OCEAN ACOUSTIC TOMOGRAPHY: A MISSING ELEMENT OF THE OCEAN OBSERVING SYSTEMS

B Dushaw   Nansen Environmental and Remote Sensing Center, Bergen, Norway

1 INTRODUCTION

Some twenty years ago the oceanographic community embarked on the grand endeavor of establishing ocean observatories. Such systems had two primary motivations. First, there was an obvious need to transition basic oceanographic research (and the significant societal investment in that research) into products and information that would be useful to society. Information on the evolution of the Earth's climate system and warning systems to mitigate natural disasters of atmospheric, oceanographic, or geologic origin are examples. Second, many oceanic processes or systems evolve at decadal to century time scales and require sustained, long-term observations to properly understand them. These two motivations highlight a semantic difference: "Ocean Observing Systems" (OOSes) are operationally focused, while "Ocean Observatories" are research focused, although the difference is often blurred. "Operational" implies the commitment of the significant bureaucracy and management required to deliver promised data, information, and products to society on a sustained basis, e.g., the national weather services. Ocean observing systems are global, basin, or regional scales. Examples of OOSes are the Arctic basin system, or the many regional systems along the coasts of the United States. Neptune Canada (www.neptunecanada.ca) and the Ocean Observatories Initiative Regional Scale Nodes (OOI-RCN) are ocean observatories programs. One view is that research capabilities or techniques that have been shown to have long-term value through the Ocean Observatories, should be transitioned to Ocean Observing Systems to become sustained and integrated. In any observing system, data management and archive are formidable issues that must be addressed.

Some observing systems include modest acoustical components. Neptune and RNC include research in acoustics. The Comprehensive Test Ban Treaty Organization (CTBTO, www.ctbto.org) hydroacoustic system is an operational system with an acoustic component. Australia's Integrated Marine Observing System (IMOS, www.imos.org.au/), has been collecting freely available sea noise data at six sites on the continental shelf since 2008. These data have been used by marine biologists for studying marine mammals and fish, e.g., their vocal behaviors, migration patterns, and populations. Natural processes in the ocean have been observed, such as seismic events, volcano activity, and ice disintegration near Antarctica.

Motivating many of these activities are the extraordinary, if not perilous, changes occurring within the global climate system, familiar to all. Given the stakes and consequences of these changes to global communities, it is evident that global observing systems are of paramount importance, objectively and conscientiously designed and implemented to make the most of all available assets.

The possible acoustical applications for an ocean observing system are myriad and cross several disciplines, and a review or survey of these applications is beyond the scope of this paper (See Dushaw et al. 2010) for bibliographical information). The discussion here therefore addresses mainly tomography and ocean observing systems,[1-5,9] but it applies equally to acoustics for biological or engineering applications, as well as pure acoustical science. Further, this document does not attempt to make the case of how and why tomography should be a part of the observing system; that case has been made elsewhere. Rather, the document attempts to describe what seem to me to be some of the impediments to implementing acoustical observations. Similarly, the references listed here are limited and selected only for my particular purpose. Another deficiency of this document is that it is written mainly from an American perspective, based as it is on my experiences of the past 20-30 years.

2 CREDENTIALS

It is likely worth reviewing my credentials for writing a document such as this. I began my post-graduate career working for the Acoustic Thermometry of Ocean Climate program run by Walter Munk, Peter Worcester, and Bob Spindel. This program ran from about 1992 to 2006, under various funding mechanisms, and it was one of the earliest instances of an ocean observing system. With this program underway (roughly), I was, early on, somewhat baffled by its estrangement from other observational programs such as the concurrent World Ocean Circulation Experiment (WOCE) or, its follow on, the Argo program. With naive optimism, I traveled to such conferences and workshops as GOOS at AGU, San Francisco (1995), OceanObs'99,[5] the CLIVAR Pacific Implementation (2001), WOCE and Beyond (2002), and OceanObs'09,[3] anticipating a thorough, comprehensive vetting and discussion of all ideas for the design of the growing observing systems. But I was naive, and it became all too apparent that such conferences were governed by powerful political forces and self interest (i.e., money) to the detriment of honest, comprehensive scientific discussion.

As the OOSes evolved, so too did ocean observatories. The Deep-Earth Observing System (DEOS, ca. 2000) was an early idea by geophysicists to instrument deep ocean basins, thus filling critical holes in the global seismological network. DEOS was absorbed into the U.S. National Science Foundation's ORION program (Ocean Research Interactive Observatory Networks), which had major workshops in San Juan, PR (2004) and Salt Lake City (2006). ORION eventually morphed into the Ocean Observatories Initiative (OOI) and its Regional Scale Nodes (RSN, the cabled system formerly known as Neptune off the coast of Washington State). Along in this process, the original geophysical goals were left on the cutting room floor. Our interest in this system was that it offered cabled systems in mid-ocean environments, hence power and communications. Those elements are requirements for sustained, routine acoustical observations such as acoustic thermometry. As for the geophysics, the acoustical capabilities were mostly set aside. As was the case for the Ocean Observing Systems, the political forces shaping the decisions were formidable. Large doses of self-serving agendas were evident and dominant.

Following this process that has now spanned the better part of 20 years, the notion of implementing ocean acoustic tomography within observing systems has made little practical headway, with the exception of recent work in the Arctic.[7] Indeed, I cannot even recall any substantive discussion of this idea at any of the workshops or conferences I have attended, despite repeated attempts to introduce the idea. The level of discussion has amounted to thin, self-serving, one-liner rhetorical comments dismissing tomography, followed by a nonsensical insistence that a "community consensus" has been reached. The process has been such that the agenda for the week-long, international OceanObs conference in 2009 included no acoustics at all, as indeed there was no representation for acoustics on the conference science steering committee. One contemplates the precise rationale by which an ocean observing system is planned with complete disregard for ocean acoustics. One aim of this document is to provide some illumination as to how this odd situation has come to pass.

To state the matter explicitly, the oceanographic community has made an error in not more fully exploiting acoustical approaches to ocean observation. This statement is based on the highest standards of scientific discourse; those standards are peer-reviewed publications in premier oceanographic journals publicly defended in open scientific fora. Acoustic tomography has won the scientific argument. Can the reader recall a substantive, scientific argument against the use of tomography in the observing system? [Why not? See Figure 1.] The failure of the wider oceanographic community to engage more constructively in developing tomographic applications, despite the proactive engagements sketched above and others, left Walter Munk to dryly comment in 2010 "We are waiting."[12]

3 OCEANOGRAPHERS

Although the value and unique quality of acoustic measurements, tomography in particular, has now long been established, general implementation of this measurement type by oceanographers has not been forthcoming. A rigorous, objective design of an observing system intended to last a century or longer includes essential contributions from both engineering (e.g., navigation or communications) and observational acoustical techniques. The concluding statement of the OceanObs'09 conference explicitly noted that “the oceans remained seriously undersampled” (www.oceanobs09.net/statement/). Acoustic techniques for ocean observing or engineering offer tremendous opportunities.

A couple of examples: In an analysis of a decade of basin-scale acoustic tomography data from the North Pacific, Dushaw et al. 2009 made direct comparisons of the tomographic time series to equivalent time series derived from Argo float data and satellite altimetry.[4] The comparison showed significant differences at all timescales, indicating that the existing observing system was badly estimating the large-scale variability of ocean temperature. Similarly, in the 1988 Greenland Sea Project experiment, the rapid sampling of integrated temperature afforded by the acoustic measurements proved to be essential in estimating the net deep water formation during the winter of 1988/1989.[8] Concurrent, extensive measurements by CTD casts proved to be inadequate to the task.

One argument for excluding active acoustic sources from observing systems has been that deploying such technology will attract environmental concerns, law suits, etc. from concern over the impact of sound on marine life. Such an argument is specious, a crass exploitation of this issue to rationalize excluding the acoustical approach. Significant resources have been expended to research this specific issue, with the published conclusion that existing research acoustic sources have no significant biological impact. Comparable acoustic sources have been regularly used to track the positions of RAFOS floats or other instruments. Scientists should be willing to stand up for correct science. Determining secular changes in the ambient sound of the world’s oceans, i.e., man-made noise, is a serious motivation for an acoustics component to a global observing system.

Another argument against tomography has been that it is too expensive. As the schematic Figure 1 shows, that is not exactly the case. While start up and participation costs for the Argo float system are modest (any country can get involved by buying a float for $25K), the cumulative cost of the Argo system increases linearly with time. Acoustic systems, on the other hand, have relatively expensive upfront deployment costs, but they are inexpensive to operate. Munk suggested a global system could be implemented with about 25 acoustic sources,[12] and to deploy and operate such a system would incur cumulative costs less than the Argo system. To the extent the two data types are complementary, which has been established, the cost comparison is moot, however. The one system cannot provide the same information the other does.

The applications of acoustic tomography (or acoustics in general) for observing systems have not yet had a rigorous, informed, quantitative examination by oceanographers, however. It is has often seemed to me that many oceanographers do not fully understand the nature of the acoustical measurements. Certainly, such measurements often require creativity to make the most of them. It seems to have taken 20 years for the beautiful tomographic measurements of the barotropic tidal currents to be accepted,[11] the simplest of oceanographic phenomena. To my knowledge oceanographers still will not accept the remarkable measurements of the baroclinic tides by tomography, though the first publication reporting those measurements appeared over 20 years ago. Carl Wunsch has commented that oceanographers are “conservative.” It seems to me that that is a proper attitude for a few years after a new measurement is reported, but after 20 years without a substantive response it becomes stark dogma. The 1999 OceanObs conference marked the beginning of the Global Ocean Data Assimilation Experiment (GODAE), a large, ambitious project to bring together all available data, modeling, and data assimilation techniques to quantitatively examine our ability to obtain accurate state estimates for the global ocean. While this decade-long Experiment would have been ideal for assessing and quantifying the information provided by tomography in comparison to other data types, to my knowledge tomographic measurements were never even contemplated in the context of GODAE.

One of the shortcomings of acousticians has been making progress on important oceanographic, rather than acoustics, questions. Oceanographers could greatly assist the processes of developing roles for acoustics in an ocean observing system and of identifying important oceanographic processes or problems amenable to acoustic measurement. One pressing example is the need for deep ocean measurements, a critical gap in the observing system (www.oceanobs09.net/). Two acoustical applications are evident. First, acoustic rays traverse the deep ocean, hence offer a natural integrating measurement of deep-ocean temperature. Second, implementation of deep Argo floats for the ocean observing system may require a 30-day cycle to conserve their energy. Acoustics offer an obvious means to determine the position of these floats during their month-long drift in the deep ocean. Both of these applications require considerable oceanographic expertise to determine how they can be best employed to address specific oceanographic questions.

The need for stronger symbiotic relations between oceanographers and acousticians on these and other questions is evident. Oceanographers have to do better with respect to acoustics.

4 ACOUSTICIANS

If oceanographers have been deficient in integrating acoustical techniques into observing systems, acousticians have not done much better. Implementing any technique for observatories requires considerable community organization, planning, and coordination to address such difficult questions as deploying and maintaining long-term observations for community use and the archival and management of those data. Partly as a result of funding limitations, acousticians have lacked adequate community will and organization to make much headway into ocean observatories. A key aspect of data from an observing system is standardization, which acousticians are only beginning to address.

With respect to tomography, one vice is the perpetual development of new techniques or tools for acoustical observation or data processing, while oftentimes failing to actually use those tools to learn about the ocean. New techniques are fine, but one must publish what one learns about the ocean using those techniques in the mainstream oceanographic journals. This vice is perhaps understandable, since acousticians are often not experts in the oceanographic questions that could be tackled using the acoustic techniques. Indeed, acousticians being acousticians, they are often more interested in the acoustical and technical problems, rather than the oceanographic science applications. Just as the oceanographers are unfamiliar with the acoustics science, acousticians are unfamiliar with the oceanographic science. Another vice is the oftentimes lengthy time interval between when data are recovered and when the results of analysis get published; this sort of delay is not inherent in the data type and will eventually be remedied. A closer collaboration between the oceanographers and acousticians is essential.

To illustrate the structural challenges, we can cite the example of the Greenland Sea tomography experiment and the formation of deep Atlantic water.[8] The experiment conducted there almost 20 years ago demonstrated the utility of tomographic measurements in quantifying the volume of deep water formation there. These processes are essential components of the deep water circulation of the North Atlantic, hence an obvious application for tomography is as part of a system for sustained observations of the Greenland Sea. Acousticians are not particularly motivated to redeploy such acoustical measurements, however (e.g., “been there, done that”), though I am sure oceanographers would be keen to have such measurements. So how can the interested oceanographer arrange to have such measurements made?

While ocean observing systems offer great opportunities for putting acoustical techniques to good use, representation of acoustics at oceanographic conferences associated with setting priorities, planning, and implementing systems has been poor. To some extent this deficiency is a product of funding limitations. Effective participation at these workshops is expensive and time consuming. Also, these workshops are often hosted by oceanographic agencies or organizations, hence often not on the acoustician's sonar. Without better representation and advocacy at these conferences, however, acoustics will continue to be left out of the process.

Acousticians have to do better with respect to oceanography. Acousticians have to get proactive and organized. Acousticians have to get political, alas.

5 NASA AND THE SATELLITE PROGRAMS

The example of National Aeronautics and Space Administration's (NASA) satellite programs for earth and ocean observation and how NASA supports science derived from them is illuminating. Satellite systems such as JASON or GRACE are deployed at costs of $100'sM. To make the most of these observations, NASA maintains a science funding program. The program serves the dual purposes of providing for the best science derived from the observations, but also providing for the continued evolution of the satellite systems themselves, which require significant scientific support. It would have been folly for satellite-based science to depend wholly on funding from the U.S. National Science Foundation. (One early critic of satellite measurements famously made the statement that he "wouldn't know what to do with such measurements if he had them;" the peer-review system has its flaws.) One hallmark of this program is a healthy, constructive dialog between scientists and its managers.

For acoustical oceanography, there is no "National Ocean Acoustics Administration," however. There is no organization dedicated to the deployment of acoustical observations, and no organization dedicated to science using such observations. In the United States, these roles have traditionally been played by the U.S. Office of Naval Research (ONR) and its Ocean Acoustics program, but this program offers relatively modest funding and is dedicated to the particular aims and requirements of the U.S. military. Sustained acoustical systems as contributions to global observing systems will not likely be supported by ONR. It seems to this author that the lack of an institution dedicated to promoting acoustical observations and related oceanographic science is a fundamental cultural or structural impediment. Depending on funding from the National Science Foundation for these purposes has had mixed and dwindling success. Many of my colleagues have given up applying to NSF for project support, not because they gave up on tomography, but because they see minimal chance of success. Groups developing tomography in Japan and France were terminated by sudden government fiat some years ago. (One critic of acoustical measurements made the statement to me that he "wouldn't know what to do with such measurements if he had them." This true statement illuminates the mindset of physical oceanographers. The education process continues.)

The importance of a healthy, constructive dynamic between scientists and supporting agencies for successful acoustical observations is illustrated by the remarkable success of the Nansen Center in making acoustical observations and integrating them into larger programs over the past decade. This success stems in a large measure from the active and encouraging interest the Norwegian Research Council and European Union science programs have taken in the acoustical program.

6 FUTURE DIRECTIONS

There are many lines of research that may be readily pursued to better set the stage for implementing acoustical components to the ocean observing systems. Here are a few examples, a by-no-means comprehensive list.

Acousticians do not today have access to reliable low-frequency, deep-ocean source technology; development of such sources has lagged. Meanwhile, passive acoustics as a remote sensing technique has had some positive developments in recent years, and remains a possibly fruitful avenue for investigation. The ability to use the ocean's natural ambient sound sources to quantitatively measure its properties would be a major breakthrough, but more work is required to establish this strategy. The use of new or abandoned transocean communications cables offers opportunities for implementing acoustic listening systems for passive or active acoustics. Such systems offer both power and real-time data access (www.itu.int/en/ITU-T/climatechange/task-force-sc/Pages/default.aspx).

Considerable work remains to be done in establishing the utility of acoustics using quantitative design studies through simulations. One remarkable recent development available to acousticians is the availability of high-resolution, realistic global ocean models. These models provide a convenient way to compute the environmental effects on acoustic transmissions, and they are a valuable asset for acousticians.

One advantage of research quality acoustic data is that historical data are often as precise as present-day data. With new understanding of acoustic and ocean properties, realistic ocean models, and new computational techniques, new analyses of historical data offer significant reward for little investment.[2] Global-scale acoustic data acquired during the 1991 Heard Islasnd Feasibility Test (HIFT) have yet to be fully exploited (taff.washington.edu/dushaw/heard/index.shtml).

As has been often noted, the tomographic data type, together with other data, is best employed in conjunction with techniques for data assimilation. Data assimilation and tomography have been discussed for many years, yet aside from a few notable instances,[6,10] these techniques are not yet developed to the point of practical or more widespread use. Data assimilation approaches that can routinely handle the acoustic data type are essential. (As a historical note, the Estimating the Circulation & Climate of the Ocean (ECCO) modeling and data assimilation consortium was originally established to support the ATOC program.)

One region that has garnered support for acoustical applications is the Arctic Ocean.[7] The Arctic is often suggested because acoustical applications there are not viewed as in competition with floats and gliders. The under-ice applications of acoustics are many, from biological measurements, to the positioning of instruments under sea ice, to low-frequency, Arctic Basin thermometry. An ongoing program for acoustical measurements within Fram Strait has been conducted by the Nansen Center in Norway over the past decade (www.nersc.no). Acoustical technologies as contributions to the Arctic Ocean Observing systems are likely to be fruitful in the near future.

7 FINAL FLOURISH

Over the past thousand years, science has evolved to have specific standards of discourse designed to optimally and definitively resolve scientific disputes. These standards include, in addition to data from observations, refereed publications in reliable journals that are defended verbally in an open forum. These elements are, not by chance, exactly those required to complete a doctoral degree. Science is unique among human endeavors. It is not autocratic – we do not decide science questions based on scientific authority. It is not democratic – we do not decide science questions based on popular support or voting. Rather, an essential facet of the endeavor is that every individual scientist has an ethical obligation to examine questions himself and decide the truth of things himself. Fundamentally, in my view, the discourse on ocean acoustic tomography has strayed from these standards over the past decades. The original bad scientific argument is “You are the only one.” One can contemplate, with an eye on Figure 1, exactly why this argument fails – it is an ad hominem argument, in the history of science it has a poor track record, etc. But, if the logic of the statement if followed, the implication that everyone else has carefully examined the question and has a ready argument that resolves it. For the question of ocean acoustic tomography, it would appear that the community has, over the past 20 or more years, carefully examined the question and there are careful publications or arguments showing why it is not a valuable contribution to the ocean observing system. What are they?

8 REFERENCES

1. B. D. Dushaw, Ocean Acoustic Tomography. *Encyclopedia of Remote Sensing*, E. G. Njoku, (Ed)., Springer, Springer-Verlag Berlin Heidelberg, doi: 10.1007/Springer Reference_331410 (2014)
2. B. D. Dushaw, and D. Menemenlis, Antipodal acoustic thermometry: 1960, 2004, *Deep-Sea Res. I*, **86**, 1−20. doi:10.1016/j.dsr.2013.12.008 (2014).
3. B. Dushaw, and many others, A Global Ocean Acoustic Observing Network. P*roceedings of OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21–25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., (Eds.), ESA Publication WPP-306 (2010).
4. B. D. Dushaw, P. F. Worcester, and others, A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res*., **114**, C07021. doi:10.1029/2008JC005124 (2009).
5. B. Dushaw, and many others, "Observing the ocean in the 2000's: A strategy for the role of acoustic tomography in ocean climate observation" in *Observing the Oceans in the 21st Century*, edited by C. J. Koblinsky and N. R. Smith (GODAE Project Office and Bureau of Meteorology, Melbourne), pp. 391−418 (2001).
6. K. V. Lebedev, M. Yaremchuk, and others, Monitoring the Kuroshio Extension through dynamically constrained synthesis of the acoustic tomography, satellite altimeter and in situ data. *J. Oceanogr.*, **59,** pp. 751–763 (2003).
7. P. N. Mikhalevsky, H. Sagen, P. F. Worcester, and many others, Multipurpose acoustic networks in the Integrated Arctic Ocean Observing System. *Arctic*, **68**,1-17 (2015).
8. W. M. L. Morawitz, P. J. Sutton, B. D. Cornuelle, and P. F. Worcester, Three-dimensional observations of a deep convective chimney in the Greenland Sea during winter 1988/1989. *J. Phys. Oceanogr.*, **26,** pp. 2316–2343 (1996).
9. W. Munk, P. Worcester, and C. Wunsch, *Ocean Acoustic Tomography*, Cambridge University Press (1995).
10. J.-H. Park, and A. Kaneko, Assimilation of a coastal acoustic tomography data into a barotropic ocean model. *Geophys. Res. Let.*, **27**, pp. 3373–3376 (2000).
11. D. Stammer, and many others, Accuracy assessment of global barotropic ocean tide models. *Rev. Geophys.*, **52**, 243–282. doi:10.1002/2014RG000450 (2014).
12. H. von Storch and K. Hasselmann, *Seventy Years of Exploration in Oceanography: A Prolonged Weekend Discussion with Walter Munk*, Springer (2010).

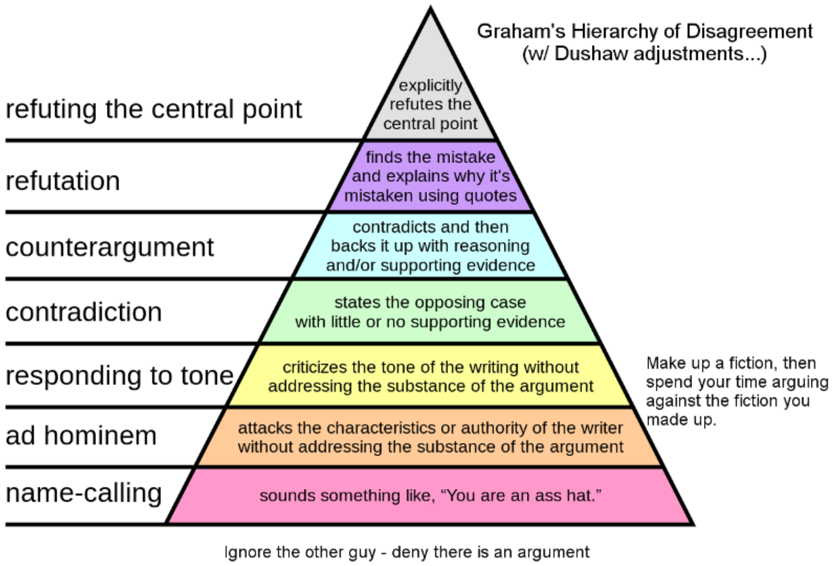

Figure 1. *Chart of Graham's Hierarchy of Disagreement, schematically illustrating the diminishing logic of some argument types towards the bottom of the chart. This author has added modifications, including the lowest tier, which is to deny that there is even a disagreement, hence avoiding the need for an argument altogether. The type of arguments used against tomography have been of the lowest tiers, while those used in favor tomography have been of the highest tiers. (The reader may object to the "tone" of this paper, but the rating of such an objection is clear.)*

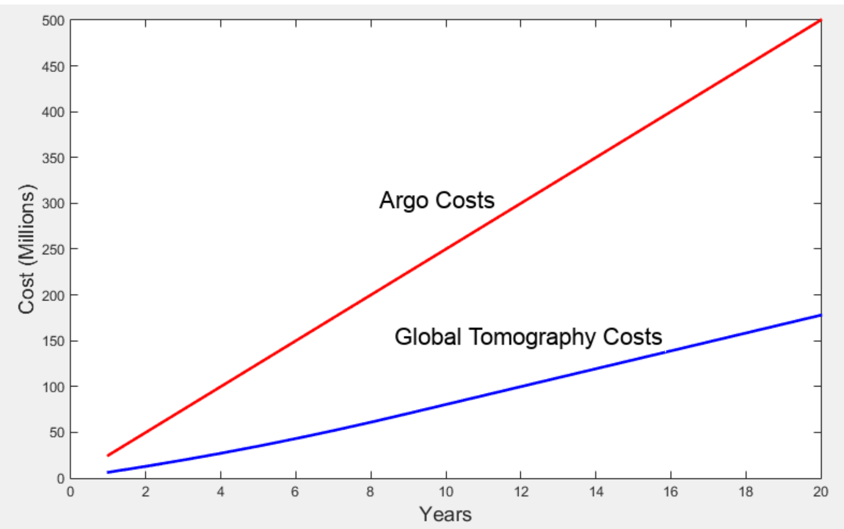

Figure 2. *A schematic comparison of cumulative Argo and global acoustic tomography costs in US dollars. The Argo costs are based on 1000 floats deployed every year costing $25K per float. The tomography costs are based on 3 cabled sources deployed per year, to a maximum of 25,*[11] *costing $2M each and with operational costs of $150K/year each. Argo float life expectancy was 4 years, tomography source life expectancy was 10 years. The costs of acoustic receivers are incidental. Irrespective of flaws in these assumptions, this figure makes the point that the costs of tomography are not as prohibitive as has been portrayed.*