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Observing the Ocean in the 2000s: A Strategy for the Role of Acoustic Tomography in Ocean Climate Observation

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Abstract – *Since it was first proposed in the late 1970s (Munk and Wunsch, 1979, 1982), ocean acoustic tomography has evolved into a multipurpose remote-sensing measurement technique that has been employed in a wide variety of physical settings. In the context of long-term oceanic climate change, acoustic tomography provides integrals through the mesoscale and other high-wavenumber noise over long distances. In addition, tomographic measurements can be made without risk of calibration drift; therefore these measurements have the accuracy and precision required for large-scale ocean climate observation. The transbasin acoustic measurements offer a signal-to-noise capability for observing ocean climate variability that is difficult to attain by an ensemble of point measurements.*

On a regional scale, tomography has been employed for observing regions of active convection, for measuring changes in integrated heat content, for observing the mesoscale with high resolution, for measuring barotropic currents in a unique way, and for directly observing oceanic relative vorticity. The remote-sensing capability has proven effective for measurements under ice in the Arctic (in particular the recent well-documented temperature increase in the Atlantic layer) and in regions such as the Strait of Gibraltar, where conventional in-situ methods are problematic.

As oceanographic science moves into an era of global-scale observations, the niches for these acoustic techniques appear to be (1) to exploit the unique remote-sensing capabilities for regional programs which are otherwise difficult to carry out, (2) to be a component of process-monitoring efforts in regions where integral heat content or transport data are desired, and (3) to move toward deployment on basin to global scales as the acoustic technology becomes more robust and simplified.

Introduction

Various potential elements of a future ocean observing system for studying climate are currently being proposed and developed for understanding, modelling, and predicting the ocean and climate system. Long-range acoustic remote sensing of the ocean interior (tomography or thermometry) can provide horizontally integrated information over large scales and over a large depth range, with high accuracy and in real time. Tomography is naturally complementary to other techniques. Altimetry senses the ocean surface (i.e. changes in ocean volume, which can in some instances be related to depth-integrated density), while tomography senses the interior (i.e. sound speed integrated over acoustic ray paths). Profiling floats provide broad spatial coverage and high vertical resolution of the upper ocean, while tomography suppresses internal wave and mesoscale noise, reaches the deep ocean, and is sometimes suitable for use in regions where floats can be problematic. Eulerian observations provide sampling at one location, while tomography can add the integrals between the Eulerian stations.

The unique properties of tomography make it suitable for addressing a variety of scientific issues within regional studies, process-oriented

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monitoring, and basin-scale observations. A number of applications of these unique properties are reviewed in the next section. The applications of tomography that are presently occurring, or are likely to occur in the near future, are described and several operational and cost issues are outlined in subsequent sections.

A review of tomographic accomplishments

The breadth of usage of acoustic techniques, including mapping and integrating applications, can be demonstrated by describing several applications with diverse scientific motivations and spatial scales. A general review of tomographic methods in the ocean and the results of past experiments are given in the monograph by Munk et al. (1995). We will give a brief review of several examples of the use of tomography. 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 smaller scale, process-oriented studies may also have direct climatological relevance.

Process-oriented studies

Convection studies in the Greenland and Mediterranean seas

Introduction

Oceanic convection is believed to be the process by which the properties of the surface ocean and deep ocean are connected, with important consequences for the global thermohaline circulation and climate. Convection to great depths occurs at only a few locations in the world. The deep convective process is temporally intermittent and spatially compact, consisting of convective plumes with scales of about 1 km clustered in convecting regions with scales of tens of kilometres. Observing the evolution of the deep convective process and quantifying the amount of deep water formed presents a difficult sampling problem. Acoustic arrays provide both the spatial coverage and the temporal resolution necessary for observing deep-water formation.

Tomographic measurements have been key components in programs to study deep convection in the Greenland Sea (1988–1989) (Worcester et al., 1993; Pawlowicz et al., 1995; Morawitz et al., 1996a,b; Sutton et al., 1997) and in the Mediterranean Sea (1991–1992) (THETIS Group, 1994; Send et al., 1995). The Greenland and Mediterranean Sea analyses are described in turn below. Ongoing convection studies are now taking place in the Labrador Sea (1996–present), as discussed later.

The Greenland Sea Project

For the Greenland Sea experiment, six acoustic transceivers were deployed from summer 1988 to summer 1989 in an array approximately 210 km in diameter (Fig. 1) as part of the intensive field phase of the international Greenland Sea Project. The acoustic data were combined with moored thermistor data and hydrographic data to estimate the evolution of the three-dimensional temperature field $T(x,y,z)$ during winter, including one convective phase. During the convective period, the hydrographic data were dominated by small-scale variability; they were not a useful constraint in determining the chimney and gyre-scale structure (Morawitz et al., 1996a,b). In addition, the hydrographic data were useful during the times they were obtained (the correlation times were O(10 days)), while the acoustic data provided a continuous time series with 4–8 hour resolution. The temporal resolution was important for observing the 'pre-conditioning' phase of convection, as well as the convection itself, which happens rapidly and unpredictably (Sutton et al., 1997).

A convective chimney reaching depths of about 1500 m was observed to the southwest of the gyre centre during March 1989. The chimney had a spatial scale of about 50 km and a time scale of about 10 days. The location of the chimney seemed to be sensitively linked to the distribution of the relatively warm, salty Arctic Intermediate Water found at intermediate depths. Potential temperature profiles extracted from the three-dimensional inverse estimates were averaged over the chimney region to show the time-evolution of the chimney (Fig. 1). A one-dimensional vertical heat balance adequately described changes in total heat content in the chimney region from autumn 1988 until the time of chimney break-up, when horizontal advection became important and warmer waters moved into the region. The average annual deep-water production rate in the Greenland Sea for 1988–1989 was estimated from the average temperature change to be about 0.1 Sv over the region occupied by the tomographic array.

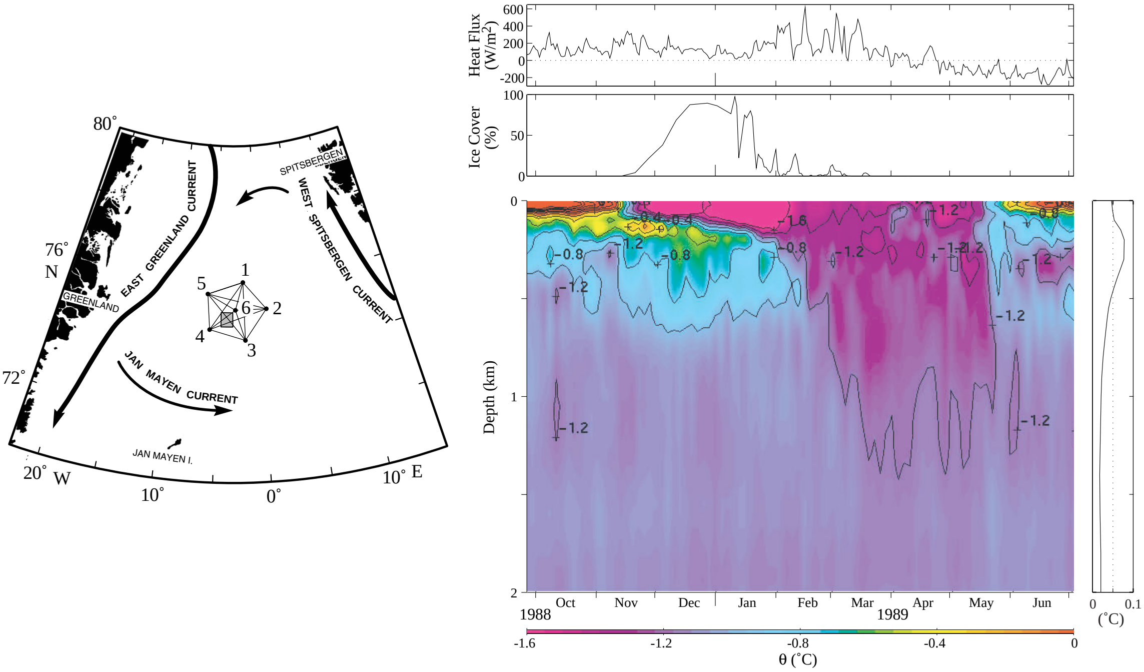

Figure 1. (a) Geometry of the tomographic transceiver array deployed in the Greenland Sea during 1988–1989. Mooring 2 failed about one month after deployment. A deep convective chimney was observed near the centre of the array during March 1989 (shaded region). (b) Time–depth evolution of potential temperature averaged over the chimney region. Contour interval is 0.2°C. Typical rms uncertainty (°C) as a function of depth is shown to the right. Total heat flux (from the British Meteorological Office) and daily averaged ice cover (derived from satellite SSM/I measurements) are shown above. Three-dimensional realizations of this convective event may be found in Morawitz et al. (1996b).

The Mediterranean Sea Experiment

The Theoretical and Experimental Tomography in the Sea (THETIS I) experiment in the Gulf of Lyon took place during the winter of 1991–1992 (THETIS Group, 1994; Send et al., 1995). The tomography component consisted of six transceiver moorings separated by 100–200 km. Additional data were obtained from ADCP and current meter moorings and intermittent hydrographic casts. The near-surface layer was well sampled by the acoustic transmissions. Cooling and subsequent entrainment of warmer Levantine Intermediate Water were apparent during the 2 months of pre-conditioning prior to the main convection event. During this time the total heat loss of the large-scale field was in approximate agreement with the (one-dimensional) surface heat fluxes, showing that little net warm-water advection took place from outside the convection region. Therefore, the local circulation confined the developing patch or chimney, and it had a major role in setting the location and extent of the deep convection patch. The volume of water modified by convection during that winter was estimated from the acoustic data to correspond to a volume with a 60-km radius and 1500-m depth; this volume corresponded to 0.3 Sv of annual-mean new water formation. The restratification occurred first by rapid capping in the near-surface layers followed by the return of less dense water in the deeper layers on a 40-day timescale.

The wide range of *in situ* measurements collected during THETIS I have been combined with the tomography data to assess the statistical properties of the mesoscale dynamics (Gaillard et al., 2000). The analysis demonstrated the complementarity of the different data types in time and space. The hydrographic data initially provided a good estimate of the baroclinic modes, while the tomography data complemented that estimate with temporal and horizontal resolution. Data from floats also included some information on the baroclinic modes, but the major contribution to resolving these modes came from the reciprocal tomography data, particularly at the largest scales.

Gibraltar transport monitoring

Introduction

The Strait of Gibraltar is a control point for the entire Mediterranean Sea (Bryden et al., 1994). Mass, heat and salt are exchanged with the Atlantic Ocean through this strait, and their fluxes depend on the integral processes in the interior of the Mediterranean, and on hydraulic effects. It is therefore of scientific interest to observe long-term transports through the Strait of Gibraltar and to provide real-time measurements of these quantities for operational modelling and forecasting applications. However, moored current meter measurements are notoriously difficult to carry out there. Shore-based 'remote' methods seem preferable to deploying moorings in the Strait, where their survival rate is low. The intense and spatially complex nature of currents in straits makes tomography an attractive measurement approach because it provides the necessary integration for estimating net transports. A larger number of current meter moorings are sometimes required to accomplish the same task. In 1996 a pilot project was carried out to test the feasibility of measuring the average flow through the Strait by making acoustic transmissions across the Strait. This project was part of the European-funded CANIGO project and additional funding was provided by ONR.

The pilot experiment has demonstrated the value of using acoustic transmissions across the Strait of Gibraltar for observing the lower-layer outflow from the Mediterranean with high precision (Send et al., 2000). For practical applications, however, the accuracy of the layer transport determined from the acoustic data needs to be known. Therefore, it is probably necessary to verify and calibrate the acoustic measurements using additional oceanographic information obtained during the initial stages of a monitoring program.

Method and setup

Three sites (T1, T2, T3) at the eastern entrance of the Strait were instrumented with high-frequency (2 kHz) acoustic equipment during April–May 1996 (Fig. 2a). This area was chosen because the water depth and horizontal distances are such that there are ray paths which exclusively sample the lower layer and which do not interact with the bottom (Fig. 2b). Observing only the lower-layer currents (outflow transport) is sufficient for many applications, since this also determines the upper-layer inflow to within the small imbalance due to evaporation. Acoustic methods inherently integrate horizontally across the Strait. The accuracy of the measurement of transport in the lower layer depends on the vertical scales of the flow, the inherent measurement accuracy of the method, and variations in layer depth (which can be observed simultaneously with a modified approach). At the shallow sill in the Strait farther west, tidal fluctuations in layer depth, which are correlated with the currents, contribute approximately 50% to the total transport. At the eastern section, however, this effect accounts for only about 0.06 Sv and can be added as a known correction. Long-term changes in interface depth may contribute an uncertainty of 3% in total transports.

Results

The accuracy of the estimates of the flow derived from the differences of reciprocal acoustic travel times along the section T1–T2 is documented in Fig. 2c. The comparison between the along-strait flow, averaged along the lower ray path using the acoustic transmissions, with the same quantity estimated from an analysis of all available moored and shipboard direct observations of the flow (Baschek, 1998; Send et al., 2000) shows agreement between the independent flow estimates to within the uncertainties of the measurements.

The comparison in Fig. 2c, however, only addresses the 'forward problem', i.e. it does not test how well the acoustic integrals along a ray path can estimate the transport in the lower layer. This depends on the vertical scales of the flow, which turn out to be large for the tidal flow and surprisingly small for subinertial periods. The uncertainty in measured transport was therefore calculated separately for tidal and low-frequency flows, based on estimates of their vertical and horizontal correlation scales. The results showed that a single integral from an acoustic ray path could determine the tidal lower-layer transports to within 0.3 Sv rms (out of 2.6 Sv rms), i.e. 98% of the *a priori* tidal transport variance is resolved. The uncertainty in the long-period transport is also about 0.3 Sv rms (out of 0.7 Sv rms), i.e. 85% of the *a priori* variance is resolved. The uncertainty can be reduced to about 0.1 Sv by adding additional acoustic transceivers to improve the sampling. This accuracy is expected to be effective for detecting long-period changes in transport. In addition, interface depth and lower-layer heat content can be monitored at the same time. These properties make the acoustic transmissions well suited for a permanent observing system in the Strait of Gibraltar.

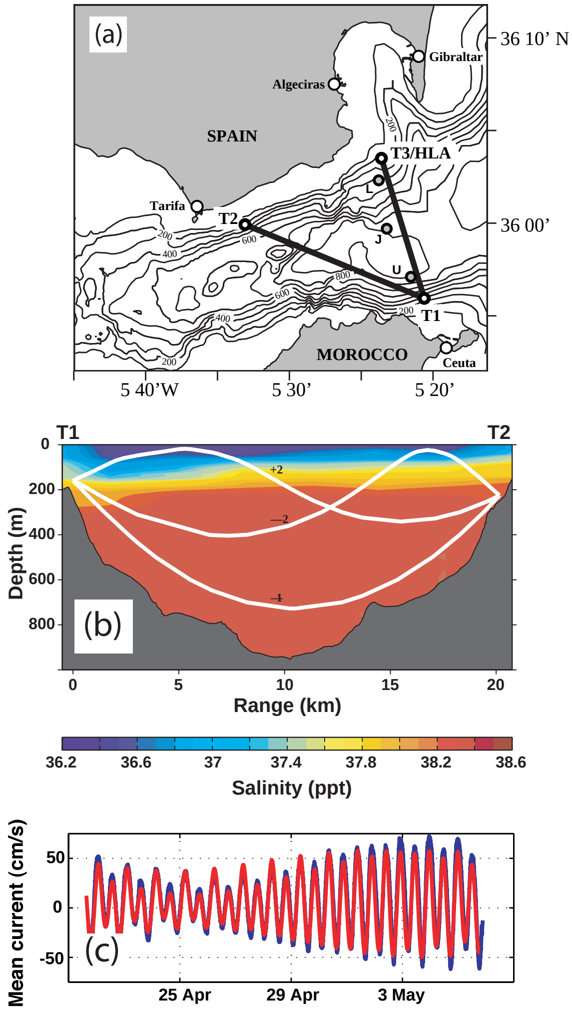

Figure 2. (a) Acoustic instruments located at the eastern entrance of the Strait of Gibraltar are used to monitor transports. (b) Horizontal and depth sampling by some ray paths on the path between instruments T1 and T2. The salinity is shown by the contour intervals and shading; all layers are sampled by the acoustic paths. (c) A two-week comparison of along-strait current through the Strait of Gibraltar averaged along the deep-turning ray path from acoustic transmissions across the Strait (black) and the tidal and low-frequency flow field determined from a wide range of direct current observations (red).

Resolution of mesoscale variability over megametre-scale domains

Introduction

One of the original goals of tomography was to synoptically observe the mesoscale variability of the ocean. Moving Ship Tomography (MST) is a method of obtaining high resolution, nearly synoptic three-dimensional maps of the ocean sound speed (temperature) field over large areas (Cornuelle et al., 1989; Gaillard, 1992; Chester et al., 1994; The AMODE Group, 1994; Cornuelle and Worcester, 1996). Acoustic travel times along a multitude of paths crossing at many different angles are measured and then used to reconstruct the sound speed field in a manner analogous to medical tomography. Using a combination of fixed and moving sources and receivers generates a large number of crossing ray paths. The number of data is equal to $N_s \times N_r$ where N_s is the number of sources and N_r is the number of receiver locations. This quadratic increase in the number of data is a strength of tomographic systems; it is contrasted with the linear increase of the number of data as point sensors are added to a system.

The theoretical basis of tomography is the Projection-Slice Theorem: a projection through the field of interest at some angle maps onto a line in two-dimensional Fourier space at the same angle. To reconstruct the field, projections at all angles are required. It is clear that the path integrals that make up a projection contain low-pass information about the medium. Spatial resolution is obtained from differences of projections.

The AMODE-MST Experiment

In the Acoustic Mid Ocean Dynamics Experiment (AMODE), six acoustic-transceiver moorings were deployed between Bermuda and Puerto Rico in March 1991. The moorings were deployed for 1 year. The pentagonal array was within a circle with a radius of 350 km, and the location of the central mooring of the array was at 25°N, 66.25°W (Fig. 3). For the MST portion of the experiment, the array was circumnavigated a little more than two times at a radius of 500 km over a time span of 51 days in June and July 1991. An acoustic-receiving array with a CTD was deployed from the ship to 1 km depth every 3 hours approximately every 25 km around the circle. Measurements from 6 horizontal paths from the acoustic sources were obtained at each of the 125 ship stops, giving data from a total of 750 horizontal paths within the circumnavigation circle. Each horizontal path typically had 15 identifiable acoustic ray arrivals from which vertical resolution is obtained. One circumnavigation therefore resulted in roughly 10^4 travel-time data; these data are to some degree independent. An order of magnitude less data (actually less by a factor of $N_s = 6$) was obtained from the CTD profiles in the same amount of time.

Results

The MST map of the mesoscale perturbation to the sound speed, δC, at a depth of 700 m is shown for the period July 15–30 in Fig. 3. A second realization of a map of sound speed was obtained for the period 4–18 July (not shown). The perturbation maps are remarkable in that they cover a large area and provide spatial resolution (65 km). Because the two maps overlapped in time, many of the same features are present in each map; the small differences between the two maps are mostly a result of simple advection. The estimated rms perturbation is 2.0 m/s, or 0.5°C, which corresponds to a nominal thermocline displacement of 100 m. (The gradient of the main thermocline, and thus the strength of thermal variations caused by mesoscale eddies, peaks at 700 m.) The estimated rms uncertainty in the interior of the circle is a nearly uniform 0.6 m/s (0.15°C). Outside the circle, the uncertainty rises to a background value (2.0 m/s) nearly that of the *a priori* state (2.2 m/s), the difference being that the acoustic data have reduced the error in the mean over the whole domain.

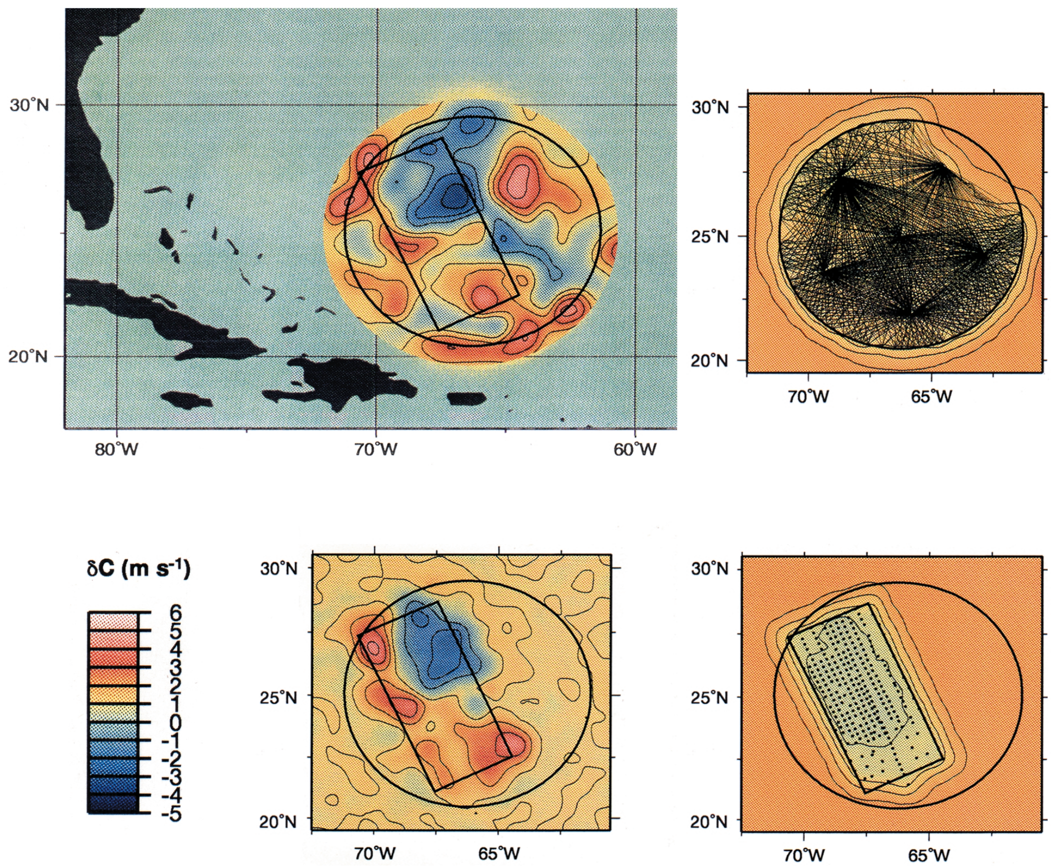

Figure 3. Top left: Sound speed perturbation, δC, at 700 m depth based on only acoustic data from the AMODE – Moving Ship Tomography Experiment (July 15–30, 1991). The contour interval is 1 m/s, which is approximately equivalent to 0.25°C. The ship with an acoustic-receiving array steamed around the 1000-km diameter circle, stopping every 3 hours (approximately every 25 km) to receive signals from six moored sources. The acoustic travel-time data were inverted to derive the map of sound speed perturbation. Bottom left: Sound speed perturbation at 700 m depth based on only AXBT data (July 18–22, 1991). The panels at right show the line-integral or point sampling that was used to obtain the maps.

An independent map of sound speed perturbation at 700 m depth corresponding to the MST map was obtained using data from 230 AXBT casts taken between 18 and 22 July (Fig. 3). The AXBTs were dropped on 25 km and 50 km grids inside the box indicated in Fig. 3. The AXBT map shows perturbations only where the measurements were made, of course, and in this domain the sound speed field is very similar to that obtained using the acoustic data. The estimated uncertainty in the field mapped using the AXBT data is 0.8 m/s. A rigorous comparison between the two independent results must take into account the errors of each estimate; the estimated uncertainty of the difference is typically about one standard deviation within the AXBT domain. Similar results were obtained in the vertical dimension.

Present research is aimed at employing tomographic data, numerical models of the ocean, and data assimilation to provide dynamically consistent interpolation (and extrapolation) of the ocean's state over time. The time dependence of the ocean, even during the 2 week time period required to circumnavigate the AMODE array, as well as the effects of variations in salinity have proved to be important aspects of an accurate estimate of the ocean state from the acoustic data (B. Cornuelle, pers. comm., 2000).

Tides and tomography: Observations of large-scale oceanic variability

Over the past several years a number of results concerning oceanic tidal variability have been determined from long-range acoustic transmissions. While these observations are not in themselves relevant to the climate problem, they are examples of how line-integral observations provide significantly better signal-to-noise capability than point measurements for detecting large-scale oceanic variability. This capability is one of the main justifications for acoustic tomography.

Barotropic tidal currents

As has been shown using data from the 1987 Reciprocal Tomography Experiment (RTE87) (Dushaw et al., 1995) and AMODE (The AMODE Group, 1994; Dushaw et al., 1996, 1997) reciprocal tomography can measure the harmonic constants of barotropic tidal currents to within about 2% uncertainty. Although the work with the tides began as a convenient way to test the tomographic measurements of current, the measurements have since proved to be a valuable asset to those concerned with estimates of the dissipation of tidal energy from global tidal models (Egbert and Ray, 2000). Such estimates rely on the accuracy of modelled tidal currents, and the acoustical measurements have provided the only data that can really test the model currents. Indeed, differences between measured and model tidal currents (the TPXO.2 model, Egbert et al., 1994) were traced to errors in the tide model (Dushaw et al., 1997). Measurements of tidal currents by current meters are apparently not accurate enough to test the model currents (Dushaw et al., 1997; Ray and Egbert, 2000) (Fig. 4). The uncertainty in the harmonic constants derived from available current meter records appears to be about 20%, even in those cases where attempts have been made to separate the barotropic and baroclinic modes.

The barotropic tides have also provided an extraordinary test of the accuracy of acoustic travel times at multimegametre ranges. Tidal variations of 10–20 ms amplitude are evident in the 5 Mm range (3600 s travel time) acoustic transmissions in the Pacific Ocean (Dushaw et al., 1999), and these tidal variations closely match the amplitude and phase of the expected signal that was derived from the TPXO.2 tidal model. These tidal variations are caused by currents; the contribution of tidal elevation to these signals is minimal.

Relative vorticity

As the height of the sea surface varies with the tides, a slight relative vorticity results from the stretching of the vortex lines. Such relative vorticity was observed using the data obtained during AMODE; 10 independent estimates of this vorticity could be made with the AMODE tomography array (Dushaw et al., 1997). The amplitude of the tidal relative vorticity was about 5×10^{-9} s^{-1} with a measurement uncertainty of about 20%. The measured relative vorticity was consistent with that derived from the TPXO.2 'global' tidal model, but not consistent with the 'local' equation governing relative vorticity. Perhaps not surprisingly, there are contributions to relative vorticity other than the local stretching of vortex lines.

As an aside, the RTE87 and AMODE acoustic arrays also measured large-scale, low-frequency relative vorticity. Dushaw et al., (1994) used the

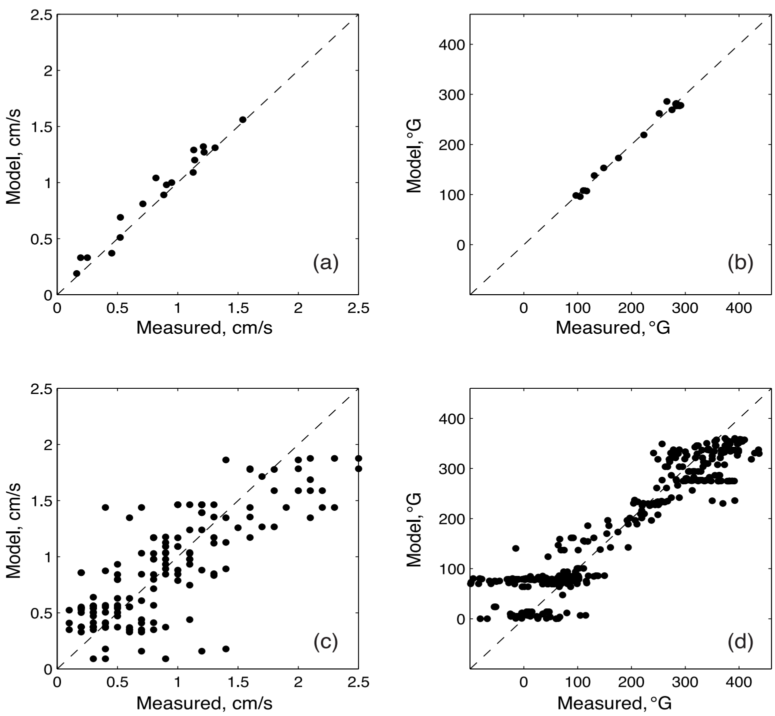

Figure 4. Comparison of amplitude and phase of M_2 barotropic tidal currents predicted by TPXO.2 (ordinate) and the values determined from tomography (absissa, top panels) and from current meters (absissa, bottom panels). The current meter valves were typically determined from data obtained at depths greater than 1000 m, and the time series had year-long record lengths (Luyten and Stommel, 1991). In cases where a number of current meters were on a single mooring (Dick and Siedler, 1985), the harmonic constants were determined from the barotropic component of the flow. The differences between the values from the model and from tomography (top panels) were found to be mainly caused by errors in the model (modified from Dushaw et al., 1997).

RTE87 data to derive measurements of megametre-scale barotropic currents of order 3 ± 2 mm/s and relative vorticity of order $1 \pm 0.6 \times 10^{-8}$ s^{-1} in the central North Pacific. The magnitudes of the observed currents and relative vorticity were an order of magnitude larger than could be computed using the low-frequency limit of the barotropic vorticity equation and the local wind-stress curl from meteorological analyses. Apparently, non-local forcing dominated the observed large-scale variability, at least in summer when the observations were made. The low-frequency relative vorticity observed by the AMODE array was O(10 s^{-1}), mainly a result of mesoscale variability in the western North Atlantic.

Internal tides

Reciprocal acoustic transmissions are capable of measuring the large-scale displacements of internal tides. This capability became apparent during the analysis of the RTE87 data, when steady, deterministic tidal variations with about 10 ms amplitude were apparent in the acoustic travel-time data (Dushaw et al., 1995). The ranges of the acoustic transmissions were 750–1250 km. The average of the travel-time data obtained on reciprocal paths is sensitive to only the sound speed fluctuations caused by isopycnal displacements. Internal-tide variations at both M_2 and S_2 frequencies were observed. The physical picture that emerged from the analysis of these data was that internal tide waves were generated along the Hawaiian Ridge, and these waves retained their spatial and temporal coherence as they propagated O(2000 km) into the interior of the central North Pacific. This interpretation was subsequently supported by analysis of TOPEX/POSEIDON data near the Hawaiian Ridge (Ray and Mitchum, 1996; 1997; see also Ray and Cartwright, 2001; Dushaw, see below).

The data obtained during 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 (Fig. 5; Dushaw and Worcester, 1998). These observations were obtained in the same region as the Mid-Ocean Dynamics Experiment (MODE) and the Internal Wave Experiment (IWEX) of the 1970s, and neither of those well-instrumented observing arrays detected this wave. The waves are also not observable by TOPEX/POSEIDON altimetry because of their small amplitude (R. Ray pers. comm., 1999). The peak-to-peak temperature variability associated with these waves was 40 m°C at 700 m, the depth of the mode maximum.

Discussion

The barotropic and baroclinic tides are examples of small amplitude, but large-scale, phenomena that can be accurately measured in the noisy ocean environment by using acoustic tomography. Measurements by conventional instruments at points often fail to accurately determine the large-scale variations of the tides. An analogy to consider is that the measurement of the diurnal internal tides, or other large-scale but small-amplitude tidal effects, is to internal-wave noise as the measurement of climate patterns is to mesoscale noise. For example, measurement of the changes in climate patterns using hydrographic data is hampered by the mesoscale and internal

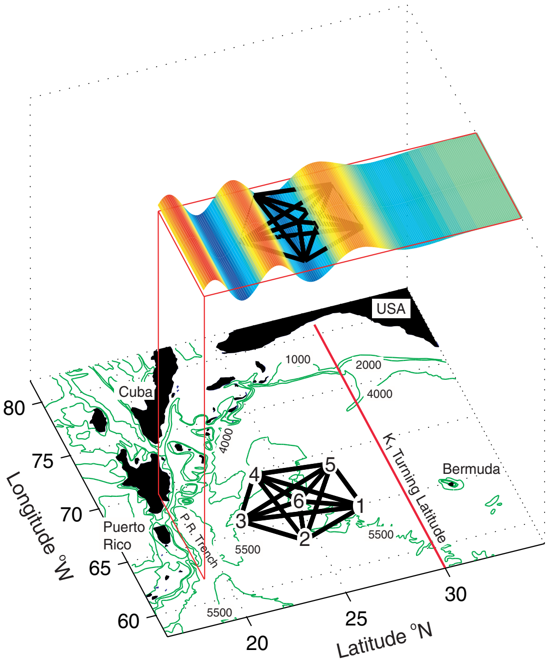

Figure 5. The AMODE acoustic tomography array detected diurnal tidal signals (K_1 and O_1 frequencies) of the lowest internal wave mode. The predicted horizontal variation of the displacement associated with this mode for the K_1 frequency is shown at the top as the coloured wave. The southern boundary is the 600-km long shelf just north of Puerto Rico (From Dushaw and Worcester, 1998).

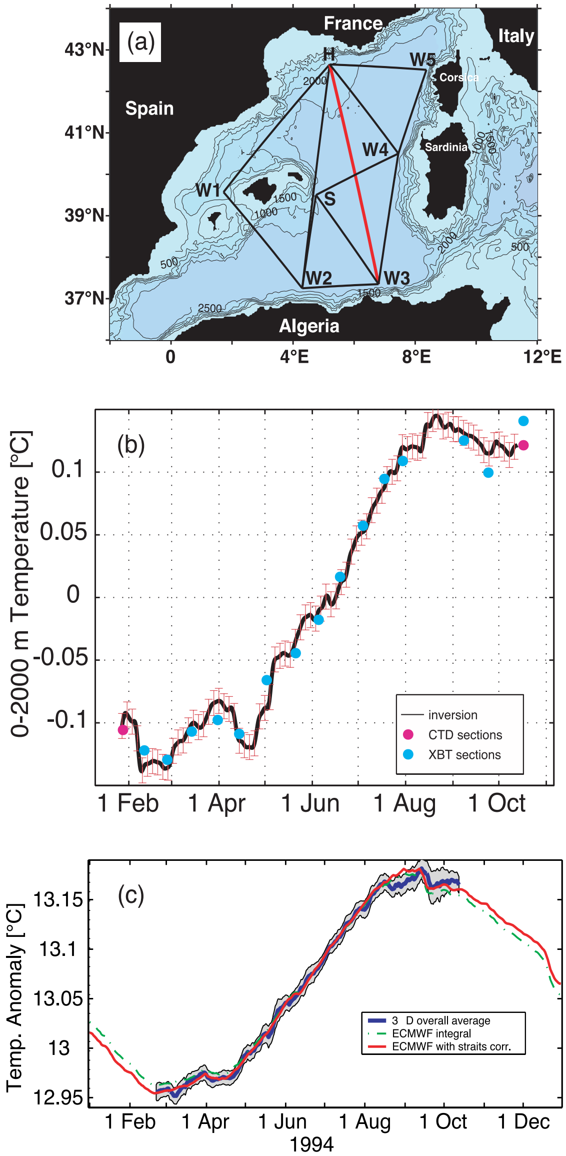

Figure 6. (a) The acoustic array of the THETIS II experiment in the western Mediterranean Sea. (b) The 0–2000 m heat content (average temperature relative to 13.11°C) in the section between instruments labelled H to W3 as calculated from acoustic tomography (line and error bars) and from CTD/XBT sections (bullets); (c) The 3D (0–2000 m depth) basin heat content estimated from several acoustic sections (blue lines with gray uncertainty), compared with the ECMWF surface heat flux integral with (solid red line) and without (dashed green line) a correction for flux through the straits.

wave noise that appears in that data type. Small but large-scale changes in ocean temperature are difficult to accurately determine using data collected at points. Just as the current meter data proved to offer only weak constraints for the tidal models, so hydrographic data may offer only weak constraints for the climate models. This notion remains to be tested by ongoing modelling programs, e.g. Davis et al., (2000).

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 (Fig. 6a; Send et al., 1997). The horizontally and vertically integrated heat content measured along one such line agreed with the heat content inferred from fortnightly XBT sections to within 30 m°C uncertainty (Fig. 6b). Acoustic measurement along 13 lines through the basin allowed estimates of the evolution of the heat content in three dimensions, and comparison with surface heat fluxes estimated by ECMWF. The results (Fig. 6c) show a surprising consistency, which helps to quantify the seasonal and shorter-term forcing of such properties as wintertime water-mass formation. Variability of the volume of Levantine Intermediate Water in the basin has now also been estimated with these data.

The final use of tomography at basin-wide scales is through assimilation into a numerical model. The THETIS II experiment served as the first demonstration of merging altimetric and tomographic data together by using a numerical model. Menemenlis et al. (1997) obtained a description of the basin-scale temperature and flow-field evolution consistent with both data and dynamics. The THETIS II experiment has also been simulated in a numerical model for twin experiments with variational data assimilation (Rémy and Gaillard, 1999). This simulation is in preparation for a more rigorous assimilation of the tomographic data than was achieved by Menemenlis et al. (1997).

The THETIS II experiment 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.

Acoustic Thermometry of Ocean Climate (ATOC)

Introduction

The Acoustic Thermometry of Ocean Climate (ATOC) project is directed at using the travel-time data obtained from a few acoustic sources and receivers located throughout the North Pacific basin to study the climate variability of the thermal field at the largest scales (Fig. 7) (The ATOC Consortium, 1998). The goals of the ATOC project are similar to those of earlier work by Spiesberger (e.g. Spiesberger and Metzger, 1991). Given an expected climate signal of order 10 m°C/year (Levitus et al., 2000) and high-wavenumber (mesoscale) noise of order 1°C rms, spatial low-pass filtering is needed to pull out the climate signatures in a reasonably short period of time. Acoustic thermometry offers naturally integrating observations of large-scale temperature with unrivalled accuracy and precision.

The ATOC project has now completed several important phases. An acoustic source off the coast of California (Pioneer Seamount) began transmissions 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 transmitted signals from late 1997 through late 1999. As a result of marine mammal research protocols, the time series are intermittent. The California source was turned off in late 1998 in accord with permit requirements. Transmissions from the Kauai source continued through fall 1999. Permits are being sought from appropriate governmental agencies to continue acoustic transmissions from the Kauai source for another 5 years. The acoustic receivers are those of opportunity such as the US Navy Sound Surveillance System receivers (SOSUS) (http://newport.pmel.noaa.gov/geophysics/sosus_system.html), as well as two dedicated vertical line arrays of hydrophones that were located near Hawaii and Kiritimati. In addition, signals transmitted from the California source were detected by a temporary receiver (a single hydrophone) located to the east of the North Island of New Zealand at 10-Mm range (Tindle and Bold, 1999). Receptions of these and other ATOC transmissions have also been made by a Russian group; for example, the Kauai Source transmissions were detected using a receiver near Kamchatka. This Russian group is interested in continuing to receive the transmissions from the Kauai acoustic source.

Results

The acoustic transmissions obtained during ATOC have shown that acoustic ray arrivals may be resolved and identified to at least 5-Mm range so that these data can be used for acoustic thermometry (The ATOC Consortium, 1998; Dushaw et al., 1999; Dushaw, 1999; Worcester et al., 1999). Prior to these measurements, there was concern that the acoustic signals at very long ranges would be sufficiently scattered by small-scale oceanic variability, such as internal waves or mesoscale features, that it would not be possible to resolve and identify individual ray arrivals (e.g. Wolfson and Tappert, 2000.) The ultimate limits on the range to which acoustic remote-sensing methods are practical depend in a complex way on acoustic frequency and the background sound speed profile, and are not yet known. The conclusion that acoustic methods can be used out to ranges of at least 5 Mm is consistent with the results of other long-range propagation experiments at 1–3-Mm range (e.g. Dushaw et al., 1993a,b; Cornuelle et al., 1993; Spiesberger et al., 1994; Worcester et al., 1999).

The resolved acoustic travel times have been used to derive time series of temperature using a simple model for ocean variability. The uncertainties in the range- and depth-averaged temperature measurements estimated from this simple model were about 10 m°C. 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.

The time series derived from the acoustic data can be compared with other available data. To derive a temperature estimate from the TOPEX/POSEIDON altimeter data, we will assume that the variations in sea surface height are caused solely by thermal expansion in the upper 100 m of ocean. The basin-wide amplitude of the annual cycle of heat content derived from altimetry appears to be larger than that derived

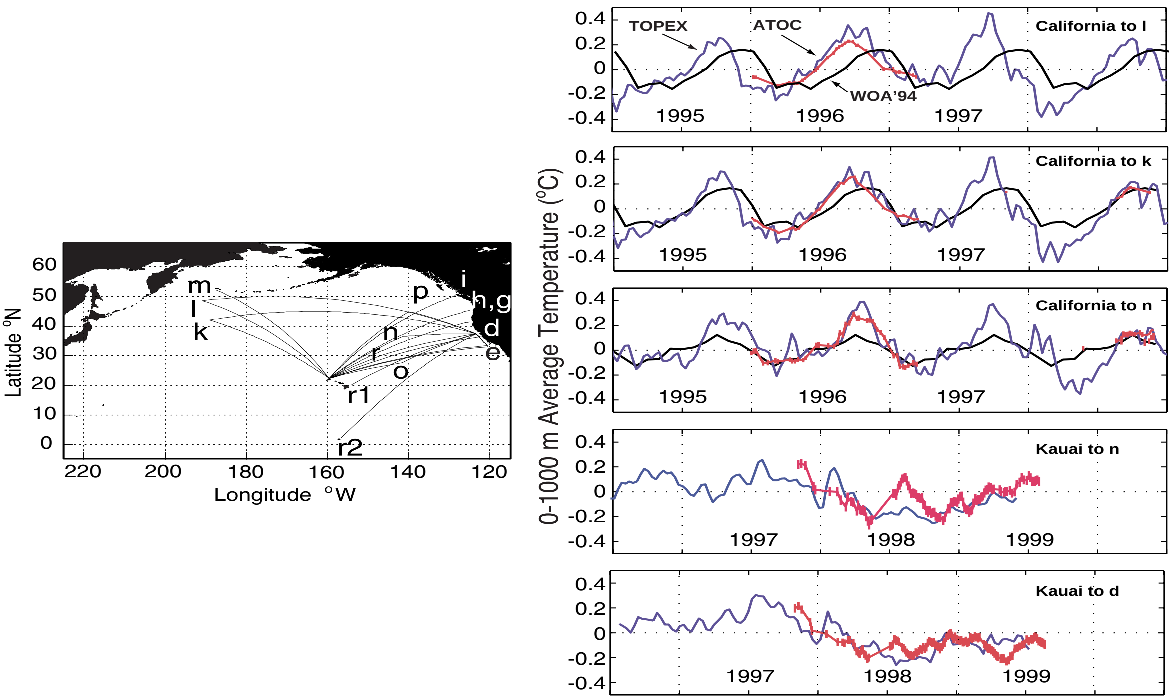

Figure 7. Map of Acoustic Thermometry of Ocean Climate (ATOC) acoustic paths in the North Pacific and a comparison of temperature time series derived from TOPEX/POSEIDON altimetry (blue) and acoustic tomography (red, with error bars). The letters k, l, m, etc. are arbitrary names of receivers such as the U.S. Navy SOSUS arrays. In the lower two panels, the annual cycle has been 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 that variations in the sea surface height are caused only by thermal expansion in the upper ocean.

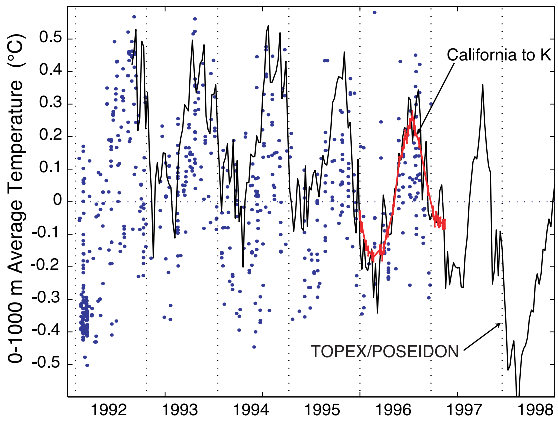

Figure 8. ATOC and TOPEX/POSEIDON (T/P) time series of temperature compared to temperature from broadcast XBTs of opportunity from a 10° square centered on 155°W, 45°N. The T/P time series was derived from the altimeter variations at a single point at the centre of this region by assuming that those variations were caused by steric expansion in the top 100 m of ocean. The XBT profiles of temperature were integrated over only the top 100 m, and then scaled by a factor of 10 so that they would have the same scaling as the acoustic measurements. Integrating the XBT data from 0–300 m results in a much noisier time series, but this data type requires careful interpretation (see, for example, Moisan and Niiler 1998).

from the acoustic data (Fig. 7), Levitus climatology (Levitus et al., 1994; Levitus and Boyer, 1994), and monthly maps of ocean temperature derived from XBTs of opportunity (the maps of upper ocean temperature based on XBTs are courtesy of White, 1999). The altimeter and XBT data were averaged along the acoustic paths for these comparisons. The 'anomalies,' or deviations of temperature from the annual cycle, are the essence of the climate problem. The heat content 'anomalies' determined from the XBT maps are comparable in size to the differences between the XBT and the acoustically derived heat contents. These differences may be due to under-sampling in space or time by the XBTs, aliasing of internal wave or mesoscale variability, errors in the XBT maps as a result of such things as fall rate errors, or the deeper sampling (below 400 m) of the acoustic data (e.g. Fig. 8).

The time series obtained from acoustic paths that begin or end near the Hawaiian Islands, including those obtained using the Kauai acoustic source, show greater variability at 100-day time scales than those from other acoustic paths (Figs. 7, 9a). This variability is presumably caused by the strong mesoscale eddy field that occurs near the Hawaiian Ridge.

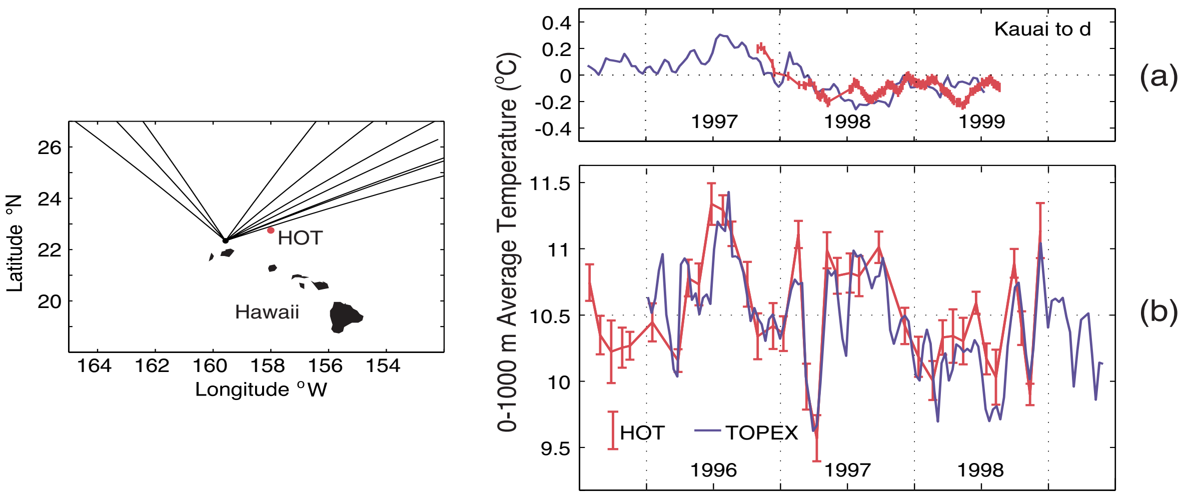

Figure 9. A comparison of line-integral and point data. (a) Acoustic thermometry (red) compared to TOPEX/POSEIDON altimetry (blue) for an acoustic path from Kauai to Pt Sur (d) as indicated in Fig. 7. The error bars on the acoustical results are small. As in the lower panels of Fig. 7, the annual cycle was removed from the TOPEX/POSEIDON data for the acoustic path. (b) The HOT site. A similar comparison of 0–1000 m averaged temperature derived from HOT hydrographic data (each point of this time series shows the average and rms of 10–20 CTD casts obtained during each HOT cruise) and from TOPEX/POSEIDON. All panels have the same scaling of both axes. A nearly identical comparison is found with a more direct comparison of dynamic height to the altimetric data. The differences between the temperature inferred from TOPEX/POSEIDON and the direct measurement at HOT (a point measurement) are comparable to the temperature signal observed in the line-integrating data. The error bars of the hydrographic data are comparable in magnitude to the signal observed in the line-integral data, and the hydrographic time series is dominated by mesoscale variability.

The 12-year time series of temperature derived from the Hawaiian Ocean Time series (HOT) data set (monthly sets of CTD casts) highlights the problem of mesoscale noise in sampling at a single point (Fig. 9b). Each point of the time series in Fig. 9b is calculated by averaging the depth-integrated temperature profiles from the 10–20 CTD casts obtained during each HOT cruise. The time series is dominated by the mesoscale; its variance is roughly 30 times the value obtained acoustically for the average temperature between Kauai and California. To achieve a similar reduction in variance using point measurements would require samples at 100-km intervals along acoustic paths between Hawaii and California. This sampling density is hard to achieve by random point sampling; the ARGO program, for example, plans for an average spacing between the floats of about 300 km. These crude numbers suggest that the areal density of ARGO floats will be nine times less than is necessary to match the signal-to-noise capability of the acoustics for detecting large-scale temperature variations. Two offsetting caveats to this calculation are: (1) The acoustic sampling near Hawaii misses the upper 200 m of ocean and so it does not detect the variability there. The error bars for the acoustic measurements are larger for acoustic paths that pass near Hawaii because of the unresolved variability in the upper ocean. (2) Each point in the HOT time series used for these calculations is the average of 10–20 CTD casts, while most often broadcast-mode point measurements offer only one hydrographic profile. In Fig. 9b, the error bars show the rms of the 10–20 CTD casts, so the error bars show the uncertainty in depth-integrated heat content for individual hydrographic casts obtained around Hawaii. The theme here is not that acoustic thermometry is a substitute for the point measurements, but that acoustic thermometry is complementary to altimetry and hydrography.

Arctic climate observations using underwater sound

Introduction

The Trans-Arctic Acoustic Propagation (TAP) experiment (Mikhalevsky et al., 1999) conducted in April 1994 was designed to determine the feasibility of using acoustic transmissions to monitor changes in the temperature of the Arctic Ocean and in the thickness and concentration of sea ice. The data showed that the quality of the measurements was an order of magnitude better than is required to detect the estimated changes of 80 ms/year in travel time caused by interannual and longer-term changes in Arctic Ocean temperature. Observations of the travel times of the first three acoustic modes allow us to measure the average temperature changes in the upper mixed layer, the Atlantic Layer, and the deeper waters in the Arctic. The acoustic thermometry technique is now being used in the Arctic Climate Observations using Underwater Sound (ACOUS, from the Greek word 'ακους' meaning 'listen!') program for year-round observation of long-term changes in the average Arctic Ocean temperature on a path from Franz Victoria Strait to the Lincoln Sea.

The Arctic is in many ways ideally suited to measurement by acoustic tomography. It has low acoustic noise levels and no internal waves so that the acoustic propagation is very clean. Travel times of the first several acoustic modes are readily resolvable, and these modes naturally sample the layers in the water column that are of oceanographic interest. Finally, it is difficult to access the Arctic water column by conventional measurement techniques; acoustics provide perhaps the only way to remotely sense the sub-surface variability.

The Trans-Arctic Acoustic Propagation Experiment

Since the early 1990s inflow of warmer Atlantic Water into the Arctic Ocean has resulted in temperature increases in the Atlantic Layer. Point measurements from icebreakers in 1991 and 1993 showed temperature increases of several tenths of a degree Celsius compared with historical climatologies (Quadfasel et al., 1991; Anderson et al., 1994). The 1994 TAP acoustic transmissions were made from a site north of the Svalbard Archipelago across the entire Arctic Ocean to receiving arrays located in the Lincoln Sea and the Beaufort Sea (Fig. 10) (Mikhalevsky et al., 1995; Mikhalevsky, 1999). These travel-time measurements revealed an average increase of 0.4°C of the maximum temperature in the Atlantic Layer. This was the first basin-scale measurement of this large-scale warming. The Arctic Ocean Section of the USCGS Polar Sea and the CCGS Louis S. St Laurent (Carmack et al., 1995) conducted in August 1994 and transects performed by the US Navy SCICEX (Submarine Science Expedition; Mikhalevsky and Gavrilov, 2001) submarines confirmed these results. Whether these results are a manifestation of a secular global climate change trend or a 'natural' oscillation (Grotefendt et al., 1998; Johnson et al., 1999) is an area of active research. Modelling has suggested that major shifts in the Arctic Ocean circulation occur on a decadal time scale (Proshutinsky and Johnson, 1997; Johnson et al., 1999) between two dominant circulation regimes which could explain some of the recent observations.

Arctic climate observations using underwater sound

On 9 October 1998, the first acoustic source as part of the ACOUS project was deployed in the Franz Victoria Strait (Fig. 10). The source is moored from the bottom at a depth of 60 m. It is autonomous and transmits 20 Hz coded signals every 4 days. The first regular transmission was on October 15, 1998. The source is designed to operate for 2.5–3 years unattended at a source level of 195 dB, or 250 W of acoustic power. At the same time that the source was installed an American–Canadian team deployed an autonomous receiving array in the Lincoln Sea approximately 1250 km away. This array is moored from the bottom in 545 m of water. The array also has five micro-CTDs that record temperature and salinity. The array is designed for an 18-month life, and recovery and data retrieval are planned for 2001. This source–receiver pair creates a propagation path that crosses the eastern Arctic just north of Fram Strait. These data will be compared with and ultimately assimilated into new models under development at the University of Alaska, Fairbanks.

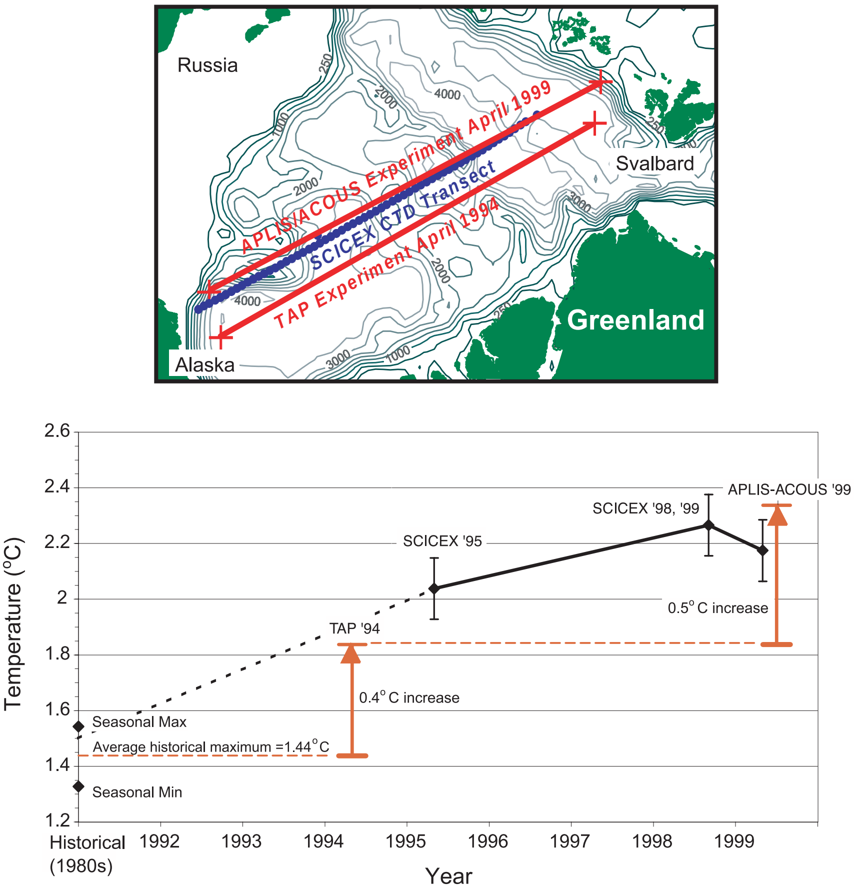

Figure 10. Upper panel: The SCICEX, TAP and APLIS-ACOUS trans-Arctic sections. Bottom panel: The maximum absolute temperature of the Atlantic Layer obtained from historical climatology and the SCICEX 1995, 1998, and 1999 transects that were close to the 1994 TAP and 1999 ACOUS/APLIS propagation paths. The red arrows indicated the change in the maximum temperature inferred from the mode 2 acoustic travel-time changes. The error bars on the SCICEX points are based on the average seasonal maximum and minimum from US Navy-compiled and Russian historical data bases (Davis et al., 1986; Teague et al., 1987; Environmental Working Group, 1997).

In April 1999, an ice camp was established in the Chukchi Sea to support the 1999 SCICEX expedition. Recordings of the ACOUS transmissions on April 9 and 13 were made at the ice camp. The 'acoustic' section travel-time measurements showed that the average maximum of the Atlantic Layer had warmed by approximately 0.4–0.5°C since the TAP measurement over essentially the same path was made in April 1994, 5 years earlier (Mikhalevsky and Gavrilov, 2001). Subsequent trans-Arctic sections by icebreakers and submarines have confirmed this ubiquitous and widespread warming, which is the subject of active research today.

Measuring the temperature of the Atlantic Layer

The travel time of the second acoustic mode can be used to measure the average temperature of the Atlantic Layer, defined as that layer of water between the 0°C temperature crossings. SCICEX 1998 and SCICEX 1999 expendable CTD casts may be used to show the correlation between the Atlantic Layer temperature and the mode-2 group velocity. Figure 11 shows these two variables as a function of range from the acoustic source to the APLIS 1999 Ice Camp in the Chukchi Sea. In addition, about 800 original CTD profiles obtained in the Arctic since the 1950s were used to calculate the mode-2 and mode-3 group velocities, as well as the average temperature between the

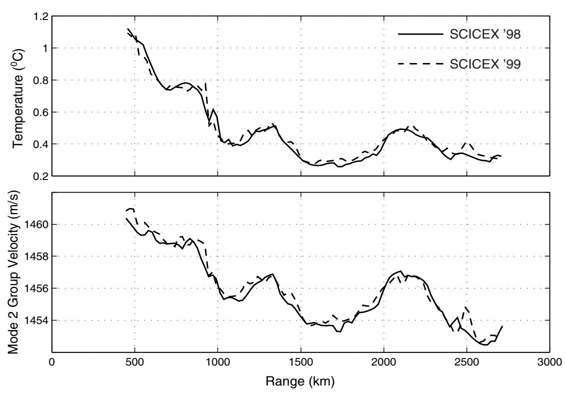

Figure 11. (a) The average temperature in the Atlantic Layer of the Arctic Ocean computed by averaging the temperature over depth between the 0°C points using SCICEX 1998 and 1999 expendable CTD transect measurements (Mikhalevsky and Gavrilov, 2001). The temperature is shown as a function of range along the acoustic path from the ACOUS source to the APLIS Ice Camp. (b) The computed group velocity for mode 2 over the same path. The travel times of the second acoustic mode are a measure of the mean Atlantic water temperature.

0°C isotherms. The resulting acoustic group speeds and the temperature of the Atlantic Layer are also highly correlated (Mikhalevsky and Gavrilov, 2001). Observations of the change of the mode-2 travel time are therefore sensitive to, and correlated with, the temperature changes in the Atlantic Layer. Figure 10 shows the maximum Atlantic Layer temperature from the SCICEX experiments and from historical climatological measurements compared to the changes in maximum temperature inferred from the acoustic measurements made in the April 1994 TAP experiment and the April 1999 ACOUS/APLIS experiment.

The present and future of acoustic tomography in ocean climate observations

Tomographic methods can be used to make regional- and basin-scale measurements of relevance to the ocean climate observation problem.

Regional measurements

Deep-ocean water-mass changes in key areas

A key topic of the CLIVAR DecCen program is the variability in deep water-mass properties, transports, and forcing processes related to the thermohaline circulation (THC). Determining this variability requires, among other things, long-term observations of the formation regions (properties, volume, depth) and of water-mass properties and mass and heat transports at sections along the path of the THC. As already described, tomographic techniques have demonstrated benefits in observing deep convection regions and the processes that form deep water masses. The convection regions may in some sense be regarded as sources for the THC.

Multi-year monitoring of convection variability using tomography and other methods is under way in the Labrador Sea as part of a German special research initiative ('Dynamics of thermohaline circulation variability' by IfM, Kiel). An array of 3–5 tomography systems has monitored the deep water-mass formation region of the central Labrador Sea since summer 1996. The simultaneous line-integral and moored-point measurements by the array are complementary observations of the convection activity. The aims of this program are to observe the interannual changes in the temperature evolution and heat balance processes on the scale of the deep-mixing region O(200 km) and to estimate the size of patches where localized deep convection occurs.

Useful data have been obtained from several of the acoustic paths over a 3-year period. Among other things, these time series allow the annual seasonal extrema of heat content in the region to be determined (the acoustic ray paths in this region sample the water column to the surface). Comparing the amplitude of seasonal heating and cooling to surface heat flux integrals can illuminate the role that horizontal advection plays in the mixed-layer deepening and the restratification after convection. Horizontal advection is a possible factor in modulating interannual convection variability.

A 3-year time series of heat content along one section in the Labrador Sea is shown in Fig. 12. The tomography measurements are horizontal and vertical integrals of temperature along the approximately 150-km section from the boundary current off Labrador (mooring K12) into the interior of the convection activity (mooring K11). The data show a long-term warming trend over the three years that is equivalent to a surface heat flux of about 10 W/m^2, i.e. this region of the Labrador Sea is gradually warming. These integral data can be compared to heat content determined

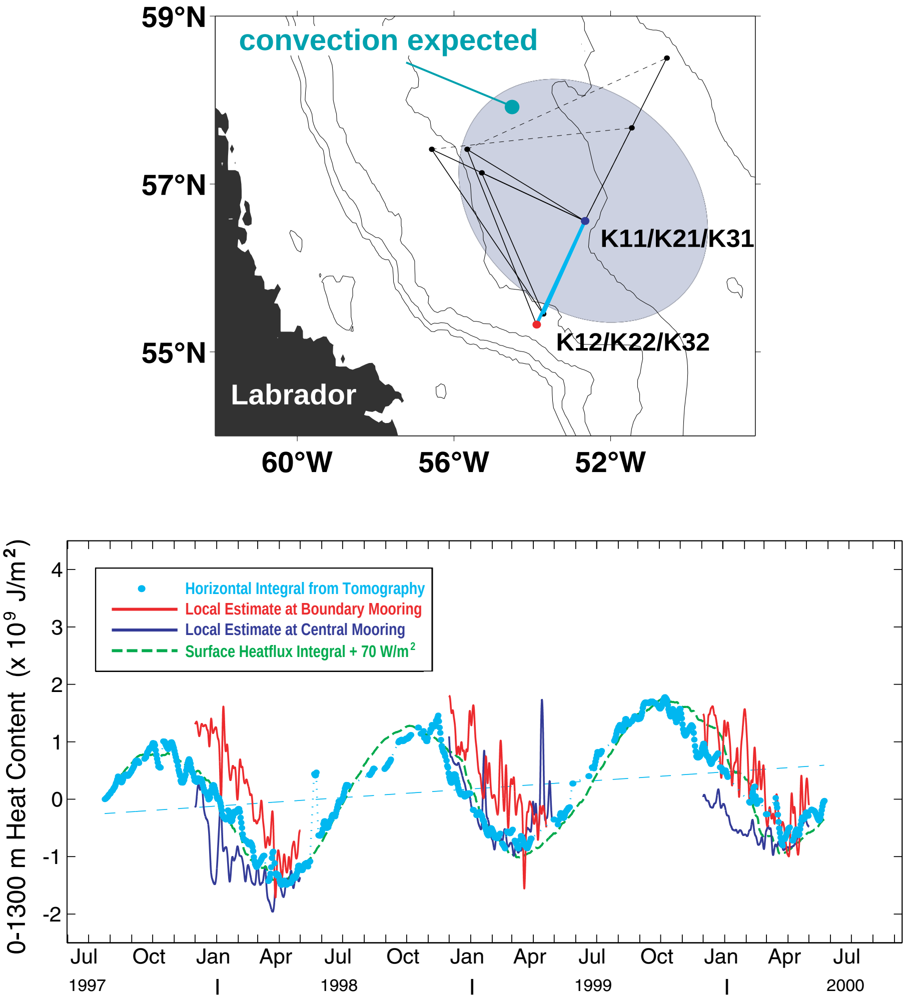

Figure 12. Three-year timeseries of 0–1300 m heat content derived from tomographic data (cyan, dots) along the section marked in the top panel and derived from data obtained at the moorings at the ends of the section (blue: K11, red: K12). The dashed line shows a three-year warming trend, equivalent to a heat flux of 10 W m^{-2}. The dashed green curve is the time-integral of the NCEP surface heat fluxes, corrected by the addition of 70 W m^{-2}, averaged over the section. The top panel shows the tomography mooring arrays in different years relative to the typical area where deep convection activity is expected (shaded).

at the locations of the moored sensors at the ends of this section (Fig. 12). Since the sensors on these subsurface moorings do not extend to the surface, they provide heat content only during December through May when the mixed-layer is deeper than the uppermost sensor. As expected, the interior, where the convection happens, is colder than the boundary current region during the cooling phase. The horizontal average of heat content from tomography is between the interior and boundary values, but sometimes it is closer to the measurement from the interior mooring. This result suggests that the cold region can extend very close to the boundary current in some years and not in others. After the convection, the difference in heat content between the end points vanishes in each year, and the heat content at both ends of the section equals the horizontal average. The implication is that a horizontal homogenization occurs between the boundary current and the interior, with a likely exchange of convected water as well. Finally, the integrated NCEP surface heat flux for this section is consistent with the tomography heat content, if the heat flux is increased by 70 W/m^2. The additional 70 W/m^2 may be caused by a nearly constant lateral heat advection in this region over the seasons and years, but this suggestion needs to be corrected for potential biases in the NCEP heat fluxes.

Overall, it is expected that the tomography data will help quantify the role of different processes in governing the year-to-year changes in convection activity and thus in deep-water formation.

Transports and heat flux through straits and passages

Volume transports through passages between ocean basins, or between marginal seas and ocean basins, are important quantities because they indicate 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 because of strong currents, shipping, fishing, etc. In addition, many instruments may need to be deployed horizontally and vertically to construct reliable transports. Therefore, integrating and shore-based methods are generally preferable, for example measuring 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 the optimal method in a given situation depends on many factors. Under certain conditions, acoustic transmissions can provide accurate horizontal integrals without the need for calibration, as already described. If the vertical shear or variability is not too large, the shore-based acoustic transmissions can be used to obtain the transports of various layers. It is proposed here that an acoustical approach may be the method of choice for certain straits or passages.

As demonstrated earlier, the Strait of Gibraltar appears to be a site that is suitable for using cross-strait acoustic transmissions for observing the outflow transport from the Mediterranean. IfM, Kiel, and SIO, San Diego, are considering 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 as part of the Acoustic Monitoring of Ocean Climate in the Arctic (AMOC) program (Johannessen et al., 1999).

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. The acoustic time series can be supplemented by occasional sampling by hydrographic transects from ships. Occasional hydrographic transects alone may suffer from aliasing. If merged with volume transports from other observations such as dynamic height moorings, the acoustically derived heat content can also be used to approximate heat fluxes through a section as a function of time. As an example, a German CLIVAR project (MOVE by IfM, Kiel) was initiated in early 2000 to observe the deep southward transports of the thermohaline overturning circulation through a section along 16°N between the shelf slope to the east of the Caribbean island arc and the mid-Atlantic Ridge. Multi-year time series of geostrophic mass transports are being estimated using moored density and pressure sensors at the ends of the section. In a few years, tomographic instruments will be added to the moorings to also obtain the section-average heat content of the water masses. Together, these data may provide an indication of the time-varying southward temperature flux through the section.

Large-scale weak ocean current measurements

Reciprocal tomography has the capability to measure very weak, but large-scale, currents and relative vorticity. The Central Equatorial Pacific Tomography Experiment was deployed from 1999–2000 to measure the weak meridional currents. The seven JAMSTEC tomography transceivers were deployed in an array about 1000 km across just north of the equator at 180°E. The tomography data were relayed to JAMSTEC in real time. This experiment may give a measurement of the shallow overturning of a meridional circulation cell. This subtropical cell (STC) has been hypothesized as one mechanism by which El Niño–La Niña events in the tropics are connected to the subtropical ocean (Gu and Philander, 1997). This hypothesis suggests that 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. While no direct measurements of the STC exist, indirect measurements and modelling support the STC hypothesis. The high sensitivity of reciprocal tomography for measuring large-scale currents is one means by which the weak meridional currents of the STC can possibly be detected. Two years of operation have been completed, though adequate measurement of the STC will require a longer time series.

Boundary current regions

The Gulf Stream, the California Current, the Kuroshio, and the North Equatorial Current bifurcation region in the Philippine Sea are examples of regions of complicated, intense, and meandering currents. Moorings at points are problematic for observing such currents, and floats tend to leave such regions. 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 deployed on Hoke Seamount off the coast of central California has been used to monitor the variability of the California Current. This source is a component of the Naval Postgraduate School's 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 Naval Postgraduate School has proposed to continue these measurements.

Following a successful pilot experiment, 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 four additional transceivers to be deployed by the Applied Physics Laboratory, University of Washington. The goals of KESS are to understand the processes that couple meanders to deep eddies (baroclinic–barotropic coupling), govern the strength of the recirculation gyre, and govern the interannual variations in the upper-ocean heat budget. One goal of KESS is to better establish the climatological relevance of these processes. The acoustic tomography component of KESS is designed to observe and map the circulation and heat content of the interior ocean at mesoscale to 1000-km scales. A combination of tomography, float and satellite altimeter measurements will be used to estimate the heat budgets for the recirculation gyre and the mixed water region.

JAMSTEC plans to deploy a tomographic array for observing the bifurcation region of the North Equatorial Current in the Philippine Sea from 2006 to 2010.

Basin-scale measurements

Acoustic thermometry holds promise of becoming a cost-effective method to make large-scale temperature and heat content 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 directly probe the existence and nature of signals at the lowest wavenumbers. Acoustic tomography is also sensitive to variability almost to the ocean bottom, and thus it can detect changes at depths below those at which 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—

tomography, floats, XBTs, altimetry, etc.—are used. For basin-wide thermometry, the number of receivers can be maximized at minimal cost by using receivers of opportunity, such as Comprehensive Test Ban Treaty (CTBT) hydrophones, or simple acoustic receivers placed on Dynamics of Earth and Ocean Systems (DEOS), GEO, and 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 about US$50 per acoustic transmission per path (see 'Ocean basin array costs' below).

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

The following projects, organized by ocean basin, are occurring or are likely to occur.

The Pacific Basin

The acoustic source deployed on Pioneer Seamount ceased transmissions in late 1998. The second acoustic source located near Kauai, Hawaii, stopped transmissions in fall 1999, and permission is being sought to continue its operation. Provided that the outcome of the environmental review process is favourable, the Kauai acoustic source will transmit for the next 5 years to US SOSUS hydrophone arrays, as well as to a Russian receiver off the coast of Kamchatka. The various time series already obtained at 10 SOSUS receivers during the past few years show that the acoustic data are an accurate measure of the low-frequency, long-wavelength thermal variability. We are therefore looking forward to extending the time series by an additional 5 years. 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, can best be combined for optimal estimation of the ocean state. These measurements will fit naturally into the Pacific Basin Extended Climate Study (PBECS) (Davis et al., 2000; Kessler et al., this volume), which is a component CLIVAR. Other possible acoustic receivers in the north Pacific Ocean, such as those deployed at or near NOAA ocean stations (e.g. MOMMA, PAPA, TSUMAMI) or as part of the proposed 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 northwest monsoon, which, in turn, has major consequences for Asian and Australian agriculture (Barton et al., 2000; Meyers et al., this volume). A strong correlation has been demonstrated 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 is estimated to correspond 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 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 toward deploying an acoustic source off Cocos Island in the Indian Ocean, whose signals would be recorded by CTBT hydrophones, as well as a receiver near Madagascar to be deployed by IFREMER, Brest, and simple inexpensive receivers to be deployed as they become available.

The Atlantic Ocean Basin

The 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 a large (>1 km) depth range), and distribution (not solely confined to the upper layers) of these temperature changes has accrued throughout WOCE. This is shown by the work of Bryden et al. (1996) on 24°N, Read and Gould (1992) and more recently Koltermann et al. (1999) in the subpolar North Atlantic, and Joyce et al. (1999) at 52° and 66°W. These results extend the changes seen at the Bermuda time-series station (Joyce and Robbins, 1996). This analysis has also been extended to the South Atlantic (Dickson et al., 2001).

Evidence for these climate changes, while compelling, is as yet sparse (Levitus et al., 2000). Only using time series 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 circulation. The fact that climate models implicate the North Atlantic in rapid climate change suggests 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 time series of the climate-scale variability in the Atlantic basins.

A prototype acoustic thermometry array was designed in 1994 by a SCOR working group led by Gould (e.g. Fig. 13; 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 IfM, Kiel, and IFREMER, Brest. One such experiment, called OVIDE, is a CLIVAR-related experiment proposed by IFREMER to study the variability in the subpolar gyre on 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 tomography, hydrography, and profiling floats. It will be based on four tomography moorings that will be installed in the Western European Basin for monitoring the variability in the heat content 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 (Johannessen et al., 1995, 1996; Bjorgo et al., 1997). Submarine measurements of sea-ice draft between 1976 and 1997 have also confirmed significant thinning of the ice cap by an average of 40% (Rothrock et al., 1999). In addition, a large decrease in annual mean atmospheric sea level pressure over much of the Arctic has been observed in the past decade. There is evidence from new modelling studies (Proshutinsky and Johnson, 1997; Johnson et al., 1999; Polyakov et al., 1999) and a historical data review (Grotefendt et al., 1998) that major changes occur in the Arctic atmospheric and oceanic circulation on a near-decadal timescale. While these decadal changes could explain some or all of the observed changes, 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 because of the sea ice cover. As the TAP experiment demonstrated, acoustic remote sensing can provide integrated, synoptic, year-round and (with receiver moorings cabled to shore) real-time data on the heat content and vertical temperature structure of the Arctic Ocean. Research is also under way to use acoustic remote sensing for measuring the average sea-ice thickness and roughness, which, when combined with satellite observations of sea-ice extent, may provide estimates of total sea-ice volume.

As described earlier, the first installations of an acoustic thermometry network for the Arctic Ocean were deployed as part of the ACOUS program (Mikhalevsky, 1999). These installations included the 20 Hz acoustic source deployed in the Chukchi Sea between Spitzbergen and Franz Josef Land and the autonomous acoustic receiver and oceanographic mooring in the Lincoln Sea. The Lincoln Sea mooring was recovered in April 2001. A cabled acoustic array is planned for installation in the Beaufort Sea. This array will be cabled to Barrow, Alaska, to a facility that is part of the former Naval Arctic Research Laboratory (NARL). The array will include thermistors, salinity recorders, and current meters as well as a tide gauge and a specially designed near-shore horizontal array for listening to and tracking marine mammals. Bowhead whale monitoring, tracking, and research are integral parts of the planned program for this array system. Finally, a second acoustic source is also planned for installation in the central Arctic. These installations are part of a larger plan to create an extended

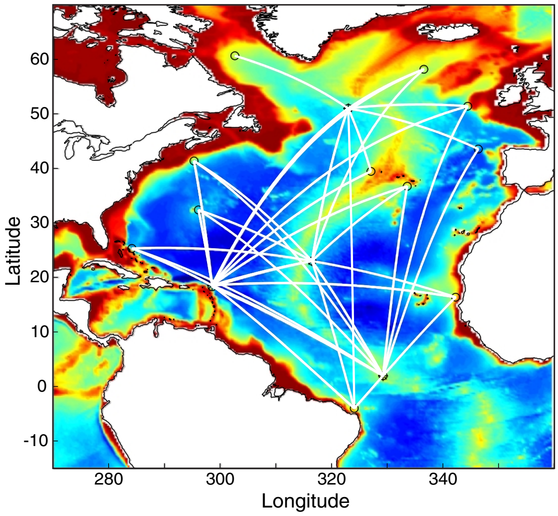

Figure 13. A notional observation network for the North Atlantic that may be realized through international cooperation and support. This array consists of 1 cabled-to-shore acoustic source (near Barbuda) and 3 sources at the nominal locations of DEOS moorings, together with about 10 receivers at SOSUS sites, on the DEOS moorings, and a few dedicated receivers specifically deployed to complete the array. DEOS moorings, in addition to providing 1000 W of power, will give real time data transmittal. Receivers may also be available where there will likely be several tomographic instruments deployed by European organizations in the North Atlantic in the coming decade. A network such as this would complement existing observation systems for ocean climate variability in the North Atlantic.

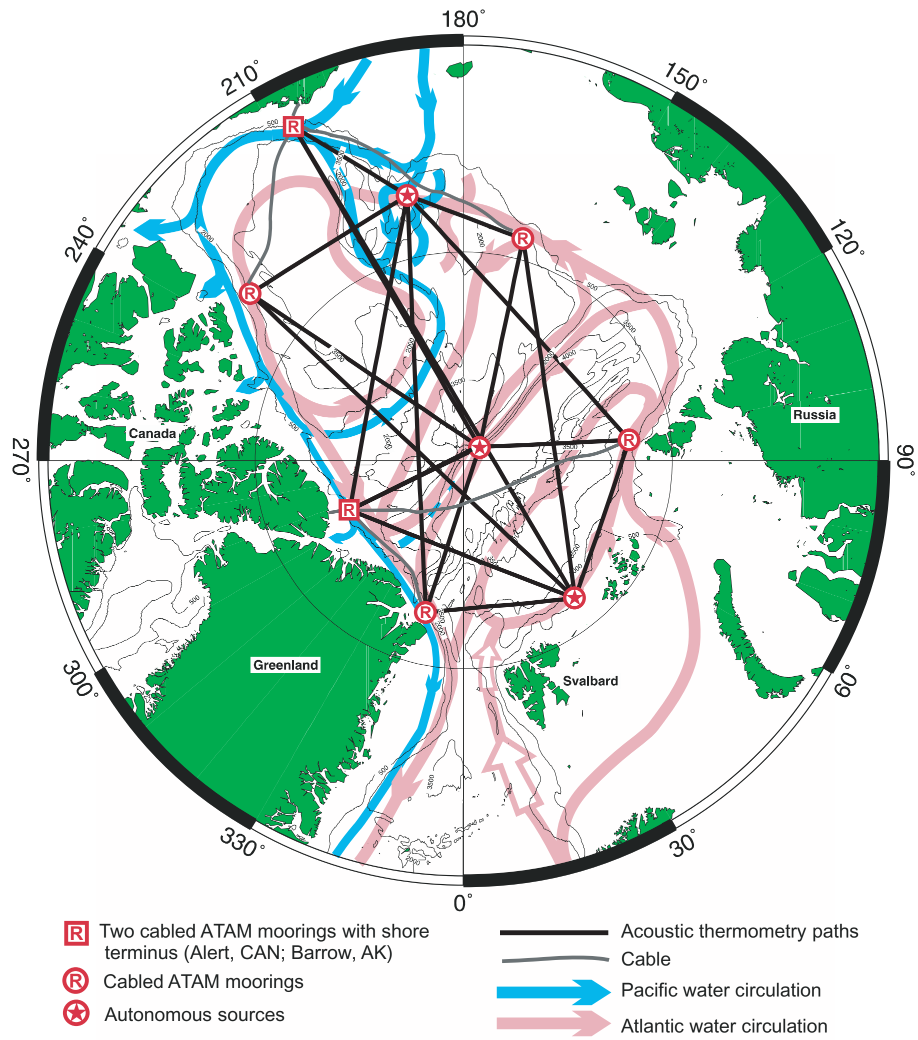

Figure 14. A future notional monitoring grid in the Arctic Ocean exploiting synoptic acoustic remote sensing with *in situ* measurements cabled to shore at Alert, Canada (where an existing slant-drilled sea-shore interface already exists), and Barrow, Alaska. ATAM, acoustic thermometry and autonomous monitoring. The Arctic Ocean circulation is taken from McLaughlin et al. (1996).

monitoring grid in the Arctic Ocean for synoptic, real-time, year-round observations.

The ultimate goal of the ACOUS program is to install and operate an acoustic network such as that depicted in Fig. 14. Plans are currently under review to extend ACOUS and start the first 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 stratification and ice thickness with point measurements. The notional grid depicted in Figure 14 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 sustained observations on these spatial and temporal scales are simply not possible by submarine, icebreaker, or ice-camp methods.

Operational issues

Data analysis

Methods of data reduction and archiving are being developed to reduce the difficulty, cost, and time involved in analysis of the tomographic data. One project targeting these issues is the European OCTOPUS effort (IfM, Kiel/IACM, Heraklion/IFREMER, Brest; see http://www.ifremer.fr/sismer/program/octopus/), which seeks to develop analysis tools, data formats, and a database to facilitate the operational application and community-wide usage of acoustic tomography. Once the initial analysis of new tomography data is completed, it is a simple matter to make the results from subsequent data available in real time, e.g. via the World Wide Web.

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, behaviour, 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 significant, shifts in the distribution of humpback (and possibly sperm) whales during transmission periods, as well as some subtle changes in the behaviour 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 Pacific 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.

RAFOS float tracking

Tomographic sources have been programmed to transmit RAFOS signals. Once tomographic acoustic sources are deployed, they can be used for tracking RAFOS floats or other vessels; i.e. navigation beacons can be provided for public use.

Ocean basin array costs

At some future time, it may become possible to extend the regional arrays to an ocean basin and, eventually, to much of the world ocean. An ocean-wide 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. If we assume present-day costs for a strawman network with 4 sources and 10 receivers, we can estimate the international costs of observing the North Atlantic basin, for example, using acoustics. The strawman array illustrated in Fig. 13 provides good coverage of the North Atlantic basin. Some of the sources can be cabled to shore, while others can be connected to DEOS mid-ocean buoys that will provide power and communications to seafloor junction boxes. Many receivers can be opportunistic or make use of platforms provided by other programs: US Navy SOSUS arrays, Comprehensive Test Ban Treaty arrays, DEOS moorings, PIRATA and other NOAA moorings. We estimate that such an array could be installed in a phased program over a 4-year period with a capital cost of about US$3M per year, assuming average capital and installation costs of US$2.5M for sources and US$150K for receivers. These costs would be shared among international partners. An idealized optimal system would evenly split the total cost between sources and receivers. Capital expenses would decrease dramatically after the installation of the array; phased equipment repair or replacement costs are estimated to be something like US$300K per year. Average annual operational costs are estimated to be US$500K per year, excluding ship time.

It appears to be a common belief that the costs of a basin-wide acoustic network are prohibitively high. A comparison of these costs to the costs of the ARGO program (Argo Science Team, 1998; ARGO, 1999) shows this is not so. Each ARGO float costs approximately US$20K (including float, deployment, and data transmission costs; S. Riser pers. comm., 2000). During the deployment period, the annual capital cost for an acoustic array is therefore roughly comparable to the capital cost of 150 ARGO floats per year. The costs of the acoustic network are not particularly greater than those of other observational approaches. We do not wish to suggest that the acoustic array is a substitute for ARGO; the two systems provide complementary data types.

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

Conclusions

The appropriate roles for acoustic tomography in an ocean observing system for climate appear to be (1) to exploit the unique remote-sensing capabilities for regional programs otherwise difficult to carry out, (2) to be a component of process-oriented programs in regions where integral or large-scale heat content or transport data are desired, and (3) to move toward deployment on basin-to-global scales as the acoustic technology becomes more robust and simplified.

Tomographic methods are now routinely applied for the measurement of temperature and velocity for scales of up to about 1000 km. Regional tomographic arrays have been employed for measuring changes in integrated heat content, for observing regions of active convection in the Greenland, Mediterranean, and Labrador seas, for measuring transports through the Strait of Gibraltar, for observing the mesoscale with high resolution in the Northwest Atlantic, for measuring barotropic currents with high precision, for directly observing oceanic relative vorticity, and for measuring barotropic and baroclinic tidal signals. The remote-sensing capability has proven particularly effective for measurements such as those in the Strait of Gibraltar, where the application of conventional *in situ* methods to measure transport has proven to be difficult. In the context of an ocean observing system for climate, the niches for regional-scale acoustic remote-sensing methods appear to be (1) in the measurement of volume transports and heat fluxes through straits and passages, such as the Strait of Gibraltar and the Fram Strait, (2) in the mapping of thermal and current fields in dynamically important boundary-current regions with complicated, intense currents, (3) in the monitoring of convection variability in regions important to the global thermohaline circulation, such as the Labrador Sea, (4) in the measurement of changes in the temperature of deep water masses on long sections, and (5) in the detection of very weak, but large-scale currents and relative vorticity.

The application of tomographic methods to measure temperature on basin-scales has been shown to be feasible over ranges of at least 5000 km. Basin-scale tomographic arrays have been employed for measuring large-scale changes in temperature and heat content in the North Pacific, Mediterranean and Arctic oceans. In the context of an ocean observing system for climate, the role for tomographic methods on these scales is in the measurement of the variability of range- and depth-averaged temperature and heat content in the world's ocean basins on timescales ranging from seasonal to annual and longer. Levitus et al. (2000) have recently described the variability over the past few decades of depth-integrated heat content of the world's ocean basins, derived from historical hydrographic data. Because of the limitations in sampling, the time series of global-average heat content were calculated using running 5-year composites of the historical observations of temperature, and the values of heat content derived this way had uncertainties of perhaps 20%. An acoustic array, such as that in the North Atlantic (Fig. 13), would provide a basin-averaged measurement of depth-integrated heat content at one-week intervals, with an uncertainty of perhaps a few per cent. The trans-basin acoustic measurements offer a signal-to-noise capability for observing ocean climate variability that is not readily attainable by an ensemble of point measurements. The ability of acoustic remote-sensing methods to provide rapid and repeated sampling of large areas makes them appropriate for monitoring of ocean regions where rapid changes are thought to be occurring, such as the North Atlantic and the Arctic. Tomographic methods are particularly suitable for measurement of the dramatic changes occurring in the Arctic, where the ice cover makes the application of other methods difficult or impossible.

At this time, greater coverage of the world's oceans by acoustic tomography can be implemented at an annual cost that is no greater than other observational approaches. The major costs of tomography are the initial capital costs of the instrumentation and its installation. Efforts are currently under way to reduce the costs of sources and receivers. Once the instruments have been installed, however, the operational costs to make continuing measurements are low. The amortized cost of the technique is therefore attractive, even using present-day source and receiver technology.

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Question and Answer Session

McKweon: Considering the large spatial coverage, is there any possibility in the future for changing the spacing or the pulsing of the sensors to improve the horizontal resolution for improving the estimate of heat content, etc.?

Send: These sensors work in the pulse mode. It's a coded signal that looks like a pulse mode. The signals that are transmitted are several minutes long, but after signal processing the pulse may appear to be only 10 msec wide. If you have a very dense network you can do horizontal inversions. The sparse networks now being used have limited horizontal resolving power. The only way to improve the horizontal resolution is to improve the density of sensors in the array or merge the acoustic array with other types of measurements or model/data assimilation efforts.

Johannesssen: Are there any plans to instrument other straits, besides the Mediterranean at Gilbraltar, for example the Denmark or Fram straits for long-term monitoring?

Send: As I mentioned during my talk, not all straits are suitable for these types of measurements. Once you get acoustic interaction with the bottom, things become more complicated. Spurious effects can occur such as shallow water acoustic propagation, for example. Also when the sections become so long that the multi-path go up and down too many times, it becomes difficult to separate the upper layer from the lower layer. It has to be evaluated on a case by case basis. I know that there are groups evaluating the feasibility of applying these techniques to the Fram Strait. One has to do careful modelling studies before conclusions can be reached about the application of acoustic techniques to straits.