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

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Abstract: *Ocean acoustic tomography now has a long history with many observations and experiments that highlight the unique capabilities of this approach to detecting and understanding ocean variability. Examples include observations of deep mixing in the Greenland Sea, mode-1 internal tides radiating far into the ocean interior (coherent in time and space), relative vorticity on multiple scales, basin-wide and antipodal measures of temperature, barotropic currents, coastal processes in shallow water, and Arctic climate change. Despite the capabilities, tomography, and its simplified form thermometry, are not yet core observations within the Ocean Observing Systems (OOS). These observing systems could benefit greatly from applied acoustical oceanography, and both the world's climatic circumstance and the difficulty in ocean observation argue that all available techniques should be implemented. A perception that the existence of the Argo float system obviates the need for the acoustical observations has been shown to be false; observations of ocean variability by tomography are distinct from those of floats or gliders. The growing application of acoustical measurements as part of the observing system (e.g., IQOE or* *underwater GPS systems) make tomography a natural component of OOSes. The developing INTAROS system is demonstrating the integration of diverse observations, including passive and active acoustical applications, into a coherent, operational system – part of the Arctic Ocean Observing System. Within the Framework for Ocean Observing (FOO), we reiterate the recommendation of the OceanObs'99 conference and advocate a tomography system in the western North Atlantic as an initial contribution. Such a system would provide unique measurements of large-scale temperature, barotropic currents, vorticity, fluxes, and abyssal variability, while providing tracking capabilities for deep floats and gliders. This initial design, and the sustained system that would evolve from it, would result in a more complete fit-for-purpose overall observing system for essential ocean variables (EOVs) and derived quantities.*

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

1. INTRODUCTION

Some twenty years ago the oceanographic community began the challenging process of establishing ocean observatories [1−5]. Such systems aim to transition the results of significant societal investment in basic oceanographic research into products and information services 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. Many oceanic processes or systems evolve at decadal to century time scales and require sustained, long-term observations to properly understand them. A semantic difference should be highlighted: "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 maintain and integrate disparate observations, and then distill them to deliver promised data, information, and products to society on a sustained basis, e.g., the national weather services, the CTBTO system. 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 (e.g., www.nanoos.org). Two examples of Ocean Observatories programs are Neptune Canada (www.neptunecanada.ca) and the Ocean Observatories Initiative Regional Scale Nodes (OOI-RCN). One view is that research capabilities or techniques that have become established and 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. For a review of the current status of the real-time in situ Global Ocean Observing System for operational oceanography see [6].

Some observing systems already 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, but a review or survey of these applications is beyond the scope of this paper (See [4,5]). The discussion here addresses ocean acoustic tomography [7,8] 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 [e.g., 4,5]. Rather, this document aims to continue the process of building acoustical communities for designing, implementing, and sustaining tomography measurements within Ocean Observing Systems.

2. MECHANICS AND REQUIREMENTS

While an acoustical oceanographer's first thought in connection with tomography and OOSes may be that "this is an opportunity to do the research I am interested in," there are two gross errors with that sentiment. First, the Ocean Observing System is an operational, rather than research, system. Its aim is to implement proven technologies applied to well-defined requirements for observing and monitoring well-determined oceanographic phenomena. Like the national weather services, the aim is then to make available information products that serve the requirements of government, industrial, and other such communities. One cannot bring research problems or technologies to OOSes. Second, observational subsystems of OOSes are integrated with a wide range of other observations, and observations and other products are required to be made available to the public in real time or near real time. The paradigm is the antithesis of the focussed interest of the research-funded principal investigator. Our goal, therefore, is to identify information that is missing from existing OOSes that could be addressed by deploying established acoustical systems – What missing Essential Ocean Variables (EOVs) can be measured by existing, established long-range acoustical systems?

One principle is, of course, that acoustic calculations should be done prior to deploying any particular system [e.g., 9,10]. It is well established that climatology can be used to compute a basic, reasonably accurate, acoustic arrival pattern in most regions of the world oceans. One development in recent years is that sometimes small-scale variability can have dramatic effects on such calculations [11]. Acoustic propagation in Fram Strait is one example, while propagation in the Canary Basin is another. The possible effects of small-scale variability cannot be ignored. In many places the topography, background sound speed profile, or other factors may not allow for data suitable to address the oceanographic problem of interest.

A critical need is the design and implementation of standards for data archive and retrieval, and standards for data management. Within and across regional and global OOSes, data is required to flow transparently and to be available to anyone at the time of acquisition or soon thereafter. In addition, any acoustical data must be coordinated with other available data types, e.g., should it be possible to identify and retrieve all available data and metadata (satellite, hydrographic, moored, or acoustical) at a particular time and place. Once systems are set up to use acoustical data within one OOS, those systems should be interoperable with other OOSes. Acoustical data has to be put in a form that works and plays well with others and that can be used transparently by anyone. Regarding the latter point, the implication is that intermediate products, that is, variables more familiar to oceanographers, derived from the acoustic data may be required from any tomography OOS subsystem. It seems unworkable that the acoustic data should require technical expertise in acoustics of all users. OOSes usually operate on a data model in which data are stored and archived on disparate servers, and brought together into a single system by networking and software. The archival system for acoustical data of Neptune Canada may provide a starting point.

3. ATLANTIC BASIN SYSTEMS

Almost 20 years ago, the OceanObs99 conference concluded [1]:

"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." [1]. 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). Nevertheless, the issue is still 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 simulations in a numerical ocean model. 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. [12] 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. In 2009, Dushaw et al. [13] 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 obtained 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 theose two data types [14]. The information from sparse hydrographic profiles is not redundant with 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 [4,5]. 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 [15]. 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 that we know of. Several notional schemes have been identified in the past, however, and remain viable options [16; 1994, perhaps an update is in order?]. Studies are required to demonstrate the utility of such observations and derive optimal configurations for deployment. The figure (Fig. 1) illustrates three possibilities: (1) an array of six transceivers to observe the western

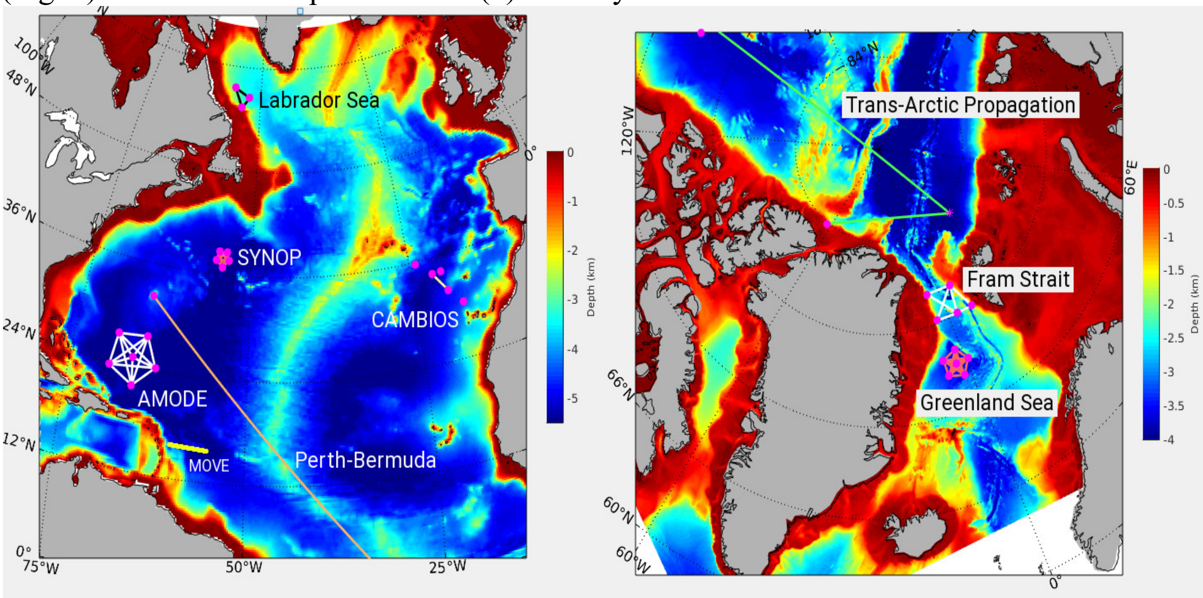

Fig. 1: Past observations in the Atlantic include the Acoustic Mid-Ocean Dynamics Experiment (AMODE), the SYNoptic Ocean Prediction (SYNOP) experiment, the Labrador Sea experiment, the Canary-Azores-Madeira Basin Integral Observing System (CAMBIOS), and the MOVE array along 16ºN for monitoring the Meridional 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.

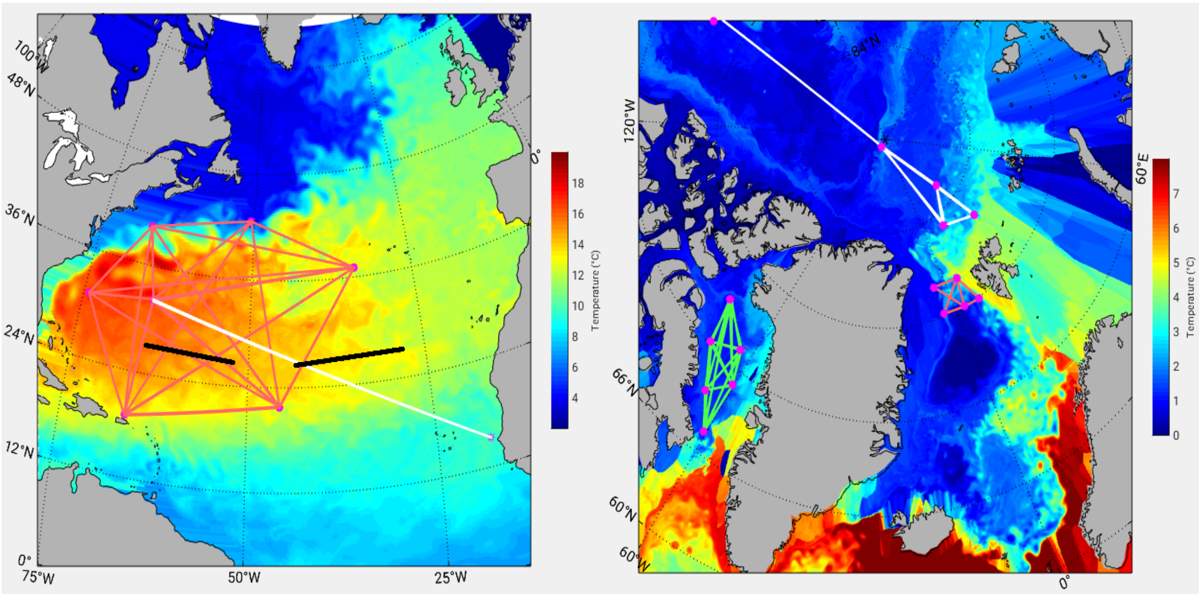

Fig. 2: Notional future observations in the Atlantic include an array in the western North Atlantic (pink), a basin-scale path from Senegal to Bermuda (white), and two paths along 26.5ºN augmenting the RAPID array monitoring of the MOC (black). Possible sustained

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.

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 redeployments of moorings in maintaining a system. Acoustical systems cabled to shore remain the ideal solution, however.

4. ARCTIC BASIN SYSTEMS

With ice cover that precludes the use of many autonomous instruments, the Arctic regions have long been accepted as regions for implementation of ocean acoustic tomography. Both OceanObs99 and OceanObs09 Conferences highlighted this application [1,3,17]. Tomography made the earliest detections of climate change in the Arctic with the TransArctic Propagation experiment in the early 1990s [17] (Fig. 1). The Greenland Sea Project employed tomography to monitor the events of deep-water formation in 1988-9. Between 2008 and 2016, the Nansen Center deployed a series of acoustic arrays in Fram Strait to enhance the measurements of the exchange of water between the North Atlantic and Arctic Oceans [17] (Fig. 1). It has proved difficult to obtain programatic support for sustaining such observations, however.

Presently, there are existing plans for deploying a modest triangular array north of Svalbard, and for combining that array with other sources and receivers to comprise trans-Arctic measurements (Fig. 2). The former is to be deployed by the Nansen Center as a continuation of their work with the Fram Strait deployments, while these systems are to be coordinated with the trans-Arctic propagation plans by the Scripps Institution of Oceanography. INTAROS, a contribution to the Arctic Ocean Observing System led by Nansen Center scientists, is developing plans for the integration of acoustical data with their system. We also have an interest in maintaining the acoustical array within Fram Strait for long-term monitoring of the Arctic and Atlantic water exchanges. Deployment of such a system requires committed support as part of an Ocean Observing System, however, since it has less of a research focus. Continued monitoring appear to be desireable from an Observing System standpoint, but the main acoustical and other research questions appear to be resolved.

5. REGIONAL SYSTEMS

A number of enclosed basins or seas appear to be amenable to acoustical observations. Such regions are Baffin Bay, the Mediterranean, or the Gulf of Mexico, which are deep, but relatively confined. Several tomography experiments have been conducted in the Mediterranean, both trans-basin experiments [4] and experiments measuring deep-water convection in the Gulf of Lyon (THETIS) [4]. Regions such as these are intriguing for tomography, since a basin-scale array can synoptically observe the entire regional basin. There is an interest in establishing an Observing System for Baffin Bay, exploiting acoustics

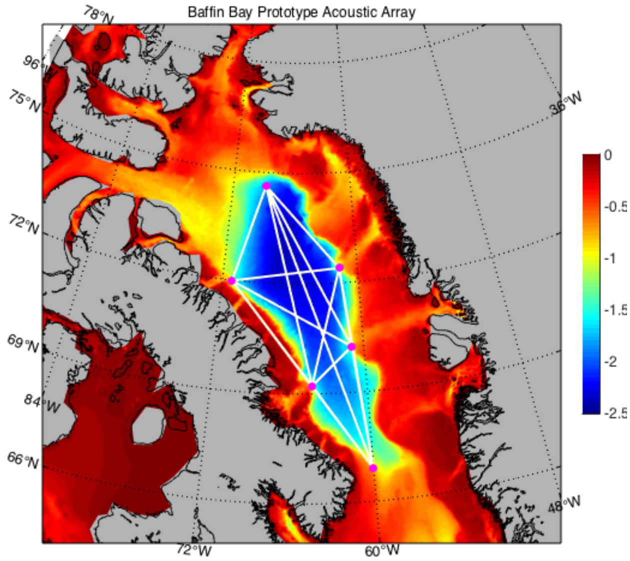

Fig. 3: In this array design for Baffin Bay, acoustic sources or receivers are moored along the ca. 500-m depth contour [10]. As much as possible, mooring locations should be selected to allow clear acoustic propagation into the basin without bottom interaction. Arrays such also as this serve as an ideal underwater acoustic GPS system

for a wide range of applications. Baffin Bay is covered by complex, moving ice fields for most of the year. This interest engendered a study of the various applications of acoustic tomography there (Fig. 3) [10].

6. SHALLOW-WATER, COASTAL SYSTEMS

While acoustic tomography is often understood to be a long-range, deep-water observing techinque, at least as originally envisioned, another class of tomography employs high-frequency acoustic transmissions over ranges of 10's of km in shallow water for ocean observation. Such observations are in coastal areas of particular interest, of course, often in areas of heavy fishing or industrial activity that preclude moored observations. These observations are "acoustic remote sensing" with the instruments deployed on the perimeter of the area of interest. Given the high-frequencies of the transmissions, the scale of the instrumentation is greatly reduced, making these observations highly economical. The possible applications of such systems are myriad. Two examples are observations of the exchange of water through the Strait of Gibraltar and the ocean transports and temperature in shallow seas or harbors around Japan.

Acoustic transceivers were deployed in the Strait of Gibraltar in 1996 to test acoustic methods for making routine, rapidly repeated, horizontally-integrated measurements of flow and temperature in straits. Reciprocal transmissions between the transceivers were used to test the feasibility of using differential travel times to monitor the flow *along* the acoustic paths. Transmissions directly across the Strait were used to test the feasibility of using horizontal arrival angle fluctuations and acoustic intensity scintillations to monitor the flow *across* the acoustic paths. The geometry was selected to provide ray paths that only sample the lower-layer Mediterranean water, hence the feasibility of monitoring the Mediterranean outflow using the various methods could be evaluated. Reciprocal travel time measurements diagonally across the Strait performed best. Sum travel times from the reciprocal transmissions provided good temperature measurements [18].

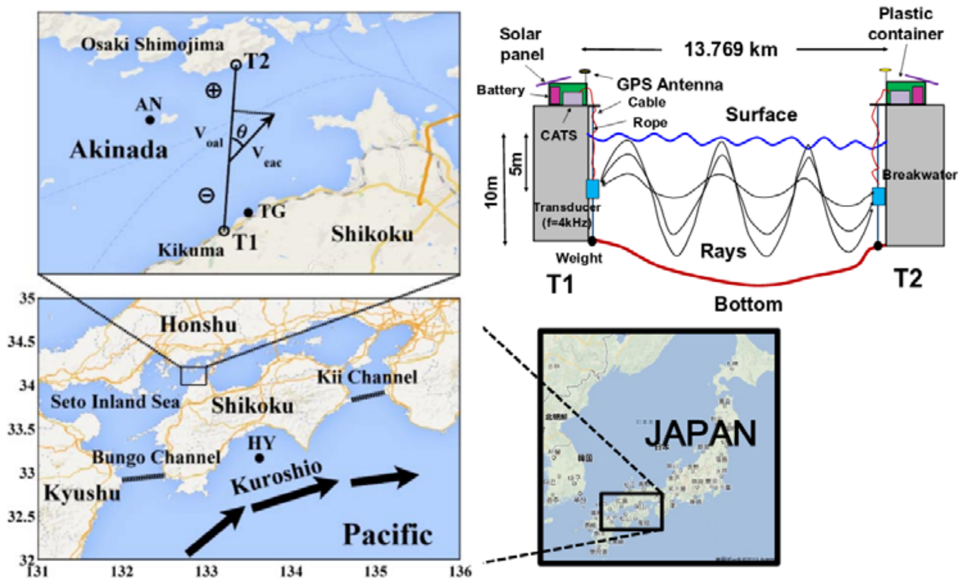

Fig. 4: To measure the temperature and transport variations of the Kuroshio intrusions into the Akinada Sea, reciprocal high-frequency sound transmissions were made between T1 and T2. The ocean depth along the 13.8-km path was 30-50 m, and the travel times of refracted and bottom-interacting rays were measured. The experiment was solar powered, with transceivers deployed from breakwaters of fishery ports. Adapted from [19].

In 2012 one research program used the coastal acoustic tomography system (CATS) developed by A. Kaneko for monitoring the environment of an inland sea of Japan. The purpose of the study was to monitor the effects of intrusions of the Kuroshio Current into the Seto Inland Sea (Fig. 4). High-frequency acoustic transmissions across a shallow choke point were used to measure the inland sea throughflow. One year of monitoring was not sufficient to determine the long-term variations of transports and temperature. The acoustic technology was essential to measure the environment because it is an area of intense fishing activity and shipping traffic [19].

7. DISCUSSION

Since its inception over 30 years ago [20], ocean acoustic tomography has proven to be a unique measurement of large-scale ocean variability. The travel times of acoustic signals have measured large-scale temperature, barotropic current, and, with an array of transceivers, relative vorticity. Applications range from measurement of currents in shallow harbors, to measurement of basin- and global-scale temperature, to monitoring the evolution of deep-water formation events at high latitudes. Acoustical measurement often extends into abyssal depths. Acoustical observations and applications in ice-covered regions are compelling (cf. INTAROS). All such systems provide the dual purpose of providing an underwater GPS system for AUVs. There is an obvious need for studies employing numerical ocean models to design optimized observing strategies that exploit the complementary nature of various ocean measurement technologies. Observing Systems rely on data assimilation techniques to derived ocean state estimates as stakeholder products, so practical techniques are needed to implement data assimilation with the line-integral measurements that tomography affords.

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 [21].

In recent years it has become apparent that one critical issue facing acoustic tomography is the attrition or lack of sufficient technical manpower to install and sustain acoustical systems. There are few scientists deploying acoustic tomography systems for ocean measurement in the world. The pool of young or emerging scientists with sufficient technical expertise in acoustics is sparse. The acoustical systems all require considerable technical backing, from the design and preparation of instruments, to deployment and recovery of moorings, to processing and distillation of the acoustic data obtained into corrected and usable form, to the final oceanographic analysis of those data. All of these aspects of tomography require considerable skilled manpower. Deployment and maintenance of a sustained acoustical system for an OOS would require a considerable investment and dedication to develop such human resources. One can contemplate the large numbers of people at institutions ensuring that satellite programs provide the steady stream of the accurate data essential to present-day OOSes.

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.

8. ACKNOWLEDGEMENTS

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