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SeaVizKit:
Interactive Maps for Ocean Visualization

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***Abstract*—With the increasing availability of high-resolution comprehensive spatio-temporal ocean models and observation systems, ocean data visualization has become ubiquitous. This is due to the major impact of ocean products on disaster management, shipping, fisheries, autonomy, coastal operations, and scientific studies. Yet, there are several challenges for effective communication of data through visualization techniques. Specifically, ocean data is multivariate (e.g. temperature, salinity, velocity, etc.), is available for multiple depths and multiple time instants, and contains uncertainties, all of which leads to large, multi-dimensional datasets. Thus, it is necessary to have an interactive multiscale multivariate visualization tool that can assist scientists, engineers, policy makers, and the public in making insights from big data produced by ocean predictions and observations. In this work, we present a 3D (spatial) + 1 (temporal) multi-resolution multivariate visualization tool that produces interactive, dynamic, fast and portable ocean maps.**

***Index Terms*—Ocean modeling, ocean visualization, data science, interactive visualization**

I. INTRODUCTION

In the field of ocean modeling or computational fluid dynamics more generally, it is nearly always the case that the terminal use of a simulation is interpretation by a scientist or an engineer as part of a larger effort to understand, predict, design for, or otherwise make use of physical phenomena [10, 11, 12, 19, 21]. Moreover, the output of an ocean simulation may be of interest to other end users (e.g., fishermen, meteorologists, robot operators, policy makers) who seek to make decisions based upon the simulation without a scientist's understanding of the simulation details. In all cases, the raw data of a simulation is virtually useless unless interpretable by the end user; visualization constitutes the link between the raw data and the conclusions in the mind of the decision maker.

It is therefore crucial to ensure that the richness of the solution is not lost in the visualization of the solution data; otherwise, the effort and computational expense of running the solution is wasted. However, effective multi-resolution multi-dimensional multivariate visualization poses a unique set of challenges [29], and it is often the case that as the simulation becomes more sophisticated (e.g., high-order or discontinuous output), its visualization becomes more challenging as well [17]. Poor visualization not only adds a so-called ”visualization error” to the total error of the solution, but also burdens researcher with the task of determining which features of the solution output are physical or simply visualization artifacts [25].

A brief survey of the existing literature on visualization of ocean data emphatically demonstrates no shortage of research challenges. Problems in visualization for oceanographic data are laid out in [60], where the authors assert the need for visualization tools capable of handling multivariate datasets (e.g., temperature, salinity, oxygen content, etc.). The chaotic, complex, and patchy nature of coastal and estuarine flows is described in [74]; therefore oceanographers may not know *a priori* zones in which interesting physics occurs—hence, an ocean visualization toolkit has the potential to emphasize these dynamic flows rather than give a static snapshot of the fields. Due to the limited observations and other sources of errors [31, 34], care is needed for the visualization uncertainties [11, 12]. The visualization of ocean data should also adapt to multiple purposes, from scientific inquiries to the optimal control of autonomous vehicles [41]. Further, using appropriate perception neutral color maps is instrumental in conveying the information without any added bias [3, 72]. A modern, open-source framework for computing quantities of interest from large ocean datasets is described in [2]; however, the emphasis of this software is an application programming interface (API) for interfacing with ocean datasets and computing quantities of interest rather than raw visualization. Our approach aims to provide a complementary framework which renders a dynamic, interactive visualization of pre-simulated data as an analysis tool.

The MSEAS software [19, 21, 53] consists of a probabilistic, data-assimilative, primitive-equation (PE) ocean modeling system that is used for fundamental research and for realistic simulations of fields and uncertainties around the world's oceans. Practical applications of MSEAS include ocean monitoring [36], acoustic predictions and data assimilation [43], biogeochemical-ecosystem predictions and environmental management [5], 3D Lagrangian transport and coherent structures [8, 26], and path planning for autonomous vehicles [47, 48, 49].

The present SeaVizKit is a novel browser-based tool used for visualizing the MSEAS ocean products. It makes use of Leaflet [9] and D3.js [77] JavaScript libraries and provides a unique and novel solution for visualizing the multivariate, multidimensional fields obtained from the MSEAS software. This is done via a highly interactive web and mobile interface that offers the user control over the selected fields, times, and depths, while ensuring a seamless transition between the

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forecast products, making SeaVizKit both portable and usable for real-time applications and decision making. Sicne the tool reads common ocean data types, it is also applicable to other ocean modeling systems.

The present paper is organized as follows: in section II, we discuss the underlying data model and visualization methodology employed by SeaVizKit; in section III, we provide use cases of SeaVizKit for real-time sea exercises and multiscale ocean modeling; and in section IV we offer possible extensions and uses of the software including fisheries management, shipping, and path planning. In section V, we provide conclusions attained from the development, deployment, and use of SeaVizKit.

II. METHODOLOGY

This section first outlines the underlying model used to obtain the ocean fields' predictions, the data-assimilative MSEAS ocean model. We then highlight the main features and basic components of SeaVizKit and provide some details on the implementation.

A. MSEAS Ocean Model

The ocean fields visualized are obtained using our MSEAS software [19, 53]. At the core of MSEAS is a nonlinear free-surface hydrostatic primitive-equation (PE) model, based on second-order structured finite volumes and configured with generalized-level vertical-coordinates and implicit two-way nesting [21]. The software has been used for fundamental research and for forecasting the ocean fields and uncertainties in many regions [1, 7, 18, 20, 24, 35, 39, 41, 42, 44, 62, 63]. Its capabilities include: fast-marching coastal objective analysis [1], initialization of fields and ensembles [40], nested data-assimilative tidal prediction and inversion [45], implicit two-way nesting [21], stochastic subgrid-scale forcing [31], ensemble forecasting and data assimilation using the Error Subspace Statistical Estimation (ESSE) methodology [32], adaptive data assimilation, sampling and learning [32, 67], real-time acoustic predictions [13, 28, 43, 76], biogeochemical modeling and environmental management [5, 8, 26], Lagrangian Coherent Structures (LCSs) [27, 37], and planning for underwater vehicles [38, 47, 49, 67].

B. SeaVizKit Implementation and Features

The ocean physics (temperature, salinity, currents, etc.) and prognostic quantities (sound speed, LCSs, optimal paths, etc.) obtained using the MSEAS software are the inputs to SeaVizKit, the new interactive multiscale visualization tool presently developed. SeaVizKit is a browser-based application which leverages the JavaScript libraries Leaflet [9] and D3.js [77]. In our implementation, we render the interactive map using Leaflet; ocean data obtained using the MSEAS software is rendered using the D3.js library and overlaid on the map. In order to account for the multivariate characteristics of the ocean data, a control panel allows the user to view different ocean variables. The user can view ocean data at different depths and timestamp with sliders; this interface allows researcher to investigate quantities of interest in time and space. In order to provide interactive frame rates, SeaVizKit employs a caching functionality, whereby recently displayed image data are stored for later redisplay. For the visualization of vector-valued quantities, such as surface and barotropic velocities, SeaVizKit uses animated pathlines allowing the user to easily interpret the velocity fields.

Due to its lightweight interactive modular design, SeaVizKit efficiently produces 3D (spatial) + 1 (temporal) multivariate ocean maps that are dynamic, fast and portable. Furthermore, the zoom and pan animations allow the user to examine rapidly both large and small-scale features, hence drawing deeper scientific insights from the displayed data. Local field values at specific locations can also be read and recorded by the user.

In the following sections, we discuss applications of SeaVizKit in real-time sea exercises and examples of its use in fisheries and hazards management. A diagram illustrating the work flow to obtain the interactive maps starting from the MSEAS predictive software is shown in figure 1.

III. USE CASES

A. POSYDON Sea Experiment 2018

SeaVizKit was used to visualize the ocean fields obtained during a real-time sea experiment that occurred in the Middle Atlantic-New York Bight Region in August 2018 as part of the DARPA-POINT project [54]. This was done using a two-step procedure:

1) MSEAS Modeling: The probabilistic MSEAS PE modeling system was utilized in real-time to provide ocean field and uncertainty forecasts at a 3 km grid resolution and using a 100-member ensemble tuned for region specific uncertainty modeling using the ESSE methodology [32]. The ocean forecasts are initialized from HYCOM [6], down-scaled to higher resolution and updated with ocean data from varied open sources of opportunity (CTDs, ARGO floats [4], gliders [61, 66], SST [52], etc.) and with the MSEAS feature models for additional corrections. These ocean simulations are forced by atmospheric flux fields forecast by the GFS 0.25° model from the National Centers for Environmental Prediction (NCEP) [57] and tidal forcing from TPXO8 [14, 15], but updated for the high-resolution bathymetry and coastlines.

2) Interactive Mapping: The SeaVizKit tool was used to produce interactive maps for the ocean physics in the area of interest, at many different resolutions, times, and depths. Figure 2 shows example visualizations of the surface velocity fields over a 12-hour period which highlights the transition capabilities between different time frames using the horizontal time slider in the bottom left, and between different variables using the control panel on the right. In addition, the animated pathlines allow deeper insight into the motion of the current on and off the shelfbreak front over the period of interest.

For the purpose of studying the operations of the acoustic-based underwater Global Positioning System (GPS) of relevance to the DARPA-POINT project, ensemble predictions of the sound speed field were also obtained. Figure 3 shows

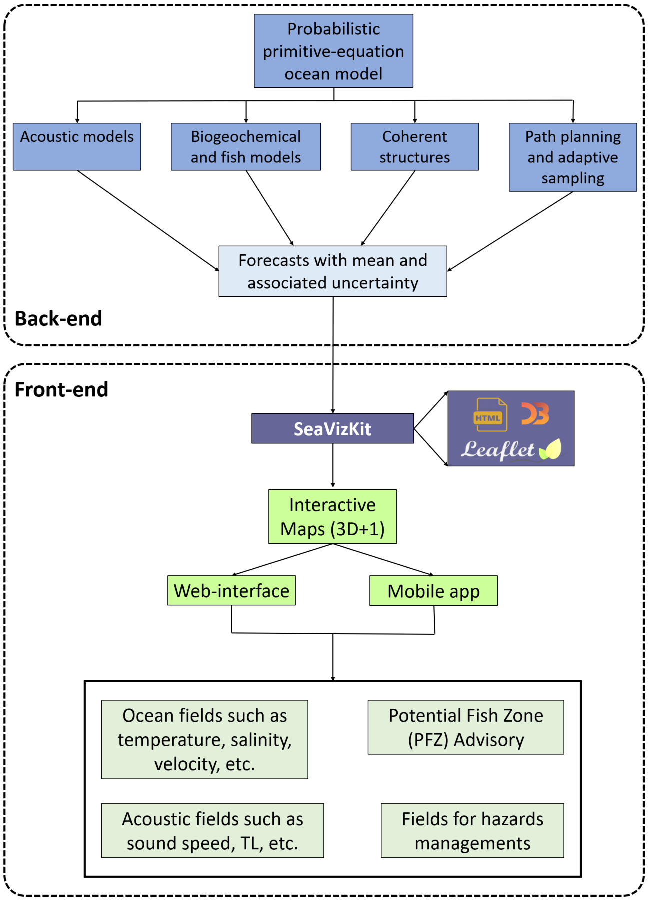

Fig. 1: Diagram illustrating SeaVizKit workflow to obtain the interactive ocean maps. The MSEAS software consists of a probabilistic data-assimilative primitive equation ocean model in addition to other acoustic, biogeochemical, fish, coherent structures, path planning, and adaptive sampling predictive models that output ocean forecasts with mean and associated uncertainty. The data obtained serves as input to SeaVizKit which uses the Leaflet and D3.js JavaScript libraries to produce the browser-based interactive visualization. The produced maps can be used in a web interface, or integrated in a mobile app and may display ocean physics fields, acoustic fields, fish fields, in addition to other fields used for hazards management (e.g. flowmaps, LCSs)

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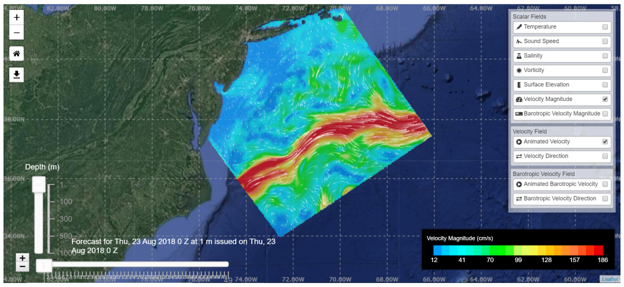
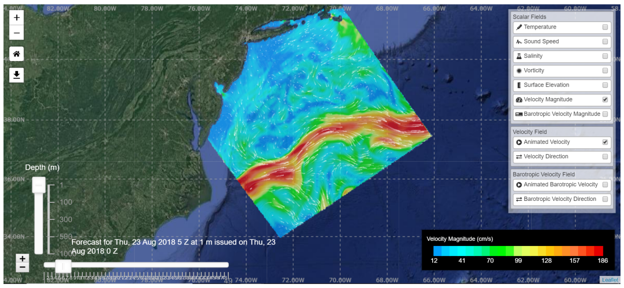
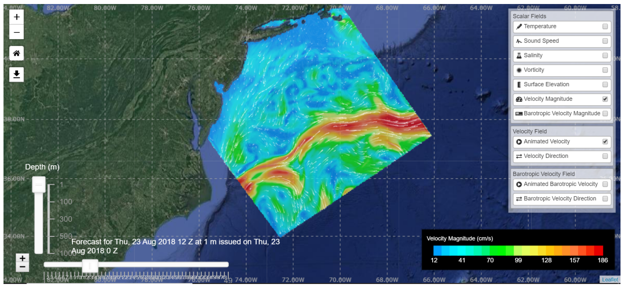


(a) Nowcast: 0 Z Aug. 23, 2018



(b) Forecast for: 6 Z Aug. 23, 2018



(c) Forecast for: 12 Z Aug. 23, 2018

Fig. 2: Visualization examples of the surface velocity field obtained using the SeaVizKit tool during the BBN POSYDON Sea Experiment in August 2018. (a) shows the velocity field nowcast at 0 Z for Aug. 23, 2018. (b) and (c) show forecasts of the velocity field for 6 Z and 12 Z on Aug. 23, 2018, respectively. SeaVizKit allows transition between the simulation time frames using the horizontal time slider on the bottom left. Additionally, animated pathlines describing the velocity field make the currents on and off the shelfbreak front visually apparent.

examples of the standard deviation and mean sound speed fields with mean pathlines at 100 m depth demonstrating the cursor-value feature of the user interface.

B. NSF-ALPHA Sea Experiment 2018

SeaVizKit was also used during a real-time sea experiment that occurred in the Nantucket and Martha's Vineyard coastal region in August 2018 as part of the NSF-ALPHA project [55]. The workflow involved two steps:

1) MSEAS Modeling: The MSEAS PE modeling system was utilized in real-time to provide ocean physics forecasts, both for Eulerian and Lagrangian fields. The modeling system was set-up using an implicit 2-way nesting configuration (200 m resolution Martha's Vineyard domain and 600 m resolution Shelf domain). The ocean forecasts were initialized using historical and synoptic ocean CTD data from the National Marine Fisheries Service (NMFS) [59] and the Martha's Vineyard Coastal Observatory (MVCO) [75], SST images from the Johns Hopkins University's Applied Physics Lab (JHU APL) [22], and other data from varied sources of opportunity. These ocean simulations were forced by atmospheric flux fields forecast by NCEP [58] and tidal forcing from TPXO8 [14, 15], but adapted to the high-resolution bathymetry and coastlines [45].

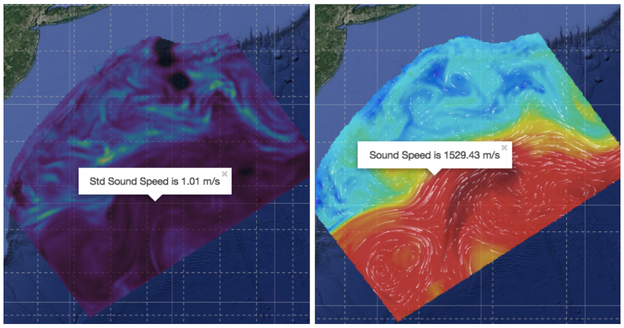


Fig. 3: Visualization examples of the ensemble standard deviation (left) and mean (right) sound speed fields at 100 m depth obtained using SeaVizKit during the BBN POSYDON Sea Experiment. The cursor-value feature in SeaVizKit allows reading off the value of the standard deviation/mean sound speed at the selected locations.

Furthermore, the MSEAS-LCS software was used to provide forecasts for the Lagrangian transport and coherent structure analyses in the region. Specifically, the software was used to forecast fields of the finite time Lyapunov exponents (FTLEs) which are commonly used to identify repelling and attracting Lagrangian coherent structures (LCSs), as well as the associatated three-dimensional forward and backward flow maps.

2) *Interactive Mapping:* The SeaVizKit tool was used to produce interactive maps for the ocean physics. Figure 4 shows example visualizations of the temperature field at surface, 10 m, and 20 m levels for the 600 m resolution Shelf domain. Transition between these levels is rather fast using the vertical depth slider on the bottom left. In addition, figure 5 shows example visualizations of the surface velocity field in the 600 m and 200 m two-way nested domains.

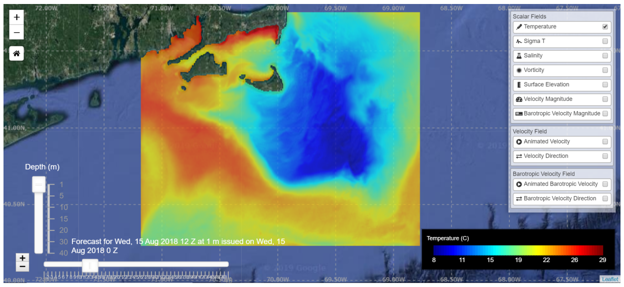
SeaVizKit was also used to produce maps for visualizing FTLEs. Figure 6 shows forward FTLE fields with attracting coherent structures around Martha's Vineyard, highlighted in the zoomed snippets around Nantucket sound and Vineyard sound. Such visualizations of the LCSs through SeaVizKit can be efficiently used for operations such as search and rescue, hazards management and pollution mitigation. Passive materials that flow with the fluid (such as oil, plastics, plankton etc.) are either attracted to or repelled by the Lagrangian coherent structures as mentioned before—by efficiently visualizing the coherent structures and overlaying them on other ocean physics fields, we can easily understand the skeleton of material flow in the ocean thereby making informed decisions regarding the management of hazardous material flow (such as oil) or protection of marine life.

C. DRI CALYPSO Sea Experiment 2019

SeaVizKit was most recently used during a real-time sea experiment in the Alboran Sea in March-April 2019 as part of the DRI-CALYPSO project [56].

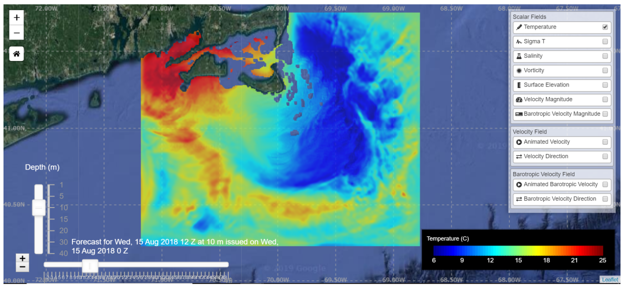
1) *MSEAS Modeling:* The MSEAS modeling system was set-up in an implicit 2-way nesting configuration ($1/200°$ resolution Alboran Sea domain and $1/600°$ resolution process domains). The ocean forecasts were initialized from either HYCOM [6] or WMOP [23] or CMEMS [16], downscaled to higher resolution and updated with ocean data from varied open sources of opportunity (CTDs, ARGO floats [4], gliders, SST [52], etc.). Ensemble forecasts were initialized using ESSE procedures [30, 33], extended to multi-region uncertainty initializations. These ocean simulations were forced by atmospheric flux fields forecast by the Global Forecast System (GFS) 0.25° model from NCEP [57] and by tidal forcing from TPXO8 [14, 15], but adapted to the high-resolution bathymetry and coastlines.

For the purpose of studying three-dimensional transport of water masses and subduction dynamics, the MSEAS-LCS software was also used to compute flowmaps and FTLE fields. The forward/backward flowmap across depth, referred to hereafter as the z-flowmap, was of particular interest as it



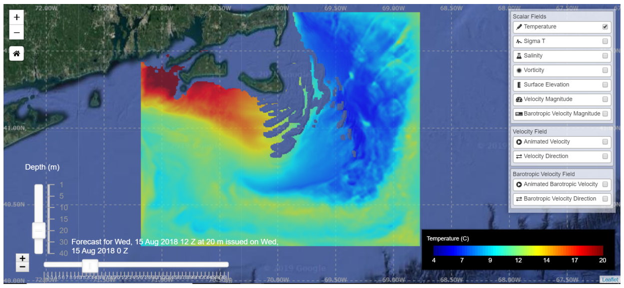
Forecast for Wed, 15 Aug 2018 12 Z at 1 m issued on Wed, 15 Aug 2018 0 Z

(a) Surface temperature



Forecast for Wed, 15 Aug 2018 12 Z at 10 m issued on Wed, 15 Aug 2018 0 Z

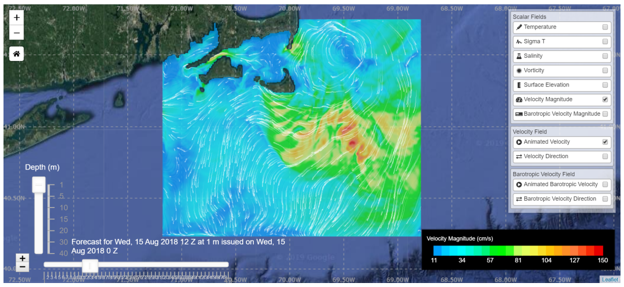
(b) Temperature at 10m depth



Forecast for Wed, 15 Aug 2018 12 Z at 20 m issued on Wed, 15 Aug 2018 0 Z

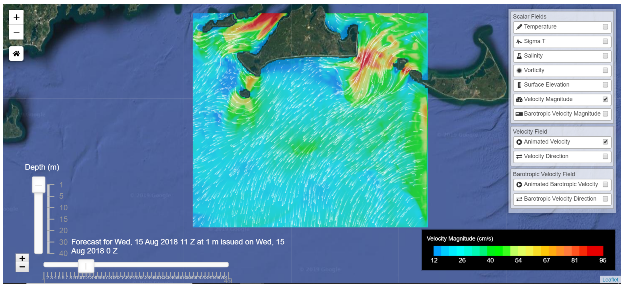
(c) Temperature at 20m depth

Fig. 4: Visualization examples of the temperature field obtained using SeaVizKit during the NSF-ALPHA Sea Experiment in August 2018. (a) shows a forecast the surface temperature field. (b) and (c) show forecasts of the temperature field at 10 and 20 m depth, respectively.



Forecast for Wed, 15 Aug 2018 12 Z at 1 m issued on Wed, 15 Aug 2018 0 Z

(a) 600 m resolution Shelf domain



Forecast for Wed, 15 Aug 2018 11 Z at 1 m issued on Wed, 15 Aug 2018 0 Z

(b) 200 m resolution Martha's Vineyard domain

Fig. 5: Visualization examples of the velocity field for the two nested domains obtained using SeaVizKit during the NSF-ALPHA Sea Experiment. (a) and (b) shows a forecast the surface velocity field for the 600 m resolution Shelf domain and 200 m resolution Martha's Vineyard domain, respectively.

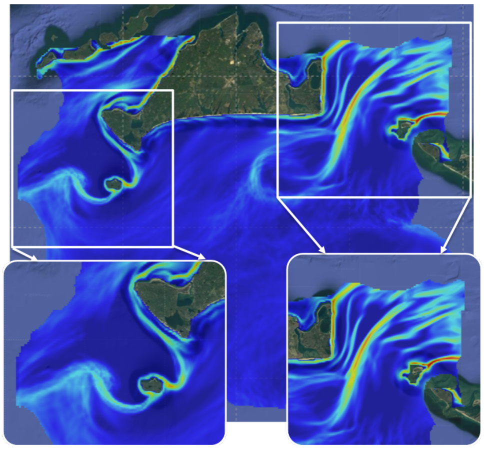
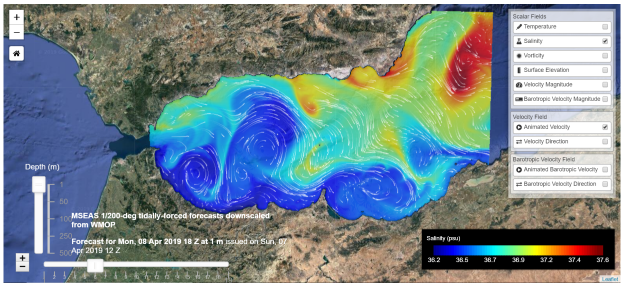


Fig. 6: Visualization example of the finite-time Lyapunov exponent (FTLE) field in the Martha's Vineyard domain obtained using SeaVizKit during the NSF-ALPHA Sea Experiment. The zoom feature in SeaVizKit over the Nantucket and Vineyard sounds shows attracting coherent structures.

helped identify the subduction regions in the domain.

2) Interactive Mapping: Figure 7 shows an example visualization of the surface salinity field in the region of interest along with pathlines of the surface velocity field as produced by SeaVizKit.

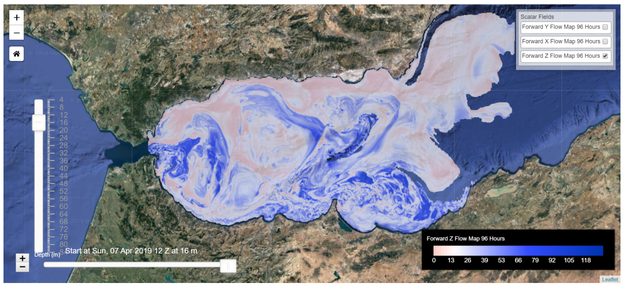
In addition, figure 8 shows example visualizations of the 96-hour integrated forward z-flowmap at different depths.



MSEAS 1/200-deg tidally-forced forecasts downscaled from WMOP

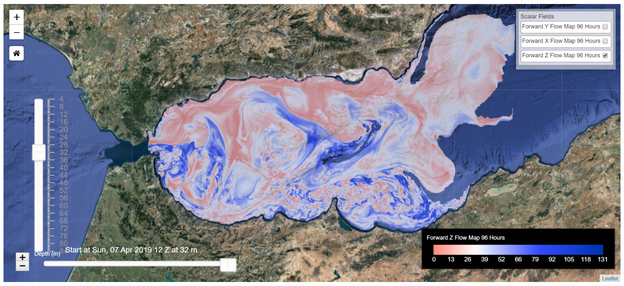
Forecast for Mon, 08 Apr 2019 18 Z at 1 m issued on Sun, 07 Apr 2019 12 Z

Fig. 7: Visualization example of the surface salinity field obtained using SeaVizKit during the DRI CALYPSO Sea Experiment in March-April 2019.



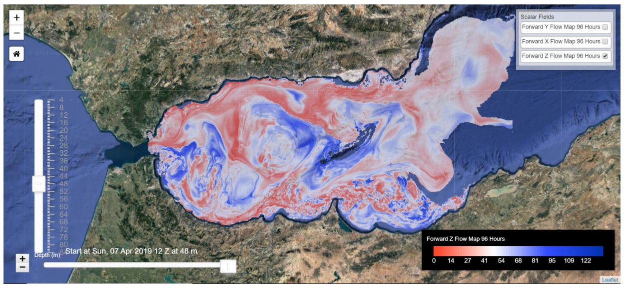
Start at Sun, 07 Apr 2019 12 Z at 16 m

(a) 16 m depth



Start at Sun, 07 Apr 2019 12 Z at 32 m

(b) 32 m depth



Start at Sun, 07 Apr 2019 12 Z at 48 m

(c) 48 m depth

Fig. 8: Visualization examples of the 96-hour integrated z-flowmaps at different depths obtained using SeaVizKit during the DRI CALYPSO Sea Experiment. (a), (b), and (c) show forecasts of the z-flowmaps at 16, 32 and 48 m depth, respectively.

IV. FUTURE EXTENSIONS

Due to the modular design of SeaVizKit, it can be flexibly integrated as a visualization tool for a broad range of applications. Extension of the SeaVizKit to applications such as fisheries management and shipping and path planning is the subject of ongoing research.

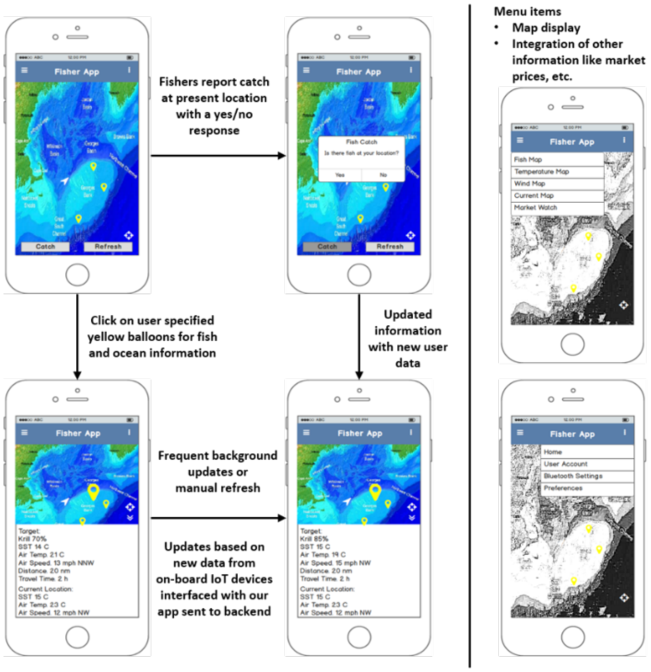
A. Fisheries

Fisheries are a major component of coastal livelihoods, especially in developing countries such as India. However, increased demand for fish, coupled with unsustainable fishing practices, can lead to over-exploitation and fast depletion of fish stocks. Coastal fisheries and aquaculture stocks often thrive on very specific water conditions. Building capabilities for coastal ecosystem forecasting and for optimal data collection will help ensure the survival and reproduction of healthy stock. Without sustainable fisheries management and conservation practices in place, disastrous consequences could arise for communities which are dependent on the ocean for food.

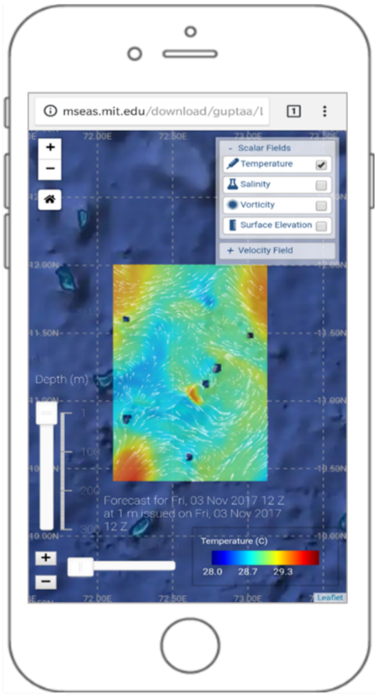
Although there is a lot of focus on developing coastal ecosystem-fisheries forecasting systems [5, 64, 65, 70], there is another important component: the often-overlooked problem of efficient dissemination of these forecasts to local fishermen. For example, INCOIS in India issues Potential Fishing Zone (PFZ) advisories uses Sea Surface Temperature data from NOAA-AVHRR satellite and Chlorophyll data from Oceansat-2 and MODIS satellites. PFZ identified from SST and Chlorophyll maps is communicated to fishermen using SMS, Radio, TV, email, phone, and web services [71, 73]. This system nonetheless lacks elements of modern UI/UX (User Interface/User Experience), ability to collect data, interactivity, portability, flexibility, and so on. These deficiencies could be overcome by an amalgamation of forecasting products delivered to fisherman via SeaVizKit, and further curating the mobile/web app centric to the needs of both local fishermen and ocean-modelers.

We present a potential wire-frame mock-up of a fisheries specific mobile app (front-end) in Fig. 9(a); the front-end could interface with oceanographic instruments on board the fishing vessel, sending real-time data to a back-end computational engine such as MSEAS. The user interface might also feature an option for fishermen to provide data on presence or absence of fish catch, which in-turn could be assimilated by the back-end to update predictions of probable fish maps. The app could also feature other information which might be of interest to the fishermen, such as weather, live market price, government defined fishing zones, etc., in order to provide value to the primary user base. In Fig. 9(b), we present the mobile web interface of SeaVizKit with sample forecasts done for the Lakshadweep islands in India, around November 3^{rd}, 2017.

Overall, our modular visualization technology could easily be integrated with existing apps, or used to develop new ones. It would greatly enhance the user experience, could be integrated with data collection systems, and eventually improve the reach of the forecasts. This could also prove to be useful to the fisheries department for analysis, monitoring, and decision-making purposes.



(a) Mobile app mock-up



(b) SeaVizKit for Lakshadweep islands

Fig. 9: (a) Mock-up of a potential fisheries app, with the ability to disseminate forecasts, market price, weather information, and collect data. (b) SeaVizKit mobile web interface showing sample forecasts for the Lakshadweep islands in India, issued on real-time on $3rd$ November, 2017.

B. Shipping and Path Planning

The shipping industry is one of the largest global industries, with massive revenues and mounting operating costs. Some studies suggest that the ports and shipping industry is responsible for up to 26% of the US GDP [51]. Further, the operational costs of large ships is typically thousands of dollars per hour, which implies that even minor decrease in the travel times would account to sizable monetary savings, along with reduced greenhouse gas emissions. Further, in addition to optimality in time, energy, or any such objective function, it is imperative to design risk-free and safe paths for these vessels with regards to ocean conditions [50].

Another area where path planning is of high importance is autonomous underwater vehicles (AUVs) [35, 38, 41]. These vehicles are designed to operate autonomously without any intervention for days or months at a time, for purposes ranging from data collection to national security. Optimal planning is imperative for these vehicles for longer endurance [68] and higher quality of collected data [46]. Further, while respecting the uncertain ocean conditions, these vehicles may be required to choose a path according to the considered risk profile of the operation, e.g. risk averse, risk seeking etc. [69].

Typically, these paths are chosen on a heuristic basis by the vessel or vehicle operators. However, these systems often lack modern capabilities that would allow for more informed decision making on the operators' part. By providing the operators with a lightweight and device-agnostic application with the requisite interactivity and flexibility, one can make this procedure more informed and efficient. We achieve this by incorporating a path planning module in SeaVizKit. The lightweight nature of the tool implies that it can be used by operators even in regions with patchy or weak network connection.

Fig. 10 shows a sample screenshot from a path planning mission. The aim of this mission is to plan a safe path with respect to large ocean waves caused by the tropical storm for an oil tanker traveling from Boston to Houston. We provide an optimal path for a risk averse user, predict for the tanker by going around the large waves caused by the storm. The platform might also feature an option to report observations by vessel operators to be assimilated, generating a better forecast. Further, once the modified forecasts are generated, one could also adaptively re-plan the path while accounting for the updated forecasts. Overall, the SeaVizKit technology can be easily incorporated in the shipping and path planning sectors to present the operators with an intuitive and informative interface to make informed decisions to achieve the desired objectives in an efficient way.

V. CONCLUSION

In this paper, we presented SeaVizKit, a novel tool for interactive visualization of multi-dimensional ocean simulation data built on top of the popular Leaflet and D3.js libraries. We outlined the data model for SeaVizKit and highlighted several desirable features of the user interface designed to facilitate interpretation of multi-dimensional probabilistic ocean fields, including interactivity of the tool and browser-based use. We provided several real-world use cases of the tool, including real-time visualization of sea exercise forecast data. Lastly, we discussed possible extensions of the visualization toolkit to applications involving fisheries management and ship routing which constitutes ongoing research.

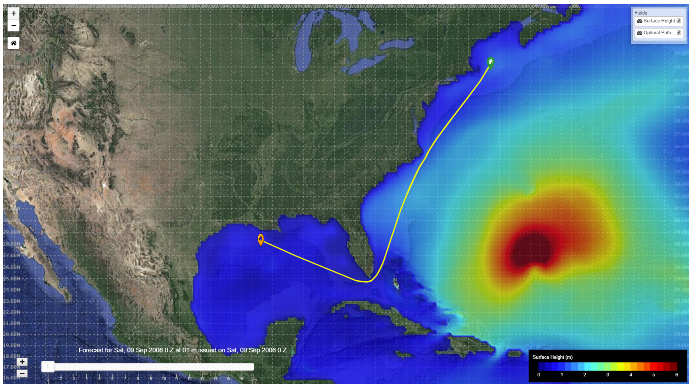


Fig. 10: Optimal path for an oil tanker traveling from Boston to Houston while avoiding rough sea conditions, demonstrated using the SeaVizKit path planning module

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