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# Real-time Ocean Probabilistic Forecasts, Reachability Analysis, and Adaptive Sampling in the Gulf of Mexico

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The integration of novel autonomous ocean monitoring and probabilistic ocean forecasting can be most beneficial to the Gulf of Mexico (GoM) and its communities and stakeholders. Such integration combines systems for high-resolution stochastic ocean modeling, multi-platform autonomous observing, data assimilation, path planning, adaptive sampling, real-time operations, and of course human interactions. The first steps towards this integration for the GoM were demonstrated in real-time during the collaborative Mini-Adaptive Sampling Test Run (MASTR) ocean experiment [1, 2]. The main MASTR effort occurred from February to April 2024, as part of the collaborative "Understanding Gulf Ocean Systems (UGOS-3)" initiative sponsored by the Gulf Research Program of the U.S. National Academies of Sciences, Engineering, and Medicine. The emphasis of the present contribution is on some of the real-time MASTR results. They include large-ensemble forecasting of physical ocean fields, uncertainties, and risks, predicting reachable regions and optimal paths for aircraft and marine platforms, forecasting optimal ocean sampling times and locations, and evaluating the skill of forecasts by comparison with observations.

For the three months of MASTR, we employed our MSEAS Primitive-Equation (PE) submesoscale-to-regional-scale ocean modeling system [3–5], processed and assimilated multiple data types, and issued and described in real-time deterministic and probabilistic forecasts of ocean fields and derived quantities [2]. For the first time in the region, we provided daily (i) multi-resolution large-ensemble forecasts with initial conditions downscaled from two global models (HYCOM and Mercator) with multi-region 3D PE-field perturbations using Error Subspace Statistical Estimation (ESSE), stochastic tidal and atmospheric forcing, and implicit 2-way nesting, (ii) mutual information forecasts for sampling and predictability studies, (iii) optimal adaptive sampling guidance for air and sea sensing platforms, and (iv) reachability forecasts for underwater vehicles [6]. All forecasts were of 5 to 14 days duration using 100 optimized vertical levels and 1/25° horizontal resolution (some at 1/12.5°). They were forced by blended NAM 12 km and GFS $1/4^\circ$ hourly air-sea fluxes from NCEP and by tides from TPXO8-Atlas of OSU adapted to the high-resolution bathymetry and coastlines [7]. We utilized the bathymetry from the Shuttle Radar Topography Mission (SRTM) 15-arcsecond global map [8], merged with the CICESE bathymetry for the Cozumel region. Forecast fields were issued daily and described using snapshot time-series maps, sections, and interactive visualization [9]. We also displayed the varied measured data sets that we processed (Argo floats CTDs, gliders CTDs, SSH, SST, Buoys data, etc.). We used these data to evaluate the skill of our forecasts in real-time, computing skill metrics that compare forecasts at data points to the measured values.

Figure 1 illustrates a few of the real-time results [2]. A forecast of optimal sampling paths for ROCIS flights for Feb 23, 2024, is shown in Fig. 1(a). The flights sample surface currents along their tracks. This defines the candidate sample observations. Our scientific objective for the flights was to maximize information about the (cyclonic) eddies along the western wall of the Loop Current (LC) near and past the Yucatan Channel (YC). The target verification fields are the eddy density anomaly $\sigma_T$ and surface velocity at future times along the western wall of the LC. The flight paths that sample the most information about these fields were forecast for different days in two steps. First, we determined all valid paths that satisfied normal operation criteria. This was computed ahead of time. Second, we used the large-ensemble MSEAS-PE forecasts to predict the mutual information (MI) [10] between surface currents along each valid path and the future target fields. Finally, we select and recommend the paths with the maximum MI value that satisfy the real-time constraints.

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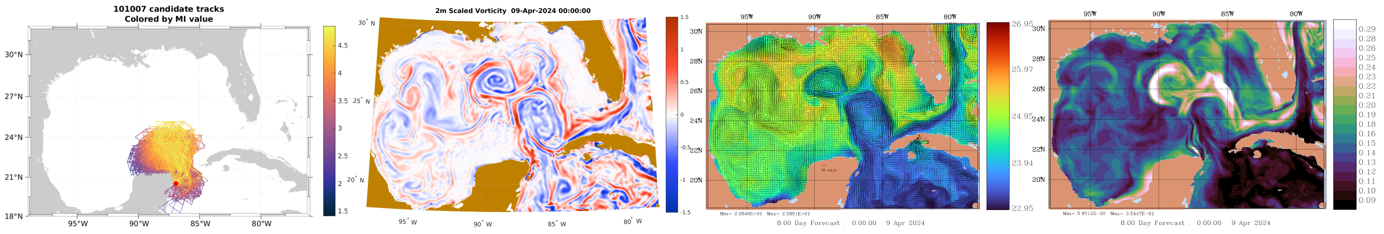
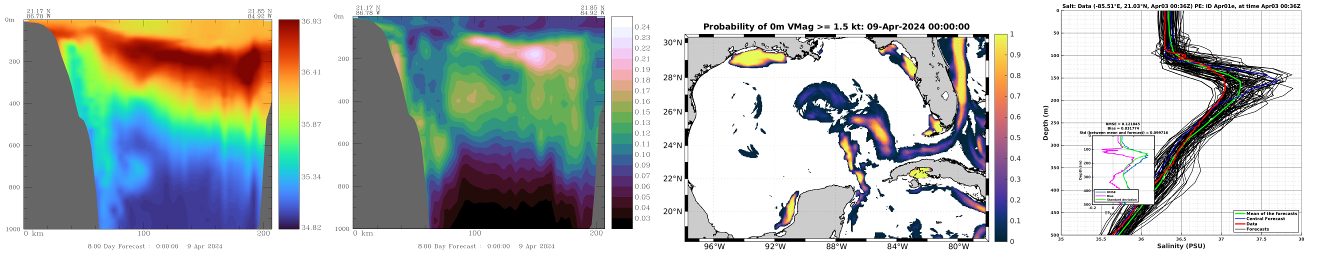


(a) Candidate Flight Paths, MI-colored (b) 2 m Vorticity (c) 0 m $\sigma_T$ (d) 0 m $\sigma_T$ Uncertainty



(e) S in Yucatan Channel (f) S Uncertainty in Yucatan Channel (g) 1.5 kt Velocity Probability (h) Ensemble Skill at Data Points

Fig. 1: Examples of MSEAS forecast products issued in real-time during MASTR [2]. Unless otherwise specified, all images are forecasts for April 9. (a) Candidate ROCIS flight paths for Feb 23, ordered and colored by the forecast mutual information (MI) about the target verification field. (b) Vorticity (scaled by $f$) at 2 m. (c) Surface $\sigma_T$. (d) Uncertainty (ensemble standard deviation) in surface $\sigma_T$. (e) Salinity in Yucatan Channel. Notice that the MSEAS forecast captures the subsurface salinity maximum. (f) Uncertainty (ensemble standard deviation) in salinity in Yucatan Channel. Peak uncertainty aligns with the upper limit of the subsurface maximum. (g) Forecast of the probability of the surface velocity being 1.5 knots or greater. The probable high velocities are limited to the vicinity of the LC, eddies, and regions of strong tides at 00Z. (h) Ensemble skill against a salinity profile on April 3. Note that the data profile is contained within the ensemble envelope.

Fig. 1(b), (c), and (d) are forecasts for April 9, 2024: the relative vorticity field at 2 m, the surface $\sigma_T$ field, and its standard deviation field, respectively. We highlight the surface eddies in the Caribbean Sea, the extended LC with the recently detached eddy Cardone, the currents and eddy Berek in the western Gulf, and the larger $\sigma_T$ uncertainties at the west side of eddy Cardone, at the LC–Cardone boundary due to interactions in some ensemble realizations, and at the eastern wall of the LC. Fig. 1(e) and (f) show forecast sections along the YC in salinity and its standard deviation for April 9. The forecasts capture the sloping subsurface salinity maximum and return flow by Cuba, and highlight the larger standard deviation on the edges of this maximum, especially on the upper edge in response to atmospheric forcing uncertainty. Fig. 1(g) is a forecast for April 9 of the probability of the surface velocity being 1.5 kt or greater, a key metric for the GoM industry. Fig. 1(g) compares the ensemble forecast for April 3 to a salinity data profile, many more of which confirm predictive skill up to 14 days and beating persistence [2].

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