CLIVAR
Exchanges
- Selected Research Papers -

Acoustic thermometry in the North Pacific

Brian D. Dushaw
Applied Physics Laboratory
University of Washington, Seattle, WA, USA
corresponding e-mail: dushaw@apl.washington.edu

1. Introduction

Ocean acoustic tomography (Munk and Wunsch 1979, 1982; Munk et al., 1995) is a multipurpose remote sensing measurement technique that has been employed in a wide variety of physical settings. Basin-wide and regional tomography were accepted as part of the ocean observing system by the OCEANOBS'99 conference (Koblinsky and Smith 2000; Dushaw et al. 2001). In the context of long-term oceanic climate change, acoustic tomography naturally integrates over the mesoscale and other high-wavenumber noise. Tomographic measurements can be made without risk of calibration drift, and they are naturally complementary to other techniques (Dushaw et al., 2001).

Measurements of large-scale temperature by long-range acoustics are now being obtained in the central North Pacific ocean as part of the North Pacific Acoustic Laboratory program (NPAL) and as a continuation of the Acoustic Thermometry of Ocean Climate program (The ATOC Consortium, 1998; Dushaw and Worcester 2001). ATOC began as an ambitious project in the early ,90's, but became embroiled with marine mammal permitting issues. These legal issues prevented acquisition of regular acoustic transmissions until now. The time series described here began in early 1997 as part of ATOC, but was intermittent during 1997-1998 and halted after that because of permitting issues. The acoustic travel time data obtained by long-range acoustic transmissions from an acoustic source near California (the Pioneer source, since removed in accord with permitting protocols), and the inversion of those data to obtain a measurement of temperature, have been described by Dushaw et al. (1999), Dushaw (1999), and Worcester et al. (1999).

In January 2002, the acoustic transmissions resumed using a single acoustic source located north of Kauai and several receivers scattered over the North Pacific basin (Fig. 1). The travel times to the distant receivers of the acoustic signals along identified ray paths are a measure of temperature averaged over the ocean section sampled by those ray paths. Regular acoustic transmissions are to be made on every fourth day, and 6 transmissions are made on that day. The travel time data on each day are averaged to reduce the noise caused by internal waves, tides, etc.; this is the only filtering that has been applied to the time series. The time series described here may be viewed at http://faculty.washington.edu/ dushaw/atoc/. It is our intention to update these time series roughly monthly as new data are acquired, and we will make these data available on a request basis.

2. Acoustic thermometry and the JPL ECCO model

Data assimilation has always been an central aspect of the line-integrating tomography data, and global ocean models have only recently become realistic enough to be able to model and assimilate this data type. The analysis of path integral data is made simpler by ocean state estimation methods, using travel times as integral constraints on the model variability. If the data estimated by the model do not match the observations, then the ocean model state is adjusted to bring the model into better agreement. In the case of the acoustics, the different ray paths have different sensitivities to the sur-

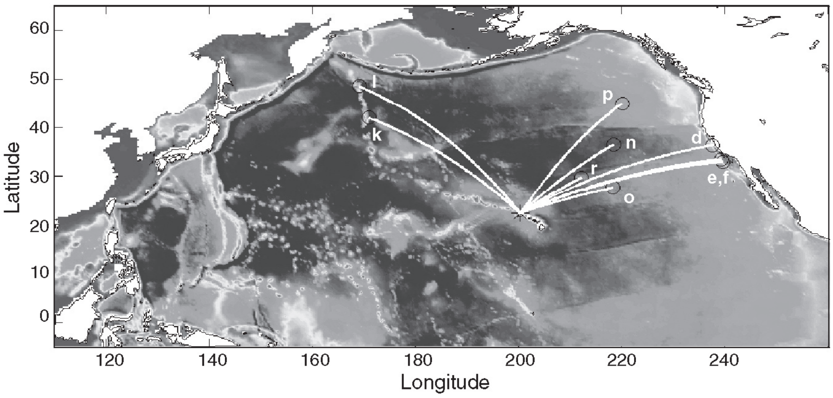

Fig. 1.: The paths from the Kauai acoustic source to various SOSUS (Sound Underwater Surveillance System) receivers in the North Pacific for which resolved ray arrivals have been obtained. An acoustic source that was deployed near California (the Pioneer source, near site d in the figure) was removed in 1999 in accordance with permitting protocols.

[1] Published in Exchanges No. 26, March 2003

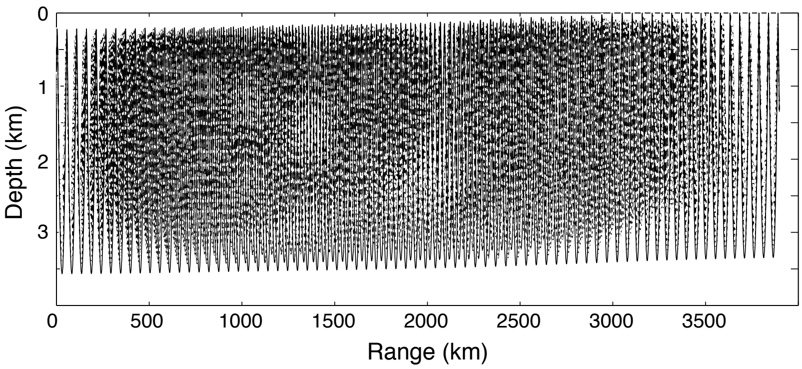

Fig. 2.: Ray paths associated with the resolved ray arrivals for the acoustic path from the Kauai source to receiver d near California. Where the path travels through warm tropical waters near Hawaii, the rays do not sample to the ocean's surface.

face and to the deep ocean, and the estimation can exploit this to obtain vertical information from a set of rays. State estimation by data assimilation also serves to best combine disparate data types, and those data types can then be evaluated for their relative contributions to reducing the uncertainty of the model solution. In addition to the obvious measurement of large-scale heat content over the next few years, one goal of this project is to use the data assimilation to test the degree of complementarity of the acoustic and float (ARGO, 1998) data types. It is not obvious that these two data types are redundant as some have suggested. The ECCO consortium (Estimating the Circulation and Climate of the Ocean; Stammer and Chassignet, 2000, Stammer et al., 2001), including groups from the Jet Propulsion Laboratory (JPL), the Massachussetts Institute of Technology, (MIT) and the Scripps Institution of Oceanography, is proceeding to incorporate the acoustic data type in its global ocean models (Stammer, 2002, personal communication).

A preliminary description of the results of assimilation of the thermometry data into an ocean model (The ATOC Consortium, 1998) had considerable uncertainty in the conversion of the sub-surface temperature measurements into a measurement of sea-surface height for comparison to the TOPEX/POSEIDON data. As a result, sea-surface height variations estimated from the acoustics were about half as large as those measured by altimetry. This issue was at the root of the exchange of Kelly et al. (1999), and the reply by the ATOC consortium; acoustic thermometry is not a measure of sea-surface height. Fig. 3 shows the comparison of some of the data used in the 1998 paper (Pioneer to receiver k) with the ECCO model predictions. The primary result of the 1998 paper was to show that all the pieces were in place to bring the acoustic data into global ocean models by data assimilation.

The ocean state estimate used here is implemented by the ECCO group at JPL. The estimate is based on integration of the MIT General Circulation Model in a global configuration that spans 75°S to 75°N, with latitudinal grid spacing of 1 degree. The model has 46-levels, 15 of which are within the top 150m at 10m resolution. The model assimilates a variety of satellite and in-situ data and data products, including TOPEX/POSEIDON, WOCE hydrography, XBT sections, etc. A description of this state estimate and the complete fields are available at http://eyre.jpl.nasa.gov/external/.

The data obtained using the Kauai acoustic source are similar to those using the Pioneer source, but interpretation of a time series of temperature that might be derived from the acoustic data is complicated by the ray path sampling. In tropical regions, the ray sampling is not completely to the ocean surface because of the warm near-surface temperatures. To the north of Hawaii, and towards the region of the California Current, the rays become surface reflecting where the near-surface water temperatures are cooler (e.g., Fig. 2). A variable that offers a more appropriate comparison for the acoustics is travel time, the quantity that is actually measured.

As a first step towards incorporating travel times into the ECCO model cost function, ECCO model output was used to calculate travel times for several source-receiver pairs (Fig. 3). The time-mean state of the model proved to have unphysical sound speed characteristics, so it was replaced with that of the 1998 World Ocean Atlas (http://www.nodc.noaa.gov/OC5/readme.html). Technically, this required correction may be viewed as a first adjustment to the ocean model required by the acoustics. The amplitude of the annual cycle in travel time for an acoustic path from Pioneer to receiver k compares quite well with the ECCO model, although the model appears to have an unphysical trend in temperature. The rays for this path are entirely surface reflecting. Note that the data and the model also show approximately the same change in the dispersal of the ray travel times in response to the seasonal cycle of temperature in the top 70 m or so of the ocean. In the central Pacific, a slight warming over the past five years is observed acoustically (Kauai to receiver k) and also in the model, while in the eastern Pacific cooling is observed acoustically (Kauai to receiver f) and by the model.

Hawaiian waters have significant mesoscale variability (particularly thermal), which is the origin of the O(30-day) variability in the acoustic time series; the mesoscale is not yet resolved by the ECCO model. The mesoscale variability of the California Current has a neg-

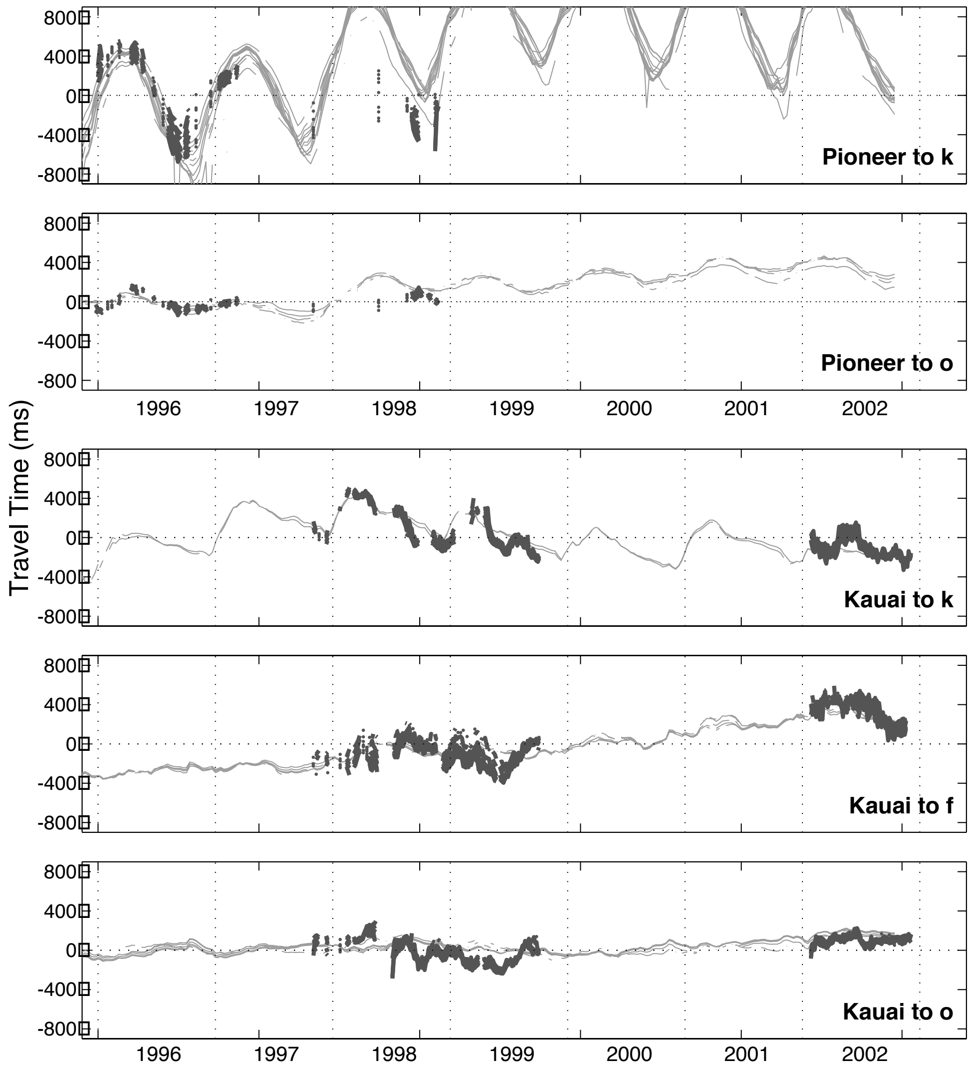

Fig. 3.: Travel time variations for the ATOC sources at Pioneer Seamount and Kauai transmitting to receivers k, o, and f (dark lines, see the ATOC map for receiver locations), compared with the travel times calculated from the ECCO state estimates (light lines). Each line represents a different ray path, which samples the ocean in a different way; typically 6-12 ray arrivals are resolved on each path.

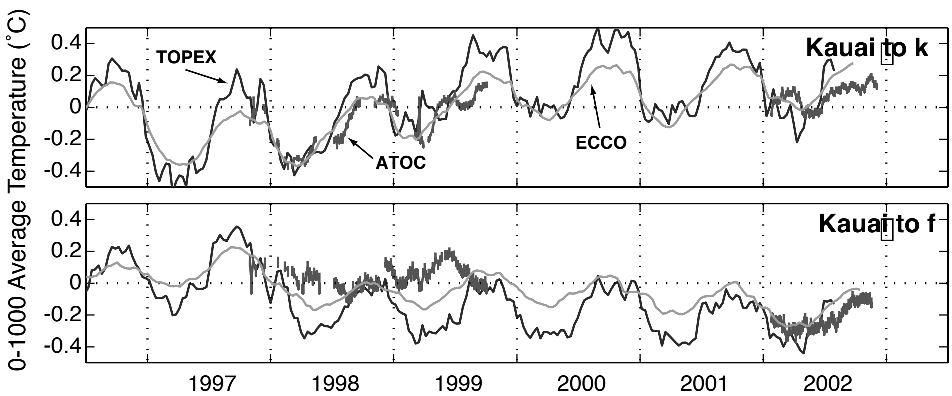

Fig. 4.: Time series of temperature, averaged over the range of the indicated acoustic path and over the upper 1000 m, derived from acoustic thermometry, TOPEX/POSEIDON altimetry and the ECCO ocean model. The ray sampling on the path from Kauai to f is not completely to the ocean surface; cf., Fig. 3. To convert the altimetry to a measure of temperature, steric expansion was assumed to occur only in the top 100 m of ocean, and a conversion factor of 48 C/m was used.

ligible thermal content.

3. Temperature

For the data obtained by the Kauai acoustic source, most of the comparisons of upper-ocean temperature (e.g., 0-1000 m) derived from the acoustics do not compare well to either TOPEX/POSEIDON or the ECCO model because of the ray path sampling. One path where a reasonable comparision might be made is the path from the Kauai to receiver k (Fig. 4), because on that 4-Mm path the rays become surface reflecting after about 1 Mm as they travel northwestward into subtropical regions. On this path, the acoustical estimates of temperature are similar to equivalent estimates from the ECCO model in terms of the annual cycle and the trend over the 5-year record length. The second example, Kauai to receiver f, shows a similar comparison for a case when the ray sampling is not completely to the surface. In this case, the time series are quite different. The formal uncertainties are mainly caused by resolution issues, i.e., the lack of sampling by the acoustic ray paths of parts of the upper ocean, rather than by data noise.

Salinity changes have only a mild effect on sound speed (1 ppt salinity roughly corresponds to 1 m/s sound speed, while 1°C temperature roughly corresponds to 4 m/s sound speed), and there is no evidence that realistic mesoscale variability has a significant effect on the ray paths and the linearity of the inversions of the travel time data to derive temperature.

The ECCO model temperatures and those derived from TOPEX/POSEIDON altimetry also significantly disagree in Figure 4, suggesting either that the model has underestimated the temperature, or that sea-surface height includes more contributions to its variations than just simple steric expansion.

4. Discussion

ARGO data are just now becoming available in the North Pacific for comparison to the acoustic time series. This comparison will be an important milestone for this project, since it will determine the extent to which the float and acoustic data are complementary. While it is true that the acoustic approach does not measure salinity and has other limitations, it is also true that the hydrographic or float approach has difficulty measuring large-scale temperature because of the small-scale noise prevalent in the ocean. Two recent examples of observations of large-scale changes in ocean temperatures by hydrography are provided by Levitus et al. (2000) and Gille (2001, 2002). While these measurements and the acoustical measurements of line-average temperature are different things, a comparison of the various numbers involved demonstrates the good signal-to-noise capabilities of the acoustical approach. Levitus examined the temperature variations in the ocean basins over the past 50 years using all available historical hydrographic data. Time series of temperature variations in these ocean basins were obtained by averaging temperature over the entire ocean basins, and then calculating a 5-year running mean of the timeseries. The error bars in 0-1000 m average temperature obtained for the North Pacific were around 0.01°C, comparable to the formal uncertainty in temperature derived acoustically on a single day on a single acoustic path. Gille (2001, 2002) compared temperatures observed in the Southern Ocean by ALACE floats parked between 700 and 1100 m depth to climatological temperatures derived using historical hydrographic data. The average temperatures from ALACE floats during the decade of the 1990's were found to be 0.17±0.06°C warmer than the historical temperatures. Over the 5 years that the acoustic data has been obtained, we find (by eye from Fig. 4) that the eastern Pacific between Hawaii and California (path from Kauai to receiver f) has cooled by about 0.2°C, while the central Pacific (path from Kauai to receiver k) has warmed by about 0.2°C, with uncertainties determined mainly by the level of mesoscale variability around Hawaii.

We look forward to seeing how the acoustic timeseries evolve over the next several years, and to a quantitative determination of the relative merits of hydrographic and acoustic data as ocean model constraints.

Acknowledgements

We would like to thank the U.S. Navy for making available the remarkable SOSUS facilities, and for continued co-operation as we use these instruments. We would also like to thank J. Bolstad, L. Buck, D. Reddaway, and J. Wigton at the Applied Physics Laboratory for continuing to acquire and process the acoustic data in a timely manner. The work described in this paper was originally described in a poster (Dushaw et al., 2002) presented at the 2002 "WOCE and Beyond" Conference (San Antonio, TX) with coauthors: B. Cornuelle, B. Howe, D. Menemenlis, J. Mercer, W. Munk, R. Spindel, P. Worcester, and the NPAL Group (http://npal.ucsd.edu/). This work is supported by the Office of Naval Research.

References

ARGO Science Team, 1998: 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. Also: http://www.argo.ucsd.edu/

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

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

Dushaw, B., and P. Worcester, 2001: Acoustic remote sensing of the North Pacific on gyre and regional scales. Pacific CLIVAR International Pacific Implementation Workshop, International Pacific Research Center at the University of Hawaii, Honolulu, Hawaii, February 5-8, 2001, 9 pp.

Dushaw, B.D., B.M. Howe, J.A. Mercer, P.F. Worcester, and the NPAL Group, 2002: Acoustic thermometry time series in the North Pacific, WOCE and Beyond Conference, November 2002, San Antonio, Texas.

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

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, 2001: Observing the ocean in the 2000's: A strategy for the role of acoustic tomography in ocean climate observation. In: Koblinsky, C.J., and N.R. Smith (Eds.): *Observing the Oceans in the 21st Century*. GODAE Project Office and Bureau of Meteorology, Melbourne, 391-418. (http://faculty.washington.edu/dushaw/epubs/OceanObs99Paper.pdf).

Gille, S., 2001: Southern Ocean ALACE float temperatures are warmer than historic temperatures. *CLIVAR Exchanges*, **6 (4)**, 22.

Gille, S., 2002: Warming of the Southern Ocean since the 1950's. *Science*, **295** (5558), 1275.

Kelly, K., F. Vivier, and L. Thompson, 1999: Heat content changes in the Pacific Ocean. *Science*, **284**, 1735.

Koblinsky, C., and N. Smith (Eds.), 2000: Observing the Oceans in the 21st Century. GODAE Project Office and Bureau of Meteorology, Melbourne.

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

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

Munk, W., and C. Wunsch, 1982: Observing the ocean in the 1990's. *Phil. Trans. Roy. Soc.*, **A307**, 439-464.

Stammer, D., and E. P. Chasignet, 2000: Ocean state estimation and prediction in support of oceanographic research. *Oceanography*, **13**, 51-56.

Stammer, D., R. Bleck, C. Böning, P. DeMay, H. Hurlburt, I. Fukumori, C. LeProvost, R. Tokmankian, M. Wenzel, 2001: Global ocean modelling and state estimation in support of climate research. In: Koblinsky, C. J., and N. R. Smith (Eds.): *Observing the Oceans in the 21st Century*. GODAE Project Office and Bureau of Meteorology, Melbourne, 511-528.

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, 1999: 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.