Environmental Issues and the Argo Array

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Introduction

The Argo array provides a vital operational and research data stream that underpins important nowcast and forecast services, science, and policy assessments. The array contributes to saving lives, avoiding property damage, informing the public and government's response to environmental variability and change, and to sustainable management of marine resources and the preservation of ocean health.

Argo uses simple profiling floats (often referred to as *robotic floats*, *robotic profiling floats*, or simply by the generic term *Argo floats*) that operate for intervals of 3-6 years in the ocean, returning profiles of ocean properties (temperature, salinity and, increasingly, oxygen, nutrients and bio-optical parameters) every 10 days. The floats operate throughout the global oceans, usually in remote regions where there is little ship traffic. Around 30 nations contribute to the ~3500 float array. To maintain global coverage, between 600 and 900 floats are deployed each year.

Data from Argo floats are returned via satellite. These data are shared within 24 hours and are freely available to the public via the internet, and are sent to operational forecasting centers globally for use in producing routine weather and environmental forecasts. No other practical technology presently exists to replace profiling floats as the workhorse for this necessary and highly utilized global ocean observing system. We attempt herein to examine the environmental impact of operating the Argo program and to consider the possible alternatives to obtaining a comparable data stream.[*] In what follows, we provide an

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[*] An earlier *Environmental Assessment* of Argo from the year 2000, created in order to address requirements in the US National Environmental Policy Act operative at that time, concluded that the project was "… in agreement with our national laws that reflect our compliance with international treaties and conventions."

updated assessment of the environmental impact of the floats in the Argo array and the concomitant ship resources required for their deployment and possible recovery.

Environmental Impact of the Floats During Their Lifecycle

(*i*) *Deployment phase*

Most Argo floats are deployed by volunteer vessels, including commercial ships, research vessels (doing other work), and sailboats. The deployment procedure is generally simple, requiring only a few minutes at the deployment station. Floats can be deployed either unclad or inside biodegradable cardboard or cornstarch boxes held together with dissolving biodegradable tape.

Argo leases one small research vessel for 40 days per year, which is used to deploy floats in the vast South Pacific and Indian Ocean basins (about 100 floats per year are deployed), where ship resources are generally extremely scarce. Otherwise, floats are often air-shipped to meet the volunteer deployment vessels. The carbon emissions due to Argo are thus relatively low compared to alternative means of obtaining the same information, such as intensive *in situ* sampling from dedicated research vessels, as will be examined in more detail below.

(*ii*) *Operational phase*

The use of modern satellite positioning and communications systems such as Iridium has allowed Argo to reduce the time a float spends transmitting a data profile while at the surface to around 20 minutes (compared to ~1 day previously, using the older Service ARGOS system). This means that floats spend very little time at or near the surface, where the vast majority of ocean biomass exists. Thus, float interaction with most marine life is limited. In the past, when float grounding rates where higher, interactions with marine life likely occurred at a higher rate. It is Argo's stated policy that floats grounding on coasts should be retrieved and safely disposed of whenever possible. Floats stranded on shallow continental shelves would quickly become subject to extreme biofouling, thus losing buoyancy and sinking to the sea floor, where they would likely be permanently trapped.   With shorter transmission times at the sea surface, floats largely remain in deep waters, resulting in many fewer groundings.

While floats are operating, a small quantity (a few milligrams) of *tributyl tin oxide* (TBTO) is released into the water column during each profile. This substance, present in tablet form inside the float's CTD sensor package, is a biocide that is weakly soluble in seawater and commonly used in the shipping industry to eliminate biological growth on vessel hulls. In Argo, it is used to prevent biological fouling of the conductivity sensors, from which salinity is derived. Some of this TBTO will be flushed into the deep ocean (near 1000 m depth) during the initial stage of each profile, after the quiescent 10-day park phase of the float mission. We expect any environmental impacts of this TBTO to be minimal, due to a speedy dilution of the substance by the ocean and the fact that the floats are hundreds of kilometers apart, ensuring vanishingly small concentrations of this substance at any single site.

(*iii*) *End-of-life phase*

As Argo floats largely operate in remote offshore ocean regions devoid of ship traffic, retrieval prior to cessation of operation is usually not practical (see below). For this reason, most Argo floats are not recovered once they reach the end of their life, having exhausted their batteries 3-6 years after deployment. Upon "death", floats will likely drift silently in the deep ocean (somewhere between their parking depth of 1000 m, and the maximum profiling depth of 2000 m) until eventually the aluminum hull is breached via corrosion, initiating a leak. At this point the float will flood with seawater and sink to the seafloor (mostly over deep abyssal regions), where the corrosion and decomposition process will take place over the course of a number of years. Most of the mass of the float (~70%) is composed of aluminum (see Table 1), which will slowly corrode into largely harmless oxides and be dispersed by the deep ocean circulation and near-bottom turbulence. Plastic float components (which have been reduced to around 8% of the float mass in modern designs) will likely degrade only very slowly. Studies[1] have shown that any TBTO remaining in the float after it sinks to the seafloor will likely end up in marine sediments, where it will break down into inert, harmless components in a few weeks. The remaining float mass is mostly comprised of the instrument's batteries, which include small quantities of potentially toxic metals, including copper, zinc, lithium, and lead. The speed at which these corrode and the level of concentration present around a dead float are not known and will likely vary with local conditions on the seafloor. However, given the generally slow corrosion rates in the deep ocean, the speed of abyssal currents and the strength of near-bottom turbulence, and the large distances between floats (~300 km), a significant, local, short-term concentration of dissolved metal salts originating from a float seems unlikely.

We have attempted to assess the impact of the products of Argo float decomposition at the seafloor by comparing the net input of each of these substances into the global ocean from floats with the fluxes from natural and other sources, as given in Table 1 below. The values given for fluxes of plastic and TBTO in the fourth column represent anthropogenic fluxes, as there are no natural fluxes of these quantities. The other quantities in the fourth column are for natural fluxes only, as they are generally several orders of magnitude larger than the corresponding anthropogenic fluxes. We have scaled the *Argo flux* (column 3) for an amount resulting from 900 floats, an upper bound on the number of floats that might die per year and require replacement. The table clearly shows that Argo's annual inputs are infinitesimally small compared to the background fluxes of these components into the ocean. We note as an example that it would take over 176,000 years of Argo operations to inject the same amount of aluminum into the ocean that is employed annually to produce soda drink cans (200 billion per year at 15 grams/can); that a single year of the human contribution of plastic to the ocean is equivalent to 4.4 million years of the input from Argo; and that one year of the natural flux of lead into the ocean is equivalent to 83 million years of Argo operations.

TABLE 1.

Material	Amount per float (kg)	Argo flux for 900 floats (kg/yr)	Total Flux into the ocean (kg/yr)	Float fraction of the total flux
Copper	0.1	90	1.7×10^{9} (2)	5.3×10^{-8}
Zinc	0.05	45	7.7×10^{8} (3)	5.8×10^{-8}
Plastic	2	1800	8×10^{9} (4)	2.3×10^{-7}
Lithium	0.2	180	2×10^{6} (5)	9×10^{-5}
Lead	0.8	180	1.5×10^{10} (6)	1.2×10^{-8}
TBTO	0.004	3.6	3×10^{3} (7)	1.2×10^{-3}
Aluminum	18	1.7×10^{4}	2.7×10^{11} (8)	6.3×10^{-8}

The impact of TBTO, which continues to be extensively employed as a biocide in paint for the hulls of ships, can be assessed by noting that it is typically present in paint in concentrations at a level of ~ 5 g/kg of paint[(7)]. For a typical vessel used in global research (~ 60 m length), as much as 2000 liters of paint might be required to cover the hull below the waterline. For a specific gravity of 1.5, this is roughly 3000 kg of paint, or about 15 kg of TBTO per vessel. Even if only 1000 such vessels (the global merchant fleet comprises ~95,000 vessels) are painted at 5-year intervals, the flux of TBTO into the ocean from commercial shipping would then be roughly 3000 kg/yr, far in excess of the amount of TBTO input from 900 Argo floats/yr sinking to the seafloor.

Environmental Impacts of Alternative Methodologies

(*i*) *Expendable bathythermographs (XBTs)*

Prior to Argo, the most common method for collecting subsurface ocean temperature profiles on a basin-scale was the widespread use of devices known as *eXpendable BathyThermographs*, or XBTs. These devices were invaluable and contributed immeasurably to our knowledge of the ocean circulation for several decades. The instruments consist of a 40 cm long torpedo-shaped body made of zinc and plastic, with a thermistor at the tip, and are connected to the launch vessel by up to 2000 meters of fine copper wire, which is used as an electrical path to return the data. Once launched from an underway vessel, the probe free-falls, collecting and reporting temperature via a shipboard acquisition system. After completing the collection of a profile, the copper wire breaks and the probe and wire fall to the seafloor. A typical XBT is comprised of 575 g of zinc in the probe nose, 112 g of expendable copper wire on the spool, and 52 g of plastic in the afterbody[(9)] . The Argo array presently collects roughly 120,000 temperature profiles per year. If these were collected using XBTs (assuming that ships were available to carry out this work where needed), this would result in 69,000 kg/year of zinc being fluxed into the ocean (compared to 45 kg/yr from Argo), 13,440 kg/year of copper (versus 90 kg from Argo), and 6240 kg of plastic (compared to 1800 kg from Argo). Thus, even discounting the important issue of a lack of deployment vessels over many major ocean regions (plus the fact that most XBTs do not measure salinity), and the fact that the temperature/depth accuracy that can be achieved with XBTs is not sufficient for Argo's climate mission, the use of XBTs instead of profiling floats would surely have a far greater environmental impact than that resulting from Argo.

(*ii*) *Profiles collected from dedicated research vessels*

Research vessels are the only other platform that can currently operate across the vast ocean areas covered by Argo and sample the subsurface ocean. Ships with appropriate salinity/temperature and depth measuring equipment can collect profiles having equal or better accuracy than can be obtained from Argo floats, and sampling from ships does not leave behind any instrumentation that might befoul the ocean. Coordinated ship-based surveys such as WOCE and GO-SHIP (*https://www.go-ship.org*) are invaluable and have demonstrated the high quality and diverse types of data that can be collected from dedicated research vessels that occupy a few thousand stations per year. As an example, in 2016 the GO-SHIP program sponsored over 20 cruises and collected more than 1200 high quality, full water column ship-based data profiles.

In contrast, Argo presently collects about 120,000 surface-to-2000 meter profiles per year from the world ocean, from an array of over 3000 floats. Assuming 300 km spacing between floats or stations, a time of 3 hours to carry out a shipboard CTD cast to 2000 m, and a typical vessel speed of 10 knots (18 km/hr), more than 15,000 days of dedicated ship time per year would be required to collect the equivalent of the annual Argo data production using ships alone. The cost of research vessels of the class required for collecting this ship-based data can be as high as $50,000 per day, amounting to a potential total cost of over $750M per year. It is obvious that such resources are not available and such a vessel-based program is not feasible, which is one main reason why the ocean was not adequately monitored prior to the advent of the Argo program.

Beyond the cost of the ship time itself in this scenario there exists the additional environmental cost in the form of the carbon footprint associated with the requisite deployment vessels. A typical research vessel might burn as much as 25,000 kg of bunker fuel per day[10], resulting in a flux to the atmosphere of roughly 75,000 kg/day of CO_2 [10], or over 27,000,000 kg per year (note: for comparison purposes, a typical passenger automobile in the US adds about 2600 kg of CO_2 to the atmosphere per year[11]). For the 15,000 dedicated ship days per year necessary to collect 120,000 ship-based data profiles, the CO_2 emission to the atmosphere would soar to over 1 billion kg of CO_2 per year. Thus, the financial burden of duplicating Argo from shipboard measurements and the associated environmental costs would be mutually prohibitive. While it is true that hundreds of Argo floats are deployed each year from several kinds of vessels, most of these floats are deployed using ships-of-opportunity (such as GO-SHIP cruises), with little or no additional CO_2 emissions required for the float deployments. An exception to Argo's reliance on ships-of-opportunity is the use of the relatively small New Zealand research vessel *Kaharoa*, which typically deploys 100 or so Argo floats per year in the South Pacific or Indian Oceans. One voyage of *Kaharoa* per year uses about 50,000 kg of fuel, resulting in CO_2 emissions of roughly 150,000 kg to the atmosphere, which is less than the carbon emissions from a single commercial transatlantic flight[12].

Recovering Argo floats

The vision of a seafloor graveyard of dead floats is aesthetically unpleasant, and the resulting efflux as these floats corrode and decay is less than desirable from an environmental perspective. With these issues in mind, the question is often raised as to whether it is possible to recover the floats while they are still operating (presumably near the end of their projected life). Assuming that ship resources were available, such recoveries would, in principle, be possible, especially for floats with two-way Iridium communications. In this case the float operator could send a command to a float to remain on the sea surface and to continue to transmit its location information at regular intervals until a vessel arrived to recover it. While this would appear to be straightforward, the exact location where the float will surface is unknown in advance, so a recovery vessel might have to spend several days patrolling a sector where the float is projected to appear, then additional time hunting for the float once it is on the surface. This projects to be an expensive operation in many instances, likely costing far more than the initial cost of the float itself. Such recoveries would likely have to rely on the fortuitous availability of a vessel in the region, as in most cases ship schedules are finalized many months in advance of an expedition, when the ultimate position of a float to be recovered would be unknown. The lack of availability of suitable vessels to carry out float recoveries is a major limitation to implementing this practice.

Yet even more limiting are the same financial and environmental costs associated with ships, as was discussed previously. If somehow enough suitable vessels were available to recover 900 floats per year, and we assume that 2 additional days of ship time were required for the recovery (in addition to whatever else the vessel was doing), then at least 1800 days of ship time per year would be required to recover 900 floats. At a cost of $50K per day for each ship, such recoveries would cost $90M per year, obviously a prohibitive number. This annual cost alone would be sufficient to fund the international Argo program in its present form for several years. Additionally, using the carbon footprint estimates provided previously, these recoveries would add an additional 135 million kg of CO_2 to the atmosphere, equivalent to the annual emissions from 52,000 passenger cars[11]. While the recovery of a few floats each year for engineering purposes might be desirable, the financial expense and the environmental cost of embarking on a major program for recovering hundreds of Argo floats annually would seem to be neither practical nor acceptable.

While a large float recovery effort as part of Argo seems undesirable, it is still useful to recover some floats where the recovery operations are simple and require little in the way of incremental ship resources, such as in marginal seas. New models of floats or prototypes with advanced technical features are often deployed near coastal research laboratories or mid-ocean islands, where recovery is simple and requires only a few hours of ship time. Such efforts are necessary and should continue. In a similar vein, the previous estimate of resources required for float recoveries assumed that 2 days of vessel might be necessary for each float recovery. But in cases where floats are near to shore or in the proximity of a research laboratory or an ongoing research cruise, or in marginal seas, this estimate could be too large, and the recovery of a float would be more economical from both financial and environmental perspectives.[13,14] Such recovery operations should be supported and encouraged whenever appropriate.

Conclusions

As the first global-scale, subsurface ocean observing system, the Argo program has revolutionized our understanding of the ocean circulation and its relation to climate. We note that if laid side-by-side, all of the Argo floats deployed to date would cover no more than two football fields. The main environmental impact of the more than 3000 floats operational in the array would appear to be the release of pollutants into the ocean environment, mostly over a period of years after the floats have exhausted their batteries, begun to corrode, and sunk to the seafloor. As indicated in Table 1, however, the chemical species injected into the abyssal waters during this process represent generally infinitesimal amounts in comparison to the natural and anthropogenic fluxes of these substances. Moreover, the relatively large spacing between floats on a statistical basis (~ 300 km) and the presence of often substantial currents and turbulent mixing near the seafloor suggests that it is unlikely that large, potentially harmful concentrations of these foreign substances will accrue at any given float site.

It has often been suggested that Argo's environmental impact might be mitigated by recovering the floats near the end of their lives. While it might be desirable to retrieve a few floats for engineering studies or where the floats are near to ongoing vessel operations, the financial cost of the recovery of many hundreds of floats per year would be prohibitive, and the resulting ship-based carbon emissions associated with such recoveries would likely be far worse than the trace quantities of foreign substances emanating from dead floats on the seafloor enumerated in Table 1.

Alternative (and historically very successful) methods of observing the subsurface ocean on a global scale consist of (1) ship-based XBT programs and (2) ship-based surveys employing CTD equipment and water samplers at fixed station locations. The first of these could be carried out from underway vessels, including container ships, although it is clear that true real-time, global coverage at 300 km spacing would be nearly impossible to achieve. In addition, a global XBT program equivalent to Argo would result in a massive quantity of copper wire being left in the ocean as a waste product, along with substantial amounts of zinc and plastic. In order to achieve even partial global coverage, it is likely that substantial dedicated deployment vessel time would be required, potentially resulting in large CO_2 emissions. And even without these issues there is the problem that XBT data (with or without measured salinity) are unlikely to be of sufficient accuracy and precision for carrying out state-of-the-art climate research.

The second alternative, ship-based global surveys using state-of-the-art instrumentation (such as the GO-SHIP program) could observe the ocean with higher precision and accuracy than Argo, with many more quantities measured. But the costs of ship resources required to do this at the space/time resolution equivalent to Argo, along with the associated carbon emissions, would be prohibitive, with the annual financial burden of the ship time alone many times higher than the cost of several years of the Argo program.

We conclude that presently there is no method of observing the subsurface global ocean that is more cost effective and less environmentally damaging than Argo. Since Argo floats are mainly deployed from ships-of-opportunity, the marginal financial and environmental costs of float deployment are each relatively small. The main environmental effect of Argo comes from foreign substances released from old, dead floats on the seafloor, but the amount of these pollutants entering the ocean is extremely small compared to natural and anthropogenic fluxes. In the future there may be a cheaper and cleaner global observing system that results from improvements in Argo technology or from some new methodology that is presently unknown. In this vein, Argo will continue to work with its manufacturers to advance the technology in order to further reduce its environmental footprint, and to carry out float recoveries in cases where the added environmental footprint is not too large.

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