Data Science Journal, Volume 13, 30 October 2014

ASSEMBLING AN ARCTIC OCEAN BOUNDARY MONITORING ARRAY

T Tsubouchi[1]*

*[*1] National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK*
Email: tt2r07@noc.ac.uk

ABSTRACT

The Arctic Ocean boundary monitoring array has been maintained over many years by six research institutes located worldwide. Our approach to Arctic Ocean boundary measurements is generating significant scientific outcomes. However, it is not always easy to access Arctic data. On the basis of our last five years' experience of assembling pan-Arctic boundary data, and considering the success of Argo, I propose that Arctic data policy should be driven by specific scientific-based requirements. Otherwise, it will be hard to implement the International Polar Year data policy. This approach would also help to establish a consensus of future Arctic science.

Keywords: Arctic Ocean boundary, Hydrographic data, Mooring data, International Polar Year, Data policy

1 INTRODUCTION

The Arctic Ocean is responding rapidly to global climate change from the physical, biogeochemical, and ecological points of view. At the same time, summer sea ice retreat attracts great socioeconomic interest from different economic sectors, such as shipping, hydrocarbons, minerals, tourism, fisheries, and insurance. However, our understanding of the climate and ecosystems of the polar oceans lags that of the rest of the world ocean. This is mainly due to the difficulty of making measurements in the ice-covered ocean. Moreover, existing Arctic observations can sometimes be difficult to access.

The Arctic boundary has been observed over many years to better understand and monitor the exchanges between the Arctic Ocean and its neighbouring oceans. The unique geometry of the Arctic—surrounded by the land masses of North America, Greenland and Siberia—has allowed researchers to enclose the Arctic Ocean with sustained hydrographic observation lines (Figure 1). Indeed, six research institutes located worldwide contribute to sustain these Arctic boundary observation lines: the University of Washington (UW) in the United States (US) for Davis Strait and for the US side of Bering Strait; the Norwegian Polar Institute (NPI) in Tromsø, Norway and the Alfred Wegener Institute (AWI) in Bremerhaven, Germany for western and eastern Fram Strait, respectively; the Institute of Marine Research (IMR) in Bergen, Norway for the Barents Sea Opening (BSO); and the University of Alaska Fairbanks (UAF) in the US and Arctic, and Antarctic Research Institute in Russia for the Russian side of Bering Strait.

In recent years, the United Kingdom (UK) Natural Environment Research Council has been delivering strategic funding for research in the Arctic via its 'Research Programme' mode. UK Arctic marine physics, encompassing both sea ice and ocean, has been developed first under the Arctic Synoptic Basin-wide Observations project (2006–2010; Principal Investigators (PIs): Prof. Laxon, University College London and Dr. Bacon, National Oceanography Centre, Southampton), and currently under The Environment of the Arctic: Climate, Ocean and Sea Ice project (2011–2015; PI: Dr. Bacon). At the heart of these two projects was the perception that Arctic ice and ocean transports could, for the first time, be objectively determined using inverse modelling. The boundary measurements define a closed box (including coastline), enabling application of conservation constraints. This in turn meant that real oceanic transports and surface fluxes could be calculated, independent of any arbitrary reference values.

Our ability to measure the global ocean has improved significantly over the last few decades. Geophysicists have been analyzing satellite-measurement based estimates of sea surface properties, such as sea surface height (since 1992), sea surface temperature (since 1998), surface chlorophyll concentration (since 1997), sea surface wind (since 2003), and sea surface salinity (since 2009). The Gravity Recovery and Climate Experiment satellite has been observing the mass of ocean and land since 2002. Regarding the interior of the ocean, the Argo programme has been monitoring upper ocean (above ~2000 m) properties since 1999. Most of these data are freely available to wider user communities to enable better understanding of the complex Earth system and to promote innovations (ICSU, 2011a; 2011b).

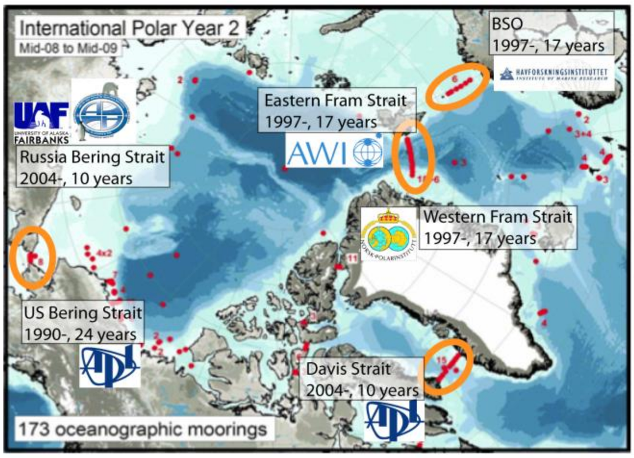

Figure 1. Mooring sites maintained during the International Polar Year (IPY) 2007–2009 (Dickson, 2009). The Arctic boundaries across Davis, Fram, and Bering Straits and BSO are highlighted by orange circles.

This paper is structured as follows: Section 2 highlights the scientific outcomes of the pan-Arctic approach. Section 3 describes the state of a polar data policy based on my data enquiry experience. I will highlight the importance of scientific motivation to assemble the pan-Arctic data. Section 4 describes the ingredients of the success of Argo. Section 5 discusses and proposes a future Arctic data policy and Arctic science in general based on sections 2–4.

2 SCIENTIFIC OUTCOMES

To construct oceanic boundary and surface heat and freshwater (FW) budgets in the Arctic, there are three main issues to address: (1) reference values, (2) synopticity, and (3) pan-Arctic volume balance (see, for example, Aagaard & Carmack (1989); Serreze, Barrett, Slater, Woodgate, Aagaard, Lammers et al. (2006); and Dickson, Rudels, Dye, Karcher, Meincke, & Yashayaev (2007)). These three issues are discussed at length in Tsubouchi, Bacon, Garabato, Aksenov, Laxon, Fahrbach, et al. (2012; hereinafter T2012), and to overcome these problems, our research group has proposed to treat the Arctic as a single box bounded by hydrographic lines and land.

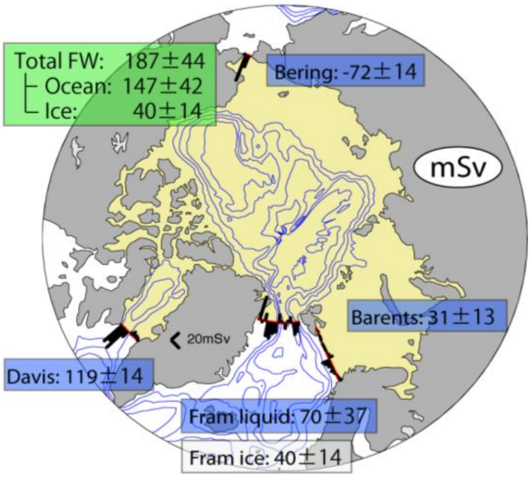

Figure 2. Arctic FW budget in summer 2005 (taken from T2012)

The pan-Arctic approach has produced significant scientific outcomes: the first quasi-synoptic net heat and FW transports in a single month from summer 2005 (T2012); the dissolved inorganic nutrient budget (Torres-Valdes, Tsubouchi, Bacon, Naveira-Garabato, Sanders, McLaughlin et al., 2013; hereinafter TV2013), and a dissolved inorganic carbon (DIC) budget (MacGilchrist, Naveira-Garabato, Tsubouchi, Bacon, Torres-Valdes, & Azetsu-Scott, 2014; hereafter M2014). T2012 proposes the latest estimate of Arctic FW budget (Figure 2), following those by Aagaard & Carmack (1989), Serreze et al. (2006), and Dickson et al. (2007). TV2013 finds that the Arctic Ocean is a net exporter of silicate (15.7 ± 3.2 kmol s^{-1}) and phosphate (1.0 ± 0.3 kmol s^{-1}) to the North Atlantic. Net transports of silicate and phosphate from the Arctic Ocean provide 12% and 90%, respectively, of the net southward fluxes estimated at 47˚N in the North Atlantic. M2013 estimates a net summertime DIC export of 231 ± 49 TgC yr^{-1}. On an annual basis, we believe that at least 166 ± 60 TgC yr^{-1} of this is due to uptake of carbon dioxide from the atmosphere.

We are currently working to define a full annual (summer-to-summer) cycle of monthly net heat and FW transports during 2005–2006. The main data sources are direct-moored array observations of temperature, salinity, and velocity obtained by 135 moored instruments. We also consider sea ice export and sea surface current variability across the defined boundary, based on satellite measurements. An important goal of this particular project is not only to calculate an annual cycle of transports but also to determine the adequacy of the instrumental configuration, as presently deployed, to the task. The project also aims to answer the question of whether any part of the boundary needs additional instrumentation.

3 STATE OF ARCTIC BOUNDARY ARRAY DATA POLICY

3.1 Assembling Arctic Boundary Data

Although the pan-Arctic approach has generated significant scientific outcomes, it was not always easy to access the necessary data. During the last five years, we have contacted 15 PIs to ask for permission to access data, and have received permission from 13 of these. The data enquiry period (the time from first request to supply of data) is 11 weeks on average; spanning from a single day to nine months. Data accessibility is different between different institutions, and can be categorized as follows:

(1) Open access databases, such as the International Council for the Exploration of the Sea and the World Ocean Database
(2) PIs who held their own data, but maintained an open data access policy
(3) PIs who held their own data, and where negotiation was required to obtain access

The statistics of data accessibility are summarized in Figure 3. It was most difficult to access data in the initial stages; when we started to gather conductivity, temperature, and depth (CTD) and mooring data for the first heat and FW transports (T2012). We needed on occasion to return to the same PIs several times in order to receive permission to access their data. However, ease of data access has been increasing as time has passed. The primary reason is that the value of our approach has been recognized by PIs; namely, gathering data around the Arctic Ocean boundary to draw a comprehensive picture (TV 2013; M 2014).

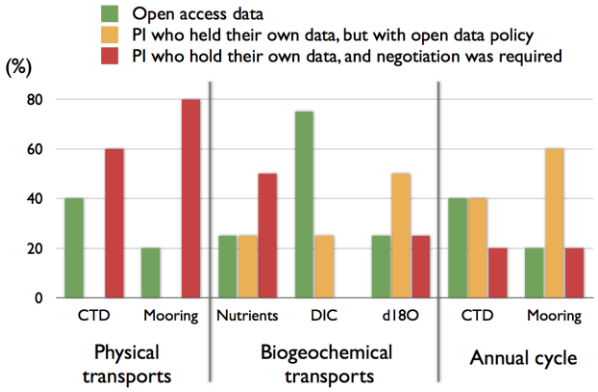

Figure 3. Data accessibility for different datasets (CTD, mooring, nutrients, etc.). Datasets are split into three types: open access (green bars), intermediate access (orange), and restricted access (red). They are also categorized into three outcome groups: physical transports (T2012), biogeochemical transports (TV2013; M2014); and annual cycles.

There are many reasons for PIs to retain pan-Arctic boundary data, depending on different time scales. For the long term, meaning longer than 10 years, it is mainly based on the philosophy of the PI's data policy. Since taking measurements in the Arctic Ocean requires significant investment and logistical effort, and the consequent bearing of higher risks, PIs might be inclined to analyze the data and to understand the underlying physics by themselves. For short to medium time scales, meaning less than 10 years, there are many reasons why PIs might not make data openly accessible. PIs may, for example, have commitments to a research student to work with the data, and therefore that student receives priority. Alternatively, PIs may need to work a few years after a research cruise to finalize calibrations. Sometimes, a PI may simply not have enough spare time to make their data public. Finally, it is worth mentioning that institutional or national priorities may also come into play.

3.2 Lessons learned

There are three main reasons why we were able to assemble the required pan-Arctic data over a relatively short time period of the last five years. Firstly, we always presented our approach and expected results when we requested the data, and so PIs were able to appreciate that we would not overlap with any of their own ongoing studies. Secondly, PIs were able to understand the scientific value of our approach. It was clear that people are inclined to be generous once they recognize the importance of the intended research. Thirdly, we occasionally had opportunities to meet PIs at international conferences. It proved beneficial to communicate with PIs face-to-face rather than relying solely on email.

On the basis of our last five years' experience, I believe that the Arctic data sharing policy should be driven by scientific motivation. Such large-scale scientific motivation has actually existed for many years, for example, see Dickson (2005) for the integrated Arctic Ocean Observation System (iAOOS), and Dickson, Meincke, & Rhines (2008) for the Arctic-subarctic Ocean Fluxes programme. However, the 'big picture' was not necessarily translated to practical levels. We, the Arctic science community, probably need to break down these big scientific aims into specific objectives so that we can recognize them as important, realistic, challenging, and feasible targets.

4 SUCCESS OF THE ARGO PROJECT

It is worth thinking about the reasons for the success of the Argo project when considering future Arctic data policy, and Arctic science in general. Argo is one of the most successful international efforts in last 10–15 years in building up a new generation of global ocean monitoring systems. The original Argo proposal was planned in 1999, and its initial goal of placing '3,000 active Argo floats in the global ocean' was achieved in October 2007. Argo data significantly contributed to the 2013 Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.

The following paragraphs are based on Prof. D. Roemmich's presentation at the 13th Argo Steering Team (AST) meeting in March 2012 in Paris (hereinafter Roemmich, 2012), and describe how the Argo program developed; focussing on the drawing-up of the Argo programme in the late 1990s. Readers are advised to refer to Roemmich (2012) and early Argo documents (Argo, 2014) for more detail. According to Roemmich (2012), the assembly of eight major components was needed to implement the Argo program. In this author's opinion, a clear and simple statement of requirements—3,000 active Argo floats in the global oceans—seems to have played an important role in building up the global Argo monitoring system. This requirement has been kept since the program started, and will be retained into the future, to ensure that we will be able to monitor climate signals in the global ocean.[1]

The idea of the Argo project first appeared in October 1997 in Boulder, Colorado (in the United States of America). A global ocean array of profiling floats was discussed between D. Roemmich, B. Owens and E. Lindstrom over lunch in the cafeteria of the National Center for Atmospheric Research. Following that conversation, a one-page Argo white paper was drafted in late 1997. 'A proposal for Global Ocean Observations for Climate: the Array for Real-time Geostrophic Oceanography (ARGO)' by D. Roemmich and 'A Program for Global Ocean Salinity Monitoring (GOSMOR)' by R. Schmitt then followed in early 1998. These two documents soon received wide scientific endorsement, and in early 1998, Argo was endorsed by the Global Ocean Data Assimilation Experiment. The Climate Variability and Predictability project also considered these two proposals, and gave them high priority in its implementation plan in August 1999. Also in that year, 'On the

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[1] At the 14th AST meeting in March 2013 in Wellington, the target number was set as 4,100 to better observe western boundary regions, the equatorial region, marginal seas, and high latitudes.

design and implementation of Argo—An initial plan for a Global Array of Profiling Floats' was prepared by AST under the chairmanship of D. Roemmich.

Thus it took only two years (1997–1999) to establish a consensus on the scientific and operational framework of the Argo project. However, it is appropriate to say that researchers' long-term (since the 1950s, for example, Bowden (1954)) ambitions and considerations of autonomous observing systems were put in place in this two year period via a practical test phase during the World Ocean Circulation Experiment (WOCE) programme of 1990–1997. During this programme, about 1,000 Autonomous Lagrangian Circulation Explorer (ALACE-) type floats were developed and deployed to measure ocean currents at about 1,000 m. Towards the end of WOCE, the majority of the ALACE floats carried sensors to measure the temperature and salinity structure throughout the water column during the ascending period (Davis, Sherman, & Dufour, 2001). Other necessary technology, such as satellite communication, had been evolving over the preceding decades.

During the implementation period, the Argo project was promoted by many different people, from individuals to those at intergovernmental level. In 1999, the multi-institution United States Argo Float consortium obtained funding, and in 1999–2001, international Argo partnerships were established among Japan, India, the United Kingdom, France, Australia, and so on. At the national level, all programmes have agreed that building and sustaining the global array has the highest priority. On the technological development side, many private companies have contributed to Argo's success, including sensor manufacturers, float manufacturers, communications providers, machine shops, electronic firms. and others. Roemmich (2012) claims that Argo succeeded—and continues to do so—because many individuals understand the value of the programme, and have made large and original contributions.

This author understands that the target of '3,000 Argo floats in the global ocean' has played an important role in attracting many different stakeholders, not only from academia but also from industry and the general public. I presume that not everyone may have understood the true meaning of having '3,000 Argo floats in the global ocean' as deeply as AST did, specifically, in terms of scientific value and contribution to the integrated global monitoring system. Rather, different groups may have interpreted it in different ways, according to their interests, and translated it to their own challenges. Manufacturing partners of Argo floats, for instance, may have taken it as a challenging target to extend float life time from three years to five years by increasing efficiency of battery power. This simple and challenging slogan worked to point people's differing intentions towards the same direction in order to build up the global monitoring array.

5 DISCUSSION AND CONCLUSION

The Arctic Ocean is of great social, economic, political, and scientific interest to many countries. In 2008, the United States Geological Survey estimated that the Arctic contains the equivalent of 13% of the undiscovered oil and 30% of the undiscovered natural gas in the world. Maritime traffic in the Arctic is already considerable. In 2011, the Sovcomflot-owned Vladimir Tikhonov became the first super tanker to sail the Northern Sea Route carrying 120,000 tonnes of iron-ore concentration. In the same year, the Japanese-owned Sanko Odyssey transported 66,000 tons of iron-ore concentrate from Russia's Kola Peninsula to Jingtang in China. In the summer of 2012, Norway's Ribera del Duero Knutsen transported the first-ever cargo of liquid natural gas from Norway to Japan. Emmerson & Lahn (2012) from Chatham House, a world-leading source of independent analysis, estimate that the Arctic is likely to attract substantial investments over the coming decade; potentially reaching 100 billion USD. Arctic oil and gas, and shipping are the two leading sectors, followed by mining, fisheries, and tourism. Emmerson & Lahn (2012) identify a number of key uncertainties around the future economic and political trajectory of the Arctic, including the scale of hydrocarbon resources, the future location and predictability of sea ice, and the wider consequence of climate change. They state that these uncertainties are the greatest risks to potential investors in Arctic economic development.

5.1 Future of Arctic Data policy

In this context, future Arctic science will be driven by many different funding sources, across public and private sectors. Public funding can be categorized into two groups. The first group is based on a long-term strategy to maintain sustained observations to address long-term (interannual to decadal) Arctic Ocean climate change and to contribute to IPCC-type reports. Sustaining and implementing iAOOS-type integrated ocean, atmosphere, and cryosphere monitoring systems to diagnose the state of the Arctic climate falls into this group. The second group is aimed at cutting-edge projects, to push the boundaries of our ability to measure the Arctic Ocean. Developing and installing biogeochemical sensors, measuring the strength of mixing under retreating sea ice, and understanding physical and biological processes of interaction between shelf seas and the open ocean all fall into this group. Conversely, private funding would likely focus on areas closer to social, economic, political interests.

Scientists are typically engaged with the setting of long-term objectives for the first group of public funding. This type of funding provides politically-neutral assessments of the state of the Arctic. Scientists must ensure that significant scientific outcomes can be produced as efficiently as possible. Open access data should be an important part of the strategy. However, in reality, it is not always easy to access Arctic data. It is not unusual for originators to retain data, even many years after the measurements. This can arise at personal up to national levels. There is no pan-Arctic data access agreement, and the IPY Data Policy was never formally enacted. On the basis of our last five years' experience of assembling pan-Arctic data, and considering the success of the Argo project, I propose that the Arctic data policy should be driven by important, realistic, challenging, and feasible targets, such as the pan-Arctic boundary approach or the aim of '3,000 Argo floats in the world ocean'. Without being able to see specific, challenging scientific targets, it will be hard to implement the IPY Data Policy.

5.2 Future of Arctic Science

There are some similarities and differences between the present situation in Arctic science and the Argo programme in the late 1990s. The similarities are (1) a long-term consideration of observation systems over the last decades and (2) the development, and practical assessment, of required technological and logistical feasibility. In terms of considering integrated observation systems, Dickson (2005) describes iAOOS as a technically available comprehensive ocean–atmosphere–cryosphere observation system. Indeed, iAOOS was one of 138 IPY coordination proposals that were endorsed by the International Council for Science–World Meteorological Organization Joint Committee. iAOOS is composed of satellites, ships, mooring, autonomous buoy measurements, and so on. These observation components were operated intensively during IPY, and its technological and logistical feasibility were assessed. We could thus view our current situation as analogous to the post-WOCE era of the Argo project. However, differences also exist between present Arctic science and the Argo program. The Arctic Ocean now attracts great socioeconomic and political interest, and it is much harder to establish a consensus of the future of Arctic science for coming decades. The good news is that we all want to better understand the Arctic climate system. Indeed, Emmerson and Lahn (2012) conclude that 'investment in science and research—both by government and private companies—is essential to close the knowledge gap, reduce uncertainties and manage risks'.

In addition to a future Arctic data policy, we need to clearly state scientific-based targets that define climate and ecosystem metrics whose value are recognized by all social sectors (academia, politicians, business, and the general public). These targets would help to bring people's differing intentions towards the same direction in order to build a sustainable Arctic monitoring system. We should find a compromise among scientific, economic, and political interests to define a future Arctic scientific strategy. We first need to clarify what types of climate and ecosystem metrics we need to establish. Then, we need to consider appropriate, affordable, technologically-feasible, logistically-efficient, and sustainable iAOOS-type observation systems. What is the Arctic equivalent of '3,000 Argo floats in the global ocean'?

6 ACKNOWLEDGEMENTS

Arctic boundary CTD and mooring data are provided by Dr. Lee at UW (Davis Strait), Dr. Hansen at NPI and Dr. Fahrbach at AWI (Fram Strait), Dr. Ingvaldsen at IMR (BSO), and Dr. Woodgate at UW and Prof. Weingartner at UAF (Bering Strait). I appreciate Dr. Bacon's advice and assistance in establishing the pan-Arctic approach. Prof. Roemmich at Scripps Institute of Oceanography kindly agreed to disseminate his presentation, and Ms. Scanderbeg has made it available (Roemmich, 2012). I finally thank the reviewer of this manuscript, whose comments helped to improve its content.

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(Article history:Available online 10 October 2014)