REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
11-02-2009	Final Report	1 Dec 2005 - 31 Dec 2008

4. TITLE AND SUBTITLE	
North Pacific Acoustic Laboratory: Analysis of Shadow Zone Arrivals and Acoustic Propagation in Numerical Ocean Models	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-06-1-0152
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Brian Dushaw	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Applied Physics Laboratory - University of Washington 1013 NE 40th Street Seattle, WA 98105-6698	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Office of Naval Research (ONR 321) 875 North Randolph Street Arlington, VA 22203-1995	ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release

13. SUPPLEMENTARY NOTES

None

14. ABSTRACT

Over the decade 1996-2006, acoustic sources located off central California and north of Kauai transmitted to receivers distributed throughout the northeast and north central Pacific. Some of the observations included "shadow-zone arrivals", that appear at travel times aligned with the lower cusps of the acoustic time front predicted by ray calculations, but with the depth of the receiver lies well below the depths of the predicted cusps. Several models for the temperature and salinity in the North Pacific Ocean were obtained and processed to enable simulations of acoustic propagation for comparison to the observations. New tools were developed to manage the large size of the model output, to extract and construct the relevant acoustic properties from the model output, and to make the acoustic calculations. Computer codes using ray tracing and the parabolic equation to calculate acoustic properties were significantly developed. The acoustic data show that WOA05 is a better estimate of the time-mean hydrography than either the JPL-ECCO or the POP estimates, which proved incapable of reproducing the observed acoustic arrival patterns.

15. SUBJECT TERMS

NPAL, LOAPEX, SPICEX, shadow zone arrivals, acoustic thermometry, acoustic propagation, ocean models

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Brian Dushaw
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	11	206-685-4198

North Pacific Acoustic Laboratory: Analysis of Shadow Zone Arrivals and Acoustic Propagation in Numerical Ocean Models

Brian Dushaw
Applied Physics Laboratory
University of Washington
Seattle, WA 98105-6698
phone: (206) 685-4198 fax: (206) 543-6785 email: dushaw@apl.washington.edu

Award Number: N00014-06-1-0152
http://faculty.washington.edu/dushaw/

LONG-TERM GOALS

My long-term goal is a complete and thorough understanding of the properties of acoustic pulses sent over basin to global scales. In particular, I want to understand the forward problem for calculating travel times of the early ray arrivals in long-range acoustic transmissions and to understand the sampling associated with those arrivals.

OBJECTIVES

This work aims to determine the extent to which existing models of ocean variability can be used for the study of long-range acoustics. To accomplish this goal, new tools were developed to manage the often large size of the model output, to extract and construct the relevant acoustic properties (e.g., full-depth sections of sound speed) from the model output, and to make the acoustic calculations. Another objective was to examine data obtained on deep hydrophone arrays during the SPICEX experiment to establish general properties of receptions that occur in the shadow zone.

APPROACH

This project consisted of two separate, but not entirely unrelated, investigations. First, long-range acoustic data obtained in the North Pacific during LOAPEX (Long-range Ocean Acoustic Propagation Experiment) and SPICEX (Figure 1) were to be analyzed to develop a quantified, phenomenological description of stable "ray like" arrivals measured by deep hydrophone arrays. These arrivals appear at travel times associated with the lower cusps of the acoustic time front predicted by ray calculations, but the depth of the receiver lies well below the depths of the predicted cusps (Dushaw et al. 1999) (Figure 2). The phenomenological description of these "shadow-zone" arrivals was to be used to test the results from theorists and numerical modelers striving to explain the origin, and calculate the properties, of these arrivals. Second, state estimates from high-resolution ocean models for the North Pacific, e.g., 3-D fields of temperature and salinity, were to be used to examine their suitability for making accurate long-range acoustic calculations.

Given the difficulty and expense of accurately characterizing the ocean environment for acoustics by data, model state estimates may eventually provide a way to obtain time-dependent acoustic

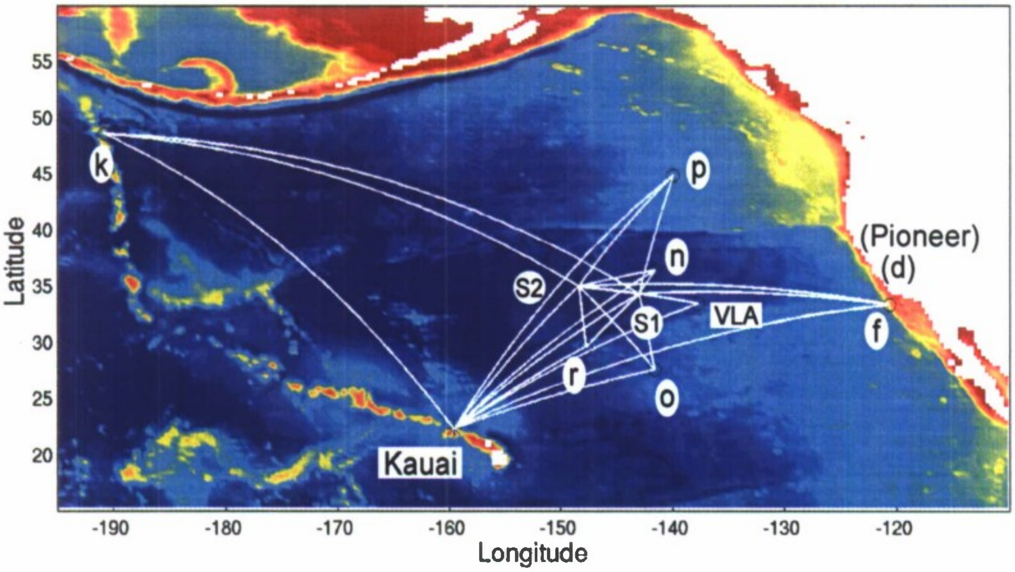

Figure 1. The 2004 NPAL Array.

[The 2004 NPAL Array consisted of three SPICEX moorings labeled S1, S2, and VLA, augmented by the 75-Hz Kauai acoustic source and bottom-mounted receivers denoted f, k, n, o, p, and r.]

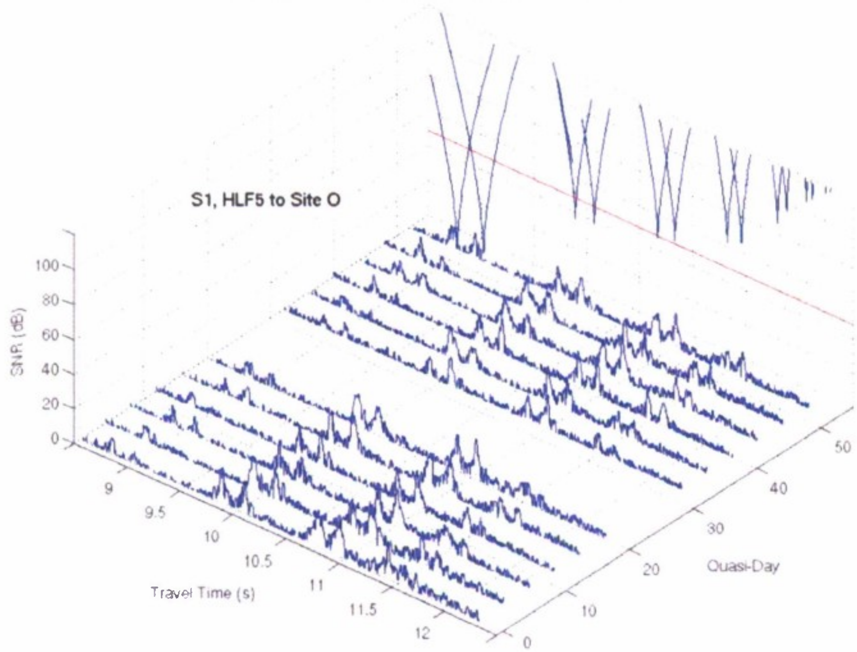

Figure 2. Shadow zone receptions from NPAL acoustic source S1 to bottom-mounted receiver O.

[Shadow zone receptions from transmissions from NPAL HLF-5 acoustic source S1 (250 Hz), located near the sound channel axis, to bottom-mounted receiver O. Receptions over the course of two days are shown in the waterfall plot with 6 receptions per day. The prediction for the acoustic time front using rays is shown in the upper right, with the receiver depth denoted by the red line.]

environments for acoustic studies, or for accurate acoustic predictions, over long ranges. Since numerical ocean models are at present mesoscale resolving at best, the effects of internal waves will be modeled separately and combined with the ocean model state estimates to approximate the most realistic acoustic environment.

WORK COMPLETED

M work has continued to focus on the acoustical calculations in numerical ocean models; a manuscript based on this work was submitted for publication in Fall 2008. Several models for the temperature and salinity in the North Pacific Ocean have been processed and developed so that ray tracing in them is routine. Figure 3 shows sound speed fields at 300 m calculated for four estimates of the ocean state in midwinter 2003. From simple to sophisticated, these models are:

The 2005 World Ocean Atlas (Locarnini et al. 2006, Antonov et al. 2006). The world ocean atlas is an important element of this work, boring though it may be, because acoustic predictions using this atlas are known to be a reasonable base state. Acoustic arrival patterns calculated with this atlas are reasonably accurate in their absolute travel time and dispersal of the multipath travel times. The atlas thus provides an important test for the acoustic accuracy of more sophisticated numerical ocean models. Sound speeds derived from the atlas can also be used to correct the time-mean state of sound speed in the models; often the time-mean state of sound speed from a model has unphysical properties.
Figure 4 shows a comparison of data obtained on the Kauai source to receiver k (see Figure 1) acoustic path with ray predictions using the monthly realizations of the atlas. For this work, the ray code employed is that of Dushaw and Colosi (1998).

Smoothed estimates of temperature derived from available hydrography and altimetry (Willis et al. 2003, Willis et al. 2004). Willis et al. have calculated smoothed estimates of upper-ocean world ocean temperatures using hydrography (e.g., Argo float data) and altimetry using objective mapping techniques. These estimates have coarse resolution and are smoothed temporally with a 1-year running mean. Thus, this product does not include internal wave, mesoscale, or seasonal variability. The upper-ocean temperature profiles have been extended to the deep ocean to allow acoustic calculations using cubic spline techniques and the world ocean atlas for the abyssal values. Salinity estimates were also not yet available, salinity values were assigned using T-S relations from the World Ocean Atlas; salinity values are required to calculate sound speed.

The "Estimating the Circulation and Climate of the Ocean" (ECCO) global ocean model (Marshall et al. 1997a, 1997b, http://www.ecco-group.org/). The ECCO model is a data assimilating model that attempts to incorporate all available data (e.g., altimetry, Argo float data) to estimate the ocean state. There are various flavors of ECCO ocean models; I am using the 1-degree resolution, 46-layer model from JPL that uses a Kalman filter for data assimilation. Newer versions of this model have greater resolution, hence provide more realistic estimates of the ocean state for acoustics (see below "Perth to Bermuda". The 1-degree model suffers from a number of problems, one of which is unphysical sound speed gradients in the time-mean state. These gradients make the results of acoustic calculations rather unphysical (if not unrecognizable), so the time-mean state of the model is replaced by the World Ocean Atlas (with the model contributing estimates of the variability). I expect that any existing model

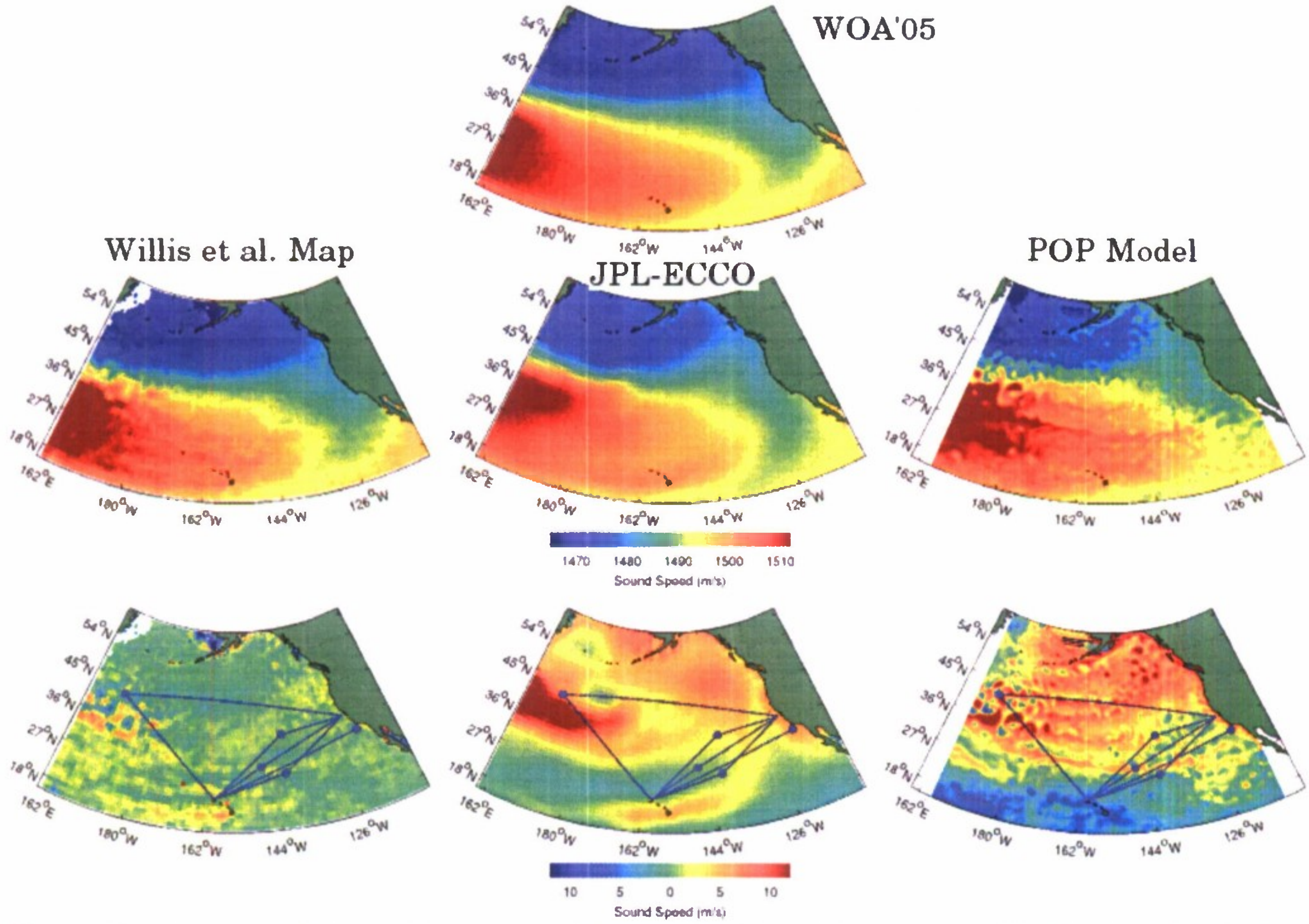

Figure 3. A comparision of four sound speed fields of the eastern North Pacific derived from different data and analysis.
[Sound speed at 300-m depth derived from four realizations of the ocean: (1) the 2005 World Ocean Atlas, (2) objective maps by Willis, (3) the ECCO model, and (4) the POP model. The three bottom realizations are all obtained for midwinter 2003. The top panels show sound speed, while in the bottom panels the world ocean atlas sound speed has been subtracted from the model sound speed to show the sound speed "anomaly".]

will have one pathology or another in terms of its acoustic properties; working around such issues is one of the challenges of this project.

A high-resolution "Parallel Ocean Program" (POP) global ocean model (Maltrud and McClean 2005). J. McClean provided me with model output from her high-resolution POP model runs for the North Pacific. While this model is not data assimilating, it is driven by estimates of actual ocean forcing such as precipitation and winds, and it is mesoscale resolving. The 0.1-degree horizontal resolution and 40 depth levels of the model are ideal for acoustical calculation purposes. The model output is available monthly but continues only through 2003.

The ray travel times calculated in the four models are compared to measured travel times in Figures 4 and 5. The calculated rays are roughly equivalent to the rays identified in the actual receptions.

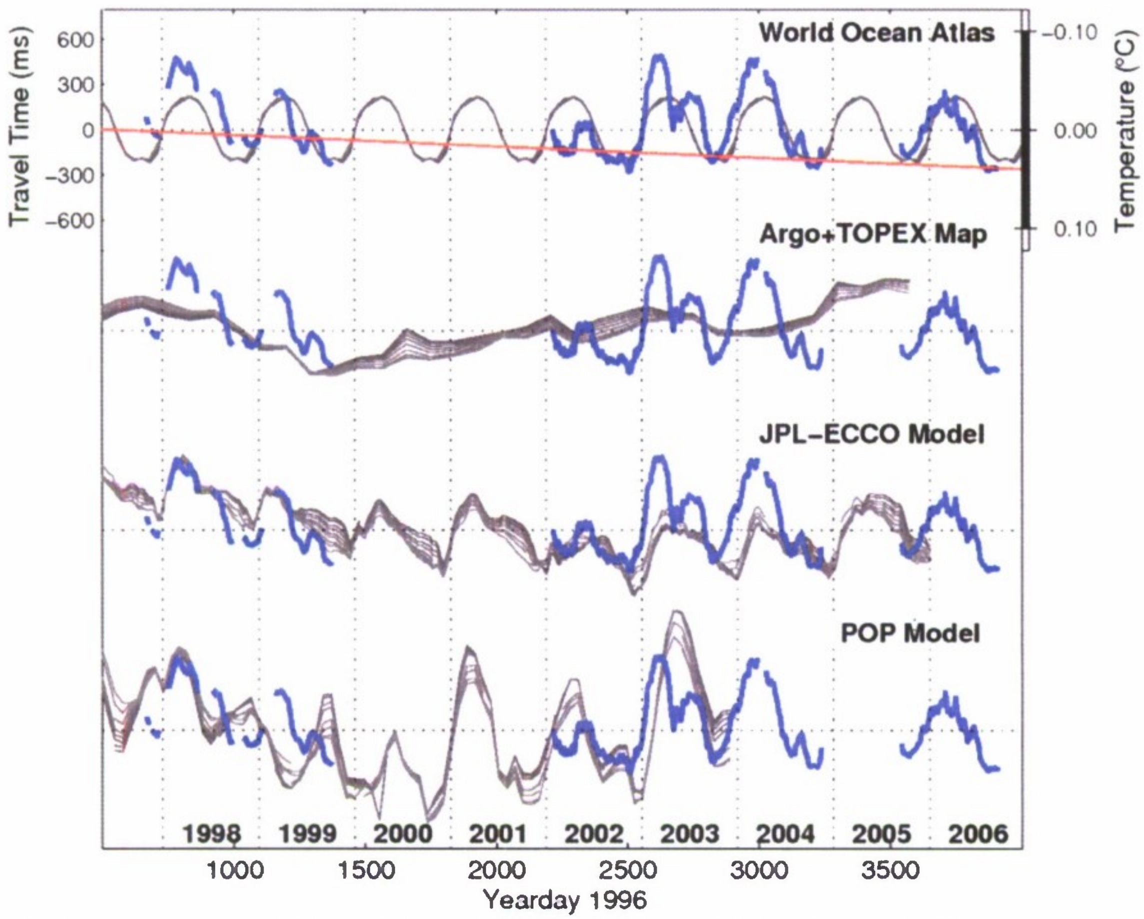

Figure 4. Measured and Model Travel Times for the 4-Mm Acoustic Path from the Kauai source to bottom-mounted receiver k in the central North Pacific.
[Blue lines: the measured ray travel time time series. Gray lines: equivalent travel times calculated using the indicated ocean model. An equivalent temperature scale is given at right. The red line in the top panel shows the expected trend corresponding to 5 m°C/yr warming near the sound channel axis. This nominal number for oceanic climate change was originally suggested by Munk and Forbes (1989).]

Of all the comparisons that have been made, including the Willis objective map based on Argo and altimetry and the ECCO data assimilation model, the POP model shows the most similarity to the observations. It seems clear that the acoustic data type offers unique information for testing or constraining the basin-scale temperature variations of numerical ocean models.

Another look at the 1960 Perth to Bermuda antipodal acoustic propagation test. In preparing a review talk on long-range acoustic propagation employed for remote sensing of ocean temperature, I had occasion to review the work published some 20 years ago describing issues associated with the acoustic propagation over antipodal distances, based on a test in 1960 (American Geophysical Union 1960; Shockley et al. 1982, Munk et al. 1988, Heaney et al. 1991; see also the new web page documenting the 1991 Heard Island Feasibility Test: http://909ers.apl.washington.edu/~dushaw/heard/index.shtml). The 1960 experiment was to test the 1940's conjecture of Ewing and Worzel (1948) that sound could easily travel great distances through

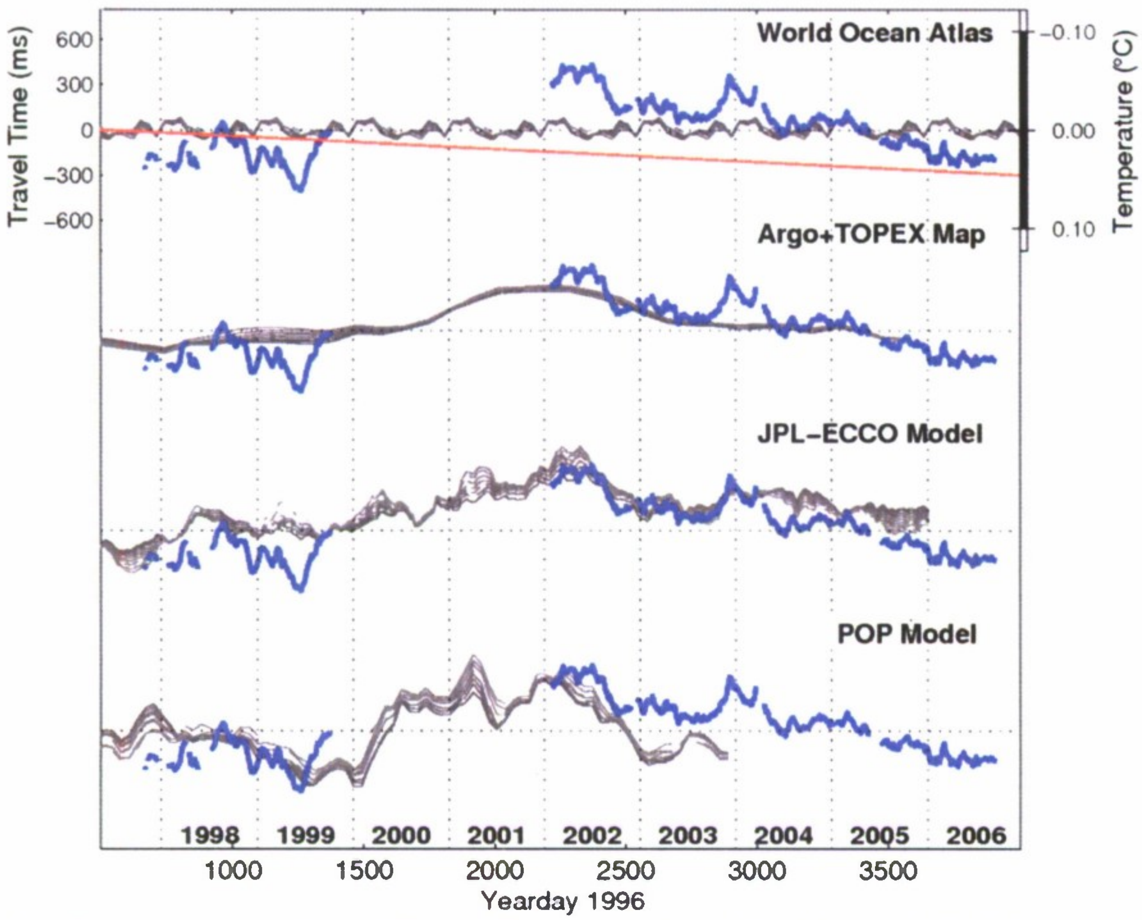

Figure 5. Measured and Model Travel Times for the 4-Mm Acoustic Path from the Kauai source to bottom-mounted receiver f off the coast of California.

[Blue lines: the measured ray travel time time series. Gray lines: equivalent travel times calculated using the indicated ocean model. An equivalent temperature scale is given at right. The red line in the top panel shows the expected trend corresponding to 5 m°C/yr warming near the sound channel axis.]

the ocean. The test was a success in that the sound from explosive sources deployed off Perth, Australia was detected at the antipode near Bermuda. A closer look at the propagation paths, however, found that if the horizontal refraction of the acoustic path was taken into account, the sound should have been blocked by the continent of Africa (Munk et al. 1988). Heaney et al. (1991) appeared toresolve the issue, by suggesting that the sound reflected off of bathymetric features to arrive at Bermuda, but, from a modern perspective, the data bases of bathymetry and sound speed employed for their calculation were too primitive for that explanation to be definitive or convincing.

I reattempted the antipodal-path calculation using the 2005 World Ocean Atlas to model the global sound speed field. I searched for direct (non-bottom interacting) acoustic paths, but successful paths were not obtained (Dushaw 2008). Detailed sound speed fields derived from one of the more recent global high-resolution ocean models (ECCO2, Figure 6), provide some interesting suggestions that may account for the successful antipodal acoustic test. In particular, the Agulhas Rings to the east of the Cape of Good Hope act as quite intense refractive lenses for acoustic propagation, with sound speed deviations of about 25 m/s larger than ambient sound speed. These features may well have

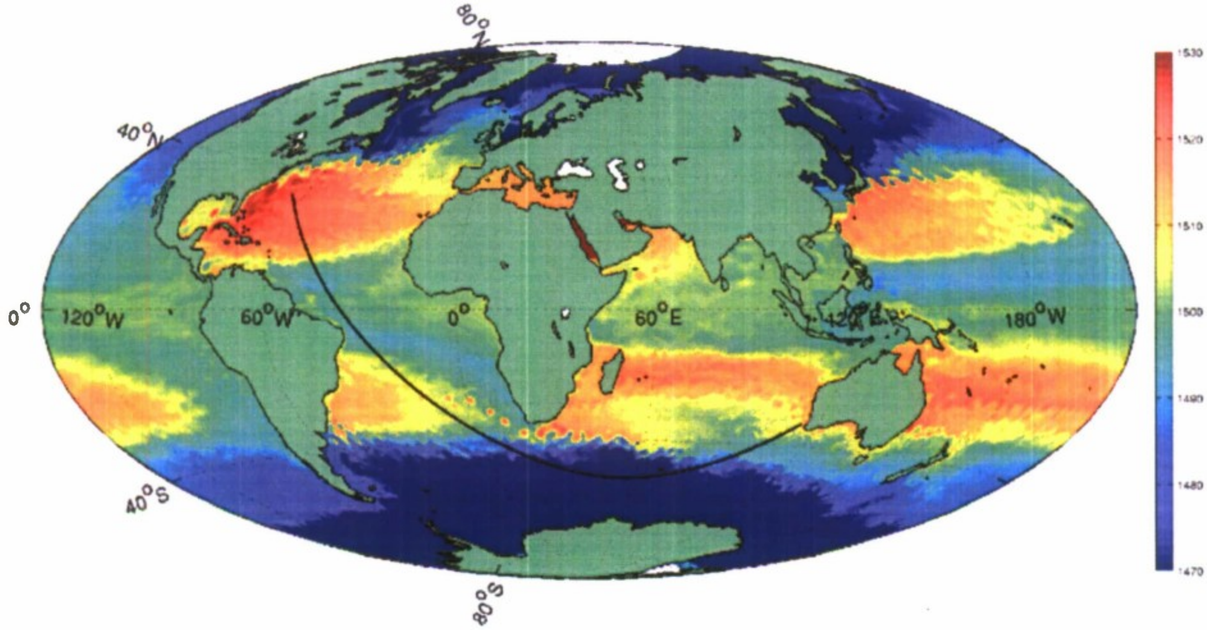

Figure 6. The geodesic path connecting the location of the 1960 explosive shots off Perth, Australia and the location of the receivers south of Bermuda. [A high-resolution ocean model snapshot of sound d speed at 300-m depth derived from the JPL-ECCO2 numerical ocean model shows some of the challenges of calculating acoustic propagation over antipodal distances.]

provided the bending required for the 1960 acoustic paths to successfully skirt the southern tip of Africa on their way to Bermuda.

Development of a Parabolic Equation Propagation Code. One of the tools required for understanding long-range acoustic propagation, and the nature of "shadow-zone arrivals" in particular, is the parabolic wave equation (PE) method for calculating acoustic propagation for a given ocean section. This solution for the acoustic propagation is "applicable in strongly range-dependent environments in which mode coupling is severe" (Munk et al. 1995). This past year, I developed a FORTRAN 95 version of the RAM Parabolic Equation code (Collins 1993a, 1993b) which is parallelized for broadband calculations using the Message Passing Interface (MPI) suite of subroutines (Figure 7). The FORTRAN 95 code was developed from a Matlab version of the RAM code developed by M. Dzieciuch, which, in turn, was developed from the original Collins' FORTRAN 77 version. The basic aims of this development were to develop a code that I was familiar with, that employed a modern computer language, and that was parallel. (Interestingly, FORTRAN 95 is similar to Matlab script code, so the development was fairly straightforward.) The FORTRAN 95 code runs some 30% faster than the Matlab version and is easy to run in parallel mode on a computer cluster of any size. A website was set up to document the code and make it available:
http://909ers.apl.washington.edu/twiki/bin/view/Main/RamFortranCode . This website complements the similar pages describing the Matlab version of the code:
http://909ers.apl.washington.edu/twiki/bin/view/Main/RamMatlabCode , and the website describing the "eigenray" geometric ray code:
http://909ers.apl.washington.edu/twiki/bin/view/Main/EigenRay . In conjunction with this work, I obtained and got working the code for simulating internal wave variability presently employed at the

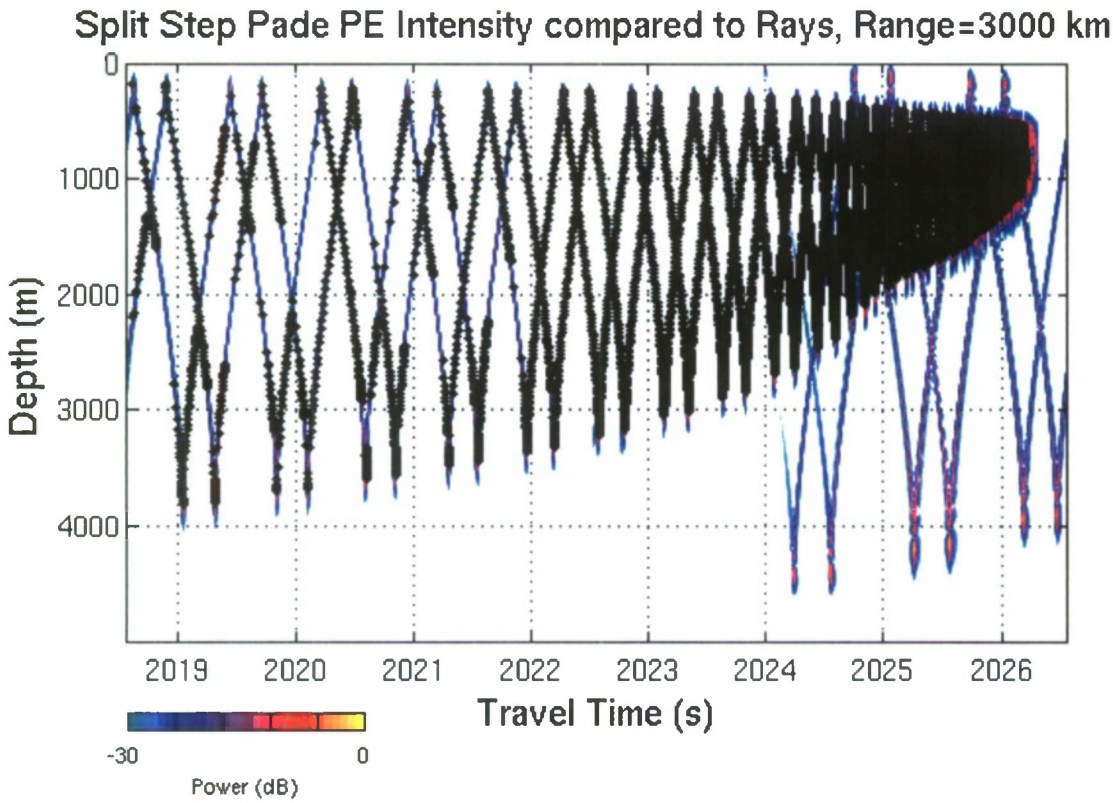

Figure 7. A comparison of a time front calculated by geometric rays (black dots) and by the Fortran 95 version of RAM developed for this project.
[The colors show the intensity of the acoustic pattern in dB as indicated by the legend at lower left. The ray "intensity" is approximated by the density of the ray arrivals along the branches of the time front. The late, deep arrivals at lower right are an artifact of the calculation; they are early arrivals "wrapped around" from the left.]

Scripps Institution of Oceanography (Van Uffelen, personal communication, 2008). This code, based on a model developed by J. Colosi and M. Brown, simulates snapshots of stochastic internal wave variability based on the Garrett-Munk spectrum for internal waves. The next step is to combine these internal wave model snapshots with numerical ocean model state estimates to obtain realistic estimates of long-range acoustic propagation using the PE model.

RESULTS

Significant effort has been directed at manipulating the oftentimes large model data files, and merging those data with acoustic propagation capabilities. It is clear that the model results are not yet directly suitable for acoustic calculations. Constraints preserving essential acoustic properties might be a useful consideration in future model development.

Acoustic arrivals in the shadow zone were ubiquitous in the data obtained from deep receivers during the SPICEX/LOAPEX experiment. This rich data set looks as if it will be very useful for deriving general properties of this type of acoustic arrival.

The acoustic ray tracing code of Dushaw and Colosi (1998) has been developed into a subroutine that can be called by any computer code, such as a numerical ocean model during its run. For tomography and data assimilation, this tool is one of the holy grails that has not been available until now.

The comparison of measured travel times and travel times calculated in the various model estimates of the ocean state show both similarities and differences. Acoustic travel times detect oceanic variability that is not captured by the numerical models. The acoustic data type is a unique observation of large-scale temperature that can be used to correct the numerical ocean models.

There is still a mystery about the nature of the antipodal acoustic path traversed during the 1960 Perth-to-Bermuda acoustic propagation experiment. A definitive explanation for the success of this experiment remains elusive. However, high-resolution numerical ocean models provide estimates for the sound speed environment that offer promising, if not obvious, avenues for further investigation. The environmental details of high-resolution models highlight the challenges of accurate acoustic calculations over long ranges in some regions of the world's oceans.

IMPACT/APPLICATIONS

Data-assimilating models will some day have enough resolution and data constraint that they can be used for accurate, real-time predictions of acoustic properties over any ranges anywhere in the world. This work aims to assess present capabilities, and perhaps develop criteria or constraints for better behaved acoustics that modelers can begin to implement.

The acoustical properties of shadow-zone arrivals, including the basic oceanographic and acoustical physics that give rise to them, are not well understood, although recently Van Uffelen et al. (2008) found that ordinary internal wave scattering could account for this phenomena. These properties are relevant to the design of deep acoustic observing systems.

The development of ray tracing code as a computer code subroutine means that numerical ocean models can now implement the basic acoustic calculations routinely. Such capability is an important step toward the routine use of long-range acoustic data for data assimilation using general circulation models.

The conclusion that the acoustic travel times offer a unique constraint of large-scale temperatures for the ocean models suggests that a long-range acoustic array might be a useful component of an ocean observing system, a complementary measurement type to Argo drifting floats and satellite altimetry. These results were submitted for publication in Fall 2008 (Dushaw et al. 2008).

The propagation of sound over very long ranges in the Southern Ocean is still as yet not altogether understood – how did sound propagation around the southern tip of Africa on the Perth-to-Bermuda path? This question has implications for such things as the performance of the Comprehensive Test Ban Treaty Organization array of monitoring hydrophone arrays in the Indian Ocean.

RELATED PROJECTS

This project is a contribution to the North Pacific Acoustic Laboratory (NPAL) collaboration, comprised of researchers from the Applied Physics Laboratory, the Scripps Institution of Oceanography, and the Massachusetts Institute of Technology, among others. (http://npal.ucsd.edu/)

REFERENCES

American Geophysical Union (1960), Notes and Personalia, *Transactions of the American Geophysical Union*, **41**, p. 670.

Antonov, J. I., R. A. Locarnini, T. P. Boyer, A. V. Mishonov, and H. E. Garcia (2006), *World Ocean Atlas 2005, Volume 2: Salinity.* S. Levitus, Ed. NOAA Atlas NESDIS 62, U.S. Government Printing Office, Washington, D.C., 182 pp.

Collins, M. D. (1993a), A split-step Padé solution for the parabolic equation method, *J. Acoust. Soc. Am.*, **93**, 1736–1742.

Collins, M. D. An energy-conserving parabolic equation for elastic media (1993b), *J. Acoust. Soc. Am.*, **94**, 975–982.

Dushaw, B. D. and J. A. Colosi (1998), Ray tracing for ocean acoustic tomography, Applied Physics Laboratory, University of Washington, **APL-UW TM 3-98**.

Dushaw, B. D., B. M. Howe, J. A. Mercer, R. C. Spindel, and the ATOC Group (A. B. Baggeroer, T. G. Birdsall, C. Clark, J. A. Colosi, B. D. Cornuelle, D. Costa, B. D. Dushaw, M. A. Dzieciuch, A. M. G. Forbes, B. M. Howe, D. Menemenlis, J. A. Mercer, K. Metzger, W. H. Munk, R. C. Spindel, P. F. Worcester, and C. Wunsch) (1999), Multimegameter-range acoustic data obtained by bottom-mounted hydrophone arrays for measurement of ocean temperature, *IEEE J. Ocean. Eng.*, **24,** 202–214.

Ewing, M., and J. L. Worzel (1948), Long-range sound transmission. *Geol. Soc. Am. Memoir*, 27, part III, 1–35.

Heaney, K. D., W. A. Kuperman, and B. E. McDonald, Perth-Bermuda sound propagation (1960) (1991), Adiabatic mode interpretation, *J. Acous. Soc. Am.*, **90**, 2586–2594.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia (2006), *World Ocean Atlas 2005, Volume 1: Temperature.* S. Levitus, Ed. NOAA Atlas NESDIS 61, U.S. Government Printing Office, Washington, D.C., 182 pp.

Maltrud, M. E., and J. L. McClean (2005), An eddy resolving global 1/10° ocean simulation, *Ocean Modelling*, **8**, 31–54.

Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey (1997a), A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers, *J. Geophys. Res.*, **102**, 5753–5766.

Marshall, J., C. Hill, L. Perelman, and A. Adcroft (1997b), Hydrostatic, quasi-hydrostatic, and nonhydrostatic ocean modeling, *J. Geophys. Res.*, **102**, 5733–5752.

Munk, M., and A. M. G. Forbes (1989), Global ocean warming: an acoustic measure?, *J. Phys. Oceanogr.*, **19**, 1765–1778.

Munk, W. H., W. C. O'Reilly, J. L. Reid, Australia-Bermuda sound transmission experiment (1960) revisited (1988), *J. Phys. Oceanogr.*, **18**, 1876–1898.

Munk, W. H., P. Worcester, and C. Wunsch (1995), Ocean Acoustic Tomography (Cambridge University Press), 433 pp.

Shockley, R. C., J. Northrop, P. G. Hansen, C. Hartdegen (1982), SOFAR propagation paths from Australia to Bermuda: Comparision of signal speed algorithms and experiments, *J. Acous. Soc. Am.*, **71**, 51–60.

Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, D. L. Rudnick (2008), The vertical structure of shadow-zone arrivals at long range in the ocean, *J. Acoust. Soc. Am.*, submitted.

Willis, J. K., D. Roemmich, and B. D. Cornuelle (2003), Combining altimetric height with broadscale profile data to estimate steric height, heat storage, subsurface temperature, and sea-surface temperature variability, *J. Geophys. Res.*, **108**, 3292, doi: 3210.1029/2002JC001755.

Willis, J. K., D. Roemmich, and B. D. Cornuelle (2004), Interannual variability in upper ocean heat content, temperature, and thermosteric expansion on global scales, *J. Geophys. Res.*, **109**, C12036, doi: 12010.11029/12003JC002260.

PUBLICATIONS

Dushaw, B. D. (2007-2008), The 1991 Heard Island Feasibility Test, http://909ers.apl.washington.edu/~dushaw/heard/index.shtml. [published, unrefereed web page]

Dushaw, B. D. (2008), Another look at the 1960 propagation experiment, *Geophys. Res. Lett.*, **35**, L08601, doi:10.1029/2008GL033415. [published, refereed]

Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger, Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, B. D. Cornuelle, and D. Menemenlis (2008), A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.*, [submitted, refereed].

HONORS/AWARDS/PRIZES

Invited to give the talk entitled "Global Acoustic Thermometry" at the *Walter Munk 90th Birthday Symposium*, Scripps Institution of Oceanography, October 19, 2007, (http://sio.ucsd.edu/special/Walter_Munk/).