Environmental Prediction, Path Planning and Adaptive Sampling

Sensing and Modeling for Efficient Ocean Monitoring, Management and Pollution Control

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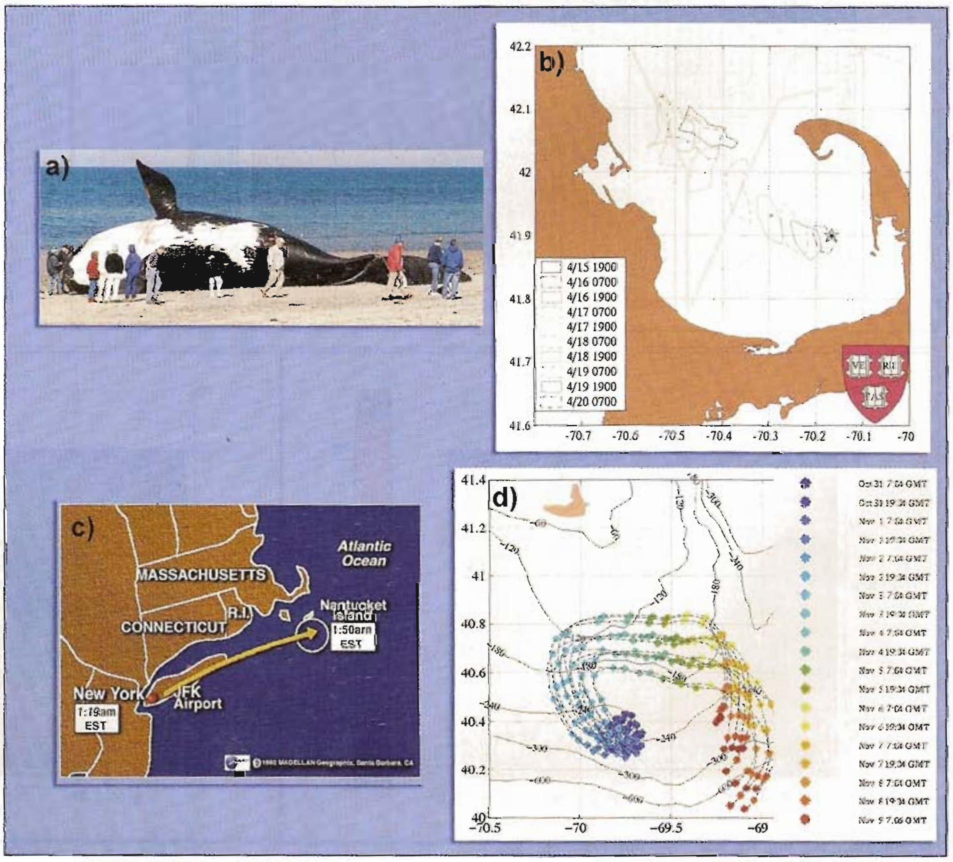
The impact of human activities on the ocean is becoming increasingly global. To successfully coexist with the ocean and utilize marine resources, civilization needs to monitor and predict the impacts of its activities and develop efficient sea-sensing technologies. In fact, better understanding and forecasting of environmental impacts requires synergy between ocean sensing and modeling.

Measurements in the ocean are expensive and difficult to acquire. Not everything can be sampled on a sustained basis. Similarly, not every molecular-to-climate process can be modeled exactly. In the ocean, it is the combination between sensing and modeling that enables sustained science, engineering and industries. This article is concerned with such a combination and its potential for efficient and quantitative environmental monitoring and pollution control.

In the past decade, the progress made by combining ocean data and models has been significant.[1] Models allow for the forecasting of ocean properties, such as currents or plankton concentrations. With predictive capabilities, one can also estimate the future impacts of human activities, carry out scenario analyses and monitor and manage ocean regions and ecosystems. Applications include climate analyses, pollution mitigation, ecosystem-based fisheries management, search and rescue and law enforcement at sea.

Since models do not capture everything, data are used to drive models and reduce uncertainties. An important modeling feedback to ocean sensing is the utilization of model predictions to plan the observations that are expected to be most useful.[2] Such quantitative planning of optimal paths for ocean



a) Staccato on Wellfleet Beach. b) Predicted possible strike locations shown as colored ellipses for 10 strike times. Ellipses estimate areas from which a virtual whale ends within two kilometers of the location at which Staccato was found dead (the star with a two-kilometer gray circle around it). Shipping lanes from Cape Cod Canal to Boston and to the Atlantic Ocean are shown. c) EgyptAir Flight 990 map. d) Predicted paths of potential Flight 990 floating debris. Twelve-hour intervals are colored by asterisks. The gray circle indicates an area of 10 kilometers in radius from the presumed crash site. Bottom contours are in feet.

platforms is referred to here as path planning. When such planning is a direct function of the data, the term adaptive sampling is used.

This article reviews applications of data-driven ocean predictions successfully utilized for environmental monitoring and pollution control. Applications include the use of modeling scenarios as an aid for marine law enforcement and data-driven ocean forecasting for search and rescue and oil spill management. Path planning and adaptive sampling are then developed. Methodologies for computing these optimal paths are outlined and examples are provided.

Data-Driven Predictions

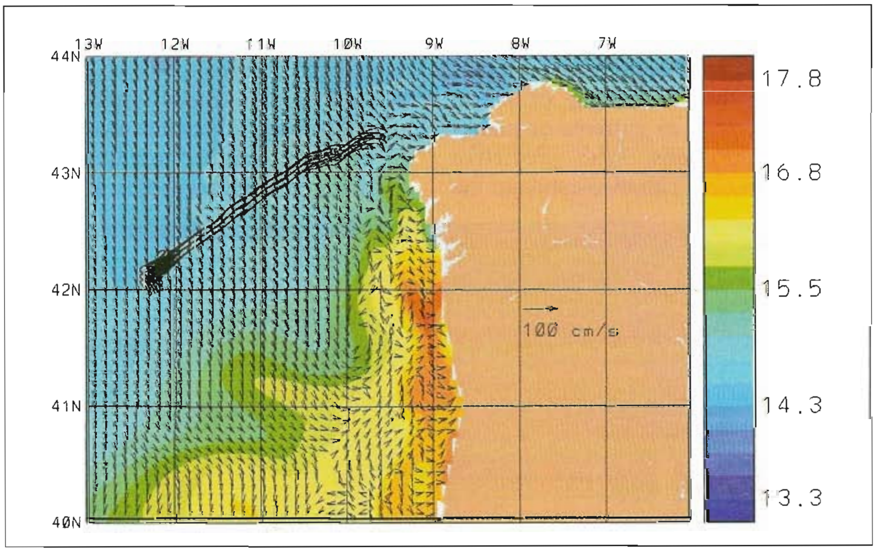
Ocean Modeling Scenarios for Marine Law Enforcement: Staccato—Death of a Right Whale. In late May 1999, the National Marine Fisheries Service Department of Compliance requested help to "back-calculate the drifting trajectory of a dead right whale, Staccato, to determine where it was struck by a ship." Staccato was found dead in the water and then pulled onto Wellfleet Beach on Cape Cod on April 20, 1999. She was last observed alive off Provincetown, Massachusetts, on April 15. During the five-day time span, Staccato might have been struck by a ship and fatally injured, as suspected in the report. Injuring or causing the death of a whale is a criminal offense, and the goal was to help find the culprit by attempting to correlate potential strike locations with the paths of vessels through Cape Cod Bay during the time in question.

Ocean data were acquired from the Massachusetts Water Resources Authority for March and April 1999, as well as atmospheric forcing variables from the Fleet Numerical Meteorology and Oceanography Center (FNMOC). Using the Harvard Ocean Prediction System (HOPS), the potential paths of virtual whales were estimated. Whales were simulated adrift from 800 different sites every 12 hours for five days—a total of 8,000 virtual whales. The key virtual whales were the ones that drifted to the site where Staccato was observed dead on April 20. The results show that if Staccato died on April 15, she most likely died in a fairly small patch of water a few miles off Plymouth, Massachusetts.

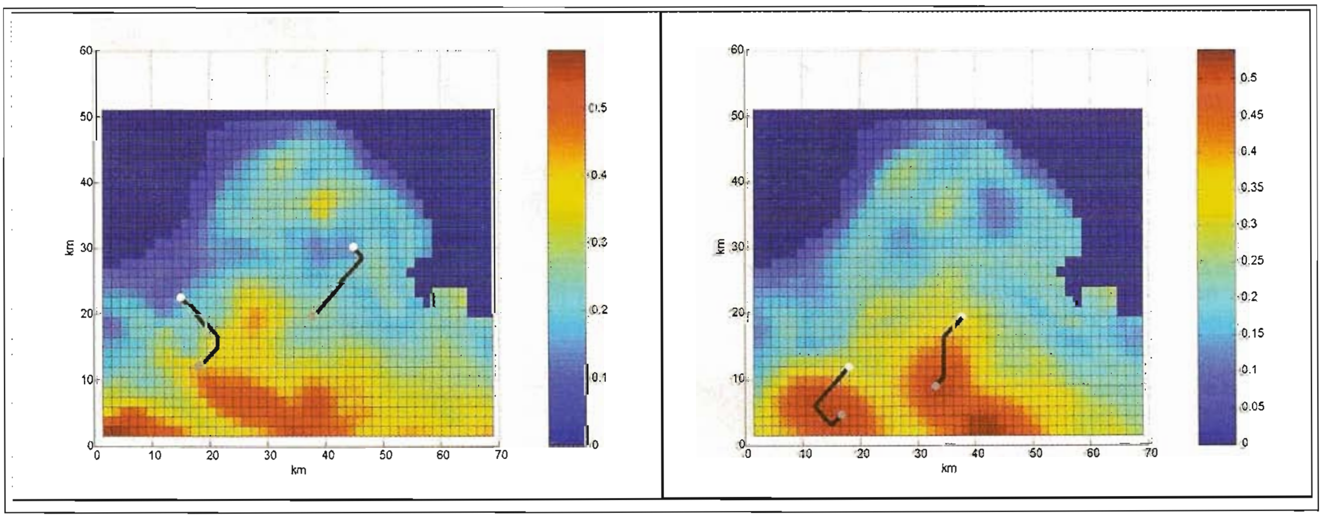
The team's computations allowed the National Marine Fisheries Service Department of Compliance to narrow down the number of potential culprits from 100 to about 10 vessels. However, the exact date and cause of the death of Staccato could not be confirmed. She may have been sick prior to being hit.

Data-Driven Ocean Forecasting for Search and Rescue at Sea: EgyptAir Flight 990. Following the accident of EgyptAir Flight 990 on October 31, 1999, the paths of floating debris were forecast for nine days. A modeling domain with a horizontal resolution of .045° (about five kilometers) and 42 vertical levels was utilized.

The simulation assimilated satellite sea surface temperatures and was forced by FNMOC atmospheric forecasts. The drift paths of floating debris were predicted for the period of October 31 to November 9 for an impact at 40.35N, 69.75W. Particles



(Left) Predictions of Prestige *oil spills during December 2002 near the coasts of Portugal and Spain. Oil spill tracks are overlaid on predicted sea surface temperature (in Celsius) and current vectors.*



(Below) Paths of two AUVs that optimally sample the uncertainty fields predicted for two consecutive days in Monterey Bay. White dots are starting points for the AUVs. Gray dots are optimal termination points, as computed by MILP.

> *"For efficient environmental monitoring, homeland security and rapid response to at-sea events, ocean sensing and modeling must be coordinated."*

located within a 10-kilometer circle at the time of impact were tracked during the simulation.

Overall, trajectories of floating debris depend on the winds (strength, direction and pattern) and internal ocean dynamics (meandering shelfbreak front, southwestward shelf currents and eddies and Gulf Stream warm-core rings). The results found that trajectories of potential debris were influenced by the location of impact with respect to the shelfbreak front, whose surface currents are west-southwestward, meandering near the 300-foot isobath.

Data-Driven Ocean Forecasting for Oil Spill Management:* Prestige *Oil Spills. On November 19, 2002, the *Prestige* tanker split in half off the northwest coast of Spain, threatening to become a major environmental disaster. In collaboration with the Portuguese Hydrographic Office, HOPS was set up for the Spain-Portugal coastal region and initialized with climatological and synoptic *in-situ* hydrographic data. In total, 197 conductivity, temperature, depth stations, taken by research vessel *Cornide Saavedra* from November 23 to 29, 2002, were assimilated. Atmospheric forcing was applied, combining fluxes from the 10-kilometer ALADIN and from FNMOC atmospheric forecasts.

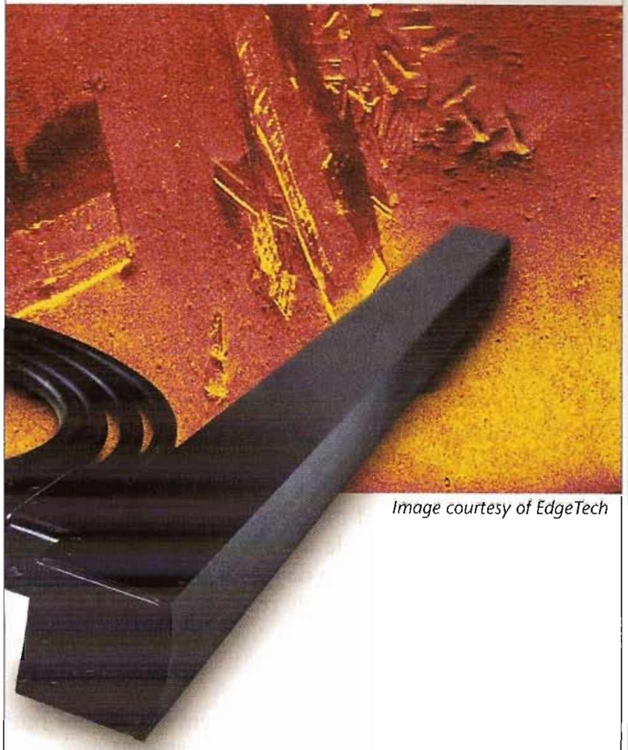
The oil spill lasted for several weeks with varying strength. The oil spill was modeled as nine Lagrangian surface drifters, released at 12Z (coordinated universal time) on December 8, 2002, within a 15 by 15-kilometer grid around the main *Prestige* location. The oil spill was predicted to reach the northern coastline of Spain, as was confirmed by the European Space Agency.

Planning and Adaptive Sampling

For efficient environmental monitoring, homeland security and rapid response to at-sea events, ocean sensing and modeling must be coordinated. In particular, data-driven model predictions and their uncertainties can be used to determine the ocean observations required for optimal predictions, management and rapid responses. Adaptive sampling refers to the prediction of the types and locations of additional observations that are most useful for specific objectives, under the constraints of the observing network. Path planning is the computation of optimal routes for assets that can be adapted. The methods the authors used to do so are based on Mixed Integer Linear Programming (MILP) and genetic algorithms.[3,4] MILP was illustrated for Monterey Bay off California using uncertainty predictions supplied by HOPS and error subspace statistical estimation (ESSE).[5]

Path planning amounts to the optimization of an objective function. The optimization is solved by MILP, which applies to linear cost functions and constraints where some unknowns are integers.

The solution is obtained by a branch and bound algorithm, which can provide exact and globally optimal solutions. The path is segmented by waypoints, and the goal is to solve for the coordinates of those points. The number of waypoints is a parameter fixed as a function of vehicle range and grid dimensions.



The first step is to define the cost function. Here, the integral of uncertainty values along the vehicle path is maximized. The cost function is, thus, the uncertainty field (predicted by ESSE) mapped onto a piecewise-linear function. The next step is to assess which constraints govern the assets, presently autonomous underwater vehicles. There are various types of constraints. The first type relates to the primary motion of the vehicles. On the discrete spatial grid, it sets the neighboring locations to which the vehicle can move. The second type of constraint inhibits path curling. The third type involves vicinity requirements and collision avoidance for multi-vehicle scenarios. Finally, there are constraints due to coordinated control and communication considerations with ships, shore stations and buoys. To establish the link between consecutive days, the end path-point of vehicles on one day was set to the starting point on the following day. Days in the future then affect the planning for the current day. Future days were weighted down as a function of the predictive capability. In this case, uncertaintied are temperature error standard deviations as forecast by ESSE, averaged over zero to 50 meter depths.The results show that a vehicle does not go north towards the smaller uncertainty peak on day one, but towards the higher peak even though it can only reach the top of the peak on day two.

Conclusions

Data-driven ocean predictions for environmental monitoring and pollution control were illustrated. It was shown that they can assist marine law enforcement, real-time search and rescue and oil spill management. Path planning and adaptive sampling to predict the most useful measurements were then introduced. Since data collection at sea is challenging and expensive, being able to guide ocean sensing platforms towards optimal locations is promising. Such optimal planning is a prerequisite to quantitative monitoring, protection and management of the oceans and necessary to sustain the growing utilization of marine resources.

> ***"Data-driven ocean predictions...can assist marine law enforcement, real-time search and rescue and oil spill management."***

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