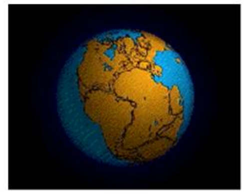
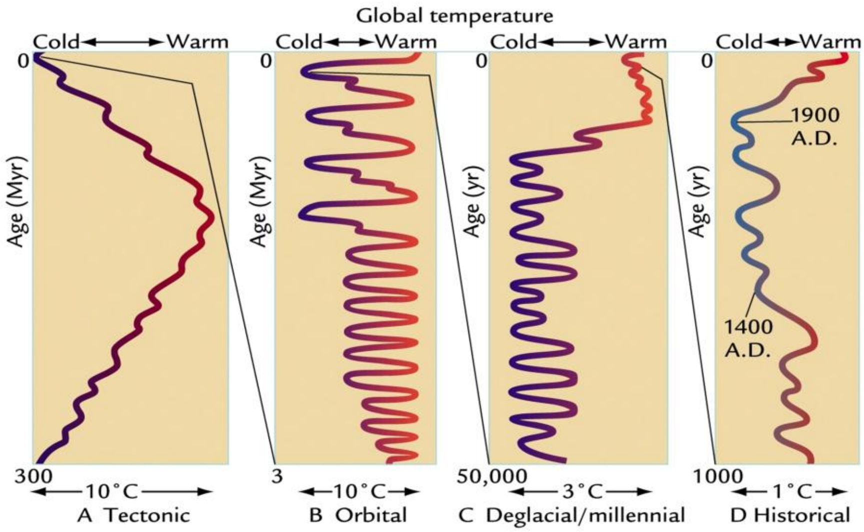
- Climate has always changed
- Millions of years: evolving atmosphere and plate tectonics

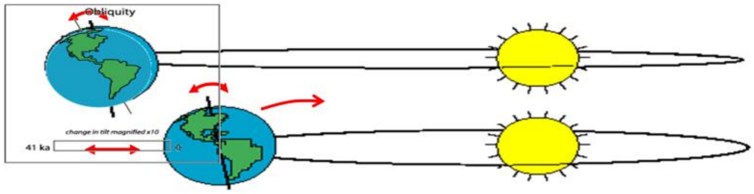




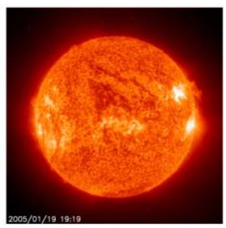
Climate changes on all time-scales. One of the most important determinants of climate is variations in the absorption of solar radiation by the planet.

Over billions of years the solar output has increased with time, as has the evolution of the Earth's atmosphere and distribution of land and ocean which modifies the efficiency at which the Earth can cool to space via thermal/long wavelength radiation as well as impacting absorption of sunlight.

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 they are widely believed to have caused glacial-interglacial cycles in which global temperatures swing by up to 10^{o}C. However, 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.



- Thousands of years: Orbital variations leading to current glacial cycles
- Tens to hundreds of years: solar and volcanic changes, natural fluctuations in ocean circulation, effect of humans on the environment…



Carbon dioxide is another amplifying agent over glacial cycles (positive feedback) since warmer oceans are less able to dissolve the gas.

Over shorter time-scales, small changes in the suns output and volcanic eruptions act to alter the Earth's radiation balance and cause small fluctuations in climate over tens to hundreds and thousands of years. Over the last hundred years a relentless rise in human produced greenhouse gases such as carbon dioxide has reduced the efficiency of the Earth's ability to cool to space, forcing temperatures upwards. So recently, the greenhouse gas carbon dioxide has begun to force climate to warm; during glacial-cycles it acts passively to amplify warming due to changes in absorbed sunlight whereas now it is actively driving the warming and other agents are amplifying or dampening the initial forcing through feedback processes.

Causes of Climate Change

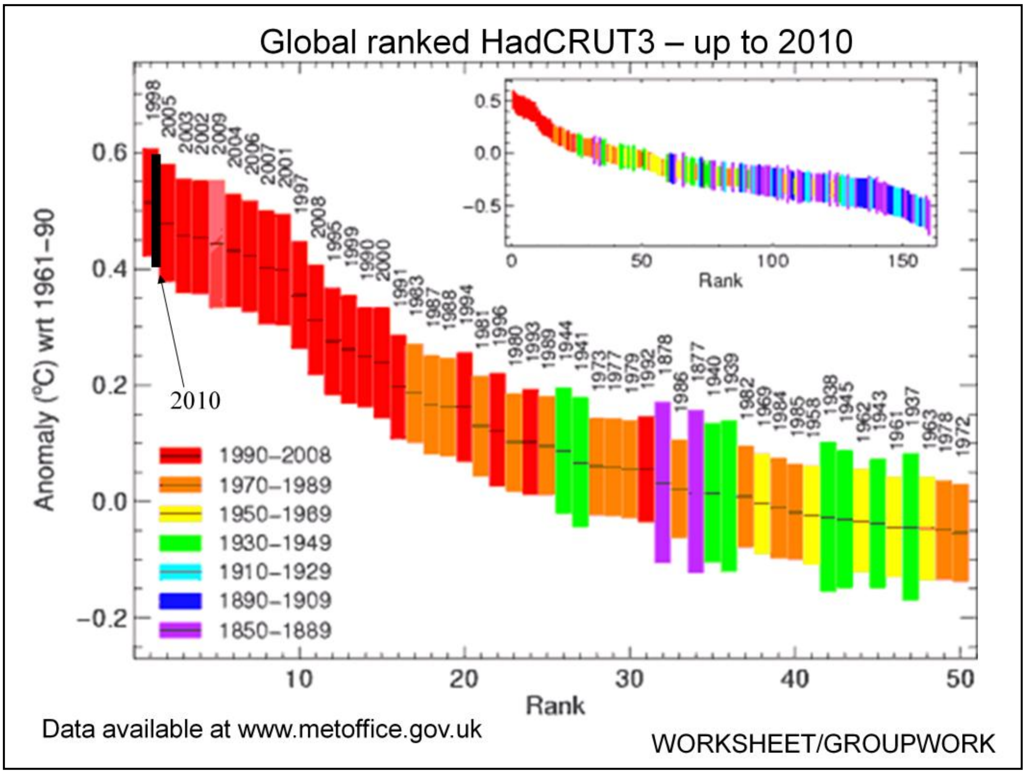
- If there is a change in the balance between absorbed sunlight (heating) and emitted thermal radiation (cooling) [Lecture 2], an ensuing change in climate can occur:
  - radiative *forcing* of climate
  - What causes climate forcings?
- The response of the atmosphere, ocean and land surface can amplify (positive feedback) or counteract (negative feedback) the initial climate forcing
  - Positive feedbacks: surface ice/snow, water vapour
  - Cloud feedbacks: uncertain
- Determining climate change requires knowledge of forcings and feedbacks
- Also, some changes in climate are “un-forced”, for example periodic fluctuations in the ocean (climate “noise”)

There is a balance between the absorbed solar radiation (heating) and outgoing longwave/thermal radiation to space (cooling). If this balance is altered the climate will change. For example, if the sun became brighter, absorbed solar radiation would be greater than the outgoing longwave radiative cooling and the Earth would begin to heat up until a new balance is attained at a higher global average temperature. As the Earth heats up, aspects of the climate system respond, such as clouds, snow/ice and water vapour. These will either amplify the initial warming (positive feedback) or counteract it (negative feedback). Understanding how these feedbacks operate is crucial in understanding how much climate will respond to a “radiative forcing” such as a change in carbon dioxide or a change in the suns output. Observational evidence, backed up by robust physics, indicate that water vapour and surface ice/snow contribute positive feedbacks, amplifying any initial change in climate. It is not known with any confidence whether clouds will amplify or counteract global climate change.

Is the planet warming?

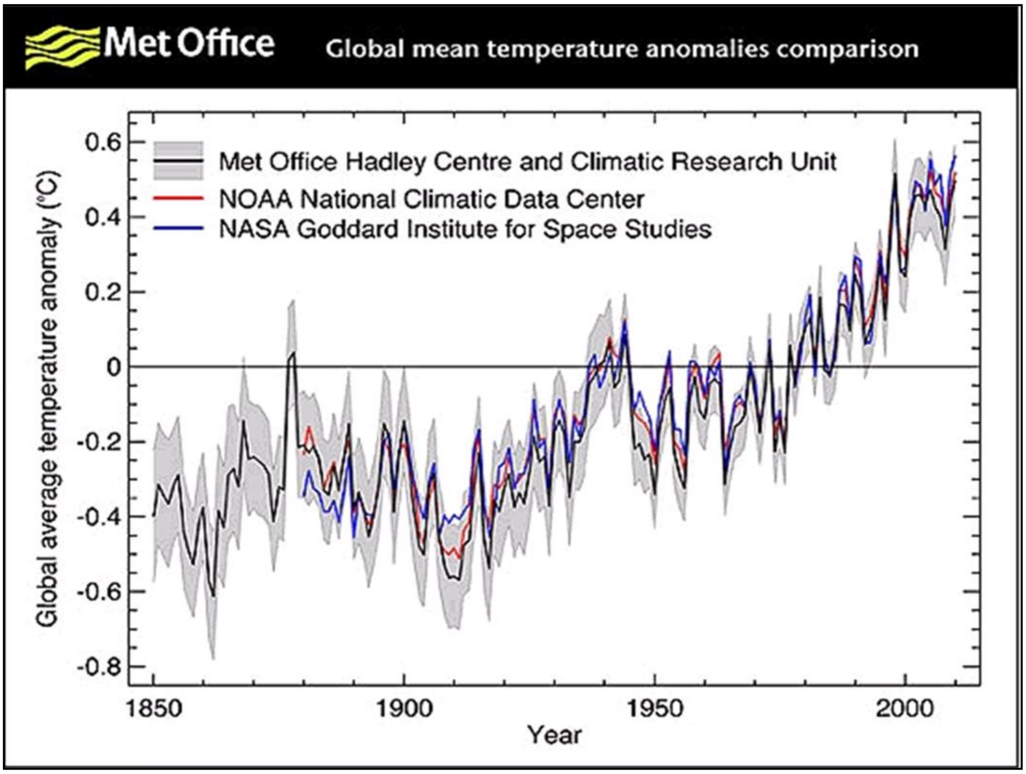
- 11 of last 12 years are in the warmest years in the instrumental record (since 1850)
  - 2010, 1998 and 2005 warmest on record
- 0.8^{o}C rise in global temperature since 1900
  - Mainly for periods 1910-1945 & 1976-present
  - Continents warming fastest (esp. Alaska, Siberia, Antarctic peninsula)
- Care has been taken to remove spurious effects due to “urban warming” and changing observing practices

The global average surface temperature (the average of near surface air temperature over land, and sea surface temperature) has increased since 1861, the earliest year for which a precise global estimate is possible. Over the 20th century the increase has been about 0·7°C. The record shows a great deal of variability; for example, most of the warming occurred during the 20th century, during two periods, 1910 to 1945 and 1976 to 2000. Continents in the northern hemisphere have warmed the most.



Data available at www.metoffice.gov.uk

The relative warmth of years and decades and their uncertainty show just how unusual the last few decades have been in the instrumental record.



The instrumental record goes back to about 1850.

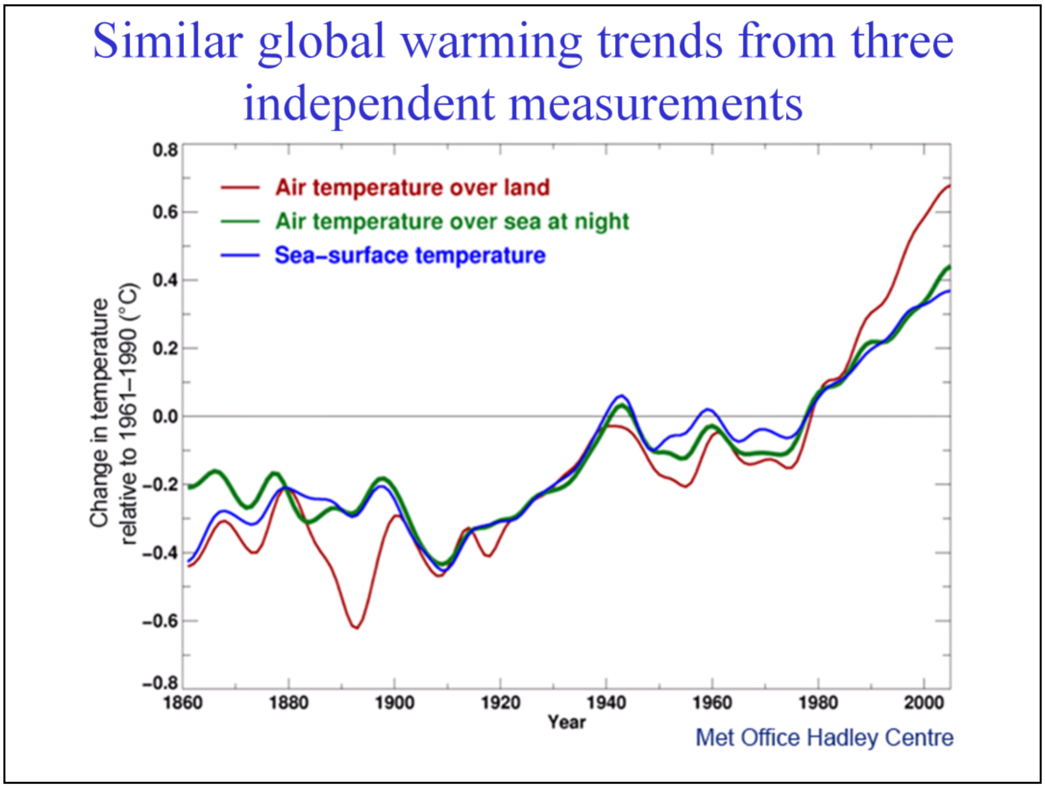
1998, 2005 and 2010 have all been crowned the warmest globally in the instrumental record

depending upon the dataset used and uncertainties assumed.

A few areas of the globe have not warmed in recent decades, mainly over some parts of the Southern Hemisphere oceans and parts of Antarctica.

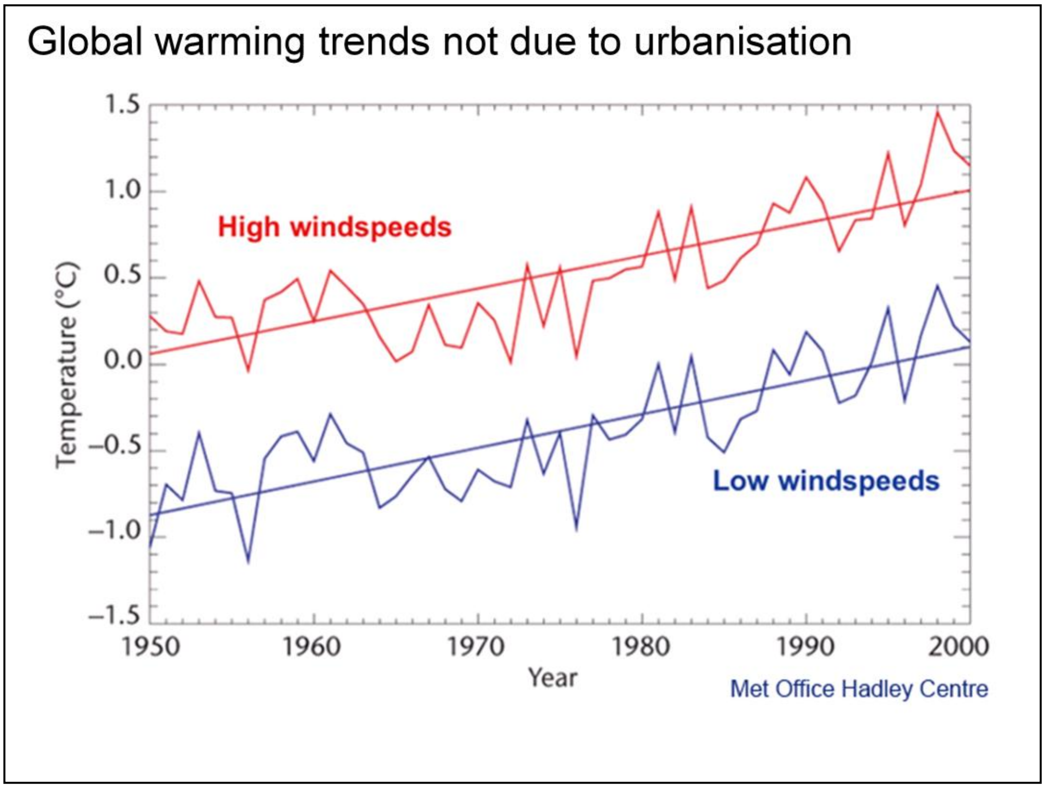
2006 and 2007 were the warmest years on record in the UK. But 2010 was one of the coldest!

http://www.metoffice.gov.uk/climate/uk/datasets/Tmean/ranked/UK.txt

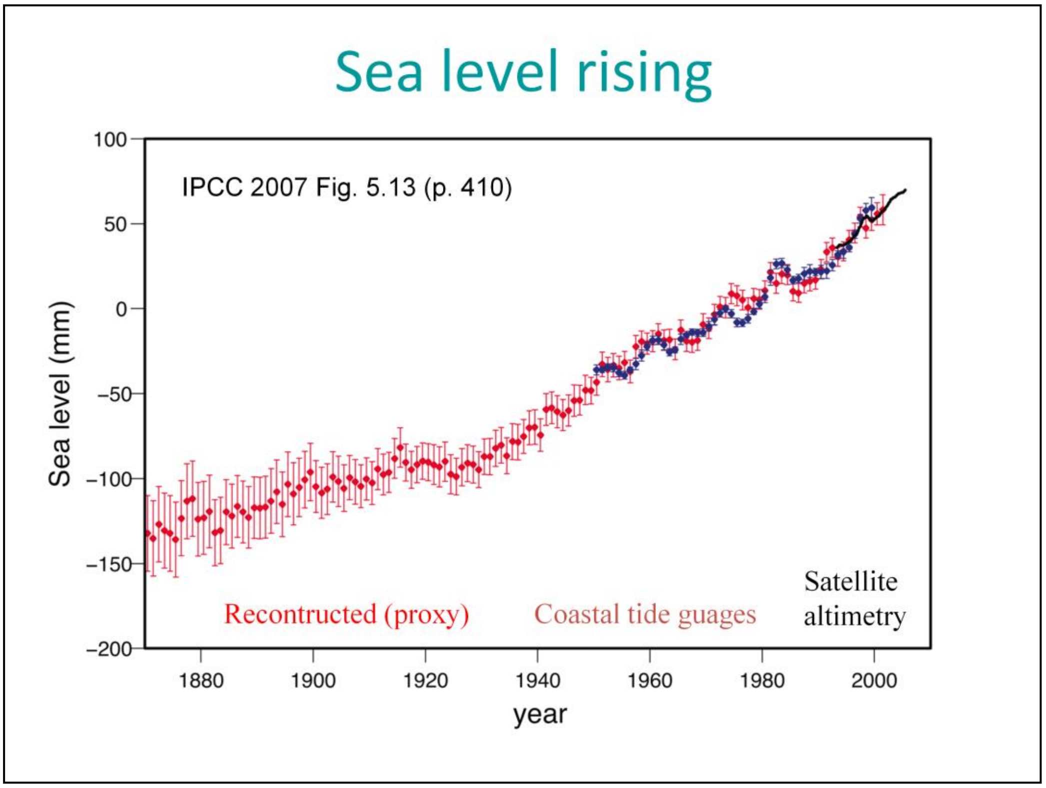


Shown in this slide are three independent measurements of global mean temperature; sea surface temperature, the air temperature over the land surface and the air temperature over the sea. For most of the time, they agree with each other reasonably well, which shows that this temperature rise is real. As can also be seen, warming since the 1970s has been more rapid over land than over the oceans, as would be expected from an increasing man-made greenhouse effect.

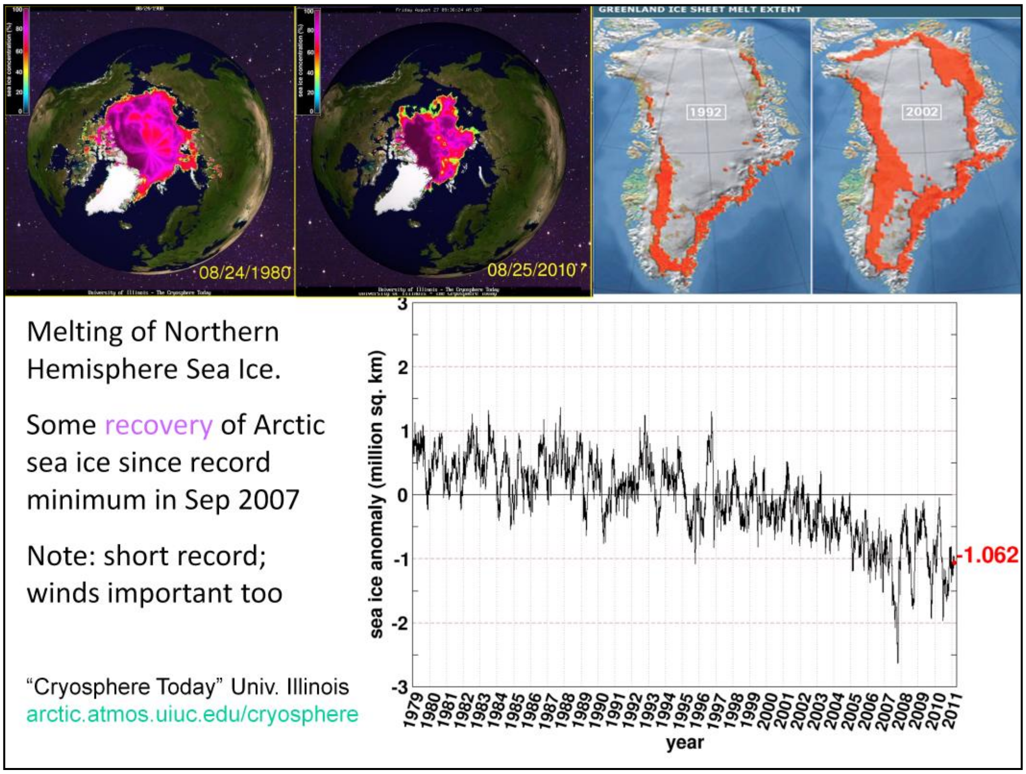
The amount of warming observed varies considerably from place to place, because natural variability of climate can add to man-made warming in some places, or subtract from it in others. Local factors (such as aerosol cooling) may also come into play. That the Earth's surface has experienced a recent warming is also supported by the widespread recession of mountain glaciers over the last few decades, and by measurements made at different depths in boreholes, which can be used to estimate the historical rise in temperatures.



At night, temperature in a city does not fall as quickly as in the country because the concrete retains heat more effectively than other surfaces and city surfaces radiate heat more slowly than in the country. This "urban heat island effect" is weakened or destroyed when winds are strong. So if the recently observed warming is an artefact of urbanisation, then one might expect the temperature rise on calm nights to show this increasing urbanisation and, hence, to be more rapid than that on windy nights. Work at the Hadley Centre (Met Office) has used daily night-time minimum temperature measurements at more than 250 land stations over most of the world, during the period 1950–2000. Data were taken for the top third most windy nights and the bottom third least windy nights (that is, the most calm conditions). Trends for these two subsets are plotted in the slide. Although, as expected, minimum temperatures in windy conditions are somewhat higher, the trend is the same in windy and calmer conditions. This clearly demonstrates that warming over the past 50 years has not been due to urbanisation.



IPCC 2007 Figure 5.13. *Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870 (updated from Church and White, 2006); the blue curve shows coastal tide gauge measurements since 1950 (from Holgate and Woodworth, 2004) and the black curve is based on satellite altimetry (Leuliette et al., 2004). The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals.*



A decreasing trend in Arctic sea ice has been observed: satellite data suggests the Arctic has lost 20% of its September sea ice since 1978.

Melting sea ice does not directly affect sea levels, as the ice is already afloat. But the melting will affect climate indirectly by changing ocean circulation patterns and reducing the amount of the sun's heat reflected back out to space – accelerating global warming. Sea ice loss is already becoming a problem for some animals, such as polar bears.

Permafrost is thawing in Alaska, Western Siberia and other arctic regions.

The Poles are an extremely important part of the Earth's system. Ice helps regulate the Earth's climate by reflecting solar radiation back out to space, insulating the oceans beneath, strongly influencing the oceans circulation. Antarctic sea ice shows no trends when averaged over the whole continent.

Some of the ice minimum in 2007 is thought to relate to circulation anomalies relating to La Nina conditions. Recent observational evidence suggests that 2008 may reach similar levels to 2007 without these amplifying circulation anomalies.

Have we reached a "tipping point" for Arctic sea ice?

Changing water cycle

- Drying over Sahel, Mediterranean, southern Africa and parts of southern Asia since 1900
- Moistening over eastern parts of N. and S. America, northern Europe and northern and central Asia
- More intense and longer droughts over tropics/sub-tropics since 1970s due to higher temperature and lower rainfall
- Frequency of heavy rainfall increased over land
- More intense tropical cyclones over N.Atlantic since 1970s but the evidence is weak elsewhere

• Long-term trends from 1900 to 2005 have been observed in precipitation amount over many large regions. Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia. Drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Precipitation is highly variable spatially and temporally, and data are limited in some regions. Long-term trends have not been observed for the other large regions assessed.

• Changes in precipitation and evaporation over the oceans are suggested by freshening of mid and high latitude waters together with increased salinity in low latitude waters.

• Mid-latitude westerly winds have strengthened in both hemispheres since the 1960s.

• More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics. Increased drying linked with higher temperatures and decreased precipitation have contributed to changes in drought. Changes in sea surface temperatures (SST), wind patterns, and decreased snowpack and snow cover have also been linked to droughts.

• The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour.

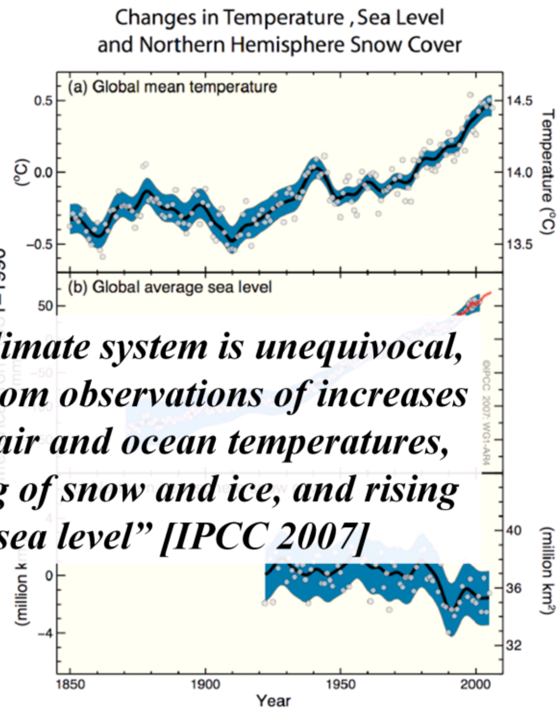
• There is observational evidence for an increase of intense tropical cyclone activity in the North Atlantic since about 1970, correlated with increases of tropical sea surface temperatures. There are also suggestions of increased intense tropical cyclone activity in some other regions where concerns over data quality are greater. Multi-decadal variability and the quality of the tropical cyclone records prior to routine satellite observations in about 1970 complicate the detection of long-term trends in tropical cyclone activity. There is no clear trend in the annual numbers of tropical cyclones.

Biological Signs

- Shorter winters
- Plant and animal ranges shifting
  - e.g. fish stocks moving north
- Declining animal populations
  - Cannot migrate as fast as movement of climatic zones
  - Habitat being affected by changing climate
  - Ocean acidification due to ↑CO_2

The seasons are changing. Spring arrives earlier: bees and butterflies can now appear in late winter, and people have seen daffodils at Christmas. Plant and animal ranges are shifting – fish are moving further north, the black kite and snow egret are expanding their ranges into the UK from southern Europe. Some plant and animal populations are declining, such as the capercaille, the snow bunting and various arctic flowers.

Is the planet warming?



"Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level" [IPCC 2007]

The total temperature increase from 1850 – 1899 to 2001 – 2005 is 0.76 [0.57 to 0.95]°C. Urban heat island effects are real but local, and have a negligible influence (less than 0.006°C per decade over land and zero over the oceans) on these values. [IPCC 2007]. More recently, the warming has been observed to heat the ocean to depths of at least 3km and to increase the average atmospheric water vapour (invisible, gaseous form of water) over land and ocean.

Global average sea level rose at an average rate of 1.8 mm per year over 1961 to 2003. The rate was faster over 1993 to 2003, about 3.1 mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear. There is *high confidence* that the rate of observed sea level rise increased from the 19th to the 20th century. The total 20th century rise is estimated to be 0.17 m.

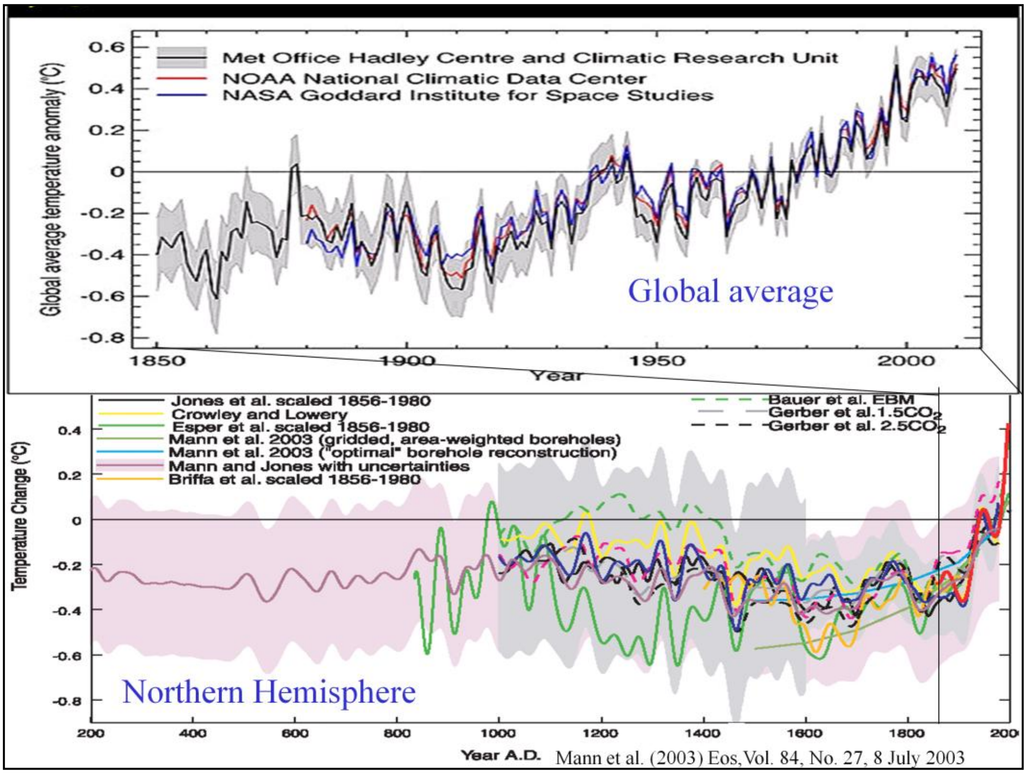
Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise (ice caps do not include contributions from the

Greenland and Antarctic ice sheets) as has the thermal expansion of the oceans in line with the ocean warming.

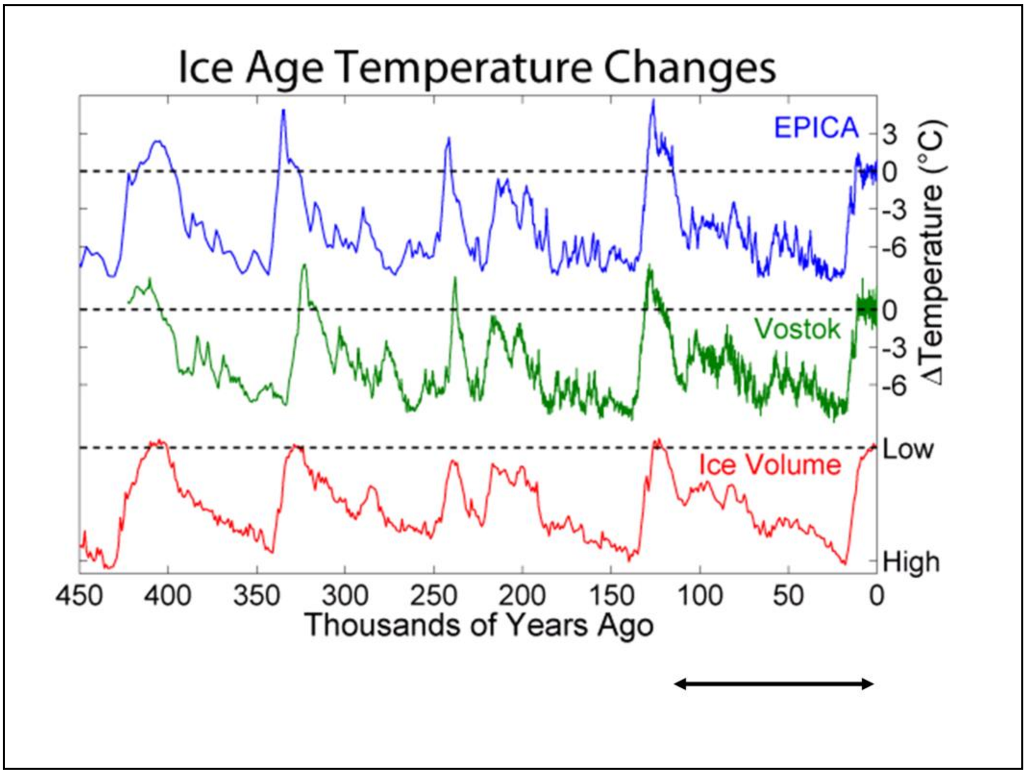
Is the warming unusual?

- Over the last 100 years the globe has warmed by about 0.8°C
- The warming appears unprecedented in at least the last 1300 years
- The last time polar regions were warmer than today was over 125 000 years ago
  – At that time sea level rose by 4-7m

Based on a multitude of proxy data it is possible to compare the recent warming found in the instrumental record, and corroborated with the proxy data, with the last 1300 years for a global dataset and for more than 100 000 years using polar ice core data. Both the magnitude of temperatures today and the rate of warming are unprecedented over the last millenium.

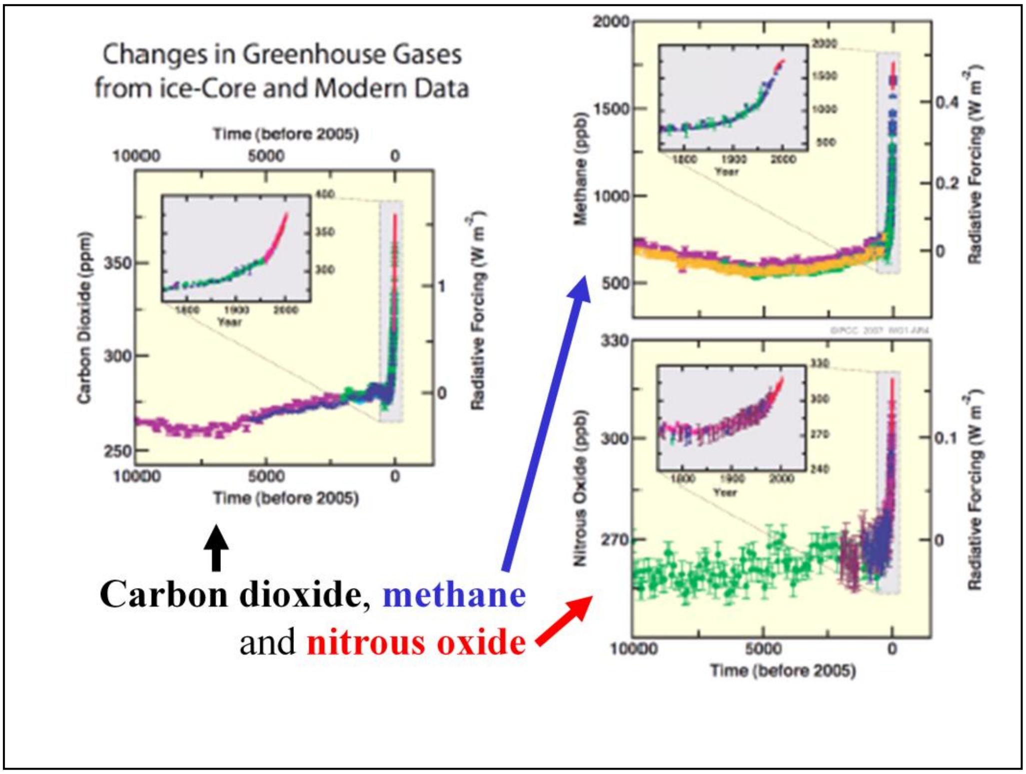


The current warming is highly unusual in the context of the last 1800 year record based on data from climate proxies such as tree rings, ice cores and historical records. The IPCC report (2007) states that "**Paleoclimate information supports the interpretation that the warmth of the last half century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



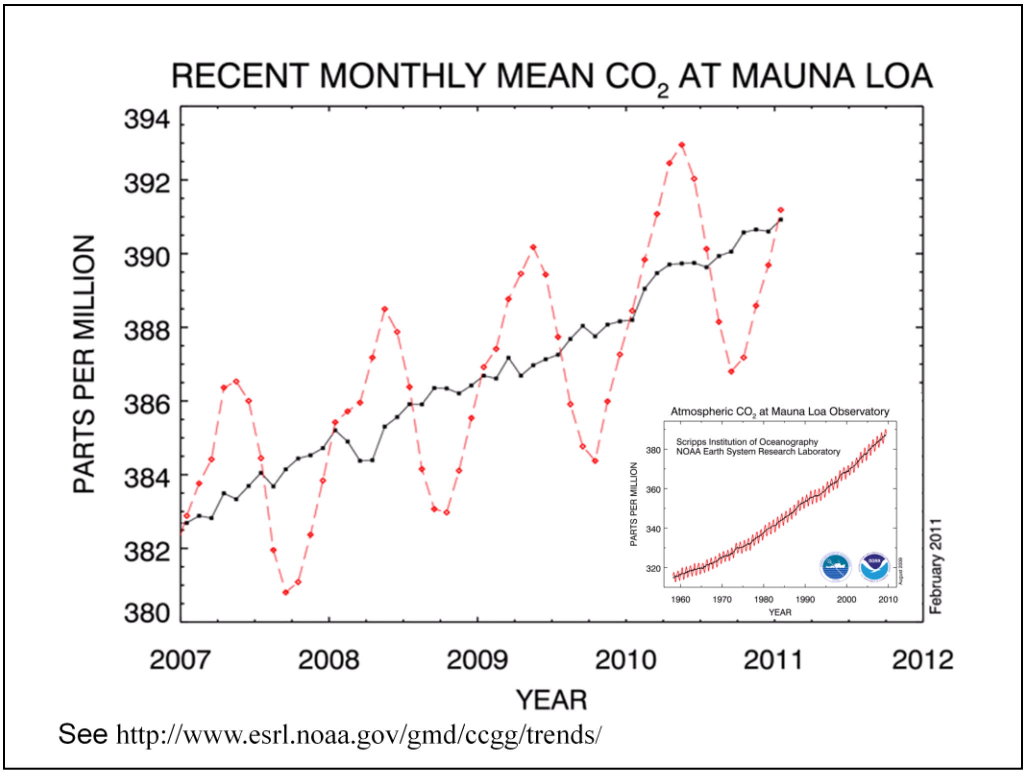
Data from ice cores shows a series of swings in climate from cold (glacial) to warm (interglacial). The timing of these appears to relate to the well known changes in Earth's orbit around the sun.

The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 metres of sea level rise.



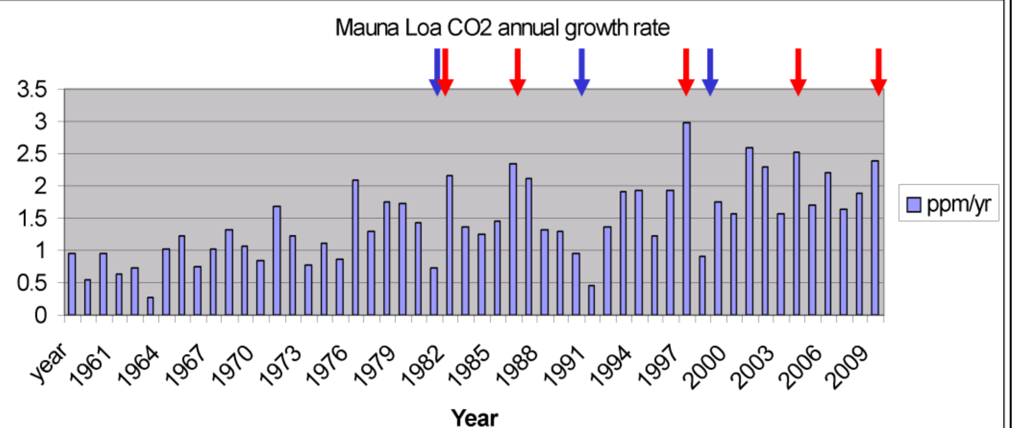
Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (above). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.

• Carbon dioxide is the most important anthropogenic (human produced) greenhouse gas. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 [more like 383 ppm in 2007]. The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores. The annual carbon dioxide concentration growth-rate was larger during the last 10 years (1995 – 2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year) although there is year-to-year variability in growth rates.



Concentrations of CO2 are likely to surpass 400ppm by 2015

- *Today's CO_2 concentration has not been exceeded during the past 650,000 years and likely not during the past 20 million years. The rate of increase over the past century is unprecedented, at least during past 10,000 yrs*
- Recent rates of **increase** in CO_2 appear to have been increasing:



http://www.esrl.noaa.gov/gmd/ccgg/trends/mlo.html#mlo_growth

The graph shows annual mean carbon dioxide growth rates based on Mauna Loa record. Red arrows denote recent strong El Nino years and blue arrows volcanos.

The Mauna Loa record shows a 19.4% increase in the mean annual concentration, from 315.98 parts per million by volume (ppmv) of dry air in 1959 to 377.38 ppmv in 2004. The 1997-1998 increase in the annual growth rate of 2.87 ppmv represents the largest single yearly jump since the Mauna Loa record began in 1958. This represents an average annual increase of 1.4 ppmv per year. This is smaller than the average annual increase at the other stations because of the longer record and inclusion of earlier (smaller) annual increases.

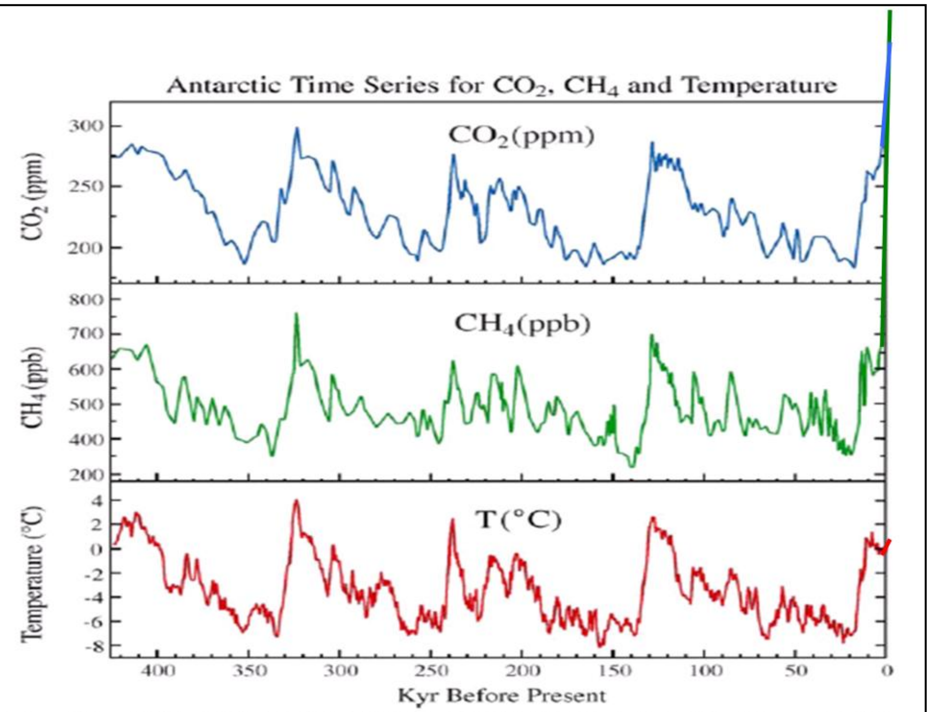
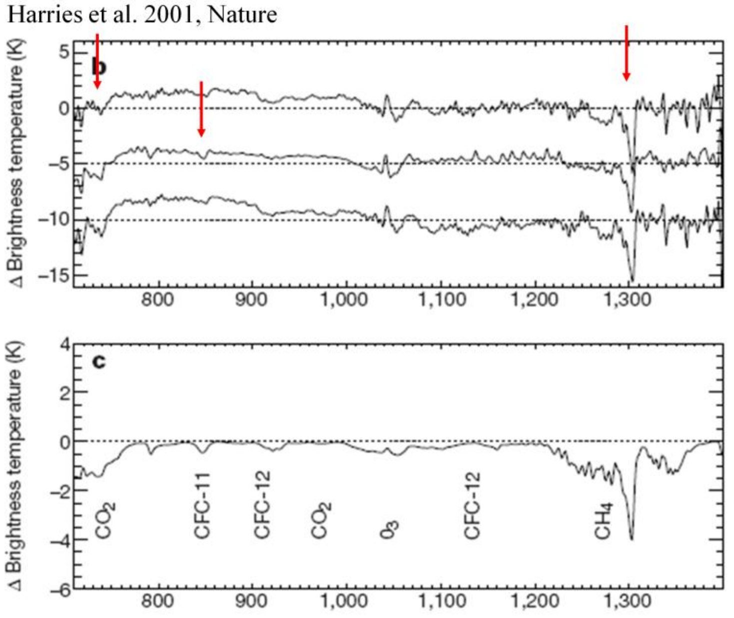


Fig. 4. CO_2, CH_4 and temperature records from Antarctic ice core data.
Source: Vimeux et al., Earth Plan. Sci. Lett., 203, 829, 2002.

There is an undoubted correlation between greenhouse gases and temperature over the glacial cycles of the last 0.5 Million years. However, correlation is not causation. Importantly, carbon dioxide is more soluble in colder water, so it is plausible that the changes in carbon dioxide are the result of changes in temperature. Also note that the current concentrations of carbon dioxide and methane are well off the scale in the above figure!

The difference in outgoing longwave or thermal spectra between two satellite instruments: 1997-1970

Harries et al. 2001, Nature



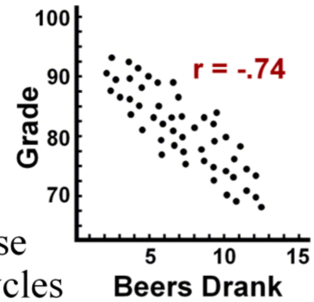
These results showed for the first time experimental confirmation of the significant increase in the greenhouse effect from trace gases such as carbon dioxide and methane

It is undoubtedly true that greenhouse gases act to warm the planet via the natural greenhouse effect.

Increases in these greenhouse gases have been shown, using satellite data, to have reduced the planets cooling from 1970 to 1997, in line with their predicted effects on the radiation budget.

Only by including the forcing of these greenhouse gas increases on the Earth’s radiative energy balance in sophisticated climate models, can the current warming trend be simulated…

Is warming due to increased greenhouse gases?

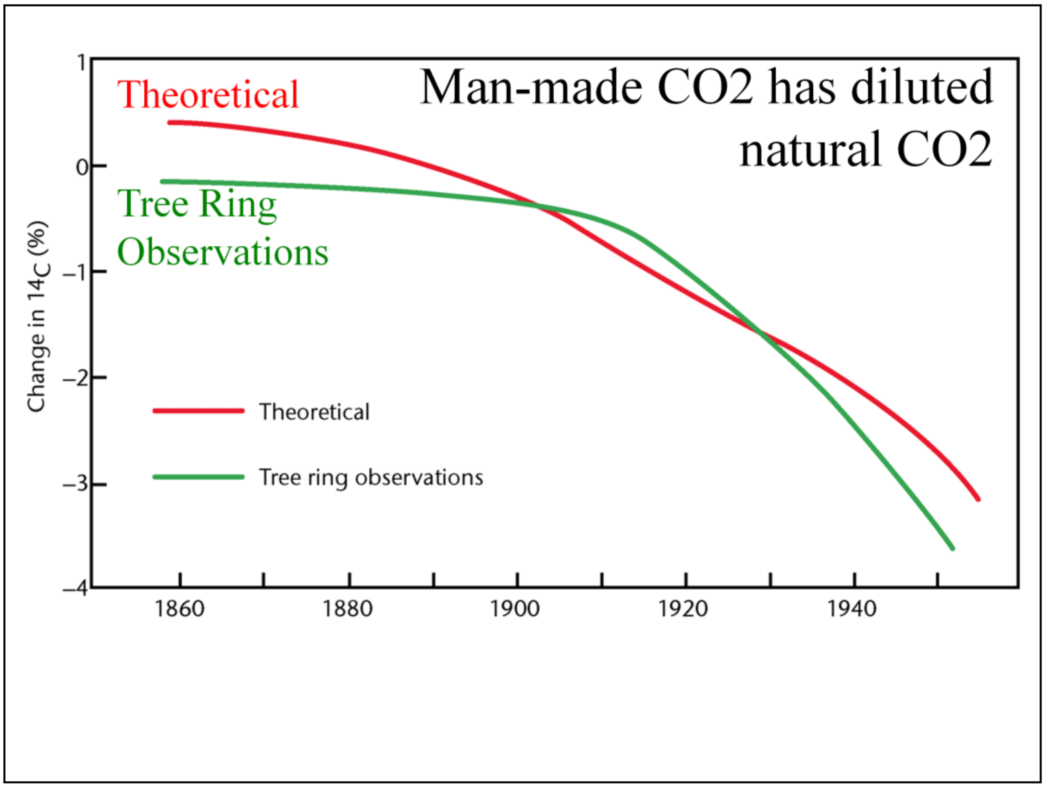


- Strong correlation between greenhouse gases and temperature over glacial cycles
  - …but correlation is not causation
  - Their estimated effect in amplifying the warming/cooling due to changes in the Earth's orbit over glacial cycles is in line with the current warming estimates
  - The greenhouse gases, carbon dioxide and methane, are at their highest levels for at least the last 650 000 years.
- Recent satellite measurements confirm that the rapidly rising greenhouse gas concentrations are enhancing the greenhouse effect in line with theory

Carbon dioxide is responsible for 60% of human-induced greenhouse warming, methane 20%, and nitrous oxide and other gases 20%.

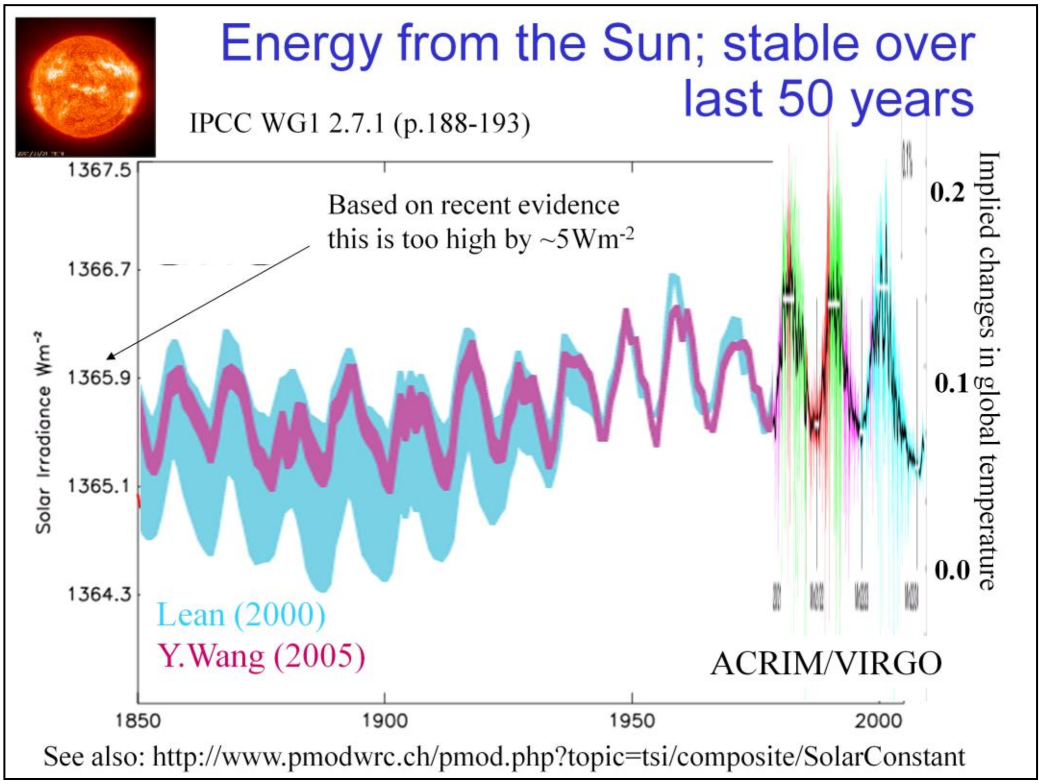
In addition to the changes in greenhouse gases, important amplification mechanisms are required to generate the current warming trend and are critical for predicting future warming.

Paleoclimate information supports the interpretation that the warmth of the last half century is unusual in at least the previous 1300 years. The last time the polar regions were significantly warmer than present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4 to 6 metres of sea level rise.



How do we know that the rise in carbon dioxide concentrations since the Industrial Revolution is due to emissions from man's activities? The carbon in CO2 has several different forms; the most common (about 99%) is called 12C, but there is a very small fraction of 14C, which is radioactive, with a half life of about 5,700 years. Because fossil fuels are so old, the 14C in them has decayed, so the CO2 given off when we burn them has very much less 14C in it. So the amount of 14C in the air is being diluted by CO2 emissions from burning coal, oil and gas, known as the 'Suess effect'. We can estimate the change in 14C in the air from 1850 to 1950 by measuring it in tree rings; this estimate is shown above in green. When we calculate what this should be, based on man-made CO2 emissions, the calculation (red line) agrees well with the measurements. This is proof that the rise in CO2 concentration is due to fossil fuel burning. The technique fails to work after about 1950, because radioactivity from atomic bombs corrupts the technique.

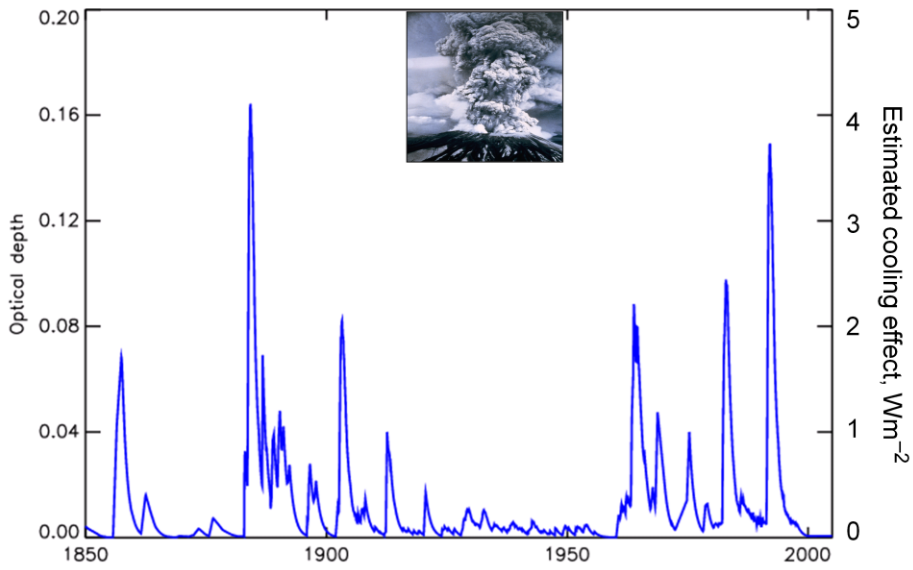
There is other supporting evidence, such as the consistency between the rise in concentration (unprecedented over the last several hundred thousand years) and man-made emissions, and the north-south gradient of CO2 concentration.



Solar irradiance before 1978 is estimated from proxy data (sunspots, etc) and is less reliable than that measured since then by satellites. However, proxy data combined with the satellite record shows clearly the 11-year solar cycle and a general rise from 1900-1950. This rise can only account for a 0.1 oC increase in temperature.

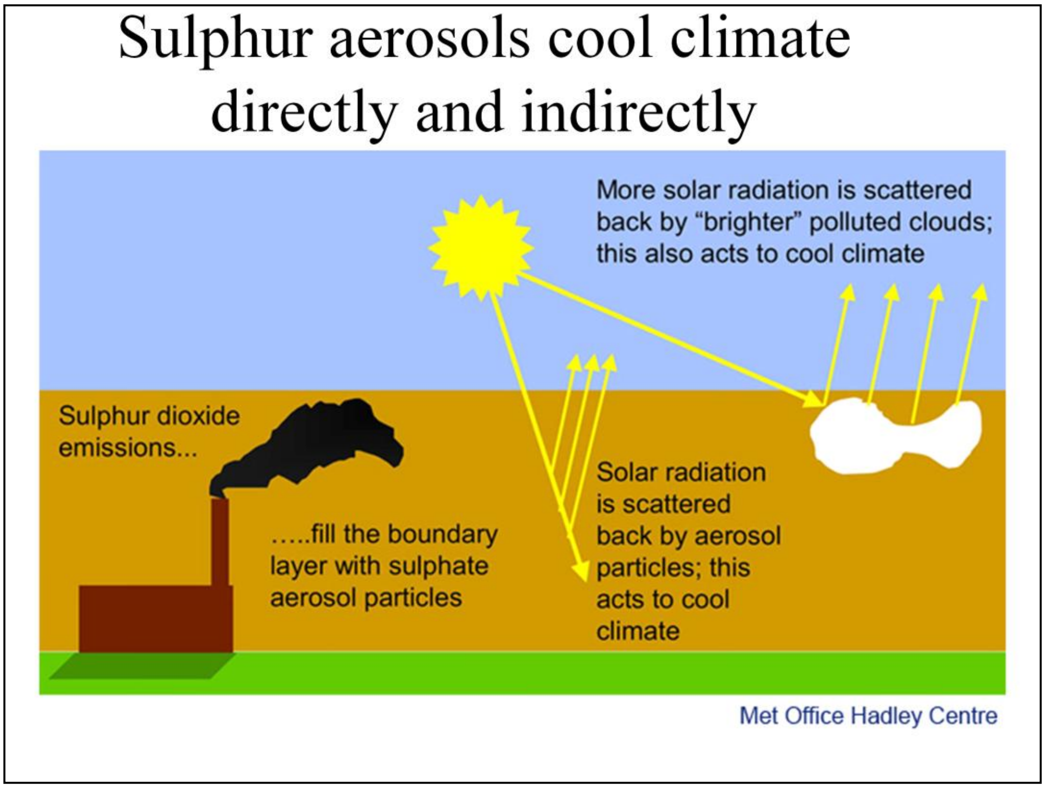
There are some theories that the solar influence on global climate could be amplified by an indirect route, for example involving stratospheric ozone or cosmic rays or clouds. A review of current understanding was prepared for the Hadley Centre by the University of Reading and Imperial College, London. This concluded that there is some empirical evidence for relationships between solar changes and climate, and several mechanisms, such as cosmic rays influencing cloudiness, have been proposed, which could explain such correlations. These mechanisms are not sufficiently well understood and developed to be included in climate models at present. However, current climate models do include changes in solar output, and attribution analyses that seek to understand the causes of past climate change by comparing model simulations with observed changes, do not find evidence for a large solar influence. Instead, these analyses show that recent global warming has been dominated by greenhouse gas-induced warming, even when such analyses take account of a possible underestimate of the climatic response to solar changes by models.

Change in volcanic aerosol



Source: Sato et al, GISS, NASA

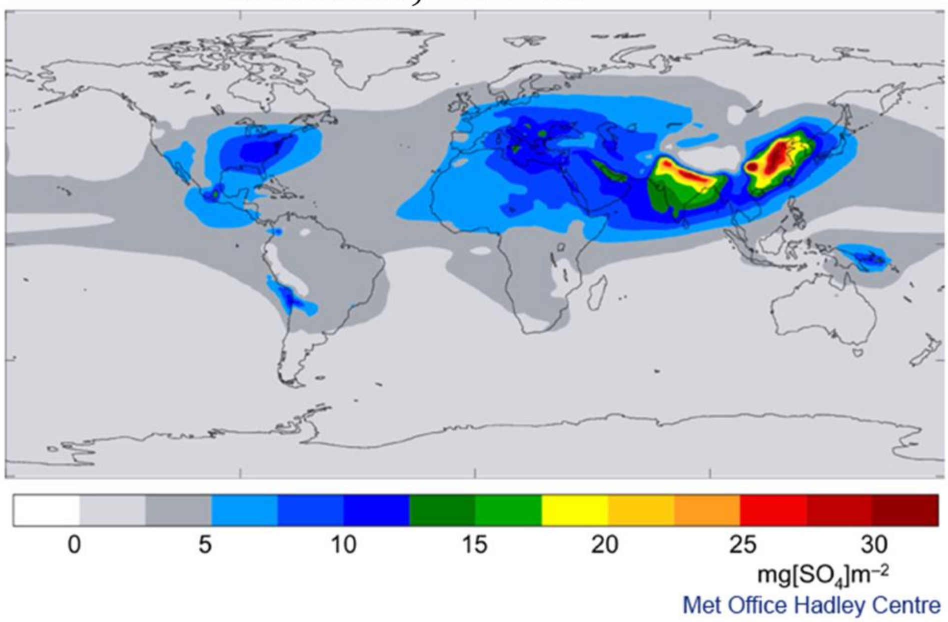
Volcanoes inject gas into the atmosphere. If they are energetic enough, this gas will reach the stratosphere and form small sulphate aerosol particles which can persist for a few years. They reflect back some of the solar radiation which otherwise would have heated the surface of the Earth, and hence act to cool the planet. The amount of volcanic aerosol in the atmosphere is very variable as is the cooling effect that this would have. Although energetic volcanoes were relatively common in the late 19th century (for example, Krakatoa in 1883) and early 20th century, and there have been substantial numbers of energetic volcanoes since the 1960s (most recently, Pinatubo in 1991), there was a period in the 1940s and 1950s when the atmosphere was relatively clear of volcanic aerosol. The amount of climate cooling due to volcanic aerosols would have been quite small in that period. This unusually low amount of volcanic cooling (together with the increase in solar radiation shown in the last slide) may have contributed to temperatures in the 1940s being relatively high compared to earlier decades. As with solar energy, optical depth due to volcanic aerosols has been estimated indirectly before about 1983, and hence is less certain.



Very small particles, known as aerosol, have a substantial effect on climate. Sulphate aerosol in the lowest part of the atmosphere (the boundary layer) is created when sulphur dioxide, emitted by human activities such as power generation and transport, is oxidised. Sulphate aerosol particles scatter some sunlight (as is the case following volcanic eruptions), which would otherwise reach the surface of the Earth and heat it, back out to Space. They therefore have a cooling influence on climate. Unlike volcanic aerosols that reach the stratosphere, their lifetime is limited and so require a constant source to keep concentrations up. The amount of sulphate aerosol in the atmosphere has increased by three or four times over the past 100 years or more due in part to fossil fuel burning.

Things are complicated because the sulphate aerosols are thought to make clouds more bright and to increase their lifetime, leading to an additional cooling effect.

Estimated burden of sulphate aerosol, 1990s



Sulphur dioxide gas and sulphate aerosols in the atmosphere can have impacts on human health, and also lead to acid rain which can fall at considerable distances from the emissions, acidifying waters such as lakes and endangering ecosystems. For these reasons, sulphur emissions have been greatly reduced in the US and Europe since the 1980s. It is expected that similar considerations will, in due course, lead to reductions of sulphur emissions in Asia and other rapidly developing parts of the world. When this happens, the current cooling effect of sulphate aerosols will be reduced, producing a warming effect which would add to that from greenhouse gases.

The above may explain why a reduction in the brightness of sunlight reaching the surface measured by ground based radiometers ("global dimming") has apparently reversed since the 1980s.

Is the warming due to increased greenhouse gases?

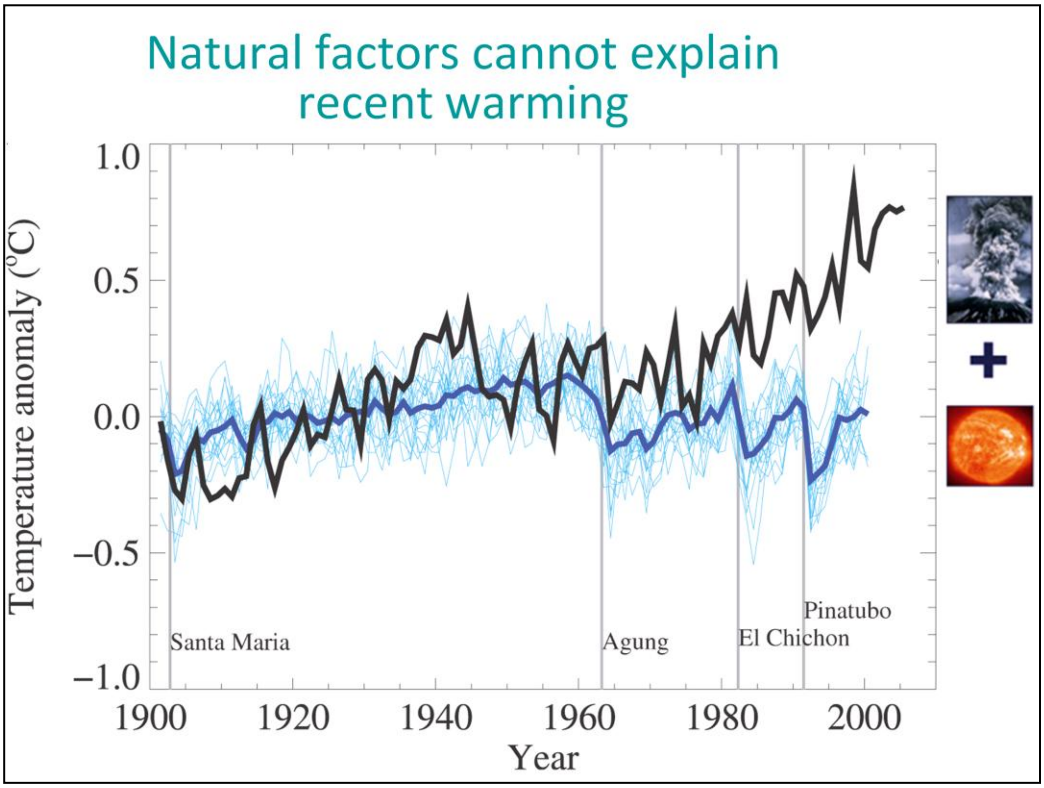
- Rapid rises in greenhouse gases since industrial revolution (CO_2, CH_4, N_20) are primarily due to human activity (fuel, agriculture, land use)
  - Also changes in ozone and CFCs/HCFCs important
- The warming effect of greenhouse gas increases outweighs the cooling effect from other pollution such as sulphate aerosols; this been the primary cause of a net heating of the planet since the 1950s.
  - Changes in the sun and volcanic input since 1750 are small in comparison

Most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations.

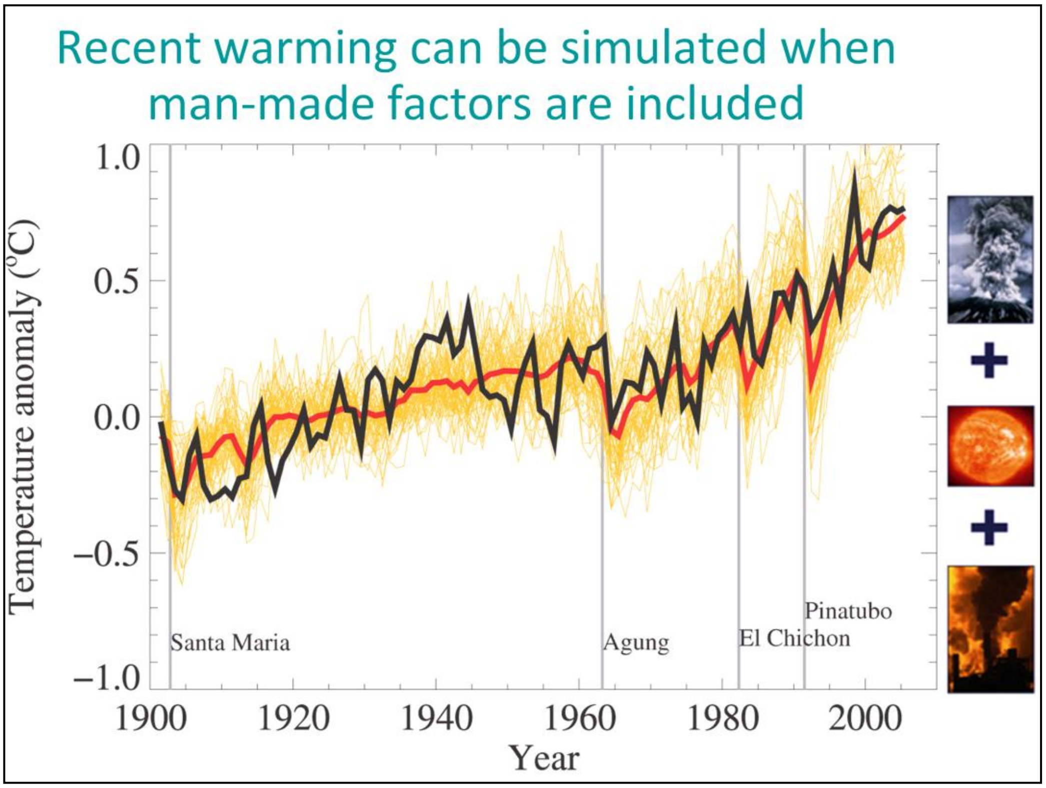
Experiments with climate models

- How much of the recent warming can be explained by natural effects?
- To answer such questions, experiments can be performed with climate models (more on this next week)

By prescribing changes in atmospheric constituents and changes in natural forcing agents such as the sun or volcanos, experiments can be run with climate models to see how well they reproduce the past climate and then what they project for future climate.

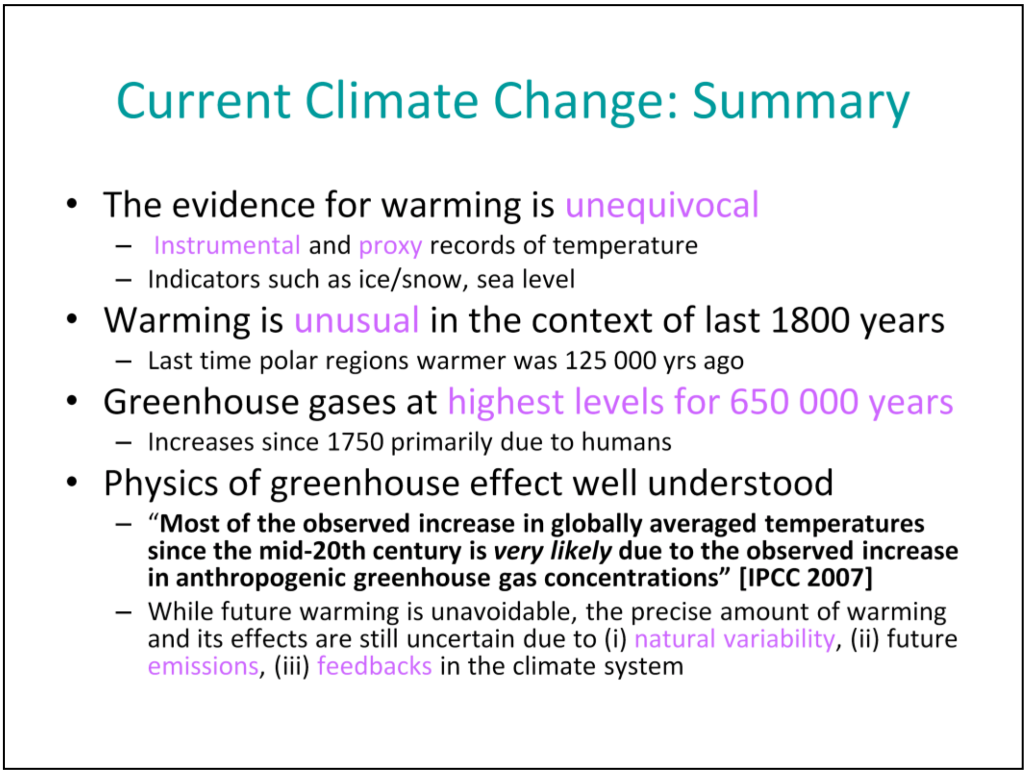


What are the causes of changes in global mean temperature observed since the early 1900s, shown in red on this slide? As we have already outlined, natural factors include a chaotic variability of climate due largely to interactions between atmosphere and ocean; changes in the output of the Sun and changes in the optical depth of the atmosphere from volcanic emissions. Climate models have been driven by changes in all these natural factors, and it simulates changes in global temperature shown by the green band in the slide above. This clearly does not agree with observations, particularly in the period since about 1970 when observed temperatures have risen by about 0.5 °C, but those simulated from natural factors have hardly changed at all.



If the climate model is now driven by changes in human-made factors — changes in greenhouse gas concentrations and sulphate particles — in addition to natural factors, observations (red) and model simulation (green) are in much better agreement. In particular, the warming since about 1970 is clearly simulated. Of course, this agreement may, to some extent, be fortuitous, for example, if the heating effect of man-made greenhouse gases and the cooling effect of man-made aerosols have been overestimated. Nevertheless, the ability to simulate recent warming only when human activities are taken into account is a powerful argument for the influence of man on climate.

In addition to simulating the global mean temperature, the model also simulates the pattern of changes in temperature, across the surface of the Earth and through the depth of the atmosphere. These ‘fingerprints of man-made warming’ have been compared to observations, providing even stronger evidence for the majority of the long-term trend over the last 50 years having been due to human activity.



Scientists are now even more certain that the current warming since the mid-20th century is primarily due to mans impact on the atmosphere via fossil fuel burning, agriculture and changes in land-use.

Much of this certainty comes from the observations but a large component comes about applying physical laws and theory, refined by the observations, to develop sophisticated computer models of the Earth's environment that help to understand the reasons for the warming and to enable predictions of future climate change over the next few hundred years…