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Data assimilation considerations for improved ocean predictability during the Gulf of Mexico Grand Lagrangian Deployment (GLAD)

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A B S T R A C T

Ocean prediction systems rely on an array of assumptions to optimize their data assimilation schemes. Many of these remain untested, especially at smaller scales, because sufficiently dense observations are very rare. A set of 295 drifters deployed in July 2012 in the north-eastern Gulf of Mexico provides a unique opportunity to test these systems down to scales previously unobtainable. In this study, background error covariance assumptions in the 3DVar assimilation process are perturbed to understand the effect on the solution relative to the withheld dense drifter data. Results show that the amplitude of the background error covariance is an important factor as expected, and a proposed new formulation provides added skill. In addition, the background error covariance time correlation is important to allow satellite observations to affect the results over a period longer than one daily assimilation cycle. The results show the new background error covariance formulations provide more accurate placement of frontal positions, directions of currents and velocity magnitudes. These conclusions have implications for the implementation of 3DVar systems as well as the analysis interval of 4DVar systems.

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1. Introduction

Ocean prediction across the globe has made great advances in recent decades (Bell et al., 2009). Its success depends critically on the process of assimilation that continually corrects a prior forecast with recent observations, a process utilized in meteorology for decades (Kalnay, 2003). Recent observations, prior information (a background state, denoted as $\mathbf{x}_b$) and dynamical understanding are combined to construct an optimal state estimate as an initial condition for the subsequent forecast period (Malanotte-Rizzoli, 1996). To do so, assumptions must be made about the relationship between the observations and amongst the background state variables and about the uncertainty in each. In particular, the error covariance of the background state, denoted as $\mathbf{P}_b$, is a key piece of information as Daley (1996) points out: "The most important element in the statistical interpolation algorithm is the background error covariance. To a large extent, the form of this matrix governs the resulting objective analysis". Specification of appropriate covariances is difficult as stated by Talagrand (2003) "Construction of these error estimates is the most challenging and scientifically important task." Without confidence in the formulation, the

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prediction process becomes suspect as Bennett (2002) points out, "It is difficult to develop covariances. It follows that the resulting inverse estimate or analysis of the circulation also lack credibility." Yet formulations of $\mathbf{P}_b$ are rarely tested due to insufficient observations (Brasseur et al., 2005). That there is room for further improvement is suggested by isolated examples, such as the one detailed in Section 2.

The ocean is severely under-sampled in both space and time, hindering advances of many studies (Derber and Rosati, 1989). The satellite era revolutionized ocean science in that respect: Since 1992, the continual presence of satellite altimeters in particular provides a preponderance of information on ocean variability across the globe (Fu, 2010). However, the satellite altimeter constellation remains inadequate for providing synoptic observations even of just the two-dimensional mesoscale field at the ocean surface along with associated fronts and eddies. Le Traon and Dibarboure (2002) demonstrated in the Gulf of Mexico that the lack of observation results in substantial errors in estimating eddy frontal positions. The ability to draw clear conclusions from prior examinations of possible specifications for $\mathbf{P}_b$ is limited by the lack of data (Lermusiaux, 2002). As $\mathbf{x}_b$ is often provided by a prior model forecast, Gawarkiewicz et al. (2011) estimate $\mathbf{P}_b$ by evaluating a prior forecast with subsequent observations made northeast of Taiwan, thus relying on a single sample to estimate a subset of $\mathbf{P}_b$. It is difficult to obtain a large enough number of independent forecast events to gain statistical confidence. Consequently, the fundamental question remains: To what degree are assimilation assumptions leading to errors in ocean state estimation?

Our purpose here is to systematically evaluate several key assumptions of the ocean data assimilation methodology by utilizing the rich drifter data set of the Grand Lagrangian Deployment (GLAD). The Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) deployed 295 CODE-type drifters in the northeastern Gulf of Mexico on July 20–July 31, 2012 (Poje et al., 2014; Olascoaga et al., 2013; Coelho et al., 2014). The unprecedented data density achieved by this campaign makes the assessment possible by sustaining coverage at high spatial density over several mesoscale ocean features and over two months. The primary focus here is on the lower frequency mesoscale circulation in the deep water as this is the typical dynamical target of operational ocean assimilation systems. The assimilation systems are designed to constrain the mesoscale, and thus the higher frequency solutions have forecast skill that is a function of the external forcing and the dynamical representation.

We investigate independent perturbations of several aspects of the $\mathbf{P}_b$ formulation, evaluating the resulting forecasts against the dense GLAD drifter observations, which are not assimilated. Perturbed features include the amplitude of the background error variance, horizontal correlation length scales, flow dependent variations in correlations and time decorrelation scales. While the system employed here is an implementation of 3DVar, the findings also impact parameter choices for 4DVar systems, which are becoming more popular (Cobas-Garcia et al., 2012; Janeković et al., 2013; Ngodock and Carrier, 2014). The detailed study presented here permits the assessment of the relative importance of each of the tested pieces of the specification of $\mathbf{P}_b$. It also provides guidance for appropriate parameter choices, in particular the decorrelation time scales.

After presenting an example to motivate the search for improved data assimilation in Section 2 and a synopsis of the GLAD experiment in Section 3, we provide details of the model setup and the experiments with perturbations on the assimilation background errors in Section 4. The results are examined in Section 5, with discussion in Section 6 and conclusions in Section 7.

2. Are our assumptions suspect?

An example from the GLAD planning phase illustrates the shortcomings of present assimilation. Daily oceanic condition forecasts are provided by numerical model systems based on the Hybrid Coordinate Ocean Model (HYCOM) and the Navy Coastal Ocean Model (NCOM), both using the same data through 3DVar assimilation within the Navy Coupled Ocean Data Assimilation (NCODA) system (Barron et al., 2006, 2007; Cummings et al., 2009; Martin et al., 2009; Rowley, 2010; Rowley et al., 2010; Metzger et al., 2010; Smith et al., 2011).

Satellite-observed chlorophyll provides an indication of Lagrangian material transport. Lagrangian Coherent Structures (LCS), which outline material transport patterns (Haller and Yuan, 2000; Haller and Beron-Vera, 2012), are computed from HYCOM and NCOM model surface currents and compared to the chlorophyll observations (Fig. 1). In Fig. 1a, the chlorophyll plume from the high productivity area around 29°N 88°W has spread to the southeast. At 26°N 86.5°W, the plume turns and extends northeastward, implying an intense cyclonic feature at roughly 27°N 86°W. The LCS computed from both models cut across the chlorophyll plume at 27.5°N 87°W, more than 100 km north of the observed plume turning. Although chlorophyll is not an ideal tracer, a misalignment of this magnitude indicates poor agreement between model currents and observed material transport. In particular, neither system captures the cyclonic turning at 26°N.

The two forecast systems based on HYCOM and NCOM share the same input data and data assimilation methodology. The sea surface height anomaly (SSHA) along altimeter ground tracks during this time (Fig. 2) indicates a cyclonic circulation at 27°N 86°W that is intruding into the Loop Current Eddy (LCE) to the southwest. An interpolation of this data constructed by AVISO (Pascual et al., 2006) is used to calculate geostrophic currents, and the LCS based on the geostrophic currents aligns with the chlorophyll imagery (Fig. 2).

Given the 3 km model resolution, a second order finite difference can reasonably represent first order derivative wavelengths of 24 km and larger, and it can represent nonlinear terms such as advection of momentum at 48 km and larger wavelengths. These are scales smaller than those resolved by the satellite data. The numerical models will produce realistic dynamical processes that are unconstrained and hence could exhibit substantial differences relative to observations. However, the mislocation relative to the chlorophyll in Fig. 1 is on the order of 100 km, the same discrepancy occurs in both dynamical systems and the feature is resolved in the satellite derived LCS in Fig. 2. The conclusion is that the altimeter data contain the essential mesoscale features but the data assimilation used to correct both models is faulty. Clear visible satellite images such as this are relatively rare. Evaluations are qualitative and provide only one snapshot. Thus it is difficult to conduct a considered evaluation of possible error sources with only this data. Fortunately, the drifter observations from GLAD prove to be quite valuable.

3. The GLAD experiment

The drifters are similar to the CODE drifter design (Davis, 1985; Ohlmann et al., 2001), which intends to measure the upper 1 m averaged currents. Table 1 summarizes the deployment locations, dates, number of drifters in the groups (LSS, S1, S2, T1, L1, L2) and initial ocean conditions. Fig. 3 shows the number of active drifters during the experiment. Initial group deployment positions are noted in Fig. 4. Initially, the reduction in the number of drifters is due to fishermen recovering some, and Hurricane Isaac inflicts damage on the observation system in late August. The slow degradation over time is