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Ocean heat uptake and the global surface temperature record

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Key points

- Over the last 16 years there has been a slowdown in the long term increase in global surface temperatures. A number of factors have contributed to this hiatus including ocean circulation processes.
- Due to its large mass and high heat capacity, the ocean has taken up most of the excess heat stored in the Earth system as a result of greenhouse gas emissions.
- Observations are insufficient to pinpoint exactly where the relevant changes in ocean circulation or heat content have occurred.
- A change in Pacific surface temperatures, driven by stronger than usual Pacific trade winds, is the leading hypothesis to explain the slowdown.
- This change is driven by a natural process that changes phase every few decades, implying that if this hypothesis is correct the rise in global surface temperatures will resume next time it changes phase.
- Changes in Atlantic Ocean circulation may also have reduced heat uptake in the deep ocean.
- Because fluctuations in the rate of warming have been observed throughout the historical record, the slowdown does not alter our understanding of the sensitivity of temperatures to carbon dioxide, and future temperature projections remain unaltered.

Executive summary

There has been a long term increase in global surface temperatures over the last century. A slowdown, sometimes referred to as a hiatus, in this long term trend has been observed over approximately the last 16 years. Whilst there is ongoing debate as to the severity of the hiatus, a slowing or even a reversal of the temperature trend is not unprecedented. Historic temperature records show a variation over decades and a similar change of pace was observed between 1940 and 1975. It is important to understand the processes that could lead to such fluctuations in global surface temperatures, and in particular the ocean's role in this.

Contents

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This most recent slowdown has occurred due to a combination of factors, but here we focus on the contribution of changes in ocean circulation and heat content. Natural variability in Pacific surface temperatures, driven by stronger than usual Pacific trade winds, is the leading hypothesis to explain the oceans' contribution to the hiatus. Several modelling and observational studies support this hypothesis. However, further research is required to understand why the Pacific surface winds may have strengthened in this manner.

In addition to the Pacific Ocean patterns, changes in the Atlantic Meridional Overturning Circulation (AMOC) system of currents that transport warm surface water north from the tropics to the North Atlantic, and cooler water at depth in the opposite direction, could have affected how much heat is taken up by the deep Atlantic Ocean. However, observations are currently insufficient to verify this theory.

It is already known that earth surface temperatures vary over timescales of years to decades, and so the observed slowdown of temperature rise does not substantially alter our understanding of the relationship between greenhouse gas emissions and surface temperature increase. There is little reason to suspect that the impacts of climate change will be any less severe than previously thought because of this change in the pace of warming. The amount of heat in the earth system as a whole has continued to increase over the last sixteen years, and climate change impacts not directly associated with global surface temperatures, including ice melt and sea level rise, have continued. It is likely that the rate of global surface temperature increase will continue to vary over timescales of years and decades due to a range of factors including ocean heat uptake.

Introduction

Global surface temperatures increased by around 0.85°C between 1880 and 2012[10], and each of the last three decades has been warmer than the previous one. This long-term warming trend is almost certainly the result of greenhouse gas emissions from human activity. However, the rate of warming since the industrial revolution has not been uniform (see Figure 1).

The average temperature increase since 1951 has been 0.12°C per decade, but surface temperatures only warmed by 0.05°C per decade between 1998 and 2012[10]. More recent analysis suggests that the warming during the latter period was 0.086°C[11]. The possible slowdown or hiatus in surface warming during this latter period is partly an artefact of the choice of start date: 1998 was an El Niño year, and El Niño conditions are characterised by a warming of the ocean surface in the equatorial Pacific which can be detected in the global surface temperature trend[29]. The severity of the slowdown is sensitive to the methods of data analysis employed[11], but even taking the choice of start date and analysis methods into account there may have been a slowdown in surface temperature rise over the last decade. In this paper we consider the contribution that changing ocean heat uptake could have made to this hiatus.

The rate of temperature rise has fluctuated over the past hundred years. Figure 2 demonstrates that these fluctuations have occurred on a range of timescales. The short-term fluctuations seen in the annual average temperature include the effects of short-acting phenomena such as volcanic eruptions, which lead to a relative cooling of surface temperatures for up to a few years. Longer-term fluctuations can be seen in the 10 and 30 year averages.

The recent slowdown is thought to have been caused by a combination of factors. A series of small volcanic eruptions releasing aerosols that reflected solar radiation reduced the amount of solar radiation entering the earth's atmosphere over this time period. In addition, the sun was in a downward phase of the solar cycle until 2009, leading to a reduction in solar radiation over a period of a few years. An overall increase in anthropogenic aerosol emissions due to factors including an increase in coal burning in China and a decrease in water vapour in the stratosphere may also have contributed to the pause because aerosols reflect sunlight, causing a relative cooling[27].

It is likely that changes in the ocean have contributed significantly to the pause. Due to its large mass and high heat capacity, the ocean absorbs a substantial amount of heat. It is estimated that the earth gained 274 ZJ[i] of heat energy between 1971 and 2010, of which around 90% was taken up by the ocean (figure 3)[28,ii]. According to one estimate, the top 2000 m of the ocean took up 240 ZJ of heat energy between 1955 and 2010, but only increased in temperature by about 0.09°C due to its high heat capacity[14]. If the lower 10 km of the atmosphere were able to absorb this same quantity of heat it would warm by 36°C.

The pause does not substantially change our understanding of the sensitivity of the climate to carbon dioxide. The so-called climate sensitivity cannot be determined from observations over just a fifteen year time period because of the above processes that change the rate of warming over years and decades. Carbon dioxide is long lived in the atmosphere, and the severity of climate change is therefore linked to our total emissions since the start of the industrial revolution. In addition, when only models that capture the hiatus are used to project the long-term warming caused by climate change, the long-term projections are unaffected, suggesting that long-term projections are not undermined by the existence of the hiatus[9].

[i] 1 ZJ (Zetta Joule) = 1021 Joules, i.e. 10 with 21 zeros. [ii] To put this in perspective, 274 ZJ roughly equates to the amount of energy output by the Ratcliffe-on-Soar coal fired power station in 4 million years. The Ratcliffe-on-Soar power station is a large coal fired power station in the East Midlands of England that achieved a degree of notoriety after attracting protests from environmental activists in 2007 and 2009.

In the next section the processes involved in ocean heat uptake are introduced, then in the following section we discuss the contribution of ocean heat uptake to the slowdown in the rate of temperature increase.

The ocean circulation and heat uptake

Solar radiation is absorbed by the top 100 m of the ocean, which is well mixed with the atmosphere due to the breaking of wind-generated waves and surface heat exchange. When the ocean surface is warmer than the atmosphere, heat is lost to the atmosphere. Conversely, when the ocean surface is cooler than the atmosphere, the upper ocean gains heat from the atmosphere. If heat did not mix from the upper ocean to the lower ocean layers at all, the ocean surface would continually increase in temperature as a result of global warming, as in Box 1, figure 4 (a). When heat uptake by the deeper ocean is taken into account the effect of global warming on ocean surface temperatures is more difficult to predict (Box 1, figure 4 (b)).

In the following sections a number of ocean processes affecting ocean heat uptake or surface temperatures are discussed, starting with processes affecting the heat content of the upper layers of the Pacific, and moving on to processes affecting deep ocean heat content in the Atlantic. The relevant processes in both the Atlantic and Pacific Oceans are summarised in Box 2.

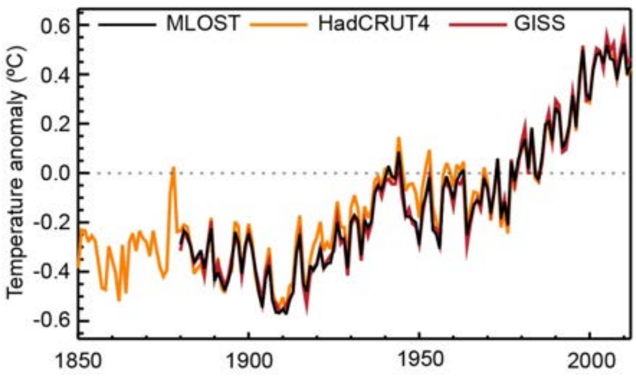

Figure 1: Past global surface temperature rise according to the MLOST, HadCRUT4 and GISS datasets. Figure from IPCC, 2013[10].

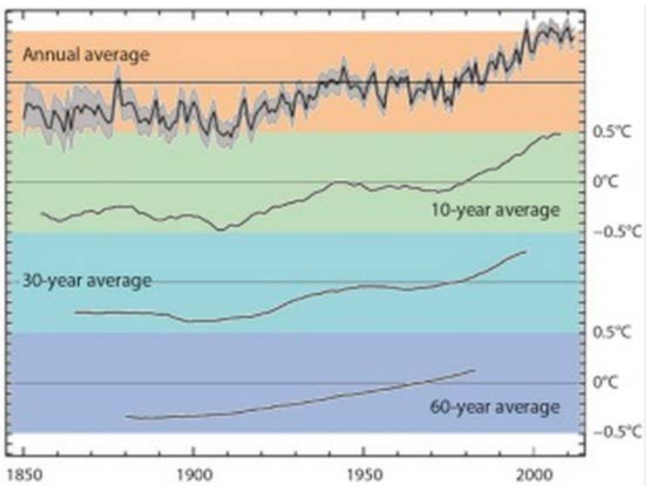

Figure 2: The rate of temperature rise since 1850 has fluctuated due to several factors. The annual average displays evidence of fluctuations due to short acting factors including El Niño events and volcanic eruptions. The 10 and 30 year averages show that there are also longer term fluctuations in the rate of temperature rise, which includes the effects of ocean processes. The 60 year average reveals the long term warming trend when these fluctuations are removed. (Image from Royal Society and National Academy of Sciences)[24].

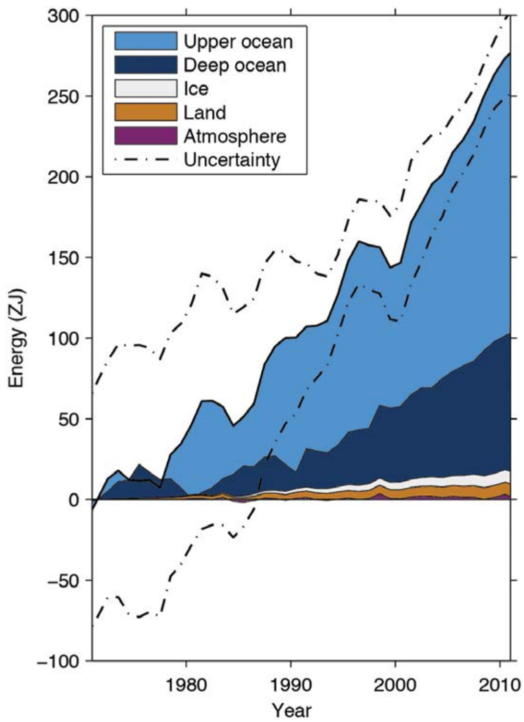

Figure 3: A graph showing the heat energy that has entered each component of the earth system since 1971 as a result of climate change. Ninety three percent of the extra energy has gone into the ocean, which is split into the upper ocean above 700 m depth shown in light blue, and the deep ocean (below 700 m) shown in dark blue. The rest of the energy went into melting ice (grey), warming the land (orange) and warming the atmosphere (purple). Figure from IPCC (2013)[10].

The El Niño Southern Oscillation

A key factor in changing Pacific surface temperatures on yearly timescales is El Niño, a large-scale climatic phenomenon that affects the weather in several parts of the world. El Niño in this context means "the Christ child"; the phenomenon was named by Peruvian fishermen who noticed the warm, wet conditions El Niño brings to Peru around Christmas time. Sea surface temperatures in the western Pacific are usually warmer than those in the eastern Pacific, but during an El Niño event warm surface water from the western Pacific spreads out to cover the eastern Pacific. Because the Pacific Ocean is so large, this El Niño-related increase in overall Pacific sea surface temperatures leads to a relative increase in global surface temperatures in El Niño years.

La Niña conditions are the reverse of El Niño conditions. The Pacific oscillates between El Niño, La Niña and neutral conditions; this is a phenomenon known as the El Niño Southern Oscillation (ENSO). ENSO is reasonably well understood, and it provides a good example of the way in which ocean surface temperatures, and therefore global surface temperatures, vary over time.

Is climate change having an effect on El Niño?

A change in El Niño conditions has been observed since the late 1990s, with greatest warming frequently occurring in the central rather than the eastern Pacific. It has been conjectured that these central Pacific El Niños, which have their own distinct pattern of global impacts, may continue to occur more often[10]. The region of temperature variability inbetween the warm top layer of the ocean and cold deep-water known as the thermocline is expected to shoal (i.e. become shallower) due to climate change[10]. A modelling study suggests that this shoaling of the thermocline in the equatorial Pacific may be associated with central Pacific El Niños[34], but subsequent research suggests that there is little difference in the thermocline in periods dominated by central Pacific events compared to periods dominated by normal El Niño events[35].

Observations show that the strength of El Niño/La Niña has increased over the past century, but it is not known whether this is due to human influence. Climate models selected for their skill at simulating strong El Niño events project a gradual increase in El Niño intensity in the future under climate change. However, this predicted change is still uncertain because the modelled future changes in El Niño intensity are not significantly larger than natural variability, and the projected change depends on which climate model is used. Although changes to El Niño/La Niña are hard to predict, it is very likely that this cycle will remain the dominant mode of natural climatic variability in the 21st century[10].

Box 1: Ocean heating – the role of heat uptake by deep ocean layers

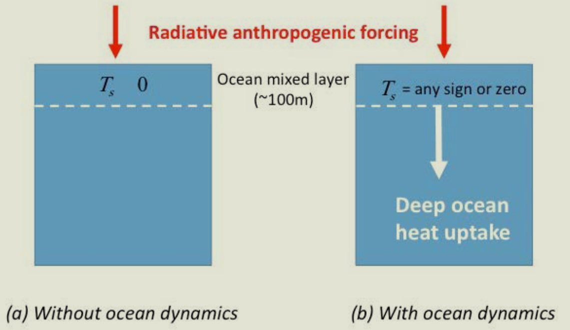

Figure 4: A simple depiction of global ocean heat uptake. In response to anthropogenic radiative forcing, the sea surface temperature can increase, remain constant or even decrease, depending on the strength of the deep ocean heat uptake

(a) In this theoretical scenario with no ocean dynamics, no heat is taken up by the deep ocean and the top layer warms continuously as a result of climate change.

(b) When ocean dynamics are taken into account, heat is exchanged with the deep ocean, (downward arrow) and the surface temperature increases, decreases, or remains constant, depending on the strength of the heat uptake.

Changes in Pacific heat content over longer timescales

There are longer term El Niño-like oscillations in Pacific sea surface temperatures, changing over decades rather than years. This longer term variability in Pacific surface temperatures is known as the Interdecadal Pacific Oscillation (IPO)[iii]. It has a warm phase and a cool phase, defined by temperatures in the tropical Pacific Ocean. In the warm phase, the sea surface temperatures warm in the eastern Pacific near North America and the central equatorial Pacific, and much of the north western Pacific cools. In the cool phase the reverse occurs. There is more El Niño activity during the warm phase and more La Niña activity during the cool phase. These longer term fluctuations in the average state of the Pacific Ocean are significant because they help explain longer term fluctuations in global surface temperatures (see page 8: *How have changes in ocean heat content contributed to the slowdown in global surface temperature rise?*).

[iii] The Pacific Decadal Oscillation (PDO) is defined in a similar manner. The IPO and PDO differ in the Southern hemisphere, but for the purposes of this paper the two are interchangeable. The term Interdecadal Pacific Oscillation or IPO will be used throughout this paper for consistency.

Box 2: Summary of relevant climate and ocean phenomena

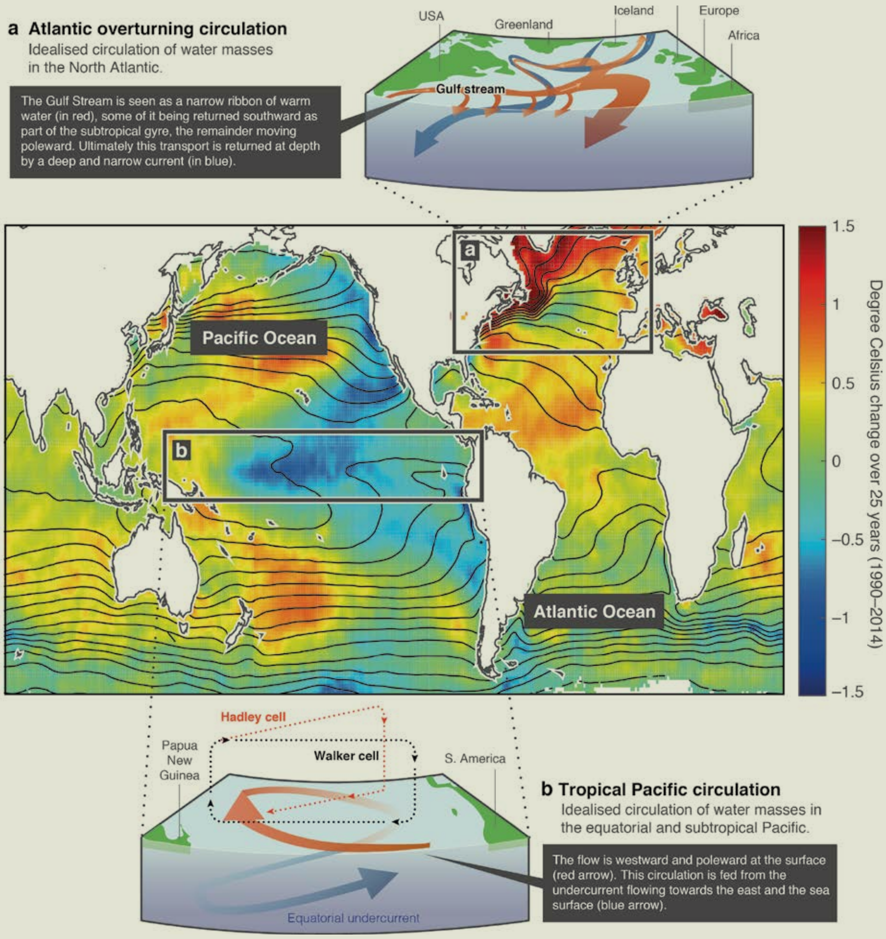

Figure 5: Some of the key oceanic features involved in the recent hiatus.

The middle panel displays the recent trend in sea surface temperature (SST, in degrees Celsius). The linear trend between 1990 and 2014 is shown in colour and was computed using the HadISST dataset from the Hadley Centre. The long term mean SST is shown in black contours with a contour interval of 2 degrees Celsius.While it has been suggested that both the equatorial Pacific and the North Atlantic oceans are instrumental in enhancing deep ocean heat uptake in recent decades, these ocean basins are associated with very different trends in SST (surface cooling in the eastern equatorial Pacific, showin in blue, and surface heating in the North Atlantic, shown in red). Schematics of the associated circulations are provided in the boxes above and below.

For the equatorial Pacific the atmospheric circulation associated with Walker and Hadley cells is indicated, in idealised form. These and the surface trade winds are strongly coupled to the strength of the SST gradient across the equatorial Pacific (seen here as the multiple black SST contours in the middle panel when going along the equator from the maritime continent to the coast of South America), being weak when the gradient is weak (and vice versa).

The large scale ocean circulation from the Atlantic to the Southern Ocean

An important feature of the large scale ocean circulation is the Meridional Overturning Circulation (MOC) – where meridional means that the circulation is in the north-south direction. This is a large system of ocean currents driven by both wind and density differences. Its Atlantic component transports warm water northwards in the upper ocean, which cools and sinks at specific locations in the North Atlantic, before being transported south in the deep ocean (see Box 2). When it reaches the Southern Ocean, wind-driven upwelling transports water to the surface[15]. The overturning circulation is an important component of the global climate because it transports on the order of 2 x 1015 Watts of heat around the globe[32]. This process could be affected by climate change: accelerated melting of the ice caps would increase the amount of fresh water in the North Atlantic, affecting the sinking process that occurs in the North Atlantic, and potentially slowing the overturning circulation[10].

Heat is transferred between the surface and the deep ocean by many processes, the most spectacular of which are the sinking and upwelling processes that occur only in specific locations when strong surface cooling occurs. If heat were to be sequestered in the deep ocean due to a change in the large scale overturning circulation it would be expected to stay there for several centuries. This contrasts with the heat sequestration in the upper layers (top 300 m) of the Pacific that occurs due to 'sloshing' motions on yearly timescales (El Niño) and decadal timescales (the IPO).

Other processes affecting heat uptake in the Atlantic Ocean

The strength and direction of the Northern Hemisphere storm tracks change between two modes, usually measured by the difference between the atmospheric pressure over Iceland and the Azores. When this relationship changes, it affects winter surface temperatures and weather patterns in the Northern Hemisphere. According to one estimate, this variability in the Northern Hemisphere storm tracks and its associated effects accounted for 31% of surface temperature variability in the northern extratropics, which include the UK and Europe, between 1935 and 1994, but subsequently it was not correlated with global temperatures[28].

The sinking in the North Atlantic that occurs as part of the Meridional overturning circulation is also affected by these north-south shifts in the storm activity over the North Atlantic. Water in the North Atlantic below 2000 m is likely to have increased in heat content between 1955 and 1975, and then lost heat between 1975 and 2005 due to this variability[20]. The role that changes in the Atlantic overturning circulation could have played in the hiatus is discussed in the section "The role of the Atlantic Ocean".

Changes in ocean heat content

Estimates of the earth surface temperature can be obtained from satellites; however, heat uptake by the subsurface ocean must be measured *in-situ* (see Box 3). *In-situ* coverage is spatially limited (see table 1), so satellite observations of the earth's energy balance have not always appeared to agree with *in-situ* measurements of ocean heat content.

The Intergovernmental Panel on Climate Change[10] present a range of previously published estimates for the heating rate of the top 700 m of the ocean between 1971 and 2010, which range from 43-105 TW[26] (Terra Watts)[iv] to 120-154 TW[5]. A more recent paper estimated the top 700 m of the ocean had warmed at a rate of 126-148 TW between 1975 and 2009[2].

Although the five different estimates presented by the IPCC all agree that the top 700 m of the ocean has warmed since 1970 (see figure 6), the different estimates do not agree on the short term fluctuations in heat uptake, so we cannot see the effects of the Interdecadal Pacific Oscillation, for example. This also reflects the fact that the Interdecadal Pacific Oscillation involves

Ocean depth range	Observational coverage	Warming due to climate change
Surface – 700 m	Argo floats have been globally deployed since about 2004. Prior to that the observations (mainly taken using bathythermographs) were very sparse, even more so before the 1970s. See Box 4.	Several different analyses all show an increase in temperature since 1970 but do not agree on the exact fluctuations that have occurred. IPCC estimates of heating between 1971 and 2010 range from 43-105 TW[26] (which roughly equates to an average temperature increase of 0.005 – 0.01 °C)[v] to 120-154 TW (which roughly equates to an average temperature increase of 0.01 – 0.02 °C)[5].
700 m – 2000 m	Argo floats take measurements down to 2000 m, so the coverage since 2004 is almost global as above. See Box 3.	Heat content has increased since 1957. Fewer observations are available than for the top 700 m.
2000 m – 3000 m	Very sparse: only about 1/3 of the ocean below 2000 m has been sampled since 1993[33].	Warming due to climate change would only be expected at specific locations: parts of the western Atlantic and Southern Ocean have warmed, but average temperatures at this level don't show any significant trend. The Indian and Pacific Oceans at this depth have not had recent contact with the surface: much of the deep Pacific ocean has not had contact with the surface for about 1000 years.
Below 3000 m	Very sparse (see above).	It is likely there has been some localised warming, particularly of Antarctic Bottom Water. Warming would only be expected in specific locations.

Table 1: The observational coverage and measured warming of the ocean at various depths.

[iv] A Terra Watt is one trillion (1012) Watts. [v] These temperature figures are approximate. They have been estimated based on the assumption that the heating rate was constant in both space and time.

a redistribution of heat in the east-west direction, which averages out when the overall heating above 700 m is considered. Cooling due to the major volcanic eruptions in 1963, 1982 and 1991 was however observed in all the estimates. Three of the five estimates measured a slower increase in upper ocean heat content between 2003 and 2010 than in the previous decade. This slowdown coincides with the change in measuring system from ship-based (Bathythermograph) measurements to Argo floats (see Box 3). Any change of measuring system can lead to discontinuities in the data being collected, so this apparent slowdown in upper ocean warming should be treated with caution.

The heat content of the ocean between 700 m and 2000 m depth has also increased since the mid-twentieth century and this increase appears to have continued unabated since 2003 (see figure 7)[10]. Much of the very deep ocean below 1500 m has not had contact with the surface in the last one hundred to a thousand years[16]. Therefore, on average, the ocean at this depth would not be expected to have warmed significantly due to climate change. Anthropogenic warming of the ocean below 1500 m is only expected in specific regions in which the water has had recent contact with the surface, due to the Atlantic Meridional Overturning Circulation (AMOC), for example.

No warming was observed below 2000 m. However, robust warming has been measured in specific locations, such as near Antarctica, where the water is thought to have been exposed to the surface recently[22, 33]. The observational coverage and the warming due to climate change by depth are summarised in Table 1.

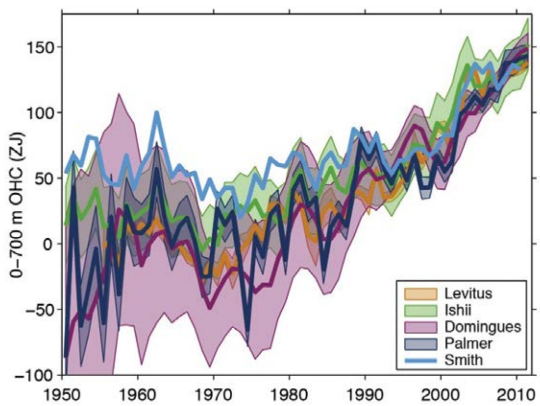

Figure 6: Five different estimates of the heat content of the upper 700 metres of the ocean in ZJ (1 ZJ is 10^{21} Joules). The data is very sparse prior to 1970. Image from IPCC, 2013[10].

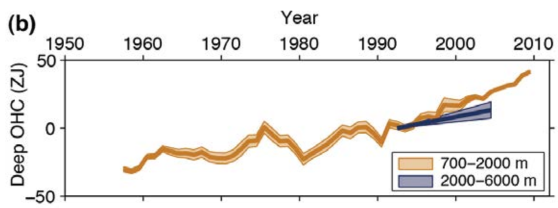

Figure 7: Deep ocean heating at 700-2000 m and 2000-6000 m since 1957. This was estimated as a 5-year running mean because estimates of heat content cannot be obtained for each individual year. Image from IPCC, 2013[10].

Box 3: Observations of ocean heat content post–2000

Measurements of subsurface ocean temperatures have historically been disparate and intermittent. Before 1950, observations were limited to very few voyages: the Challenger expedition of the globe in the 1870s, the Meteor survey of the Atlantic in the 1920s and the Discovery voyage in the Southern Ocean in the 1920s. More frequent sampling began in the 1950s, and coverage has gradually increased since then[10].

There has been near-global coverage of the ocean to a depth of up to 2000 m since the Argo programme, a research effort in which autonomous buoys are deployed to measure temperature and salinity, was scaled up in the mid-2000s[1]. The deployment of Argo floats began in 2000, and as of 25th June 2015 there were 3,880 floats covering most regions of the ocean (see figure 8 for the coverage in June 2015). Argo floats are designed to drift at depth and take readings at 10 day intervals. When a reading needs to be taken, the float gradually moves up to the surface over a period of six hours whilst taking measurements, before surfacing so that its location can be detected and its data can be transmitted by satellite. The depth of the float is controlled by a hydraulic bladder, which is inflated to move the float upwards, and deflated to move it downwards (figure 9).

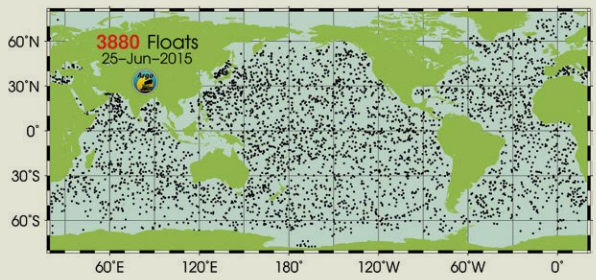

Figure 8: Argo float locations as of June 2015.

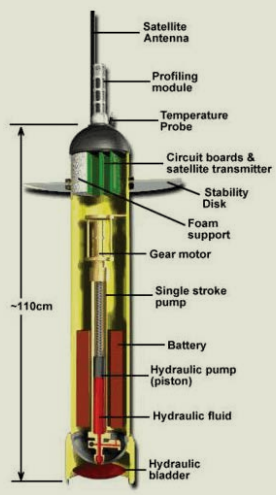

Figure 9: A typical Argo float design. Figure from NOAA Ocean Climate Observation Program[21]. Figure from University of California San Diego[30].

Box 4: Observations of ocean heat content pre-2000

Previously, much of the available data for subsurface ocean temperatures came from sensors known as bathythermographs. Bathythermographs are deployed from ships, and measure temperatures in the top kilometre of the ocean. They are generally deployed on commercial "ships of opportunity", and much of the data is therefore limited to major shipping routes. A limited amount of temperature and salinity data has been collected by research ships, covering the whole depth of the ocean (figure 10).

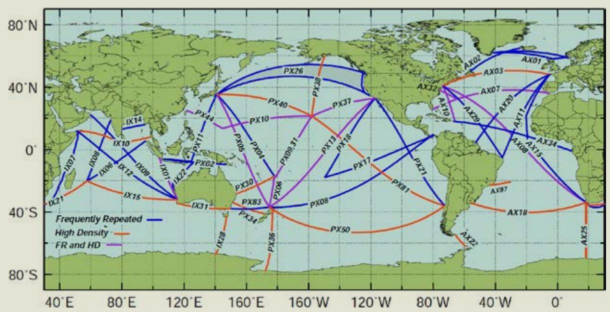

Figure 10: The spatial coverage of bathythermograph measurements. They are split into 2 categories. Frequently Repeated (FR) measurements are spaced out by 150 km and repeated 18 times a year. High Density (HD) measurements are spaced out by 25 km and repeated 4 times per year. Image from NOAA Ocean Climate Observation Program[21].

How have changes in ocean heat content contributed to the slowdown in global surface temperature rise?

Although the extent of the slowdown in global surface temperature rise is still under debate[11] several modelling and observational studies have attempted to explain why global surface temperatures may have risen more slowly over the last fifteen years. Changes in the Pacific Ocean constitute the leading hypothesis to explain the pause, but the Atlantic and Southern Oceans may also have played a role. The leading theories are described in this section.

The role of the Pacific Ocean

Changes in the Pacific Ocean appear to account for most of the decadal variability in global surface temperatures[28], and constitute the leading hypothesis to explain the oceanic contribution to the slowdown. The Pacific trade winds have strengthened since the late 1990s, which would be expected to cause an increase in heat uptake in the near-surface equatorial Pacific. This intensification has led to cooling in the eastern Pacific, contributing to the slowdown in global surface temperature rise (see Box 5).

Box 5: A change in ocean currents in the equatorial Pacific is the leading explanation for the oceanic contribution to the hiatus.

The ocean is likely to have played a role in causing the hiatus, and the most likely process for this is a change in the temperature of the surface of the Pacific. This change has likely occurred due to a change in the state of the Pacific Ocean which occurs naturally every few decades.

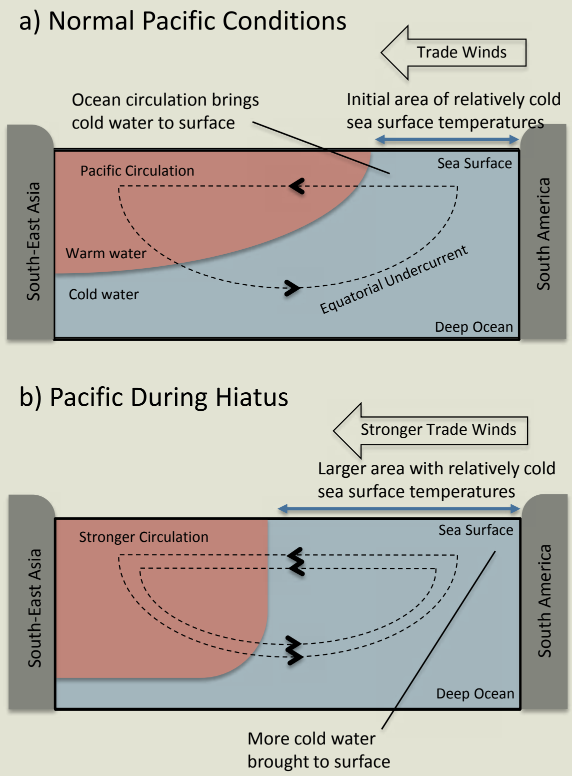

Figure 11: (a) During normal Pacific conditions the trade winds flow from east to west and this drives an ocean current flowing from the South American coast towards South-East Asia, with deep currents flowing in the opposite direction. This circulation brings relatively cold water to the surface. **(b)** During the hiatus the trade winds have strengthened, driving stronger ocean currents. These are thought to bring more cold water to the surface, increasing the area of the Pacific that is covered with cold surface waters. This larger area of cold surface water keeps the atmosphere colder than it would otherwise be on average.

Box 5, part (a) shows conditions in the Pacific pre-1990, with a relatively small area of cold water at the ocean surface, and part (b) shows the conditions during the hiatus. There is now a larger area of cold water at the ocean surface due to changes in the ocean circulation caused by a strengthening of the trade winds. Although there has been no increase in Pacific Ocean heat content during the hiatus period, there is evidence that the heat entering the Pacific is being transported into the Indian Ocean[13].

Globally, sea surface temperatures over the period 1992-2011 warmed in the Atlantic, the Indian Ocean and the western subtropical Pacific, and cooled in the eastern Pacific[17]. These changes are associated with the ongoing negative phase of the IPO. The previous hiatus period in the historical record (1940-1975) also occurred during a period of negative IPO[8]. By contrast, the positive IPO in 1976-1998 enhanced warming, suggesting that a future switch to the positive phase of the IPO may lead to an enhanced warming in surface temperatures.

Model simulations forced either with observed winds in the tropics or with observed sea surface temperatures in the eastern Pacific were found to reproduce the recent trend in global mean surface temperature. These results suggest that changes to the trade winds over the Pacific and the consequent changes to sea surface temperatures are an important cause of the hiatus[12, 31]. Models also suggest that the increase in the intensity of the Walker Circulation (see Box 2) and changes to sea surface temperatures in the eastern Pacific may have been caused by rapid surface warming in the Atlantic[17].

It is possible for global surface temperatures to decrease slightly in individual decades even as the planet continues to gain heat. A modelling study simulated so-called hiatus decades, and showed that in these decades the ocean took up less heat above 300 m and more heat below 300 m. The conditions simulated by the models were similar to the negative phase of the IPO, but changes in the AMOC also contributed to the hiatus periods[18]. In addition, model simulations show that accelerated warming decades are associated with the positive phase of the IPO[19]. However, it has been argued that the model used in these studies does not represent the observed variability in Atlantic salt and heat content well[3] suggesting that it may not encompass all the possible explanations for the slowdown.

The role of the Atlantic Ocean

The role of heat uptake in the Atlantic linked to changes in the Atlantic MOC could also be involved in the hiatus, although this is still the subject of research, and less is known about the processes involved than with the Pacific. An observational study which evaluated ocean heat content during the recent hiatus concluded that the hiatus was caused mainly by changes in Atlantic and Southern Ocean heat content below 300 m, possibly due to changes in the Atlantic part of the Meridional Overturning Circulation driven by changes in sea surface salinity[3]. This mechanism has not been verified observationally, so the theory remains speculative.

Box 6: A slowdown in the Atlantic Meridional Overturning Circulation (AMOC) is thought to have played a role in the hiatus.

It is possible that a change in the Atlantic branch of the Meridional Overturning Circulation, a large system of currents in the Atlantic (see Box 1) has contributed to the hiatus. A plausible mechanism is that the Atlantic MOC has slowed, causing less heat to be lost from the ocean to the atmosphere. This diagram illustrates the process[6].

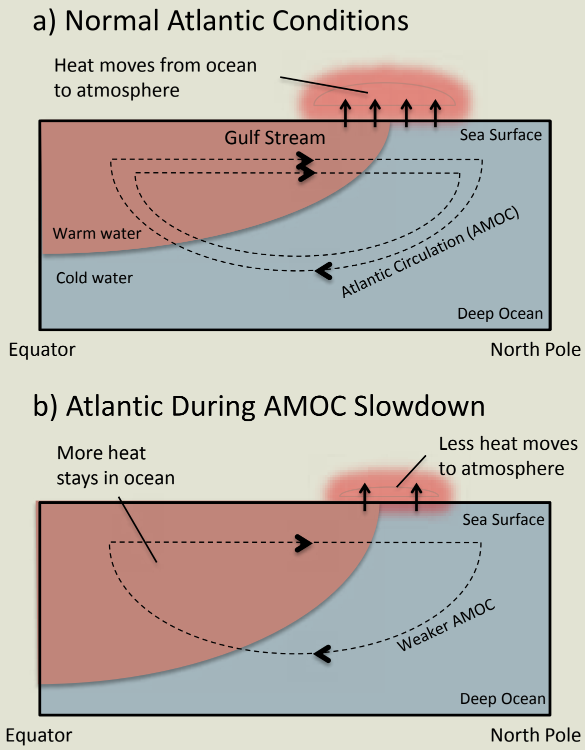

Figure 12: (a) Normal Atlantic conditions: The AMOC moves heat from the Equator towards the North Atlantic via the Gulf Stream where it loses heat to the atmosphere. This contributes to Europe's mild climate.
(b) Atlantic during Atlantic MOC slowdown: less heat is moved northward and lost to the atmosphere. This leads to lower atmospheric surface temperatures and more heat being trapped in the ocean.

Observations indicate that the overturning circulation weakened slightly at 26 °N between 2004 and 2012, although this by no means confirms that the MOC has slowed overall[25]. This weakening is small relative to the yearly variability in the MOC strength, and there is no indication that it has been persistent, however, it may have affected recent ocean heat uptake. The observed decline in the MOC strength could have contributed to the hiatus by reducing heat loss to the atmosphere[6] rather than by sequestering heat in the deep ocean[3]. Box 5 illustrates the proposed mechanism. Before the hiatus the ocean circulation was stronger, and a relatively large amount of heat was lost to the atmosphere (Figure 12 (a)). During the hiatus, the ocean circulation weakened and less heat was lost to the atmosphere (Figure 12 (b)).

Changes in Pacific sea surface temperatures and Atlantic heat sequestration could be occurring independently due to unrelated processes as proposed above. Alternatively, it is possible that the near-surface changes in the Pacific are the fundamental cause of the warming, and that these processes have affected heat uptake in the Atlantic via atmospheric processes such as the Walker circulation. It is also possible that the changes in the Atlantic could be causing the changes in the Pacific[17].

The role of the Southern Ocean

Roemmich et al. (2015)[23] analysed ocean heat content using Argo data and found that most of the change in heat content since 2006 (67-98%) was in the Southern Ocean. Argo coverage was near global during this time period. Durack et al. (2015)[7] concluded that warming in the top 700 m of the ocean since 1970 had been underestimated due to poor sampling in the Southern Hemisphere. The analysis techniques that had previously been used led to low estimates in poorly sampled regions. Because of the scarcity of observations prior to 2006 the Southern Ocean remains a major unknown in accounting for ocean heat uptake.

Conclusions

The Earth system has gained a substantial amount of heat since the start of the industrial revolution as a result of anthropogenic greenhouse gas emissions. This increase in the total heat content of the earth system is ongoing. There has been a slowdown in global surface temperature rise since around 1998, although the impacts of climate change that are not directly associated with rising surface temperatures, in particular sea level rise and ocean acidification, have continued unabated. Due to their large mass and high heat capacity, the oceans have taken up most of the extra heat that has been sequestered in the earth system due to climate change. While there are other factors involved, this paper has focused on the role ocean heat uptake could have played in the slowdown.

Several studies have attributed the hiatus partly to changes in Pacific surface temperatures which occur due to a natural fluctuation in the climate system. A strengthening in the trade winds has affected ocean circulation and surface temperatures. The previous hiatus occurred during a period of similar conditions in the Pacific. This phenomenon changes phase every few decades, implying that the warming trend will likely reassert itself or become stronger in the future. A slowing of the Atlantic overturning circulation could have played a role in the hiatus although the exact mechanism is not known. The most plausible theory is that heat loss to the atmosphere was reduced by a decline in the strength of the oceanic overturning circulation.

Irrespective of the current hiatus, the ocean is a hugely important part of the climate system and there is a need to understand the effect that it has on global surface temperatures. There are still several open research questions in this field. We do not yet fully understand the contribution of the ocean to the slowdown in surface temperature rise, although it is highly likely that changes in Pacific surface temperatures are an important factor. The Argo programme has only been running for just over a decade, and more observations are still needed to refine our knowledge and understanding of ocean heat uptake. Our physical understanding of the processes involved in the hiatus would be enhanced by further research. Whilst it is known that the recent changes in the Pacific were caused by a strengthening of the trade winds, it is not known exactly why the trade winds have changed over the last decade. Whilst it is highly likely that the heat content of the Atlantic Ocean below 300 m has increased since the 1970s, more research is needed to verify or disprove the mechanism linking a slowdown of the overturning circulation to deep ocean heat uptake.

The hiatus is not unprecedented: changes in the rate of warming over years and decades have occurred throughout the observational record. The current hiatus therefore does little to change our overall understanding of the sensitivity of the climate to carbon dioxide, known as climate sensitivity. This means that estimates of the severity of climate change impacts or the timescales on which they are likely to occur remain substantially unchanged, and serious efforts to curb carbon dioxide emissions are still necessary.

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