Taking the Ocean's Pulse

A Vision for the Canadian Biogeochemical Argo Program

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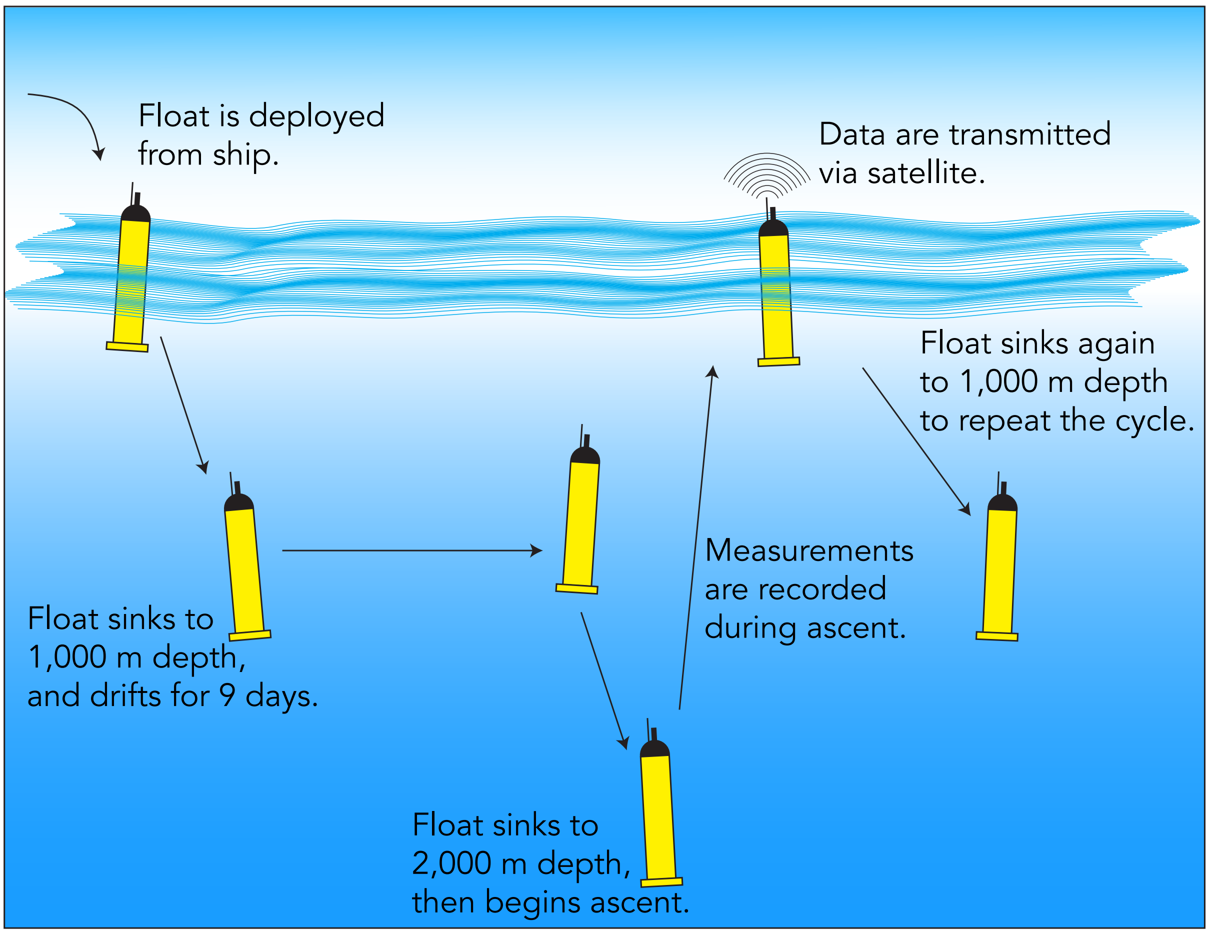
and

Participants of the Canadian BGC Argo Workshop



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MARINE ENVIRONMENTAL OBSERVATION PREDICTION & RESPONSE NETWORK

This report is a contribution to the international biogeochemical Argo (BGC Argo) program.

Workshop funding from the Department of Fisheries and Oceans and the MEOPAR Network of Centres of Excellence is gratefully acknowledged.

To be cited as:

Katja Fennel, Blair Greenan, and participants of the Canadian BGC Argo workshop, (2017), Taking the Ocean's Pulse: A vision for the Canadian Biogeochemical Argo program, doi:10.13155/52451.

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Executive Summary

The international Argo Program, described in the NYTimes[1] as *one of the scientific triumphs of our time,* has fundamentally transformed our ability to measure interior properties of the ocean. Argo is a global array of almost 4,000 autonomous profilers measuring temperature and salinity in the upper 2,000 m. These observations are relayed by satellite and available within hours of collection. While traditional sampling from research vessels is important, it is too infrequent and geographically limited to observe the dynamic and rapidly changing ocean adequately. Satellites provide broad-scale views, but are limited to the surface and in terms of the properties they can observe. Over the past two decades, Argo floats have collected over a million profiles of temperature and salinity, twice the number obtained by research vessels during all of the 20th century. These unprecedented views of the ocean's interior physical properties have enabled quantification of ocean warming due to climate change, and resulted in significant improvements in ocean and weather forecasting.

The ocean's biogeochemical properties are also changing rapidly, with profound impacts on ecosystems and climate, but to date, our ability to observe these changes is limited. The proposed biogeochemical extension of the Argo network (BGC-Argo) would revolutionize our ability to observe the ocean's changing biogeochemical state enabling us to observe seasonal to decadal-scale variability in biological productivity, ocean acidification, and ocean deoxygenation, as well as allowing quantification of the ocean's uptake of CO_2.

In 2016, the Science Plan[2] for BGC-Argo was formulated by an international group of experts. The plan calls for an additional 1,000 biogeochemical floats that would measure pH, oxygen, nitrate, chlorophyll, suspended particles, and light. The biogeochemical extension of Argo has been specifically mentioned by the G7 Science Ministers in their Tsukuba Communiqué in May 2016, which calls for *an enhanced and sustained global observing system that integrates new chemical and biological observations, while sustaining critical ongoing observations.*

In January 2017, a group of scientists from the Canadian federal government and universities gathered to discuss opportunities for Canada that arise from the international BGC-Argo initiative. Their recommendations are summarized in this document. It is clear that Canada is well positioned to play a leadership role in an expanded global ocean measurement program, and that the nation would derive significant scientific and technological benefits from it. In addition to addressing fundamental questions about our changing ocean—questions that have significant societal implications—the program holds economic opportunities for Canada's vibrant and thriving ocean economy sector.

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[1] Gillis, J. (12 August 2014), In the Ocean, Clues to Change, *New York Times*, D3.

[2] http://biogeochemical-argo.org/cloud/document/science-implementation-plan/BGC-Argo_Science_Implementation_Plan.pdf

Pressing Issues in Canada's Oceans

Anthropogenic perturbations of the global carbon and nitrogen cycles are leading to fundamental changes of physical and chemical ocean properties, including water temperature, density stratification, circulation patterns, nutrient regimes, oxygen levels, carbon storage, and pH. Global warming is primarily ocean warming, in the sense that the ocean has absorbed over 90% of the heat added to the Earth system by man-made greenhouse gases (Rhein et al. 2013). A warmer ocean and increased vertical stratification diminish oxygen supply to the subsurface and deep ocean (Schmidtko et al. 2017). This deoxygenation results in expanding oxygen minimum zones in coastal and open ocean regions with direct negative impacts on ecosystems. Deoxygenation and changes in stratification will likely also reduce the availability of nitrate, the major plant nutrient that limits primary production in the ocean. A reduction in nutrient availability will strongly affect planktonic communities that support the marine food web, and play a major role in regulating the ocean's uptake of carbon and thus in the overall climate system.

In addition to absorbing heat, the ocean absorbs atmospheric CO_2. This mitigates global warming, but decreases ocean pH—a process referred to as ocean acidification. Low pH has direct negative impacts on organisms that form calcium carbonate structures such as oysters, lobsters, and marine snails (pteropods). Ocean acidification may also disrupt feeding relationships with effects cascading through marine feed webs, e.g., by threatening wild Pacific salmon, which rely on pteropods as their primary ocean food source.

Despite the expected effects of anthropogenic carbon and nitrogen cycle perturbations on ocean circulation, climate, the base of the marine food web, and higher trophic levels of the marine ecosystem (including species of commercial importance or endangered status), our ability to observe ocean biogeochemical changes is limited. Vast areas of the ocean are presently sampled only once per decade or less by research vessels. While this direct sampling provides high-quality reference observations important for calibration of autonomous sensor measurements, the severe undersampling inherent in ship-based observations greatly hampers our ability to observe natural variability and detect anthropogenic changes in the ocean. This limits our capacity to understand, quantify, and predict changes in carbon storage, and its effects on climate and marine ecosystems.

Some of the most rapid changes and globally most important processes are occurring in Canadian ocean waters. Deep convection in the Labrador Sea in late winter produces a cold, relatively fresh, carbon- and oxygen-rich water mass, which together with other deep-water masses formed in the Nordic Seas feeds the deep branch of the global overturning circulation. The overturning circulation supplies the subsurface of the global ocean with oxygen and modulates global climate (Pérez et al. 2013). Deep convection in the Labrador Sea is thus important for ventilating the subsurface ocean, in particular in the

North Atlantic (Wolf 2017), and in driving ocean uptake of anthropogenic CO_2, but also exacerbates ocean acidification along Canada's sensitive and commercially important eastern continental margin (Azetsu-Scott et al. 2010). Access by ship to the Labrador Sea during the winter convection period is difficult and expensive. Biogeochemical Argo observations can fill this crucial gap.

In the subsurface North Pacific, which is naturally low in oxygen and pH because it lies at the end of the global overturning circulation, oxygen and pH levels are declining rapidly in mid-depth waters (Whitney et al. 2007, Keeling et al. 2010, Byrne et al. 2010). The resulting hypoxia and acidification are already impacting marine ecosystems along Canada's west coast (Irvine and Crawford 2011, Haigh et al. 2015). Oxygen trends show significant temporal and spatial variability, making them difficult to discern from sparse ship-based measurements (Crawford and Peña 2016). A network of biogeochemical Argo floats would vastly improve our ability to observe and understand these trends.

The Arctic is the most rapidly warming region on Earth and is projected to be free of summer sea-ice by the middle of this century (Wang and Overland 2012). Since most primary production in the Arctic Ocean occurs at the ice edge, the rapid decline in ice cover profoundly affects marine ecosystems, but our understanding of these impacts is limited. Some studies suggest that increased stratification due to ice melt favours small phytoplankton and therefore limits the transfer of energy to higher trophic levels (Li et al. 2009, 2013), while other studies have suggested that expanding open water regions may become more productive due to increased mixing from intensifying Arctic winds (Arrigo et al. 2011, Ardyna et al. 2014). Given the challenges related to fieldwork in the Arctic, autonomous biogeochemical Argo floats represent an unprecedented opportunity for seasonal monitoring of chemical and biological ocean properties.

Another key benefit of biogeochemical Argo observations is the ability to detect episodic and unexpected ocean and climate phenomena. A striking example of this was the occurrence of very warm surface waters (>3°C warmer than normal) that developed offshore British Columbia in the winter of 2013-14. This warming phenomenon, which became known as "The Blob," was unprecedented in the historical record (Bond et al. 2015). Temperature and salinity observations from Argo floats were instrumental in detecting this event, demonstrating its magnitude, spatial extent, and duration (Freeland 2014). Fortuitously, some biogeochemical impacts of this event were measured by Argo floats with oxygen and nitrate sensors, which showed that the warm surface layer prevented deep winter mixing and resulted in low nutrient replenishment to the surface waters, suppressing ocean productivity in 2014 (Plant et al. 2016, Whitney 2015).

These examples, along with others that could be listed for all three ocean basins adjoining Canada, make it clear that we need to find a new way to monitor ongoing, and predict future, changes in Canadian ocean waters. The BGC-Argo program can provide an ideal solution to the undersampling problem. With it, Canadian researchers would be enabled to identify trends in crucial ocean and ecosystem properties and investigate the underlying causes. This would drive a transformative shift in our ability to observe and predict the effects of climate change on ocean productivity, its uptake of CO_2, loss of oxygen, and acidification in Canadian waters. The resulting scientific breakthroughs will enable Canada to address pressing societal questions ranging from accurate accounting of ocean carbon sinks to science-based management of its living marine resources.

An Opportunity to Transform Ocean Observation

The recent maturation of autonomous robotic platforms and miniaturized sensors provides, for the first time, the technological capability to make sustained observations of physical, biological, and chemical ocean properties as they vary globally in three-dimensional space. BGC-Argo is an envisioned extension of the highly regarded and successful international Argo program (Riser et al. 2016), that measures ocean temperature and salinity with ~4,000 autonomous profiling floats distributed throughout the global ocean (see top panel on back cover). Canada has been, and continues to be, a significant contributor to the Argo program. BGC-Argo will significantly expand the existing Argo capabilities by adding floats equipped with sensors that measure chemical and bio-optical properties.

Argo floats are free-drifting, battery-powered devices that park at 1,000 m for 5 to 10 days, then profile the water column by first descending to 2,000 m depth before rising to the surface and collecting measurements at prescribed depth intervals (see cover image). At the surface, float location is determined by GPS, its position and ocean measurements are communicated to receiving stations via satellite, and made publicly available within 24 hours. Each float measures 150 to 300 profiles over the course of its battery life depending on its sensor load.

Currently available biogeochemical sensors measure dissolved oxygen, chlorophyll fluorescence, particle backscatter, light, nitrate, and pH. The maturity of these chemical and bio-optical sensors for deployment on profiling floats has been demonstrated in numerous research studies, and their accuracy and stability for climate-quality observations is proven (see footnote 2 and references therein). Initial biogeochemical float studies used single or a small number of floats, but resulted in important new insights. Currently ongoing biogeochemical float studies are focussing on regional to basin scale processes (e.g. the Southern Ocean, the North Atlantic, the Mediterranean Sea, the Kuroshio region and the Indian Ocean; see bottom panel on back cover). The chemical and bio-optical sensors enable measurement of several variables that have been identified by the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the World Meteorological Organization (WMO) as Essential Ocean Variables (EOVs), ecosystem EOVs (eEOVs) and essential climate variables (ECVs)[3]. This means that measurements of these variables are required to shed light on the biogeochemical cycles of carbon, oxygen, and nitrogen and are fundamental for addressing the scientific and societal issues related to global change.

In January 2016, a planning meeting for a global biogeochemical Argo program was held in Villefranche-sur-Mer, France, with attendees from 8 nations currently deploying Argo floats, including Canada. Following the meeting, a Science and Implementation Plan was formulated (see footnote 2) that calls for the addition of 1,000 biogeochemical profiling floats, uniformly distributed throughout the global ocean. In addition to the routinely measured physical properties, these floats would measure pH, oxygen, nitrate, chlorophyll, suspended particles, and light. Given an endurance of four years, maintaining an array of 1,000 floats will require the deployment of 250 floats per year.

With a clear need and defined plan, the BGC-Argo program has already received attention from the highest levels of governments of G7 countries. The program was discussed at the Science and Technology Ministers' Meeting in Tsukuba, Japan in May 2016, and the joint communiqué specifically calls for *Increasing the capability of the global Argo network to include more biological and biogeochemical observation and observation of the deep sea* (see Recommendation 1 in Attachment 2 of the Tsukuba Communiqué).

Case for Canadian Leadership

Canada was instrumental in helping to launch the first array of Argo floats, and is poised to take a leadership role in implementing the BGC-Argo program by supporting the core program in Canadian ocean spaces and by expanding the program's scope. This would be a natural step, since Canada is already a leading contributor to the existing Argo program, with Canadian scientists being well networked and represented on the international Argo steering committees. Another key factor is that Canadian companies have developed several of the chemical and bio-optical sensors that are used on today's biogeochemical floats and are working towards expanding the suite of observable parameters through new sensor development.

BGC-Argo will allow Canada to address pressing national issues related to all three of its adjacent ocean basins. These include issues related to the sustainability of aquaculture, quantification of Canada's ocean carbon sinks, questions about the variability of

[3] http://www.geowow.eu/downloads/GEOWOW-WP6-DEL-D6.2.pdf; https://www.wmo.int/pages/prog/gcos/index.php?name=EssentialClimateVariables

anthropogenic carbon sequestration and ventilation of the global ocean through air-sea exchanges, and questions surrounding the dramatic changes in the Arctic Ocean. The latter is an area in which Canada is at the leading edge. Canadian scientists and engineers are actively pursuing innovations in under-ice sensing and navigation, which will enable the routine deployment of BGC-Argo floats in the Arctic Ocean

It must also be noted that Canada is well positioned to take advantage of the data streams that will result from the BGC-Argo array, given its cutting-edge capabilities in marine modelling and prediction. Canadian researchers in academia, at the Department of Fisheries and Oceans, and at Environment and Climate Change Canada are leaders in ocean modeling and prediction. With enhanced investment in this area, they will be able to spearhead methods for transforming the new observation streams into the data products and environmental forecasts that are needed by a broad base of end users, including those engaged in fisheries and aquaculture, tourism, alternative energy industries as well as efforts related to marine planning, policy, and conservation.

Benefits to Canada

Full participation in the international BGC-Argo initiative would have significant benefits to Canada across academic, government, and private sectors. In addition to the resulting scientific breakthroughs, BGC-Argo will enable significant innovations in marine prediction and the management of living marine resources, will provide opportunities for Canadian technology developments and will contribute to enhancing Canadian national security and asserting sovereignty in the Arctic.

Interannual fluctuations of fish stocks linked to variations in ocean temperature and primary production are a major challenge to fisheries management and can have significant economic impacts. BGC-Argo will enable improved observations and modelling, facilitating innovations in fisheries management.

Ocean deoxygenation and acidification are threatening ecosystems and jeopardizing aquaculture operations. BGC-Argo will allow the provision of real-time observations along with the detection of long-term trends, enabling the monitoring of ecosystem health indicators for regulation of aquaculture and implementation of conservation efforts.

Through leveraging Canada's expertise in satellite remote sensing of ocean color, BGC-Argo will advance the quantification of primary production in Canada's oceans. Canadian researchers are recognized as world leaders in this field and incorporation of BGC-Argo observations will further advance this international standing.

Participation in BGC-Argo will provide exceptional training opportunities to science and engineering students. The program will also provide early career scientists and engineers with opportunities to mount impactful research programs in this important new field.

BGC-Argo will expose expanding global markets to biogeochemical sensor development by Canadian enterprises. Several Canadian companies are already at the forefront of this technology sector.

Recommendations for Canada

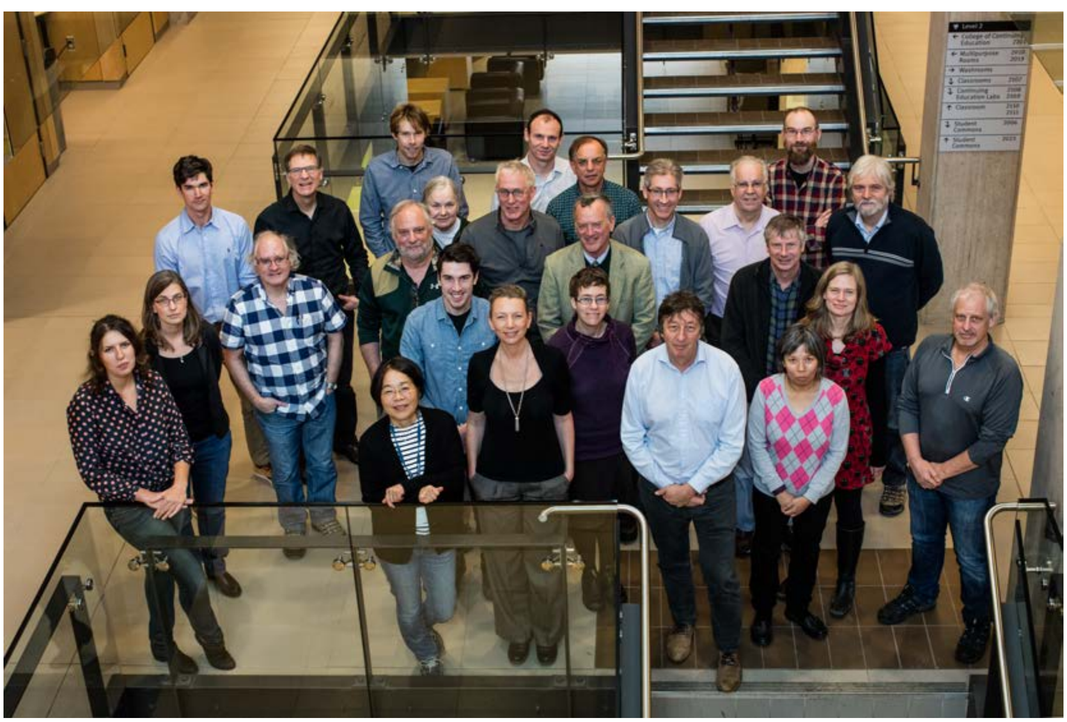
1. Actively strive to maintain and enhance our position as an international leader in ocean observation through strong participation in the global BGC-Argo program.

2. Enhance Canadian scientific capacity in biogeochemical modelling and prediction, in order to capitalize fully on the potential of BGC-Argo.

3. For Canada to reap maximum scientific and societal benefit from BGC-Argo, ample training opportunities for young scientists should be provided, which would also help to ensure that "eyes are on the data" at all times.

4. Ensure free and near real-time access to the emerging data streams through properly resourcing data management.

5. Form a national BGC-Argo steering committee to facilitate communication within the Canadian user community.



References

Ardyna, M., M. Babin, M. Gosselin, E. Devred, L. Rainville, and J.-É. Tremblay (2014), Recent Arctic Ocean sea ice loss triggers novel fall phytoplankton blooms, *Geophys. Res. Lett.*, 41, 6207–6212.

Arrigo, K. R., and G. L. van Dijken (2011), Secular trends in Arctic Ocean net primary production, *J. Geophys. Res.*, 116, C09011, doi:10.1029/2011JC007151.

Azetsu-Scott, K., A. Clarke, K. Falkner, J. Hamilton, E. P. Jones, C. Lee, B. Petrie, S. Prinsenberg, M. Starr, and P. Yeats (2010), Calcium carbonate Saturation states in the waters of the Canadian Arctic Archipelago and the Labrador Sea, *J. Geophys. Res.*, 115, C11021, doi:10.1029/2009JC005917.

Bond, N. A., M. F. Cronin, H. Freeland, and N. Mantua (2015), Causes and impacts of the 2014 warm anomaly in the NE Pacific, *Geophys. Res. Lett.*, 42, 3414–3420.

Byrne, R. H., S. Mecking, R. A. Feely, and X. Liu (2010), Direct observations of basin-wide acidification of the North Pacific Ocean, *Geophys. Res. Lett.*, 37, L02601, doi:10.1029/2009GL040999.

Crawford W. R., and A. Peña (2016), Decadal trends in oxygen concentration in subsurface waters of the Northeast Pacific Ocean, *Atmosphere-Ocean*, 54, 171–192.

Freeland, H. (2014), Something odd in the Gulf of Alaska, February 2014, *CMOS Bulletin SCMO,* 42, 57–59.

Haigh R., D. Ianson, C. A. Holt, H. E. Neate, and A. M. Edwards (2015), Effects of Ocean Acidification on Temperate Coastal Marine Ecosystems and Fisheries in the Northeast Pacific, *PLoS ONE,* 10, e0117533, doi:10.1371/journal.pone.0117533.

Irvine, J. R., and W. R. Crawford (2011), State of the Ocean Report for the Pacific North Coast Integrated Management Area (PNCIMA), *Can. Manuscr. Rep. Fish. Aquat. Sci.*, 2971, xii + 51 p.

Keeling, R. F., A. Körtzinger, and N. Gruber (2010), Ocean deoxygenation in a warming world, *Annu. Rev. Mar. Sci.*, 2, 199–229.

Li, W. K. W., F. A. McLaughlin, C. Lovejoy, and E. C. Carmack (2009), Smallest algae thrive as the Arctic Ocean freshens, *Science*, 326, 539.

Li, W. K. W., E. C. Carmack, F. A. McLaughlin, R. J. Nelson, and W. J. Williams (2013), Space-for-time substitution in predicting the state of picoplankton and nanoplankton in a changing Arctic Ocean, *J. Geophys. Res.*, 118, 5750–5759.

Pérez, F.F., H. Mercier, M. Vázquez-Rodríguez, P. Lherminier, A. Velo, P. C. Pardo, G. Rosón, and A. F. Ríos (2013), Atlantic Ocean CO_2 uptake reduced by weakening of the meridional overturning circulation, *Nature Geoscience*, 6, 146–152.

Plant, J. N., K. S. Johnson, C. M. Sakamoto, H. W. Jannasch, L. J. Coletti, S. C. Riser, and D. D. Swift (2016), Net community production at Ocean Station Papa observed with nitrate and oxygen sensors on profiling floats, *Global Biogeochem. Cycles*, 30, 859–879.

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley, and F. Wang (2013) Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Eds. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Riser, S. C., et al. (2016), Fifteen years of ocean observations with the global Argo array, *Nat. Clim. Change*, 6, 145–153.

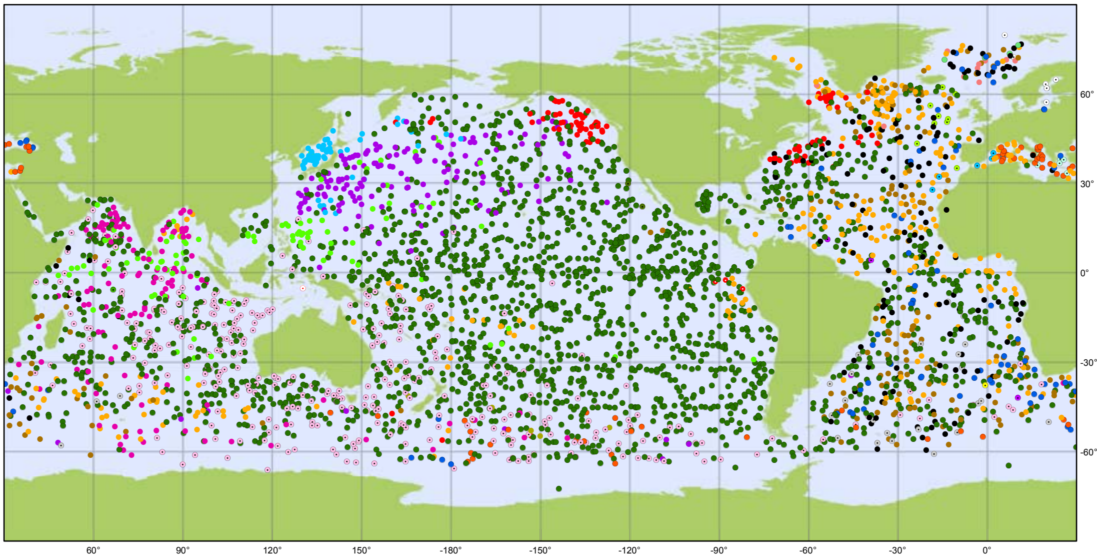
Schmidtko, S., L., Stramma, and M. Visbeck (2017), Decline in global oceanic oxygen content during the past five decades, *Nature*, 542, 335–339.

Wang, M. and J.E. Overland (2012), A sea ice-free summer Arctic within 30 years: An update from CMIP5 models, *Geophys. Res. Lett.*, 39, L18501, doi:10.1029/2012GL052868.

Whitney, F. A. (2015), Anomalous winter winds decrease 2014 transition zone productivity in the NE Pacific, *Geophys. Res. Lett.*, 42, 428–431.

Whitney, F. A., H. J. Freeland, and M. Robert (2007), Persistently declining oxygen levels in the interior waters of the eastern subarctic Pacific, *Prog. Oceanography*, 75, 179–199.

Wolf, M. (2017), Oxygen saturation surrounding deep-water formation events in the Labrador Sea from Argo-O_2 data, MSc thesis, University of Victoria, Victoria, BC, Canada.



Argo — **National contributions - 3862 Operational Floats** — **November 2017**

Latest location of operational floats (data distributed within the last 30 days)

ARGENTINA (1) · AUSTRALIA (352) · BRAZIL (4) · CANADA (92) · CHINA (103) · EUROPE (81) · FINLAND (7) · FRANCE (288) · GERMANY (145) · GREECE (6) · INDIA (126) · INDONESIA (1) · IRELAND (9) · ITALY (64) · JAPAN (158) · KENYA (1) · MEXICO (2) · NETHERLANDS (25) · NEW ZEALAND (6) · NORWAY (10) · PERU (3) · POLAND (4) · KOREA, REPUBLIC OF (61) · SPAIN (6) · UK (172) · USA (2136)

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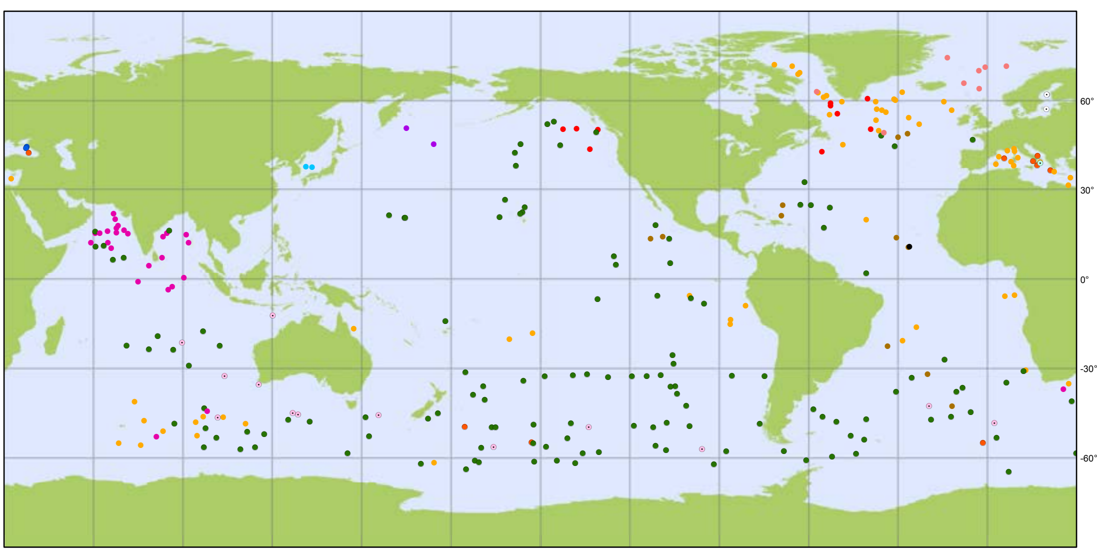

Argo BioGeoChemical — **National contributions - 282** — **November 2017**

Latest location of operational floats (data distributed within the last 30 days)

AUSTRALIA (13) · CANADA (10) · EUROPE (2) · FINLAND (3) · FRANCE (61) · GERMANY (1) · GREECE (1) · INDIA (26) · ITALY (9) · JAPAN (2) · KOREA, REPUBLIC OF (2) · NORWAY (8) · UK (11) · USA (133)

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