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Estuary/ocean exchange and tidal mixing in a Gulf of Maine Estuary: A Lagrangian modeling study

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Abstract

A Lagrangian particle method embedded within a 2-D finite element code, is used to study the transport and ocean–estuary exchange processes in the well-mixed Great Bay Estuarine System in New Hampshire, USA. The 2-D finite element model, driven by residual, semi-diurnal and diurnal tidal constituents, includes the effects of wetting and drying of estuarine mud flats through the use of a porous medium transport module. The particle method includes tidal advection, plus a random walk model in the horizontal that simulates sub-grid scale turbulent transport processes. Our approach involves instantaneous, massive [O(500,000)] particle releases that enable the quantification of ocean–estuary and inter-bay exchanges in a Markovian framework. The effects of the release time, spring–neap cycle, riverine discharge and diffusion strength on the intra-estuary and estuary–ocean exchange are also investigated.

The results show a rather dynamic interaction between the ocean and the estuary with a fraction of the exiting particles being caught up in the Gulf of Maine Coastal Current and swept away. Three somewhat different estimates of estuarine residence time are calculated to provide complementary views of estuary flushing. Maps of residence time versus release location uncover a strong spatial dependency of residence time within the estuary that has very important ramifications for local water quality. Simulations with and without the turbulent random walk show that the combined effect of advective shear and turbulent diffusion is very effective at spreading particles throughout the estuary relatively quickly, even at low (1 m^2/s) diffusivity. The results presented here show that a first-order Markov Chain approach has applicability and a high potential for improving our understanding of the mixing processes in estuaries.

Keywords: estuarine dynamics; residence time; tidal mixing; numerical models; Lagrangian particle tracking; water exchange

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1. Introduction

Estuaries, which act as the transition zone between the upland wetlands and the coastal ocean, are important nursery regions and feeding grounds for a very large number of marine species. However, due to increasing development pressure, they are more and more being called upon to act as repositories for immediate direct point discharges of contaminants, indirect pollutant input through non-point land sources and atmospheric pollutant deposition. Unfortunately, neither the estuaries nor the coastal ocean are capable of assimilating pollutants indefinitely and the environmental concerns now require that any pollutant released in the coastal zone should be heavily regulated and properly managed. Predicting the transport and fate of pollutants in the estuaries and the coastal zone appears as one of the most important challenges of the environmental sciences.

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Lagrangian particle methods appear as a very handy and naturally suited set of tools to investigate and model the transport pathways, mixing and ocean–estuary exchange of the sediment bound and suspended pollutants (Zimmerman, 1986; Pearson and Barber, 1996; Pearson and Barber, 1998; Davies et al., 2000; Inoue and Wiseman, 2000; Thompson et al., 2002; Bilgili et al., 2003). In this paper, we apply Lagrangian transport and exchange estimation methods to the Great Bay Estuarine System in New Hampshire, USA, and focus specifically on the characterization of the estuarine/coastal ocean mixing and exchange processes and quantification of the estuarine residence times. While these concepts are useful from a water quality point of view, their practical definition has been problematic (Takeoka, 1984; Zimmerman, 1986). The difficulty lies in the fact that historically definitions have been based on Eulerian measurements such as estuary volume and tidal prism. However, residence and exchange are inherently Lagrangian concepts and are best treated as such. The motivation for this study is to improve the understanding of the transport and fate of contaminants in similar systems and the capabilities that they have to handle the various pollutant streams. This knowledge would provide resource managers with the ability to more effectively deal with the water quality and resource issues that they face.

2. The Great Bay Estuary

The Great Bay Estuarine System (Fig. 1), which is the centerpiece of this effort, is a relatively shallow estuary with a tidal amplitude to mean depth ratio of 0.18. The Little Bay and the Great Bay proper, which together form the inner estuary, have main channel depths on the order of 10 m and 3 m, respectively, and currents on the order of 0.5 m/s. Extensive tidal flats in this section mean that more than 50% of the system's surface is exposed as mud flats at low tide. The inner estuary connects to the Gulf of Maine by way of the Lower Piscataqua River and Portsmouth Harbor. These connector channels have depths on the order of 15 m with maximum tidal currents reaching up to 2.0 m/s. These fast currents cause tidal excursions on the order of 18 km. Several freshwater tributaries exist but their net input to the system is low, representing only 2% or less of the tidal prism under normal conditions (Reichard and Celikkol, 1978; Brown and Arellano, 1979). The vertical variability of tidal currents in the estuary has been shown to be negligible (Swenson et al., 1977). This makes the Great Bay Estuary a tidally dominated, well-mixed system.

Swift and Brown (1983) showed that the M_2 tidal constituent is dominant by at least an order of magnitude over the other semi-diurnal and diurnal constituents in the Great Bay Estuary. They also showed that the principal force balance is between the pressure gradient and total bottom stress, a characteristic also observed in other shallow and narrow tidal embayments (Friedrichs et al., 1992). They suggested that the narrow channel at Dover Point (see Fig. 1), which connects the Lower Piscataqua River, Upper Piscataqua River and Little Bay acts as a hydraulic choke that separates the Great Bay system into two different dynamic regimes: a more dissipative lower section that extends from the mouth at the Gulf of Maine to Dover Point, in which the tidal signal has a progressive wave nature; and a less dissipative upper section that extends from Dover Point into Great Bay, in which the tidal signal behaves like a standing wave.

Although several modeling and field studies have been performed on the Great Bay system in the past (Swenson et al., 1977; Swift and Brown, 1983; Ertürk et al., 2002; Bilgili et al., 2003; McLaughlin et al., 2003), few investigations focused on the exchange and mixing characteristics. The two exceptions are the studies of Brown and Arellano (1979) and Schmidt (1980), but these focused on specific parts of the Great Bay system and not the system as a whole. In this paper, we attempt to help fill this important gap by concentrating on the mixing and exchange characteristics of the Great Bay Estuary with the coastal Gulf of Maine through a Lagrangian modeling approach embedded within a highly resolved circulation model.

3. Numerical model

The vertically-averaged numerical circulation model (BELLAMY) accounts for flooding and drying of tidal flats and solves for the state of the estuarine system and the coastal ocean based on tidal forcing and wind stress. The model includes riverine inputs, although salinity effects are ignored. The non-linear system of governing equations of the model is solved iteratively at each time step. At the beginning of each of the iterations, the state of the system is examined to determine elemental designations for physics type. Any element that contains a node with an open channel depth of 0.5 m or less is assigned to be governed by the kinematic physics set (that is without the accelerations) described by Ip et al. (1998), while all other elements are assigned to be governed by the dynamic physics set (that is with local and Coriolis accelerations) described by McLaughlin et al. (2003). The reader is referred to these references for the standard governing equations and detailed numerics of the solution scheme.

Lagrangian particle tracking is performed using a 4th order Runge–Kutta (RK) scheme detailed in Section 3.2. Superimposed upon this is a random walk model of horizontal eddy diffusion (Fischer et al., 1979; Visser,