Met Office

The recent pause in global warming (2): What are the potential causes?

July 2013

Contents

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Executive summary

It is not possible to explain the recent lack of surface warming solely by reductions in the total energy received by the planet, i.e. the balance between the total solar energy entering the system and the thermal energy leaving it. Observations of ocean heat content and of sea-level rise suggest that the additional heat from the continued rise in atmospheric carbon dioxide concentrations has been absorbed in the ocean and has not been manifest as a rise in surface temperature. Changes in the exchange of heat between the upper and deep ocean appear to have caused at least part of the pause in surface warming, and observations suggest that the Pacific Ocean may play a key role.

Global mean surface temperatures rose rapidly from the 1970s, but there has been little further warming over the most recent 10 to 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 second 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?

The purpose of this report is to assess the significance of the current pause and its potential causes, using observations and simulations with state-of-the-art climate models. For the period of 1970 to 2000 the median surface temperature trend from observations was 0.17 ± 0.02°C. Analysis of simulated natural variability indicates that even with a long term warming rate of 0.2°C per decade, at least two periods with apparently zero trend for a decade would be expected on average every century. The current pause in global surface temperature rise is not exceptional, based on recent model simulations.

There are potentially two distinct mechanisms to explain the recent pause; the first involves changes to the total energy received by the planet (radiative forcing), and the second involves the low frequency variability of the oceans and the way in which the oceans take up heat and store it below the surface, potentially into the deeper ocean. It is possible that a pause in surface warming could result from both mechanisms acting together.

It is not possible to explain the recent lack of surface warming solely by reductions in the total energy received by the planet. Radiative forcing by greenhouse gases has continued unabated; that heat is being held in the system but is not manifest as a rise in global mean surface temperature.

Observations of ocean heat content and of sea-level rise suggest that this additional heat has been absorbed in the ocean. Changes in the exchange of heat between the upper and deep ocean appear to have caused at least part of the pause in surface warming, and observations suggest that the Pacific Ocean may play a key role.

The scientific questions posed by the current pause in global surface warming require us to understand in much greater detail the flows of energy into, out of, and around the Earth

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system. Current observations are not detailed enough or of long enough duration to provide definitive answers on the causes of the recent pause, and therefore do not enable us to close the Earth's energy budget. These are major scientific challenges that the research community is actively pursuing, drawing on exploration and experimentation using a combination of theory, models and observations.

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1. Pauses in global warming: Is the current lack of warming unusual?

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. So the recent pause in global surface temperature rise is of considerable interest and has raised a number of questions around its possible causes, whether a pause of this duration is exceptional, and the implications for projections of future warming.

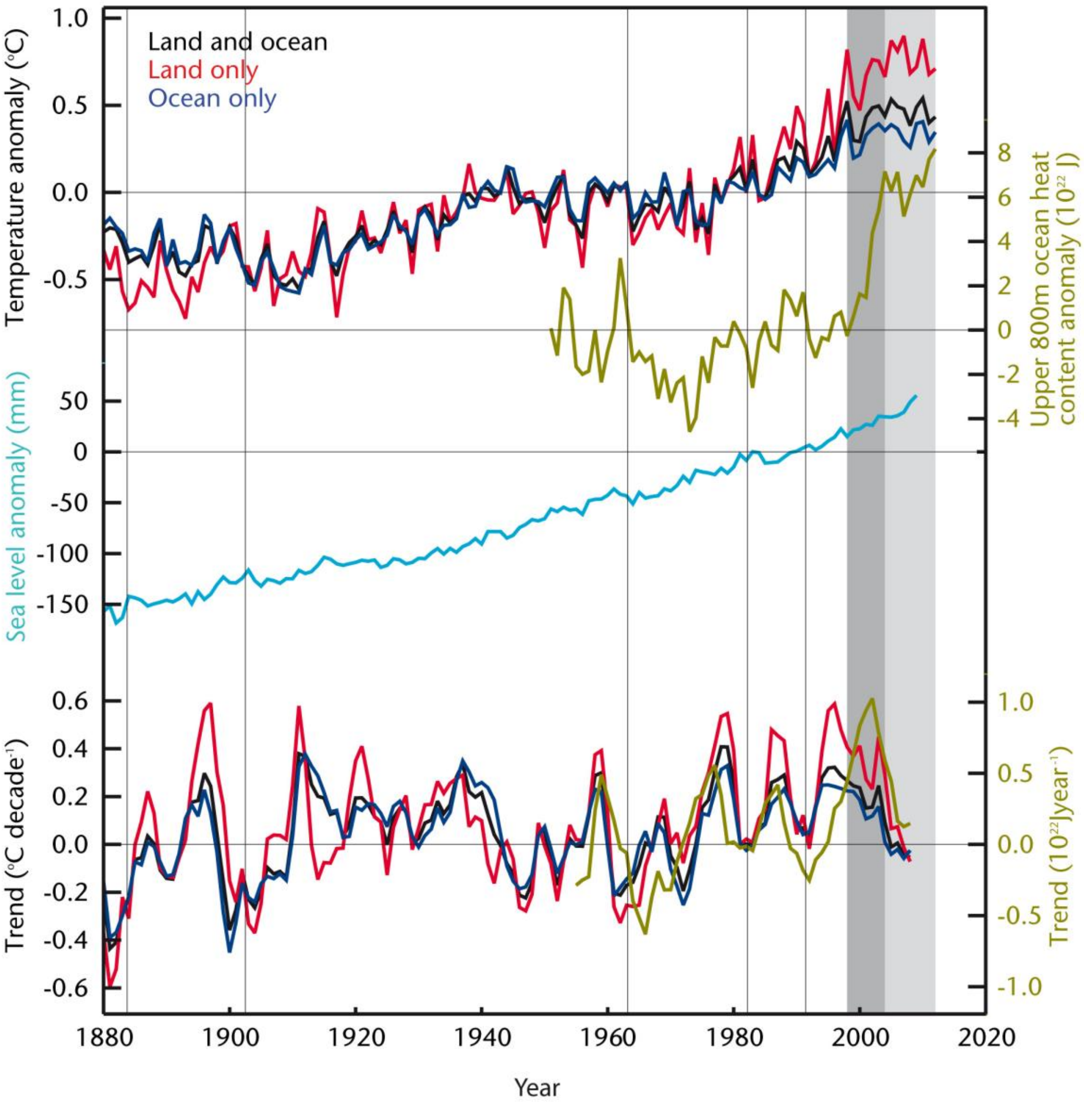

Figure 1: Observations of the recent pause in surface warming. *Top panel shows time series of annual mean surface temperature anomalies (relative to 1961 to 1990) averaged over the whole globe (black, from HadCRUT4), land (red, from CRUTEM4) and ocean (blue, from HadSST3). The second panel shows the heat content of the upper 800m of the ocean (from Met Office analyses, anomalies relative to 1951 to 2006, updated from Smith and Murphy, 2007). The third panel shows annual globally averaged sea level from tide gauges (Church and White, 2011). The lower panel shows running nine-year trends in surface warming and upper ocean heat uptake. The recent slowdown in global warming is highlighted by the grey shading. This is split into onset (dark) and continuation (light) periods, where upper-ocean heat uptake increased during the onset, but was relatively flat during the continuation. Vertical lines indicate major volcanic eruptions.*

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The recent pause in global surface warming is shown in Figure 1 in the context of historical observations. Following a period of rapid warming since the 1970s[1], there has been little further warming of the surface, particularly over the ocean in the most recent 10 to 15 years. As discussed in the first paper in this series, there is substantial evidence from other components of the climate system, beyond the global mean surface temperature, that the Earth has continued to warm over the last decade.

It is clear that there have been other periods with little or no surface warming in the relatively recent past, a good example being the period between the 1940s and the 1970s (Figure 1). The trend in warming over that period is well understood, and linked to a substantial increase in the amount of aerosol in the atmosphere.

The start of the current pause is difficult to determine precisely. Although 1998 is often quoted as the start of the current pause, this was an exceptionally warm year because of the largest El Niño in the instrumental record. This was followed by a strong La Niña event and a fall in global surface temperature of around 0.2^{o}C (Figure 1), equivalent in magnitude to the average decadal warming trend in recent decades. It is only really since 2000 that the rise in global surface temperatures has paused.

Furthermore, upper ocean heat content continued to increase for a few years after 1998 (Figure 1). Nevertheless, it is clear that the rate of warming both at the surface and in the upper ocean has declined recently (Figure 1, lower panel). This is despite a continuing rise in atmospheric carbon dioxide concentrations, which act to trap radiation within the Earth system.

Extended simulations with state-of-the-art climate models can be used to explore whether the duration of the current pause in warming is exceptional or whether it lies within the natural, low frequency variability of the climate system (Knight et al, 2009; Meehl et al, 2011; Katsman and van Oldenborgh, 2011).

Based on several thousand years of simulation, Figure 2 compares the probability distributions for 10, 15, 20 and 30-year temperature trends with and without a long-term warming trend of 0.2^{o}C per decade, commensurate with the observed increase in global land surface temperature over the latter part of the 20th century (Figure 1).

There are several important messages to be taken from this study. Firstly, it demonstrates that very little can be concluded from 10-year trends with respect to global warming since the distributions of trends overlap substantially. It is only with averaging periods of 30 years or longer that climate change can be detected robustly. Secondly, the results show that a pause of 10 years' duration is likely to occur due to internal fluctuations about twice every century. Thirdly, the results also show that beyond periods of 20 years and longer, a pause of that duration occurring from natural, internal variability *in the absence of other changes in external forcing* appears to be unlikely.

There are potential limitations to this study because it is based on a single model, and therefore these results cannot be viewed as definitive. It is also the case that the rate of temperature rise used in the study, 0.2 ^{0}C per decade, is at the upper end of what has been observed over recent decades (Figure 1, bottom panel). If a lower rate of warming were used then the likelihood of a pause in surface warming lasting 10 or 15 years would be higher.

[1] For the period 1970 to 2000 the median surface temperature trend was 0.17 ± 0.02°C (95% confidence range, observational uncertainty only) based on HadCRUT4.

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More research remains to be done to investigate to what degree the current pause in global surface warming is unusual.

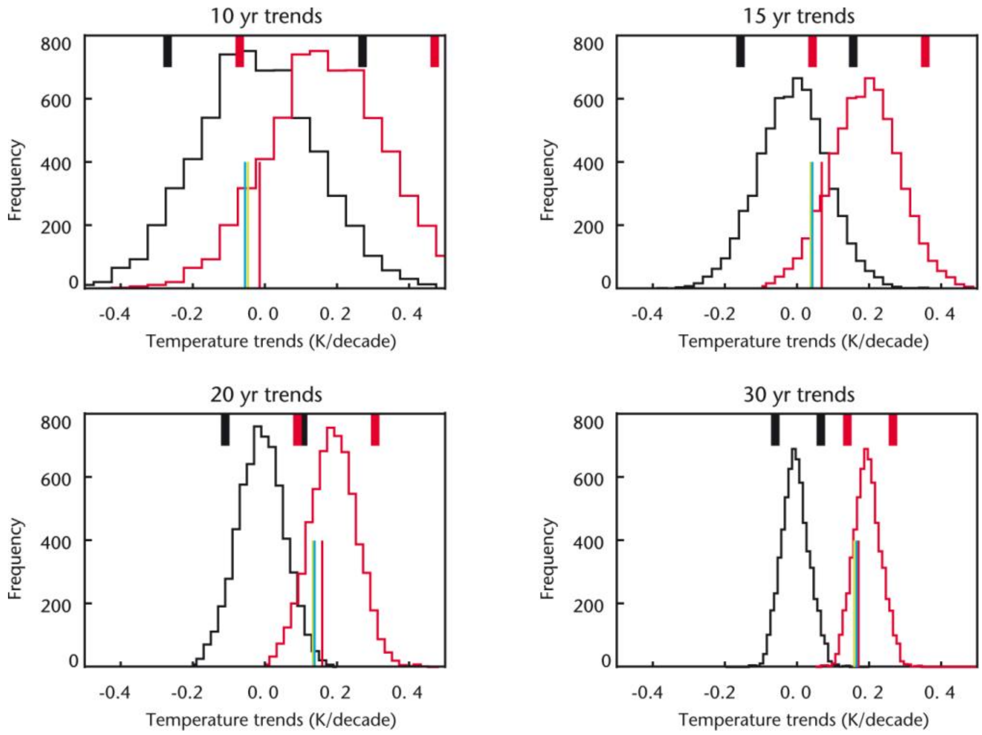

Figure 2: Internal climate fluctuations. *Distribution of model surface temperature trends without (black) and with (red) underlying 0.2 ^{0}C per decade linear trend for 10, 15, 20 and 30 year periods. The vertical lines are the observed trend in global average surface temperature over the most recent periods from observational records compiled by various institutions, HadCRUT3 (blue), NOAA GISS (red), NCDC (green) and HadCRUT4 (turquoise). Thick coloured lines at the top of each panel show the 5 and 95 percentiles of the distributions. The distributions were estimated from 6293 years of a control integration with the Met Office model HadCM3. (Figure courtesy of Peter Stott, personal communication).*

2. Understanding the potential cause of the recent pause in global surface temperature rise.

There are two main ways to explain the recent surface temperature behaviour; firstly, through changes in the net amount of incoming energy to the climate system (radiative forcing) or, secondly, through redistribution of energy within the climate system, particularly through exchange between the upper and deep ocean, which can temporarily hide the warming below the surface. Both explanations have been put forward in the literature. For instance, several studies (e.g. Solomon et al 2010, 2011, Church et al 2011) have considered potential radiative forcing explanations, while others (e.g. Knight et al 2009, Meehl et al 2011, Katsman and van Oldenborgh 2011) have examined the potential ocean heat redistribution.

2.1 Changes in incoming energy

The Earth's temperature is controlled, fundamentally, by the balance between the solar energy absorbed by the planet and the thermal energy that it loses, which in itself depends on the temperature of the planet. The case for global warming rests on the greater trapping of thermal energy by increasing greenhouse gas concentrations within the Earth system,

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thereby moving from a net energy balance at the top of the atmosphere of zero, to one that is positive. A representative estimate of the current rate of increase in energy trapped in the system due to enhanced greenhouse gas emissions is about 0.35 Wm^{-2}/decade (Solomon et al, 2007).

We also know that the Earth will not instantaneously return to a net energy balance of zero if greenhouse gas concentrations are stabilised. This is because some elements of the Earth system, such as the oceans, have a large thermal inertia. It takes at least a century for the surface temperature of the ocean, which determines some of the thermal energy leaving the planet, to come into balance with the other energy flows in the Earth system. This is discussed in detail in the third report.

So in terms of the current pause, we can conclude that to stop the rise in global mean surface temperatures would require more than just eliminating the current energy gain of $0.35Wm^{-2}$ from increasing greenhouse gas concentrations (see above). It must also deal with the fact that the ocean would not be in balance and would continue to warm. For these reasons, to produce an *immediate cessation* of warming of the climate system requires balancing the whole of the current net energy imbalance at the top of the atmosphere. A typical estimate of this current imbalance is about $0.6Wm^{-2}$ (e.g. Hansen et al, 2011 based on model simulations; Levitus et al, 2012, based on ocean heat uptake). This gives an estimate of the size of reduction in total energy input (radiative forcing) that would be required to give a pause in global surface temperature rise.

Here we estimate changes in the Earth's radiation budget over the last 15 years to see if it has changed, and if the changes are large enough to explain the recent pause in global surface warming.

Some of the observed cooling periods in surface temperature in Figure 1 coincide with a short–lived radiative cooling associated with major volcanic eruptions. During a major eruption, more of the incoming solar radiation is reflected back to space by volcanic sulphate aerosols ejected into the stratosphere, resulting in a cooling signal at the Earth's surface. Over the latter part of the 20th Century there have been three major eruptions, Mount Agung (1963), El Chichon (1982) and Mount Pinatubo (1991), leading to temporary slowing of global warming (see Figure 1).

However, unlike the warming from increased concentrations of greenhouse gases, the cooling effect of volcanic eruptions wanes over two to three years as the sulphate particles precipitate from the stratosphere. Given the recent lack of major volcanic eruptions, this cannot explain the current pause in global surface temperature rise. However there have been a number of smaller eruptions which may have contributed to an increase in background aerosol concentrations, particularly in the stratosphere, but this is probably a very small effect. A new study of stratospheric aerosol optical depths and their impact on global mean surface temperatures by Haywood and Jones (2013; submitted) suggests a global mean cooling induced by these volcanoes in the period 2008-2012 of around -0.02K to -0.03K, which will not be detectable above climate variability.

Another possible candidate for changes in the radiative forcing is stratospheric water content which has been declining recently. This would contribute to less trapping of thermal energy and potentially a cooling. Solomon et al. (2010) have estimated that recent decreases in stratospheric water vapour may have contributed a cooling of about $0.1Wm^{-2}$ over part of the period covered by the pause in global temperature rise.

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Tropospheric aerosol concentrations are closely linked to human activities and typical estimates for the present day effect of aerosols is a cooling of around $1Wm^{-2}$ (Solomon et al 2007). Hence, to offset the increased warming due to greenhouse gases, this would require an increase in aerosol cooling of 50% or more over the last decade. In fact *reported* sulphate emissions peaked in the middle of the last decade and are now declining (Klimont et al 2013). A recent study by Murphy (2013) also discusses the changes in the distribution of aerosols around the world and suggests that this has had little direct net effect on global average clear-sky radiative forcing from 2000 to 2012. It seems unlikely, therefore, that tropospheric aerosols, alone, can provide an explanation for the pause in global mean surface temperature rise, although the uncertainties are large.

A notable feature of recent years has been the pronounced minimum in the 11-year solar cycle and the slow rise towards the next solar maximum (Figure 3). The most recent cycle, Cycle 24, suggests a maximum difference in total solar irradiance from solar maximum to solar minimum of around 1 Wm^{-2}, implying a maximum possible overall reduction in incoming energy to the Earth of less than 0.2 Wm^{-2} (allowing for the Earth's geometry and reflectivity). There is no doubt that the declining phase of the 11-year cycle of total solar irradiance has contributed to a reduction in incoming energy over the first decade of the 21st century, but still not enough to explain the pause in global surface temperature rise.

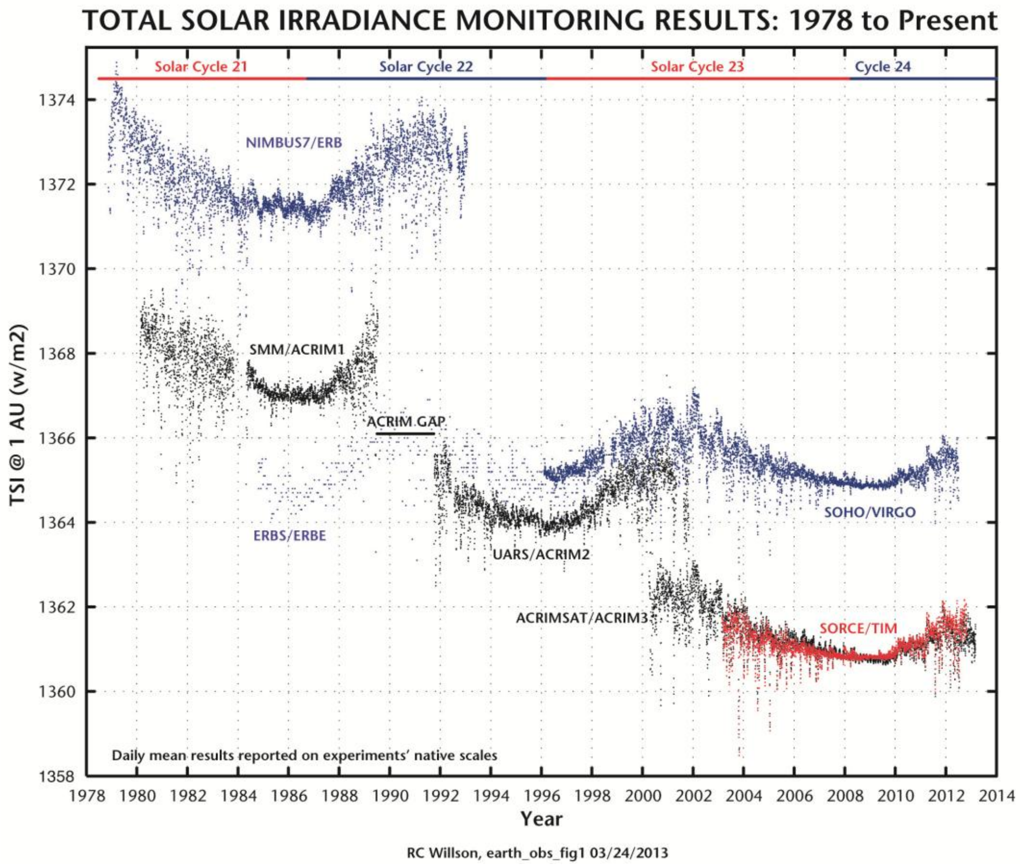

Figure 3: Variations in total solar irradiance *(TSI) from http://acrim.com/ over recent 11-year solar cycles. The absolute difference between cycles is due to instrument changes.*

In summary, any reduction in incoming energy to the climate system is unlikely to explain the recent pause in global surface warming. Even if all the potential contributions are operating

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fully and in combination it is hard to argue that they would exceed 0.3Wm^{-2}, half of what is required to bring surface warming to a halt.

2.2 Redistribution of energy within the climate system – Storing the heat below the surface.

We know that atmospheric CO_2 concentrations have continued to rise unabated, and as decreases in the net energy input at the top of the atmosphere from other sources are not sufficient to explain the current pause in global surface temperature rise, then the heat content of the Earth system must have continued to increase and this heat must in some way be stored below the Earth's surface.

The most likely candidate is the ocean since it is possible, through changes in vertical ocean circulations, to subduct heat from the surface ocean to depth and bring colder sub-surface water to the surface. Changes in ocean-atmosphere circulations can draw up colder water from the deep ocean, leading to a surface cooling or, conversely, prevent upwelling of colder waters, leading to a surface warming. Variations in surface temperature can then occur without any change of total heat in the climate system. Similarly, changes in the density of ocean water can also induce vertical motions, remembering that ocean density depends not only on temperature but also on salinity - warm, salty water can have the same density as cool, fresh water. In both cases the heat in the ocean is merely being rearranged; it is effectively 'hidden' from the surface only to re-emerge at some later date. The El Niño-Southern Oscillation (ENSO) and variations in the Thermohaline Circulation are examples of such processes in operation.

ENSO occurs irregularly every three to seven years in the tropical Pacific Ocean and its evolution is reasonably well understood. During the cold La Niña phase, the strong surface easterly winds "pile up" warm water in the western tropical Pacific and colder water wells up from below in the eastern tropical Pacific; this spreads westward giving a net cooling of the surface ocean. During the opposite El Niño phase, the surface winds over the tropical Pacific weaken, allowing the warm water in the West Pacific to spread eastwards and reducing the upwelling of cold water from below, thereby increasing ocean surface temperatures.

The atmosphere responds to these changes in tropical Pacific Ocean temperatures, giving rise to the Southern Oscillation and influencing weather patterns all around the world. Other ocean basins in turn respond to changes in the atmospheric circulation with the result that El Niño/La Niña events imprint themselves on the global mean surface temperature in terms of increased warming/cooling (see 1998 and 1999 in Figure 1). The peak-to-trough El Niño to La Niña variation in global mean temperature is typically 0.2 to 0.3^{o}C (Lean and Rind 2009). To put this in context, this range is at least as large as the estimated decadal rate of warming due to increases in greenhouse gases in recent decades.

Since 2000 there have been no major El Niño events and indeed the tropical Pacific has been predominantly in La Niña states. It is likely that this too has made a small contribution to the recent pause in global mean surface temperature rise, although the timescales of ENSO do not lend themselves to explaining the duration of the current pause.

Longer timescale internal fluctuations in the oceans also occur, such as large scale warming and cooling periods of the North Atlantic known as the Atlantic Multidecadal Oscillation or

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AMO (Figure 4). The AMO is related to variations in the strength of the Atlantic Meridional Overturning Circulation (or Thermohaline Circulation), which in turn alters the poleward heat transport. What drives these multi-decadal variations in the North Atlantic temperatures is still unclear and there is a debate about the role of anthropogenic aerosols in forcing the AMO (Booth et al 2012, Zhang et al 2013).

As Figure 4 shows, the North Atlantic warmed rapidly during the latter half of the 20th century and this may well have contributed to the rate of global surface temperature rise in that period. It has been estimated that variations in the AMO can give fluctuations of about 0.1°C in global temperature (Knight et al 2005). Since then the AMO has remained fairly constant, so it is unlikely that fluctuations in North Atlantic surface temperatures have contributed to the recent pause in global surface warming, although the deeper Atlantic may be storing some of the heat.

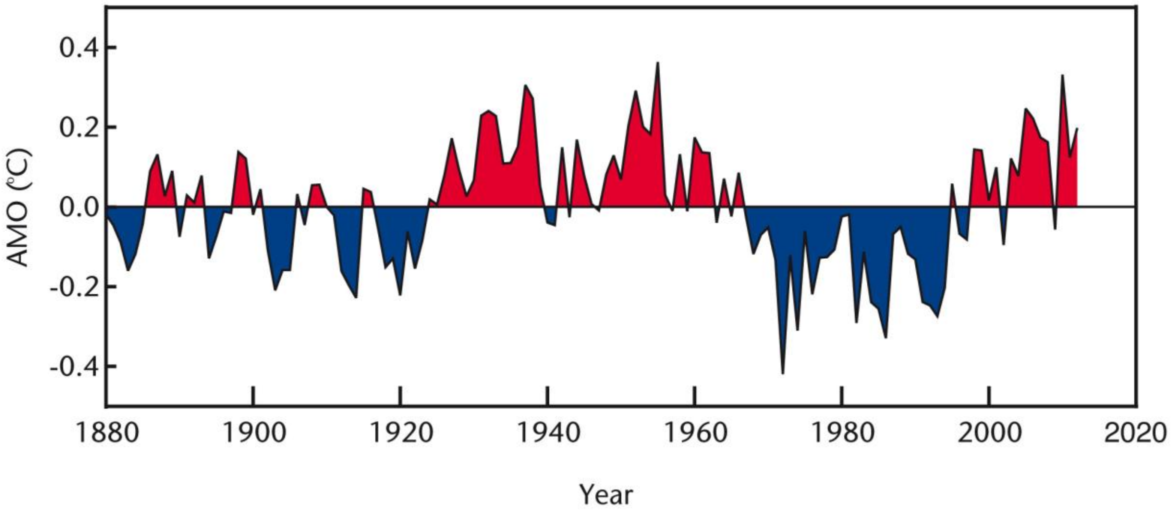

Figure 4: Observed AMO time-series. *Annual mean AMO index computed from the HadISST dataset as SST averaged over the North Atlantic (80-0°W, 0-60°N) minus global SST between 60°S and 60°N (Trenberth and Shea 2006).*

The Pacific Ocean also displays longer timescale variations (Figure 5), variously referred to as the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), Pacific Decadal Variability (PDV; Deser et al. 2012) and the Interdecadal Pacific Oscillation (IPO; Power et al. 1999). The characteristics and mechanisms for the PDO are less well understood than for the AMO and there is some debate whether it just represents low frequency behaviour of ENSO and its influence on mid-latitude atmospheric circulations and surface fluxes (Deser et al. 2012), or whether ocean dynamics are involved too. There is some evidence that changes in the ocean heat transports associated with the Kuroshio Extension region (an eastward flowing ocean current in the North Pacific Ocean), and the generation of internal ocean circulations called Rossby waves by the surface winds may be contributory factors (e.g. Alexander 2010)

Nevertheless there is an increasing body of evidence to suggest that these decadal variations in the Pacific Ocean have a substantial impact on the climate system. The upper panels of Figure 5 show systematic changes in the surface pressure and winds over the Pacific Ocean with a weakening of the Aleutian Low, as also occurs during La Niña events. As noted previously, changes in atmospheric circulation can induce upwelling or downwelling in the ocean. They can also generate low frequency internal Rossby waves in the ocean,

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which can alter the structure of the thermocline and redistribute heat within the deeper ocean.

The timeseries of the PDO index (Figure 5, lower panel) shows multi-decadal variations in the phase of the PDO. The transition from the negative to the positive phase in the late 1970s has been widely documented, and is often referred to as the ‘1976 climate shift’ (e.g. Miller et al. 1994, Trenberth and Hurrell 1994). The PDO index has shifted back to its negative phase since the turn of the Millennium and the question is whether this has been a contributor to the recent pause in global mean surface warming.

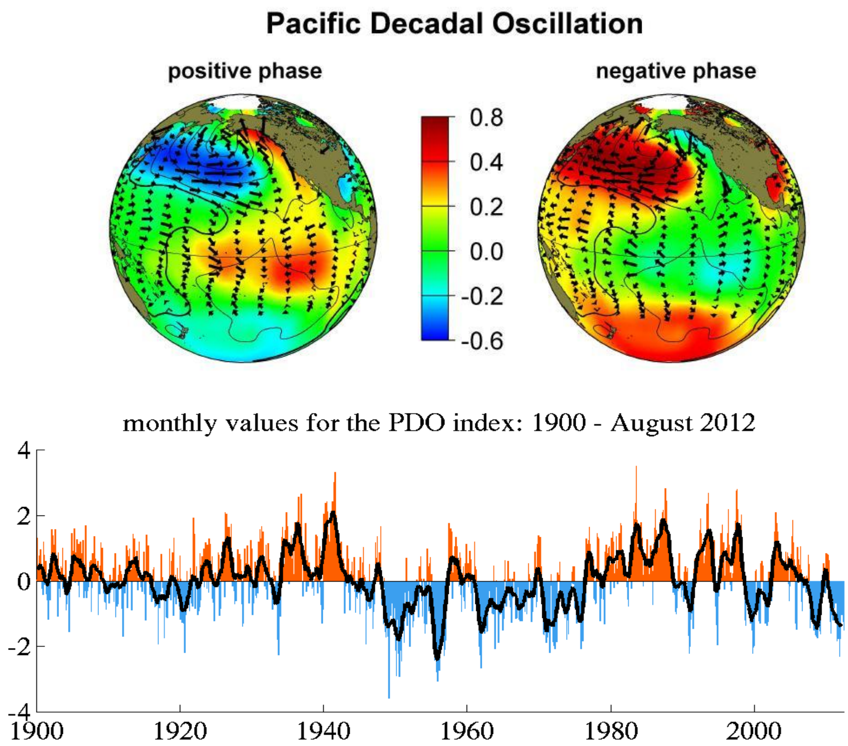

Figure 5: Observed pattern and time-series of the Pacific Decadal Oscillation (PDO). *Typical pattern of the ocean surface temperature anomalies (colour) mean sea level pressure anomalies and surface winds associated with the PDO (upper panel). Time series of the PDO index (lower panel). Source: Mantua et al. (1997) and University of Washington.*

As expected from the PDO index (Figure 5, lower panel), an analysis of the recent trends in observed ocean surface temperatures (Figure 6; lower right panel) shows a strong cooling contribution from the Pacific Ocean, with a pattern that is very reminiscent of the negative phase of the PDO (Figure 5, upper panel). The equatorial cooling is a manifestation of the persistent La Niña conditions that have prevailed over much of the last decade. Overall these observations suggest that decadal variability in the Pacific Ocean may have played a substantial role in the recent pause in global surface temperature rise.

The importance of decadal variability in the Pacific Ocean for driving extended periods of surface cooling has also been identified in multi-century simulations with fixed radiative forcing. Figure 6 shows the spatial distribution of the temperature trend averaged over extreme cooling periods from a number of climate model simulations from the Met Office Hadley Centre, including the most recent model (HadGEM2) that has contributed to the IPCC 5th Assessment Report. They all look remarkably like the observed pattern over the most

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recent decade (Figure 6, lower right panel), and provide fairly robust evidence of the importance of understanding the role of the Pacific Ocean in the current pause in global mean surface warming.

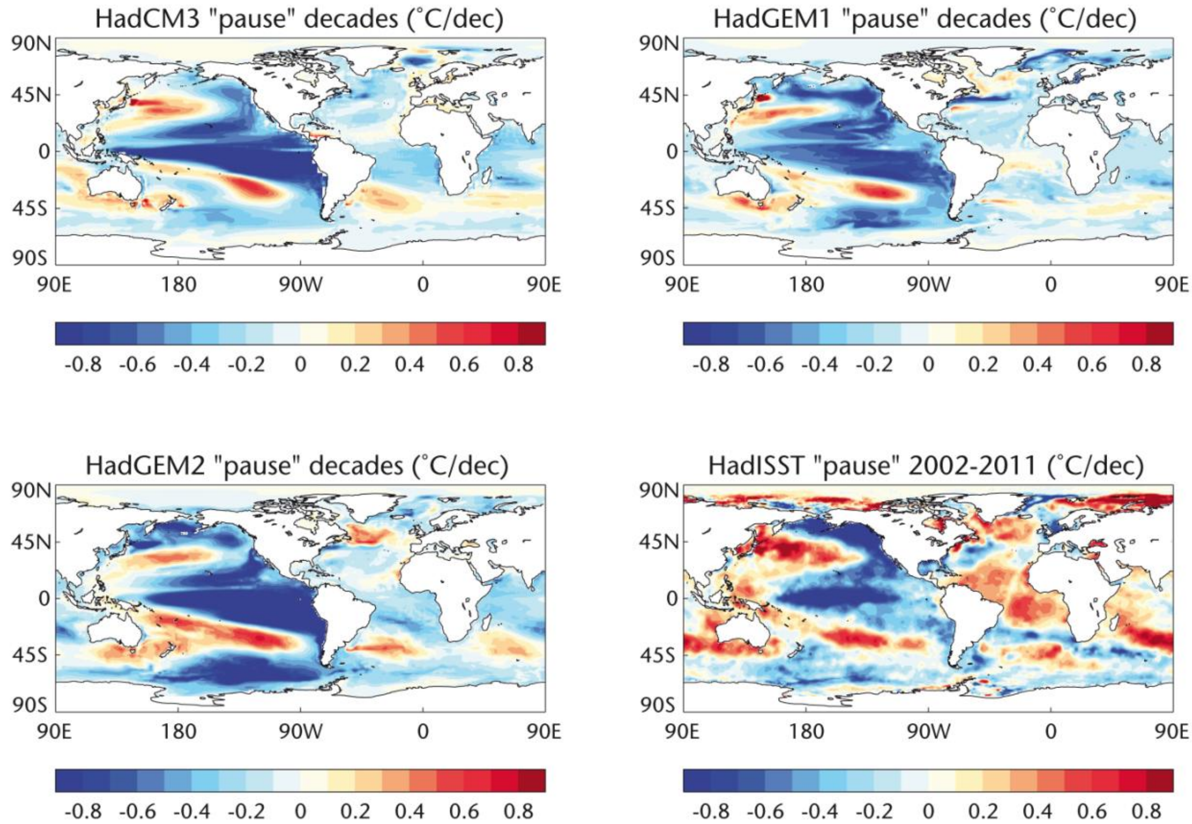

Figure 6: Pattern of trends in global ocean surface temperatures. *Simulated (upper panels and lower left) and observed (lower right) surface temperature trends (^{0}C per decade) during pause decades. Model fields are diagnosed from control integrations consisting of 3000 years for HadCM3 and 1000 years for HadGEM1 and HadGEM2.*

Similarly, in an analysis of climate model simulations of the 21st century that maintain a positive radiative imbalance at the top-of-atmosphere of about 1 W m^{-2}, Meehl et al (2011) found that several decades could be identified with a slightly negative global mean surface temperature trend. Again the pattern of trends in surface temperature resembled the negative phase of the PDO. Furthermore, Meehl et al. (2011) were able to show that significantly less heat is absorbed by the upper ocean down to 300m and significantly more heat is absorbed by the deep ocean, below 300m, during these periods of cooling compared with periods of warming. They argued that this is associated with increased subtropical thermocline ventilation in the Pacific and Atlantic (implying increased lower-thermocline heat uptake), and weakened convective mixing in the North Atlantic and Southern Ocean (implying decreased deep-ocean heat loss).

2.3 What do we know about changes in the ocean heat budget?

In an observationally based study of the Earth's energy balance, Murphy et al. (2009) showed that about 10% of the integrated positive forcing by greenhouse gases and solar radiation since 1950 has been stored in the Earth, almost all into the oceans (Figure 7). The

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rest has been balanced by loss of energy from increased reflection of solar radiation by aerosols and by increased loss of thermal radiation through higher temperatures. So we know that the ocean is an important player in the planet's response to radiative forcing.

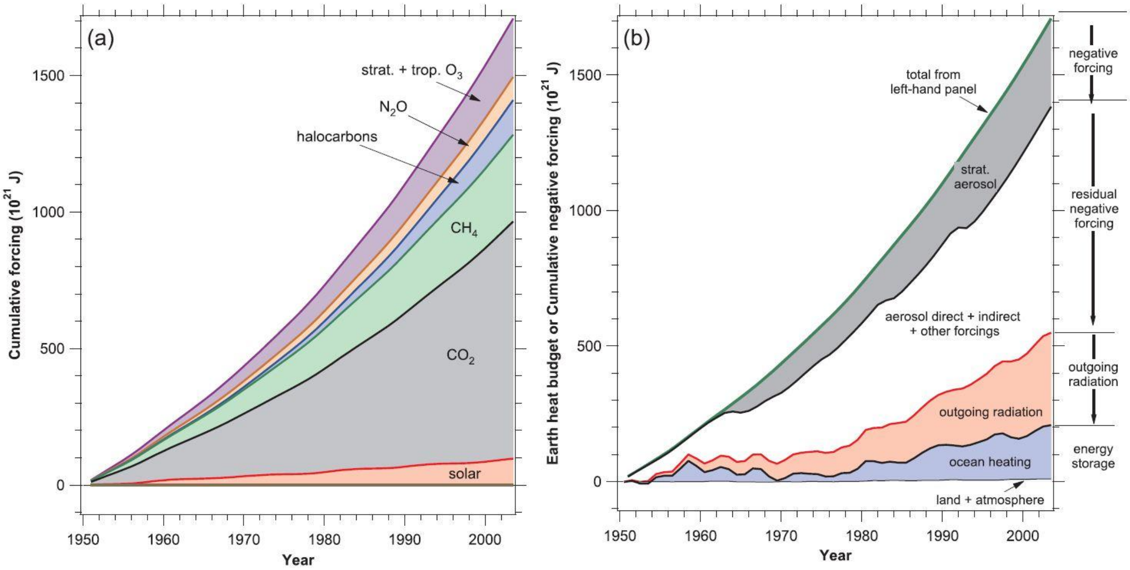

Figure 7: Cumulative energy budget for the Earth since 1950. *(a) Mostly positive and mostly long-lived forcing agents from 1950 through 2004. (b) The positive forcings have been balanced by the increased loss of energy from the system through reflection of solar radiation by stratospheric aerosols, direct and indirect tropospheric aerosol forcing, increased outgoing radiation from a warming Earth, and the amount of energy stored within the Earth. The aerosol direct and indirect effects portion is a residual after computing all other terms. Figure from Murphy et al. (2009).*

If indeed the ocean has hidden heat below the surface, then the question is whether changes in heat content, especially in the deeper ocean can be detected. There have been important advances in estimates of ocean heat storage over the last decade due to the correction of biases in conventional soundings, and the deployment of Argo[2] floats (Figure 8).

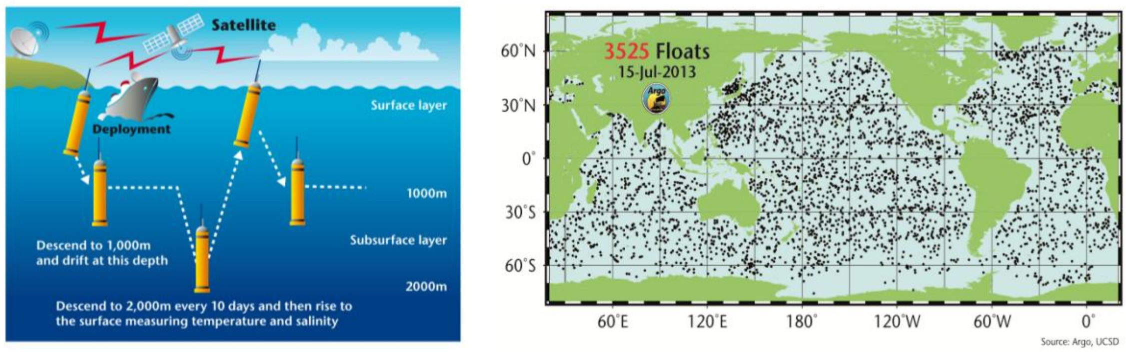

Figure 8: Measurements of upper ocean heat content using Argo floats. *Schematic showing the operation of Argo floats and their sampling of upper ocean temperatures (left panel), and the distribution of Argo floats as of July 2013.*

The Argo measurements indicate a rapid increase in heat content down to 700m between 1999 and 2004 (Guemas et al, 2013), as indicated in Figure 1, but the rate of increase is

[2] Argo consists of a large collection of small, drifting oceanic robotic probes deployed worldwide. The probes float as deep as 2 km. Once every 10 days, the probes surface, measuring conductivity and temperature profiles to the surface. From these, salinity and density can be calculated. The data are transmitted to scientists on shore via satellite. The Argo programme was designed to complement satellite measurements of sea surface height.

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lower thereafter. This period does, however, coincide with substantial changes in the observing system due to the rapid introduction of Argo floats. Although Argo floats are increasingly providing robust global measurements of the upper ocean, drawing conclusions from periods during which there are large changes in an observing system must be treated with caution.

Measurements of heat content in the deeper ocean are much sparser and hence less certain. Using a combination of satellite and ocean measurements down to 1800m, Loeb et al (2012) estimate the Earth system has been accumulating energy at a rate of 0.5±0.4 Wm^{-2} from 2001 to 2010, similar to the 0.4Wm^{-2} from 2005 to 2010 down to around 1500m estimated from Argo floats alone (von Schuckman and Le Traon 2011). Reanalyses[3] of ocean data give an average rate of warming from 2000 to 2010 of about 0.9Wm^{-2} averaged over the globe, with 30% of the increase occurring below 700m (Balmaseda et al. 2013). We conclude that the Earth system has continued to absorb a substantial amount of heat during the last 15 years, despite the pause in surface warming.

The sea level budget can also be used to constrain the ocean heat budget. As discussed earlier, the pause in global mean surface warming requires either a reduction in the energy input to the planet of ~0.6Wm^{-2}, or the storage of that amount of energy within the ocean. If an additional heating of 0.6Wm^{-2} was indeed stored in the ocean, then this would lead to a thermosteric (thermal expansion) rise in sea level of about 1.2mm/year, assuming all the increase in heat is confined to the top 700m. This number would be smaller if some of the heat was mixed below 700m where the coefficient of expansion is smaller.

Church et al (2011) have estimated that the thermosteric sea level rise from the full ocean depth is 0.80±0.15 mm/year for the period 1972 to 2008, and 0.88±0.33 mm/year for the more recent period, 1993-2008. As shown in Figure 1 and discussed in the first report in this series, sea level has continued to rise throughout the period of the recent pause. The numbers quoted by Church et al. (2011) suggest a rate of heat storage that is compatible with the rate required to explain the current pause, particularly if some of the heat is going into the deep ocean. Furthermore, as discussed in Section 2.1, we estimate that there has also been a small reduction of net energy input to the Earth system of less than 0.3Wm^{-2}.

In summary, observations of ocean heat content and of sea-level rise suggest that the Earth system has continued to absorb heat energy over the past 15 years, and that this additional heat has been absorbed in the ocean.

Given the evidence for heat being sequestered into the ocean during the pause in global mean surface warming, we analyse changes in ocean heat content in more detail. Changes in the energy content of the atmosphere, land and cryosphere are thought to be negligible compared to changes in energy in the ocean. The rate of change of upper ocean temperature is therefore simply governed by the net radiative flux at the top of the atmosphere (R_{TOA}) and the energy flux from the deep ocean (F_D) (Figure 9) according to:

$$\frac{\rho V C_p}{A}\frac{dT}{dt} = F_D - R_{TOA} \qquad (Wm^{-2}) \qquad (1)$$

[3] Ocean reanalysis uses a global ocean model, driven by driven by historical estimates of surface winds, heat, and freshwater fluxes, to synthesise historical observations of the ocean from a range of platforms using the process of data assimilation, in order to reconstruct historical changes in the state of the global oceans.

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where T is the temperature of the upper ocean layer of volume V and density ρ, C_p is the specific heat capacity of the ocean, A is the total surface area of the Earth, and $\frac{\rho V C_p}{A}\frac{dT}{dt}$ is the upper ocean heat uptake.

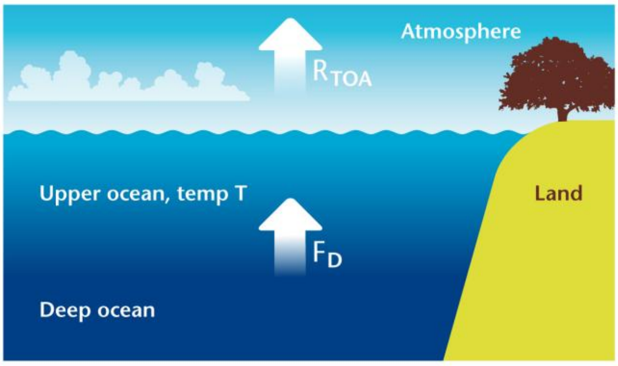

Figure 9: Upper ocean energy budget. *Changes in upper ocean temperature reflect the balance of energy fluxes at the top of the atmosphere and between the upper and deep ocean.*

The net radiative flux at the top of the atmosphere (TOA) is a balance between incoming shortwave radiation, outgoing shortwave radiation, and outgoing longwave radiation. All of these are currently measured by satellites, but uncertainties in each accumulate such that the *absolute* value can only be observed directly to within a few Wm^{-2} (Stephens et al 2012), especially because of discontinuities within the satellite observing system (e.g. transition from ERBE to CERES in 1999/2000). This means that the observations are not accurate enough to close the Earth's energy budget and explain changes in upper ocean heat content that would typically be less than 1 Wm^{-2} on decadal timescales. However, uncertainties in observed *changes* are much lower, allowing observations of R_{TOA} to be anchored by ocean heat content observations (Loeb et al, 2012).

Figure 10 shows observations of ocean heat uptake for the upper 800m, computed from five-year trends using the Met Office ocean analysis (updated from Smith and Murphy 2007), and estimates of radiative forcing from models and satellite observations. Prior to the start of satellite measurements of the Earth's radiation budget, we have to fall back on model simulations driven by the observed sea surface temperatures.

We expect that the upper ocean heat uptake should be largely balanced by the incoming TOA radiation and that differences between them represent uptake of heat by other parts of the climate system, most likely the deep ocean below 800m. However, as already noted, uncertainties in the observations and model estimates of radiative forcing are non-negligible, and these will also be manifested in the differences.

During the period 1965 to 1995 it appears that the net radiative flux is largely balanced by the upper ocean heat uptake. During this period the upper ocean heat uptake is positive, but with temporary negative minima in the mid-1960s, early 1980s and 1990s immediately following the eruptions of Mount Agung, El Chichon and Mount Pinatubo. These reductions in ocean

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heat uptake appear to be, at least partly, explained by changes in radiative forcing following these volcanic eruptions, as shown by the agreement between the solid black and coloured curves in Figure 9 during these periods. This agreement gives us some confidence in the observations, model estimates and the analysis.

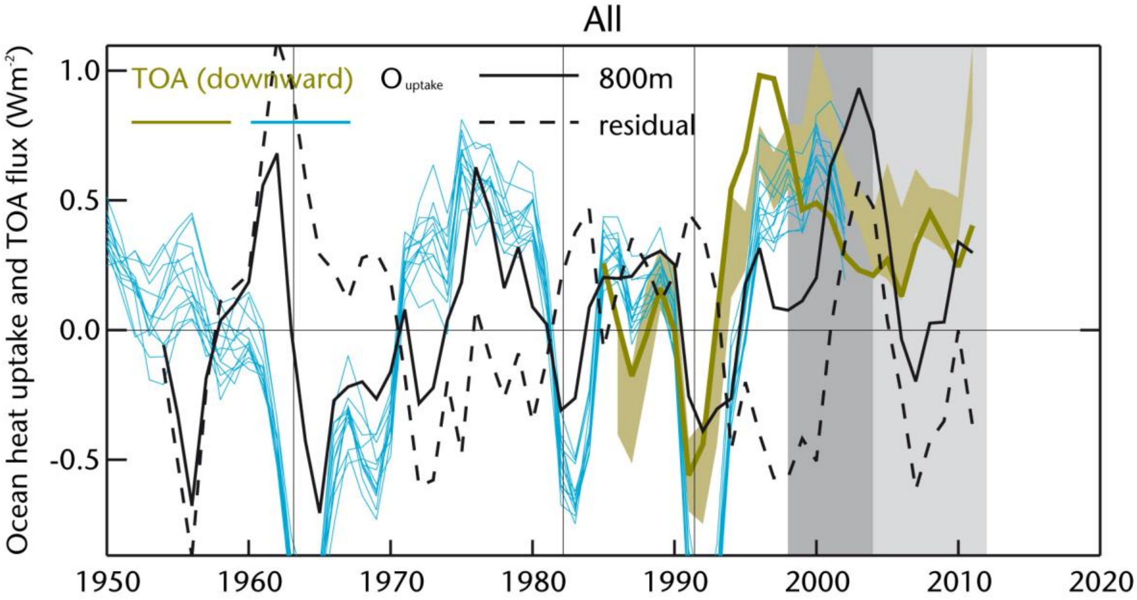

Figure 10: Observed upper ocean heat uptake and net radiative heat input at top of atmosphere. *Annual ocean heat uptake (* $\frac{\rho V C_p}{A}\frac{dT}{dt}$ *) for the top 800m (solid black curve) computed from five-year trends using the Met Office ocean analysis (updated from Smith and Murphy 2007), and net incoming downward TOA fluxes (* $-R_{TOA}$ *) from satellite observations (khaki curve, Allan 2011), and model simulations driven by observed sea surface temperatures (khaki shading and blue lines). The residual (difference between upper ocean heat uptake and incoming TOA flux, black dashed curve) implies heat taken up by other components of the climate system, most likely the deep ocean, or through uncertainties in the observations. Vertical lines show the dates of major volcanic eruptions. Grey shading highlights the onset and continuation periods of the current pause as defined in Figure 1.*

However, prior to 1965 and from 2000 to the present day, there are substantial differences between the net radiative flux and the upper ocean heat uptake (black dashed curve in Figure 9), implying heat taken up by other components of the climate system, most likely the ocean below 800m. It is notable that there is a pause in the global mean surface temperature rise during both periods, and that the PDO was also in a strong negative phase (Figure 5).

Focussing on the recent period in more detail, the onset of the current pause coincides with a maximum in upper ocean heat uptake around 2002, and may reflect a recovery both from Mount Pinatubo and from the record 1997/98 El Niño. A recent study (Guemas et al, 2013) shows that, in 2002, the upper ocean below the mixed layer took up heat, while the mixed layer and sea surface temperature did not warm. The onset of the pause may therefore have been caused by ocean processes, predominantly in the tropical Pacific, in which energy trapped by greenhouse gases was buried below the surface of the ocean.

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However, the continuation of the pause in global surface warming beyond 2004 coincides with a decline in upper ocean heat uptake (Figure 9). Previous minima in heat uptake are often associated with volcanic eruptions, but the decline in heat uptake after 2002 cannot be explained by a major volcanic eruption. Understanding the cause of this decline in upper ocean heat content is therefore crucial for explaining the continuation of the pause in surface warming. As already noted the monitoring of upper ocean heat content has changed substantially over the last decade with the rapid increase in deployment and hence global coverage of floats.

If, however, the observations are robust, then the maximum in upper ocean heat uptake in the early part of this decade and the subsequent minimum in upper ocean heat uptake cannot be explained by changes in net radiative fluxes, as shown by large residuals in Figure 10. This suggests that the pause in global surface warming is unlikely to have been caused solely by systematic changes in the top of the atmosphere radiation associated with solar variability and minor volcanic eruptions, anthropogenic aerosol emissions, or changes in stratospheric water vapour as suggested in other studies (Solomon et al, 2010, 2011; Church et al 2011).

Although this analysis suggests that exchanges of energy between the upper and deep ocean, calculated here as a residual (see black dashed line in Figure 10), may be of a similar magnitude to upper ocean heat uptake and net radiative forcing, we cannot show definitively that this has been the dominant factor in the recent pause in global surface warming. The fact is that uncertainties in estimating upper ocean heat content from the current monitoring network, along with uncertainties in observing the net radiation budget already discussed, mean that the residual calculation of deep ocean heat flux has to be treated with limited confidence.

In addition, direct measurements of the exchange of heat between the upper and deep ocean do not exist because the present ocean observing network does not sample the ocean below 2000m adequately. Even if it did, the potential changes in temperature could be very small, remembering that the energy imbalances involved are less than 1Wm^{-2} (Figure 10) and therefore potentially not detectable as temperature changes. However, some ocean analyses (Balmaseda et al, 2013; Levitus et al, 2012) show a continued uptake of heat by the deeper ocean throughout the period, consistent with our conclusion that changes in R_{TOA} may not play a leading role.

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Concluding remarks

What can we conclude from all this? First, periods of slowing down and pauses in surface warming are not unusual in the instrumental temperature record. Second, climate model simulations suggest that we can expect such a period of a decade or more to occur at least twice per century, due to internal variability alone. Third, recent research suggests that ocean heat re-arrangements, with a contribution from changes in top of the atmosphere radiation, could be important for explaining the recent pause in global surface warming.

We note, however, the need for better continuous long-term records of the net radiation at the top of the atmosphere in general, and of solar radiation in particular, to understand decadal changes in global climate. We also need to maintain and extend to deeper levels (below 2000m) the monitoring of the heat content and thermal structure of the oceans by in situ measurements, building on the tremendous advances made in recent years with the introduction of Argo floats, and the constraints using the sea level measurements from satellites and tide gauges. Finally we note the importance of understanding the dynamics of the global oceans, and how this acts to rearrange heat within the system. Of particular relevance here is a greater understanding of decadal variability in the Pacific Ocean.

The scientific questions posed by the current pause in global surface warming require us to understand in much greater detail the flows of energy into, out of, and around the Earth system. Current observations are not detailed enough or of long enough duration to provide definitive answers on the causes of the recent pause, and therefore do not enable us to close the Earth's energy budget. These are major scientific challenges that the research community is actively pursuing, drawing on exploration and experimentation using a combination of theory, models and observations.

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