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Understanding the Earth's Climate Warming Hiatus: Putting the pieces together

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The slowdown in the rate of global mean surface temperature warming over the past 15 years or so has arguably led to one of the most contentious debates in the climate community. This phenomenon is so singular that it has developed proper noun status and is referred to as the "Hiatus." In fact, there have been other slowdowns in the past, but they have received nowhere near as much attention.

There has been little shortage in the number of mechanisms proposed as responsible for this Hiatus, ranging from internally generated climate variability related to various climate modes to changes in solar radiation, atmospheric water vapor, and aerosols, where the different ocean basins play a dominant role. In fact, some studies have suggested that there is no

Decadal climate variability and the early-2000s hiatus

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There have been recent claims that the early-2000s hiatus (or more accurately a slowdown; the term "hiatus" will be used here to denote that slowdown), when the rate of global warming slowed compared to the previous two decades, was an artifact of problematic sea surface temperature (SST) data (Karl et al. 2015), lack of Arctic data (Cowtan and Way 2014), or both. Such claims indicate that when corrections are made to SST data, by taking into account various measurement methods that introduce biases in the data, then "there was no 'hiatus' in temperature rise…[and] a presumed pause in the rise of Earth's average global surface temperature might never have happened" (Wendel 2015). Often there are issues with observed data that need adjusting - in this case such claims of "no hiatus" are artifacts of questionable interpretation of decadal timescale variability and externally forced response - not problems with the data. Thus, the hiatus is symptomatic of the much broader and very compelling problem of decadal timescale variability of the climate system. Recent research has shown that decadal variability in the Pacific associated with the Interdecadal Pacific Oscillation (IPO) plays a major role in driving naturally-occurring global decadal timescale climate fluctuations that are superimposed on the long term warming trend from increasing greenhouse gases (GHG) emissions throughout the 20th and early 21st centuries.

Linear trends and decadal variability

It has long been known that long term trends (50 years or longer) in observed globally averaged surface air temperature reflect mainly increases in human-produced GHGs (e.g., Bindoff et al. 2013). However, superimposed on this long-term forced trend are decadal timescale fluctuations of global climate (Figure 1). The climate science fields of climate change detection/attribution

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Hiatus in the increase of global surface temperature, but rather the slowdown is an artifact of bias in the observational record.

Because there is still controversy concerning the Hiatus amongst climate scientists, this has been misinterpreted by the public and provided fodder for debate that a slowdown in anthropogenic climate change is occurring. The intensity of the scientific and public discussion suggests an opportune time to review our current understanding of the mechanisms. This edition of US CLIVAR *Variations* aims to identify the scientific gaps in our knowledge of the Hiatus, facilitate discussion of the dominant mechanistic processes, and suggest an integrated strategy and coordinated effort towards improving observations, simulations, and predictions of the phenomena.

In addition, many authors from this publication will be presenting on the warming hiatus topic during a special session at the upcoming 2015 US CLIVAR Summit on August 4 in Tucson, Arizona.

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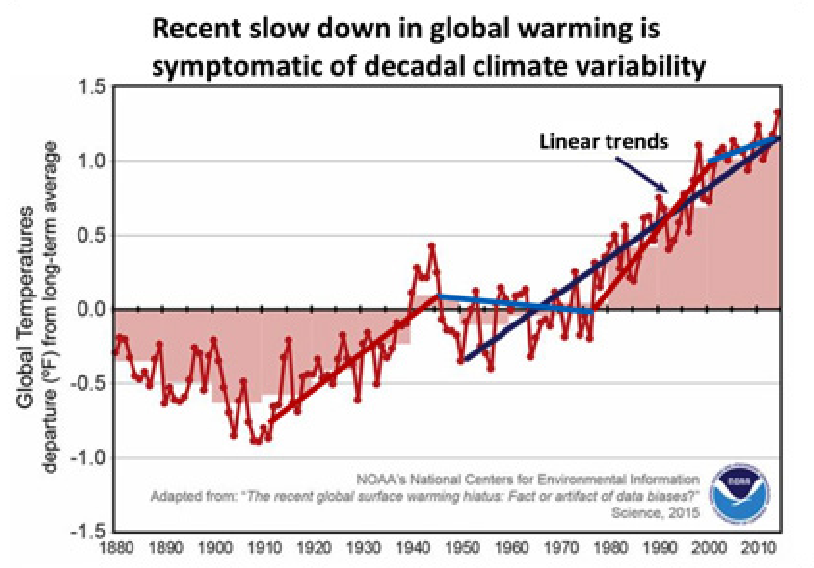

Figure 1: Time series of annual mean globally averaged surface temperature anomalies (dots) based on data from Karl et al. (2015). Black line is linear trend computed from 1950-2014 showing long-term trend forced mainly by increasing GHGs. Red lines are epoch linear trends for positive phases of the IPO, blue lines for negative phases of the IPO, highlighting the need for process-based interpretation of decadal temperature trends in context of the long-term forced trend (after http://www.noaanews.noaa.gov/stories2015/noaa-analysis-journal-science-no-slowdown-in-global-warming-in-recent-years.html).

and decadal climate variability/prediction are focused on interpreting and attempting to predict such decadal climate variability (e.g., Meehl et al. 2014) in the context of long term trends of warming from increasing GHGs, as well as effects from other natural (e.g., volcanoes, solar) and human-produced (e.g., sulfate aerosols, ozone) factors.

Zhang et al. (1997) first identified an El Niño-like decadal timescale SST pattern in the Pacific that was subsequently named the Pacific Decadal Oscillation (PDO, Mantua et al. 1997) or the Interdecadal Pacific Oscillation (IPO, Power et al. 1999). The former was defined based on North Pacific SSTs, and the latter for Pacific basin-wide SSTs. The two terms are often used interchangeably since they are closely related (Han et al. 2013). Typically the observed IPO pattern is defined as the second empirical orthogonal function (EOF) of low-pass filtered Pacific SSTs (Figure 2a). The principal component (PC) time series of this EOF shows a positive phase of the IPO in the first half of the 20th century, negative from the 1940s to 1970s, positive from the 1970s through the 1990s, and negative again from the late 1990s to 2013 (Figure 2b). There is evidence that most of this pattern is internally generated because the first EOF of low pass filtered SSTs from multi-century un-forced climate model control runs show a similar pattern (Figure 2c).

Thus, when performing a process-based interpretation of the time series of globally averaged surface air temperature, epochs (noted above) when the IPO is positive show warming trends greater than the long-term forced trend, and when the IPO is negative, the temperature trends are less than the long-term warming trend (Figure 1). Using the new adjusted surface temperature data from Karl et al. (2015), the warming trend when the IPO was most recently positive (1971-1995) was +0.18°C per decade, compared to the hiatus (typically defined as lasting from 2000-

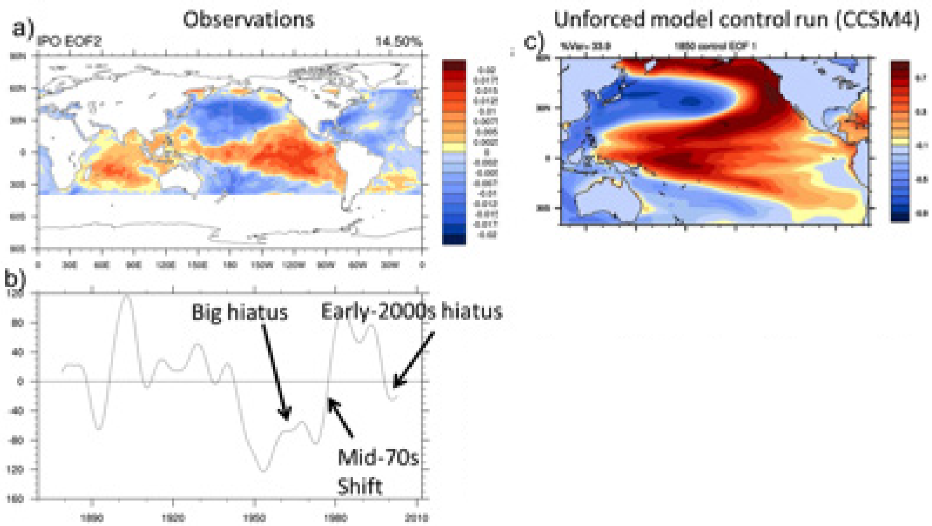

Figure 2: a) Second EOF of low-pass filtered SSTs computed over the Pacific domain and projected over the global domain (SST data are from Hurrel et al. (2008), a merge of the HadISST and NOAA OI.v2 SSTs from 1870—2010); b) PC time series of IPO pattern in (a); c) First EOF of low-pass filtered Pacific SSTs from a multi-hundred year pre-industrial control run from the CCSM4 climate model with no changes in external forcings showing IPO pattern is internally generated in the model (after Meehl et al. 2009; Meehl and Arblaster 2011).

2013 when the IPO was negative, e.g., Meehl et al. 2014) with a linear trend of +0.10°C per decade; this is nearly half (44%) the warming rate compared to the previous two decades during a positive phase of the IPO. Thus there was clearly a slowdown in the rate of global warming in the early 21st century that was not an artifact of the data. The nominal period of the hiatus addressed in the IPCC AR5, 1998-2012, showed an even smaller amplitude linear trend of +0.08°C per decade.

Earlier trends in globally averaged surface temperature were also affected by the phase of the IPO in the Pacific. The accelerated warming from 1910-1941 showed a trend of +0.12°C per decade, while the so-called “big hiatus” from 1941-71, when there was a negative phase of the IPO, showed a small negative trend of -0.04°C per decade, though there is evidence that much of that was externally forced (Bindoff et al. 2013; Figures 1 and 2).

Karl et al. (2015) show that a linear trend from 1998-2014 is the same as the long-term warming trend calculated from 1950-99 and is close to the longer-term trend from 1950-2014 (solid black line in Figure 1), with values of around +0.11°C per decade. But this ignores the process-based interpretation of trends driven at least in part by the IPO (as shown by Kosaka and Xie 2013). The period 1950-99 averages across two decadal regimes of negative and positive IPO (Figure 2b) and is thus representative of the long-term forced trend. There are indications that the IPO/PDO transitioned to positive in 2014 (https://www.ncdc.noaa.gov/teleconnections/pdo/). Thus, including 2014 in a linear trend for the early 21st century also averages across two decadal regimes of negative and positive IPO and should, by definition, be more representative of the long-term forced trend. Indeed the two linear trend values from those two periods are the same. But, as noted above, calculating linear trends across multiple internally-generated decadal regimes averages out the underlying decadal timescale climate variability and leaves the forced trend.

Mechanisms

Given the intrinsic decadal timescale variability arising from the Pacific that contributes to global decadal climate variability at least since 1920 (Dai et al. 2015), there have been numerous efforts to not only identify this variability in observations and models but also to attribute it to processes and mechanisms. Easterling and Wehner (2009) first related the slow-down in observed global warming in the early-2000s to intrinsic internally-generated climate variability in observations and models. In a series of two papers, Meehl et al. (2011, 2013) analyzed climate model simulations to show, for the first time, that hiatus decades were associated with greater rates of increase of ocean heat content below 300 m and a negative phase of the IPO, while accelerated warming decades showed the opposite response (Figure 3). Meehl et al. (2011, 2013) identified three ocean mixing processes in those model simulations that could affect subsurface ocean heat content on decadal timescales: i) the subtropical cells in the Pacific; ii) Southern Ocean processes associated with Antarctic Bottom Water formation; and iii) the Atlantic Meridional Overturning Circulation (AMOC). A subsequent modeling study confirmed the Meehl et al. results for the hiatus (Guemas et al. 2013).

With regards to observations, Trenberth et al. (2014a) analyzed satellite observations to confirm that indeed heat was still being trapped in the climate system during the hiatus, and convective heating anomalies associated with IPO-related tropical SST

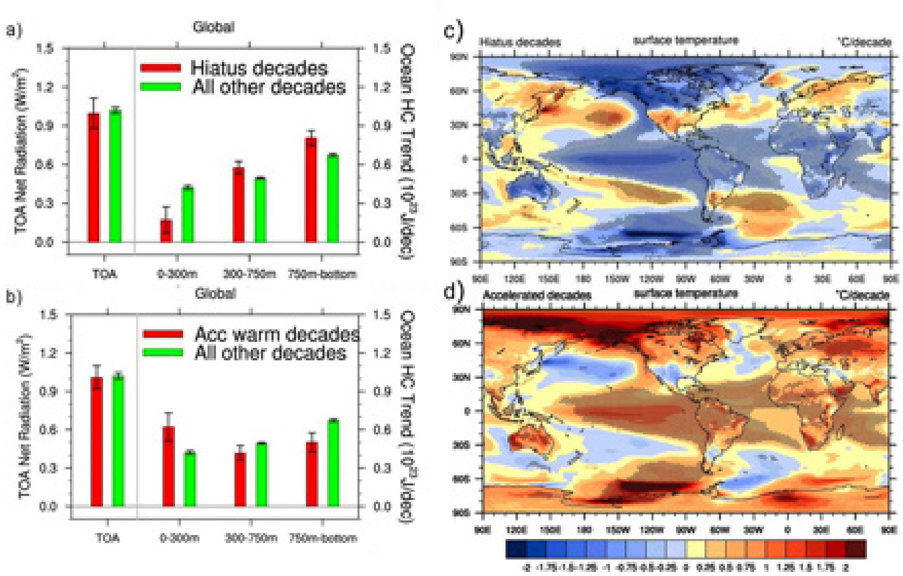

Figure 3: a) Composite mean global linear trends for decades when there is a hiatus of global warming (red bars), and mean linear trends for all other decades (green bars) for top of atmosphere (TOA) net radiation at left (W m^{-2}, positive values denote net energy entering the system); right part of panel depicts decadal trends of global ocean heat content (1023 J decade^{-1}) for the upper ocean (surface to 300 m), and two deeper ocean layers (300-750 m and 750-3000 m) for the composite hiatus decades (red bars) and average for all other decades (green bars); error bars denote 5% significance; b) same as (a) except for accelerated warming decades; c) composite average SST linear trends for decades when there is a hiatus of global warming; stippling indicates 5% significance computed from a two sided t test; d) same as (c) except for accelerated warming decades (after Meehl et al. 2013).

anomalies in the Pacific could drive atmospheric teleconnections to far-field processes that could connect the three ocean mixing processes noted earlier by Meehl et al. (Trenberth et al. 2014b). Subsequent analyses of observations confirmed the Meehl et al. model results to show that more heat was likely being mixed into the subsurface ocean during the hiatus (Balmaseda et al. 2013; Chen and Tung 2014; Drijfhout et al. 2014). Probably the most compelling observational study of recent changes in ocean heat content involved analyses of Argo float data to show the recent maximum ocean heat content increase in the upper 2000 m has occurred in the layer from 700 to 1400 m (Roemmich et al. 2015). However, there are still questions regarding what is happening in the ocean below 2000 m. One study indicated that there might not be a significant signal of ocean warming below 2000 m as determined indirectly from sea-level rise measurements (Llovel et al. 2014). Therefore, one of the major uncertainties regarding decadal timescale variability is what is happening in the deep ocean below 2000 m.

Though the prolonged minimum in the 11-year solar cycle could have contributed somewhat to the hiatus, that effect would have only been a factor for several years of the nominal fourteen years (2000-2013) of the hiatus. However, a series of moderate volcanic eruptions likely contributed some cooling during the early 2000s (Ridley et al. 2014). Quantification of the climate effects of small eruptions is a challenge, and by first removing ENSO effects, a possible contribution to the hiatus from those eruptions was found to be around 15% (Santer et al. 2014). A subsequent study indicated values could be somewhat greater than that (Santer et al. 2015). In any case, the evidence to date indicates that decadal climate variability associated with the hiatus, or accelerated warming periods (such as the warming after the mid-1970s climate shift, Figure 2b) is predominantly due to internally generated processes (e.g., Meehl et al. 2009) that redistribute the heat trapped by increasing GHGs into different ocean layers.

With regards to the three ocean mixing processes first identified by Meehl et al. (2011, 2013) as likely playing a role in internally generated decadal timescale variability associated with hiatus and accelerated warming periods, England et al. (2014) showed that strong Pacific trade winds during the recent negative phase of the IPO in the Pacific could mix about half of the heat being trapped by the atmosphere into the subsurface ocean. This leaves the AMOC (Chen and Tung 2014) and southern Indian and Southern Oceans (Drijfhout et al. 2014) to account for the other half. Roemmich et al. (2015) analyzed the Argo ocean observations to show that, for the upper 2000 m, the southern subtropical cell in the South Pacific has likely contributed to this heat uptake as well as areas in the southern Indian Ocean and near Antarctica.

What we know about the hiatus so far

The hiatus is a characteristic of ubiquitous internally-generated decadal timescale variability in observations and models, with decade and longer periods of reduced globally averaged surface air temperature trends compared to the long-term multi-decadal forced trend. Hiatus periods are typically associated with the negative phase of the IPO. Accelerated warming epochs longer than a decade the flip side of the hiatus periods - are associated with the positive phase of the IPO with larger amplitude trends of global surface temperature compared to the long-term externally forced trend. There is evidence that while GHGs continue to trap heat in the atmosphere on the order of somewhat less than 1 Wm^{-2} during the hiatus, this heat is distributed in the ocean below 300 m by three ocean mixing processes identified by Meehl et al. (2011, 2013): i) the subtropical cells in the Pacific; ii) Southern Ocean mixing connected to Antarctic Bottom Water formation; and iii) the AMOC in the Atlantic. Various subsequent modeling and observational studies have shown that all three of these processes have likely contributed to the mixing of heat into the subsurface ocean in the recent hiatus, with the largest observed increases of ocean heat content in the upper 2000 m of the ocean occurring in the 700-1400 m layer (Roemmich et al. 2015). However, the lack of long-term measurements of deep ocean temperatures below 2000 m inhibit our understanding of how that part of the ocean responds during hiatus and accelerated warming decades. There are indications that the IPO/PDO in the Pacific transitioned from negative to positive in 2014, thus signaling the end of the hiatus, which nominally lasted fourteen years from 2000-2013. Previous positive phases of the IPO have heralded more rapid globally averaged surface temperature increases, which could ensue with a positive phase of the IPO/PDO.

Acknowledgements

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Lack of evidence for a slowdown in global temperature

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The climate science community has reached a near consensus that the warming rate of global surface temperature has exhibited a slowdown over the last decade to decade and a half. However, genuine robust statistical evidence of its existence is lacking. We test the hypothesis by numerous statistical tests applied to global temperature time series and find no evidence to support claims of a slowdown in the trend.

Introduction

Climate change resulting from increases in atmosphere concentrations of greenhouse gases generally lead to increased temperatures of the Earth's thermal reservoirs. The vast majority of the excess heat ultimately is deposited within the Earth's oceans (approximately 90%). The added ocean heat content is perhaps the most clear evidence that the Earth is out of energy balance. Ocean heat content is measured by a variety of instrumentation that have evolved over the past decades. A review of the history of ocean temperature measurements is provided by Abraham et al. (2013). Combined with ocean measurements are reanalysis studies, which infill measurement gaps with numerical simulations (Balmesada et al. 2013a, 2013b). Summaries of recent ocean heat content results can be found in Nuccitelli et al. (2013) and Abraham et al. (2014), among others. All of these studies show a continued uptake of heat since at least 1970.

As an alternative to heat content measurements, some studies have used satellites to measure energy flow at the top of the Earth's atmosphere. These studies reinforce ocean measurements in that they too result in an energy imbalance of approximately 0.5 – 1 W m^{-2} (Trenberth et al. 2009; Trenberth and Fasullo 2010; Trenberth et al. 2014).

When focus is given to the relatively small thermal reservoir of the lower atmosphere, it is found that the trend is less monotonic than the oceans with much larger inter-annual fluctuations and shorter response time. It remains to be determined whether the recently observed fluctuations superimposed on a longer trend constitute a measurable change in the warming process. This topic has received recent attention such as Karl et al. (2015) who have incorporated improvements to measurement techniques. Here, a different approach to quantifying the so-called "hiatus" is described.

New research (Cahill et al. 2015) searched for changes in the warming rate of global surface temperature by applying a test designed for exactly that: change-point analysis. The change-points they identified, i.e. the times at which the warming rate changed, include those which are undeniably present, with their analysis estimating them at about 1912, 1940, and 1970. But no change-point was found after 1970, and when the authors attempted to force a recent change-point not only did it fail statistical significance, it led to convergence problems for the estimate.

Yet much of the climate science community seems to embrace the slowdown or hiatus claim, not merely as a hypothesis to be investigated but as an established fact. Rather than study the reality of the phenomenon, scientists have by and large taken to attempting to understand its causes. In fact *Nature Climate Change* and *Nature Geophysics* have recently joined forces to produce a special issue devoted to the topic. In our opinion, all such attempts will be beneficial whether the "slowdown" is real or not. But we argue that the question "is the slowdown real" deserves serious attention too, which it has not yet received.

Cahill et al. (2015) investigated multiple global temperature datasets, including those from NASA GISS, NOAA, HadCRU, and the revised version of HadCRU from Cowtan and Way (2014). Here, we will utilize only the NASA data, to which we will apply a suite of tests for rate changes in addition to change-point analysis.

Isolating the issue

Some important steps can be taken to isolate and focus on the genuine issue at hand. First, the analysis of Cahill et al. (2015) identifies the search period: with their final change-point in 1970, the relevant question to answer is whether the trend has changed since 1970. Hence we will study the data from 1970 onward in an attempt to show that it reveals some trend pattern other than just a linear rise at constant rate.

A simplifying procedure is to remove a linear trend (estimated by least squares regression) from the data since 1970, then test whether or not the residuals show any trend. If none is detected in the residuals, one cannot claim solid evidence of any recent change in warming rate.

A complication is introduced by the strong autocorrelation in monthly global temperature time series. We therefore study annual averages, rather than monthly values, a process that does not seriously weaken the certainty with which trends can be estimated and trend changes confirmed (e.g., Foster and Brown 2015). Annual averages will still show autocorrelation, but its effect can be neglected. Nonetheless, its presence slightly increases the chance of detecting a trend change when there is none.

It has been suggested that whatever "slowdown" may have occurred did not extend as far as 2014, so that a proper search for evidence of a slowdown should include 2013 but not 2014. Consequently, we chose to study the data from 1970 through 2013 but omit the record-setting hottest year 2014.

Therefore our focus is to study the time series of linearly de-trended annual average land-ocean global temperature anomaly (NASA GISTEMP LOTI) from 1970 through 2013. Temperature data are shown in Figure 1, and the residuals from a linear fit in Figure 2.

Change-point analysis

The essence of the analysis of Cahill et al. (2015) is to model the data as a continuous, piecewise linear function of time. The change point (moment at which the slope changes) is allowed to vary, testing all reasonable possibilities from beginning to end, and that which gives the best fit is selected if it passes statistical significance. Each such model fit, for a fixed change point, can be used to compute a single-trial, statistical test for significance in isolation; but when multiple change points are tested the result must be adjusted for multiple trials. In many cases, compensating for multiple trials will show that results, which are apparently significant, are in fact not. In no case will any result which fails statistical significance when treated as a single trial, be significant when multiple trials are accounted for.

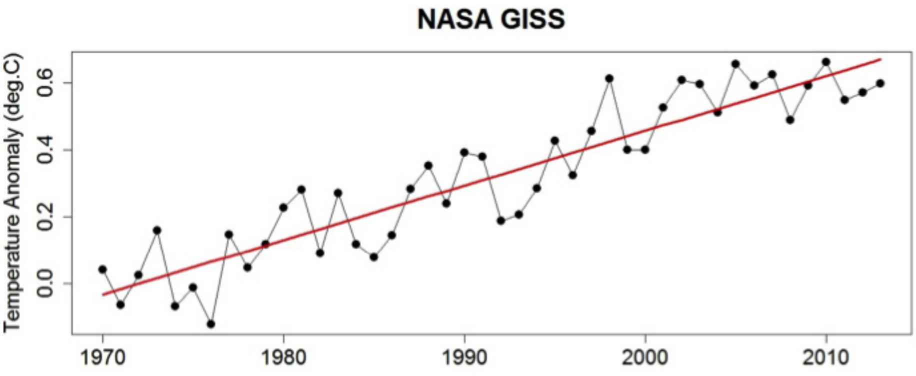

Figure 1: Annual average land-ocean temperature anomalies (°C) from 1970 through 2013 from the NASA GISS temperature dataset.

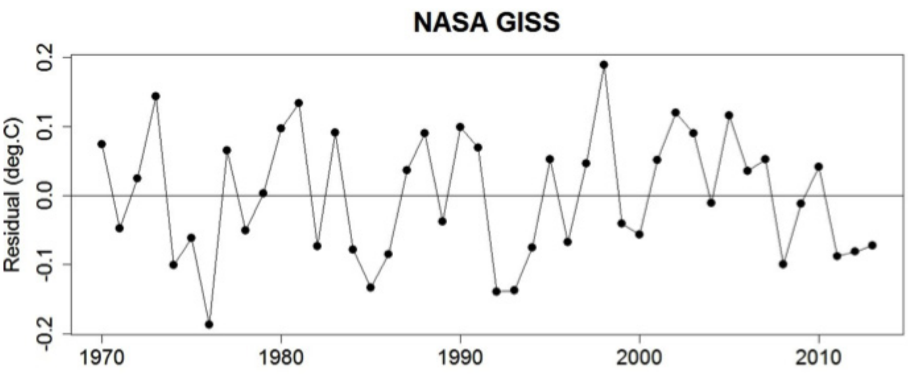

Figure 2: Residuals from a linear fit to annual average land-ocean temperature anomalies (°C) (from Figure 1).

It is very revealing that for these data, that crucial step isn't even needed, because no possible change point gives a result which is even apparently significant. The best fit is a change point in 2006, but it yields a p-value of 0.074 even if it were the only possibility tested; not as low as the cutoff limit 0.05 which is the de facto standard for statistical significance. The clear and dominant conclusion from change-point analysis is that real evidence for any recent trend change is nonexistent.

Other patterns

We searched the residuals for other patterns that might reveal a trend change, starting with polynomials of degree 2 through 10. Such a search also must be compensated for multiple trials since many possibilities are tested (one of the inherent complications involved in stepwise regression). But again, compensation for multiple trials was not needed because none of the results were even apparently significant.

To search for more general changes, we divided the residual data into segments of a fixed time length, for instance 10-year segments, such that the final one culminated with 2013 (the end of the data, when a slowdown has been claimed to occur). We then applied the one-way analysis of variance (ANOVA) to test whether any of these segments showed evidence of behaving differently than any of the others. In many cases the first segment had fewer years' data than the others, but that is not a problem for ANOVA. Trying all possible segment lengths from three years to 20 years, no compensation for multiple trials was needed because once again, none of the attempts yielded significant results.

The graph of temperature data gives the visual impression that the final three years of our time span (2011 through 2013) may have been distinctly different from what came before. Hence we also did a t-test of that three-year episode compared to the prior data from 1970 through 2010. One must bear in mind the null hypothesis that these three years come from the same distribution as their predecessors, so it is necessary to apply the equal variance version of the t-test. Doing so gives a p-value of 0.1109, again failing to establish any change with statistical significance.

As a last attempt to find evidence of a trend in the residuals, we allowed for models in which not only the slope (the warming rate) changes, but the actual value itself. These are discontinuous trends, which really do not make sense physically (cf. the discussion in Cahill et al. 2015) but because our goal is to investigate as many possible changes as is practical, we applied these models too. This is yet another version of change-point analysis, in which we test all practical values of the time at which the slope and value of the time series change. Hence it too must be adjusted for multiple trials.

Once again we neglected to apply any compensation for multiple trials because none of the tested change-points returned a significant result. As with all the tests we have applied, the evidence for any change in the surface temperature trend since 1970 not only fails to pass statistical significance, it fails by a large margin. The best fit using a discontinuous model is shown in Figure 3, despite its failure to pass statistical significance.

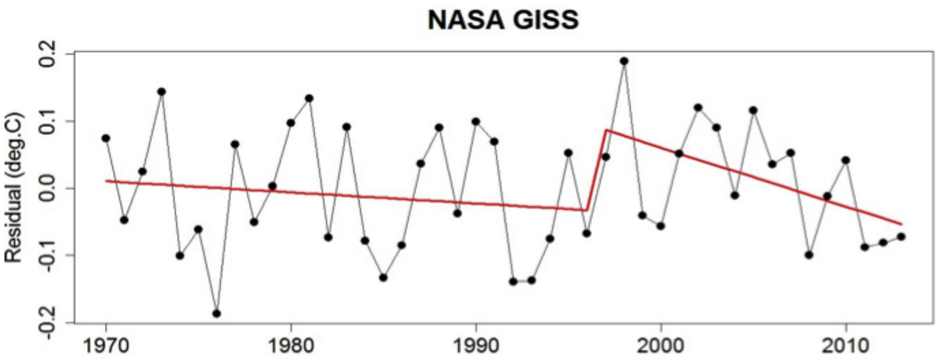

Figure 3: Best-fit model of residuals using a change point with change in both slope and value.

Conclusion

A barrage of statistical tests was applied to global surface temperature time series to search for evidence of any significant departure from a linear increase at constant rate since 1970. In every case, the analysis not only failed to establish a trend change with statistical significance, it failed by a wide margin.

Our results show that the widespread acceptance of the idea of a recent slowdown in the increase of global average surface temperature is not supported by analytical evidence. We suggest two possible contributors to this. First, the natural curiosity of honest scientists strongly motivates them to investigate issues which appear to be meaningful even before such evidence arrives (which is a very good thing). Second, those who deny that man-made global warming is a danger have actively engaged in a public campaign to proclaim not just a slowdown in surface temperature increase, but a complete halt to global warming. Their efforts have been pervasive, so that in spite of lack of evidence to back up such claims, they have effectively sown the seeds of doubt in the public, the community of journalists, and even elected officials.

An unfortunate habit in public discourse has been to graph only the data since the supposed "pause" began and state only the trend estimate since that moment, in order to avoid having to show that such a practice implicitly models temperature with a "broken" trend like that of Figure 3. Claims based on failing to reveal what happened before a purported trend change, are inevitably misleading.

It is certainly possible that some change in the trend has occurred since 1970, and it is very beneficial to look for causes, whether it is present or not. But we suggest that scientists should stop speaking of a "slowdown" in temperature increase as though it were a known fact, when it simply isn't. Furthermore, the inclusion of 2014 and the first part of 2015 which are both at record levels makes the case clearer that global warming is continuing without halt or reduction.

Data and computer code (in R) to reproduce this analysis are available as supplemental information; please contact Grant Foster at tamino_9@hotmail.com.

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Tropical Pacific influence on the recent hiatus in surface global warming

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Since around the beginning of this century, increase of the annual global-mean surface temperature (GMST) has been slower than the preceding decades (Stocker et al. 2013; Meehl 2015, this issue, page XX). The GMST trend for 1998-2012 is 0.03 ºC per decade, which is about a quarter of the 1951-2012 trend (0.11ºC per decade), based on HadCRUT 4.3.0.0 dataset (Morice et al. 2012). The HadCRUT trend for 1998-2012 is smaller than 111 out of 114 Coupled Model Intercomparison Project phase 5 (CMIP5) simulations for the same period (Fyfe et al. 2013; Stocker et al. 2013). The deviation of the observed decadal GMST trend from the CMIP5 ensemble mean may be due to inaccurate radiative forcing, too large climate sensitivity, or the influence of internal variability. Here we focus on internal variability.

CMIP5 coupled general circulation model (GCM) simulations are useful as their large ensembles include a range of possible causes of the recent hiatus (Fyfe et al. 2013). Generally, the inter-member spread with the ensemble includes inter-model diversity in radiative forcing and climate sensitivity as well as internal variability. Marotzke and Forster (2014) developed a statistical model to isolate internal variability in GMST trend in CMIP5 simulations. They concluded that the difference of the 15-year GMST trend, between simulations and observations, is dominated by internal variability.

Attempts have been made to identify modes of internal variability that influence decadal GMST. It has been known for a long time that El Niño-Southern Oscillation (ENSO) affects GMST (Pan and Oort 1983). It is thus likely that the decadal La Niña-like cooling, since the massive El Niño of 1997/98 (Figure 1a), has contributed to the hiatus. Statistical analyses of coupled GCMs confirm such a tropical Pacific influence. The pioneering work of Meehl et al. (2011, 2013) found that decadal events of slowed and accelerated GMST increase are ubiquitous in a coupled GCM experiment forced by Representative Concentration Pathway 4.5 (RCP4.5) radiative forcing. They further showed that sea surface temperature

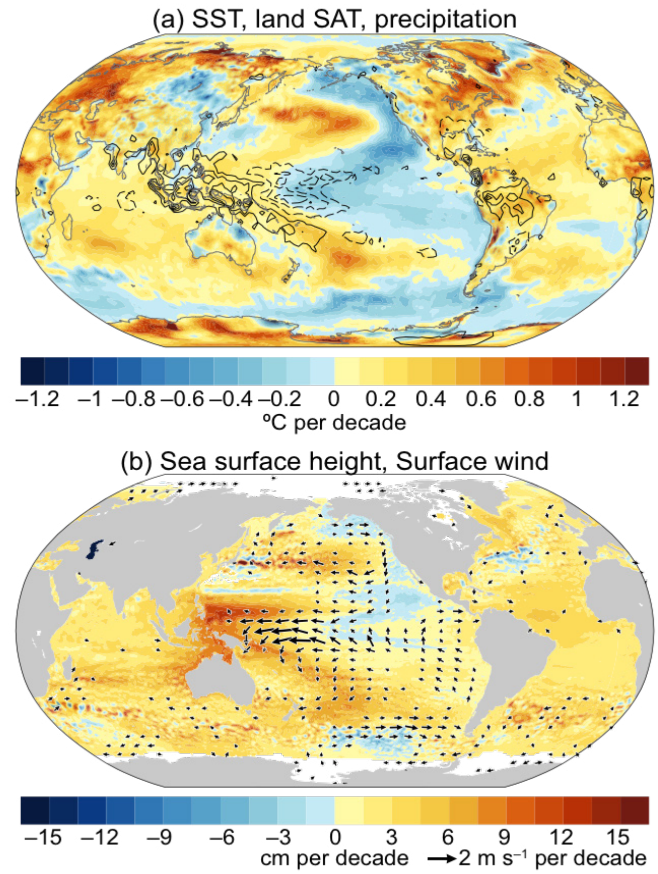

Figure 1: 1993-2013 trend patterns of (a) SST, land surface air temperature (shading), and precipitation (contours for ±0.5, ±1, ±1.5, ±2 mm day-1 per decade), (b) sea surface height (shading) and surface winds (arrows). Based on National Oceanic and Atmospheric Administration optimum interpolation SST (Reynolds et al. 2002), Climate Prediction Center Merged Analysis of Precipitation (Xie and Arkin 1997), sea surface height of the archiving, validation, and interpretation of satellite oceanographic dataset (AVISO), and surface air temperature and wind of European Centre for Medium-Range Weather Forecast Interim Reanalysis (Dee et al. 2011). Evaluated as Sen's slope of annual-mean data.

(SST) trend patterns composited for hiatus and accelerated warming events feature negative and positive Interdecadal Pacific Oscillations (IPO; Zhang et al. 1997; Power et al. 1999), respectively. IPO is the leading mode that induces decadal GMST variability in unforced CMIP5 runs (Brown et al. 2015). Maher et al. (2014) identified IPO, in addition to volcanic and anthropogenic aerosol radiative forcing, as a driver of decadal hiatuses in a multimodel framework. IPO features SST anomalies with a broad peak in the equatorial Pacific, somewhat similar to ENSO, but dominates on decadal and longer time scales. The spatial pattern indicates that IPO can also influence global climate and GMST via atmospheric teleconnections much as ENSO does. In coupled GCMs, the evolution of IPO is apparently unforced and an internal mode with random phase. Thus the timing of the slowdown and acceleration of GMST increase is not synchronized with observations.

These studies highlighted the IPO influence on decadal GMST variability, but it remained to be quantified how much the negative IPO trend since the 1990s contributed to the observed GMST hiatus. Several studies employed statistical models for this evaluation. Lean and Rind (2009), Foster and Rahmstorf (2011) and Kaufman et al. (2011) developed regression models of GMST with multiple regressors including ENSO. All these studies found a significant influence of ENSO on GMST. Santer et al. (2014) and Schmidt et al. (2014) also used ENSO indices to regress the tropical Pacific influence out of the observed GMST trend. A caveat is, however, that IPO-induced GMST change likely differs in magnitude from that of ENSO, since IPO features a broader meridional structure of tropical Pacific SST anomalies, and the extratropical North Pacific SST anomalies are more pronounced in IPO than ENSO (Zhang et al. 1997). The tropical SST anomaly pattern, such as ENSO "flavors" (Banholzer and Donner 2014), affects the GMST response. The tropical Pacific pacemaker experiments using coupled GCMs can sidestep these issues by considering observed IPO evolution and spatial pattern, permitting year-by-year and region-by-region comparison during the hiatus.

Attribution of the GMST hiatus

In a pacemaker experiment, part of a coupled GCM is nudged to or overridden with its observed history, so that modes of variability in the model evolve in realistic phase. Recent studies highlight the success of tropical Pacific pacemaker experiments in quantifying ENSO and IPO influence on GMST. Kosaka and Xie (2013) restored tropical eastern Pacific SST in a coupled GCM to the observed anomalies. When forced with historical radiative forcing extended by RCP4.5, their pacemaker experiment reproduced the observed GMST variability remarkably well, including the recent hiatus (Figure 2a). They concluded that the recent hiatus is mostly due to tropical Pacific decadal cooling that reduces the radiative-forced increase in GMST.

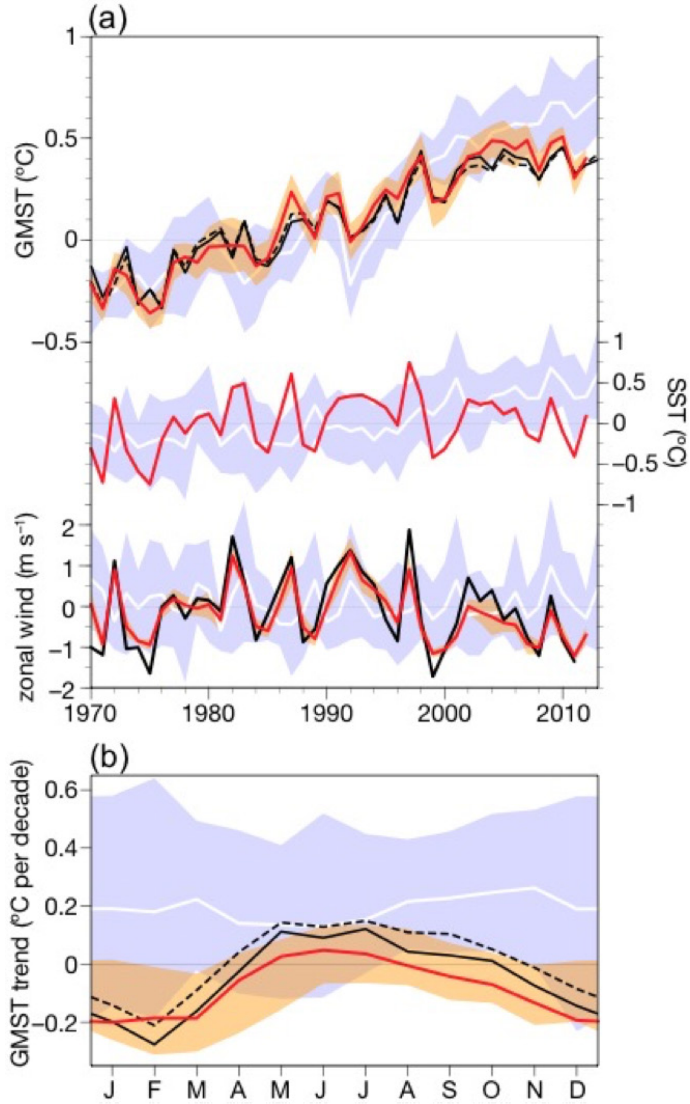

Figure 2: (a) Anomalies of annual-mean (top) GMST, (middle) tropical eastern Pacific SST (20ºS-20ºN, 175ºE eastward to American coast), and (bottom) equatorial Pacific zonal winds (5ºS-5ºN, 150ºE-150ºW) in observations and model experiments. (b) Trend of seasonal (three months)-mean GMST for 2002-2012. Black solid curves are based on HadCRUT4 GMST and wind- and anemometer-based sea surface wind (WASwind; Tokinaga and Xie 2011). Black dashed curves are Karl et al.'s (2015) GMST data. White curves with blue shading are based on the historical experiment extended by RCP4.5 scenario (HIST). Red curves with orange shading are the tropical Pacific pacemaker experiment forced by HIST radiative forcing (POGA-H) of Kosaka and Xie (2013). These two experiments were performed with Geophysical Fluid Dynamics Laboratory (GFDL) Coupled Model (CM) 2.1. Shading represents ±1 inter-member standard deviation. Anomalies are deviations from the 1970–1999 (ensemble-mean) averages, except for HIST, for which the reference is the 1970-1999 average of POGA-H ensemble mean.

Seasonality of the GMST trend characterizes the recent hiatus (Kosaka and Xie 2013). GMST has decreased in boreal winter, while increasing in boreal summer. The pacemaker experiment of Kosaka and Xie (2013) captures this seasonality while the forced response of the same model does not (Figure 2b), suggesting that this seasonality is a distinctive IPO fingerprint. It is noteworthy that this seasonality is observed also in the new GMST dataset of Karl et al. (2015).

Tropical Pacific SST variability is intrinsically coupled to surface winds (Figure 2a; Watanabe et al. 2014). Instead of nudging SST, England et al. (2014), Watanabe et al. (2014) and Delworth et al. (2015) overrode the tropical Pacific wind stress to pace IPO and ENSO in models. England et al. (2014) applied linear trends of the surface wind stress for 1992-2011, whereas the other two studies used the observed history of stress anomalies with interannual variability. All reproduced the slowed GMST increase during the hiatus. Because of model biases, the wind stress-overriding method may have had difficulty in reproducing observed SST anomalies and thereby GMST changes, as demonstrated by a sensitivity experiment with flux adjustments in Delworth et al. (2015). But this method did permit a closed ocean heat budget unlike the SST nudging (Douville et al. 2015). England et al. (2014) and Watanabe et al. (2014) showed heat was sequestered into the subsurface tropical Pacific Ocean in response to the intensification of the trade winds.

Complementary to pacemaker experiments, Fyfe and Gillett (2014) examined 1993-2012 trends of GMST and tropical Pacific SST in 117 simulations from 37 CMIP5 models, which encompass various phase trajectories of ENSO and IPO. The ensemble scatter reveals a clear correlation between GMST and tropical Pacific SST trends, and the observed trend rides on the regression line of the ensemble scatter. However, the observed trend sits outside the range of the ensemble, suggesting too weak IPO or its phase transition speed, or too large radiative forcing or climate sensitivity in CMIP5 models. Huber and Knutti (2014) and Risbey et al. (2014) adopted another way and searched the CMIP5 ensemble for members and periods during which the Niño 3.4 SST evolution resembles observations during the hiatus. Both studies identified significant contributions of ENSO/IPO for the hiatus, although the quantitative attribution depends on details of analysis methods.

Dai et al. (2015) evaluated contributions of internal modes to GMST variability by tapping into spatial information in observations from 1920 to 2013. By regressing out the forced change at each grid point using the CMIP5 ensemble mean GMST, they showed that the leading empirical orthogonal function (EOF) mode is IPO and has a large GMST projection, consistent with pacemaker experiments. The fourth mode resembles the Atlantic Multidecadal Oscillation (AMO) with a significant contribution to GMST. The second and third modes, while explaining more regional variability than AMO, do not project onto GMST. Superimposing the leading and fourth EOF modes with the model forced response, they successfully reproduced GMST and its decadal trend since the 1920s, including the recent hiatus.

Impacts on regional climate

Modes of climate variability are characterized by their spatial structures, which generally differ from radiative-forced response. Regional decadal climate changes are a superposition of the forced response and internal variability, and their relative contributions vary with region and season. Coupled pacemaker experiments are useful for understanding and attribution of regional climate changes during the hiatus (Kosaka and Xie 2013).

IPO induces precipitation anomalies worldwide (Dai 2013). Specifically, negative IPO decreases precipitation in the southwestern US, while models also project drought there in the warming climate (Christensen et al. 2013). This complicates attribution of the prolonged California and Texas droughts for the past decade. Delworth et al. (2015) compared their Pacific pacemaker experiment with the historical experiment forced solely by radiative forcing (Figure 3). They found that the negative IPO phase greatly increased likelihood of the observed level of decadal precipitation deficit, with a much smaller contribution from radiative forcing. The result suggests that the current drought will not simply continue into the future but will end with the GMST hiatus.

Meehl and Teng's (2014) analysis of decadal predictions showed improved precipitation simulations in parts of South and East Asia, the Maritime Continent and eastern Australia during the recent hiatus, compared to uninitialized experiments. The regions and signs are consistent with the negative IPO and suggest benefits from improved IPO state by model initialization. Based on an atmospheric GCM experiment, Trenberth et al. (2014) pointed out that the recent negative IPO has increased the chance of cold surges in Europe. Urabe and Maeda (2014) found an expansion of the temperature seasonal range in Japan since around 2000 and suggested a linkage with the negative IPO trend from statistical relationship.

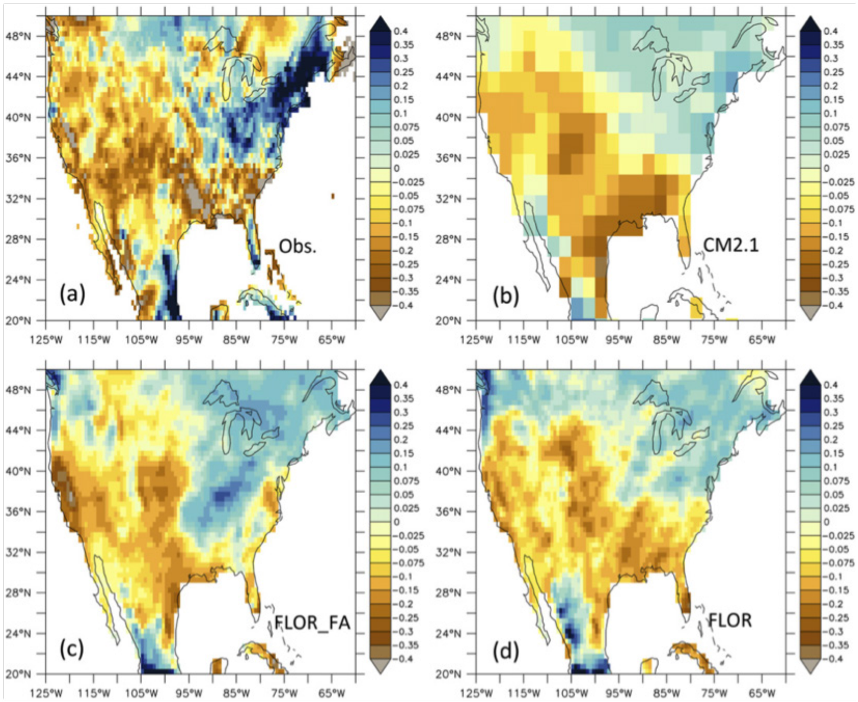

Figure 3: Difference in annual mean precipitation for 2002-2012 minus 1979-2000 (mm day–1). (a) Observations from CRU. (b-d) Simulations with pacemaker experiments by GFDL (b) CM2.1, (c) CM2.5 forecast-oriented low ocean resolution (FLOR) with flux adjustment (FA), and (d) CM2.5 FLOR without FA. After Delworth et al. (2015). ©American Meteorological Society. Used with permission.

Lin et al. (2014) examined possible influence of the recent negative IPO on the devastating typhoon Haiyan, which hit the Philippines on November 8, 2013. Negative IPO accumulates warm water in the tropical western Pacific, as manifested in higher sea level (Figure 1b). The warmer subsurface ocean set a favorable condition for tropical cyclone growth by limiting the cold wake (Mei et al. 2015). The stronger trade winds also facilitated the growth of Haiyan by speeding up the cyclone's movement, another effect unfavorable for the cold wake development.

Conclusions and remaining issues

The IPO began the transition toward negative phase in the 1990s (Figure 1). Empirical models, the CMIP5 ensemble, and pacemaker experiments agree that the recent negative IPO trend has offset a large part of radiative-forced warming and substantially contributed to the hiatus. However, the magnitude of the tropical Pacific SST contribution differs among analysis methods, due in part to the time scale and model dependency and the difficulty in separating the observed GMST into forced and internal components. The use of a "future" radiative forcing scenario after 2006, instead of observational estimates, introduces additional errors in model simulations.

The magnitude of the IPO effect on GMST may vary among coupled GCMs. The IPO features rich spatial structures, and the GMST is the residual of temperature anomalies of opposite signs. The degree of the model dependency needs to be assessed with a multi-model ensemble of Pacific pacemaker experiments, as is planned for CMIP6 within the Decadal Climate Prediction Project of World Climate Research Programme.

While recent studies all pointed to the negative IPO event as a driver of the current global warming hiatus, the cause of this IPO event remains unclear. External influence from the tropical Indian Ocean (Luo et al. 2012; Han et al. 2014) and Atlantic (Kucharski et al. 2011; Chikamoto et al. 2012; McGregor et al. 2014) has been proposed. A warmer tropical Atlantic or Indian Ocean cools the tropical Pacific by strengthening the Pacific Walker Circulation. The tropical Atlantic warming may be tied to AMO and hence the Atlantic Meridional Overturning Circulation, while such an internal mode has not been identified for decadal warming of the Indian Ocean. It is worth noting that, given strong internal variability in the tropical Pacific (i.e., ENSO), such external influence is not deterministic but merely modulates the probability of IPO phase.

The current global-warming hiatus highlights importance of internal climate variability in modulating decadal GMST trend. This recognition, along with the specific IPO effect, explains some of the peculiar regional anomalies that seem incompatible with global warming, e.g., record-setting heat waves in the U.S. and the record Arctic sea ice retreat in summer/fall. Nearly two decades ago, with fresh success on ENSO, CLIVAR was launched with great enthusiasm to tackle decadal variability like IPO. The importance of IPO in the current global warming hiatus provides impetus to a new campaign to uncover the mechanisms for decadal variability and develop predictability. The outcome will help answer important questions of why the hiatus occurred and when it will end.

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Warming the abyss: The deep ocean's contribution to global warming

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The rate of increase of the global mean surface temperature has shown a high level of variability despite a steady increase in greenhouse gases, including periods of zero or relatively low warming, often referred to as a warming "hiatus" (e.g., Trenberth and Fasullo 2010; Foster and Rahmstorf 2011). During the hiatus periods the top of the atmosphere radiative imbalance has remained at roughly 1 W m^{-2}. This suggests that either the observational record of surface temperature is incorrect owing to under sampling or data corrections or the heat is accumulating in other parts of the climate system, raising the question of where this excess heat is going (Trenberth et al. 2009; Karl et al. 2015; Kosaka and Xie 2013). In order to address this question and quantify the planetary heat gain, it is necessary to monitor all sinks of energy within the Earth's climate system. Atmospheric warming only accounts for roughly 1% of the excess radiative heat gain, with the vast majority, approximately 93%, absorbed by the global oceans and the remaining 6% accounted for by warming land and melting ice (Rhien et al. 2013). Despite the large role the ocean plays in absorbing the excess heat, much of it remains unmonitored, and historical estimates of ocean heat content are mostly limited to the upper 700 m. Since the early 2000s, the Argo array has revolutionized ocean monitoring above 2000 m, however, the deep (below 2000 m) and abyssal (below 4000 m) ocean remains sparsely sampled in space and time (Lyman and Johnson 2014).

The abyssal ocean communicates with the surface at high latitudes where deep and bottom waters are formed and fed into the bottom limb of the Meridional Overturning Circulation (MOC). North Atlantic Deep Water (NADW) is formed through open water convection in the Labrador and Nordic Seas when surface waters cool and sink (LeBel et al. 2008). In the Southern Ocean, Antarctic Bottom Water (AABW) is produced when cold, dense shelf water - formed through complex ice shelf-ocean interactions - flows down the Antarctic continental slope and mixes with ambient waters (Gordon 2009). While advective timescales for these waters to circulate from the surface through the bottom and deep limbs of the MOC is on the order of 1000s of years, dynamical effects can quickly communicate high latitude changes throughout the globe via isopycnal heave (e.g., Masuda et al. 2010). For example, a decrease in deep water formation rates at high latitudes will cause a deepening of isopycnals, appearing as a warming on isobars communicated via Rossby and Kelvin waves on decadal timescales (Kouketsu et al. 2009, 2011; Masuda et al. 2010; Purkey and Johnson 2012). Therefore, the deep ocean can increase its heat storage by either advection of warmer water or through a dynamical response.

Since the 1990s, the deep and abyssal oceans have been warming, contributing roughly 10% to the total ocean heat content (Purkey and Johnson 2010). However, limited deep ocean data only allows for estimates of decadal heat content trends, and makes it hard to assess short-term changes in the deep ocean's heat content, such as the change over the most recent hiatus period. Nonetheless, here we present a current assessment of deep and abyssal ocean heat content changes since the 1990s. We compare two studies: one covering 1990-2010 and the other 2000-2015 to show that there is little evidence that this rate has increased over the hiatus period. We end with a description of a proposed deep observing system that will allow for the necessary monitoring of the deep ocean in order to close ocean heat and sea level rise budgets over the next century.

Monitoring the abyss

High quality deep ocean temperature data are primarily limited to ship based hydrographic work. In the early 1990s, the international World Ocean Circulation Experiment (WOCE) Hydrographic Program completed a full-depth, high resolution oceanographic survey producing a climatological baseline for the deep ocean's hydrographic properties. The WOCE one-time survey occupied over 50 coast-to-coast zonal and meridional sections gridding the global ocean with high quality conductivity-temperature-depth (CTD) profiles nominally every 55 km. An important subset of the WOCE sections have been reoccupied in support of the Climate Variability and Predictability (CLIVAR) and Carbon Cycle Science programs now coordinated by the international Global Ocean Ship Based Hydrographic Investigations Program (GO-SHIP), allowing for the first estimates of the variability in the global deep ocean heat content over recent decades.

Using all repeated sections between 1990 and 2010, Purkey and Johnson (2010) quantified the heat flux across the 2000 and 4000 m isobaths within 32 deep basins around the globe, which is required to account for the observed warming trend below 2000 and 4000 m, respectively (Figure 1a). Since the timing of the first and last occupation of the sections varies, the basin heat content for each basin is calculated over a slightly different time period, with a mean time period of 1993-2006. During this period a clear southern-intensified warming pattern emerged, with the Southern Ocean warming below 2000 m at a rate of 0.03 °C per decade, and a smaller, but statistically significant, warming to the north below 4000 m following the deep flow of AABW along the bottom limb of the MOC (Figures 1a; 2). The warming along isobars is equivalent

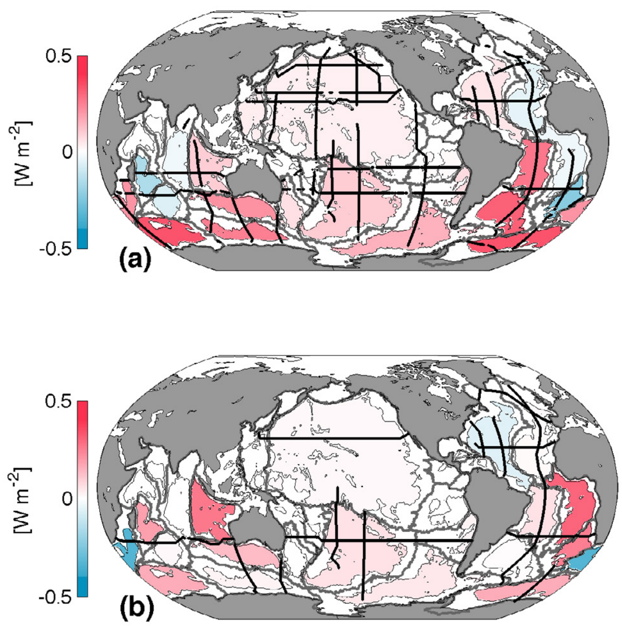


Figure 1: Basin (gray lines) mean local heat fluxes through 4000 m (color) implied by abyssal warming below 4000 m from the period centered around a) 1993-2006 and b) 2004-2013 with the location of repeated sections for each time period (black lines). Data for a) following Purkey and Johnson (2010) and b) following Desbruyères, McDonagh, and King (in prep.).

to a downward isotherm heave - or a volume loss of the cold, dense water - suggesting that the warming is being driven by a slowdown in the bottom limb of the MOC (Purkey and Johnson 2012). This total abyssal global ocean heat content change is equivalent to a heat flux of 0.03 W m^{-2} applied over the surface of the Earth. Including deep warming (2000-4000 m) increases the deep heat content to 0.07 W m^{-2}, mostly owing to warming in the deep Southern Ocean[2].

Following the Purkey and Johnson (2010) methodology, Desbruyères, McDonagh, and King (in prep.) derived a new estimate of deep ocean heat content post-2000, obtained from 18 hydrography sections occupied at least twice between 2001 and 2014. Comparing these two periods suggests weak variability in the magnitude and vertical structure of the trend between the 1990's and the mid-2010's. Between 2000-2014, the total deep heat flux remained at 0.07 W m^{-2}, with the deep layer accounting for a higher percentage of the total heat gain (Figure 2). Warming trends were primarily observed in the North Atlantic and Southern Ocean, and slightly damped by a cooling trend in the Pacific. After 2001, the warming signal was weaker within the bottom water (below 4000 m; Figure 2), and only accounted for a 0.025 W m^{-2} heat flux. Abyssal warming was, however, still observed in most ocean basins, making its contribution to the global heat flux of continued importance (Figure 1b).

Near source of deep water variability

The deep and abyssal changes around the globe can be traced back to their deep-water formation sites at high latitudes. NADW fills the deep and abyssal North Atlantic before flowing over the denser AABW in the South Atlantic and into the Antarctic Circumpolar Current (ACC). In the Pacific and Indian, the deep and abyssal ocean is primarily (over 50%) filled with AABW (Johnson 2008). These two water-masses dominate the global ocean below the thermocline, and play a critical role in climate through deep ocean carbon and heat storage (Johnson 2008; Meehl et al. 2006).

NADW

The North Atlantic is seen as a key region for recent climate variability due to ventilation of the deep ocean with newly formed NADW. This basin is also among the most adequately sampled by hydrography sections (Figure 1). The deep and abyssal warming

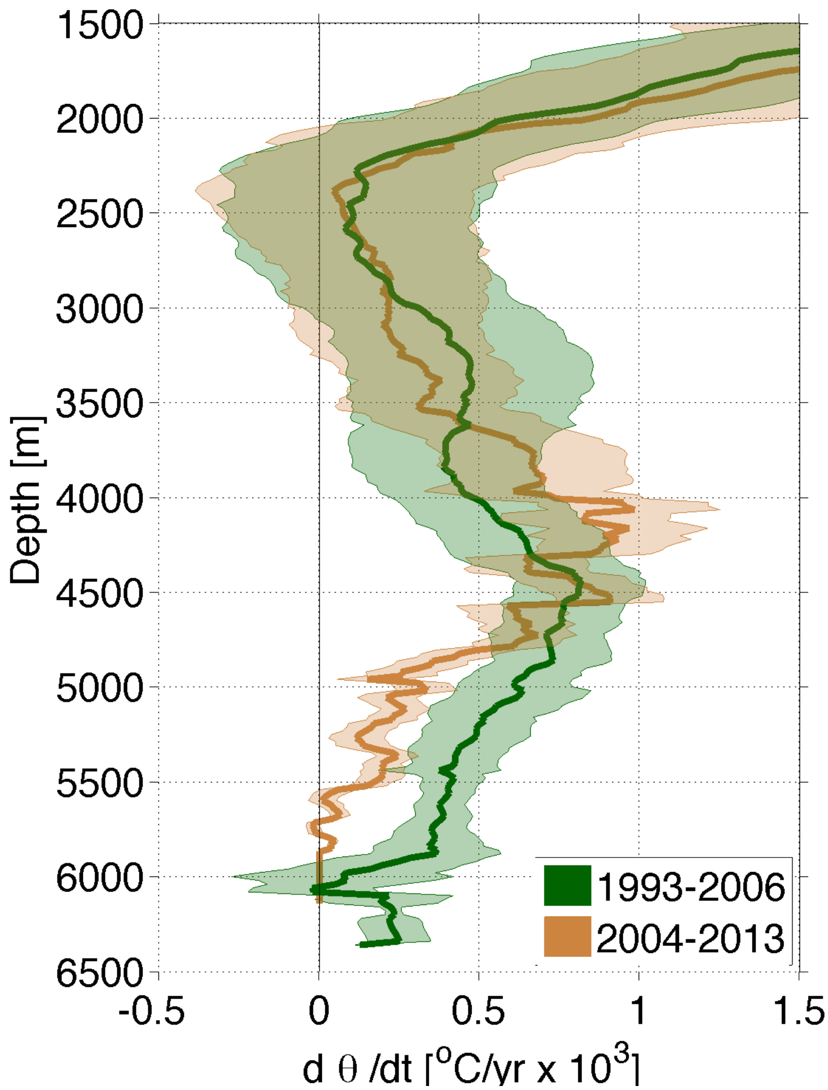


Figure 2: Global mean (thick lines) rate of change in potential temperature with 95% confidence intervals (shading) using repeated sections between 1990-2010 centered between 1993-2006 following Purkey and Johnson (2010; green) and repeated sections between 2001-2014 centered between 2004-2013 following Desbruyères, McDonagh, and King (in prep.; orange).

rate between 2000 and 2014 shows a predominant warming signal in the upper deep layer (0.03 ± 0.004 °C per decade between 2000 m and 3000 m) observed in both the western and eastern subpolar region (Desbruyères et al. 2014). This warming signal in the upper deep layer overlies an abyssal cooling signal of smaller magnitude (−0.004 ± 0.002 °C per decade; Figure 1b) primarily seen in the western subtropics – one of the main gateways for NADW to the Southern Hemisphere. Overall, the deep and abyssal North Atlantic warming rates during the period contribute to the global heat uptake by 0.017 ± 0.016 W m^{-2}.

Such opposing trends of the deep and abyssal regions may reveal the distinct forcing and timescales of the main NADW components: the Labrador Sea Water and the Greenland-Scotland Overflow Water. The former possesses a strong interannual and decadal response to atmospheric forcing and will be significantly influenced by wind-driven dynamics through its eastward and southward journey within the intermediate layers of the subpolar gyre (Desbruyères et al. 2014). Longer timescales will dominate at deeper levels, with changes in water-mass properties potentially becoming increasingly important.

AABW

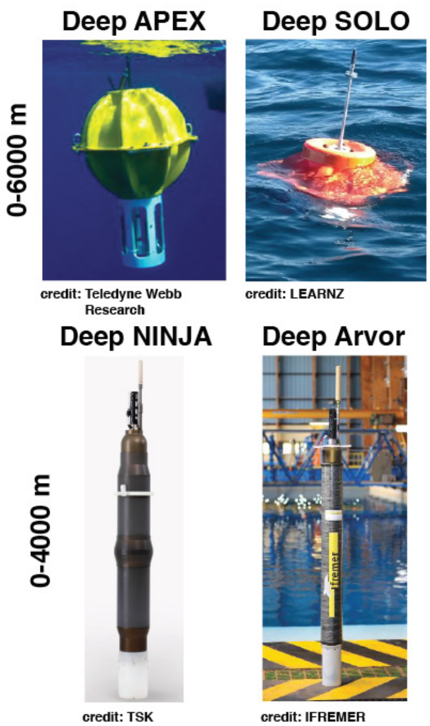
The abyssal and deep Southern Ocean, filled with the most recently formed AABW, has warmed significantly between the 1990s and 2010s, albeit the warming rate has decreased in recent years (Figures 1 and 2). AABW warming in these southern basins has been attributed to multiple factors. In the South Pacific and South Indian, the Ross Sea Shelf Water, an important end member of AABW found in this region, has freshened at a rate of 0.03 PSU per decade since the 1950s, likely owing to the increase in glacial melt rates along West Antarctica (Jacobs and Giulivi 2010). The resulting freshening decreases the density and volume of the recently ventilated AABW, causing an apparent warming along isobars (Aoki et al 2005; Swift and Orsi 2012; Purkey and Johnson 2013; Katsumata et al. 2015). In the Weddell Sea, however, the bottom and deep waters have been warming and decreasing in volume with no freshening, possibly owing to changes in local wind stress spinning up and down the Weddell gyre (Fahrbach et al. 2004, 2011; Purkey and Johnson 2012, 2013; Jullion et al. 2010).

Conclusion

Multiple studies have suggested the recent warming hiatus is due to a vertical redistribution of heat toward the ocean bottom, and indeed there is evidence of a redistribution of heat from the surface layer (upper 700 m) to intermediate depths (700-2000 m; e.g., Chen and Tung 2014). However, there is no pronounced change in the magnitude and vertical structure of temperature trends below 2000 m between the 1990-2010 and 2001-2014 periods, with both periods contributing 0.07 W m^{-2} to the global heat budget (Figure 2). This warming accounts for about 10% of the total oceanic heat uptake estimate between 1993-2010 of 0.71 W m^{-2} (Rhien et al. 2013). Together these estimates appear in line with a net downward radiative flux imbalance at the top of Earth's atmosphere of 0.62 ± 0.43 W m^{-2}, estimated from satellite data and atmospheric reanalyses between 2000 and 2012 (Allan et al. 2014).

Because of the importance of a deep ocean temperature record, a global ocean observing system is required to resolve temperatures from the top-to-bottom ocean and not just the upper-half of the water column. Upper-ocean sampling, largely carried out by the conventional Argo array, has nearly global coverage and resolves large-scale features on seasonal timescales. Since the end of 2007, Argo has reached its target of a sustained array of 3,300 floats at 3° x 3° spacing. The Argo array currently provides over 100,000 temperature and salinity profiles per year. Deep ocean hydrographic observations are limited to sparse shipboard hydrographic sections repeated roughly every decade, with a bias toward the summer time and high latitudes. Additionally, short-lived moored arrays of confined spatial coverage tend to be concentrated towards the coastline of continents in the Northern Hemisphere. Less than 100,000 profiles have been collected in the deep ocean since 1995.

The development of a new generation of deep-profiling Argo floats, capable of diving and recording temperature and salinity below 2000 m, is underway. The Deep Argo fleet consists of Deep Arvor and Deep NINJA floats designed to sample to 4000 m, and Deep APEX and Deep SOLO floats capable of reaching 6000 m (Figure 3). The primary focus of Deep Argo is to resolve interannual to decadal signals in deep ocean temperature, salinity, and circulation. The pilot implementation of regional Deep Argo arrays has begun in the Southern Ocean, the southwest Pacific Ocean, and the North Atlantic Ocean. The driving motivation for the Deep Argo deployments in the North Atlantic and Southern Oceans is to reduce uncertainties in deep water formation rates as well as to detect deep property changes. The rationale for implementing pilot arrays in the southwest Pacific Ocean is to quantify interannual variability in deep water mass characteristics and investigate pathways of water masses in the deep ocean. The pilot arrays are expected to continue for the next two to three years before transitioning to global implementation. Current plans include the



deployment of Deep Argo floats by US and European partners in the North Atlantic in 2016. The Deep Argo community envisions an array of 1,200 floats at 5° x 5° spacing, capable of sampling the full water column, starting in a few years (Johnson et al. 2015). From its beginning in 1998, Argo's objective has always been to sample the full-depth global ocean. Earlier technology limitations on sampling in marginal seas, seasonal ice-covered oceans, and the deep ocean have all been overcome and a global array is now not only exciting, but also possible.

Figure 3: The four Deep Argo float models: the Deep APEX floats, developed by the University of Washington and Teledyne/Webb; the Deep SOLO floats, developed by Scripps Institution of Oceanography; the Deep NINJA floats, developed by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Tsurumi-Seiki Co. (TSK); and the Deep Arvor floats, developed by Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Centre National de la Recherche Scientifique (CNRS), and nke Instrumentation.

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Global warming slowdown—An energy perspective

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When the global-mean surface temperature did not warm as expected in the presence of ever increasing atmospheric concentration of greenhouse gases that enhance the long-wave radiation to space, there can only be two possible reasons, both involving the energy budget of the earth: (1) the radiative heating was not appreciably reaching the surface - most of it presumably was reflected back to space by, for example, increasing aerosols from volcanoes and anthropogenic pollution; or (2) that the heating was reaching the surface and below, but was sequestered in the oceans. Of course, a combination of the two is possible. It then follows that no resolution of the "mystery" of the global warming slowdown can be accomplished without a proper accounting of the "missing heat," including whether any heat was indeed "missing." The pioneering work of Meehl et al. (2011; 2013) supports hypothesis (2) as a possible explanation. The studies found, at least in the Community Climate System Model version 4 (CCSM4) run under an emission scenario that happens to have an almost constant top of the atmosphere (TOA) radiative imbalance, that the surface hiatus periods are associated with enhanced storage of heat in the intermediate layers of the global ocean. On the other hand, the work of Schmidt et al. (2014) showed that the recent warming slowdown could be simulated in a model with newly adjusted radiative responses to aerosols from small volcano eruptions and to increased Asian aerosol pollution, supporting hypothesis (1).

To distinguish between the two possibilities, we need to look beyond models. By examining the energy budget of our climate system during the past 15 years, when there appeared to be a slowdown in global warming at the surface, it is possible to discriminate between possibilities (1) and (2). If one finds that the ocean has been absorbing more and more of the radiative heat during this period, it can be concluded that the heat *was reaching the surface*. Furthermore, we hope to establish quantitatively the amount of heat sequestration – the "missing heat" – that is needed to explain the slowdown by (2).

Energy balance involving the global ocean

Let $\Delta H_{TOA} = H_{sw} - H_{lw}$ be the radiative imbalance between the shortwave (sw) and longwave (lw) radiation at the TOA per unit area of the planet (note: we always use the total surface area of the globe, not just the ocean's surface area). Since the heat capacity of the ocean is much larger than that of the atmosphere and of the cryosphere (see Trenberth et al. (2014) for a review), we have

$$\Delta H_{TOA} = \frac{\partial}{\partial t} OHC_{total}$$

where OHC_{total} is the total ocean heat content of the world's oceans. Loeb et al. (2012) estimated that for the period 2001-2010, $\Delta H_{TOA} \sim 0.5 \pm 0.43\ Wm^{-2}$, using TOA satellite radiative measurements anchored to a well-observed, but shorter period (2005-2010) of the OHC change in 0-1800 m. Note the large uncertainty range.

As previously shown (Chen and Tung 2014), the global-mean sea-surface temperature (SST) from the Ishii dataset (Ishii and Kimoto 2009) has an almost zero trend since the turn of the 21st century up to 2012, which is the last year of availability of that dataset. Figure 1 here shows that not only was the SST in hiatus from 2000 to 2012, so too was the heat content in the upper 200 m layer of the ocean.[1] This is not surprising as the two are intimately related and highly correlated (r=0.82 with 12-month running mean data). The surface cannot sustain a cold anomaly for long if the underlying ocean is warm. Therefore, the question of why the global SST did not warm as much as expected should also be asked of the global upper ocean. If hypothesis (2) is the explanation for why the upper 200 m of the ocean has not warmed, one has to look below 200 m. Because of data coverage problems (e.g., Argo floats do not go below 2000 m, and the coverage is relatively sparse between 1500 and 2000 m), we have not included the heat content below 1500 m. Nevertheless the reported amounts of deep ocean warming are one order of magnitude smaller (Purkey and Johnson 2010). On the other hand, it also follows that finding shallow heat storage in particular parts of some ocean basins - for example, finding that the upper 100 m of the Indian Ocean has been warming, or proposing that the intensifying trade wind is blowing the warm waters from the surface in the eastern equatorial Pacific to the western Pacific, where they are subducted below the surface in shallow convection cells - is probably not relevant to the "missing heat" that we are looking for below 200 m.

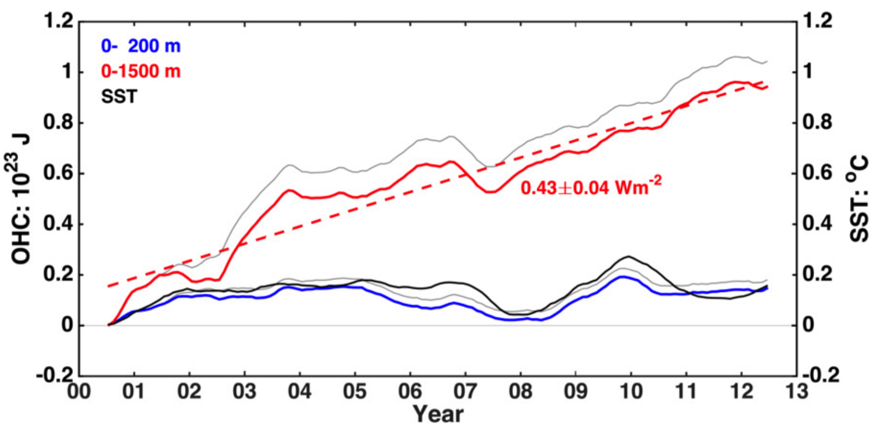

Figure 1: Globally averaged SST and adjusted OHC: SST in black, upper 200 m OHC in blue, and upper 1500 m OHC in red. Unadjusted OHC values are in grey. The adjustment, suggested by Cheng and Zhu (2014) involved adjusting the slope of the warming before and after 2002 so that they are consistent. It in effect made the Southern Ocean warmer pre-Argo, and therefore the later warming less relative to 2000. The upper 1500 m OHC increases at the rate of 0.43 Wm^{-2}, as indicated by the red dashed line. Data source: Ishii dataset of mostly Argo float measurements for both SST and OHC.

[1]Since the extended and reconstructed sea-surface temperature (ERSST) datasets did not include Argo measurements, the SST shown here is independent of the ERSST and is useful in providing a comparison of the latter's latest revision (ERSST.v4) discussed in Karl et al. (2015).

In contrast, the total OHC, as approximated by that of the 0-1500 m of the world's oceans, is increasing at the rate of ~0.43 Wm^{-2}, matching approximately the TOA net radiative imbalance, though the latter is more uncertain. The difference between the two OHC curves in Figure 1 is the amount of heat stored between 200 m and 1500 m. From 2000 to 2012, this heat storage has increased by approximately 81 ± 5 zetajoules (linear trend and regression error)[2];. This amount of heat storage explains why the upper 200 m of the oceans did not warm during this period. If this heat storage were absent, but the TOA radiative imbalance remained the same, the 0-1500 m OHC would still increase at the same rate as shown, but the 0-200 m OHC curve would lie on top of the 0-1500 m curve, and therefore increase at the same rate. Hence, no slowdown would have been seen in the top 200 m of the world's oceans.

There does not appear to be an appreciable change in the slope of the 0-1500 m OHC curve as a function of time (Balmaseda et al. 2013; Chen and Tung 2014; Trenberth et al. 2014), although the OHC data are admittedly not good enough before 2000 for us to know definitively. Nevertheless a change in slope as large as 50% around year 2000 should have been detectable even with the data uncertainty. Thus we can infer, though tentatively, that the warming slowdown of the surface or the upper layer of the ocean was not due "in equal measure" by a reduction of radiative forcing and by the oceans storing the remaining heat.

Data quality and heat storage in individual ocean basins

Figure 2 shows that of the 81 zetajoules of global heat storage in the 200-1500 m of the global oceans from 2000-2012, the Indian Ocean subducted 14 ± 1 zetajoules, and the Pacific 13 ± 3 zetajoules. The Atlantic and Southern Oceans accounted for the rest (54 zetajoules), about 70% of the heat storage increase. Data quality of the subsurface OHC measurements was reviewed by Abraham et al. (2013). Levitus et al. (2012) estimated a near 100% global coverage of OHC since 1994 at 700 m in 1° x 1° grids with at least four measurements available in five years (see their Figure 1). Cheng and Zhu (2014) pointed out that there was a rapid transition from no-Argo to Argo-based measurements between 2001 and 2003 in the Southern Ocean, which had sparser ship-based measurements compared with the North Atlantic and the Pacific, giving rise to an artificial jump in the Southern Ocean OHC in the upper 700 m, which is present in all *in situ* datasets including the Ishii dataset used by Chen and Tung.

The background of Figure 2 shows the percentage of coverage in monthly resolution (instead of five years), confirming Cheng and Zhu. We made an adjustment in the Southern Ocean data between 2002 and 2003 following their suggestion. It is the adjusted result that is shown in Figure 2, and all OHC numbers quoted above and below are for the adjusted values. Figure 1 shows the results before and after our adjustment.

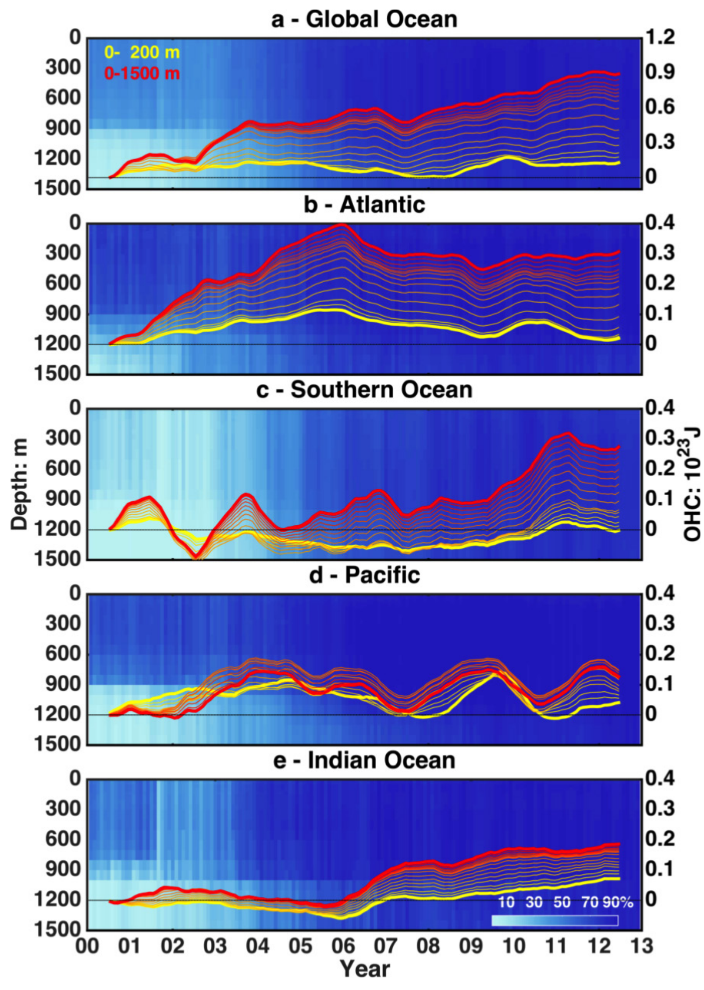

Figure 2: Ocean heat content globally and in each ocean basin. Yellow is the 0-200 m OHC and red is the 0-1500 m OHC. The other colors are the OHC in 0-300 m, 0-400 m, etc. Percentage coverage of the oceans are given in background color as a function of depth and time in monthly resolution and in 5°x 5° grids. Data source: Ishii and Kimoto (2009).

[2] 1 zetajoule=10^{21} joules, about twice the world's energy consumption per year; when 81 zetajoules are divided by 13 years and the area of the planet, it yields 0.43 Wm^{-2}; and 1 W=1 Js^{-1}

The Southern Ocean[3] achieved adequate coverage since 2005, and since that time it sequestered an additional 20 ± 4 zetajoules of heat in the layer between 200 m and 1500 m. The Atlantic's heat storage peaked in 2005 and the heat stored did not increase after that. Between 2000 and 2005, the Atlantic Ocean sequestered a massive 30 ± 3 zetajoules in the 200-1500 m layer. The story is still intact even without using the Southern Ocean data before 2005 — the 81 zetajoules that the global ocean sequestered since 2000 that is needed to explain the global warming hiatus was carried mostly by the Atlantic before 2005 and Southern Ocean after 2005 (note, however, linear trends from different periods cannot be added).

In Chen and Tung (2014), we mentioned an estimate of errors to the global mean by Lyman and Johnson (2014) due to infilling of under-sampled areas of the oceans, especially in the Southern Ocean, as $0.05x10^{23}$ J since 1993. It was a misreading. It should have been $0.1x10^{23}$ J, which is still small when compared to the global heat uptake of 81 zetajoules found here. Furthermore much of the quoted error was pre-Argo, while here we used mostly Argo measurements.

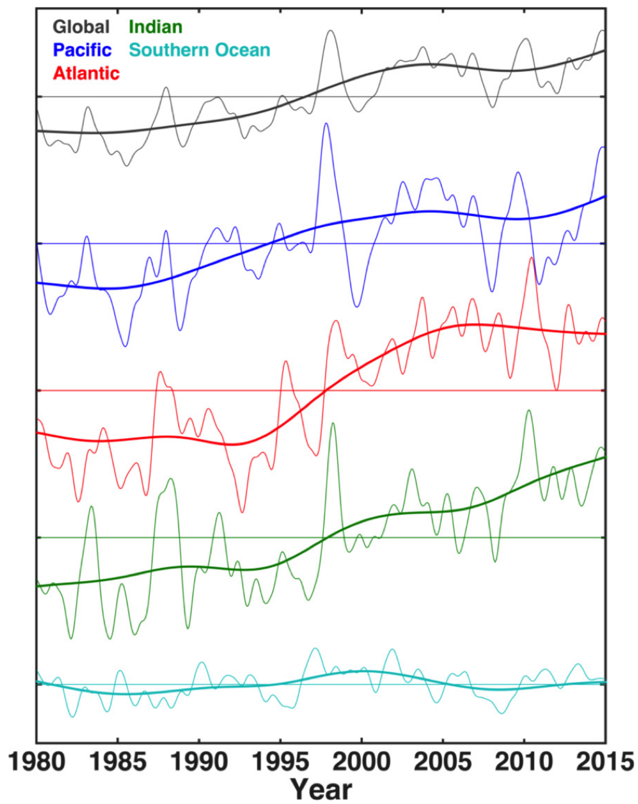

Figure 3: Mean SST in the global ocean (black) and in each ocean basin (colors), and their smoothed version (bold) (obtained by Empirical Mode Decomposition). Data source: ERSST.v3b.

Surface mean SST in individual ocean basins

The mean SST in each of the four ocean basins is shown in Figure 3. The big picture, which is consistent with the finding above that there is a planetary sink of energy, is that there is no appreciable decadal trend, warming or cooling, in all the ocean basins with the exception of the small Indian Ocean, which probably has received some small fraction of the warm water blown over from the Pacific by the intensified trade wind (Lee et al. 2015). Looking at it in finer detail, the Pacific Ocean did not cool, and in fact has a slight warming trend during the recent period. The cooling in the eastern tropical Pacific that Kosaka and Xie (2013) focused on was compensated by the warming in the western Pacific, so that the basin as a whole probably did not contribute to the global warming slowdown. The claim by some that the Pacific Ocean was the only ocean basin that cooled, thereby offsetting anthropogenic warming elsewhere, is not apparent in the data. The Atlantic Ocean warmed between 1995 and 2005, as the Atlantic Meridional Overturning Circulation (AMOC) sped up (Willis 2010), and then it cooled after 2005 when the AMOC slowed, as measured by RAPID (Smeed et al. 2014). The warming in the Atlantic before 2005 was compensated in part by the cooling in the Southern Ocean and to a smaller extent by the Pacific Ocean.

Conclusion and discussion

There did not appear to be a substantial (at least 50%) change in the top of the atmosphere radiative imbalance in the warming slowdown in the 21st century from the prior non-hiatus decades in the 20th century. The rate of increase of OHC for the global ocean is calculated to be approximately 0.43 Wm^{-2}, using the top 1500 m of the ocean, and appears to be within the range of the TOA measurements. The upper OHC (the upper 200 m) became flat in the 21st century, signaling a slowdown of the upper ocean warming. The observed SST accompanied the upper ocean into a slowdown. There is no disconnect between the two. The amount of heat stored between 200 m and 1500 m of the global ocean increased by approximately 81 zetajoules since year 2000, and we argued that this amount is sufficient to account for the slowdown of warming at the surface and the upper 200 m of the global ocean up

[3] As in Chen and Tung (2014), the Southern Ocean here is defined as ocean waters south of 35°S, which is also the southern boundary of other ocean basins.

to 2012. The North Atlantic sequestered most of the heat increase during the period 2000-2005, while the Southern Ocean took over the role after 2005 and continued the heat sequestration up to the present. Although the subsurface coverage by the Argo floats appears to be sufficient for the North Atlantic, the Southern Ocean did not achieve adequate coverage until after 2004. Between 2001 and 2003, the rapid transition from no-Argo to Argo seemed to have produced a suspicious blip of warming. Nonetheless, since the bulk of the heat absorption in the Southern Ocean occurred after 2005 (in particular after 2010), our picture of the North Atlantic and the Southern Oceans taking turns in sequestering most of the heat required to account for the recent slowdown holds, even if Southern Ocean data are ignored prior to 2005. The data of the Pacific Ocean, which had adequate coverage in recent decades, revealed very little heat storage anomaly throughout the recent warming slowdown.

The heat storage below 200 m is the explanation for why the top 200 m of the ocean has been in a warming slowdown. Since there is no barrier to the atmospheric transport of heat, the SST in all ocean basins behave more or less similarly: they are all in a warming slowdown, with the exception of the small Indian Ocean, which appeared to have been warmed by a small fraction of the warm Pacific waters blown over through the Indonesian Through Flow by the intensified trade wind (Lee et al. 2015). The trade wind in the equatorial Pacific simply moves warm waters from the east to the west (and northwest) in the Pacific basin. It subducts very little heat below 200 m. Because of atmospheric transports and diffusion, it is difficult to deduce the source of the heat sink (i.e., whether it is in the Pacific or the Atlantic basin) just by examining the spatial pattern of the surface signals. Mathematically, this may be an ill-posed inverse problem. The mean surface temperature in different ocean basins probably would behave roughly the same whether the heat sink is located in the Atlantic or the Pacific basin. In models that do not alter the TOA radiative forcing, but are able to produce a hiatus by specifying part of the SST or winds from observation and nudging the model (which was too warm and the winds too weak) into the observed values, there must be an artificial sink of energy introduced somewhere in the system by the model setup. The energy perspective presented here applies to both observation and models, even if it often is not discussed in the latter.

With the record warm year of 2014, it appears that the slowdown might have ended, though only time will tell. The "warm blob" (Bond et al. 2015; Hartmann 2015) that persisted from the winter of 2013 into 2014 contributed significantly to the warming of the northern Pacific in 2014 and also to the global mean SST, but it may not last. The El Niño that is brewing in the Pacific may make 2015 another warm year, but we are more interested in monitoring when the heat uptake in the Southern Oceans stops increasing.

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Sensitivity to factors underlying the hiatus

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What is the hiatus?

Recent trends in global mean surface air temperature fall outside the 90% range predicted by models using the CMIP5 forcings and scenarios (Fyfe and Gillett 2014); this recent period of muted warming is dubbed the "hiatus". The hiatus has attracted broad attention in both the popular press and the scientific literature (Boykoff 2014; Hawkins et al. 2014), primarily because of its perceived implications for understanding long-term trends (Lewis and Curry 2014; Otto et al. 2013). Many hypotheses have been offered to explain the warming slowdown during the hiatus, and comprehensive studies of this period across multiple variables and spatial scales will likely improve our understanding of the physical mechanisms driving global temperature change and variability.

We argue, however, that decadal temperature trends *by themselves* are unlikely to constrain future trajectories of global mean temperature and that the hiatus does not significantly revise our understanding of overall climate sensitivity. Instead, we demonstrate that, because of the poorly constrained nature of the hiatus, model-observation disagreements over this period may be resolvable via uncertainties in the observations, modeled internal variability, forcing estimates, or (more likely) some combination of all three factors. We define the hiatus interval as 1998–2012, endpoints judiciously chosen to minimize observed warming by including the large 1998 El Niño event and excluding 2014, an exceptionally warm year. Such choices are fundamentally subjective and cannot be considered "random", so any probabilistic statements regarding the likelihood of this occurring need to be made carefully. Using this definition, the observed global temperature trend estimates from four datasets fall outside the 5–95% interval predicted by the CMIP5 models (Figure 1a). Here we explore some of the plausible explanations for this discrepancy, and show that no unique explanation is likely to fully account for the hiatus.

Is the hiatus an artifact of biases in the observations?

The horizontal lines in Figure 1a show the 1998–2012 surface temperature trend in four different observational datasets. The left-most vertical bar shows the 5–95% confidence range for the trends in the individual CMIP5 historical simulations, each of which have been extended to 2012 using the relevant RCP8.5 simulation. The observational trends for the HadCRUT4 (Morice et al. 2012), GISTEMP (Hansen et al. 2010), NCDC (Karl et al. 2015) and Cowtan and Way (2014) datasets lie well below this range, but if uncertainty in the trend is included, there is some overlap. Recent improved accounting for various biases in land and ocean temperature measurements have increased trends over those initially estimated, and corrections for Arctic coverage bias increase them further (Cowtan and Way 2014; Simmons and Poli 2014). Accounting for known observational biases has revised global mean surface temperature trends upward in recent years, reducing the magnitude of the apparent anomaly that was seen with previous versions of the products (i.e., HadCRUT3).

Is the trend uncertain due to the short time period?

Fifteen years is a relatively short time period. We might therefore expect large uncertainties in 1998-2012 global mean surface

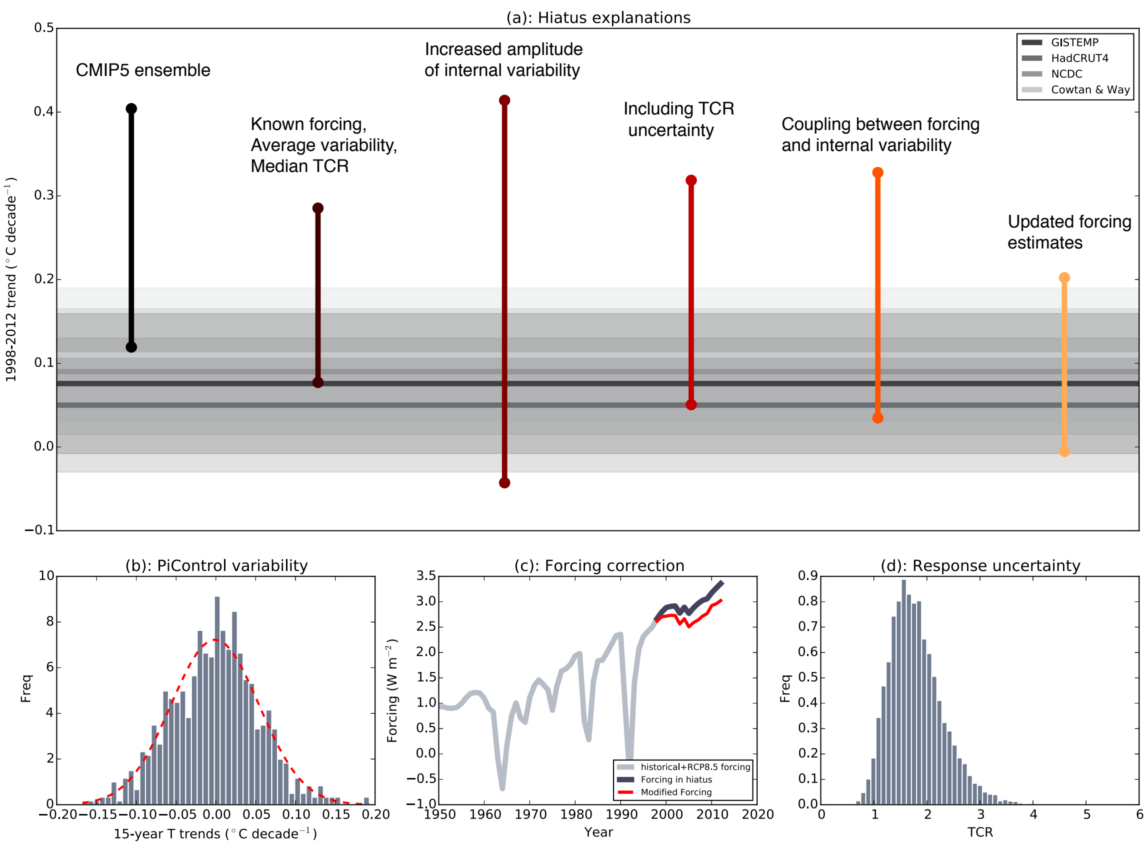

Figure 1: a) Estimates of 1998–2012 global mean surface temperature trends. Each vertical line derives from a different estimate (from left-to-right): i) the CMIP5 ensemble; ii) a theoretical estimate assuming known forcing (from the GISS-E2-R historical simulations), median TCR, and average model internal variability; iii) as (ii) but with an augmented internal variability; iv) as (ii) but with transient climate response (TCR) uncertainty; v) as (ii) but with a strong coupling between the forcing and internal variability; vi) as (ii) but with updated forcing estimates, assuming unit efficacy for each forcing.. Horizontal lines are the observational estimates from four data products, and the horizontal gray bands show the 5–95% confidence interval on the regression slope of each observational dataset over the hiatus period. b) Histogram of piControl variability in 15-year trends. c) Forcing timeseries from the GISS-E2-R historical simulations (gray and black lines) and an update based on more recent analyses (red line). d) Distribution of TCR uncertainty.

temperature trends calculated using annual-average, global-average temperatures due to the short length of the record. The shaded regions in Figure 1a show the 5–95% confidence interval on the regression slope of each observational dataset over the hiatus period, assuming no adjustment for autocorrelation in the residuals. Each of these regions overlaps the CMIP5 90% confidence interval, indicating that the uncertainties in the observed trend for 1998-2012 are one plausible scenario for explaining the divergence with the CMIP5 model trends.

Is the hiatus compatible with model-estimated internal variability?

The observed global temperature trend may simply be attributable to a particular realization of a mode (or modes) of internal variability (Huber and Knutti 2014; Marotzke and Forster 2015; Meehl et al. 2014; Roberts et al. 2015; Watanabe et al. 2014). We do not expect free-running coupled models to simulate this exact realization; a model may produce hiatus-like trends, but the chances of doing so over the period 1998–2012 are very small. Moreover, the CMIP5 models over 1998–2012 do not constitute perfect ensembles designed to incorporate all possible manifestations of internal variability. Arguably, the far longer CMIP5 preindustrial control (piControl) simulations provide a more comprehensive picture of internal variability. Concatenating piControl temperature anomalies from multiple models (e.g., Santer et al. 2009) yields a single time series of over 6,000 years in duration.[1] We calculate 15-year overlapping trends in this long concatenated time series and obtain a probability distribution of trends (Figure 1b). The width σ_c=0.06°C per decade of this distribution constitutes a reasonable estimate of the CMIP5 model ensemble internal variability, or noise.[2] For individual models, the width ranges from 0.04°C to 0.14°C per decade.

Suppose that all model climates experienced identical radiative forcing, which we will approximate using the RF time series for the GISS model (Figure 1c).[3] Suppose, moreover, that every model has the same transient climate response (TCR) to 2xCO_2 of 1.8°C (the CMIP5 multimodel mean). In this case, every model would experience an identical temperature response to forcing, and any intermodel differences would be attributable to internal variability. To approximate this "model average internal variability," we add to samples drawn from a distribution, where μ=0 and σ_c is drawn from concatenated piControl runs to the expected forced change. The resulting 5–95% interval (second vertical line in Figure 1a) appears different from the forced CMIP5 trends, due to unknown differences in forcing (not all models used the same forcings as GISS), known differences in response (TCR varies across models), and the presence of specific manifestations of internal variability such as ENSO or the Pacific Decadal Oscillation (PDO) in the historical CMIP5 models. However, given this "best-guess" forcing and response, the observed trend overlaps the 90% confidence interval produced by internal variability alone.

Do models underestimate the amplitude of internal variability?

It is possible that the 1998–2012 global mean surface temperature trend results from some mode of internal variability that is poorly simulated by the models. CMIP5 models may collectively underestimate the amplitude of internal variability such that the σ_c obtained from the concatenated control runs is an underestimate of the true internal variability. If we calculate the 15-year trend distribution on a model-by-model basis, we find that the GFDL-CM3 model has the largest standard deviation (i.e., the widest trend distribution) with σ_{GFDL}= 0.14°C per decade. Replacing σ_c with the larger σ_{GFDL} expands the 90% confidence interval such that the observed trend is comfortably within the nominal model spread (third vertical line in figure 1a). Here, we assume that the short term climate results from the superposition of a forced trend and white noise. There are of course other statistical models one could use (red noise, ARMA etc.) which would result in a larger spread in internal variability; the white noise assumption is therefore a conservative one.

Are model responses too strong?

Due to differences in climate feedbacks, CMIP5 models exhibit different values of TCR. The 5–95% confidence interval given by the IPCC is 1.0–2.5°C, with a best-guess value of 1.8°C. Several recent papers have argued that current temperature trends necessitate a revision of this range downward; however, other work has highlighted the need to consider the different efficacies of various forcing agents affecting temperature over the historical period (Hansen et al. 2005; Kummer and Dessler 2014; Shindell 2014). Given identical forcing and uniform internal variability, we draw TCR samples from a lognormal distribution with 5–95% range 1.0-2.5°C (Figure 1d) and recalculate the confidence interval for model 1998–2012 trends. Once again, the observed trend lies within the 90% confidence interval (fourth vertical line in Figure 1a).

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[1] Only the first 200 years of each model control run are used here to prevent assigning undue weight to models with long control runs.

[2] This estimate is likely biased slightly high because of the concatenation and residual drift in the control runs.

[3] This is the only complete forcing time series as seen by any of the CMIP5 models (Miller et al. 2014).

Is the hiatus caused by externally forced changes to internal variability?

External forcing may couple to internal variability, changing the amplitude or frequency of known modes such as ENSO (Cai et al. 2014, 2015). For example, it has been posited that the observed widening of the tropical belt is partially attributable to a reversal of the PDO, aided by aerosol-forced changes to sea surface temperatures (Allen et al. 2014). In the piControl simulations, the distribution of 15-year trends are centered around zero; there is no a priori reason for positive or negative trends to be more or less likely. However, any interaction between forcings and internal variability may shift the trend distribution, for instance, making lower 15-year trends more likely and higher 15-year trends less likely. In Figure 1a (fifth vertical line), we demonstrate the impact on the distribution of a shift of the "noise" mean by a factor of σ_c is roughly equivalent to assuming that negative trends are favored 5 to 1 over positive trends (or vice versa).

Does the hiatus result from errors in the forcing?

It is difficult to precisely calculate forcing uncertainty across the multi-model archive, as few modeling groups specified the radiative forcings used in their historical simulations, and they are not provided as standard CMIP5 output. However, the CMIP5 experimental design has known errors in the forcings used. All CMIP5 historical experiments end in 2005, after which simulations are extended through 2012 by splicing with RCP experiments (we use RCP8.5 here). These future projection experiments contain no volcanic aerosol loading beyond 2000 (Santer et al. 2014) and use projected updates to solar output or tropospheric aerosols that did not exactly match the real world after 2005 (Huber and Knutti 2014; Kaufmann et al. 2011). Estimates of the net effect suggest that the real world had more negative forcings than projected (Schmidt et al. 2014). Updating the forcing (Figure 1c), but holding TCR and noise parameters constant, we find that reduced forcing can also reconcile observed and modeled temperature trends over the hiatus period (last vertical line in Figure 1a).

Moving forward

Evidently, if the hiatus is defined solely as a short-term temperature trend, there are many possible ways to reconcile models and observations. We suggest that, moving forward, it is more useful to focus on regional or seasonal characteristics of the hiatus mechanisms (e.g., Kosaka and Xie 2013; Trenberth et al. 2014), such as ocean heat uptake (Meehl et al. 2011), or signatures across non-temperature variables (England et al. 2014). This is because attribution of climate variability is fundamentally a signal-to-noise problem, regardless of whether the drivers are external or associated with internal modes of variability. Detection and attribution studies have established that a deep understanding of underlying physical processes can lead to detailed and complex "fingerprints" of any driver. Multiple coherent, physically expected processes may result in a stronger signal and, moreover, yield a pattern substantially different from leading modes of natural variability, increasing the strength of the signal. Additionally, complex fingerprints will distinguish processes that will not be apparent in a single short-term trend in a single variable. Studying the hiatus may not tell us much about future climate trajectories, but if we can move beyond global mean temperature to a more complete understanding of current climate conditions, internal variability, and the physical mechanisms underlying decadal fluctuations in temperature, it will be worth the time spent.

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ANNOUNCEMENTS

CLIVAR-Relevant Sessions at Upcoming Conferences

The US CLIVAR community may be interested in attending one of the many relevant sessions at three large upcoming conferences. The AGU Fall Meeting (San Francisco, December 14-18, 2015), the AMS 96th Annual Meeting (New Orleans, January 10-14, 2016) and the 2016 Ocean Sciences Meeting (New Orleans, February 21-26, 2016) are all now accepting abstracts. View some of the relevant sessions that have been collated by the US CLIVAR Project Office, including those specific to US CLIVAR Panels and the Science Plan.

Abstracts Due August 5

Abstracts Due August 3

Abstracts Due September 23

CLIVAR Open Science Conference Qingdao, 2016

SAVE THE DATE

On September 16-23, 2016 CLIVAR will hold an Open Science Conference in Qingdao, China to engage the wider collection of scientists who work on the coupled ocean-atmosphere system. In addition to the main event, two side meetings will occur, one for early career scientists and another for regional stakeholders.

Check the website for additional details and dates.

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