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3 Fifteen years of ocean observations with the global Argo array

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Abstract

More than 90% of the heat energy accumulation in the climate system between 1971 and the present has been in the oceans. Thus, the ocean plays a crucial role in determining the climate of the planet. Observing the oceans is problematic even under the most favorable of conditions. Historically, ship-board 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 2000m 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 2000 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, multi-decadal climate change, improved initialization of coupled ocean/atmosphere climate models, and constraining ocean analysis and forecasting systems.

Introduction

In the late 1990s it was recognized that little progress would be made monitoring the changing climate of the Earth without systematic global observations. A small group of oceanographers proposed that some 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 was born the Argo program. This article reviews the progress made in the first 15 years of Argo and attempts to provide an outline of how the program is likely to change over the next decade.

History and present status

The Argo program[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-meter 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 1000 meters (known as the parking depth). A typical duty cycle of an Argo float is shown in Figure 1. Floats are launched at the sea surface and dive to a so-called parking depth of 1000 meters. After a ~9-day interval at the parking depth, the floats descend to 2000 meters, 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 program since the beginning of Argo, with almost 3900 floats presently operating over the world-ocean. A defining aspect of Argo is that all data are reported in near real-time to meteorological forecasting centers 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.

Argo float deployments began in 1999. The original program plan called for an array with global coverage of about 3000 floats by the year 2007, a goal that was achieved in November of that year. The resulting improvement in sampling 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. Though Argo floats cannot sample in shallow coastal waters, the program has helped eliminate these spatial biases. Argo has also eliminated a major seasonal bias in sampling, particularly in the polar oceans; presently Argo delivers more winter profiles in the Southern Ocean in one year than the total of all winter data collected during the 100 years

64 prior to Argo, and the majority of the temperature and salinity observations from the Southern Ocean (defined

65 here as the ocean south of 30°S) in the global database now originate from Argo.

66 In Chapter 3 of its Fifth Assessment Report (hereinafter AR5)[5], the Intergovernmental Panel on Climate Change

67 (IPCC) Working Group 1 included an Appendix on the *Availability of Observations for Assessment of Change*

68 *in the Oceans* showing the distribution of temperature and salinity profile data from the 1950-1955 to the 2005-

69 2010 pentads; these results indicate the general lack of observations prior to 2000, as well the Northern

70 Hemispheric bias within the pre-Argo observing system. Although not shown in AR5, there is also a known

71 seasonal bias, with the local winter season being generally under-represented in the pre-Argo observing system.

72 It is apparent from this report that the recent expansion of the ocean observing system clearly sets AR5 apart

73 from its predecessor[6], with most of this change ascribed to the existence of the Argo array. Some issues remain

74 that are being addressed. Since Argo floats must reach the sea surface to transmit their data, Argo could not

75 originally target ice-covered parts of the oceans; now floats are successfully operating in the Antarctic seasonal

76 ice zone[7,8]. Within the temperate oceans coverage is not homogeneous, but there are efforts to increase coverage

77 in under-sampled regions such as near western boundary currents.

78 While the volume of Argo data easily overwhelms traditional sources, the quantity is of value only if the quality

79 of the data is high. The original Argo target called for temperature and salinity accuracies of 0.005°C and 0.01

80 salinity units, with a pressure accuracy of 2.5 decibars (equivalent to a depth error of about 2.5 meters).

81 Experience has shown that about 80% of the raw profile data transmitted from the floats meet these standards,

82 with little or no correction required. The other 20% of the data are corrected using delayed-mode quality control

83 procedures developed over the past decade[9,10,11], with nearly all of these profiles eventually meeting the

84 accuracy goals. Agencies developing operational forecast systems require data in a timely fashion. Currently,

85 about 90% of Argo profiles are distributed electronically within 24 hours of acquisition.

86

87 **Recent Results and Findings**

88 Perhaps the single most powerful metric of the value of Argo is the widespread use of the data produced by the

89 program: since the beginning of Argo in the late 1990s, more than 2100 papers in the refereed science literature

90 have used Argo observations, attesting to the array's value in expanding our understanding of the oceans and

91 climate. The key ocean state variables, temperature and salinity varying with pressure and velocity were

92 measured (or for velocity, mostly inferred) in the world ocean for at least a century prior to the initial

93 deployment of the Argo array. During the 1980s and 1990s the World Ocean Circulation Experiment (WOCE)

94 produced about 8000 high quality ship-based profiles along a number of tracks across the ocean that provide a

95 high quality baseline estimate of the state of the ocean at that time. However, a great deal of the ocean was left

96   unobserved in WOCE due to the limited number of lines that could be occupied, particularly in the Southern
97   Ocean. In this context, the high sampling density and repeat frequency of the Argo observations, in conjunction
98   with their overall quality, have led to important new insights into the nature of the general circulation of the
99   ocean.

100   While compilations of thousands of ship-based observations of ocean temperature and salinity have been
101   averaged and made available as digital atlases since at least the 1980s[12], they suffer from the sampling biases
102   previously noted. With data collected by Argo now becoming the overwhelming majority of observations in the
103   global database, there is an unprecedented opportunity to map the detailed structure of the global ocean
104   temperature and salinity fields, at both surface and subsurface levels, and both globally and locally[13]. These
105   estimates allow the development of climate indicators such as the recent changes in ocean heat content and
106   thermosteric sea level. The global velocity dataset produced by Argo floats[14] is beginning to be used in
107   systematic (and previously impossible) studies[15,16] to quantify directly the subsurface interior flow fields. The
108   Argo data have also been used to improve our view of the complex structure of oceanic variability at spatial
109   scales smaller than the climate scale. A number of studies have examined properties of mesoscale eddies using
110   Argo profiles[17,18], and it has been possible to describe the spatial variability in the internal gravity wave field[19],
111   even though such applications were not envisioned when Argo began.

112   Argo complements the other elements of the global ocean observing system, in particular satellite altimetry.
113   The combination of *in situ* Argo data with sea surface height anomalies derived from satellites allows the
114   construction of time series of the dynamical state of the ocean circulation (such as the North Atlantic meridional
115   overturning circulation[20]) and high-resolution three-dimensional temperature fields[21]. Techniques have been
116   presented[22,23] whereby geostrophic computations relative to 1000 decibars can be merged with a combination of
117   satellite altimetry observations and trajectory data to yield estimates of the absolute circulation fields, in well-
118   sampled areas. Argo data are now systematically used together with altimeter data for ocean analysis and
119   forecasting. Most climate models assimilate the subsurface temperature observations from Argo, leading to
120   improved forecasts of intraseasonal waves in the atmosphere, monsoon activity, and ocean-atmosphere
121   interactions such as the El Nino Southern Oscillation (ENSO)[224].

122   Given that they provide a comprehensive baseline of today's ocean state, the Argo observations have been
123   especially useful in examining ocean changes on time scales of decades and longer. A stunning example[25] has
124   used contemporary Argo observations in conjunction with data from the HMS *Challenger* expedition, carried
125   out in the second half of the 19th Century. The study reveals a warming of the ocean over the past 135 years of
126   nearly 0.6°C near the sea surface, tapering to near zero at depths near 1000 m (Fig. 3). Over the upper 900 m of
127   much of the ocean there is an average increase in temperature of over 0.3°C over the 135-year study interval.
128   This work, further supported by analogous results in climate models[26], underscores the changing nature of ocean

129 properties and the need to sustain global observing systems over long periods and, further, that recent changes in

130 ocean temperature likely predate the sparse global-scale ocean datasets of the past half century.

131 A more detailed comparison of Argo profiles available in the time frame 2004-2008 with data in the ship-based

132 data archive (containing data collected through 2001[27]) shows global-scale changes in both temperature and

133 salinity[28] in the upper kilometer of the world ocean in recent decades. The comparison suggests that most

134 regions of the world ocean are warmer in the near surface-layer than in previous decades, by over 1°C in some

135 places.   A few areas, such as the eastern Pacific from Chile to Alaska, have cooled by as much as 1°C, yet

136 overall the upper ocean globally has warmed by nearly 0.2°C since the mid-20th century.   A recent update of

137 this work[29] shows the warming continues to be observed through at least 2013.

138 Prior to the beginning of Argo, ocean salinity was much more poorly sampled than temperature. The highest

139 quality salinity measurements that existed prior to Argo were made during WOCE in the 1980s and 1990s, with

140 periodic reoccupation of some of these sections continuing. With the advent of Argo, it is possible to examine

141 the global variability of salinity above 2000 m with some confidence for the first time. As with temperature, a

142 comparison of Argo results with earlier data[30] clearly shows decadal-scale changes in ocean salinity. A related

143 study that compared the Argo results with the data in the older archives[31] identified a pattern of change in upper

144 ocean salinity in each of the major ocean basins. This change appears consistent with a general warming of the

145 surface layers, causing a poleward migration of wintertime density outcrops. Because there are pole-to-equator

146 temperature and salinity gradients at the sea surface, the surface waters at any latitude are subducted below those

147 at lower latitudes as they circulate towards the equator, with a poleward migration of density yielding a

148 generally lower salinity at higher latitudes. At mid-latitudes, surface warming is accompanied by increased

149 evaporation from the sea surface, thus increasing the salinity of the near-surface waters. When compared,

150 surface and basin-scale contrasts in salinity are found consistently to be strengthening[29,30,31]. This amplification,

151 with fresh areas getting fresher and salty areas becoming more saline, is consistent with an overall net increase

152 of water vapor transport through the atmosphere, and is also seen to occur in climate models that very closely

153 follow Clausius-Clapeyron thermodynamics[32].

154 On more regional scales, Argo data have been used to examine the variable nature of deep ocean ventilation,

155 which is important in sequestering heat and gases into the vast subsurface layers of the ocean. This process

156 occurs at a few high latitude sites in the North Atlantic and the Antarctic, and the resulting circulation induced

157 by this sinking has long been thought to have an important influence on century-scale climate variability[33]. The

158 Labrador/Irminger Sea region in the high-latitude N. Atlantic has been extensively examined by Argo in the past

159 decade, with the observations (combined with ship-based datasets and atmospheric heat flux estimates) showing

160 the high sensitivity of the strength of deep convection to year-to-year variations in the wintertime atmospheric

161 conditions[34]. That work has recently been brought up to date[35] and the result is a spectacular demonstration (Fig.

162   4) of the power of Argo to show variability of deep convection in the Labrador Sea and in 2014 the deepest

163   convection observed since 2008.

164   More detailed, regional views of the effects of changing near-surface temperature and salinity, from the central

165   North Pacific, using Argo profiles together with older, ship-based data in the region, have shown a general

166   decrease in upper ocean salinity in the tropics and subtropics, caused by a freshening of the source waters for the

167   upper ocean in the region, essentially water in the surface mixed layer at higher latitudes in winter[36,37]. This

168   freshening can be attributed to a combination of factors, including increased local precipitation or the poleward

169   migration of the source region due to regional warming. The data availability in this region (including Argo and

170   other datasets) is rich enough to allow an actual heat budget to be constructed, suggesting that precipitation and

171   wintertime entrainment of subsurface water into the mixed layer are the most important factors in determining

172   the surface density over time, and hence also the surface salinity. It appears likely that these factors will change

173   in response to a changing climate state. Elsewhere in the North Pacific, temperature and salinity properties

174   along a track originating off Vancouver Island have been regularly surveyed by research vessels since the 1950s,

175   and in the past decade these surveys have been augmented by Argo observations. The combination of the older

176   data and Argo[38] also show that subpolar surface waters are warming and freshening, resulting in a lower surface

177   density (and higher near-surface stratification), thus limiting the direct influence of the atmosphere on the

178   subsurface ocean.

179   As noted, a number of observation-based studies have concluded that the upper layers of the global ocean have

180   warmed in recent decades, or even over a longer term. Yet it is the change in heat storage by the ocean

181   (essentially the vertical integral of temperature change) that is likely to be directly related to the planetary

182   radiation imbalance[39,40]. It appears that the observed increase in ocean heat content in the upper 700 m over the

183   past 40 years, inferred from Argo and hydrographic observations, is the dominant term in the global inventory of

184   heating changes, with over 90% of the excess heat in the climate system being stored in the oceans[41]. Without

185   Argo, it is unlikely that such a conclusion could have been drawn. The data have also allowed temporal spatial

186   variations in ocean heat content to be discerned[42], suggesting that most of the increase in heat content in the past

187   decade has occurred in the Southern Ocean (which was poorly sampled prior to Argo); it has also been noted[43]

188   that ENSO variability in the tropical Pacific has for now somewhat obscured the global increase in sea surface

189   temperature. Some of these ideas have been tested using Argo data alone (Fig. 5[29]), by examining the change in

190   heat content of the upper 2000 m of the ocean in three latitudinal bands from 2006 to the present time; during

191   the Argo era it can be seen that the ocean is warming, mostly south of 20°S. In Figure 5 the Argo-only plots

192   (shown as an inset) are only for the years 2006-2014, inclusive, the period when global coverage from Argo

193   exists. So these short plots are overlaid on a plot of heat content estimates 0-2000 m for the period 1955-2010[44].

194   The Argo estimates show a very similar trend. This is a crucial result in making an assessment of the ocean's

195 role in climate change, one that would have likely been impossible prior to Argo. Indeed, a recent detailed and

196 systematic analysis of the change in ocean heat content and our ability to observe it[45] concludes that estimates of

197 the upper ocean heat content based on data collected prior to Argo systematically underestimate the amount of

198 heat content change, mostly due to under-sampling of the Southern Hemisphere ocean; with the advent of a

199 significant amount of Argo data becoming available around 2004, the estimates are greatly improved and show

200 much improved agreement with climate models.

201

Future prospects

203 When Argo began in the late 1990s, it was by no means clear that the project would be successful in deploying

204 and sustaining an array of 3000 floats over the global ocean, as the required technology was in its infancy and

205 the degree of international cooperation required was unprecedented in the oceanographic community. Now, in

206 the second decade of the 21st century, the float technology is well proven, and over 30 countries are contributing

207 resources to Argo, making it sensible to contemplate expansions of its mission. The Argo Steering Team

208 (hereinafter AST) has provided a roadmap[46] for how the project might evolve and expand in the next decade,

209 and some of this proposed development is now underway via test deployments or regional pilot arrays. One

210 project is to support an increase in the spatial sampling resolution in special parts of the world ocean where the

211 ocean is especially turbulent (challenging the array's signal resolving power) and the interaction of the ocean

212 and the atmosphere and the resulting climate impacts are especially strong. Improved technology also allows us

213 to expand Argo into previously unsampled regions such as marginal seas and the seasonal ice-zone, implying

214 that the array is more truly global in its coverage than its original design.

215 Intense western boundary currents such as the Gulf Stream and Kuroshio are some of the most striking features

216 of the ocean circulation, serving to transport heat poleward as they carry warm tropical and subtropical waters to

217 higher latitudes. A sizeable portion of this heat is exchanged with the atmosphere along the path of the flow,

218 especially after these currents separate from the boundary and enter the interior of the ocean, altering the tracks

219 of storms and perhaps ameliorating continental climates[47]. When Argo data are used to map monthly and

220 seasonal evolution of the large-scale ocean structures in these regions, the errors are relatively high compared to

221 other regions due to the presence of the vigorous ocean turbulence associated with these boundary current

222 regimes and the lack of spatial resolution of the Argo array. This limits the ability of Argo to achieve one of its

223 main goals, which is to observe the slow evolution of the large-scale ocean structure in these important regions.

224 The AST has suggested that extra float resources should be committed to the study of these regions, and some of

225 the nations that contribute to the array have responded to this call.   In the western North Pacific, for example,

226 the boundary domain adjacent to China, South Korea, and Japan is already sampled at a spatial density nearly

227 three times the standard Argo protocol.   In the western North Atlantic, between Cape Hatteras and the mid-

228   Atlantic Ridge, the sampling is similarly dense. The ability of the program to enhance sampling in all western

229   boundary current regions is unclear, but these pilot activities will help demonstrate the gains made and thus

230   guide the future sampling recommendations.

231   A similar increase in sampling density is called for in near-Equatorial regions, where strong air-sea coupling can

232   produce global-scale atmospheric anomalies. The tropical Pacific, for example, is the gestation site of the

233   ENSO phenomenon, an irregular seesaw of oceanic warming and cooling that can, via strong coupled

234   amplification, drive global climate variability and cause economic impacts at sites far removed from the low-

235   latitude Pacific.   The Indian Ocean Dipole (IOD) is an analogous phenomenon that impacts Indian Ocean rim

236   nations[46]. The surface temperature and salinity associated with these phenomena can be monitored via satellites,

237   but Argo is now the main source of information on their deeper, subsurface expressions. Argo data are used in

238   model forecasts for ENSO and the IOD, and, along with the existing tropical moored arrays, are central to

239   providing and improving predictions of the onset and strength of these scientifically interesting yet socially

240   disruptive events.

241   Additionally, the AST has encouraged the deployment of floats in marginal seas, environments that are

242   regionally important to natural resources and trade. During the early stages of Argo it was decided to avoid

243   deployments in such areas, due to the likely premature loss of floats and troublesome political issues. More than

244   a decade later some of these issues remain, yet the scientific success of Argo has encouraged a number of groups

245   to begin Argo-like programs in several of the marginal seas of the world. Within the Euro-Argo European

246   Research Infrastructure Consortium that is coordinating European contributions to Argo, the MedArgo initiative

247   has maintained an array of more than 50 floats in these regions since 2008 and has plans for expansion. This has

248   helped to clarify the details of water mass formation in the Mediterranean and to improve predictions of the

249   basin-scale circulation by assimilating profile data into numerical models of the circulation. Argo-type efforts in

250   the marginal seas of East Asia have yielded new insights into the interplay of the local ocean and the regional

251   climate in these regions and the nature and causes of long-term changes in their properties, and data resulting

252   from deployments now underway in the Gulf of Mexico will likely eventually be useful in improved hurricane

253   prediction.

254   Argo was originally planned to cover the open ocean equatorward of 60°, thus purposefully avoiding regions

255   seasonally covered in sea ice.   A float trapped under sea ice cannot transmit its data, and, for floats that are

256   somehow able to get to the surface in the presence of ice, the danger of being crushed between floes is sizable.

257   In the past decade algorithms have been developed[48] that greatly increase a float's chances of surviving the

258   winter in the ice zone by inferring the presence of ice from the near-surface temperature structure.   Simply

259   stated, if the float determines that ice is present through an on-board analysis of the stratification, then it avoids

260   the surface (thus avoiding the ice), stores its profile and descends for another cycle. In the spring, when the ice

261 retreats and the float can reach the surface, all of its winter data can be transmitted, though without tracking

262 information. This concept has worked well[7,8] with floats in the seasonal ice zone surviving at about the same

263 rate as floats at lower latitudes. Based on this success, the large fraction of the area of the global ocean that

264 exists at high southern latitudes, and the importance of ice-covered regions around the Antarctic in setting the

265 conditions for meridional overturning, the AST has suggested that deployments in such regions should be

266 systematically increased. Several float deployment groups are now staging pilot deployments in these regions.

267 Beyond deployments in new regions and advances in float software, technological developments have provided

268 new capabilities to profiling floats that allow a larger range of scientific questions to be examined. As

269 originally designed, Argo was intended to be a program to examine the temperature, salinity, and heat content of

270 the world ocean and the climate implications of the variability in these quantities. In the past decade new

271 sensors have come into existence that also allow biogeochemical variables such as dissolved oxygen, nitrate,

272 chlorophyll, and pH to be measured from Argo-type floats. These sensors are small in both physical size and

273 power consumption and barely affect the duration of the basic float mission, and thus floats equipped with such

274 sensors allow the prospect of examining the impact of physical aspects of the ocean circulation on key

275 biogeochemical processes sensitive to the climate state, such as the biogeochemical cycle of carbon, ocean

276 deoxygenation, and ocean acidification[50]. These floats will also contribute to the improvement of the capabilities

277 of biogeochemical models[51] and to the extension of surface biogeochemical properties monitored by ocean color

278 satellites to deeper levels of the water column[52]. The AST has endorsed the general idea of taking advantage of

279 these new developments, while at the same time moving cautiously as the Argo data system gains experience in

280 ingesting and disseminating these new data types. While it is expected that the number of biogeochemical Argo

281 floats deployed will increase dramatically in the coming years, pilot projects in a few key oceanic areas where

282 carbon uptake is crucial will be carried out before envisaging the implementation of a biogeochemical float

283 program at the global scale. Several European efforts in this regard are underway in the North Atlantic.

284 Similarly, the mating of the under-ice capabilities and biogeochemical floats has led to plans by the Southern

285 Ocean Carbon and Climate Observations and Models (SOCCOM) group to examine the carbon cycle around the

286 Southern Ocean, a region responsible for roughly 40% of the global oceanic carbon uptake.[53,54]

287 In recent years a series of papers[55,56,57,58] have shown that the deep ocean well below 2000 m contributes a

288 significant fraction of the total water column increases in heat content and thermosteric sea level rise, especially

289 in (but not confined to) the high southern latitudes. This warming, in many cases present at all depths below

290 3000 m, has been deduced from an analysis of sparse but repeated high-quality ship-based observations of

291 temperature and salinity conducted since the 1980s. While the capability of making such measurements from

292 ships has existed for several decades, the cost of the vessels carrying out such work is high, often as much as

293 US$35K per day. Argo floats, on the other hand, are a seemingly more economical way to observe the ocean,

294   although the present generation of Argo floats generally samples no deeper than 2000 m. The economy may or
295   may not be illusory depending on the strategy used to deploy floats. If floats are deployed on a ship of
296   opportunity there may be no incremental launch costs, but strategic launches do often require a dedicated vessel.
297   In order to begin to explore the abyssal ocean and to refine present estimates of the warming of the deep sea, the
298   AST, has since 2012, supported efforts to develop floats capable of profiling deeper than 2000 m (to as deep as
299   6000 m) and to begin deploying these floats increasingly in 2015 and beyond. This is by far the most ambitious,
300   and technically challenging, development in Argo since the initial float deployments took place in the late
301   1990s. At the present time several prototypes have been tested that use new technologies, such as carbon-epoxy
302   filament wound cylindrical hulls for a 4000 m prototypes being developed in Europe and Japan, or hulls made
303   from glass spheres, for two 6000 m versions being developed in the US.   An additional issue is that the
304   temperature, salinity, and pressure sensors on these floats must be more accurate than for standard Argo floats,
305   since the variability in the abyssal ocean is likely to be considerably smaller than in the upper 2000 m of the
306   water column. Prototypes for the 4000 m versions have been successfully deployed in the N. Atlantic and N.
307   Pacific. A dedicated test cruise for deployment of 6000 m prototype floats and for calibration and validation of
308   new ultra-accurate temperature/salinity/pressure sensors took place in the western S. Pacific in mid-2014 and
309   successfully showed the promise of both the new deep floats and sensors. While the deep floats will surely be
310   more costly than present Argo floats, it is hoped that by 2020 systematic sampling of the abyssal ocean will be
311   implemented, with as much as 30% of the Argo array comprised of these deep floats. High-quality sampling of
312   the deep sea from dedicated hydrographic vessels will need to continue far into the future, however, even after
313   the full complement of deep floats is in place; the shipboard surveys together with Argo will provide a more
314   complete global sampling of the abyssal ocean, and the ship-based data will be necessary to monitor the quality
315   of the Argo data in the abyss.

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

323   The development of Deep Argo appears to be an especially crucial step in the evolution of the program.   The
324   present array has done a credible job of providing estimates of the heat content change in the upper 2000 m of
325   the world ocean over the past few decades, with the measured increases being significant but somewhat smaller
326   than the predictions of model-based global heat budgets.   Other studies[57,58] point to the even deeper waters of

327 the world ocean, beneath the present limits of Argo sampling, as a possible repository of the increased heating

328 necessary to close the global heat budget. Assessing this question, and making progress in other new directions

329 such as observing the oceanic carbon cycle from floats, helping to make improved forecasts of ENSO and IOD,

330 and probing the depths of marginal seas, will likely challenge the abilities of future leaders of Argo to push the

331 limits of evolution and revolution of the program in order to further increase our understanding of the circulation

332 of the ocean and its role in climate.

333 In conclusion, it is important to remember that the prize we are aiming for is an understanding of how the ocean

334 is changing both naturally and as a result of human activities. That said, Argo is indeed a major accomplishment

335 but it does not stand alone. Recently five programs have been brought together in the JCOMMOPS (Joint

336 Commission on Oceanography and Marine Meteorology Operations) office. This includes moored buoy

337 activities such as the equatorial arrays and the individual moorings sponsored by the OceanSites program, also

338 the XBT surveys and the repeat ship-board hydrographic surveys sponsored by the GO-SHIP program. Many of

339 these supply data in real-time in parallel with the Argo program. With all of these programs now operating

340 under a single umbrella the supply of data from the oceans is undergoing a profound transformation.

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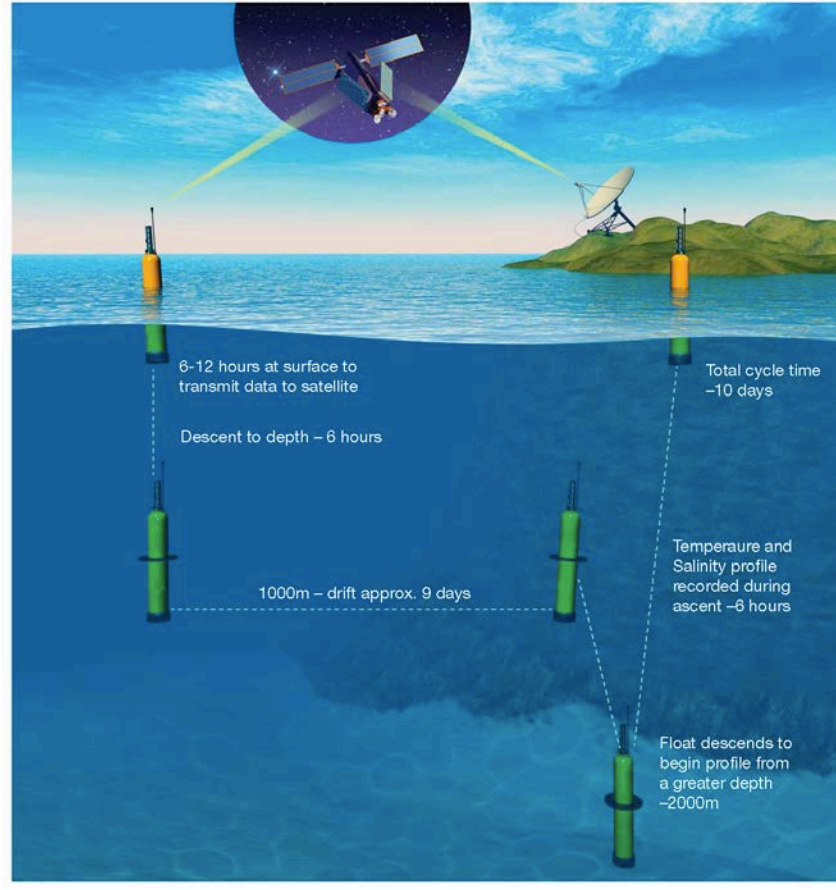
Figure 1. In the cycle typical of an Argo float, a float starts at the surface and dives to a depth of 1000 meters
(the parking depth) where it rests for 9 to 10 days. After 9 days at rest it dives to a depth of 2000 m, turns on its
sampling equipment and measures ocean properties as it rises to the surface where it rests for sufficient time to
transmit the data collected to Argos 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.

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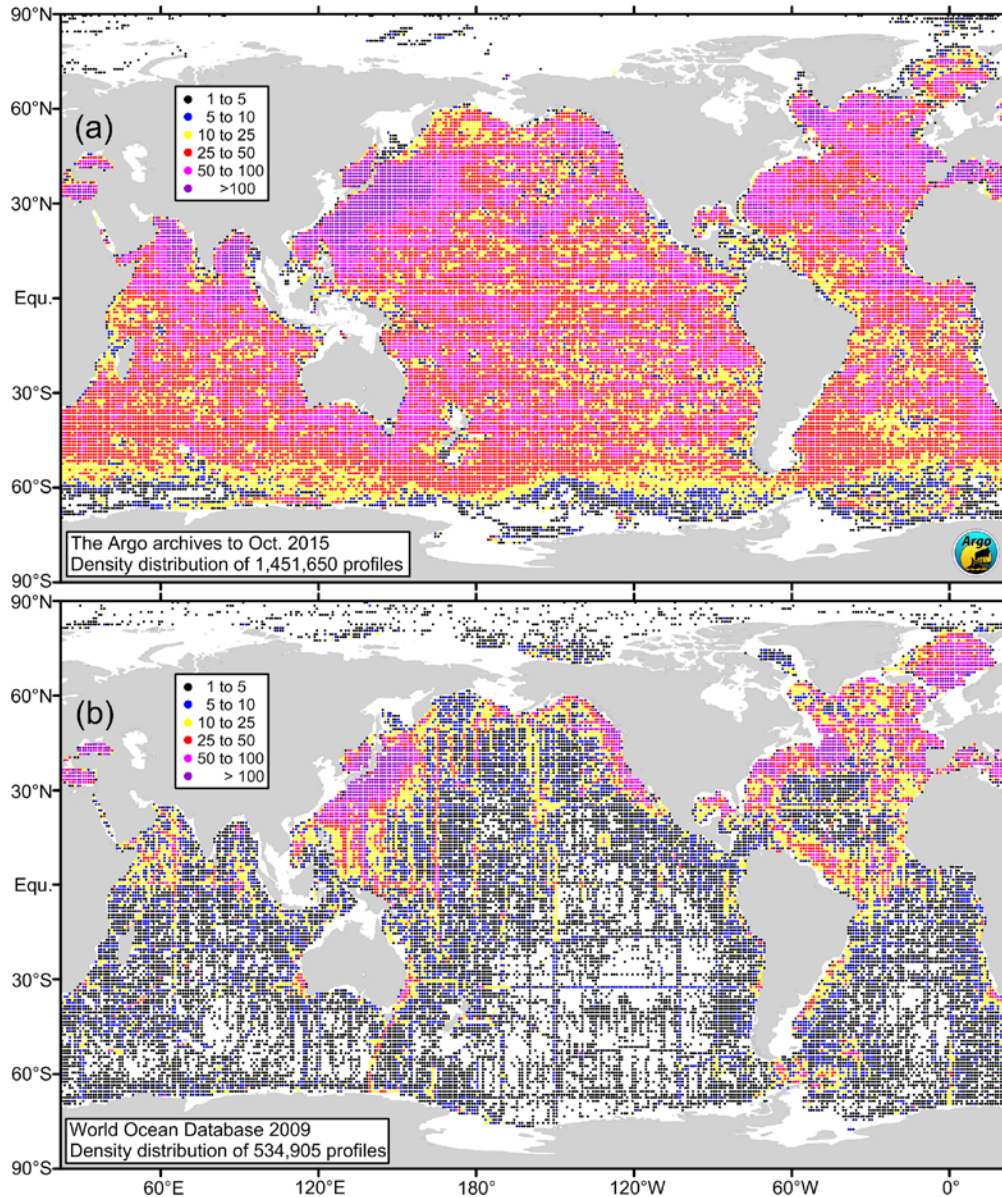
Figure 2. The sampling density of profiles reported by Argo floats[4] (upper panel; ~1.5 million collected between 1999 to Oct. 2015), and (lower panel) by the most complete assembly of all previous historical efforts (0.5 million largely shipboard observations collected over the past 100 years from the World Ocean Data Base 2009[3]) . This sampling density is computed as the total number of samples in each $1°$ latitude $\times$ $1°$ longitude square and is color coded according to the legend on each panel. The analysis only includes profiles that sample both temperature and salinity to a depth

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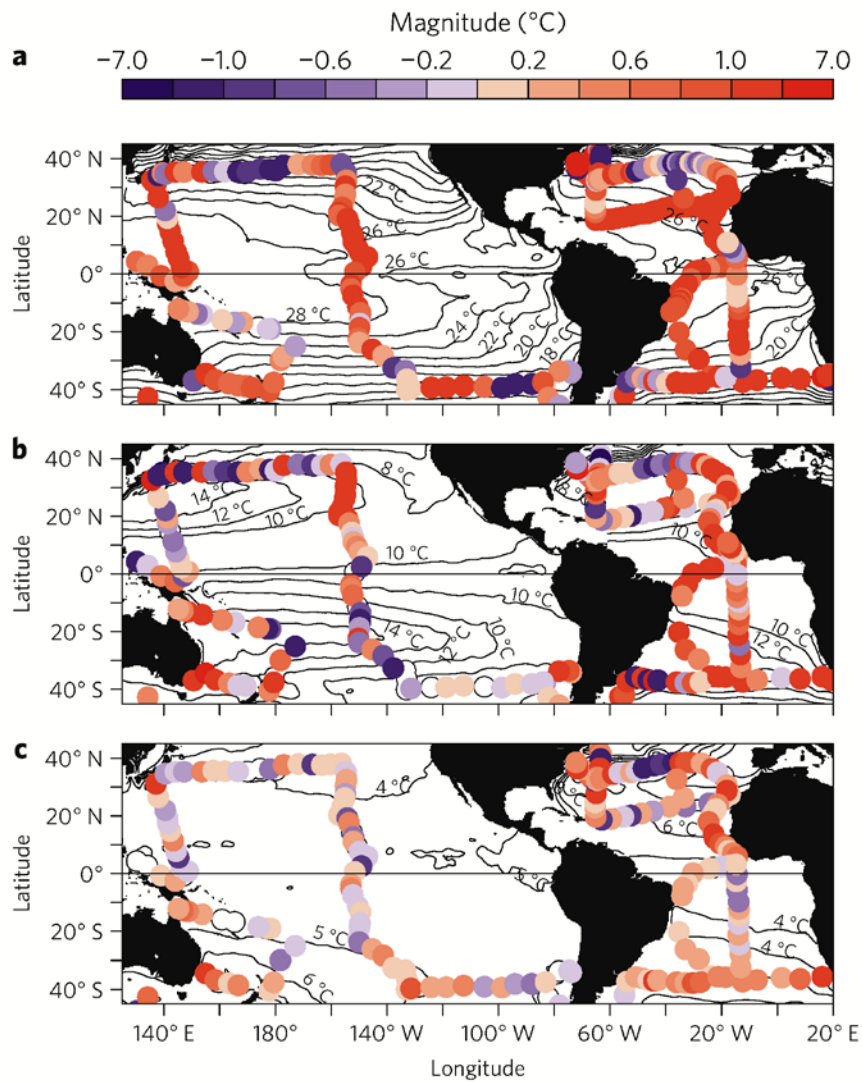
of 1000 m or deeper.

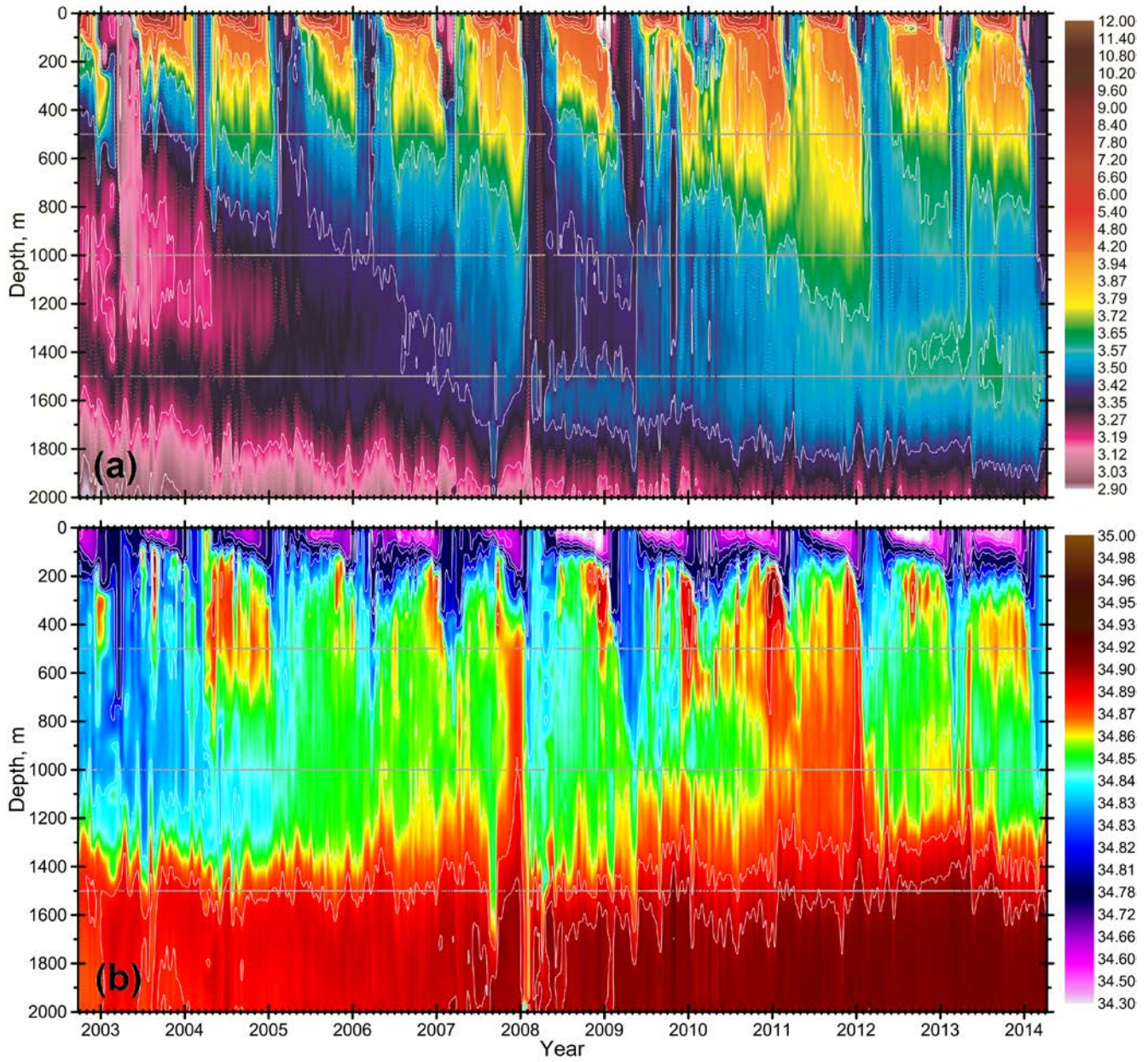**Figure 3**: Contours of the mean temperature over the period 2004-2010 in the global ocean[26] at (*a*) the sea surface, (*b*) a depth of 366 m, and (*c*) a depth of 914 m, using Argo data; the dots denote the Argo minus *Challenger* temperature difference, according to the color scale. Reprinted from (*23*).
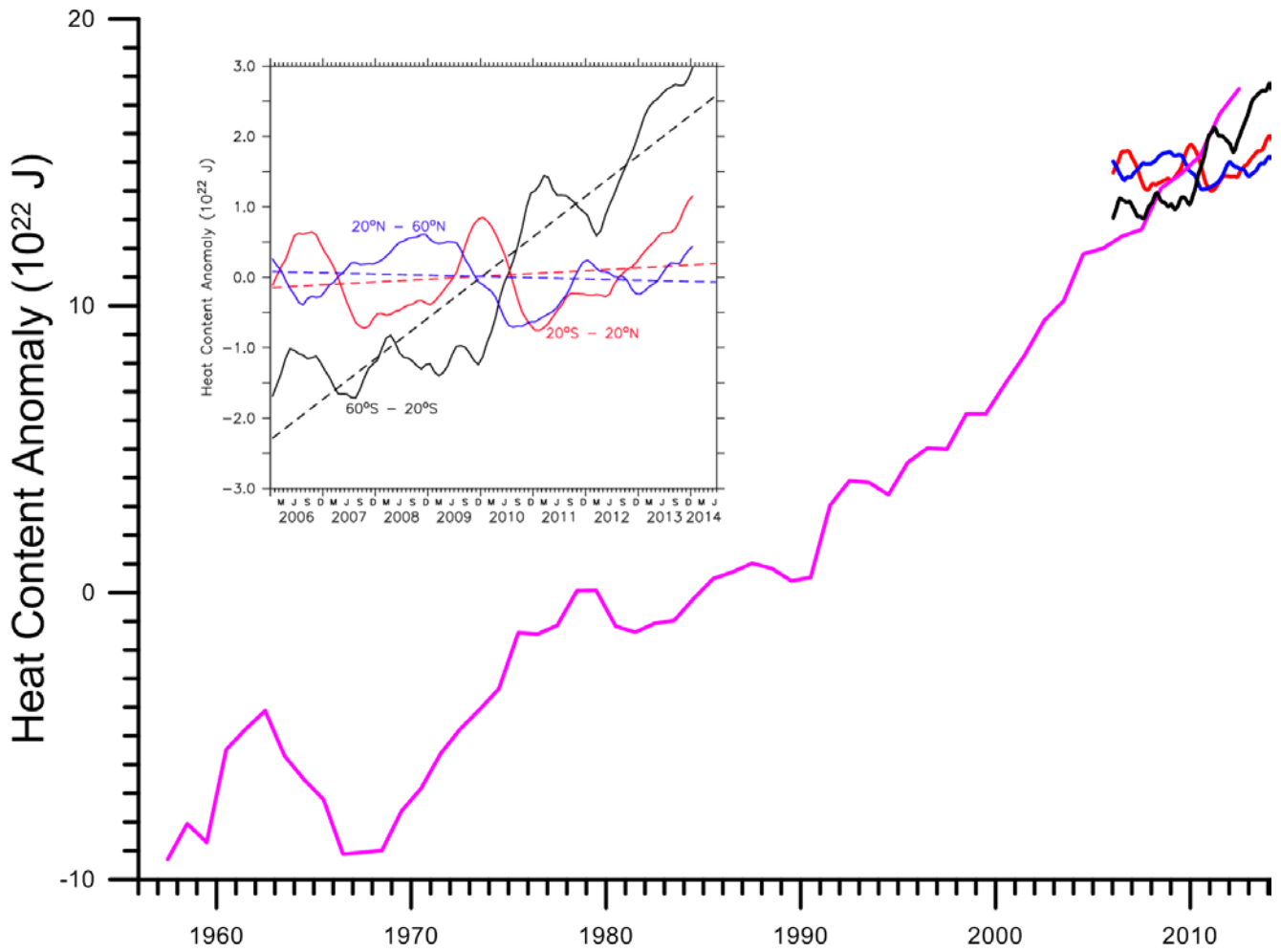
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610　Figure 4. The seasonal to interannual evolution of potential temperature (a) and salinity (b) in the upper 2000 m

611　of the Labrador Sea during the period 2002-2014, compiled from Argo observations and recomputed from data

612　forming the original figure published by Kieke and Yashayaev[33].

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Figure 5: Estimates of the global heat content anomaly[27], for latitude ranges 60°S–20°S (black), 20°S– 20°N (red), and 20°N–60°N (blue), computed as 12-month running mean values and shown as an inset. Smoothed trends are shown as the dashed lines on the figure in the same colors; the colored numbers in parentheses refer to the estimate of the trend of the same color in units of 10^{22} Joules yr^{-1}. In the main diagram the mean values are changed so that they overlay the 0-2000m heat content computed by Levitus et al.[44]