Estuary/Ocean Exchange and Tidal Mixing in a Gulf of Maine Estuary: A Lagrangian Modeling Study

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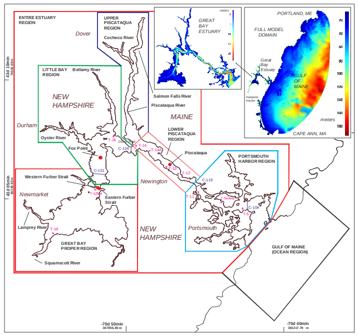
MOTIVATION

Estuaries are more and more 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. Predicting the transport and fate of these pollutants is an important challenge for environmental scientists and managers. 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 sediment-bound and suspended pollutants. The motivation for this study is to improve the understanding of these processes in these coastal systems and the capability that they have to handle the various pollutant streams.



MODEL DOMAIN

The domain of interest is the Great Bay Estuarine System and the coastal Gulf of Maine extending between Portland, ME, and Cape Ann, MA (shown on the left). The Great Bay system is a tidally dominated, shallow, well-mixed estuary characterized by extensive tidal flats in the upper reaches and low freshwater input (< 2% of the tidal prism). Currents up to 2 m/sec are observed in more constricted channels. The principal force balance is between the pressure gradient and the total bottom stress (Swift & Brown, 1983). This domain is discretized using a grid which consists of 73762 linear triangles with a characteristic length ranging between 3 m in the estuary and 4 km in the coastal ocean.

RESEARCH QUESTIONS

- **How strong are material exchanges within the estuarine system and between the estuarine system and the coastal ocean?**
- **What are the transport pathways?**
- **How does exchange and mixing vary with release location and timing relative to tidal phase?**
- **What are the spatially varying residence time scales within the estuary?**
- **How dependent are exchanges and pathways on the existence of the freshwater discharge, strength of the diffusivity and the spring/neap cycle?**

MODELING TOOLS

The vertically averaged finite element 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 local and Coriolis accelerations and riverine inputs, although salinity effects are ignored. The non-linear system of governing equations is solved iteratively at each time step (McLaughlin *et al.*, 2003).

Lagrangian particle tracking is performed by advecting passive particles in the simulated and interpolated Eulerian flow field at the end of each circulation model step. Superimposed upon this is a random walk model of horizontal eddy diffusion, which enables a particle-based statistical treatment of turbulent mixing (Proehl *et al.*, 2003). The particle tracking code is parallelized using MPI to allow massive particle releases (up to 1 million) on multiple CPU's.

SIMULATION SETUP

Forcing: **$M_2N_2S_2O_1K_1$ tidal constituents and Z_0 subtidal flow to define the coastal current according to Sept-Oct climatology**. Also, perpetual spring and perpetual neap tides with M_2 frequency to investigate the spring-neap effect range.

Bottom Stress: $C_D = 0.0025$ in the open ocean and 0.01 in the estuary with linear transition zone in between.

Diffusivity: None, **1m²/sec (low)** and 10 m²/sec (high), constant in time and space.

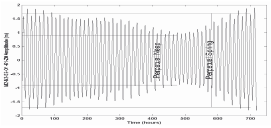
Simulation Length: 60 M_2 cycles with a 99.36 sec time step.

River Discharge: Off / **On (Mean yearly discharge for all rivers)**.

Number of Particles: 611814 (ocean), 23702 (estuary) with 50 m uniform spacing.

Synoptic Release Times: **Max-Flood**, High Tide, Max-Ebb, Low Tide

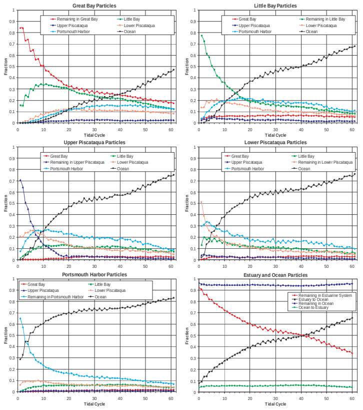
Note: Bold letters define the case presented in this poster.



PARTICLE EXCHANGE

To study the mixing characteristics within Great Bay and the exchange with the Gulf of Maine, the estuary and the neighboring coastal ocean are divided into six regions based on their hydrodynamic characteristics and potential ecological sensitivity (shown above). A seventh region encompassing the entire estuarine system is added to characterize the behavior of the estuary as a whole. Exchange predictions are summarized in the figures on the right showing the fraction of particles either remaining in their region of origin or exported into other regions (lines are color-coordinated with region outlines).

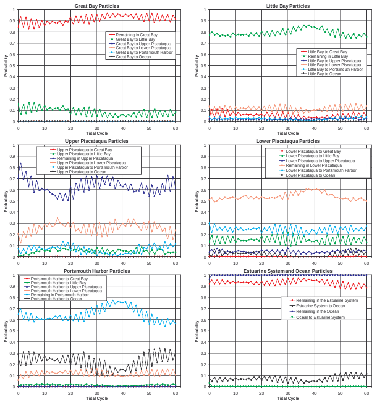
Plots show an overall seaward transport as indicated by the seaward neighboring domain receiving a larger fraction of particles than the landward neighboring domain for a given region. It is observed that about 68% of all the estuarine particles are exported into the ocean at the end of 60 M_2 cycles (black curve, lower right plot). The ocean to estuary exchange averages 6% (green line). The effect of the neap tides is shown by a dip (or bump) around the 40th cycle.



EXCHANGE PROBABILITY

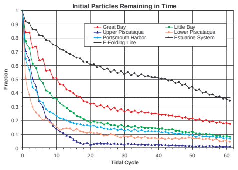
The exchange and mixing problem is characterized using a first-order Markovian approach (Thompson *et al.*, 2002). A transition probability matrix, whose elements are the probability of going from sub-region i to sub-region j (P_{ij}), is calculated using an integration time step of one M_2 tidal cycle. The requirement for the first-order Markov process is that each time step, the probability that a particle will either remain or move to a new sub-domain over the next time step only depends upon the sub-domain in which it presently resides and not on where it came from. This requirement is satisfactorily met, but not shown here.

Exchange probability estimations are presented as a function of simulation time in the figure on the right. It is observed that particles are most likely to stay in the domain they were last in after one M_2 cycle. Consistent with the particle exchange results, plots show a seaward tendency to the transition probabilities since the probability of a particle being found in a seaward neighboring domain is larger than the probability of a particle being located in a landward neighboring domain after one tidal cycle. This suggests estuarine flushing. The Great Bay and Little Bay sub-domains appear to be the most retentive regions owing to their constricted connections to the rest of the system and extensive tidal flats. Effects of the spring-neap and the diurnal cycles are also clearly seen (compare Portsmouth Harbor frame (lower left) with the elevation BC time series given above).



E-FOLDING TIME

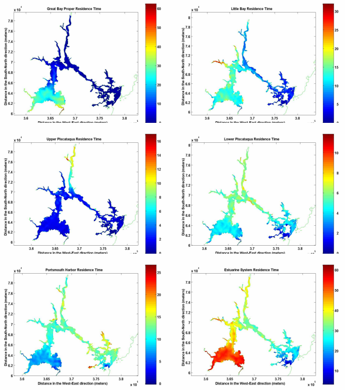
The-folding time, which is defined as the time required to decrease the initial number of particles in a region by a factor of *e*, is used as an approach to characterize the flushing time. Estimates, presented below, show that all sub-domains e-fold (shown as a horizontal black line) quickly in less than 10 days. The estuarine system as a whole also e-folds in roughly 30 days. Note that particles in the intermediate sub-domains may leave the region from either landward or seaward boundaries. Therefore, the e-folding times are not necessarily directly associated with the time it takes for the particles to permanently leave a region. This is not an issue for boundary domains such as Great Bay proper, the Upper Piscataqua and the entire estuarine system since particles can only leave these domains across seaward boundaries.



FLUSHING TIME MAPS

Another view of the residence time is obtained by asking how long it takes for a specific region to flush. This is visualized by constructing a map that displays the amount of time a particle spends within a specific region depending upon where it originated. These maps are plotted on the left for all estuarine sub-regions, plus the entire estuarine system. A 200x200m moving box average is applied to derive a smoother picture of the flushing time. The colorbar shows time in M_2 tidal cycle units.

For Great Bay proper (upper left panel), it is seen that particles which begin at the heart of this region spend anywhere between 10 (blue) and 40 (yellow) tidal cycles in residence there. It is also observed that particles that begin in the lower sections of the estuary (i.e., Lower Piscataqua, Portsmouth Harbor) almost never reside in Great Bay. Expectedly, the map for the entire system (lower right) shows increasing residence times as one moves landward. It is observed that particles originating in Great Bay proper spend an average of 50 cycles in the estuarine system before being flushed into the ocean, while Portsmouth Harbor particles are flushed into the Gulf of Maine relatively quickly (≤ 25 cycles).



FIRST PASSAGE TIME

Subdomain	Great Bay	Little Bay	Upper Piscataqua	Lower Piscataqua	Portsmouth Harbor
First Passage Time to the Ocean	*40 cycles*	*28.6 cycles*	*21.6 cycles*	*19.2 cycles*	*10.3 cycles*

The third approach that we take expresses the residence times by using the Markovian first passage time to the ocean of particles originating in various sub-domains. This method is a direct extension of the transition probabilities presented earlier. If we denote the first passage time from region i to region j as μ_{ij} and the transition probability as P_{ij}, then we have the standard relation:

$$\mu_{ij} = 1 + \sum_{k \neq j} P_{ik}\mu_{kj}$$

If we let $j = 6$ be the ocean region and $i = 1$ through 5 the estuarine regions, we then have 5 equations with 5 unknowns to calculate μ_{16} through μ_{56}. The estimations obtained this way are shown above. The first passage time of 40 M_2 cycles obtained for Great Bay proper sub-region agrees well with the predictions by Brown and Arellano (1979) who estimated flushing times on the order of 53 cycles for a particle entering at the head of the estuary.

OVERALL PARAMETER EFFECTS

- The particle release time has an overall bi-modal effect with low tide and maximum-flood releases causing more retention than high tide and maximum-ebb releases, especially in shorter time scales (≤ 20 M_2 cycles). This effect is found to be dependent on region geometry.
- The introduction of a low diffusion (1 m²/sec) considerably increases the mixing and exchange in an out of the estuary compared to the non-diffusive case. Increasing the strength of the diffusion tenfold (10 m²/sec) does not yield a substantial increase in the overall exchange characteristics except in sub-domains such as Great Bay proper, where exchange processes are dominated by diffusive processes due to weaker tidal currents.
- Addition of river discharge into the estuary increases the exchange in the upper reaches such as Great Bay and Upper Piscataqua by roughly 10%, but yields little or no increase in other regions.
- Perpetual spring simulation shows considerable increase in the mixing and exchange over the perpetual neap simulation (36.5 cycle e-folding versus >60 cycle e-folding respectively), confirming the important role that the tidal amplitude plays in the flushing of the estuary.

CONCLUSIONS

- The Lagrangian modeling experiments described here employ a useful set of tools which are able to address the research questions posed for the Great Bay Estuarine system.
- The results show that the first-order Markov Chain approach is likely a very useful framework for understanding estuarine mixing and exchange processes.
- The latest advances in computer and modeling technology provide very valuable tools that allow the researchers to do Lagrangian or IBM (Individual Based Model) experiments using a large number of particles. These experiments hold great promise in ecosystems modeling.

FUNDING

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