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JASA LETTER TO THE EDITOR

Real-time joint ocean acoustics and circulation modeling in the 2021 New England Shelf Break Acoustics experiment (L)

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ABSTRACT:
During the spring of 2021, a coordinated multi-vessel effort was organized to study physical oceanography, marine geology and biology, and acoustics on the northeast United States continental shelf, as part of the New England Shelf Break Acoustics (NESBA) experiment. One scientific goal was to establish a real-time numerical model aboard the research vessel with high spatial and temporal resolution to predict the oceanography and sound propagation within the NESBA study area. The real-time forecast model performance and challenges are reported in this letter without adjustment or re-simulation after the cruise. Future research directions for post-experiment studies are also suggested. https://doi.org/10.1121/10.0015139

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I. INTRODUCTION

Complex environmental features exert strong influences on sound propagation in the northeast continental shelf environment of the United States. In recent decades, the 1995 Shallow Water Acoustics in Random Media (SWARM) experiment,[1] the 1996 shelf break PRIMER study,[2] and the Shallow Water 2006 (SW06) experiment[3] have investigated some of the acoustically significant phenomena present on the continental shelf. Building on these pioneer projects, the New England Shelf Break Acoustics (NESBA) experiment was conducted in the spring of 2021 to focus on the acoustic effects of shelf break fronts, warm-core ring intrusions,[4,5] mesopelagic organisms, and other marine geological and biological features. The NESBA experiment included coordinated efforts of research vessels (RVs) Neil Armstrong, Hugh R. Sharp, and Endeavor. A network of fixed source moorings, hydrophone receivers, and physical oceanographic moorings was deployed along and across the shelf break. Additionally, water column measurements from the Ocean Observatories Initiative (OOI) Coastal Pioneer Array were used to supplement the NESBA network observations. Last, shipboard conductivity, temperature, and depth (CTD) and expendable bathythermograph (XBT) cast data from the participating RVs collectively provided a regularly updated library of ocean state information. One of the primary objectives of the NESBA experiment was to identify acoustically sensitive oceanic processes and features and study their influence on the planned 15-min duty cycle acoustic transmissions within the NESBA network. In pursuit of this goal with a combined numerical and *in situ* observational approach, RV Armstrong carried specialized high-performance computing (HPC) equipment for generating real-time Physical Oceanographic (PO) and ocean acoustic (OA) numerical forecasts with high spatial and temporal resolution during one of the NESBA experiment cruises from May 10 to May 17. The PO modeling was based on the Regional Ocean Modeling System (ROMS), specifically the data assimilative ROMS-based DOPPIO model[6] and North American Mesoscale Forecast System (NAM). Ocean and meteorological fields of these baseline models used for PO boundary conditions had a spatial resolution of 7 km and were downloaded daily from land-based servers to force the real-time model with a higher resolution (as small as 300 m) implemented on a small computer cluster of ten Intel® Xeon® Gold 6226R central processing units (CPUs) aboard RV Armstrong. This real-time PO model forced by DOPPIO and NAM boundary conditions generated forecasts with a time interval of 15 min. The predicted PO fields were then funneled into the OA model of broadband sound propagation based on the two-dimensional (2D) broadband parabolic equation (PE) and ray-tracing methods carried out on two additional shipboard HPC workstations equipped with four NVIDIA® DGX V100 graphics processing units (GPU) each. The OA models used a 25-m resolution bathymetry grid provided by the United States Geological Survey (USGS). To demonstrate the true predictive capability of the onboard system, two separate sets of NESBA acoustic transmissions and the corresponding real-time OA model predictions obtained during the 8-day cruise are presented in this

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letter, without model adjustment or re-simulation after the cruise.

One of the challenges this *in situ* real-time numerical modeling effort encountered was limited observational and computational resources. The three ships coordinating field sampling efforts were not enough to cover the entire NESBA study area of 30 km × 30 km for measuring time-varying three-dimensional (3D) PO and OA fields. Furthermore, the performance of numerical models was constrained by the HPC equipment the research vessel could carry. Another challenge was the limited time window given to complete this at-sea exercise, with a total of 6 days to initiate, fine-tune, and test the real-time models for predicting the highly temporally variable PO and OA fields. Despite these challenges, the shipboard physics-based prediction system was still able to provide real-time forecasts that compared favorably to observed data. While detailed sub-bottom surveys were carried out during the NESBA experiment, sediment layer interfaces and properties were not included in the shipboard modeling, with a goal of refining the simulations during post-cruise model and data analysis. The acoustic transmissions within the NESBA network were then simulated with high spatial resolution two-dimensional broadband parabolic equation (2DBBPE) and acoustic ray models. Using these computing resources, acoustic forecasts produced while at sea could be compared directly with real-time observed data.

II. NESBA NETWORK ACOUSTIC TRANSMISSIONS AND SAMPLING TRACKS

To study acoustic propagation in the presence of Gulf Stream warm-core ring interactions with cooler shelf water masses, the NESBA network was designed to form along- and across-shelf break tracks connecting the center of the network to the four corner moorings [labeled as TM2, TM3, TM4, and SM1 in Fig. 1(a)]. The primary objective of the experiment was to predict signals received on a vertical hydrophone array at the center of the network, AT [Fig. 1(a)]. Other propagation paths in the study that can motivate post-experiment data analyses and research include along-shelf propagation (TM2 East and TM3 West) and cross-slope propagation (SM1 North and TM4 South). Water depth, instrument depth, frequency band, and transmission signal types at all of the NESBA network nodes are summarized in Table I. This letter focuses primarily on cross-shelf propagation along the south path with transmissions between TM4 and AT.

III. SHIPBOARD REAL-TIME PREDICTIVE MODELING AND VALIDATION

To accomplish the real-time *in situ* acoustic predictions, daily PO and OA forecasts were produced for time-stepping range-dependent broadband impulsive sound propagation to the center of the NESBA network from the moored sources. The sub-bottom environment in the real-time prediction system was modeled as a homogeneous sand-like bottom with

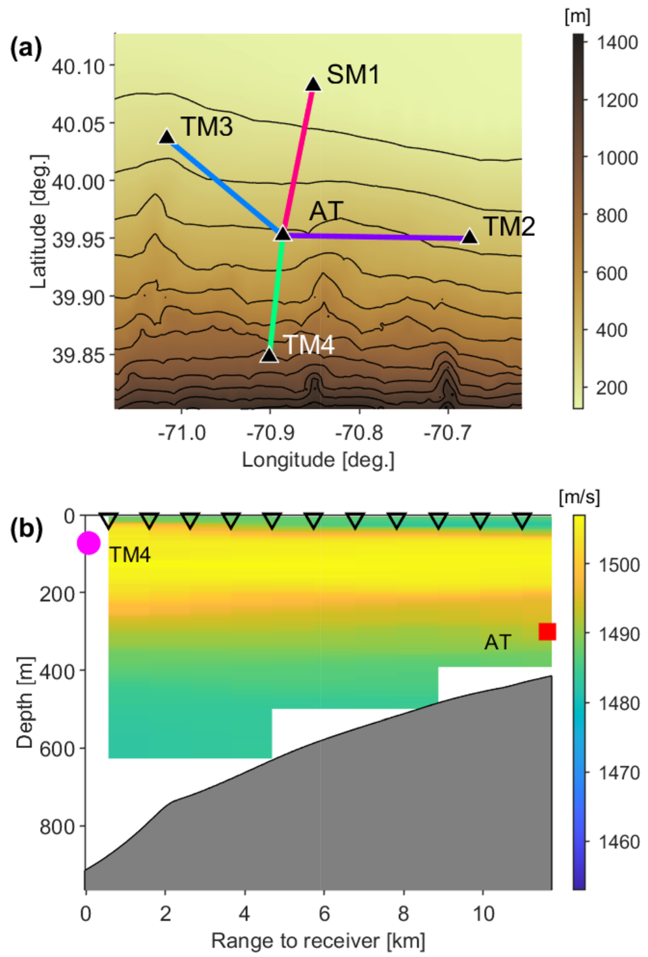

FIG. 1. (Color online) (a) The NESBA network. Solid lines connecting the four corner moorings denote the acoustic propagation paths. (b) CTD sound speed transect from RV Sharp, demonstrating the existence of an acoustic surface duct. Triangles at the surface denote the location of CTD casts.

a sound speed of 1650 m/s, a density of 1800 kg/m^3, and attenuation of 0.5 dB per acoustic wavelength. Note that the simulated acoustic arrivals were predictive, produced prior to collecting (both PO and acoustic) experimental data, such that predictions could be used to assess the predictive skill of the PO and OA models in capturing future ocean states.

Figure 1(b) shows CTD measurements from the RV Sharp in the form of a sound speed transect along the south NESBA track. This transect clearly includes an acoustic

TABLE I. The list of fixed key instruments in the NESBA network. All moorings were equipped with hydrophone arrays even though they are not listed here.

Mooring	Water depth (m)	Instrument depth (m)	Instrument type	Frequency band	Signal
AT	415	300	Hydrophone	—	—
SM1	150	90	Source	475–775 Hz	4 s up-sweep
TM2	369	89	Source	575–925 Hz	4 s up-sweep
TM3	262	66	Source	575–925 Hz	4 s down-sweep
TM4	893	73	Source	475–775 Hz	4 s down-sweep

surface duct, a low sound speed feature that was associated with the shelf water streamer[4,5] and is known to trap acoustic energy near the sea surface at frequencies determined primarily by the thickness of the layer. Figure 2(a) shows a PO prediction (model 1) of sound speed along the south track used prior to May 11 (day 2), in which the surface duct is absent due to the lack of a predicted shelf water streamer layer. Real-time model-observation comparison onboard in the beginning of the cruise on May 11 showed that the model deficiency resulted from temperature and salinity biases in the imported DOPPIO ocean boundary conditions. Persistent model biases in temperature and salinity were identified at all available CTD casts at the time, which were likely caused by over-mixing in the DOPPIO model in the thin surface layer of cold and fresh shelf water over the warm and salty ring water. To correct the bias in real time, vertical profiles of the mean model-observation differences in temperature and salinity in the first day of the cruise on May 10 were subtracted from the DOPPIO output in the subsequent days before providing boundary conditions to the real-time NESBA PO model. After correcting the bias, the real-time forecast model (model 2) produced on May 12 (day 3) started qualitatively capturing the thin surface layer of shelf water streamer overlying the mid-layer of warm-core ring water [Fig. 2(b)], which was confirmed with the observation on May 13 (day 4) [Fig. 1(b)]. Through the use of acoustic ray models, the effect of the thin surface layer was observed to significantly alter the sound propagation paths between the source and receiver, by trapping acoustic energy in the shelf water streamer for many kilometers.

Data–model comparisons of acoustic arrivals at the center of the NESBA network (AT) on May 14 (day 5) at 300 m depth using both versions of the ocean circulation model (pre- and post-bias correction—models 1 and 2, respectively) demonstrate the acoustic importance of the surface duct. Note that the model prediction was produced at the end of May 13 (day 4), prior to the observation. Figure 2(c) contrasts real acoustic data (labeled Data) in the bottom panel, with acoustic predictions generated by PO models 1 and 2 from Figs. 2(a) and 2(b). The bottom-most panel of Fig. 2(c) (labeled Data) presents real data collected along the south track during the NESBA experiment. A visual inspection shows significant offset and mismatch in all of the predicted arrivals from model 1. On the other hand, two features of model 2 suggest a better agreement with the data than model 1: (1) presence of initial acoustic arrivals that were absent in model 1 (around 8 s travel time) and (2) re-alignments of later arrivals that propagated through the mid-layer of warm-core ring water. To highlight the improvement in model 2, four distinct arrival groups are outlined in Fig. 2(c).

In the final validation test of this real-time *in situ* PO and OA prediction study on May 16 (day 7), a WHOI REMUS 600 autonomous underwater vehicle (AUV) equipped with a towed hydrophone array was deployed at a depth of 300 m to record the range-dependent acoustic

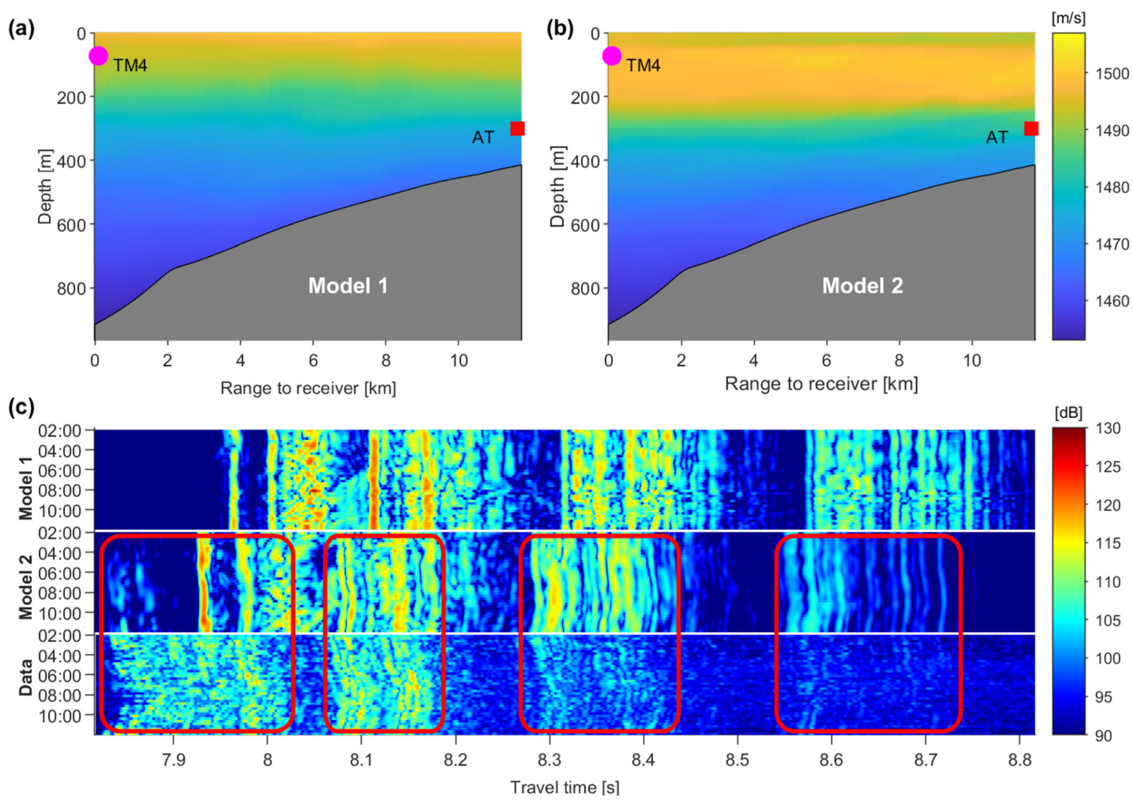

FIG. 2. (Color online) Comparison of NESBA data to predictive models. Shown are vertical sound speed transects along the south track in (a) PO model 1 with no surface duct and (b) PO model 2 with a surface duct. (c) Comparison of predicted and observed acoustic arrivals from TM4 to AT on May 14. The vertical axis is the signal transmission time in UTC.

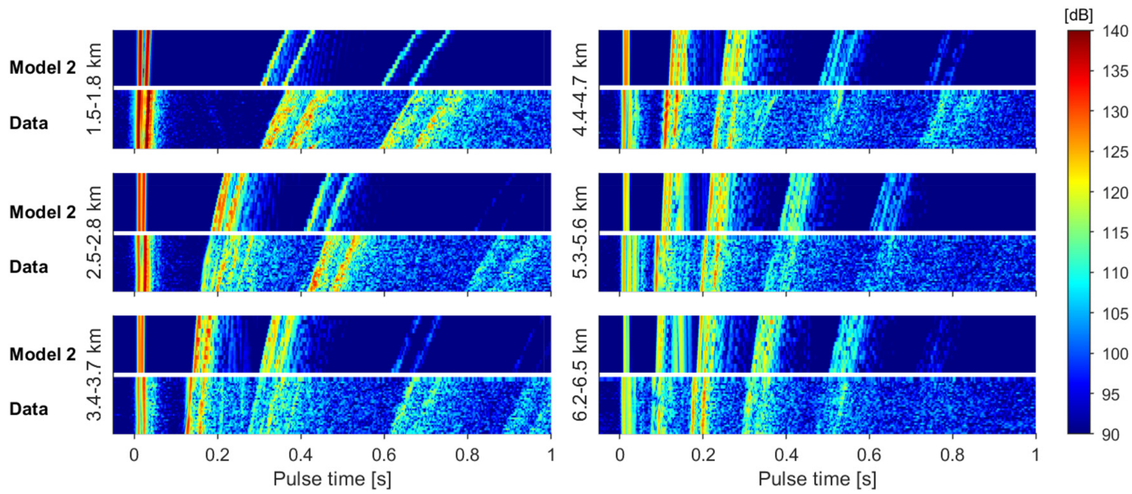

FIG. 3. (Color online) Comparison of acoustic signal strength in the south track model to the AUV towed array data. The AUV recorded six TM4 transmission cycles. Pulse time is estimated using AUV position and average ocean sound speed.

transmissions along the south track of the network originating from the TM4 source. Figure 3 presents a comparison between the AUV hydrophone recordings and the acoustic forecast based on PO model 2 prior to the final test on May 15 (day 6). The model is compared at six range bands, which coincide with the location of the AUV during the TM4 15-min transmission cycles, illustrating the ability of PE modeling to capture the physics of acoustic propagation at multiple positions along a range-dependent sampling track. The first band at 1.5–1.8 km from the source shows strong alignment of arrivals between data and prediction, while the later bands show a shift in arrival times by tens of milliseconds after the first arrivals, which was likely caused by AUV 3D position errors. Despite some data–model mismatch due to overpowering oceanographic dynamics and geological complexity, the two model validation efforts exercised at sea indeed demonstrate the possibility of producing *in situ* high resolution PO and OA forecasts at a fine temporal scale, identifying the presence of acoustically sensitive ocean processes.

IV. CONCLUSION

The 2021 NESBA experiment provided the opportunity to demonstrate real-time PO and OA forecast simulations using shipboard HPC resources. This timely process enabled the *in situ* analysis of observed ocean and acoustic data to identify acoustically sensitive environmental processes from a PO perspective. Future testing of this real-time forecast method will include more realistic mesopelagic biological and seabed sub-bottom layering representations, and efficient 3D propagation simulation may be considered to address strongly range-variable ocean environments. Additional modifications to the modeling techniques could employ knowledge of small scale PO features and biological scattering to aid in accounting for signal fluctuation that is not currently predicted by the models. Another future direction is whether to include prediction of the ambient noise caused by either natural processes or anthropogenic activities in the field.

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