ACOUSTIC REMOTE SENSING OF THE NORTH PACIFIC ON GYRE AND REGIONAL SCALES

B. DUSHAW
Applied Physics Laboratory,
University of Washington, Seattle, WA, USA
e-mail: dushaw@apl.washington.edu

P. WORCESTER
Scripps Institution of Oceanography,
University of California, San Diego, CA, USA
e-mail: pworcester@ucsd.edu

Abstract - Since it was first proposed in the late 1970's (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; these measurements have the accuracy and precision required for large-scale ocean climate observation.

On a regional scale, tomography has been used for observing regions of active convection, for measuring changes in integrated heat content, for observing the mesoscale with high resolution, for measuring barotropic ocean 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 and in regions such as the Strait of Gibraltar, where conventional *in situ* methods may fail.

As the community moves into an era of global-scale observations, the highest priorities for these acoustic techniques appear to be (1) to exploit the unique remote sensing capabilities for regional programs otherwise difficult to carry out, and (2) to move toward deployment on basin to global scales as the acoustic technology becomes more robust and simplified. The transbasin acoustic measurements offer a signal-to-noise capability for ocean climate variability that is not readily attainable by an ensemble of point measurements.

A number of tomographic efforts are currently planned or contemplated in the North Pacific Ocean. The goals range from the measurement of gyre-scale temperature (heat content) variability to the study of the Kuroshio Extension.

1. INTRODUCTION

Various potential elements of a future ocean observing system for studying climate are currently being proposed and developed for understanding, modeling and predicting the ocean and climate system. Long-range acoustic remote sensing of the ocean interior (tomography or thermometry) can provide horizontally integrated synoptic 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., depth-integrated density), while tomography senses the interior (i.e., horizontally-integrated sound speed*). 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 the floats can be problematic. Eulerian observations provide excellent 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 relevant to CLIVAR in the Pacific, including basin-scale observations of temperature (heat content) and regional, process-oriented studies.

2. BASIN-SCALE OBSERVATIONS

Basin-scale 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. These data are also sensitive to variability almost to the ocean bottom, and thus can detect changes below the depths 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, ARGO, XBTs, TOPEX, 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 DEOS (Dynamics of Earth and Ocean Systems), 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 around $50 per acoustic transmission (see **Costs** below); the per transmission cost declines with the number of receivers that are available.

The Acoustic Thermometry of Ocean Climate (ATOC) project. ATOC (Figure 1a) has been using acoustic travel time data obtained from 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 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 Fall 1999. 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. 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 who have detected the Kauai Source transmissions using a receiver near Kamchatka. This Russian group is interested in continuing to receive the transmissions from the Kauai acoustic source.

---

* With the bottom-mounted instruments presently employed in the North Pacific the acoustics can only measure the depth-average sound speed. With instruments deployed near the sound channel axis, however, 2–3 degrees of freedom in the vertical can be resolved. The available vertical resolution varies from region to region. In most cases, the measured sound speed can be converted to a measurement of temperature with very little error, because sound speed is only weakly influenced by salinity.

The data 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. When acoustic travel time data obtained over 2–4 days of transmissions are used, the estimated uncertainties in the range- and depth-averaged temperature measurements are about 10 m°C. The time series obtained using the California acoustic source showed a clear annual cycle whose amplitude was similar to that derived from climatology (World Ocean Atlas 94: Levitus et al. 1994; Levitus and Boyer 1994) and from XBTs of opportunity, yet smaller than the amplitude of the annual cycle derived from TOPEX/POSEIDON altimetry (The ATOC Consortium 1998). The time series obtained using the Kauai acoustic source is of similar quality in its ability to measure the thermal variability, but it shows greater variability at 100-day timescales (Figure 2, and Dushaw et al. 2000). 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 study patterns of climate variability such as the Pacific Decadal Oscillation (PDO) (Latif and Barnett 1994).

In accordance with marine mammal protocols, the acoustic source deployed on Pioneer Seamount ceased transmissions in late 1998 and has now been decommissioned. 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 favorable, the Kauai acoustic source will transmit for the next 5 years to U.S. SOSUS hydrophone arrays, as well as to other potential receivers. 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. The goals of these extended 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), which is a component of 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; NRC 2000), would greatly enhance the spatial coverage of the thermometry array in an opportunistic way (e.g., Figure 1b).

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 significant, 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 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 Kauai source provides one of the few controlled sound sources available for such longer-term studies.

Costs. It appears to be a common belief that the costs of basin-wide acoustic networks are prohibitively high. A comparison of these costs to the costs of the ARGO program (ARGO 1998, 1999) shows this is not so. Each ARGO float costs roughly $20K (including float, deployment, and data transmission costs; S. Riser personal communication 2000). Should an extended Pacific Basin acoustic array be developed over a 5-year period, the annual capital cost for it would be roughly comparable to the capital cost of a few hundred ARGO floats. The costs of the acoustic network are not particularly greater than 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 (e.g., Figure 2).

Summary. A timeseries of sampling of the Pacific ocean by acoustic tomography has begun with the installation of the Kauai acoustic source. Measurements using this source are funded by ONR to continue for the next five years. Should these data be shown to be an important contribution to resolving the climate variability of the North Pacific Basin, additional basin-wide sampling can be implemented at a 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.

Duration: Start 2001, acoustic transmission for five years.
Location: North Pacific Ocean.
Sample Rates: Every four hours at four day intervals.
Parameters Measured: 1000–5000-km range and depth averages of ocean temperature (heat content) to high accuracy and precision.
Contact Person: Peter Worcester (pworcester@ucsd.edu) and Brian Dushaw (dushaw@apl.washington.edu).

3. REGIONAL, PROCESS-ORIENTED STUDIES

Recently Completed Measurement Programs.

The Central Equatorial Pacific Tomography Experiment (CEPTE). CEPTE (Figure 3) is a program conducted by JAMSTEC (Iwao Nakano, Humio Mitsudera, Gang Yuan) to observe the very weak meridional currents of the SubTropical Cell (STC) (Gu and Philander 1997). Analysis of this data is underway (G. Yuan).

Duration: Two years, completion in Fall 2000.
Location: About 180° East and 2–14° North.
Sample Rates: Every few hours for a day, and every few days.
Parameters Measured: 500–1000-km averages of ocean temperature and ocean currents to high accuracy and precision.
Contact Persons: Iwao Nakano (nakanoi@mstip5.jamstec.go.jp) and Humio Mitsudera (humiom@soest.hawaii.edu).

Planned Measurement Programs.

The Hawaiian Ocean Mixing Experiment (HOME) Farfield Program. HOME is a program funded by NSF. The Farfield component of HOME (Figure 3) is to observe internal and external tides near Hawaii. Two separate tomographic arrays of 500-km scale are to be deployed on either side of the Hawaiian Ridge for about six months each beginning in April 2001. This is a short-term, process oriented experiment, but efforts will be made to record the signals at SOSUS receivers in the North Pacific to obtain larger-scale temperature data.

Duration: April – September 2001, October 2001 – May 2002.

Locations: North of French Frigate Shoals, and South of Kauai.
Sample Rates: Every 3 hours.
Parameters Measured: 500-km averages of ocean temperature and ocean currents to high accuracy and precision.
Contact Persons: Brian Dushaw (dushaw@apl.washington.edu) and Peter Worcester (pworcester@ucsd.edu).

The Kuroshio Extension System Study (KESS) Tomographic Array. JAMSTEC is funded to deploy 8 reciprocal tomography moorings in the Kuroshio Extension (centered on 35N, 150E; Figure 3) for four years to study the climatological relevance of the Kuroshio Extension/mode water variability. A U. S. component designed to build upon the Japanese efforts was proposed to NSF (submitted August 15, 2000); this additional component has been declined by NSF, but portions of it may be resubmitted. Contacts for the Japanese KESS project are Iwao Nakano (JAMSTEC) and Humio Mitsudera (IPRC). The complete U. S. KESS proposal had numerous P.I.s from several institutions.

Duration: Summer 2001 – Summer 2005.
Location: Kuroshio Extension.
Sample Rates: Every three hours on every fourth day (?).
Parameters Measured: 500–1000-km averages of ocean temperature and ocean currents to high accuracy and precision.
Contact Persons: Iwao Nakano (nakanoi@mstip5.jamstec.go.jp) and Humio Mitsudera (humiom@soest.hawaii.edu).

Contemplated Measurement Programs.

The North Equatorial Current Bifurcation Region Experiment. It is our understanding that JAMSTEC plans to make tomographic observations of the North Equatorial Current bifurcation region in the Philippine Sea (Figure 3), after the conclusion of the Kuroshio Extension work, starting in about 2006.

Duration: 2006 (?)
Location: North Equatorial Current Bifurcation Region, Philippine Sea.
Sample Rates: ?
Parameters Measured: 500–1000-km averages of ocean temperature and ocean currents to high accuracy and precision.
Contact Persons: Iwao Nakano (nakanoi@mstip5.jamstec.go.jp) and Humio Mitsudera (humiom@soest.hawaii.edu).

REFERENCES

ARGO: A Global Array of Profiling Floats: To Understand and Forecast Climate, Woods Hole Oceanographic Institution, 12 pp., 1999. Also: http://www.argo.ucsd.edu

ARGO Science Team, On the Design and Implementation of ARGO: A Global Array of Profiling Floats. International CLIVAR Project Office Report No. 21, GODAE Report No. 5, 32 pp., 1998. Also: http://www.argo.ucsd.edu

The ATOC Consortium, Ocean climate change: Comparison of acoustic tomography, satellite altimetry, and modeling, *Science,* **281,** 1327–1332, 1998.

DEOS, http://victory.ucsd.edu/whitepaper/oceanus.html,
http://vertigo.rsmas.miami.edu/deos.html, or
http://victory.ucsd.edu/whitepaper/front.html, 1999.

Dushaw, B. D., G. Bold, C.-S. Chiu, J. Colosi, B. Cornuelle, Y. Desaubies, M. Dzieciuch, A. Forbes, F. Gaillard, J. Gould, B. Howe, M. Lawrence, J. Lynch, D. Menemenlis, J. Mercer, P. Mikhalevsky, W. Munk, I. Nakano, F. Schott, U. Send, R. Spindel, T. Terre, P. Worcester, and C. Wunsch, 2000. Observing the ocean in the 2000's: A strategy for the role of acoustic tomography in ocean climate observation. Proceedings of the 1999 conference on Ocean Observation (OceanObs'99), St. Raphael, France, 25 pp., submitted. (This document is available on the web at: http://staff.washington.edu/dushaw/TomographyJune2K.pdf)

Dushaw, B. D., B. M. Howe, J. A. Mercer, R. C. Spindel, and the ATOC Group, Multimegameter-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature, *IEEE J. Oceanic Eng.,* **24,** 202–214, 1999.

Dushaw, B. D., Inversion of multimegameter-range acoustic data for ocean temperature, *IEEE J. Oceanic Eng.,* **24,** 215–223, 1999.

Gu, D., and S. G. Philander, Interdecadal climate fluctuations that dependupon changes between the tropics and extratropics, *Science,* **275,** 805–807, 1997.

Latif, M., and T. P. Barnett, Causes of decadal climate variability over the North Pacific and North America, *Science,* **266,** 634–637, 1994.

Levitus, S., R. Burgett, and T. P. Boyer, *World Ocean Atlas 1994, Vol. 3: Salinity*. NOAA Atlas NESDIS 3, U.S. Government Printing Office, Washington, DC, 99 pp., 1994.

Levitus, S., and T. P. Boyer, *World Ocean Atlas 1994, Vol. 4: Temperature*. NOAA Atlas NESDIS 4, U.S. Government Printing Office, Washington, DC, 117 pp., 1994.

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

Munk, W., and C. Wunsch, Ocean acoustic tomography: a scheme for large scale monitoring, *Deep-Sea Res.,* **26,** 123–161, 1979.

Munk, W., and C. Wunsch, Observing the ocean in the 1990's, *Phil. Trans. Roy. Soc.,* **A307,** 439–64, 1982.

National Research Council (NRC), *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, National Academy Press, Washington D.C., 2000.

Tindle, C. T., and G. E. J. [Bold], ATOC and Other Acoustic Thermometry Observations in New Zealand, *Marine Tech. Soc. J.,* **33,** 55–60, 1999.

Worcester, P. F., B. D. Cornuelle, M. A. Dzieciuch, W. H. Munk, B. M. Howe, J. A. Mercer, R. C. Spindel, J. A. Colosi, K. Metzger, T. G. Birdsall, and A. B. Baggeroer, "A test of basin-scale acoustic thermometry using a large-aperture vertical array at 3250-km range in the eastern North Pacific Ocean," *J. Acoust. Soc. Am.*, **105**, 3185–3201, 1999.

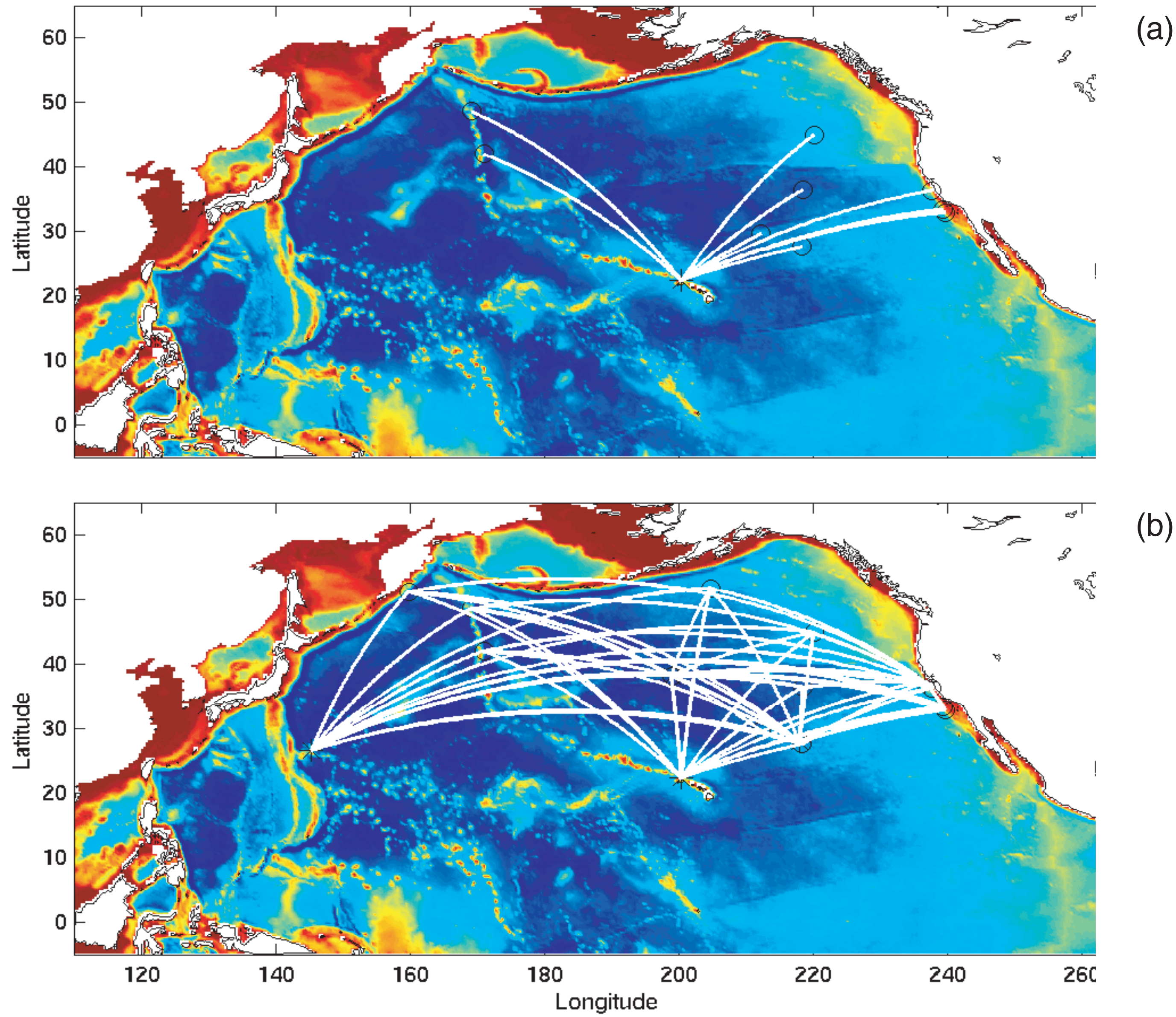

Figure 1. (a) Acoustic data will be obtained on this minimal acoustic array for the next five years. The acoustic receivers are U.S. Navy SOSUS receivers. The first ATOC acoustic source that was deployed near the California coast has been removed. (b) Fairly dense acoustic sampling of the North Pacific can be obtained with the addition of the following acoustic sources: a replacement source off the coast of California, a source near Japan, an "H2O" acoustic source midway between Hawaii and California, and an acoustic source that might be attached to a DEOS mooring in the central North Pacific. Simple receivers mounted on moorings-of-opportunity can further increase the acoustic sampling at little additional cost.

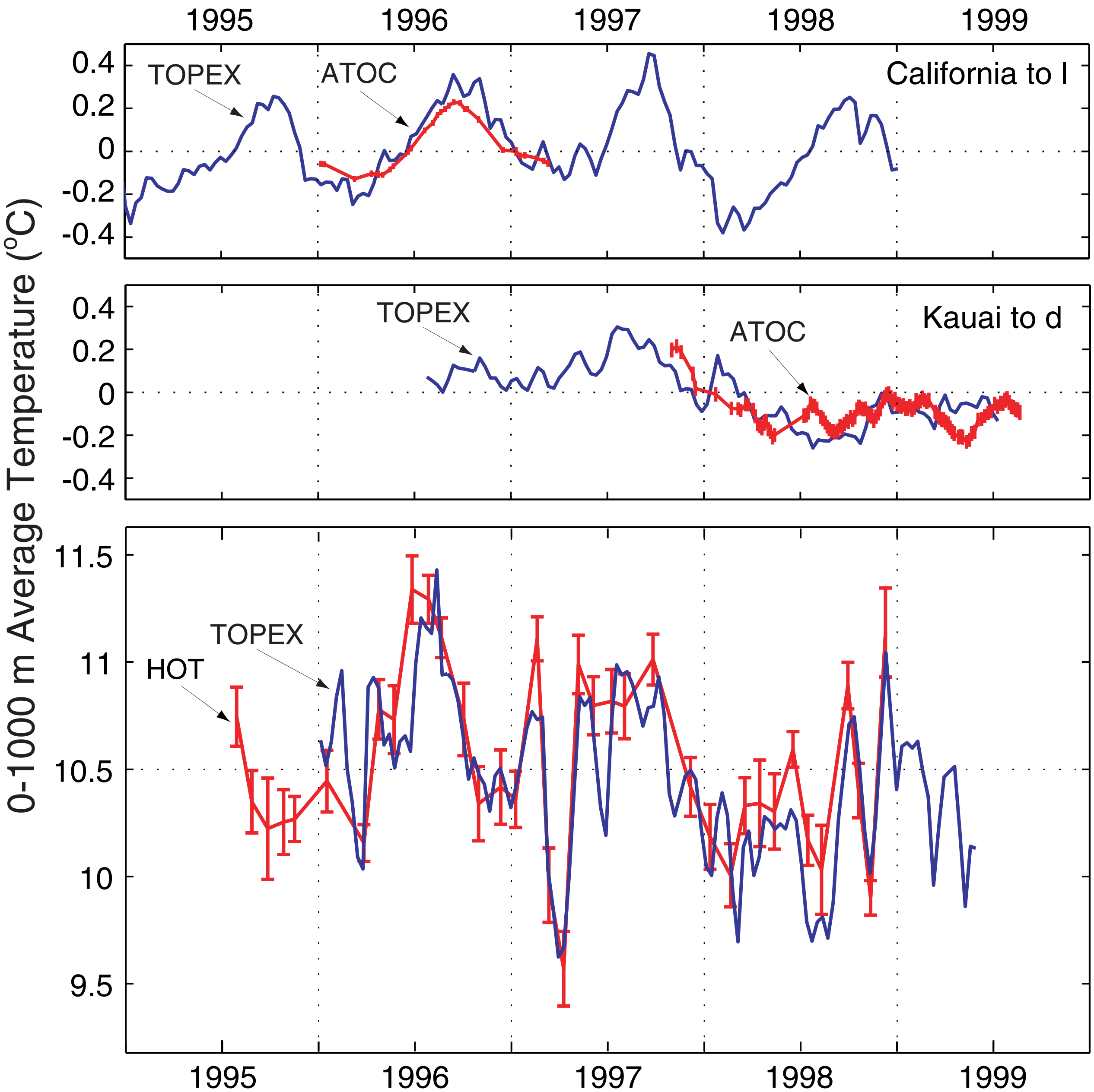

Figure 2. A comparison of line-integral, altimetry and point data. (a) Acoustic thermometry (red) compared to TOPEX/POSEIDON altimetry (blue) for two acoustic paths as indicated (See Figure 1; receiver "d" is located near the California coast, receiver "k" is located in the central North Pacific). The error bars on the acoustical results are small. The annual cycle was removed from the TOPEX/POSEIDON data for the acoustic path from Kauai to d; the acoustic data on this path sample below the seasonally varying surface layer so that the annual cycle is not observed. (b) 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.* 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. [Modified from Dushaw et al. 2000.]

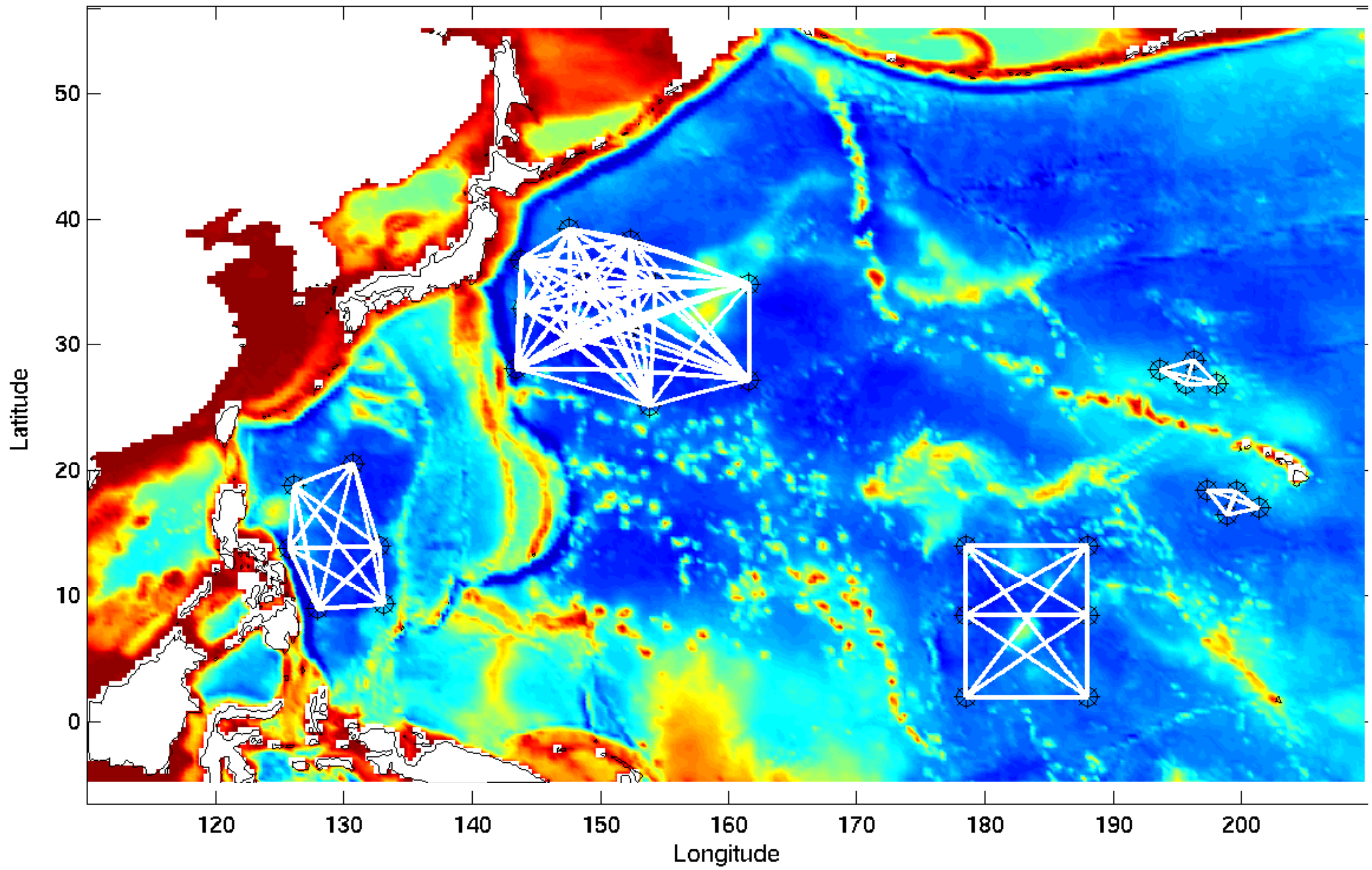

Figure 3. Regional acoustic tomography arrays in the North Pacific: The Central Equatorial Pacific Tomography Experiment (CEPTE) just north of the equator has recently finished. The Hawaiian Ocean Mixing Experiment (HOME) tomography arrays will be deployed this year. Kuroshio Extension System Study (KESS) tomography array is to be deployed this summer with a duration about five years, although the details of this array are not yet firm. The North Equatorial Current Bifurcation Region Experiment in the Philippine Sea may begin in 2006.