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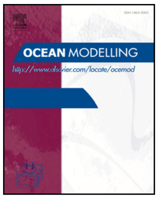

Oceanic ensemble forecasting in the Gulf of Mexico: An application to the case of the Deep Water Horizon oil spill

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ABSTRACT

This paper demonstrates the potential of ocean ensemble forecasting in the Gulf of Mexico (GoM). The Bred Vector (BV) technique with one week rescaling frequency is implemented on a 9 km resolution version of the Regional Ocean Modelling System (ROMS). Numerical experiments are carried out by using the HYCOM analysis products to define the initial conditions and the lateral boundary conditions. The growth rates of the forecast uncertainty are estimated to be about 10% of initial amplitude per week. By carrying out ensemble forecast experiments with and without perturbed surface forcing, it is demonstrated that in the coastal regions accounting for uncertainties in the atmospheric forcing is more important than accounting for uncertainties in the ocean initial conditions. In the Loop Current region, the initial condition uncertainties, are the dominant source of the forecast uncertainty. The root-mean-square error of the Lagrangian track forecasts at the 15-day forecast lead time can be reduced by about 10 – 50 km using the ensemble mean Eulerian forecast of the oceanic flow for the computation of the tracks, instead of the single-initial-condition Eulerian forecast.

1. Introduction

The Deepwater Horizon (DWH) oil spill of 2010 in the Gulf of Mexico (GoM) was an unfortunate and devastating disaster. The oil spill started on 20 April 2010 and was sealed about 86 days later. It is estimated that about 185 million gallons of oil was released into the GoM (Crone and Tolstoy, 2010). Since the DWH disaster, a significant amount of research has been done covering many different aspects of the oil spill, including, but not limited to, the effect of surface dispersants (John et al., 2016), microbial activity in GoM (Joye et al., 2016), contamination of water, damage to the seashore (Murawski et al., 2016), and the transport and dispersion of spilled oil. The research into the various facets of oil transport and dispersion is particularly important, because it is a fundamental aspect of any oil spill event. In this paper, we present a systematic investigation into the transport aspect of the spilled oil in the aftermath of DWH.

Numerical models are routinely employed to produce forecasts of atmospheric and oceanographic states. These forecasts are imperfect because of inevitable errors in the initial conditions, boundary conditions and the models themselves. In regional model forecasts, both lateral boundary conditions and atmospheric forcing at the surface are required, in addition to the initial conditions. In this work, we examine the effects of uncertainties in the initial conditions and atmospheric forcing on the forecasts by employing the ensemble approach. Some work on oil transport in the aftermath of DWH has already been done (North et al., 2011; Liu et al., 2011; Dietrich et al., 2012; Jolliff et al., 2014). An important difference between the previous investigations and our work is that the previous studies used a single initial condition and a single atmospheric forcing for each forecast case, while we adopt an ensemble approach. The ensemble approach is called for by the considerable uncertainty in the specification of the initial conditions and the atmospheric forcing. The experience from operational forecasting of the spilled oil from the DWH incident demonstrates value of information of the forecast uncertainty (MacFadyen et al., 2011). Another important difference between our investigations and earlier studies is that these previous investigations focused on the near coast region, while we take a Gulf wide view at time scales of weeks to a few months.

The ocean circulation in the Gulf of Mexico (GoM) is highly energetic and dynamically complex. As the southernmost part of the Gulf Stream system, Yucatan inflow enters the GoM through the Yucatan Channel with a topographic sill at approximately 1500 m.

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This energetic current with speed excessive of 1 m/s rarely turns to enter the Straits of Florida directly, but instead often forms a significant Loop within a major portion of the eastern GoM, which is known as the Loop Current (LC), before its exit from the Gulf through the Florida Strait with a sill at 800 m. The LC transports approximately 23 – 27 Sv of warm salty water northwards from the Caribbean Sea into the GoM in the upper 1000 – 1200 m (Candela et al., 2002; He and Weisberg, 2003). Over the course of several months to over a year, part of the LC flow pinches off from the current and migrates farther into the Gulf in forms of anticyclonic warm eddies, known as the Loop Current Eddies (LCEs). The LCE shedding period varies in the range of 6 to 19 months with an average of 9 months (Vukovich, 2012). These eddies typically have a size of 200 – 300 km in diameter, 1000 m vertical extend, rotational speed about 1.8 – 2 m/s, and westward translation speeds in the range of 2 – 5 km/day (see Oey et al. (2005b) and references therein). The detached LCEs propagate westward through the gap between the Campeche Bank and the Mississippi Fan, transporting heat and momentum to the western GoM before finally dissipated in few months to a year time period. In addition to the LCEs, two distinct types Cyclonic Eddies (CCEs) are often observed in the GoM. The first type is known as frontal eddies formed in the cyclonic shear zone along the edge of the Yucatan inflow. Some of these frontal eddies are observed to traverse round the LC and form edge eddies in the Florida Current. Others are more stagnant and may contribute to the eddy field west of the LC. The second type can be formed by the LC interacting with the West Florida Shelf. Understanding the mechanism behind these LCEs and CCEs is an active research area. Interested readers are referred to the Sturges and Lugo-Fernandez (2005) for more detailed discussions.

The LCEs and CCEs can have a significant impact on oil transport within the GoM. This impact is clearly illustrated by Walker et al. (2011) for the 2010 DWH oil spill. Using satellite measurements combined with in situ observations, Walker et al. (2011) documented how the fate and transport of the spilled oil were strongly affected by the merger of three CCEs along the LC's northern margin, which resulted in a larger and more energetic CCE. They concluded that the lack of oil exposure in the Florida Keys and along the U.S. eastern seaboard in the aftermath of the DWH disaster is likely to be attributed to two major factors related to the CCE merger: First, a significant amount of the spilled oil was accumulated within the large CCE emerged from smaller CCEs, that prevented the oil to move along the LC frontal zone to the southeast toward the Florida Straits. Second, the large CCE stayed put in its position for a long time after its merger and reduced the movement of the spilled oil. Clearly, an accurate prediction of ocean eddies in the GoM has an important bearing on oil spill forecast and prevention.

The prediction and predictability of GoM is a crucial topic of research with practical implications. Gopalkrishnan et al. (2013) employed the 4DVAR assimilation technique to estimate an optimal state and used it to determine the predictability of the LC to be about 4 weeks. It has been shown (Lugo-Fernandez, 2007) that the LC is not chaotic but rather nonlinear and it behaves like a dampened oscillator with a very short memory. Lugo-Fernandez (2007) show that the eddy shedding period is nonlinearly dependent on the initial state, the lateral boundary conditions and the forcing. In the same work it is proposed that the North Atlantic Oscillation (NAO) affects the amplitude and period of the Loop Current variability. In Counillon and Bertino (2009) it is demonstrated that the perturbations in the lateral boundary conditions and forcing affect the propagation of cyclonic eddies on the time scale of 3 weeks. It is shown in Oey et al. (2003) that wind-induced transport fluctuations through the Greater Antilles Passage decreases the period of eddy shedding while the Caribbean eddies increases it. In a case study of forecasting the LC (Oey et al., 2005a), the model predictability is shown to be about 3 weeks.

This paper is arranged as follows. Section 2 delineates the methodology employed in this work. Section 3 describes the Eulerian single initial condition and ensemble forecast experiments. It also describes the verification results for the Eulerian forecasts. The Lagrangian forecasts and their verification are presented in Section 4. Section 5 summarizes the findings of our work.

2. Methodology

This section describes the model used in this work. It also provides information about the lateral boundary conditions, forcing and ensemble generation technique employed in this work.

In this work, the Regional Ocean Modelling System (ROMS) is used. ROMS (Shchepetkin and McWilliams, 2005; Haidvogel, 2009) is a primitive-equation, free-surface, split-explicit oceanic model. It uses z-sigma vertical coordinate (Shchepetkin and McWilliams, 2009; Lemarie et al., 2012) and horizontal curvilinear coordinates to solve the three dimensional primitive equations. Our model configuration employs the K-Profile Parametrization (KPP) scheme (Large et al., 1994) for the vertical mixing,second-order Laplacian horizontal mixing for the tracers and the momentum multidimensional positive definite advection transport algorithm (MPDTA) scheme (Margolin and Smolarkiewicz, 1998) for three-dimensional advection of tracers, and the COARE 3.0 bulk formulation (Fairall et al., 2010) for surface forcing. The open boundaries use a combination of radiation and nudging schemes for both the three-dimensional velocities and tracers and the Chapman scheme (Chapman, 1985) for the two-dimensional velocities and Father scheme (Flather, 1976) for the free surface. Throughout this work ROMS model with horizontal resolution of 9 km and 50 vertical levels is used.

The HYCOM analysis (Cummings, 2005), interpolated to the model grid, is used as the deterministic initial condition and lateral boundary condition. The lateral boundary conditions are *not* perturbed in this work.

The atmospheric forcing is obtained from the TIGGE-ECMWF (Richardson et al., 2005; Bougeault et al., 2010; Herrera et al., 2016) operational analysis and forecast. This product is downloaded from http://apps.ecmwf.int/datasets/data/tigge. The control forecast is used as the deterministic forcing and the ensemble forecast is used as the perturbed forcing. The control and ensemble analysis/forecast has a spatial resolution of 3 × 3°. The temporal resolution of control and ensemble analysis is 12 h and that of the corresponding forecast is 6 h.

In ensemble forecasting, an ensemble of model integrations, is started from initial conditions that sample the presumed probability distribution of the uncertainty in the knowledge of the initial condition. This uncertainty is known to be state- (flow-) dependent and several ensemble generation techniques exist to account for this state dependence. One of these techniques, which we use in our study, is based on Bred Vectors (BVs) (Toth and Kalnay, 1993; Yin and Oey, 2007). We choose this technique, because it is easy to implement, computationally inexpensive, and can be implemented independently of the choice of the data assimilation system. We compute 20 BVs for each analysis time by integrating the ROMS model. These BV perturbations are added to the HYCOM analysis to obtain the ensemble of perturbed initial conditions. The ensemble of initial conditions is used to prepare an ensemble of ROMS forecasts.

The importance of wind forcing on the spread of oil during the DWH event has been demonstrated by several studies (Walker et al., 2011; Huntley et al., 2011; LeHenaff et al., 2012). In Sections 3 and 4, to simulate the effects of the uncertainty in the surface forcing, each member of the forecast ensemble is computed