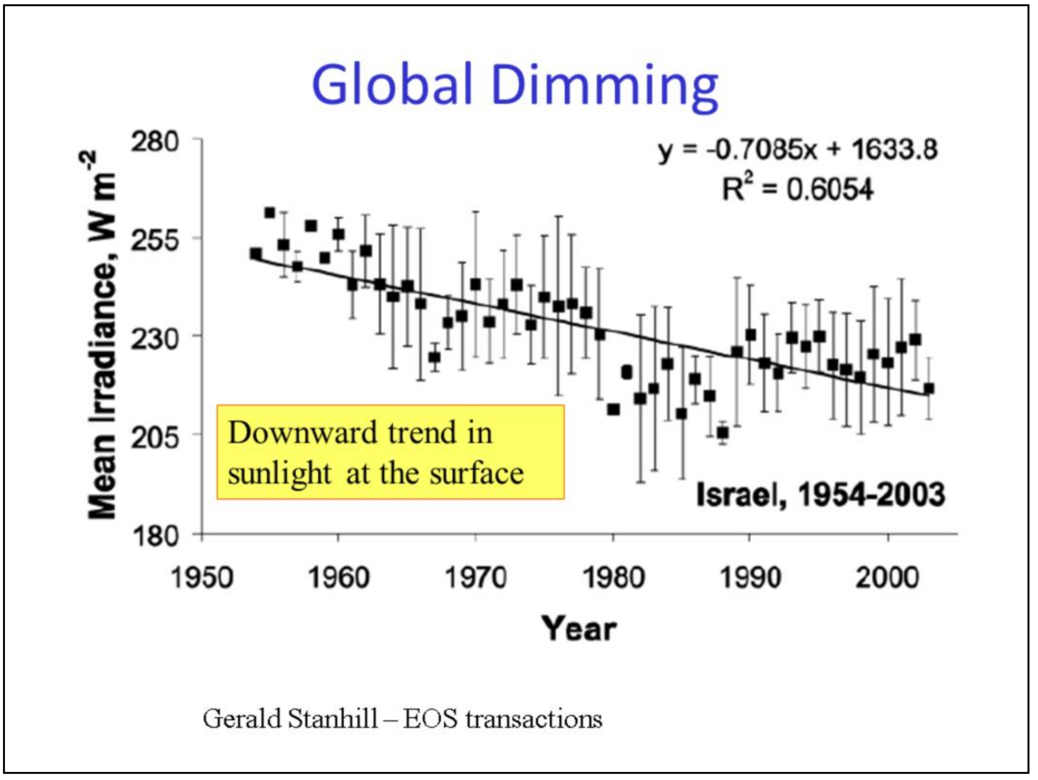
CLIMATE CHANGE:
Past, Present and Future

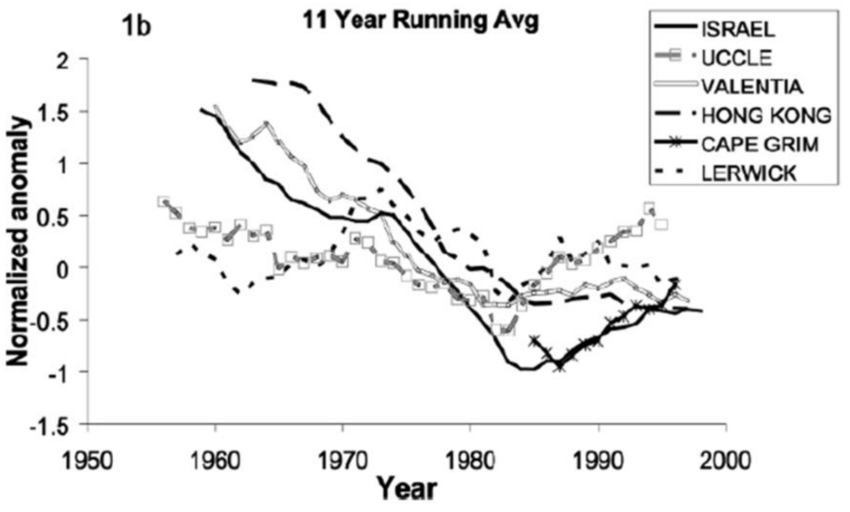
- Session 10: Climate Issues
  - Recap: Clouds and Climate
  - Global Dimming
  - Thermohaline Circulation
  - Tea/coffee break
  - El Nino
  - The Far Future



There is evidence of a widespread reduction in solar radiation at the earth's surface, often referred to as global dimming, lasted from the mid-1950s until the mid-1980s when a recovery, referred to as global brightening, started.

Some evidence suggests that this effect is not so much "global" as "land-based" since surface measurements of sunlight are primarily available only over the land.

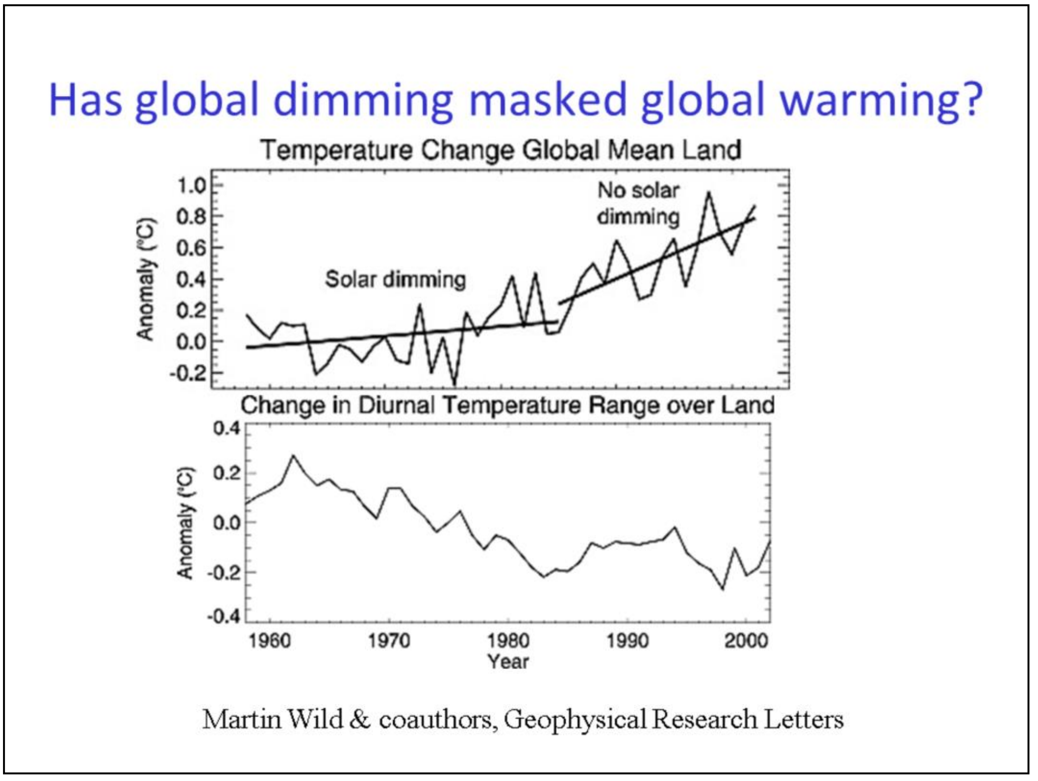
Global Dimming and Brightening



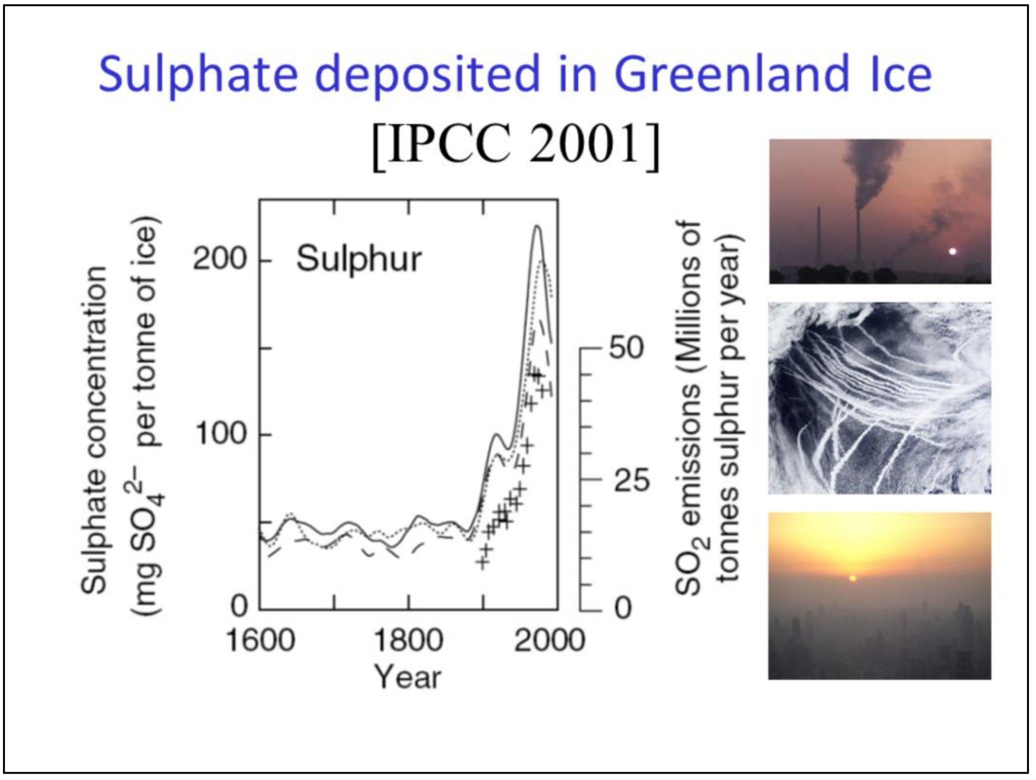
Gerald Stanhill – EOS transactions

Almost as soon as “global dimming” was generally accepted, scientists discovered global brightening! The downward trends in sunlight at the surface seemed to reverse in the 1980s and become an upward trend.

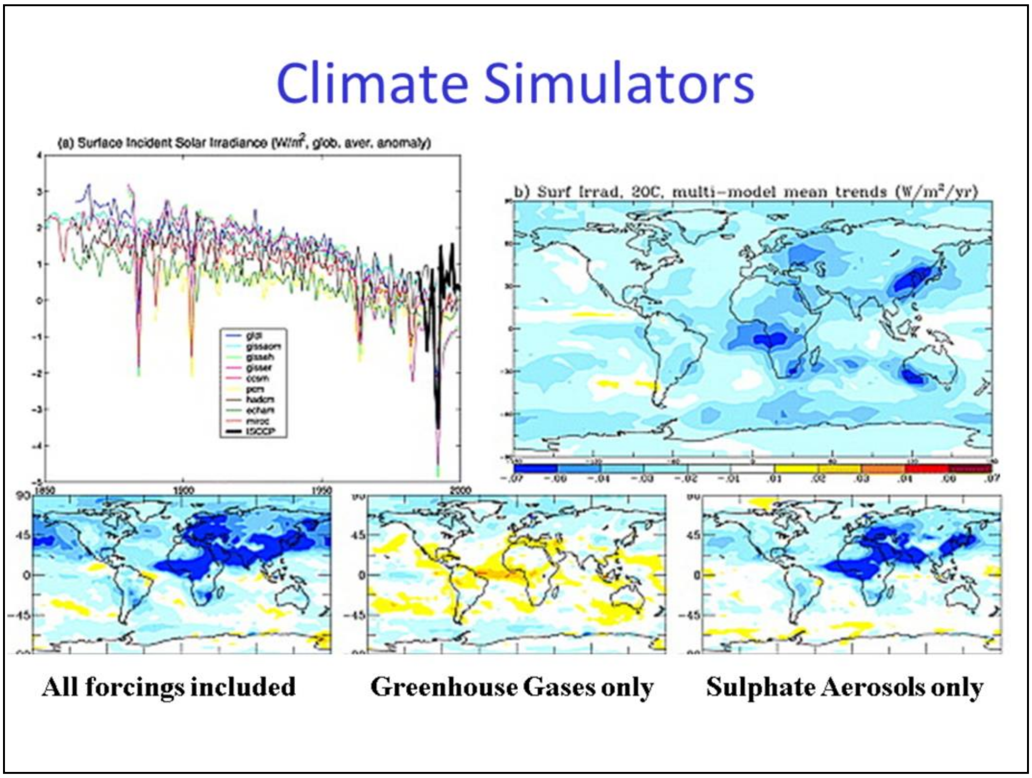
Where was the “missing” sunlight going? Some of it may have been absorbed in the atmosphere (in which case the Earth still received the suns energy) but satellite measurements suggest that some of the sunlight may have been reflected back to space. What was the likely cause?



Recent research suggests that the dimming effect may have masked global warming and that the reversal of this trend in the 1990s contributed to the strong warming in this decade (although recovery from the eruption of Mt. Pinatubo and natural fluctuations in the ocean probably also contributed to this). The dimming effect is thought to relate to increases in aerosols, by-products in the combustion of fossil fuels, especially coal. This is backed up by analysing changes in the diurnal temperature range. Aerosols cool the surface in the day so if there are more aerosols one might expect the range in temperatures between night and day reduces with increased aerosol. This was indeed found to have occurred from 1960-1980. Since the 1980s, the diurnal temperature range has remained stable suggesting an end to the increase in aerosols.



The above plot illustrates the influence of industrial emissions on atmospheric sulphate concentrations, which produce negative radiative forcing (cooling influence on climate). Shown is the time history of the concentrations of sulphate, not in the atmosphere but in ice cores in Greenland (shown by lines; from which the episodic effects of volcanic eruptions have been removed). Such data indicate the local deposition of sulphate aerosols at the site, reflecting sulphur dioxide (SO2) emissions at mid-latitudes in the Northern Hemisphere. This record, albeit more regional than that of the globally-mixed greenhouse gases, demonstrates the large growth in anthropogenic SO2 emissions during the Industrial Era. The pluses denote the relevant regional estimated SO2 emissions (right-hand scale). [From IPCC 2001 report]



Climate model simulations include the changes in Sulphate Aerosols and also simulate "global dimming". Recall that the IPCC reports identify that Sulphate aerosols offset the warming effect of greenhouse gas increases although the uncertainty in representing this effect is high, especially concerning the "indirect effect" on clouds.

Interestingly, simulations and basic physics indicate that dimming is also caused by increases in water vapour in the atmosphere as temperatures rise (recall that as well as absorbing thermal infra-red radiation, the gaseous water vapour also absorbs sunlight therefore shading the surface slightly).

Global Dimming: summary

- Observed reduction in sunlight at the surface since the 1950s: "dimming"
  - Reversal of trend in 1980s: "brightening"
- Thought to relate to increases in Sulphate aerosols up to the 1980s and then a decline
- Observed dimming/brightening effect may be overestimated
  - Observations mainly over more polluted land
  - Some of "missing" solar radiation absorbed by atmosphere
- Simulators do represent this effect so there are not strong grounds for suggesting that global dimming invalidates climate models
  - Simulations may underestimate the effect
  - There may be an influence on rainfall patterns too

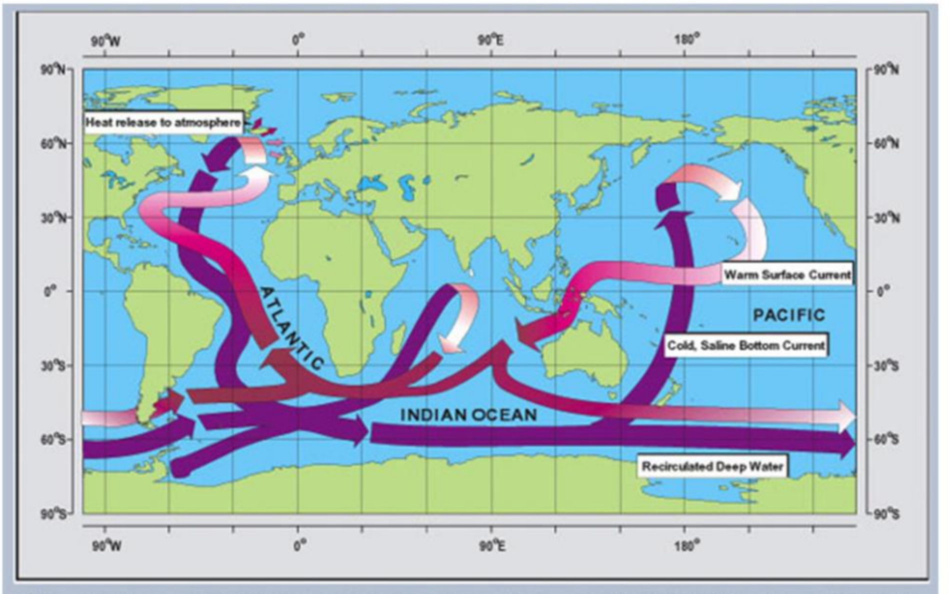
The burning of fossil fuels, in addition to adding CO_2 to the atmosphere, also added Sulphate aerosols. These aerosols have a cooling effect on climate by reflecting some of the sunlight back to space, and consequently depriving the surface of this sunlight. This is the result of the direct effects of the aerosols and their indirect effect on clouds (brighter, more long-lived clouds). The dimming effect was noticed by scientists making measurements of solar raditaion at the surface since the 1950s and has recently been termed "global dimming". Following acid rain concerns in the 1980s, pollution acts helped to reduce this aerosol pollution in some regions (e.g. N America, Europe) leading to a reversal of the dimming or "brightening". The dimming effect may have masked some of the greenhouse-gas induced warming since the 1960s in some regions although this effect is represented in climate model simulations.

Thermohaline Circulation and the Gulf Stream

- Temperature and salinity determine **density** of sea water which in turn determines ocean circulation
- Wind-driven ocean currents such as Gulf Stream cool and become salty and therefore dense
- Dense water off Greenland sinks, driving a global ocean "thermohaline" circulation
- Thermohaline circulation important for climate:
  - Supplies heat to polar regions
  - Influences the ocean mixing including carbon dioxide

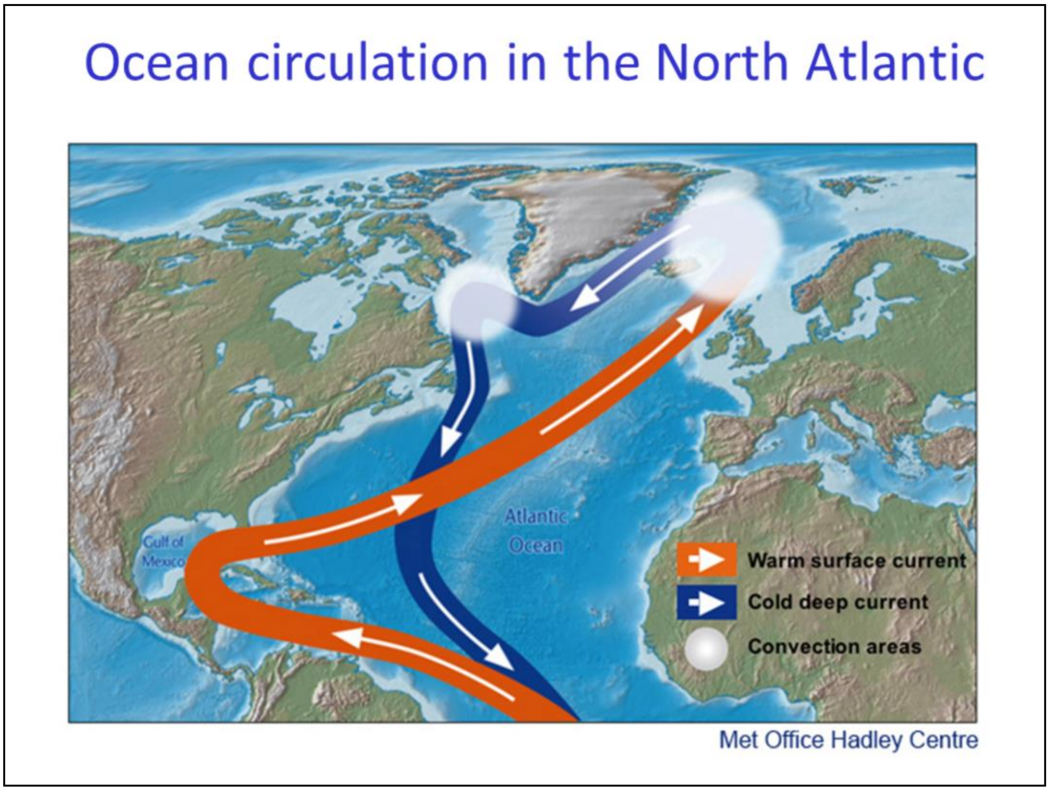
The **thermohaline circulation** (**THC**) is a term for the global density-driven circulation of the oceans. Derivation is from *thermo*- for heat and -*haline* for salt, which together determine the density of sea water. Wind driven surface currents (such as the Gulf Stream) head polewards from the equatorial Atlantic Ocean, cooling and becoming salty through evaporation all the while and eventually sinking at high latitudes (forming North Atlantic Deep Water). This dense water then flows into the ocean basins. Extensive mixing therefore takes place between the ocean basins, reducing differences between them and making the Earth's ocean a global system. On their journey, the water masses transport both energy (in the form of heat) and matter (solids, dissolved substances and gases) around the globe. As such, the state of the circulation has a large impact on the climate of the Earth.

The global ocean “conveyor belt”

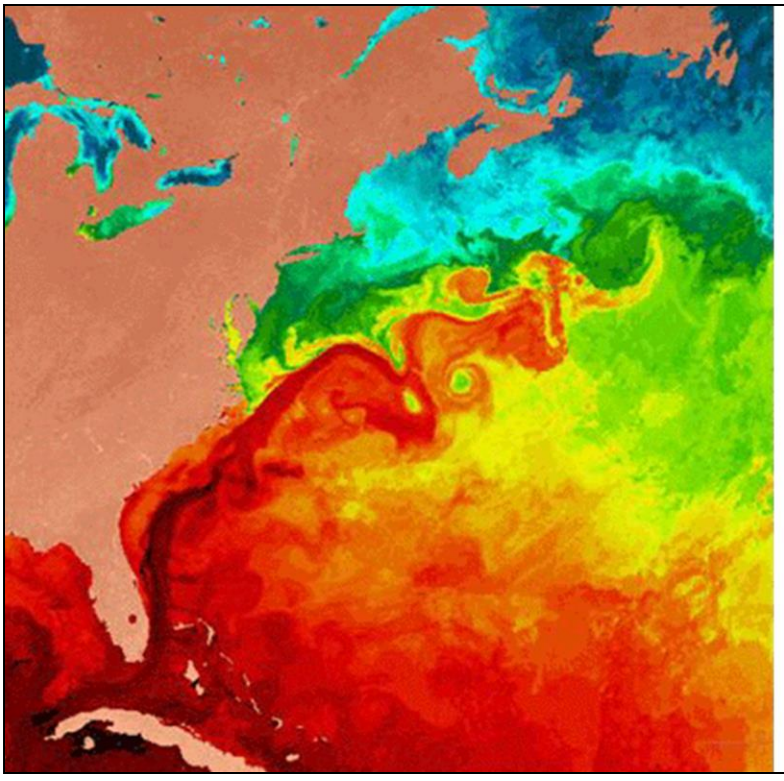


Schematic diagram of the global ocean circulation pathways, the ‘conveyer’ belt (after W. Broecker, modified by E. Maier-Reimer).

The thermohaline circulation is sometimes called the **ocean conveyor belt**, the **global conveyor belt**, or, most commonly, the **meridional overturning circulation** (often abbreviated as **MOC**). The thermohaline circulation is important for climate because it supplies heat to high latitudes and mixes the ocean thereby influencing the amount of carbon dioxide that is absorbed or outgassed. It is one of the reasons why European climate is relatively warm for its latitude but not the only reason.



There have been some concerns expressed that global warming could lead to massive changes in ocean currents such as the Gulf Stream. Currents in the ocean are responsible for about half the work of the climate system in redistributing heat between the equator and the poles. The current system in the N Atlantic is driven by ‘convection’ which takes place in two areas, near Labrador and in the Greenland-Iceland-Norway sea. Here, the surface water is cooled by arctic winds, and sinks a few thousand metres to the bottom of the ocean. This cool dense water then flows southwards, with a flow equivalent to a hundred Amazon rivers, crossing the equator and heading south. The sinking cold water in the north has the effect of drawing northwards warm near-surface water from the Gulf of Mexico, which travels across the North Atlantic.

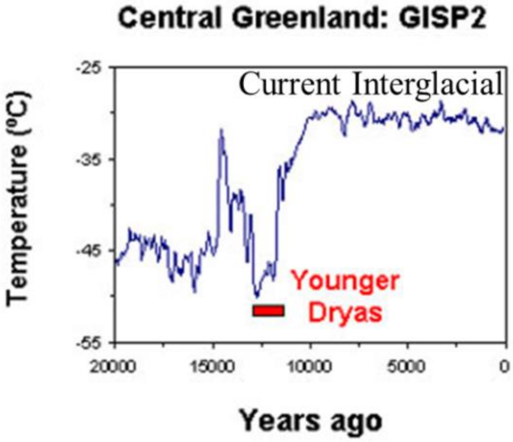


The Gulf Stream

The warm near-surface current moving north eastwards from the Gulf of Mexico is often called the Gulf Stream, but is more properly referred to as the North Atlantic Drift. The heat which it transports towards north-west Europe is part of the reason why countries such as the British Isles and Norway are a lot warmer than, for example, those parts of western Canada at the same latitudes. This global ocean circulation, which extends to other oceans of the world, is known as the thermohaline circulation (THC), as it is driven by differences in temperature and salinity of the water masses.

The Younger Dryas

- Warming temperatures at end of last glacial was interrupted around 13 000 yrs ago



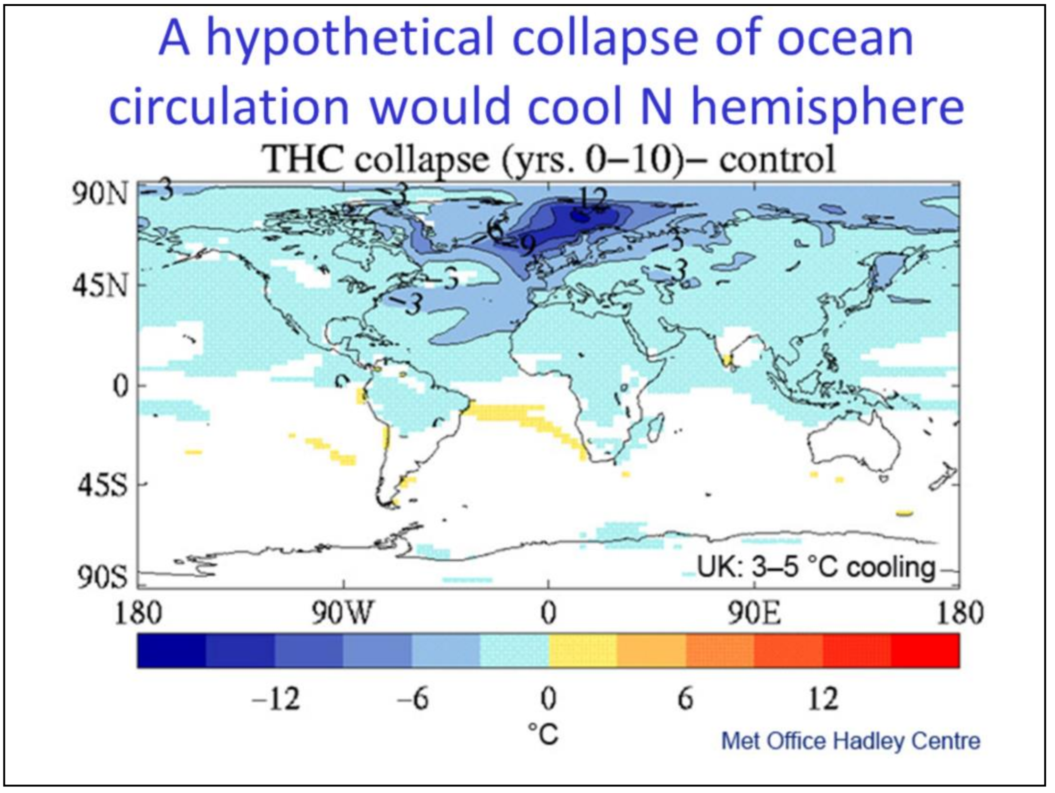
- Thought to relate to release of fresh water into N.Atlantic which dramatically slowed the thermohaline circulation

The Younger Dryas saw a rapid return to glacial conditions in the higher latitudes of the Northern Hemisphere between 12,900 – 11,500 years before present (BP) in sharp contrast to the warming of the preceding interstadial deglaciation. The transitions each occurred over a period of a decade or so. Thermally fractionated nitrogen and argon isotope data from Greenland ice core GISP2 indicates that the summit of Greenland was ~15 °C colder than today during the Younger Dryas. In the UK, coleopteran (fossil beetle) evidence suggests mean annual temperature dropped to approximately -5 °C, and periglacial conditions prevailed in lowland areas, while icefields and glaciers formed in upland areas. Nothing of the size, extent, or rapidity of this period of abrupt climate change has been experienced since.

Response of Atlantic THC to greenhouse gas forcing

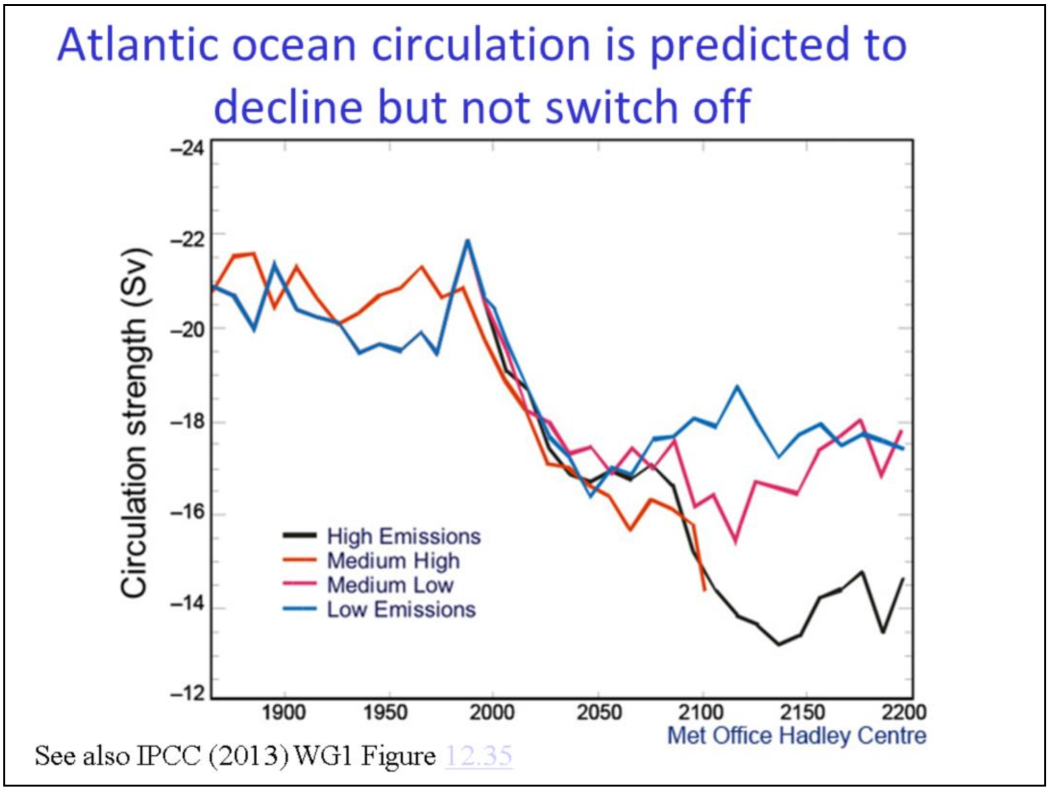
- Warming and increases in precipitation at higher latitudes decrease surface water density
- Increased river run off and melting of sea and land ice (Greenland) also contribute to freshening
- Reduction in deep water formation
- THC expected to slow down
- Abrupt shutdown a possibility (but unlikely?)

The prevailing theory holds that the Younger Dryas was caused by a significant reduction or shutdown of the North Atlantic thermohaline circulation in response to a sudden influx of fresh water from Lake Agassiz and deglaciation in North America. The global climate would then have become locked into the new state until freezing removed the fresh water "lid" from the north Atlantic Ocean. This theory does not explain why South America cooled first. Previous glacial terminations probably did not have younger-dryas like events, suggesting that whatever the mechanism is, it has a random component [text from Wikipedia]. There is strong evidence that the Gulf Stream has switched off more than once over the last ten thousand years, due to natural causes..



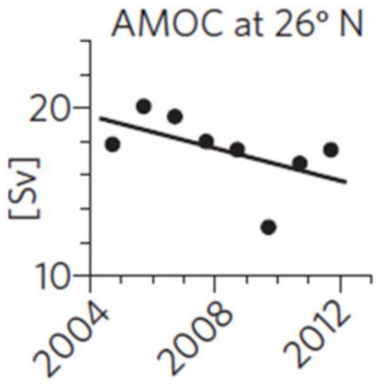
The warming of surface waters in the convection areas, due to the man-made greenhouse effect, will reduce their density. We also expect there to be increased rainfall over the convection areas, and this freshwater will also act to reduce the density of surface waters. Increased precipitation in high latitudes in a warmer world will also increase the outflow of fresh water from rivers – this has already been observed and, as mentioned earlier, recent work at the Hadley Centre has been able to attribute this to man-made climate change. And lastly, as the amount of sea ice decreases, a further mechanism for driving convection (the seasonal freezing of sea ice which rejects salt and thus make surface waters denser) will also decrease.

Climate model simulations indicate (above) that if the thermohaline circulation were to shut off completely, UK temperatures would cool by 3-5^{o}C but this is highly unlikely.



The IPCC (2013) states that it is very likely that Atlantic Meridional Overturning ocean circulation will weaken over the 21st century. However, simulations indicate that it is unlikely to shut down completely. The Hadley Centre climate model experiments above show a weakening of this circulation: larger negative values indicate a stronger circulation (the unit of current strength is a sverdrup, a million cubic metres of water per second). The resulting cooling of the North Atlantic region due to a weakening of the overturning ocean circulation will only offset some of the warming due to increasing concentrations of greenhouse gases.

Observations indicate slowing of Atlantic Meridional Overturning Circulation (AMOC)

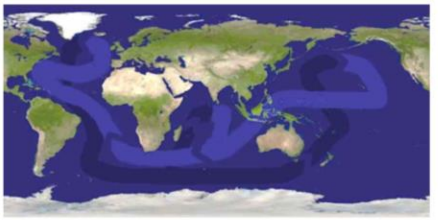


Robson et al. (2014) Nature Geosciences;
see also: Smeed et al. (2014) Ocean Sci.

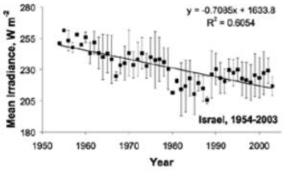
- “Rapid array” of observations measures strength of AMOC at 26°N
- Declining strength of circulation
- Is this natural variability or part of a longer term trend?

Observations suggest that the Atlantic meridional overturning circulation (AMOC) has been slowing down. It is only since 2004 that the “Rapid Array” has been measuring these changes accurately at 26oN and it remains to be seen whether this decline is part of a longer term trend relating to global warming or part of natural variability of the ocean.

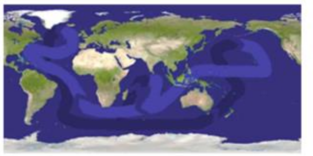
Thermohaline circulation



- **Density** driven global ocean circulation determined by sea temperature and salinity
- Supplies heat to high latitudes and mixes the ocean thereby influencing CO_2 fluxes
- Likely to have determined an interruption in the warming following the last glacial: the Younger Dryas
- Climate simulations generate a slow down in the circulation but not a shut down
  - Some observations also suggest a slow down of this circulation but the circulation is also variable on short time-scales
- Projected future slowing of the circulation cools Europe but the cooling merely offsets some warming from greenhouse gas forcing



Re-cap:



global dimming; ocean circulation

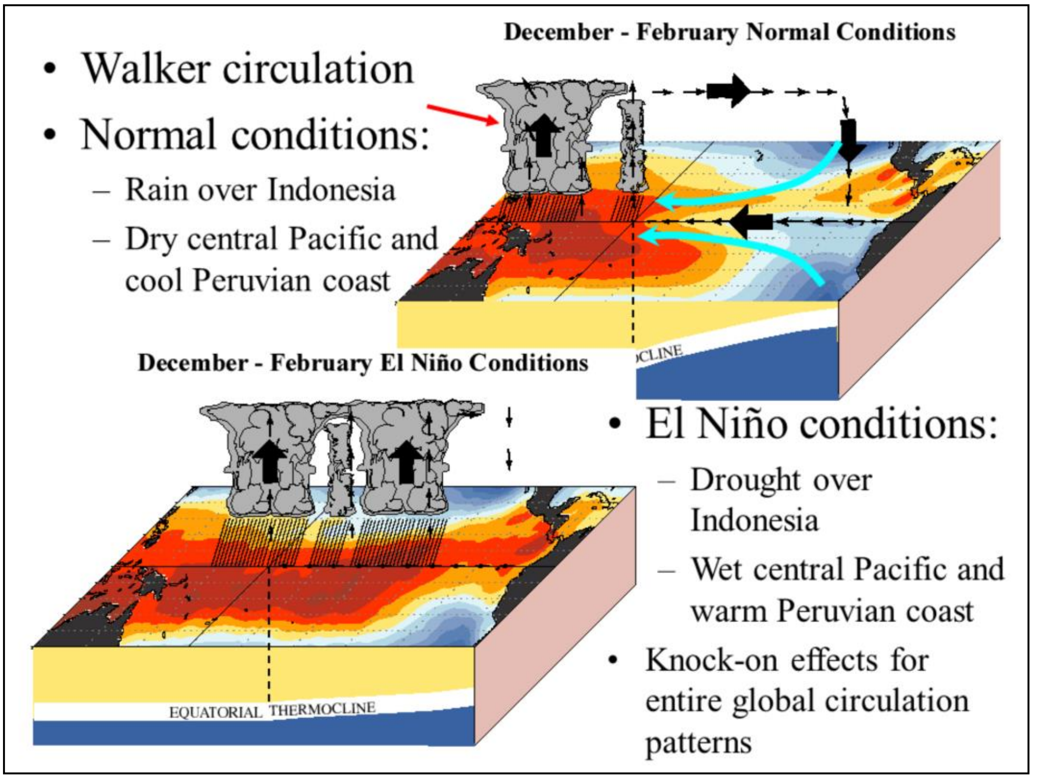
- Global dimming
  - The rise and fall of the Sulphate aerosol
  - Masking full extent of greenhouse gas increases?
- Thermohaline circulation
  - Warms north Atlantic; sinking cold, salty, dense water
  - Catastrophic effects of shut down; Younger Dryas
  - Models & observations: future slow down?
  - Offset some of greenhouse gas warming in north Atlantic / European region?

El Niño Southern Oscillation (ENSO)

- Massive reorganisation of atmospheric and oceanic circulation occurring every few years
- First documented by Spanish in Peru late 1400s
  - Warming of normally cold, nutrient-rich ocean *(animation)*
  - Catastrophic for fishing
  - Translates to "Christ Child" as onset near to Christmas
- Gilbert Walker in 1923 researching Asian monsoon
  - discovered oscillation in pressure between Darwin/Tahiti

- In 1960s, linked **E**l **N**iño to "**S**outhern **O**scillation" (**ENSO**)
- Positive Phase: **E**l **N**iño, negative phase: La **N**iña
  - Note, negative phase first termed "anti **E**l **N**iño": bad connotations!!

El Niño-Southern Oscillation (ENSO) is a global-scale interaction between the atmosphere and the oceans. Its effects are strongest in the Pacific and climate in the southern hemisphere are profound.

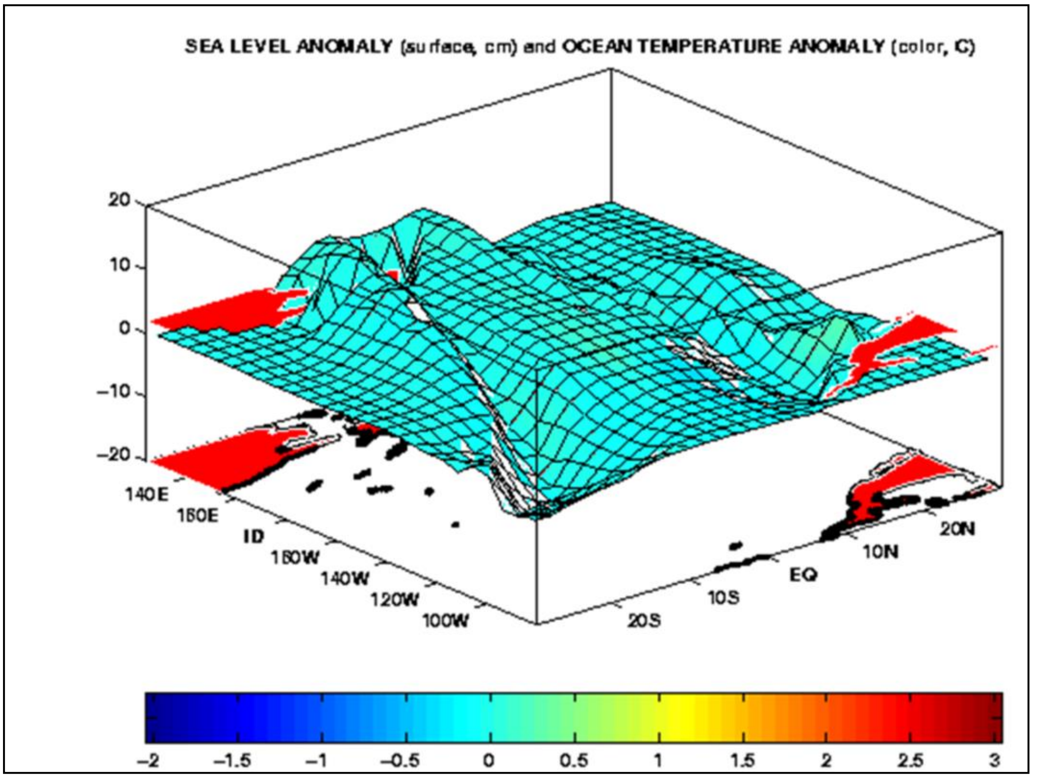


Under normal conditions, trade winds blow from east to west, piling up warm water and associated convective storms over the Indonesian region. The wind-driven ocean currents produce upwelling in the east-Pacific, providing cool, nutrient rich water, excellent for fish stocks.

Under El Niño conditions, the winds and ocean currents decline and the east Pacific warms. Convection and rain move from Indonesia over the central Pacific and fish stocks decline in the east.

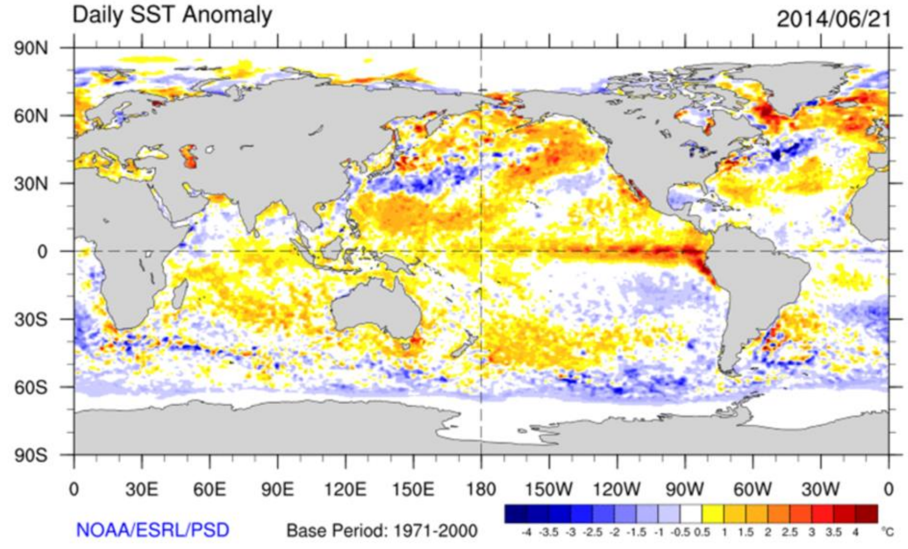
There are knock on effects across the globe.

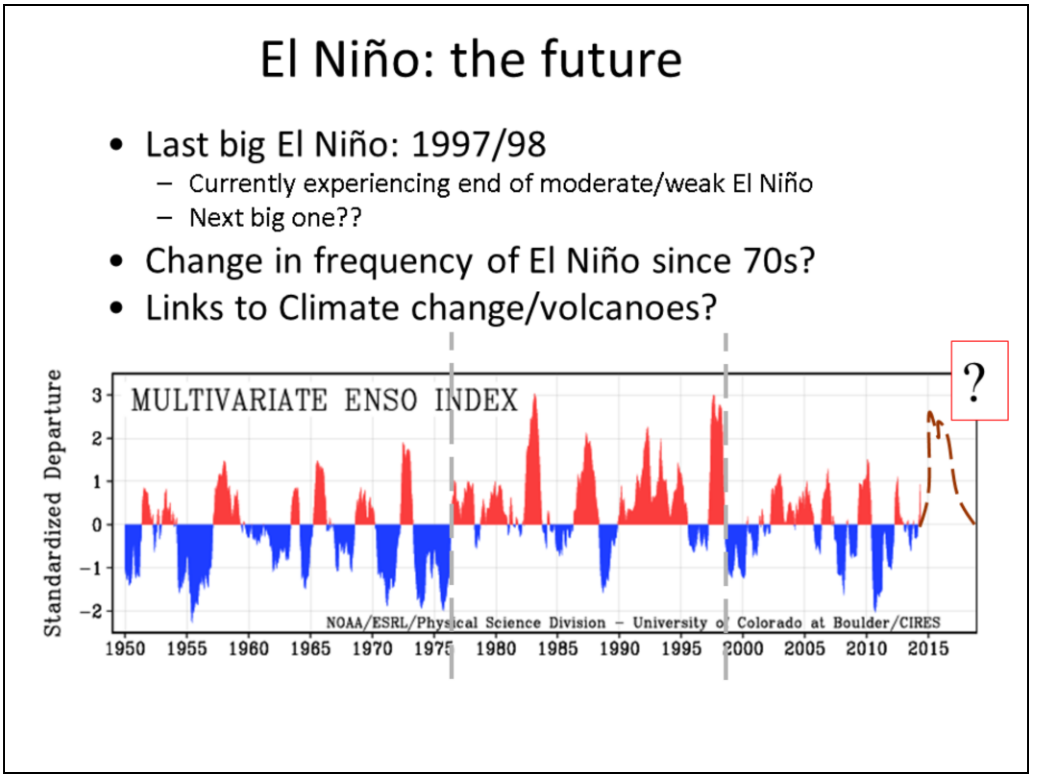
Following the rapid decline of El Niño conditions, the system often overshoots to produce a reverse El Niño (or exagerated normal conditions) termed La Niña.



The changes in ocean temperature and height (dependent on temperature and winds) slops backward and forward in an oscillation from El Niño to la Niña and back again every few years.

Current sea surface temperature anomalies





There have been more La Niña events in the 2000s than the 1980s or 1990s and this probably reflects decadal variability. Recent research also demonstrates that there are different types of El Niño with eastern Pacific events affecting global temperatures more than central Pacific events.

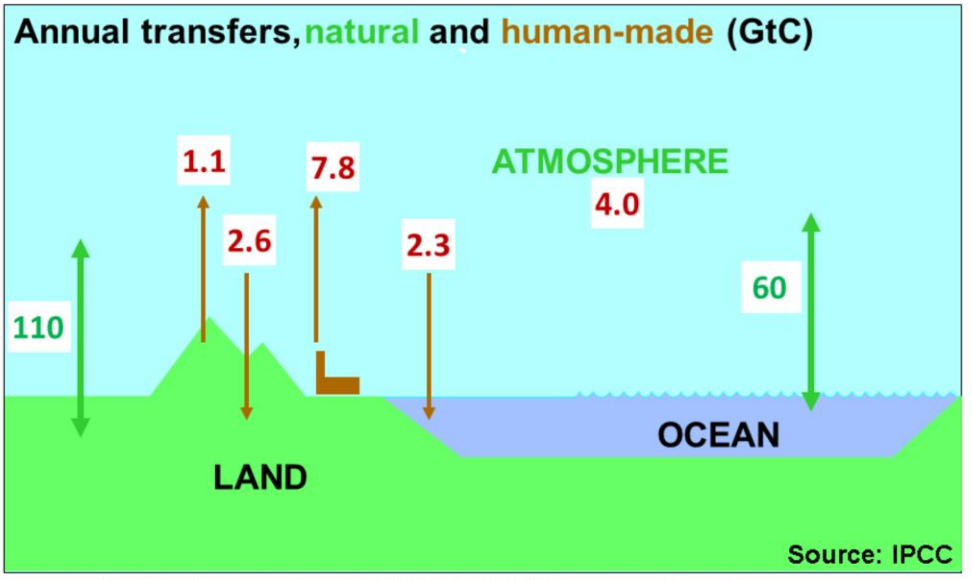
The last big El Niño was 1997/98. An El Niño is currently developing (2014); the chaotic nature of these oscillations, involving so many interactions, limits our ability to make predictions.

Climate models simulate ongoing El Niño variability in the future. Combined with the projected intensification of droughts and flooding events with warming of climate it is expected that variability associated with El Niño will also become larger and potentially more damaging.

Slow Carbon Feedbacks

- Man-made fluxes of carbon are much smaller than the fluxes in the natural carbon cycle.
- However, the natural carbon cycle is in balance, and has led to concentrations of CO_2 in the atmosphere remaining relatively constant for the thousand years before the industrial revolution.
- Understanding this natural balance and how the man-made input will affect it are crucial in predicting future concentrations of CO_2

Natural and man-made carbon cycles

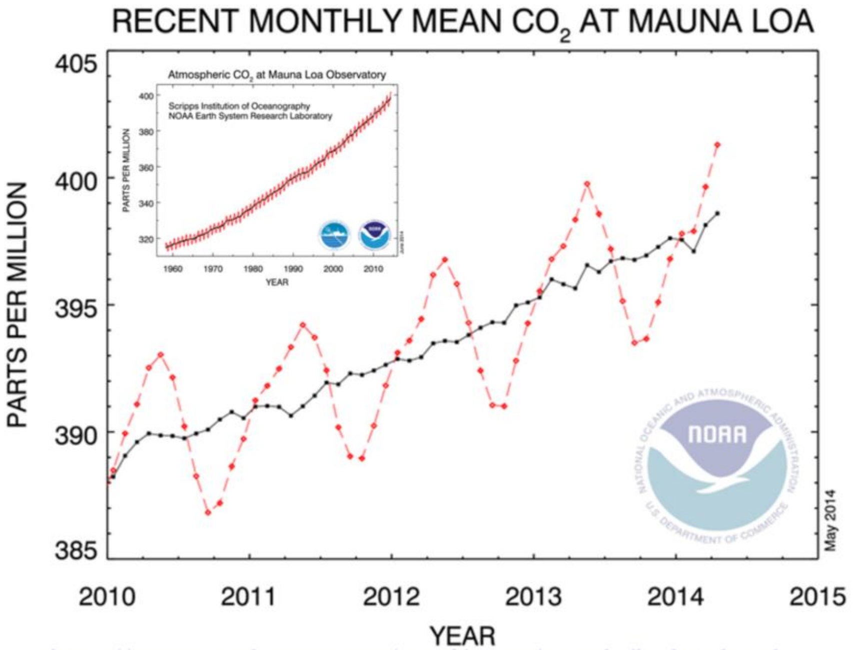


Updated values from IPCC (2013) WG1 report Fig. 6.1

The emission of CO_2 into the atmosphere (7.8 Giga tonnes of Carbon, GtC, per year) is small relative to the natural fluxes between land/ocean and atmosphere (170 GtC/year). Crucially, however, the natural carbon budget is in balance, so the emissions of CO_2 from fossil fuel burning (and land use changes) are causing a perturbation to the carbon balance of the atmosphere not seen for more than 800 000 years based upon ice core measurements.

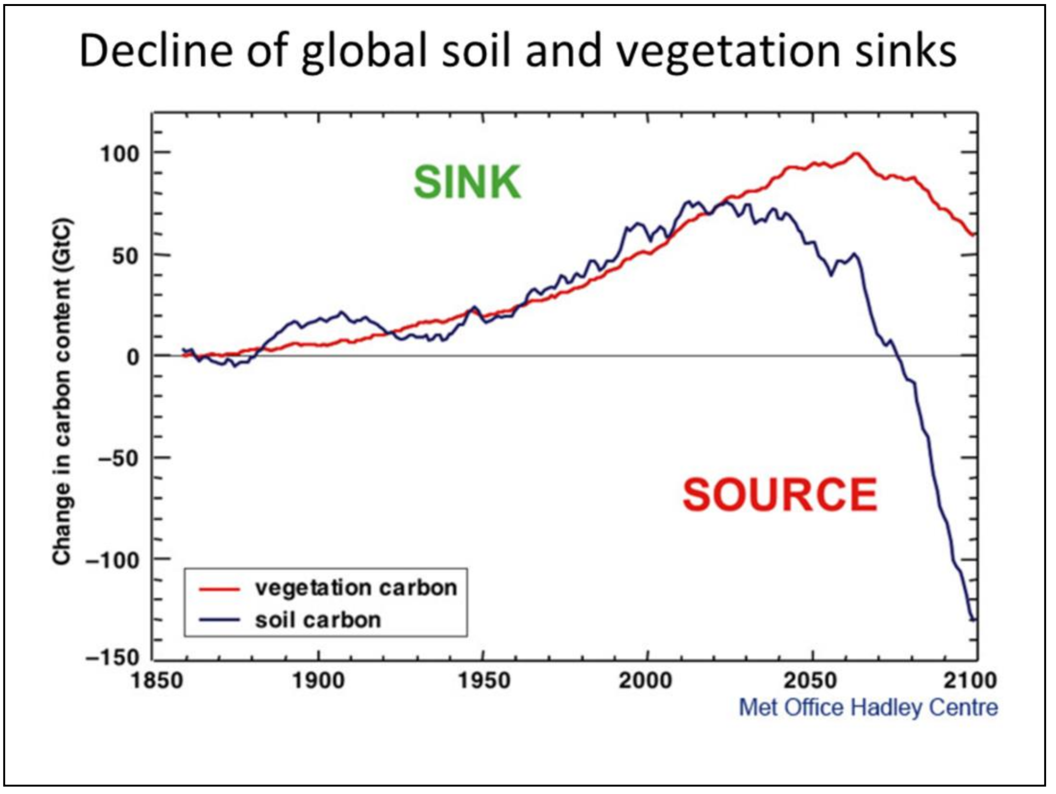
Some of the excess CO_2 in the atmosphere is absorbed by the land and ocean but a large amount is stored in the atmosphere as CO_2. This build up of Carbon in the atmosphere at the rate of 4 GtC per year primarily reflects the increased atmospheric concentrations of CO_2.

Changes in this carbon balance in the future may yield a further slow positive feedback to climate change…



http://www.esrl.noaa.gov/gmd/ccgg/trends/index.html

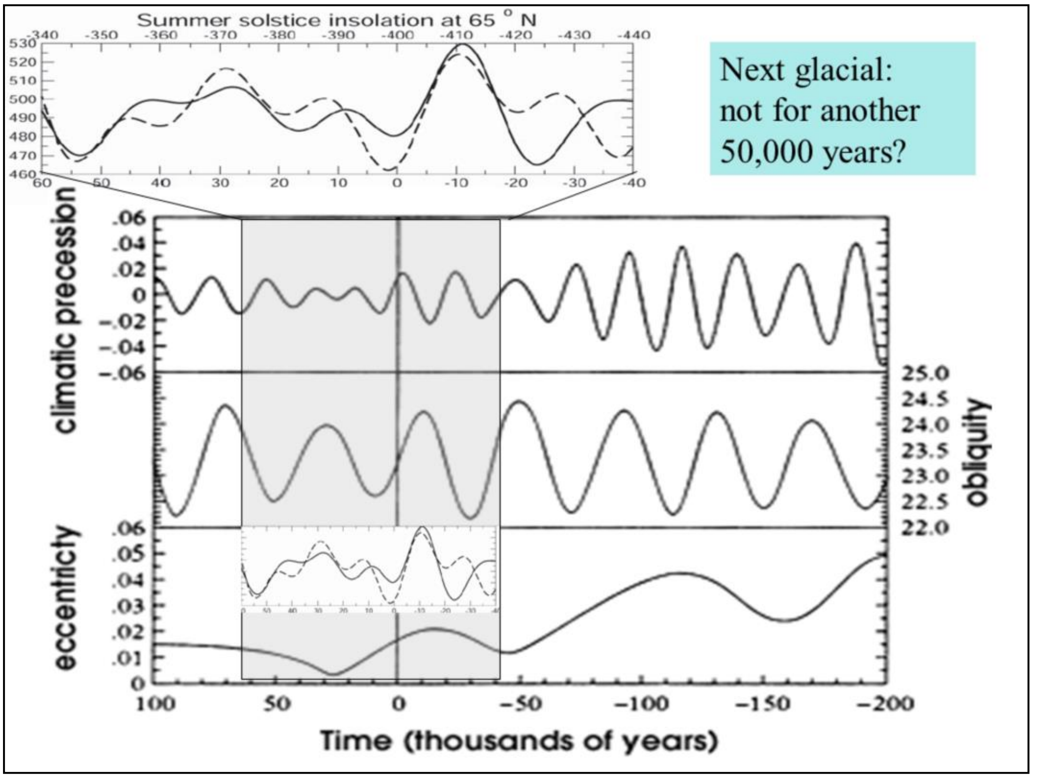
Current changes in CO_2 at Mauna Loa (and other measuring stations) show a yearly cycle relating to changes in vegetation and changes in ocean emission and absorption of the gas. Superimposed upon these cycles are a longer term trend; CO_2 concentrations are rising at about 2 parts per million every year. This is faster than any other time over the past million years, based on 850,000 year long ice core records. It is important to be able capture the trend as well as the yearly cycles and also fluctuations relating to the El Nino Southern Oscillation if we are to have confidence in our carbon-cycle models and the resulting slow carbon feedbacks.



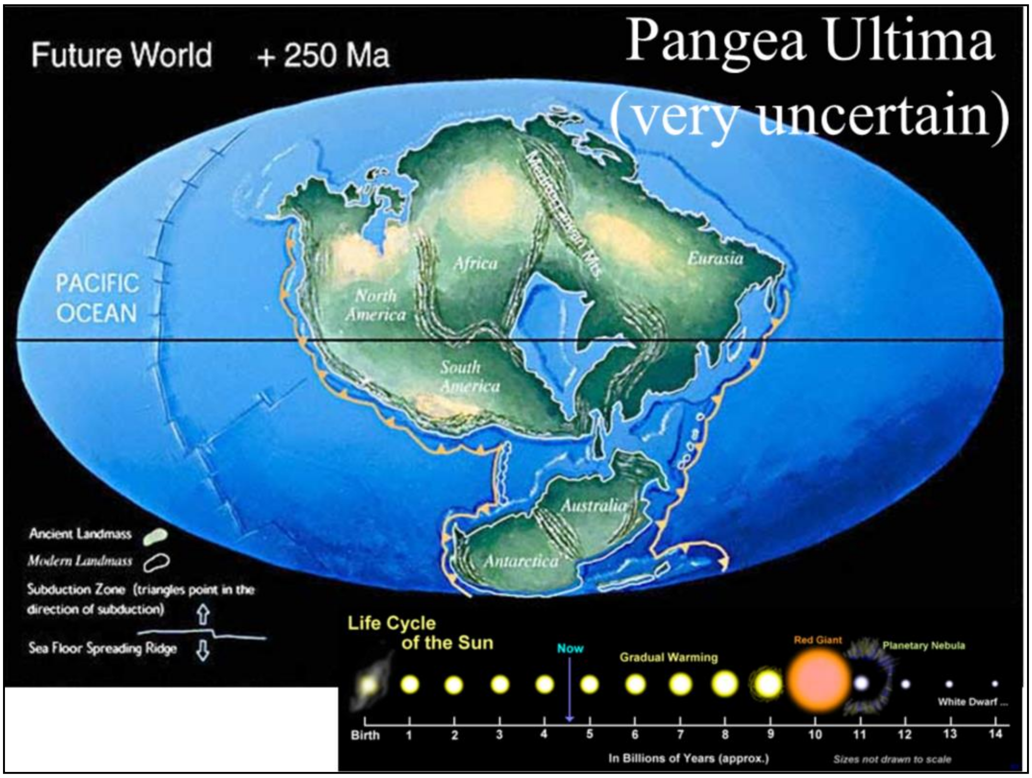
As global temperatures rise, and rainfall patterns change, several changes to carbon absorption are likely to take place. Firstly, in the right conditions, CO_2 fertilises vegetation and speeds up its growth; this will absorb more of our CO_2. Secondly, higher temperatures and more rainfall will encourage growth of high latitude forests, and this will also help to mop up more of our CO_2. However, as soils get warmer, the microbial action which breaks down humus works faster, and this will cause more CO_2 to be emitted into the atmosphere. Lastly, higher temperatures (and thus higher evaporation) and lower rainfall are predicted for some forests in the tropics, and this is predicted to cause them to die back, with their carbon store being returned to the atmosphere. The majority of climate models simulate that the land and ocean will continue to take up carbon in the future. However, a minority of models indicate a decrease in land uptake of carbon (for example see the simulation above) leading to a positive carbon cycle feedback. Over glacial time-scales the carbon cycle feedbacks are positive (amplifying effect on temperature changes).

The Far Future

- Over next 20,000-50,000 years, the Earth's orbit does not appear conducive to glaciationfor the current CO_2 concentration
- Over next 100,000 years the next glacial period will evolve
- What about longer periods of time?
- Changes in positions of the continents will influence climate over millions of years…



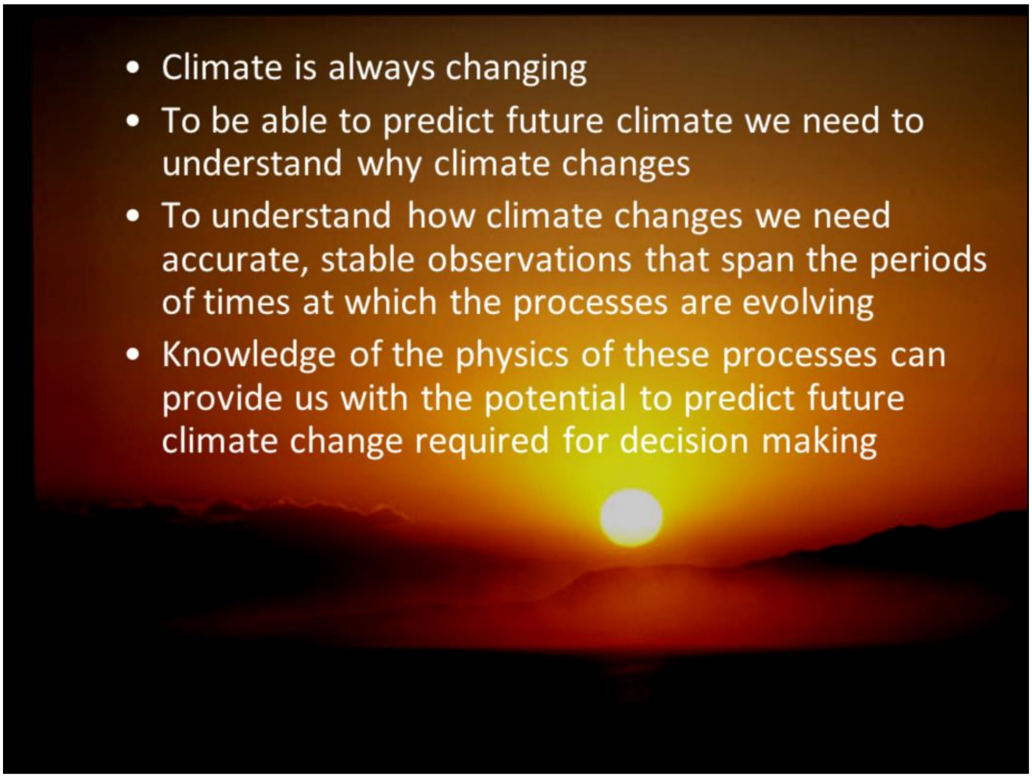
The future orbital parameters are predictable. Due to low eccentricity (combination of regular 100,000 and 400,000 cycles) and elevated carbon dioxide concentrations it is unlikely that we will finish the current interglacial for another 50,000 years.



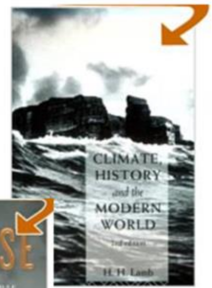
The Earth is going to be a very different place 250 million years from now. Africa is going to smash into Europe as Australia migrates north to merge with Asia. Meanwhile the Atlantic Ocean will probably widen for a spell before it reverses course and later disappears. The formation of a new super-continent is suggested by some scientists although this is highly uncertain.

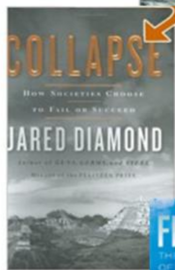
What will this mean for climate? There are 3 factors that are thought to make ice ages more likely:
1) A continent sits on top of a pole, as Antarctica does today.
2) A polar sea is almost land-locked, as the Arctic Ocean is today.
3) A supercontinent covers most of the equator, as Rodinia did during the Cryogenian period.

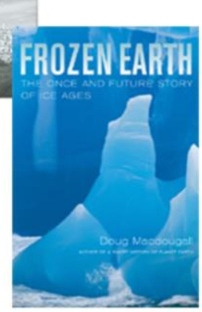
Since the above suggested configuration of the continents meets precisely none of these criteria, it is unlikely that this hypothesised period will be too parky! In addition, the sun is likely to become slowly brighter over the next 5 billion years, producing a warming trend. A very long forecast…


• Climate is always changing
• To be able to predict future climate we need to understand why climate changes
• To understand how climate changes we need accurate, stable observations that span the periods of times at which the processes are evolving
• Knowledge of the physics of these processes can provide us with the potential to predict future climate change required for decision making

Further Reading:







Popular science books:

- Rough Guide to Climate Change (Henson)
- Very Short Introduction:
  - Climate Change (Maslin)
  - The Ice Age (Woodward)
- Collapse (Jared Diamond)
- Frozen Earth (MacDougall)
- Climate History and the Modern World (Lamb)

SOME INTERNET LINKS…

- www.met.rdg.ac.uk/~sgs02rpa/CONTED/climat
- www.ipcc.ch [IPCC(2013) available]
- royalsociety.org/policy/projects/climate-evidence-causes/
- www.realclimate.org [informed blog]
- www.metoffice.gov.uk/education/higher
- www.climateprediction.net [run your own model]