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The influence of surface wave on water exchange in the Bohai Sea

Weijun Guo [a,b,*], Guoxiang Wu [c], Bingchen Liang [d], Tiaojian Xu [b], Xiaobo Chen [e], Zhiwen Yang [f], Mingxiao Xie [f], Meirong Jiang [g]

[a] College of Environmental Sciences and Engineering, Dalian Maritime University, Dalian 116026, China
[b] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116023, China
[c] College of Engineering, Ocean University of China, Qingdao 266100, China
[d] Shandong Province Key Laboratory of Ocean Engineering, Ocean University of China, 238 Songling Road, Qingdao 266100, China
[e] School of Investment and Construction Management, Dongbei University of Finance and Economics, Dalian 116025, China
[f] Key Laboratory of Engineering Sediment, Tianjin Research Institute for Water Transport Engineering, M.O.T., Tianjin 300456, China
[g] Offshore Oil Engineering Co., Ltd., Tianjin 300451, China

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ABSTRACT

A three-dimensional wave-current coupled modeling system has been applied to analyze the water motions for the Bohai Sea and its adjacent waters. Two different methods of estimating the water exchange through the Bohai Strait have been employed, consisting of particle tracking and passive dye. The objectives of this study are to account for the surface wave role in the water exchange processes between the Bohai Sea and the outer waters, to test the response of the flushing characteristics of the Bohai Sea to different aspects of wave actions, and to obtain a quantitative and qualitative estimate of the half-life time under different experiment conditions. By comparing the simulations of water exchange with or without wave-current interactions, we find that waves can improve the Bohai Sea vertically mean water exchange capability, with more obvious enhancements for the surface layer where concentrated actions function. A series of numerical experiments indicate that turbulent kinetic energy from wave dissipation is the major positive influence, while wave-dependent surface stress, radiation stress, and Stokes drift have a minor effect. These results suggest that wave-driven mixing should be considered in the Bohai Sea water exchange processes, preferably using a half-life model based on concentration advection-diffusion model.

1. Introduction

Water exchange between shallow sea and the open ocean is a key process which affects the distribution and fate of nutrients, pollutants and sediments. Since there are various dynamic phenomena in coastal seas, different definitions and methods for the calculation of water exchange times have been presented. The flushing time concept is widely employed, defined as the time for a concentration to decrease to 1/e of its initial concentration (Takeoka, 1984; Andutta et al., 2013), analogous to the half-life time, i.e. time needed to reduce the concentration to 50% of that (Luff and Pohlmann, 1995; Liu et al., 2004). Due to the equivalency between tracking particles and solving a mass transport equation for a conservative substance (Dimou, 1992), the Lagrangian method is also capable for calculating the residence time (Marinone et al., 2011), which is the time taken for a water particle to cross the specified boundary. It remains unsolved faced with how to reasonable distribution of particle distribution in space, especially for the unstructured mesh.

Huthnance (1995) gave preliminary assessment of various influential processes contributions to water exchange at the ocean margin according to scale analysis. Tides, winds and density differences are the principal agents for the exchange of water between the shallow coastal waters and the outer offshore zone (Guyondet et al., 2005; Safak et al., 2015). Delpey et al. (2014) adopted a three-dimensional wave-current model to investigate wave-induced circulation in a small estuarine bay and its influences on freshwater exchange with the inner shelf, concluding that the effect of the surf zone current on the bay flushing time is larger than that of wind. However, wave-driven significance (dominant in the surf zone) in the marginal sea has not yet been fully analyzed on the basis of the estimation that the time scale of water renewal time is much longer than the wave period. Recent studies suggest that smaller scales surface waves can yield a series

* Corresponding author at: College of Environmental Sciences and Engineering, Dalian Maritime University, Linghai Road 1, 116026 Dalian, China.
E-mail address: gwj5268@126.com (W. Guo).

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of significant contributions to water dispersion (Jones and Monismith, 2008), one of which is the Stokes drift. McWilliams and Restrepo (1999) pointed out that wind-driven current in the presence of Stokes drift should be modified by the addition of so-called vortex forces and wave-induced advection. Other effects from waves to currents include radiation stress gradients, wave dissipation as a source term in the energy equation, the effective surface drag coefficient varied with the wave age, and the modified bottom frictions (Davies and Lawrence, 1994). Jordá et al. (2007) stated that the main effect of waves on current structure is through the modification of the wind drag, and the Stokes drift also played a role due to its spatial and temporal characteristics. Numerical model demonstrated that wave breaking was overwhelmingly dominant factor for the circulation and flushing of Ningaloo throughout the whole year (Taebi et al., 2012). The inclusion of radiation stress in the momentum equation could produce an excess flow in the same order of magnitude as the one produce by considering a sea-state dependent wind stress formulation (Osuna and Monbaliu, 2004). When the effect of bottom friction are taken account may act equally strong on the mean current, and the friction-dependent wave-induced mean Eulerian current is even more larger than the Stokes drift for idealized shelf topography (Weber and Drivdal, 2012). By using wave-current model to investigate water exchanges, Delpey et al. (2014) regarded wave as a positive factor, while Malhadas et al. (2010) gave an opposite perspective of residence time in Óbidos Lagoon. The distinct contradiction reflects that a comprehensive analysis of these aspects of wave motion on water exchange processes is required to clarify their relative importance.

The Bohai Sea is a shallow, semi-enclosed marginal sea of the West Paciffic Ocean, with east-west width about 300 km and north-south length about 550 km and an area of 77,000 km^2. Surrounded by the mainland and Liaodong peninsula, it has the sole passage in the east connecting to the outer Yellow Sea, the Bohai Strait. The Bohai Sea is shallow with 95% of the area having a depth of <30 m, and an average water depth of 18.7 m. Many potential or actual sources of pollution are located around the Bohai Sea, such as Hongyanhe nuclear power plant, dotted harbors, large industries, oil platforms, waste water treatment plants, etc. As a result, the Bohai Sea is a particularly vulnerable area due to the different types of potential spills and to its semi-enclosed nature. Therefore, new scientifically based tools for adequate response and coastal management are specially needed. The time scale for the renewal of the Bohai water masses has been an issue with different views, ranging from a few months to several decades (Qiao, 2012). It is normal for the large-scale flows vary interannually, and the shorter time scale circulation also shows large variability (Huthnance et al., 2002). While a wide range of hydrodynamic studies have been carried out to investigate the Bohai Sea environmental problems, there is less information on comprehensively evaluation of water exchange timescales due to various dynamic factors.

In the Bohai Sea the tidal movement from the Yellow Sea propagates through the Bohai Strait is one of the prominent hydrodynamic processes. Huang et al. (1999) investigated baroclinic circulation in the Bohai Sea due to seasonal density variations, finding that inflow was mainly confined to a narrow passage in the northern Bohai Strait, but the outflow was weak in the rest of the strait. Based on half-life water quality model, Wei et al. (2002) pointed out that there were evident regional variations for exchange ability distributed in different areas. Laizhou Bay has the highest exchange ability, while Liaodong Bay, especially in the northwest part, has the lowest one. Hainbucher et al. (2004), using a three-dimensional, prognostic baroclinic hydrodynamics model, calculated turnover times and taken into account comprehensive environmental conditions, such as river runoff, wind, tides and thermohaline effects except surface waves. By calculating water age of Yellow River in the Bohai Sea, Liu et al. (2012) found that tidal forcing was the dominant role for water renewal in the Bohai Sea, followed by the wind forcing. Wave actions significantly impact on the spatial distribution of suspended sediment in the Bohai Sea (Wang et al., 2014) and temperature pattern in the Yellow Sea (Zhang et al., 2011), so it is of considerable reason to investigate their impacts on water exchange processes with the outer open waters.

This paper presents results of a numerical study undertaken at the Bohai Sea, China, with the purpose to evaluate the role of surface waves in different aspects on the Bohai water exchange capacity. The paper is structured as follows: In Section 2 the water exchange model framework is described, which employs a third-generation wind wave model (SWAN version 40.85) and a three dimensional hydrodynamic model (SELFE version 3.1dc) to offer transport filed incorporating wave-current interactions. The influences of the variation of the surface wave on the water half-life time and concentration of passive material are examined in Section 3, and the conclusions are presented in Section 4.

2. Methodology

2.1. Coupled current-wave model SELFE-SWAN

The numerical model system is employed with the purpose of simulating the hydrodynamics and water exchange processes in coastal regions under the effect of winds, tides and waves. The core current model of the system is built based on SELFE (Semi-implicit Eulerian–Lagrangian Finite Element), an open-source community-supported modeling system, based on unstructured grids, designed for the effective simulation of 3D baroclinic circulation across river-to-ocean scales (Zhang and Baptista, 2008).

In a Cartesian frame, the continuity equation can be written as:

$$\nabla\bullet\mathbf{u}+\frac{\partial w}{\partial z}=0 \tag{1}$$

The 3D Reynolds momentum equations are:

$$\frac{\partial\eta}{\partial t}+\nabla\bullet\int_{-h}^{\eta}\mathbf{u}dz=0 \tag{2}$$

$$\frac{D\mathbf{u}}{Dt}+\nabla\bullet\int_{-h}^{\eta}\mathbf{u}dz=-f\mathbf{k}\times\mathbf{u}-\frac{1}{\rho_0}\nabla p_A-\frac{g}{\rho_0}\int_{z}^{\eta}\nabla\rho d\zeta+\nabla\bullet(\mu\nabla\mathbf{u})-g\nabla\eta+\frac{\partial}{\partial z}\left(\nu\frac{\partial\mathbf{u}}{\partial z}\right)+R_s \tag{3}$$

where $\mathbf{u}=(u,v)$ is the horizontal velocity, w is the vertical velocity, η is the surface elevation, h is the still water depth, $\nabla=(\partial/\partial x,\partial/\partial y)$ is the horizontal gradient operator, g is the gravitational acceleration, k is a unit vector of the z-axis (pointing vertically upward), f is the Coriolis factor, ν and μ are the vertical and horizontal eddy viscosities respectively solved from turbulence closure schemes, ρ_0 is a reference water density, and p_A is the atmospheric pressure. The formulations of radiation stress term R_s we adopted were proposed by Mellor (2008). Despite of some controversy to this formulation, it should be noted that recent numerical studies have shown the validation of Mellor (2008) formulation (Kumar et al., 2011; Sheng and Liu, 2011; Liu and Sheng, 2014; Guo et al., 2014). So, we think employing Mellor (2008) formulation in the wave-current coupled model is feasible.

The model Simulating WAves Nearshore (SWAN; Booij et al., 1999), a phase-averaged wave model that solves transport equations of wave action density, is employed to provide the surface