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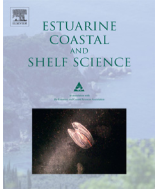

Modeling studies of the far-field effects of tidal flat reclamation on tidal dynamics in the East China Seas

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ABSTRACT

In recent decades, the reclamation of tidal flat carried out by the authorities around the Bohai Sea, Yellow Sea, and East China Sea (BYECS) has reached new heights as a consequence of significant economic expansion in the coastal areas. We are concerned that the tidal flat reclamation may have not only local but also far-field effects on tidal dynamics in the entire BYECS. Numerical study shows different tidal patterns due to tidal energy redistribution when tidal flats around the BYECS are removed, in which the tidal range and phase are changed, and the amphidromic points are displaced. Tidal flats provide storage and dissipation for tidal energy; the former is much more significant than the latter. Loss of these functions caused by tidal flat reclamation will induce a redistribution of the extra tidal energy. Furthermore, we show that far-field effects on tidal dynamics would be observed on the west coast of Korea following significant reclamation on the Chinese Jiangsu coast. In turn, reclamation on the west coast of Korea may generate the far-field effects on the Chinese coast. Reclamation in the BYECS can result in rise of tidal amplitude and onshore sediment transport. The former may enhance the coastal hazards such as storm surge, and the latter may result in severe siltation. Therefore, careful consideration must always be given to any proposed artificial changes to tidal flat, given the effects of these on both the local environment and further afield.

1. Introduction

Tidal motion is one of the major dynamical processes in the East China Seas (the Bohai Sea, Yellow Sea, and East China Sea, BYECS), where the tidal dynamics are quite complicated and the tidal ranges relatively large. Since 1970s, numerical methods have been applied to study the tidal dynamics in the BYECS (e.g. Guo and Yanagi, 1998; Kang et al., 1998; Bao et al., 2001). However, the wetting and drying (WAD) is always assumed to be a peripheral process due to the sparse model resolution. Therefore, the role of tidal flats in the tidal system of the BYECS has never been studied.

Hydrodynamic models with WAD simulation have already been applied to study estuarine process (e.g. Ip et al., 1998; Ji et al., 2001; Ertürk et al., 2002). The significance of the WAD process for coastal ocean systems has also been addressed by many researchers. For tidal dynamics, numerical experiments without the WAD process would either underestimate or overestimate the tidal elevation and tidal current (Zheng et al., 2003; Oey et al., 2007). In addition, Xue and Du (2010) found the WAD process enhances the mixing and entrainment processes near the estuary, which results in stronger tidal intrusions into the estuary. They also speculated that the WAD process can affect much larger areas than the inter-tidal zone, especially via river plumes that feed into coastal currents. Essentially, tidal flats in the numerical experiments without the WAD process had to be set to either water or land, both of which change the local geomorphology. However, in previous studies only the local- and regional-scale processes due to the local geomorphologic modification were examined (e.g. Picado et al., 2010; Min et al., 2011; Li et al., 2012). Hasegawa et al. (2011) found tidal energy extraction in the Minas Passage, Bay of Fundy would alter the tidal elevations and tidal currents throughout the Gulf of Maine. This is proposed as a "far-field" effect. Thus, we wondered if the tidal flat reclamation also has far-field effects on the tidal dynamics in the entire BYECS, although the total area of the tidal flats is rather small compared to that of the BYECS (less than 2% of the surface area).

The land reclamation carried out by the authorities around the BYECS has reached new heights as a consequence of significant economic expansion in the coastal areas. For example, in 2000 the Shanghai municipal government in China proposed to reclaim

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400 km^2 of tidal flats in the Yangtze River Estuary by 2010 (Li et al., 2004). Between 2004 and 2020, the Caofeidian Reclamation Project in the city of Tangshan, Hebei Province, northern Bohai Bay, planned to reclaim a total of 129.7 km^2 of tidal flats from the Bohai Sea (SOAPRC, 2009). Since 1995, Tianjin New Coastal Zone Project, located in the municipality of Tianjin, western Bohai Bay, has also reclaimed 265.5 km^2 of tidal flats from the Bohai Sea and the coastline has been pushed seaward 3.8–16.0 km (SOAPRC, 2009). Recently, the Chinese Central Government has approved a major project that will reclaim over 2000 km^2 of land including tidal flats along the Jiangsu coast by 2020 (Wang et al., 2011) and another 4400 km^2 in the Yellow River Delta are under discussion (SOAPRC, 2009). In 1991, South Korea embarked on the Saemangeum Reclamation Project to reclaim nearly 401 km^2 of land and tidal flats from the Yellow Sea (Son and Wang, 2009). Similarly, a 16 km^2 area of tidal flats in the Ariake Bay has been destroyed through the Japanese government-managed Isahaya Reclamation Project since the early 1990s (Hodoki and Murakami, 2006). The environmental response to those land reclamation projects has been studied by many researchers (e.g. Kang, 1999; Byun et al., 2004; Manda and Matsuoka, 2006), who showed that those projects changed the local hydrodynamics and resulted in pollution, contamination, siltation, and wetland losses. Between 1949 and 2002, reclamation has already turned approximately 12,000 km^2 of coastal wetland into industrial and farming lands, about 55% of the total coastal wetland in China (Cao and Wong, 2007). Table 1 indicates that the amount of coastal area annually reclaimed in China has been increasing as its Gross Domestic Product grown with a double digit rate since 2002, in order to satisfy the demand for land-use and to pursue economic profits and wealth accumulation. The morphology alteration of tidal flats will change the tidal energy dissipation generally dominated by friction in shallow water, where tidal currents are stronger than in deep seas as described by Le Provost and Lyard (1997). In this context, we are interested in investigating how this influence is extended to the entire basin due to the large-scale destruction of tidal flats around the BYECS. On the other hand, overtides and compound tides arise primarily from distortion of astronomical tides in shallow water, where the nonlinearities in the equations of motion are responsible for tidal asymmetry in rise- and fall-duration of water elevation, which may be manifested as an inequality in flood/ebb tidal current magnitudes (Nidzieko, 2010). An increase in flood tidal current may generate a net onshore sediment transport and results in a siltation; in opposite, an increase in ebb tidal current may induce a net offshore sediment transport and leads to coastal erosions. Thus, in this point of view, how the tidal flat reclamation influences on local environment and further afield will also be explored in this study.

To answer those questions, we establish a very-fine-resolution model that includes all tidal flats to study the tidal dynamics in the BYECS. The effect of tidal flat reclamation on tidal energy distribution and tidal asymmetry will be investigated using this model. In Section 2, a description of the numerical model is presented. The model results, following different treatments of the tidal flats, are described and discussed in Section 3. Finally, conclusions of this study are presented in Section 4.

2. Model description

The present study covers the area from 24°N to 42°N and from 116°E to 132°E, containing the seas bounded by the Chinese mainland, Korean peninsula, Kyushu Island, Ryukyu Islands, and Taiwan Island (Fig. 1). This area of approximately 1.22 million km^2 includes the Bohai Sea, Yellow Sea, and East China Sea. The Bohai Sea is China's inland sea, with an average depth of 18 m. The Yellow Sea is a semi-enclosed shallow sea located on the continental shelf, with an average depth of 44 m. The East China Sea is on the margin of the western Pacific Ocean, with a vast area of continental shelf in the west and deep troughs in the east. The average depth is 370 m, with the deepest point 2719 m in the Okinawa Trough. The East China Sea has the broadest continental shelf and the steepest continental slope in the world; water depth ranges from 200 m on the shelf to more than 9000 m east of the Ryukyu archipelago in the Pacific Ocean. Tidal flats in this region occur on a large scale, which is between 3 and 18 km in width and with gradient less than 1/1000. Tidal flats along the Chinese coast are of two types: the plain type and the embayment type, neither of which supplies sufficient fetch for wind/wave interaction due to the very gentle coastal slope; thus, the tidal flat coast is dominated by tidal process and is often associated with a large sediment supply (Wang and Zhu, 1994). However, the west coast of Korea differs from the Chinese coast in being subjected to a more-intense monsoon wind regime because of its exposed location; thus, it alternates between a tide-dominated process in summer and a wave-dominated process in winter (Yang et al., 2005). Detailed descriptions on hydrodynamics and sedimentation processes on the tidal flats in this region can be found in the literature (e.g. Chough et al., 2000; Wang et al., 2002).

Here we use the latest published Stony Brook Parallel Ocean Model (sbPOM) (Jordi and Wang, 2012), which is a parallel ocean modeling code based on the Princeton Ocean Model (POM). The latter is a simple-to-run yet powerful ocean modeling code used by the scientific community for a wide range of applications. We incorporate the WAD scheme (Oey, 2005, 2006) into the parallel model to make it suitable for a coastal region study. When the horizontal grid spacing is sparse or the time step is relatively long, the water surface may rapidly descend to be on or below the seabed during an external time step, so that the total water depth approaches zero or even becomes negative. To avoid this occurrence, a minimum water depth ($D_{\min}$) is given and the water elevation (ζ) is limited to

$$\zeta = \max(\zeta, -H + D_{\min}), \quad (1)$$

where H is the mean water depth and $D_{\min}$ is less than the minimum water depth (H_{dry}), below which the grid is considered dry. The WAD scheme is much more robust with a non-zero $D_{\min}$ if a large external time step or very sparse grids are used. This modification to the WAD scheme, with $D_{\min} = 0.01$ m and $H_{dry} = 0.05$ m, works well in the tidal simulation in the BYECS.

Table 1
The annually reclaimed coastal area (unit: km^2) in China* and China's Gross Domestic Product (unit: billion yuan)** and its growth rate† since 2002.

Year	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Area	20.33	21.23	53.52	116.62	112.94	134.25	110.00	178.88	135.99	139.55
GDP	12033.27	13582.28	15987.83	18493.74	21631.44	26581.03	31404.54	34090.28	40151.28	47288.16
Growth Rate	9.1%	10.0%	10.1%	11.3%	12.7%	14.2%	9.6%	9.2%	10.4%	9.3%

* Data obtained from State Oceanic Administration People's Republic of China (in Chinese). Available at http://www.soa.gov.cn/soa/hygb/hygb/A010904index_1.htm.
** Data obtained from National Bureau of Statistics of China. Available at http://www.stats.gov.cn/tjsj/ndsj/2012/html/C0201e.htm.
† Data obtained from National Bureau of Statistics of China. Available at http://www.stats.gov.cn/tjsj/ndsj/2012/html/C0204e.htm.