Continental Shelf Research 97 (2015) 7–20

Contents lists available at ScienceDirect

Continental Shelf Research

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

Controls on residence time and exchange in a system of shallow coastal bays

I. Safak [a,*], P.L. Wiberg [a], D.L. Richardson [a], M.O. Kurum [b]

[a] Department of Environmental Sciences, University of Virginia, 291 McCormick Rd, Clark Hall, Charlottesville, VA 22904, USA
[b] W.F. Baird & Associates, 1267 Cornwall Rd, Suite 100, Oakville, Ontario, Canada, L6J 7T5

ARTICLE INFO

Article history:
Received 28 July 2014
Received in revised form
18 January 2015
Accepted 21 January 2015
Available online 7 February 2015

Keywords:
Residence time
Shallow bays
Coastal lagoons
Lagrangian particle tracking
Hydrodynamic modeling
Virginia Coast Reserve

ABSTRACT

Patterns of transport and residence time influence the morphology, ecology and biogeochemistry of shallow coastal bay systems in important ways. To better understand the factors controlling residence time and exchange in coastal bays, a three-dimensional finite-volume coastal ocean model was set up and validated with field observations of circulation in a system of 14 shallow coastal bays on the Atlantic coast of the USA (Virginia Coast Reserve). Residence times of neutrally buoyant particles as well as exchange among the bays in the system and between the bays and the ocean were examined with Lagrangian particle tracking. There was orders of magnitude variation in the calculated residence time within most of the bays, ranging from hours in the tidally refreshed (repletion) water near the inlets to days–weeks in the remaining (residual) water away from the inlets. Residence time in the repletion waters was most sensitive to the tidal phase (low vs. high) when particles were released whereas residence time in the residual waters was more sensitive to wind forcing. Wind forcing was found to act as a diffuser that shortens particle residence within the bays; its effect was higher away from the inlets and in relatively confined bays. Median residence time in the bays significantly decreased with an increase in the ratio between open water area and total area (open water plus marsh). Exchange among the bays and capture areas of inlets (i.e., exchange between the bays and the ocean) varied considerably but were insensitive to tidal phase of release, wind, and forcing conditions in different years, in contrast to the sensitivity of residence time to these factors. We defined a new quantity, termed shortest-path residence time, calculated as distance from the closest inlet divided by root-mean-square velocity at each point in model domain. A relationship between shortest-path residence time and particle-tracking residence time provides a means of estimating residence time over an entire model domain.

1. Introduction

Physical processes in coastal waters, including transport of water parcels and associated dissolved and particulate materials, are essential components of water quality, nutrient availability, contamination, and fate of flora and fauna (Kim et al., 2010). Therefore, temporal scales of transport, such as particle residence time, and their spatial variation within coastal waters, are essential in the evaluation of the physical controls on coastal ecosystems together with temporal scales of chemical and biological processes, and have significant influence on the health of coastal ecosystems (Anderson et al., 2003; Zhang et al., 2010; Lee et al., 2011). Residence time determines the time these processes act on water and therefore affects the vulnerability of coastal bay systems to pollutants and the survival of seagrass (Orfila et al., 2005). Patterns of residence time reflect transport and mixing processes in coastal systems, such that regions with short residence times undergo rapid exchange with surrounding waters while regions with long residence times are relatively isolated hydrodynamically, biologically, and biogeochemically. As a result, for example, benthic primary producers tend to dominate in areas with short residence times while phytoplankton dominate in areas with long residence times (Valiela et al., 1997). Transport and mixing processes are also responsible for exchange of water parcels with different chemical and biological content among bays in shallow coastal bay systems. Therefore, patterns of residence time and exchange in shallow coastal bay systems have significant practical importance as they provide coastal managers with a preliminary evaluation of the possible impact of physical processes on ecological and biogeochemical drivers in these systems.

In shallow coastal bay systems such as the Venice Lagoon (Solidoro et al., 2004) and Virginia Coast Reserve (Fugate et al., 2006; McLoughlin et al., 2015), wind- and tide-induced circulation is among the major controls on particle residence times and,

* Corresponding author. Fax: +1 508 457 2310.
E-mail addresses: ilgar@virginia.edu (I. Safak), pw3c@virginia.edu (P.L. Wiberg), dlr2n@virginia.edu (D.L. Richardson), okurum@baird.com (M.O. Kurum).

http://dx.doi.org/10.1016/j.csr.2015.01.009

therefore, redistribution and availability of sediment, nutrients, seagrass, algae, etc. (Cucco and Umgiesser, 2006). Simple approaches to estimate residence time (e.g., the tidal prism method) do not account for spatial variations within bay systems or the fact that ocean water entrained into a bay during flood is not necessarily fully removed from the bay during the consecutive ebbs due to tidal asymmetries and mixing (Geyer and Signell, 1992). Therefore, assessment of water circulation patterns based on hydrodynamic models forced by realistic ocean conditions is essential. Accordingly, a fully nonlinear process-based model that accounts for three-dimensional (3-D) Lagrangian flow fields (e.g., Aikman and Lanerolle, 2004) was shown to be necessary for accurately estimating fluid and particle trajectories (Tian et al., 2009).

As a step toward evaluating the impact of hydrodynamics on ecological and physical processes in shallow coastal bay systems, a process-based circulation model is used herein together with two two-month-long field observations of water flow in a barrier island–lagoon–marsh system along the mid-Atlantic coast of the USA. The goals are to evaluate, within a comparative framework, the spatial patterns of residence times in bays with varying size, coastline geometry, and exchange capacity with the ocean, to investigate the controls on bay-to-bay differences in residence time, and to quantify exchange among these bays. The effects of tidal phase when particles are released, location of particle release, bay geometry, and different forcing conditions are considered, as are approaches for generalizing residence time estimates from particle tracking at a limited number of locations to maps of residence time over a whole system of coastal bays.

2. Study site

The Virginia Coast Reserve (VCR) extends about 100 km on the eastern shore of Virginia along the Atlantic side of the Delmarva Peninsula from Wallops Island at the north to the mouth of the Chesapeake Bay at the south (Fig. 1), and is one of the sites of the Long Term Ecological Research (LTER) program. The VCR is typical of many shallow coastal bay systems that lack a significant fluvial source of freshwater and sediment. Human impact on the system is relatively small which allows natural conditions to largely control system behavior (McGlathery et al., 2007). The bays in the VCR vary considerably in terms of size, geometry and connectedness to the ocean and the other bays and, therefore, provide a valuable range of conditions for comparative analysis. The system is bordered on the ocean side by 14 barrier islands that help us to enclose at least as many shallow bays. The bays are cut through by relatively deep tidal channels which are 5-m deep on average but exceed 10-m near inlets such as Great Machipongo Inlet; these channels connect the bays to the Atlantic Ocean through a series of relatively stable inlets (Fig. 1, Section 4.2). Shallow flats with depths averaging about 1-m below mean sea level (Table 1) comprise the majority of the bay bottoms. The bays are fringed by

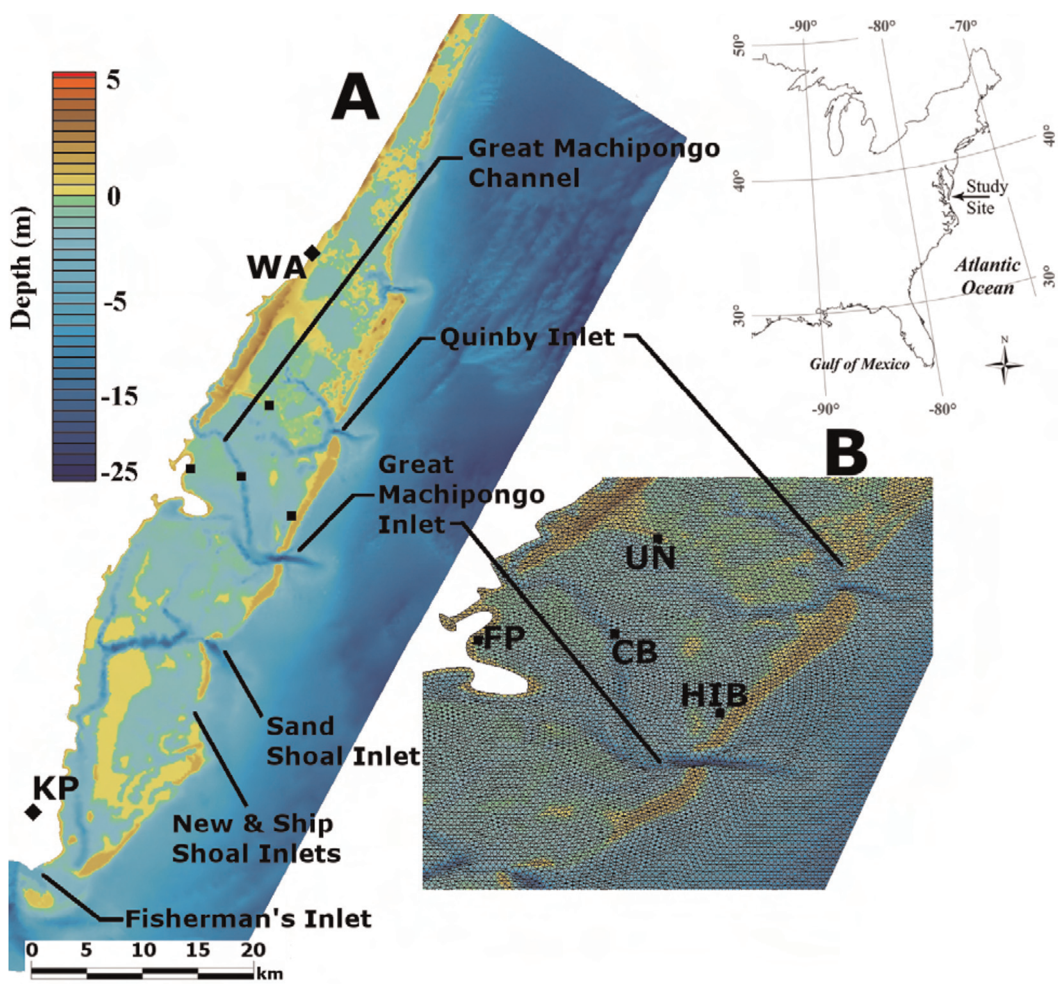

Fig. 1. (A) Bathymetry of the Virginia Coast Reserve and major inlets; (B) Hog Island Bay section of the unstructured model grid. HIB, UN, FP, and CB correspond to locations of measurements near Hog Island, Upshur Neck, Fowling Point, and close to the center portion of the bay; WA and KP correspond to locations of wind measurements at the Wachapreague and Kiptopeke stations of NOAA. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)