REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
9/30/94

3. REPORT TYPE AND DATES COVERED
Final Report 11/1/92 - 6/30/94

4. TITLE AND SUBTITLE
Oceanographic Analysis of the Acoustic Mid-Ocean Dynamics Experiment

5. FUNDING NUMBERS
ONR Contract:
N00014-93-1-0461

6. AUTHOR(S)
Peter Worcester, Bruce Cornuelle, David Chester

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Scripps Institute of Oceanography
8604 La Jolla Shores Drive
La Jolla, CA 92093

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Code 1122ML
800 N. Quincy
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
SEE ATTACHED

14. SUBJECT TERMS
Ocean acoustic tomography, general ocean circulation

15. NUMBER OF PAGES
4

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

13. Abstract

Reciprocal acoustic transmissions made in the Northwest Atlantic have been analyzed to determine the general circulation of the region between Bermuda and Puerto Rico. Six tomographic transceivers were moored from March 1991 to March 1992 in the region centered at 25°N, 66°W during the Acoustic Mid-Ocean Dynamics Experiment (AMODE). The goals of the research performed under this contract have been (i) to study large-scale (300 to 1000 km) circulation and variability in temperature, current, and relative vorticity fields, (ii) to study mesoscale eddy kinematics and dynamics, and (iii) to study the value of integral constraints on eddy-resolving numerical ocean models. Large-scale range averages (over 300 to 700 km sections) of temperature and velocity and large-scale areal averages (over regions comprising $10^5 km^2$) of relative vorticity in the upper 3500 m of the water column have been estimated through inversion of the tomographic travel time data.

FINAL TECHNICAL REPORT

Oceanographic Analysis of the Acoustic Mid-Ocean Dynamics Experiment

ONR Contract N00014-93-1-0461

1 November 1992 - 30 June 1994

Peter Worcester   Bruce Cornuelle   David Chester

Research Goals:

The goals of the research performed under this contract have been (i) to study large-scale (300 to 1000 km) circulation and variability in temperature, current, and relative vorticity fields, (ii) to study mesoscale eddy kinematics and dynamics, and (iii) to study the value of integral constraints on eddy-resolving numerical ocean models.

Tasks Completed:

Reciprocal acoustic transmissions made in the Northwest Atlantic have been analyzed to determine the general circulation of the region between Bermuda and Puerto Rico. Six tomographic transceivers were moored from March 1991 to March 1992 in the region centered at 25°N, 66°W during the Acoustic Mid-Ocean Dynamics Experiment (AMODE).

The raw acoustic data have been beamformed and tracked, yielding absolute travel times for each source and receiver pair of the array. Sources of noise, such as mooring position, clock drifts, and tides, have been largely removed from the travel time data. The tracked acoustic data is the highest quality to date for a tomographic venture. This is in large part due to GPS positioning of the mooring location, with rms position uncertainties reduced to roughly 1 m.

Large-scale range averages (over 300 to 700 km sections) of temperature and velocity and large-scale areal averages (over regions comprising 10^5 km^2) of relative vorticity in the upper 3500 m of the water column have been estimated through inversion of the tomographic travel time data.

Scientific Results:

Initial inversions of the travel time data indicate that the barotropic and first baroclinic mode are well resolved by the acoustic sampling, with poorer resolution of the second baroclinic mode. The 300-day mean circulation of the region is described by a general westward flow of a few cm s^{-1} in the surface and thermocline waters. An active and resolvable mesoscale eddy field is present in the AMODE region, with variability typically dominated by motions with spatial scales of 100–200 km, and with a general westward drift of mesoscale eddy features. The inverted sound speed (temperature) field is consistent with that estimated from the Moving Ship Tomography component of AMODE. Variability is similar in level and scale to that observed during the MODE experiment, but AMODE provides much larger spatial coverage. Areal-averaged relative vorticities are typically three order of magnitude smaller than the local planetary vorticity, with significant variability on mesoscale time-scales.

The analysis of the acoustic data is ongoing, as is the blending of the AMODE data into a numerical ocean model to test the detailed model evolution against the observations. A nonlinear quasi-geostrophic numerical ocean model has been tailored to the region, and is being used as a dynamic interpolator for the tomographic and hydrographic data. The model is presently being initialized with the high-resolution Moving Ship Tomography fields, and run forward in time. The mismatch between the observations and the evolved model field is used to adjust the initial conditions in order to evaluate the impact on model parameter evolution. Optimized model forecasts will then be used to investigate the evolution of a realistic oceanic eddy field.

Publications

*AMODE-MST Group: T.G. Birdsall, J. Boyd, B.D. Cornuelle, B.M. Howe, R. Knox, J.A. Mercer, K. Metzger, Jr., R.C. Spindel, and P.F. Worcester, 1994: Moving ship tomography in the northwest Atlantic Ocean. *EOS*, 75, 17, 21, and 23.

Chester, D.B., and P. Malanotte-Rizzoli, 1994: A tomographic view of the Gulf Stream southern recirculation gyre at 38°N, 55°W: Structure and variability. Submitted to *J. Geophys. Res.*

Chester, D., P. Malanotte-Rizzoli, J. Lynch, and C. Wunsch, 1994: The eddy radiation field of the Gulf Stream as measured by ocean acoustic tomography. *Geophys. Res. Let.*, 21, 181-184.

Cornuelle, B.D., P.F. Worcester, J.A. Hildebrand, W.S. Hodgkiss, Jr., T.F. Duda, J. Boyd, B.M. Howe, J.A. Mercer, and R.C. Spindel, 1993: Ocean acoustic tomography at 1000-km range using wavefronts measured with a large-aperture vertical array. *J. Geophys. Res.*, 98, 16,365-16,377.

Dushaw, B.D., P.F. Worcester, B.D. Cornuelle, and B.M. Howe, 1993: On equations for the speed of sound in seawater. *J. Acoust. Soc. Am.*, 93, 255-275.

Dushaw, B.D., P.F. Worcester, B.D. Cornuelle, and B.M. Howe, 1993: Variability of heat content in the Central North-Pacific in summer 1987 determined from long-range acoustic transmissions. *J. Phys. Oceanogr.*, 23, 2650-2666.

Dushaw, B.D., P.F. Worcester, B.D. Cornuelle, and B.M. Howe, 1994: Barotropic currents and vorticity in the central North Pacific Ocean during summer 1987 determined from long-range reciprocal acoustic transmissions. *J. Geophys. Res.*, 99, 3263-3272.

Fisher, F.H., and P.F. Worcester, 1994: Section IV, Underwater Sound, Part 31: Essential Oceanography, in *Handbook of Acoustics*, M. Crocker, Ed.-in-Chief, in press.

Jin, Guoliang, J.F. Lynch, R. Pawlowicz, and P.F. Worcester, 1994: Acoustic scattering losses in the Greenland Sea marginal ice zone during the 1988–89 tomography experiment. *J. Acoust. Soc. Am.*, in press.

Lynch, J.F., H.X. Wu, R. Pawlowicz, P.F. Worcester, R.E. Keenan, H.C. Graber, O.M. Johannessen, P. Wadhams, and R.A. Shuchman, 1993: Ambient noise measurements in the 200–300-Hz band from the Greenland Sea Tomography Experiment. *J. Acoust. Soc. Am.*, 94, 1015-1033.

Sutton, P.J., W.M.L. Morawitz, B.D. Cornuelle, G. Masters, and P.F. Worcester, 1994: The incorporation of acoustic normal mode data into tomographic inversions in the Greenland Sea. *J. Geophys. Res.*, 99, 12,487-12,502.

Sutton, P.J., P.F. Worcester, G. Masters, B.D. Cornuelle, and J.F. Lynch, 1993: Ocean mixed layers and acoustic pulse propagation in the Greenland Sea. *J. Acoust. Soc. Am.*, 94, 1517-1526.

Worcester, P.F., B.D. Cornuelle, J.A. Hildebrand, W.S. Hodgkiss, Jr., T.F. Duda, J. Boyd, B.M. Howe, J.A. Mercer, and R.C. Spindel, 1994: A comparison of measured and predicted broadband acoustic arrival patterns in travel time–depth coordinates at 1000-km range. *J. Acoust. Soc. Am.*, 95, 3118-3128.

Worcester, P.F., J.F. Lynch, W.M.L. Morawitz, R. Pawlowicz, P.J. Sutton, B.D. Cornuelle, O.M. Johannessen, W.H. Munk, W.B. Owens, R. Shuchman, and R.C. Spindel, 1993: Evolution of the large-scale temperature field in the Greenland Sea during 1988–1989 from tomographic measurements. *Geophys. Res. Letters*, 20, 2211-2214.

Technical Reports

*Dushaw, B.D., D.B. Chester, and P.F. Worcester, 1993: A review of ocean current and vorticity measurements using long-range reciprocal acoustic transmissions. *Oceans '93 Conference Record*, I-298–I-305.

*Howe, B.M., and P.F. Worcester, 1993: Ocean acoustic tomography in the High Gain Initiative. Applied Physics Laboratory, University of Washington, Technical Report APL-UW TR 9308.

Lynch, J.F., H.X. Wu, P. Wadhams, and P.F. Worcester, 1993: Ice edge noise observations from the 1988–89 Greenland Sea Tomography Experiment. *Proceedings of the European Conference on Underwater Acoustics*, M. Weydert, Ed., Elsevier Applied Science, London, Luxembourg, 14-18 September 1992, 611-619.

Worcester, P.F., 1993: Measuring thermal and velocity structure in the northwestern Atlantic with acoustic tomography. In: *The North Atlantic Current System: A Scientific Report*, P. Malanotte-Rizzoli and T. Rossby, Ed., Proceedings of the North Atlantic Current System Workshop, Woods Hole, Massachusetts, 19–20 April 1993, 65–84.

*Worcester, P.F., and B.D. Dushaw, 1993: The Acoustic Mid-Ocean Dynamics Experiment (AMODE): Recovery cruise report, February 28–March 23, 1992, R/V ENDEAVOR Voyage EN-233. Scripps Institution of Oceanography Reference Series 93–8, University of California at San Diego, La Jolla, California.

Abstracts

*Chester, D.B., P.F. Worcester, B.D. Dushaw, and B.D. Cornuelle, 1994: Large-scale circulation and variability in the Northwest Atlantic between Bermuda and Puerto Rico. Submitted to *EOS* for 1994 AGU Fall Meeting.

*These publications were prepared with support from ONR Contract N00014-93-1-0461.