A GLOBAL OCEAN ACOUSTIC OBSERVING NETWORK

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ABSTRACT

Passive and active acoustic measurements are effective and unique approaches to ocean observation. Both approaches have techniques that are well-established and suitable for immediate deployment as part of an operational observing system. Many of these techniques exploit the remarkable ability of low-frequency sounds to traverse great distances in the ocean. Passive acoustic measurements of natural or man-made sounds are made for diverse purposes ranging from assessing the environmental impact of human activities, to geophysics, to monitoring changes in biodiversity in response to climate change. Active acoustic systems are employed for tracking instruments and acoustic tomography. Tomography has a role in the ocean observing system that is complementary to altimetry and profiling floats, particularly in the context of data assimilation and ocean modeling. Modest systems of acoustic receivers and sources deployed across ocean basins can make cost effective, sustained observations of a variety of ocean processes.

1. INTRODUCTION

The ocean is largely transparent to sound, but opaque to electromagnetic radiation. Underwater sound is therefore a powerful tool for remote sensing of the ocean interior. Sound is widely used for remote sensing of the ocean on small scales (e.g., acoustic Doppler current profilers), but acoustical measurements have been underexploited in regional and global ocean observations relative to in situ instruments and electromagnetic radiation. Instruments in situ (e.g., floats, moorings, CTDs) measure local properties. Electromagnetic radiation (e.g., satellite altimetry, radar from satellites, airplanes or shore) measures properties at the ocean's surface. We encourage OceanObs'09 to take an expansive view of ocean observations and work toward integrating all approaches into a comprehensive measurement and modeling program.

Acoustic measurements can be made either passively, using sound generated by nature, or actively, using sound generated by sources engineered to produce optimal acoustic signals. Both approaches offer powerful ways to observe the ocean that are not readily available by other means, and both approaches have techniques that are well-established and suitable for immediate deployment as part of an operational observing system [38], [13], [21], [11].

As an educational tool, the sounds of the ocean offer a diverse and lively introduction to oceanography and the motivations for ocean observation (c.f., Discovery of Sound in the Sea - http://www.dosits.org/).

Basin-wide and regional tomography were accepted as part of the ocean observing system by OceanObs'99 [26], [13]. Since then, a decade of measurements of basin-scale temperature using the long-range travel times have been completed in the North Pacific Ocean. Section 2 briefly reviews the comparison of these measured travel times with travel times derived from four independent estimates of the North Pacific. Section 3 then describes the role of passive acoustic measurements in the global ocean observing system. The ability of a relatively sparse network of acoustic sources to provide the underwater equivalent of the Global Positioning System is discussed in Section 4. Section 5 describes how these same sources can be used for acoustic tomography on a variety of scales, with particular emphasis on the Arctic and North Atlantic Oceans. Section 6 briefly summarizes the result of extensive research on the effects of the sources used for acoustic thermometry on marine life. While there are measurable effects on distribution and behavior, all effects are small and well within the range of natural variability. Recommendations are given in Section 7.

2. A DECADE OF ACOUSTIC THERMOMETRY IN THE NORTH PACIFIC

Large-scale temperatures in the North Pacific Ocean measured by long-range acoustic transmissions over the decade 1996-2006 demonstrate the uniqueness and sustainability of the acoustical measurements [14], (Cross reference OceanObs'09 proceedings paper (XR): [49]). Acoustic sources located off central California (1996-1999) and north of Kauai (1997-1999, 2002-2006) transmitted to receivers distributed throughout the northeast and north central Pacific (Fig. 1). Daily-average travel times at four-day intervals provide excellent temporal resolution of the large-scale thermal field (XR: [40]). The interannual, seasonal, and shorter period variability was large; substantial changes sometimes occurred in only a few weeks. Linear trends estimated over the decade were small compared to the interannual variability and inconsistent from path to path, with some acoustic paths warming slightly and others cooling slightly.

In a test of the accuracy of ocean state estimates by various means, the measured travel times were compared with travel times derived from four independent estimates of the North Pacific (Fig. 1): (i) climatology, as represented by the World Ocean Atlas 2005 (WOA05), (ii) objective analysis of the upper ocean temperature field derived from satellite altimetry and in situ profiles (OA), (iii) an analysis provided by the Estimating the Circulation and Climate of the Ocean project as implemented at the Jet Propulsion Laboratory (JPL-ECCO), and (iv) simulation results from a high-resolution configuration of the Parallel Ocean Program (POP) model. The effect of salinity variations on the acoustic travel times was negligible. The acoustic data show that WOA05 is a better estimate of the time-mean hydrography than either the JPL-ECCO or the POP estimates, both of which were unable to reproduce the observed acoustic arrival patterns. With the time-mean states of these estimates corrected to that of the World Ocean Atlas, the comparisons of computed and measured time series (Fig. 1) provided a stringent test of the large-scale temperature variability in the models. The differences are sometimes substantial, indicating that acoustic thermometry data does provide significant additional constraints for numerical ocean models. The computation of these differences is also the first step in the process of assimilating the acoustic data as constraints in ocean state estimates (XR: [3],[17],[20], [22],[31],[32],[39]).

3. PASSIVE ACOUSTICS

Passive acoustics can be employed for a variety of purposes, for example: (1) tracking, counting and studying the behavior of vocalizing marine mammals and fish; (2) assessing and monitoring the ecological impacts of ocean warming and acidification on marine ecosystems and biodiversity (XR: [6],[28]); (3) detecting undersea explosions such as blast fishing or nuclear tests; (4) detecting and quantifying tsunamis; (5) measuring rainfall; (6) measuring the properties of undersea earthquakes and volcanoes; (7) monitoring the sound produced by high-latitude sea ice; (8) monitoring anthropogenic activities in marine protected areas. Hydrophones deployed for sound measurement are robust, lasting for decades. The U.S. Navy SOund SUrveillance System (SOSUS - the archetypical passive acoustic observing system) has been operational for over a half century. In addition to local measurements at higher frequencies, acoustic observing arrays can exploit the remarkable ability of low-frequency acoustic signals to propagate great distances in the ocean.

Each of the receivers in an operational global system would comprise a few hydrophones and a small electronics/processing package with modest power needs. They are easily integrated on platforms of opportunity such as moorings, floats, gliders and cable systems, although the data rates for real-time, unprocessed signals can be high.

3.1. Environmental assessment and the climate of acoustic noise

Regional and global ocean observing systems serve many environmental assessment purposes. Low-frequency oceanic ambient sound levels have increased over the past few decades in response to the exponential growth in the world economy, in effect a change in the acoustic climate of the world's oceans. The consequences of these changes are not yet understood

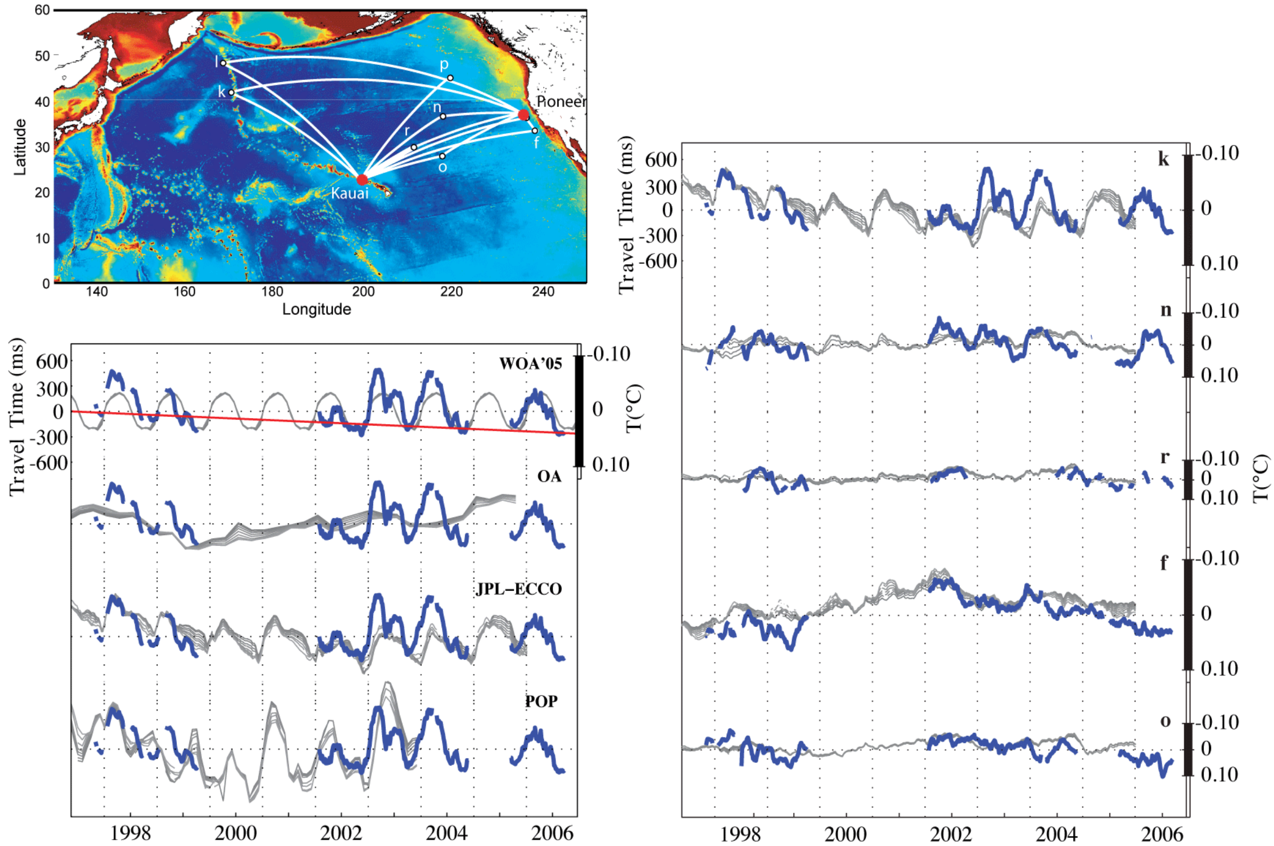

Figure 1. ***(Upper left)*** *The acoustic thermometry array in the North Pacific Ocean superimposed on bathymetry. Acoustic sources were located on Pioneer Seamount off central California and on the north slope of Kauai. The bottom-mounted hydrophone arrays indicated by letters were receivers of opportunity employed during this decade-long program.* ***(Lower left)*** *Measured travel times for transmissions from Kauai to receiver k located to the northwest of Kauai (blue) compared with travel times calculated using sound-speed fields derived from (1) the 2005 World Ocean Atlas, (2) estimates of upper ocean temperature profiles by an objective analysis (OA) procedure that combines satellite altimetric height with in situ temperature profiles, (3) the JPL-ECCO model solutions, and (4) the POP model (gray). The time means have been removed from all of the time series. The nominal travel-time trend corresponding to a warming of 5 m°C per year on the sound-channel axis, as suggested by Munk and Forbes [37] is given by the red line.* ***(Right)*** *Comparison of measured travel times from transmissions from Kauai (blue) to the indicated receiver with equivalent travel times calculated using temperature and salinity fields from the JPL-ECCO solution (gray). To give a sense of scale in temperature, nominal temperature perturbations averaged along the ray paths inferred from the travel times are shown on the right-hand axis. (From Dushaw et al. [14], XR: [49]).*

(e.g., on the behavior of marine mammals), but clearly monitoring of such properties is important. Such monitoring will be possible only through long-term observations by readily accessible acoustic instrumentation. To cite one example, offshore wind energy development projects are being proposed along suitable coastlines. Each of these projects requires a suite of meteorological, oceanographic and other observations, including acoustics, to support siting, installation and operation of offshore wind farms in coastal waters. The acoustic measurements supporting these projects can be real time and provide information about local ambient noise sources such as shipping, wind, rain, as well as noise from the offshore wind farm.

Increasing human activities in the Arctic will lead to additional sound from fishing vessels, oil and gas installations, seismic exploration and ship transportation. The European Commission has begun to develop an Arctic policy in which one of the proposed actions is to "Contribute to assessing the impact on marine mammals of increased acoustic noise generated by human activities." The Arctic Council has made similar recommendations in their 2009 Arctic Marine Shipping Assessment report [1]. Recently, year-round recorders were included on moorings spanning Davis Strait, with three others deployed across Fram Strait and

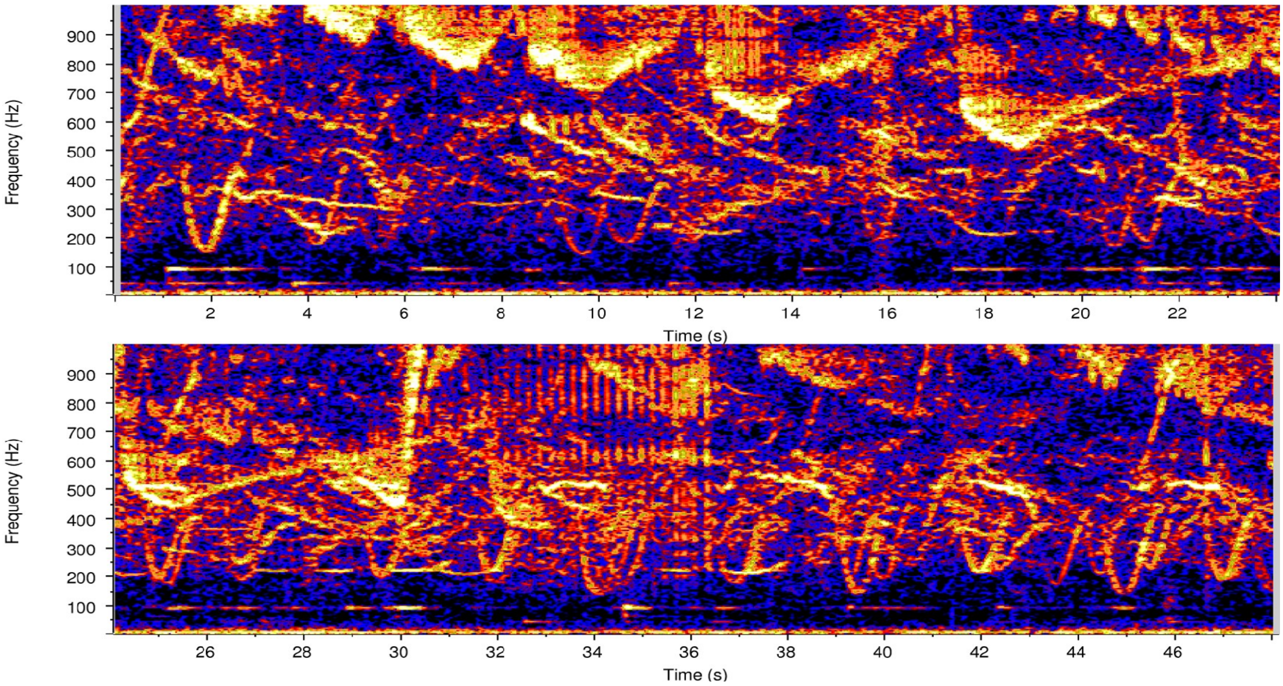

Figure 2. Spectrogram of under ice recordings of bowhead and beluga whale and walrus sounds from the northern Bering Sea in May 2007 (FFT 512 pts, 94% overlap, Hann window). Acoustic data such as these can provide year-round information on animal habitat use under conditions and from locations where more traditional survey methods are impossible.

near the Chukchi Sea (XR: [43]). To obtain more systematic data, an acoustic listening system for autonomous and continuous monitoring of vocalizations from marine mammals and ambient noise needs to be included in a future Arctic ocean observatory (XR: [7]). Observations of marine mammals in the Arctic are mainly obtained from ships and aircraft and are sparse both in time and space.

3.2. Biological and anthropogenic sounds in marine habitats

Observation of long-term biological trends in many marine habitats is a challenging task that is exacerbated when the habitats in question are in remote locations (XR: [28]). Monitoring the ambient sound field is a means of assessing biological activity since many behavioral processes are accompanied by sound production.

The use of SOSUS for tracking the seasonal distribution and vocalization of whales precipitated the development of autonomous recorders for year-round deployment in remote ocean habitats (e.g., [34],[36]) − a development that has revolutionized the science of large whale ecology (Fig. 2).

Biological activity on coral reefs and in surrounding waters are monitored for periods of a year or longer using the Ecological Acoustic Recorder (EAR) [27] (XR: [4]). The system is now operationally recording the sound field of coral reefs and other marine habitats at 29 sites around the Pacific and Europe. Snapping shrimp produced the dominant acoustic energy on the reefs examined and exhibited clear acoustic trends associated with changes in the physical environment. Other biological sounds recorded included those produced by fish and cetaceans, which exhibit distinct temporal variability. Examples of other such systems include the High-frequency Acoustic Recording Package (HARP) and NOAA's "Haruphone". Sueur et al. [48] demonstrated that passive acoustics provide a valuable tool to monitor changes in biodiversity at the ecosystem level in response to global climate change, particularly ocean acidification.

3.3. Rainfall rates

Sound made by rainfall at sea can be used to measure the types and rate of that rainfall [33]. The characteristics of the sound are used to infer the quantity and type of rain falling over an area with a diameter of a few kilometers. Passive Acoustic Listener (PAL) systems have been adapted for use on deep ocean moorings and remote satellite-linked ocean drifters in order to make climate observations of rainfall patterns over the oceans. The simple acoustic receivers can also be used to provide long-term detection and quantification of sound-producing biological and anthropogenic activities in the ocean.

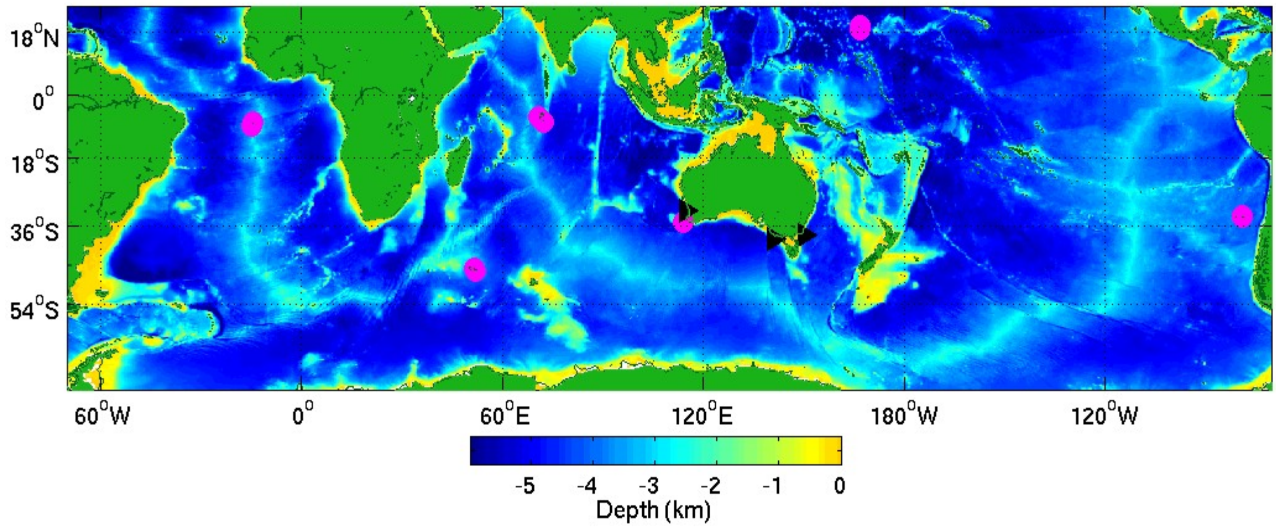

Figure 3. The locations of existing CTBTO hydrophone stations (magenta circles) and the regional Australian hydrophone facilities (black triangles), together with ocean bathymetry derived from the Smith-Sandwell atlas. Each CTBTO receiver consists of a triplet of hydrophones for directionality. Data are recorded, processed, and shipped to shore in real time from these arrays.

3.4. Existing operational hydrophone systems

In addition to SOSUS, which is not readily accessible to scientists, two other systems are presently operating.

The Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) operates eleven passive hydroacoustic monitoring stations around the world (six hydrophone and five T-phase stations using seismographs on small islands), which routinely detect, locate, and characterize man-made and natural underwater events including explosions, volcanoes, earthquakes and marine mammal vocalizations (Fig. 3). The CTBTO hydroacoustic stations are also capable of monitoring long-term changes in the disintegration rate of the Antarctic ice shelves and icebergs, including climate-driven changes, through observation of underwater noise produced by ice rifting and breaking events. The system was also used to track the breakage of the large fault responsible for the 2004 Sumatra tsunami (e.g., [18]) and could be used in real-time in the future to assess event size and the likely scale of the resultant tsunami. Unfortunately, this low-frequency system is not readily available for general scientific usage, because of its specific United Nations mandate and associated controls on the distribution of IMS data.

Autonomous underwater acoustic observatories are to be deployed and operated around Australia and off Eastern Antarctica in 2009-2012 as part of the Australian Integrated Marine Observing System (IMOS; http://imos.org.au). These acoustic observatories will be used for studying abundance and migration patterns of marine mammals and for monitoring natural sources of underwater noise, including Antarctic ice calving processes.

3.5. Geophysical observations and ocean acoustics

Marine geophysics is a close cousin to ocean acoustics; what a geophysicist terms a "T-phase" is to an ocean acoustician just sound within the water column created by an earthquake. Within the context of an ocean observing system, the separation of geophysics from ocean acoustics is by-and-large artificial. Instruments for both sciences require similar power and communication capabilities, and once one has instrumented for acoustical oceanography, the addition of instruments for geophysical observations is incidental (and vice-versa). The case for a network of geophysical observing platforms in the ocean has been made many times (e.g., [41]). The rationale for such platforms merges with the rationale for the ability to measure and monitor ocean acoustic signals.

4. TRACKING, OR THE UNDERWATER GLOBAL POSITIONING SYSTEM

With a modest set of active acoustic sources with known location and accurate time keeping, the precise locations of underwater instruments and mobile platforms can be determined by triangulation [12]. Such an underwater tracking system can provide the position, navigation, and time keeping that GPS presently provides for terrestrial and space use. An underwater GPS system will support a host of new science applications.

4.1. Tracking drifting instruments

According to Davis and Zenk [10]: "Some studies place a high premium on using floats to represent fluid-parcel trajectories requiring the uninterrupted current following that can be achieved only with acoustic tracking. ... For acoustic floats a major limitation to economical sampling can be overcome by widespread deployment of high-energy sound sources. It is, for example, entirely feasible today to install enough sound sources that a float could be continuously tracked ... sound sources, like radio stations, can serve different users, ... on a basin-wide scale. Miniaturization of receiver electronics and production in great numbers could result in significant decline in float prices. This, and the development of new sensors, could open other fields of research…" The frequency of the position fixes is set by the transmission rate of the acoustic sources. This rate can be quite frequent and is independent of cost, so long as sufficient power is available to drive the source. Frequent and accurate tracking of acoustic floats allows true subsurface Lagrangian velocity to be determined.

This technology enables the operation of floats, gliders, and AUVs for long-term sustained operation beneath the ocean surface and under ice. One such program is the Acoustic Navigation and Communication for High Latitude Research (ANCHOR; http://anchor.apl.washington.edu). A medium-range (200 km) acoustic navigation system for glider operations beneath ice has been developed and successfully implemented in the Davis Strait [29]. Efforts are in progress to implement the system in Fram Strait [42] (XR: [30],[43]).

4.2. Tracking, monitoring, and counting of marine animals; tagged tracking

Marine mammals such as fin, blue and humpback whales routinely "sing," and this behavior has been used to establish the seasonal presence and migratory movements of these populations over broad scales [47]. Some animals such as salmon, tuna, and sharks are tagged with very small active acoustic sources which are then tracked by a network of receivers (see, e.g., The Ocean Tracking Network – http://oceantrackingnetwork.org/; Australian Acoustic Tagging and Monitoring System - http://www.imos.org.au/aatams.html.) Such measurements also allow behavioral studies and analysis of migration patterns (XR: [8]).

5. OCEAN ACOUSTIC TOMOGRAPHY

Acoustic tomography is now well established, and the approach was accepted as part of the ocean observing system during OceanObs'99 [26],[13]. The North Atlantic and Arctic were highlighted as regions that would be most suitable for implementing tomographic observing arrays. OceanObs'99 also identified key areas appropriate for tomography such as the Strait of Gibraltar; such an observing system has been implemented in Fram Strait [42] (XR: 43).

Tomography has a role in the ocean observing system as a measurement type that complements altimetry and profiling floats. We disagree with the notion that the existence of the profiling floats obviates the need for tomography (e.g., Hadfield et al. [19] assess the accuracy of upper ocean temperature measurements by Argo). The acoustic travel times are inherently spatially integrating, naturally suppressing mesoscale variability and providing precise range-averaged temperature. Tomography is a subsurface measurement of temperature; salinity contributes negligibly. Tomographic measurements extend into the abyssal ocean (XR: [15]). The measurement can be made without risk of calibration drift - time is the fundamental measurement. Tomographic measurements are nearly instantaneous (a measurement of an ocean basin in an hour) and can be made at any sampling rate (increased sampling adds essentially no additional cost). The number of acoustic paths increases as the product of the number of sources and receivers. By combining data from multiple paths crossing at many different angles, the interior structure of the temperature field can be determined with a spatial resolution that depends on the number of paths and geometry. The difference of reciprocal travel times, derived from the simultaneous transmission of acoustic pulses in opposite directions along an acoustic path, is a precise measure of the range-averaged current. Because of the integral nature of the data, tomography is best employed in conjunction with numerical ocean models and data assimilation. Through programs such as ECCO, tomography can make a unique contribution to the task of ocean state estimation at time scales from days to decades.

5.1. Pacific Ocean

The prototypical ATOC experiment demonstrated the feasibility of a sustained array for acoustic thermometry in the North Pacific. The region is of climatological importance to North America. There are a number of on-going and planned platforms in the North Pacific that could potentially be instrumented with small hydrophone arrays for sustained, real time operation. An observing array using several acoustic sources spanning the North Pacific along existing undersea cables, employing platforms of opportunity such as DART buoys or OceanSites (XR: [46]) for additional receivers, would give extensive acoustic sampling, while minimizing long-term operation and maintenance costs.

5.2. Atlantic Ocean

As noted by OceanObs'99, the scientific rationale for employing acoustic tomography in the North Atlantic is compelling. Prior to OceanObs'99, a subgroup of the Scientific Committee on Ocean Research (SCOR) began the process of designing an acoustical observing array in the Atlantic [45]. This is a dynamic, highly variable region, with significant variability in the abyssal ocean. Deep convection in the Labrador Sea was monitored from 1997 to 2003 using tomography [2]. Harbingers and signals of oceanic climate change are expected to be found in the North Atlantic.

Separating the North Atlantic wind-driven circulation from the thermohaline circulation is difficult. Long-term measurements of surface forcing, polar and equatorial boundary forcing, and basin-scale conditions (response to either or both) are needed to quantify the effects on circulation and allow future prediction. The mooring and EM-based mass transport measurements at 26.5°N (RAPIDMOC - http://www.noc.soton.ac.uk/rapidmoc/) are helpful, but do not include barotropic flow and upper-ocean response to local winds. Satellite estimates of heat content use models to extrapolate surface measurements to the interior. Additional data are needed to better understand the physics and the response.

Uncertain isopycnal and diapycnal mixing, combined with complex transport pathways, imply that ocean heat content and transport are difficult to deduce by spatially diverse transport measurements. Acoustic thermometry allows an accurate and precise measurement of heat content changes (the result of flux divergence; the accuracy of temperature measurements is of order millidegrees) in limited volumes surrounding vertical slices. These measurements of the true net response in areas such as the North Atlantic between 25°N and 40°N, where a petawatt is lost to the atmosphere, can constrain and/or guide models or dynamical studies. Locations such as the Bahamas, Azores, Canaries, away from the meandering noise of the upper ocean western boundary currents, may be best for this, with essentially zonal tracks recommended. Multiple zonal tracks may usefully average over spatially localized effects.

Heat transport is the crucial factor in Atlantic Meridional Overturning Circulation (XR: [9]). Although this transport is difficult to measure directly, full-depth thermometry measurements at critical latitudes, constrained by other observations such as upper ocean Argo floats, can potentially detect effects of changing fluxes and flux divergences. Ray paths for transmissions over long ranges typically extend from the near surface to 3-4 km depths. Although there is an up-down ambiguity in the interpretation of travel time variability (Did the variations occur because of changes to the near surface or changes to the deeper ocean?), when combined with additional information or data from, e.g., profiling floats or satellite altimetry, the temperature changes in the abyss can be inferred. Fig. 4 illustrates a possible acoustical observing array in the western North Atlantic.

5.3. Arctic Ocean

There is increasing evidence that the Arctic is undergoing significant changes due to global warming, with the most obvious being the melting of the ice cover [25]. In September 2007 the Arctic sea ice reached a record summer-time minimum, the smallest ice cover since satellite monitoring of sea ice began in 1978. In the last 20 years submarine measurements of sea ice draft have shown a 40% reduction in average sea ice thickness, while satellite remote sensing has shown a 14% reduction in sea-ice extent over the same period, decreasing at a rate of 3-5%/decade (thicker multi-year ice at 7-10%/decade). Forecasts suggest that the Arctic Ocean could be ice-free during summer before the end of this century. Even advanced, state-of-the-art, numerical models struggle to accurately represent the natural spatial and temporal variability in sea ice; they did not predict the extreme minimum in sea ice extent. Annual decreasing Arctic Sea ice extent has been shown to mirror increasing CO_2 on decadal time scales [23]. Based on this empirical relationship between CO_2 and ice extent, ice extent is decreasing much more rapidly than predicted by the coupled climate models. Sea ice variability is complex, however, dependent on both dynamic and thermodynamic factors, e.g., surface air temperature, albedo effects, atmospheric heat transport, and ocean heat flux. It is therefore important to measure both ice thickness and the internal temperature of the Arctic Ocean, which presently is not done in a routine way (XR: [5]).

Acoustic tomography can contribute substantially to this research, since it has been shown to be effective for monitoring average heat content and average temperature in the Arctic Ocean, particularly in the Arctic Intermediate Water layer. The 1994 “Transarctic Acoustic Propagation” experiment (TAP) and the 1999 “Arctic Climate Observations using Underwater Sound” (ACOUS) experiment measured warming which was confirmed by submarine measurements during the Submarine Ice Exercises (SCICEX) [35].

Satellites monitor changes in the surface of the polar oceans (http://www.arctic-roos.org), but the thickness of the ice cover and the interior of the ocean remain poorly observed due to lack of technological capability to obtain systematic ice thickness and ocean data. In addition to travel time measurements for acoustic thermometry, measurements of acoustic amplitude during ACOUS demonstrated the feasibility of monitoring average sea ice thickness changes along the propagation path [16].

A major challenge is to develop and install oceanographic-observing systems in the ice-covered polar seas for climate and ocean research. Use of Argo floats, which is an important component of the Global

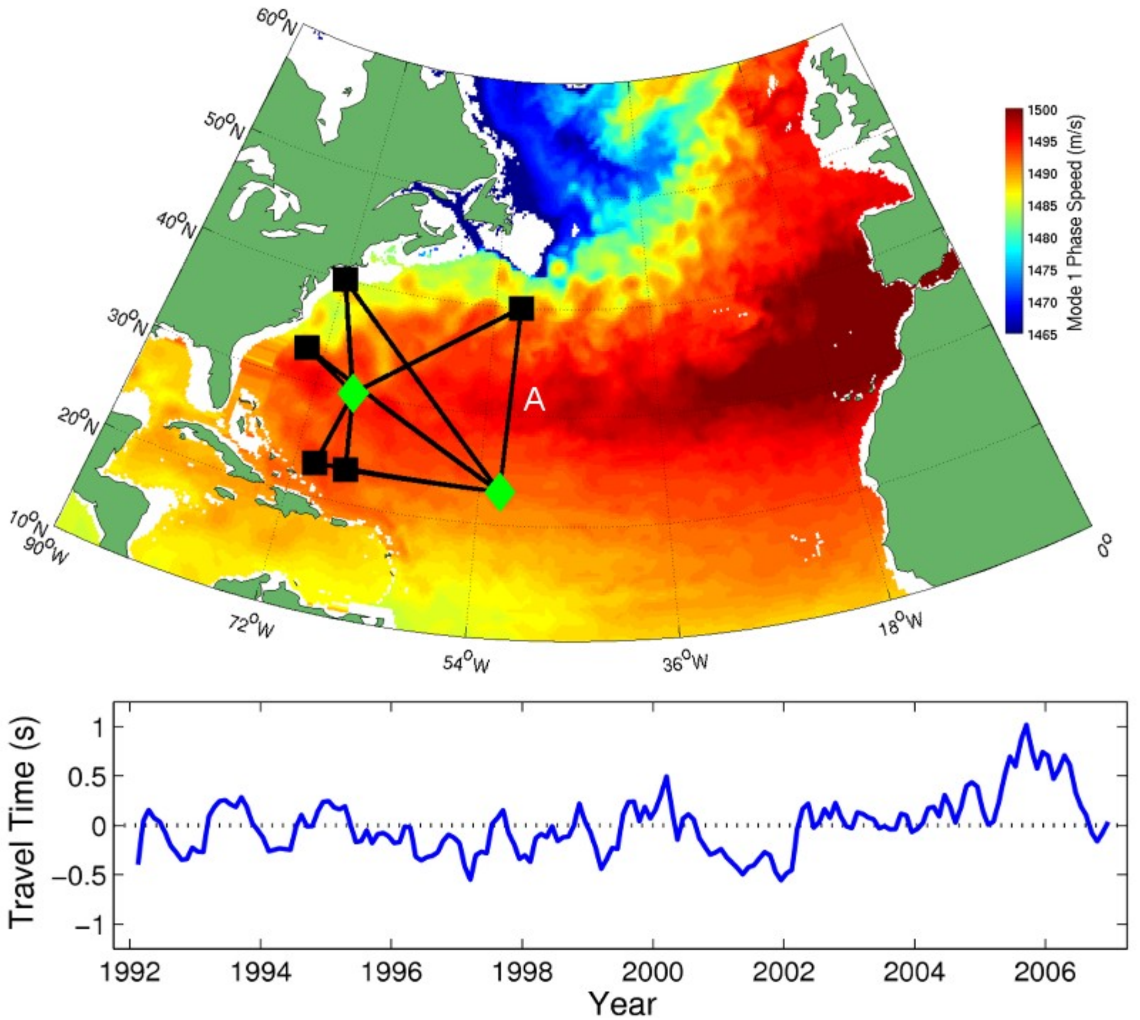

Figure 4. A notional array of acoustic sources and receivers employed for tomography in the North Atlantic, using five NOAA DART buoys as receivers of opportunity (black squares) and two sources (green diamonds). The colors show acoustic mode-1 phase speed for 50-Hz frequency derived from a snapshot of the high-resolution (1/6º) ECCO2 numerical ocean model; this quantity indicates the travel time variability for acoustic propagation along the sound channel axis. This system would record mean temperatures between the ray turning depths (500-3200 m) along the paths, including seasonal and interannual variability. This area includes the deep western boundary component of the Atlantic thermohaline circulation (THC) that comprises a portion of the meridional overturning circulation (MOC). The area also includes subtropical mode water (18°C water) and upper and lower North Atlantic deep water. The lower panel shows the 15-year time series of mode-1 travel time derived from the model along the path marked "A". This time series gives the temperature variability of the model averaged along the sound channel axis at around 1500 m depth. Increasing travel time corresponds to decreasing temperature.

Ocean Observing System (GOOS), is difficult to implement in ice-covered regions. Acoustic tomography is therefore a promising tool for ice-covered areas (Fig. 5). Two ongoing EU projects, the "Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies" integrated project (DAMOCLES - http://www.damocles-eu.org) and the ACoustic technology for OBserving the interior of the ARctic Ocean (ACOBAR - http://acobar.nersc.no), have also introduced several new technologies based on acoustics, such as "Acoustic Ice Tethered Platforms" (AITP) and acoustic navigation systems for float and glider operations under the ice, in addition to acoustic tomography (XR: [43]). Furthermore, advanced three-dimensional sonars are being tested to monitor ice thickness and ice drift locally.

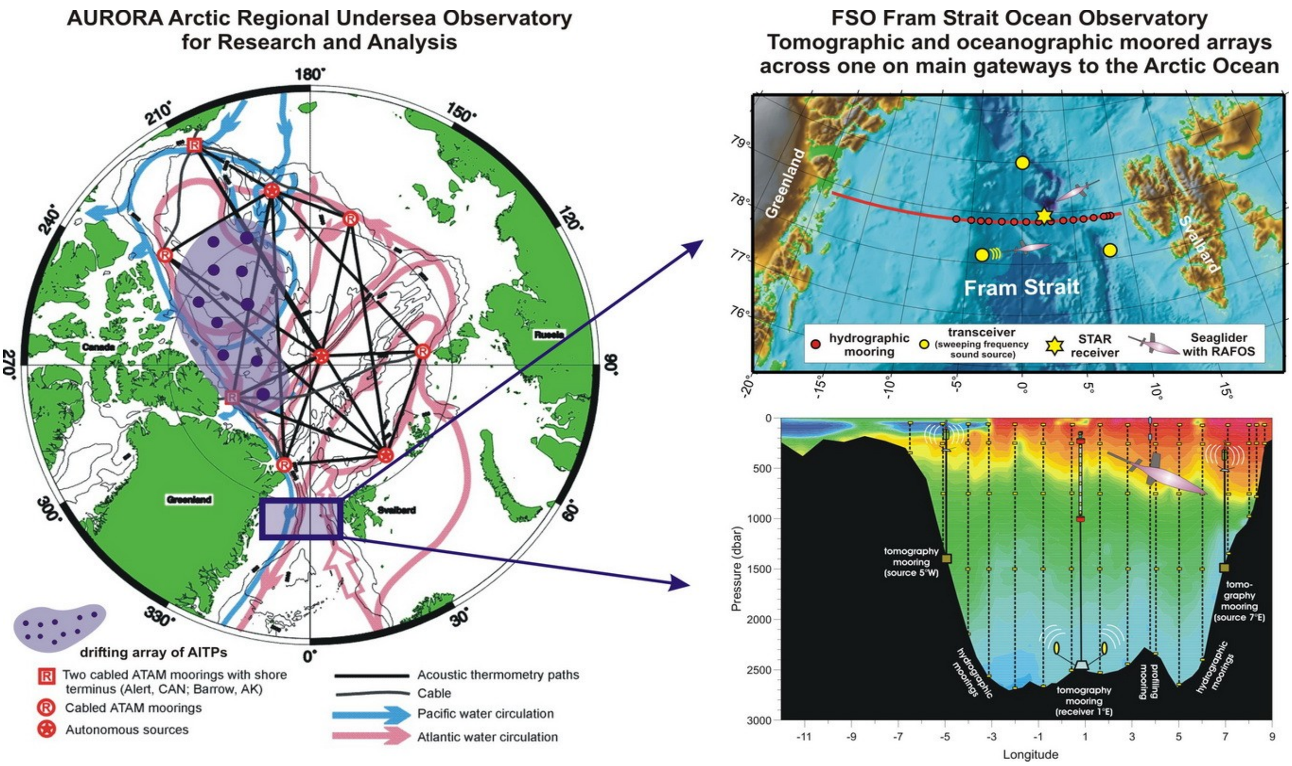

Figure 5. The envisioned basin-wide AURORA mooring grid in the Arctic Ocean (left panel) and the existing moored observatory in Fram Strait (right panels). In addition to moored instrumentation, an array of drifting Acoustic Ice Tethered Platforms (AITP) with acoustic modems for communications will be deployed in the Arctic Ocean, while in Fram Strait profiling gliders, capable of under-ice acoustic navigation, will be employed. In the right lower panel, positions of moorings are overlaid on the temperature distribution in Fram Strait, an inflow of the warm Atlantic water in the West Spitsbergen Current depicted by red color (XR: [43]).

5.4. Fram Strait

One role of tomography is to monitor temperature and mass fluxes through "choke points", or narrow, constricted regions that control the exchange between two larger bodies of water. An ongoing experiment in the Fram Strait provides a good example of this approach.

The deep and wide Fram Strait, between Greenland and Spitzbergen, is the main passage through which mass and heat exchanges between the Atlantic and the Arctic ocean take place. Although major resources are invested in measurements of current and temperature in the strait, the flux estimates still have significant deficiencies and errors [44]. An acoustic system for tomography and navigation of gliders is under development and implementation in the Fram Strait through European projects [24],[42] (XR: [43]). As part of the DAMOCLES integrated project, a prototype acoustic tomography system was installed in the Fram Strait in August 2008. An extended acoustic system serving both tomography and glider navigation under ice is planned for implementation in 2010 under the ACOBAR project (Fig. 5). The acoustic system is co-located with the fixed array of oceanographic moorings across the strait at 78° 50' N and the planned bottom-mounted Hausgarten system for biology and geology studies (http://www.esonet-emso.org). The ESONET project is planning a cabled system for the Hausgarten system, and it would be cost effective to link the acoustic/oceanographic systems to the Hausgarten system in the future. Furthermore, the acoustic system will be integrated with ocean circulation models, satellite remote sensing, mooring data, and data from gliders through data assimilation [42].

6. ACTIVE ACOUSTICS AND MARINE MAMMALS

Extensive studies have established that the active acoustic signals employed for tracking or tomography do not adversely affect marine life. The 1996-2006 ATOC and NPAL programs included an extensive multi-year study of the effects of the signals on a variety of marine mammals. The conclusion of that study was that the signals had no significant biological impact. The sound sources are not particularly loud (typical source levels of 195 dB re 1 μPa @ 1 m, equivalent to about 250 Watts). The signals employ specially coded signals (e.g., m-sequences) that spread the acoustic energy out over time. Such signals are employed in lieu of single acoustic pulses from explosives that were employed a half century ago. In addition, the duty cycle of the signals is typically low (ca. 2%), consisting of eight brief transmissions every few days, for example. Nevertheless, it is clear that it is important to be sensitive to the concerns society has about such sound sources.

7. RECOMMENDATIONS

- Optimal design of acoustical observing systems (indeed observing systems in general) requires observing system studies or simulations using numerical ocean models (e.g., Fig. 4). Such studies address how the acoustical data type can address ocean observing requirements, taking into account what other complementary data types may be available. Such studies are also needed to select the optimal placement of acoustic sources or receivers, the relevant considerations being the ocean observing requirements, the ambient sound speed conditions, and the sea floor topography.
- Assisted by optimal array design studies, initial acoustic observing arrays, comprising roughly ten receivers and 3-4 low-frequency broadband acoustic sources should be installed in each of the Arctic, Northeast Pacific, and western North Atlantic basins. These systems will begin acquisition of data for passive listening, tracking of instruments, and basin-scale measurement of currents and temperatures.
- Those groups focused on modeling and data assimilation for state estimates of the world's oceans should include the capability to assimilate acoustic time-of-flight data in addition to other data types.
- In order to best take advantage of platforms of opportunity for acoustical observations, such platforms (e.g., moorings, gliders, floats) should be designed with adequate power, communication, timing, etc. to facilitate installation of acoustical instrumentation.
- Standard acoustic receiver packages should be integrated and deployed with other components of the global observing system. This package should accommodate as many of the purposes of passive acoustic observation and monitoring, tracking, and tomography as possible. Wherever possible, instrumentation should serve the several purposes of physical oceanography, marine geophysics and biology.
- International cooperation in the design and implementation of basin-scale acoustic systems is essential.
- We urge the relevant government agencies to develop competitive opportunities for developing acoustical capabilities within the global and regional observing systems. The last serious study of an acoustic system in the Atlantic occurred 15 years ago [45].

7. CONCLUSIONS

Almost 20 years ago, the Heard Island Feasibility Test (HIFT) [38] demonstrated not only the remarkable distances that low-frequency man-made acoustic signals can travel within the ocean, but also that global acoustical oceanography is well suited to international collaboration. The HIFT transmissions were recorded by receivers of opportunity the world over, suggesting that acoustic measurements over O(10,000 km) ranges were possible. Simple, inexpensive acoustic receivers were developed and distributed to research groups in several countries by the HIFT collaboration. The acoustic receivers had the admirable qualities of Argo floats - they were small, inexpensive and easy to deploy, which makes wide international participation possible. The societal benefits are myriad. For example, a passive acoustic observing system could support better coastal marine resource management through a more accurate assessment of the ecological impacts of climate change. This community white paper argues that modest systems of acoustic receivers and sources deployed across ocean basins can make effective, sustained observations of a variety of ocean processes.

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N.B. References marked with an asterisk (*) can be obtained in digital form from: http://909ers.apl.washington.edu/~dushaw/OceanObs09_Acoustics/

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