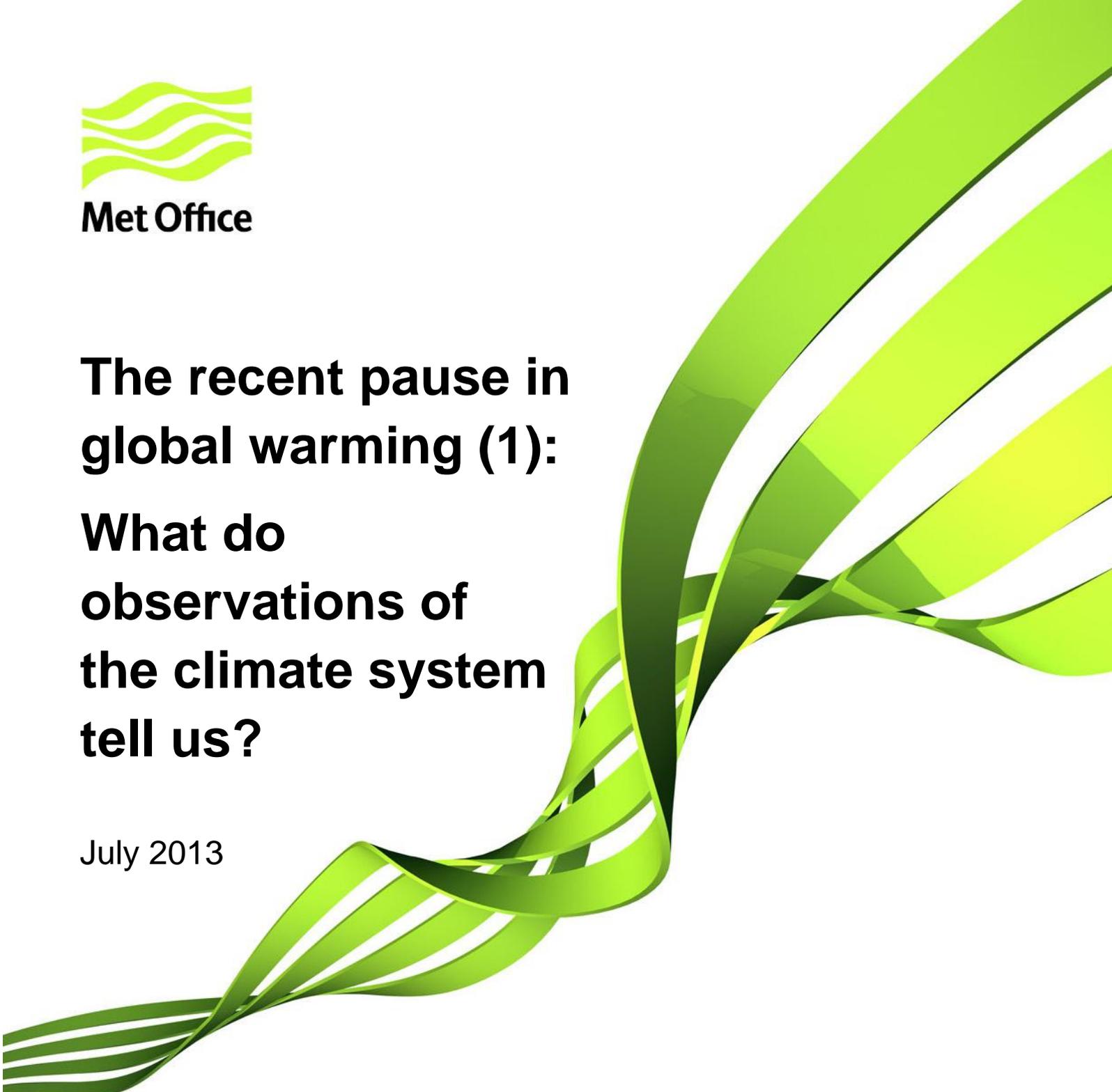




**Met Office**

**The recent pause in  
global warming (1):  
What do  
observations of  
the climate system  
tell us?**

July 2013





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## Executive summary

**A wide range of observed climate indicators continue to show changes that are consistent with a globally warming world, and our understanding of how the climate system works.**

Global mean surface temperatures rose rapidly from the 1970s, but have been relatively flat over the most recent 15 years to 2013. This has prompted speculation that human induced global warming is no longer happening, or at least will be much smaller than predicted. Others maintain that this is a temporary pause and that temperatures will again rise at rates seen previously.

This paper is the first in a series of three reports from the Met Office Hadley Centre that address the recent pause in global warming and seek to answer the following questions. What have been the recent trends in other indicators of climate over this period; what are the potential drivers of the current pause; and how does the recent pause affect our projections of future climate?

Weather and climate science is founded on observing and understanding our complex and evolving environment. The fundamental physics of the Earth system provides the basis for the development of numerical models, which encapsulate our understanding of the full climate system (i.e. atmosphere, ocean, land and cryosphere), and enable us to make projections of its evolution.

It is therefore an inherent requirement that climate scientists have the best possible information available on the current state of the climate, and on its historical context. This requires highly accurate, globally distributed observations and monitoring systems and networks. This is also dependent on robust data processing and analysis to synthesise vast amounts of data, properly taking into account observational uncertainty resulting from both measurement limitations and observational gaps, in both space and time. Only through exercising due diligence and applying rigorous, unbiased, scientific assessment, can climate scientists provide the most complete picture on the state, trends and variability of the climate system's many variables and phenomena. This provides the basis on which the science can advance the evidence and advice required by users.

This document provides a short synthesis of that global picture as it stands today. A fuller briefing is produced in conjunction with vast numbers of scientists each year, and published in a Special Supplement to the Bulletin of the American Meteorological Society (BAMS) (Blunden and Arndt, 2013).

The observations show that:

- A wide range of climate quantities continue to show changes. For instance, we have observed a continued decline in Arctic sea ice and a rise in global sea level. These changes are consistent with our understanding of how the climate system responds to increasing atmospheric greenhouse gases.
- Global mean surface temperatures remain high, with the last decade being the warmest on record.

- Although the rate of surface warming appears to have slowed considerably over the most recent decade, such slowing for a decade or so has been seen in the past in observations and is simulated in climate models, where they are temporary events.

## Our changing climate

The global mean temperature near the surface of the Earth is often used as the primary indicator of climate change, and often as the only indicator in many discussions. National and international negotiations on climate change tend to focus on ways of limiting global mean surface temperature rise to no more than 2°C above pre-industrial levels, this being a goal of the United Nations Framework Convention on Climate Change (UNFCCC).

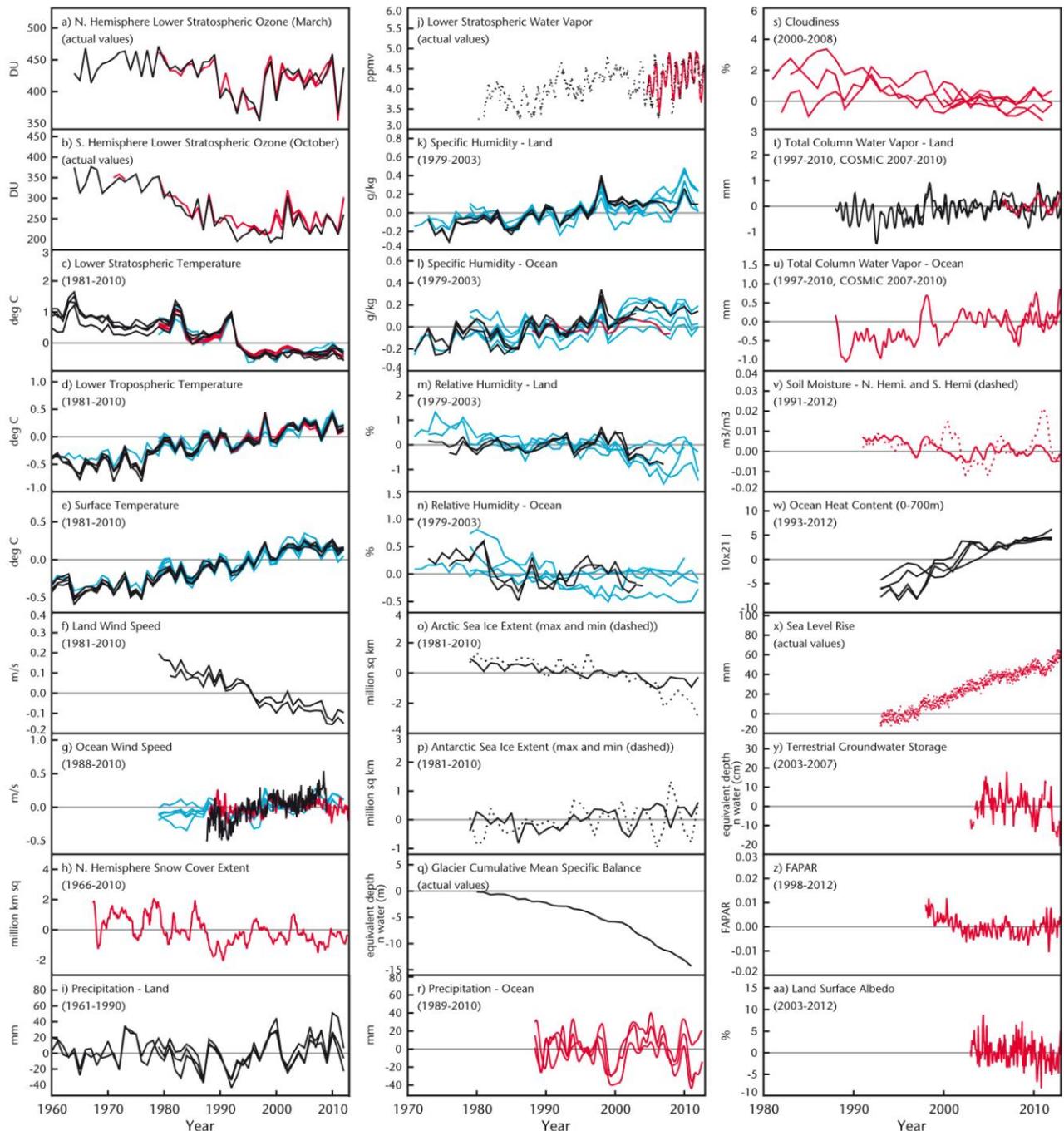
However, in addition to surface air temperature, there are other key indicators that can help to gauge the state of the climate, drawn from observations of the atmosphere, the ocean and the cryosphere (snow and ice). Through such observations, we increase our understanding of climate change trends and variability at global and, importantly, regional scales, providing a more comprehensive picture of the real state of the climate than through global mean surface temperature alone.

A number of 'Essential Climate Variables (ECVs)' have been defined by the Global Climate Observing System (GCOS) programme, and provide the broadest possible picture of the Earth's climate. These include:

- Atmospheric surface: air temperature, precipitation, air pressure, water vapour
- Upper atmosphere: earth radiation budget, temperature, water vapour, cloud properties
- Atmospheric composition: carbon dioxide, methane, ozone, nitrous oxide, chlorofluorocarbon (CFCs), sulphur hexafluorides, perfluocarbons, aerosols
- Ocean surface: temperature, salinity, sea level, sea ice, currents, ocean colour
- Ocean subsurface: temperature, salinity
- Terrestrial: snow and ice cover, albedo

A number of additional ECVs are monitored and others are likely to be added in future.

Figure 1 shows the observed time-series of a large number of ECVs. Each time-series includes data from a number of sources (either plotted separately, or combined into a single line). Many show long term trends which are consistent with our understanding of how the world is expected to respond to an increasing atmospheric burden of greenhouse gases. Many of the trends continue over the most recent decade.



**Figure 1:** Global (or representative) average time-series for a number of Essential Climate Variables from a range of observation datasets. Time-series are presented as differences from a baseline<sup>1</sup> period shown in parentheses. (Source: “State of the Climate in 2012”, Bulletin of the American Meteorology, Blunden and Arndt, 2013)

<sup>1</sup> To show how observations are changing it is common to show the anomaly – that is the difference of the observed values from the average of a particular period. The period used is referred to as the baseline.

# 1. Atmosphere

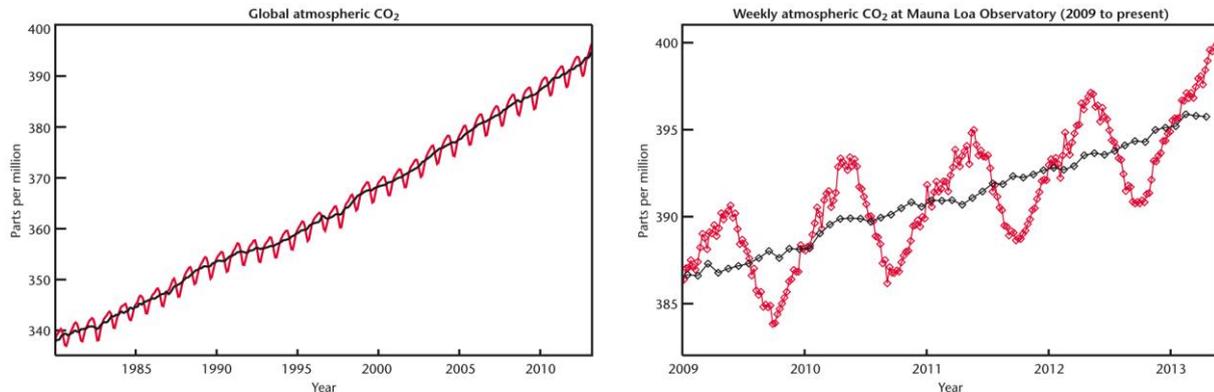
The atmosphere is constantly measured and monitored throughout its depth. Here we consider the atmosphere at the surface of the planet, and in the troposphere<sup>2</sup> and further up, in the stratosphere<sup>2</sup>. Monitoring the atmosphere at different heights, in conjunction with our understanding of the physics of the atmosphere, can tell us whether our climate is changing.

## 1.1 Atmospheric composition – carbon dioxide

Human activities – changes in land use and burning fossil fuels – have increased the levels of greenhouse gases (principally carbon dioxide and methane) substantially since pre-industrial times (pre-1850s), and the levels continue to rise (Figure 2).

Carbon emissions continue to grow at 3.1% per year (Peters et al, 2012). This is comparable to the high-end Intergovernmental Panel on Climate Change (IPCC) emissions scenarios that do not include specific climate change mitigation policy actions. The likely range of 21st century warming<sup>3</sup> is projected from the IPCC 4th Assessment Report high emission scenario as 1.4 °C to 6.4°C (IPCC 2007).

Atmospheric carbon dioxide levels are around 30% higher today than at any other time over at least the last 800,000 years (Lüthi et al, 2008). In March 2013, globally averaged atmospheric CO<sub>2</sub> reached 396.52 parts per million (ppm) (NOAA), while in May 2013, the weekly average CO<sub>2</sub> levels at the Mauna Loa Observatory surpassed 400ppm for the first time. Levels are now over 40% higher than pre-industrial levels.



**Figure 2:** (left) Long-term atmospheric globally averaged CO<sub>2</sub> measurements, and (right) recent weekly averaged CO<sub>2</sub> levels from a single site (Mauna Loa, Hawaii). The red line shows monthly (left) and weekly (right) mean values and the black line shows values corrected for the average seasonal cycle. (Source: based on The National Oceanic and Atmospheric Administration (NOAA))

<sup>2</sup> The atmosphere is made up of a number of layers. The lowest layer is the troposphere and this is where most of the weather we experience exists. It extends from the surface of the planet to its upper limit, the tropopause, typically between 8 km at the poles and 17 km at the equator. The second layer is the stratosphere, which extends from the tropopause to the stratopause at an altitude of 50–55 km.

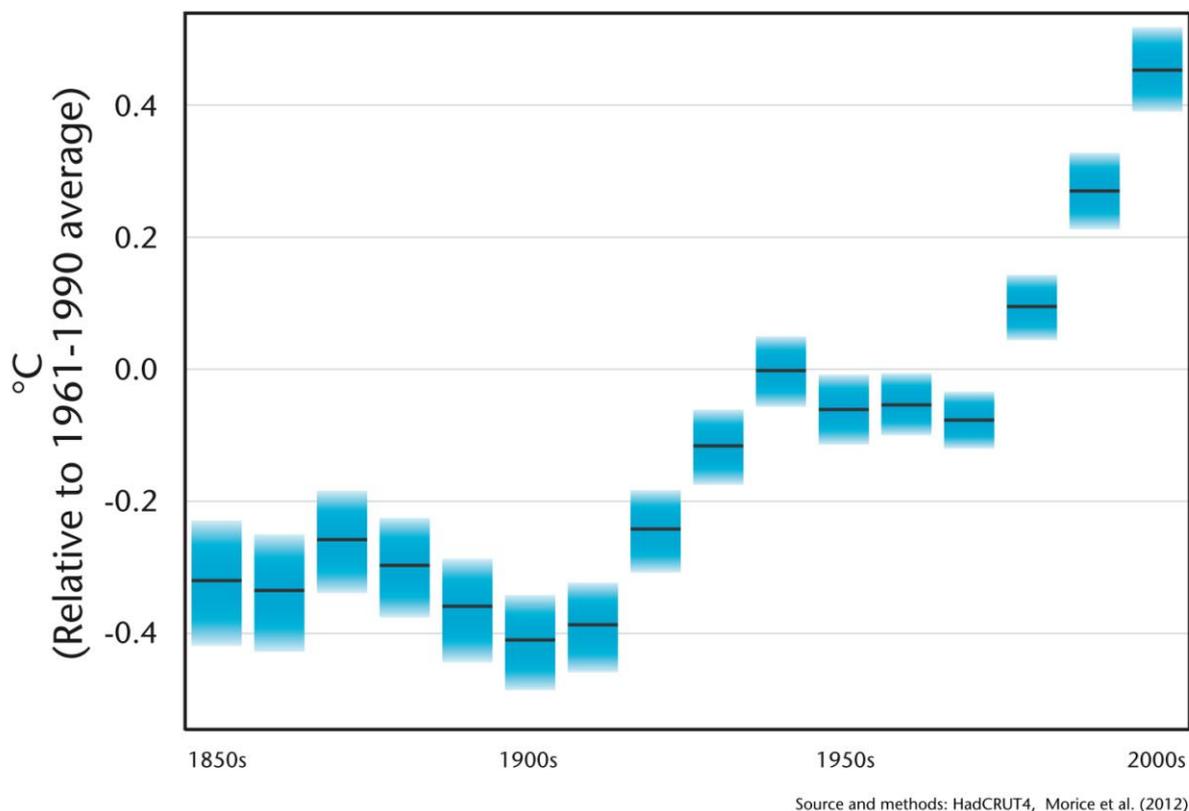
<sup>3</sup> Projected global average surface warming for the end of the 21st century (2090–2099) relative to 1980–1999.

## 1.2 Near surface air temperature

Considerable debate has focused on observations of the global mean surface temperature. Comprehensive global mean surface temperatures from the instrumental record stretch back to the 1850s. Over that period, a number of independently prepared datasets (including Met Office Hadley Centre, NOAA and NASA data) show that the temperature has risen by around 0.8 °C; over the last century the temperature rise has been around 0.7°C.

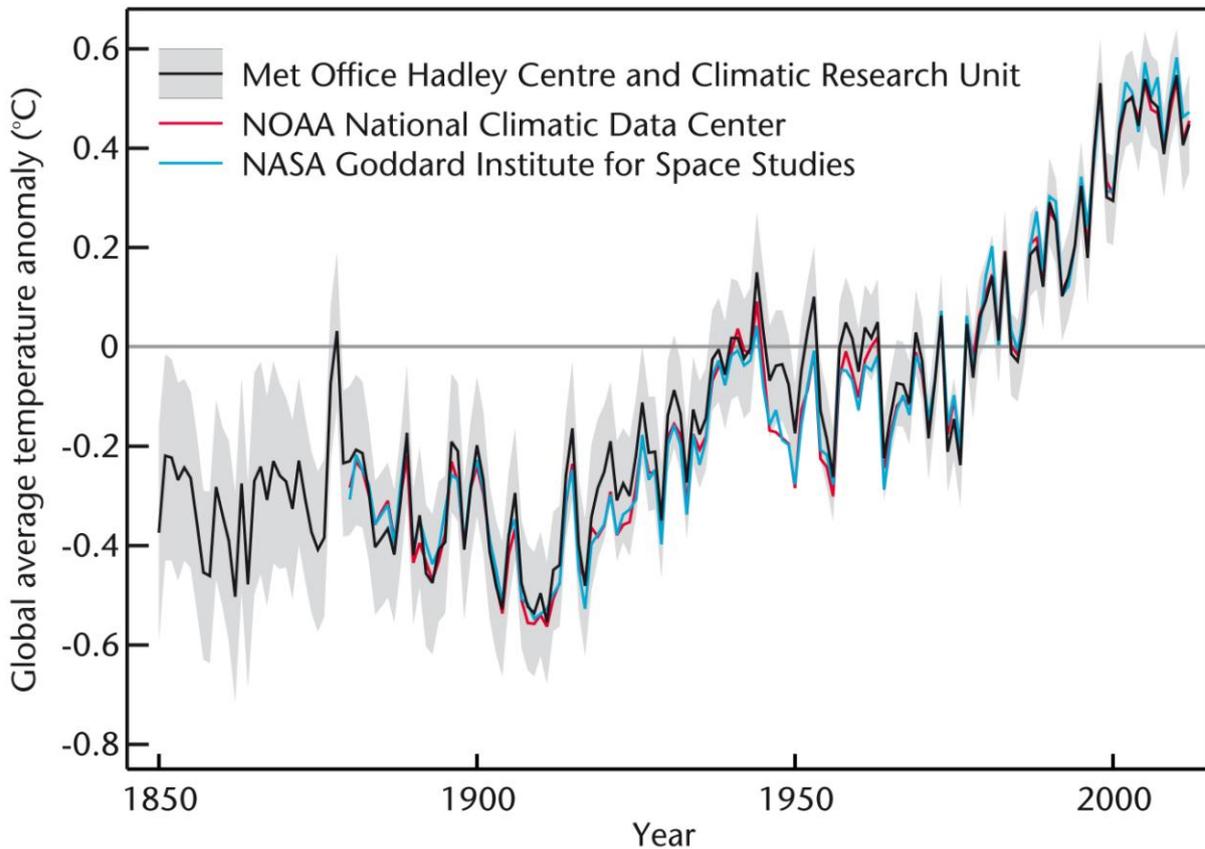
### Decadal and annual means

Despite slowing of the rate of warming in recent years, the first decade of the 21<sup>st</sup> century (2000–2009) is the warmest in the observational record. Even allowing for uncertainties in the observations, each of the last three decades has been markedly warmer than the decade before (Figure 3).



**Figure 3:** Observed global mean surface temperature for each decade from 1850 to 2009 relative to 1961–1990 baseline. Blue shading shows the uncertainty range in the temperature data. (Source: Met Office)

Looking at the time-series of annual, rather than decadal, mean values brings out the detail of year-to-year variations (Figure 4). There is good agreement between the three independent datasets, with NOAA and NASA data generally within the observational error of the HadCRUT4 – this gives further confidence in the records.

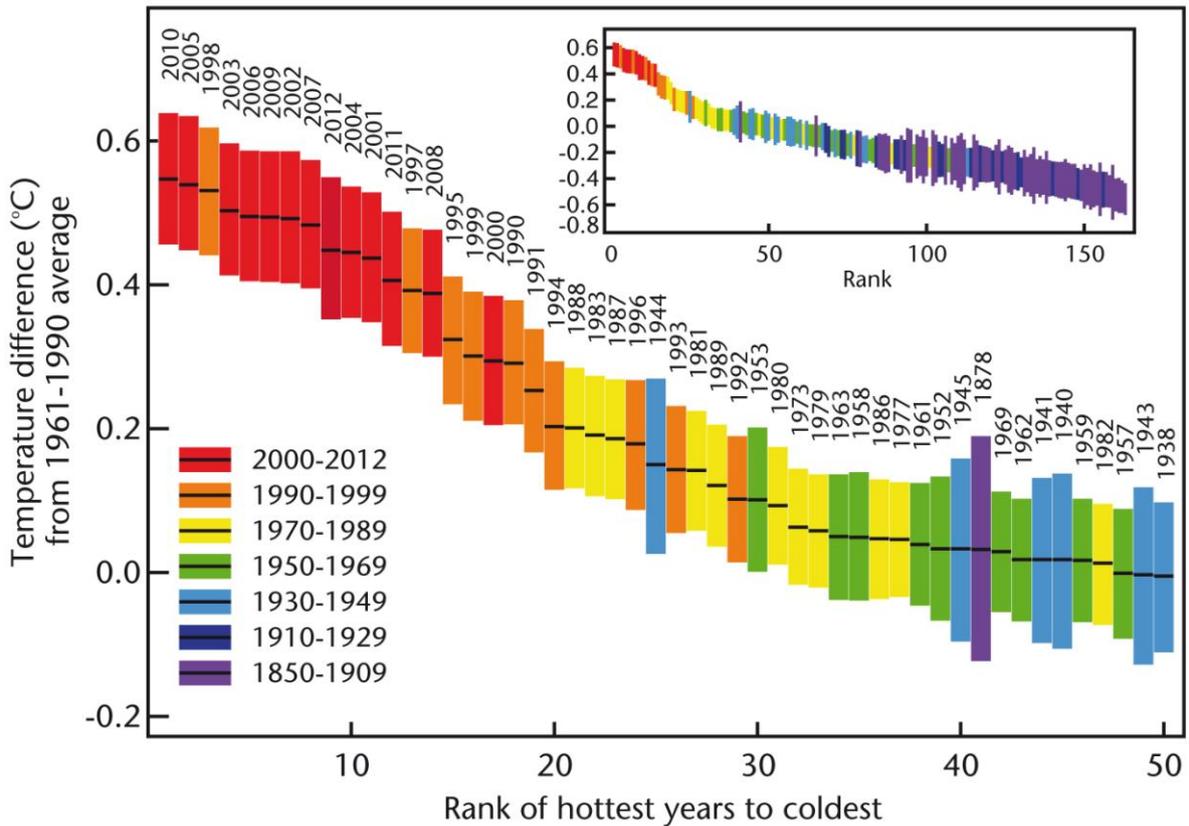


**Figure 4:** Comparison of 12-month running mean of three independent global mean surface temperature records (relative to the 1961–1990 baseline). The grey shaded area shows the approximate 95% confidence range for the HadCRUT4 data (the ‘true’ global average is expected to lie outside this range around only 5% of the time). (Source: Met Office)

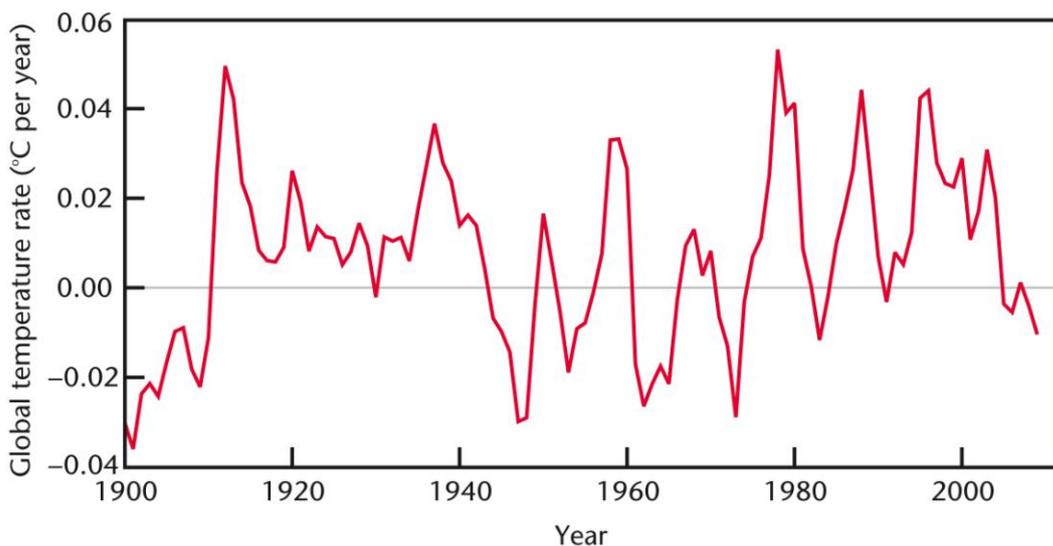
Year-to-year variations of global mean surface temperature are strongly affected by natural variations in the climate system (for example the temporary global warming and cooling influences of El Niño and La Niña). These are quite small when compared to the total magnitude of global warming but nevertheless reach about  $\pm 0.2^{\circ}\text{C}$ , and can strongly influence the average temperature of any individual year. For example, 1998 saw a particularly strong El Niño with a global temperature anomaly of  $\sim 0.5^{\circ}\text{C}$ , whereas 1999, when La Niña dominated, the temperature anomaly was  $\sim 0.3^{\circ}\text{C}$ , relative to the 1961–1990 baseline. Despite this natural climate variability, the observed surface temperature dataset, HadCRUT4, shows that 12 of the 14 warmest years on record have occurred since 2000 (Figure 5).

### Trends

By taking the time-series shown in Figure 4, the variations in the *rate* of warming can be computed (Figure 6). This shows that relatively long periods (of at least 10 years) of slow-down (in some cases actual cooling) and speed-up in global temperature trends occur, and have been observed a number of times in the relatively recent past. The data in figure 6 have been processed to remove the noise from the year-to-year variability and thus to highlight the underlying climate change signal. Each point on the graph is the average rate of warming for the eight years around that point, and so the last point, plotted at 2009, is calculated from 2005–2012.



**Figure 5:** Ranking of the annual global mean surface temperature in the HadCRUT4 dataset for each year since 1850. Bars are colour-coded by time period, and the length of each bar indicates the observation uncertainty. (Source: HadCRUT4, Met Office)

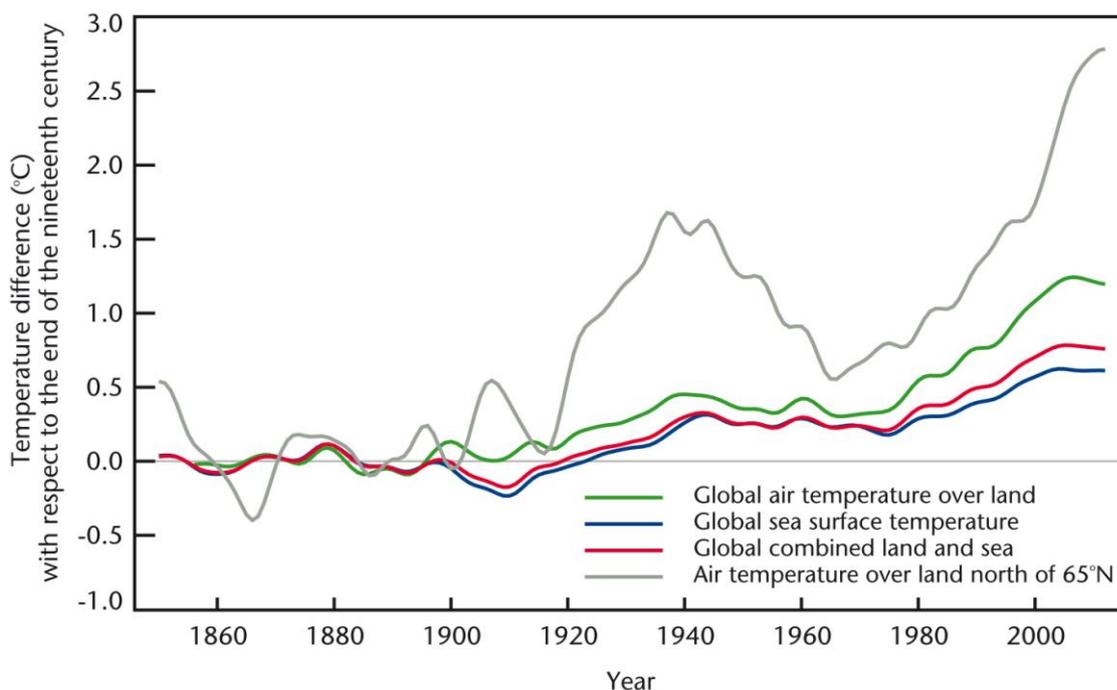


**Figure 6:** Illustration of the rate of change of annual mean global mean surface temperature (°C per year, filtered to smooth over eight years) since 1900, showing periods of speed up and slow down in the rate of warming. (Source: based on Murphy et al, 2009)

## Regional temperature changes

One characteristic feature of climate change (in both observations and models), is that the land warms faster than the sea (Sutton et al, 2007). A number of studies have investigated the physical reasons for this feature (e.g. Joshi et al, 2008). Observations bear this out as shown in Figure 7. Globally since 1970, the land has warmed at a rate of 0.26°C per decade, compared to 0.13°C over ocean areas.

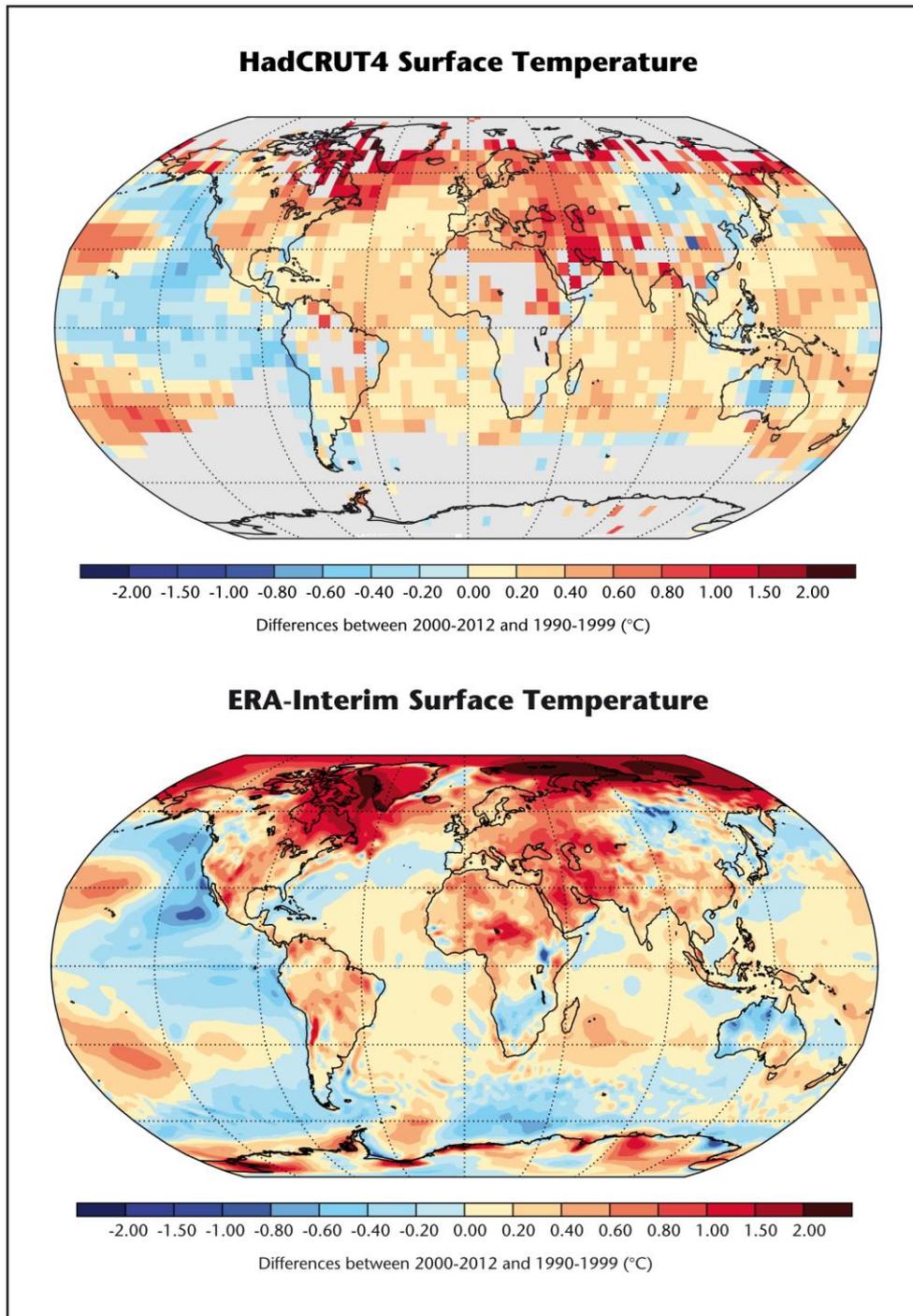
Regionally we also see variations in the rate of warming (Figure 7). Over the last century, the Arctic has warmed at approximately twice the rate of the global average (IPCC 2007, Working Group 1). Over the last decade, while global surface temperature rise has paused, the Arctic land areas have continued to warm markedly even allowing for uncertainties of the observing system (see Figure 8 below).



**Figure 7:** Observed annual average (smoothed) near-surface temperature relative to the end of the 19<sup>th</sup> century (1861–1900 baseline) for global land only (green); global sea surface temperature (blue); global combined land-sea (red); Arctic land above 65°N (grey). (Source: HadCRUT4, Met Office)

The greater warming over the Arctic and over land is also evident in Figure 8 where the regional changes in surface air temperature during the period of reduced global warming trend (2000–2012) versus the previous decade (1990–1999) are shown. As the top panel indicates, there are still some significant gaps in the observing system especially in polar regions. The values in these gaps may be estimated with a technique known as a reanalysis<sup>4</sup>. Figure 8 (bottom panel), from the European Centre for Medium range Weather Forecasting (ECMWF) Reanalysis (ERA-Interim) shows how much the Arctic has continued to warm over the past decade.

<sup>4</sup> A reanalysis uses a physically based synthesis of observations using a state-of-the-art model. This technique is increasingly valuable for estimating and understanding changes in the climate system.



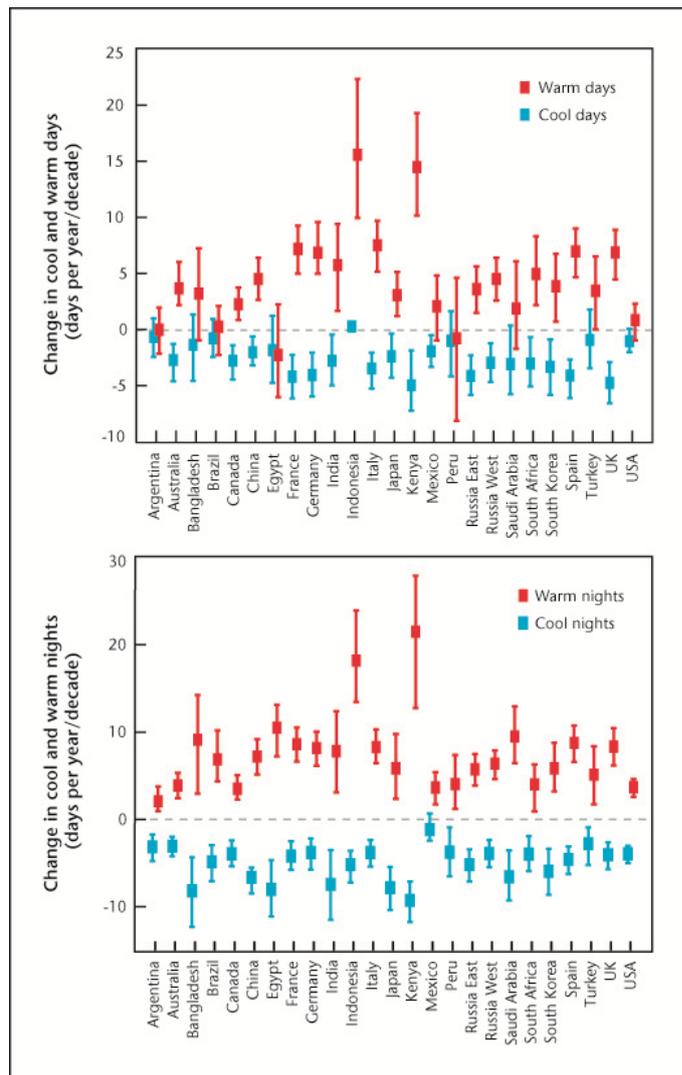
**Figure 8:** Near-surface average temperature for the period 2000–2012 relative to 1990–1999 from surface observations (HadCRUT4: top) and ECMWF Reanalysis (ERA Interim: bottom). (Source: Met Office, ECMWF)

Figure 8 also suggests that much of the recent pause in global mean surface warming is associated with the sea surface temperature (particularly in the eastern Pacific) and that many land areas have continued to warm for at least part of the most recent period. The patterns of relative warming and cooling in the ocean are not random but indicative of changes in ocean circulation (such as the Pacific Decadal Oscillation – see second report in

this series). Furthermore, changes in the pattern of ocean temperatures affect the atmosphere, and through the process of teleconnection<sup>5</sup>, can also leave an imprint on changes in land surface temperatures in many regions.

### Temperature extremes

As the mean temperature of the Earth has increased, changes are also evident in weather extremes across the world, such as extreme heat and intense flooding. Other meteorological aspects, such as the length of the growing season and the diurnal temperature range, also show changes that are consistent with a warming world. Over the last 50 years we have detected that cool days and nights have become less frequent, while warm days and nights have become more frequent for many countries (Figure 9).



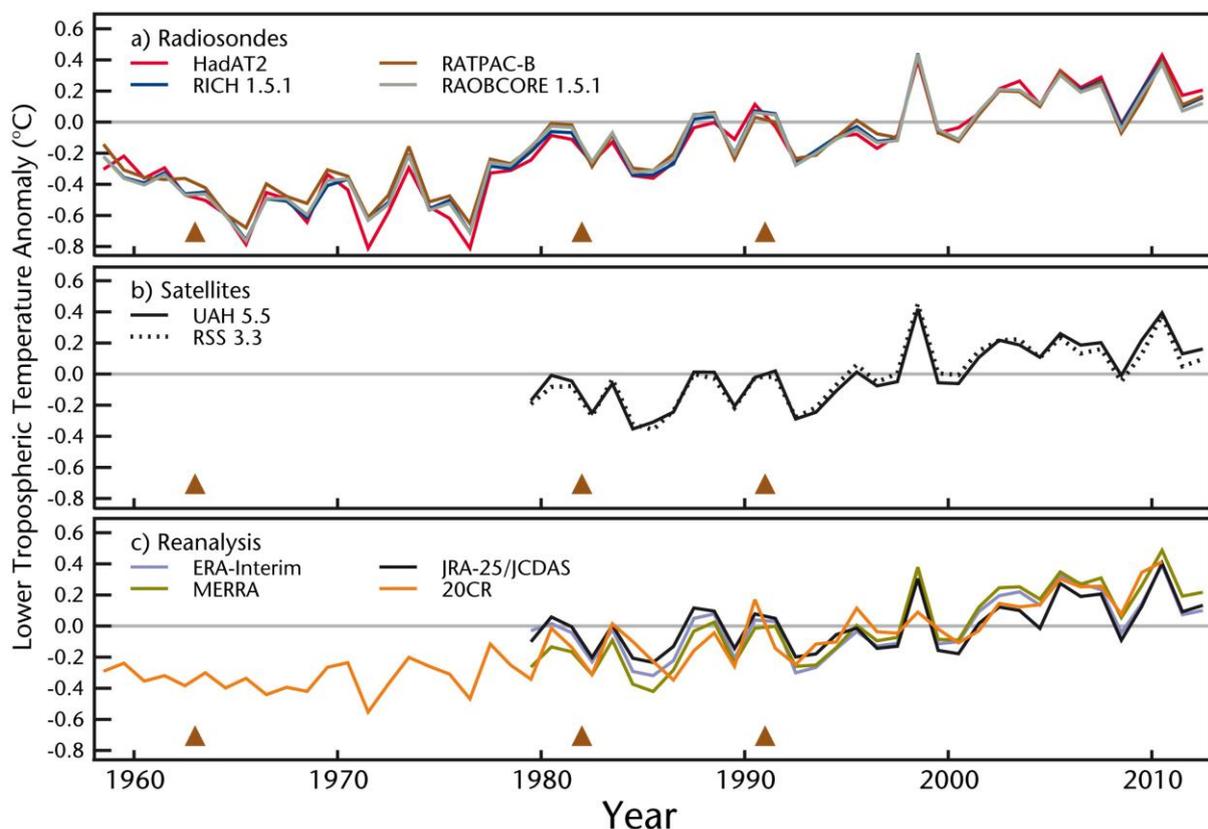
**Figure 9:** Observed changes in number of cool/warm days and cool/warm nights since 1960 for 24 countries. (Source: Met Office)

<sup>5</sup> Teleconnection refers to climate anomalies that are related to one another despite being large distances (typically thousands of km) away. For example the relationship between the sea-level pressure at Darwin, Australia and Tahiti that defines the Southern Oscillation, and the relationship between the sea-level pressure at Iceland and the Azores that defines the North Atlantic Oscillation.

### 1.3 Lower tropospheric temperature

Warming rates in the troposphere (the lowest layer of the atmosphere) are largely consistent with those at the surface. Observational datasets tend to focus on the lower levels of the troposphere because satellite retrievals are less likely to be contaminated by stratospheric temperatures and more likely to show a detectable signal.

Figure 10 shows several analyses of changes in lower tropospheric temperature over the last 50 years (this covers a region between the surface and around 8km). There are several ways of measuring this; directly through radiosondes; indirectly through satellite radiances; and finally through a synthesis of all available observations known as reanalysis<sup>4</sup>. As is the case for surface air temperature, there is substantial year-to-year variability associated, for example, with volcanic eruptions and El Niño-Southern Oscillation (ENSO) cycles, alongside the long-term warming trend.



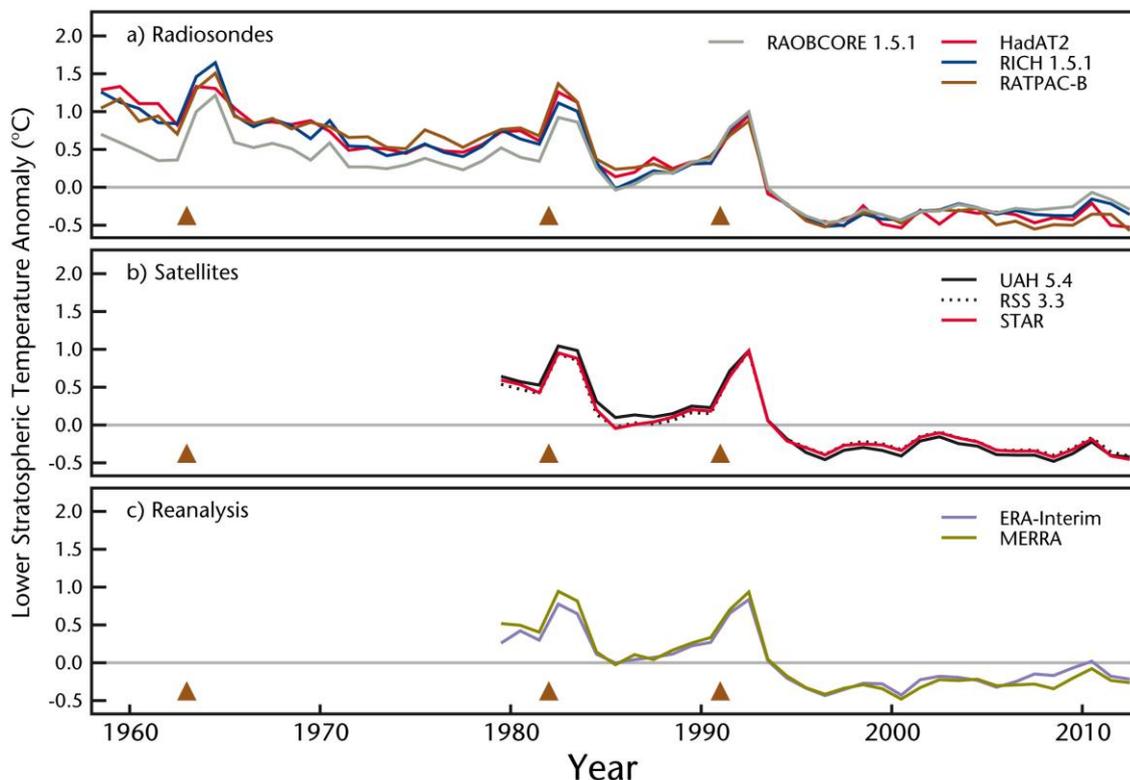
**Figure 10:** Various observed estimates of lower tropospheric temperature changes over the last 50 years relative to a 1981–2010 baseline. The brown triangles show the timing of major volcanic eruptions. (Source: “State of the Climate in 2012”, *Bulletin of the American Meteorology*, Blunden and Arndt, 2013)

## 1.4 Stratospheric temperature

Conversely, under anthropogenic greenhouse gas (GHG) induced climate change, the stratosphere is expected to cool. This is mainly because with increased anthropogenic GHG concentrations, the stratosphere can radiate energy more effectively to space. In addition, GHGs trap some of the outgoing thermal (infrared) radiation within the troposphere, reducing the amount of outgoing thermal radiation reaching the stratosphere and therefore the absorption of this heat within the stratosphere.

Cooling of the stratosphere is regarded as one of the important fingerprints of climate change because only increases in anthropogenic GHG can both warm the surface and cool the stratosphere over a long period. For example, increased solar activity would warm both the stratosphere and the surface. Note that reduced ozone (due to high levels of CFCs) also contributes to stratospheric cooling because there is less absorption of incoming solar radiation. This factor has been declining since the Montreal Protocol banned CFC usage.

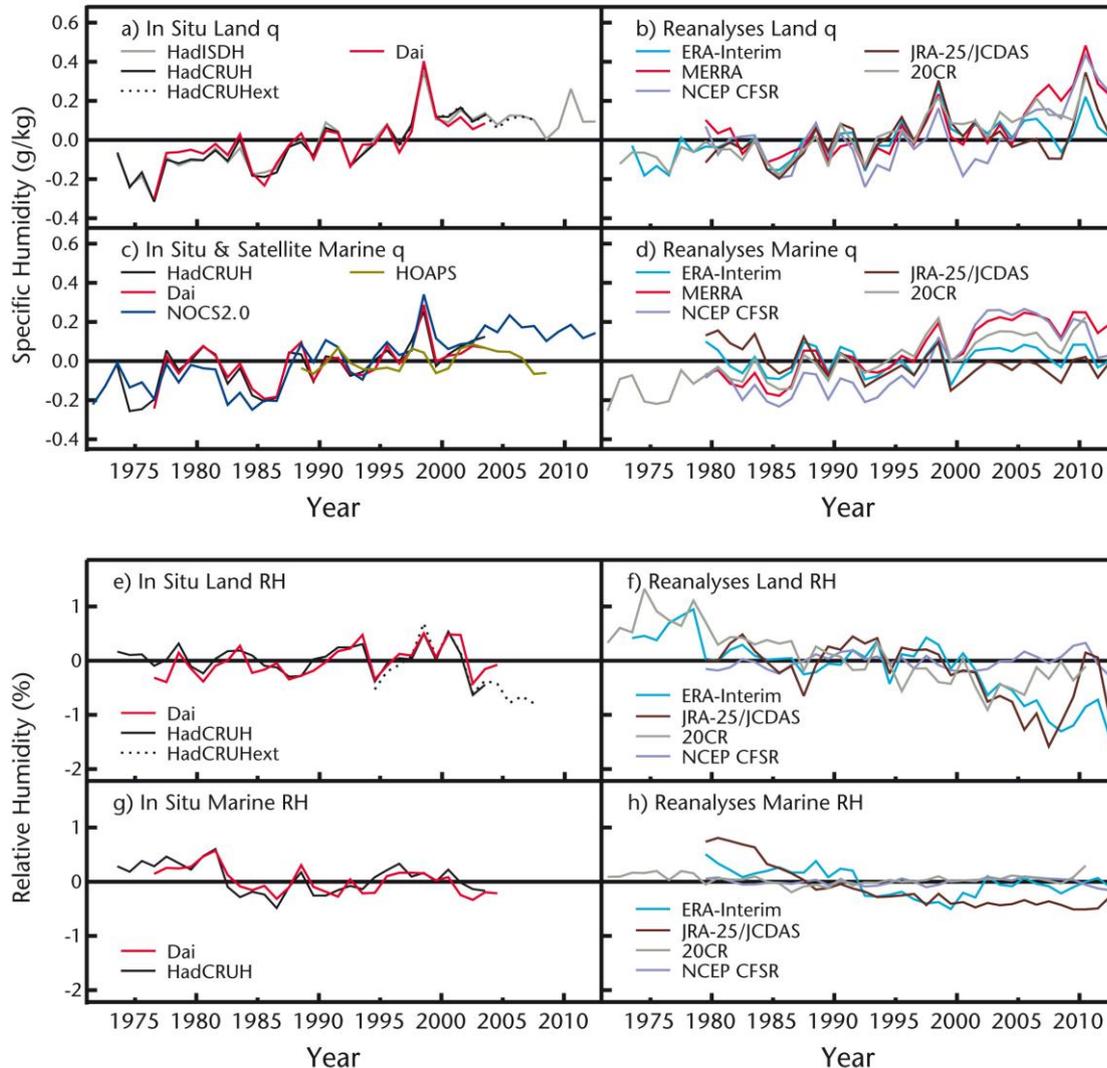
Observations show that overall the stratosphere has indeed cooled over the last 50 years (Figure 11). Interestingly, cooling appears to have levelled off since the mid-1990s in all the measures, including the reanalysis. This has occurred at a time when stratospheric ozone appears to have been increasing (see Figure 1), which, as described above, radiatively warms the stratosphere. Also there is evidence that decreases in stratospheric water vapour since 2000 may also be contributing (Solomon et al, 2010) – decreases in stratospheric water vapour act to warm the stratosphere but to cool the troposphere.



**Figure 11:** Three measures of changes in lower stratospheric temperatures over the last 50 years relative to the 1981–2010 baseline. The brown triangles show the timing of major volcanic eruptions. (Source: “State of the Climate in 2012”, *Bulletin of the American Meteorology*, Blunden and Arndt, 2013).

## 1.5 Atmospheric water vapour

Atmospheric water vapour content is important for a number of reasons. Not only is water vapour a very important greenhouse gas, it provides a pathway for energy and water transport within the energy and hydrological cycle respectively. Furthermore, it has implications for human and livestock health and wellbeing.



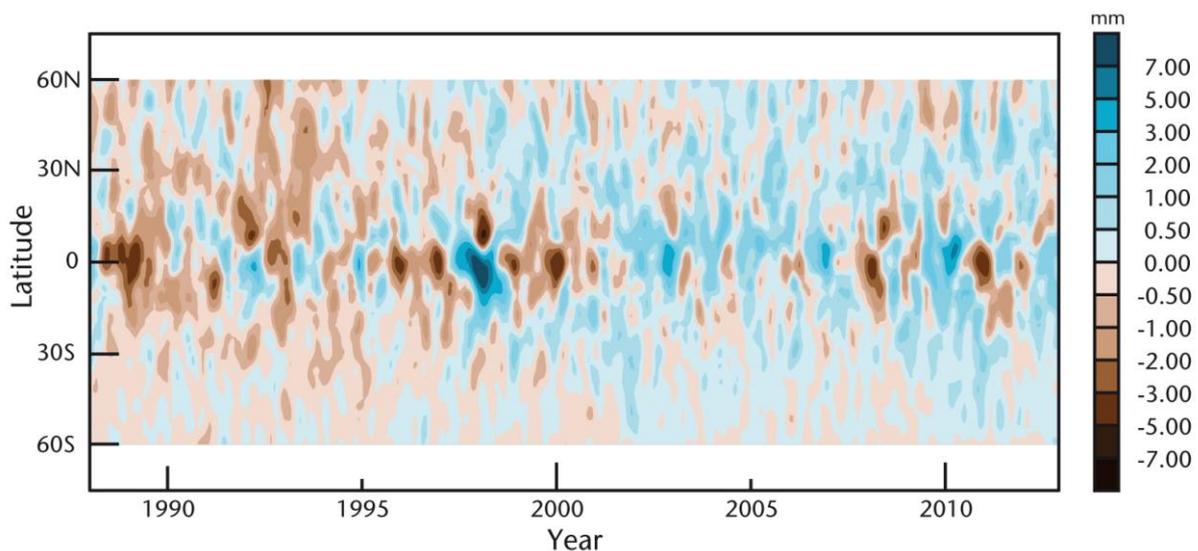
**Figure 12:** Measures of changes in near surface specific humidity ( $q$ ) and relative humidity (RH) over land and ocean separately relative to a 1979–2003 baseline. (Source: “State of the Climate in 2012”, *Bulletin of the American Meteorology*, Blunden and Arndt, 2013)

As the atmosphere warms, its capacity to hold water in a vapour form increases. An increase in near-surface specific humidity since the 1970s has been observed over land and oceans. Over the last decade however, as with surface temperature, there appears to have been a levelling off (Figure 12). There is greater uncertainty in recent changes in surface specific and relative humidity (RH) over the oceans than over the land. It is also important to note that changes in relative humidity (RH)<sup>6</sup>, a measure which more directly relates to human comfort and other societal impacts, has declined over land during the last decade. This drying out

<sup>6</sup> *Specific* humidity refers to the weight of water vapour contained in a unit weight of air (in grams per kg). *Relative* humidity refers to the amount of water vapour in the air compared with the total amount of water vapour that could exist in that air at its current temperature.

over land (in the relative sense) may be linked to the fact that the oceans, the major source for water vapour, have warmed slower than the land. This may also be linked to changes in global circulation and therefore regional rainfall patterns. Provisional research suggests that a decrease in RH in the mid-latitudes is partially offset by an increase in some other regions.

Satellites can estimate the total water content of the atmosphere, expressed as millimetres of water. Figure 13 shows the changes in total water content over the oceans since 1988 as a Hovmöller diagram, where the average for each latitude is plotted against time. The overall moistening of the atmosphere is clearly evident as the diagram becomes increasingly blue (higher values of total water content) through time. As in many other measures of climate change, the imprint of ENSO in the Tropics can be seen in the wet anomalies in 1998 associated with El Niño, and the dry anomalies associated with the recent La Niña conditions (such as the 2010–2011 event).



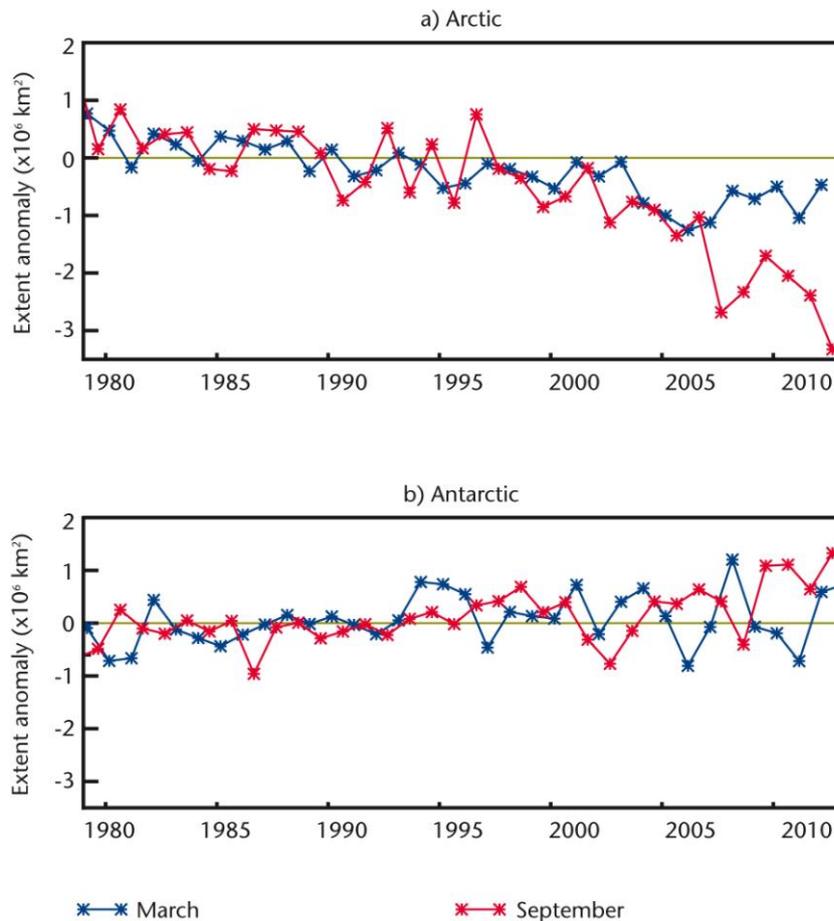
**Figure 13:** Satellite radiometer (SSM/I, SSMIS, AMSR-E and WindSat measurements) monthly mean anomalies (mm; 1997–2010 baseline period) for total column water vapour (ocean only) by latitude. Data were smoothed in the time direction to remove variability on time scales shorter than four months. (Source: “State of the Climate in 2012”, *Bulletin of the American Meteorology*, Blunden and Arndt, 2013)

## 2. Cryosphere

Changes in the coverage and thickness of ice over land and sea areas are often highlighted as particularly dramatic and visible indicators of a changing climate. Robust long-term observation and monitoring networks are again critical to enable climate scientists to build a more complete picture of the trends, and long-term and short-term variability.

### 2.1 Arctic sea-ice extent

Satellite records of Arctic sea ice extent began in 1979 and have shown a long-term decline with an annual rate of over 5.0% per decade<sup>7</sup>. The seasonal minimum (September) ice extent has declined at the faster rate of 12.9% per decade<sup>7</sup>, and this rate of decline has accelerated in the past 15 years (Figure 14). The record low summer Arctic sea ice extent observed in 2012 represents a 50% reduction in ice cover compared to the 1980s. This is consistent with surface temperature observations, which show that the Arctic is warming approximately twice as fast as the rest of the world (Figure 7).

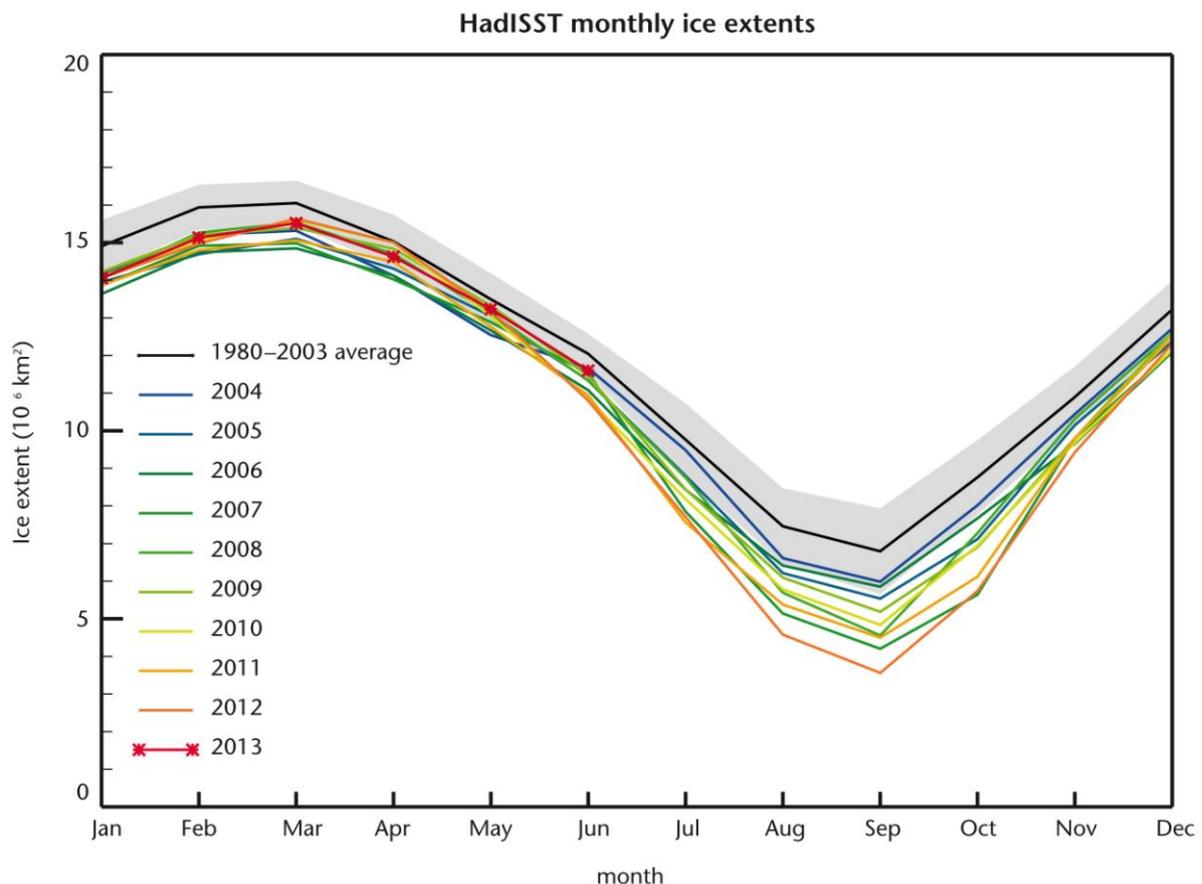


**Figure 14:** Time-series of a) Arctic and b) Antarctic sea ice extent anomalies in March (blue) and September (red) from the HadISST dataset (Rayner et al 2003). Anomalies are taken with respect to the 1979–2000 average. (Source: Met Office)

<sup>7</sup> Percentage decrease is for the period 1979–2012 relative to a 1981–2000 baseline.

Since 2003, the September minimum Arctic sea ice extent has moved outside the internal variability of the 1980–1999 period. The six lowest minimum extents in the 32-year record occurred in the past six years, with notably low extents observed in 2007, 2011 and 2012 (Figure 15). A new record minimum Arctic sea ice extent was observed in 2012 which was 3.29 million square kilometres below the 1979–2000 average.

The difference between winter and summer Arctic sea ice extents has been widening since 2007, as shown in Figure 14. Over 1979–2006 the systematic decrease in summer minimum and winter maximum has been similar, characterised by relatively small random excursions from the long-term trend. This changed dramatically in 2007 when a large area of open water was exposed in response to an anomalous atmospheric circulation pattern. Since then the Arctic has shown a different behaviour through the seasonal cycle of freezing and melting with much greater excursions in ice extent between winter and summer indicating a more seasonal ice pack. An ongoing decline in the amount of thicker, multiyear sea ice in the Arctic means that larger and larger areas of the ice become vulnerable to melting away completely over the summer.



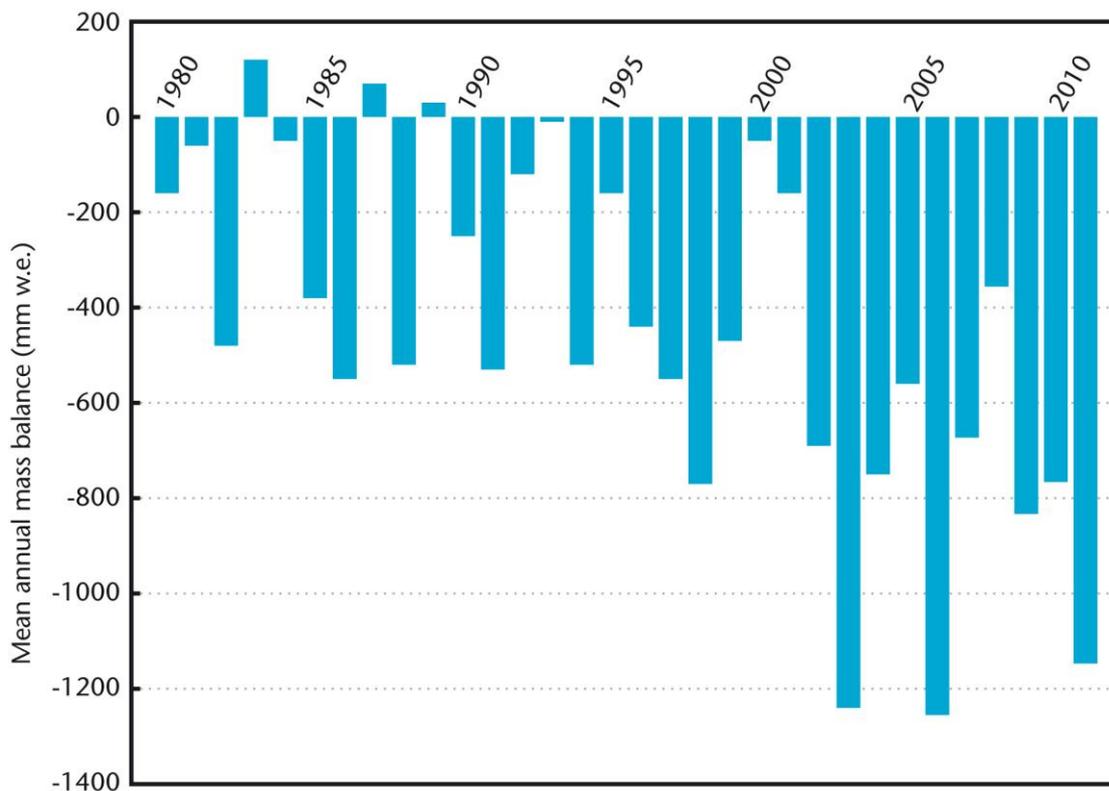
**Figure 15:** HadISST annual seasonal cycle of Arctic sea ice extent as of June 2013 for the years since 2004 compared to the 1980–2003 average. (Source: Met Office)

The Arctic and Antarctic are very different systems. Most notably, the Arctic is ocean surrounded by land in contrast to the continental Antarctic surrounded by ocean. The winter Antarctic sea ice extent has been increasing over the satellite era (i.e. since 1979), in contrast to the rapid decline in Arctic summer ice extent. The overall Antarctic increase is a composite of a decline in ice in the Bellingshausen and Amundsen Seas and an increase in extent in the Ross Sea and Indian Ocean sector. The changes appear to be caused by a

shift in the regional winds. However, the recent change should be put in context with an earlier 20<sup>th</sup> century decline in the ice extent, suggesting that natural variability cannot be ruled out.

## 2.2 Glacier mass balance

Continuing retreat of most of the world's mountain glaciers is one of the clearest signals of ongoing climate change. The World Glacier Monitoring Service (WGMS) record of glacier mass balance (the difference between ice accumulation and removal) provides a global index for glacier behaviour. Observations to 2011 show a 22<sup>nd</sup> consecutive year of negative annual mass balance (i.e. retreat) since 1980 (Figure 16). The BAMS State of the Climate report (Blunden and Arndt 2013) indicates "remarkably consistent" trends from region to region, and suggests that the cumulative mass balance loss of the last 30 years is equivalent to cutting a 15 metres thick slice off the top of the average glacier.

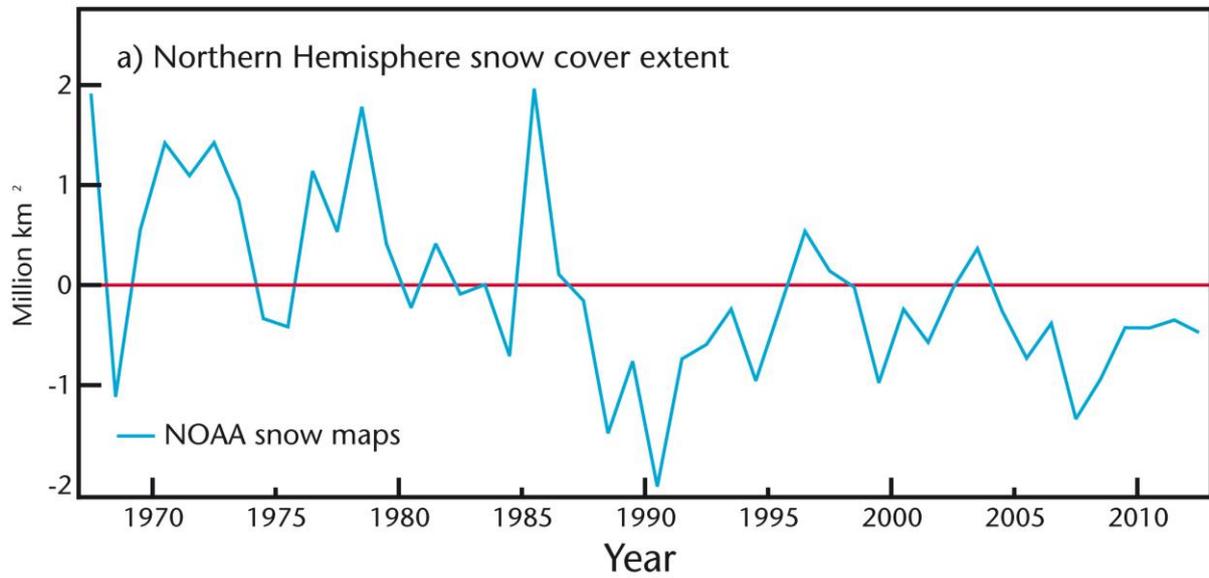


**Figure 16:** Time-series of the cumulative mean annual mass balance for all glaciers reported to the WGMS since 1980. (Source: [WGMS](#))

## 2.3 Northern Hemisphere snow cover

Consistent with the picture of glacier retreat, observations of the annual mean snow cover extent over the Northern Hemisphere show relatively low snow extents since the mid-1980s relative to the earlier period in the record (Figure 17). The inter-annual variability in snow cover observations again reflects the distinction between the prevailing patterns in any given year (which is affected by natural climate variability and cycles such as the Arctic Oscillation),

and longer-term shifts in our climate (related to both longer-term modes of natural variability such as the Atlantic Multidecadal Oscillation and human-induced climate change).



**Figure 17:** Time-series of the annual snow cover extent anomaly (relative to the 1966–2010 baseline) over Northern Hemisphere lands (including Greenland). (Source: NOAA)

### 3. Ocean

We now turn our attention to the ocean. As discussed in more detail in the second report in this series, the ocean is a very important component of the climate system as it acts as the planet's primary heat store (Murphy et al. 2009, Palmer et al, 2011). Monitoring of the upper ocean, for example using the Argo array of drifting probes<sup>8</sup>, has not yet produced sufficiently long-term records to determine robust trends. However, as a key part of our observation of the full climate system these records are beginning to provide new insights and deepen our understanding. Below the depths reached by the Argo floats (2,000m maximum), observations of the ocean heat content are spatially sparse and temporally discontinuous.

#### 3.1 Ocean heat content

Approximately 90% of the heat trapped in the Earth system by increases in atmospheric greenhouse gases will eventually be stored in the ocean. The ocean heat content is a function of the huge mass of water that is in communication with the surface, and the massive thermal capacity of water compared to air.

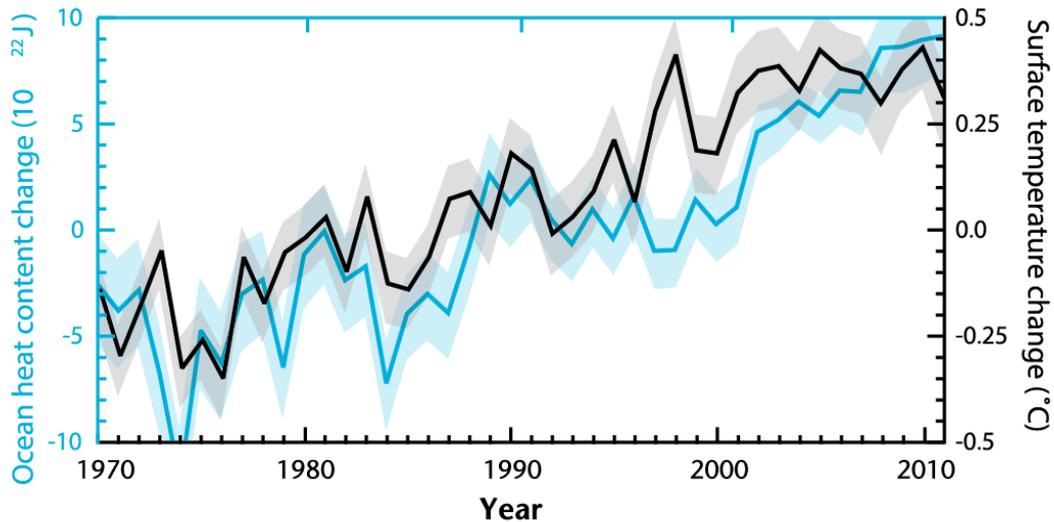
Although surface temperature can be readily measured by satellites, and good historic records exist, the thin surface layer (i.e. millimetres in the case of satellites) represents a very small volume (relatively), and so is fairly unimportant in terms of heat content. It is much more difficult to measure the temperature of the interior of the ocean, as it cannot be done remotely (from satellites). For a long time, ship-borne instruments were the only way of measuring the sub-surface ocean temperature. The development of expendable BathyThermograph (XBT) in the 1960s allowed "ships of opportunity" with limited expertise to make measurements, and so the number of observations greatly increased.

Since about 2000, the Argo array of autonomous robotic ocean profiling floats has led to near global coverage with measurements of temperature to 700m (15-20% of the average open ocean depth), with more recent buoys measuring down to 2,000m (the upper 50%). However, the ice-covered and marginal seas still remain a technical challenge. Combining data from the Argo array with XBT and ship measurements, enables relatively long estimates of the heat stored in the upper 700m to be made (Figure 18). Comparing this record to the surface temperature record shows that, despite the surface warming pause since 2000, the ocean heat content in the upper ocean continued to rise.

There are much fewer observations below 700m, and the ocean below 2,000m has remained largely un-monitored. However, there is evidence of warming below 700m, and even below 2,000m. Careful processing of the available deep ocean records shows that the heat content of the upper 2,000m increased by  $24 \times 10^{22}$ J over the 1955–2010 period (Levitus, 2012), equivalent to 0.09°C warming of this layer. To put this into context, if the same energy had warmed the lower 10km of the atmosphere, it would have warmed by 36°C! While this will not happen, it does illustrate the importance of the ocean as a heat store.

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<sup>8</sup> Argo floats are small, drifting oceanic robotic probes that are deployed worldwide and drift with the ocean currents. The probes descend down to at most 2km, and once every 10 days they rise to the surface, measuring salinity and temperature profiles. The data are transmitted to shore via satellite. Argo floats began to be deployed in the early 2000s and currently there are over 3,500 floats across the global oceans.



**Figure 18:** Change in globally averaged annual ocean heat content (blue) for the upper 700 m of the ocean and global average near-surface temperature (black) relative to 1970-2011. The shaded regions show the uncertainty in the observational estimates. (Source: HadCRUT4, Met Office)

### 3.2 Sea level rise

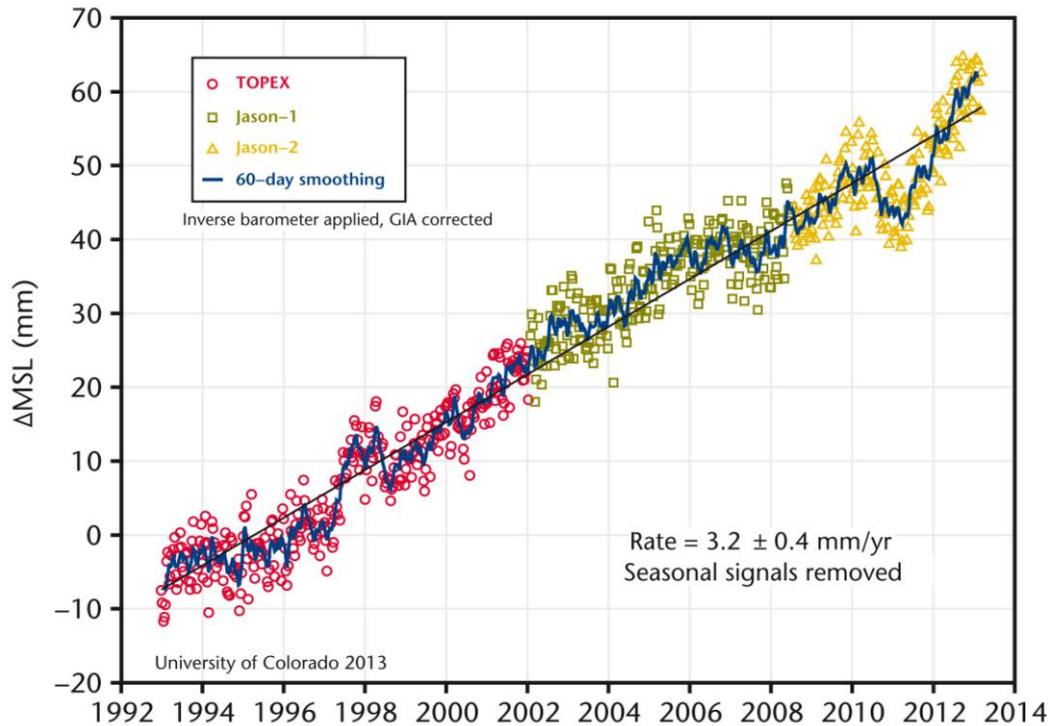
Sea level is a primary indicator of climate variability and change over a wide range of time and space scales and integrates other parameters such as ocean heat content and glacial run off. Long term sea level rise is also one of the more high profile projected impacts of a changing climate. Global mean sea level data provide a measure of the volume changes associated with ocean heat content changes (i.e. thermal expansion) and exchange of water between oceans and the land (i.e. ice sheet melt).

Over the past few decades, tide gauges along the coasts, and altimeters on satellites, have documented a gradual rise in global average sea level. We have observed an increase in global mean sea level, with a rise of  $3.2(\pm 0.4)$ mm/yr between 1993 and 2011, again consistent with a long-term changing climate (Figure 19).

Year-to-year variations in sea level reflect changes in weather patterns and longer-term modes of climate variability. For example, relative to the long-term trend, global sea level dropped noticeably in mid-2010 and reached a local minimum in 2011. This temporary drop has been linked to the strong La Niña conditions which prevailed during that time, and an associated change in land water storage as a result of the changes in weather patterns associated with La Niña.

During the IPCC 3rd and 4th Assessment Reports the sum of the observations of the various components known to affect sea level was considerably less than the observed sea-level rise. These components include the effect of the thermal expansion of the ocean (due to ocean heat content) and addition and removal of water from the ocean (such as from the glaciers and icecaps, the Greenland and Antarctic ice sheets, and terrestrial storage such as dam building and water extraction). The lack of agreement raised concerns about the model projections of sea-level rise.

Significant progress has now been made to close the sea-level budget, through updated time-series of the contributions to sea-level rise (Church et al, 2011). There is now good agreement between the observed rate of sea level rise according to tide gauges ( $1.8 \pm 0.2\text{mm/yr}$ ), combined satellite altimeters and tide gauges ( $2.1 \pm 0.2\text{mm/yr}$ ) and the sum of the observed components ( $1.8 \pm 0.4\text{mm/yr}$ ) over the period 1972–2008 (Church et al. 2011, Table 1).



**Figure 19:** Time-series of global average sea level since 1993 based on satellite altimeter observations. (Source: <http://sealevel.colorado.edu>, Nerem et al, 2010).

## Concluding remarks

This report aims to summarise the diversity of information and sources that encompass our observation of our climate system and our understanding of how it is changing. There is considerable effort within the climate science community, not least through endeavours such as the annual State of the Climate update report and the IPCC cycle of reporting, to present the most robust, balanced and holistic picture of the current state of our climate system as we can – this is the basis of the scientific method.

It has shown that a wide range of observed climate indicators continue to show changes that are consistent with a globally warming world, and our understanding of how the climate system works.

Even in this short report we have needed to present 19 different figures to begin to encapsulate the variety of information about our climate that is provided by the numerous (yet incomplete) globally-distributed monitoring systems. These data are the result of very considerable international investments of both financial and human capital. This work is a grand international challenge, dependent on rigorous analysis and deep physical understanding.

Observing and understanding our climate remains a critical endeavour; it provides robust information on the changes that we see today, and is vital for underpinning the projections of future change from climate models, which enable society to make more effective decisions, now and in the future. With this in mind, it is essential that there remains adequate, long-term and continuous measurement and processing of key climate variables. This report also emphasises that considerations of our climate and its long-term change must continue to be made on the basis of robust, holistic assessments – including, but not limited to, global mean surface temperature – to reflect the fullest possible picture of our changing climate.

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