



REVIEW

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Xiao-Hai Yan and Tim Boyer contributed equally to the study and are co-first authors.

Key Points:

- From 1998 to 2013, the rate of global mean surface warming slowed (some have termed this a global warming hiatus); we argue that this represents a redistribution of energy within the Earth system
- Natural, decadal variability plays a crucial role in the rate of global surface warming
- Improved understanding of ocean distribution and redistribution of heat will help us better monitor Earth energy budget and will maintain and increase ocean monitoring

Corresponding author:

X.-H. Yan, xiaohai@UDel.Edu

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The global warming hiatus: Slowdown or redistribution?

Xiao-Hai Yan¹, Tim Boyer², Kevin Trenberth³, Thomas R. Karl⁴, Shang-Ping Xie⁵, Veronica Nieves^{6,7}, Ka-Kit Tung⁸, and Dean Roemmich⁵

¹Joint Institute of CRM, University of Delaware and Xiamen University, Newark, Delaware, USA & Xiamen, Fujian, China, ²National Centers for Environmental Information, NOAA, Silver Spring, Maryland, USA, ³National Center for Atmospheric Research, Boulder, Colorado, USA, ⁴Independent Consultant, Mills River, North Carolina, USA, ⁵Climate, Atmospheric Science & Physical Oceanography, Scripps Institution of Oceanography, San Diego, California, USA, ⁶Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles, California, USA, ⁷Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, ⁸Applied Mathematics, University of Washington, Seattle, Washington, USA

Abstract Global mean surface temperatures (GMST) exhibited a smaller rate of warming during 1998–2013, compared to the warming in the latter half of the 20th Century. Although, not a “true” hiatus in the strict definition of the word, this has been termed the “global warming hiatus” by IPCC (2013). There have been other periods that have also been defined as the “hiatus” depending on the analysis. There are a number of uncertainties and knowledge gaps regarding the “hiatus.” This report reviews these issues and also posits insights from a collective set of diverse information that helps us understand what we do and do not know. One salient insight is that the GMST phenomenon is a surface characteristic that does not represent a slowdown in warming of the climate system but rather is an energy redistribution within the oceans. Improved understanding of the ocean distribution and redistribution of heat will help better monitor Earth’s energy budget and its consequences. A review of recent scientific publications on the “hiatus” shows the difficulty and complexities in pinpointing the oceanic sink of the “missing heat” from the atmosphere and the upper layer of the oceans, which defines the “hiatus.” Advances in “hiatus” research and outlooks (recommendations) are given in this report.

1. The Hiatus: A Redistribution of Energy

Global mean surface temperature (GMST) is a key indicator of climate change. It was noted by the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) that “... the rate of warming over the past 15 years (1998–2012; 0.05°C [–0.05°C to +0.15°C] per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12°C [0.08–0.14°C] per decade)” [Hartmann *et al.*, 2013], despite the continued increase in atmospheric greenhouse gas concentrations (Figure 1) [Trenberth, 2015]. Although neither is shown to be a statistically significant change in the rate of warming nor a “true” hiatus in the strict definition of the word, this difference has been referred to as the “global warming hiatus” in the IPCC Assessment Report [IPCC, 2013]. Note that the IPCC AR5 came out before the “hiatus” was over in 2013, and more recently, GMST shows substantial increases when viewed over the past 10 or 15 years ending in 2016 (0.34°C/decade and 0.17°C/decade, respectively).

Before going further, a particular question relevant to the understanding of the hiatus is the time period over which it occurred, more specifically the starting point of the hiatus. The IPCC AR5 uses the time period 1998–2012 in comparison to the period 1951–2012. The 1951–2012 period coincides with previous detection and attribution work cited by IPCC with respect to human contributions to global surface and tropospheric spatial and vertical patterns of change, that is, anthropogenic fingerprints. The IPCC report goes on to note that changing the starting point of the hiatus period significantly changes the GMST rate of change and, similarly, its statistical significance in comparison to the longer baseline trend (see also Karl *et al.*, 2015). Moving back the start point just one or two years means a rate of change close to the long-term trend. There was a large El Niño event ending in 1998, which led to an increased GMST and which flattens out the GMST curve when using 1998 as a starting point. It is found [Fyfe *et al.*, 2016] that the time period chosen for the hiatus is important, and a more apt description of the so-called “hiatus” is a decadal climate fluctuation or variation [Lewandowsky *et al.*, 2015b]. In fact, the GMST increase was only around 0.02°C/decade

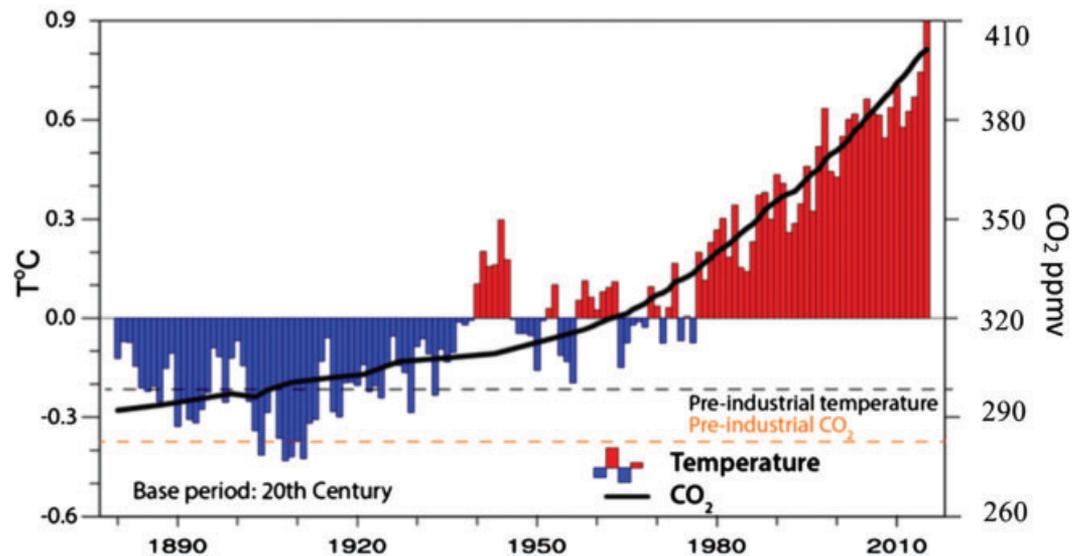


Figure 1. Time series of annual values of global mean temperature anomalies and carbon dioxide concentrations at Mauna Loa and from the ice core record. Time series of annual values of global mean temperature anomalies (red and blue bars) in degrees Celsius, and carbon dioxide concentrations at Mauna Loa, both from NOAA. Data are relative to a baseline of the 20th century values. Also given as dashed values are the preindustrial estimated values, with the scale in orange on the right for carbon dioxide, where the preindustrial value is 280 ppmv (parts per million by volume). The latest values exceed 400 ppmv. For temperature, the 2015 value is more than 1°C above preindustrial levels. Updated from *Trenberth and Fasullo* [2013].

from 1951 to 1970. There was a much stronger increase in GMST from the mid-1970s (e.g., 1974–1998) of 0.19°C/decade, possibly in association with a positive phase of the Pacific Decadal Oscillation (PDO) [*Trenberth*, 2015] or the Atlantic Multidecadal Oscillation (AMO) [*Tung and Zhou*, 2013]. These trends are based on NOAA data ERSSTv4 and GHCNv3 and are robust with other datasets, including satellite-derived ocean surface temperatures, as shown by IPCC [*Hartmann et al.*, 2013; *Huang et al.*, 2016]. Hence, studies on the hiatus cited here do not necessarily follow the IPCC definition, and although it makes it harder to compare results, many studies refer to a slowdown in rate of change of GMST in the early 21st century as the hiatus, as compared to the decades after the mid-1970s.

There are a number of differing views, uncertainties, and knowledge gaps regarding the hiatus, starting with the very name [*Lewandowsky et al.*, 2015a, 2015b; *Fyfe et al.*, 2016]. As a hiatus is a pause in a process, a global warming hiatus might imply a pause in the rate of increase of heat energy in the Earth's system, but the definition above really defines a slowdown in the rate of increase of GMST over a decade or more, not a hiatus of the rate of energy increase. Why the observed GMST was much less (by a factor of two) than many model projections needs to be understood.

GMST represents only a surface manifestation of the Earth's heat energy accumulation. Rather than a change in accumulation of heat in the Earth's system, the lower-than-predicted GMST rise can be traced to a redistribution of heat within the Earth's system [*Balmaseda et al.*, 2013; *Chen and Tung*, 2014; *Trenberth et al.*, 2014a, 2014b; *von Schuckmann et al.*, 2016]. The Earth's system includes not only the atmosphere but also the land (including ice cover) and ocean. Most of the excess heat in the Earth's system does not accumulate in the atmosphere. Heat energy is absorbed by the land surface as well as used in state changes in the Earth's water cycle (melting/forming ice, evaporation/precipitation), but it is the liquid ocean that absorbs the vast majority (>90%) of excess heat in the Earth's system. Not only does the ocean have a much higher heat capacity than the atmosphere, allowing it to hold more heat energy within the same volume, but the motion of the ocean, the constant horizontal and vertical advection and mixing, removes water from direct contact with the atmosphere, sequestering heat at depths far from surface interaction and direct influence on GMST. Arguably, the most appropriate single variable in the Earth's system that can be used to monitor global warming is ocean heat content (OHC), integrated from the surface to the bottom of the ocean [*von Schuckmann et al.*, 2016]. This is a difficult task, requiring instrumentation to be deployed to the most remote regions of the ocean, under ice, and to the deepest depths. Placing the present and future ocean

measurements in historical context requires investigation using a relatively short and incomplete historical record of in situ measurements [Abraham *et al.*, 2013] and/or the use of models, which introduce their own uncertainties [Meehl *et al.*, 2013]. Unfortunately, the OHC record is not nearly as long as for GMST. The recent “hiatus” period presents an excellent opportunity to understand the short- to long-term variability in the ocean/atmosphere climate system and how it resulted in a noticeable change in the rate of GMST increase. It also offers a chance to explore the uncertainties in measurements of our climate system and a chance to potentially fill the gaps in observing the system [Roemmich *et al.*, 2015].

2. Uncertainties

A recent paper [Karl *et al.*, 2015] describes corrections to ocean surface temperatures, also known as sea surface temperatures (SSTs). Corrections for systematic differences between colocated ship and drifting buoys measuring SSTs and systematic differences between merchant ship-measured SSTs and simultaneous ship-deck nighttime marine air temperatures were primarily responsible for revealing previously undetected warming in recent decades in IPCC and other work. It is also noteworthy that by using nighttime marine air temperatures to correct SSTs, the index of global surface mean temperature is not a direct measure of SSTs as these trends are modified by marine air temperatures. In addition, studies found that by including the polar regions in the global mean temperature trend estimation, the trend increases [Cowtan and Way, 2014; Karl *et al.*, 2015]. Karl *et al.* [2015] showed that global surface temperature, even with recent corrections, still underestimates the global mean temperature increase by more than 0.02°C/decade from 2000 to 2014 in their regularly updated global mean temperature data set. Nonetheless, the global mean temperature trend of 2000–2014 is still not as fast and steep as in the 1980s and 1990s. As different methods of trend estimation on only the land surface temperature (e.g., nonlinear estimation by Ji *et al.* [2014]) did not reveal a hiatus feature, the ocean plays the main role. Moreover, the continents occupy only 30% of the surface area. Accurate SST and GMST are important as they measure that part of the Earth's system with which we are in direct contact, and were used by IPCC and climate community to define climate change and “global surface warming hiatus” [IPCC, 2013]. If there are difficulties in estimating changes at the surface of the earth, it is not hard to fathom that there can be even more difficulties in estimating subsurface ocean changes. The Argo Program [Roemmich, 2009] of autonomous ocean profiling floats has revolutionized a process that previously required specially equipped ships to travel the global ocean, including the most remote and hostile environments. Since 2006, the Argo floats provide spatially and temporally consistent temperature and salinity data from the surface to nearly 2000 m over the ice-free ocean, excepting continental shelves/coastal regions and marginal seas. There has never been such a good view of the ocean's physical structure. However, as the 2000 m depth is little more than half of the ocean's mean depth, we do not yet have regular measurements for the lower half of the Earth's heat reservoir. Fortunately, the ocean deeper than 2000 m does not sequester nearly the amount of heat that is stored in the 0–2000 m layer, but it still makes a significant contribution to OHC change [Purkey and Johnson, 2010]. The capacity to regularly monitor the ocean below 2000 m is changing dramatically with the introduction of Deep Argo [Johnson *et al.*, 2015; Riser *et al.*, 2016]. This program has started introducing floats that can dive as deep as 6000 m, providing ocean profiles of temperature from the surface to the bottom (or near bottom), usually delivered within 48 h of measurement. Argo and Deep Argo will give us a more complete three-dimensional picture of the ocean's temperature structure and, hence, will allow us to track OHC changes over most of the ocean as long as these programs are fully supported.

Historical subsurface oceanographic data are sparse, and there are not sufficient data even near surface (20 m) before 1950 [Gouretski *et al.*, 2012]. Similar to SST data, certain instrumentation used to measure temperature has biases. The most notable is the depth and temperature biases in historical expendable bathythermograph (XBT) data. These instruments revolutionized subsurface ocean temperature measurements and dominated the observing system from 1967 until the advent of Argo because they could be released from a ship moving at normal speed. This allowed deployment from a network of merchant ships without an appreciable time cost. The XBT was and is still a very useful instrument, but it was not manufactured for climate change accuracy. The XBT community has worked very hard in recent years to quantify and correct biases in the instrument's depth calculation algorithm and in the temperature measurement/recording system to great success [Cheng *et al.*, 2016], although work still needs to be done in this area. Furthermore, the poor spatial and temporal coverage of early data necessitates techniques for

estimating temperature and OHC change in historically data-sparse ocean regions. While this does cause uncertainty in the estimation of OHC change, it does not obviate the use of global OHC integrals as a measure of global warming [Lyman *et al.*, 2010; Boyer *et al.*, 2016; Cheng *et al.*, 2016]. Note that, even though it has been shown that most observational decadal-scale upper-ocean (above 700 m) temperature trends since the 1990s are robust signals using different types of error analysis [Nieves *et al.*, 2015], the variable quality of the subsurface ocean measurements through the entire water column is a factor in the uncertainty of OHC estimation. While many projects, such as the World Ocean Circulation Experiment (WOCE) from 1990–1998, were geared to high-quality climate standard measurements, other applications, such as fisheries research or sound speed investigation, do not require such precise measurements and painstaking procedures and calibration. As all measurements are important in a data sparse-environment, this results in a polyglot data set of varying quality. The International Quality Controlled Oceanographic Database (IQuOD) project (<http://www.iquod.org/index.php/about>) aims to examine the data and metadata for all historical subsurface oceanographic temperature observations to determine the quality of the individual ocean profiles and assign quality flags and uncertainties based on instrumentation and procedures used on each observation project. This will help to standardize the historical database for climate studies and reduce, or at least identify, uncertainties in the observations.

Beyond their direct investigative value, observations are an indispensable check on climate models. One possible reason that the CMIP5 model ensemble did not show the hiatus is that “forced and internal variations might combine differently in observations and models” [Fyfe *et al.*, 2013]. As Fyfe *et al.* [2013] went on to note, the simulated ENSO cycle is not expected to match the observed cycle, but there are solutions to this problem. Meehl *et al.* [2014] noted that some members of the CMIP5 ensemble had individual runs that did exhibit the global warming hiatus in GMST. These runs had a phase of the Interdecadal Pacific Oscillation (IPO), which, by coincidence, matched the negative phase of the IPO in observations that occurred during the warming hiatus. If hindcasting methodology of initialized decadal climate prediction were used in the mid-1990s, the CMIP5 ensemble could have exhibited the global warming hiatus over the multimodel average [Meehl *et al.*, 2014].

Another tool for monitoring the ocean's energy uptake is satellite altimetry. Sea level rise as measured from altimeters represents, in part, the expansion of ocean volume due to increase in thermal energy, and coverage is near global since 1992. Changes in sea level are also due to the addition of freshwater from melting continental glaciers and other changes to water storage on land. Additionally, thermal expansion, although usually the dominant steric component of sea level, can be compensated in some regions by haline contraction [Antonov *et al.*, 2002]. The contributions of these different factors have been widely reported [Willis *et al.*, 2008; Levitus *et al.*, 2012; Llovel *et al.*, 2014; Rietbroek *et al.*, 2016]. However, there are significant differences in the inferred Earth's net energy imbalance across studies (subject to data, methodology, error estimates, and time periods) that range from 0.5 Wm^{-2} to 1 Wm^{-2} since the early 2000s [Trenberth *et al.*, 2016]. Some other challenges in monitoring the Earth's energy imbalance were described in von Schuckmann *et al.*, 2016.

3. Advances: What We Know About the Hiatus

The phenomenon of the “hiatus” has spurred much research into the repository for the heat that would have otherwise increased GMST more rapidly over the recent period. Most research has been looking at increased heat sequestration over regions of the ocean or to depths far removed from atmospheric forcing at the surface. The problem in detecting changes in the OHC that can account for a decrease in atmospheric heat uptake is that the rate of change in atmospheric temperature, although robust, when converted to units of heat energy is so small relative to the ocean change that it is lost in the noise. Figure 2 gives the heat content change in zeta joules (ZJ, 10^{21} joules) for the atmosphere and the ocean for 1980–2011 from the IPCC AR5 report [Rhein *et al.*, 2013]. Rates of change in 1980–2011 in the atmosphere are $0.06 \pm 0.1 \text{ ZJ yr}^{-1}$ compared to $6.98 \pm 1.5 \text{ ZJ yr}^{-1}$ in the ocean. However, it should be pointed out that the SST change does not simply reflect changes in atmospheric heat content. SST change reflects the change in the mixed layer of the ocean. The latter's heat capacity is not negligible. Furthermore, full-depth (or even surface to 700 m) OHC change and GMST are not well correlated for unforced natural variability [Palmer *et al.*, 2011; von Schuckmann *et al.*, 2016; Xie *et al.*, 2016]. Hence, ocean heat uptake must be inferred from changes in ocean state and ocean/atmosphere interaction due to other physically observed and/or theoretically postulated phenomena.

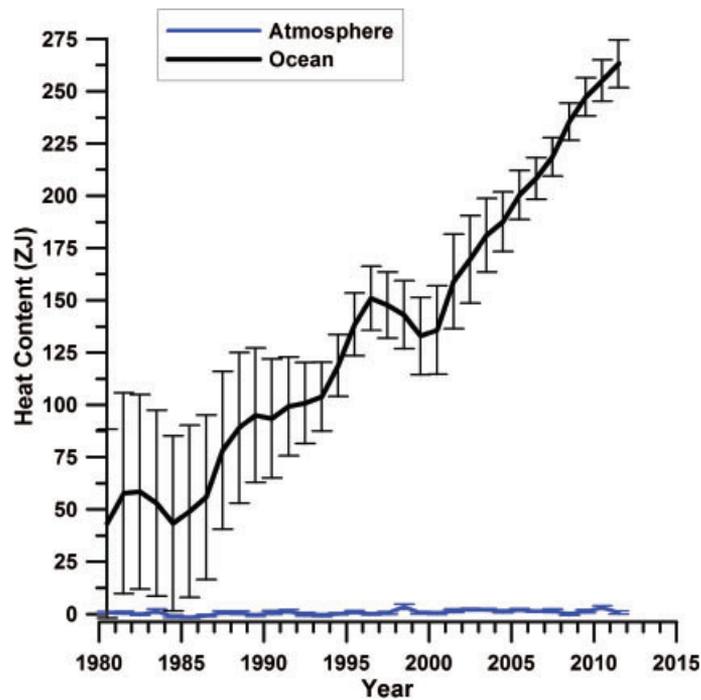


Figure 2. Yearly ocean and atmosphere heat content anomaly. Yearly ocean (black) and atmosphere (blue) heat content anomaly (data from IPCC AR5 report, [Rhein et al., 2013]). Ocean heat content combines upper and deep ocean heat content values for each year from that report. Microwave Sounding Unit (MSU) temperatures were used instead of GMST as GMST is a hybrid of 2-m land air temperatures and SSTs, while MSU temperatures cover the troposphere and stratosphere, giving an indication of change over a larger portion of the atmosphere.

GMST depending on the stage of the oscillation [Meehl et al., 2011, 2013; Trenberth and Fasullo, 2013; Chen and Tung, 2014; Trenberth, 2015] and with greatest effects in northern winter [Trenberth et al., 2014b]. Intermittent events, such as the eruptions of major volcanoes like El Chichón (began erupting in 1982) and Pinatubo (began erupting in 1991), can temporarily counteract long-term warming [Church et al., 2011; Santer et al., 2014]. Man-made signals, other than greenhouse gas accumulation, can have an effect on heat energy in the Earth's system; before the Clean Air Act of the 1970s, accumulated tropospheric and stratospheric aerosols likely slowed global warming by reflecting incoming solar radiation back to space [Trenberth, 2015]. There is uncertainty in the future extent and variability of aerosols, both man-made and natural, which will enter the atmosphere [Solomon et al., 2011].

So, which of the many possible short-term to decadal-scale climate system phenomena was responsible for the "hiatus?" With our current understanding of the Earth's climate system, especially regarding the ocean, and the relatively minute signal of atmospheric heating relative to the ocean, it is not easy to come to a definitive answer, especially in identifying the specific oceanic heat sink. Cooling in the central and eastern equatorial Pacific surface waters [Kosaka and Xie, 2013], indicative of increased wind-driven subduction and attendant heat sequestration [Trenberth and Fasullo, 2013; England et al., 2014], is one possible means by which heat has been removed from the atmosphere during the hiatus. Some recent studies show that the cooling shallow equatorial Pacific not only sequesters heat to upper ocean (100–300 m) depths in the Pacific [Nieves et al., 2015] but also shifts heat to the upper layer of the Indian Ocean [Lee et al., 2015; Nieves et al., 2015; Liu et al., 2016]. Going one step further, other studies posit that the concurrent effects of changing amplitudes of the PDO and the AMO are responsible for the hiatus [Steinman et al., 2015]. It has also been suggested that the main cause of the hiatus is movement of heat to deeper layers of the Atlantic and Southern Ocean due in part to the multidecadal variability of the AMOC [Chen and Tung, 2014]. Finally, a recent study shows a global water column pattern of cooling (0–100 m), warming (100–300 m), cooling

It is generally understood that on top of the long-term ocean-warming signal, there are shorter time period fluctuations, from seasonal to interannual to decadal. The El Niño/Southern Oscillation (ENSO) phenomenon, for instance, at interannual time scales, can transfer large quantities of heat energy from the atmosphere to the shallow central Pacific Ocean. This energy is released back to the atmosphere or shifted vertically and horizontally in the ocean during the transition from El Niño to mean conditions and to cooler La Niña conditions [Mayer et al., 2016]. The buildup to the 2009 El Niño transferred approximately 66 ZJ of heat energy to the upper 100 m of the Equatorial Pacific, with a similar heat loss between 100 and 300 m [Roemmich and Gilson, 2011]. Other variabilities, such as the PDO and Atlantic Meridional Overturning Circulation (AMOC), rearrange heat around the ocean and in the vertical on decadal time scales, damping or enhancing the

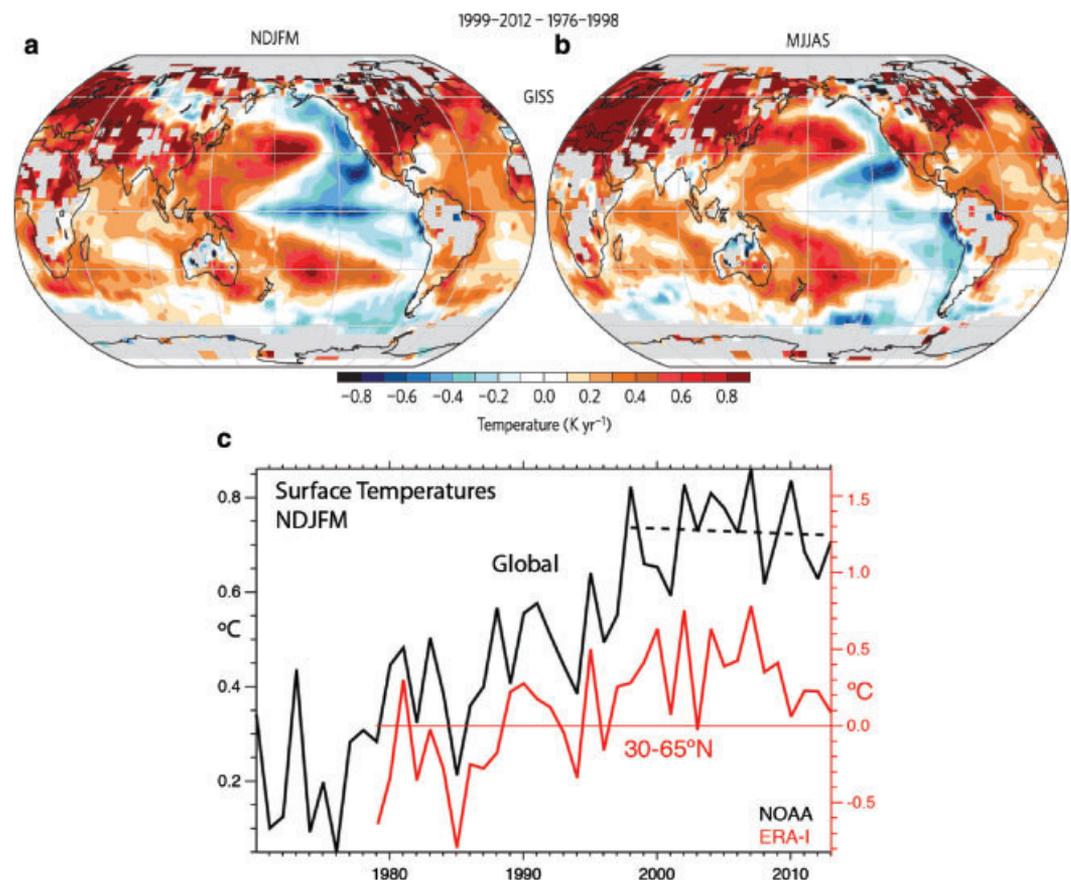


Figure 3. Regime differences between 1999–2012 and 1976–1998. Mean surface temperature differences between 1999–2012 and 1979–1998 for NDJFM (a) and MJJAS (b) for surface temperature from the Goddard Institute for Space Studies. For NDJFM, the global mean temperature for 1970–2013 and the linear trend for 1998–2013 (c) using NOAA data relative to the base period 1900–1999. Also shown in red are the temperature anomalies for 30–65°N relative to the mean for 1979–2013 from ERA-I data. In northern winter, when ENSO is the strongest, the slight cooling trend in the 2000s exacerbates the hiatus and the coldest values are in La Niña years; however, the coldest years for 30–65°N are years of negative NAO. Cited from *Trenberth et al.* [2014].

(300–700 m), and warming (700–1500 m), which the study hypothesizes is indicative of the mechanisms leading to the hiatus [*Cheng et al.*, 2015].

None of these findings is necessarily contradictory. Many go beyond the global aspects of GMST to emphasize the regional and seasonal patterns (such as with the PDO, AMO, ENSO) where regime-like behavior is more clearly evident. However, they show the difficulty and complexities in pinpointing the oceanic sink of the missing heat that defines the “hiatus” [*Trenberth et al.*, 2016]. They also point to the immense amounts of heat being advected vertically and horizontally in the ocean and our still limited ability to piece together a complete picture of ocean heat advection and uptake from our present observing system. In light of these findings above, we note that the surface temperature difference (Figure 3) clearly shows that the central and eastern Pacific failed to warm in the “hiatus” years, in a pattern associated with the PDO. To show the seasonality, two extended seasons—November–March (NDJFM), northern winter (Figure 3a), and May–September (MJJAS), northern summer (Figure 3b)—were examined [*Trenberth et al.*, 2014b]. The Pacific cooling is stronger in northern winter (Figures 3a and 3c), noting that Figure 3c uses a 1900–1999 baseline, different from IPCC. The surface temperature warming in the 21st century over the land centered around 45°N ± 15°N was net zero and, similarly, around Antarctica and was significantly less 0°S–30°S (Figure 4). Everywhere else, it was warmer generally. However, cold patterns occur also in a few areas, e.g., Southern Ocean, Siberia, Australia. In general, surface warming deviates considerably from the PDO pattern outside of the Pacific basin, perhaps signaling a substantial role for external forcing of the climate system and other factors such as internal variability beyond that associated with the PDO [*Trenberth and Fasullo*, 2013; *Trenberth et al.*, 2014b, 2016].

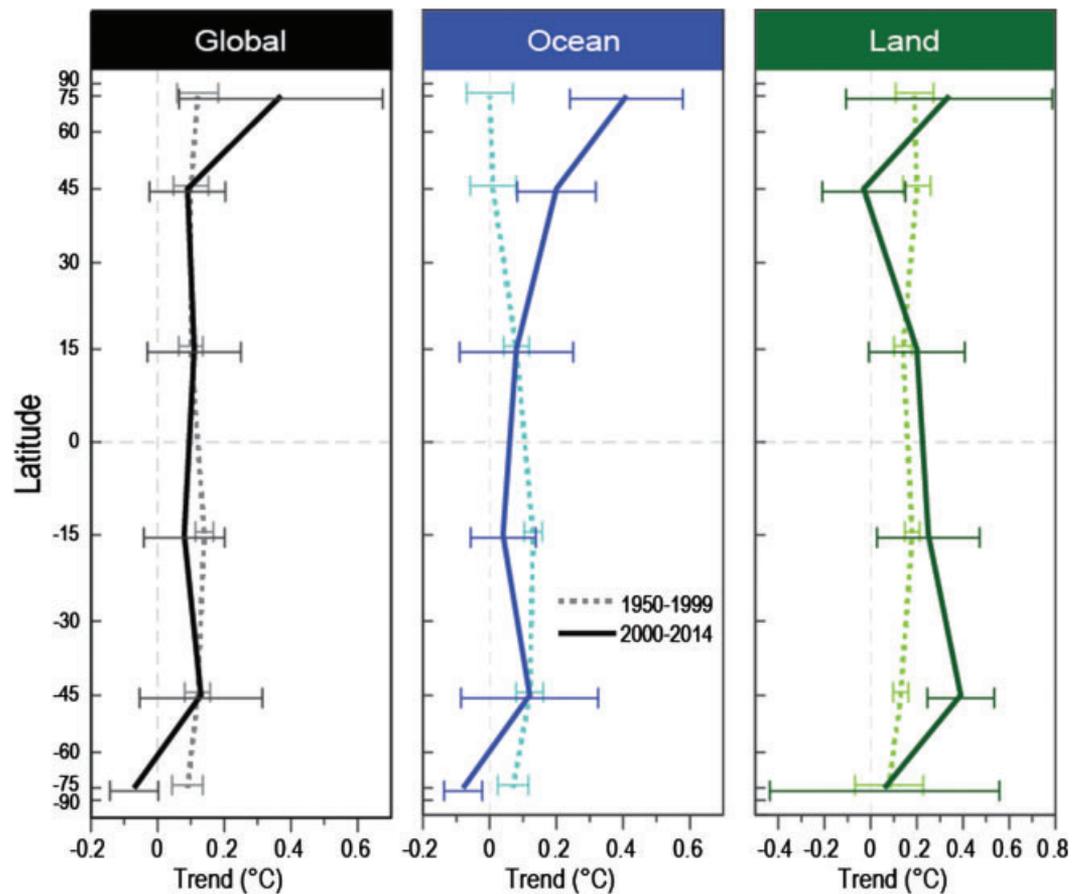


Figure 4. Latitudinal profiles of surface temperature trends. Zonal mean trends and statistical uncertainty of the trend estimates for global, ocean, and land surface temperature, averaged in 30° latitudinal belts, for the second half of the 20th century (dashed) compared to the past 15 years (solid). Trends are cosine-weighted within latitude belts, and the vertical axis is on a sine scale to reflect the proportional surface area of the latitude bands. Note that only the uncertainty related to the trend estimates is provided because zonal standard errors of estimates are not available in contrast to the global averages. Cited from *Karl et al.* [2015].

In spite of the aforementioned challenges in examining the hiatus, there is more confidence now that warming of the ocean as a whole has continued [Levitus et al., 2012; Nieves et al., 2015; Boyer et al., 2016; Cheng et al., 2016; Wijffels et al., 2016]. The physical drivers of such an increase in ocean heat content vary depending on regions, which limits full understanding of this global phenomenon. However, it is still important to understand the potential mechanisms driving decadal variability in all basins. First, there is a westward heat pathway connecting the Pacific and the Indian Ocean. A previous study has identified the subsurface warming in the Pacific due to more La Niña events and the formation of a La Niña-like cooling pattern at the surface of the tropical Pacific [Kosaka and Xie, 2013], although this cooling pattern is reversed by the strong 2016 El Niño [Wijffels et al., 2016] (Figure 1e). Some recent studies found that the accumulated subsurface heat anomaly in the Western tropical Pacific can propagate into the Indian Ocean by the Indonesian Through Flow on a decadal scale [Lee et al., 2015], where heat was mostly stored in the 100- to 300-m layer of the Indo-Pacific warm pool during the most recent hiatus [Nieves et al., 2015]. The Southern Hemisphere Ocean played a strong role in the warming of subsurface layers in the past decade, with 75–99% of global ocean heat gain occurring south of the Equator [Roemmich et al., 2015; Wijffels et al., 2016]. There are other studies suggesting a different pathway for the warming signal (also westward) from the Atlantic to the Pacific through teleconnection that directly links enhanced warming in the Atlantic region since the early 1990s with strengthening of the Walker circulation and La Niña-like Pacific anomalies [McGregor et al., 2014]. The precise mechanisms that control variability in the Atlantic Ocean are also still a topic of debate, but one possible explanation for increased heat storage in the Atlantic is a salinity-driven mechanism [Chen and Tung, 2014]. Further assessment of basinwide and regional distributions of heat, and of atmospheric

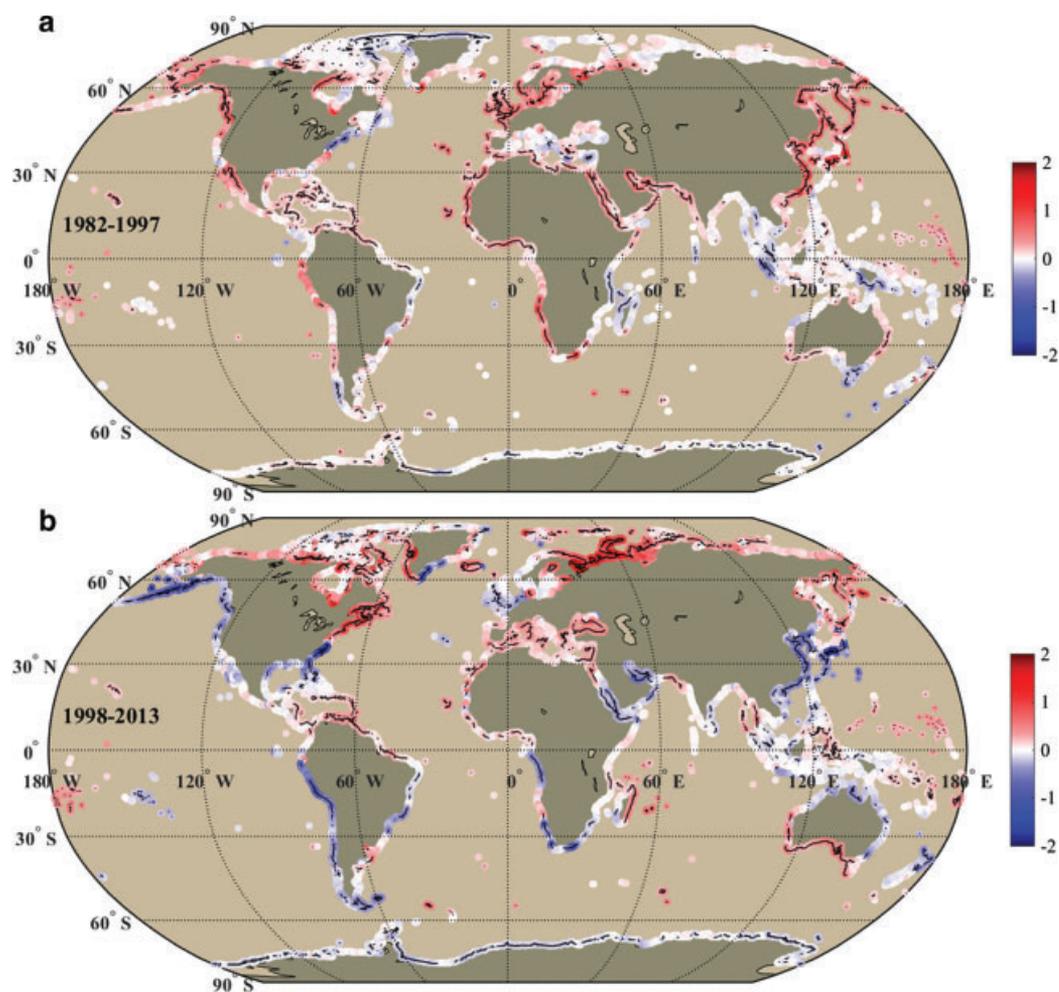


Figure 5. The linear SST trends along the world's coastlines in the warming and "hiatus" periods. The linear SST trends (unit: °C/decade) along the world's coastlines in the warming (1982–1997, a) and hiatus periods (1998–2013, b). Black points/lines in the shading color indicate that the trends in those locations are significant in statistics ($P < 0.05$). Cited from Liao *et al.* [2015].

versus ocean bridges, will be needed to predict future decadal variability. Besides explaining the periodical upper-ocean heat migration that mainly regulates the global temperatures, it will be critical to know how much of the trapped heat will be absorbed into the deeper layers of the ocean in the coming decades.

4. Outlook and Recommendations

To truly understand the flow of heat into and through the ocean, the oceanography/climate community must first maintain and increase support for Argo, the main system monitoring OHC [von Schuckmann *et al.*, 2016]. We must also ensure the continued development of Deep Argo in order to monitor the lower half of the ocean [Roemmich *et al.*, 2015], but even this is not sufficient. Argo's basic mission is to monitor the global ocean, subject to technical limitations of profiling floats. Earlier problems in observing the seasonal ice zones and marginal seas have been overcome, and coverage is expanding in those regions. Continental shelves and permanent ice zones remain problematic for Argo floats. It is imperative to support and enhance ship-based subsurface ocean temperature monitoring through programs such as the Ship of Opportunity Program and GO-SHIP [Hood *et al.*, 2009]. The increased and more concerted use of gliders [Rudnick *et al.*, 2004; Rudnick, 2016] to monitor marginal seas and shelf and coastal regions is imperative for improved coverage in these areas. Although these areas are only a fraction of the ocean volume, their changing rate of ocean heat content is much faster than the global ocean (e.g., for East/Japan Sea, the changing rate of ocean heat content is four times faster than that of the global ocean mean), and their contribution to overall

ocean heat content is not trivial when compared with atmospheric heat content [Trenberth *et al.*, 2014a; Liao *et al.*, 2015; Yoon *et al.*, 2016].

In addition, there is considerable scope to further improve the past record [Boyer *et al.*, 2016; Cheng *et al.*, 2016] both in terms of improved quality information about observations as well as much improved mapping and gap filling—in both space and time—techniques.

Efforts to improve climate models need to be implemented to enhance hindcast and predictive skill in order to ensure prediction and mechanisms of future warming “hiatus.” The ability of models to learn from observations and exhibit indicators of slowdown in GMST is present [Meehl *et al.*, 2014] and can be applied to the existing climate models.

For several decades, satellite sensors have been providing sea surface observations at various spatial and temporal scales. Satellite remote sensors cannot see far beneath the surface layers of the ocean. However, currently, new algorithms are being developed to estimate ocean interior thermal and thermohaline structures and subsurface flow fields using multisatellite sensors and in situ measurements to improve the spatial and temporal coverage of these physical properties [Yan *et al.*, 2006; Wu *et al.*, 2012; Klemas and Yan, 2014; Su *et al.*, 2015]. Further improvements are needed in the accuracy of large-scale subsurface thermal structures in near-real time for the heat content estimations of deeper layers. Finally, innovative Arctic monitoring programs, such as the Ice Tethered Profilers [Toole *et al.*, 2011], are necessary to contribute measurements from ice-covered regions.

While many studies have focused on the mechanisms that caused the purported hiatus, few have paid attention to the coastal response to the hiatus. It was found by a recent study [Liao *et al.*, 2015] that there have been large-scale changes in the rates of coastal SST change. The cooling and warming rates in some coastal areas (e.g., China coast, U.S. eastern coast) are three times larger than in the open ocean (Figure 5). A significant cooling trend occurred in the low and mid-latitudes (31.4% of the global coastlines) after 1998, while 17.9% of the global coastlines changed from a cooling trend to a warming trend concurrently (Figure 5). Is it significant to the energy budget for the hiatus? Is that a signature of hiatus or just a coincidence? This area of study is needed not only to answer the above questions but also because approximately 50% of the world's population live within 200 km of coastal waters, with many more relying on the world's coasts for commerce and natural resources [Trenberth *et al.*, 2014a; Liao *et al.*, 2015]. Once we have a full monitoring system for OHC, we can begin to answer with more precision questions of atmospheric changes in heat content related to OHC variations. Moreover, to understand the redistribution of OHC by the ocean circulation requires observations of ocean boundary current transports and interbasin exchanges, and these key elements of the circulation are not yet systematically measured in the Global Ocean Observing System. Hopefully, before the next decadal fluctuation in the rate of GMST or so-called “hiatus,” we will be able to discern the oceanic sink with more certainty and thus be able to inform our climate models and our understanding of future climate change.

The community would be well served to more vigorously assess observing uncertainties, help to prioritize observing system gaps in the oceans, and analyze rates of change in context with multiple data sets that represent different components of the climate system. Also, an important part of the difficulty in understanding the recent “hiatus” is in poor definitions, incomplete assessments, and confusion about what might have been expected to occur in the climate system using appropriate modeling experiments. In the future, comprehensive problem-focused assessments, e.g., perhaps like the Synthesis and Assessment Reports of the USGCRP or National Academy Reports, would do well to focus on the abovementioned aspects of climate change.

Finally, the term “global warming hiatus” is a misnomer, although we will continue to use the widely used phrase to describe the slowdown or pause in the increase of GMST in the late 20th to early 21st century, with quotation marks. Alternatively, we would like to suggest to the climate community to use “global surface warming slowdown” instead in the future to avoid confusion. There is no absolute consensus on the specific oceanic sink for the excess heat that led to the slowdown in rising GMST (the Southern Ocean may be worth further attention though), but there is a general agreement in this group and in the literature that rather than a “global warming hiatus,” the slowdown of GMST increase in 1998–2013 was a result of the increased uptake of heat energy by the global ocean during those years.

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