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EVALUATING EXPLOITABILITY OF OCEANIC FEATURES IN USW

EXECUTIVE SUMMARY

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Project Summary

As adversaries build increasingly advanced submarine fleets and expand their detection networks and capabilities, it is critical to exploit the underwater battlespace to detect and track adversary submarines, hold their strategic assets at risk, protect U.S. Navy (USN) forces and evade detection.

To inform USN decisions regarding developing, deploying, disseminating and using oceanographic products in undersea warfare (USW) decision-making, we conducted a multidisciplinary study using the Ocean Conditions Testbed for Operational USW Support (OCTOpUS), an experimental high-performance computing (HPC) system developed at the Naval Postgraduate School (NPS), which combines USN oceanographic and acoustic propagation models with NPS-developed mission models. We found that oceanic variability has important implications for acoustic predictions and search planning, but Navy oceanographic models may underperform in reproducing this variability. In the Kuroshio Extension (KE) region, mesoscale features substantially degraded detection range within a day, and using the Generalized Digital Environmental Model Version 4 (GDEM4) instead of the Hybrid Coordinate Ocean Model (HYCOM) produced large differences in estimated near-continuous range and lowered cumulative probability of detection in simulated searches. In the Eastern Mediterranean (EMED), USN models failed to reproduce the acoustically relevant vertical structure created by a semi-permanent warm-core eddy and complex bathymetry, because of the models' insufficient vertical resolution. In searcher-evader missions, these deficiencies led to substantial differences in the searcher's and evader's strategies and results depending on the fidelity of the oceanographic model.

Keywords: *acoustic propagation modeling, anti-submarine warfare, ASW, Eastern Mediterranean, EMED, genetic algorithm, Hybrid Coordinate Ocean Model, HYCOM, Kuroshio Extension, KE, eddies, meteorology and oceanography, METOC, mixed layer connectivity, model resolution, Navy Coastal Ocean Model, NCOM, oceanographic model, bathymetry, secondary sound channel, submarine search, tactical decision support, transmission loss, underwater acoustics, undersea warfare, USW*

Background

Knowing the location of adversary submarines is critical for protecting high-value assets and maintaining awareness of the adversary's operations. Some regions, such as the EMED and the KE, are important transit zones and have bathymetric, geoacoustic and ocean dynamic features that adversaries may be able to exploit to evade detection or escape. The operational understanding of how adversaries can best exploit these features, and how Navy assets can best counter them, is largely anecdotal and lacks systematic classification of the most influential modes of oceanic variability for different underwater domains of Navy interest. The spatiotemporal scales and predictability horizons of mesoscale variability vary with regional forcing, bathymetry and coastline geometry. The contested battlespace of energetic western boundary current systems is dominated by propagating eddies, jet meanders and frontogenesis, while coastal regions and marginal basins are often characterized by more localized quasi-permanent dynamical features affected by local bottom topography. A refined understanding of these distinct tactical environments will improve critical decision making in various eddy-rich regions of the World Ocean.

Understanding the general dynamics that govern the local acoustic environment is not sufficient for operational purposes. When acoustic transmission loss is used to estimate detection ranges for ASW, accurate representation of the acoustic environment is essential. The Navy commonly relies on oceanographic forecasting models, such as HYCOM and various configurations of NCOM, to represent the ocean environment for acoustic predictions. Expendable Bathythermograph (XBT) temperature profiles are often used to assess the validity of the available model forecast or to represent a homogeneous environment when the model forecast is unavailable or unrealistic. However, it remains unclear what level of model fidelity, such as accurate representation of the thermohaline structure, is required to adequately represent the sound speed structure and produce reliable acoustic predictions needed to anticipate the adversary's exploitation of oceanic features and guide counter-exploitation tactics.

This research builds on results and infrastructure developed in prior and ongoing studies. The choice of two distinct energetic underwater domains (the EMED and the KE) was partially driven by the operational experience of the involved Meteorology and Oceanography (METOC) and Operations Research (OR) students who completed their master's thesis projects in 2025-2026. Students' contributions included data collection, analysis design and setup, conduction of HPC runs, results analysis and writing thesis manuscripts. Historical *in situ* and remotely sensed oceanographic information and Fleet Numerical Meteorology and Oceanography Command (FNMOC) oceanographic model outputs were used within the OCTOpUS system to study the acoustic effects of region-specific oceanographic conditions and the operational implications of oceanographic models' ability to reproduce them.

Findings and Conclusions

This research found that mesoscale variability and its nonlinear interaction with the bottom topography have important implications for acoustic predictions, search planning and searcher-evader missions, and that Navy oceanographic models may underperform in reproducing this variability. In the KE region, mesoscale features substantially degraded detection ranges within a day (Brenneman, 2025), and the use of GDEM4 instead of HYCOM produced large differences in estimated near-continuous range and lowered cumulative probability of detection in simulated searches (Richwine, 2025). Comparison of environment-aware and environment-naïve search paths, as well as search paths based on a realistic and a homogeneous environment done by Richwine (2025) showed that the environment makes a noticeable difference. The realistic environment was modeled using HYCOM reanalysis and forecasts with different lead times. HYCOM reanalysis gave the best probability of detection even with 72-hour lead time. GDEM4-based probability of detection was inferior to that of HYCOM but outperformed predictions based on homogeneous environment.

In the EMED, a semi-permanent warm-core eddy and complex bathymetry created acoustically relevant vertical structure that was not reproduced by USN models because of insufficient vertical resolution (Munion, 2025). Specifically, the models failed to reproduce secondary sound channels and underestimated sonic layer depth and thus the potential for surface ducting. Operationally, using the modeled sound speed fields for acoustic propagation modeling may produce erroneous predictions and mislead decisions on asset deployment. In searcher-evader missions, these deficiencies led to substantial differences in the searcher's and evader's strategies and results depending on the fidelity of the oceanographic model (Haist, 2026).

Based on these findings, it is recommended that ASW search planning in eddy-rich western boundary systems similar to the KE prioritize HYCOM forecasts, use GDEM4 as a viable alternative, accept either 24- or 72-hour HYCOM lead time for advance planning, and invest in Tactical Decision

Aids that incorporate environmental optimization. For ASW operations in the EMED, effective planning requires a proactive *in situ* sampling to identify the mixed layer connectivity, while Navy oceanographic models with high horizontal resolution may help guide sampling plans.

Preliminary results of this research were briefed to the Submarine Group 2 Operations Research and Operations Analysis group, CAPT Pearman (Naval Oceanographic Office), CAPT Casey Gon and Dr. Lea Locke-Wynn (the Naval Oceanography Operations Command) and CDR Charlotte Benbow (Commander Submarine Force U.S. Pacific Fleet) and will be presented at FNMOC in June 2026.

The project findings were shared with N2/N6 to solicit input on implementation of the findings. The results should be shared with fleet oceanographers to increase Navy awareness of the effect of mesoscale variability, mixed layer connectivity and limitations of oceanographic models on acoustic predictions, search planning and tactical decision making. EMED results should be considered in future NCOM and RNCOM model updates with respect to resolving subsurface mesoscale features that affect secondary sound channels, sonic layer depth and surface ducting.

Recommendations for Further Research

The mission models in this study involved a single search asset using passive sonar. Undersea warfare (USW) missions often involve allocating multiple assets, and some use active sonar. This raises the question of how much environmental variability in the North Pacific affects optimal sonobuoy distribution and detection outcomes. The Ocean Conditions Testbed for Operational USW Support (OCTOpUS) system could be expanded to include active sonar combined with a multi-asset allocation optimization algorithm to explore the effects of oceanic variability on mission outcomes and how the fidelity of oceanographic products affects the allocation and outcomes.

Results of Brenneman (2025), Munion (2025), and Regnier et al. (2025) in the North Pacific and Eastern Mediterranean raise questions about how eddies interact with bathymetry in the open ocean. The existing OCTOpUS system, which includes a region in the North Atlantic (Cantwell, 2023; Regnier et al., 2023), can be used to study this question.

Haist's (2026) analysis of the resolution of the game grid suggests that horizontal resolution of 12 km is sufficient to capture the effects of environmental variability on the searcher-evader problem, and a coarser resolution may be sufficient. However, the impact of the grid resolution may vary geographically or as a function of horizontal features. Experiments designed to understand the effect of resolution on the performance of solutions and other factors such as bathymetry and proximity to horizontal features are recommended. In addition, just as the vertical resolution of oceanographic models is denser near the surface, variable resolution for the game grid may also be appropriate, and experiments with varying this resolution are recommended.

Haist's (2026) searcher-evader game framework can be used to study how oceanic variability affects exploitation of the complex bathymetry and ocean features in other seasons and modes of variability. In addition, it can be used to characterize sub-regions as creating relative advantage for the searcher or the evader. Understanding the stability of this relative advantage could help provide guidance to the fleet on specific tactics for the region, as well as on how to best use oceanographic products in USW in the region. The framework can similarly be applied in other regions of interest.

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Acronyms

ASW	anti-submarine warfare
EMED	Eastern Mediterranean
FNMOC	Fleet Numerical Meteorology and Oceanography Command
GDEM4	Generalized Digital Environmental Model Version 4
HPC	high-performance computing
HYCOM	Hybrid Coordinate Ocean Model
KE	Kuroshio Extension
METOC	meteorology and oceanography
NCOM	Navy Coastal Ocean Model
NPS	Naval Postgraduate School
OCTOpUS	Ocean Conditions Testbed for Operational USW Support
RNCOM	Regional Navy Coastal Ocean Model
USW	undersea warfare
USN	U.S. Navy
XBT	Expendable Bathythermograph