Dynamics of Atmospheres and Oceans 66 (2014) 77–93

Contents lists available at ScienceDirect

Dynamics of Atmospheres and Oceans

journal homepage: www.elsevier.com/locate/dynatmoce

Observing System Simulation Experiments of cross-layer Lagrangian data assimilation

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ARTICLE INFO

Article history:
Received 28 January 2013
Received in revised form 1 February 2014
Accepted 14 February 2014
Available online 25 February 2014

Keywords:
Lagrangian data assimilation
Data assimilation
Particle filtering
Observing System Simulation Experiments
Point-vortex systems
Baroclinic vortices

ABSTRACT

We conduct Observing System Simulation Experiments (OSSEs) with Lagrangian data assimilation (LaDA) in two-layer point-vortex systems, where the trajectories of passive tracers (drifters or floats) are observed on one layer that is coupled to another layer with different dynamics. Depending on the initial position of the observed tracers, the model studied here can exhibit nonlinear features that cause the standard Kalman filter and its variants to fail. For this reason, we adopt a Monte Carlo approach known as particle filtering, which takes the nonlinear dynamics into account. The main objective of this paper is to understand the effects of drifter placement and layer coupling on the precision skill of assimilating Lagrangian data into multi-layered models. Therefore, we analyze the quality of the assimilated vortex estimates by assimilating path data from passive tracers launched at different locations, on different layers and in systems with various coupling strengths between layers. We consider two cases: vortices placed on different layers (heton) and on the same layer (non-heton). In both cases we find that launch location, launch layer and coupling strength all play a significant role in assimilation precision skill. However, the specifics of the interplay of these three factors are quite different for the heton case versus the non-heton case.

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http://dx.doi.org/10.1016/j.dynatmoce.2014.02.002
0377-0265/

1. Introduction

Floats and drifters make up a critical source of ocean observations; they provide Lagrangian trajectory path data (Perry and Rudnick, 2003; DiMarco et al., 2005) and sometimes measurement of physical variables along their paths. Floats typically travel at depth (≈1000 m below the surface), surfacing every ten days or so (Park and Kim, 2012). Although much non-path related data is collected upon ascent, float location data (and path data that is inferred between surfacing) reflect Lagrangian paths at depth. On the other hand, drifters travel near the surface (≈50 m below the surface) and can offer nearly continuous path data through satellite communication. A primary objective of this paper is to demonstrate and explore the limitations of assimilating data collected at one level (surface or depth) into a two-layer dynamic model. Specifically we are interested in the case where the dynamics driving the system have their primary expression on the opposite layer to where the data is collected. Consider for example a case where one uses trajectory data from floats to assimilate into a layered model with vortices near the surface. We will show that this can work quite well. However, as one may anticipate, success in assimilating opposite-layer data depends on the strength of the coupling between the layers. We will also show that even same layer assimilation can be difficult if that layer's dynamics are strongly coupled to and influenced by dynamics in another layer.

Incorporating these Lagrangian observations into a geophysical model, hence the name Lagrangian data assimilation (LaDA), has increasingly received interest (Carter, 1989; Hernandez et al., 1995; Kamachi and O'Brien, 1995; Ishikawa et al., 1996; Mariano et al., 2002; Molcard et al., 2003; Ide et al., 2002). A new approach for assimilating Lagrangian data into a geophysical model was introduced in Ide et al. (2002) whereby the model advecting the drifters is augmented to the underlying flow model, called the augmented system. This approach was shown to be effective in assimilating the Lagrangian data into shallow-water models based on the extended Kalman filter. With the augmented state space, the ensemble Kalman filter (EnKF) can also be readily implemented (Salman et al., 2006). It was shown in Salman et al. (2008), Salman et al. (2006), and Vernieres et al. (2011) that when the initial position of the drifter is near a hyperbolic trajectory or the observation period is longer than the autocorrelation time scale, a divergence of passive tracers becomes a prominent problem due to a highly nonlinear behavior of the drifters. To overcome this obstacle, modified particle filtering methods were employed in Spiller et al. (2008) where the (single layer) two-point vortex system was used in the experiment (Spiller et al., 2008) as a proof of concept to compare the performance of the extended Kalman filter (EKF) and particle filter for Lagrangian data assimilation. It was reported therein that the modified particle filter method outperforms the extended Kalman filter. Furthermore, there has been an attempt to understand the correlation between the information value and the launch position of Eulerian and Lagrangian drifters in a single-layer point vortex system based on the observability rank condition, which showed that the reduced order extended Kalman filtering with Lagrangian observation provides more accurate results than the extended Kalman filtering with Eulerian observation (Krener, 2008).

In this paper, we conduct Observing System Simulation Experiments (OSSEs) using a two-layer point vortex system, where vortices are allowed to influence the velocity field not only on the layer in which they reside but also on the other layer. This two-layer point-vortex system was first studied in Hogg and Stommel (1985) to model the heat transport induced by an interaction of particular baroclinic pairs of vortices referred to as a "heton", the overlay of cyclonic and anticyclonic vorticity on the two different layers. After this seminal paper, the heton model was further studied to demonstrate that nonlinear (in)stability leads to an explosion of the heton cloud (Pedlosky, 1995). It was also demonstrated that the heton model can allow for baroclinic instability in convective columns (Legg and Marshall, 1993, 1998). In the context of data assimilation, there was an attempt to understand how information propagates vertically between the two layers in Liu (1998). In particular, the extended Kalman filter was implemented to assimilate the drifter observation on the top layer in order to track the vortex positions and estimate the circulation strength of the vortices in both layers (Liu, 1998). The results in Liu (1998) showed that in such a scenario the Eulerian velocity field in the bottom layer can be consistently assimilated through the vertical correlation of the two layers, which was given in term of the inverse coupling strength, λ, in (2). However, the study in Liu (1998) did not examine the effect of λ on different configurations of vortices.