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Research paper

A modelling study of residence time and exposure time in the Pearl River Estuary, China

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Abstract

This paper presents an investigation into two transport timescales, i.e. the residence time and exposure time, of a conservative matter in the Pearl River Estuary (PRE) using a depth integrated hydrodynamic-dispersion model. The model has been verified against field measured tidal and salinity data in three typical seasons, including the wet, dry and average rainfall seasons. The model predicted distributions of tidal wave amplitude and salinity level agree generally well with the field measurements. The model is then enhanced by including capabilities for calculating the two timescales. The numerical model predictions show that both the freshwater discharge and tidal water elevation affect significantly the values of residence time and exposure time. The return coefficient is found to be about 0.5. Using a regression analysis, an exponential function has beenderived to correlate the timescales to the freshwater discharge. In the dry season the average residence time and exposure time are up to about 6 days and 12 days, while in the wet season these values are reduced to 3 days and 5 days, respectively. Generally, in all three types of seasons, the exposure time is about two times greater than the residence time, which demonstrates that there is a high possibility for water to re-enter the PRE after leaving the estuary. Both the residence time and exposure time decrease as the initial water elevation increases, which indicates that a contaminant will stay in the PRE for a longer time if it is released at a low tide. The effects of monthly averaged wind forcing on the resident time and exposure time are also investigated.

Keywords: Residence time; Exposure time; Water exchange; Modelling; Pearl River Estuary

1. Introduction

In estuarine and coastal zones, water exchange usually plays an important role on the fate of various materials, including chemical and biological species. To describe this process, the concept of timescales has been introduced and applied to real coastal waters (Bolin and Rodhe, 1973; Takeoka, 1984; Deleersnijder and Delhez, 2007; Okada et al., 2011). One of widely used timescales is the residence time. It is defined as a time interval it is taken for a water parcel to reach the outlet, i.e. the time taken by a water parcel to leave the control domain, for the first time (Bolin and Rodhe, 1973; Takeoka, 1984; Zimmerman, 1988; Monsen et al., 2002). According to this definition, the residence time does not include the time interval spent by a water parcel when it re-enters the domain. Due to this limitation another timescale, namely the exposure time, has been introduced to measure the total amount of time spent by a water parcel in the control domain, which considering all subsequent re-entries in the domain (Monsen et al., 2002; Delhez et al., 2004, 2006).

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Whether the residence time, or the exposure time, is a more relevant timescale for expressing the time period a water parcel stays in a certain region has been debated (de Brauwere et al., 2011). Each timescale may relate to a property of water exchange, while the real conditions affecting the transport timescales are usually complex, especially for tidal estuaries where both freshwater discharge and tidal forcing play important roles.

This paper outlines a numerical model study to investigate the residence time and exposure time in the Pearl River Estuary (PRE), China. The effects of freshwater discharge, tidal flow and monsoon wind are taken into account in computing the two timescales. Section 2 is a brief introduction of the study site. Section 3 presents some details of the numerical model. In Sections 4 and 5, the model predicted residence time and exposure time are shown and analysed. Finally, the main conclusions are given in Section 6.

2. Study area

The Pearl River Estuary (PRE, also called Lingdingyang in Chinese) is one of the largest estuaries in China (see Fig. 1a). The total annual freshwater discharge of the Pearl River is about 330×10^9 m^3 and the total basin area is about 400,000 square kilometers (PRWRC, 1991; Zhang et al., 2011). During the past three decades, the rapid economic growth and urban development around this catchment have led to an excessive volume of waste water being released into the sea through this estuary. The surface area and volume of the PRE are about 2000 km^2 and 12×10^9 m^3, respectively. In the current study, the whole of the PRE and the adjacent coastal areas are included, with the numerical model domain being defined by 21°30′∼23°00′N and 112°30′∼115°30′E (see Fig. 1).

The freshwater discharged into the PRE accounts for about half of the total discharge of the Pearl River passing through four major entrances. As shown in Fig. 1 these four major entrances are located at the west bank inside the PRE, namely Hu-men, Jiao-men, Hongqi-men and Heng-men from north to south (Zhang et al., 2009). It is well known that the freshwater discharge has a large seasonal variation, with about 80% being in the wet season (from April to September) and about 20% in the dry season (from October to March) (Cai et al., 2004; Dong et al., 2004). Fig. 2 shows the distribution of monthly discharge passing through the four major entrances to the PRE based on the records obtained during the period from 1959 to 2004 (MEP-PRC, 2008). It has been observed that the mean tidal range varies between 0.8 and 1.7 m from the mouth to the head of PRE (Wong et al., 2003a; Lin and Liang, 1996; Zhao, 1990). The tidal cycle mainly follows a semi-diurnal mixed tidal regime but with daily variations, and among the tidal constituents M2 is the dominant component, followed by K1, O1 and S2 (Mao et al., 2004).

Diamonds: eight major entrances; triangles: sampling stations; solid circles: hydrodynamic stations from Admiralty Tidal Tables (1990); hollow circles: hydrodynamic stations from Mao et al. (2004); broken lines: boundary of the PRE.

3. Methods

3.1. Description of hydrodynamic model and dispersion model

In this study, an integrated hydrodynamic-dispersion model is used to predict the water elevation, velocity field and the distributions of tracer concentration and salinity. This model is based on the shallow water equations and depth integrated advection−diffusion equation, with the governing equations being written as the following (Sun and Tao, 2010):-

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=S_m \tag{1a}$$

$$\frac{\partial p}{\partial t}+\frac{\partial(\beta pU)}{\partial x}+\frac{\partial(\beta pV)}{\partial y}=fq-gH\frac{\partial \zeta}{\partial x}-\frac{gH^2}{2\rho}\frac{\partial \rho}{\partial x}-\frac{gp\sqrt{p^2+q^2}}{H^2C_z^2}+\frac{\tau_{sx}}{\rho}+\varepsilon\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right) \tag{1b}$$

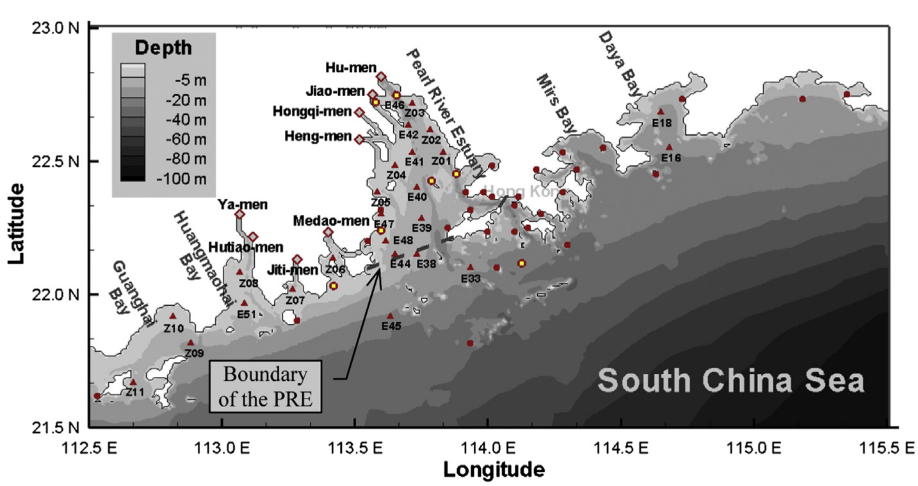

Fig. 1. Topography of the Pearl River Estuary and the adjacent coastal areas.