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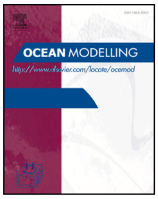

Assimilating Lagrangian data for parameter estimation in a multiple-inlet system

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ABSTRACT

Numerical models of ocean circulation often depend on parameters that must be tuned to match either results from laboratory experiments or field observations. This study demonstrates that an initial, suboptimal estimate of a parameter in a model of a small bay can be improved by assimilating observations of trajectories of passive drifters. The parameter of interest is the Manning's n coefficient of friction in a small inlet of the bay, which had been tuned to match velocity observations from 2011. In 2013, the geometry of the inlet had changed, and the friction parameter was no longer optimal. Results from synthetic experiments demonstrate that assimilation of drifter trajectories improves the estimate of n, both when the drifters are located in the same region as the parameter of interest and when the drifters are located in a different region of the bay. Real drifter trajectories from field experiments in 2013 also are assimilated, and results are compared with velocity observations. When the real drifters are located away from the region of interest, the results depend on the time interval (with respect to the full available trajectories) over which assimilation is performed. When the drifters are in the same region as the parameter of interest, the value of n estimated with assimilation yields improved estimates of velocity throughout the bay.

1. Introduction

Bottom stress is important to circulation in shallow water, and its inclusion in numerical models can have significant impacts on the simulation results. However, it is difficult to measure spatially-varying bottom stress directly in the field (Trowbridge et al., 1999; Sanford and Lien, 1999; Biron et al., 2004), and thus often stress is approximated with a bottom drag coefficient derived from laboratory experiments or by tuning numerical model simulations to observations, which usually involves iterations of model results that are time-consuming and costly (Cheng et al., 1999; Chen et al., 2015; Orescanin et al., 2016). Drag coefficients also can be estimated from observations of the flow by assuming a balance between pressure gradients and bottom stress (Feddersen et al., 2000; Seim et al., 2002; Apotsos et al., 2008; Kim et al., 2000; Orescanin et al., 2014). These coefficients have been estimated in other regions by assimilating sea-level data into numerical simulations (Mayo et al., 2014). Here, the Manning's n drag coefficient in a multiple tidal inlet system on Martha's Vineyard, MA is estimated by assimilating observed Lagrangian drifter trajectories into a numerical model for sea level and circulation.

Martha's Vineyard is separated from Chappaquiddick Island by Katama Bay, which is connected to Vineyard Sound via Edgartown Channel and to the Atlantic Ocean via the ephemeral Katama Inlet (Fig. 1A). Norton Point, the sand spit between the bay and the Atlantic, was breached by a storm in 2007 (yellow arrow, Fig. 1B), forming Katama Inlet. Over the following years, the inlet became narrower, longer, and shallower as it migrated eastward (Fig. 1B, C), and friction became more important to sea level and circulation in the bay (Orescanin et al., 2016).

Data assimilation provides a framework for combining uncertain estimates from numerical models with noisy observations to estimate a variable that changes in time (Kalnay, 2003). For geophysical fluid flows, velocity fields and bathymetry can be estimated by assimilating Eulerian observations from in-situ sensors (Madsen and Cañizares, 1999; Oke et al., 2002; Kurapov et al., 2005; Wilson et al., 2010) or Lagrangian observations from drifting

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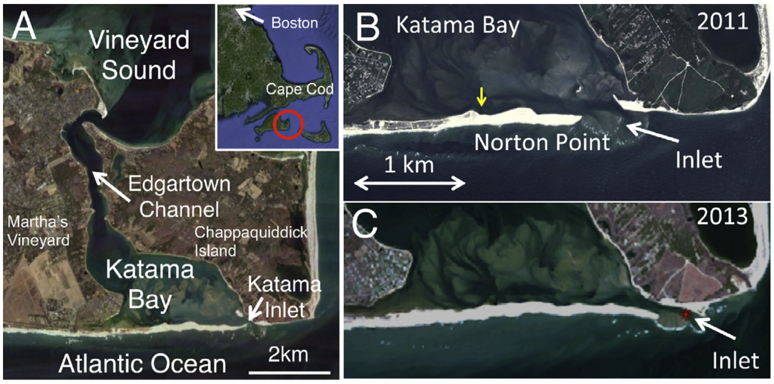

Fig. 1. A) Satellite image (Google Earth, 2012) of Katama Bay, Katama Inlet, and Edgartown Channel, with an inset showing the location of Katama Bay (red circle on Martha's Vineyard) relative to Boston and Cape Cod, B) Katama Inlet in 2011 showing the location of the initial breach of Norton Point (yellow arrow), and C) Katama Inlet in 2013 during drifter deployments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

sensors (Ide et al., 2002; Mariano et al., 2002; Molcard et al., 2005, 2006; Salman et al., 2006; Apte et al., 2008). Drifters follow (approximately) the motion of fluid parcels, and assimilation of their trajectories leads to improved estimates of large-scale circulation patterns (Taillandier et al., 2006; Jacobs et al., 2014) and flows in vortices (Vernieres et al., 2011). Lagrangian observations also have been assimilated in models that estimate the topography in a laboratory channel (Honnorat et al., 2010) and the bathymetry in a river (Landon et al., 2014). Synthetic experiments have compared the Eulerian flow fields estimated by assimilating velocities derived from Lagrangian data (so-called pseudo-Lagrangian data assimilation) and by assimilating Lagrangian trajectories directly, and the results show that the direct assimilation of trajectories outperforms pseudo-Lagrangian data assimilation (Molcard et al., 2003).

In 2011, when Katama Inlet was open (Fig. 1B), current meters were deployed throughout the bay (Orescanin et al., 2014; 2016). A numerical model (ADCIRC, Luettich and Westerink, 1991) of the circulation in the bay at this time was developed, using boundary conditions from pressure gauges deployed in 2011, and the Manning's n coefficient in the region of Katama Inlet was tuned to match the data from the current meters in 2011. In 2013, after the inlet had begun to migrate and narrow (Fig. 1C), current meters were again deployed throughout the bay. Results from the numerical model using boundary conditions from the gauges deployed in 2013, but with the same estimates of Manning's n from 2011, were compared with the 2013 observations from the current meters. Orescanin et al. (2016) found that discrepancies between the 2013 observations and the numerical model were due to changes in friction, and therefore, the value of Manning's n in Katama Inlet estimated from 2011 data was suboptimal when modeling the 2013 system.

Here, drifter tracks observed in the Katama Bay system are assimilated into a numerical circulation model (ADCIRC) to estimate the bottom friction. The model uses bathymetry measured throughout the system and is driven with observed tides, and simulations with and without assimilating drifter data are compared with Eulerian observations of currents in Katama Bay. As a proof of concept, synthetic observation experiments are performed first. Experiments assimilating real drifter data are performed next. Results from assimilating synthetic and real drifter trajectories in two distinct regions of Katama Bay are compared.

2. Numerical model and observations

2.1. Numerical model of Katama Bay

Sea level and depth-averaged currents in Katama Bay are simulated with the two-dimensional version of the Advanced Circulation Model (ADCIRC, Luettich and Westerink, 1991), which solves a version of the shallow water equations via a finite-element method. This model assumes no stratification in the domain; this was supported by observations in Katama Bay. Casts from CTD (conductivity, temperature, depth) instruments throughout the system show little to no temperature or salinity stratification. Within the bay, the depths are very shallow, so this is expected. Offshore in Vineyard Sound and the Atlantic, in depths less than 10 m, the same lack of vertical structure was observed. Winds were light ($<$ 2 m/s) and waves were small ($<$ 1 m) during the drifter deployment periods, and are not included here. The numerical grid consists of a finite-element triangular mesh with spacing ranging from 10 m in the inlets and 15 m in the bay to 200 m outside the inlets in both the Atlantic Ocean and Vineyard Sound (Fig. 2A). Bathymetry (5 to 20 m horizontal and 0.05 m vertical resolution) in the bay, the inlets, and the ebb tidal delta (Fig. 2A) was measured in 2013 with GPS and an acoustic altimeter mounted on a personal water craft, and interpolated onto the model grid (Orescanin et al., 2016). Pressure gauges and current meters were co-located at ten locations within Edgartown Channel, Katama Bay, and Katama Inlet (orange circles in Fig. 3) (Orescanin et al., 2016). The northern boundary of the model is forced with the sea-level observations in Edgartown Harbor (yellow circle in Fig. 2A), and the southern boundary is forced with observations from the Martha's Vineyard Coastal Observatory (12 m depth, 4 km west of Katama Inlet; not shown).

To estimate quadratic bottom stress, the model converts bottom roughness given by a user-defined value of Manning's n (units s/m$^{1/3}$) at each node to an equivalent quadratic drag coefficient given by:

$$C_d(t) = \frac{gn^2}{(D+\eta(t))^{1/3}}, \tag{1}$$

where g is gravity, t is time, D is the local mean depth, and $\eta(t)$ is the water surface elevation above D (Luettich and Westerink, 1991).

The Katama Bay domain is divided into several subregions based on bathymetry, each with a different value of Manning's n (see Fig. 2B.) In the original 2011 simulations, the deep boundary regions (dark blue in Fig. 2B) outside of the bay were assigned the value $n = 0.020$ s/m$^{1/3}$, which is standard for open water. The bay (light blue) was assigned $n = 0.030$ s/m$^{1/3}$, which was calculated by converting the bottom stress estimated from a pressure gradient balance (Orescanin et al., 2014) into n using an average depth of the bay. However, model-data comparisons (Orescanin et al., 2016) suggested that the friction coefficient needed to be increased to $n = 0.035$ s/m$^{1/3}$ in an area surrounding Katama Inlet (green area in Fig. 2B) in 2011. This spatial and temporal variation in n is