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Observational Advances in Estimates of Oceanic Heating

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Abstract Since the early twenty-first century, improvements in understanding climate variability resulted from the growth of the ocean observing system. The potential for a closure of the Earth's energy budget has emerged with the unprecedented coverage of Argo profiling floats, which now provide a decade (2006–2015) of invaluable information on ocean heat content changes above 2000 m. The expertise gained from Argo and repeat hydrography sections motivated the extension of the array toward the ocean bottom, which will progressively reveal the poorly known deep ocean and reduce the uncertainty of its presumed 10–15 % contribution to the 2006–2015 global ocean warming trend of 0.65–0.80 W m^{-2}. The sustainability and synergy of various observing systems helped to corroborate numerical models and decipher the internal variability of distinct ocean basins. Due to unique observations of the circulation in the North Atlantic, particular attention is paid to heat content changes and their relationship to dynamic variability in that region.

Keywords Oceanic heating · Argo · Repeat hydrography · GO-SHIP · North Atlantic

Introduction

Observational data show an unequivocal warming of the Earth's climate system since the mid-twentieth century [57]. Every past decade has been warmer than its predecessor, and the year 2015 now stands as the warmest ever recorded [67]. This positive temperature trend at the Earth's surface is driven by a radiative imbalance at the top of the atmosphere (e.g. [2]), which is widely attributed to human activities and the increased concentration of greenhouse gases in the troposphere (e.g. [70]). The global surface signal is, however, being constantly modulated by natural fluctuations of the climate system acting over a wide range of spatial and temporal scales (e.g. volcanic eruptions, solar cycles, oceanic circulation). For instance, those natural changes can significantly reduce the increase in global mean surface temperature over periods of decades (e.g. [45]), and mislead the wider community regarding the fate of global warming [68].

The observational record, however, is becoming complete enough to ascertain the on going rise of the Earth's energy content. Amongst the heat reservoirs, the global ocean plays a critical role in capturing heat from the atmosphere and slowly redistributing it around the globe. More than 90 % of the anthropogenic heat entered the ocean during 2006–2015 at a rate of 0.65–0.80 W m^{-2} [57, 72]. For a few decades, global and regional ocean variability have been increasingly revealed by the synergy of several observing systems maintained and coordinated by strong international collaborations. The repeat of full-depth hydrography sections [66], the remote detection of sea-level changes [10], the systematic sampling of the upper ocean by profiling floats [59] and the maintenance of trans-basin moored arrays [43] became the heart of our current understanding of the ocean's role in climate change. They have, for instance, validated numerical models that provided complete explanations of the recent surface warming slowdown at global scale (e.g. [19, 74]), and also explained regional patterns of heat content changes (e.g. [7]). Important observational

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gaps, however, remain, with the Achilles' heel of climate studies residing in the under-sampled deep ocean and its uncertain contribution of 10–15 % to recent changes in the global heat and sea-level balances [51]. The systematic observation of the deep and abyssal layers at sufficient resolution is needed to average out vertical rearrangements of the heat field and hence capture the anthropogenic warming more effectively. The emergence of a Deep Argo array [30] represents a significant step forward in that direction.

Abraham et al. [1] provided a comprehensive review of the observing systems used to assess temperature and oceanic heat content (OHC) changes in the ocean, and detailed the major OHC indices and their uncertainties from five decades of in situ measurements (1960–2011). Here, we (1) review recent findings on the twenty-first century OHC variability revealed by the growing observational record, (2) report innovative approaches for elucidating regional mechanisms of OHC variability from in situ measurements (North Atlantic focus) and (3) inform on the upcoming opportunities for closing the global energy budget.

The Unabated Heating of the Upper Ocean

The Global Picture Drawn by the Argo Array

The first deployments for the Argo array of autonomous profiling floats were made in 2000. The array reached its target fleet size in 2007 with 3000 floats sampling the top 2 km of the water column on a nominal 10-day cycle [59]. Today, in 2016, the Argo database provides more than a million profiles of temperature (and salinity) with nominal accuracy of 0.002 °C for temperature and 2.4 dbar for pressure [1]. More than 80 % of the profiles in the current (to 2016) Argo database were obtained after 2006, and the earlier description of the 0–2000 m OHC was consequently found to depend strongly on the choice of climatological references in data-sparse regions [9, 20, 39]. Undersampled areas, particularly located in the southern Hemisphere, may have significantly biased low the estimates of global OHC trends between 1970 and 2004 [16]. The uncertain nature of the multi-decadal record was further highlighted by the difficulty of correcting significant biases in expendable bathythermograph measurements, which represented the main source of upper-ocean temperature profiles before the launch of Argo [23, 40]. Overall, the OHC curves prior to the mid 2000s have large error-bars, and the year-to-year variations typically show limited agreement with the net TOA fluxes estimated from satellite products [38, 64]. It is therefore for about a decade (since the Argo fleet neared completion) that the observing system has been adequate for the global analysis of upper OHC changes, although a persistent spread between the various 0–2000 m OHC estimates still hampers a robust closure of the current Earth energy budget [71].

Through comparison of three Argo analyses, the global OHC trend above 2000 m during the period 2006–2015 was estimated as 0.50–0.65 W m^{-2} over the effectively sampled ocean (Fig. 1—from [72]). As expected, the global warming rate shows its strongest magnitude in the first few hundred meters of the water column and the interannual variability above 500 m shows pronounced changes that control the global temperature variations at the air-sea interface [60]. Those upper OHC changes reflects in large part the El-Niño/Southern Oscillation (ENSO) and its influence on the horizontal tilt of the equatorial thermocline in the Pacific. In addition to this interannual signal, the shift from a positive to a negative phase of the Pacific Decadal Oscillation in the early 2000s significantly cooled the Eastern Pacific, which reduced the positive trend in global mean surface temperature while increasing subsurface heat uptake (e.g. [17, 28, 45]). It is now widely accepted that the global mean surface temperature is a poor indicator of the global heat gain (e.g. [50]).

The most recent OHC trend (2006–2015) was marked by a clear hemispheric asymmetry, with the southern hemisphere heating much faster than northern latitudes [60]. A full understanding for such a striking warming of the Southern Hemisphere extra-tropics across the three oceans is, however, still missing. The inhomogeneous radiative forcing by ozone and aerosols may have played a role [61], so did internal ocean variability. In fact, the horizontal distribution of the OHC trend in the upper layer emphasizes substantial redistribution of heat driven by the intrinsic dynamics of each ocean basin. Amongst them, a strong OHC rise in the Indian Ocean stood out, with a temperature trend between 2006 and 2015 accounting for 50–70 % of the global OHC trend above 700 m [49]. Such a rise in the Indian Ocean's OHC presumably originated in the western Pacific following a dynamical response to a shift toward a negative phase of the Interdecadal Pacific Oscillation, and a subsequent intensification of the heat transport through the Indonesian Archipelago [35].

Moving down through the water column, the contribution of the intermediate layer (700–2000 m) to the global OHC change above 2000 m was about 50 % of the full water column during 2006–2015 (Fig. 2), that is 20 % higher than the long-term (1955–2010) estimation of [36]. This recent and ongoing increase in the sequestration of heat below the upper layer has been supported by model-based analysis [22] and linked to a combination of multiple underlying mechanisms driven by the local modes of atmospheric variability [69]. In particular, the significant warming of the North Atlantic and Southern Ocean in the depth range of Labrador Sea Water and Antarctic Intermediate Water [8] reinforced the idea of a strong link between convective

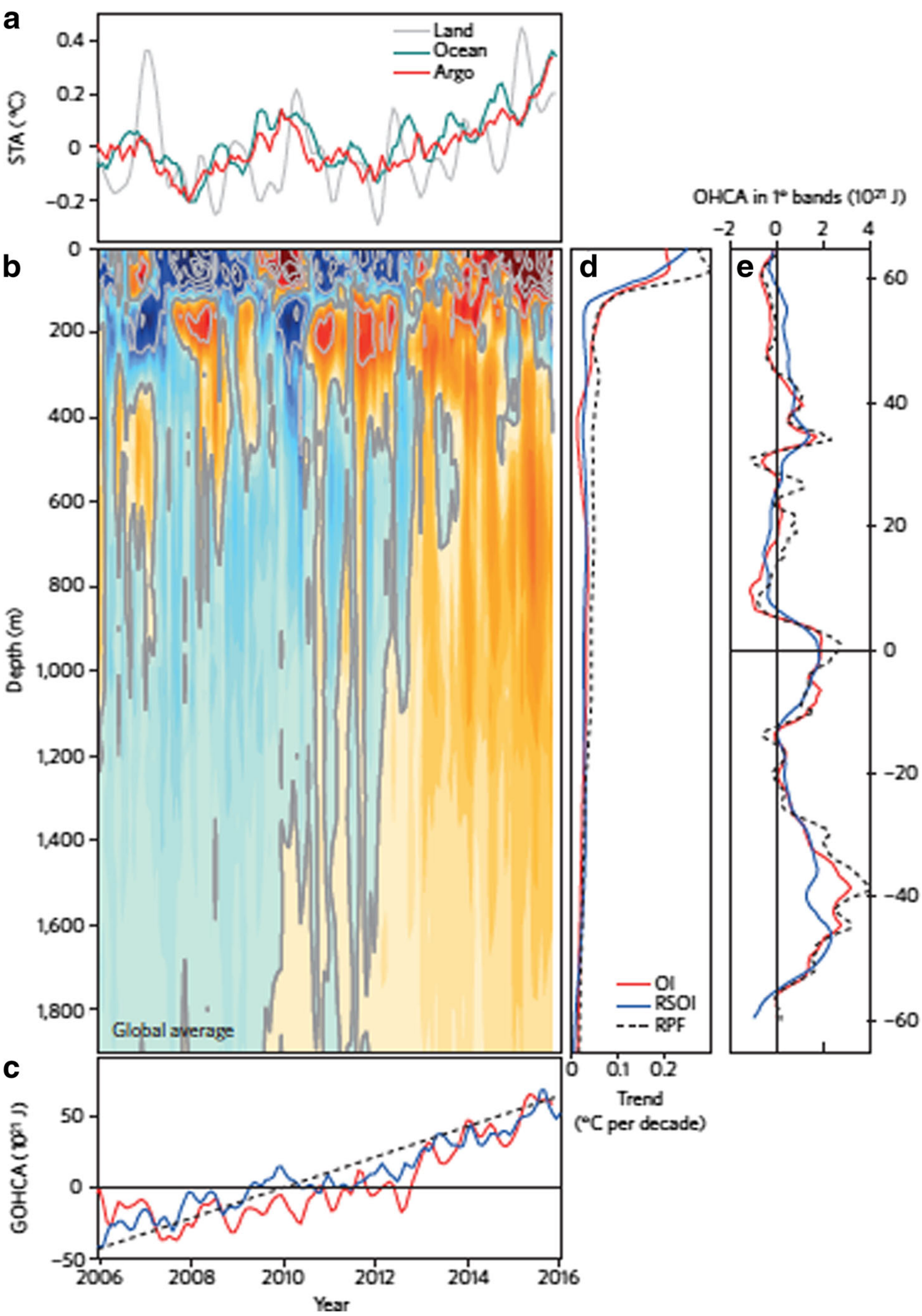

Fig. 1 Ocean warming rates and distributions. **a** Globally averaged surface temperature anomaly (STA, °C), from 5 m Argo OI temperature (*red*), NOAA (National Oceanic and Atmospheric Administration) global ocean (turquoise) and a 6-month running mean of NOAA global land averages (*grey*). **b** Global average ocean temperature anomalies from the Argo OI (contour interval is 0.01 for colours, 0.05 °C in *grey*). **c** Global ocean 0–2000 m heat content anomaly as a function of time, with the OI version a 4-month running mean. **d** Global average 2006-November 2015 potential temperature trend (°C per decade). **e** Zonally integrated heat content trends in 1° latitude bands from the three mapping methods. For line plots **c**, **d** and **e**, the sources are OI (*red*), RSOI (*blue*) and RPF (*black-dashed*). From Wijfells et al. (2016), Nature Climate Change

processes, meridional overturning cells (MOC) and intermediate/deep heat storage (e.g. [15, 31, 45, 56, 58, 73]). This link has received increased attention from the observational community in recent years, through the development of sustained observing systems and innovative methodologies.

Observational Insights into the Regional Dynamics: an Atlantic 'Lead'

Direct and sustained observations of the ocean circulation are difficult tasks, and there exist very few observational records capable of linking ocean dynamics and decadal variability of the climate system. Ocean reanalysis (ORA) that assimilate in situ and satellite data in a dynamical and statistical way can be used to provide such a link with satisfactory degrees of consistency (e.g. [4]). Yet, the multitude of assimilation-based analysis has to be interpreted in the light of poor observational constrains below the upper layer and large spreads between models due to the different dynamic schemes employed [52]. These sources of uncertainties and model biases are being tackled within the ocean reanalysis inter-comparison project [5], but their understanding will

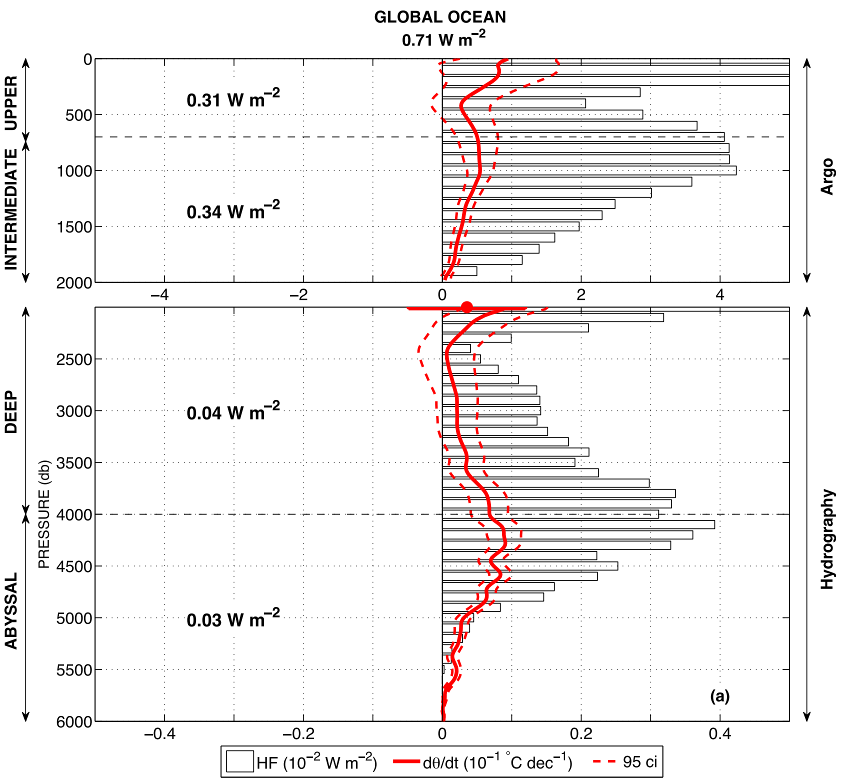

Fig. 2 The surface-to-bottom profile of global temperature trend (*solid red line*) computed from Argo and repeat hydrography data. The associated 95 % confidence intervals are shown in *dashed red lines*. The *bars* indicate the contribution of 100-m-thick layers to the global heat uptake (relative to global surface area). Numerical values indicate the heat content trend within the upper (0–700 m), intermediate (700–2000 m), deep (2000–4000 m) and abyssal (4000–6000 m) layers. Note the different x-axis scales used for Argo and hydrography-related profiles. The *dot* indicates the Argo-derived trend values and uncertainties at 2000-m depth

also rely on valuable observations that infer the dynamics of OHC changes.

Due to its major role in the meridional and vertical rearrangement of heat, the Atlantic became in the last decade a targeted field for innovative observational experiments. The establishment in 2004 of the RAPID-MOCHA observing system to measure the MOC at 26° N has led to unprecedented views on the internal dynamics of a critical ocean basin in the climate system [65]. In addition to detecting a MOC weakening over a decade of magnitude exceeding the strength predicted by climate models [63], the RAPID time-series proved the close relationship between short-term changes in oceanic heat transport (30 % AMOC reduction in 2009/10) and rapid OHC events in the North Atlantic sector ($\sim$1.3 $\times$ 10^{22} J lost between 25° N and 45° N) [7]. Promising use of altimetry data for retracing past MOC changes at 26° N have been proposed [18], while alternative methodologies based on coastal sea-level changes along the US east coast demonstrated the hypothesized multi-decadal correlation between circulation changes and upper OHC in the mid-latitude North Atlantic [44]. The dominant role of heat transport convergence in driving long-term OHC changes in the North Atlantic was also deduced through comprehensive analyses of ORA models [26, 73]. These multi-decadal OHC changes exert a strong influence on surface temperature patterns such as the Atlantic Multi-decadal Oscillation [11], which subsequently drive turbulent heat fluxes at the air-sea interface and associated atmospheric responses [24].

At higher latitudes, an exceptionally long hydrography time series (1975-present) of full-depth temperature and salinity in the northeastern Atlantic also showed significant interannual and decadal OHC fluctuations likely to be driven by circulation changes [27]. The observed upper cooling of the eastern subpolar gyre during the most recent years (2006–2014) derived from repeat hydrography appeared in line with Argo-derived trends [13], and suggested an on going eastward expansion of cold subpolar waters and a southward retreat of warm subtropical waters (e.g. [12, 25]). A similar hydrography time series in the western subpolar gyre has recently revealed the return of intense deep convection in the winter of 2013/14, generating a new vintage of Labrador Sea Water (LSW) currently spreading within the subpolar gyre [33] and affecting the heat content of the intermediate and deep layers (e.g. [42]). The intensity of deep convection in the Greenland and Icelandic seas conversely shows a multi-decadal decline, with potential implication for the properties of the densest water masses filling the Atlantic bottom layer [48].

During the summer of 2014, the North Atlantic's observing system made another step change with the deployment of a mooring array in the Labrador Sea, Irminger Sea and Iceland basin ('Overturning in the Subpolar North Atlantic Program'—OSNAP—http://www.o-snap.org). The OSNAP array will reveal the mechanisms governing changes in the subpolar overturning circulation, and complement existing local indices based on Argo, altimetry and repeat hydrography (e.g. [47]). The combination of findings from RAPID and OSNAP, along with the continuing efforts to continuously monitor the meridional circulation at southern latitudes [3, 6, 46], will soon provide new insights into ocean dynamics connectivity and the associated evolution of the Atlantic OHC.

Tackling Uncertainties: a Deep Ocean Perspective

Our understanding of OHC changes in the deep and abyssal ocean comes from the synoptic shipboard occupations of repeat hydrographic sections [66]. While these sections represent the most accurate component of the observing system (accuracy of 0.002 °C), they have limited temporal resolution and spatial coverage. Following the first mapping of water masses over the globe by the World Ocean Climate Experiment (WOCE) [21], the follow-up surveys coordinated by the "Climate Variability (CLIVAR)" and the "Global Ocean Ship-based Hydrographic Investigations (GO-SHIP)" programs have yielded quantifications of the global and regional deep and abyssal changes in OHC. Purkey and Johnson [54] estimated a 0.07 ± 0.06 W m^{-2} heat flux across the 2000 m isobar during 1993–2006 from hydrography sections occupied in 1990s and 2000s. The abyssal warming below the 4000 m isobar was estimated as 0.027 ± 0.009 W m^{-2}, with the strongest trends observed in the Southern Ocean and in deep western boundary currents along the northward routes of Antarctic Bottom Water (AABW) [34, 62]. Both slow advective processes and comparatively fast wave-like dynamics can lead to deep and abyssal OHC trends (e.g. [41]). Multiple factors have accordingly been proposed to explain the decadal warming of AABW, including freshening of the Ross Sea Shelf Water and the associated downward heave of isopycnal surfaces, as well as wind-driven variability of the Weddell gyre [32, 53, 55]. Updating the hydrography dataset with section repeats up to 2015 has enabled a calculation and comparison of deep and abyssal warming rates during the 1990s and 2000s decades. The comparison of these decadal changes revealed no statistically significant difference in the magnitude and structure of the global decadal warming rate at deep and abyssal levels [14]. However, there are differences in the regional trends, specifically trend reversals in the deep Atlantic and deep Pacific consistent with the simulated redistribution of heat during hiatus periods [45]. Estimations of deep temperature trends from repeat hydrography during 2003–2012 have been further combined with the Argo-based analysis of the 0–2000 m layer to yield a blended estimate of the full-depth ocean heat uptake (0.71 ± 0.12 W m^{-2}, 10 % found below 2000 m) and a new representation of its vertical structure from the last decade of sustained observations (Fig. 2).

The reported uncertainties of hydrography-derived temperature trends below 2000 m remain large. There are still significant gaps in the sampling coverage that introduce an unknown bias in the above estimates (see for instance the mismatch between the Argo-derived trend and the hydrography-derived trend at 2000 m in Fig. 2), and alternative methodologies based on sea-level and Argo measurements raised further concerns about the significance of the reported trend in deep ocean and its contribution to the global planetary energy budget [37]. An emerging technology that will bring us closer to the closure of the global heat budget is Deep-Argo: a new observing system of profiling floats that will operate deeper than 2000 m [29]. The array design has been informed by analysis of core-Argo and repeat hydrographic sections [30]. Specifically, estimations of temporal and spatial decorrelation scales using full-depth CTD profiles and Argo-derived time series showed that an array deployed at 5 latitude × 5 longitude × 15-day cycle (about 1200 floats) would provide decadal trends of local temperature and global OHC below 2000 m with unprecedented accuracy (1 to 26 m °C decade^{-1} and 3 TW, respectively). The program is at an early stage, priority is now to monitor the mechanical behaviour of deployed floats and to assess sensor behaviours and drift to validate the first temperature and salinity profiles.

Conclusion

The precise quantification and understanding of global and regional climate change is strongly dependent on how well the oceans are observed. The systematic sampling of the upper water column by Argo profiling floats marked a transition for the historical oceanographic record, until then hampered by under-sampled areas and instrumental biases that made any quantification of global OHC changes challenging. The Argo array has now captured a decade of temperature changes, including the warming trend driven by anthropogenic forcing. This upward ocean temperature trend is being constantly deformed by internal and external fluctuations of the climate system acting over a wide range of spatial and temporal scales. The most recent variability in global and regional OHC within the upper water column has been particularly assessed in the context of a significant slow-down of surface temperature rise, and focuses were consequently made on vertical rearrangements of the oceanic heat field. These global rearrangements, which appear to be dominated by variability in the top 500 m of the Pacific related to El-Nino type regime shifts, have been primarily understood from the analysis of numerical model output. However, innovative observational experiments have effectively elucidated some essential mechanisms of regional OHC variability. Amongst the major ocean basins, the extensive observation of the North Atlantic by a sustained moored array in the subtropics and hydrography records of unprecedented length at higher latitudes was used to decipher some links between ocean dynamics (MOC and horizontal gyres) and interannual to decadal OHC signals.

The repeat of hydrographic sections has demonstrated the likelihood of a concomitant warming of the water column below 2000 m, representing about 10–15 % of the whole oceanic heat uptake, and showing no sign of significant intensification during the hiatus era. The uncertain nature of this deep warming trend has highlighted the need for a sustained and systematic deep observing system that will complement the crucial repeat of shipboard measurements. The community response is the nascent Deep-Argo array, which promises to yield, in about a couple of decades, unprecedented insights into the dynamics of the abyssal circulation while providing measurements of the "missing heat" for closing the Earth energy and sea level budgets.

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Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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