Time Optimal Path Planning and Ocean Monitoring in the Portugal-Azores-Madeira Ocean Region

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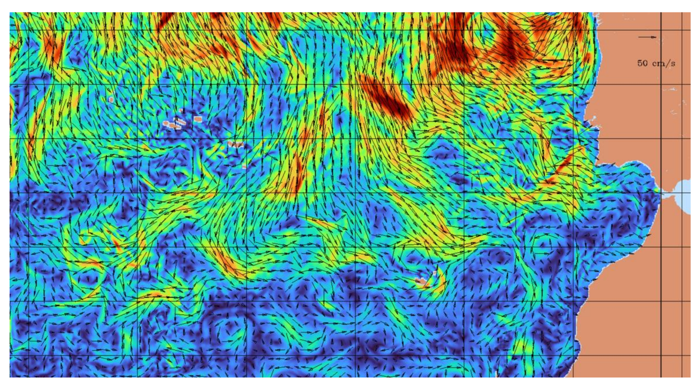
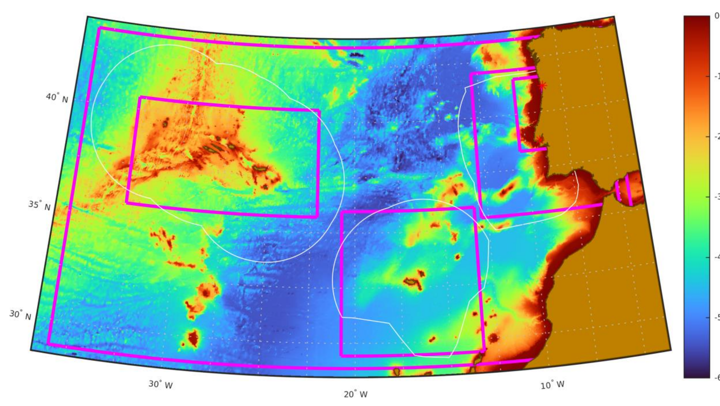
mseas multidisciplinary simulation, estimation, and assimilation systems
MIT Portugal

Background

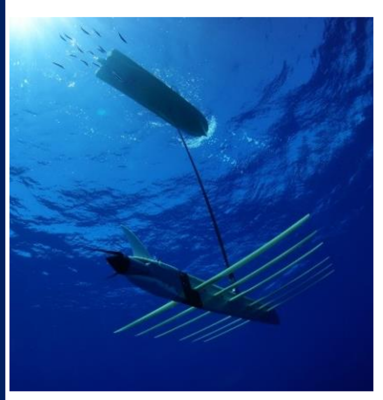
For intelligent ocean exploration and sustainable ocean utilization, the need for smart autonomous underwater vehicles, surface craft, and small aircrafts is rapidly increasing. Applications include scientific studies, solar-wind-wave energy harvesting, transport and distribution of goods, naval operations, security, acoustic surveillance, communication, search and rescue, marine pollution, ocean cleanup, conservation, fisheries, aquaculture, mining, and monitoring and forecasting. Designing optimal paths leads to cost savings, longer operational time, and environmental protection.



Surface Velocity (cm/s)

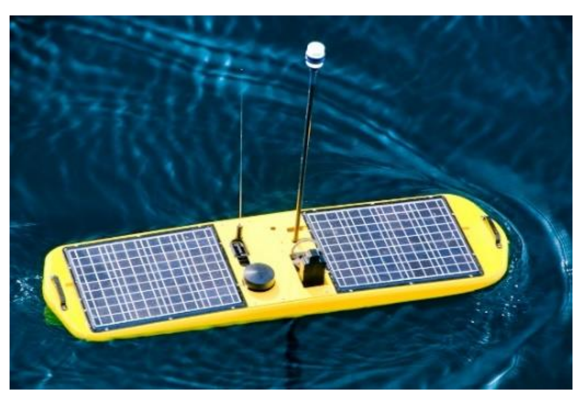


Bathymetry (m)



Liquid Robotics

Saildrone



Solar Liquid Robotics

Goals: Optimal Planning and Monitoring

- Further develop and apply our physical-biogeochemical-acoustical multi-resolution ocean modeling and data assimilation, Bayesian inference and scientific machine learning, and exact optimal planning for coordinated fleets of AUVs, ASVs, UAVs and other aircrafts, and near space assets
- Theory and schemes for optimal time-energy path planning, energy harvesting (e.g. solar, wind, wave, and thermal energy; algae biofuels), dynamic ocean cleanup (e.g. marine plastic and litter; oil spills; natural and man-made sediment plumes), and risk minimization under realistic ocean conditions
- Information-optimal theory for scientific exploration, ocean monitoring and Bayesian machine learning of model parameterizations and turbulence closures
- Collaborate with colleagues (D. Hart, O. de Weck, J. Leonard, D. Newman, etc., Eduardo B. Pereira, J. Tasso de Figueiredo Borges de Sousa, etc.)

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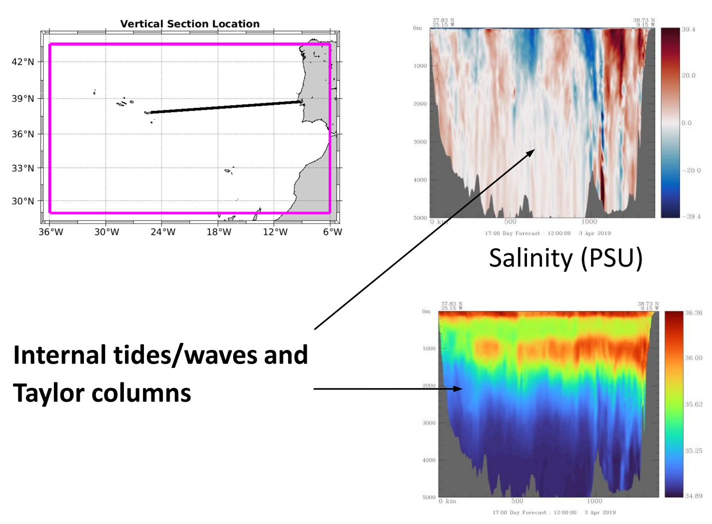
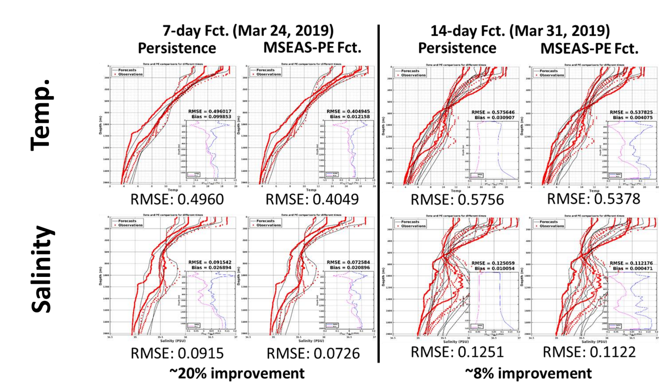
Multi-Resolution Ocean Monitoring and Modeling

- **34-day MSEAS PE Hindcast: Mar 17-Apr 20, 2019**
- Multiple nested domains (4.5, 1.5, and 0.5 km resolution)
- High-resolution bathymetry
- 100 optimized vertical levels
- TPXO9-Atlas tidal forcing
- Atm. forcing: NCEP CFS (1/5º)
- 1/12º HYCOM initial and open boundary conditions
- Collected/processed data (ARGO, BioGeoARGO, Gliders, XBT, SST, SSC, SLA, HF Radar, tide gauges, buoys, drifters)

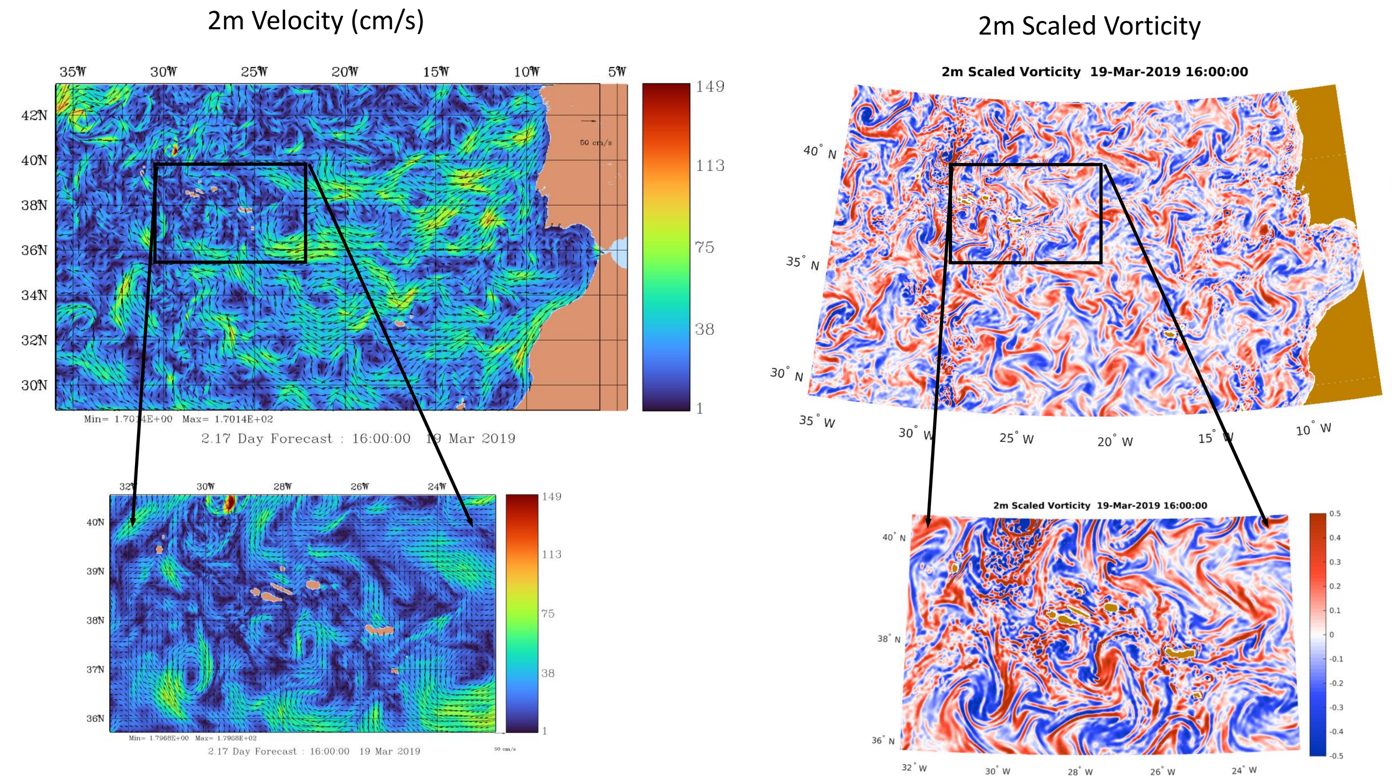
(Nordeste, Sao Miguel to Lisbon)



Model Skill: Beats persistence for 2 weeks, w/o DA (similar skill for other variables)



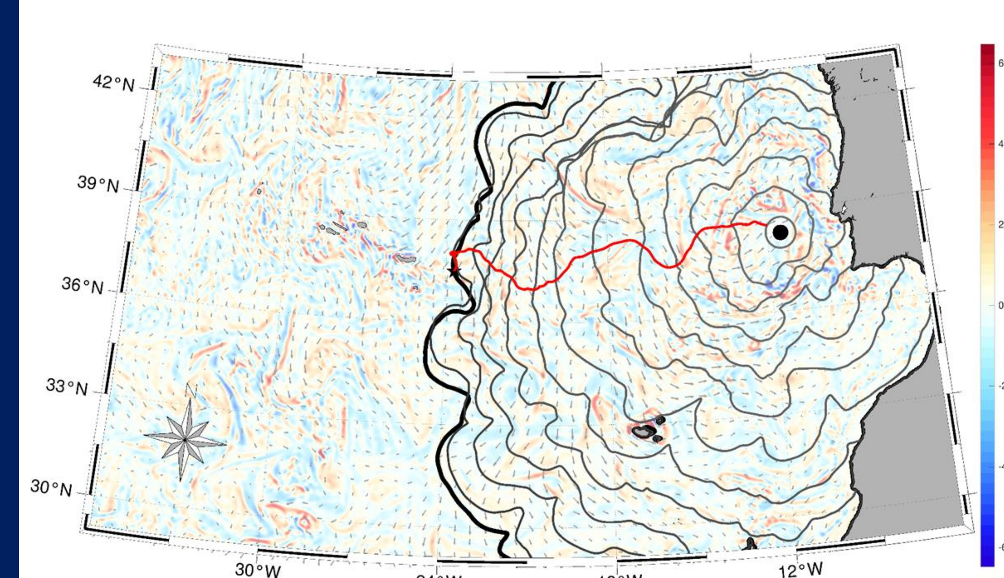
Nesting: High-resolution 1.5 km Azores domain implicit two-way nested in larger 4.5km domain



Time-Optimal Path Planning

Computational Methods: Employed our exact time-optimal path planning theory and schemes based on Hamilton–Jacobi PDE and Level Set method

- Reachability Front: We evolve the reachability front and reachable set (positions that can be reached at a given time by the vehicle)
- Time-optimal trajectories backtracked from *any point* on reachability front
- Reachability front predicts important results such as:
  - Reachability front extends further in the south → Faster to travel south
  - Smooth reachability front → No strong persistent currents in domain of interest

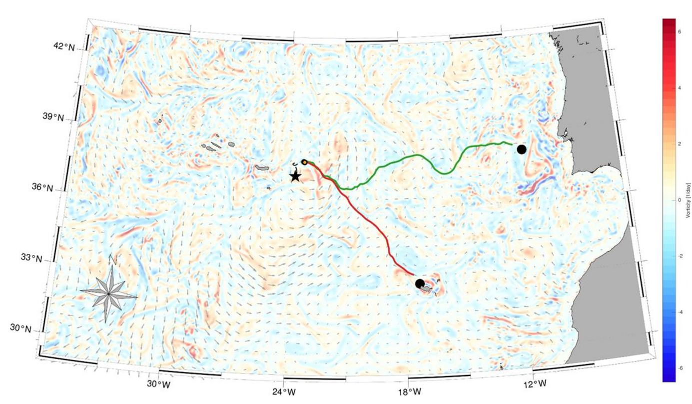


Surface Craft Lisbon to Azores: Time-Optimal path for a surface craft travelling from offshore Lisbon to offshore Azores with a vehicle speed of 0.5 m/s (~1 knot). For this period, our data-driven ocean modeling and optimal path planning predict that the journey will take 23.4 days.

Time-Optimal Path Planning Aplications

Fastest Interception/Rendezvous: Solve complicated dynamic model predictive control problem such as finding time-optimal paths to moving destinations in dynamic environments

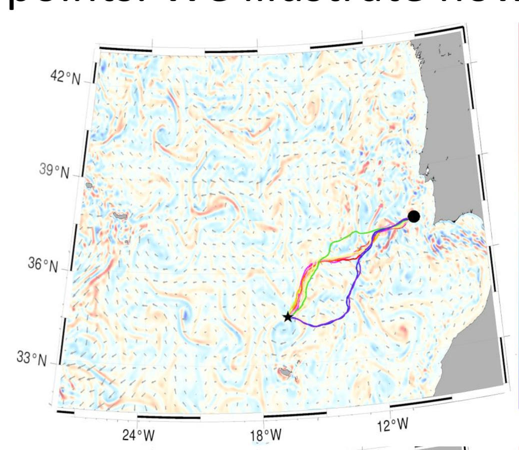
- In this method, a faster ship intercepts in shortest-time the time-optimal ASV previously shown. The intercepting ship is released when the ASV is halfway through its mission



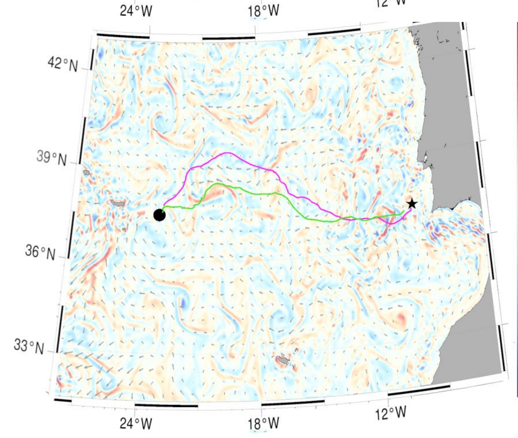
A second surface craft starting from offshore Madeira will intercept the above surface craft, with a vehicle speed of 1 m/s (~2 knots). Within this ocean model, the journey will take 9.1 days to intercept and rendezvous with the other surface craft.

Several possible other applications: multi-vessel interceptions, search and rescue operations, naval operations, and management of underwater platforms, subsea cables, or small-satellites

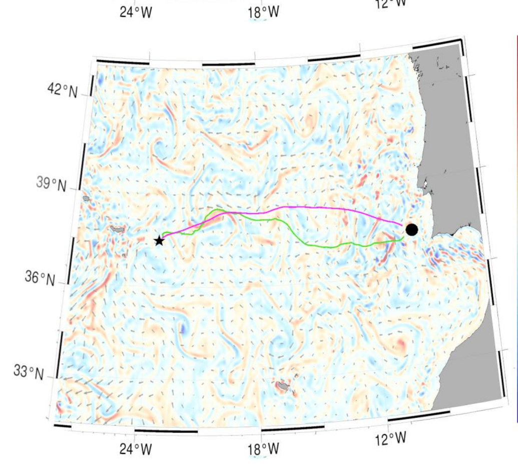
Sensitivity of time-optimal paths to start time, direction and vehicle speed: Time-optimal paths can be predicted between any points. We illustrate how they vary with different parameters.



Start Time: For a surface craft of 0.5 m/s speed, the path from Lisbon to the Madeira is affected by its start time. The paths starting on days 1-7 follow a similar path (red colors), but on day 8 (green) the optimal path goes North and then South for day 9 (blue) and 10 (purple), as currents turn South during that time window.



Travel Direction: For a surface craft of 0.5 m/s speed, the path from Lisbon to the Azores (green) differs from the path from the Azores to Lisbon (pink) due to ocean currents and their effects on the paths that varies with travel direction.



Vehicle Speed: Paths differ with the speed of the surface craft. The green path from Lisbon to the Azores has a speed of 0.5 m/s while the pink path has a speed of 1.5 m/s. Faster speeds have a "smoother" and more direct path, as they are less affected by ocean currents.

Acknowledgements and Collaborators

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