

## **Northern Arabian Sea Circulation - autonomous research: Optimal Planning Systems (NASCar-OPS)**

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### **LONG-TERM GOALS**

Our long-term goal is to *apply our theory and schemes for rigorous optimal path planning and persistent ocean sampling with swarms of autonomous vehicles and further quantify the dynamics and variability of the circulation features and mixed layer, and the responses to monsoon winds, utilizing multi-resolution data-assimilative ocean modeling and process studies.*

### **OBJECTIVES**

Our specific objectives for the present four-year project in the NASCar region are to:

- Utilize and further develop our optimal planning schemes (time, energy, swarm and LCS optimal paths) for real ocean vehicles (gliders, drifters, floats, and/or wave-gliders)
- Provide guidance for persistent optimal sampling, including for long-duration observation system design and for adaptive sampling during sea operations, using advanced Bayesian information theoretic approaches
- Improve the understanding of the variability and interactions of the regional wind-driven and buoyancy-driven circulation features and mixed-layer dynamics, using dynamical analyses and process-oriented scientific modeling.
- Provide multiscale data-assimilative ocean field estimates using multi-resolution numerical ocean modeling, both for real-time sea operations and for optimized re-analyses
- Collaborate and transfer data, expertise, approaches, algorithms and software to NRL and other colleagues. Utilize and leverage the MIT Naval Officer education program.

### **APPROACH**

*Optimal Path Planning of Swarms of Autonomous Vehicles for Persistent Sampling.* We plan to apply our theory and schemes for rigorous optimal path planning and persistent ocean sampling with swarms

of autonomous vehicles in the NASCar ocean region, utilizing inputs from our multi-resolution data-assimilative ocean modeling. We will employ and further develop our rigorous planning schemes for reachability studies and for specific optimality objectives (e.g. time, energy, swarm-formation, Lagrangian Coherent Structures or uncertainty optimal paths), to be selected in accord with the needs of the DRI. Our predicted optimal headings and relative operating speeds will be provided to the operational fleets of instruments and vehicles (e.g. gliders, drifters, floats or wave-gliders). We plan to use models specific to vehicle types (floats, wave-gliders, etc.). We also plan to further parallelize and optimize our codes for planning, OSSEs, and adaptive sampling using distributed computing. We propose to complete numerical algorithms and efficient implementations of these codes for 3D in space and time-varying realistic ocean flows. Finally, we can provide guidance for persistent optimal sampling. This can include data-driven modeling guidance for the design of optimal long-duration observation systems and for adaptive sampling, using advanced Bayesian information theoretic approaches.

*Quantitative Dynamics Analyses using Process-oriented and Multi-resolution Modeling.* In collaborations with the DRI team, we plan to further quantify the dynamics and variability of the circulation features and mixed layer, and the responses to monsoon winds. We will set-up and apply our MSEAS systems (MSEAS, 2009; Haley and Lermusiaux, 2010; Haley et al., 2015) for process-based modeling studies and dynamics analyses, and for multi-resolution data-driven modeling of tidal-to-mesoscale processes. We are planning to contribute to the description and quantification of the variability of circulation features, transports, and mixed-layer properties, as well as of the effects of atmospheric forcing and of internal tides and long internal waves (if sufficiently resolved by observations). We also plan to participate in field campaigns, providing ocean forecasts, dynamics descriptions and sampling guidance. We propose to complete multiscale ocean re-analyses (using improved data processing, parameters, resolution, boundary and initial conditions), to be used for dynamics analyses. This will allow us to map the time and space variability and to utilize term-by-term, flux balances, and Lagrangian analyses as needed. Finally, we will transfer data, approaches, and algorithms to the DRI team and naval laboratories.

## **WORK COMPLETED**

Since the start of NASCar-OPS in September, we have been educating a new student in optimal path planning and have started idealized planning tests for the nascar region. We started a literature review of the dynamical processes occurring in the Arabian Sea and the connections between the Arabian Sea and the Bay of Bengal. HYCOM fields have been downloaded from the FSU site at a resolution of 1/12 degree. We are in the process of obtaining access to higher resolution HYCOM fields (1/25 degree) from NRL. We have also begun obtaining relevant data (bathymetry, atmospheric forcing, tides, satellite observations, present and historical in situ data, etc) for the Arabian Sea and the Bay of Bengal. We have completed a set of draft multi-resolution model domains of the NASCar-OPS region for use in our multiscale modeling systems, including a large, regional domain spanning both the Bay of Bengal and the Arabian Sea, down to 10S, in order to capture the connections between the two basins. New schemes for the automated creation and quality control of land masks for complex regions have been devised. These include algorithms for the automatic detection and correction of invalid land mask configurations.

## **RESULTS**

One early result from the literature review is the observation that at certain times of the year, there is a current from the Bay of Bengal, around both sides of Sri Lanka, into the Arabian Sea. Our set of modeling domains have been designed to model this flow. The HYCOM fields obtained so far have been used as another guide for designing our domains, for example the southern extent of the largest domain was chosen to accommodate the connections between the Bay of Bengal and the Arabian Sea and any inflow from Indonesia but to avoid cutting across persistent eddies between Africa and Madagascar. We have found that the new schemes and algorithms for the automatic creation and quality control of land masks vastly improve the efficiency of creating new multi-resolution domains, making it practical to create even more complex 2-way nested telescoping domains than were previously possible.

## **IMPACT/APPLICATIONS**

Our research is relevant to naval interests in improving the understanding of ocean dynamics and nonlinear interactions in ocean regions that are especially relevant for today's naval operations. Impacts include a better understanding of optimal guidance and control of autonomous ocean sampling systems in uncertain environments with rapid responses to marine conditions. Applications include efficient regional path planning and observing system optimization for naval operations, undersea surveillance, homeland security and coastal management. Our results aim to improve ocean forecasting and impact acoustic performance forecasting. The research also addresses naval interests for heterogeneous and collaborative groups of autonomous vehicles which maneuver and operate efficiently in a given ocean region, optimizing time, energy or other operational relevant criterion, and optimally collecting observations.

## **TRANSITIONS AND COLLABORATIONS**

We plan to collaborate with the other scientists involved in the DRI and provide them with our results.

## **RELATED PROJECTS**

Our NOPP project on "Seamless Multiscale Forecasting: Hybridizable Unstructured-mesh Modeling and Conservative Two-way Nesting" (N00014-15-1-2597) will benefit from, and contribute to, the present study.

## **REFERENCES**

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