- Some very severe droughts and flooding events have been associated with ENSO events in the last 30 years
- El Nino events tend to suppress tropical cyclones in the North Atlantic (increased wind shear), and in the western Pacific (lower SSTs), but tend to increase frequency of tropical cyclones in the eastern tropical Pacific
- La Nina tends to have the opposite effect on tropical cyclone formation
- http://www.pmel.noaa.gov/tao/vis/explorer/t-dyn-med.html

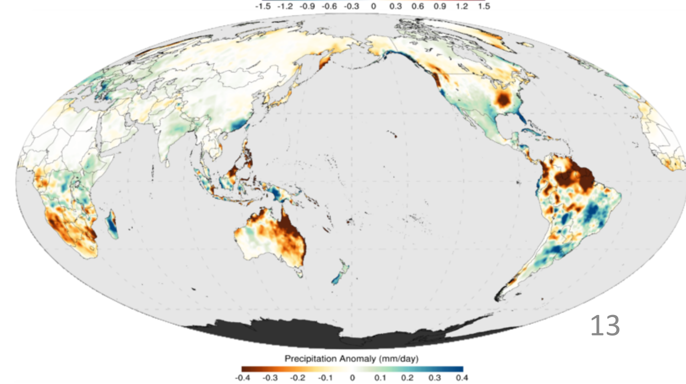


Pacific Decadal Oscillation (PDO)



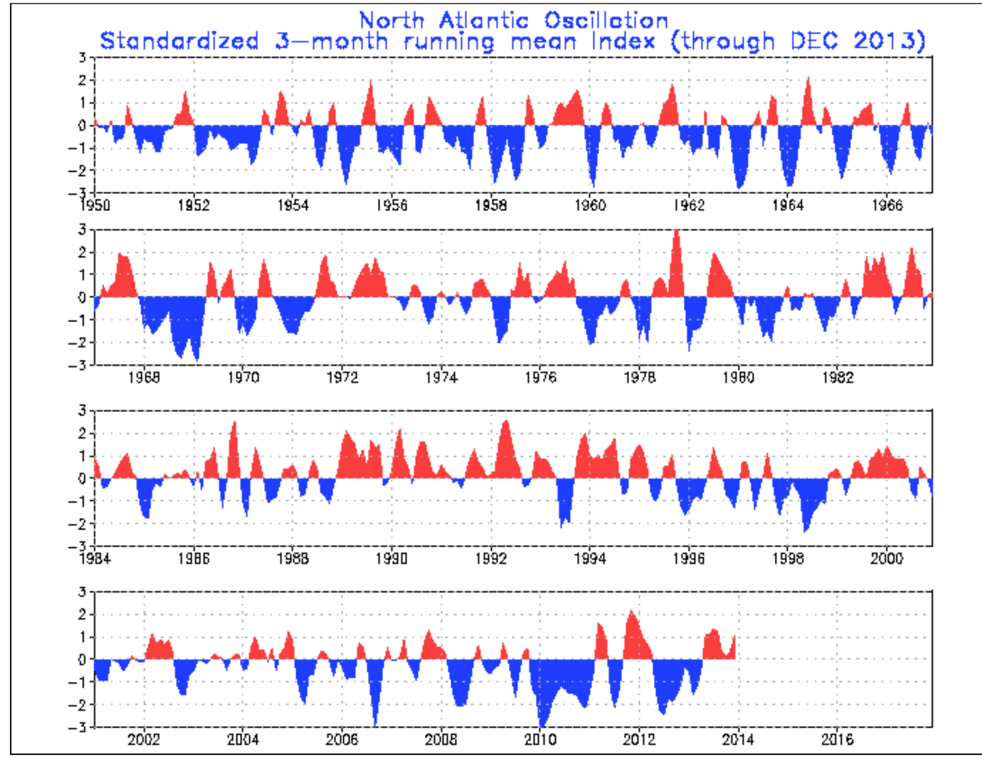
- Multidecadal oscillation in the Pacific
- In the tropics, positive phase has a similar signature to ENSO, but there are more pronounced SST anomalies and climate impacts on the extratropics
- Positive phase has warmth in NW North America, cool in NE Asia and SE US
- Precipitation anomalies right along the NW coast of the US are wet (positive phase) and other precipitation anomalies in the tropics are similar to ENSO





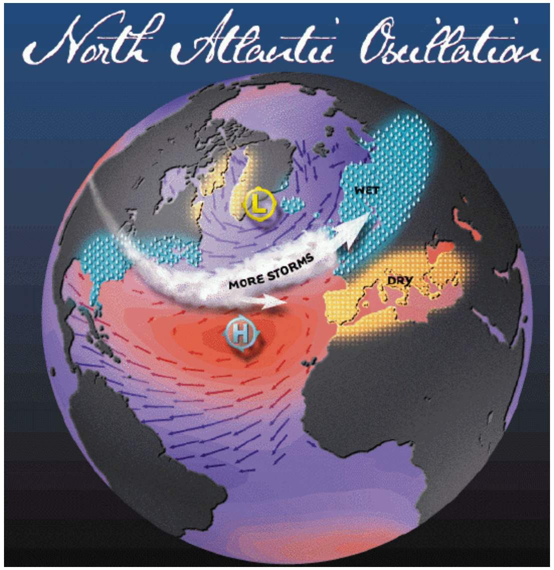
North Atlantic Oscillation (NAO)

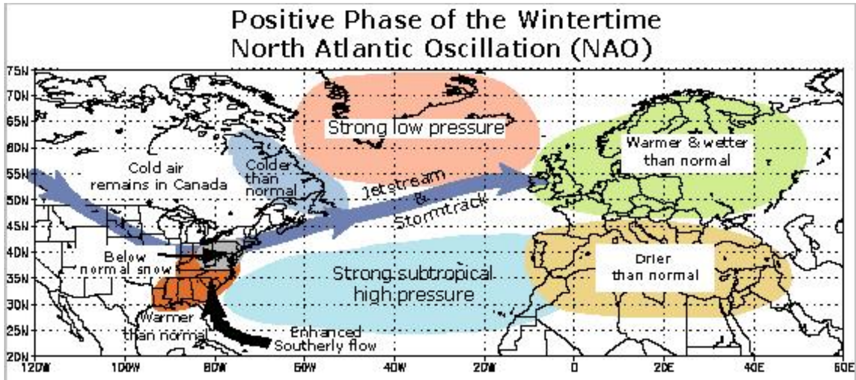
- Under neutral conditions, sea level pressure around the Azores is high and around Iceland is low
- This, along with the prevailing winds, serves to steer midlatitude systems from west to east
- However, this pressure gradient varies from year to year and plays an important role in the climate of eastern North America, Europe and Northern Africa, especially during the winter
- NAO has an annual to interannual period



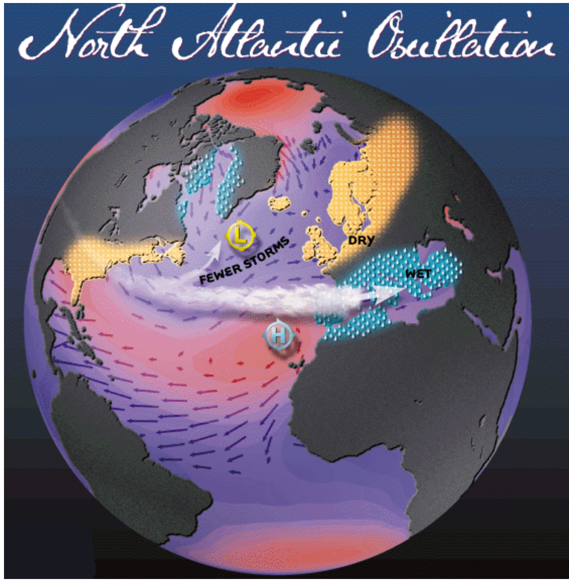
NAO Positive phase

- In the positive phase of the NAO, the pressure gradient is intensified (deeper low around Iceland and stronger high around the Azores)
- This effectively steers weather systems in a more meridional direction (from south to north)
- The east coast of the US tends to be warm and northern Europe tends to be warm and wet
- The Mediterranean tends to be drier than normal and Labrador and Greenland tend to be colder and drier than normal



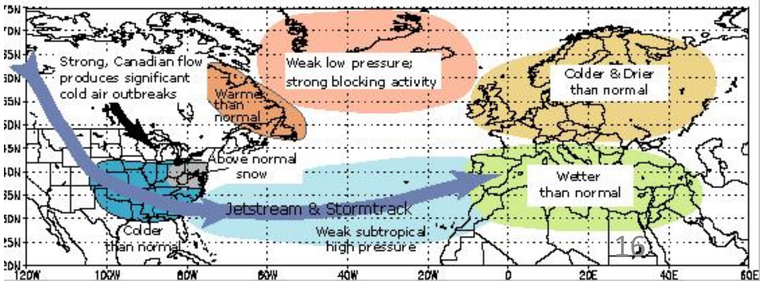


NAO negative phase



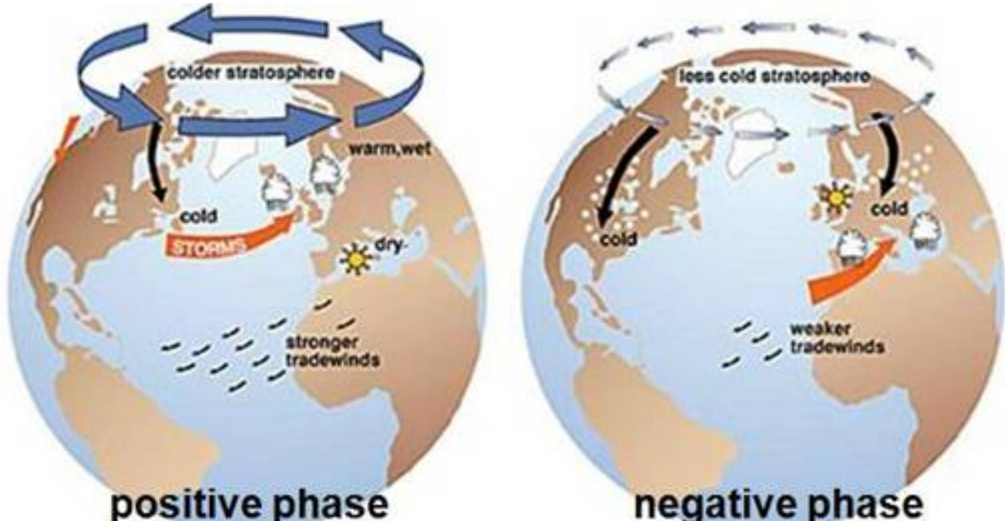
- In the negative phase of the NAO, the pressure gradient is weakened (weaker low around Iceland and weaker high around the Azores)
- This effectively steers weather systems in a more zonal direction (from west to east)
- The east coast of the US tends to be cold and snowy and northern Europe tends to be cold and dry
- The Mediterranean tends to be wetter than normal and Labrador and Greenland tend to be warmer and wetter than normal
- The cold, snowy winters of 2010 and 2011 for NJ were negative NAO winters
- The NAO phase has a particularly large impact on the Mediterranean because so much of the annual precipitation comes during the winter

Negative Phase of the Wintertime North Atlantic Oscillation (NAO)



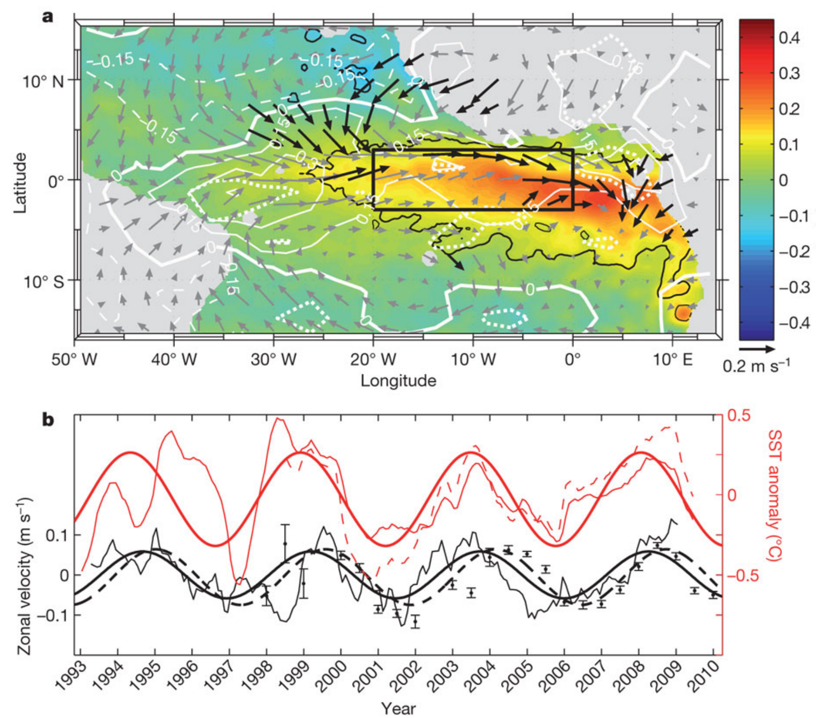
Arctic Oscillation

- No particular time scale
- In the Arctic, the strength and position of the polar vortex (westerly winds aloft) varies
- In the positive phase, the vortex is very strong but relatively stationary over the pole and polar air outbreaks to lower latitudes are rare
- In the negative phase the polar vortex weakens and polar air outbreaks to lower latitudes are more common (like we've had this past month)
- Also an Antarctic Oscillation with similar characteristics



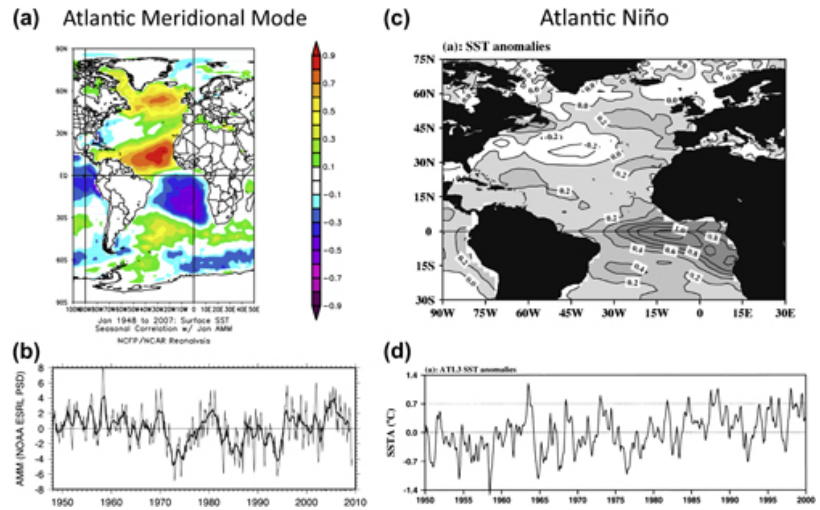
Atlantic ENSO

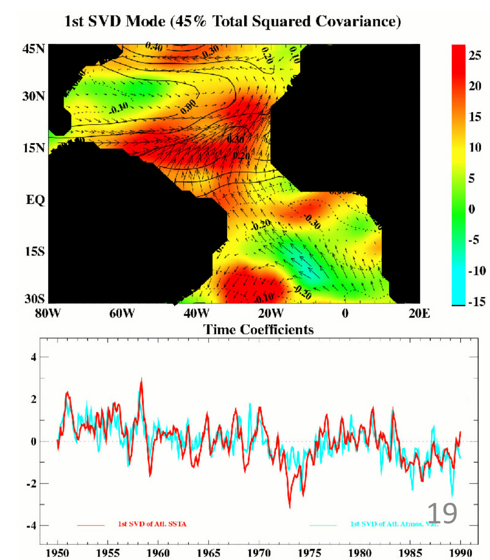
- Like its Pacific counterpart, there is an “El Nino like” phenomenon in the tropical Atlantic on interannual time scales, also known as the Atlantic equatorial mode
- when trade winds relax, equatorial upwelling can be suppressed, causing the tropical Atlantic to warm – this phase tends to suppress west African and NE Brazil precipitation
- when trade winds intensify, equatorial upwelling is more intense and SSTs drop, this tends to increase west African and NE Brazil precipitation



Atlantic dipole

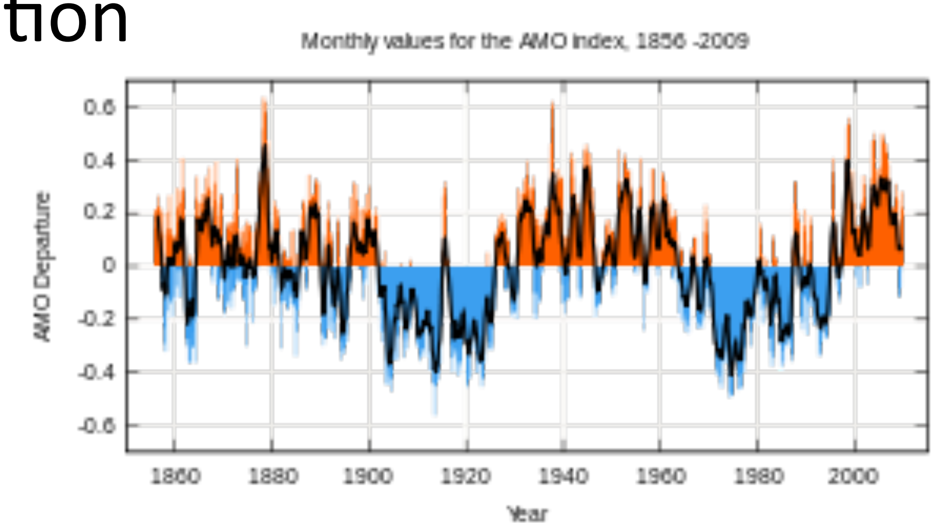
- Sometimes called the Atlantic Meridional Mode, this is a longer time scale process (decadal time scale) involving the shifting the peak SST to the north and south
- This causes a latitude displacement of the ITCZ and response in the precipitation anomalies
- Positive phase (northward shift of warm SSTs and convective precipitation)
- Negative phase (southward shift of warm SSTs and convective precipitation)





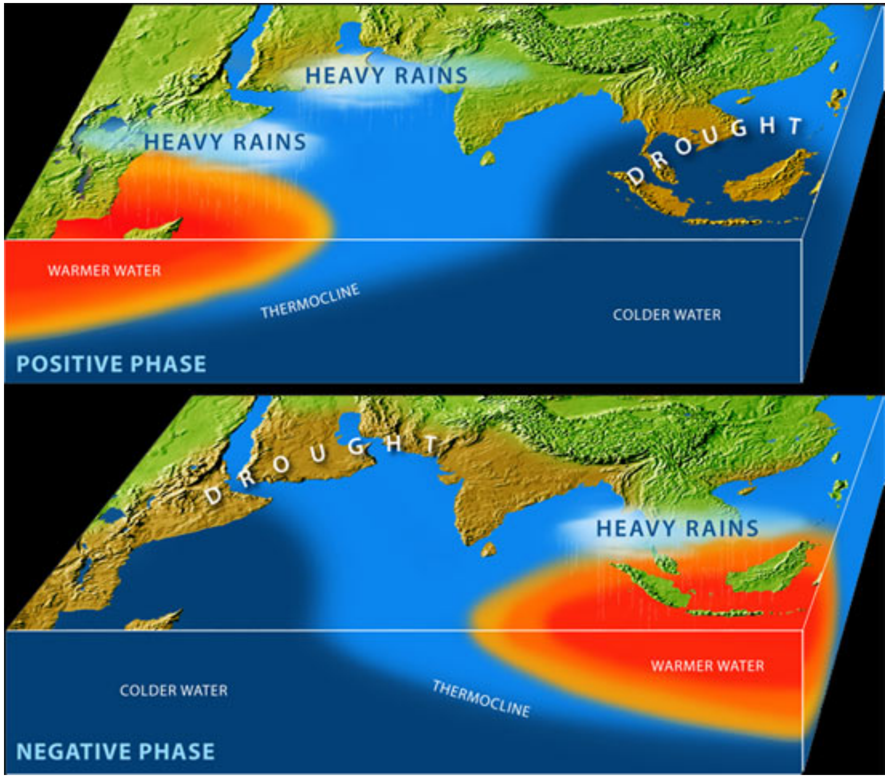
Atlantic Multidecadal Oscillation (AMO)

- The AMO is a longer period oscillation that is generally measured by the SST anomaly in the NH extratropical Atlantic
- There tends to be a positive correlation between AMO index and north Atlantic tropical cyclone frequency and between AMO and West African precipitation



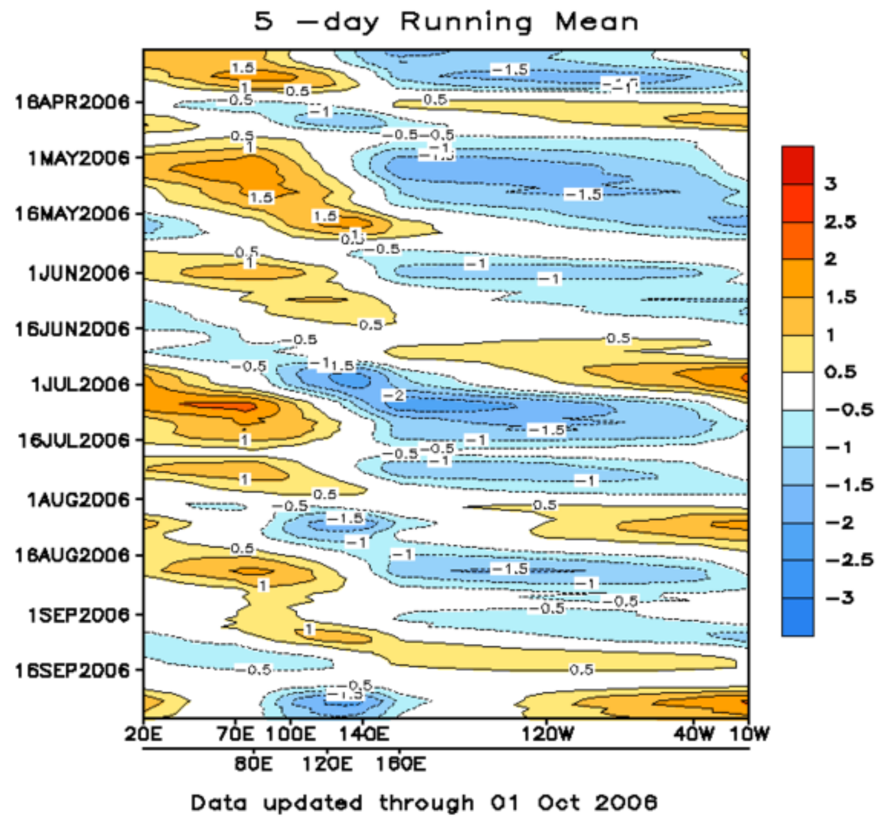
Indian Ocean Dipole (IOD)

- Interannual mode of coupled variability in the tropical Indian Ocean – related to ENSO
- Positive phase associated with warmer SSTs, deeper thermocline and more precipitation in western part of Indian Ocean (flooding in East Africa, suppressed precip in Australia, Indonesia and India)
- Negative phase associated with warmer SSTs, deeper thermocline and more precipitation in eastern part of Indian Ocean (flooding in Indonesia and Australia, East African drought)
- Attributed to some of the severe weather in Australia



Madden Julian Oscillation (MJO)

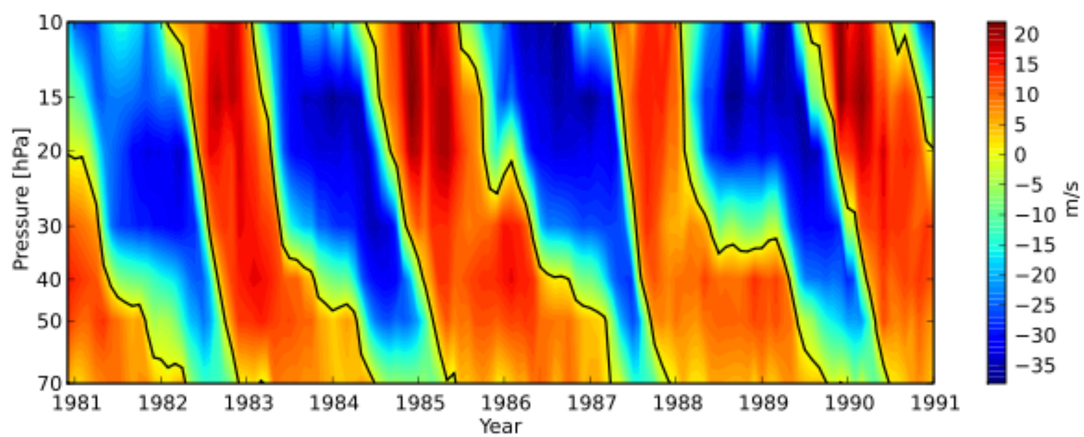
- A 30-90 day oscillation of pressure and convective rainfall that propagates eastward across the tropics, especially across the Indian and Pacific Oceans
- Can affect the timing of the monsoons, the formation of tropical cyclones, etc.



Outgoing longwave radiation as a function of longitude and time

Quasi-Biennial Oscillation

- A quasi periodic two year oscillation of the equatorial stratospheric zonal winds – the wind anomalies propagate towards the surface from the tropopause and have a subtle effect on the jet stream, monsoons and midlatitude climates



Paleoclimatology

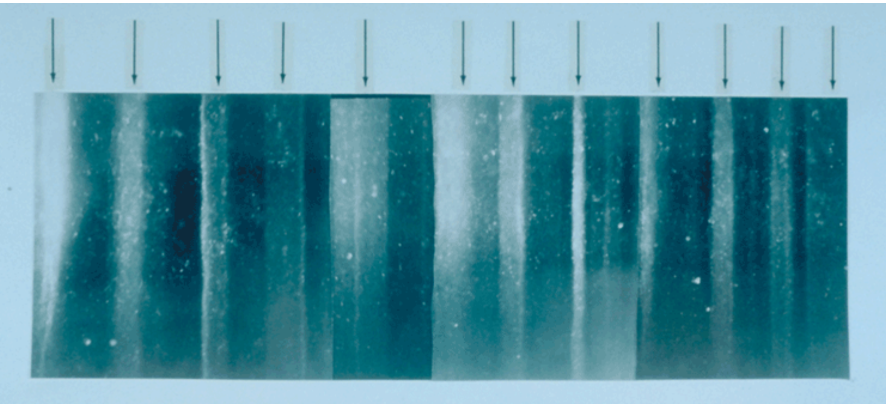
- The study of Earth's past climates (before modern instrumental records)
- Paleoclimatology relies on a wide range of proxy records and inferential methods to draw conclusions about the prior state of the climate
- The paleoclimate record is also cross-checked with fossil and geological evidence

Paleoclimate methods: oxygen and hydrogen isotopes

- There are two naturally occurring stable isotopes of oxygen: ^{16}O and ^{18}O and hydrogen comes in its conventional form and as deuterium ^{2}H
- ^{16}O and ^{1}H are the more naturally abundant isotopes, but the small concentrations of ^{18}O and deuterium can be used to understand how the climate changes over time
- Since ^{18}O and ^{2}H are heavier, more thermal energy is required to evaporate ^{18}O and deuterium enriched water into the atmosphere – this energy is more readily available at warm temperatures
- Since ^{18}O and deuterium are heavier, water vapor rich in ^{18}O and deuterium tend to fall as precipitation before water vapor rich in ^{16}O "normal" hydrogen
- This process is known as fractionation
- During glacial times, the oceans are relatively rich in ^{18}O and deuterium, while the precipitation is relatively depleted in ^{18}O and deuterium
- The opposite is true during interglacial times
- This can be seen in the glacial and sediment core records

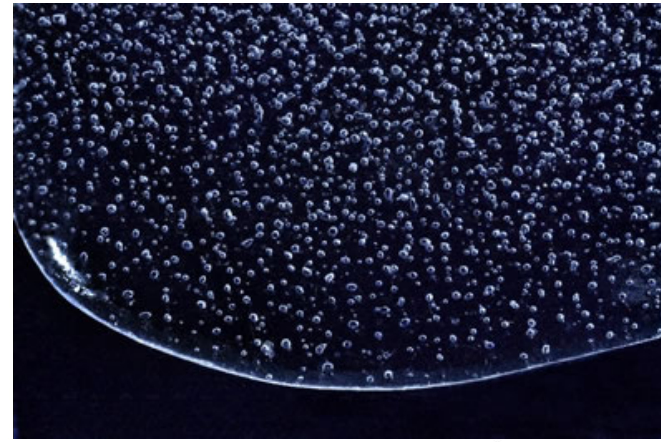
Ice Cores

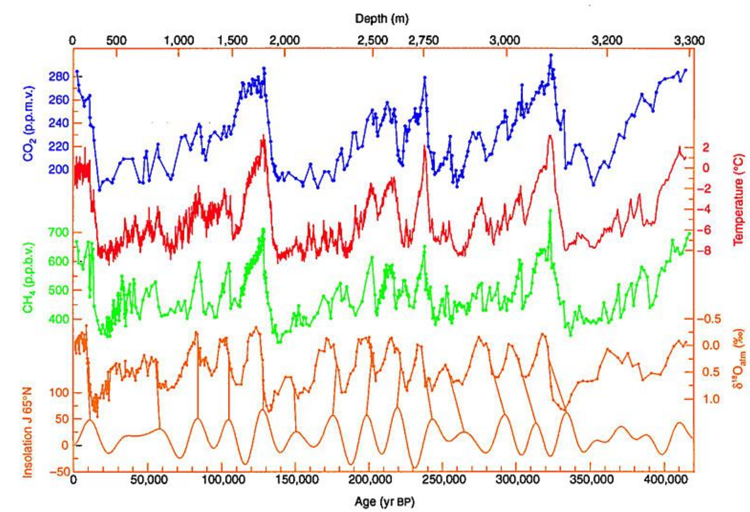
- Ice cores drilled from glaciers contain trapped gases and particulates from the Earth's past that can help to understand paleoclimates
- Each year's ice appears distinct near the top of the ice core because of partial melting and the accumulation of debris during the summer
- As one descends down an ice core, the layers squeeze together and identifying annual layers becomes more challenging, but significant events with large signatures can still serve as benchmarks



Ice Cores

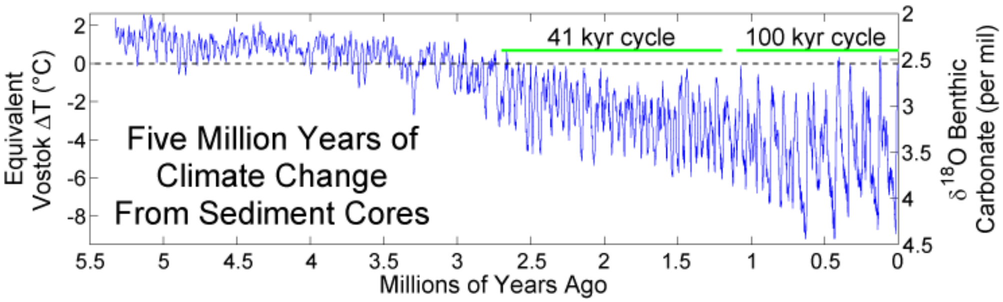
- The ice must be melted under carefully controlled laboratory settings
- Particulate concentration and the concentration of various gases in the trapped air bubbles are measured
- Between the visual layering and the chemical and/or particulate signature, an age/depth relationship can be extrapolated – the thickness of the annual layers gives a sense of precipitation rate
- Then the understanding of fractionation can be applied and extrapolated temperature can be plotted alongside the chemical and particulate concentration as a function of age
- The majority of ice core research is done in Greenland and Antarctica (where the ice is often several km thick) and the oldest ice cores in Antarctica have records that go back 800,000 years
- However, some researchers do low and midlatitude sampling from high mountain peaks





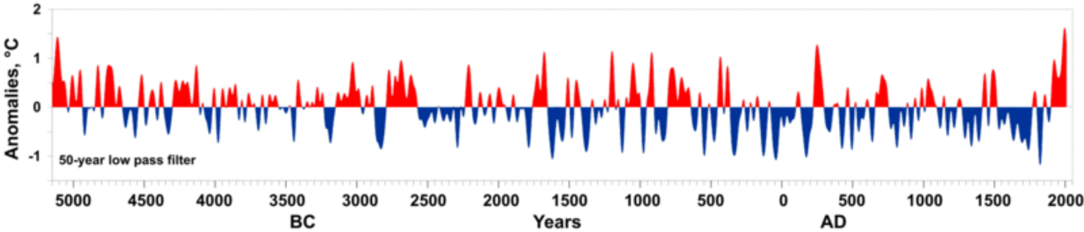
Paleoclimate methods: sediment cores

- As with glaciers, lakes and marine environments accumulate sediments every year
- Peat bogs also accumulate sediment over time
- Measuring the physical and chemical properties of sediment cores (including ^{18}O), examining any trapped fossils and studying embedded isotopes can give insight into the past climate
- Thick sedimentary deposits in lakebeds can be an indication of severe storms and intense runoff
- Marine and lake sediments are taken from most regions of the globe
- The oldest sediment cores go back to 5 million years ago



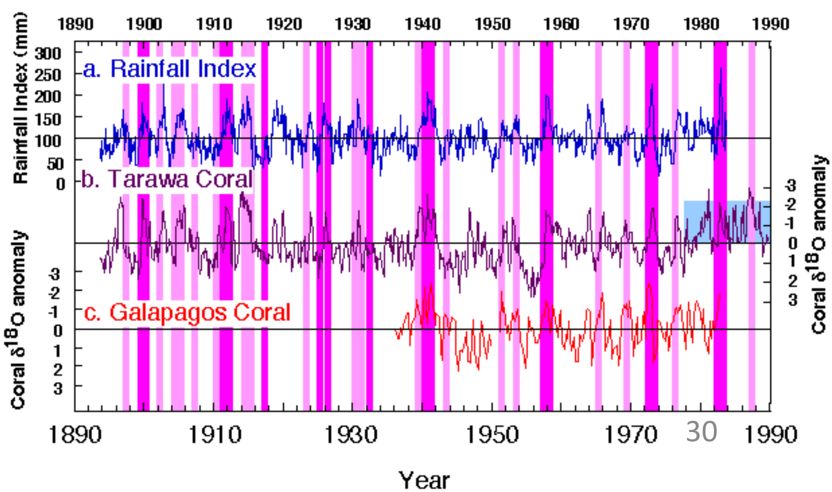
Tree rings (dendrochonology) and pollen

- Each year a tree grows by another layer
- Ring thickness correlates with temperature and precipitation (generally warmer and wetter conditions are favorable for thick rings)
- Dendrochronological records can be cross matched between living and dead trees and extended back over 20,000 years
- Pollen concentration in sediments can also be used as a paleoclimate proxy



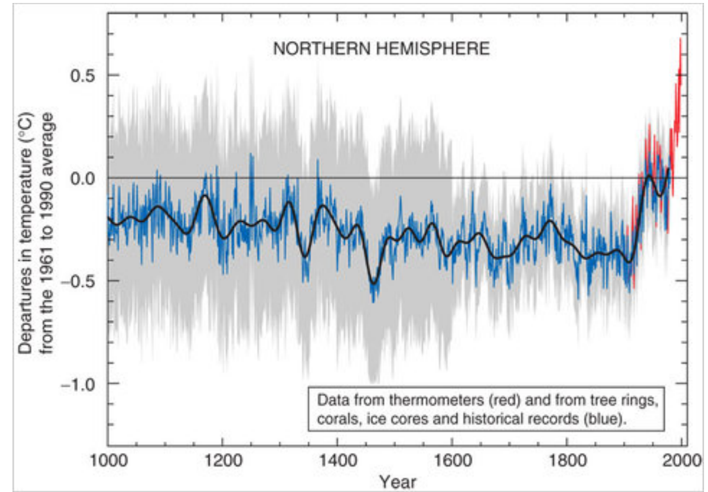
Coral data

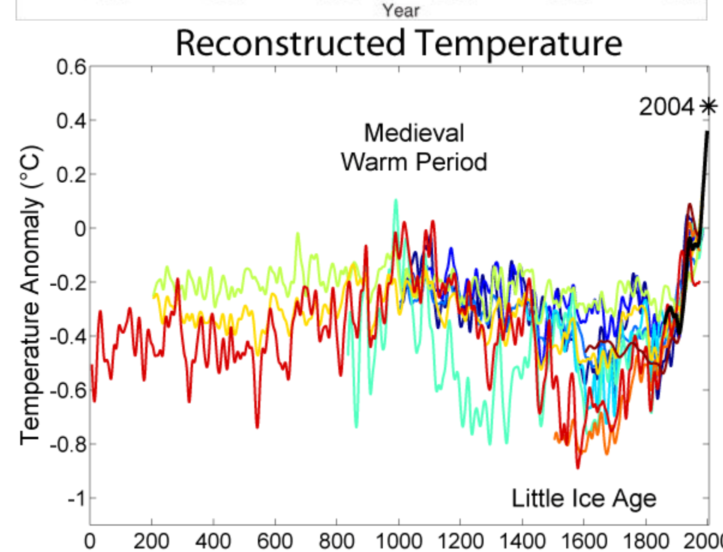
- Corals grow in annual bands, the thickness of which is a proxy for temperature, nutrient availability and water clarity
- further oxygen isotopes can be extracted from a coral sample to get a sense of past climates
- Some fossil coral records date back to over 100,000 years before present
- http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets



The common era

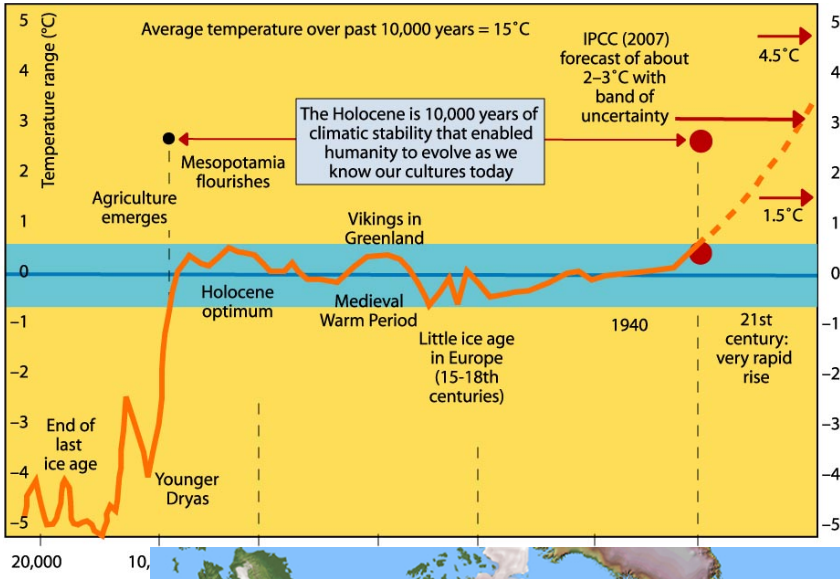
- Mann, Bradley and Jones "the hockey stick" centerpiece of the IPCC TAR
- The error bars before the instrumental record reflects uncertainty inherent in paleoclimatic proxy records
- Subject of considerable controversy, but basic finding upheld and amplified by subsequent IPCC reports
- Medieval warm period, Little Ice Age, post-Industrial Revolution warming





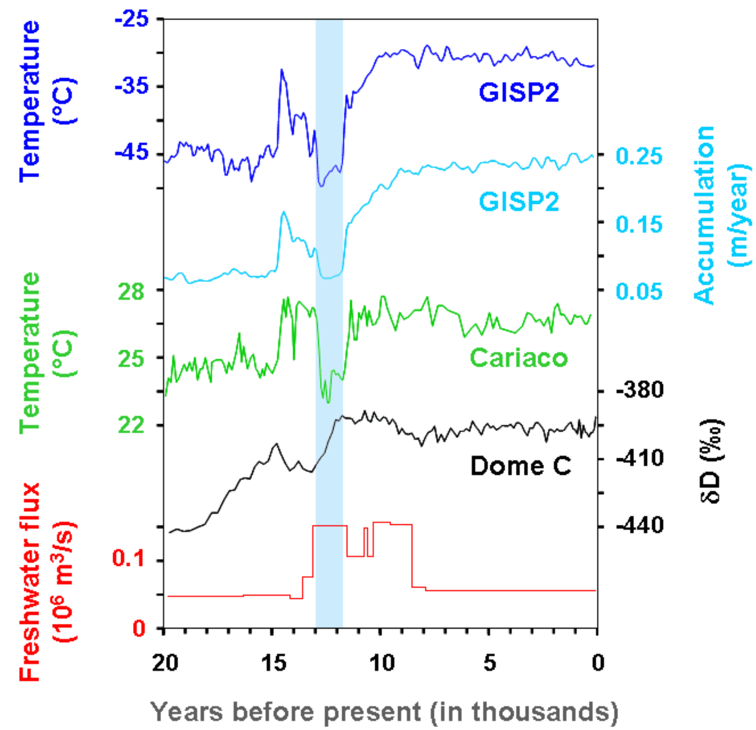
From 20kya to the present

- Last glacial maximum around 20-18kya (global mean temperature about 5 C colder than today)
- Glaciers covered North America down to New Jersey
- Warm up to about 13-12kya
- Cool down (Younger Dryas), especially in the Northern hemisphere
- Continued warming to about 10 kya
- Roughly stable temperature until recent record



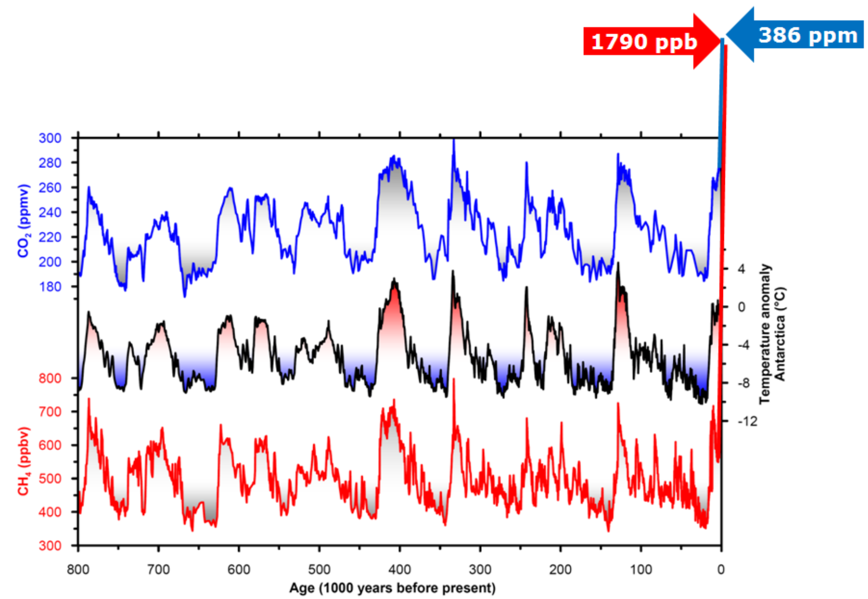
The Younger Dryas and the thermohaline circulation

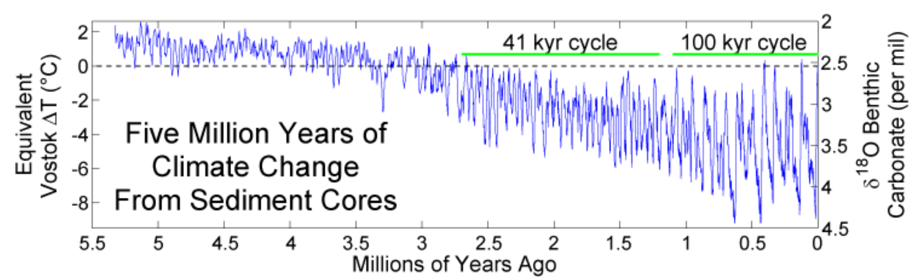
- The Younger Dryas was a period of pronounced cold between 12 and 13kya, especially in the Northern Hemisphere with a rapid onset and rapid termination
- It is thought that meltwater from the receding Laurentide ice sheet flooded the North Atlantic with fresh, buoyant water, limiting/weakening the thermohaline circulation and inducing the cold by limiting poleward advection of heat in the ocean atmosphere system
- In the Pleistocene, during the last glaciation, there is evidence of ice rafted debris (Heinrich events) from abrupt meltings right before slight warmings (Dansgard-Oeschger events)



Pleistocene temperatures

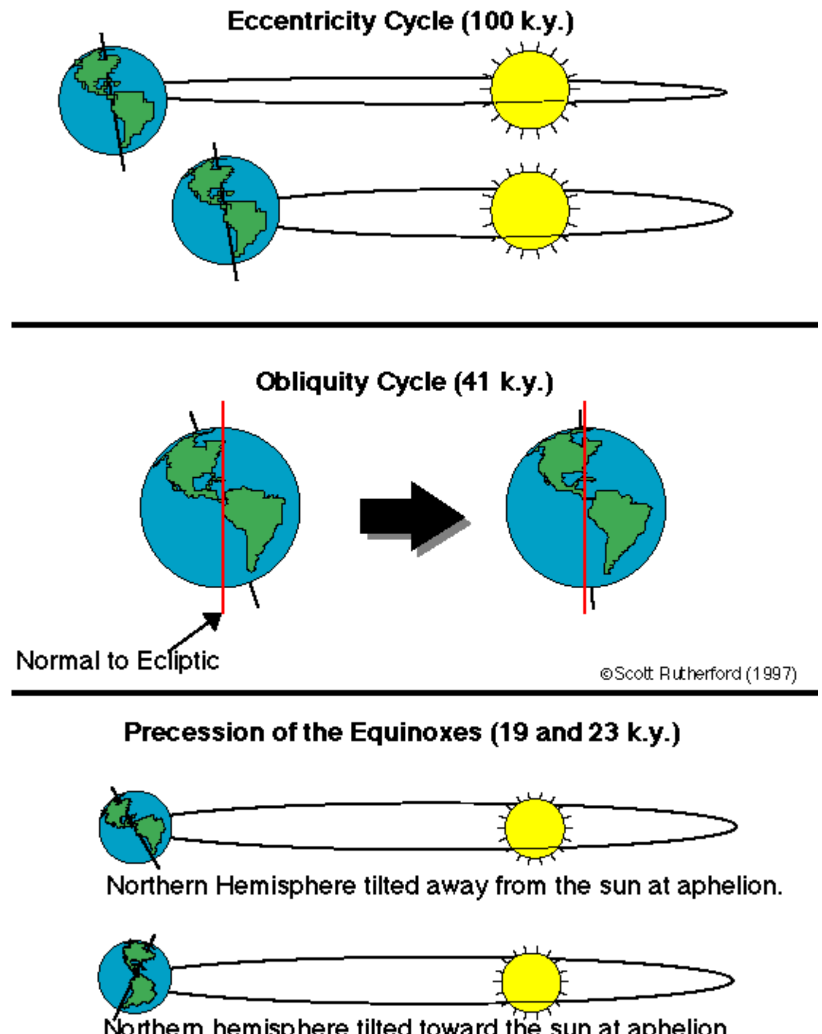
- 100kya cycle to interglacial and glacials over the last million years
- Shorter cycle before that
- In the last million years, rapid transition to interglacials and slow transition to glacials
- Before the Pleistocene, temperatures were warmer and there was less glaciation





Milankovitch/orbital forcing

- It's thought that the cycles of Pleistocene glaciation are connected to subtle changes in the Earth's orbit on 3 different time scales – the premise being that when more heat gets to higher latitudes during the summer months, glaciers will start to melt
- The radiative variability from eccentricity changes is not large enough by itself to effect significant changes – some recent research suggests that the 100kya cycle may in fact be 2 or 3 40kya obliquity cycles
- The obliquity angle oscillates between 22.5 to 24.5 degrees
- This forcing may then be amplified by internal mechanisms and positive feedbacks like the ice-albedo feedback or the binge-purge idea



Climate Change on longer time scales

- Largely inferred from fossils
- Much of the Cenozoic was comparatively warm
- Most of the Mesozoic was comparatively warm too
- There is also evidence of extreme glaciation before 500 mya
- The major changes in climate have coincided with major changes in glaciation and sea level because the total amount of water is conserved