N000141613072 : Characterizing along- and cross-channel variability in optical and acoustic backscatter during USRS using AUVs

FINAL REPORT

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1) Major Goals

Our long-term goals starting this project were to: (a) Characterize along- and cross-channel variability of the saltwater intrusion into the estuary, and (b) Relate suspended sediment transport, and in particular turbidity maximum occurrences, to the principle forcing variables (river flow, tidal mixing, stratification). Our primary objective while studying any particular estuary was to identify and resolve hydrodynamic features (e.g., salt wedge front, internal hydraulic jumps, fronts) that exhibit anomalous optical and acoustic backscatter so we can ultimately better understand the importance of these hydrodynamic features on mixing of fresh and salt water and sediment and bubble transport. A secondary objective was to develop a better predictive capability for the quality of acoustic communications in the presence of hydrodynamic features. While achieving these goals we aimed to advance approaches to autonomous surveying of estuaries using autonomous underwater vehicles (AUVs). Of relevance to ONR, this work contributes to a better understanding of how different hydrodynamic features affect optical and acoustic backscatter and transmission by altering distributions of suspended sediment and bubbles in the dynamic and variable estuarine environment. We are also developing advanced adaptive sampling capabilities based on sensor-equipped AUVs in combination with numerical circulation models.

2) Accomplishments Under Goals

During USRS we participated in three major experiments using two REMUS-100 AUVs carrying CTDs for temperature and salinity, ADCPs for currents and high frequency acoustic backscatter, marine optic sensors for turbidity and fluorescence, and optodes for dissolved oxygen (O_2). In addition, the AUVs carried broadband hydrophones in collaboration with Dr. D. Benjamin Reeder (NRL). Each experiment was conducted in a different estuary that was chosen to provide a wide range of river and tidal forcing. Each estuary also had a prominent frontal feature associated with a particular phase of the tide that was the primary focus of study during the experiment (see Table 1). Launch and recovery of the vehicles was typically by small boat. A Gateway Buoy was purchased prior to the second experiment (courtesy of a DURIP grant) and used to redirect the AUVs through the front to increase the density of sampling at the front.

After the first Connecticut River experiment, it was clear that a novel feature of the AUV data set was the O_2 saturation level anomaly measured across the front. Figure 1 shows an example section with an approximately 2 % dissolved O_2 saturation change. Concurrent acoustic backscatter intensity from the ADCP revealed the presence of a large subsurface bubble plume caused by the salty coastal ocean waters of Long Island Sound subducting under fresher Connecticut River ebb plume waters. These observations had strong similarities to prior investigations made in much larger fronts of coastal systems and fjords, but these were the first detailed measurements at the smaller scales associated with fronts near the mouths of many estuaries. The observed oxygenation was hypothesized to be associated with dissolution of the bubbles at the front and became a research focus for the next two USRS experiments. A comparison of the measured oxygenation anomaly across the fronts from all three experiments (see Table 1) shows that the O_2 anomaly varied over 2–6 % and was strongest at the James River V-shaped front which had strong convergent flow during the flood tide (see Fig. 2).

During the third USRS experiment in Mobile Bay, measurements were made in the vicinity of two merging ebb plume fronts that originated from the shoals near the mouth. As these fronts propagated offshore, they merged and formed a Y-shaped front where we made our measurements. A more detailed analysis of the water masses at the front was performed using water mass decomposition analysis (ie., optimal multiparameter analysis, OMP). Reconstruction of the water mass mixtures from the source waters provided a convenient way to compare a conservative model-prediction of dissolved oxygen to the measured non-conservative dissolved oxygen. The

OMP analysis assumed that any water in the vicinity of the front could be described as a mixture of three source waters (see Fig. 3). Applying OMP analysis to the observations at the front provided a model estimate of dissolved O_2 that conserves oxygen in the mixtures, in other words the modeled mixtures have no additional sources or sinks of O_2. The difference between the model and observed O_2 therefore provided an estimate of the in-situ source of O_2. Slow time varying deviations were assumed to be associated with net community biological production of oxygen – we observed a slow increase in O_2 during the daytime consistent in sign with daytime primary production by phytoplankton. The remaining rapidly varying source was attributed to bubble dissolution (see Fig. 4), our targeted calculation. We found that mid-salinity waters had the largest bubble-attributed source of O_2. This observation is consistent with the processes we expect to occur at the front, namely water mass mixing, creation of new formed mid-salinity waters by active shear-induced mixing processes, wave steepening and breaking at the front and injection and subduction of bubbles into he mid-salinity waters, and subduction and subsequent dissolution of the bubbles causing anomalously high dissolved O_2 in mid-salinity waters.

Collectively, due to the repeatability of the elevated oxygen levels at all three fronts measured during USRS (see Table 1, last column on right) and the consistent story of oxygenation having occurred in the mid-salinity band during Mobile Bay we conclude that estuarine fronts oxygenate coastal waters, depending on their size/intensity/duration. This is an important finding given that eutrophication associated with population expansion and Global Warming effects tend to deoxygenate and stress coastal ecosystems. It is also interesting to note that man-made structures, such as bridges and tunnels, in the coastal zone can cause hydrodynamic features suitable for enhancing oxygenation and this may be a useful tool for mitigation of coastal hypoxia.

During the Mobile Bay experiment, we were able to use, for the first time, the Nortek Signature 1000 ADCP's on the REMUS-100's. An example of acoustic backscatter (echosounder-type) data collected by running the vehicles through the ebb-plume front are shown in Figure 5. The data reveal some of the complexity that is intrinsic to the dynamic stratified nearshore environments studies in USRS, including multiple layering due to active and prior mixing processes and internal waves in the vicinity of the ebb plume front. These observations enhance the oxygenation data sets by providing groundtruth for the types of mixing processes that occur at these fronts and their importance in creating mid-salinty waters. Note that these small-scale processes are parameterized in hydrostatic models.

Finalization of the data for publication is underway. The optodes and CTDs were factory recalibrated in December 2022 after being used and returned late from another ONR funded CALYPSO experiment in the Mediterranean.

3) Training Opportunities

A summer student (Jeff Adams, US Navy submariner) was employed to assist with lake tests and use of a rental M3 sonar during the preparation for Mobile Bay. He received PHY 499 credit for Fall 2020 and worked for few months in Spring 2021.

4) Participants

Craig McNeil (PI), Andrey Shcherbina (co-PI), and Trina Litchendorf (Field Engineer) from the Applied Physics Laboratory at University of Washington.

5) Acknowledgments

We value the collaborations we have had over the last 6 years with our USRS colleagues at WHOI, OSU, NRL, ARL-UT, and PennState and the generous support of ONR and the USRS program managers.

6) Presentations and Publications (including in prep)

-Kidwell, A.N., A.S. Davis, K. Cullen, X. Dawson, D. Huff et al., Developments in Mapping Riverine and Coastal Environmental Features Utilizing an AUV-based High Frequency Sonar System in the James River, Ocean Sciences Meeting, San Diego, 16 – 21 Feb (2020).

-McNeil, C.L., A. Shcherbina et al., Observations of river plume fronts oxygenating the coastal ocean, in prep for Geophysical Research Letters (2023).

-McNeil, C.L., A. Shcherbina et al., Observations of acoustical and optical variability in estuaries made using REMUS-100, in prep for Oceanography (2023).

-McNeil, C.L., E. D'Asaro and A. Shcherbina, Passing on the excitement of experimental oceanography, oral presentation at Acoustics'17, Boston MA, 25–29 Jun, see abstract in The Journal of the Acoustical Society of America, 141(5):3546 (2017).

-McNeil, C. et al., Overview of Under Sea Remote Sensing (USRS), oral presentation at Unmanned Maritime Systems Technology (UMST), ONR Program Review, 29 Jan – 01 Feb (2018).

-McNeil, C., A. Shcherbina, T. Litchendorf, M. Isakson, M. Story, A. Kidwell, D.B. Reeder, R. Geyer (2018), Observing fronts in the Connecticut River estuary using AUVs and advanced sonars, poster [E34A-0290] presented at Ocean Sciences Meeting, Portland, OR, 12–16 Feb (2018).

-McNeil, C.L., Shcherbina, A., Isakson, M.J., A.N. Kidwell, D.B. Reeder, A.C. Lavery *and* W.R Geyer, Progress on the use of autonomous underwater vehicles to study estuaries, The Journal of the Acoustical Society of America 143, 1728(2018); https://doi.org/10.1121/1.5035636 (2018).

-McNeil, C. et al., Overview of Under Sea Remote Sensing (USRS), oral presentation at Unmanned Maritime Systems Technology (UMST), ONR Program Review, 28 Jan – 31 (2019).

-McNeil, C.L., "AUV observations of oxygenation at a river plume front (Part 1)", Chemical Oceanography Seminar Series, School of Oceanography, University of Washington, 15 February (2019).

-McNeil, C.L. et al., Overview of Under Sea Remote Sensing (USRS), oral presentation at Unmanned Maritime Systems Technology (UMST), ONR Program Review, 27 Jan – 30 (2020).

-McNeil C.L., A. Shcherbina, T. Litchendorf et al., "Observations of Bubble Plumes at Convergent Estuarine Fronts Leading to Enhanced Oxygenation and Degraded Acoustic Communications", poster presentation at the Ocean Sciences Meeting, San Diego, 16-21 Feb (2020).

-McNeil, C.L. and A. Shcherbina, Oxygenation by Bubble Dissolution at Estuarine Fronts, poster presentation at AGU, Chicago, 12-16 December (2022).

-Reeder, D.B., D. Honegger, J. Joseph, C. McNeil, T. Rago, and D. Ralston, Acoustic propagation at low-to-mid-frequencies in the Connecticut River, Proc. Mtgs. Acoust. 33, 005001 (2018); doi: 10.1121/2.0000811.

-Shcherbina, A. and McNeil, C.L., Coordinated Autonomous Underwater Vehicle Observations of Coastal Fronts, oral presentation at AGU, Chicago, 12-16 December (2022).

-Spicer, B., Jessamin, A., et al., Scalable autonomous solutions for shallow-water environments, in prep, maybe IEEE Robotics

Estuary	Date	Frontal shape	Tidal Phase	O_2 anomaly (% saturation)
Connecticut River (CT)	June 2018	C	ebb	2
James River (VA)	April 2019	V	flood	6
Mobile Bay (AL)	June 2021	Y	ebb	4

Table 1: Summary of the three estuaries studied in USRS along with a description of the shape and tidal phase of the major front studied, and the observed oxygen saturation level anomaly associated with oxygenation at the front.

FIGURES

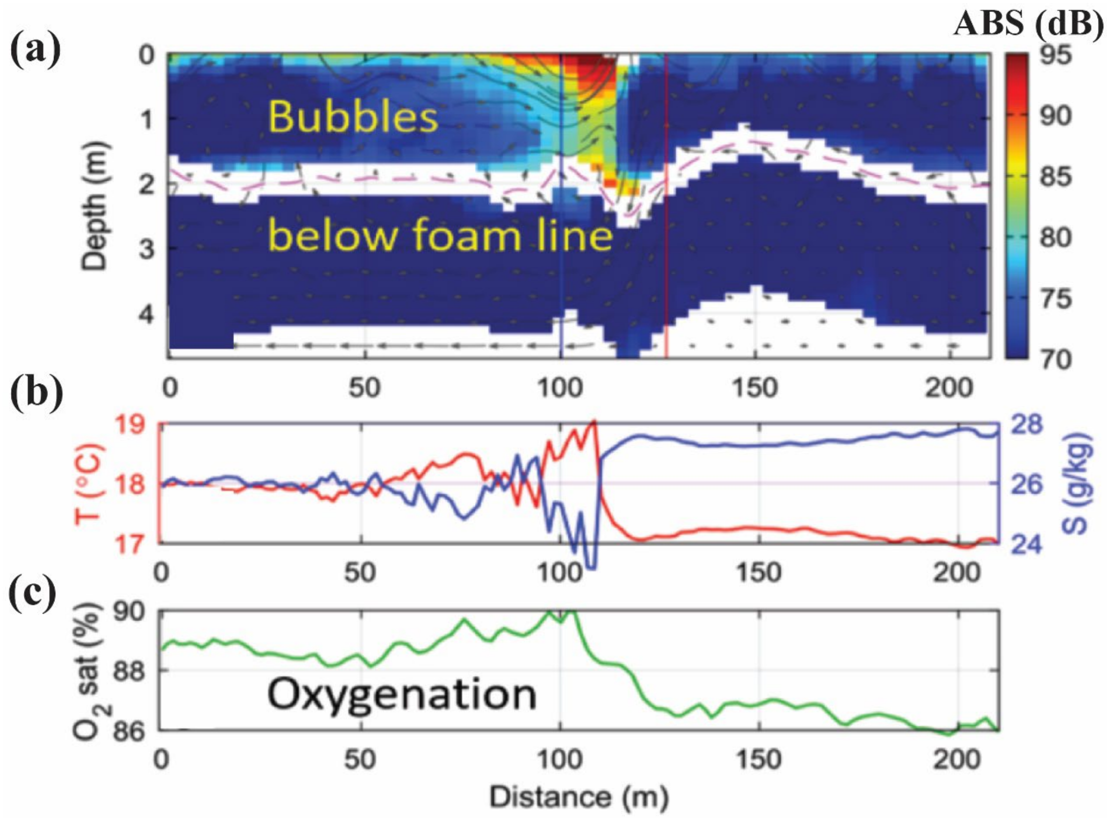

Figure 1: Measurements made by AUV across the Connecticut River ebb plume front showing: a) acoustic backscatter intensity (ABS) from the ADCP versus depth, water temperature (T) and salinity (S), and c) dissolved oxygen saturation level (raw data, a calibration offset needs to be applied).

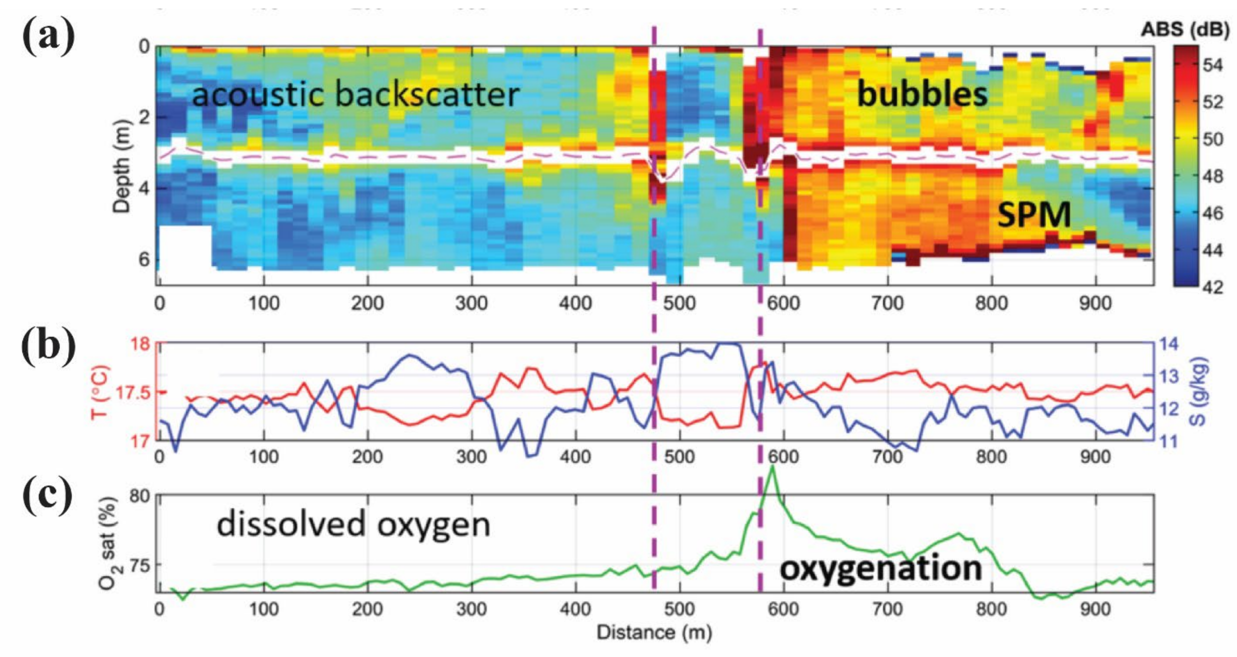

Figure 2: Measurements made by AUV across the James River tidal intrusion front, see Fig. 1 for a description of the measurements. Notice that there are two submerged bubble clouds in Fig. 2a since the front was V-shaped. Notice also the stronger near riverbed acoustic backscatter (Fig. 2c) likely associated with suspended particulate matter (SPM).

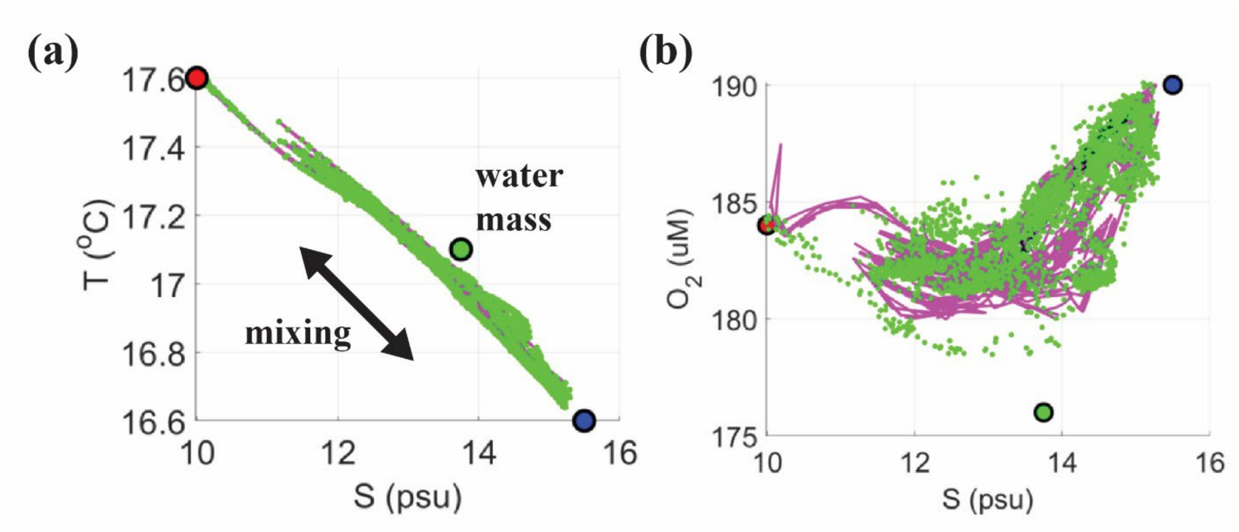

Figure 3: Water mass analysis of the ebb plume frontal crossings at Mobile Bay, showing: (a) temperature (T) versus salinity (S) plot using CTD data (small green dots) and a conservative-model reconstruction (magenta lines) along with three identified source water masses (large red, green, and blue dots with black circle edges), and (b) salinity versus dissolved oxygen concentration (O_2) using the same markings and color coding.

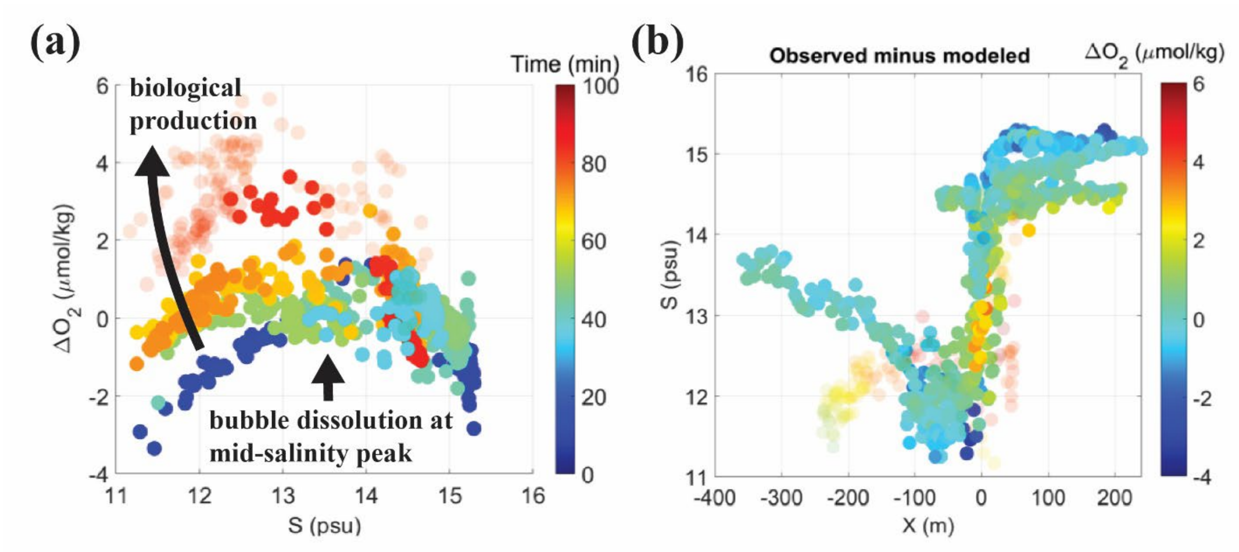

Figure 4: In situ source of dissolved oxygen calculated as the difference between model and observed dissolved oxygen (ΔO_2) from Fig. 3 plotted as: (left) versus salinity, and (right) as a function of distance from the front (X) and salinity (S), see color bar for ΔO_2 values. The slowly varying increase in oxygen is assumed to be associated with net biological production.

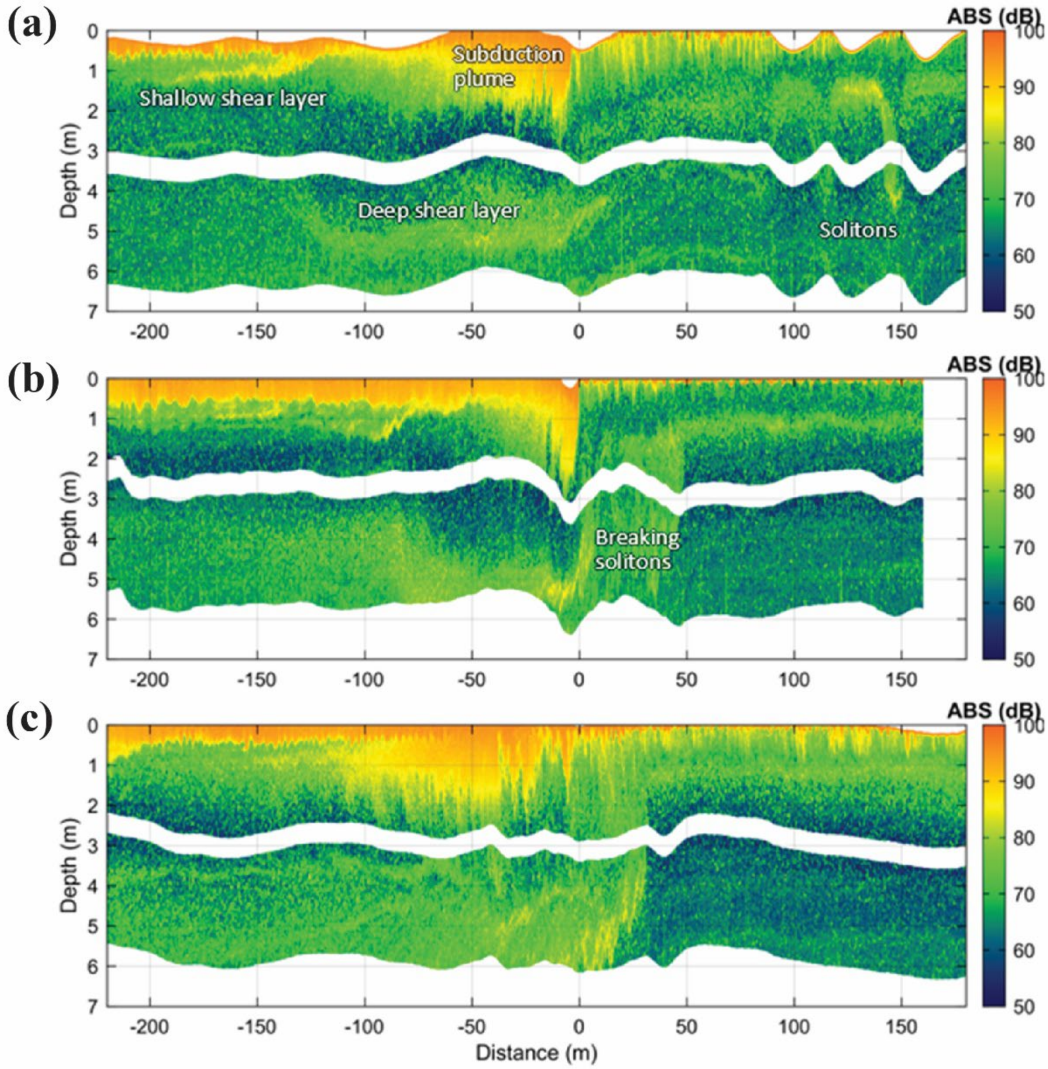

Figure 5: Evolution of acoustic backscatter during three consecutive crossings of the freshwater plume outside Mobile Bay on 15 June 2021. (a) During the first crossing (16:34 CDT), acoustic backscatter visualizes a broad frontal subduction plume propagating offshore. Ahead of the front, a train of 2–3 solitons is seen approaching from offshore. (b) During the second crossing seven minutes later (16:41 CDT), the solitons can be seen compressed and likely breaking underneath the front. (c) During the third crossing an hour later (17:43 CDT), the front is no longer well-defined, with the fragmented subduction plume and an additional deeper front at depth.

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14. ABSTRACT
During the ONR funded program called Under Sea Remote Sensing (USRS), we investigated optical and acoustic variability in three estuaries (Connecticut River, James River and Mobile Bay) using sensors mounted on REMUS 100 Autonomous Underwater Vehicles (AUVs). Our most relevant and interesting data was collected using optodes (for dissolved oxygen), ADCPs (for bubbles inferred from acoustic backscatter) and turbidity sensors (for suspended sediments). The largest variability in opto/acoustic signals was found at estuarine fronts. The size, shape and movement of these fronts varied significantly depending on the bathymetry, tidal and freshwater forcing, and stratification. The major scatterers of light or sound were bubbles, especially at near surface fronts, and suspended sediments, especially at subsurface fronts, and likely microsalinity variability also was important wherever active mixing of fresh and saltwater occurred. We intensively sampled three fronts. One V-shaped tidal intrusion front was mostly stationary at the sea surface and setup just inside the estuary mouth during flood. Another C-shaped front had temporarily setup just outside the estuary mouth during ebb then swept over the coast ocean for several hours. The third Y-shaped front formed outside the estuary mouth as two fronts merged. Fronts connected to the sea surface had increased dissolved oxygen saturation in the newly formed mid-salinity waters produced by the front. Oxygenation resulted from the subduction of bubbles produced by wave steepening at the front, subduction of the bubbles by convergent flow at the front, and subsequent dissolution of the bubbles at increased hydrostatic pressure. Our observations imply that local estuarine fronts help oxygenate the coastal ocean. Large submerged bubble plumes at fronts also reduced acoustic transmission across the front resulting in degraded ACOMMS. Increased scattering at subsurface fronts resulted from resuspension of riverbed sediments and indicates regions where 'pickup velocity' is larger than the settling velocity.

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