Journal of Marine Systems 158 (2016) 140–164

Contents lists available at ScienceDirect

Journal of Marine Systems

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

Analyses of intermittent mixing and stratification within the North Passage of the Changjiang (Yangtze) River estuary, China: A three-dimensional model study

Xiang Pu [a], John Z. Shi [a,*], Guo-Dong Hu [b]

[a] State Key Laboratory of Ocean Engineering, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, 1954 Hua Shan Road, Shanghai 200030, China
[b] Survey Bureau of Hydrology and Water Resources of the Changjiang River Estuary, Changjiang Water Resources Commission, Shanghai 200136, China

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form 19 February 2016
Accepted 23 February 2016
Available online 3 March 2016

Keywords:
Mixing
Stratification
Potential energy anomaly
Intermittent
Changjiang River estuary

ABSTRACT

The TELEMAC-3D, incorporating a stability function, and the potential energy anomaly equation (ϕ-equation), are used to analyze neap-spring tidal and intratidal variability of intermittent mixing and stratification within the North Passage of the Changjiang (Yangtze) River estuary in the wet season. Eight terms in the ϕ-equation are used to examine physical mechanisms and the relative importance of each term for the lower reach of the North Passage. As revealed by the gradient Richardson number (Ri), the Simpson number (Si) and the potential energy anomaly (ϕ), weak mixing and persistent stratification appear on a neap tide, while strong mixing and periodic stratification on a spring tide within the main channel in the middle and lower reaches of the North Passage. The landward subtidal flow is much stronger on a neap tide than that on a spring tide. Within the main channel in the lower reach, large magnitude of *longitudinal ϕ-advection* (A_u) reflects the important effect of saltwedge movement on stratification. Large magnitude of *lateral ϕ-advection* (A_v) may be enhanced by large lateral gradient of ϕ due to the complex bathymetry and artificial structures. Both *longitudinal* (A_u) and *lateral ϕ-advections* (A_v) are temporally and spatially intermittent. Large *longitudinal depth-mean straining* (B_u) overlays the combined effect of *tidal straining*, *circulation* and river discharge. Large *lateral depth-mean straining* (B_v) is generated by large lateral density gradient interacting with the shear flow. The magnitude of *integrated vertical turbulent buoyancy flux* (E) mainly depends on *tidal stirring* at the bottom, while *wind stirring* at the surface and *shear instability* at the pycnocline are secondary contributors. The magnitudes of the other physical mechanisms including *longitudinal non-mean straining* (C_u), *lateral non-mean straining* (C_v) and *vertical advection* (D) are relatively smaller than those above. Neap-spring tidal variability of mixing and stratification mainly results from combined effect of three principal physical mechanisms, i.e. *tidal stirring*, *longitudinal* (B_u) and *lateral depth-mean strainings* (B_v). Intratidal variability of mixing and stratification is apparent on a spring tide. It seems that Advection, Straining and Stirring Induced Periodic Stratification (ASSIPS), rather than Advection and Straining Induced Periodic Stratification (ASIPS) and Straining Induced Periodic Stratification (SIPS), controls intratidal variability of mixing and stratification within the North Passage.

1. Introduction

1.1. Basics

The physical properties of mixing and stratification in tidal estuary, which are significant in both estuarine oceanography and hydraulics, have been considered by a number of workers ever since Fleming (1816). Mixing and stratification in an estuary exhibit apparent temporal variability, including seasonal variability due to the river discharge (e.g. Bowden and El Din, 1966; Bowden and Gilligan, 1971; Pritchard, 1952 and Pu et al., 2015), neap–spring tidal variability (e.g. Bowden, 1967; Haas, 1977; Geyer and Farmer, 1989; Jay and Smith, 1990; Uncles and Stephens, 1990; Nunes Vaz and Simpson, 1994; and Li and Zhong, 2009), and intratidal variability due to tidal straining (e.g. Simpson et al., 1990, 1993; Nepf and Geyer, 1996; Peters, 1997; Geyer et al., 2000; Simpson et al., 2002; Souza et al., 2008; Li et al., 2010; and Pu et al., 2015).

Spring–neap variation of the estuarine circulation is closely related to the variation of the stratification, which was first reported by Geyer and Cannon (1982), according to MacCready and Geyer (2010, 3rd paragraph, p. 52). On the one hand, circulation responds to temporally varying mixing and stratification. For example, Geyer and Cannon (1982) find strong circulation on a neap tide and weak circulation on

* Corresponding author. Tel.: +86 21 62933027.
E-mail address: zshi@mail.sjtu.edu.cn (John Z. Shi).

http://dx.doi.org/10.1016/j.jmarsys.2016.02.004
0924-7963/

a spring tide at the entrance to Puget Sound, USA. This results from neap–spring tidal variability of mixing. Similar finding was revealed in other different estuaries (e.g. Geyer et al., 2000; Uncles and Stephens, 1990). On the other hand, circulation could in turn persistently strengthen stratification and weaken mixing (e.g. Pu et al., 2015; Simpson et al., 1990).

To quantitatively analyze the physical mechanisms contributing to mixing and stratification in an estuary, Simpson (1981) uses the potential energy anomaly (ϕ), which represents the mechanical energy required to bring about complete mixing. Van Aken (1986) incorporates the effect of *straining* into the potential energy anomaly equation (such a mechanism is originally termed as *differential advection* in the literature). From a viewpoint stimulated by laboratory experiments on the interaction of density currents and vertical mixing (Linden and Simpson, 1986), Simpson et al. (1990) address the question of freshwater-induced stratification and derive a one-dimensional ϕ-equation of the growth and decay of stratification based on previous heating-stirring model, which includes the contributions of four different physical mechanisms, i.e. *tidal straining*, *circulation*, *tidal stirring* and *wind stirring*.

However, mixing and stratification in an estuary are three-dimensional due to the complex bathymetry and cannot be fully understood by a one-dimensional ϕ-equation derived in Simpson et al. (1990). For example, Simpson and Souza (1995) suggest that *cross-shore tidal straining* is a contributor to stratification in the Rhine ROFI. Ralston and Stacey (2005) reveal that differential advection of salinity front induced lateral circulation could significantly affect salinity budget in an estuary. A number of studies further reveal that lateral advection has important influence on dynamical balance in an estuary (e.g. Scully and Friedrichs, 2007; Scully et al., 2009). Lateral advection may also be an important contributor to mixing and stratification in an estuary (Lacy et al., 2003). Therefore, it is desirable to develop a three-dimensional ϕ-equation. After Simpson et al. (1990); de Boer et al. (2008) derive a three-dimensional ϕ-equation based on the Reynolds averaged advection–diffusion equation for density. Using the dynamic equations for potential temperature and salinity, the continuity equation and an equation of state for the potential density, Burchard and Hofmeister (2008) also derive a three-dimensional ϕ-equation and then apply it to an idealized estuary. Hofmeister et al. (2009) further apply it to the Limfjord in Denmark and have found that the stratification and destratification processes are a complex interaction of *differential advection*, *heating* and *turbulent mixing* in the central Limfjord. Wang et al. (2011) derive a three-dimensional ϕ-equation based on density transport equation and its integrated form. This ϕ-equation is then applied to a macrotidal saltwedge estuary, the San Francisco Bay, in order to understand mixing, stratification and the development of saltwedge. Similar studies have been reported from many estuaries (e.g. Basdurak et al., 2013; Howlett et al., 2011; Lian and Liu, 2015; Marques et al., 2010 and Purkiani et al., 2015).

Most notably, using five terms in the ϕ-equation (Burchard and Hofmeister 2008, Eq. (14), p. 681), Purkiani et al. (2015) examine stratifying processes in a tidal energetic, weakly stratified inlet in the Wadden Sea and find that *lateral straining* is much stronger within the main channel than that within the southern shoal, consequently leads to stratification during flood tide within the main channel.

As discussed by Warner et al. (2005), a three-dimensional numerical model is important for modeling an estuary. While using a one-dimensional model, two common failures are "runaway stratification" and "independent longitudinal density gradient" (e.g. Monismith and Fong, 1996; Nunes Vaz and Simpson, 1994). Three-dimensional simulation could solve these problems by using the higher order turbulence closure scheme and considering longitudinal salinity gradient as a dependent variable. Furthermore, the proper use of a turbulence closure scheme is of great importance to three-dimensional modeling of an estuary (e.g. Li et al., 2005). Warner et al. (2005) simulate mixing and stratification in an estuary and find out that results vary slightly between different two-equation turbulence closure schemes including k-ε, k-Ω, and k-l. In addition, a gradient Richardson number-dependent vertical mixing parameterization to realistic estuary modeling is critical in understanding the impact of buoyancy effect (e.g. Burchard and Baumert, 1998; North et al., 2004).

1.2. The Changjiang (Yangtze) River estuary

The Changjiang River estuary is a mesotidal estuary (Figs. 1 and 2). The discharge is very large and intermittently variable (Fig. 3). The maximum value could reach up to about 5×10^4 m^3·s^{-1} in the wet season, while the minimum value about 1×10^4 m^3·s^{-1} in the dry season. Mixing and stratification in the Changjiang River estuary are rather complicated due to the combined effect of river discharge, tide, circulation, wind, complex bathymetry, and artificial structures (e.g. Gao et al., 2009; Lu and Shi, 2007; Pu et al., 2015; Rong and Li, 2012; Shi et al., 2010a, b; Shi and Lu, 2011; Wu et al., 2011; Ge et al., 2012).

Numerous numerical studies have been carried out in the Changjiang River estuary, including the Changjiang River plume (e.g. Bang and Lie, 1999; Chang and Isobe, 2003; Chen et al., 2008; Lu and Shi, 2007; Moon et al., 2010; Rong and Li, 2012; Shi and Lu, 2011; Shi et al., 2010a; Wu et al., 2014; Wu et al., 2011; Xuan et al., 2012 Zhu et al., 2015; and Yuan et al., 2016), circulations (Zhu et al., 2004a,b,c; Wang et al., 2010), saltwater intrusion (e.g. An et al., 2009; Qiu and Zhu, 2013a; Wu and Zhu, 2010; Wu et al., 2010 and Xue et al., 2009; Wu et al., 2006; Qiu et al., 2012; Li et al., 2011, 2014; Zhang et al., 2011), hypoxia (Zhu et al., 2016) and fine sediment transport (e.g. Hu et al., 2009; Ma et al., 2013; Qiu and Zhu, 2013b; Li et al., 2015; Shi, 2010; Song and Wang, 2013 and Wan et al., 2014).

However, the fundamental physics of mixing and stratification is still challenging in the Changjiang River estuary. No detailed numerical study has been performed to quantitatively understand the temporal and spatial variability of mixing and stratification, as well as the relative importance of each of their physical mechanisms in the Changjiang River estuary. Due to the complex bathymetry and the dike–groyne systems, numerical modeling of the North Passage in the Changjiang River estuary (hereinafter the North Passage) requires a high resolution unstructured triangle mesh. Therefore, a three-dimensional hydrodynamic model (TELEMAC-3D) is used in this study.

The objective of this paper is to quantitatively understand the temporal and spatial variability of mixing and stratification and their physical mechanisms within the North Passage. Section 2 describes the setup and implementation of the TELEMAC-3D and sensitivity and uncertainty analyses. Section 3 shows calibration and validation of the model. Section 4 discusses the temporal and spatial variability of mixing and stratification and the relative importance of each of their physical mechanisms within the North Passage.

2. Numerical model and other calculations

2.1. Model description

The TELEMAC-3D solves the RANS (*Reynolds Averaged Navier–Stokes equations*) in the x (east oriented) and y (north oriented) axes based on the Boussinesq approximation on a finite element grid. The vertical momentum equation is calculated using hydrostatic pressure approximation.