Acoustic tomography as a component the Atlantic Ocean Observing System: Opportunities and Challenges

B. Dushaw

Nansen Environmental and Remote Sensing Center, Thormøhlens gate 47, N-5006 Bergen, Norway
brian.dushaw@nersc.no

Abstract: Ocean acoustic tomography is a unique measurement of large-scale ocean variability. The travel times of acoustic signals measure large-scale temperature, barotropic current, and, with an array of transceivers, relative vorticity. Applications include measurements of currents in shallow harbors, basin- and global-scale temperature, and deep-water formation events at high latitudes. Acoustical observations in ice-covered regions are compelling. All such systems provide for underwater GPS. The common perception that the Argo float system obviates the need for acoustic tomography is an error. While tomographic systems as components of regional or global-scale Ocean Observing Systems represent real opportunities for new insights into long-term ocean variability, the practical implementations of sustained acoustical systems are challenging. Such challenges are programmatic or cultural, rather than scientific, however. Given the extraordinary climatological changes presently occurring, it is imperative that all available observational capabilities be thoroughly considered. Studies employing numerical ocean models are required to design optimal observing strategies that exploit the complementary nature of different measurements. Observing Systems require practical techniques to implement data assimilation with the tomographic measurements. Programmatic technical capability and manpower to sustain acoustical measurements is lacking. Successful implementation of tomographic systems will require a stronger symbiotic relation between acousticians and oceanographers.

Keywords: ocean acoustic tomography, integrated temperature measurement, physical oceanography, underwater GPS, long-range acoustic propagation, basin-scale acoustics

1. INTRODUCTION

The possible acoustical applications for an ocean observing system are myriad and cross several disciplines, but a review or survey of these applications is beyond the scope of this paper (See Dushaw, et al. 2001; Dushaw, et al. 2010; Mikhalevsky, et al. 2015). The discussion here addresses ocean acoustic tomography (Munk 1986; Munk et al. 1995; Dushaw 2013) and ocean observing systems. This document does not present a technical case for why tomography should be a part of the observing system; that case has been made elsewhere (Dushaw, et al. 2001; Dushaw, et al. 2010; Mikhalevsky, et al. 2015). Rather, this document aims to continue the process of building communities for designing, implementing, and sustaining tomography measurements within Ocean Observing Systems (e.g., Dushaw 2016).

2. ATLANTIC BASIN ACOUSTICAL SYSTEMS

Almost 20 years ago, the OceanObs99 conference concluded ("Conference Statement" 1999):

"that acoustic tomography did represent a potentially valuable approach and that, initially, it should be implemented in the Arctic and at specific locations such as the Strait of Gibraltar. The Conference also encouraged an exploratory implementation in the North Atlantic in the presence of substantial profiling floats to test the complementarity and/or redundancy between tomography and other measurements."

As the Conference Statement explicitly noted, "For tomography, there is support for a pilot project in the N. Atlantic." ("Conference Statement" 1999). Unfortunately, there was little organized effort by acousticians to follow up and build on this consensus (the focus of many of those working on tomography at the time was the North Pacific). The issue remains unresolved, and an acoustic tomography program in the North Atlantic still has every indication of providing substantial new information about the evolving state of the ocean.

The effectiveness of an acoustic tomography observing network for the North Atlantic can be assessed using simulated acoustic transmissions in a high-resolution numerical ocean model. The North Atlantic is a region of rapid climate variability, with temperature changes expected to extend into the abyssal ocean at time scales much shorter than in other ocean basins. Long-range acoustic transmissions may effectively sense average temperature, including abyssal volumes. The optimal design and cost effectiveness of a basin-wide acoustical observing network can be assessed using the simulations. In particular, the simulated acoustic data can be considered in combination with data assimilation techniques and existing data types to quantify the enhanced resolution of large-scale or deep oceanic variability afforded by the acoustic data.

As the 1999 OceanObs conference statement highlighted, one long-lingering question has been the degree of difference between Argo float and tomography measurements. Despite the lack of evidence supporting it, one common perception is that the existence of the Argo float system obviates the need for acoustic tomography. There is considerable evidence that perception is an error. In 1996, Morawitz, et al. (1996) examined the combination of hydrographic, acoustic, and moored data in resolving events of deep water formation in the Greenland Sea (Fig. 1). Even during a time of dense hydrographic sampling, the tomography data was essential to resolving the variability. Dushaw, et al. (2009) compared basin-scale acoustic data obtained in the North Pacific with equivalent data computed from objective maps of the ocean based on Argo float data and satellite altimetry. The comparison showed little agreement, indicating little redundancy between Argo and acoustic data. Similarly, a direct comparison of the information content of a line array of moored thermistors with tomography using objective mapping techniques explicitly illustrated the complementarity of those two data types (Dushaw and Sagen 2016). The information from sparse hydrographic profiles is not redundant with the information from the line- and depth-averages of tomography.

Over the past few decades, the Atlantic has hosted a number of tomography or long-range propagation experiments. Fig. 1 shows the locations of several tomography experiments from 20-50 years ago; no such experiments have been conducted in recent years. The AMODE, SYNOP, CAMBIOS, MOVE, and Labrador Sea experiments were regional, process-oriented studies, from mesoscale dynamics to meridional overturning circulation to deep-water formation (Dushaw et al. 2001; Dushaw et al. 2010). The Perth-Bermuda experiment was a test of antipodal acoustic propagation in 1960 that was analyzed as a measure of global-scale temperature change over a half century (Dushaw and Menemenlis 2014). The acoustic propagation spanned the South and North Atlantic Oceans, with the acoustic signals confined near the sound channel axis.

At present there are no specific plans for deployment of acoustic tomography in the Atlantic. Several notional schemes have been identified in the past, however, and remain viable options (SCOR WG 96, 1994; an update is in order!). Studies are required to demonstrate the utility of such observations and derive optimal configurations for deployment (e.g., Dushaw and Rehm 2016, Johannessen et al 2001). Figure 1 illustrates three possibilities: (1) an array of six transceivers to observe the western subtropical Atlantic basin, (2) trans-Atlantic Ocean measurements modeled after the basin-scale ATOC measurements of the North Pacific, and (3) two acoustic paths to augment the RAPID measurements of meridional overturning along 26.5°N. Since 2004, the RAPID program (www.rapid.ac.uk) has maintained an array of about 20 moorings along 26.5°N across the Atlantic to observe the strength and structure of the meridional overturning circulation (MOC). The western Atlantic array could certainly be used to map and monitor the climatic variations of the region, and perhaps to monitor the net volume of mode (18°C) water (an idea due to Wunsch). Acoustic propagation along the notional basin-scale path was originally tested by Ewing in 1945. The measurement highlights Bermuda as a convenient location for a sustained receiving array. Deployments such as these are modest by today’s standards, and the maintenance of the RAPID array of moorings over the past decade illustrates the successful strategy of yearly deployments of moorings in maintaining a system. Acoustical systems cabled to shore remain the ideal solution, however.

3. DISCUSSION

Despite the compelling case for the information provided by acoustic tomography and community support for such measurements, tomographic systems have yet to be implemented as part of an Observing System. This difficiency has been disappointing. Its ultimate causes appear to have been a failure of the acoustic and oceanographic communities to meld and a challenging funding environment. At the programmatic level, avenues of funding for sustained acoustical measurements have been precluded. Ultimately, successful implementation of tomographic systems will require a stronger symbiotic relation between acousticians and oceanographers (Dushaw, et al. 2016).

While deployments of tomographic systems as components of the Ocean Observing Systems (regional or global scales) represent real opportunities for new insights into long-term ocean variability, the practical implementations of sustained acoustical systems are a challenge. At present, such challenges are programmatic or cultural, rather than scientific, however. Given the extraordinary climatological changes presently occurring in the Earth's ocean-atmosphere system, it is imperative that all available observational capabilities undergo a thorough consideration.

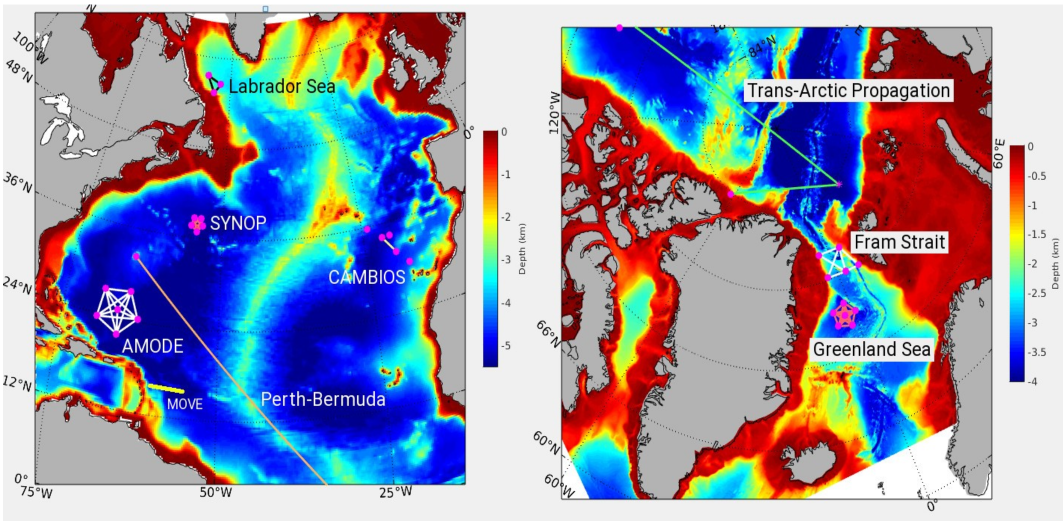

Fig. 1: Past observations in the Atlantic include the Acoustic Mid-Ocean Dynamics Experiment (AMODE), the SYNoptic Ocean Prediction (SYNOP) experiment, the Labrador Sea experiment, the Canary-Azores-Madeira Basin Integral Observing System (CAMBIOS), and the MOVE array along 16ºN for monitoring the Meridional Overturning Circulation. The Perth-Bermuda experiment was antipodal, with acoustic propagation across the South and North Atlantic. Experiments in the Arctic Regions include the Greenland Sea Project, the Trans-Arctic Acoustic Propagation (TAP) experiment, and the series of deployments in Fram Strait (DAMOCLES, ACOBAR, UNDERICE). Azimuthal equal area projection.

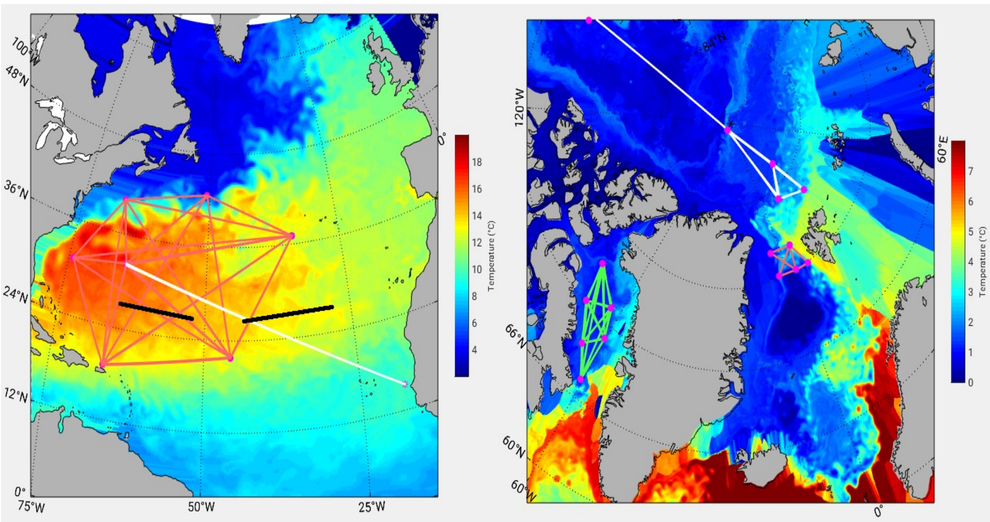

Fig. 2: Notional future observations in the Atlantic include an array in the western North Atlantic (pink), a basin-scale path from Senegal to Bermuda (white), and two paths along 26.5ºN augmenting the RAPID array monitoring of the MOC (black). Possible sustained observations in the Arctic Regions include an array in Fram Strait (pink), a regional and trans-Arctic array north of Svalbard (white), and a regional observatory in Baffin Bay (green). Both panels show temperature (@500 m Atlantic, @300 m Arctic) derived from ECCO2 project state estimates.

Acknowledgements

B.D.D. was supported by ONR Grant N00014-15-1-2186. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

REFERENCES

"Conference Statement" of the First International Conference on the Ocean Observing System for Climate (OceanObs99), St Raphael, France, 18-22 October 1999. http://unesdoc.unesco.org/images/0012/001205/120594eo.pdf

"Conference Statement" in *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society (Vol. 1)*, Venice, Italy, 21-25 September 2009, Hall, J., Harrison, D.E. & Stammer, D., Eds., ESA Publication WPP-306, doi: 10.5270/OceanObs09.Statement.

Dushaw, B. (2016). Ocean acoustic tomography: A missing element of the ocean observing system, in *Proceedings Acoustic & Environmental Variability, Fluctuations and Coherence*, Institute of Acoustics, Cambridge, U.K. 12−13 December 2016, 5 pp., http://staff.washington.edu/dushaw/epubs/Dushaw_Tomography_Opinion_Cambridge_2016.pdf.

Dushaw, B. D. (2013). ''Ocean Acoustic Tomography'' in *Encyclopedia of Remote Sensing*, E. G. Njoku, Ed., Springer, Springer-Verlag Berlin Heidelberg, 2013, ISBN: 978-0-387-36698-2.

Dushaw, B. and E. Rehm (2016). Acoustic Tomography in Baffin Bay: A Preliminary Survey, NERSC Technical Report No. 375, 20 October 2016, 33 pp., doi: 10.13140/RG.2.2.15772.28806, https://www.researchgate.net/publication/313844561_Acoustic_Tomography_in_Baffin_Bay_A_Preliminary_Survey.

Dushaw, B. D., and H. Sagen (2016). A comparative study of moored/point and acoustic tomography/integral observations of sound speed in Fram Strait using objective mapping techniques, *Journal of Atmospheric and Oceanic Technology*, 33, 2079−2093, doi: 10.1175/JTECH-D-15-0251.1.

Dushaw, B. D., and D. Menemenlis (2014). Antipodal acoustic thermometry: 1960, 2004, *Deep-Sea Research I*, 86, 1−20, doi: 10.1016/j.dsr.2013.12.008.

Dushaw, B. D., G. Bold, C.-S. Chui, J. Colosi, B. Cornuelle, Y. Desaubies, M. Dzieciuch, A. Forbes, F. Gaillard, J. Gould, B. Howe, M. Lawrence, J. Lynch, D. Menemenlis, J. Mercer, P. Mikhaelvsky, W. Munk, I. Nakano, F. Schott, U. Send, R. Spindel, T. Terre, P. Worcester, and C. Wunsch (2001). "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.

Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, B. D. Cornuelle, and D. Menemenlis (2009). A decade of acoustic thermometry in the North Pacific Ocean, *Journal of Geophysical Research*, 114, C07021, doi: 10.1029/2008JC005124.

Dushaw, B., W. Au, A. Beszczynska-Möller, R. Brainard, B. D. Cornuelle, T. Duda, M. Dzieciuch, A. Forbes, L. Freitag, J.-C. Gascard, A. Gavrilov, J. Gould, B. Howe, S. R. Jayne, O. M. Johannessen, J. F. Lynch, D. Martin, D. Menemenlis, P. Mikhalevsky, J. H. Miller, S. E. Moore, W. H. Munk, J. Nystuen, R. I. Odom, J. Orcutt, T. Rossby, H. Sagen, S. Sandven, J. Simmen, E. Skarsoulis, B. Southall, K. Stafford, R. Stephen, K. J. Vigness-Raposa, S. Vinogradov, K. B. Wong, P. F. Worcester, and C. Wunsch (2010). A Global Ocean Acoustic Observing Network, In *Proceedings 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.

Johannessen, O. M., S. Sandven, H. Sagen, T. Hamre, V. J. Haugen, P. Wadhams, A. Kadetzky, N. R. Davis, K. Hasselmann, E. Maier-Reimer, U. Mikolajewicz, V. Doldatov, L. Bobylev, I. B. Esipov, E. Evert, and K. A. Naugolnykh (2001). Acoustic monitoring of the ocean climate in the Arctic Ocean, AMOC Final Report, NERSC Technical Report No. 198, January 2001.

Mikhalevsky, P. N., H. Sagen, P. F. Worcester, A. B. Baggeroer, J. Orcutt, S. E. Moore, C. M. Lee, K. J. Vigness-Raposa, L. Freitag, M. Arrott, K. Atakan, A. Beszczynska-Möller, T. F. Duda, B. D. Dushaw, J. C. Gascard, A. N. Gavrilov, H. Keers, A. K. Morozov, W. H. Munk, M. Rixen, S. Sandven, E. Skarsoulis, K. M. Stafford, F. Vernon, and M. Y. Yuen (2015). Multipurpose acoustic networks in the integrated Arctic Ocean observing system, *Arctic*, *68*, *Suppl. 1*, 17 pp., doi: 10.14430/arctic4449.

Morawitz, W. M. L., B. D. Cornuelle, and P. F. Worcester (1996). A case study in three-dimensional inverse methods: Combining hydrographic, acoustic, and moored thermistor data in the Greenland Sea. *Journal of Atmospheric and Oceanic Technology*, 13, 659–679.

Munk, W. (1986). Acoustic monitoring of ocean gyres, *Journal of Fluid Mechanics*, 173, 43−53, doi: 10.1017/S0022112086001064.

Munk, W., P. Worcester, and C. Wunsch (1995). *Ocean Acoustic Tomography,* Cambridge, UK: Cambridge University Press, 456 pp.

SCOR WG 96 (Scientific Committee on Ocean Research Working Group 96) (1994). Atlantic sub-group: W. J. Gould, Y. Desaubies, B. M. Howe, D. R. Palmer, F. Schott, and C. Wunsch, Acoustic Thermometry in the Atlantic: A Report to SCOR WG 96, http://staff.washington.edu/dushaw/epubs/SCOR_WG96.pdf.