Acoustic studies of the large scale ocean circulation

Detailed knowledge of ocean circulation and its transport properties is prerequisite to an understanding of the earth’s climate and of important biological and chemical cycles. Results from two recent experiments, THETIS-2 in the Western Mediterranean and ATOC in the North Pacific, illustrate the use of ocean acoustic tomography for studies of the large scale circulation. The attraction of acoustic tomography is its ability to sample and average the large-scale oceanic thermal structure, synoptically, along several sections, and at regular intervals. In both studies, the acoustic data are compared to, and then combined with, general circulation models, meteorological analyses, satellite altimetry, and direct measurements from ships. Both studies provide complete regional descriptions of the time-evolving, three-dimensional, large scale circulation, albeit with large uncertainties. The studies raise serious issues about existing ocean observing capability and provide guidelines for future efforts.
estimating baroclinic errors in OGCM using ATOC

Figure 4. Estimates of system error variance based on the lag-1 difference sample covariance, $\hat{R}_1$, for simulated acoustic tomography data. Dotted lines indicate the values of $\sigma_1 \ldots \sigma_n$ used to generate the data. The error bars represent the standard error of the estimates. The figure demonstrates the increasing accuracy of the algorithm with increasing number of measurements.

Figure 5. Estimates of system error variance based on the diagonal elements of $\hat{R}_1$ for simulated altimeter data. Dotted lines indicate the prior variances used to generate the data. Error bars represent the standard uncertainty of the estimates and they can be compared to those of Fig. 4 which was created using simulated acoustic data. The large error bars associated with the altimetric estimates suggest that altimeter data are ill-suited to the estimation of baroclinic GCM errors.
1. THETIS-2 experiment
   (Western Mediterranean)

2. CALIPSO experiment
   (North Pacific)

3. Global-ocean data assimilation system
   (SCRIPPS, MIT, JPL effort)
Global-ocean data assimilation system

(SCRIPPS, MIT, JPL effort)

Objective

Estimate global time-evolving ocean circulation by combining modern large scale data sets and general circulation models.

Science Goals

Understand the basic state of the ocean, its variability, and its interaction with

Estimate meridional fluxes and flux divergences of heat, fresh water, carbon, and nutrients.

Study global physical processes linking ocean with changing atmosphere, and their role in climate variability.
PRESENT STATUS

completed

2°, 20-level, 1-year adjoint model computation
(https://www.ritz.de/aoa/CMEM)

2·10^7 / 10^25 approximate Kalman filter
(Fukumori et al., in press)

underway

1°, 20-level, 5-year adjoint model computation

1° → ½°, 46-level, KPP, GN forward integration

1985-2000 optimization, eventually at
¼° global.
(Menemenlis et al. '97)
Path H-W1

Path H-W3

Path H-W5

(Menemenlis et al. '97)
Estimation problem

GCM errors:

\[ \mathbf{p}(t + 1) = \mathbf{A} \mathbf{p}(t) + \mathbf{q}(t) \]

Measurements:

\[ y_{\text{data}}(t) = H(t) x_{\text{ocean}}(t) + r(t) \]

Residuals:

\[ y(t) = H(t) x_{\text{GCM}}(t) - y_{\text{data}}(t) \]
\[ = H(t) p(t) - r(t) \]

Covariance matrices:

\[ R = \text{cov } r, \quad Y = \text{cov } y \]

Cost function:

\[ J = \mathbf{p}^T(0) \mathbf{P}^{-1} \mathbf{p}(0) + \sum_t \left[ r^T(t) R^{-1} r(t) + q^T(t) Q^{-1} q(t) \right] \]
The text contains statistical data and includes a table. Here is the transcribed information:

**RMS Difference Between**

Naltim and Nacoust: 2.4 cm

**RMS Difference Between**

(Continued on next page)

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(The ATOC Consortium '98)
Fig. 5. (a) $\log_{10}$ of the water column average kinetic energy per unit mass in the North Pacific Ocean. (b) Percentage of water column average kinetic energy per unit mass found in the barotropic mode. (c) Percentage of water column average kinetic energy per unit mass found in the first baroclinic mode. (d) Percentage of water column average kinetic energy per unit mass found in the second baroclinic mode.

Fig. 6. (a) $\log_{10}$ of estimated surface kinetic energy per unit mass. (c–d) Same as in Fig. 5c–d except for the surface kinetic energy per unit mass $T^2$. Owing to the surface intensification of the baroclinic modes, little of the surface kinetic energy is barotropic.
**SALT ANOMALY**

Taiwan  Guam  Honolulu  San Fran.

16 Pacific cruises over 4 years

![Graph showing standard deviation cruise-to-cruise salinity changes](image)

![Graph showing difference in steric height compared to historical salinity](image)

![Graph showing salinity difference compared with historical data](image)

(Gilson et al. '97)
\[ \Delta M_{\text{ocean}} + \Delta M_{\text{water vapor}} + \Delta M_{\text{continental water}} = 0 \]

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(Minster et al. 1998)

Fig. 5
Heat content change in top 4000 m
Heat content change in 160°-240°E
16°-56°N box.

(ATOC Consortium '98)
Concluding Remarks

Acoustic tomography can be an effective data set for understanding general circulation model errors and its internal variability.

Global ocean data assimilation system provides a framework for assimilating past and future ocean acoustic tomography data; it also provides boundary conditions for high resolution regional studies.