The US Navy's RELO Ensemble and its Application to Lagrangian Trajectory Prediction in the Gulf of Mexico

Mozheng Wei [a], Gregg Jacobs [a], Clark Rowley [a], Charlie Barron [a], Pat Hogan [a], Peter Spence [b], Ole Martin Smedstad [b], Paul Martin [a] and Emanuel Coelho[c]

[a] Naval Research Laboratory, Stennis Space Center, MS 39529
[b] Qinetiq-North America, Stennis Space Center, MS 39529, [c] University of New Orleans at Naval Research Laboratory, Stennis Space Center, MS 39529

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Introduction

Real-time ocean forecasts with two RELO (Relocatable) ensembles and three single models using NCOM and HYCOM with different resolutions were carried out to support and provide guidance to the CARTHE GLAD at-sea experiment during the summer 2012. A calibrated ensemble system with enhanced spread and reliability, which is proposed for this project, outperforms the un-calibrated ensemble in terms of quantitative forecasting accuracy, skill and reliability for all the variables and observation spaces we have evaluated. The advantages of ensembles over single models are demonstrated. RELO ensembles are applied to the Lagrangian trajectory prediction, and it is demonstrated that either ensemble can provide valuable uncertainty information in addition to predicting the particle trajectory with highest probability in comparison with a single ocean model forecast. The calibrated ensemble with more reliability is able to capture some trajectories in different, even opposite directions which are missed by the un-calibrated ensemble.

CARTHE GLAD Background

The GLAD (Grand Lagrangian Deployment) at-sea experiment in the northern Gulf of Mexico (GOM) was supported by CARTHE and GoMRI and conducted from July 17 to August 3, 2012. During the experiment, 317 near-surface drifters were released to directly measure transport and dispersion processes down to spatial scales as small as 100 meters. On Oct. 18, 2012, there were still 142 drifters working properly and transmitting data through GPS. Among 317 drifters deployed, only 3 ran out of GOM through Florida Straits. On Nov. 4, 2012, total data transmissions passed 5 million, 110 drifters were still working.

As the modeling team for CARTHE at NRL, we focus on the numerical modeling, data assimilation (DA) and forecasting to support and provide numerical guidance to the GLAD experiment.

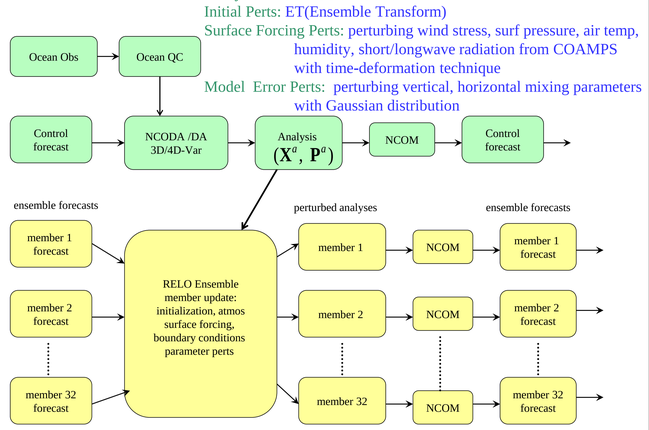
GoMRI: the Gulf of Mexico Research Initiative, funded by BP following the Deep Water Horizon (DWH) drilling rig explosion approximately 60 km off the coast of Louisiana on April 20, 2010. (http://gulfresearchinitiative.org/)
CARTHE: the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment, one of the consortia of GoMRI, comprises scientists from 12 universities and research institutions. (http://www.carthe.org)

Experimental Setup

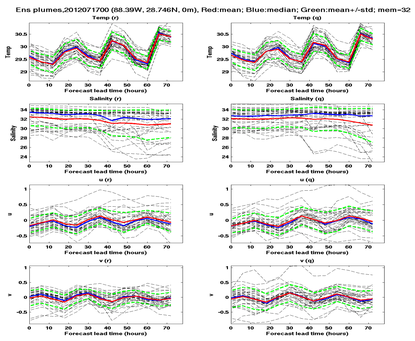
Domain: GOM; **Forecast Length:** 72 hours.
Verification Period: 00Z June 1, 2012 - 00Z September 17, 2012 (109 days).
Experiments and IDs:

	gom32r (r)	gom32q (q)	ncom3km (3k)	ncom1km (1k)	hycom4km (4k)
Model	NCOM	NCOM	NCOM	NCOM	HYCOM
Resolution	3km 49 hybrid sigma-z levels	3km 49 hybrid sigma-z levels	3km 49 hybrid sigma-z levels	1km 49 hybrid sigma-z levels	4km 20 hybrid levels
Tidal Forcing	on	on	on	on	off
Ensemble Members	32	32	1	1	1
Ensemble Perturbations	Analysis Error: NCODA 3D-Var Initial Perturbations: ET (Ensemble Transform) Surface Forcing Perturbation: perturbing COAMPS atmospheric fields based on time-deformation technique Model Error: perturbing vertical and horizontal turbulence mixing parameters based on Gaussian distribution	gom32r + Initial Perturbation Calibration	-	-	-

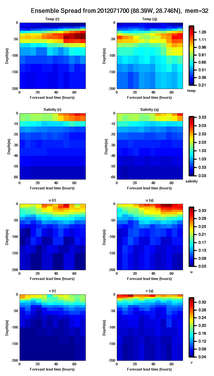
A Schematic of RELO Ensemble Forecast System



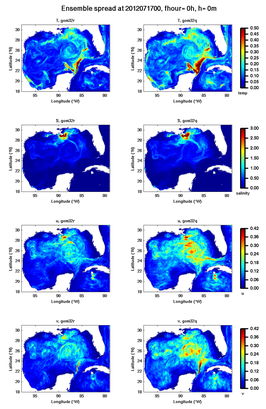
RELO Ensemble Spread



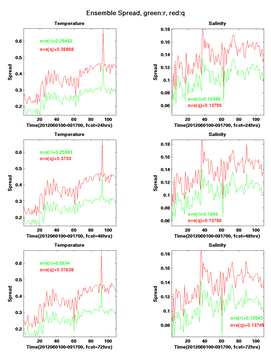
Ensemble Plumes 2012071700, 0m (88.39W, 28.74N) BP/DWH-acciden

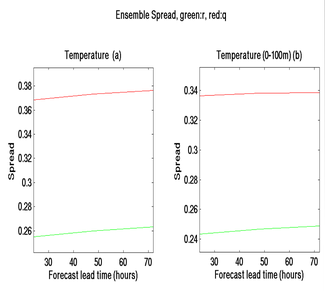


Ensemble Spread from 2012071700 (88.39W, 28.74N) BP/DWH-accident



Ensemble Spread at 2012071700 0hour, 0m

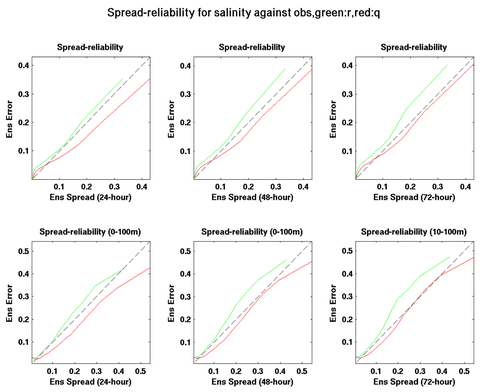




Ensemble Spreads gom32r, gom32q at 24, 48, 72hours

Ensemble spreads for gom32r, gom32q, averaged over 109 days and in the whole observation space (a) and space of 0-100m (b)

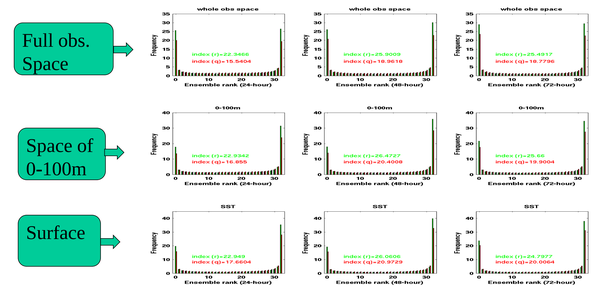
Ensemble Reliability



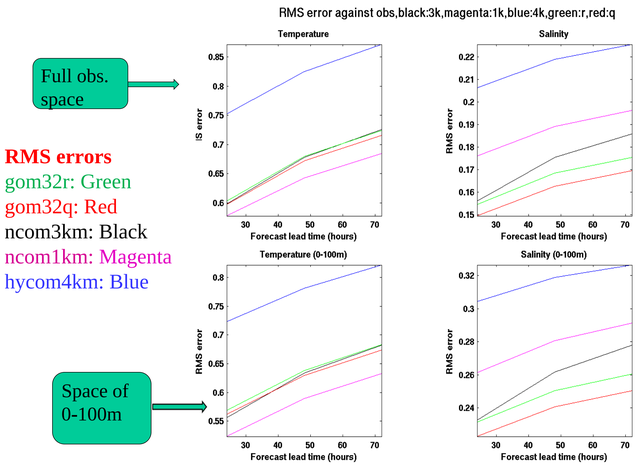
Spread-reliability /Salinity/truth= obs. Ave. 109 days

Ensemble spread r is under-dispersive
Ensemble spread q is closer to diagonal line except for 24hour fcst in whole obs space
For temperature: q is better in all cases

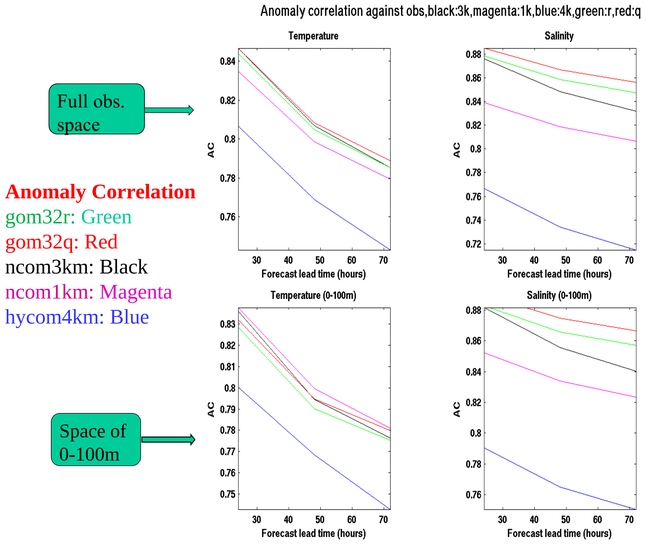
Talagrand Histogram/Temp/truth=obs. Ave. 109 days



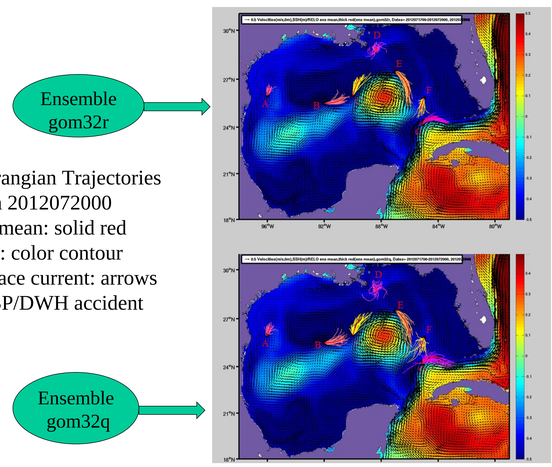
Forecast Accuracy



Forecast Skill



Ensemble in Lagrangian Trajectory Prediction



Lagrangian Trajectories from 2012072000
Ens mean: solid red
SSH: color contour
Surface current: arrows
D: BP/DWH accident

Ensemble in Lagrangian Coherent Structure (LCS)

The ocean dynamical equation is given by $\frac{d\mathbf{x}}{dt} = \mathbf{v}(x, y, t)$

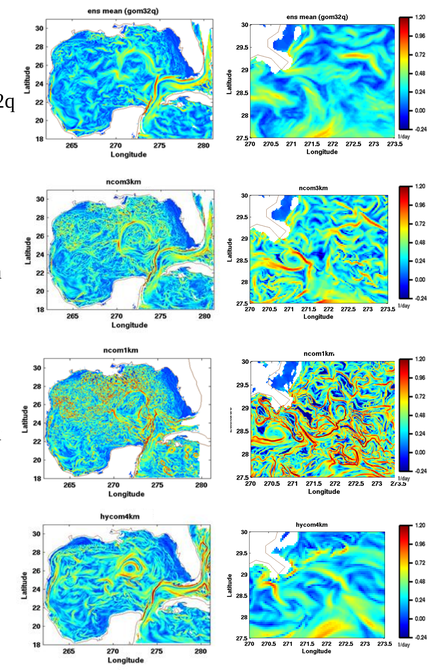
If we follow a particle, integration will provide a flow map $F(t_0,\ t)$ such that $\mathbf{x}(t) = F(t_0,\ t)\mathbf{x}(t_0)$ The right Cauchy-Green deformation tensor (matrix C) can be constructed as $C = (\frac{dF}{d\mathbf{x}})^T(\frac{dF}{d\mathbf{x}})$

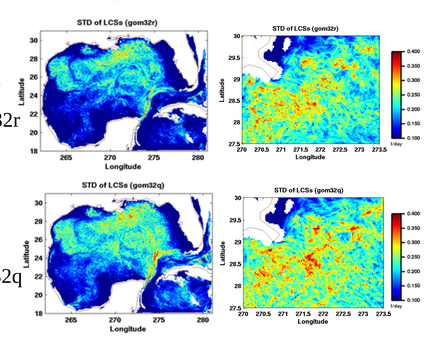
The largest FTLE (finite-time Lyapunov exponent) associated with the trajectory over this time interval is

$$\sigma(\mathbf{x}_0, t_0, \mathbf{x}, t) = \frac{1}{|t - t_0|}\log\sqrt{\lambda_{\max}(C)}$$

where $\lambda_{\max}(C)$ is the largest eigenvalue of C. The ridges of the largest FTLE represent the LCS. Forward integration of a set of trajectories generates the **repelling LCS** at the initial time, while backward integration in time produces the **attracting LCS** at later time.

Repelling LCS at 2012072000





Conclusions

- The ensemble mean is more accurate and skillful than a single deterministic forecast at the same resolution, but in some cases it is less accurate than a single model forecast at much higher resolution.
- Analysis error is under-estimated in NCODA 3D-Var, leading to a underestimate of the initial ensemble spread.
- While perturbing vertical and horizontal mixing parameters improves (increases) the ensemble spread somewhat, future development of a stochastic parameterization package is expected to better account for the various sources of ocean model uncertainties.
- The calibrated ensemble has higher accuracy, skill and reliability than the un-calibrated for all variables in all observation spaces tested.
- The more-reliable calibrated ensemble is able to capture some aspects of the observed trajectories, including local eddies and small scale flow reversals, that are missed by the un-calibrated ensemble, indicating the importance of reliable ensembles in Lagrangian prediction.
- The ensemble methods can quantify the uncertainties of Lagrangian trajectories and LCS (Lagrangian Coherent Structure).
- LCS depends on model resolution; high resolution is essential to revealing meso-scale LCS structures, such as eddies.