Assessing the Lagrangian Predictive Ability of Navy Ocean Models

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Award Number: N00014-09-1-0559
http://laplace.ceoe.udel.edu/MAIN/results.html

LONG-TERM GOALS

We focus on understanding energetic sub-mesoscale and mesoscale processes responsible for ocean transport throughout the water column. Since the evolution of these processes is typically nonlinear and often driven by brief, episodic forcing events, understanding and modeling them remain fundamental challenges for oceanographers.

OBJECTIVES

We have developed a variety of Lagrangian analysis tools with prior ONR support and we have studied the role of submesoscale and mesoscale dynamics in ocean transport by applying these tools to archived ocean model velocities. In many of the regions we've studied, Lagrangian analysis of model forecasts reveals complex, slowly evolving Lagrangian coherent structures (LCS) that define mixing boundaries in the flow. Increasing model spatial resolution allows more small-scale variability in these mixing boundary structures to emerge.

Since LCS maps are constructed from tens of thousands of modeled trajectories, their usefulness depends entirely on the Lagrangian forecast skill of the underlying ocean models. Our objective is to assess the Lagrangian forecast skill of operational Navy ocean models in different geographic regions. Since it is extremely difficult to benchmark LCS maps with observations (thousands of observed drifters would be needed), we focus on a more practical objective: quantifying trajectory forecast skill over one forecast cycle (typically 72 hours) by comparing predicted and observed trajectories. We are also interested in exploring the range of Lagrangian forecast skill among all members of an ocean model ensemble, since this indicates the impact of model Eulerian uncertainties on the quality of trajectory forecasts.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2011		**00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Assessing the Lagrangian Predictive Ability of Navy Ocean Models**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Delaware,Robinson Hall,Newark,DE,19716**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Our Lagrangian analysis approach relies on computing large numbers of trajectories directly from archives of ocean model velocities. The trajectories can be compared with observations, for model assessment, or can be used to compute synoptic maps showing the spatial distribution of Lagrangian properties. LCS maps are one example.

Model trajectories are computed at one model depth, using path equations that describe simple 2D advection in the horizontal. Linear interpolation of model velocities in both space and time is used. The path equations are integrated using a Runge-Kutta scheme with adaptive time-stepping. For the analysis here we make no attempt to include the effects of vertical motion, velocity uncertainties, or processes at scales below the model grid resolution. Also, no corrections are applied to account for wind slip of the observed drifters.

To assess Lagrangian forecast skill, we define a metric, *separation after three days*, the distance between an observed and modeled trajectory (in km) after a three-day period. We have explored other metrics, but they will not be discussed here. For model Lagrangian skill assessments, we used small groups of observed trajectories for drifters launched as part of four Navy acoustics experiments (FAST-04, LWAD-05, LWAD-06, and LWAD-07) during the period 2004 through 2007. To increase the sample size, observed trajectories were divided into three-day segments with "launch" times chosen as 0000 UT daily. Although these segments overlap in time, each launch is treated as an independent event. In addition, drifters from the LWAD-07 experiment (with "launches" separated by three days, to eliminate their overlap in time) were used to assess the Lagrangian predictive skill of twenty-four RELO model ensemble members.

Because of the focused ocean observations supporting the Deepwater Horizon spill mitigation, we also began a preliminary assessment of the mixing characteristics of the Gulf of Mexico HYCOM model. We computed LCS at each model depth using trajectories for particles launched at each model grid point. Vertical velocities were ignored. By "stitching together" LCS results from each model layer, we examined the three-dimensional structure of the mixing boundaries associated with energetic mesoscale eddies.

WORK COMPLETED

The following tasks were completed during this two-year effort, which ended in February 2011:

- Assessed the Lagrangian predictive skill of the Navy EAS16 model in the western Pacific using drifter trajectories from four Navy acoustic experiments during the period 2004 through 2007. Detailed comparisons of ten-day LWAD-07 observed trajectories with EAS16 model hindcasts were documented in Huntley et al. (2011).

- Assessed the uncertainties associated with trajectory predictions at each model grid point using a 32-member ensemble Navy RELO model around Hawaii and a 24-member Navy RELO model ensemble around Japan.

- Assessed the Lagrangian predictive skill of a 24-member Navy RELO model ensemble using 30 drifter trajectories from the LWAD-07 experiment in early October 2007.

- Completed a preliminary assessment of the Lagrangian predictive skill of the Gulf of Mexico HYCOM model during the Deepwater Horizon spill by comparing estimates of the evolving spill boundary from satellite imagery with model predictions.

- Examined the three-dimensional structure of LCS in the Gulf of Mexico by computing LCS maps (as direct Lyapunov exponents) at each model depth using GOM HYCOM velocities during the Deepwater Horizon spill period.

- As part of project *N00014-09-1-0703* (see below), adapted tools for normal mode analysis (developed with prior ONR support) to blend observed trajectories with model forecast velocities to improve trajectory forecasts.

RESULTS

Lagrangian skill assessment of the EAS16 model using observed drifters – The Lagrangian predictive skill of the EAS16 model was assessed using observed drifters from four Navy acoustic experiments conducted during the 2004-2007 period. Figure 1 shows a map of the western north Pacific Ocean and the geographic limits of all drifter trajectories for each of the four experiments. Table 1 summarizes the Lagrangian predictive skill statistics. The limits of the standard deviation window were computed as the mean minus the negative one-sided standard deviation and the mean plus the positive one-sided standard deviation. One-sided standard deviations are appropriate for this metric, which is positive definite. Figure 2 shows histograms of separation after three days for each experiment. The mean value and the limits of the standard deviation window are also shown.

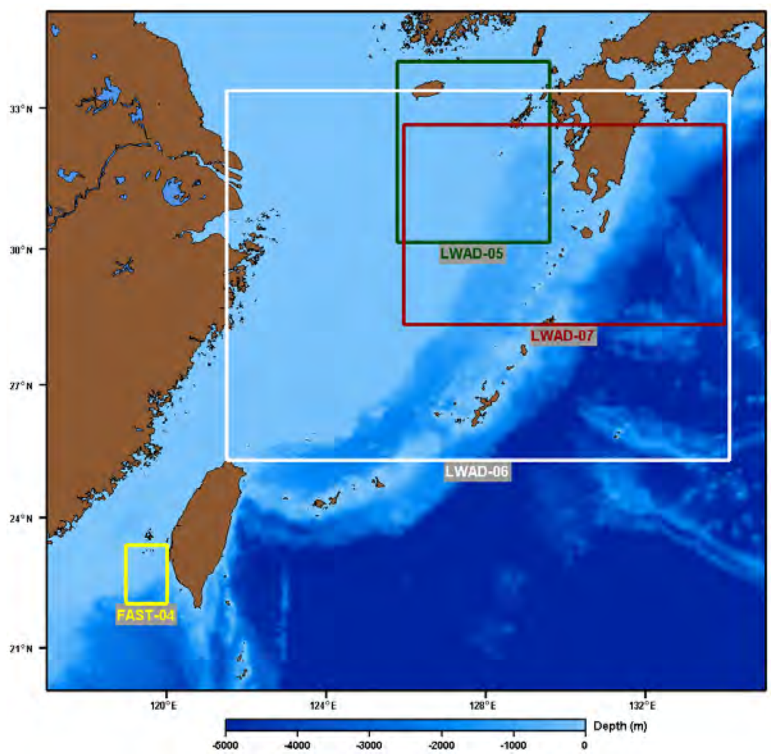

Figure 1: Map of the western north Pacific Ocean showing the geographic boundaries of four Navy acoustic experiments that included drifter launches during the period 2004 through 2007.

Table 1: Lagrangian skill assessment statistics for the EAS16 model (2004-2007)

	FAST-04	**LWAD-05**	**LWAD-06**	**LWAD-07**
Number of drifters	12	16	10	30
Number of trajectory segments	71	243	264	286
Mean separation after 3 days (km)	56.7	27.8	49.9	72.4
Standard deviation window	[31.5 79.6]	[14.2 46.2]	[26.0 100.4]	[31.0 136.3]

Table 1 and Figure 2 show that separation after three days varies substantially among individual trajectories in a single experiment. Mean values also vary widely between the experiments, ranging from a minimum of 27.8 km (LWAD-05) to a maximum of 72.4 km (LWAD-07). Differences in the ocean circulation among the four experiment areas likely account for some of this variability. A detailed analysis of EAS16 Lagrangian predictive skill for the LWAD-07 experiment (Huntley *et al.*, 2011) based on ten-day trajectories suggests that model errors in the position of the Kuroshio may contribute to degraded forecast skill. That analysis also showed that forecast skill was insensitive to the removal of model tidal currents and to coarsening of the model velocity archive in both space and time by up to a factor of eight.

Lagrangian skill assessment of a RELO model ensemble north of the Kuroshio – The Lagrangian predictive skill of a twenty-four member RELO ensemble was also assessed using 104 observed trajectory segments ("launched" at three day intervals) from the LWAD-07 experiment. Histograms show wide-ranging variability of three-day separation distributions among ensemble members, with mean values ranging from 60 to 80 km. Although the RELO model had twice the spatial resolution compared to EAS16 (3 km vs. ~7 km), it did not demonstrate any statistically significant improvement in Lagrangian predictive skill.

Lagrangian uncertainty estimates from RELO ensembles around Hawaii and Japan – RELO model ensembles around Hawaii and Japan were used to assess the influence of model uncertainties on the final positions of 72-hour model trajectories. At a depth of 12.5 m, trajectories were launched at each model grid point for each ensemble member. The launch location ($\vec{x}_o$) and final position ($\vec{x}_f$) for these 72-hour gridded trajectories were then used to compute a mean Lagrangian velocity ($\vec{v}_L$), defined as:

$$\vec{v}_L = \frac{\vec{x}_f - \vec{x}_o}{\Delta t}$$

Figure 3 shows example maps of the standard deviation of $\vec{v}_L$ for a 32-member ensemble around Hawaii (upper panel) and a 24-member ensemble around Japan (lower panel). In each region, the largest variability in $\vec{v}_L$ is associated with the energetic mesoscale field. This is not surprising, since mesoscale features like rings are poorly constrained by the assimilated data. This is evident in the statistics of the Eulerian velocity field variations among ensemble members (not shown). The example ensemble trajectories shown in Figure 3 also give some indication of the trajectory spread among ensemble members.

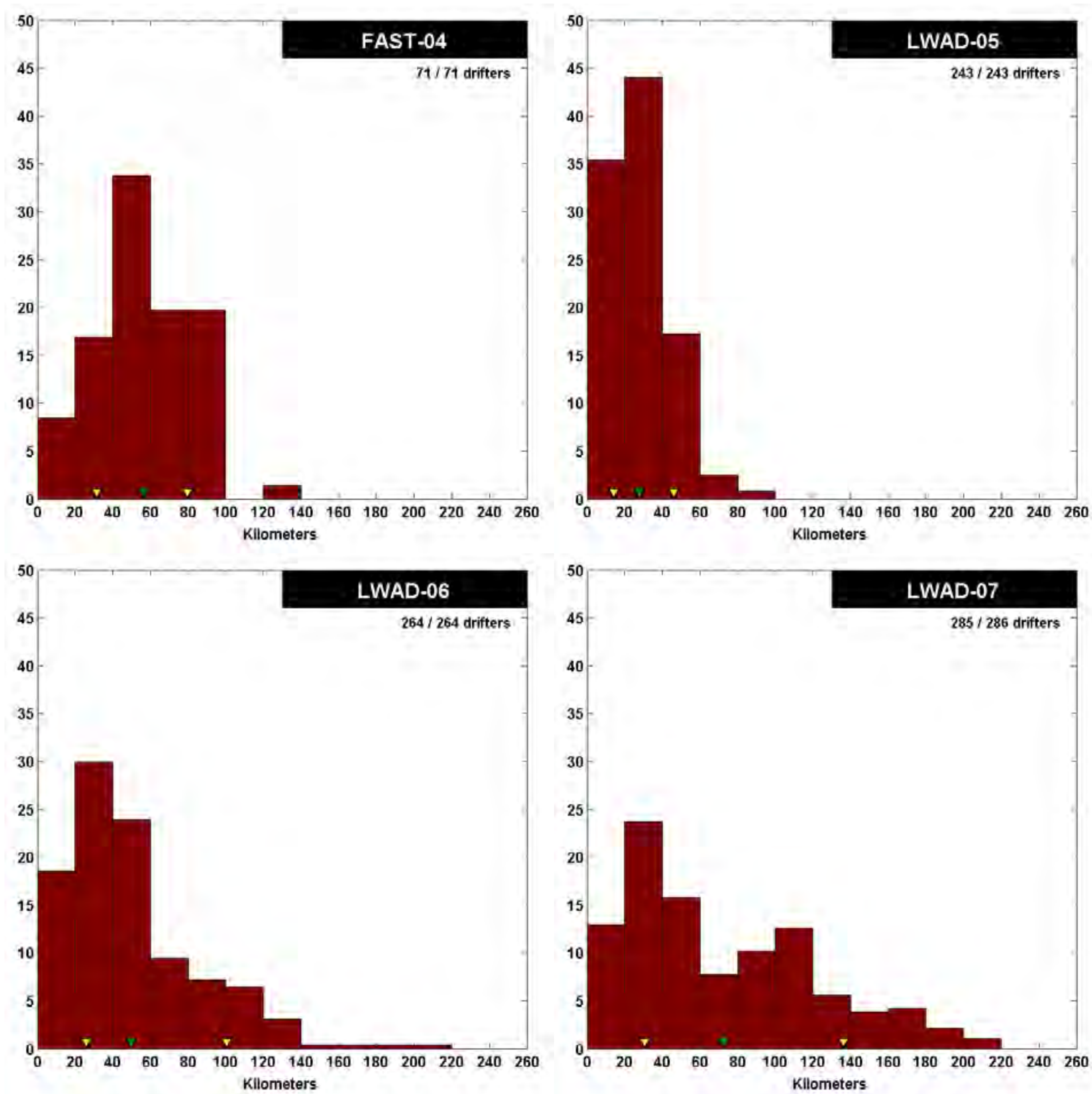

Figure 2: Distributions of separation (in km) between observed and modeled trajectories (from EAS16 model forecasts) after three days for drifters launched during four Navy acoustic experiments. Histogram counts (y-axis) have been normalized by the total number of trajectories analyzed for each experiment. Mean values are shown as green triangles. The limits of one standard deviation from the mean (computed as positive and negative, one-sided) are also shown, as yellow triangles.

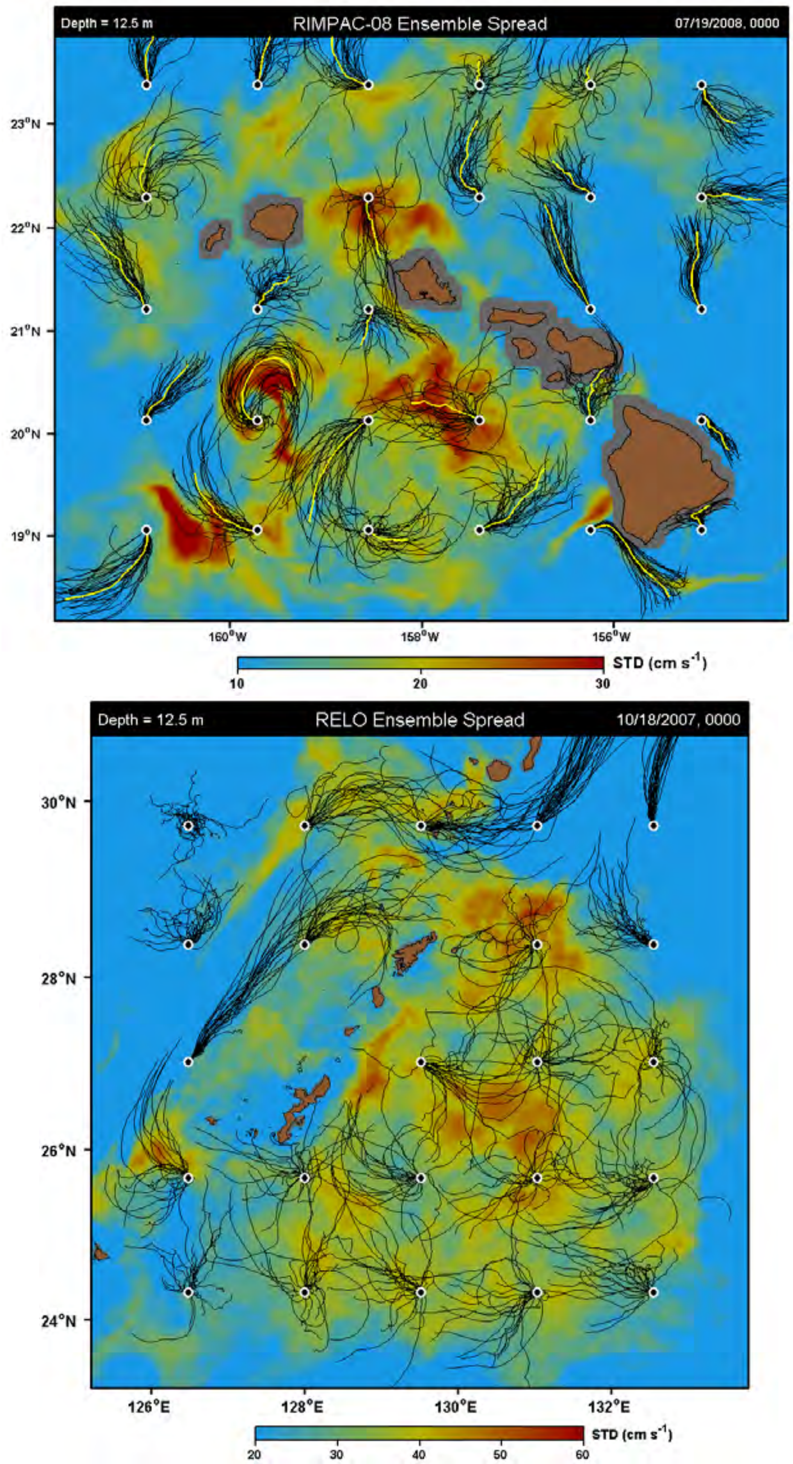

Figure 3: Color maps of the standard deviation of Lagrangian velocity (for trajectories computed over 72 hours) with representative ensemble trajectories (black) overlaid. All results are at a depth of 12.5 meters. (Top) 32-member RELO model ensemble around Hawaii; particles launched on 0000 UT on 19 July 2008. (Bottom) 24-member RELO ensemble around Japan; particles launched at 0000 UT on 18 October 2007.

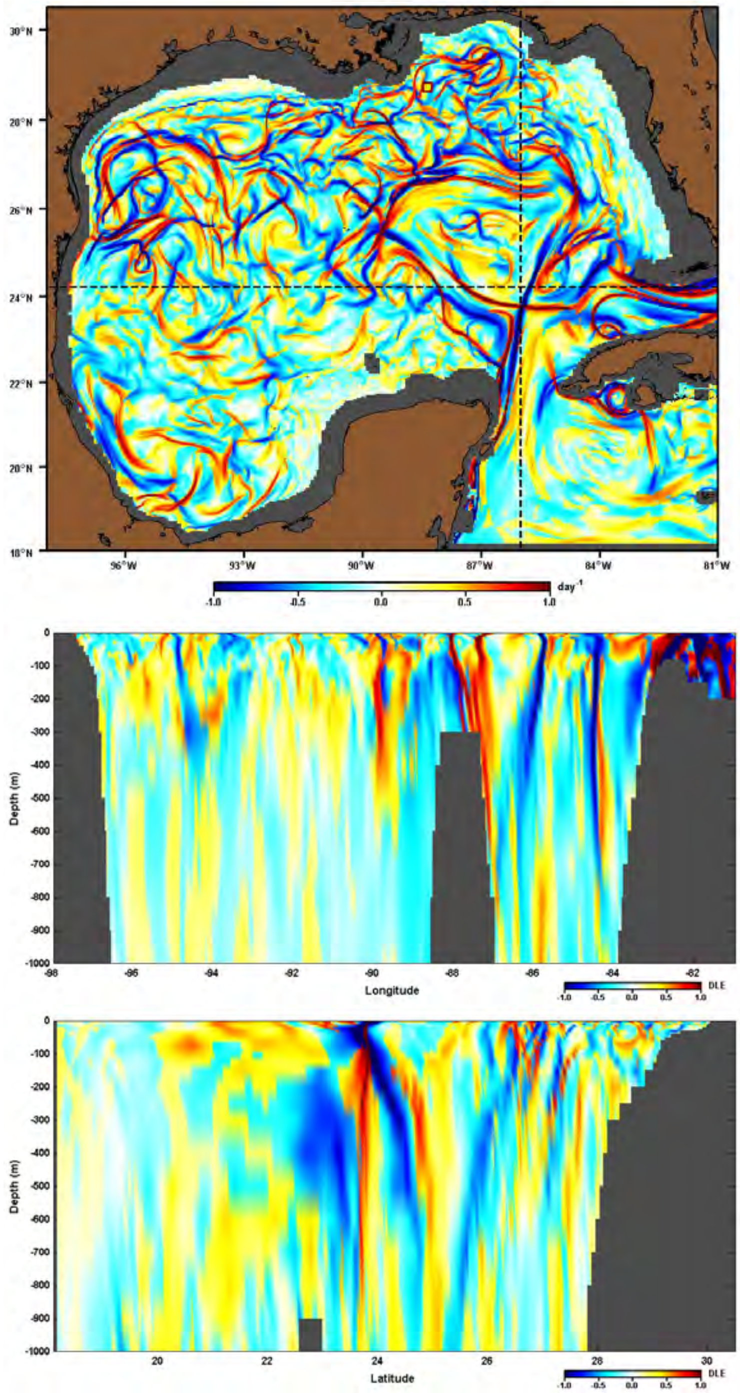

Figure 4: Views of the three-dimensional LCS (in days^{-1}, computed as the maximum direct Lyapunov exponent from forward and backward time trajectory integrations) for the GOM HYCOM model for particles launched at 0000 GMT on 4 June 2010. (Top) Horizontal slice of the LCS field at a depth of 20 meters; (middle) vertical LCS section along the line of constant latitude (24.2° north) shown as a dotted line in the top panel; (bottom) vertical LCS section along the line of constant longitude (86° west) shown as a dotted line in the top panel.

Three-dimensional LCS maps for the Gulf of Mexico – Daily velocities from the GOM HYCOM model were used to compute LCS maps at each model depth during the period of the Deepwater Horizon spill. These LCS maps were computed as direct Lyapunov exponents (DLE) from trajectories for particles launched at each model grid point. Figure 4 shows three views of the three-dimensional LCS field for particles launched at 0000 GMT on 4 June 2010. The top panel shows a horizontal slice at a depth of 20 meters. The middle panel shows a vertical section along a line of constant latitude (24.2° north). The lower panel shows a vertical section along a line of constant longitude (86° west). This LCS field was constructed by "stitching together" horizontal maps in each model layer. The maps in each layer were constructed from two-dimensional trajectories, with zero vertical displacements. Since vertical velocities were ignored, this LCS field is only an approximation to the full 3D LCS field. The vertical LCS sections shown in Figure 4 indicate that there is quite a bit of vertical structure in the model mixing boundaries near the surface, with the strongest mixing boundaries associated with mesoscale eddies.

IMPACT/APPLICATIONS

The Navy acoustic community requires Lagrangian forecasts for sensor deployment planning and for tracking the evolution of deployed acoustic arrays. Recently completed work on a related project (*N00173-08-1-G009*, see below) explored how Lagrangian analysis tools could be incorporated into Navy acoustic tactical decision aids. As Lagrangian forecast products become more available, quantitative assessments of Lagrangian forecast skill like those reported here are vital for users who need to know the expected forecast accuracy as well as quantitative estimates of uncertainties.

The Lagrangian skill assessments reported here represent a first step. Similar skill assessments using observed drifters for other geographic regions and time periods are needed to explore the range of model forecast skill in regions of Navy tactical interest. Model ensembles in these other geographic areas will also be valuable for characterizing the range of model uncertainty.

RELATED PROJECTS

The investigators for this effort, along with Dr. Helga Huntley, are also investigators on three other closely related ONR efforts:

N00014-11-1-0087: Dynamical systems theory in 4D geophysical fluid dynamics – This MURI effort involves a large group of investigators at several institutions focused on extending Lagrangian analysis of general circulation models to three spatial dimensions.

N00014-10-1-0522: Lagrangian transport signatures in models and observations – This work focuses on identifying circulation features like fronts and eddies in satellite imagery and comparing the evolution of these features with ocean model forecasts as a model assessment tool.

N00173-08-1-G009: Prediction of evolving acoustic sensor arrays – This effort is focused on demonstrating how Lagrangian analysis of Navy ocean model predictions can be performed at a Navy operational center and how Lagrangian products can be delivered to fleet operators on scene in near-real time to support tactical decision making.

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