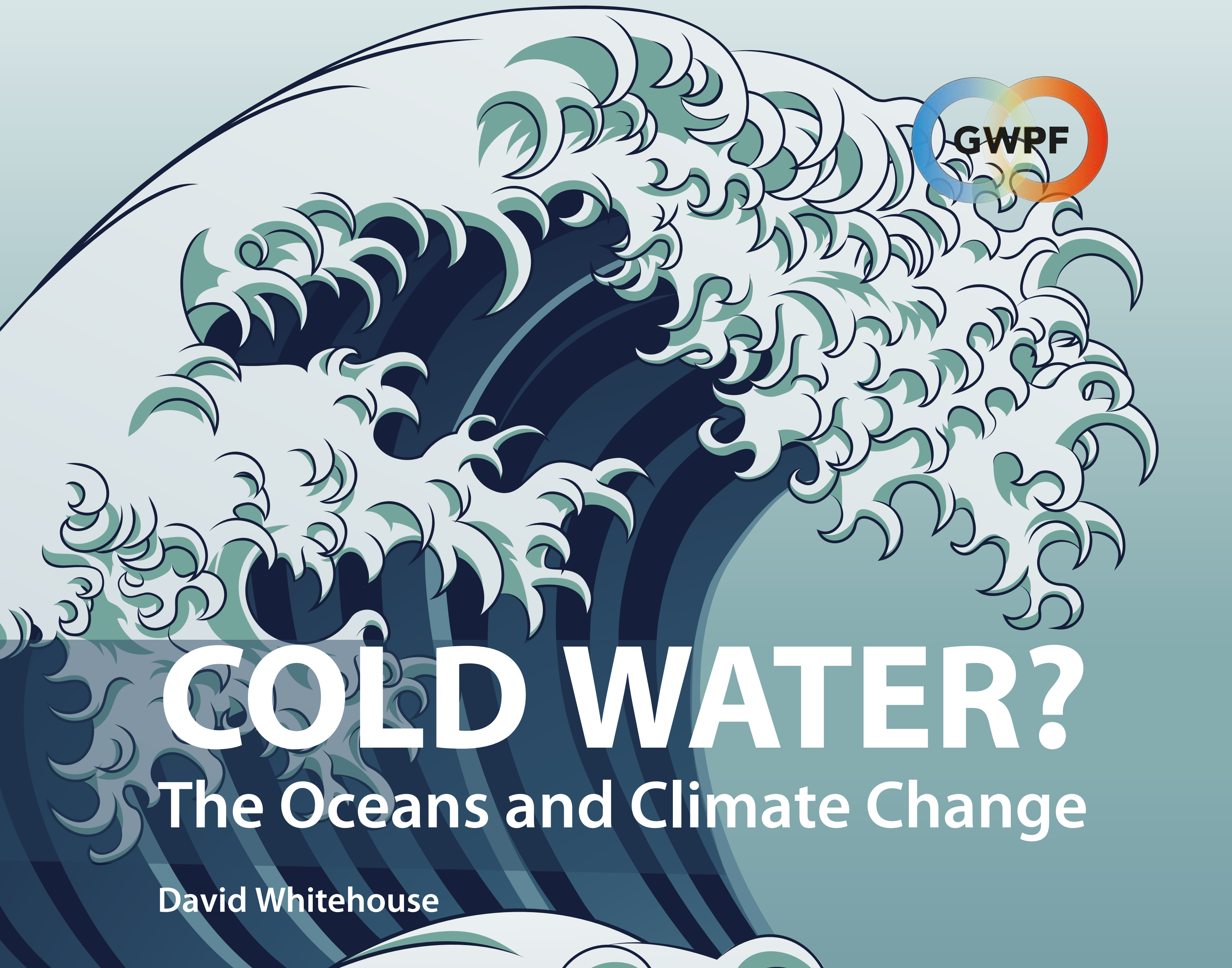

COLD WATER?

The Oceans and Climate Change

David Whitehouse

The Global Warming Policy Foundation

GWPF Briefing 44

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The Oceans and Climate Change

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About the author

The science editor of the GWPF, Dr David Whitehouse is a writer, journalist, broadcaster and the author of six critically acclaimed books. He holds a PhD in astrophysics from the Jodrell Bank Radio Observatory. He was the BBC's Science Correspondent and Science Editor of BBC News Online. Among his many awards are the European Internet Journalist of the Year, the first Arthur C Clarke Award and an unprecedented five Netmedia awards. Asteroid 4036 Whitehouse is named after him.

> Convenient assumptions should not be turned prematurely into 'facts', nor uncertainties and ambiguities suppressed…Anyone can write a model: the challenge is to demonstrate its accuracy and precision…Otherwise, the scientific debate is controlled by the most articulate, colorful, or adamant players.
>
> Prof Carl Wunsch

Executive summary

- The study of ocean heat content (OHC) is a subject struggling with inadequate data, but exposed in a public forum.
- Only since the introduction of data from the Argo array have there been convincing estimates of errors. The inhomogeneity of different data sets is a major problem.
- There is no real understanding of the difference between random and systematic errors in OHC data.
- Changes in OHC are at the limits of our ability to measure, and made with much uncertainty and many unknowns.
- It is likely that OHC has increased over the past few decades, although this is not a highly robust result. Movements in energy are typically 10^{22} J from year to year, with large uncertainties. For comparison, this is about the energy the Earth receives from the Sun every day and about twice the world's energy consumption. It represents a small change in the ocean's total heat content (about 165×10^{25} J).
- It is difficult to put these changes into a proper historical context. There is much uncertainty about long-term ocean cycles, and the OHC earlier in the Holocene seems to have been larger than today and changing on the same timescales as seen today. In addition, the timescales for change in the deep ocean are very long. This could mean that some (possibly most) of what is happening there has nothing to do with recent human activity.
- The jump in the OHC data seen at the time of the introduction of the Argo floats is a big problem. Post-Argo behavior is different to what it was before Argo. A case could be made to disregard all OHC observations made before the Argo deployment and treat Argo data on its own, and this is sometimes done; when it is, evidence for changes in OHC is much reduced.
- There are major uncertainties in our understanding of the way heat is transported from the ocean surface to the depths.
- Almost all of the ocean warming is coming from one region, 30°–50°S, in the Pacific Ocean.

1 The oceans

The oceans comprise 1.3 billion cubic kilometres (1.3×10^{18} m^3) of water spread over most of the earth's surface comprising 3.6 of the 5.1×10^{14} m^2 area of our planet. Their average depth is 3,796 m. The largest ocean is the Pacific (45% by area, 49% by volume), followed by the Atlantic (23.5% by area, 23.3% by volume) and the Indian (19.5% by area, 19.8% by volume).

Because the oceans' mass is 1.4×10^{21} kg compared to the atmosphere's 5×10^{18} kg, it is the largest thermal reservoir in the climate system. But changes can be small. The energy that would cause a 4°C increase in the atmosphere when applied to the ocean would result in a change of 10^{-3}°C.

Historically, ocean temperature sampling is inhomogeneous, both by geographic region and depth, and with major shifts in observing techniques and programs from decade to decade. Accurate but sparse temperature measurements using reversing thermometers, sometimes to full depth, commenced after 1874. Starting in the 1960s, these were gradually replaced with conductivity-temperature-depth (CTD) thermometers. In the 1930s, mechanical bathythermographs (MBTs) made it easier to measure the upper-ocean temperature and were widely used in the 1950s and 1960s.

In 1966, the expendable bathythermograph (XBT) began to replace the MBT for upper-ocean measurements, with shallow XBTs (as deep as 460 m) dominant in the 1970s and 1980s, and deep XBTs (as deep as 760 m) dominant in the 1990s. MBTs and XBTs are not very accurate (±0.1°C for temperature and ±2% for depth), but have provided a large part of the data we have for upper-ocean temperatures.

The revolutionary profiling CTD floats of the Argo program began to provide accurate, year-round sampling of upper-ocean temperatures in 2000. The array started regionally, but became near-global and largely replaced the XBTs by 2005. Some of the early floats sampled to around 1000 m, but subsequently more floats have sampled as deep as 2000 m. By November 2007, the array reached 3000 floats.

2 The data

In 2007 the Intergovernmental Panel on Climate Change (IPCC) published its fourth assessment (AR4) of the Earth's climate (Climate Change 2007: Working Group I: The Physical Science Basis, 2007)

The report estimated that between 1961 and 2003 the OHC for 0–700 m had increased by $8.11 \pm 0.74 \times 10^{22}$ J (Figure 1). It said there was a 'significant increasing trend in ocean heat content.' Despite the obvious differences between OHC estimates, AR4 concluded that because they are broadly consistent it had a 'high confidence' in their use for climate studies.

AR4 was concerned that errors introduced from different data sets could lead to spurious variability in OHC. It is obvious there is substantial inter-decadal variability. AR4's graph shows little change between 1955 and 1970. Then there is an increase of 10^{23} J, followed by a fall of 5×10^{22} J between 1974 and 1987, and a slower rise of about 10^{23} J to a peak in 2004. Most of this cooling occurred in the Pacific and may be associated with a reversal of polarity of the Pacific Decadal Oscillation (PDO).

It is interesting to compare AR4 with AR5 of a few years later after newly appreciated biases were taken into account. Concerning biases, Lyman *et al.* said;[1]

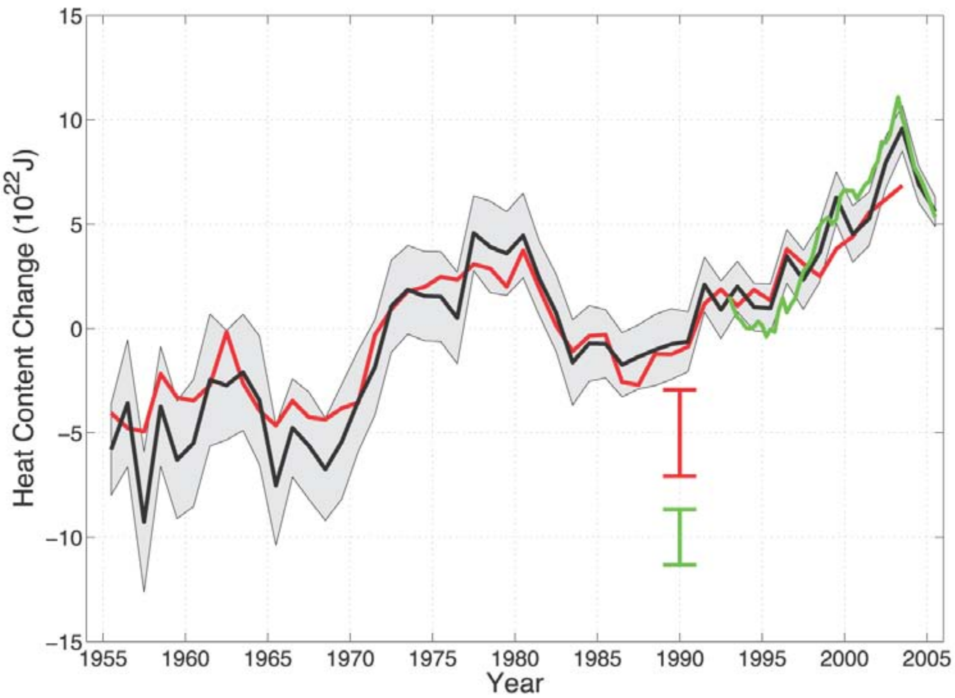

Figure 1: The Fourth Assessment Report take on upper-ocean heat content (0–700m).

Original legend: The black curve is updated from Levitus et al. (2005a), with the shading representing the 90% confidence interval. The red and green curves are updates of the analyses by Ishii et al. (2006) and Willis et al. (2004, over 0 to 750 m) respectively, with the error bars denoting the 90% confidence interval. The black and red curves denote the deviation from the 1961 to 1990 average and the shorter green curve denotes the deviation from the average of the black curve for the period 1993 to 2003.

> Since the Fourth Assessment Report, the discovery of a time-varying bias in XBT data has prompted re-evaluations of the rate of upper-ocean warming. We have carried out an inter-comparison of these estimates of ocean warming and made a comprehensive estimate of the total uncertainty. We find that uncertainties in XBT bias corrections are the dominant error source over the period 1993–2008, which limits our ability to resolve inter-annual changes in ocean heat content. However, despite these uncertainties, we still find a robust warming over the 16-yr record.

They found a 10^{23} J globally averaged warming signal in the top 300 m.

Lyman *et al.* found a clear reduction in the slope around 2004 (Figure 2).[1] Trenberth and Fasullo pointed out that this occurred around the time that the Argo array achieved near-global coverage.[2] It could be coincidental, but it also raises the possibility of a yet another undiscovered bias in the observing system.

The change of slope, suggesting that ocean warming had stalled in its upper levels, was received with alarm by some scientists who were just beginning to realise that there was a concurrent 'hiatus' in global surface temperature – both for land and ocean. Lyman *et al.* looked at full-depth Argo floats (0–2000 m) for 2003–2008 and said that the OHC increase was equivalent to a temperature rise of about 0.01°C.

Meehl *et al.* confirmed that the Argo data and other sources indicated that the OHC above about 700 m did not increase appreciably during the 2000s,[3] a time when the rise in surface temperatures stalled. They concluded that when surface temperature is flat there is

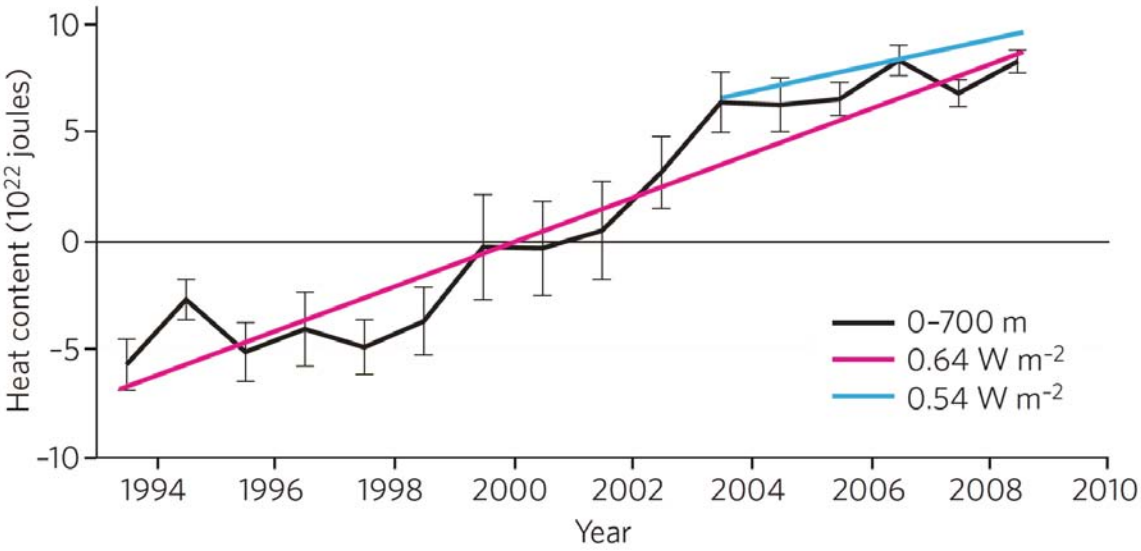

Figure 2: Warming rate slows in the top 700 m.

less heat in the upper ocean layers and more in the lower ones.

Looking deeper, but using sparse data, Purkey and Johnson found some evidence of ocean warming beneath 2000 m, although the quality of the observations was insufficient to adequately quantify its contribution to the OHC budget.[4]

Katsman and van Oldenborgh[5] analysed Argo data between 2003– 2010, confirming the finding of Meehl *et al.* that the upper ocean has not gained any heat despite the general expectation that the ocean will absorb most of the Earth's current radiative imbalance.

Levitus *et al.*[6] give estimates of OHC change for 0–700 m and 0–2000 m for 1955–2010, including some historical data not previously available. For the 0–2000 m layer, the previously seen kink is clearly evident at the introduction of the Argo floats (Figure 3). For 0–2000 m, the OHC increase was $24 \pm 1.9 \times 10^{22}$ J. This corresponds to a temperature increase of 0.09°C. For 0–700 m, it was 0.18 °C.

Staying with the longer timeframe, Huber and Knutti[7] said that between 1950 and 2010 the climate system accumulated a net energy of 1.40×10^{24} J. Later the IPCC AR5 put the 1971–2010 energy accumulation at 2.74×10^{23} J. These figures for net energy accumulation are inconsistent.

Levitus[8] gives annual average global integrals of measurements of OHC for 0–700 m (see Figure 4). The change in slope is coincident with the introduction of the Argo array.

According to Robson and Sutton,[9] during the 1990s there was a major change in the state of the world's oceans as the North Atlantic underwent a rapid warming. The sea surface temperature of the sub-polar gyre increased by 1°C.

Balmaseda *et al.*[10] reanalysed OHC data, filling in unsampled regions and found a new plateau, apparently related to the Pinatubo volcanic eruption in 1991 (Figure 5). From 2000, their three depth levels show increasing OHC, with the increase being greater in the total depth. In 2004 there was a change. The upper 300 m shows no increase in OHC while the top 700 m does, but at a lower pace. This suggests the heat is being sequestered between 300 and 700 m. That, and the suggestion that the warming increases with increasing depths, is surprising.

The same authors also showed a large increase between the El Chichón and Pinatubo

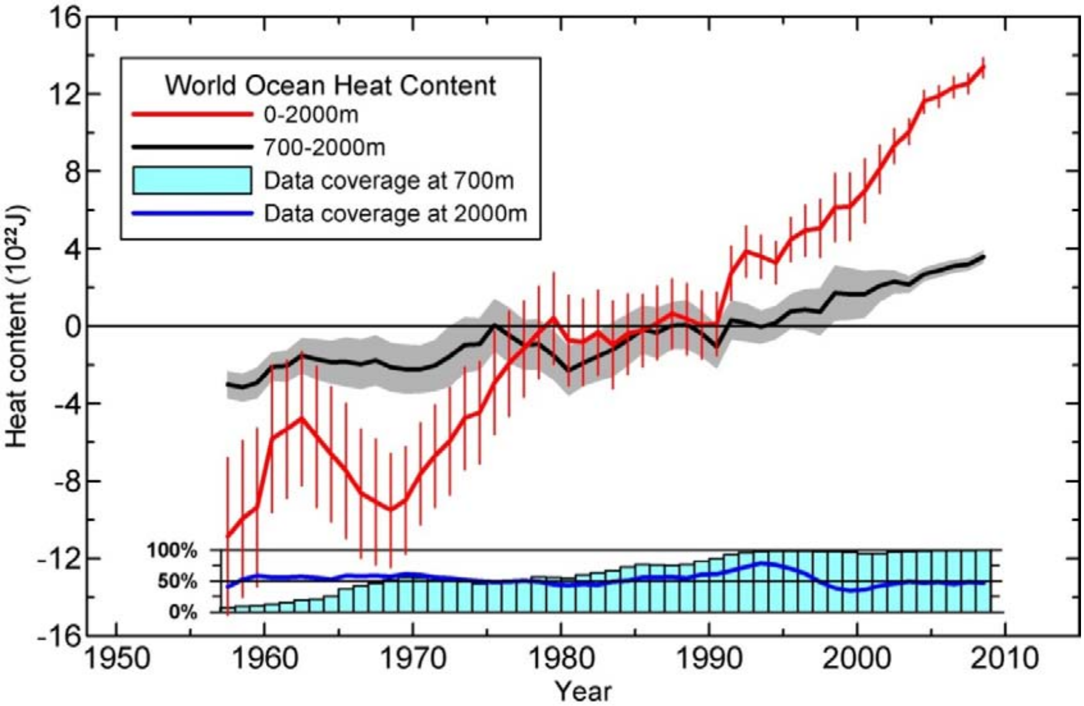

Figure 3: Warming kink in Levitus *et al.*

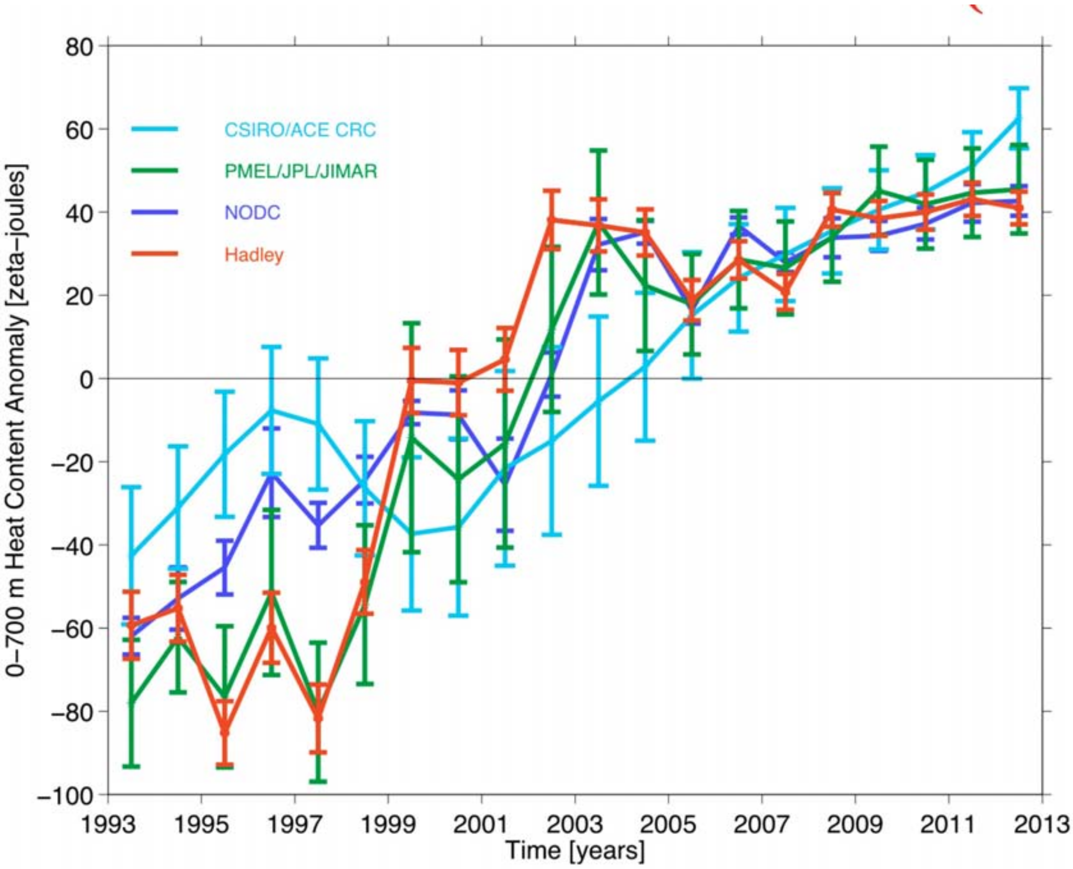

Figure 4: Apparent slowdown in warming coincident with introduction of Argo.

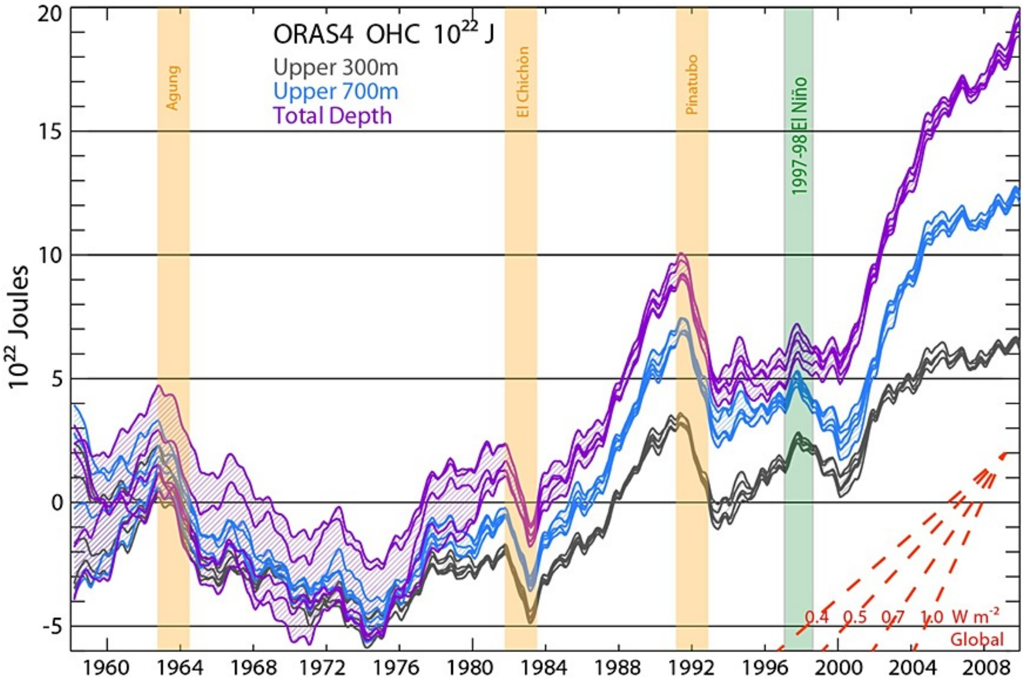

Figure 5: The new plateau of Balmaseda *et al.*

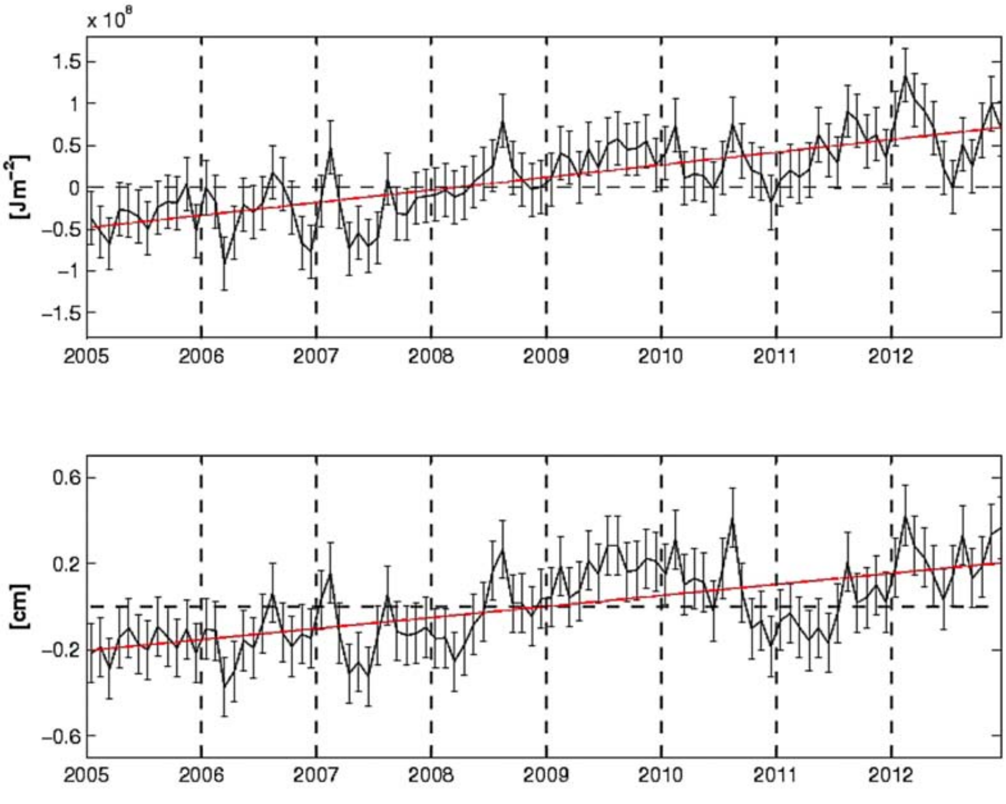

Figure 6: Von Schuckmann's linear trend.

Original caption: Global ocean (60°S–60°N) heat content (upper, GOHC) and steric sea level (lower, GSSL) during the period 2005–2012 from Argo…The 8-year trends (red line) of GOHC/GSSL account for 0.5±0.1 W/m^2, and 0.5±0.1 mm year^{-1} for the 10–1500 m depth layer, respectively…

eruptions, whilst AR4, and later AR5, show little trend during this period. Also the plateau between 1993 and 2000 followed by the large warming is not seen in AR4 and AR5. The paper concludes with the comment,

> The elusive nature of the post-2004 upper-ocean warming has exposed uncertainties in the ocean's role in the Earth's energy budget and transient climate sensitivity.

Von Schuckmann *et al.*[11] analysed Argo data from 2005 to 2014. However, the linear trend they superimposed on the data is unimpressive (Figure 6). Looking more closely at the data, can a case be made for *any* significant warming after 2007, or between 2005 and 2008?

Lyman and Johnson[12] looked at OHC from 1950 to 2011 in different depth layers[13] (Figure 7). The post-2003 hiatus is clear. The limitations of the data should be noted, however. The 0–100 m layer is measured over 50% of the globe annually starting in 1956, the 100–300 m layer starting in 1967, the 300–700 m layer starting in 1983, and the deepest two layers considered only started in 2003 and 2004, with the introduction of the Argo floats.

The authors say that, for adequately sampled time periods, warming trends generally increase with increasing depth, as the surface-intensified warming signal penetrates to at least 1500 m. They find that for 2004–2011, while the upper ocean is not warming, the ocean as a whole continues to absorb heat over 0–1800 m. The rates for 0–100, 0–300, and 0–700 m they obtain are larger than in other analyses, such as Levitus's *World Ocean Heat Content*.[8]

By 2014 it had become established in scientific circles, though not so much in the public debate, that there had been no upper-ocean warming in two decades and that warming in deeper levels was difficult to establish with a high degree of certainty. Martin Visbeck of the GEOMAR Helmholtz Center for Ocean Research at Kiel University wrote an article in *Nature Geoscience* pointing out that three of five analyses of upper-ocean heat content suggest that ocean heat uptake, at least in the top 5,000 m or so, has not changed significantly over the past two decades.[14]

Cheng and Zhu[15] say, as others have pointed out, that the step change noted above, which they describe as a 'dramatic shift', was coincident with the introduction of the Argo system. They provide an explanation based on sampling procedures.

Wunsch and Heimbach laid out some of the problems in measuring OHC far more plainly than had been done before.[16] Their paper, 'Bidecadal thermal changes in the abyssal ocean' is a highly significant paper. It shows that ocean warming cannot explain the surface temperature slowdown and also that parts of the deepest ocean appear to be cooling. It also discusses the important question of how heat is transferred to the deep ocean by the movement of water masses. Mixing due to small-scale movement of water molecules is too slow to be of significance for recent changes. They say there are some regions of the deep ocean, such as the western Atlantic and the Southern Ocean in the Antarctic, that have been in thermal contact with the surface relatively recently, suggesting that they would have warmed due to global warming. In contrast, much of the Pacific Ocean below 1500 m has been isolated from the surface for around a thousand years.

The point Wunsch and Heimbach make is that it is unknown if these results reflect a genuine cooling below 2000 m, and their equivocation extends to other analyses as well. Because there was heating in some places and cooling in others and measurements are relatively sparse, it is problematic to determine a mean. The globally integrated heat content changes represent a small fraction of much larger regional changes, themselves a small fraction of the ocean's total heat content. The global ocean temperature changes over 20 years

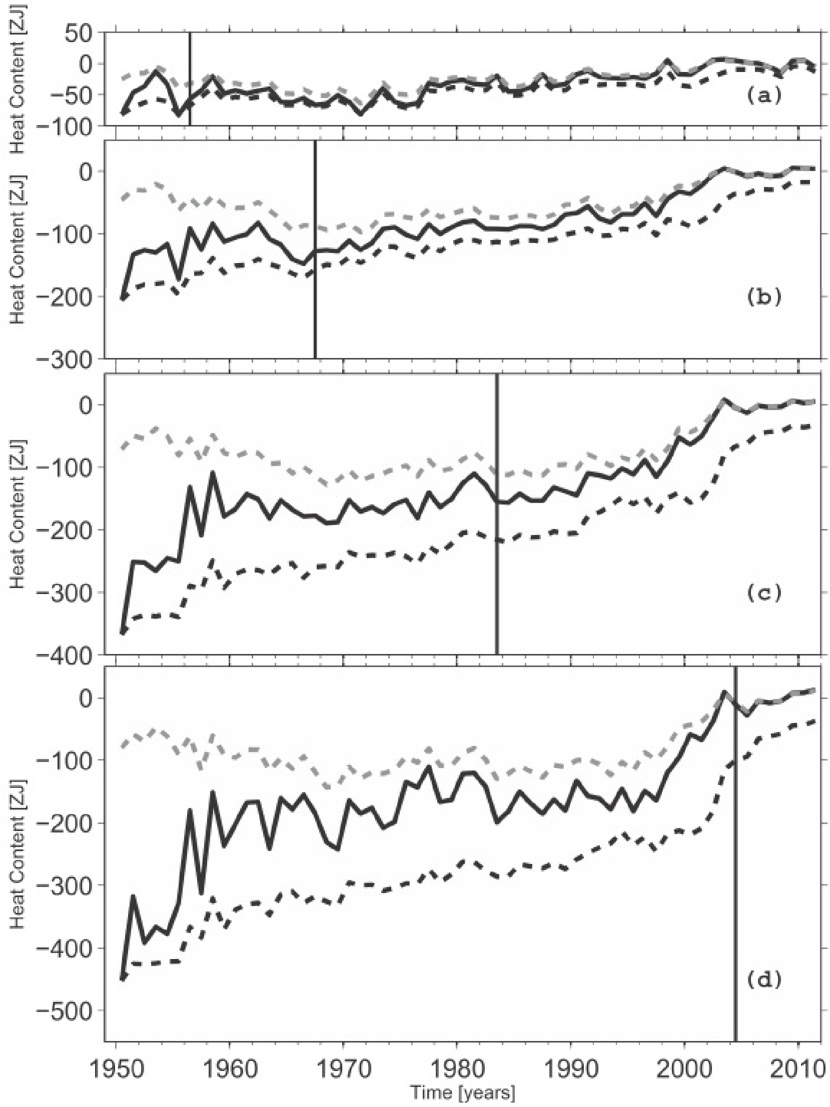

Figure 7: Lyman and Johnson's analysis of OHC by depth.
Original legend: Time series of annual average global integrals of upper ocean heat content anomaly [zettajoules (ZJ)] for (a) 0–100, (b) 0–300, (c) 0–700, and (d) 0–1800 m. Time series are shown using ZIF estimates relative to both ClimArgo (dashed gray lines) and Clim1950 (dashed black lines). Time series are also shown using REP estimates (black solid lines), which are not affected by shifts in the mean climatology… Thin vertical lines denote when the coverage…reaches 50% in (a)–(d). ZIF, zero infil mean – a technique that assumes there are no anomies in unsampled regions).

are usually very slight compared to the shorter-term temporal variations from numerous other physical sources. Because of this, attention must be paid to what might otherwise appear to be small errors in data calibration, sampling and model biases. Also, because ocean heat is stored asymmetrically and that heat is continually shifting, any limited sampling scheme will be riddled with large biases and uncertainties.

Apparently associated with its greater salinity, most of the central North Atlantic stores twice as much heat as any part of the Pacific and Indian Oceans. Regions where there are steep heat gradients require a greater sampling effort to avoid misleading results. Wunsch and Heimbach warn,

> The relatively large heat content of the Atlantic Ocean could, if redistributed, produce large changes elsewhere in the system and which, if not uniformly observed, show artificial changes in the global average.

They also express concerns over previous attempts to construct changes in OHC, such as the paper of Balmaseda *et al.*:[10]

> Data assimilation schemes running over decades are usually labeled 'reanalyses.' Unfortunately, these cannot be used for heat or other budgeting purposes because of their violation of the fundamental conservation laws.

They add;

> Direct determination of changes in oceanic heat content over the last 20 years are not in conflict with estimates of the radiative forcing, but the uncertainties remain too large to rationalize e.g., the apparent 'pause' in warming.

If the Balmaseda *et al.* model of deep-ocean warming was correct, any increase in OHC must have occurred between 700 and 2000 m, but the mechanisms that would warm that 'middle layer' remain elusive. Regarding the jump seen with the introduction of Argo data they say, 'clear warnings have appeared in the literature – that spurious trends and values are artifacts of changing observation systems'.

Wunsch and Heimbach recognise that their 'results differ in detail and in numerical values from other estimates, but the determination of whether any are 'correct' is probably not possible using existing data sets.' They also note,

> As with other extant estimates, the present state estimate does not yet account for the geothermal flux at the sea floor, which is small but not negligible compared to any vertical heat transfer into the abyss.

They conclude, 'As with many climate-related records, the unanswerable question here is whether these changes are truly secular, and/or a response to anthropogenic forcing, or whether they are instead fragments of a general red noise behavior seen over durations much too short to depict the long time-scales…or the result of sampling and measurement biases, or changes in the temporal data density.'

Wunsch and Heimbach make another important point concerning the long-term memory of the deep ocean. Meteorological forcing of hundreds to thousands of years ago should still be producing trend-like changes in OHC, making it impossible to determine what variation is newly added to the system and what is ancient, the 'meteorological forcing of decades to thousands of years ago', as they phrase it.

NASA reported on a significant study showing that the deep ocean had not warmed since 2005,[17] 'leaving unsolved the mystery of why global warming appears to have slowed in recent years', it said. The study also showed that the temperature in the top half of the world's oceans is rising, but not fast enough to account for the stalled surface temperatures.

'The deep parts of the ocean are harder to measure', said Llovel *et al.*[18] 'The combination of satellite and direct temperature data gives us a glimpse of how much sea level rise is due to deep warming. The answer is – not much.' The study was called 'deeply flawed' by Kevin Trenberth of the National Center for Atmospheric Research, who criticised the data and sampling methodology.

Durack *et al.*[19] said that Llovel *et al.* had investigated changes to OHC over a much shorter time period than they had (1970–2004). However, they added that Llovel *et al.* had confirmed that the ocean has continued to take up significant amounts of heat.

> This supports the conclusion of our study, that the inconsistency between upper-ocean warming in models and observations disappears when the more recent and better observed period is compared to models and satellite observations. While (Llovel, Willis, Landerer, & Fukumori, 2014) find no detectable warming of the ocean below 2,000 meters since 2005, the upper-ocean has continued to take up significant amounts of heat.

Unfortunately this is not exactly what they claimed.

The analysis of OHC had changed considerably between AR4 and AR5, the latter being delivered by the IPCC in November 2014.[20] It indicated that the 1955–70 rise was lost in the greater level of noise (see Figure 8). The OHC was stable until 1985, when it started rising by 15×10^{23} J. In the AR5 graph there are markedly different post-2003 trends, some showing no post-2003 OHC increase.

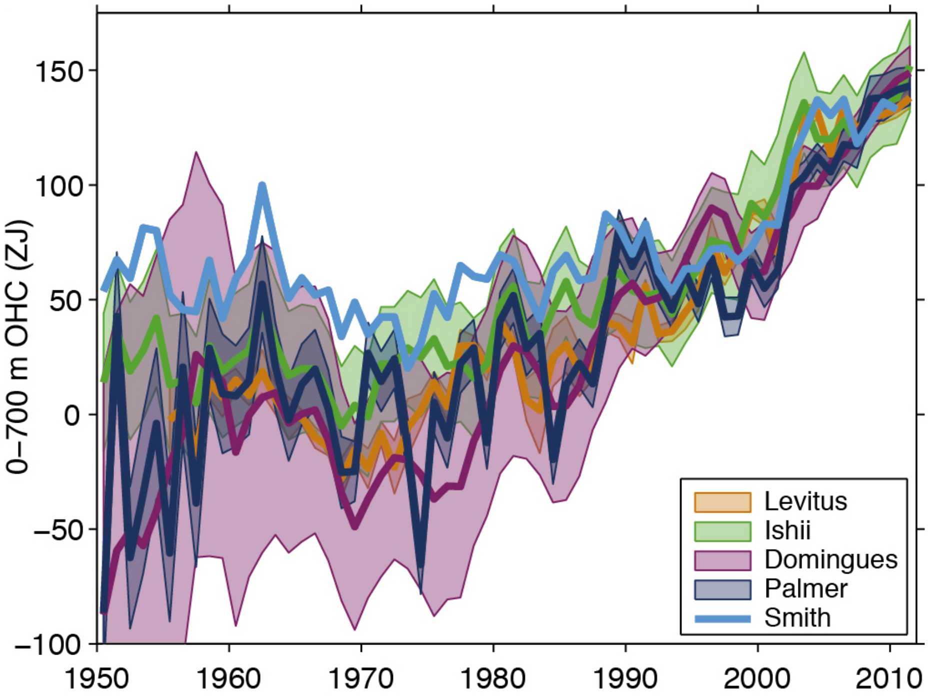

Figure 8: Upper-ocean heat content according to AR5.

AR5 concluded, 'It is virtually certain that the upper ocean (0–700 m) heat content increased during the relatively well-sampled 40-year period from 1971–2010.' The fundamental problem with this analysis, however, is that it assumes a linear trend between 1971 and 2010, thereby obscuring any information in and explanation of shorter-term variations.

Nonetheless, in AR5 it was obvious that OHC increased more slowly after 2003, almost concurrent with the 'pause' in global surface temperatures. AR5 sidestepped this issue by saying that because this change occurs when XBT data gives way to Argo, the 'apparent recent change should be viewed with caution.'

Below 700 m, the IPCC considered the data is too sparse to be treated the same way as that between 0–700 m. Despite this, AR5 also concluded that the 'warming of the ocean between 700 and 2000 m likely contributed about 30% of the total increase in global ocean heat content (0 to 2000 m) between 1957 and 2009.' It went on to say that globally the OHC in some of the 0–700 m estimates increased more slowly from 2003–2010 than over the previous decade and that it was only 'likely' that OHC from 700–2000 m increased during this period. AR5 concludes the warming rate for 0–75 m is 0.11 °C per decade, decreasing to 0.015°C per decade for 700 m. If anything, AR5 left the situation more open than before.

Liang *et al.*[21] said that estimated values of ocean heat uptake are of the order of a few tenths of a watts per square metre and are a very small fraction of air–sea exchanges, with annual average regional magnitudes of hundreds of watts per square metre. They say this small heat exchange is unlikely to represent interaction with an ocean that was in thermal equilibrium at the start of modern global warming, and is more likely part of a cycle that takes from over hundreds and up to a thousand years.

Cheng *et al.*[15] obtained a 0–700 m OHC trend of 0.0061 ± 0.0018°C yr^{-1}, which is equal to $0.56 \pm 0.15 \times 10^{22}$ J yr^{-1}, from 1970 to 2005 on average globally, and 0.0060 ± 0.0018°C yr^{-1} ($0.55 \pm 0.14 \times 10^{22}$ J yr^{-1}) from 1970 to 2014 (Figure 9).

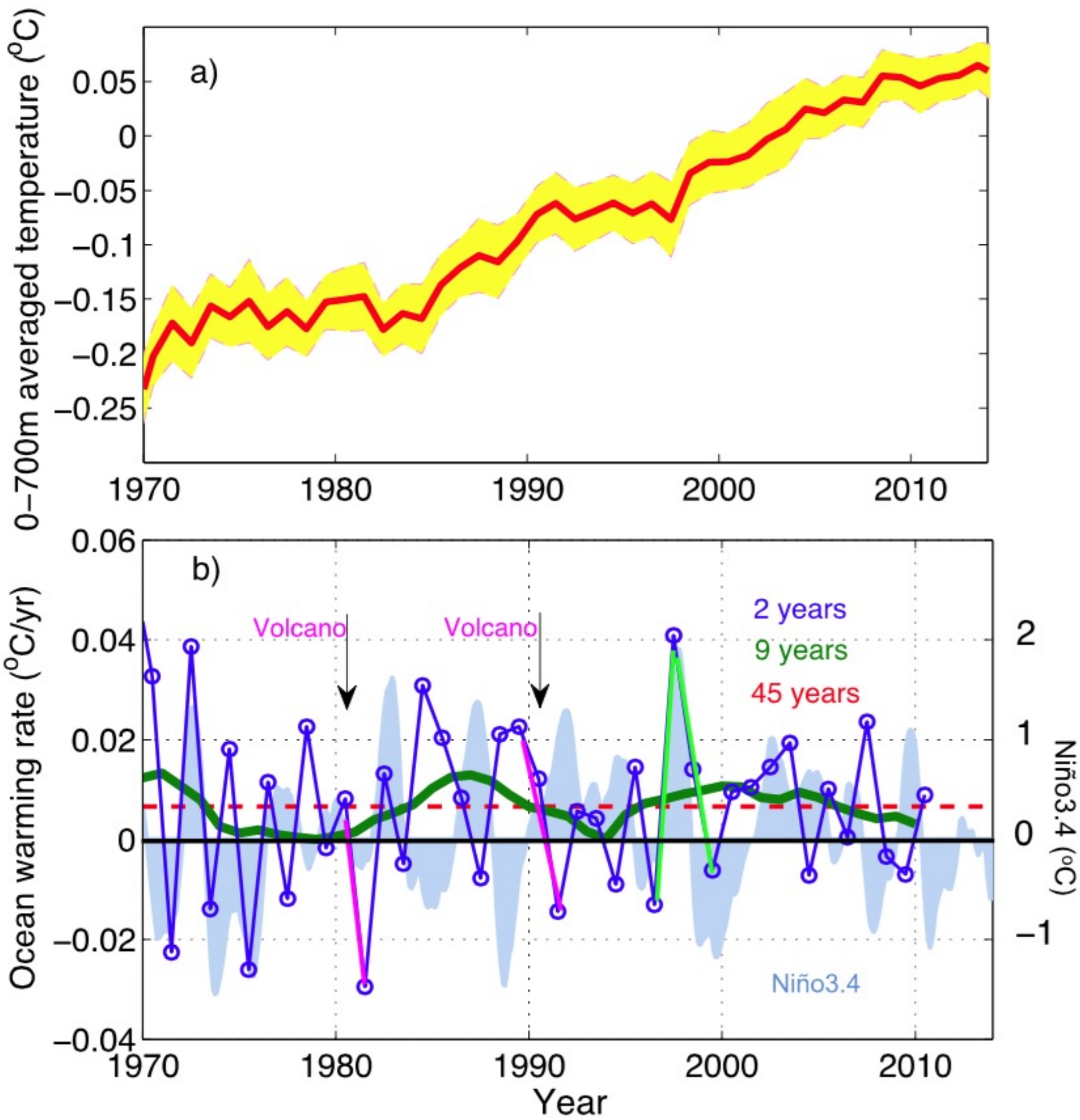

Figure 9: Cheng's *et al.*'s determination of the warming trend.

It is clear that there is much more going on in their data than a long-term increase in OHC (Figure 10). It is also apparent that there is significant decadal variation of the ocean warming, as exhibited by almost decadal trends of OHC at 700 m. Ocean warming decreased during the late 1970s, early 1980s, and early 1990s; the reasons are unknown. During the most recent 10 years there has also been a slowdown of upper-ocean warming.

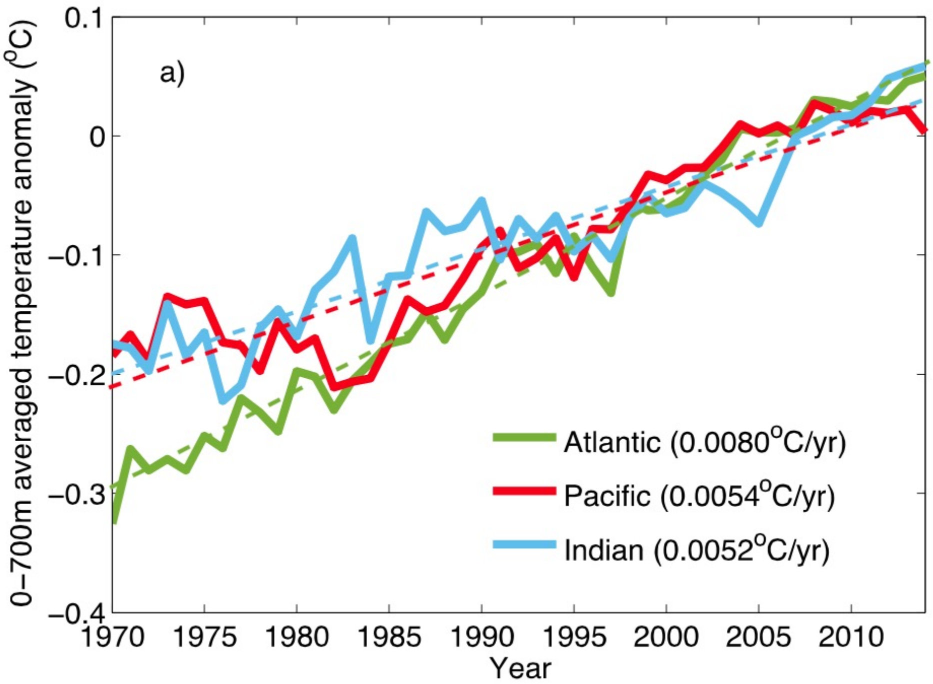

Figure 10: Much more than simple warming.

Lee *et al.*[22] show the global mean surface warming has stalled since the end of the twentieth century, but the net radiation imbalance at the top of the atmosphere continues to suggest an increasingly warming planet, which they say is reconciled by an anomalous heat flux into the ocean (some dispute that top-of-the-atmosphere measurements are accurate enough to establish this). They note that a significant portion of the heat missing from the atmosphere is therefore expected to be stored in the Pacific, contrary to observations.

They suggest that the enhanced heat uptake by the Pacific Ocean has been compensated for by increased heat transport from the Pacific Ocean to the Indian Ocean (19.5% global ocean area, 19.8% global ocean volume), carried by a current called the 'Indonesian through flow'. Consequently, the Indian Ocean heat content has increased abruptly, which they say accounts for more than 70% of the global ocean heat gain in the upper 700 m during the past decade.

Nieves *et al.*[23] suggest that the low rate of warming at the ocean surface (which is nearly identical to the rate of global surface temperature increase) is compensated by more rapid warming at depth, despite Llovel *et al.*[18] and others finding 'little to no evidence' for an increase in the rate of the rate of ocean warming at depth in the most recent decade.

Palmer *et al.*[24] reviewed the temporal and spatial characteristics of OHC variability as represented by an ensemble of dynamical and statistical ocean reanalyses (ORAs). They suggest that spatial patterns of OHC change for the period 1997–2009 show good agreement in the upper 300 m, characterised by a strong dipole pattern in the Pacific Ocean. There is less agreement in the patterns of change at deeper levels.

The Atlantic and Southern Oceans are regions in which many ORAs show widespread warming below 700 m over the period 1997–2009 although there are significant uncertainties.

In 2017, Cheng *et al.*[25] found some more heat in just the place it was missing! They concluded that changes in OHC were relatively small before about 1980, but since then OHC has increased fairly steadily and, since 1990, has increasingly involved deeper layers of the ocean. Also, contrary to many earlier studies, they found no slowdown in global OHC change since 1998 compared with the previous decade.

The total OHC increase 1998–2015 is 15.2×10^{22} J in the upper 2000 m, with 17% stored in the Pacific Ocean, 24% in the Indian Ocean (30°S northward), 31% in the Atlantic Ocean, and 28% in the southern oceans (south of 30°S). They add that total OHC change calculated here is not well characterised by a linear trend because of the relatively short time period considered and the presence of strong decadal variability:

> It is evident that all six ocean basins have experienced significant warming since 1998 but that heat was mainly stored in the southern oceans, the tropical/subtropical Pacific Ocean and the tropical/subtropical Atlantic Ocean from 1960 to 1998. Understanding how this heat has been transported or redistributed in the ocean continues to be an important research topic.

Roemmich *et al.*[26] found that the top 2000 m of the world's oceans warmed at a rate of roughly 0.005°C per year in the top 500 m of ocean and 0.002°C per year at depths between 500 and 2000 m. They say,

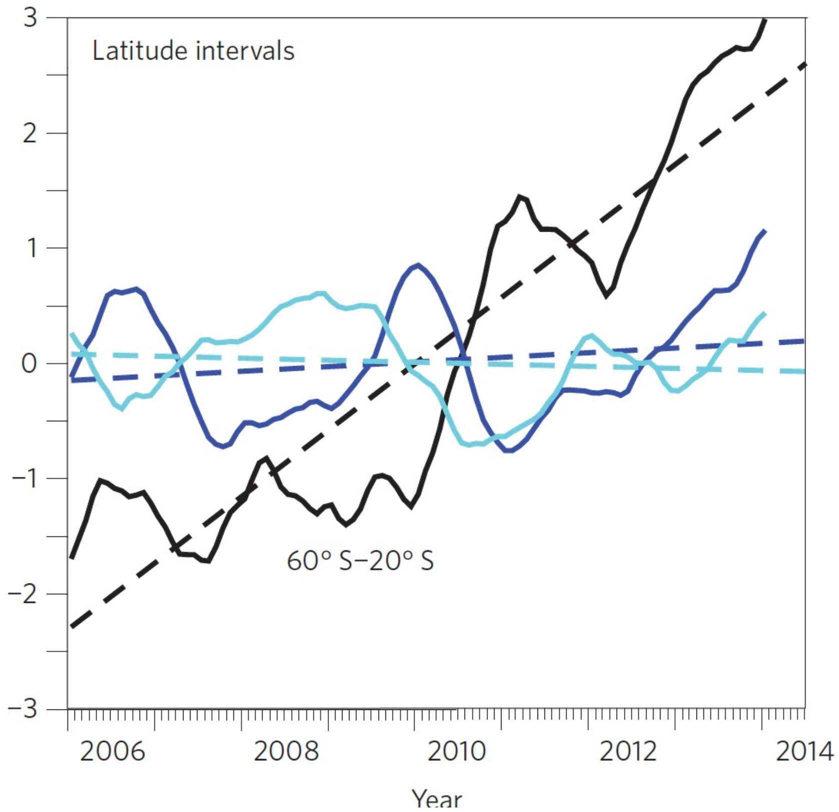

Figure 11: Roemmich *et al.*'s key result.

> The rate of ocean heat gain during the past eight years is not unusual – indeed many studies of ocean data over the past 50 years and longer have produced similar rates. What is new is that the rate and patterns of ocean heat gain are revealed over a period as short as eight years, thanks to the Argo array, that the warming signal is shown to extend to 2000 meters and deeper, and that it is occurring predominantly in the Southern Hemisphere ocean south of 20°S.

They go on to say the Atlantic Ocean has experienced the fastest and sustained warming over the past 45 years, with a long-term trend of 0.0080 ± 0.0020°C yr^{-1}, which is equal to $0.78 \pm 0.18 \times 10^{22}$ J yr^{-1}. Meanwhile, the Pacific Ocean warmed a little slower, with a trend of 0.0054 ± 0.0017°C yr^{-1} ($0.50 \pm 0.15 \times 10^{22}$ J yr^{-1}). The rate of Indian Ocean warming is similar to the Pacific Ocean, with a trend of 0.0052 ± 0.0016°C yr^{-1} ($0.49 \pm 0.13 \times 10^{22}$ J yr^{-1}).

Boyer *et al.*[27] investigated the impact of different instrument bias corrections, baseline climatologies, and mapping methods. They found that for 1993–2008, the uncertainty due to instrument bias corrections varied from 10.9 to 22.4×10^{21} J, that due to mapping methods was 17.1×10^{21} J, and that due to baseline climatologies was $2.7–9.8 \times 10^{21}$ J. They found the 1993–2008 trend was from 1.5 to 9.4×10^{21} J yr^{-1} depending on the choices.

Desbruyerer *et al.*[28] say that, from a comparison of three Argo analyses, the global OHC trend is marked by a clear hemispheric asymmetry, with the southern hemisphere heating much faster than the northern. They add that a full understanding of this observation is missing.

Llovel and Terray is a significant paper,[29] showing that ocean warming is happening in one place in the South Pacific, a finding compatible with the findings of Roemmich *et al.* The three datasets in the paper all show a global OHC increase for the recent decade (see Figure 12).

Over 2005–2014, the southern hemisphere appears to explain a large part of the linear increase of the global OHC change, with a linear trend of about 10^{22} J yr^{-1}. In other words, they say the southern hemisphere explains 90%, or possibly more, of the net ocean heat uptake for 2005–2014. For them it raises important questions. Why have the south Indian and Pacific oceans experienced such a recent upper-ocean warming? What are the physical processes involved in such a rapid warming? Furthermore, they find that the warming is centered at 40°S, which corresponds to the center of the subtropical gyres, with two main structures located in the Indian and Pacific oceans.

According to Oka and Watanabe[30] the warming rate of global mean surface temperature slowed down during 1998–2012. They note that some previous studies pointed to a role of increasing ocean heat uptake during what they explicitly call a global warming *slowdown*, but they stress that the mechanism remains unknown. Their simulations suggest that subsurface warming in the equatorial Pacific took place during the initial phase of the global warming slowdown (1998–2002), as had been previously reported.

Su *et al.*[31] calculated changes in OHC for different depths, suggesting that the heat content between 300 and 2000 m increased over the world's ocean basins during 1998–2013, indicating significant warming during the recent global surface warming hiatus. They say the role of the Indian Ocean is particularly important, as it has accounted for about 30% of global heat uptake during the hiatus.

Su *et al.* also say the heat uptake during the hiatus could be estimated as about 2.37, 5.44, 3.75, and 2.44×10^{22} J according to different datasets. These present obviously inconsistent warming signals. They suggest that the global 300–2000 m region has sequestered a significant amount of heat: about 3.50×10^{22} J. They add that there remain substantial uncertain-

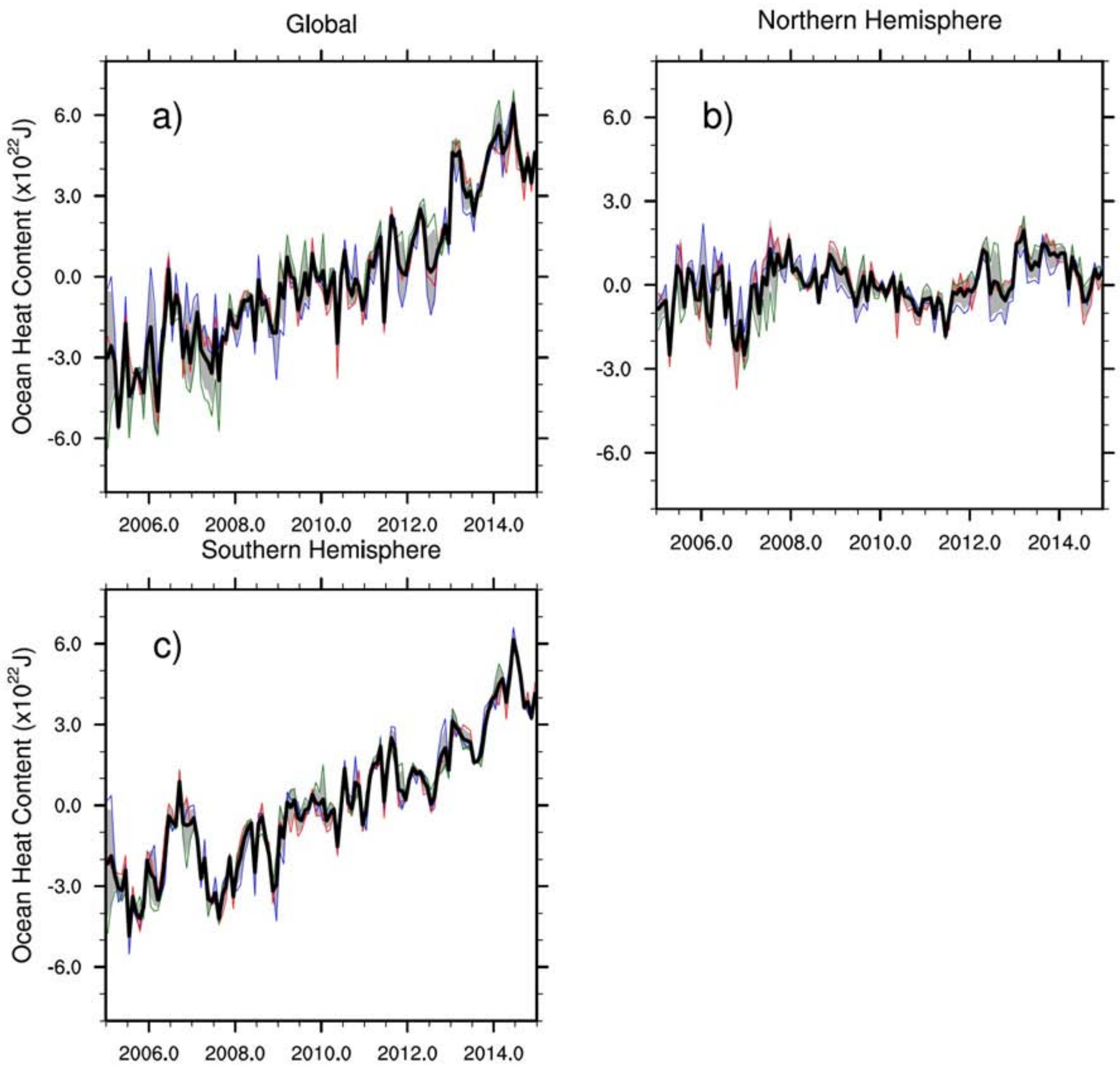

Figure 1. Ocean heat content change above 2000 m depth with respect to the temperature climatology. Curves show estimates based on SCRIPPS (blue curves), IPRC (red curves), JAMSTEC (green curves) and the mean estimate (black curves) for (a) the global ocean (between $\pm$ 65° of latitude), (b) the northern hemisphere and (c) the southern hemisphere. The grey envelope denotes one standard deviation around the mean.

Figure 12: Llovel and Terray's results were compatible with those of Roemmich *et al.*

ties and discrepancies in the available warming information due to insufficient subsurface observation coverage and variations in the dataset generation techniques used among different researchers.

Cheng *et al.* say the OHC change in the North Atlantic Ocean shows strong decadal variability, which they say is likely linked to the strengthening of Atlantic Meridional Overturning Circulation up to the middle 1990s and a subsequent weakening during the 2000s. They add that the cause for these changes is unknown. The paper also says the southern oceans and the tropical/subtropical Atlantic Ocean have experienced continuous and monotonic long-term warming since the 1960s, revealing a robust footprint of global warming. This is a contentious statement. In conclusion, Cheng *et al.* say there is a total full-depth ocean warming of $33.5 \pm 7.0 \times 10^{22}$ J

Contradicting Cheng *et al.*, Dieng *et al.*[32] found that between 2003 and 2013, both global land surface temperature and global sea surface temperature have increased at rates significantly lower than over the previous decades. While confirming cooling of the eastern tropical Pacific during the last decade, as reported in several recent studies, their results show that the reduced rate of change of the 2003–2013 timespan is a global phenomenon.

Wang *et al.*[33] show inconsistent global/basin OHC changes for different ocean subsurface temperature analyses, especially in recent studies related to the slowdown in global surface temperature rise. All of their results show an increase of OHC since 1970 in each ocean basin, revealing what they call a 'robust warming', although the warming rates are not identical. Large discrepancies are found in the percentage of basinal ocean heating related to the global ocean, with the largest differences in the Pacific and Southern Ocean. There is also a large discrepancy of ocean heat storage in different layers, especially at 300–700 m in the Pacific and Southern Oceans.

Sallée emphasises that the Southern Ocean is a key region for connecting the surface ocean with the deep seas.[34] He reports that recent examinations of global ocean temperature show that the Southern Ocean plays a major role in global ocean heat uptake and storage. Since 2006, an estimated 60–90% of the global OHC change associated with global warming is based in the Southern Ocean. But the warming of its water masses is inhomogeneous.

Cheng *et al.*[35] say that 2018 set a new record for global heating, with the total 0–2,000 m anomaly (relative to 1981–2010) reaching 19.67±0.83 ×1022 J, adding that it has been accelerating since the 1990s. The researchers maintain that the heating is distributed throughout the world's oceans, but their map shows the heating to be very inhomogeneous. They find a pause in ocean temperature increase, which they say is due to the redistribution of heat in the ocean interiors.

Kolodziejczyk *et al.*[36] say that the recent overall ocean warming trend is mainly explained by warming of the upper ocean layer (above 2000 m) of the water column at sub-tropical and midlatitudes of the Southern Hemisphere, or, more precisely, within southeastern Indian and southern Pacific Ocean sub-tropical gyres. Their analysis shows that, over the last decade, global OHC (0–2000ṁ) has increased by about 8 ×1022 J. Since 2006, the upper ocean layer (0–700 m) has contributed significantly, accounting for about half of the global warming (about 5 ×1022 J) while the deepest layer (700–2000 m) contributed to an increase of less than 4 ×1022 J.

Their global map of the 0–2000 m depth OHC trend shows that Southern Hemisphere sub-tropical basins and the tropical Indian Ocean have positive OHC trends ,while the subpolar North Atlantic and subtropical North Pacific have lost heat. The map's most striking feature is that most of the warming is in the Southern Hemisphere. They conclude that only a few, localised water masses are responsible for most of global OHC.

changes in global OHC?

In September 2019 the IPCC issued their *Special Report on the Ocean and Cryosphere in a Changing Climate*.[37] It concluded that:

> The ocean has warmed unabated since 2005, continuing the clear multi-decadal ocean warming trends documented in [AR5]. The warming trend is further confirmed by the improved ocean temperature measurements over the last decade. The 0–700 m and 700–2000 m layers of the ocean have warmed at rates of 5.31±0.48 and 4.02±0.97 ZJyr^{-1} from 2005 to 2017. The long-term trend for the 0–700 m and 700–2000 m layers have warmed 4.35±0.80 and 2.25±0.64 ZJyr^{-1} from 1970 to 2017, and is attributed to anthro-

> pogenic influences. It is *likely* the ocean warming has continued in the abyssal and deep ocean below 2000 m (southern hemisphere and Southern Ocean).

It continued:

> It is likely that the rate of ocean warming has increased since 1993. The 0–700 m and 700–2000 m layers of the ocean have warmed by 3.22±1.61 ZJ and 0.97±0.64 ZJ from 1970 to 1993, and 6.28v0.48 ZJ and 3.86±2.09 ZJ from 1993 to 2017. This represents at least a two-fold increase in heat uptake.

It adds that

> ...critically, the high confidence and high agreement in the ocean temperature data means we can detect discernible rates of increase in ocean heat uptake (Gleckler et al., 2012; Cheng et al., 2019) The rate of heat uptake in the upper ocean (0–700m) is very likely higher in the 1993–2017 (or 2005–2017) period compared with the 1969–1993 period (see Table 5.1). Updated observationally-based estimates of ocean heat uptake are consistent with simulations of equivalent time-periods from an ensemble of CMIP5 ESMs (Table 5.1 and the inset panel in Figure 5.1) (high confidence), once the limitations of the historical ocean observing network and the internally generated variability with a single realisation of the real world are taken into account.

In a letter to the IPCC dated 11th October the GWPF pointed out that this conclusion is based to a significant degree on Cheng et al. (2019), which itself relies on an estimate by Resplandy et al. (2018). The latter paper and its ocean heat uptake estimate was under review for nearly a year and was recently retracted by *Nature* due to manifest errors.

The GWPF continues;

> While the SROCC's conclusion that the rate of ocean heat uptake has increased in recent years may probably be right, the evidence you cite for there being 'high confidence' and 'high agreement' is rather doubtful in the light of your inclusion of flawed evidence of the retracted paper by Resplandy et al. (2018).
>
> Moreover, the only study other than Cheng et al (2019) cited in support of the statement regarding discernable rates of increase in [ocean heat uptake], Gleckler et al (2012), is seven years old and does not appear to show that [ocean heat uptake] increased during the period that it studied.
>
> In light of the important role Cheng et al. (2019) plays in your overall assessment on ocean heat uptake their claim that 'All four recent studies show that the rate of ocean warming for the upper 2000 m has accelerated in the decades after 1991 to 0.55 to 0.68W/m^2' (Cheng et al. 2019) is incorrect.
>
> There is also doubt about your conclusion that ocean heat uptake ...has been accelerating recently. According to your own report..., based on the mean of a compilation of observational estimates...0–2000 m [ocean heat uptake] was nearly 10% higher over 1993–2017 than over the second half of that period, 2005–2017, suggesting that [ocean heat uptake] may have been declining slightly rather than accelerating over the last 25 years.

3 The Holocene

A key question is how the changes seen in the oceans today compare to those earlier in the Holocene. Because we have little information about long-term changes in OHC, it is difficult to put the changes being observed into a proper historical context. Murphy *et al.*[38] asked what part of the changes is due to human activity and what part is due to recovery from the

Little Ice Age. They note evidence that OHC during the Medieval Warm Period was greater than it is today, even though temperatures are about the same.

Rosenthal and Linsley[39] say that North Pacific and Antarctic waters were warmer – by 2.1±0.4 and 1.5±0.4°C respectively – during the Holocene thermal maximum than over the last century. They added that both were 0.9°C warmer in the Medieval Warm Period and about 0.65°C warmer than in recent decades. The paper attracted substantial criticism. Many commented that even if the oceans were warmer than in the past few centuries, it was the rate of change that was unprecedented, as the oceans were heating up faster than in the past 10,000 years. *Climate Audit* (McIntyre, 2013) tackled this idea, and found errors in the paper, concluding that the claim that the oceans are warming faster today than at certain times in the Holocene was incorrect.

Bereiter *et al.*[40] point out that little is known about the ocean temperature's long-term response to climate perturbations because of limited observations and a lack of robust reconstructions. Although most of the anthropogenic heat added to the climate system has been taken up by the ocean up until now, its role in a century and beyond is uncertain. They used noble gases trapped in ice cores to show that the mean global ocean temperature increased by 2.57±0.24 °C over the last glacial transition (20,000–10,000 years ago).

They found that the mean global ocean temperature is closely correlated with Antarctic temperature and has no lead or lag with atmospheric CO2, thereby confirming the important role of southern hemisphere climate in global climate trends. They also found evidence for a 700-year warming about 12,000 years ago that surpasses estimates of modern ocean heat uptake.

In a follow-on paper, Rosenthal and his team reviewed proxy records of intermediate water temperatures from sediment cores and corals in the equatorial Pacific and north eastern Atlantic Oceans, spanning 10,000 years beyond the instrumental record.[41] These records suggest that intermediate waters were 1.5–2°C warmer during the Holocene Thermal Maximum than in the last century. Intermediate water masses cooled by 0.9°C from the Medieval Climate Anomaly to the Little Ice Age. These changes are significantly larger than the temperature anomalies documented in the instrumental record. One concludes that what is happening to the oceans today is not unusual.

Moffa-Sanchez *et al.*[42] note that the Indo-Pacific Warm Pool (IPWP) contains the warmest surface ocean waters on our planet, making it a major source of heat and moisture for the atmosphere. They present new paleoceanographic sea-surface temperature reconstructions from the heart of the Western Pacific Warm Pool (WPWP), which is the warmest region within the IPWP, across the last 17,000 years. They conclude that the IPWP was warmer in the early Holocene than in the late Holocene. Additionally, the late deglacial sections of the records mostly show a gradual IPWP warming similar in structure to the atmospheric CO_2 and/or Antarctic temperature rises.

Gebbie and Huybers[43] conclude that the deep Pacific is cooling, a trend which revises Earth's overall post-1750 heat budget down by 35%. The also conclude that the OHC was larger during the Medieval Warm Period than at present, not because surface temperature was greater, but because the deep ocean had a longer time to adjust to surface anomalies. On multi-centennial timescales, changes in upper- and deep-ocean heat contents have similar ranges, underscoring how the deep ocean ultimately plays a leading role in the planetary heat budget.

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The Global Warming Policy Foundation is an all-party and non-party think tank and a registered educational charity which, while openminded on the contested science of global warming, is deeply concerned about the costs and other implications of many of the policies currently being advocated.

Our main focus is to analyse global warming policies and their economic and other implications. Our aim is to provide the most robust and reliable economic analysis and advice. Above all we seek to inform the media, politicians and the public, in a newsworthy way, on the subject in general and on the misinformation to which they are all too frequently being subjected at the present time.

The key to the success of the GWPF is the trust and credibility that we have earned in the eyes of a growing number of policy makers, journalists and the interested public. The GWPF is funded overwhelmingly by voluntary donations from a number of private individuals and charitable trusts. In order to make clear its complete independence, it does not accept gifts from either energy companies or anyone with a significant interest in an energy company.

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