OBSERVING THE OCEAN IN THE 2000'S: A STRATEGY FOR THE ROLE OF ACOUSTIC TOMOGRAPHY IN OCEAN CLIMATE OBSERVATION

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Abstract - Since it was first proposed about 1977, ocean acoustic tomography has evolved into a multi-purpose oceanic remote sensing measurement tool that has been employed in a wide variety of physical settings. In the context of long-term oceanic climate change, these acoustic techniques are unique among measuring systems in providing integrals through the mesoscale and other high-wavenumber noise over long distances and with remarkable accuracy and precision. In addition, tomographic measurements may be made without risk of calibration drift.

On a regional scale, tomography has produced valuable results by its integrals through regions of active convection, through direct observations of oceanic vorticity, its vertical resolution, and filtering of short-spatial scales. The remote sensing capability has proven extremely valuable for measurements under ice in the Arctic and in regions such as the Strait of Gibraltar where conventional in situ methods fail.

As the community moves into an era of global scale observations (ARGO, 1999), the highest priorities for these acoustic techniques appear to be to (1) exploit the unique remote sensing capabilities for regional programs otherwise difficult to carry out, and (2) to gradually move toward deployment on the basin-to-global scales as the acoustic technology becomes more robust, simplified, and inexpensive.

1. INTRODUCTION

Various elements of the future ocean observing system for climate are currently being proposed and developed, each of which contributes in a unique way to our needs for understanding, modelling and predicting the ocean and climate system. Long-range acoustic remote sensing of the ocean interior (like tomography or thermometry) can provide horizontally integrated information over large scales and over a large depth range, with high accuracy. This makes such techniques suitable for addressing a variety of scientific issues, including regional process-oriented studies and more basin-scale observations. These potential benefits and applications are detailed in section 3. We begin here with a few examples of recent applications to highlight the range of usages of tomographic methods.

2. SELECTED EXAMPLES OF RECENT TOMOGRAPHIC ACCOMPLISHMENTS.

This section is meant to demonstrate the breadth of usages of long-range acoustic techniques, including mapping and integrating applications, by selecting a few particular and more recent applications with very diverse scientific motivations and spatial scales of the experiments. A more general review of tomography methods in the ocean and the results of previous experiments can be found in (Worcester, et al., 1991; Dushaw, et al., 1993), as well as a complete textbook (Munk, et al., 1995), which describes the methodology in detail. Here, we will confine ourselves to a brief overview of the more recent, and varied tomographic applications.

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These selected examples are related to particular regions or processes, or to basin-scale observations. Naturally, the basin-scale observations are most relevant to the large-scale data most needed for climate studies, but other process-oriented studies may also have direct climatological relevance.

a. Process Oriented Studies

Convection studies in the Greenland and Mediterranean Seas. Tomographic techniques are ideally suited for observing regional-scale changes in the water-mass structure and thus lend themselves immediately for integral measurements of convection processes. This was demonstrated in the Greenland Sea in 1988–89 (Morawitz, et al., 1996) and in the northwestern Mediterranean in 1991–92 (Send, et al., 1995). These applications yielded estimates of the extent of the convectively homogenized region and of the volume of "convected" water. Further, they used the deviation from 100-km scale, 1-D heat balances to quantify the lateral mixing/advection into the region, and the rate of removal of the mixed dense water after convection. The tomographic arrays provided both the spatial coverage and the temporal resolution necessary for observing the deep water formation; conventional hydrographic data obtained at the same time were contaminated by mesoscale variability.

New ongoing convection studies are taking place in the Labrador Sea (see below).

Gibraltar Transport Monitoring. In 1996, a pilot experiment (shared by IfM Kiel and SIO) demonstrated the value of using acoustic transmissions across the Strait of Gibraltar for observing the lower-layer outo w from the Mediterranean with high precision (see Send, et al., AN ACOUSTIC OBSERVING SYSTEM FOR THE STRAIT OF GIBRALTAR, this conference). The currents averaged acoustically along the ray path through the lower layer across the Strait had a correlation of 0.97 with the best available estimate of the same quantity from independent (direct) flow measurements (Figure 1). Such shore-based "remote" methods seem preferable to moorings in the Strait where their survival rate is low. For practical applications however, it needs to be known how well the layer transport can be determined from the acoustic data. From the additional oceanographic information gathered, the error in the tidal transports from using a single acoustic ray was estimated to be 0.3 Sv (out of ±5 Sv range), and 0.1–0.2 Sv for low-frequency changes (out of 0.8 Sv mean).

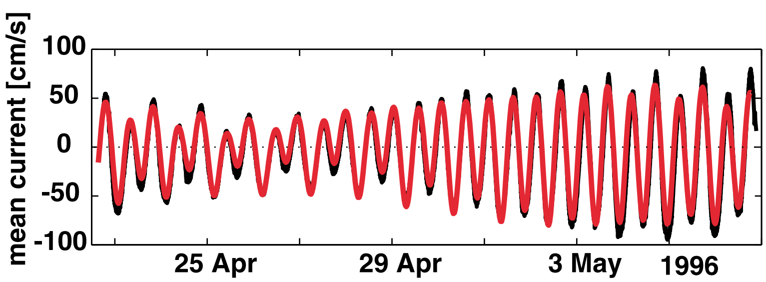

Figure 1. A two-week comparison of along-strait current through the Strait of Gibraltar averaged along a deep-turning ray path from a) acoustic transmissions across the Strait (black) and b) the tidal and low-frequency flow field determined from a wide range of direct current observations (red).

Because of the intense and highly turbulent nature of currents in straits, tomography is an attractive approach for measurement because it provides the necessary integration for estimating net transports. A prohibitive number of current meter moorings are sometimes required to accomplish the same task (e.g., Robert Dickson once received the Albatross Award from the American Miscellaneous Society for trying to dam the flow through the Denmark Strait with a dense current meter array.)

Resonant Diurnal Internal Tides. The 1991 Acoustic Mid Ocean Dynamics Experiment (AMODE) provided evidence for diurnal internal tide waves resonantly trapped between the north Caribbean island chain and the diurnal turning latitudes at about 30°N (Dushaw and Worcester, 1998). The amplitude of the temperature variability associated with this wave was a mere 40 m°C at 300 m, the depth of mode maximum. This result is cited here because it is an example of a small amplitude, but large-scale signal that may extracted from the noisy ocean environment using acoustic tomography. The analogy here is that these diurnal internal tides are to the internal-wave noise as the climate patterns are to the mesoscale noise.

b. Basin Scale Studies

Monitoring the Western Mediterranean basin (THETIS-II). Much of the Western Mediterranean basin was observed acoustically for 9 months in 1994, including cross-basin transmissions from Europe to Africa (Send, et al., 1997). The water column and horizontally-integrated heat content along one such line could be compared with coordinated fortnightly XBT section data, and yielded complete agreement to within 0.03 °C error bars (Figure 2a). Using the same type of acoustic measurement along several lines through the basin allowed estimates of the 3-D heat content evolution and comparison with ECMWF surface heat fluxes. The result (Figure 2b) shows a surprising consistency of the curves, which helps to quantify the seasonal forcing of e.g., wintertime water mass formation. Also, this experiment served as the rst demonstration of merging altimetric, tomographic and numerical model data into a consistent description of the basin-scale temperature and flow field evolution (Menemenlis, et al., 1997). This application is a prototype of a system for determining the variability of an entire ocean basin. The ATOC experiment described next, represents the same type of system on a much larger scale.

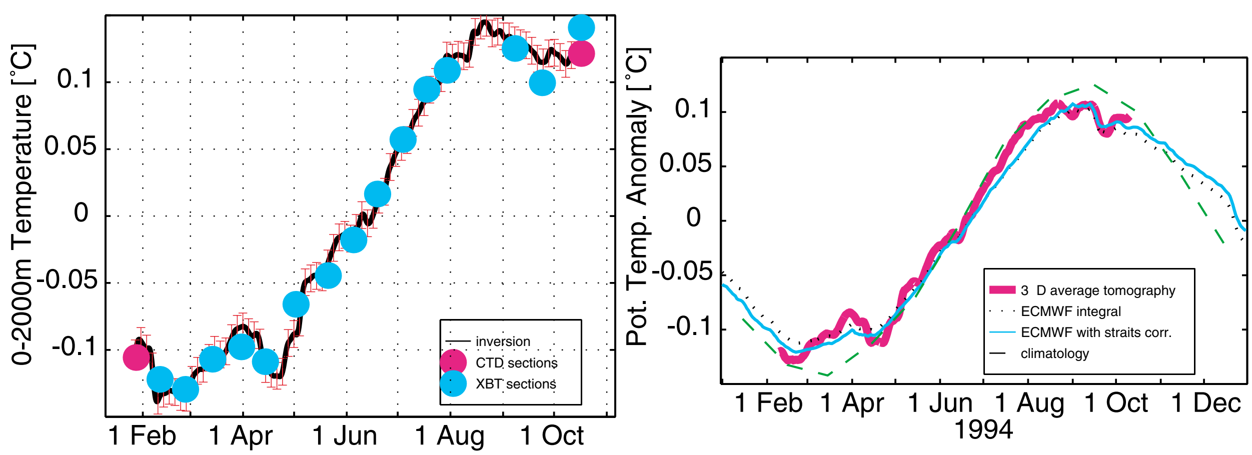

Figure 2. (a) The 0-2000 m heat content (average temperature) in a section across the Mediterranean from tomography (line and error bars) and from CTD/XBT sections (bullets). (b) Estimate of 3-D basin heat content from several acoustic sections, compared with surface heat ux integral (including a correction for ux through the straits) and climatolgy .

Acoustic Thermometry of Ocean Climate (ATOC). ATOC is directed at using the travel time data obtained by a few acoustic sources and receivers located throughout the North Pacific basin to study the climatic variability of the thermal field at the largest scale (The ATOC Consortium, 1998). The acoustic receivers are those of opportunity such as the U.S. Navy SOSUS receivers, as well as two dedicated vertical line arrays that were located near Hawaii and Kiritimati.

The ATOC project has now completed several important phases. An acoustic source began transmissions off the coast of California in early 1996; this source transmitted for about 24 months at irregular intervals in accord with marine mammal research protocols. A second acoustic source north of the Hawaiian island of Kauai has been transmitting since late 1997.

The data obtained during ATOC has shown that resolved acoustic ray arrivals may be used for acoustic thermometry at ranges to at least 5 Mm. The estimated uncertainties in the range- and depth-averaged temperature measurements were about 10 m°C. The timeseries obtained using the California acoustic source showed a clear annual cycle whose amplitude was similar to that derived from climatology (WOA 94) and XBTs of opportunity, yet smaller than the amplitude of the annual cycle derived from TOPEX/POSEIDON altimetry (The ATOC Consortium, 1998). The timeseries obtained using the Kauai acoustic source is of similar quality in its ability to measure the thermal variability, but with greater variability at 100-day timescales (Figure 3) (see Dushaw, et al., A COMPARISON OF ACOUSTIC THERMOMETRY, XBT, TOPEX, AND HOT OBSERVATIONS OF OCEAN TEMPERATURE IN THE NORTHEAST PACIFIC OCEAN, this conference). Focus of the ATOC research has recently shifted from establishing the integrity of the acoustical measurements (Dushaw, et al., 1999; Dushaw, 1999; Worcester, et al., 1999) to employing the data oceanographically. One original and continuing goal of the ATOC program is to use the line-integral data to detect the patterns of climate variability such as the Pacic Decadal Oscillation (PDO) (Latif and Barnett, 1994).

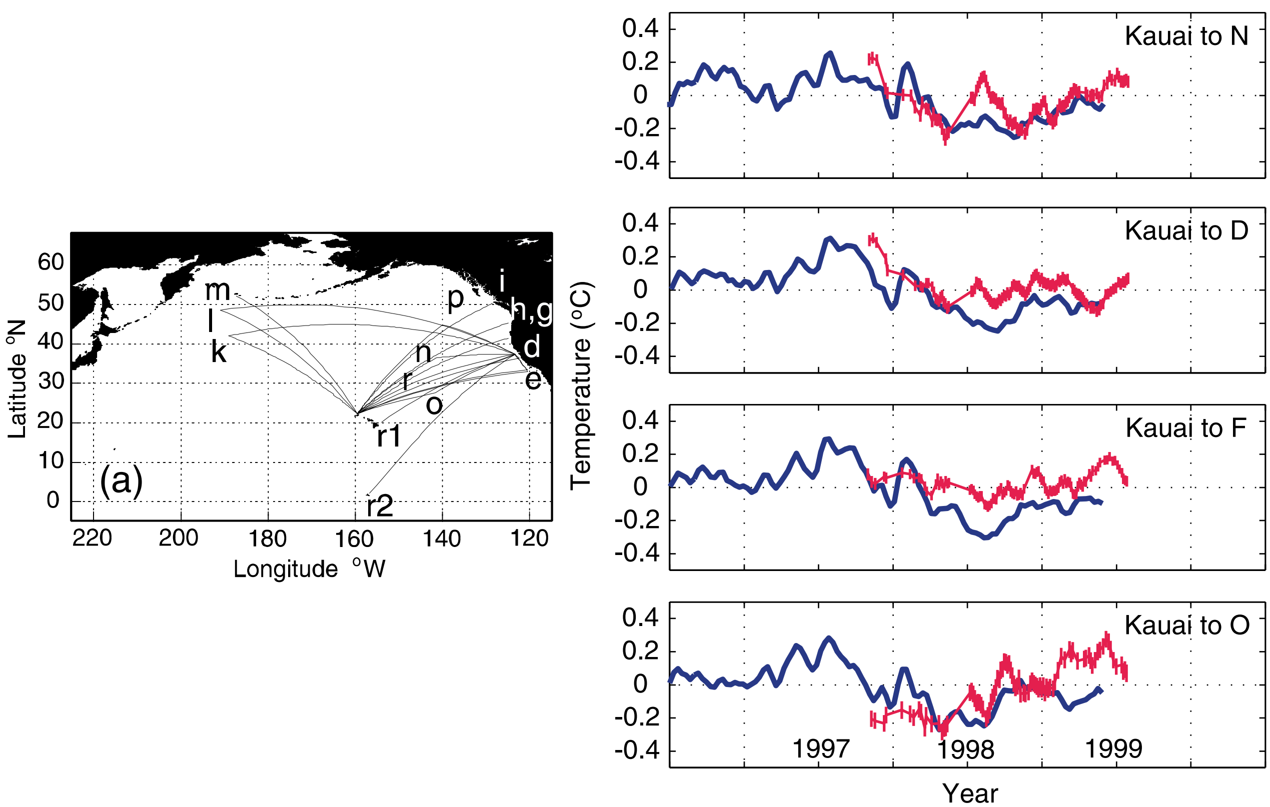

Figure 3. The Acoustic Thermometry of Ocean Climate (ATOC) acoustic paths in the North Pacic and a comparion of temperature timeseries derived from TOPEX/POSEIDON altimetry (blue) and acoustics (red, with error bars). The annual cycle was removed from the TOPEX/POSEIDON data; the acoustic data on these particular paths sample below the seasonally-varying surface layers so they do not observe the annual cycle. High-resolution TOPEX/POSEIDON data were interpolated onto the acoustic paths using objective mapping techniques, and then averaged along the paths. The conversion of altimetry to temperature assumes the sea surface height variations are caused only by thermal expansion in the upper ocean.

The Trans-Arctic Acoustic Propagation (TAP) Experiment. The TAP experiment (Mikhalevsky, et al., 1999) conducted in April, 1994 was designed to determine the feasibility of using acoustic transmissions to monitor changes in Arctic Ocean temperature and changes in sea ice thickness and concentration. The data showed that the quality of the measurements was an order of magnitude better than is required to detect the estimated 80 ms/yr changes in travel time caused by interannual and longer term changes in the Arctic Ocean temperature. The travel times measured in TAP indicated that the average temperature in the Atlantic layer had warmed by almost 0.4 °C compared to historical climatology. The TAP acoustic section was in fact the first basin-scale observation of this warming. Subsequent ice-breaker and submarine transarctic sections have confirmed this ubiquitous and widespread warming which is the subject of active research today. This pilot project has led to the longer-term ACOUS monitoring program, which is discussed below (see also: Mikhalevsky and Gavrilov, YEAR ROUND ACOUSTIC OBSERVATION OF TEMPERATURE VARIATIONS IN THE ARCTIC OCEAN, this conference.)

3. THE PRESENT AND FUTURE OF ACOUSTIC TOMOGRAPHY IN OCEAN CLIMATE OBSERVATIONS.

Tomographic methods may be used to make regional and basin scale measurements of relevance to the ocean climate observation problem. There are both on going experiments and a large number of possible future experiments that apply tomography in regions or ocean basins to specific scientific issues.

a. Regional Measurements

Deep ocean water mass changes in key areas or on reference sections. Variability in deep water mass properties, transports, and forcing processes related to the thermohaline circulation (THC) are a key topic of the CLIVAR DecCen program. This requires, among other things, long-term observations of the formation regions (properties, volume, depth), and of water mass properties and mass/heat transports at sections along the path of the THC. As already pointed out in section 1a, tomographic techniques have demonstrated benefits in observing deep convection regimes, i.e. the processes that form deep water masses, and thus what may in some sense be regarded as a source region for the THC.

The average temperature or heat content of specific deep water masses may also be "remotely sensed" with good temporal resolution and over significant distances using tomographic techniques. This may be used to supplement occasional ship sampling of hydrographic transects, in order to reduce of aliasing. If merged with volume transports from other observations (like dynamic height moorings), the acoustically derived heat content may also be used to approximate heat fluxes through a section as a of function time.

A German CLIVAR project (MOVE) has been initiated (IfM Kiel) to observe the deep southward transports of the THC along 16°N in the Atlantic (between the shelf slope to the east of the Carribbean island arc and the mid-Atlantic ridge). The mass transports will be estimated using moored geostrophic techniques (density and pressure sensors). It is envisioned that in later years, tomographic instruments will be added to the moorings in order to additionally obtain the section-average heat content of the water masses. This may provide an indication of the time-varying southward temperature flux through the section.

Transports and heat flux through straits and passages. Volume transports through passages between ocean basins or marginal seas and ocean basins are important quantities because they are indicators of, or govern, basin-average budgets of heat, freshwater, etc. Long-term observations of these quantities are required in order to detect possible changes in these processes. In many such constricted places it is difficult to maintain moored current meters over long periods of time (strong current, shipping, fishing,...), and also many instruments (horizontally and vertically) may be needed to construct reliable transports. Therefore, integrating and shore-based methods are generally preferable, like sea level differences, electric potentials along cables, or acoustic transmissions across the passage. Some of these methods need to be empirically calibrated against other data (providing transport "indices"), and which method is best suited where depends on many factors. Under certain conditions, acoustic transmissions can provide accurate horizontal integrals (without need for calibration), as described in section 1. If the vertical shear/variability is not too large, this can be used to obtain layer transports using shore-based acoustic transmissions. It is proposed here that this may be the method of choice for certain straits or passages (to be determined on a case-by-case basis).

As demonstrated earlier, the Strait of Gibraltar appears to be a site which is suitable for using cross-strait acoustic transmissions for observing the outflow transport from the Mediterranean. Joint proposals are planned by IfM Kiel and SIO to begin installing a shore-cabled, long-term acoustic observing system which would provide a real-time capability for detecting changes in the lower-layer transports. A similar experiment is planned to monitor Atlantic/Arctic throughflow in the Fram Strait.

Laborador Sea convection. A multi-year monitoring of convection variability, which includes tomography moorings, is under way in the Labrador Sea (IfM Kiel). It is entering the 4th year now, and is funded by a special German research initiative which has a 10-15 year time-scale. The hope is to maintain 3-5 moorings in each year, in order to study the variability and forcing factors for the generation of Labrador Sea water, one of the water masses which circulates in the deep THC (Send, 1999).

Large-scale weak ocean current measurements. Reciprocal tomography has the capability to measure very weak, but large-scale currents. The ongoing Central Equatorial Pacific Tomography Experiment is now measuring the weak meridional currents in the central Pacific. In Fall 1998, five JAMSTEC tomography moorings were deployed in an array about 1000 km across just north of the equator at about 180°E. The tomography data is relayed to JAMSTEC in real time. The purpose of this experiment is to measure the shallow overturning of a meridional circulation cell. This subtropical cell (STC) has been hypothesized as one mechanism by which El Nino/La Nina events in the tropics are connected to the subtropical ocean (Gu and Philander, 1997). The subtropical surface waters are affected by the tropical ocean through atmospheric forcing, and the modified subtropical surface waters are then subducted and return to the equator via the STC. No direct measurements of the STC exist however, though indirect measurements and modeling support the hypothesis. The high sensitivity of reciprocal tomography for measuring large-scale currents is one means by which the weak meridional currents of the STC may be detected. At this time, two years of operation are planned, though adequate measurement of the STC will require a longer timeseries.

Boundary current regions. The Gulf Stream, California Current, Kuroshio, and North Equatorial Current bifurcation in the Philippine Sea are examples of regions of complicated intense currents where it is difficult to retain floats. Tomography provides a means to make accurate, averaging, Eulerian observations of both the thermal and current fields of these dynamically important regions.

An acoustic source recently deployed on Hoke Seamount off the coast of Central California is being used to monitor the variability of the California Current region near central California. This source is a component of the Naval Postgraduate School Ocean Acoustic Observatory (OAO, 1999). Receptions of the acoustic signals by a receiving array at Pt. Sur, California, as well as at a number of other SOSUS arrays, allow temperatures of the coastal ocean to be monitored. The Hoke Seamount source will stop broadcasting on 1 May, 2000, although plans are in place to extend the timeseries of transmissions.

An eight-mooring tomographic array is to be deployed in the Kuroshio Extension region by JAMSTEC for four years starting in 2001. This array will be part of the Kuroshio Extension System Study (KESS). The observational array may be extended to the south into the mode water region by 3 additional sources and 10 receivers to be deployed by the Applied Physics Laboratory, University of Washington. The goals of KESS are to understand the processes coupling meanders to deep eddies (baroclinic/barotropic coupling), to determine and quantify how North Pacific Intermediate Water forms and crosses the Kuroshio Extension, to determine the processes that govern the strength of the recirculation gyre, and to determine the processes that govern the interannual variations in the upper-ocean heat budget. Acoustic tomography is a component of KESS to observe and map the circulation and heat content of the interior ocean at mesoscale to 1000-km scales. A combination of satellite altimetry and in situ tomographic measurments will be used in estimating the heat budgets for the recirculation gyre and the mixed water region.

JAMSTEC will be deploying a tomographic array in the bifurcation region of the North Equatorial Current in the Philipine Sea in 2006-2010.

b. Basin-Scale Measurements

Global thermometry holds promise of becoming a cost-effective method to make large-scale temperature observations on a long-term basis. Temperature measurements from tomography are robust, eulerian measurements of the large-scale variability with no calibration drift. Tomographic measurements get directly at the existence and nature of signals at the lowest wavenumbers. These data are also sensitive to variability almost to the ocean bottom, and thus can detect changes below the depths that XBT and float data are obtained. The impact of the integral measurements on the quality of ocean estimation using numerical models remains an open question, however. This impact is best assessed when all data types - ARGO, XBTs, TOPEX, etc. are used. For basin-wide thermometry the number of receivers can be maximized at low cost using receivers of opportunity, such as the Comprehensive Test Ban Treaty (CTBT) hydrophone arrays, or simple acoustic receivers placed on DEOS, GEO, or TAO moorings, or on PALACE floats. Amortized over a few decades of ocean monitoring, the cost of operating a tomography array to observe an ocean basin is estimated to be around $50 per acoustic transmission (see *Global Array Costs* below); the per transmission cost declines quadratically with the number of receivers that are available.

At this time, several areas of the oceans are monitored by acoustic tomography as part of climate studies. Some of these tomographic facilities are providing the first elements of larger observing systems.

Organized by basin, the following experiments are occurring or are being planned to occur:

The Pacific Basin. The acoustic source deployed on Pioneer Seamount ceased transmissions in late 1998, and it is to be recovered. The second acoustic source located near Kauai, Hawaii is scheduled to stop transmissions in Fall 1999, but permission is being sought to continue its operation. Provided that the outcome of the environmental review process is favorable, the Kauai acoustic source will transmit for the next 5 years to U.S. SOSUS hydrophone arrays, as well as to a Russian receiver off the coast of Kamchatka. Since the various timeseries obtained at 10 SOSUS receivers using the transmissions obtained during the past few years look promising for detecting the low-frequency, long-wavelength thermal variability, we are looking forward to the prospect of the 6-year-long timeseries of data. The goals of these observations are to study the spatial structure of the thermal variability of the Northeast Pacific at the largest scales and to determine the extent to which the acoustic data and other data types, such as TOPEX/POSEIDON altimetry, may be best combined for optimal estimation of the ocean state. These measurements will fit naturally into the Pacific Basin Extended Climate Study (PBECS), which is a component CLIVAR. Other possible acoustic receivers in the North Pacific Ocean such as those deployed at or near NOAA ocean stations, or as part of the proposed Deep Earth Observatories on the Seafloor (DEOS) moorings (DEOS, 1999), would greatly enhance the spatial coverage of the thermometry array in an opportunistic way.

The Indian Ocean Basin. Interannual variability of the heat content of the northern Indian Ocean influences the intensity of the NW Monsoon, which in turn has major consequences on Asian and Australian agriculture. A strong correlation has been demonstrated to exist between sea surface temperature anomalies of the Northeastern Indian Ocean and Australian agricultural production, linked by variations in rainfall. A 1 °C variation from year to year corresponds to a variation in production of about US$6B. Measuring the ocean temperature on regional to basin scales is therefore crucial to predicting rainfall for the agriculturally sensitive regions bordering the northern and eastern Indian Ocean. Because the Indian Ocean is the only major ocean basin that is completely bounded to the north by a continental landmass, it is simpler to balance a heat budget in this basin. Exchange takes place with the Southern Ocean, and to a limited extent, with the Pacific Ocean through the Indonesian Archipelago; both of these exchange regions may be monitored by acoustical and other means. Plans are proceeding towards deploying an acoustic source on Cocos Island in the Indian Ocean whose signals would be recorded by CTBT hydrophone arrays, a receiver near Madagascar to be deployed by IFREMER, and simple inexpensive receivers as they become available.

The Atlantic Ocean Basin. WOCE has provided us with a baseline against which past and future changes in ocean subsurface temperatures can be assessed. In the Atlantic, evidence for the magnitude (few tenths of a degree), extent (across the whole ocean basin and over large (>1 km) depth range) and distribution (not solely confined to the upper layers) has accrued throughout WOCE. This is shown by the work of Parilla, et al. on 24 °N, Read and Gould and more recently Koltermann, et al. in the subpolar North Atlantic, and Joyce, Pickart and Millard at 52 and 66 °W. These results extend the changes seen at the Bermuda time series station (Joyce and Robbins, 1996). This analysis has been extended to the South Atlantic as well (Dickson, et al., 2000).

Evidence for these climate changes, while compelling, is as yet sparse. Only at time series sites can we assess interannual variability or detect the actual timing of the onset of such changes. Their cause is likely to be an interplay of changes in air-sea exchanges and of circulation. The fact that climate models implicate the North Atlantic in rapid cimate change suggest that the Atlantic is a key region in which monitoring of subsurface ocean variability should be given high priority. Acoustic thermometry is a means to obtain accurate timeseries of the climate-scale variability in the Atlantic Basins.

A prototype acoustic thermometry array was designed by a SCOR working group in 1994 (SCOR, 1994). Such an observational array for the North Atlantic may well develop out of extensions to a set of experiments using tomography that are planned by groups at Kiel and IFREMER. One such experiment, called OVIDE, is a CLIVAR-related experiment proposed by Laboratoire de Physique des Océans, IFREMER to study the variability in the subpolar gyre from seasonal to decadal time scales. The goals are to document the transformation of the subpolar mode water and the amplitude of the thermohaline circulation. OVIDE is planned to start in 2002 and includes hydrography, profiling floats, and tomography. It will be based on four tomography moorings that will be installed in the Western European Basin for monitoring the heat content variability of the waters entering and leaving the basin.

ACOUS in the Arctic Ocean. It is known today that the Arctic ice/ocean/atmosphere system is undergoing dramatic changes and is intrinsically a more variable and dynamic system than previously understood. In addition to the warming in the Atlantic layer, analysis of satellite passive microwave images shows a 3% per decade decrease in sea-ice extent since 1978, with a more rapid decline of 4.3% between 1987 and 1994 (Bjorgo, et al.,1997; Johannessen, et al.,1995, and 1996). In addition, a large decrease of the annual mean atmospheric sea level pressure over much of the Arctic has been observed in this decade. There is evidence from new modeling studies (Proshutinsky and Johnson, 1997; Johnson, et al.,1999; and Polyakov, et al., 1999) and historical data review (Grotefendt, et al., 1998) that major changes occur in the Arctic atmospheric and oceanic circulation on a near decadal time scale which could explain some or all of the observed changes. However, there is also evidence of secular trends with an anthropogenic fingerprint (Overpeck, et al., 1997; Vinnikov, et al., 1999).

The problem of understanding this dynamic system is significantly compounded by the extreme difficulty of working in the Arctic. Observations have historically been limited to point measurements in space with limited temporal duration. Synoptic measurements of the Arctic *Ocean* are not possible with satellites due to the sea ice cover. As the TAP experiment demonstrated acoustic remote sensing is a technology that can provide integrated, synoptic, year-round, (and with cabled receiver moorings), real-time data on the heat content of the Arctic Ocean, and vertical temperature structure. Research is also underway to use acoustic remote sensing for measuring the average sea-ice thickness and roughness which when combined with satellite sea-ice extent will provide estimates of total sea-ice volume.

The first installations of an acoustic thermometry network grid for the Arctic Ocean under a program called the Arctic Climate Observations using Underwater Sound (ACOUS), were deployed in October 1998 (Mikhalevsky, 1999). These installations included a 20-Hz acoustic source deployed between Spitzbergen and Franz Josef Land and an autonomous acoustic/oceanographic receive array/mooring in the Lincoln Sea approximately 1250 kms away. Transmissions from the source were recorded at an ice-camp in the Chukchi Sea in April 1999 and showed an almost 0.5 °C increase in the Atlantic Layer over essentially the same path as the TAP experiment exactly 5 years earlier. This result is in agreement with the CTD transects taken by submarine annually during SCICEX's 1995-1999. The Lincoln Sea mooring is planned to be recovered in 2000.

The ultimate goal of the ACOUS program is to install and operate a network, depicted in Figure 4. A 5-year $7M proposal is currently under review to extend ACOUS and start the rst cabled installations in the Arctic. The network would include autonomous sources, and cabled Acoustic Thermometry and Autonomous Monitoring (ATAM) moorings as shown. The moorings would include oceanographic, chemical, biological, and seismic sensors as well as the acoustic hydrophone arrays, combining synoptic acoustic remote sensing measurements of Arctic Ocean heat content, temperature stratication, and ice thickness with point measurements. The notional grid depicted in Figure 4 shown could provide a snapshot of the entire Arctic Ocean in less than one hour every four days, and could operate unattended for years with all of the data being provided to researchers in real-time. Such observations on these spatial and temporal scales are simply not possible by submarine, ice-breaker, or ice camp methods.

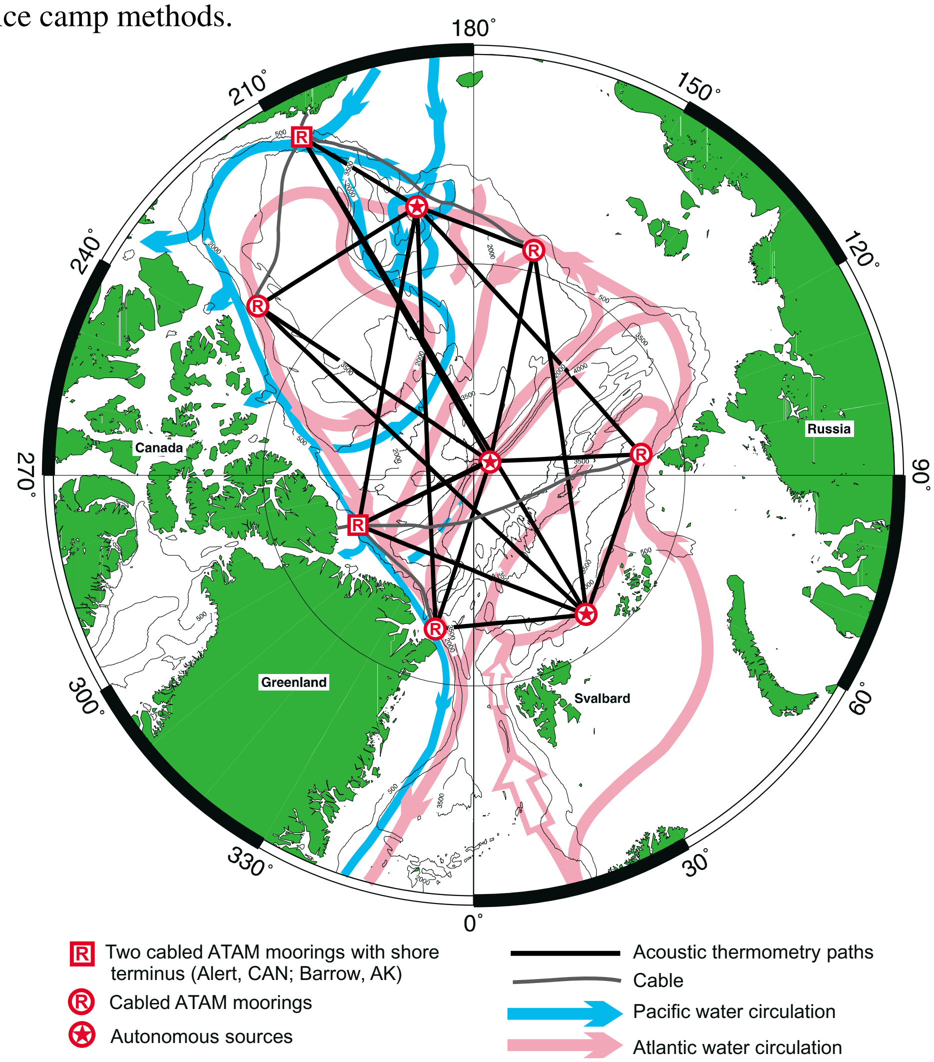

Figure 4. A future notional monitoring grid in the Arctic Ocean exploiting synoptic acoustic remote sensing with in-situ measurements cabled to shore at Alert, Canada (where an existing slant-drilled sea-shore interface already exists), and Barrow, AK. ATAM is Acoustic Thermometry and Autonomous Monitoring. The Arctic Ocean circulation is from McLaughlin, et al., 1996.

4. OPERATIONAL ISSUES.

Data Analysis. Methods of data reduction and archiving are being developed to reduce the dif-culty, cost, and time involved of tomographic data analysis. One project targetting these issues is the European OCTOPUS effort (IfM, Kiel/IACM, Heraklion/IFREMER, Brest), which seeks to develop analysis tools, data formats and a data bank to facilitate the operational application and usage of acoustic tomography. Once the initial analysis of new thermometry data is completed, it is a simple matter to make the thermometric results from subsequent data available in real time. Such data may be made readily available on World Wide Web sites set up for this purpose.

Marine Mammals and Acoustic Tomography. The ATOC project included a Marine Mammal Research Program (MMRP) to study the potential effects, if any, of the ATOC sound sources on marine mammals and other marine life. The MMRP did not find any overt or obvious short-term changes in the distribution, abundance, behavior, or vocalizations of marine mammals in response to the playback of ATOC-like sounds or in response to the transmissions of the ATOC sound sources themselves. No species vacated the areas around the sound sources during transmissions. Statistical analyses of the data showed some subtle, but statistically signicant, shifts in the distribution of humpback (and possibly sperm) whales during transmission periods, as well as some subtle changes in the behavior of humpback whales. The MMRP investigators concluded that these subtle effects would not adversely impact the survival of an individual whale or the status of the North Pacic marine mammal populations.

Nonetheless, monitoring of the distribution and abundance of marine mammals around the Kauai source is planned as part of the proposed continuing operation of that source over the next five years, to look for possible longer-term changes in distribution and abundance, if any. The ATOC source provides one of the few controlled sound sources available for such longer-term studies.

Global Array Costs. At some future time, it may become possible to extend the regional arrays to the full globe. Assuming present-day costs for instrumentation and excluding the Arctic Ocean, a strawman array with 21 sources (3 in each basin) and 85 receivers (Figure 5) may be used to estimate the international costs of global climate observation using acoustics. This array will more than adequately sample the first few climate EOF's of each basin. Many of the sources are cabled to shore, while some are connected to DEOS mid-ocean buoys. Many receivers are opportunistic or make use of platforms provided by other programs: Navy (22), Comprehensive Test Ban Treaty (CTBT, 6), DEOS (16), TAO, Pirata and other NOAA moorings (18); there are 23 dedicated receivers. The assumed average capital costs are $2.5M for sources and $150K for receivers giving a total capital expense of $65M. An idealized optimal system would evenly split the total cost between sources and receivers. Average annual maintenance costs are estimated to be $2M per year, half being salaries, and excluding ship time. Assuming a 20-year project duration, the average total cost per year is $5.3M. What does this mean in terms of cost per datum? Assuming that each receiver detects 2 sources (170 paths), that there are 2 transmissions per day on average, and that the array operates for 20 years, a cost of $47 per path per transmission per path (per independent datum) is obtained. If the average path length is taken to be 2000 km, then the total sampled path length is on the order of 400,000 km, or 10 times around the globe.

At this time, there exist various research programs on reducing the cost and complexities of instrumentation for acoustic thermometry; these efforts will continue. Essential aspects of this research include the development of less-expensive acoustic sources and simple, user-friendly receivers that may be deployed either opportunistically or as an incidental addition to moorings or research platforms deployed for other reasons.

5. CONCLUSION.

Both regional and basin-scale tomographic measurements can make important contributions to monitoring the climate of the world's oceans. Regional tomographic methods are ready for application now out to scales of about 1000 km. Basin-scale measurements hold great promise for the future. A global observing network of acoustic paths may be readily and opportunistically derived by considering the acoustic transmissions of disparate experiments as part of a larger whole (e.g., Figure 5). Such networks would augment and complement existing observation methods. At this time, one of the greatest impediments to implementing greater coverage of the world's oceans by acoustic tomography are the high costs of the instrumentation and its installation. Efforts are currently underway to reduce the costs of sources and receivers. The operational costs to make continuing measurements once the instruments have been installed are in either case minimal, however. The amortized cost of the technique is therefore attractive, even using present-day source and receiver technology. An investment in technological improvement would however, probably pay great dividends in the future.

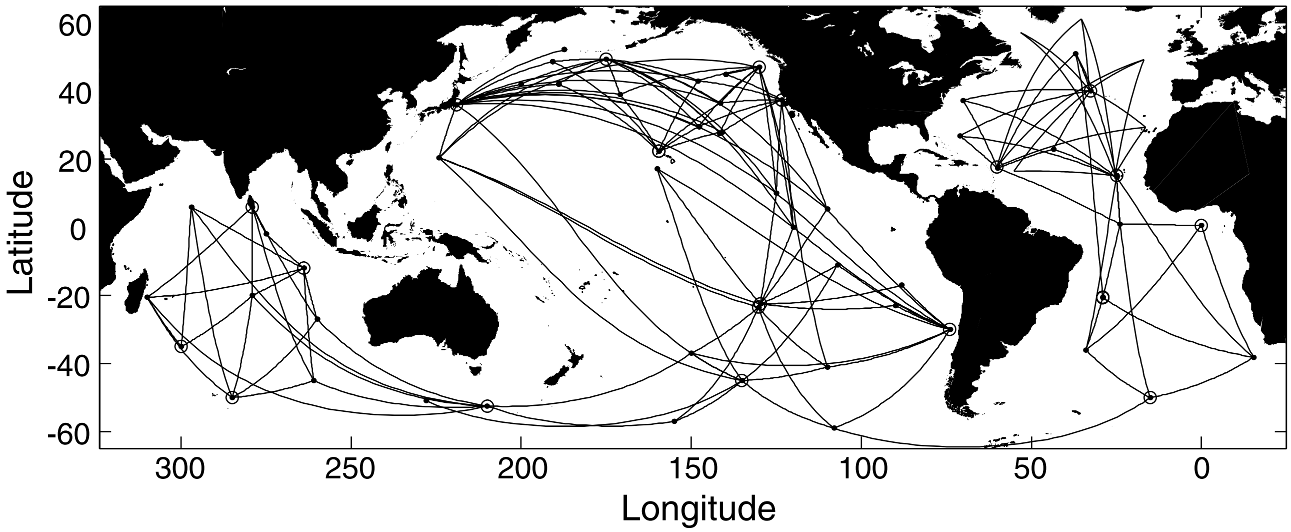

Figure 5. A global observation network that may be realized through international cooperation and support. This hypothetical array consists of about 20 cabled-to-shore or autonomous acoustic sources, together with about 80 receivers at SOSUS sites, on DEOS moorings, at CTBT receiving sites and a few dedicated receivers specifically deployed to complete the global array (e.g., a receiving array that may be deployed by IFREMER near Madagascar.) Receivers are also located where there will likely be several tomographic instruments deployed by European organizatons in the North Atlantic in the coming decade. Not all possible receivers are shown. A global network such as this would augment and complement existing observation systems for ocean climate variability.

APPENDIX: CONTACT INFORMATION FOR ACTIVE PROJECTS EMPLOYING TOMOGRAPHY

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Strait of Gibraltar (CANIGO): Uwe Send or Peter Worcester, as above.

Central Equatorial Pacic Ocean Tomography Experiment and Kuroshio Extension System Study (JAMSTEC tomography moorings): Iwao Nakano, Japan Marine Science and Technology Center, Yokosuka, Japan. e-mail: nakanoi@jamstec.go.jp

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