Estuarine, Coastal and Shelf Science xxx (2016) 1–11

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

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

Water age in the Columbia River estuary

Tuomas Kärnä*, António M. Baptista

NSF Science and Technology Center for Coastal Margin Observation & Prediction, Oregon Health & Science University, Portland, OR, USA

ARTICLE INFO

Article history:
Received 4 March 2016
Received in revised form
30 August 2016
Accepted 3 September 2016
Available online xxx

Keywords:
Residence time
Water renewal
Water age
Circulation model
Columbia river estuary

ABSTRACT

The concept of water age is applied to the Columbia River estuary to investigate water renewing time scales. Water age tracers were implemented in a three-dimensional circulation model. The model was run for a nine month period in 2012, covering both high and low flow conditions. In the lower estuary renewing water age ranges from roughly 20 h during high flow season (typically April–June) to 70 h during lowest river discharge (typically September–October). The age of riverine water is strongly dependent on river discharge. Dense oceanic waters, in contrast, are always relatively young in the estuary (roughly 20 h) although their age does vary with tidal range and river discharge. Compared to the main channels, water age tends to be larger in the lateral bays throughout the simulation period; this is especially true under low flow and neap tides conditions when water age can exceed 120 h in the bays. During low flow conditions a strong lateral circulation pattern emerges and leads to higher water age near Grays Bay. The maximal water age in the main channels is associated with mixed water mass (around 6–12 psu) located in front and above the salt wedge. The circulation model results are used to derive simple regression models that can be used to predict renewing water time scales without the need of a circulation model.

1. Introduction

Transport time scales of water in estuaries are important for understanding the fate of pollutants and assessing the likelihood of microbial activity (Wolanski, 2007; Crump et al., 2004; Lucas et al., 2009). The time scale of physical exchange of water is also one of the characteristic parameters of estuaries (Dyer, 1973; Jay et al., 1997; Jay et al., 2000; Valle-Levinson, 2010).

There are many methods for estimating transport time scales. Following Zimmerman (1988) the time scales can be divided into *integrative* and *local* time scales: Integrative time scales (henceforth box-model time scales) apply to the estuary as a whole and yield a scalar time scale for the entire system. They are often derived assuming a perfect and instantaneous mixing within the estuary volume. The simplest box model time scale is the flushing time, i.e. $T_F = V/Q$. T_F is based on the assumption that the entire estuary volume V is flushed by the net outward flux Q. The time scale is usually defined as the e-folding time, i.e. time required to decrease the concentration of initial water to $1/e$ of its initial value. Various box model estimates have been derived to take into account different physical exchange processes (see Andutta et al., 2014, and references therein), for example tidal exchange or estuarine circulation.

In contrast to the box model time scales, local time scales are defined for each point in the estuary. They provide detailed information of the past and/or future of the water masses at the said location. In the Constituent-oriented Age and Residence time Theory (CART, Deleersnijder et al., 2001; Delhez and Deleersnijder, 2002; Delhez et al., 2004; www.climate.be/CART) local residence time is defined as the time that a water parcel at location (x,y,z) and time t is *going to spend* in the estuary. Water age, on the other hand, is defined as the time that a water parcel at location (x,y,z) and time t *has spent* in the estuary.

Local time scales are usually computed with a numerical circulation model, and yield a four dimensional (x,y,z,t) time scale field. Residence time can be solved with an adjoint model that is run backwards in time (Delhez et al., 2004; Zhang et al., 2010; de Brye et al., 2012). The practical difficulty is that the adjoint model is not often available, and integrating the equations backwards in time may not be straightforward. Water age, on the other hand, can be solved with a conventional forward circulation model (Delhez and Deleersnijder, 2002). It does not however provide information of the future fate of the water masses.

Water renewal in estuaries is controlled by the exchange of water at the river and ocean boundaries, driven by the river

* Corresponding author.
E-mail address: karna@ohsu.edu (T. Kärnä).

http://dx.doi.org/10.1016/j.ecss.2016.09.001
0272-7714/

discharge and tides. Higher river discharge leads to a lower transport time scale due to stronger residual seaward flow. The influence of the ocean boundary, however, is more complex: Water renewal depends on the strength of estuarine circulation (i.e. density-driven bi-directional flow) and tidal dispersion processes at the ocean boundary (Warner et al., 2010; Shen and Haas, 2004), both of which are influenced by the tides. On the one hand, stronger tides imply stronger mixing, which tends to decrease estuarine circulation, leading into longer transport time scale. On the other hand, stronger tides imply larger tidal excursion and therefore shorter transport time scale. The balance between these competing processes depends on the characteristics of the estuary, and in some cases the forcing conditions.

In this work we use the water age method to study water renewal in the Columbia river estuary. The water age method was implemented in a hindcast circulation model that has previously been shown to capture the main characteristic of the system (Kärnä et al., 2015; Kärnä and Baptista, 2016). The simulation was carried out for a nine month period in 2012 (February 15 to November 15), covering both the river freshet and low flow conditions in the fall. To obtain a system-wide estimate of the water renewal time scale, we computed the *renewing water age* (RWA, de Brye et al., 2012), i.e. the water age that does not differentiate the origin of the waters. In addition, three specific water masses were simulated: riverine, oceanic and plume waters. The oceanic and plume waters, both originating from the estuary mouth, were differentiated by a salinity threshold.

We compare simulated water age values against box model time scales. Simple regression models are used to illustrate how water age depends on the estuary forcing conditions. These models only depend on the river discharge and tidal range, and can therefore be used as predictive tools in cases where running a three-dimensional circulation model is not feasible. We also derive a predictive regression model for the instantaneous RWA, that depends on mean estuary salinity in addition to riverine discharge. These regression models are used to generate long term averages of water age, partially relying on previous multi-annual hindcast simulations for the Columbia River estuary (Kärnä and Baptista, 2016).

2. Columbia River estuary

The Columbia River estuary is a mesotidal estuary characterized by strong river discharge and distinct forcing-dependent flow regimes (Hansen and Rattray, 1966; Jay and Smith, 1990; Geyer and MacCready, 2014). The contemporary annual mean discharge is 5500 m^3s^{-1} and spring freshet typically exceeds 10 000 m^3s^{-1} (Kärnä and Baptista, 2016; Kärnä et al., 2015; Chawla et al., 2008). The maximum daily tidal range varies from less than 1.7 m–3.8 m, and tidal currents can exceed 3 m s^{-1} near the mouth.

Due to strong river discharge the estuary is a rapidly flushing system, typical residence time being of the order of days or less. Despite the short residence time, there are several physical and microbial processes in the estuary that depend on the spatial or seasonal variability residence time. Such processes include the estuary turbidity maxima and biogeochemical processes therein (Prahl et al., 1998;), biogeochemical processes in the lateral bays and marshes (Smith et al., 2015), riverine plankton blooms during spring (Needoba et al., 2012), and estuarine *Mesodinium* spp. blooms in the fall (Peterson et al., 2013). Columbia River estuary is also subject to hypoxia and acidification during low flow season, associated to inflow of dense low-oxygen waters from the ocean (Roegner et al., 2011). To better understand the likelihood and magnitude of such processes, it is important to better characterize the temporal and spatial variability of water masses and their transport time in the system.

The Columbia River estuary is typically classified as a moderately to strongly stratified system during low flow conditions, shifting towards a salt wedge system as flows increase (Hansen and Rattray, 1966; Hughes and Rattray, 1980; Geyer and MacCready, 2014). Recently Kärnä and Baptista (2016) used the Geyer and MacCready (2014) classification scheme in conjunction with long term hindcast simulations to identify four dominant flow regimes that correspond to high/low river discharge and spring/neap tidal conditions. The four regimes, illustrated in Fig. 2, are strongly stratified (low flow, neap tides), partially mixed (low flow, spring tides), salt wedge (high flow, neap tides) and time dependent salt wedge (high flow, spring tides) regimes. This classification scheme is used herein to analyze the magnitude and spatial patterns of water age under different flow conditions.

3. Methods

3.1. Box model estimates

Following Andutta et al. (2014) the flushing time $T_F = V/Q$ can be generalized as:

$$T = \frac{V}{Q_R + Q_D}, \tag{1}$$

where Q_R and Q_D are the volume fluxes at the river and ocean boundary, respectively. Different box model time scale estimates usually differ in their definition of Q_D.

Using the Knudsen salt balance (Knudsen, 1900), results in $Q_D = Q_R S_E/(S_0 - S_E)$, where S_0 is the (constant) ocean salinity and S_E, $0 < S_E < S_0$ is the mean salinity in the estuary (Andutta et al., 2014). This choice leads into the well-known freshwater fraction time scale,

$$T_{frac} = \frac{S_0 - S_E}{S_0} \frac{V}{Q_R}, \tag{2}$$

which can be interpreted as the renewal time scale of the fresh water mass. While T_{frac} only depends on the river discharge, it does incorporate exchanges at the ocean boundary though the time-dependent mean salinity S_E.

Another choice is to use the salt balance by Fischer et al. (1979) which results in (Andutta et al., 2014)

$$T_{fi} = \frac{S_0 - S_{up}}{S_0 - S_{up} + S_E} \frac{V}{Q_R}, \tag{3}$$

where S_{up} is the up-estuary salinity (salinity at the upstream boundary).

The Land Ocean Interaction Coastal Zone (LOICZ, Swaney et al., 2011) model is obtained by setting $Q_D = Q_R(S_0 + S_E)/(S_0 - S_E)$ (Andutta et al., 2014):

$$T_{LO} = \frac{S_0 - S_E}{\frac{3}{2}S_0 - \frac{1}{2}S_E} \frac{V}{Q_R}, \tag{4}$$

Assuming that $S_{up} = 0$ (relevant for the Columbia river estuary) we get

$$T_{LO} < T_{frac} < T_{fi}. \tag{5}$$

We evaluate these time scales from the circulation model. In this work V is taken as the long term mean volume of the estuary as defined by the up- and downstream boundaries used for age tracers (see Fig. 1; $V = 2.1 \times 10^9$ m^3). Value $S_0 = 34$ psu is used for the ocean