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Fifteen years of ocean observations with the global Argo array

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More than 90% of the heat energy accumulation in the climate system between 1971 and the present has been in the ocean. Thus, the ocean plays a crucial role in determining the climate of the planet. Observing the oceans is problematic even under the most favourable of conditions. Historically, shipboard ocean sampling has left vast expanses, particularly in the Southern Ocean, unobserved for long periods of time. Within the past 15 years, with the advent of the global Argo array of profiling floats, it has become possible to sample the upper 2,000 m of the ocean globally and uniformly in space and time. The primary goal of Argo is to create a systematic global network of profiling floats that can be integrated with other elements of the Global Ocean Observing System. The network provides freely available temperature and salinity data from the upper 2,000 m of the ocean with global coverage. The data are available within 24 hours of collection for use in a broad range of applications that focus on examining climate-relevant variability on seasonal to decadal timescales, multidecadal climate change, improved initialization of coupled ocean–atmosphere climate models and constraining ocean analysis and forecasting systems.

In the late 1990s it was recognized that little progress would be made in monitoring the changing climate of the Earth without systematic global observations. A small group of oceanographers proposed that readily available technology could be adapted and, with sufficient international cooperation, be used to create a global array of floats that could supply real-time global views of the ocean. Thus the Argo programme was born. This Review considers the progress made in the first 15 years of Argo and attempts to provide an outline of how the programme is likely to change over the next decade.

History and present status

The Argo programme[1] is a major component of the Global Ocean Observing System[2] and strives to monitor the evolving temperature and salinity fields of the upper ocean The profiling floats used in Argo are 2 m-long, freely drifting robotic devices that adjust their depth in the ocean by changing their buoyancy. In the context of Argo, the majority of these instruments are programmed to drift at a nominal depth of 1,000 m (known as the parking depth). A typical duty cycle of an Argo float is shown in Fig. 1. Floats are launched at the sea surface and dive to the parking depth. After a ~9-day interval at the parking depth, the floats descend to 2,000 m, then rise over a period of roughly 6 hours to the sea surface, sampling ocean properties such as temperature and salinity during their ascent. At the surface the data are transmitted to land stations via satellite; the floats then descend back to the parking depth to begin another cycle. A typical float will repeat this 10-day cycle in excess of 200 times over the course of five years or more. Over 10,000 floats have been deployed by the nations participating in the programme since the beginning of Argo, with almost 3,900 floats now operating over the world ocean. A defining aspect of Argo is that all data are reported in near real-time to meteorological forecasting centres and to the two Argo Global Data Assembly Centers (GDACs, localized in the USA and France), from which the accumulated data are made freely available without limitation.

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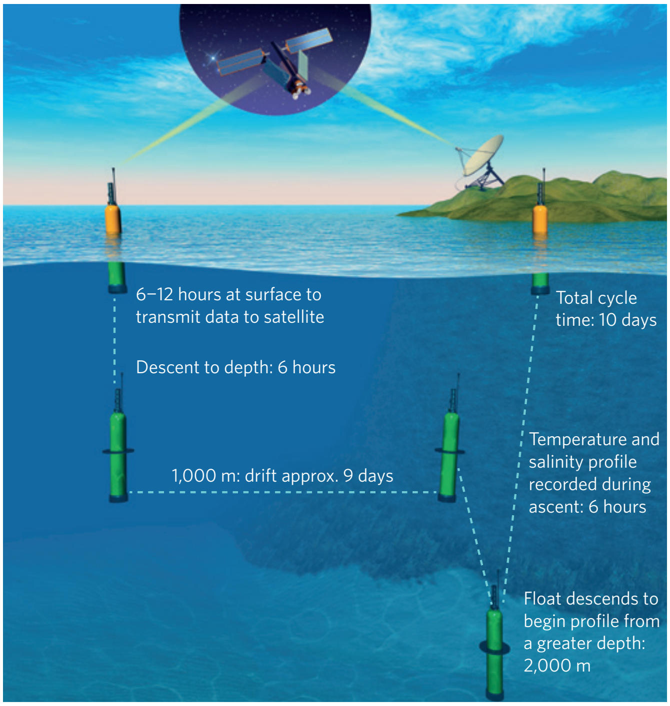

Figure 1 | The typical cycle of an Argo float. The float starts at the surface and dives to a depth of 1,000 m (the parking depth) where it rests for 9 to 10 days. After 9 days at rest it dives to a depth of 2,000 m, turns on its sampling equipment and measures ocean properties as it rises to the surface, where it rests for sufficient time to transmit the data collected to Argo or Iridium satellite systems. It then returns to the parking depth to start another cycle. The typical duration of a complete cycle is 10 days. Figure courtesy of Megan Scanderbeg, Scripps Institution of Oceanography, UC San Diego.

Argo float deployments began in 1999. The original programme plan called for an array with global coverage of about 3,000 floats by the year 2007, a goal that was achieved in November of that year. The resulting improvement in sampling of the ocean achieved by Argo compared with the previous century of measurements is dramatic (Fig. 2). Historically, oceanographic sampling has had a bias towards areas that are more easily sampled, so the Northern Hemisphere and coastal regions are over-represented. Although Argo floats cannot sample in shallow coastal waters, the programme has helped to eliminate these spatial biases. Argo has also eliminated a major seasonal bias in sampling, particularly in the polar oceans; Argo delivers more winter profiles in the Southern Ocean in one year than the total of all winter data collected during the 100 years before Argo, and the majority of the temperature and salinity observations from the Southern Ocean (defined here as the ocean south of 30° S) in the global database now originate from Argo.

In Chapter 3 of its Fifth Assessment Report (hereafter AR5)[3], IPCC Working Group I included an Appendix on the availability of observations for assessment of change in the oceans, which showed the distribution of temperature and salinity profile data from the 1950–1955 to the 2005–2010 pentads; these results indicate the general lack of observations before 2000, as well the Northern Hemisphere bias within the pre-Argo observing system. Although not shown in AR5, there is also a known seasonal bias, with the local winter season being generally under-represented in the pre-Argo observing system. It is apparent from this report that the recent expansion of the ocean observing system clearly sets AR5 apart from its predecessor[4], with most of this change ascribed to the existence of the Argo array. Some issues remain that are being addressed. As Argo floats must reach the sea surface to transmit their data, Argo could not originally target ice-covered parts of the oceans; now floats are successfully operating in the Antarctic seasonal ice zone[5,6]. Within the temperate oceans coverage is not homogeneous, but there are efforts to increase coverage in under-sampled regions such as near western boundary currents.

While the volume of Argo data easily overwhelms traditional sources, the quantity is of value only if the quality of the data is high. The original Argo target called for temperature and salinity accuracies of 0.005 °C and 0.01 salinity units, with a pressure accuracy of 2.5 dbars (equivalent to a depth error of about 2.5 m). Experience has shown that about 80% of the raw profile data transmitted from the floats meet these standards, with little or no correction required. The other 20% of the data are corrected using delayed-mode quality control procedures developed over the past decade[7–9], with nearly all of these profiles eventually meeting the accuracy goals. Agencies developing operational forecast systems require data in a timely fashion. At present, about 90% of Argo profiles are distributed electronically within 24 hours of acquisition.

Recent results and findings

Perhaps the single most powerful metric of the value of Argo is the widespread use of the data produced by the programme: since the beginning of Argo in the late 1990s, more than 2,100 papers in the refereed science literature have used Argo observations, attesting to the array's value in expanding our understanding of the oceans and climate. The key ocean state variables, temperature and salinity, varying with pressure and velocity, were measured (or for velocity, mostly inferred) in the world ocean for at least a century before the initial deployment of the Argo array. During the 1980s and 1990s the World Ocean Circulation Experiment (WOCE) produced about 8,000 high-quality ship-based profiles along a number of tracks across the ocean that provide a high-quality baseline estimate of the state of the ocean at that time. However, a great deal of the ocean was left unobserved in WOCE due to the limited number of lines that could be occupied, particularly in the Southern Ocean. In this context, the high sampling density and repeat frequency of the Argo observations, in conjunction with their overall quality, have led to important new insights into the nature of the general circulation of the ocean.

Although compilations of thousands of ship-based observations of ocean temperature and salinity have been averaged and made available as digital atlases since at least the 1980s[10], they suffer from the sampling biases previously noted. With data collected by Argo now becoming the overwhelming majority of observations in the global database, there is an unprecedented opportunity to map the detailed structure of the global ocean temperature and salinity fields, at both surface and subsurface levels, and both globally and locally[11]. These estimates allow the development of climate indicators such as the recent changes in ocean heat content and thermosteric sea level. The global velocity dataset produced by Argo floats[12] is beginning to be used in systematic (and previously impossible) studies[13,14] to quantify directly the subsurface interior flow fields. The Argo data have also been used to improve our view of the complex structure of oceanic variability at spatial scales smaller than the climate scale. A number of studies have examined properties of mesoscale eddies using Argo profiles[15,16], and it has been possible to describe the spatial variability in the internal gravity wave field[17], even though such applications were not envisioned when Argo began.

Argo complements the other elements of the global ocean observing system, in particular satellite altimetry. The combination of *in situ* Argo data with sea surface height anomalies derived from satellites allows the construction of time series of the dynamical state of the ocean circulation (such as the North Atlantic

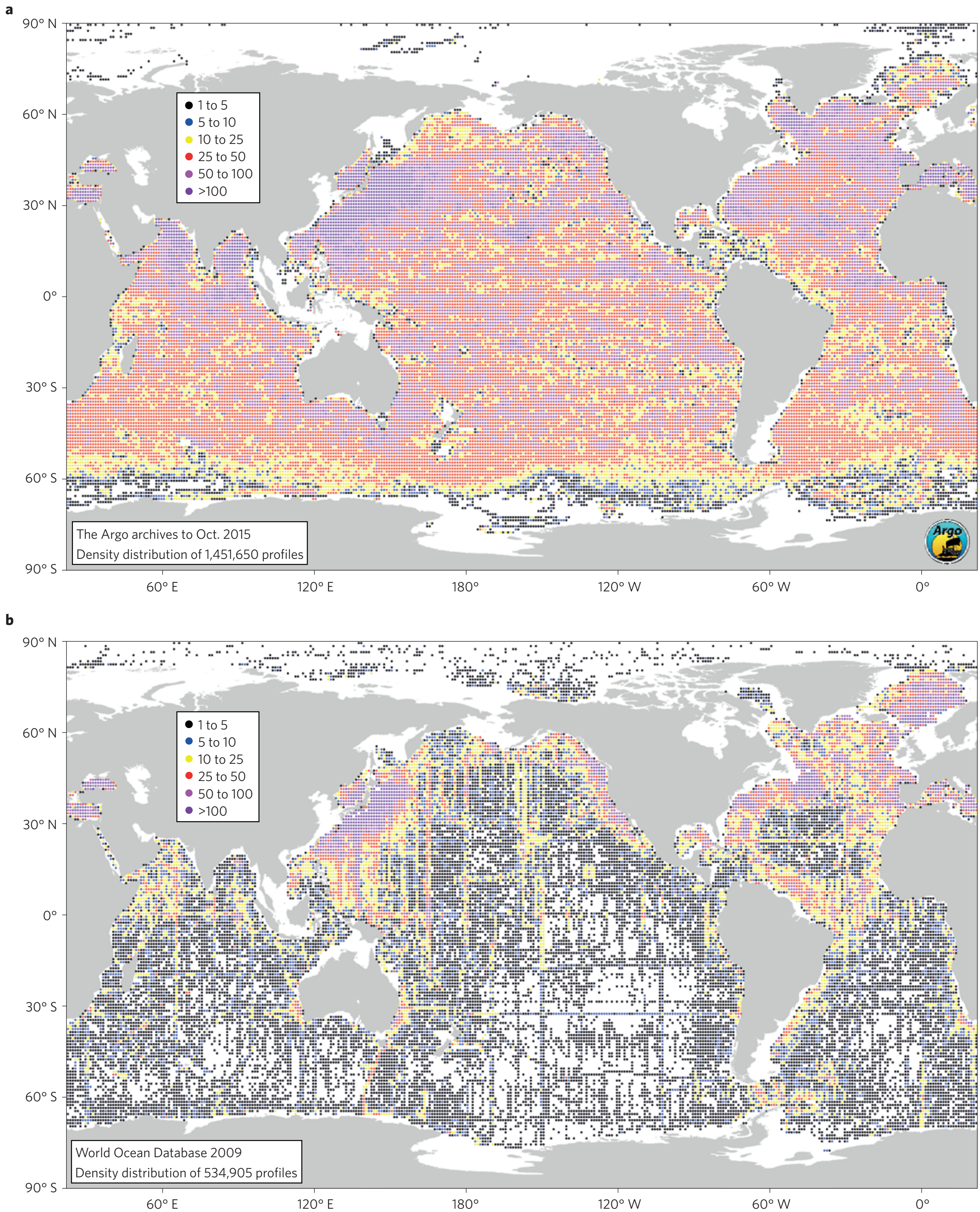

Figure 2 | The sampling density of profiles reported by Argo floats. a, ~1.5 million profiles collected between January 1999 and October 2015. Data from ref. 57. **b**, The most complete assembly of all previous historical efforts (0.5 million largely shipboard observations collected over the past 100 years). Data from the World Ocean Data Base 2009[58]. This sampling density is computed as the total number of samples in each 1° latitude × 1° longitude square and is colour coded according to the legend in each panel. The analysis only includes profiles that sample both temperature and salinity to a depth of 1,000 m or deeper.

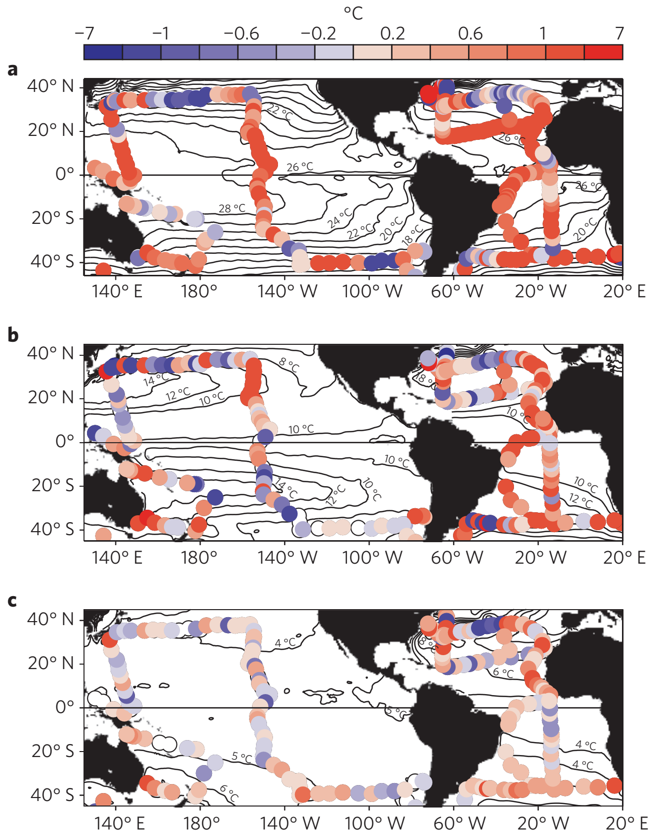

Figure 3 | Mean temperature over the period 2004–2010 in the global ocean. a, Sea surface temperature. **b**, Temperature at a depth of 366 m. **c**, Temperature at a depth of 914 m. The dots (colour scale) denote the temperature differences between Argo and Challenger data. Figure reproduced from ref. 23, Nature Publishing Group.

meridional overturning circulation[18]) and high-resolution three-dimensional temperature fields[19]. Techniques have been presented[20,21]whereby geostrophic computations relative to 1,000 dbar can be merged with a combination of satellite altimetry observations and trajectory data to yield estimates of the absolute circulation fields in well-sampled areas. Argo data are now systematically used together with altimeter data for ocean analysis and forecasting. Most climate models assimilate the subsurface temperature observations from Argo, leading to improved forecasts of intraseasonal waves in the atmosphere, monsoon activity, and ocean–atmosphere interactions such as the El Niño/Southern Oscillation (ENSO)[22].

Given that they provide a comprehensive baseline of today's ocean state, the Argo observations have been particularly useful in examining ocean changes on timescales of decades and longer. A stunning example[23] has used contemporary Argo observations in conjunction with data from the HMS *Challenger* expedition, carried out in the second half of the nineteenth century. The study reveals a warming of the ocean over the past 135 years of nearly 0.6 °C near the sea surface, tapering to near zero at depths close to 1,000 m (Fig. 3). Over the upper 900 m of much of the ocean there is an average increase in temperature of over 0.3 °C over the 135-year study interval. This work, further supported by analogous results in climate models[24], underscores the changing nature of ocean properties and the need to sustain global observing systems over long periods and, further, that recent changes in ocean temperature probably predate the sparse global-scale ocean datasets of the past half century.

A more detailed comparison of Argo profiles available in the time frame 2004–2008 with data in the ship-based data archive (containing data collected through 2001[25]) shows global-scale changes in both temperature and salinity[26] in the upper kilometre of the world ocean in recent decades. The comparison suggests that most regions of the world ocean are warmer in the near-surface layer than in previous decades, by over 1 °C in some places. A few areas, such as the eastern Pacific from Chile to Alaska, have cooled by as much as 1 °C, yet overall the upper ocean has warmed by nearly 0.2 °C globally since the mid-twentieth century. A recent update of this work[27] shows that the warming continues to be observed through at least 2013.

Before the beginning of Argo, ocean salinity was much more poorly sampled than temperature. The highest-quality salinity measurements that existed were made during WOCE in the 1980s and 1990s, with periodic reoccupation of some of these sections continuing. With the advent of Argo, it is possible to examine the global variability of salinity above 2,000 m with some confidence for the first time. As with temperature, a comparison of Argo results with earlier data[28] clearly shows decadal-scale changes in ocean salinity. A related study that compared the Argo results with the data in the older archives[29] identified a pattern of change in upper-ocean salinity in each of the major ocean basins. This change seems to be consistent with a general warming of the surface layers, causing a poleward migration of wintertime density outcrops. Because there are pole–Equator temperature and salinity gradients at the sea surface, the surface waters at any latitude are subducted below those at lower latitudes as they circulate towards the Equator, with a poleward migration of density yielding a generally lower salinity at higher latitudes. At mid-latitudes, surface warming is accompanied by increased evaporation from the sea surface, thus increasing the salinity of the near-surface waters. When compared, surface and basin-scale contrasts in salinity are found consistently to be strengthening[28–30]. This amplification, with fresh areas getting fresher and salty areas becoming more saline, is consistent with an overall net increase in water vapour transport through the atmosphere, and is also seen to occur in climate models that very closely follow Clausius–Clapeyron thermodynamics[30].

On more regional scales, Argo data have been used to examine the variable nature of deep ocean ventilation, which is important in sequestering heat and gases into the vast subsurface layers of the ocean. This process occurs at a few high-latitude sites in the North Atlantic and the Antarctic, and the resulting circulation induced by this sinking has long been thought to have an important influence on century-scale climate variability[31]. The Labrador/Irminger Sea region in the high-latitude North Atlantic has been extensively examined by Argo in the past decade, with the observations (combined with ship-based datasets and atmospheric heat flux estimates) showing the high sensitivity of the strength of deep convection to year-to-year variations in wintertime atmospheric conditions[32]. That work has recently been brought up to date[33] and the result is a spectacular demonstration (Fig. 4) of the power of Argo to show the variability of deep convection in the Labrador Sea, and in 2014 the deepest convection observed since 2008.

More detailed, regional views of the effects of changing near-surface temperature and salinity from the central North Pacific using Argo profiles together with older, ship-based data in the region have shown a general decrease in upper-ocean salinity in the tropics and subtropics, caused by a freshening of the source waters for the upper ocean in the region — essentially, water in the surface mixed layer at higher latitudes in winter[34,35]. This freshening can be attributed to a combination of factors, including increased local precipitation or the poleward migration of the source region due to regional warming. Data availability in this region (including Argo and other datasets) is rich enough to allow

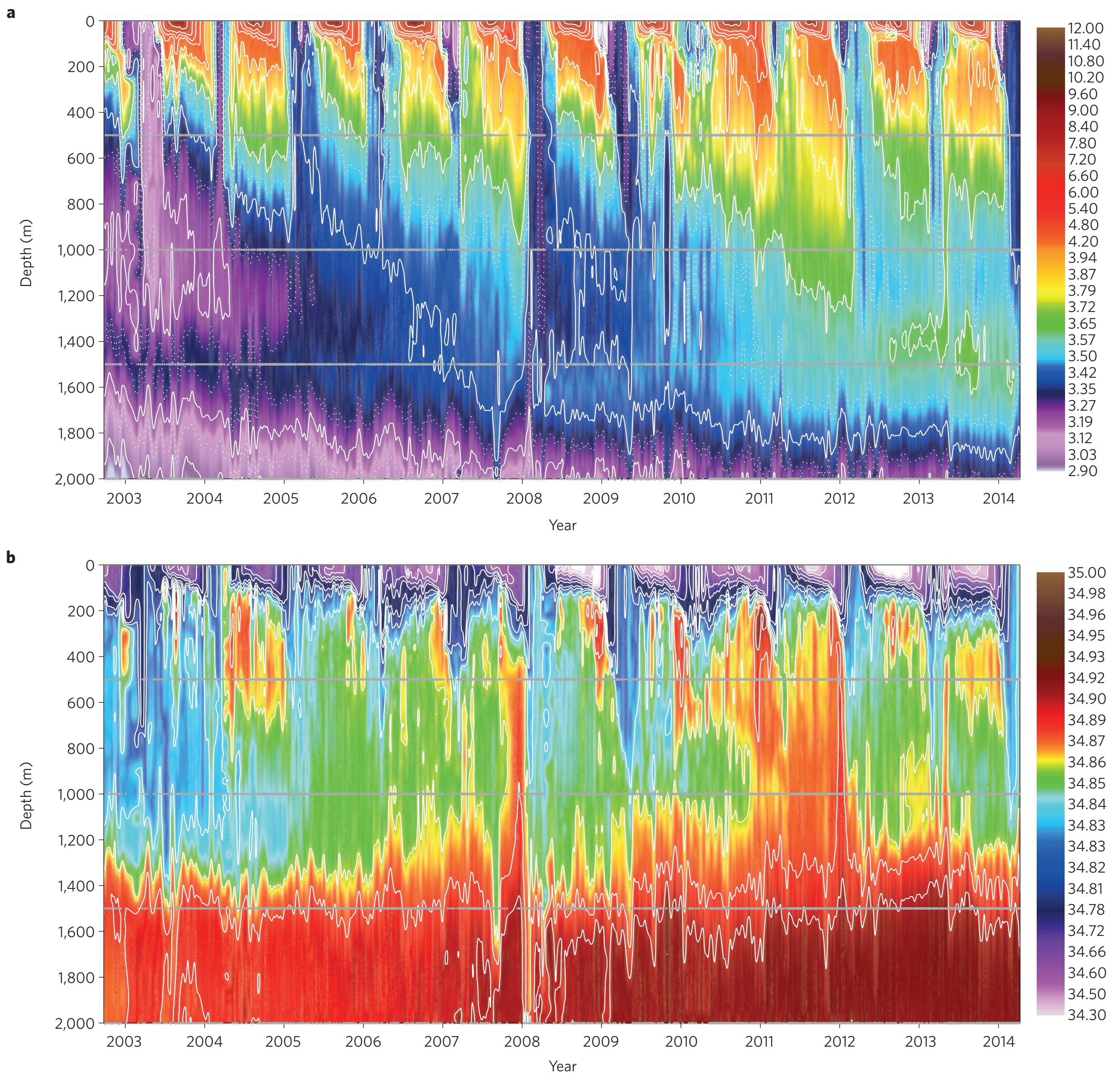

Figure 4 | Convection in the Labrador Sea. a,**b**, The bi-weekly to interannual evolution of potential temperature (**a**) and salinity (**b**) in the upper 2,000 m of the Labrador Sea during the period 2002–2014; data compiled from quality-controlled Argo float and vessel profiles. Figure courtesy of Igor Yashayaev (Bedford Institute of Oceanography, Canada), updating data from refs 32,33.

an actual heat budget to be constructed, suggesting that precipitation and wintertime entrainment of subsurface water into the mixed layer are the most important factors in determining the surface density over time, and hence also the surface salinity. It seems to be likely that these factors will change in response to a changing climate state. Elsewhere in the North Pacific, temperature and salinity properties along a track originating off Vancouver Island have been regularly surveyed by research vessels since the 1950s, and in the past decade these surveys have been augmented by Argo observations. The combination of the older data and Argo[36] shows that subpolar surface waters are warming and freshening, resulting in a lower surface density (and higher near-surface stratification), thus limiting the direct influence of the atmosphere on the subsurface ocean.

As noted, a number of observation-based studies have concluded that the upper layers of the global ocean have warmed in recent decades, or even over a longer period. Yet it is the change in heat storage by the ocean (essentially the vertical integral of temperature change) that is likely to be directly related to the planetary radiation imbalance[37,38]. It seems that the observed increase in ocean heat content in the upper 700 m over the past 40 years, inferred from Argo and hydrographic observations, is the dominant term in the global inventory of heating changes, with over 90% of the excess heat in the climate system being stored in the oceans[39]. Without Argo, it is unlikely that such a conclusion could have been drawn. The data have also allowed temporal spatial variations in ocean heat content to be discerned[40], suggesting that most of the increase in heat content in the past decade

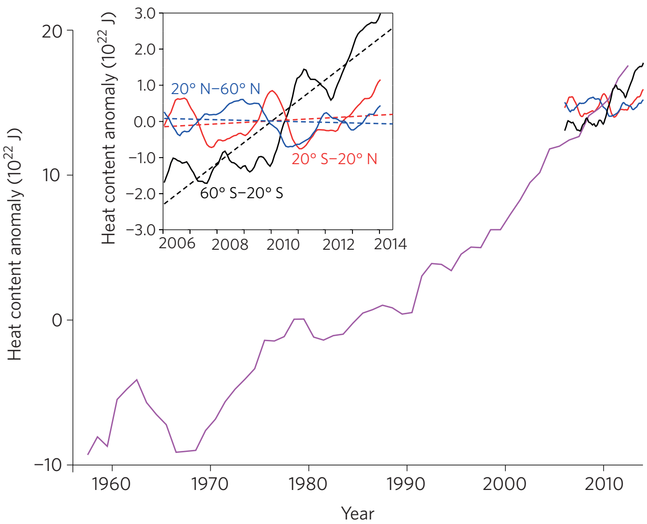

Figure 5 | Argo estimates of global heat content. Estimates of the heat content anomaly[27] for 60° S–20° S (black), 20° S–20° N (red) and 20° N–60° N (blue), and a global estimate (purple)[42]. Regression lines (dashed) are shown in the inset; adapted from ref. 27, Nature Publishing Group.

has occurred in the Southern Ocean (which was poorly sampled before Argo); it has also been noted[41] that ENSO variability in the tropical Pacific has for now somewhat obscured the global increase in sea surface temperature. Some of these ideas have been tested using Argo data alone (Fig. 5), by examining the change in heat content of the upper 2,000 m of the ocean in three latitudinal bands from 2006 to the present time; during the Argo era it can be seen that the ocean is warming, mostly south of 20 °S. In Fig. 5 the Argo-only plots (inset) are only for the years 2006–2014, the period when global coverage from Argo exists. So these short plots are overlaid on a plot of heat content estimates for 0–2,000 m depth for the period 1955–2010[42]. The Argo estimates show a very similar trend. This is a crucial result in making an assessment of the ocean's role in climate change, one that would have probably been impossible before Argo. Indeed, a recent detailed and systematic analysis of the change in ocean heat content and our ability to observe it[43] concludes that estimates of the upper-ocean heat content based on data collected before Argo systematically underestimate the amount of heat content change, mostly due to undersampling of the Southern Hemisphere ocean; with the advent of a significant amount of Argo data becoming available around 2004, the estimates are greatly improved and are in better agreement with climate models.

Future prospects

When Argo began in the late 1990s, it was by no means clear that the project would be successful in deploying and sustaining an array of 3,000 floats over the global ocean, as the required technology was in its infancy and the degree of international cooperation required was unprecedented in the oceanographic community. Now, in the second decade of the twenty-first century, the float technology is well proven, and over 30 countries are contributing resources to Argo, making it sensible to contemplate expansions of its mission. The Argo Steering Team (hereinafter AST) has provided a roadmap[44] for how the project might evolve and expand in the next decade, and some of this proposed development is now underway via test deployments or regional pilot arrays. One project is to support an increase in the spatial sampling resolution in particular parts of the world ocean where the ocean is especially turbulent (challenging the array's signal resolving power) and the interaction of the ocean and the atmosphere and the resulting climate impacts are especially strong. Improved technology also allows us to expand Argo into previously unsampled regions, such as marginal seas and the seasonal ice-zone, meaning that the array is more truly global in its coverage than its original design.

Intense western boundary currents such as the Gulf Stream and Kuroshio are some of the most striking features of the ocean circulation, serving to transport heat polewards as they carry warm tropical and subtropical waters to higher latitudes. A sizeable portion of this heat is exchanged with the atmosphere along the path of the flow, especially after these currents separate from the boundary and enter the interior of the ocean, altering the tracks of storms and perhaps ameliorating continental climates[45]. When Argo data are used to map the monthly and seasonal evolution of the large-scale ocean structures in these regions, the errors are relatively high compared with other regions due to the presence of the vigorous ocean turbulence associated with these boundary current regimes and the lack of spatial resolution of the Argo array. This limits the ability of Argo to achieve one of its main goals, which is to observe the slow evolution of the large-scale ocean structure in these important regions. The AST has suggested that extra float resources should be committed to the study of these regions, and some of the nations that contribute to the array have responded to this call. In the western North Pacific, for example, the boundary domain adjacent to China, South Korea, and Japan is already sampled at a spatial density nearly three times the standard Argo protocol. In the western North Atlantic, between Cape Hatteras and the mid-Atlantic Ridge, the sampling is similarly dense. The ability of the programme to enhance sampling in all western boundary current regions is unclear, but these pilot activities will help demonstrate the gains made and thus guide the future sampling recommendations.

A similar increase in sampling density is called for in near-Equatorial regions, where strong air–sea coupling can produce global-scale atmospheric anomalies. The tropical Pacific, for example, is the gestation site of the ENSO phenomenon, an irregular seesaw of oceanic warming and cooling that can, via strong coupled amplification, drive global climate variability and cause economic impacts at sites far removed from the low-latitude Pacific. The Indian Ocean Dipole (IOD) is an analogous phenomenon that impacts Indian Ocean rim nations[46]. The surface temperature and salinity associated with these phenomena can be monitored via satellites, but Argo is now the main source of information on their deeper, subsurface expressions. Argo data are used in model forecasts for ENSO and the IOD, and, along with the existing tropical moored arrays, are central to providing and improving predictions of the onset and strength of these scientifically interesting yet socially disruptive events.

In addition, the AST has encouraged the deployment of floats in marginal seas, environments that are regionally important to natural resources and trade. During the early stages of Argo it was decided to avoid deployments in such areas, due to the probable premature loss of floats and troublesome political issues. More than a decade later some of these issues remain, yet the scientific success of Argo has encouraged a number of groups to begin Argo-like programmes in several of the marginal seas of the world. Within the Euro-Argo European Research Infrastructure Consortium that is coordinating European contributions to Argo, the MedArgo initiative has maintained an array of more than 50 floats in these regions since 2008 and has plans for expansion. This has helped to clarify the details of water mass formation in the Mediterranean and to improve predictions of the basin-scale circulation by assimilating profile data into numerical models of the circulation. Argo-type efforts in the marginal seas of East Asia have yielded new insights into the interplay of the local ocean and the regional climate in these regions and the nature and causes of long-term changes in their properties, and data resulting from deployments now underway in the Gulf of Mexico are likely to eventually be useful in improved hurricane prediction.

Argo was originally planned to cover the open ocean equatorward of 60°, thus purposefully avoiding regions seasonally covered in sea ice. A float trapped under sea ice cannot transmit its data, and, for floats that are somehow able to get to the surface in the presence of ice, the danger of being crushed between floes is sizable. In the past decade algorithms have been developed[47] that greatly increase a float's chances of surviving the winter in the ice zone by inferring the presence of ice from the near-surface temperature structure. Simply stated, if the float determines that ice is present through an onboard analysis of the stratification, then it avoids the surface (thus avoiding the ice), stores its profile and descends for another cycle. In the spring, when the ice retreats and the float can reach the surface, all of its winter data can be transmitted, although without tracking information. This concept has worked well[5,6], with floats in the seasonal ice zone surviving at about the same rate as floats at lower latitudes. Based on this success, the large fraction of the area of the global ocean that exists at high southern latitudes, and the importance of ice-covered regions around the Antarctic in setting the conditions for meridional overturning, the AST has suggested that deployments in such regions should be systematically increased. Several groups are now staging pilot deployments in these regions.

Beyond deployments in new regions and advances in float software, technological developments have provided new capabilities to profiling floats that allow a larger range of scientific questions to be examined. As originally designed, Argo was intended to be a programme to examine the temperature, salinity, and heat content of the world ocean and the climate implications of the variability in these quantities. In the past decade new sensors have come into existence that also allow biogeochemical variables such as dissolved oxygen, nitrate, chlorophyll, and pH to be measured from Argo-type floats. These sensors are small in both physical size and power consumption and barely affect the duration of the basic float mission, and thus floats equipped with such sensors allow the prospect of examining the impact of physical aspects of the ocean circulation on key biogeochemical processes sensitive to the climate state, such as the biogeochemical cycle of carbon, ocean deoxygenation, and ocean acidification[48]. These floats will also contribute to the improvement of the capabilities of biogeochemical models[49] and to the extension of surface biogeochemical properties monitored by ocean colour satellites to deeper levels of the water column[50]. The AST has endorsed the general idea of taking advantage of these new developments, while at the same time moving cautiously as the Argo data system gains experience in ingesting and disseminating these new data types. While it is expected that the number of biogeochemical Argo floats deployed will increase dramatically in the coming years, pilot projects in a few key oceanic areas where carbon uptake is crucial will be carried out before envisaging the implementation of a biogeochemical float programme at the global scale. Several European efforts in this regard are underway in the North Atlantic. Similarly, the mating of the under-ice capabilities and biogeochemical floats has led to plans by the Southern Ocean Carbon and Climate Observations and Models (SOCCOM) group to examine the carbon cycle around the Southern Ocean, a region responsible for roughly 40% of the global oceanic carbon uptake.[51,52]

In recent years, a series of papers[53–56] have shown that the deep ocean well below 2,000 m contributes a significant fraction of the total water column increases in heat content and thermosteric sea-level rise, especially in (but not confined to) the high southern latitudes. This warming, in many cases present at all depths below 3,000 m, has been deduced from an analysis of sparse but repeated high-quality ship-based observations of temperature and salinity conducted since the 1980s. While the capability of making such measurements from ships has existed for several decades, the cost of the vessels carrying out such work is high, often as much as US$35,000 per day. Argo floats, on the other hand, are a seemingly more economical way to observe the ocean, although the present generation of Argo floats generally samples no deeper than 2,000 m. The economy may or may not be illusory depending on the strategy used to deploy the floats. If floats are deployed on a ship of opportunity there may be no incremental launch costs, but strategic launches do often require a dedicated vessel. To begin to explore the abyssal ocean and to refine present estimates of the warming of the deep sea, the AST has since 2012 supported efforts to develop floats capable of profiling deeper than 2,000 m (to as deep as 6,000 m) and to begin deploying these floats increasingly in 2015 and beyond. This is by far the most ambitious and technically challenging development in Argo since the initial float deployments took place in the late 1990s. At the present time several prototypes have been tested that use new technologies, such as carbonepoxy filament-wound cylindrical hulls for 4,000 m prototypes being developed in Europe and Japan, or hulls made from glass spheres, for two 6,000 m versions being developed in the USA. A further issue is that the temperature, salinity, and pressure sensors on these floats must be more accurate than for standard Argo floats, since the variability in the abyssal ocean is likely to be considerably smaller than in the upper 2,000 m of the water column. Prototypes for the 4,000 m versions have been successfully deployed in the North Atlantic and North Pacific. A dedicated test cruise for the deployment of the 6,000 m prototype floats and for calibration and validation of new ultra-accurate temperature/salinity/pressure sensors took place in the western South Pacific in mid-2014 and successfully showed the promise of both the new deep floats and sensors. Although the deep floats will surely be more costly than present Argo floats, it is hoped that by 2020 systematic sampling of the abyssal ocean will be implemented, with as much as 30% of the Argo array comprised of these deep floats. High-quality sampling of the deep sea from dedicated hydrographic vessels will need to continue far into the future, however, even after the full complement of deep floats is in place; the shipboard surveys together with Argo will provide a more complete global sampling of the abyssal ocean, and the ship-based data will be necessary to monitor the quality of the Argo data in the abyss.

It is possible that a decade or two from now the science community will barely recognize the deployment strategies or the instruments being used by Argo or its successor programmes at that time. For the next few years, the AST has suggested continuing with its long-term plan while also moving in new directions that are part evolution (deploying floats in new and special regions, and the addition of new sensors) and part revolution (designing and testing floats capable of operation in the abyss). The goals of all of this work are to sustain the present systematic observations of the global ocean and to further improve our assessment of the ocean's role in climate.

The development of Deep Argo seems to be a particularly crucial step in the evolution of the programme. The present array has done a credible job of providing estimates of the heat content change in the upper 2,000 m of the world ocean over the past few decades, with the measured increases being significant but somewhat smaller than the predictions of model-based global heat budgets. Other studies[55,56] point to the even deeper waters of the world ocean, beneath the present limits of Argo sampling, as a possible repository of the increased heating necessary to close the global heat budget. Assessing this question, and making progress in other new directions such as observing the oceanic carbon cycle from floats, helping to make improved forecasts of ENSO and IOD, and probing the depths of marginal seas, is likely to challenge the abilities of the future leaders of Argo to push the limits of the evolution and revolution of the programme to further increase our understanding of the circulation of the ocean and its role in climate.

In conclusion, it is important to remember that the prize we are aiming for is an understanding of how the ocean is changing both naturally and as a result of human activities. That said, Argo is indeed a major accomplishment but it does not stand alone. Recently five programmes have been brought together in the JCOMMOPS (Joint Commission on Oceanography and Marine Meteorology Operations) office. This includes moored buoy activities such as the equatorial arrays and the individual moorings sponsored by the OceanSites programme, also the XBT surveys and the repeat shipboard hydrographic surveys sponsored by the GO-SHIP programme. Many of these supply data in real-time in parallel with the Argo programme. With all of these initiatives now operating under a single umbrella the supply of data from the oceans is undergoing a profound transformation.

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Additional information
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Competing financial interests
The authors declare no competing financial interests.