Oceanographic and Sound Speed Fields for the ESME Workbench

Christopher A. Linder and Glen G. Gawarkiewicz

Abstract—**The authors describe the effort to provide three-dimensional global thermohaline and sound speed fields for use in the effects of sound in the marine environment (ESME) workbench suite of programs. The primary fields used are from the modular ocean data assimilation system (MODAS), developed by Fox *et al.* The system provides global thermohaline and sound speed fields on a daily basis using environmental inputs from the U.S. Navy as well as remote sensing of sea surface temperature and sea surface height. To examine the MODAS fields, the authors also used data from the Southern California Bight collected by the California Cooperative Fisheries Investigations as well as high-resolution hydrographic data collected over the continental shelf south of New England as part of the shelfbreak PRIMER experiment. MODAS performs well for features such as large-scale boundary currents and eddies but is more limited in resolving features such as shelfbreak and coastal fronts, which have small spatial and temporal correlation scales. Because of the considerable computational needs of other ESME modules and its use as a planning tool, the authors present a pragmatic approach for future applications.**

Index Terms—**Acoustic application, climatology, marine mammal, physical oceanography, thermohaline.**

I. Introduction

The effects of sound in the marine environment (ESME) team of scientists and engineers was presented with the considerable challenge of designing a risk assessment system for use by planners to reduce the possible effects of naval operations on marine mammals in different regions. The system requires representation of water column and ocean bottom properties, the use of acoustic propagation models to determine acoustic energy levels within the ocean, and the geographical distribution and hearing of marine mammals within a selected region. We will describe the efforts to collect and furnish the three-dimensional (3-D) thermohaline and sound speed fields for use in the ESME workbench suite of programs.

Two important constraints shaped our development of the "Water Column" module. 1) The coverage was required to be global, because naval operations occur over the entire planet in both shallow and deep waters. 2) Because the ESME workbench was primarily intended as a risk assessment tool to guide the future planning of naval operations, it was not possible to use atmospheric forecast fields for forcing an ocean model. The elapsed time between running the workbench and the planned operation (order of 6 months) is beyond the limits of predictability for both the ocean and the atmosphere. These requirements led us to consider global environmental products presently used by the operational U.S. Navy.

We will briefly describe the thermohaline and sound speed fields that we use, which consist of Naval Research Laboratory modular ocean data assimilation system (MODAS) and historical hydrographic fields. In Section II, we describe the MODAS system and historical data fields used for assessment. In Section III, we describe a deep-water case in the Southern California Bight (SCB). In Section IV, we describe a shallow-water case in the Middle Atlantic Bight (MAB). Limitations of the present approach are discussed in Section V, along with suggestions for future directions.

II. Methodology and Test Cases

A. Methodology

To calculate 3-D sound speed fields, it is necessary to obtain reasonable temperature and salinity fields. Although no single model or assimilated field can resolve all scales of variability, MODAS provides a blend between existing climatologies and assimilated in situ data. MODAS utilizes the Naval Oceanographic Office master oceanographic observation data set (MOODS) database, which contains a large number of classified sound speed profiles that are not accessible to academic oceanographers. In addition, satellite-collected surface temperature and height fields and bathythermograph temperature profiles from around the world can be assimilated to improve the climatological data.

As discussed earlier, the spatial and temporal constraints of the ESME system precluded our direct use of time-dependent numerical models for ocean temperature and salinity fields. Because of the large time lag between the expected use of the ESME workbench and the actual fleet operations, our approach was to identify one day out of the seasonal cycle (February 1 and August 1 for winter and summer, respectively) and use individual days over five separate previous years, so that some aspects of interannual variability could be addressed. For the comparison with the California Cooperative Fisheries Investigations (CalCOFI) data, we also considered the cases at various stages of the El Niño/Southern Oscillation (ENSO) cycle because of the long time period of this data set. We will now briefly describe the geographical setting of the two test cases, namely 1) the method for producing MODAS fields and 2) the other data sets used for comparison.

Manuscript received March 12, 2004; revised September 7, 2004; accepted June 10, 2005. This work was supported by the Office of Naval Research (ONR) under Grant N00014-00-10931. **Guest Editor: M. Siderius.**

The authors are with the Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA (e-mail: clinder@whoi.edu).

Digital Object Identifier 10.1109/JOE.2006.872206

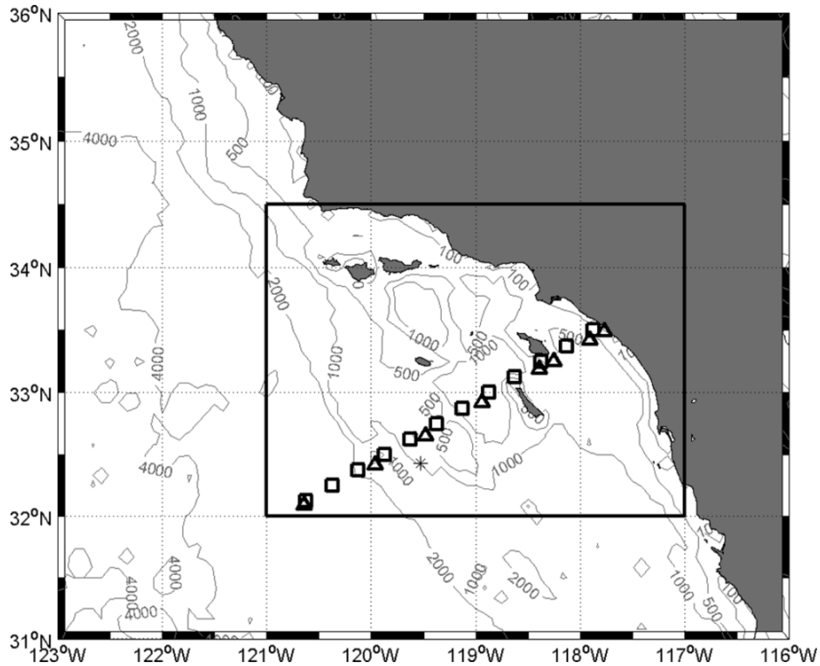


Fig. 1. SCB study area (denoted by the box) and location of data used in the study (triangles indicate CalCOFI stations and squares indicate MODAS stations). The bottom topography (in meters) is contoured in gray.

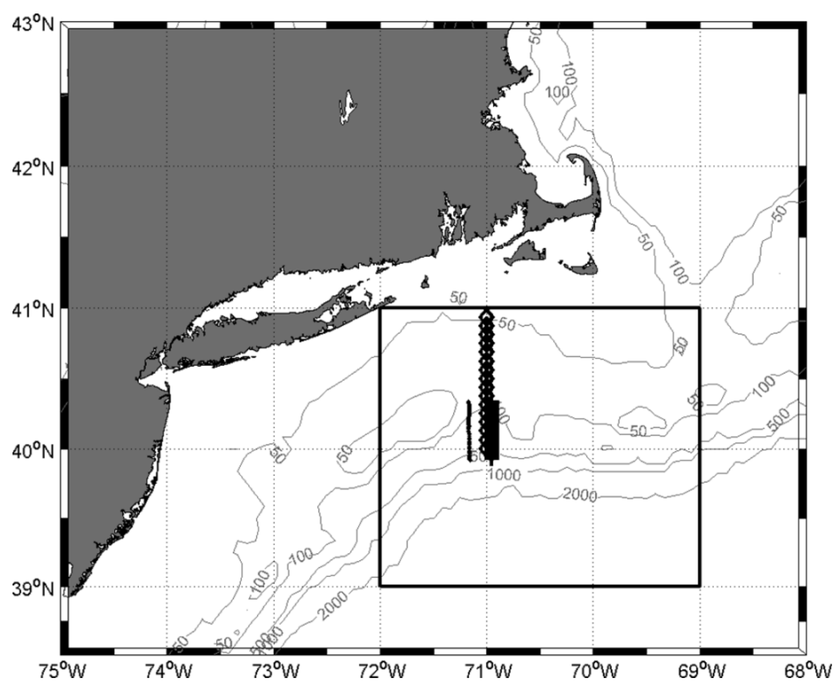


Fig. 2. MAB study area (denoted by the box) and location of data used in the study (diamonds indicate MODAS stations, the western line indicates summer PRIMER transect, and the eastern line indicates the winter PRIMER transect). The bottom topography (in meters) is contoured in gray.

B. Test Cases

We consider two ESME test regions, namely: 1) the SCB and 2) the MAB. These study areas reflect two different cases in acoustic propagation. The SCB is a deep-water case in which ray-tracing propagation models such as BELLHOP are effective, whereas the MAB is a shallow-water environment necessitating the use of modal technique code such as KRAKEN. Both types of codes are implemented in the ESME workbench [22], and the two test cases reflect the two major techniques for calculating acoustic propagation. We note that subbottom characteristics have been provided in a separate module for these two regions.

The SCB test region (Fig. 1) stretches from Point Conception to San Diego and is bounded by 32–34.5° N and 121–117° W.

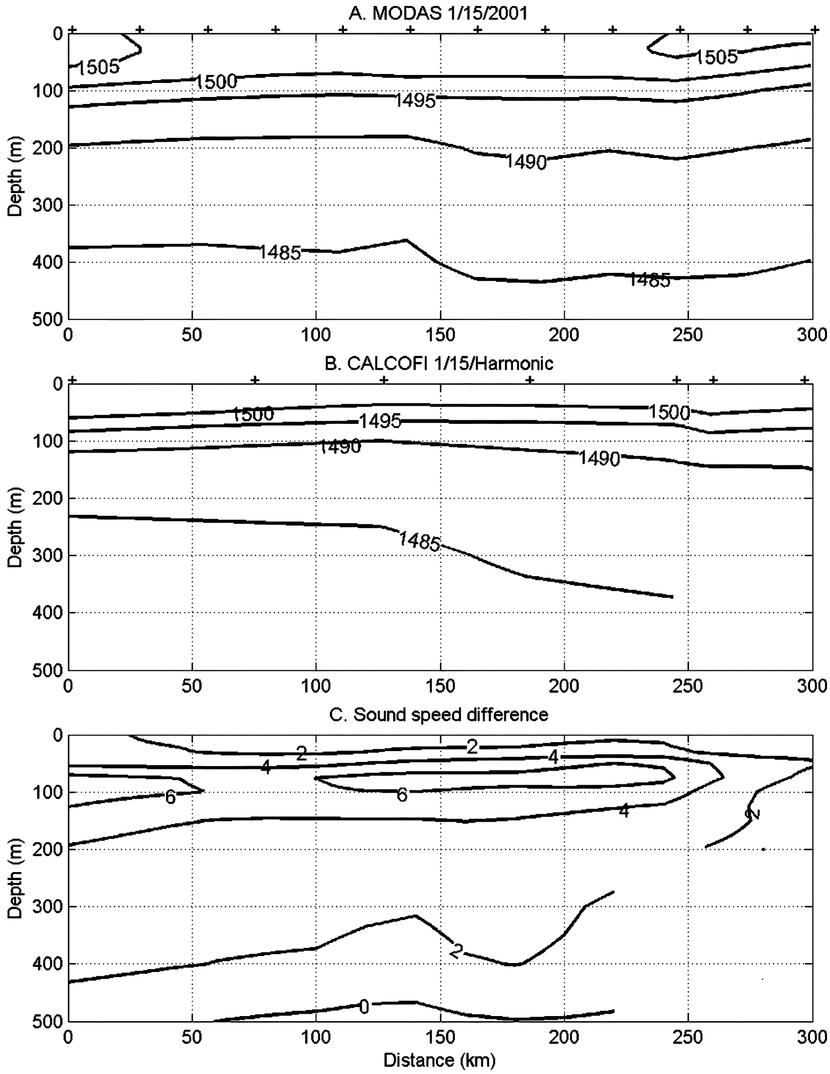


Fig. 3. Winter sound speed section from the SCB study area. (a) Dynamic MODAS field from January 15, 2001. (b) CalCOFI harmonic mean field from January 15, 2001. (c) Sound speed difference. Crosses indicate the position of vertical profiles.

The California coast is dominated by the eastern boundary current system known as the California Current System (CCS) [8]. The CCS includes the equatorward-flowing California Current, the poleward-flowing (in winter) Davidson Current, and the poleward-flowing California Undercurrent. The CCS is subject to strong wind forcing and, thus, considerable upwelling/downwelling. The SCB is a unique portion of the CCS; the oceanography is complicated by weaker wind forcing, narrower shelves (< 10 km), and a number of deep offshore basins (depth > 500 m). The region's complex bathymetry reduces the alongshelf scale, amplitude, and seasonal variation of the wind-driven signals. The annual cycle of temperature and salinity (T/S) variation in the deep-water (depth >1500 m) CCS has been well established by the CalCOFI project, but there are many smaller scale shallow-water processes in the SCB that have yet to be understood [20]. The CCS is also impacted by interannual ENSO forcing, which can cause temperature anomalies of the order of 2–4°C in water depths of 50–200 m.

The MAB (Fig. 2) is part of a large-scale coastal current extending from the Labrador shelf down to Cape Hatteras [16]. Mean currents are typically to the southwest, with inflows from the Gulf of Maine and Georges Bank contributing to interannual variability [19]. We have focused on the region bounded by 39–41° N and 70–72° W, which is the continental shelf south of southern New England. An important feature over the outer shelf is the shelfbreak front, a sharp transition in both temperature (up to 12°C over 20 km) and salinity that occurs near the shelfbreak [15]. In winter, mixing from storms homogenizes the shelf water, so that stratification over the shelf is weak or nonexistent. As insolation increases in spring, the seasonal thermocline (and pycnocline) begins to develop. The cold shelf waters that are bounded by the shelfbreak front and the seasonal thermocline during this time of year are known as the "cold pool." As the thermocline deepens through the summer, the slope of the frontal isopycnals decreases. Autumn, like spring, is a transition season—synoptic sections from this time tend to resemble either a summer regime or a winter regime depending on storm activity. As is the case with many midlatitude shelves, the changes in shelf stratification through the seasons are large, and the dominant physical processes change during the seasons as the stratification changes.

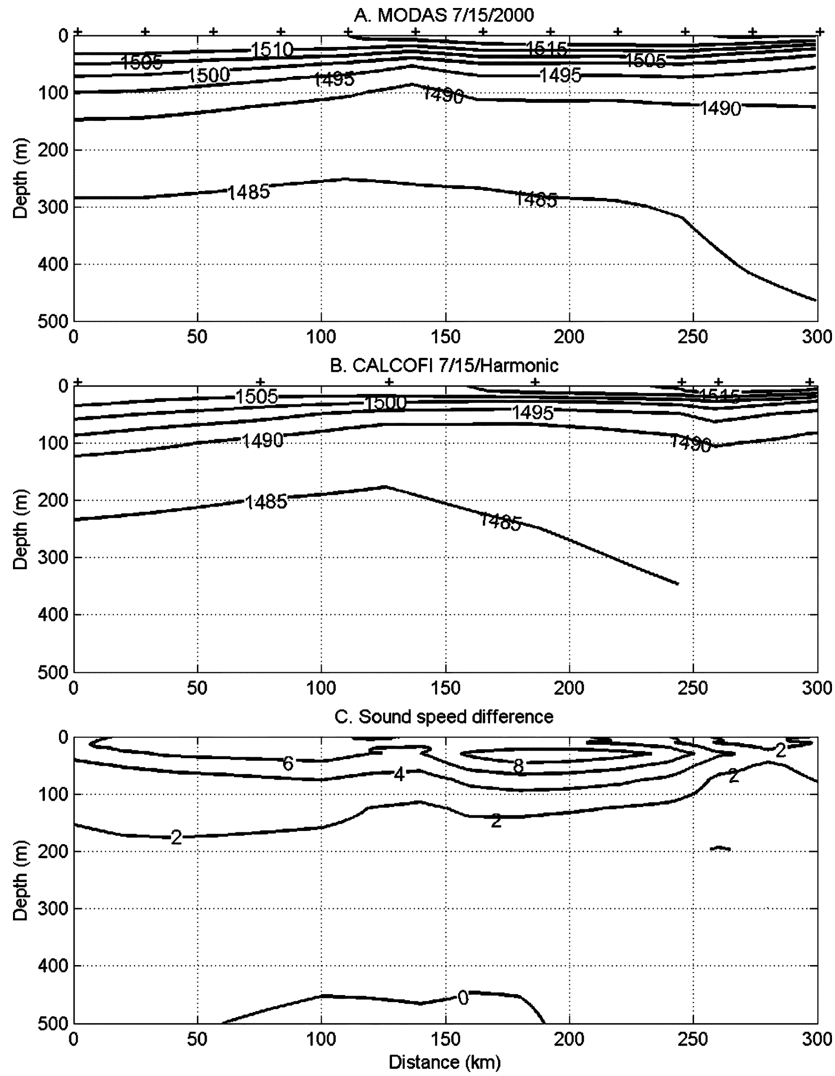


Fig. 4. Summer sound speed section from the SCB study area. (a) Dynamic MODAS field from July 15, 2000. (b) CalCOFI harmonic mean field from July 15, 2000. (c) Sound speed difference. Crosses indicate the position of vertical profiles.

C. MODAS

The Naval Research Laboratory MODAS [3] is a system for estimating global 3-D T/S. The program, primarily used by the U.S. Navy, consists of both static and dynamic climatology modes. In static mode, MODAS yields mean bimonthly T/S fields. Data in the upper 1500 m of the water column come from the MOODS database [21], and data below that come from *The World Ocean Atlas 1994* (U.S. Department of Commerce) [10]–[12]. In dynamic mode, MODAS merges in situ measurements such as bathythermograph traces, satellite altimetry, and sea surface temperature data with the static field via optimum interpolation. The assimilation of data in dynamic mode improves on the static climatology by more accurately depicting mesoscale ocean features such as fronts and eddies. MODAS spatial resolution varies from 1.0° in the deep ocean to one-eighth of a degree near the coast.

D. Other Data Sources

In addition to the MODAS data fields, we have analyzed several other data sources for the two study regions. The different data sets allow us to evaluate the strengths and weaknesses of the MODAS fields for the deep- and shallow-water cases.

In the SCB test region (Fig. 1), we analyzed repeat hydrographic sections from the CalCOFI data set [18]. The CalCOFI project was initiated in 1949 to study the collapse of the sardine fishery. Hydrographic stations have been occupied from 1950 to the present along cross-shelf transects. We analyze both mean fields and synoptic fields from strong El Niño and La Niña years.

For the shelf south of New England (Fig. 2), we have used both high-resolution in situ data from a recent field project as well as a recent climatology of the shelfbreak front. The Shelfbreak PRIMER Experiment [7] consisted of a set of cruises with SeaSoar [a towed undulating conductivity–temperature–depth (CTD)] sampling. Numerous cross-shelf SeaSoar sections were obtained during 1996 (spring and summer) and early 1997 (winter) [6], [7]. Details of the processing of these data are described in the two cited papers. The SeaSoar sections were located near 71° W, with cross-shelf transects sampled between the 90- and 500-m isobaths. Typical profiles were generally spaced 1 km apart in the cross-shelf direction.

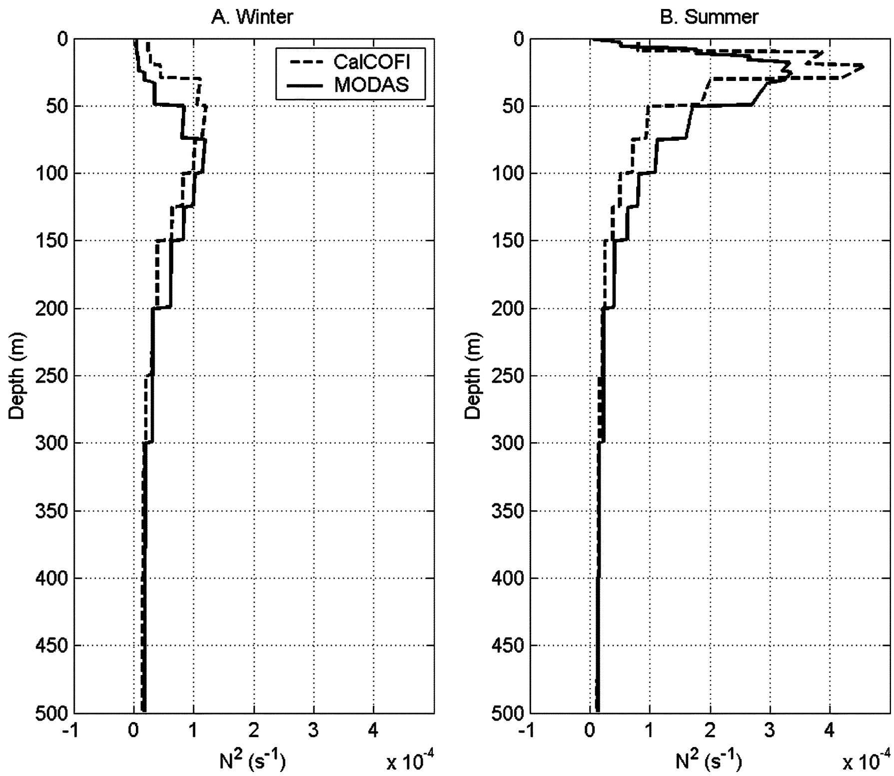


Fig. 5. Vertical profiles of (a) winter and (b) summer buoyancy frequencies (stratification) at $x = 150$ km cross-shelf distance from CalCOFI (dashed) and MODAS (solid) fields.

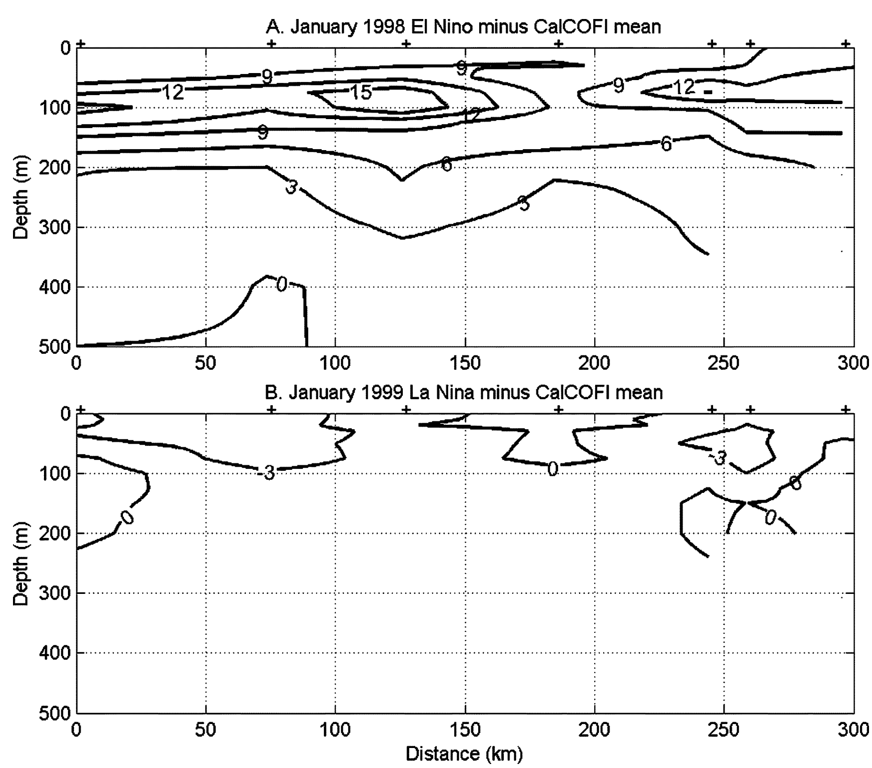


Fig. 6. Synoptic CalCOFI sound speed anomaly sections from the SCB study area. (a) January 1998 El Niño minus CalCOFI mean. (b) January 1999 La Niña minus CalCOFI mean. Crosses indicate the position of vertical profiles.

In addition, we have used a two-dimensional (2-D) (cross-shelf) climatology [15] of the shelfbreak region. The climatology averages 90 years of hydrographic data from the area south of Nantucket Shoals (the box delineated by 39–41° N, 69–72° W). The resulting bimonthly mean cross-shelf T/S fields describe the seasonal evolution of the shelfbreak front. Geostrophic ve-

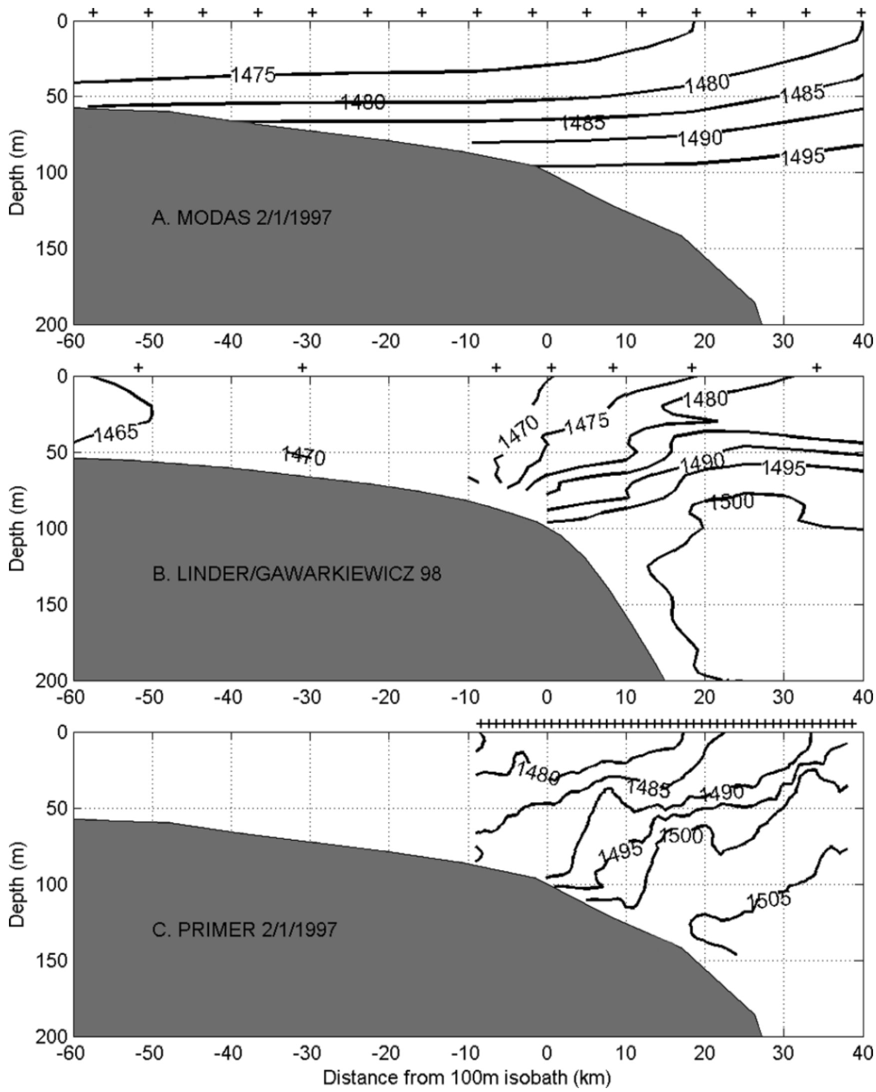


Fig. 7. Winter sound speed section from the MAB study area. (a) Dynamic MODAS field from February 1, 1997. (b) Linder and Gawarkiewicz 1998 climatology. (c) PRIMER February 1, 1997 synoptic section. Crosses indicate the position of vertical profiles.

locity calculations are also used to identify both the location and strength of the associated shelfbreak frontal jet.

III. Comparison of Fields in the SCB

A. MODAS and CalCOFI Mean Fields

To examine the water column features that affect sound propagation in the SCB, we have extracted 2-D cross-shelf sections from dynamic MODAS and CalCOFI harmonic fields from the southwest to northeast corners of the SCB study area. The CalCOFI section is the longest SCB section (number 90), and the MODAS section was extracted from the 3-D field. The sections are nearly coincident (data point locations are shown in Fig. 1). The MODAS data come from dynamic runs in midwinter (January 15, 2001) and midsummer (July 15, 2000). The CalCOFI fields are mean data for the same days. Fig. 3 shows the comparison of winter MODAS and CalCOFI data, whereas Fig. 4 shows that of the summer. Fig. 5 presents the buoyancy frequency (stratification) for winter and summer profiles located at $x = 150$ km.

Horizontal gradients in the SoCal region for both winter and summer are negligible compared to vertical gradients. Although the seasonal stratification profiles agree well qualitatively (Fig. 5), we computed the root-mean-square (rms) difference between horizontally averaged MODAS and CalCOFI sound speed fields to better quantify the differences. In winter, the rms difference is a maximum at a depth of 80 m with a value of 5 $\mathrm{m \cdot s^{-1}}$. The rms difference drops below 2 $\mathrm{m \cdot s^{-1}}$ at depths greater than 200 m. In summer, the rms difference is a maximum at a depth of 40 m with a value of 6.5 $\mathrm{m \cdot s^{-1}}$, with a similar decrease below 200 m. In both seasons, the CalCOFI field has a slightly lower (5–10 $\mathrm{m \cdot s^{-1}}$) average sound speed. We have examined several different winter and summer fields, both synoptic CalCOFI sections and dynamic MODAS runs, and found the magnitude and distribution of the differences to be similar.

B. Interannual Variability

The SCB is subject to interannual variability from El Niño and La Niña events. To quantify the effect of these events on the

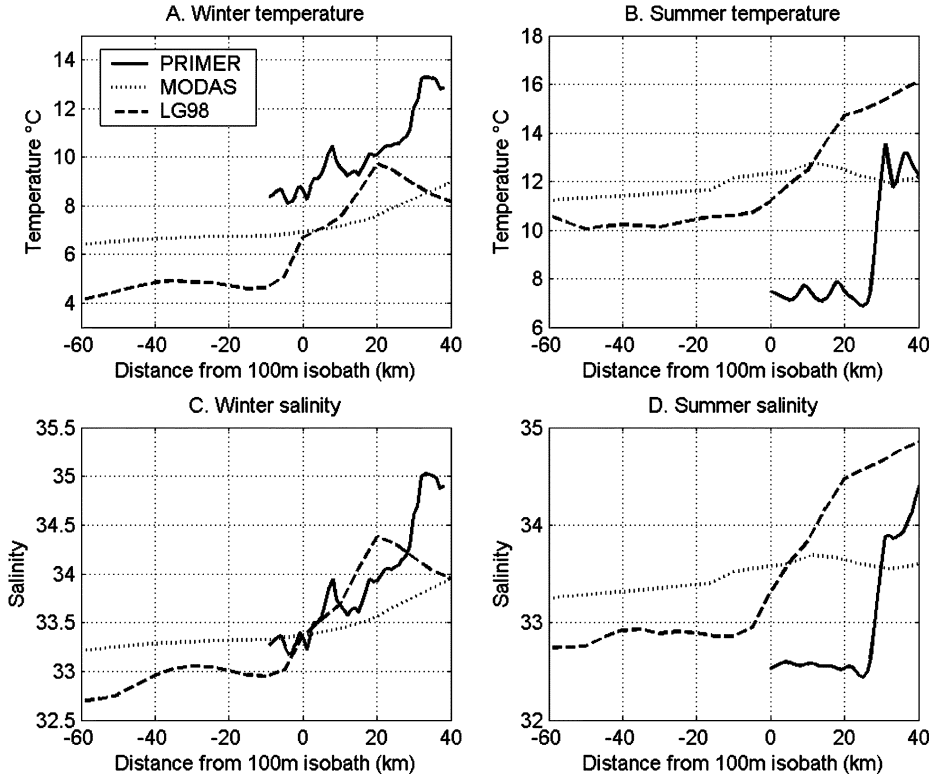


Fig. 8. Cross-shelf (a) winter temperature, (b) summer temperature, (c) winter salinity, and (d) summer salinity gradients at a depth of 40 m from the PRIMER (solid), Linder and Gawarkiewicz 1998 climatology (dashed), and dynamic MODAS (dotted) fields.

sound speed field, we selected strong El Niño (January 1998) and La Niña (January 1999) events for examination. During these two time periods, synoptic sections were collected as part of the CalCOFI program. We generated anomaly sections by subtracting the mean section data from the synoptic data. The resulting warm (El Niño) and cool (La Niña) plots are shown in Fig. 6.

The strong El Niño event was limited to the upper 200 m of the water column and produced a maximum sound speed anomaly of 15 $\mathrm{m \cdot s^{-1}}$. The La Niña event was also observed most strongly in the upper 200 m but was much weaker—the anomaly was a maximum of 5 $\mathrm{m \cdot s^{-1}}$. These anomalies show that interannual variability in the form of ENSO events has a significant effect on sound speed variability in this region. Prior knowledge of interannual patterns such as El Niño or the North Atlantic Oscillation is useful in selecting possible scenarios. However, there are few long-term data sets with regular sampling such as CalCOFI, so that in many regions of the world, one does not have the capability of selecting hydrographic data from known maximal interannual anomalies.

IV. Comparison of Fields for the MAB

A. Winter Conditions

Three different data sources are used to analyze a winter (early February) cross-shelf sound speed field in the MAB from 1997 (Fig. 7). The winter environment in the MAB is characterized by a cool fresh generally well-mixed shelf water mass, strong vertical and cross-shelf temperature and salinity gradients at the shelfbreak (the shelfbreak front), and a warm saline slope water mass. A comparison of three different winter cross-shelf fields appears in Fig. 7, namely: 1) dynamic MODAS for February 1, 1997; 2) Linder and Gawarkiewicz 1998 climatology (LG98); and 3) synoptic Shelfbreak PRIMER SeaSoar data from February 1, 1997. LG98 and PRIMER show the steep winter front stretching from its outcrop at the shelfbreak to its termination at the surface with a slope of 0.3°, whereas MODAS shows a broad diffuse front (slope 0.06°). In the MODAS field, the sound speed difference across the frontal region is roughly 20 $\mathrm{m \cdot s^{-1}}$ compared with nearly 30 $\mathrm{m \cdot s^{-1}}$ for both LG98 and PRIMER. This is due to the slope temperature and salinity in MODAS being much lower than those observed [Fig. 8(a) and (c)]. The LG98 field also underestimates the cross-shelf temperature and sound speed gradients for the same reason.

In general, the shelfbreak front provides a severe test of the MODAS fields. Correlation scales for the front are of the order of 8 km and 1 day [7], and in the absence of high-resolution hydrography, it is difficult to accurately capture both the cross- and alongshelf thermal and sound speed structures within the front. Underestimating the gradients affects acoustic mode coupling within the front, which will be discussed in Section V.

B. Summer Conditions

In summer, insolation creates a strong seasonal thermocline and pycnocline in the upper 40 m of the MAB (Fig. 9). The shelfbreak front is still present, but the cross-shelf thermal and sound speed gradients in the upper 40 m of the water column are

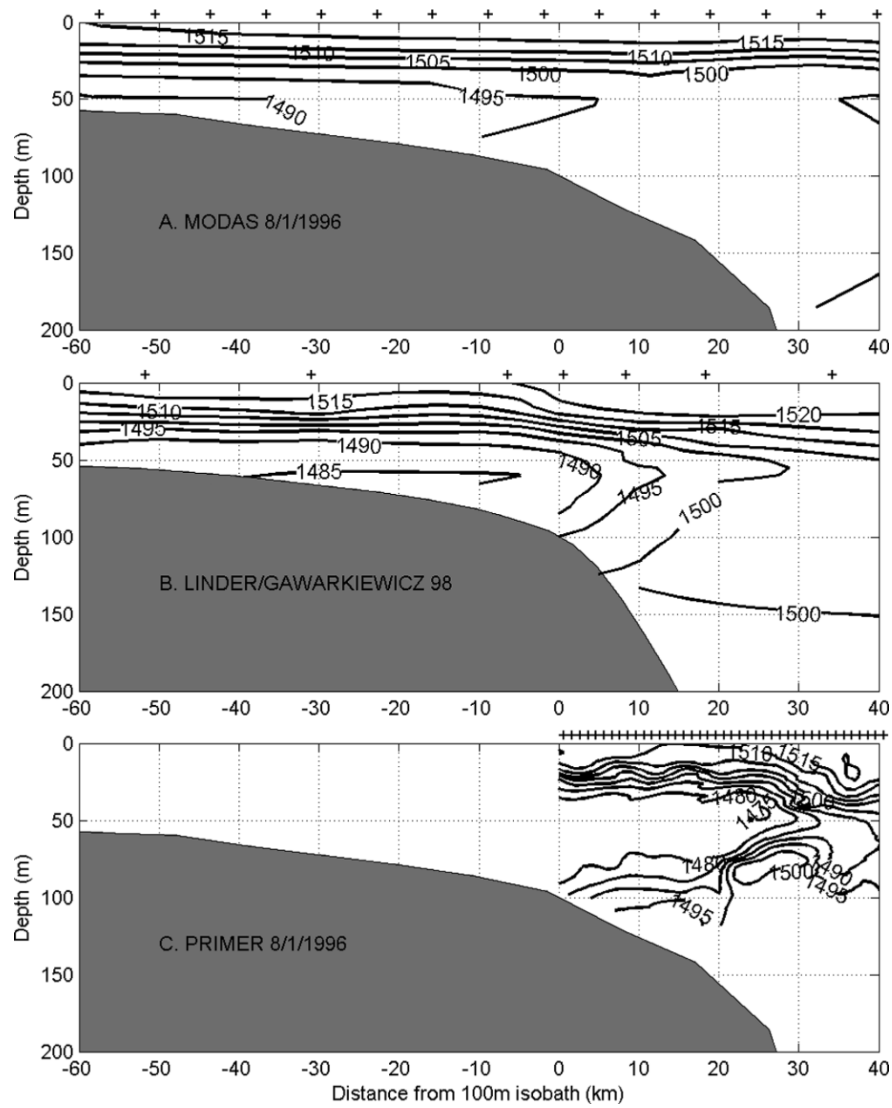


Fig. 9. Summer sound speed section from the MAB study area. (a) Dynamic MODAS field from August 1, 1997. (b) Linder and Gawarkiewicz 1998 climatology. (c) PRIMER August 1, 1997 synoptic section. Crosses indicate the position of vertical profiles.

substantially reduced due to warming. However, gradients beneath the upper 40 m remain large and comparable to winter subsurface gradients [Fig. 8(b) and (d)]. Differences in sound speed between the shelf water cold pool and the warmer slope waters can be almost 50 $\mathrm{m \cdot s^{-1}}$ across only 15 km. This is roughly comparable to a 10°C temperature difference across the front, which is fairly common. Whereas the MODAS field captures the vertical stratification (Fig. 10), the cross-shelf gradients are once again underpredicted (2°C/0.2 PSU over 20 km) compared with the synoptic PRIMER observations (7°C/1.5 PSU over 5 km) [Fig. 8(b) and (d)]. The cross-shelf gradients are slightly stronger (5°C/1.0 PSU over 20 km) within the LG98 climatology but still are not as large as those in the synoptic observations. For both summer and winter seasons, the MAB is clearly a range-dependent environment unlike the SCB.

V. Discussion

We will briefly discuss the limitations of the MODAS fields in the two test regions, focusing on physical processes that are not resolved in the fields. We note that high-frequency processes such as internal solitary waves are treated in a separate study [23]. We will conclude by discussing the possible future directions for the oceanographic inputs to the ESME workbench.

The cross-comparison between the MODAS data and the CalCOFI data is somewhat biased, because the CalCOFI data are sampled with a fairly coarse spatial resolution. Thus, smaller scale eddies such as those recently studied by Oey *et al.* [20] would not be resolved in the CalCOFI data. Similarly, the structure of the wind stress curl near Point Conception gives rise to some complicated alongshelf variability during coastal upwelling [1]. During periods of cloud- and fog-free conditions, the surface thermal data assimilation should provide useful information for the MODAS fields, but periods of extended fog or cloud cover would be problematic in resolving the alongshelf variability of the upwelling. In addition, temperature and sound speed fluctuations adjacent to the coast due to barotropic and baroclinic tides and diurnal sea breezes off land are not resolved [13], [14].

Overall, however, the dynamic MODAS fields provide a daily varying 3-D sound speed field that shows agreement within 6

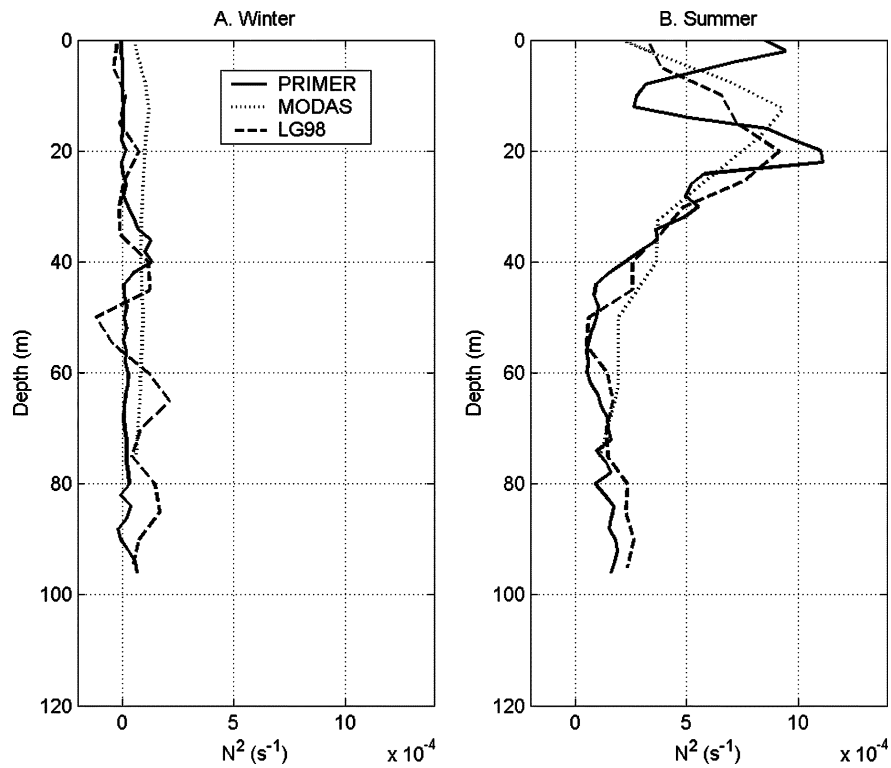


Fig. 10. Vertical profiles of (a) winter and (b) summer buoyancy frequencies (stratification) at the 100 m isobath from the PRIMER (solid), Linder and Gawarkiewicz 1998 climatology (dashed), and dynamic MODAS (dotted) fields.

$\mathrm{m \cdot s^{-1}}$ of the CalCOFI fields. In the deep-water portions of the domain (deeper than 200 m), the fields agree within 2 $\mathrm{m \cdot s^{-1}}$. The SCB can generally be characterized as a deep-water case in which there are no substantial horizontal gradients.

The shallow-water case in the MAB is complicated because of the presence of the shelfbreak front. Correlation scales are of the order of 8 km and 1 day [7]. A significant amount of data is necessary even to initialize a 3-D time-dependent model. Both the dynamic MODAS and the LG98 climatology underestimate the thermal and sound speed gradients relative to synoptic measurements (Fig. 8). This has a number of implications for acoustic propagation. First, mode coupling is strongly affected by the horizontal gradients within the front. Smoother fields result in less transfer of energy between modes within the frontal zone [17]. Second, meandering of the shelfbreak front also modulates the amplitude of shoreward-propagating internal solitary waves [2]. Whereas these internal waves are not present in our sound speed fields, they are present in the ocean and would lead to a variety of effects including scintillation. Third, the large lateral velocity shear within the front also traps inertial motion within the frontal zone [9] and affects the internal tide. Each of these effects would tend to increase the uncertainty of the transmission loss obtained from the ESME workbench relative to sound propagation in the real ocean at the shelfbreak.

Inasmuch as resolving horizontal gradients is difficult in such an energetic frontal zone, dynamic MODAS captures the vertical gradients of temperature and sound speed over the shelf (Fig. 10). For both the winter conditions with weak stratification over the shelf and the highly stratified summer conditions over the shelf, the dynamic MODAS field provides an accurate vertical structure for the sound speed field, which is important for acoustic modal structures and mode coupling.

To estimate the variability that MODAS can resolve, we examined the standard deviation of the temperature, salinity, and sound speed of a summer climatology field. The standard deviation was a maximum at mid-depth (30–50 m), matching PRIMER observations, but was spread equally over the shelf, shelfbreak, and slope [Fig. 11(a)]. The Shelfbreak PRIMER observations and the LG98 climatology both show a strong local peak in the variance of sound speed within the front, which is surface-trapped in winter and centered beneath the seasonal pycnocline at a depth of 30m in summer [Fig. 11(b) and (c)]. This is consistent with frontal modal structures computed from a linear stability model [5].

We have deliberately avoided quantifying the effects of the differences in sound speed fields on acoustic energy intensity fluctuations. Because of the possible effects of frequency dependence, the oceanographic processes not resolved in the MODAS fields such as internal waves, and the relative contribution of uncertainties from other modules, we feel that a simple answer that only covers a few cases of propagation would be misleading. For a thorough analysis of intensity fluctuations in the Shelfbreak PRIMER region, we direct the reader to [4], which has a detailed discussion of the impact of oceanographic processes on the observed temporal variability in intensity fluctuations. Lynch *et al.* [23] directly address high-frequency and 3-D propagation effects not treated in the ESME toolbox.

In the future, the use of regional time-dependent models with higher horizontal resolution (order of 1 km) would be useful in resolving the coastal ocean response to synoptic wind forcing

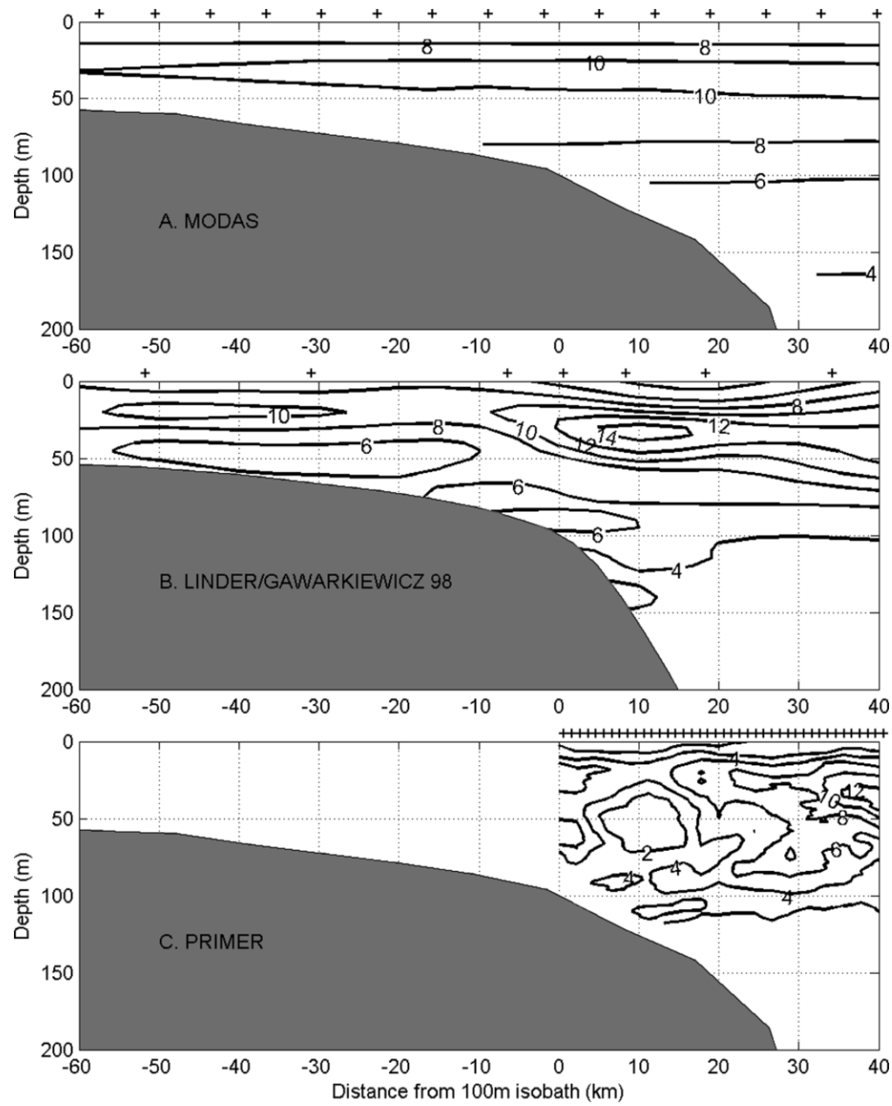


Fig. 11. Summer MAB sound speed variance of (a) MODAS climatology, (b) Linder and Gawarkiewicz 1998 climatology, and (c) 18 cross-shelf SeaSoar synoptic sections. Crosses indicate the position of vertical profiles.

and would help resolve processes such as the baroclinic tides. Eventually, if the ESME workbench is used in fixed locations, the assimilation of data from fixed sites such as coastal oceanographic observatories or naval test ranges would be extremely useful in augmenting global products and models.

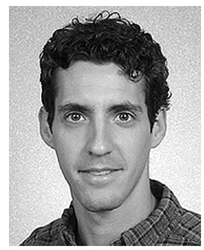
ACKNOWLEDGMENT

The authors would like to thank D. Fox for generously providing the MODAS data and for the rapid response to the numerous questions and requests for fields, B. Northridge of CNMOC for suggestions and advice, other ESME investigators for many stimulating discussions, particularly H.-J. Shyu and R. Hillson for pulling the modules together, and, finally, B. Gisiner for being an inspiring leader and motivator throughout this complicated project, who was ably assisted by A. Hansen. Discussions with J. Lynch, J. Colosi, M. Porter, and M. Siderius were helpful in appreciating some of the acoustic issues involved in this process.

REFERENCES

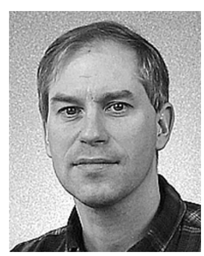
[1] K. H. Brink and R. D. Muench, “Circulation in the Point Conception–Santa Barbara channel region,” *J. Geophys. Res.*, vol. 91, no. C1, pp. 877–895, Jan. 1986.
[2] J. A. Colosi, R. C. Beardsley, J. F. Lynch, G. Gawarkiewicz, C.-S. Chiu, and A. Scotti, “Observations of nonlinear internal waves on the outer New England continental shelf during the summer Shelfbreak Primer study,” *J. Geophys. Res.*, vol. 106, no. C5, pp. 9587–9602, May 2001.
[3] D. N. Fox, W. J. Teague, and C. N. Barron, “The Modular Ocean Data Assimilation System (MODAS),” *J. Atmos. Ocean. Technol.*, vol. 19, no. 2, pp. 240–252, 2001.
[4] A. Fredricks, J. Colosi, J. Lynch, G. Gawarkiewicz, C.-S. Chiu, and P. Abbot, *J. Acoust. Soc. America*, vol. 117, no. 3, pp. 1038–1057, 2005.
[5] G. Gawarkiewicz, “Linear stability models of shelfbreak fronts,” *J. Phys. Oceanogr.*, vol. 21, no. 4, pp. 471–488, 1991.
[6] G. Gawarkiewicz, F. Bahr, R. Beardsley, and K. Brink, “Interaction of a slope eddy with the shelfbreak front in the Middle Atlantic Bight,” *J. Phys. Oceanogr.*, vol. 31, no. 9, pp. 2783–2796, 2001.
[7] G. Gawarkiewicz, F. Bahr, K. Brink, R. Beardsley, M. Caruso, J. Lynch, and C.-S. Chiu, “A large amplitude meander of the shelfbreak front in the Middle Atlantic Bight: Observations from the Shelfbreak PRIMER Experiment,” *J. Geophys. Res.-Oceans* , vol. 109, 2004.
[8] B. Hickey, “Coastal oceanography of western North America from the tip of Baja California to Vancouver Island,” in *The Sea*, A. R. Robinson and K. H. Brink, Eds. New York: Wiley, 1998, vol. 11, pp. 345–393.

[9] E. Kunze, "Near-inertial wave propagation in geostrophic shear," *J. Phys. Oceanogr.*, vol. 15, no. 5, pp. 544–565, 1985.
[10] S. Levitus, "Climatological Atlas of the World Ocean," *NOAA Prof. Paper*, vol. 13, p. 173, 1982.
[11] S. Levitus and T. Boyer, "Temperature," *National Oceanic and Atmospheric Administration (NOAA) Atlas National Environmetnal Satellite, Data, and Information Service (NESDIS)*, vol. 4, p. 150, 1994. World Ocean Atlas 1994.
[12] S. Levitus, R. Burgett, and T. Boyer, "Salinity," *National Environmetnal Satellite, Data, and Information Service (NESDIS)*, vol. 3, p. 150, 1994. World Ocean Atlas 1994.
[13] J. A. Lerczak, M. C. Hendershott, and C. D. Winant, "Observations and modeling of coastal internal waves driven by a diurnal sea breeze," *J. Geophys. Res.*, vol. 106, no. C9, pp. 19 715–19 729, 2001.
[14] J. A. Lerczak, C. D. Winant, and M. C. Hendershott, "Observations of the semidiurnal internal tide on the southern California slope and shelf," *J. Geophys. Res.*, vol. 108, no. C3, Mar. 2003.
[15] C. Linder and G. Gawarkiewicz, "A climatology of the shelfbreak front in the Middle Atlantic Bight," *J. Geophys. Res.*, vol. 103, no. C9, pp. 18 405–18 423, Aug. 1998.
[16] J. W. Loder, B. Petrie, and G. Gawarkiewicz, "The coastal ocean off northeastern North America: A large-scale view," in *The Sea*, A. R. Robinson and K. H. Brink, Eds. New York: Wiley, 1998, vol. 11, pp. 105–133.
[17] J. F. Lynch, A. Newhall, B. Sperry, G. Gawarkiewicz, A. Fredricks, P. Tyack, C. S. Chiu, and P. Abbot, "Spatial and temporal variations in acoustic propagation characteristics at the New England shelfbreak front," *IEEE J. Ocean. Eng.*, vol. 28, no. 1, pp. 129–150, Jan. 2003.
[18] R. Lynn, K. Bliss, and L. Eber, "Vertical and horizontal distributions of seasonal mean temperature, salinity, sigma-t, stability, dynamic height, oxygen, and oxygen saturation in the California Current, 1950–1978," *CalCOFI Atlas no. 30*, 1982.
[19] D. G. Mountain, "Variability in the properties of shelf water in the Middle Atlantic Bight, 1977–1999," *J. Geophys. Res.*, vol. 108, no. C1, Jan. 2003.
[20] L.-Y. Oey, C. Winant, E. Dever, W. R. Johnson, and D.-P. Wang, "A model of the near-surface circulation of the Santa Barbara channel: Comparison with observations and dynamical interpretations," *J. Phys. Oceanogr.*, vol. 34, no. 1, pp. 23–43, 2004.
[21] W. J. Teague, M. J. Carron, and P. J. Hogan, "A comparison between the generalized digital environmental model and Levitus climatologies," *J. Geophys. Res.*, vol. 95, no. C5, pp. 7167–7183, May 1990.
[22] M. Siderius and M. B. Porter, "Modeling techniques for marine-mammal risk assessment," *IEEE J. Ocean. Eng.*, vol. 31, no. 1, pp. 49–60, Jan. 2006.
[23] J. F. Lynch, J. A. Colosi, G. Gawarkiewicz, T. F. Duda, A. D. Pierce, M. Badiey, B. G. Katsnelson, J. E. Miller, W. Siegmann, C.-S. Chiu, and A. Newhall, "Consideration of fine-scale coastal oceanography and 3-D acoustics effects for the ESME sound exposure model," *IEEE J. Ocean. Eng.*, vol. 31, no. 1, pp. 33–48, Jan. 2006.



Christopher A. Linder received the S.B. degree from the Department of Oceanography, United States Naval Academy, Annapolis, MD, in 1994, and the M.S. degree in ocean engineering from the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in ocean engineering, Woods Hole, MA, in 1996.

He is a Research Associate in the Physical Oceanography Department, Woods Hole Oceanographic Institution. His research interests include dynamics and modeling of shelfbreak fronts, climatic variability of shelf and slope waters, and data visualization.



Glen G. Gawarkiewicz received the S.B. degree in ocean engineering from the Department of Ocean Engineering, Massachusetts Institute of Technology, Cambridge, in 1981, and the Ph.D. degree in physical oceanography from the University of Delaware, Newark, in 1989.

He is a Physical Oceanographer at the Woods Hole Oceanographic Institution, Woods Hole, MA. His research interests include frontal dynamics, continental shelf processes including shelf/slope exchange and water mass formation, impact of oceanographic processes on acoustic propagation, and marine mammal habitats and their relation to ocean features.